# Preliminary Agenda

## Meeting of the 'Forschungsausschuss' on GSI Heavy Element Program

## October 15th, 2004

Seminar Room Theory, 4th floor

10:00 Prospects for New Heavy Element Production at GSI (40 min talk 20 min discussion)

11:00 Future Program for the Study of the Chemistry of the Heaviest Elements (40 min talk 20 min discussion)

12:00 Lunch

13:00 Summary of the Proposed Hardware (40 min talk 20 min discussion)

14:00 Committee discussion and break

15:00 Question session with the Heavy Element group

16:00 Committee discussion

17:30 Meeting with the heavy element group to present initial conclusions

# The GSI Heavy Element Program

## Review and Proposal

**Prepared for the Meeting of the**
**Forschungsausschuss**
**on October 15, 2004**

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**and**

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# I. Contents and introductory remarks

This report serves as source of information on the achievements made at GSI in the field of heavy element research, obtained both from physical and chemical investigations. It should help to range in the results obtained in the past, the present situation in comparison with achievements made at other laboratories, and the planning of further improvements with respect to technical developments and financial possibilities. This report is prepared for the meeting of the Forschungsauschuss (Research Committee) of the Wissenschaftlicher Rat of GSI (Scientific Council) for evaluation of the GSI heavy element program on October 15, 2004. In addition to more general considerations concerning the GSI heavy element program, some detailed information is given in a number of attachments.

The presentation of the current program together with the experiences obtained during the last 30 years of experiments clearly shows that superheavy element research was always based on efforts to extend the limits of technical possibilities. Of these the increase of beam intensity and of the overall detection efficiency is the major contribution. These were the necessary goals in the past and they will be the same in the future.

The following outline of the report was prepared:

**Attachments**

A. SHIP – 2000, a proposal for the study of superheavy elements, GSI Report 99-02

B. Search for SHE using the hot fusion reaction $^{48}Ca + ^{238}U$
Proposal for the continuation of experiments at SHIP, August 2004

C. Active proposals and current research activities in SHE chemistry program

D. The TASCA (**T**rans**A**ctinide **S**eparator and **C**hemistry **A**pparatus) project

E. Steps towards an optimized LINAC, U. Ratzinger, February 2004

F. Most relevant publications based on SHIP experiments

G. Most relevant publications based on chemical experiments and theory

H. Chart of nuclei, September 2004, and Periodic Table

# II. What we achieved

## A. Studies at SHIP

SHIP was the first recoil separator for heavy ion reaction products worldwide. It was designed for separation of superheavy nuclei, which requires high transmission at high background suppression. First experiments started at the end of 1975. During the first years of operation auxiliary equipment was developed, among which the rotating target wheel synchronized to the beam macro-pulses and the position sensitive detector system are the most important. At that time the combination of these devices was unique. The range of measurable lifetimes was considerably broadened, down to microseconds due to separation of the reaction products in flight and up to hours due to the newly developed position-time correlation method.

After five years of development and testing, which resulted in the discovery of proton radioactivity and of about fifty new isotopes in the region of neutron deficient nuclei of elements at and below lead and close to N = 126 of elements above lead, the first new elements, bohrium, meitnerium, and hahnium were discovered in 1981, 1982, and 1984, respectively.

The cross-sections for the synthesis of the new elements continuously decreased, and a value of 10 pb was measured for the production of meitnerium. Theoretical estimates for the synthesis of elements beyond meitnerium gave rather pessimistic prognosis, both for cold fusion based on Pb or Bi targets as well as for hot fusion based on actinide targets. It was predicted that in the case of cold fusion an extra-push energy would be needed, which would result in high excitation energy of the compound nucleus and thus low cross-sections due to fission. In the case of hot fusion resulting in compound nuclei closer to the region of spherical superheavy nuclei at N = 184 strong shell effects and high and broad fission barriers are expected. However, the excitation energy of the compound nucleus is already high at beam energies close to the Coulomb barrier and a predicted enhancement of level density due to deformation already at low excitation energies would result in high probabilities for fission. Despite of this pessimistic prognosis technical developments were supported with an amount of about 40,000 DM per year, and a new high charge state injector was constructed, which was based on a 14 GHz ECR ion source and RFQ and IH-structure accelerator components. This upgrade was also needed for the ongoing electron-positron pair creation experiments at that time.

A relatively save extrapolation of measured cross-sections for the production of element 110 resulted in a value of 1.5 pb using the reaction $^{62}$Ni + $^{208}$Pb. During the years 1988 to 1993 the apparatus was improved so that a cross-section of 1 pb could be reached in 10 days instead of 100 days as necessary before. Simultaneously the background in the focal plane of SHIP was reduced and the stability of the whole system increased, so that experiments could run without personnel being present continuously. In detail a gain factor of 3.5 was achieved due to a higher beam current from the ECR source and an increase of the accelerator duty factor from 22 to 28 % (factor 1.3) becoming possible due to higher charge states of the projectiles from the ECR ion source. At SHIP we moved the target closer to the first quadrupoles (gain factor 1.5) and built a new larger detection system (80 mm × 35 mm) including new electronics for signal processing (gain factor 1.3). The detector resolution was improved to 18 keV (FWHM) for α particles and a 150 μm position resolution was achieved. By now

these values are best values in comparison with similar systems worldwide. For detection of escaping α particles or fission fragments a new detector box was built covering 85 % of the backward hemisphere of the stop detector. Positions of the implanted nuclei or positions from their decay are measured twofold, and two energy branches overlapping in the region of α particle energies result in redundant information for a save signal assignment. The area of the targets was considerably enlarged in order to reduce the background by avoiding scattering of the beam at the target frames. For the same reason, background reduction, another deflection magnet was installed behind SHIP.

The upgrade was finished in 1994 and the three elements darmstadtium, roentgenium, and element 112 were measured within two years. Valuable information was obtained by accurate measurement of excitation functions, which demonstrated that heavy nuclei fuse in cold fusion reactions at beam energies just high enough to reach a contact configuration. Maximum cross-sections of 16, 3.5, and 0.4 pb were measured for elements 110 to 112, respectively.

The cross-section for the synthesis of element 113 using the reaction $^{70}$Zn + $^{209}$Bi was expected to be at 0.1−0.3 pb. Search experiments were performed in two runs, each of 4 weeks duration, resulting in a cross-section limit of 0.16 pb. A realistic meaningful beam time estimate for production of element 113 including statistical fluctuations resulted in about 300 days of beam time, which presently cannot be obtained at the UNILAC. Therefore further search for element 113 was cancelled.

The overall sensitivity of heavy element experiments at the UNILAC and SHIP at the end of 1998 can be summarized in the two concatenated quantities, namely a cross-section of 1 pb reachable in 10 days of measuring time. Therefore we prepared already in 1998 a proposal how to further improve the technical prerequisites, and we suggested experiments for further investigation of superheavy elements. Most of the aspects presented in this proposal are still valid. Therefore we attach it to this report.

# B. Chemical studies – experiment and theory

Nuclear chemistry experiments were among the first which were performed at the new built UNILAC in 1975. During the first decade the research program concentrated on (i) the search for superheavy elements in a variety of heavy-ion reactions mainly with $^{238}$U and $^{248}$Cm targets and projectiles ranging from $^{238}$U to $^{48}$Ca, (ii) measuring and interpreting deep-inelastic multi-nucleon transfer cross sections from targets of $^{238}$U, $^{248}$Cm and $^{254}$Es leading to the heaviest, most n-rich actinides, and (iii) systematic investigations of multi-nucleon transfer reactions and of fusion reactions by means of chemical methods to shed light on details of the respective reaction mechanism.

In the mid-80 the emphasis shifted towards chemical investigations of the transactinide elements including nuclear reaction and nuclear structure aspects. In this extremely successful and ongoing research program only hot-fusion reactions with actinide targets ($^{244}$Pu, $^{248}$Cm, $^{249}$Bk) were utilized to synthesize the most n-rich, long-lived nuclides needed for chemical studies. During the last decade a worldwide community of nuclear chemists joint to carry out the most ambitious experiments and GSI became the world leading centre for forefront chemical investigations of superheavy elements.

Transactinides begin with element 104 and 105. They are placed in group 4 and 5 of the Periodic Table, as it was shown in pioneering experiments by the Dubna and the Berkeley-Livermore groups in the course of or soon after the discovery of these elements. The central question about the influence of relativistic effects on the chemical behavior of these elements remained open and was only approached in the more recent experimental programs. The increasingly strong relativistic effects when going to even heavier elements makes this field most thrilling for chemists. Continuous developments of new and constantly advanced techniques for many experimental facets - like the irradiation/production part, automated chemical separation apparatuses and detection techniques - allowed to improve the sensitivity over about four orders of magnitude from 10 nb to a few pb.

Quite natural, because of relatively high cross sections and long half-lives, the most detailed knowledge is now available for Rf and Db. While the GSI group played – together with the collaborating partners from Bern, Mainz and Berkeley - a leading role in the first detailed investigations, the centre of gravity for studies in the aqueous phase has shifted now to experiments performed at Tokai. This was established and is continued in the course of a very fruitful GSI-JAERI collaboration. Right from the very first experiments Db and Rf showed surprising properties as compared with empirical extrapolations. Fully relativistic theoretical calculations are now able to explain many of these unexpected findings. However, we are far away from a good understanding of the chemistry of Rf and Db in a general sense.

A very large international collaboration, consisting of 16 institutes from 8 countries, joint at the GSI to perform over several years in series of beam times all experiments which establish today's knowledge about the Sg chemistry – in the gas-phase and in the aqueous phase. They placed Sg into group 6 of the Periodic Table. What was found, as described by one of our colleagues, is an "oddly ordinary seaborgium". Sg is the heaviest element for which information about the behavior in aqueous solution is available and more detailed studies are in preparation. For the first time, chemistry experiments provided samples for good nuclear decay studies of the most n-rich Sg isotopes 7.4-s $^{265}$Sg and 21-s $^{266}$Sg.

The first chemical property of Bh was investigated at the Paul Scherrer Institut (PSI), Villigen, in collaboration with the GSI group and others. The determined volatility puts $BhO_3Cl$ into group 7 of the Periodic Table. The isotopes $^{266}$Bh and $^{267}$Bh were discovered and investigated in the preparation and during the Bh chemistry experiments.

One of the more recent highlights are the two Hs gas-phase chemistry experiments both performed at the GSI. The first experiment, headed by PSI Villigen – University Bern - group, showed the formation of the volatile compound $HsO_4$ - a typical group-8 property - and established somewhat surprising a slightly lower deposition temperature along a thermochromatographic column/detector as compared with $OsO_4$. The second experiment probed the first chemical reaction of $HsO_4$ and found similarities to $OsO_4$ in the formation of a chemical compound – the hassate. Moreover, these experiments did not only provide an independent confirmation of the discovery of element 112 but they also yielded new information on the nuclear decay properties of $^{261}$Rf and $^{269}$Hs and an indication for the new N=162 neutron-shell nuclide $^{270}$Hs. Chemical and nuclear investigations of Hs are continuing.

The most recent and most exciting experimental program is the gas-adsorption study of element 112 in comparison with Hg and Rn – presumably the two extremes in the range of possible element 112 properties. While first experiments were performed at Dubna a much more detailed, ongoing investigation began at GSI. First results indicate that element 112 shows a significantly different behavior as compared with Hg. These experiments will be continued and will be extended to cover also the element 114 behavior. These experiments also bear the potential to independently confirm results obtained with recoil separators.

Extremely important, not only for the work at GSI but for the theoretical understanding of the entire superheavy element chemistry, was the theoretical work performed at the GSI. Since 15 years it became an indispensable part of all chemical studies of SHE. It has now reached a new level of predictive power due to spectacular developments in the relativistic quantum-chemical theory, calculational algorithms and hardware.

Accurate calculations with the use of the fully relativistic density functional theory (DFT) methods have been performed. Thus, electronic structures and properties of a large number of gas-phase halides, oxides and oxyhalides of elements 104 to 108 have been calculated serving as a basis for predictions of their gas-chromatographic behavior. Especially valuable were those about the volatility of $SgO_2Cl_2$, $BhO_3Cl$ and $HsO_4$. Extensive calculations have been carried out to model the volatility and adsorption behavior of element 112 in comparison with Hg on very large embedded metal (mainly gold) clusters. Utilizing thermodynamic models, adsorption temperatures have been predicted for element 112 and Hg.

Series of calculations have been performed for complexes of SHE in solutions to study their complex formation and chemical behavior. Predictions of extraction sequences and anion/cation separations were made for Zr, Hf and Rf in HF and HCl solutions, for Nb, Ta and Db in HF, HCl and HBr solutions and for Sg in HF and HCl solutions. For Rf and Db results were confirmed by experiments, and those for Sg are still awaiting an experimental outcome. The role and magnitude of relativistic effects on properties, behavior and trends in chemical groups have particularly been elucidated.

The future theoretical work will focus on: (i) Predictions of more detailed chemical properties of the transactinides Rf through Hs in the gas-phase and the aqueous phase, (ii) volatility predictions for elements 112, 114 and possibly 116, (iii) calculations of electrode potentials for the electrodeposition of these elements from aqueous solutions, and (iv) complex formation and extraction of heavier elements like Mt, Ds and Rg in aqueous solutions.

# III. What we need

## A. The future program at SHIP

What we need for the future study of superheavy elements are systematic measurements of highest accuracy and reliability both on the reaction processes for the synthesis of these nuclei as well as on their decay properties. Concerning the reaction process the new results on the synthesis of elements 112 to 118 obtained at FLNR Dubna open most interesting perspectives for further investigation of isotopes at and near the double magic shell closures at N = 184 and Z = 114 to 126. Obviously, as revealed by the data, relationships exist between stability of these nuclei, which is determined by shell effects, and their production yield which increased up to 5 pb for the synthesis of element 114 and 116. The relatively long half-lives, up to minutes were measured for the most neutron rich isotopes and up to days for isotopes near N = 162, open possibilities for the application of new techniques, as e.g. the trapping of these ions in ion traps and measuring the masses and other atomic and nuclear properties with high precision. Details of the planned experimental program at SHIP and possible and necessary improvements of the targets, the separator and detection system are given in Attachment A.

The prerequisites for an extended program on the study of superheavy elements are projectile beams of highest intensity, long term stability and sufficient long irradiation times. These conditions are not achieved enough satisfactorily at the present UNILAC. Together with the accelerator groups at GSI and at the University Frankfurt we propose an upgrade of the present facility and present herewith (Chapter V) three options of accelerator upgrades for further discussion.

## B. The future chemical research program

Highest priority has **TASCA**, the **T**rans**A**ctinide **S**eparator and **C**hemistry **A**pparatus, which we propose to build and operate at the GSI in strong collaboration with TU München and the majority of nuclear chemistry groups worldwide. Such kind of recoil separator is mandatory to maintain – in combination with the proposed ion-beam improvements (see above) - the leading role of GSI in chemical investigations of SHE around Z=114 over the next decade. Under preparation are already experiments in the aqueous phase, e.g. the University Mainz is developing a dedicated electrochemical experiment, and in the gas-phase, e.g. the PSI group is developing a very fast vacuum thermo-chromatography and the LBL group is already testing organic compounds for gas-chromatography. In addition, a nuclear physics program concentrating on nuclear decay studies of the most n-rich nuclides produced in hot fusion reactions is envisaged at TASCA. In the presently proposed configuration TASCA is seen as the first but crucial step towards "the best" separator which can be and should be built in the mid to long-term future. More details are outlined in the Attachment D.

Second highest priority has a series of "traditional" SHE chemistry experiments with advanced and newly developed techniques. Detailed chemical investigations of the transactinide elements Sg, Bh and Hs are planned and developed which will begin to shed more light on detailed chemical properties and on the influence of relativistic effects in these elements. In addition, we will focus on the elements around Z=114 and their decay products. Improvements in the personnel situation and the availability and intensity of beams are mandatory.

# IV. Achievements and plans at other laboratories

## A. Based on physical investigations

Until 1998 the GSI heavy element group had practically no competition at other laboratories. The situation changed when at about 1996 **at FLNR in Dubna** the cyclotron was equipped with an ECR ion source and the duty factor was increased from 30 to 100 % in order to generate efficiently an intensive $^{48}$Ca beam. The planning at Dubna was to use this beam for irradiation of various actinide targets ($^{238}$U, $^{244}$Pu, $^{242}$Pu, $^{243}$Am, $^{245}$Cm, $^{248}$Cm, and $^{249}$Cf) for synthesis of elements 112 to 118.

The separators at FLNR, an energy filter VASSILISSA and a gas-filled separator, were upgraded and equipped with detection systems which were a copy of that used at SHIP. The upgrade was ready in 1998. Long beam times could be scheduled because the U400 cyclotron was used mainly for superheavy element synthesis. The results of the Dubna work are summarized in Fig. 1 of the proposal attached (see proposal "Search for SHE using the hot fusion reaction $^{48}$Ca + $^{238}$U").

Californium is practically the heaviest possible target material. Fusion reactions with $^{48}$Ca result in element 118. For the synthesis of heavier elements one must use heavier projectiles. Therefore the plans at FLNR are to upgrade the U400 cyclotron so that beams of $^{50}$Ti, $^{54}$Cr, etc. will have enough high intensity and can be accelerated up to sufficient energies.

**The BGS at Berkeley** became ready for experiments in 1999. It was also equipped with a detector system similar as the one used at SHIP. This is the case also at all other set-ups being used for heavy element research. After initial difficulties (Z = 118) the research program consolidated. The SHIP experiment on element 110 was confirmed by measurement of two decay chains of $^{271}$Ds and element 111 was synthesized in the reaction $^{65}$Cu + $^{208}$Pb. For the time being the experiments at BGS continue.

**The RILAC at RIKEN** is needed as injector into the RRC ring cyclotron for high energy beams. After completion of the radioactive beam facility it will be used for production of radioactive isotopes which will be injected into the RRC for acceleration. However, before the RIBF will start, the RILAC could be used, after an energy upgrade, solely for a heavy element program for a limited period. These experiments started in 2002 and the gas-filled separator GARIS was used. After a successful repetition and confirmation of the GSI elements 110, 111, and 112 a search for element 113 was started using the reaction $^{70}$Zn + $^{209}$Bi. The experiment was performed in two beam time blocks (September 5 to December 29, 2003 and July 8 to August 2, 2004) of a total of 140 days. The net irradiation time was 79 days. A typical beam current was 380 pnA, and the total beam dose was $1.7 \times 10^{19}$. One decay chain was measured on July 23, 2004, which was assigned to the new isotope $^{278}$113. The chain decays via the new isotopes $^{274}$Rg, $^{270}$Mt to the known isotope $^{266}$Bh and ends by spontaneous fission at the known isotope $^{262}$Db. A cross-section of 55 fb was measured.

The plans at RIKEN are to measure an excitation function of element112 and to repeat the element 113 experiment. The experiments could be continued with beams of $^{76}$Ge, $^{82}$Se, etc. as long as RILAC is not needed for the production of radioactive isotopes. This will be the

case at the end of 2004. For the time beyond, under discussion is a beam sharing mode similar as the one at the UNILAC and SIS.

**The experiments at GANIL** using the LISE separator suffer from too short and too rare beam times due to competition from other experimental programs. For the future it is planned to use the deuteron driver linear accelerator (for production of a high neutron flux) also for acceleration of heavy ions. Beams of heavy ions of very high currents up to 1000 pμA with energies up to 14 MeV/u are expected.

**In-beam experiments** using the recoil decay tagging (RDT) method were successfully performed **at the FRM separator at Argonne** and **at the gas-filled separator RITU at Jyväskylä**. Using cold fusion reactions isotopes of No and Lr were studied. It seems likely that these experiments could be extended up to Sg and Hs, which can be produced at relatively high cross-sections of 2500 and 75 pb, respectively. However, at these in-beam experiments with Ge γ-detectors or Si $e^-$-detectors located around the target, the beam currents are limited to about 100 pnA.

**At Lanzhou** the new isotopes $^{259}$Db and $^{265}$Bh were produced recently using light ion beams and targets of $^{241}$Am and $^{243}$Am, respectively. Presently under discussion is the construction of a dedicated accelerator for synthesis and study of superheavy nuclei and production of new elements.

Finally, more **neutron rich radioactive beams** will become available at several laboratories (**RIA, GANIL, RIKEN**). The use of radioactive beams will extend the study of the reaction mechanism and new neutron rich isotopes could be produced which are not accessible with stable beams. However, the open question is the height of intensity of radioactive isotopes, which can be produced by fragmentation or induced fission. At GSI the experiments at other laboratories using radioactive beams will be followed attentively and a possible application at GSI will be discussed again after results will have been obtained elsewhere.

## B. Based on chemical investigations

The for many years very strong heavy element chemistry program at **Dubna** - with recent highlights like first approaches towards an element 112 chemistry - was for a few years severely hampered for a number of reasons including personnel problems. Within the last few months, a new group of scientist started exciting experiments on the chemistry of long-lived Db isotopes as "grand-daughters" from the decay of element 115. The **PSI-Bern** group, performing the chemistry, played a crucial role in this collaboration. These experiments are likely to be continued and are of importance not only for the confirmation of the discovery of SHE with chemical methods but also to get access to and to make use of long-lived nuclides of SHE. It is worthwhile pointing out that such programs can only be carried out with sufficient beam time and manpower.

The nuclear chemistry program at **Berkeley**, one of the traditional strongholds of heavy element chemistry, is still very lively. Last years decision to continue operation of the 88-inch cyclotron and to make large amounts of beam time available for the SHE program was very helpful in this context and will certainly yield many new and interesting results. The development of the superconducting VENUS ECR-source will even improve the already good situation concerning the availability of heavy-ions and their intensities. Recently, the emphasis of the chemical program of the Berkeley group has shifted towards transactinide chemistry experiments behind the recoil separator BGS. The **Oslo-Göteborg-Mainz** collaboration installed the fast centrifuge system SISAK at the BGS and was, with this combination, for the first time successful to perform a continuous, on-line aqueous chemistry experiment with a short-lived transactinide nuclide. Recent developments of on-line gas-chromatographic separations with organic compounds, which can only be applied after a pre-separator, show the potential of this new method as a new and powerful tool with an excellent future. The Berkeley group is also participating in a number of SHE chemistry experiments at the **GSI**.

The combined **Swiss** groups from the **PSI**, Villigen, and the University of **Bern**, are one of the leading groups in the field of superheavy element chemistry. One SHE experiment – the Bh chemistry – was performed in a large international collaboration at the PSI Philips cyclotron, which is otherwise used the develop new techniques and to test new chemical separation schemes and detectors. Almost unlimited beam time is available for the in-house group at the PSI, as the cyclotron is not an open, outside user oriented facility anymore. Also in the coming decade the PSI/Bern group will play one of the major roles in SHE chemistry. Their preference would be to do these experiments at the **GSI** in **Darmstadt**. However, sufficient beam time, the necessary infrastructure and a strong GSI support group are mandatory requirements for this in addition to the need for the TASCA separator. The PSI-Bern-group is presently also performing SHE experiments at **Berkeley** and at **Dubna**.

As a consequence of the filling of the chair for nuclear and radiochemistry at the **TU München**, a new nuclear chemistry group concentrating on the chemical research with superheavy elements was established two years ago. The group is actively involved in the TASCA project and in all aspects of SHE gas-phase chemistry, including detector developments and nuclear oriented investigations. It gave a strong boost to the SHE research in Germany and it provides an important basis for the long term future of this research field. Within a very short period of time, intense links were established to the **GSI** nuclear chemistry group in joint experimental programs at the UNILAC and, as a perspective, at SPIRAL.

The **JAERI, Tokai,** group has presently taken over the leading role in the Rf chemistry and is preparing more detailed studies of Db. With the help of the GSI group - including a large technology transfer - the JAERI group established only within a few years this leading position. This provided the basis to establish a strong Japanese heavy element chemistry program which now includes many students and almost 20 scientists from six institutes. Within the very successful framework of the official JAERI-GSI collaboration the GSI nuclear chemistry group is collaborating with the Tokai group.

The above mentioned Japanese nuclear chemistry community is presently preparing an experimental program at **RIKEN**, which, from the experience at Tokai, will move ahead very fast and is anticipated to become a strong player in the field within a short period of time. An important and very competitive aspect is the coupling of chemistry set-ups to the GARIS separator which is under preparation.

At **Lanzhou** preparations started to establish a chemistry program in the heavy and superheavy element region. Collaborations with the nuclear chemistry groups at GSI, PSI/Bern and JAERI, Tokai, provide basic skills and knowledge towards this aim.

A few years ago, the **French** nuclear chemistry community had performed first and successful experiments on Rf and Db, and, traditionally, they were strongly involved in heavy element chemistry programs at **Dubna**. Presently, no strong efforts towards a heavy element chemistry program in France are visible.

Efforts are made in collaboration mainly between GSI Darmstadt, IPN Orsay, GANIL, TU München, and University Mainz to exploit the potential of n-rich radioactive beams for the synthesis and investigations of the heaviest elements by means of chemical methods. Presently, the collaboration is waiting for an increase of the available beam intensity at the **SPIRAL** facility at **GANIL**. While first experiments are planned for the coming years it is not anticipated that the region of transactinide elements will be reached in the mid-term future.

# V. Versions of accelerator upgrades at GSI

The accelerator upgrades at GSI for experiments at Coulomb barrier energies have the primary goal to provide optimum beams for study of superheavy elements. No estimate is possible, how many new elements can be made with a new accelerator. Instead we compare the measuring time needed for the synthesis of a recently produced nucleus, $^{278}113$, at RIKEN, for which an extremely small cross-section of 55 fb was measured. Details of this experiment are presented in Chapter IV.A. The present GSI parameters are taken from recent search experiments for element 113, which resulted in a cross-section limit of 0.16 pb. This value is valid for the case that one event would have been observed. The given examples demonstrate which beam times are needed using the present facilities and what kind of improvements will be obtained with various options of an accelerator upgrade.

Three possible versions of accelerator upgrades for the GSI heavy element program have been worked out by the GSI accelerator group (W. Barth, L. Dahl, K. Tinschert, et al.) and by the members of the Institute for Applied Physics of the University Frankfurt (U. Ratzinger, A. Schempp, et al.). All three versions are based on a new high charge state injector consisting of a 28 GHz ECR source and improved versions of RFQ and IH-structure accelerators providing beam energies of 1.4 MeV/u. Version one, presented in Col. 3 of the table, will use the present or upgraded Alvarez sections for further acceleration. In this version the duty factor is increased from now 27.5 to 50 % for medium heavy projectiles like $^{70}$Zn, e.g. In version two, Col. 4, the maximum energy is 6 MeV/u achieved by normal conducting IH structures. And finally, version three includes a superconducting linac with a maximum energy of 7.5 MeV/u. The two latter systems are stand alone machines both with 100 % duty factor.

A detailed report on the various possibilities will be given by U. Ratzinger and K. Tinschert at the meeting on October 15. As first information we add a power point presentation of a recent talk by Ratzinger to this report. In Table 1 the various options are compared. The table includes also the parameters of the presently running facilities at RIKEN and GSI plus SHIP, which were obtained in the recent studies or searches for element 113. A detailed explanation, except for the obvious data, is given in the following.

| | | RIKEN now | UNILAC now | UNILAC 50% | CW-Linac Room T. | CW-Linac Supercond. | |
|---|---|---|---|---|---|---|---|
| | | C1 | C2 | C3 | C4 | C5 | |
| **Experiment parameters:** | | | | | | | |
| 1 | Cross-section | 55 | 55 | 55 | 55 | 55 | fb |
| 2 | Target thickness | 450 | 450 | 450 | 450 | 450 | $\mu g/cm^2$ |
| 3 | Duty factor wheel | 79 | 96 | 95 | 92 | 92 | % |
| 4 | Efficiency separator | 80 | 50 | 50 | 50 | 50 | % |
| 5 | Total exp. efficiency | 63 | 48 | 47 | 46 | 46 | % |
| 6 | Beam dose from accelerator (= $1.40\times10^{19}$ at $\varepsilon$ = 100 %) | 2.2 | 2.9 | 3.0 | 3.0 | 3.0 | $10^{19}$ |
| **Accelerator performance:** | | | | | | | |
| 7 | Frequency (ECR) | 18 | 14 | 28 | 28 | 28 | GHz |
| 8 | Charge state ($^{70}$Zn) | 16 | 10 | 12 | 14 | 10 | |
| 9 | Current ECR source ($^{70}$Zn) | ? | 5 | 18 | 10 | 22 | pμA |
| 10 | Transmission accelerator | ? | 50 | 50 | 50 | 50 | % |
| 11 | Width beam pulses | DC | 5.5 | 10 | DC | DC | ms |
| 12 | Duty factor HF | ? | 27.5 | 50 | 100 | 100 | % |
| 13 | SIS pulses | --- | 1 | 5 | --- | --- | /sec |
| 14 | UNILAC pulses – SIS pulses | --- | 98 | 90 | --- | --- | % |
| 15 | Total accelerator efficiency | ? | 13.5 | 22.5 | 50 | 50 | % |
| 16 | Beam current at target, mean | 0.52 | 0.6 | 5 | 5 | 11 | pμA |
| 17 | Beam-at-target time needed for dose given in L6 | 79 | 88 | 11 | 11 | 5.1 | days |
| 18 | Breaks (change of source, wheel, HF, etc.) | 43 | 25 | 30 | 10 | 10 | % |
| **19** | **Experiment time, total** | **140** | **117** | **16** | **12** | **5.7** | **days** |
| **Accelerator parameters:** | | | | | | | |
| 20 | A/q | ? | 7 | 6 | 5 | 7 | |
| 21 | Charge state q($^{136}$Xe) | 20 | 19 | 23 | 27 | 19 | |
| 22 | I($^{136}$Xe) extracted from ECR | 5 | 2 | 30 | 15 | 53 | pμA |
| 23 | Charge state q($^{48}$Ca) | ? | 7 | 8 | 10 | 7 | |
| 24 | I($^{48}$Ca) | ? | 5 | 18 | 10 | 22 | pμA |
| 25 | E-min | ? | 1.4 | 1.4 | 3.8 | 3.8 | MeV/u |
| 26 | E-max | 6 | 13 | 13 | 6.0 | 7.5 | MeV/u |
| 27 | Costs construction | | --- | 2.5 | 8.0 | 20 | Mill. Euro |
| 28 | Power consumption | | 3 | 4 | 2 | 1 | Megawatt |
| 29 | Available beam | | 146 | --- | --- | --- | days/year (≤2006) |
| 30 | Available beam, SHIP+Chem. | | 59+44 | --- | --- | --- | days/year (≤2006) |
| 31 | Available beam | | 240 | 240 | 300 | 300 | days/year (≥2007) |
| 32 | Available beam, SHIP+SHIPtrap+Chem. | | 170 | 170 | 210 | 210 | days/year (≥2007) |
| 33 | Time per $1.8\times10^{22}$ beam dose | | 225 | 28 | 22 | 10 | years |
| 34 | Power costs (0.10 Euro/kWh) | | 390 | 63 | 32 | 7.2 | Mill. Euro/$1.8\times10^{22}$ |
| 35 | $^{48}$Ca costs (100 Euro/mg) | | 12.9 | 4.8 | 4.8 | 2.2 | Mill. Euro/$5.9\times10^{21}$ |
| **36** | **Costs for constr. plus operation normalized to $1.8\times10^{22}$ beam dose** | | **403** | **70** | **45** | **29** | **Mill. Euro** |

**Explanations to Table 1:**

C1 – C5:
In C1 are listed the parameters of the recent experiment at RIKEN, in which one decay chain of $^{278}113$ was measured using the reaction $^{70}Zn + ^{209}Bi$. The measured cross-section was 55 fb. C2 gives the parameters of recent search experiments for element 113 at SHIP and in line 6 the beam dose from the accelerator is given, which would be needed on the basis of the given parameters, to reach the 55 fm cross-section. The same consideration was applied for the three different upgrades presented in C3, C4, and C5. The upgrades are described in the text before.

L3:
The duty factor of the wheel considers the spokes between the target segments. It is considerably higher at SHIP due to the longer targets. At the same wheel diameter of 300 mm, we use 8 targets compared to 16 at RIKEN. At a 10 ms wide pulse, C3, only one spoke will cross the beam, which results in 95 % duty factor of the wheel.

L4:
The separator efficiency in the case of heavy element synthesis is considerably different for cold and hot fusion. Before a separator upgrade can be taken into account, reliable measurements of the efficiencies of the different reactions are needed (accuracy better than 10 %), which is, however, difficult to obtain for synthesis of heavy elements. The calculated efficiency given for SHIP is 50 % for cold fusion reactions (uncertainty factor of 2) and 10 to 30 % for hot fusion reactions (depending on the number of emitted neutron, uncertainty factor of 3).

L6:
At 100 % efficiency of the experimental set-up, the projectile dose needed to measure a cross-section of 55 fb would be $1.40 \times 10^{19}$. The beam dose needed at the total experiment efficiencies given in L5 is listed in L6.

L8:
Minimum ionic charge states needed with respect to the maximum A/q values of the different accelerator options given in L20.

L9:
Current estimate for $^{70}Zn$ ions extracted from the ECR ion source at the charge states given in L8 of the different accelerator options.

L10:
At relatively low beam currents (45 el. μA), the measured accelerator transmission is now 50 %. The main losses happen just after the ECR source due to low acceptance of the RFQ. A new RFQ would be designed for higher acceptance, however, at high beam currents (400 el. μA) we must expect losses due to space charge effects. Therefore we use a 50 % transmission also for the new machines.

L13:
Presently about 1 pulse from 50 per second is switched into the transfer channel for acceleration at SIS. At higher ramping frequency at SIS in the future, an average value of deflected pulses will be at 5 /sec. This amount of lost pulses means only a small reduction of beam intensity of 10 % for low energy UNILAC experiments. However, more problematic is the difference of magnetic rigidity of two different projectile ions at UNILAC and SIS, which, for certain combinations, will permit a time sharing operation only at the expense of reduced beam intensity and beam quality for both branches.

L16:
These beam currents are reached at the given properties of ion sources and accelerator performance.

L18:
Breaks, given in percent of the total beam time (L19), are caused by instabilities of the whole experimental set-up, from ion source up to data acquisition. They also include necessary interrupts as, e.g., refilling of material into the ECR source or change of the target wheel. Average values of recent experiments are given in C1 and C2. We expect an increase of these failures in C3 (30 %) due to higher load of the Alvarez, especially its HF components due to the multi user operation.

L19:
The total number of days needed for detection of one event which is produced at a cross-section of 55 fb.

L20 to L36:
The accelerator parameters, including costs of construction and of operation are given here.

L20:
Maximum A/q values for the different accelerator options C2 – C5.

L21:
Minimum charge state needed of $^{136}$Xe for the different accelerator options.

L22:
Expected currents of $^{136}$Xe ions extracted from the ECR source for the ionic charge state given in L21.

L23 and L24:
Same as L21 and L22, but for $^{48}$Ca.

L29 and L30:
Concerning the availability of the low energy beam at the UNILAC we encounter severe restrictions since 1999, which will last until 2006, due to the cancer therapy project. Cancer therapy is dependent on a $^{12}$C beam of high reliability and stability of intensity. This can be achieved only with the ECR ion source which, therefore, is not at disposal for heavy element experiments during therapy periods. E.g., in 2004, the therapy program will use the ECR source for 90 days from a total of 236 days of UNILAC running time for experiments. Maintenance and machine tests amount to 118 and 11 days, respectively. The remaining 146 days of ECR beam time are shared between SHIP (38 days), nuclear chemistry (44 days) and other experiments (64 days) including SIS experiments which also need beams from

rare isotopically enriched source material from the ECR source. Two experiments at SHIP with a total of 21 days were using the PIG source.

L31 and L32:
Here the expected beam times are given for the years after 2006 at the various options of accelerator upgrade. The ratio between heavy element experiments at SHIP, SHIPtrap and for nuclear chemistry including experiments at the gas-filled separator TASCA (being under construction) and other experiments at low energy is assumed to be similar to that given in L28 and L29. At the dedicated linacs presented in C4 and C5 considerably longer operation times (300 days) are expected.

L33:
The most interesting number from the experimental point of view is the projectile dose which can be achieved from the accelerator. This value determines the cross-section limits which can be reached or, at a given cross-section, the number of atoms which can be produced. As a reference we use $^{70}$Zn and the optimum currents as given in L16 for the option C5. During a period of 10 years and a beam availability of 300 days per year (L31) a maximum projectile dose of $1.8 \times 10^{22}$ can be obtained. At such a beam dose the number of experiments that can be performed at a cross-section level of 55 fb amounts to 593, using the data given in L6. Or, in other words, a cross-section level of 0.093 fb can be reached in a 10 years irradiation. The time needed in the case of options C2 and C3 is given in L33 taking into account the different currents given in L16 and the different periods of operation given in L31. The latter two numbers appear peculiarly, however, they reflect the number of experiments which can be performed at the different versions of accelerators.

L34:
The costs for electricity at GSI are presently 0.07 Euro/kWh. For a long term comparison we calculate in L34 the total costs for electricity during the periods given in L33. During this time the electricity costs will probably rise, therefore we assumed 0.10 Euro/kWh for the cost estimate and the power consumption as given in L28.

L35:
Most of the heavy element experiments will use enriched source material which contributes considerably to the total operation costs. Taking the beam current estimated for option C5 (given in L16) and assuming that an expensive material like $^{48}$Ca is only used for 1/3 of the time (1000 days), then we obtain a projectile dose of $5.9 \times 10^{21}$. In the case of $^{48}$Ca the consumption is 0.3 mg/h presently (C2) and will increase to 3 mg/h at the new 28 Ghz ECR source (C3 – C5). The present costs are 100 Euro/mg for source material enriched to 97 % (the costs of less enriched $^{48}$Ca are 60 Euro/mg at 70 % enrichment and 30 Euro/mg at 50 % enrichment, however, the beam current will be reduced accordingly). These data result in material costs of 2.2 Million Euro for option C5 and 4.8 Million Euro for option C4. In order to collect the same beam dose in the case of option C2 and C3, the material costs are 12.9 and 4.8 Million Euro, respectively.

L36:
The total costs for construction (L27) and operation time (L32) are listed (sum of the numbers in L27, L34, and L35). L35 represents 3.3 years of $^{48}$Ca operation in the case of option C5. Compared to this the costs for source material for the other 6.7 years were neglected. Again, as already mentioned at L33, the large numbers in C2 and C3, but especially that in C2 seem farcical, however, they reflect the experimental possibilities in comparison with the data given in C4 and C5.

# VI. Personnel and external participation

## A. At SHIP

The experimental program at SHIP is carried out by a permanently employed GSI staff consisting of 3 physicists and 2 technicians and 1 doctorand and 1 postdoc, both having their fixed working place at GSI. During the heavy element experiments we have support from guest groups, 2 physicists from FLNR Dubna, 1 physicist plus 2 doctorands from the University Bratislava and 2 physicists from the University Jyväskylä.

A relatively strong guest group around A. Andreyev performs experiments in the region of neutron deficient Pb and Po nuclei. As an example, this group identified the triple shapes of the nucleus $^{186}$Pb.

The SHIPtrap group is working with relatively many (up to 20) physicists and doctorands during experiments. At an extended program 2 fixed positions are needed.

At an extended heavy element program at SHIP the personnel has to increase. This is possible by participation of more guest groups from Universities or other laboratories.

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## B. In nuclear chemistry

The experimental heavy and superheavy element program of the nuclear chemistry group was until 2003 carried out by a permanently employed GSI staff of 3 scientist and 3 technicians. Since one of the scientists left the group for an early retirement more than one year ago, the workload for the remaining two scientists is stretched beyond any reasonable limit even if only the service for external experimental groups is considered. **The nuclear chemistry group most urgently needs a third scientist**. Moreover, because of an unfavorable age structure in the group - the next scientist and a very experienced technician, who is responsible for all the mechanics, self-build chemical apparatuses, vacuum systems etc., will leave the group in 3.5 years – it is of utmost importance to make now decisions about the future of this group - and to begin to employ new personnel. It will also be of importance in the next few years to find a way to transfer the knowledge of experience personnel to their successors, i.e., a certain overlap in time between the person leaving GSI and his successor is badly needed. Independent of the above mentioned urgent need for a third experimentalist in the nuclear chemistry group it would be of great help to have more regularly one postdoc in the group.

Nuclear chemistry experiments usually require much more manpower than, e.g., SHIP experiments. This is already true in the preparation phase of each experiment, i.e. developing a new chemical separation technique, building an automated system to perform the separation and to detect the desired species. This is usually performed by one or two diploma and doctoral students and technicians at one of the collaborating institutes like the University Mainz, TU München, University of Bern or the Paul Scherrer Institute. In the course of the experimental program at GSI between 20 and 50 scientists and technicians from about a dozen institutes carry out the experiments. These collaborations change from experiment to experiment – so do the leadership in each experimental program. Often essentially the worldwide community in superheavy element chemistry research gathers at the GSI. The envisaged personnel involvement setting up and operating TASCA is sketched in the Attachment D.

The theoretical chemistry program at the GSI, recognized as world leading in its specific field, is a "one-woman-science"; as it was put by one of our colleagues. However, also in this field collaborations, like the one with the University Kassel, are of great benefit or even essential for this top position. It would be of enormous help, to have more frequently a doctoral student and /or postdoc working here at GSI in the field of theoretical chemistry.

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A. Rosen

# SHIP-2000

*A proposal for the study of superheavy elements*

S. Hofmann for the SHIP collaboration

January 8, 1999

## 1 Physical aims

The outstanding aim of experimental investigations of heavy nuclei is the exploration of spherical *Superheavy Elements* (SHEs). On the basis of the nuclear shell model, the next double magic shell-closure beyond $^{208}$Pb is predicted at proton numbers between Z=114 and 126 and at neutron number N=184 (Fig. 1). The uncertainty of locating exactly the proton number arises from the uncertainty of locating energetically the proton subshells $2f_{5/2}$, $3p_{3/2}$ and $3p_{1/2}$, which are filled between Z=114 and 126. Their energy is determined mainly by the spin-orbit energy, which is difficult to predict for these heavy nuclei due to effects based on the strong Coulomb forces. As a consequence, the various models predict highest stability at proton number 114, 120 or 126. In the case of an even distribution of the subshell energies, the shell effect forming SHEs will be smeared out across the region from Z=114 to 126, resulting in a wider, however, less stable region of SHEs. The question, if Z=114 is a magic proton shell and how big is the shell strength, could be answered by the synthesis of element 114 and observation of $\alpha$ decay of the produced isotope.

All experimental efforts aiming at identifying SHEs (Z$\geq$114) were negative so far. The most sensitive search experiment was performed in November-December 1995 at SHIP. The isotope $^{290}$116 produced by *radiative capture* was searched for in the course of a 33 days irradiation of a $^{208}$Pb target with $^{82}$Se projectiles. Cross-section limits of 5 pb were reached at four different beam energies, which resulted in free reaction energies between 0 and 10 MeV. Radiative capture is a possible reaction mechanism for the synthesis of SHEs, however, is known so far only for lighter elements.

Positive results were obtained at SHIP in two series of experiments. Firstly, the elements 107 to 109 were synthesized and cross-sections were measured down to 10 pb. After an upgrade of SHIP the elements 110 to 112 were produced, the latter one with a cross-section of 1 pb. Through the upgrade the performance

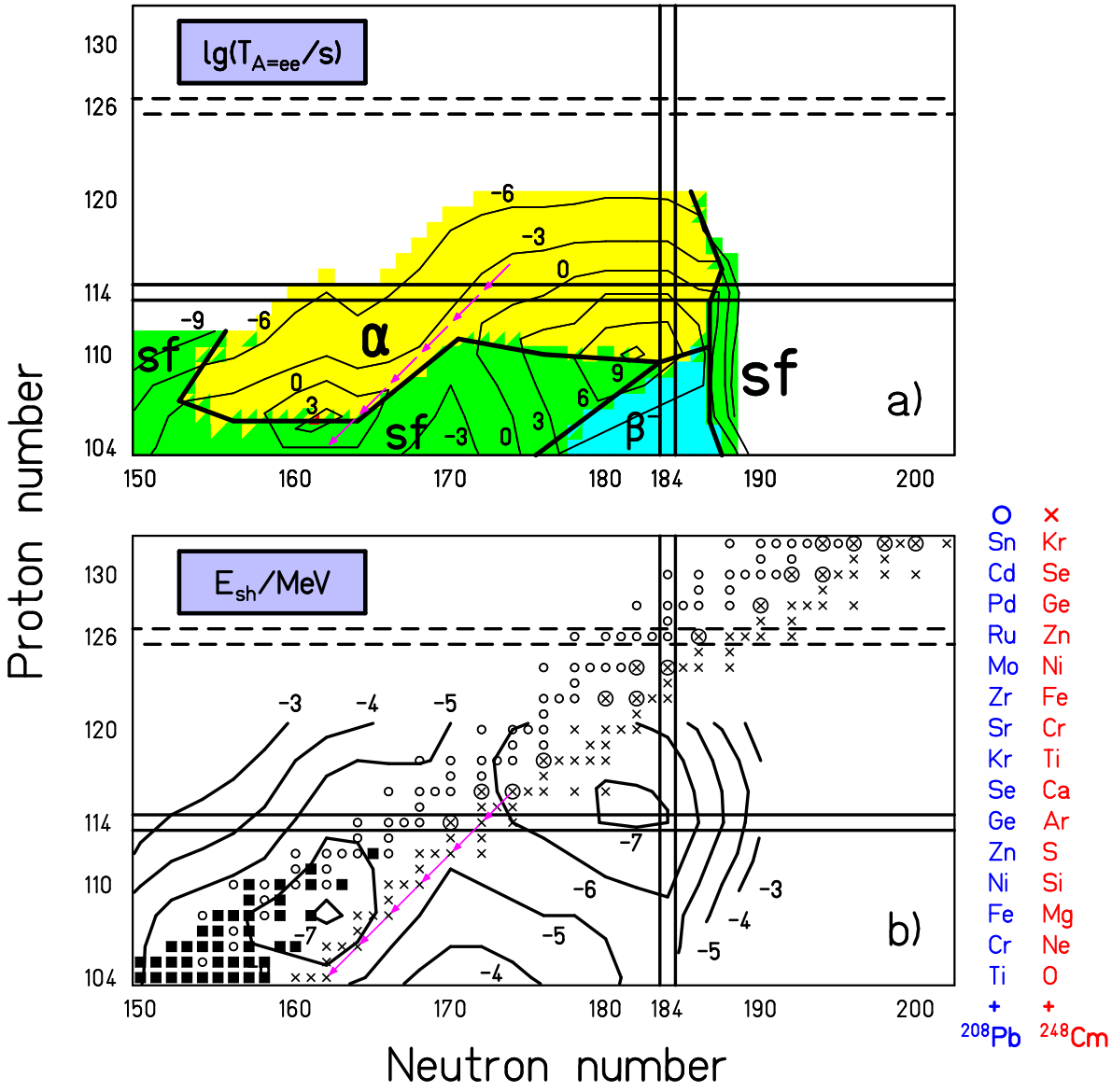


Figure 1: Dominating partial $\alpha$, $\beta$ and fission half-life for even-even nuclei (a). Diagram (b) shows the calculated ground-state shell-correction energy. Also marked are compound nuclei, which can be reached in reactions with targets of $^{208}$Pb or $^{248}$Cm and stable projectile isotopes. The presently known nuclei are marked by filled squares. The sequence of arrows indicates the hypothetical decay chain of $^{290}$116 synthesized by the reaction $^{82}$Se+$^{208}$Pb.

was considerably improved of the target, the separator, the detector and the signal processing, as well as on the accelerator side of the ion sources (PIG and ECR source with RFQ and IH accelerator). Also increased was the transmission of the beam through the accelerator and the beam line. As a result, the overall sensitivity could be increased by an order of magnitude, which allowed for extending the number of known elements up to 112. All presently known isotopes are shown in Fig. 2.

The elements from 107 to 112 were synthesized by cold fusion. However, uncertainty remains concerning the optimum reaction mechanism for the production of SHEs. We measured that the cross-sections decrease rapidly for production of elements beyond about rutherfordium (Z=104), see Fig. 3. From there on the nuclear surface tension can no longer compensate for the increasing Coulomb repulsion, a macroscopic effect, which increasingly hinders fusion of heavy systems. The reason that heavy elements can still be produced, is due to microscopic effects of both the reaction partners and, possibly, also of the compound nucleus. The latter effect may become important in the presence of strong shell effects, as predicted for SHEs by some models. However, the question remains, if these shell effects could be preserved in a compound nucleus, at least partially, and thus result in a positive modulation of the fusion cross-section for production of SHEs.

In spite of the extremely low cross-sections, the knowledge of the stability of heavy elements and of their synthesis was considerably widened in recent years. A region of increased stability for deformed nuclei with center at Z=108 and N=162 was experimentally proved. Longest half-lives were measured for $^{266}$Sg (21 s) and $^{269}$Hs (9.3 s). Values up to 1000 s are expected for A=267 isobars of the elements Rf, Db and Sg, see Figs. 1 and 2. Not fission, but $\alpha$ decay is the main decay mode up to element 112, a result which is well reproduced by calculations. The measurement of excitation functions revealed that the cross-section maxima arise at decreasing excitation energy with increasing element number, see Fig. 3. This trend is opposite to conclusions drawn from macroscopic models, which predict an extrapush in order to fuse heavy systems. Such an additional energy would have heated the compound nuclei up to several tens of MeV and thus reducing the survival probability by many orders of magnitude. Instead, the measurements revealed the importance of microscopic effects for the reaction process, and the cross-section trend shows that elements beyond 112 may still be possible to synthesize. Prerequisite for the detection, however, is an upgrade of the experimental set-up in order to make search experiments for further new elements promising and to sufficiently prepare such searches by measurement of excitation functions for the synthesis of lighter elements, i.e. up to element 112.

After the upgrade of the set-up, not only experiments aiming at synthesizing new elements will be possible to perform in reasonable measuring time, but also a whole number of various investigation covering reaction physics and spectroscopy. A list of most significant proposals is given herewith:

1. Search for the new elements 113 and 114, possibly also for 115 and 116, proof of the shell effect at Z=114 and establishing the location of SHEs. According to the calculations shown in Fig. 1, the isotopes of those elements, which are reachable using stable projectile isotopes, should be $\alpha$ emitters. If this is so, then the experimentally obtained $\alpha$-decay data ($\alpha$ energy and half-life) will give a direct information on the value of the shell effect at Z=114. The predicted decay chain of $^{283}$114 is shown in Fig. 2. On the basis of the present cross-section data, we extrapolate values of 0.3 – 1.0 pb for production of element 113 and 0.1 – 1.0 pb for element 114 using $^{209}$Bi and $^{208}$Pb targets, respectively (see Fig. 3). However, the experimental program also has to take into account that strong shell effects may exist at Z=120 or 126. Then, this region of SHEs would be well accessible with stable projectiles in both, cold and hot fusion, with targets of lead or isotopes of the actinide elements (see Fig. 1). Although the synthesis of these very heavy systems seems to be unlikely on the basis of our present knowledge, it cannot be excluded that strong shell effects of the compound system may lead to an increase of the fusion probability.

   A search for element 113 was performed in March-April 1998. In the course of a 46 days experiment using a $^{70}$Zn beam a cross-section limit of 0.6 pb was obtained, Fig. 3. This value does not contradict the expectations, however, the experiment revealed a necessary upgrade of the experimental set-up by an order of magnitude at least.

2. Ground-state to ground-state $\alpha$ decay of even-even nuclei for more accurate evaluation of nuclear binding energies and extraction of shell strength.

3. Search for $\alpha$ transitions of even-even nuclei into rotational levels for determining the degree of deformation. These experiments are especially important in the region of nuclei near N=162, where locally high stability is expected due to a relatively wide energy gap between the relevant Nilsson single particle levels.

4. Fission branching of even-even nuclei for comparison of the extracted partial fission half-lives with the results of calculations. Fission half-lives are the most sensitive parameter to test the predictions of nuclear models with respect to the stability of SHEs.

5. Gamma and conversion-electron spectroscopy of separated fusion products. Many isotopes of heavy nuclei have considerable $\beta$ or electron capture branching, are formed and separated in long lived isomeric states, or excited levels are populated by $\alpha$ decay. Therefore, partial level diagrams could be established even in the case of small production cross-sections using highly efficient $\gamma$ or electron detectors. For these applications, as also in the case of experiments using SHIPtrap (see the subsequent item no. 6), the detectors are mounted in

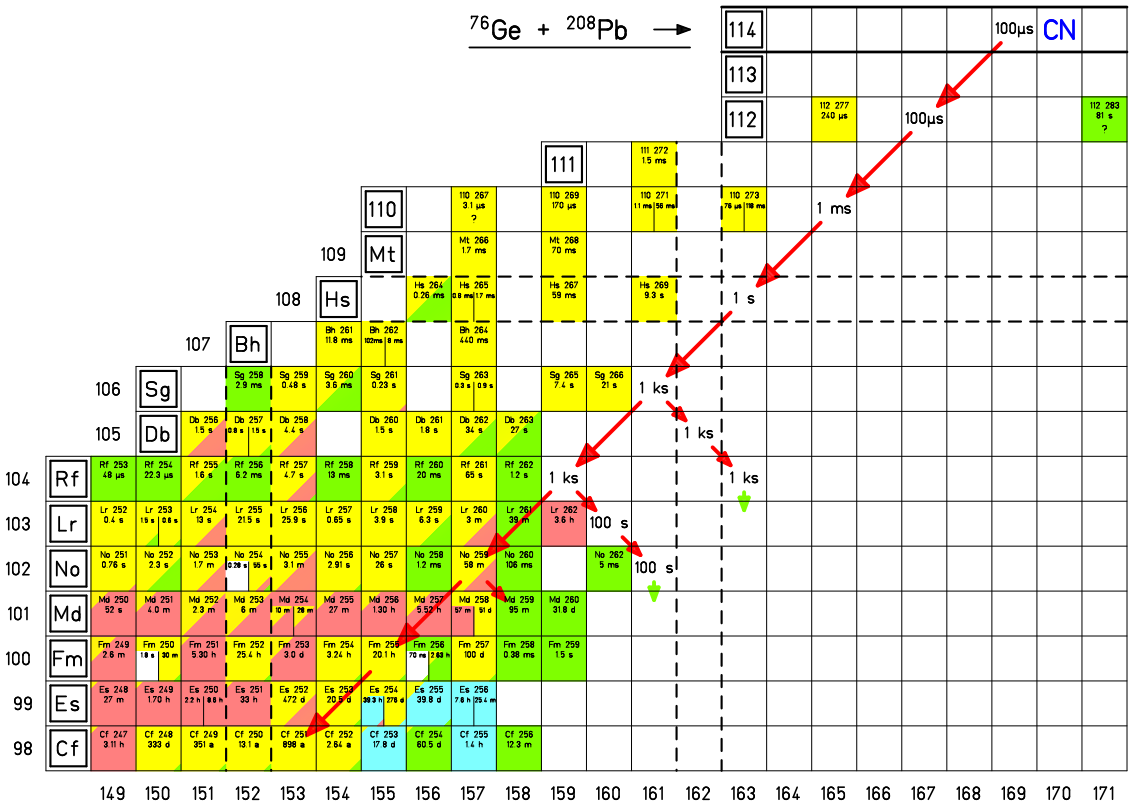


Figure 2: The presently known isotopes of the heaviest elements and the predicted decay chain of $^{283}114$. Evidence for the possible synthesis was claimed for $^{267}110$ at Berkeley and for $^{283}112$ at Dubna.

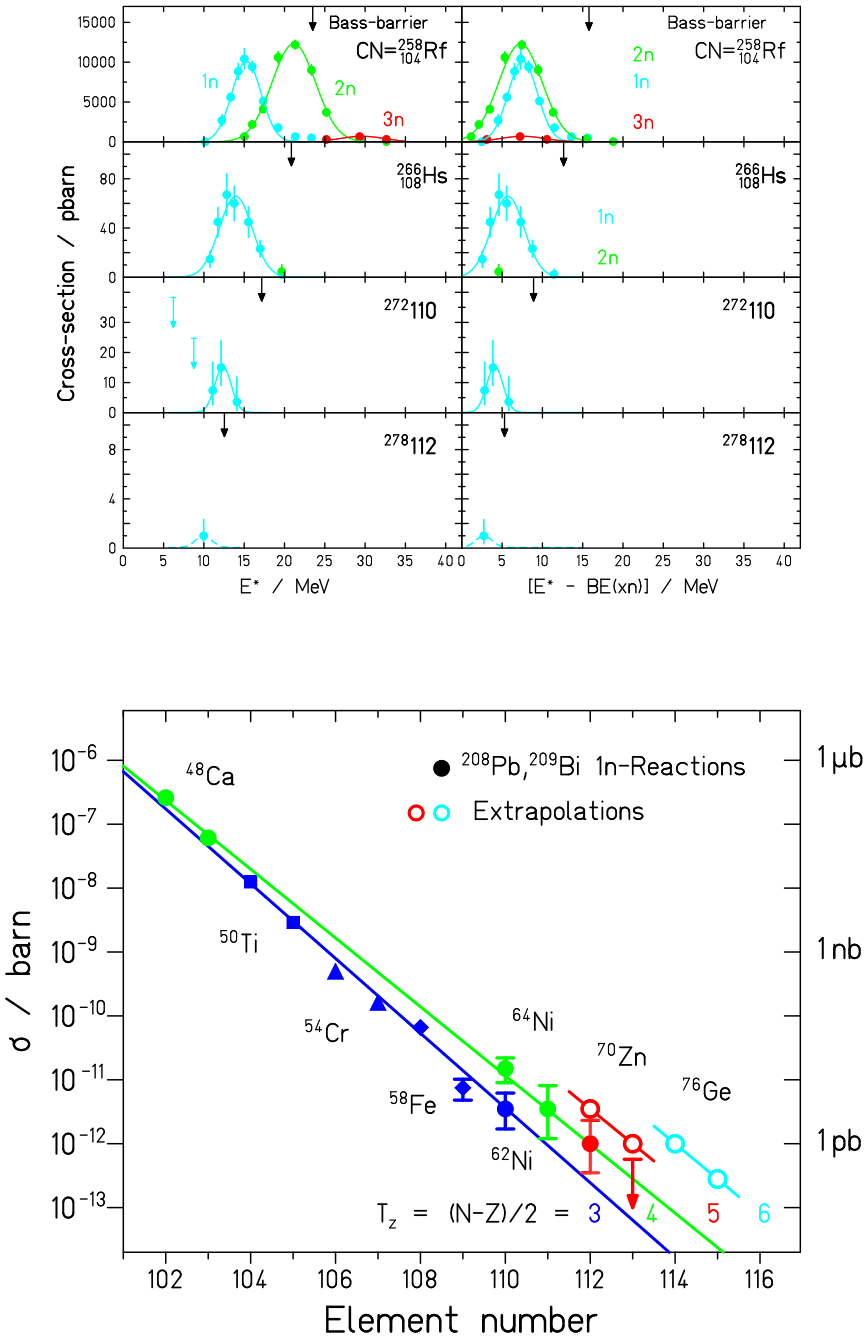


Figure 3: Upper part: Measured even-element excitation functions (solid curves) and extrapolation (dashed curve in the case of element 112). Lower part: Measured cross-sections for cold-fusion reactions (1n channel) using $^{208}$Pb and $^{209}$Bi targets.

a region of low background behind SHIP, and the highest currents can be used for producing the wanted species.

6. The installation of an ion-trap behind SHIP will considerably widen the possibilities for investigation of separated nuclei. Precise mass measurement, e.g., can be performed, and the electronic configuration of heavy ions can be studied by laser spectroscopy. These methods are well applicable to the study of relatively long lived species, as predicted for isotopes close to the center region of SHEs. More details of planned experiments are given in the SHIPtrap proposal.

7. The measurement of excitation functions is the most important topic in order to estimate the optimum beam energy for production of new elements and to learn more about the reaction mechanism. Particularly, the reactions $^{64}$Ni+$^{209}$Bi $\rightarrow$ $^{272}$111+1n and $^{70}$Zn+$^{208}$Pb $\rightarrow$ $^{277}$112+1n need to be studied for an optimum preparation of experiments searching for element 113 and 114.

8. Important for a better understanding of the cold-fusion reaction mechanism on a microscopic level is also the investigation of reactions using neighboring projectile or target nuclei and thus making small, however well defined changes. E.g., the reason for the cross-section increase for production of element 110 isotopes using $^{64}$Ni instead of $^{62}$Ni is not yet understood. An explanation would help in clarifying the usefulness of more neutron rich, radioactive projectiles for the synthesis of SHEs.

9. The energy window for production of heavy elements by cold fusion and 1n-evaporation channels gets more and more narrower with increasing element number. A possibility to overcome this limitation could be the *radiative capture* process or the use of less bound neutron deficient projectiles. The former reaction type is possible at free reaction energies less than the neutron-binding energy and the latter would increase the excitation energy at the fusion barrier to values needed for emission of a neutron.

10. A possible alternative to synthesizing SHEs by cold fusion is the hot fusion using actinide targets. Advantageous at increasing element number could be the decreasing excitation energy at the fusion barrier. The use of the strongly bound $^{48}$Ca as projectile is especially favorable. Studies using $^{48}$Ca as a beam are presently undertaken at FLNR–JINR in Dubna. At SHIP, the hot fusion was not investigated extensively so far, because of low transmission values. However, the investigation of more neutron rich isotopes using stable projectiles is only possible with actinide targets. The measurement of excitation functions, which are are known only very insufficiently, would provide a solid basis for extension of the experiments into the region of SHEs.

11. The reaction studies should be completed by investigating also symmetric reactions. In this case the projectile and target nuclei are close to the magic proton and neutron shell Z=50 and N=82 resulting in cold compound nuclei. In spite of great amount of extrapush energy predicted for symmetric reactions, the use of closed shell nuclei as projectile and target could result in interesting, so far not observed entrance-channel effects. The proposed reactions range from $^{124}$Sn+$^{124}$Sn $\rightarrow$ $^{248}$Fm$^{*}$ to $^{136}$Xe+$^{136}$Xe $\rightarrow$ $^{272}$Hs$^{*}$. The latter reaction would be the ideal case for the use of a gas-jet target.

12. Study of the deexcitation of the compound nucleus by in-beam $\gamma$ spectroscopy using the recoil-tagging technique. This method was recently applied in Argonne and in Jyväskylä for studying the 3-$\mu$b 2n-evaporation channel of the reaction $^{48}$Ca+$^{208}$Pb $\rightarrow$ $^{256}$No$^{*}$. With the use of the new highly efficient $\gamma$-detector arrays and a highly efficient recoil separator, these experiments could be extended to in-beam studies of lawrencium and possibly rutherfordium isotopes.

13. Experiments using the inverse reaction (beams of lead or uranium isotopes and targets of light elements) have different kinematic properties. The kinetic energy of the reaction products is high, and their momentum is directed into a more narrow cone. These properties may allow for an identification in flight at almost 100 % transmission through the separator.

14. Finally, the chemistry of the transactinide elements is of particular interest. Using SHIPtrap, the possible studies will be extended considerably compared with conventional radiochemical methods. The chemical behavior of relatively short lived isotopes ($T_{1/2}$<100 ms) can be investigated. Also, the study of the reaction kinematics using trapped ions will become possible.

# 2 Program for the upgrade of SHIP

The necessity for an upgrade of SHIP (Fig. 4) is based on the recently made and for the future expected ion-source developments at the UNILAC, both at the HLI injector as well as the new high current injector. Beam intensities ranging up to $5\times10^{13}$ and $3\times10^{14}$ /s, respectively, will become available. These currents are 1 – 2 orders of magnitude higher as used in SHIP experiments by now. Therefore, the upgrade will cover primarily three items:

1. **Development of target cooling and gas-jet targets for experiments at high beam intensities.**

2. **Improvement of the ion-optical properties of the separator with respect to high transmission and reduced background.**

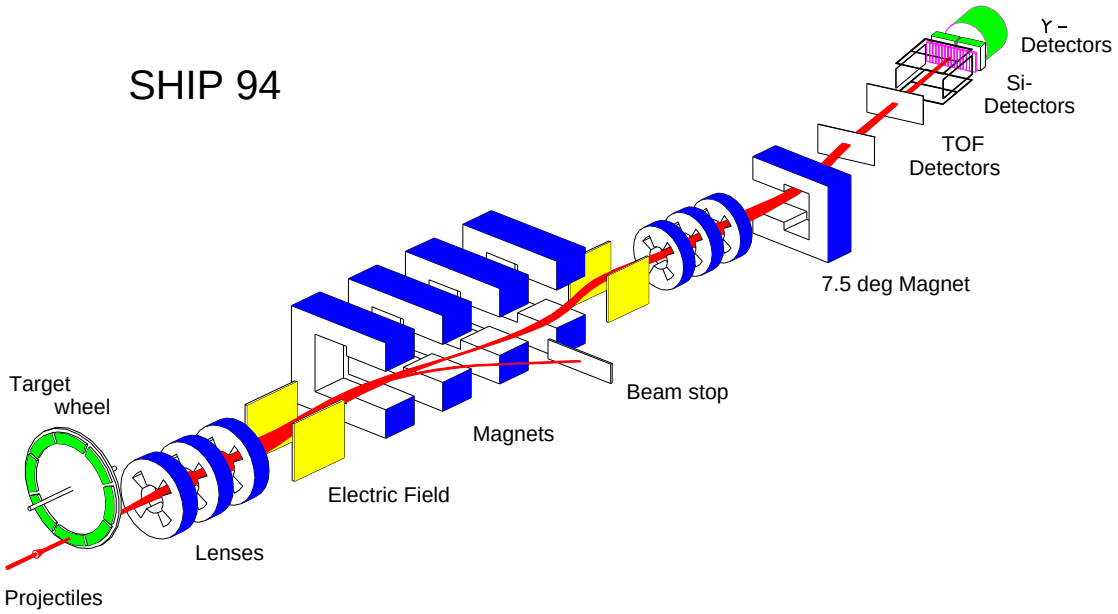


Figure 4: The 1994 version of SHIP. The proposed upgrade of SHIP-2000 is not yet drawn into the figure.

**3. Increase of the detector granularity and installation of an appropriate signal processing and data acquisition system.**

In the following Table estimates are given for the costs and the time schedule. Details of the planned upgrade are described in Appendix A to C.

An extensive reference list concerning the physics motivation can by found in Rep. Prog. Phys. 61, 639 (1998).
For the SHIPtrap proposal see http://www.gsi.de/∼shiptrap.
VEGA is a proposal for Versatile and Efficient GAmma-detctors, by J. Gerl et al., GSI, October 1998, p. 1-18, unpublished.

**Table 1: Costs and time schedule.**

| | Topic | Costs/1000 DM | Year |
|---|---|---|---|
| **1.a.** | **Gas-cooled target wheel**<br>vacuum chamber, pumps, target control, IR camera | **600** | **1999** |
| **1.b.** | **Gas-jet target**<br>extension of the gas-cooled target pumping system,<br>roots pumps, compressor, cleaner and gas cooler | **400** | **2000** |
| **2.a.** | **Separator upgrade for background suppression**<br>using existing NASE quadrupoles behind SHIP | **50** | **2000** |
| **2.b.** | **Separator upgrade for higher transmission**<br>large acceptance quadrupoles,<br>power supplies, vacuum chambers | **350** | **2001** |
| **3.b.** | **Detector and data acquisition upgrade** | **300** | **2001** |
| | **Total** | **1,700** | |

# 3 Collaborations

The work of the upgrade of SHIP and later of the experimental program will be performed within the following collaboration:

GSI SHIP
GSI KPII nuclear chemistry
GSI ion-source, accelerator and target laboratory, experiment electronic and data acquisition

Univ. Bochum
Univ. Bratislava
JINR Dubna
JYFL Jyväskylä
LBL Berkeley
GSI SHIPtrap collaboration
GSI VEGA collaboration

# Appendix

## A Target developments

The following aspects make the development of an improved or new target necessary:

1. Presently, we use low melting targets: lead with a melting point of 327 °C and bismuth, 271 °C. Bismuth is used for the investigation of odd elements and its lower melting point already caused a reduction of the UNILAC beam intensity during our last experiment searching for element 113.

2. The energy-loss in the target increases quadratically with the element number of the projectile. The values are, e.g., 6.2 MeV/(mg/cm$^2$) for 5 MeV/u argon in lead for production of fermium and 12.7 MeV/(mg/cm$^2$) for 5 MeV/u zinc in lead for production of element 112.

3. The recent ion source developments (PIG and ECR) resulted in currents up to about 1 p$\mu$A for $^{70}$Zn, e.g., and further increase of the current can be expected also from these conventional ion sources. Much higher currents will become available at the new 'High Current Injector'. For certain projectiles we may expect an increase by a factor of 10 to 50. Also important for the performance of the target and the separator is a change of the macropuls structure from now 50 Hz and 5.5 ms wide pulses to 16.7 Hz and 1 ms wide pulses at HCI.

In order to use the high currents in experiments searching for SHEs, we plan to develop two kinds of high current targets at SHIP, a gas-cooled target and a gas-jet target.

### A.1 Gas-cooled target, beam focusing and monitoring

In a first step, we plan to cool the presently used thin foil targets mounted on a rotating wheel. The cooling medium will be a stream of He, blown with low pressure (1 – 10 mbar) from both sides into the direction of the beam spot. The cooling effect of a gas acting on a target is well known from gas-filled separators and He-jet systems, where the currents could be increased by a factor 5 – 10 compared to targets in vacuum with only radiative cooling.

The gas-cooled target will be used in experiments, where the maximum current is limited by the accelerator to values from 1 – 5 p$\mu$A. This may the case in experiments using projectile isotopes of rare natural abundance, e.g. neutron rich isotopes from $^{48}$Ca to $^{70}$Zn. In these cases the ECR source will be used also in future because of its low consumption of material.

The cooling method will be also interesting in the cases, where the target material is not available in gaseous form or where radioactive, fixed targets will be used, e.g. curium or californium.

Another advantage concerns the ion-optical properties of the separator. These are mainly determined by the mean charge state of the projectiles and reaction products escaping from the target. In a low pressure helium medium of short length the charge states of the ions escaping from the solid target will not be changed, and thus the separator properties will not change compared to the presently used technique.

For the technical realization a differential pumping system has to be built, using for the main stream a turbo-molecular pump just below the target and two turbo pumps on either side of the target in order to reach a vacuum of $10^{-5}$ to $10^{-6}$ mbar at the exit of the UNILAC beam-line and to the entrance of SHIP. No windows will be installed to separate the different vacuum sections. A new target chamber has to be constructed allowing for the differential pumping. The four ion-getter pumps mounted at SHIP have to be replaced by turbo-molecular pumps.

A crucial item is also the intensity distribution of the beam across the target. The presently installed ion-optical elements allow only for a gaussian shaped beam intensity with still the highest intensity in the center region and tails at the outer areas. The former most likely melts the target in the middle and the latter causes background when hitting the target frame. The intensity distribution can be optimized using one or two octupole magnets in addition to the quadrupoles in the beam line in front of the target. With the use of these magnets an almost rectangular intensity distribution should be achievable.

The intensity distribution and the resulting temperature distribution across the target will be monitored by an infrared video camera. The monitor system will be developed so that it can be used also as a control of the beam current and beam position during the irradiation.

The gas-cooled target system should be available by the end of 1999. The preparations are underway. The work is being performed together with the people from the target laboratory, the ion-source group and the UNILAC.

## A.2 Gas-jet target

At the highest beam currents ($\geq$5 p$\mu$A) gas-jet targets will be mandatory. Densities of the order of $10^{18}$ atoms/cm$^2$ are required. Gas-jet targets of this type are already in use, e.g. in experiments for investigating reactions of astrophysical interest at the University of Bochum. There, helium is used as a target gas. In our case, gaseous compounds of lead and bismuth will be examined. Also experiments will become possible using targets of elements, which exist only on gaseous form, like krypton or xenon. The alternative of using high temperature vapor targets was examined,

however rejected, because of the complications due to the high temperatures needed ($\gtrapprox$ 1500 °K) and the less flexibility.

We are aware of some possible complications, which may arise from the use of a gas-jet target and are trying to estimate quantitatively their influence on the operation of SHIP. Using a gas-jet target, the separation properties of SHIP will be different, because of the smaller charge state of the ions escaping from a gaseous medium compared with a solid target. A resulting higher background, more than due to the higher beam current, may cause an additional separation stage behind SHIP. The interaction of an intense projectile beam with a jet of chemical compounds will result in cracking of a part of the molecules into its components. This effect may result in failures of the pumping system.

The technical design of the gas-jet target is so that the target wheel will be replaced by a Lavalle nozzle. In order to reach the desired density, gas pressures of 10 to 30 bar are needed. The resulting flow is about 40 g/s or 100 kg/h of a gaseous lead compound. This high amount of material demands appropriate pumping power and a recycling system. Therefore, the main parts of the pumping system will be a roots pump with subsequent compression, cleaning and cooling stage.

The gas-jet target will be able to accept the highest currents, however, the system is complicated, especially in the case of gaseous metallic compounds as target material. Therefore, we start with the gas-cooled target and design the target chamber and the differential pumping system so that most parts can be used also for the gas-jet target. Experience concerning the interaction of an intense heavy ion beam with a gas-jet and the resulting separation properties will be studied already using the pumping system prepared for the gas cooling, however, at a factor of 1000 lower gas densities.

In the case that the results of the preexperiments do not reveal severe objections, the final version of a gas-jet target could be available by the end of the year 2000. The developments are made together with people from the ion-source group, the target laboratory and the nuclear chemist group.

# B Upgrade of the separator SHIP

The purpose for the upgrade of SHIP is a further reduction of background and an increase of transmission.

## B.1 Background

Using high currents, we expect that the background rate will increase more than proportional with the intensity. The reason is an unavoidable beam halo due to space charge effects. This means that at a factor of 10 higher currents the background

rate on the detector will increase to more than 500 /s on the average. In reality, the beam is pulsed and the background rate during the 1 ms wide macropulses from HCI will be 30,000 /s. This high rate does not allow for data taking during the macropulse, only the pauses can be used, which restricts the experiment to search for daughter decays with half-lives longer than about 1 ms.

A solution to reduce the background considerably will be the extension of the already installed magnetic dipole behind SHIP by a quadrupole doublet. As proper elements we plan to use the already existing quadrupoles of the postseparator NASE. The complete NASE is not suitable, because its dispersive element is a 30° deflection magnet, which widens the beam too much, resulting in a transmission of only 30 %. The deflection angle of the presently used magnet is variable between 0° and 25°. In operation with the NASE quadrupoles the deflection angle will be optimized for highest background suppression and transmission.

This part can be finished in 1999, because all elements are on site, only a flexible support for the magnets has to be constructed and manufactured.

## B.2 Transmission

The calculated transmission for asymmetric, hot fusion reactions using actinide targets is a few percent only. The reason is the wider solid angle filled by the relatively slow reaction products due to recoil effects from the emitted neutrons (n≥3) and scattering in the target. Therefore, the potential of hot fusion for the production of heavy elements was not investigated yet systematically. In order to make this reaction type better accessible for SHIP, we plan to increase the solid angle after a careful study of ion optical calculations and reproduction of the results by transmission measurements.

The design work will profit from the experience gained at the VAMOS spectrometer at SPIRAL, GANIL. For VAMOS a large-acceptance quadrupole doublet was developed with an aperture of 200 mrad, whereas SHIP has presently 70 mrad opening angle.

The improvement of the transmission for hot-fusion reaction products takes also into account the requirements of SHIPtrap experiments for investigation of long lived isotopes of heavy elements. One region of long lived isotopes is situated at neutron number N=162 and accessible only by hot fusion. A larger aperture will also increase the transmission for the reaction products from cold fusion, our present method for the synthesis of new elements. A calculated value is 40 to 50 %, which could be increased to a value close to 100 %.

# C Detectors, signal processing and data acquisition

The presently used position-sensitive silicon detector array was developed during the years 1988 – 1990 for the identification of new isotopes by establishing $\alpha$-decay chains. The granularity of the detectors and the connected electronics allows for the measurement of decay sequences with lifetimes in a range from 3 $\mu$s to about 2 min. The upper time limit depends sensitively on the background rate. It could be prolongated by increasing the detector granularity, which is possible using new detectors with smaller pixel size or by defocusing the reaction products across a larger detector area. In both cases the signal processing has to be adapted to the higher number of channels. Automatic procedures for the setting of the electronics (amplification, baseline, threshold) and for the detector calibration are mandatory.

The extension of the SHIP detectors by $\gamma$ arrays and SHIPtrap demands medium-term an appropriate interface between the devices in order to take full advantage of the combined facilities.

Because the target and SHIP upgrade has priority, the upgrade of the detector and electronic system will not start before the year 2001.

# D Availability of the beam and concluding remarks

Experiments for the investigation of phenomena, which determine the limits of stability, will always need relatively long irradiation time. This will be the case also at higher beam currents and soon after realization of the proposed upgrades. In recent years the activity of work at SHIP was concentrated on the investigation of heavy elements. This strategy will be kept in the future. However, the investigation of heavy-ion fusion reactions by SHIP is promising also in the region of lighter nuclei. Examples are the proton radioactivity, isomeric states and other phenomena discussed in the VEGA and SHIPtrap proposal. Even concentrating on reactions with beams of stable projectiles only, the demand for beam time will increase in the future.

Presently, the extension of the GSI accelerator facilities is discussed, aiming at higher currents at relativistic beam energies and radioactive beams. Some of the proposals do not allow for a time sharing of the beam for high energy experiments and such at the Coulomb barrier. Trying to reach maximum beam intensities and high availability of the beam, showed up some problems in organizing an optimum beam schedule already using the present mode of parallel operation of ECR and PIG source. Several proposed experiments had to be postponed or were rejected.

The investigation of SHEs and the experimental program using the supplemen-

tary equipment like VEGA and SHIPtrap will need almost permanently a high current beam with energies at the Coulomb barrier ($E_p \leq 6$ MeV/u). Therefore, the planning of the future GSI accelerators should possibly take into account the construction of a specific accelerator for low energy experiments delivering high current DC beams. Such a solution may become necessary in the case that a high energy accelerator does not allow for a parallel operation with more than 80 % duty cycle and a permanent availability for low energy experiments, as it was possible by now.

The combination of an ECR ion-source and an accelerator capable of delivering DC beams would instantaneously result in an increase of the beam intensity at minimal consumption of source material. An intensity increase by a factor of 3.3 would arise from the prolongation of the duty factor from now 30 % to 100 %. Another factor of $\approx 2$ can be expected, if the accelerator could be constructed for ions of lower charge state, for which the ECR source delivers higher currents. Further options for increasing the current at high charge states are sources operating at higher microwave frequency: the development of a 30-GHz ECR sources is in progress at Grenoble.

# Attachment B

# Search for SHE using the hot fusion reaction $^{48}Ca + ^{238}U$

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**Continuation of experiments at SHIP, proposal no. 184, August 2004**

## Review

Our last proposal on the study of superheavy nuclei was presented to the users committee on June 25, 2001. Due to the relatively long period elapsed we want to present a short review at the beginning of our new proposal. This summary also explains why we propose to search for SHE at SHIP using hot fusion reactions, too.

An overview of the experiments performed since 2001 is given in Table 1. In Column 1 and 2 of the table we list the reactions and approved beam time which amounted to a total of 120 days. The beam time used actually is given in Column 5. Also listed are irradiations which were performed parasitically to a main user (R-201) or which became necessary due to technical trouble (R-205, R-212). The reasons for that will be explained in more detail below.

Experiments running perfectly were the searches for element 110 using a hot fusion reaction (R-200) and the search for element 113 using cold fusion (R-213). In R-200 we used an $UF_4$ target and two beam energies resulting in 39 and 48 MeV excitation energy, where the maximum of the 3n and 4n channel is expected. Cross-section limits of 1 pb were reached in both cases. In R-213 we used a $Bi_2O_3$ target. At 12.2 MeV excitation energy (1n channel) we reached a cross-section limit of 0.4 pb. This value is equal to the measured value for element 112 in the reaction $^{70}Zn + ^{208}Pb$. From cross-section systematics we expect about a factor of three less yield for element 113, which would correspond to a beam time of approximately 100 days. Another factor of three is needed, if statistical fluctuations are taken into account. This example clearly shows that the experimental sensitivity is reached, and a further machine upgrade towards higher beam intensity is needed.

R-201, although not approved, was performed using a parasitic beam to an SIS experiment; otherwise the low energy beam at the UNILAC would have been lost. In 2001 the Berkeley result on element 118 was still under discussion and we tried to further lower the cross-section limit. But we also used the $^{86}$Kr beam – as an investigation into the future – to get first experience with irradiation of a PbS target which has a significantly higher melting point (1118 °C) than metallic Pb (327 °C).

R-205 was twofold troublesome. After realizing instability of the beam energy due to failure of the single resonators we changed the beam to $^{58}$Fe in order to test both the beam energy and the PbS targets using the well studied reaction $^{58}$Fe + $^{208}$Pb → $^{266}$Hs*. Because the previous data (70 pb maximum cross-section corresponding to 10 events per day) could not be reproduced, we stopped this experiment and planned a detailed investigation of the new target material. We selected the reaction $^{54}$Cr + $^{208}$Pb → $^{262}$Sg* in order to compare the data using metallic Pb and PbS targets and to study the excitation function which was measured only insufficiently in the past.

Before starting this experiment, we made extensive studies of the structure of the PbS targets using electron microscopy. It turned out that PbS, if evaporated on a cold carbon backing, condenses in form of needles of about 10 µm length, which gives this material a nice velvety black surface, but makes it unusable as a target (a homogenous layer of 450 µg/cm$^2$ PbS would have a thickness of 0.6 µm). However, evaporated onto a heated backing, the PbS forms a homogenous layer. The three types of Pb targets were used and compared with each other in R-212. The result using the newly prepared PbS targets was very encouraging. The 1n excitation function was identical to the one measured with metallic Pb. As physical results we measured a new, unexpected high cross-section maximum of 2.5 nb for the 1n channel, we determined the positions of the 1n and 2n excitation functions accurately, and we obtained a first data point for the 3n channel. For that reason we plan to continue the investigation of Sg isotopes, for which high spin K isomers are predicted making these nuclei especially interesting. A proposal on this subject will be presented by B. Sulignano.

The two previously proposed experiments $^{70}$Zn + $^{207}$Pb and $^{70}$Zn + $^{198}$Pt were postponed, because of insufficient beam time available.

R-219 became possible, because another experiment at the UNILAC had to be unintentionally skipped. In our irradiation aiming to produce a heavy nucleus in a symmetric reaction we were confronted with a projectile background of several kHz at 100 pnA beam current. Nevertheless we determined an upper cross-section limit of 1 nb for the 2n channel (production of $^{258}$Rf) compared to 18 nb for the reaction $^{50}$Ti + $^{208}$Pb → $^{256}$Rf + 2n. For the future the study of symmetric reactions demands higher background suppression or as in the special case of detection of the spontaneously fissioning nucleus $^{256}$Rf ($T_{1/2}$ = 6.2 ms) a fission fragment detector which is not destroyed by a high projectile background during the macro-pulse. The data can be taken during the macro-pause due to the long enough half-life.

The beam time schedule allowed for running an experiment during the present period (R-222). The original plan to irradiate $^{238}$U with $^{48}$Ca had to be postponed, because a new evaporation set-up for the preparation of weakly radioactive targets is needed, which is presently under construction and will go in operation in autumn 2004. Therefore we chose to repeat the reaction $^{70}$Zn + $^{208}$Pb → $^{278}$112* in order to confirm the two decay chains measured at SHIP and to use the new PbS target prepared by evaporation of the target material on a heated carbon backing. First results should be available at the meeting of the users committee. For this beam time of 26 days we ask the users committee for subsequent permission.

Our results on the second decay chain of $^{277}$112 showing previously unknown spontaneous fission of $^{261}$Rf were confirmed recently at RIKEN. Using the same reaction two decay chains were measured [1]. Despite this positive result obtained at RIKEN we plan to improve the statistical accuracy of the data and to confirm the data from our first decay chain (measured on February 9$^{th}$, 1996), which showed α decay of $^{261}$Rf. The decay chain from February 1$^{st}$, 1996, was retracted [2].

In 2001 the original planning was to perform the approved experiments of a total of 120 days within about 1½ years. However, due to the energy and target problems at the beginning, the program had to be modified. Including the presently running experiment we used a beam time of 163 days within 3 years (54 days per year). At this point we would like to mention that with this comfortable amount of beam time available for SHIP experiments the actual planning was considerably simplified. This was especially important considering the limited total beam time available for experiments which have to use the ECR ion source and which makes the preparation of the beam time schedule extremely difficult. For that reason a sufficient amount of approved beam time is very useful. However, compared to the beam time available at Dubna and RIKEN, our mean value of 54 days per year is not enough to compete with these laboratories. As already mentioned before, an upgrade of the experimental facility is urgently needed. The improvement is especially important, because cold fusion reactions like $^{76}$Ge or $^{82}$Se plus $^{208}$Pb or $^{209}$Bi, which result in nuclei at and beyond the closed proton subshell Z = 114 and at increased neutron number, are still of highest interest in research of SHE beside the new region opened at Dubna using hot fusion reactions.

**Proposal**

For several reasons we postponed to use hot fusion reactions based on actinide targets in the past. 1. SHIP has lower transmission (10 – 30 %) for the evaporation residues produced in hot fusion reactions due to lower velocity and higher number of evaporated neutrons from the compound nuclei resulting in higher angular and velocity straggling, compared to the transmission of 40 – 50 % for residues produced in cold fusion reactions. 2. The limited beam time did allow for systematic work only for one type of reactions. 3. The high costs of enriched $^{48}$Ca and 4. It was widely believed that cold fusion is the better reaction for synthesis of superheavy nuclei.

This opinion was disproved by the results of a systematic study of hot fusion at FLNR in Dubna, which was performed since 1998 using the U400 cyclotron mainly for this purpose. All experiments were performed using a $^{48}$Ca beam which was developed with respect to high intensity (CW beams) and low consumption of material using an ECR ion source. Targets were prepared from isotopes of U, Pu, Am, Cm, and Cf. In the early experiments decay chains were measured only at one beam energy, which was too low as experienced in later experiments. Due to the high neutron number of the compound nucleus and the chains terminating after a few α decays by spontaneous fission, the newly measured chains were not connected to known isotopes. However, this drawback could be almost compensated by measurement of excitation functions and performing cross-bombardments. The recent Dubna results were published in [3]. A summary of the reactions and produced decay chains is given in Fig. 1.

Realistically the heaviest element which can be produced with a $^{48}$Ca beam is at Z = 118, because the targets of Es and Fm needed for heavier elements are only available in µg or ng quantities, respectively. Therefore beams beyond Ca are needed. In order to get information on the different properties of reactions using beams of $^{48}$Ca, $^{50}$Ti, $^{54}$Cr, etc. we propose to begin with an investigation of the reaction $^{48}$Ca + $^{238}$U → $^{286}$112* at the UNILAC, which later could be continued with the heavier beams, but keeping uranium as a target.

Preliminary data from Dubna [4] result in cross-section values of 0.5 and 2.4 pb at excitation energies of 31 and 35 MeV, respectively, for the 3n channel ($^{283}$112). A number of 1 and 7 decay chains were measured. For the 4n channel ($^{282}$112) a cross-section of 0.6 pb was deduced from 1 event measured at E* = 40 MeV.

According to the Dubna data the following decay properties of element 112 isotopes and daughter products which are relevant for our proposal are deduced:

| **Isotope** | **Events** | **Decay mode** | **Half-life** | **$E_\alpha$ / MeV** |
|---|---|---|---|---|
| $^{284}$112 | 12 | 100 % sf | 101 ms | |
| $^{283}$112 | 18 | > 90 % α | 4.0 s | 9.54 |
| $^{279}$Ds | 21 | 90 % sf + 10 % α | 180 ms | 9.70 |
| $^{275}$Hs | 2 | 100 % α | 150 ms | 9.30 |
| $^{271}$Sg | 2 | 50 % sf + 50 % α | 2.4 min | 8.53 |
| $^{267}$Rf | 1 | 100 % sf | 2.3 h | ≤ 8.22 |
| $^{282}$112 | 6 | 100 % sf | 0.5 ms | ≤ 10.82 |

The number of events includes those produced by α decay of heavier elements. At a total of 18 decays of $^{283}$112 in one case a decay chain down to $^{267}$Rf was measured. It belongs to the group of decay chains measured at 35 MeV excitation energy, where the maximum cross-section of 2.4 pb was obtained. This chain which occurred with a probability of 5 % is certainly the most interesting case of decays of Z = 112 isotopes which can be pro-

duced with a $^{238}$U target, because it leads down to N = 163, where strong shell correction energy exists due to a large single particle energy gap at N = 162. In this region also the most accurate theoretical data exist allowing for a reliable comparison with the experimental data.

To estimate the beam time for production of $^{283}$112 at the UNILAC and SHIP we use the following parameters:

| | |
|---|---|
| Beam current: | 500 particle nA ($^{48}$Ca) |
| Target thickness: | 400 μg-cm$^2$ ($UF_4$) |
| Efficiency of SHIP: | 25 % |
| Cross-section: | 2.4 pb |
| Time / event: | 8.0 days |

In order to detect a decay chain occurring with 5 % probability we would need 20 weeks of beam time, not taken into account statistical fluctuations. Because this is beyond the present possibilities, we ask for 6 weeks of beam time to start with an investigation of hot fusion reactions at SHIP by production of the isotope $^{283}$112 and study of its decay properties.

Before performing the main experiment using the expensive $^{48}$Ca beam, we propose to use for 8 days a $^{51}$V beam prepared by the PIG source and thus running in parallel to the therapy program, in order to sufficiently test the $UF_4$ targets prepared with the new evaporation set-up. This reaction would result in the compound nucleus $^{287}$115*, and if the cross-section would be on the order of 3 pb for the 3n channel like in the case of $^{48}$Ca + $^{243}$Am → $^{291}$115* [3], then there could be a small chance to observe one decay chain from $^{284}$115, which could decay down to the known isotope $^{260}$Lr ($T_{1/2}$ = 3 min, $b_\alpha$ = 0.75, $b_\varepsilon$ = 0.25).

The further planning of heavy element experiments at SHIP depends from the results of the proposed experiment. Proposals on the continuation of this work will be elaborated as soon as the new data are available.

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2. S. Hofmann et al., Eur. Phys. J. **A14**, 147, 2002.
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4. Yu.Ts. Oganessian and V.K. Utyonkov, private communication.

## Beam time request and expected number of events

| Reaction | σ / pb | events | days | goal |
|---|---|---|---|---|
| **$^{70}$Zn + $^{208}$PbS → $^{277}$112 + 1n** | **0.4** | **2** | **26** | **confirmation, presently running, subsequent permission asked for** |
| **$^{51}$V + $^{238}$UF$_4$ → $^{284}$115 + 3n** | **< 3** | **< 1** | **8** | **target test** |
| **$^{48}$Ca + $^{238}$UF$_4$ → $^{283}$112 + 3n** | **2.4** | **5** | **42** | **starting the study of hot fusion reactions at SHIP** |

**Table 1.** Beam time allocated on June 26, 2001 and experiments performed since then.

| Reaction | time allocated / day | run-nr. | date | time used / day |
|---|---|---|---|---|
| $^{40}$Ar + $^{238}$UF$_4$ → $^{278}$110 | 40 | R-200 | 23.08. - 19.09.2001 | 26 |
| $^{86}$Kr + $^{208}$PbS → $^{294}$118 | -- | R-201 | 07.11. - 20.11.2001 | 13 |
| $^{70}$Zn + $^{208}$Pb → $^{278}$112 | 15 | R-205 | 01.05. - 21.05.2002 | 20 |
| $^{70}$Zn + $^{198}$Pt → $^{268}$Hs | -- | R-205 | 21.05. - 23.05.2002 | 2 |
| $^{58}$Fe + $^{208}$Pb → $^{266}$Hs | -- | R-205 | 25.05. - 06.06.2002 | 13 |
| $^{70}$Zn + $^{207}$Pb → $^{277}$112 | 15 | ------ | | |
| $^{54}$Cr + $^{208}$PbS → $^{262}$Sg | -- | R-212 | 29.05. - 24.06.2003 | 21 |
| $^{70}$Zn + $^{209}$Bi → $^{279}$113 | 30 | R-213 | 11.09. - 17.10.2003 | 36 |
| $^{70}$Zn + $^{198}$Pt → $^{268}$Hs | 10 | ------ | | |
| $^{136}$Xe + $^{124}$Sn → $^{260}$Rf | 10 | R-219 | 06.05. – 11.05.2004 | 5 |
| $^{70}$Zn + $^{208}$Pb → $^{278}$112 | -- | R-222 | 17.08. - 13.09.2004 | 26 |
| total | 120 | | | 162 |

Zr Y Sr Rb Kr Br Se As Ge Ga Zn Cu Ni Co Fe
Zn Cu Ni Co Fe Mn Cr V Ti Sc Ca K Ar Cl S
Fm Es Cf Bk Cm Am Pu Np U Pa Th
X X X
$X_e$ + $^{208}Pb, ^{209}Bi$
X + $^{238}U$
$^{48}Ca$ + X
Proton number
Neutron number

# Attachment C

# Active proposals and current research activities in SHE chemistry program

## At SHIP

UNILAC proposal No. U179 (beam time allocated April 2004)
**Nuclear Structure Investigations of Neutron Deficient Nuclei in the Region Z=103 to 105**
F.P. Heßberger (GSI, Spokesman) for a
GSI Darmstadt – JINR Dubna – University Bratislava – University Jyväskylä - collaboration

UNILAC proposal No. U184 (beam time allocated 2001-2004, continuation request appraised at EA meeting 09/04)
**Search for SHE using the hot fusion reaction $^{48}$Ca + $^{238}$U**
(title of continuation request)
S. Hofamnn (GSI, Spokesman) for a
GSI Darmstadt – JINR Dubna – University Bratislava – University – Universität Frankfurt – Universität Mainz - University Jyväskylä – collaboration

UNILAC proposal No. U207 (approved by EA, two exp. runs in 2004)
**Optical Spectroscopy of the Element Nobelium (Z=102)**
H. Backe (Universität Mainz, Spokesman) for a
Universität Mainz – GSI Darmstadt – collaboration

UNILAC proposal No. U209 (approved by EA, beam time requested for 01/05)
**Nuclear Structure Investigations of Neutron Deficient Isotopes of Nobelium and Lawrencium**
F.P. Heßberger (GSI, Spokesman) for a
GSI Darmstadt – JINR Dubna – University Bratislava – University Jyväskylä - Universität Mainz - collaboration

UNILAC proposal No. U211 (submitted to be appraised by EA 09/04)
**Study of the even-even nucleus $^{260}$Sg using the reaction $^{54}$Cr + $^{207}$Pb**
B. Sulignano (GSI, Universita di Napoli, Spokeswoman) for a
GSI Darmstadt – JINR Dubna – University Bratislava – University Jyväskylä - Universität Mainz – Universita di Napoli - collaboration

## In nuclear chemistry

UNILAC proposal No. U182
**Studies of chemical properties of element 106 (Seaborgium) and 108 (hassium) and methodological developments for studies of the spherical superheavy elements**
J.V. Kratz (Univ. Mainz, Spokesperson) for a
University Mainz – GSI Darmstadt – JAERI Tokai – Niewodniczanski Insitute Krakow – University Warsaw – IMP Lanzhou – collaboration

UNILAC proposal No. U185/U208
**Gas phase chemical investigation of element 112**
H.W. Gäggeler (Univ. Bern, Spokesperson) for a
University Bern – PSI Villigen – GSI Darmstadt – University Mainz – TU München – LBL Berkeley – IMP Lanzhou – collaboration

UNILAC proposal No. U205
**Decay porperties of nuclides near Z=108 and N=162 and development of a gaschemical separation scheme for element 112 and 114**
A. Türler (TU München, Spokesperson) for a
TU München – GSI Darmstadt – University Mainz – FLNR Dubna – JAERI Tokai – IMP Lanzhou – collaboration

UNILAC proposal No. U210 (submitted to be appraised by EA 09/04)
**Search for "missing" α emitters in the transuranium region for mass evaluation of superheavy elements**
Yu.N. Novikov (Nuclear Physics Insitute Gatchina, Spokesperson) for a
Petersburg Nuclear Physics Institute Gatchina – GSI Darmstadt – IMP Lanzhou - University Mainz - collaboration

GANIL proposal No. E474S (pending)
**Isospin dependence in the production of heavy-element nuclei from complete-fusion neutron-evaporation reactions with n-rich, radioactive ion-beams from SPIRAL**
M. Schädel (GSI Darmstadt, Spokesperson) for a
GSI Darmstadt – IPN Orsay – University Mainz – GANIL Caen – FLNR Dubna – TU München – collaboration

Within the framework of GSI's official collaboration with the Japan Atomic Energy Research Institute (JAERI) the GSI nuclear chemistry group is involved in and is collaborative partner of the JAERI Tokai group in experiments on the **chemistry of elements 104 and 105**. These are performed at Tokai in a large Japanese collaboration.

# The
# *T*rans*A*ctinide *S*eparator and *C*hemistry *A*pparatus
# "TASCA"

**A very brief project description prepared for the**
**Meeting of the Heavy Element Evaluation Committee**
**at the GSI on October 15, 2004**

**by Matthias Schädel (GSI)**
**for the TASCA collaboration**

# I. Introductory remarks, aims and developments

After the first series of detailed experiments on the chemistry of elements 104 and 105, first successful steps towards the chemistry of element 106, and the perspective to move on to even heavier elements it became clear by the mid-90's that for a large number of chemistry experiments in the superheavy element region, a physical (recoil) pre-separator would be extremely helpful or even mandatory. Important reasons are:

- The need to get rid of the very intense primary heavy-ion beams for an efficient transport of the desired superheavy elements to a chemistry apparatus.
- The need to get rid of strongly interfering and unwanted nuclear reaction products, like Po isotopes.
- The option to apply completely new chemical systems and techniques if attached to a recoil separator.

First specific proposals in this direction were discussed at the "Workshop on the Physics Using Compound Nucleus Separators" at Berkeley in April 1997. The Berkeley Gas-filled Separator (BGS), also serving many other purposes, was the logical next step in this direction. It is presently the first and only site at which a heavy element chemical program is carried out behind a recoil separator. Successful heavy element experiments have been performed - and a continuation is planned – with the fast continuous liquid-liquid extraction system SISAK. A first glimpse into what is possible if the large variety of organic compounds can be utilized in the gas-phase was demonstrated at the BGS.

One of the essential ingredients of such a coupling is the technologically not so trivial recoil transfer chamber (RTC) which replaces the focal plane detectors in a chemistry experiment. The Berkeley group has already significantly improved earlier versions of this chamber also developed at LBL. Most recently, the RIKEN group has built a miniaturized RTC – an important ingredient to minimize the transport time. This can be seen as the start to couple chemistry set-ups to the GARIS separator for heavy and superheavy element chemistry.

The scientific motivation, envisaged experiments, desired and required constraints on the separator performance, alternative separator schemes – e.g. gas-filled recoil separators vs separation in vacuum, and many other aspects were discussed in great depth in three workshops. The first "Workshop on Recoil Separator for Superheavy Element Chemistry" was held at the GSI (March 2002). The participation of about 80 scientists from 20 institutes and 11 countries demonstrated the great interest in this subject and the community was formed; at first dubbed "ChemSep" now TASCA.

Among others, the community agreed on the following items and design goals:

- There is an urgent need for a "ChemSep" (now called **TASCA**) at the GSI
  - for **SHE chemistry (104≤Z≤116)** experiments coupled to TASCA
  - for **nuclear structure and nuclear reaction studies** of the heaviest most n-rich nuclides
- TASCA will be a tool **complementary to SHIP**
- TASCA shall separate products from **hot fusion** reactions with **actinide targets**
- TASCA targets shall accept the **highest possible beam intensities** (windowless operation)
- The main goal is the **highest possible transmission / efficiency** and the use of **thick targets**
- A **separation factor of $>10^4$** for interfering transfer products is desirable and seems feasible
- The hot fusion **reactions $^{48}$Ca + $^{238}$U, $^{248}$Cm** shall be used as a reference for design optimization
- High efficiency also for products from **more asymmetric reactions** ($18 \leq A \leq 40$ projectiles)
- **Small focal spot size** to minimize transport times into chemistry set-ups

The second workshop was held at Berkeley (Nov 2003). Originally intended to discuss a large variety of topics related to the "ChemSep" community, including a move of the BGS to GSI if operation of the 88-inch cyclotron would not continue into the mid-term future, the emphasis of this workshop shifted when it became clear that the 88-inch cyclotron would continue operation. Physics and chemistry at the BGS and the continuation of this research was discussed under the specific conditions that the 88-inch cyclotron is not a completely open, international user facility anymore.

The most recent and third workshop, TASCA04, Aug 2004 at GSI, with 50 participants from 12 countries concentrated on

- the status of the superheavy element "discovery" experiments,
- preparations and first results of heavy element chemistry experiments behind recoil separators,
- the status of the actual preparation of TASCA@GSI, and
- the formation of working groups for specific tasks to built and operate TASCA

The rest of this document is mainly based on contributions given to the TASCA04 workshop. Many details, like the list of participants, the program, downloads of all contributions etc., can be found on the following web sites:

1. For the first workshop at GSI (March 2002): http://www-w2k.gsi.de/chemsep02/

2. For the most recent workshop at GSI (August 2004): http://www-w2k.gsi.de/tasca04/

# II. Status of the TASCA project

Due to severe budget limitations on the one hand and the urgent need for a pre-separator on the other hand the TASCA community proposes a two step procedure. **At first**, design, build, test and operate TASCA as (an inexpensive) gas-filled separator making use of the existing components of the old NASE (or HECK) separator. **In a second step**, use the experience at TASCA and other separators to design and build an optimized separator – gas-filled or separation in vacuum - according to the needs of the community and to the, at that time, technical and financial constraints. The following part will only deal with the first step mentioned above.

After it became clear in November of 2003 that the BGS could continue an experimental program at the 88-inch cyclotron – and therefore would not move to GSI -, immediately preparations began to built TASCA at GSI. At first, this started as a joint effort of A. Türler's group at the Institute für Radiochemie, TU München - with A. Semchenkov as the most experienced person -, the GSI nuclear chemistry group and participation of the SHIP group (D. Ackermann). Soon, the UNILAC user community, the UNILAC accelerator group, and all relevant infrastructure groups at GSI were informed and got involved (see below). In the course of the TASCA04 workshop many other institutes joint (see Section III.). While there was **always strong "moral" support from the GSI administration** to move into this direction, **now is the time that we need a decision of the GSI directorate to support this project, make the financial resources available and to give us a green light**.

# A. The separator

Design studies and ion-optical calculations were performed based on the premise to build a gas-filled separator mainly with the remaining NASE components – one dipole and two quadrupole magnets (with vacuum chambers and support structures) and two power supplies. As the model reaction for the design studies we used 240 MeV **$^{48}$Ca($^{238}$U,3n)$^{283}$112** assuming a target thickness of 0.5 mg/cm$^2$ and a He filling of the separator. All figures in this Subsection A are from the contribution of A. Semchenkov at the TASCA04 workshop who also did the calculations and the optimization (see http://www-w2k.gsi.de/tasca04/ for the complete contribution).

We started out to determine the expected charge state of $^{283}$112 in the recoil energy range of 30 MeV to 40 MeV. Figure 1 shows the results of three different approaches to calculate the charge state – according to the the formulas determined by Yu.Ts. Oganessian et al. several years ago, by K.E. Gregorich used for the actual BGS operation, and by the GARIS group at RIKEN (reported by H. Kudo).

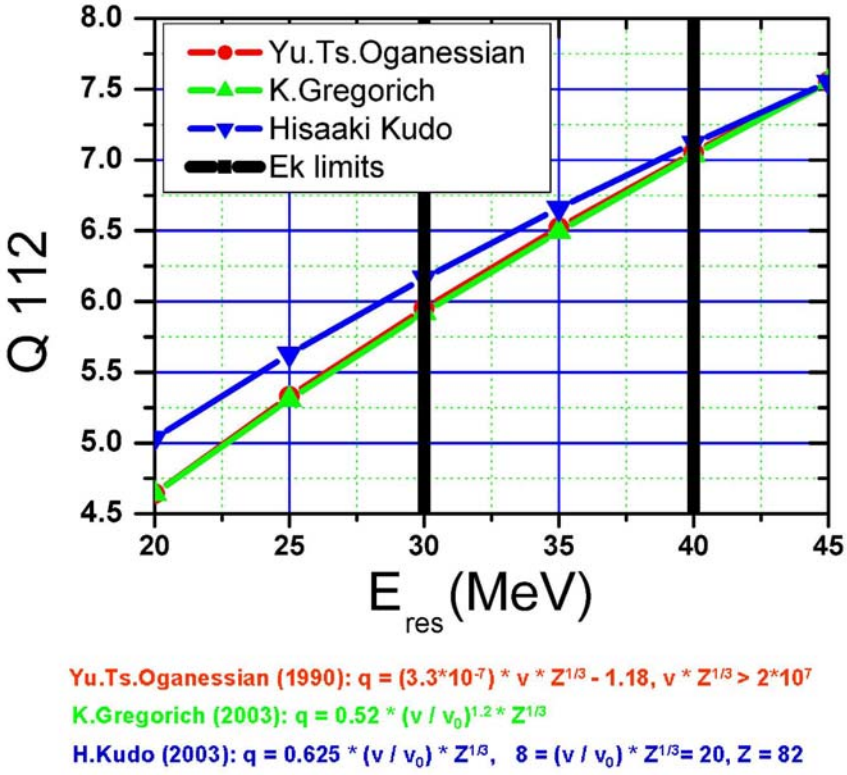



**Figure 1.** Charge states calculations for $^{283}$112 recoils in the energy range of 30 MeV to 40 MeV.

In our next step, we compared the magnetic rigidity of $^{283}$112 with the maximum rigidity of the existing NASE dipole magnet, see Figure 2. It was found that at the highest possible magnetic field, and assuming the lower charges states according to Oganessian and Gregorich, a separation of $^{283}$112 recoils with energies as low as 30 MeV should be possible. The charge states used in the GARIS settings would allow separating even much slower $^{283}$112 recoils in the NASE dipole. From this result, and from the option to slightly change the entrance and exit angle into and out of the dipole, in other words change the radius or flight path length, we are confident that the NASE dipole can be used in the TASCA project.

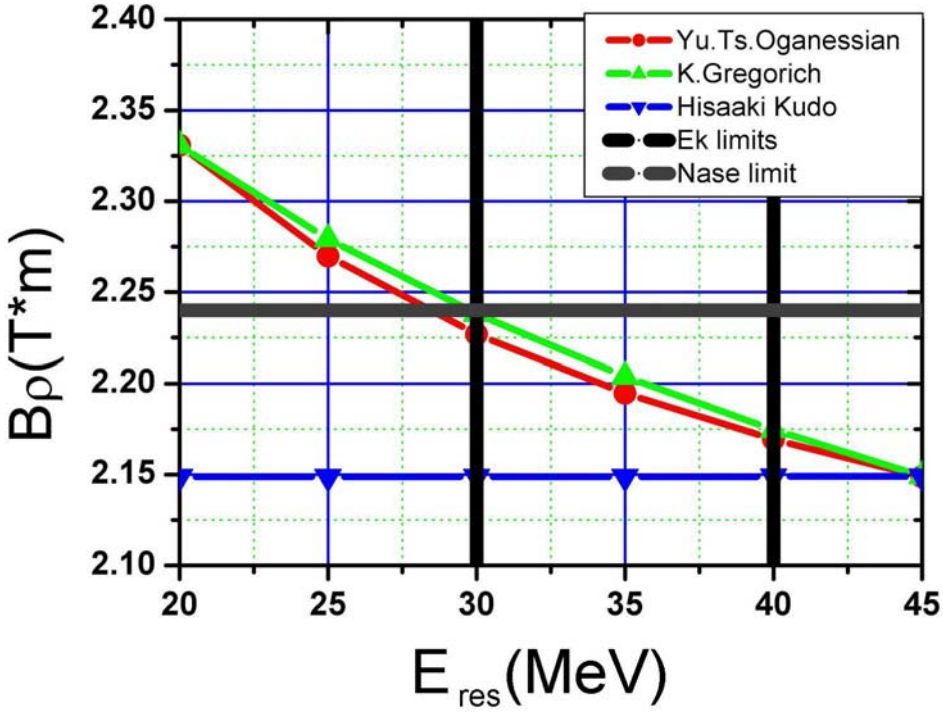



**Figure 2.** Magnetic rigidity calculations according to three assumed different charge states. The black horizontal line indicates the magnetic rigidity limit of the existing NASE dipole magnet and vertical lines the expected $^{283}$112 recoil energy range of 30 MeV to 40 MeV.

Based on these considerations, and on the option that we can get an additional spare quadrupole magnet from the UNILAC group, transport calculations were made for a number of combinations of the dipole magnet and the quadrupole magnets. As additional input parameters we used the following data:

- 54% of $^{283}$112 recoils will appear within ±40 mrad (according to simulations made by K.E.Gregorich)
- Horizontal and vertical beam size is ± 2.5 mm
- Horizontal and vertical inclination of the beam is ± 40 mrad
- Momentum dispersion is ± 5% (92% of all $^{283}$112)
- Magnetic rigidity is 2.24 T*m

One example of such a transport calculation with a $DQ_HQ_V$ configuration is shown in Figure 3 using the existing NASE components. A summary of all these calculations is depicted in Figure 4. It also gives the calculated image size (without straggling in He) and the transmission through TASCA for each configuration. From these calculations, which will be complemented by Monte Carlo calculations, we propose to start the TASCA project with a DQQ configuration but leave additional space in front of the dipole magnet to possibly install an additional quadrupole magnet in front of the dipole at a later stage. Such a QDQQ configuration has given best results for the improved version of the RITU separator at Jyväskylä.

In the DQQ configuration we have the advantage that we can easily switch from a $DQ_HQ_V$ configuration – the optimum for experiments which need highest efficiency – to a $DQ_VQ_H$ configuration – the optimum for experiments which require a very small image size -, as shown in Figure 4.

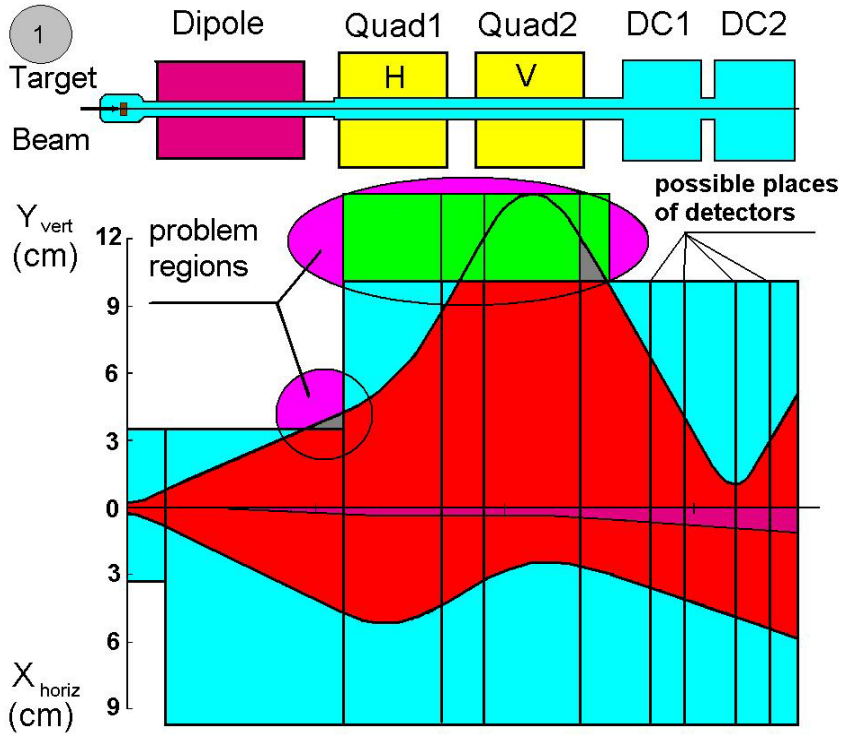



**Figure 3.** Transport calculation for a $DQ_HQ_V$ configuration also showing problematic regions in the existing vacuum chambers and the change of image size for various positions along the two existing detector boxes (DC1 and DC2).

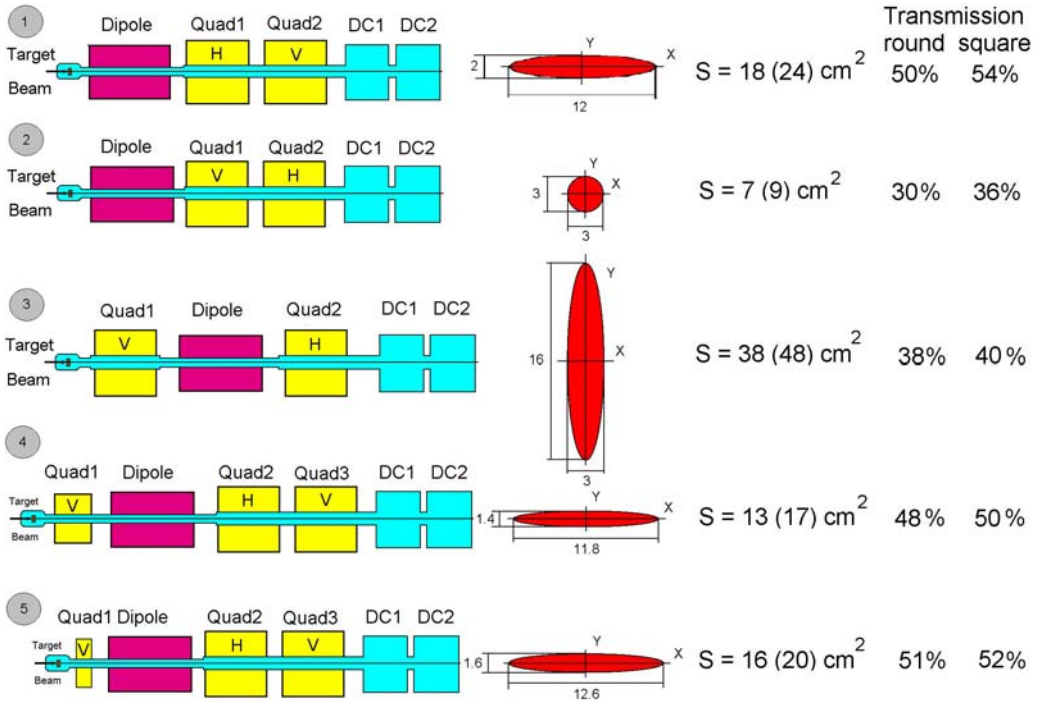



**Figure 4.** Results of the design optimization of TASCA with existing magnets (1-4) and one case (5) with a superconducting quadrupole in front of the dipole. The dimensions of the image size is given for each configuration. Transmissions (in absolute numbers) are listed for the situation with the existing vacuum chambers in the quadrupole magnets ("round") and an improved version with squared tubes.

As mentioned before, the dipole magnet and the two quadrupole magnets are at our disposal. Presently, mapping of the magnetic field of the dipole is under way at a test bench at GSI to confirm data from an earlier specification. Also existing are the two power supplies for the quadrupole magnets, one set of vacuum chambers, all support structures and the detector chambers.

What we need is a third power supply (80 V, 700 A) for the dipole magnet. We would be able to begin experiments with the existing vacuum chambers and beam dump. However, it would be highly desirable to start right from the beginning with at least an improved version of the (far away from optimum) vacuum chamber and beam dump in the dipole magnet. Squared vacuum tubes in the quadrupoles will increase the efficiency and it would be desirable to put them into place before going to experiments with superheavy elements.

## B. Beam line, cave, infrastructure

The **X8/9 UNILAC beam line** and cave position was selected as an ideal position for TASCA. It has several advantages which, in this combination, can only be found at X8/9:

- Sufficient space for the separator and the attached experimental set-ups
- Sufficient space for the necessary shielding
- Beam sharing (parasitic operation) between Y-branch (SHIP) and X-branch (TASCA) possible
- Existing beam line capable to deliver beams in the desired intensity and "quality"
- The controlled area radiochemistry laboratory to handle high level open radioactive sources, targets and to perform chemical separation is in close vicinity.

A floor plan of TASCA in the X8/9 area is shown in Figure 5 assuming the maximum number of envisaged ion-optical components in a QDQQ configuration which will require the maximum space. The beam line to TASCA includes components of beam diagnostics, a fast acting valve, a beam wobbler, a section for differential pumping (windowless operation) and a target box for rotating actinide targets.

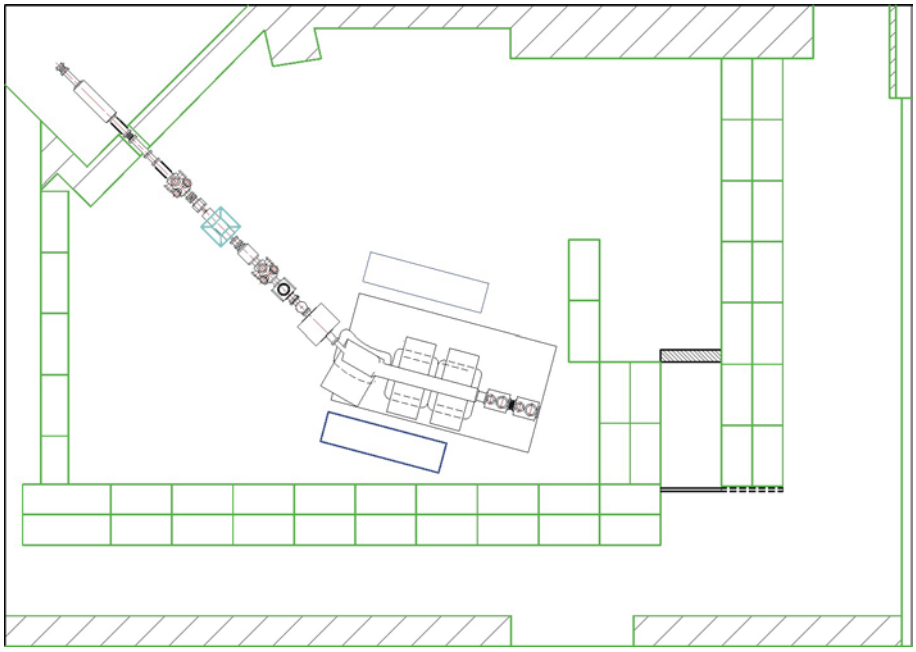


**Figure 5.** Floor plan of TASCA in a QDQQ configuration in X8/9. Green lines represents concrete shielding walls and the two blue rectangles mobile paraffin shielding walls.

The proposed **location of TASCA in the UNILAC experimental hall** is shown in Figure 6. This figure shows one of the possible options which is currently under consideration. It would allow using presently existing concrete shielding blocks (no more shown in this Figure 6) along the X beam line to build the new walls around X8/9. Taking out the existing wall would also make service and repair work along the X beam lines much easier. A cost estimate is under way, whether this option is more favorable as compared with a second option to simply leave the existing shielding walls along the X beam line and build the X8/9 cave independently.

The statics of the floor of the experimental hall was checked - whether it will support the extra concrete shielding - and a solution was found to build the shielding walls without any need for extra support structures in the basement.

Cost estimates are also almost completed for all other infrastructure measures, like a crane, connections of the magnets to the power supplies, electricity for beam line and experimental components, pressurized air, cooling water, filtered and unfiltered exhaust lines for gases, communication systems, and connections to the computer network.

While a number of components in the beam line to TASCA exist already, including chambers and large components like a roots pump and a turbo-molecular pump (TMU), more components are needed to complete the beam line. These are one additional TMU, a beam wobbler, a fast acting safety valve, the chamber for differential pumping, and a target chamber for the rotating actinide targets. In addition, an automated gas supply and control system is needed to maintain a constant gas pressure in the separator.

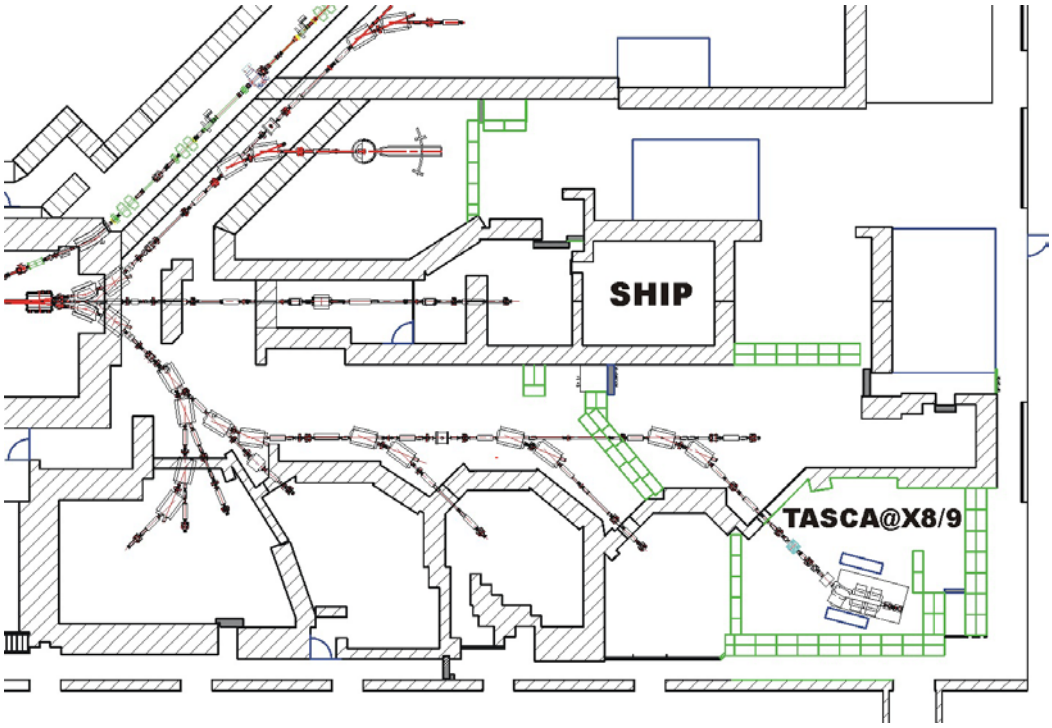



**Figure 6.** Location of TASCA at X8/9 in the south-east corner of the UNILAC experimental hall.

**Radiation dose calculations** were performed by G. Fehrenbacher (Head of the Radiation Safety at GSI). They were **based on the shielding shown in Figures 7 and 8** and on the heavy-ion beam intensities listed in Table 1. As a maximum energy 6 MeV/u was assumed together with Ta as the beam dump material located in the vacuum chamber of the dipole magnet. These **calculations show that the planned shielding is sufficient also for a future operation with high beam currents**.

**Table 1.** List of typical maximum heavy-ion beam intensities

| Ion | max. beam current until 2008 ions /s | max. beam current after 2008 ions /s |
|---|---|---|
| $^{4}$He | 1 x E+13 | 2 x E+13 |
| $^{12}$C | 1 x E+13 | 2 x E+13 |
| $^{18}$O | 1 x E+13 | 6 x E+13 |
| $^{22}$Ne | 1 x E+13 | 6 x E+13 |
| $^{40}$Ar | 1 x E+13 | 6 x E+13 |
| $^{48}$Ca | 1 x E+13 | 3 x E+13 |
| $^{86}$Kr | 1 x E+13 | 3 x E+13 |

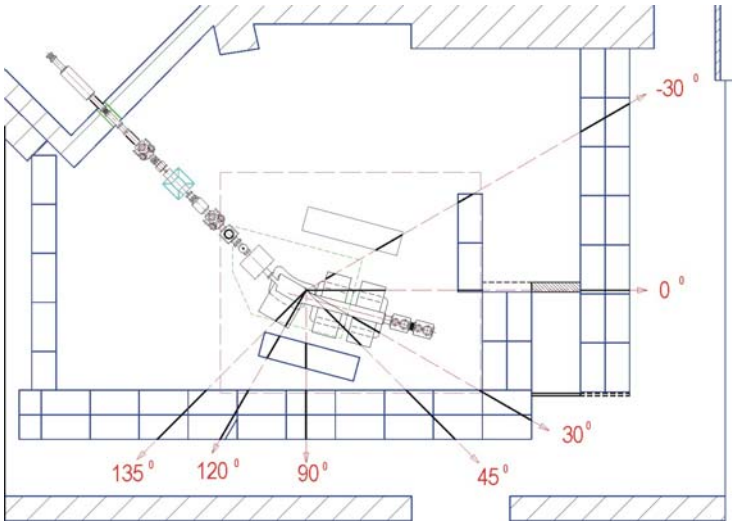



**Figure 7.** View from the top into the cave X8/9 used for radiation dose calculations.

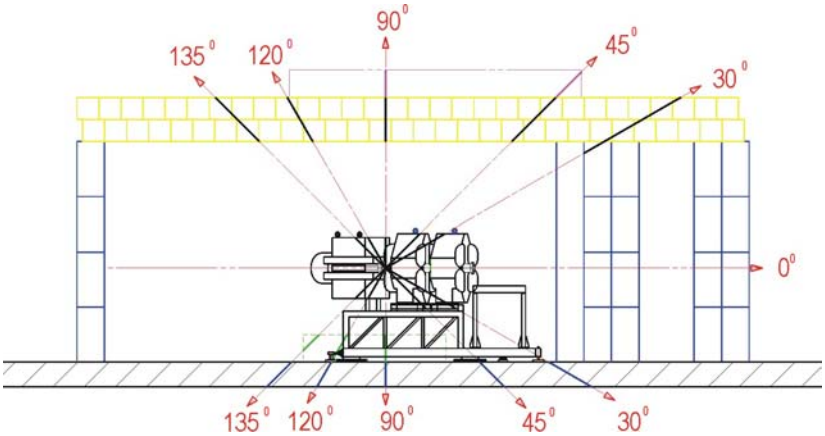



**Figure 8.** View from the side into the cave X8/9 used for radiation dose calculations.

# III. Collaboration partners and duties

At the end of the TASCA04 workshop **groups formed to start working on designated tasks and working packages**. For each task one person was elected to coordinate the work within his group and to be the contact person for the project coordination which lies at the GSI (M. Schädel). In addition, a number of consultants and advisors volunteered to help, guide and assist us in the TASCA project. Tasks, the responsible coordinator and collaborating institutes are summarized in the following part (the list of collaborations include the advisors):

**Task A: Differential pumping and gas control** (pressure, purity, exhaust, recycling, ...)
A. Türler (TU München) with JYFL Jyväskylä – GSI Darmstadt – LBL Berkeley - RIKEN

**Task B: Target** (preparation, rotation, safety, control, cooling ...), **window and collimator**
K. Eberhardt (Univ. Mainz) with GSI Darmstadt – LBL Berkeley - FLNR Dubna

**Task C: Separator**

**Subtopic 1: Ion optics, magnets and power supplies**
A. Semchenkov (TU München and GSI) with LBL Berkeley - FLNR Dubna - JYFL Jyväskylä

**Subtopic 2: Mechanics** (support structures, vacuum chambers, beam dump, ...)
M. Schädel (GSI Darmstadt) with JYFL Jyväskylä

**Task D: Focal plane**

**Subtopic 1: Detectors, data acquisition**
D. Ackermann (GSI Darmstadt) with TU München - JYFL Jyväskylä

**Subtopic 2: RTC, transport**
A. Yakushev (TU München) with LBL Berkeley – PSI Bern – Univ. Mainz – Univ. Oslo

There was a general consensus that many additional working packages, like civil engineering, infrastructure, operation permits, beam lines, wobbler, beam trafo, safety interlocks and controls, are the duty of the GSI group(s).

While the preparation of the separator part of the TASCA project is under way as discussed above, it is necessary to stress the point that, simultaneously, many nuclear chemistry groups worldwide are investing significant amounts of manpower and money in the **development of chemical separation schemes, new techniques and automated chemistry set-ups specifically devoted to the use in combination with a physical recoil separator**. Most active are the groups at Berkeley, Bern, Mainz, München, Oslo, and Villigen.

# IV. Time table

Under the assumption that the TASCA project would get "a green light" from the GSI directorate before end of 2004 - together with the allocation of financial resources for the year 2005 -, we would be able to set up the separator within the year 2005, commission and testing it in 2006 and do the first heavy element experiments in 2007.

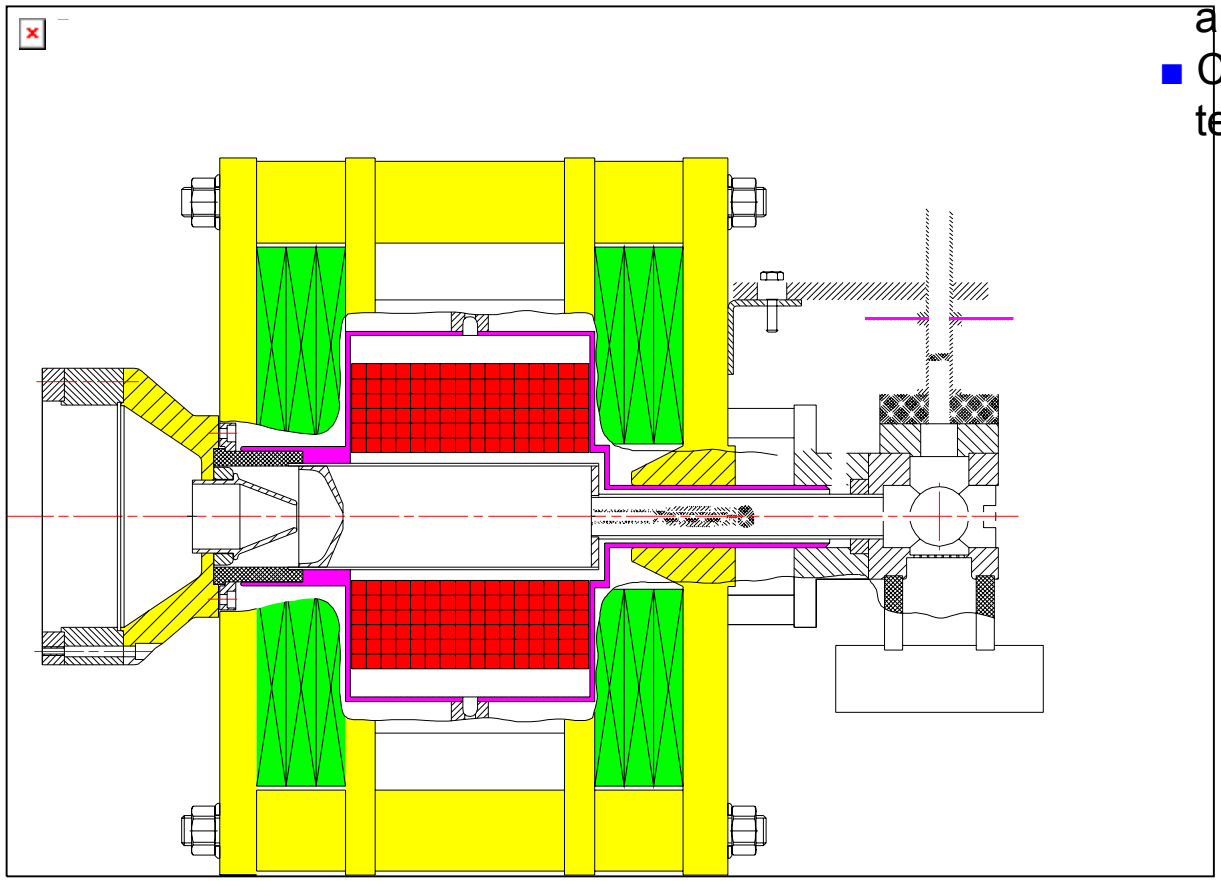
# Steps towards an Optimized Linac for SHE Production at GSI

U.Ratzinger

**Workshop on the Future of Superheavy Element Research**
February 17 - 18, 2004, GSI Darmstadt, Germany

- Improved ion source for high charge state production.
- Upgrade of the existing UNILAC.
- Two heavy ion linacs for different duties.
- Design of a cw superconducting linac.

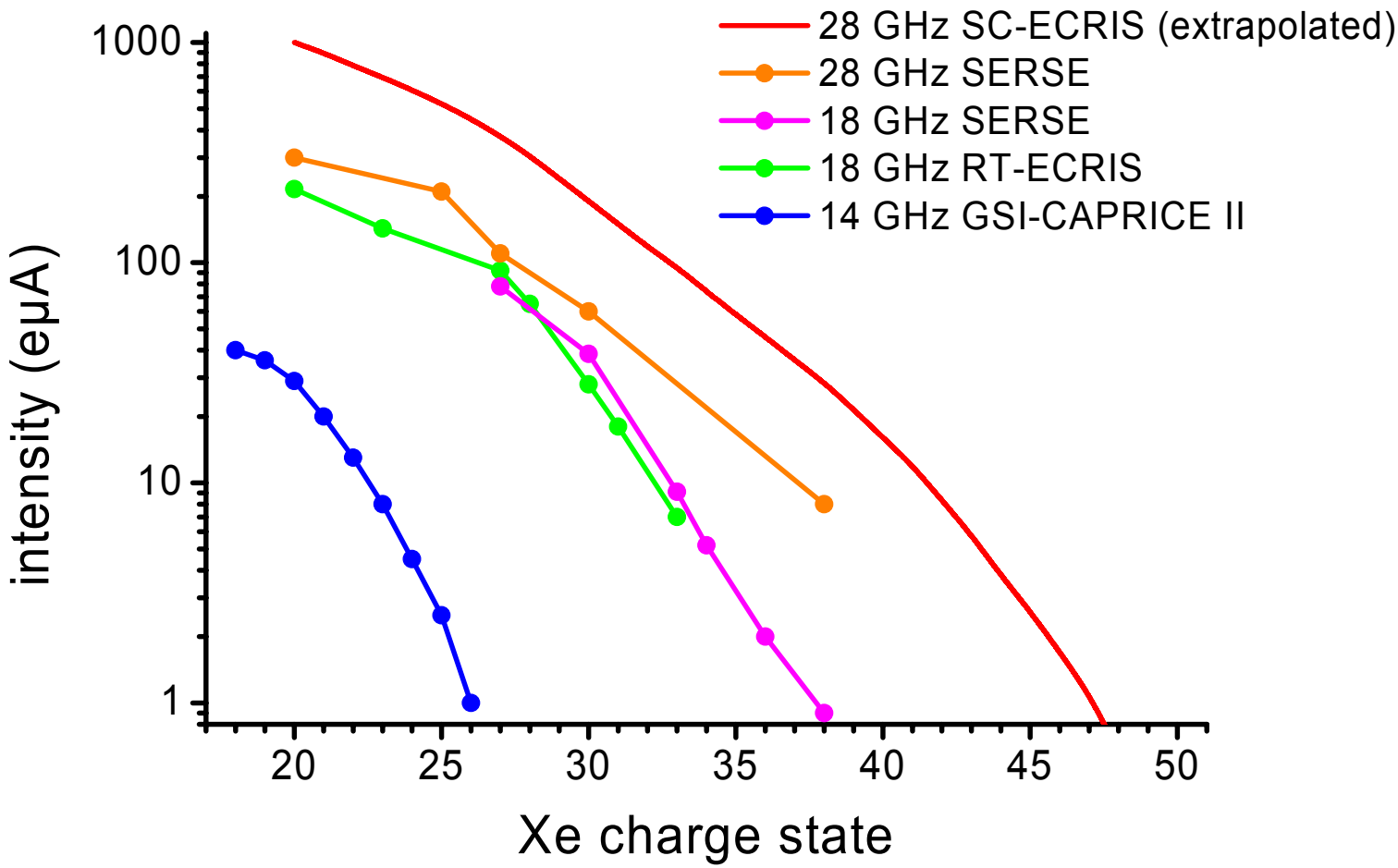
# GSI-CAPRICE ECR Ion Source



- Technical standard of 1990 and status quo until now at GSI
- Continuously improved oven technology

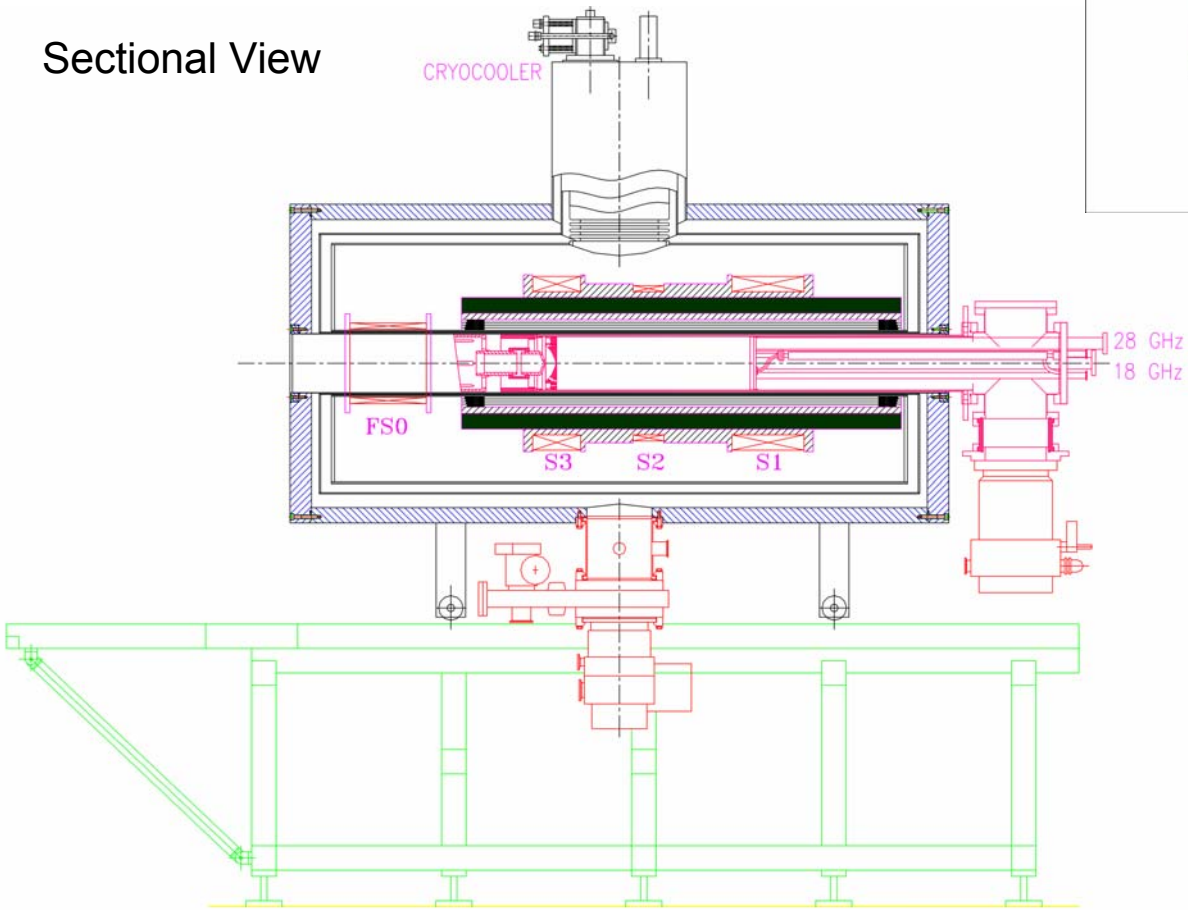
| Ion Species | Intensity (eμA) |
|---|---|
| $^{26}Mg^{5+}$ | 80 |
| $^{50}Cr^{8+}$ | 40 |
| $^{58}Fe^{9+}$ | 50 |
| $^{70}Zn^{10+}$ | 70 |

# Comparison of Performances for Different ECR Ion Sources

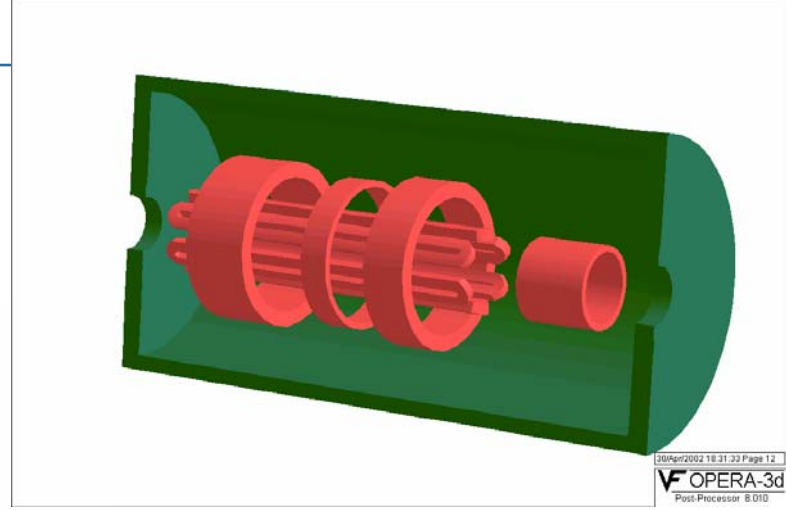


# The GyroSerse Project

Sectional View




S. Gammino, private communication

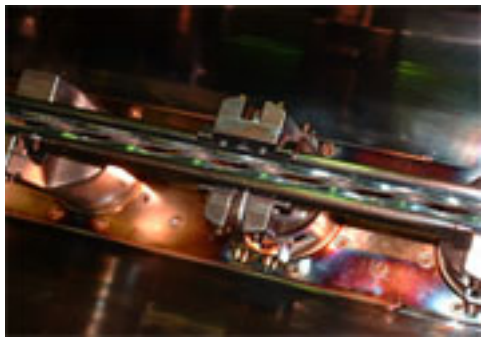


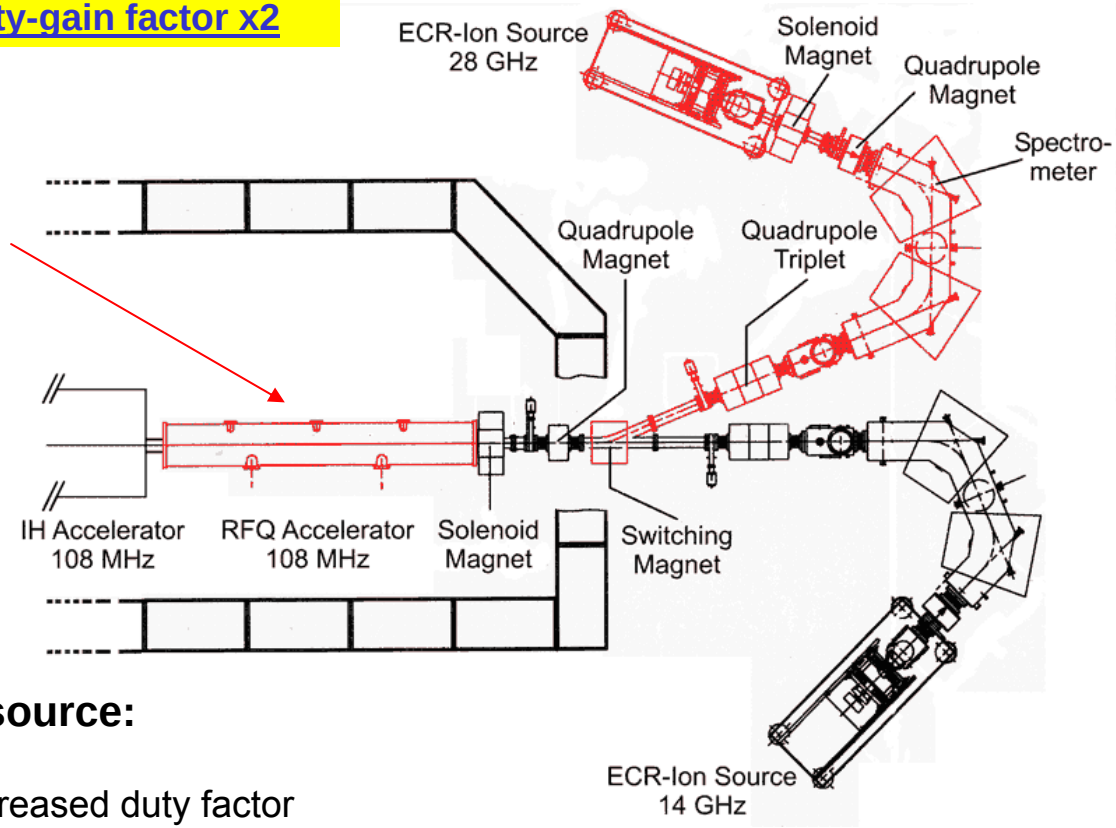

## Magnetic System

| | |
|---|---|
| Frequency | 28-37 GHz |
| Max. RF power | 10 kW |
| $B_{radial}$ | 3 T |
| $B_1$ (injection) | 4.5 T |
| $B_2$(extraction) | 3.5 T |
| $\phi_{chamber}$ | 180 mm |
| $L_{chamber}$ | 700 mm |
| $\phi_{cryostat}$ | 1000 mm |
| $L_{cryostat}$ | 2150 mm |

# New Front-end for the High Charge State Injector

**50% duty factor → intensity-gain factor x2**





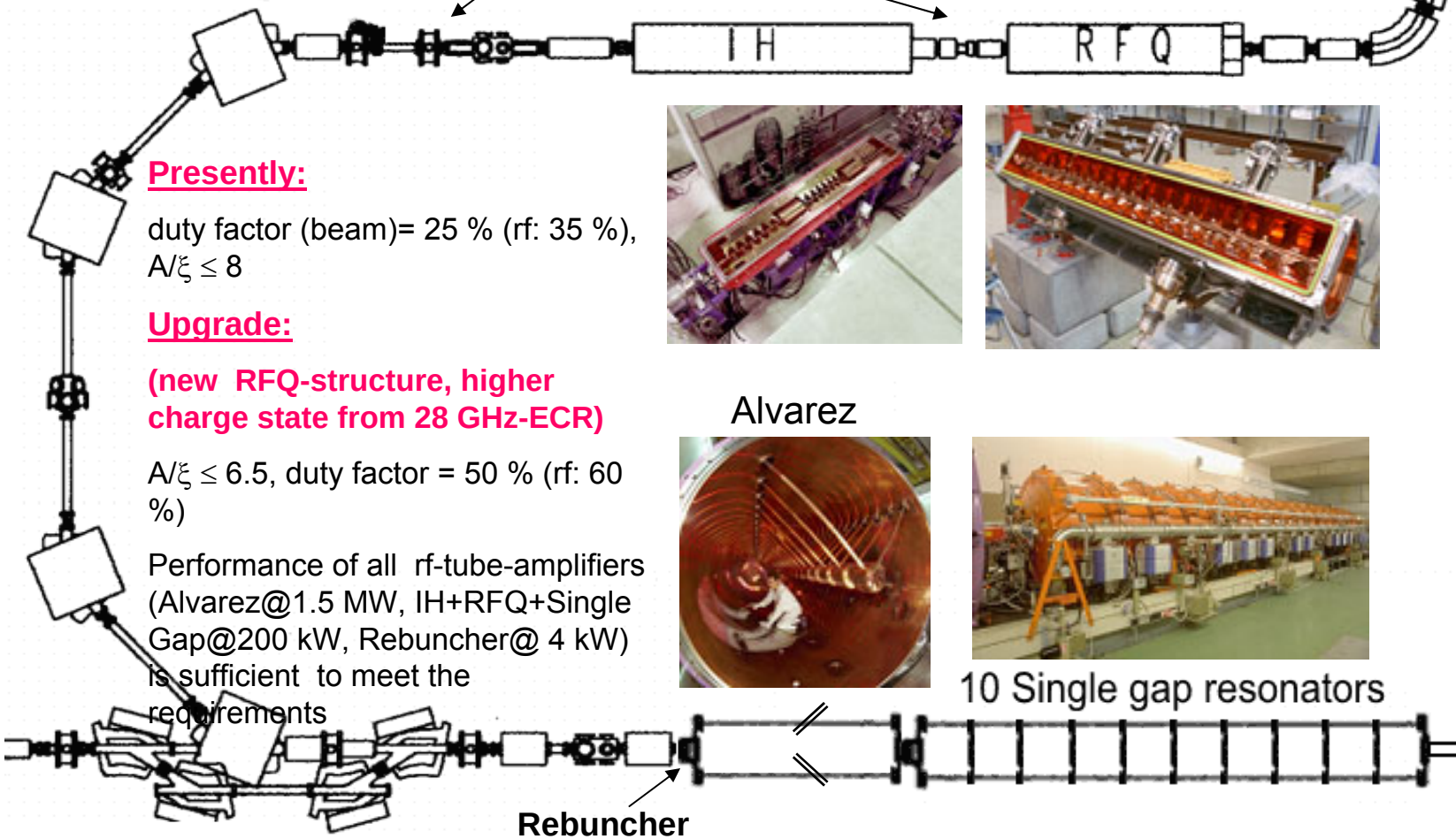

**New RFQ-structure:**
- gain of the duty factor
- higher injection energy
- increased acceptance

**Additional 28 GHz-ion-source:**
- intensity gain of factor two
- higher charge states for increased duty factor

**LEBT – Laminated magnets:**
- redundance for ion sources
- preparation for future pulse to pulse operation with different ion-species

# High Duty Cycle RF-Operation of the GSI- High Charge State Injector (HLI) and the Alvarez-accelerator

Rebuncher








**Presently:**

duty factor (beam)= 25 % (rf: 35 %), $A/\xi \leq 8$

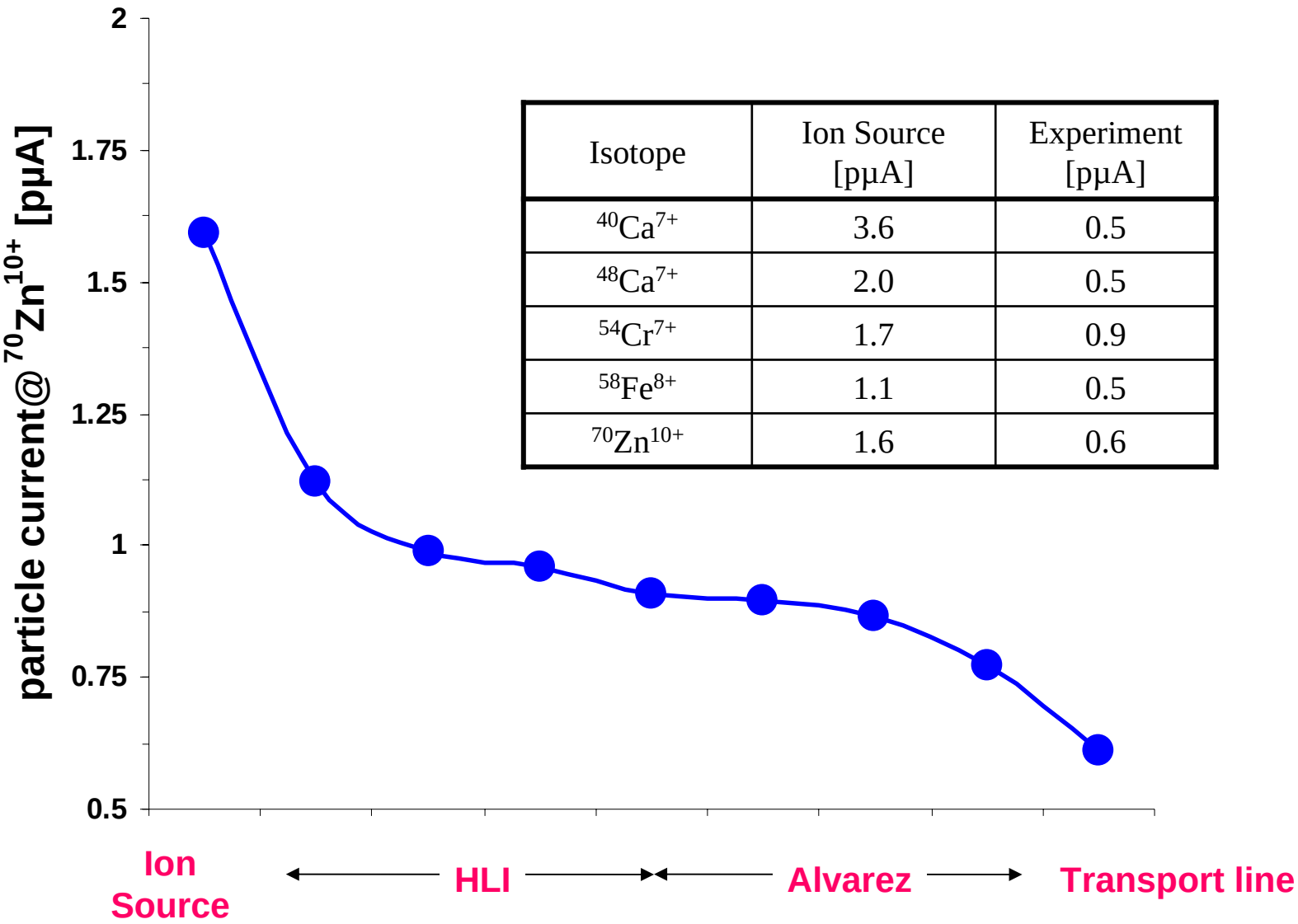
**Upgrade:**

**(new RFQ-structure, higher charge state from 28 GHz-ECR)**

$A/\xi \leq 6.5$, duty factor = 50 % (rf: 60 %)

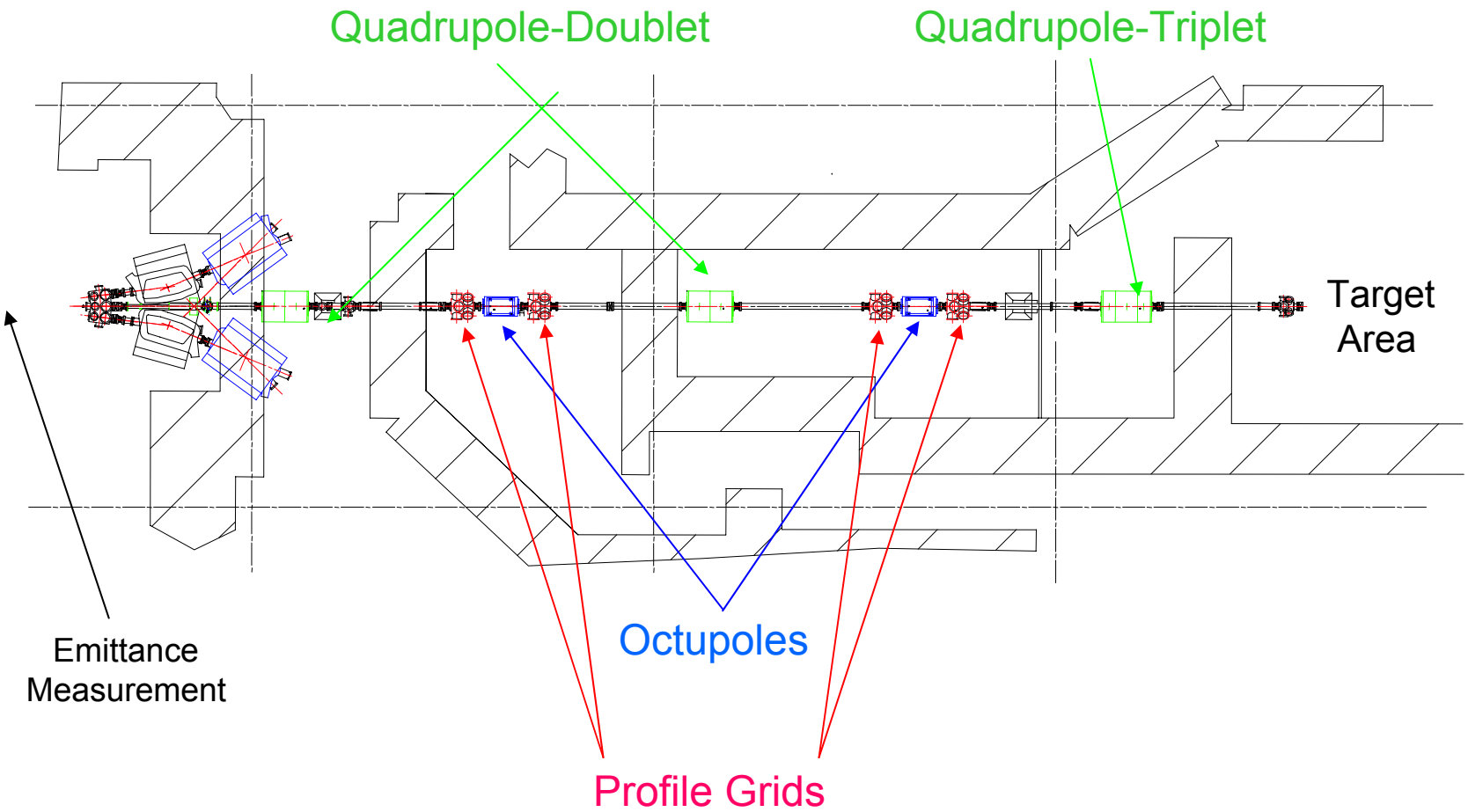
Performance of all rf-tube-amplifiers (Alvarez@1.5 MW, IH+RFQ+Single Gap@200 kW, Rebuncher@ 4 kW) is sufficient to meet the requirements

# Particle Current in the GSI-Unilac (routine operation)

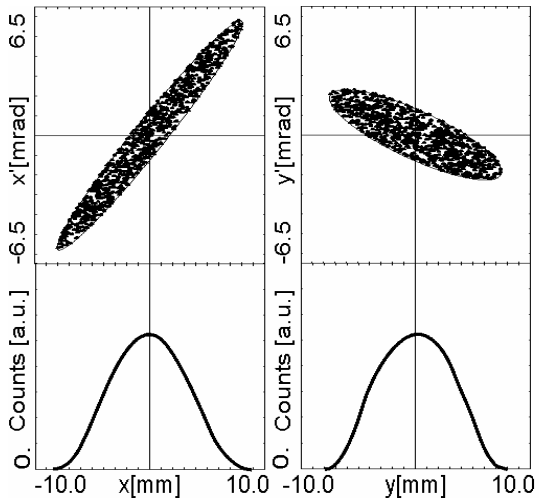



| Isotope | Ion Source [pμA] | Experiment [pμA] |
|---|---|---|
| $^{40}Ca^{7+}$ | 3.6 | 0.5 |
| $^{48}Ca^{7+}$ | 2.0 | 0.5 |
| $^{54}Cr^{7+}$ | 1.7 | 0.9 |
| $^{58}Fe^{8+}$ | 1.1 | 0.5 |
| $^{70}Zn^{10+}$ | 1.6 | 0.6 |

# Upgrade of the Beam Transport to the SHIP-Target



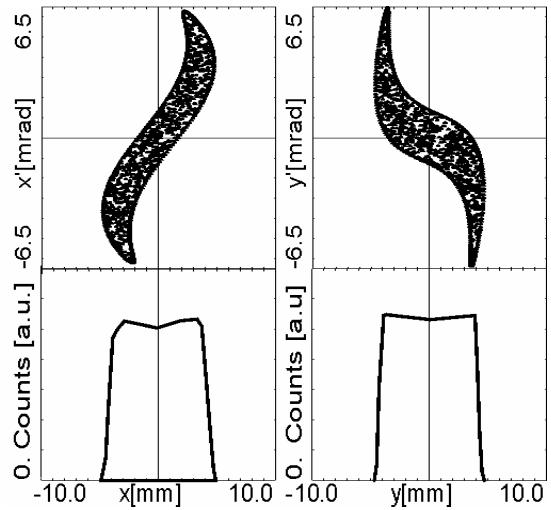
# Transverse Beam Shaping with Octupole lenses



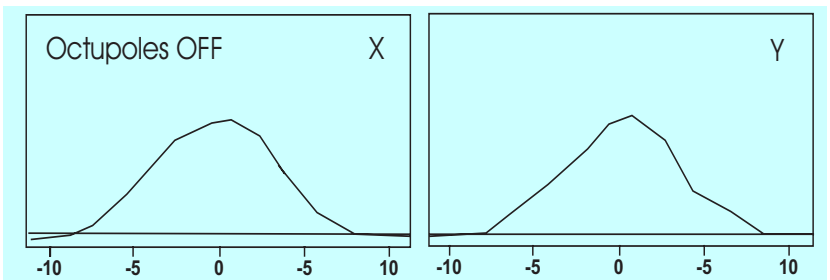

$B_x = G(y^3 - 3x^2y)$

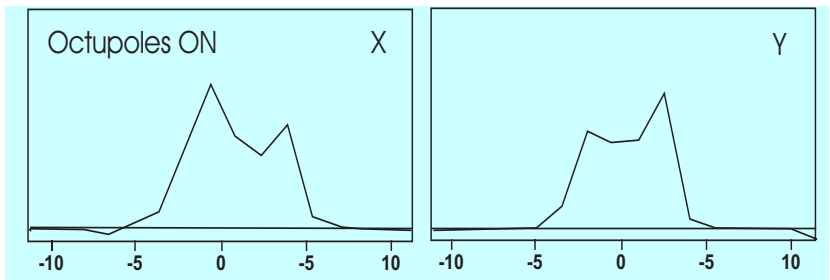
$B_y = G(3y^2x - x^3)$

G: pole tip field




**Measured beam profiles at the target position**




- Transmission losses of 30%
- Increase of underground noise by a factor of 1000

# Two Heavy Ion Linacs for Different Duties

## Synchrotron Injector

- Poststripper section in operation since 30 years.
  - Alvarez structure operation among the highest duty factors worldwide.
  - Drift tubes with internal quadrupoles.
  - 108 MHz rf power amplifiers in use from the beginning.

## Option

- Rebuilt of the Poststripper section.
  - Low duty cycle.
  - High voltage gain.
  - Emittance growth reduction.
  - New operating rf frequency.
  - New beam inflector into SIS 18.

$\Rightarrow$ Relaxed SIS 18 operation.

$$N_{\max} \propto \beta_i^2 \gamma_i^3 \frac{A}{q^2}$$

25 *A MeV* $U^{28+}$ increases $N_{max,SIS18}$ by a factor of 2.

# A Dedicated cw Linac for SHE Production

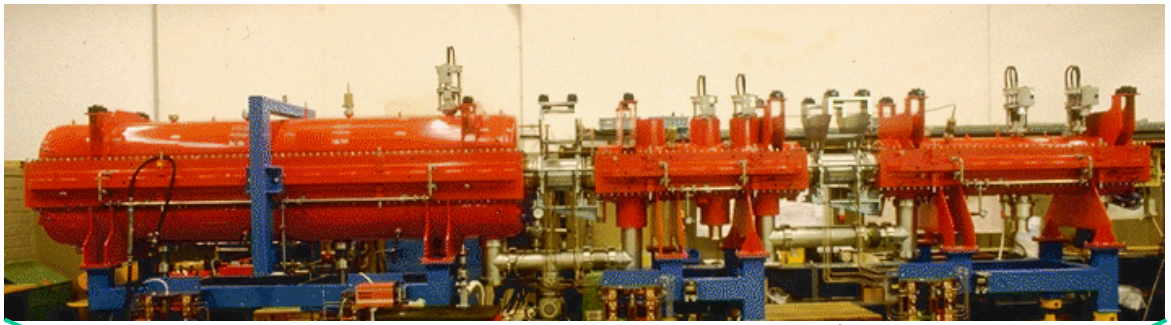
- No interference with synchrotron operation.
- Significant increase in available time and in flexibility for tests and for experiments.
- Optimum beam matching to the target wheel; highest counting rates.

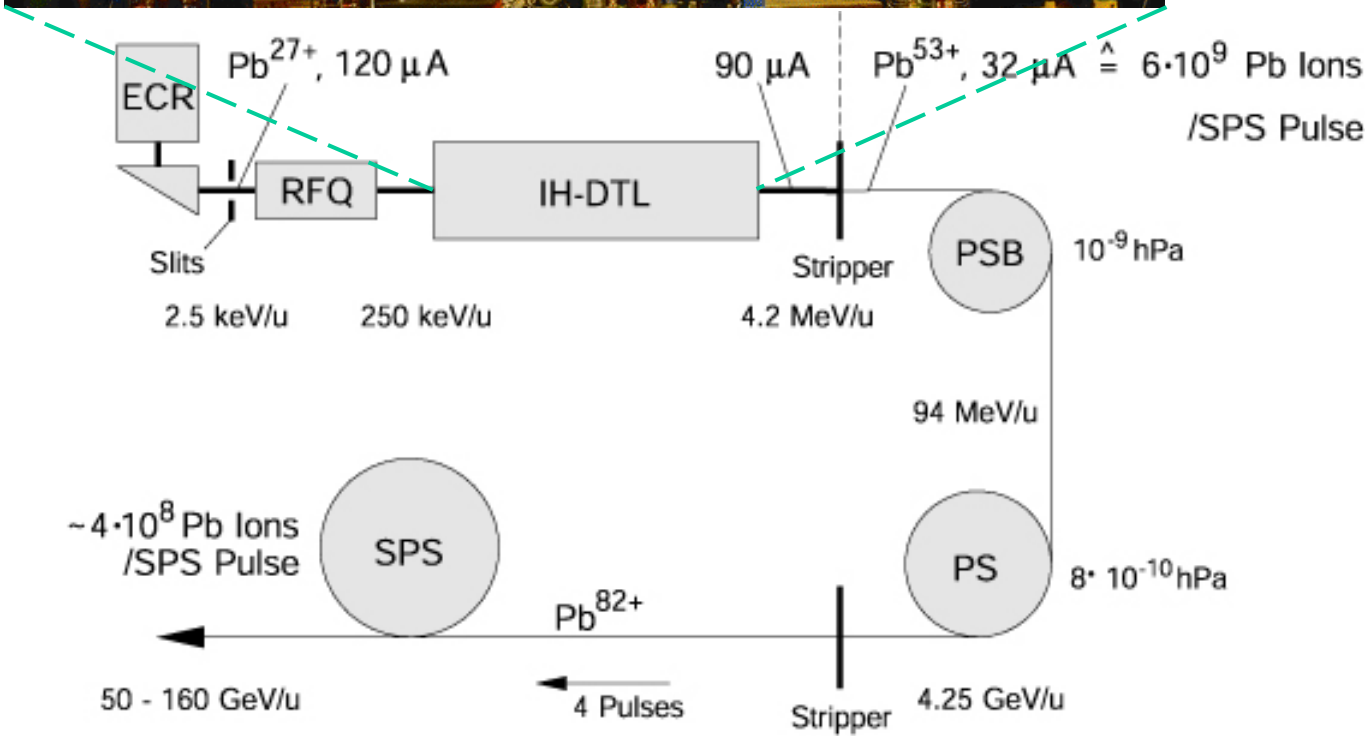
# Small and Fast Solution

- Room temperature linac :
  HLI (1.4 *AMeV*) & 217 MHz DTL ( IH section, 4 tanks
  $P_{rf} \lesssim 100$ *kW* each).
  $A / q \lesssim 5$ ; $W \lesssim 6$ *AMeV* ;
  $\overline{Z}_{eff} \simeq 140$ *MW/m*; $L_{tot} \simeq 20$ *m* ;
  $P_{tot,rf} \simeq 320$ *kW* ;
  $P_{plug} \simeq 700$ *kW*, for 217 *MHz* cavities !

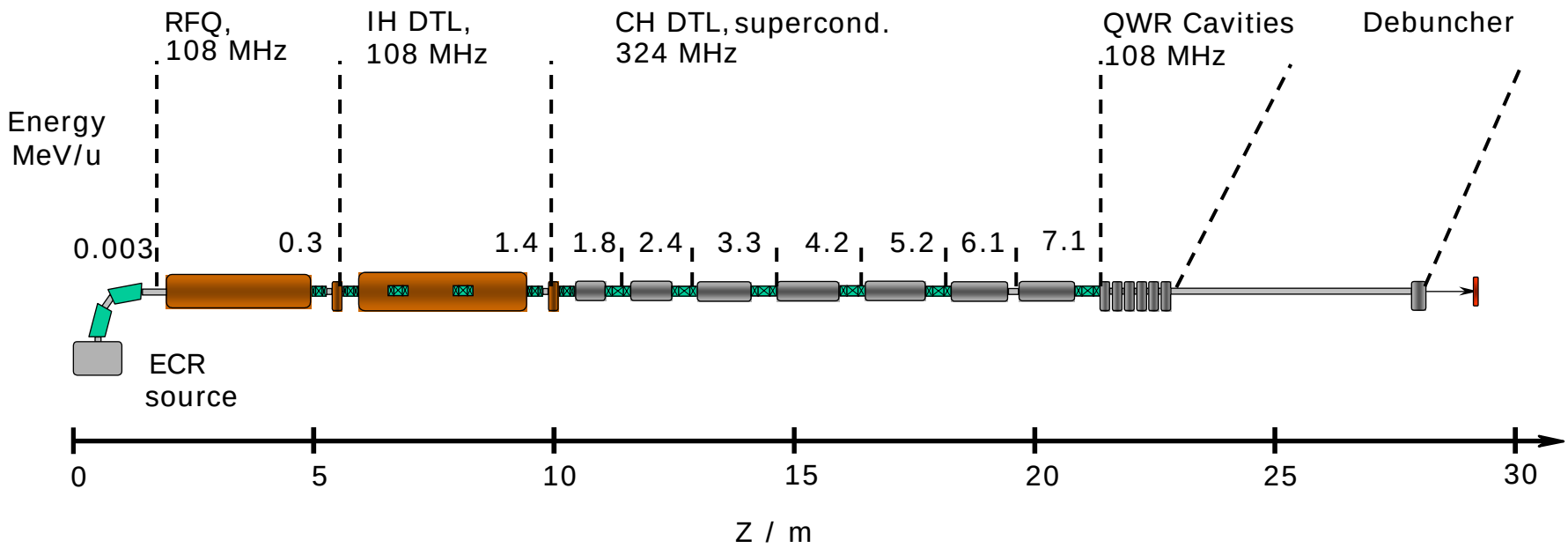
- $4 \times \lambda/4$, 108 MHz, 2 gap cavities for energy variation, superconducting (two cryostats).

# Lead Acceleration at CERN





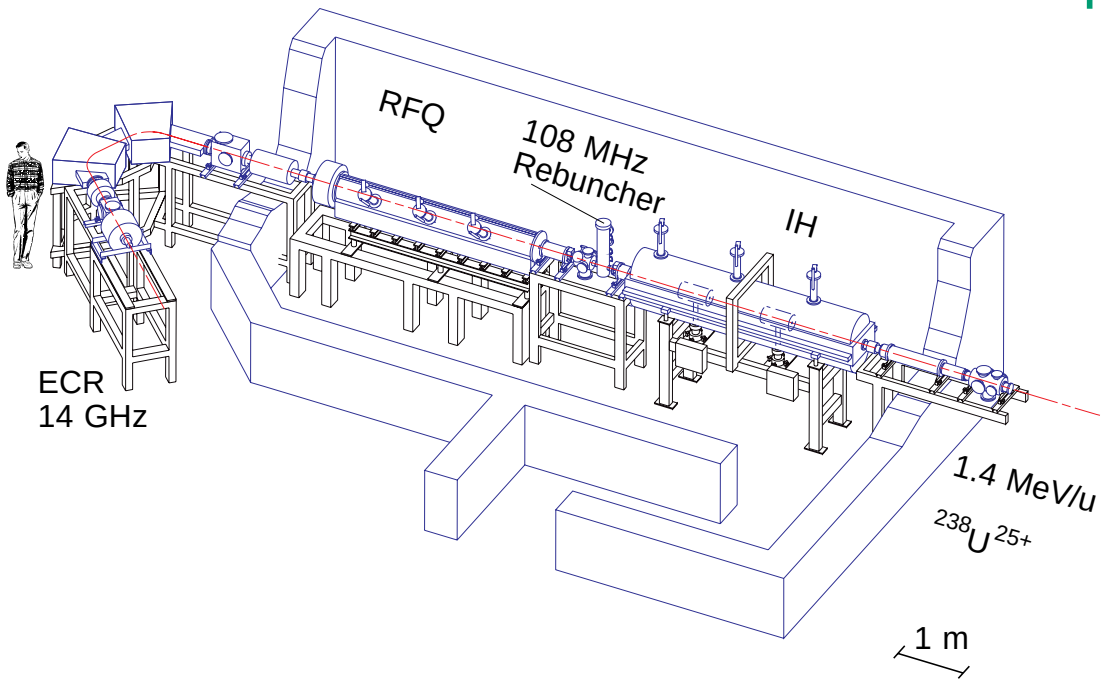
# Layout of the Proposed cw Superconducting Linac

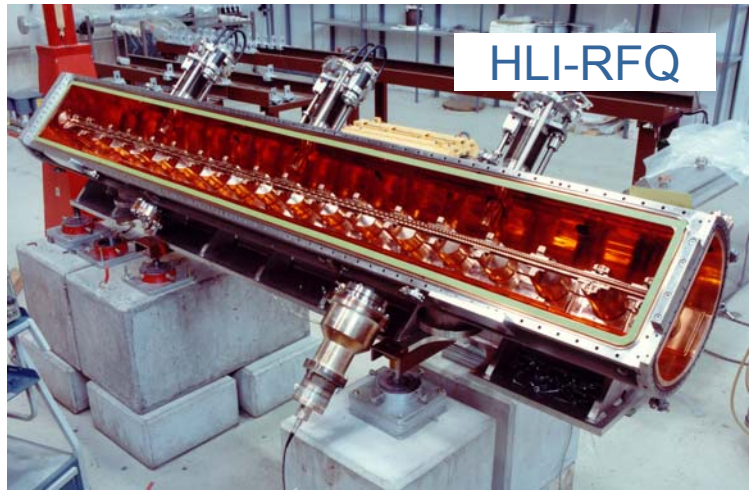


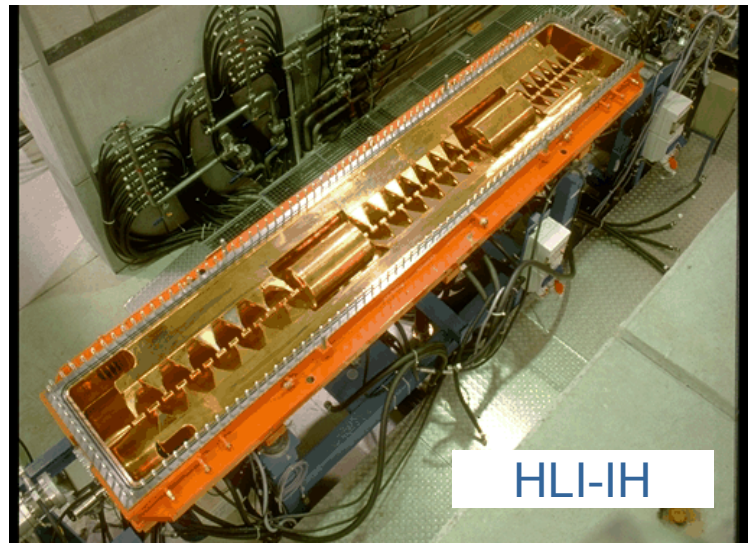

Main components:

- Room temperature RFQ and IH-DTL at 108 MHz
- Superconducting CH-DTL (324 MHz) and QWR (108 MHz)

# cw Linac – Room Temperature Part




Rebuilt of the HLI with small modifications :

- Improved mechanical design with respect to cooling, especially:
- Cooling of the IH drift tubes.
- Cooling of the RFQ mini vanes.
- Improvement of longitudinal beam dynamics.

# Radio Frequency Quadrupole (RFQ) accelerator

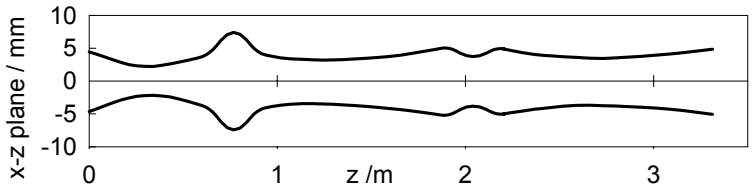
| GSI cw-RFQ | GSI HLI-RFQ |
|---|---|
| A/q = 7 (A < 150) | A/q = 8.5 ($U^{28+}$) |
| W = 3 – 300 keV/u | W = 2.5 – 300 keV/u |
| f = 108.48 MHz | f = 108.48 MHz |
| L ≈ 3m | L ≈ 3m |
| $U_{el}$ = 60 kV | $U_{el}$ = 80 kV |
| a = 3.2 – 2.5 mm | a = 4 – 3 mm |
| P = 70 kW cw | P = 125 kW 25% |

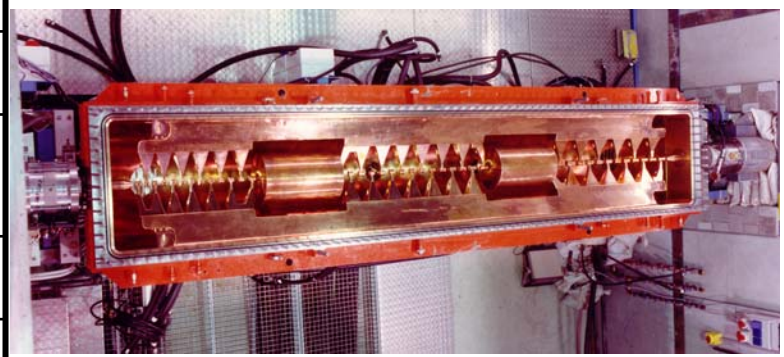
At 108 MHz the 4-rod-RFQ type is preferred

# Interdigital H-Type (IH) - DTL

| Resonator parameters | |
|---|---|
| Accel. sections | 3 |
| Magn. quad. lenses | 2 |
| No. Of gaps | 44 |
| Total length /m | 3.5 |
| Max. eff. gap volt. /kV | 231 |
| Avg. accel. gradient / MV/m | 2.3 |
| Avg. power loss / kW/m | 26 |
| **Beam parameters** | |
| $\varepsilon_{n,transv,input}$ /mm mrad | 0.8 |
| $\varepsilon_{n,long,input}$ /keV/u*ns | 1.7 |

Beam dynamics for the IH – DTL (transverse envelopes) :



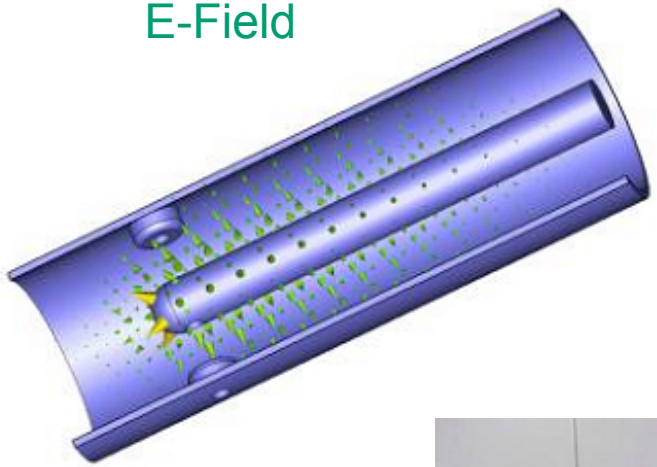



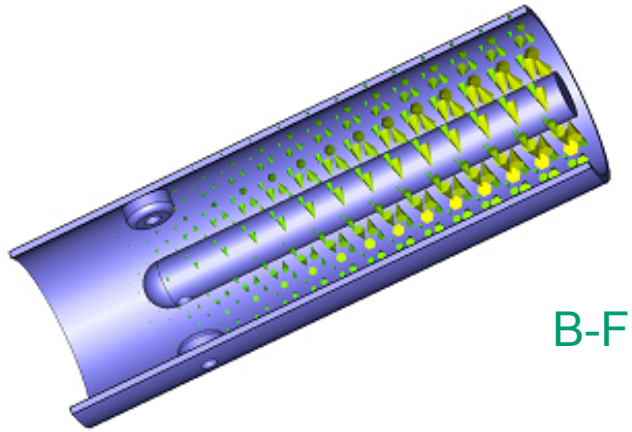
# Cavity Options for the S.C. DTL

SC Splitring resonators for ATLAS (f = 115 MHz)

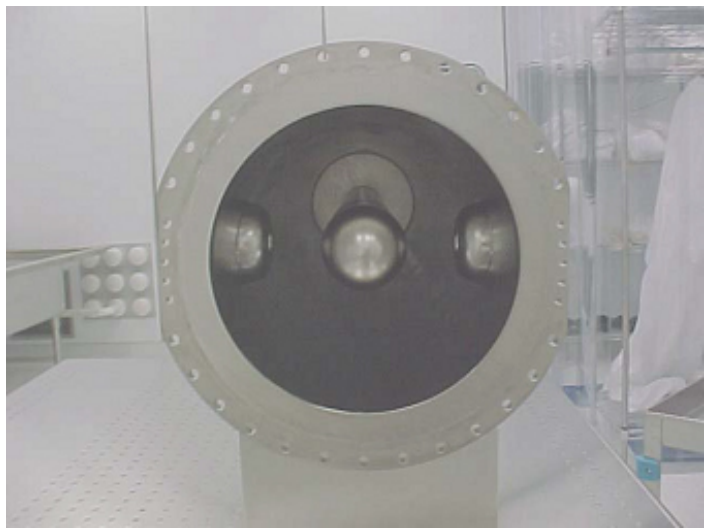
# Quarter Wave Resonators

E-Field

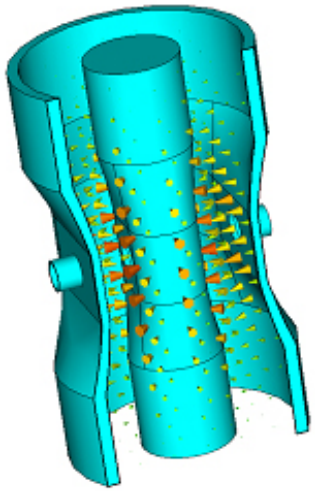




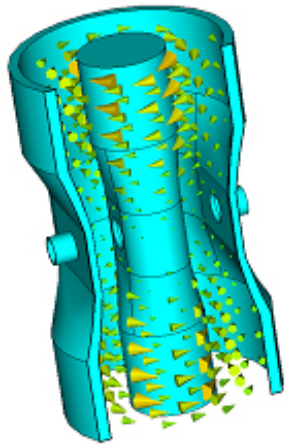
B-Field



# Half Wave Resonators

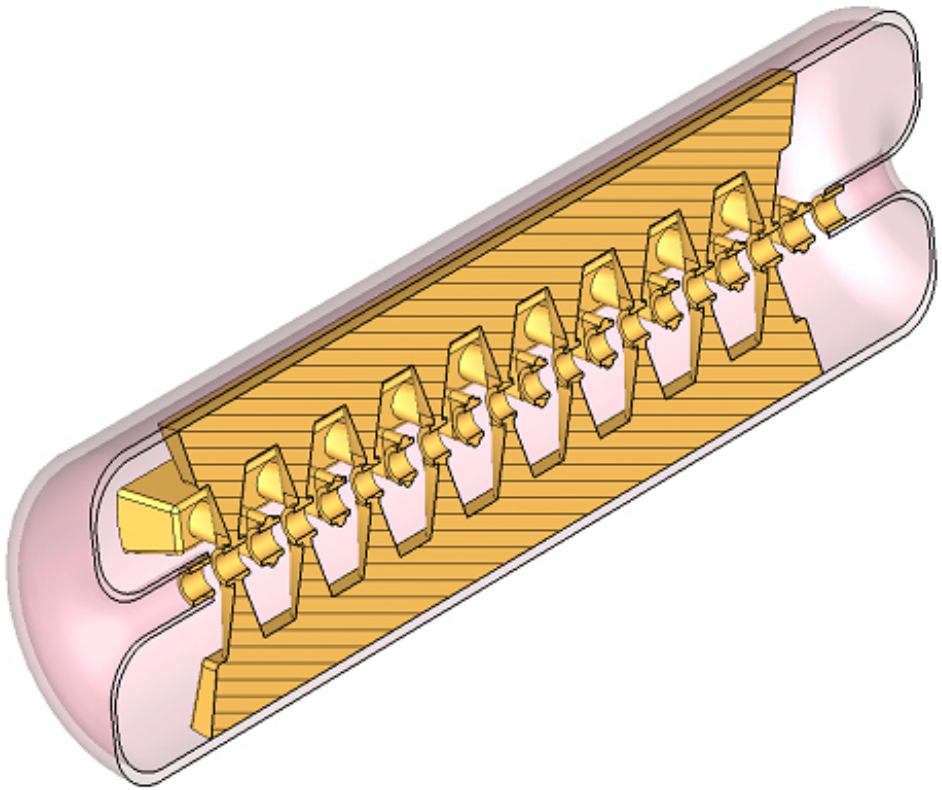


E-Field



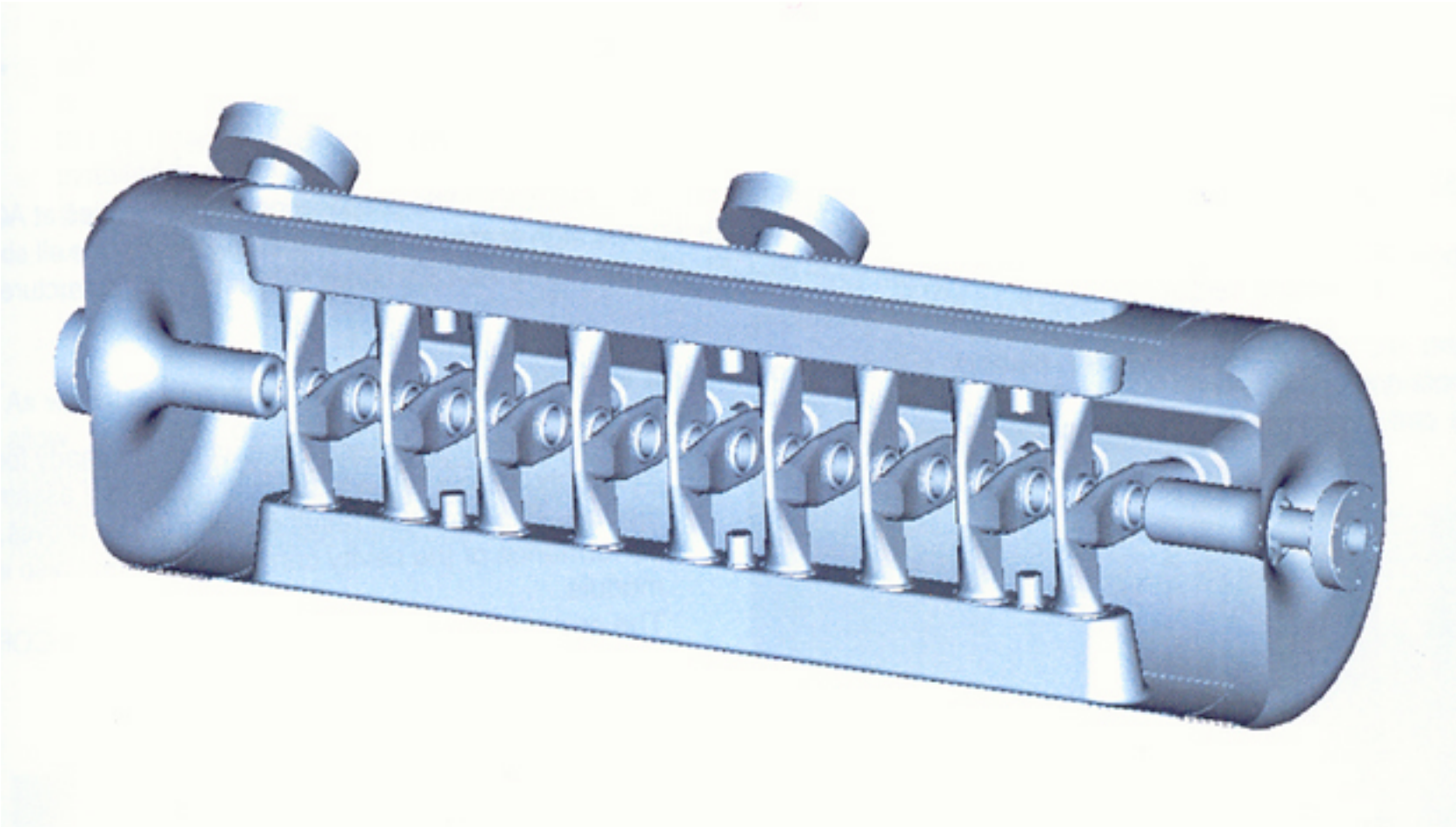
B-Field

# Superconducting CH-prototype
# Microvawe Studio™ Design and Parameter List

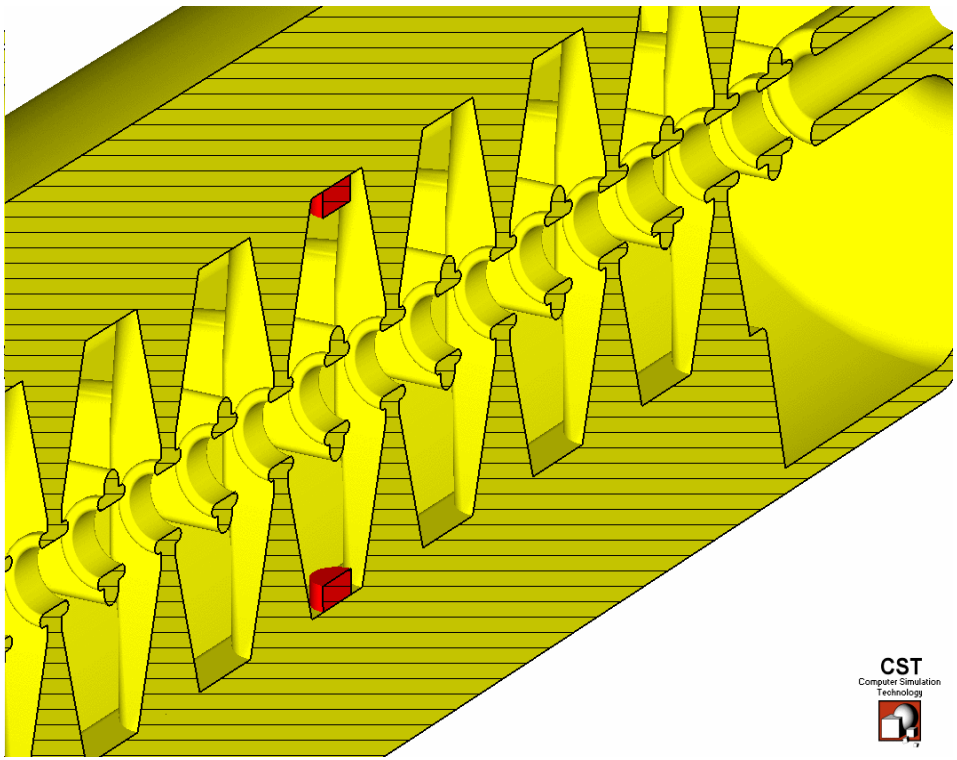


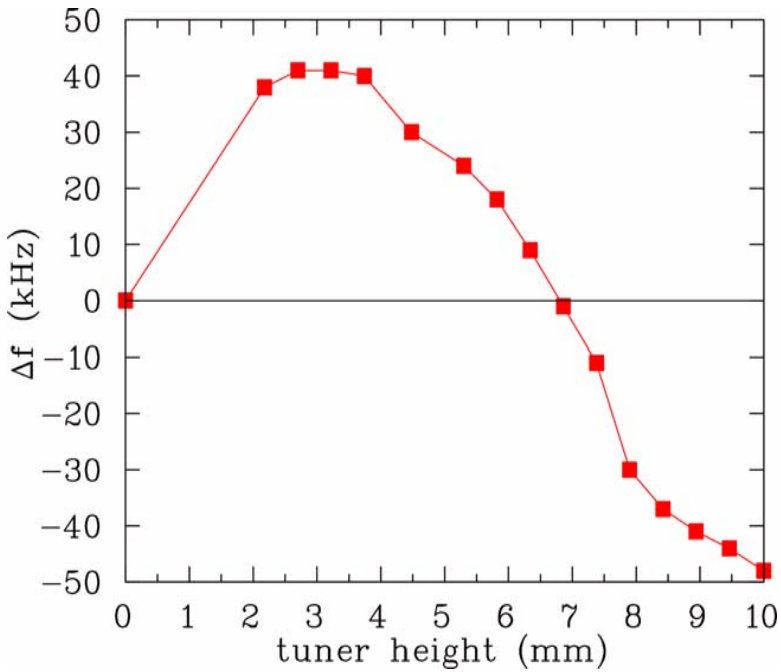
| | |
|---|---|
| **Gap number** | **19** |
| **Length (m)** | **1.05** |
| **Frequency (MHz)** | **352** |
| **β** | **0.1** |
| **Material** | **bulk Niobium** |
| **$E_0$ (MV/m)** | **4** |
| **$E_a$=ET (MV/m)** | **3.2** |
| **$E_p$ (MV/m) at 3.2 MV/m** | **21.0** |
| **$B_p$ (mT) at 3.2 MV/m** | **23.3** |
| **$G=R_sQ_0$ (Ω)** | **56** |
| **$R_a/Q$ (Ω) (T incl.)** | **3220** |
| **$(R_a/Q)G$ ($Ω^2$)** | **180000** |
| **$Q_0$ (BCS, 4K, 352 MHz)** | **$1.5x10^9$** |
| **$Q_0$ (total $R_s$=150 nΩ)** | **$3.7x10^8$** |
| **W ($mJ/(MV/m)^2$)** | **155** |
| **W at 3.2 MV/m (J)** | **1.58** |
| **P at 3.2 MV/m and $R_s$=150 nΩ =(W)** | **9.5** |

# Superconducting CH-prototype :
# 19-cell, 352 MHz SC CH-structure to be built by an industrial manufacturer

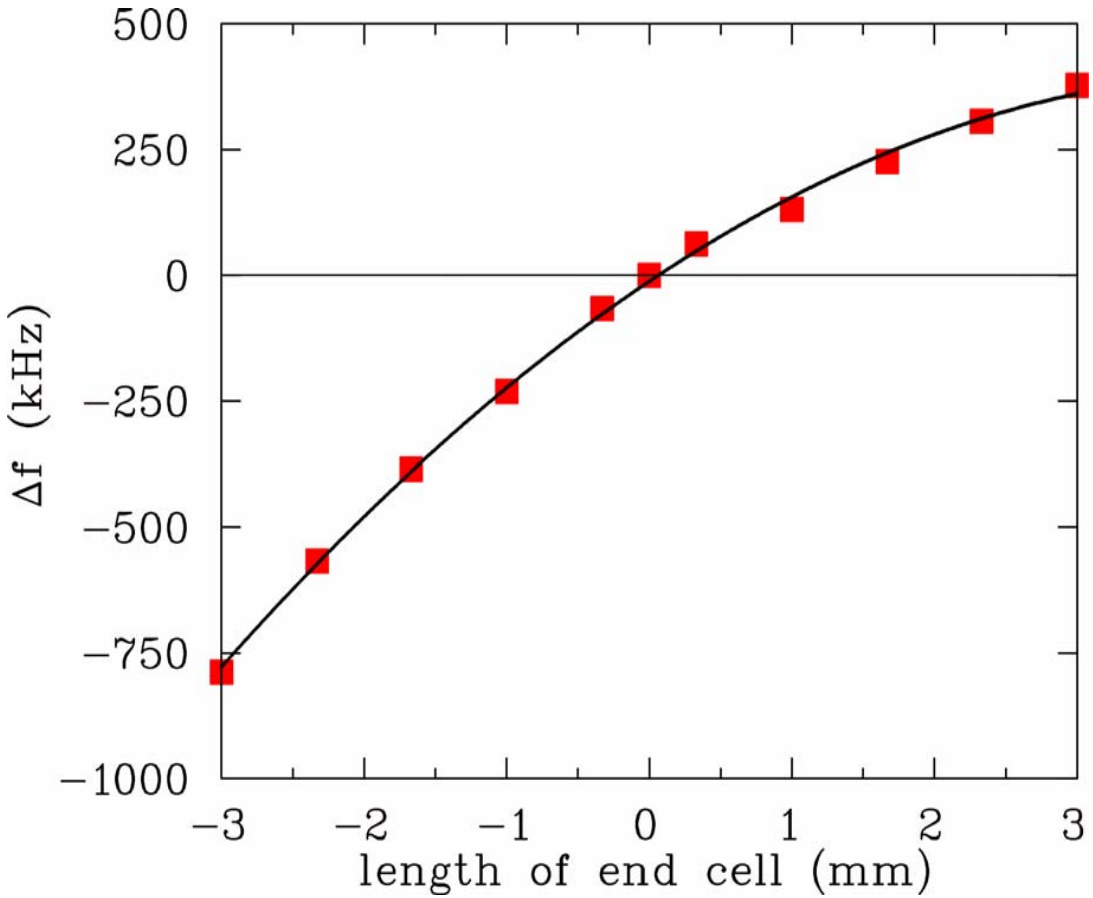


# Tuning of CH-cavities

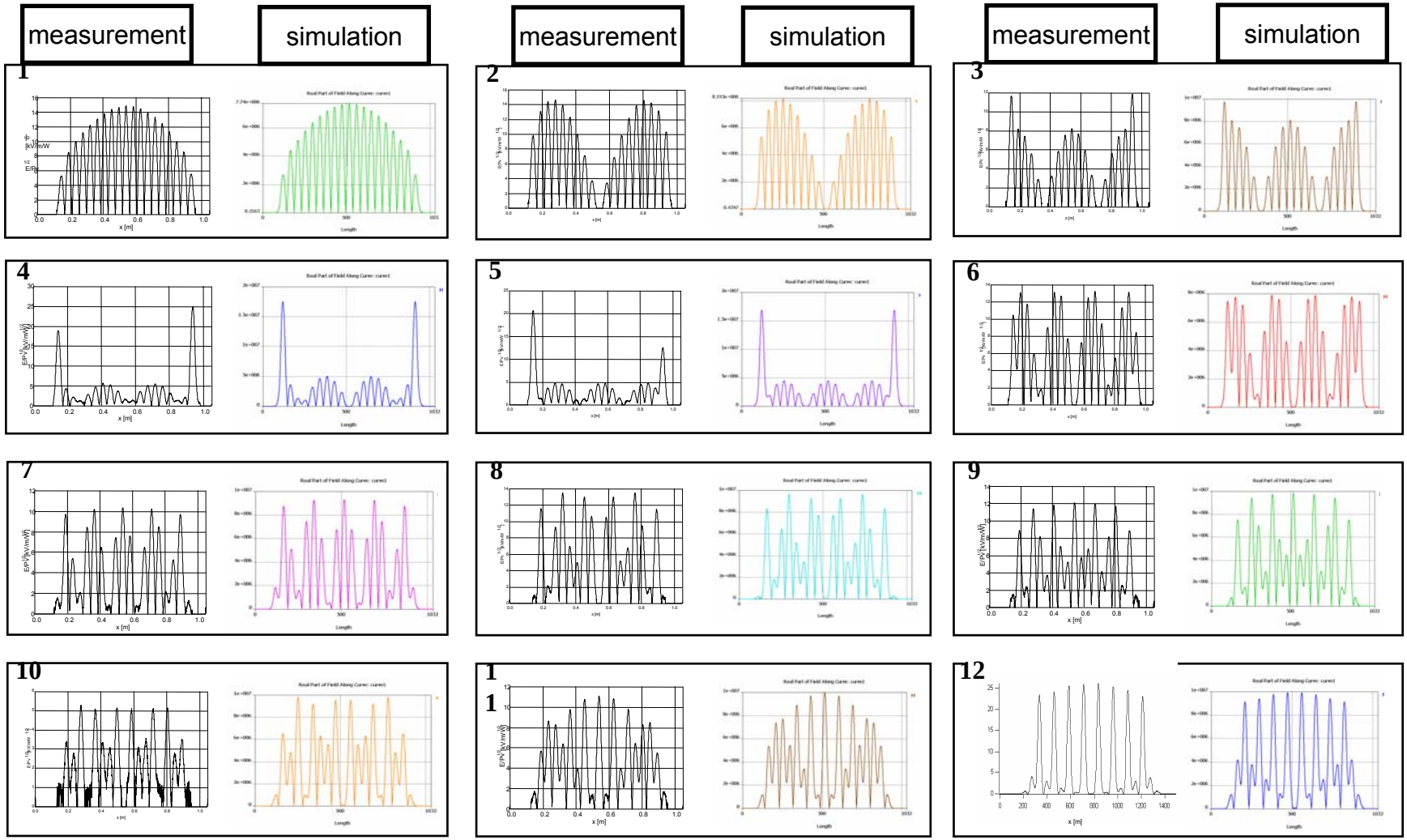


# Tuning of CH-cavities : Changing the Length of the End Cells



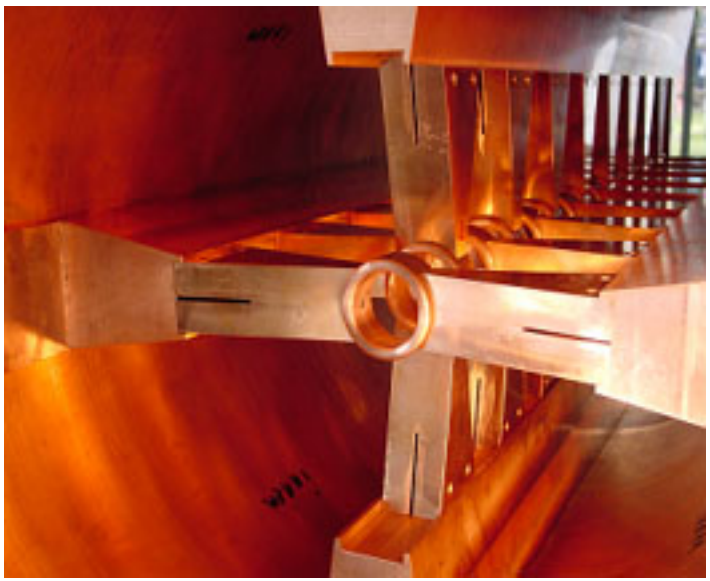
# Higher Order Modes in the CH-Structure

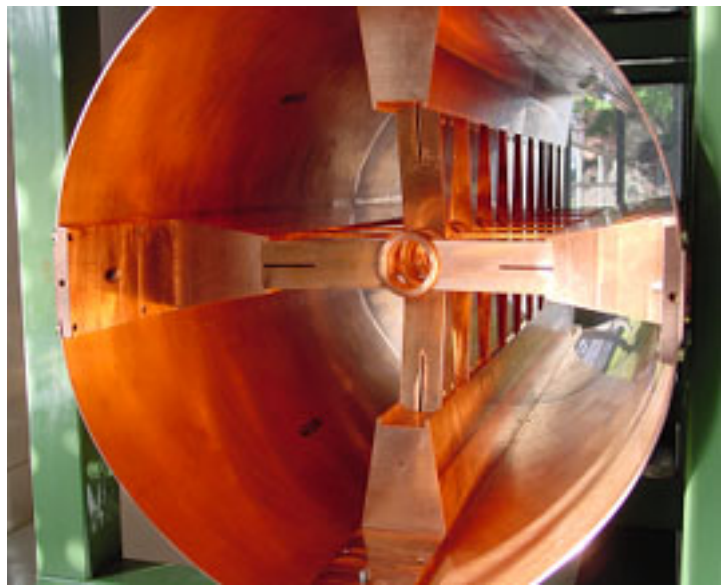


# Room temperature CH-model (copper)

- 19 gaps
- β=0.08
- L=105 cm
- Ø 34 cm

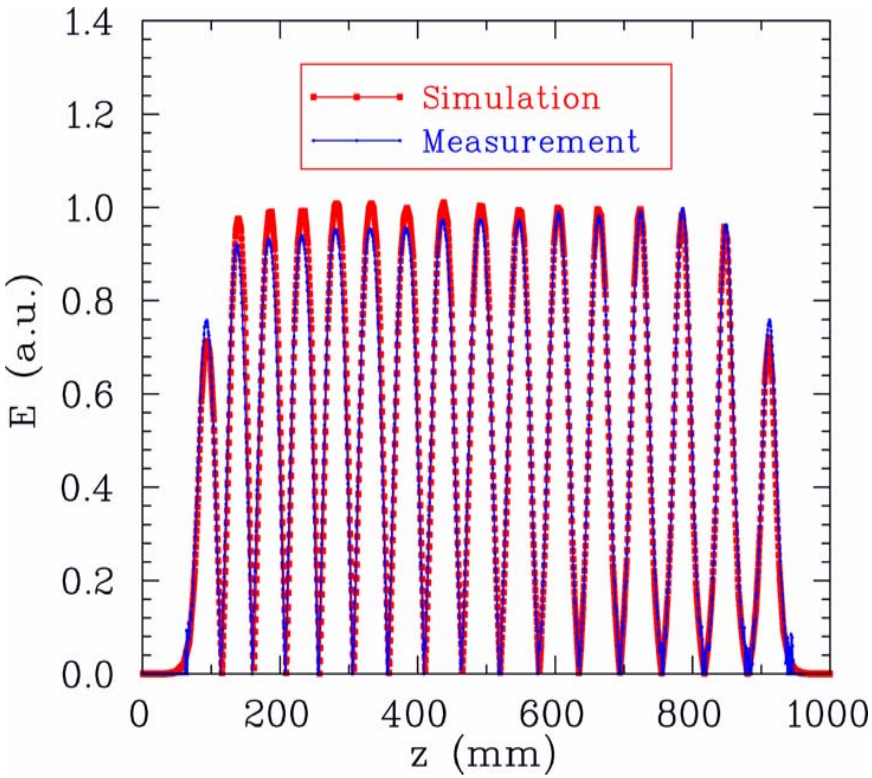
- Validation of the simulatios
- Tuning (Frequency- and field distribution)
- Higher Order Modes (HOM)



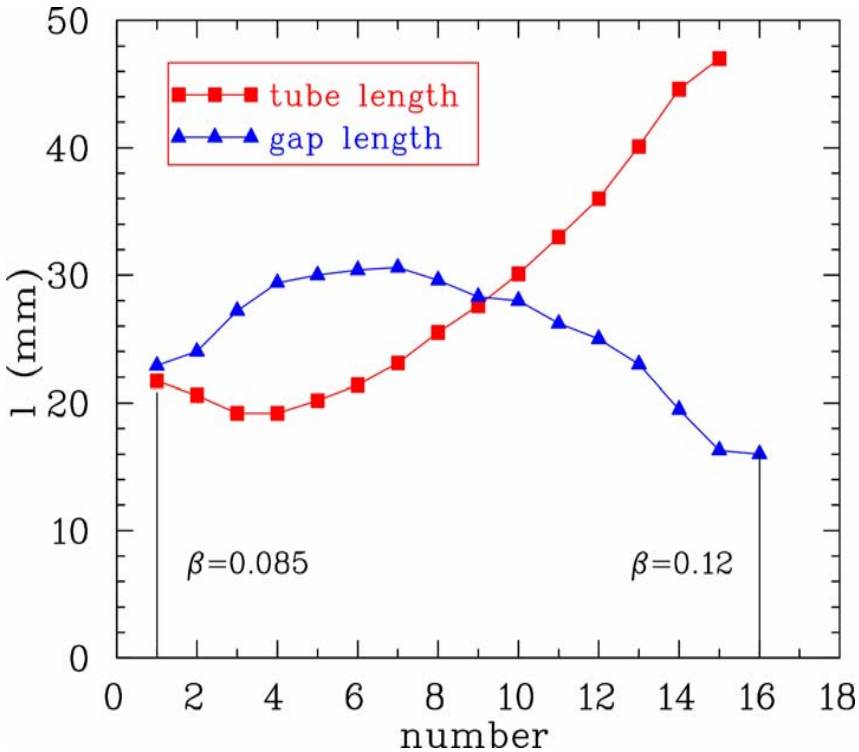


# Flatness in a CH-DTL With β-Profile

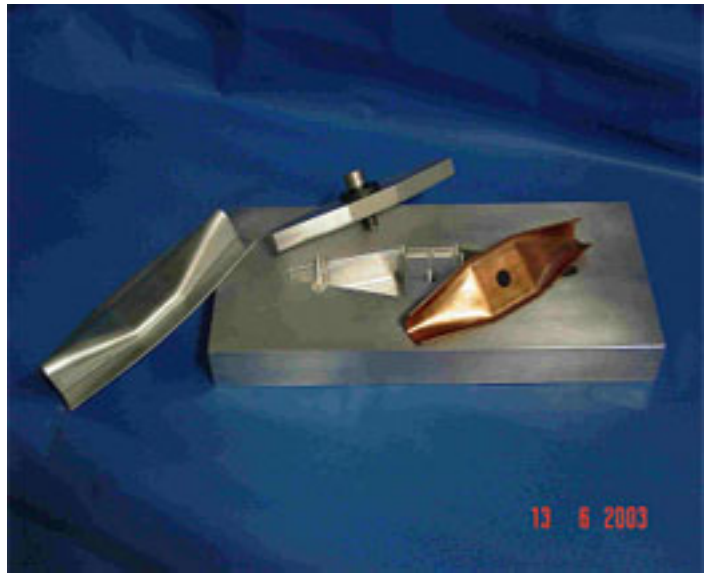
Field distribution with beta profile

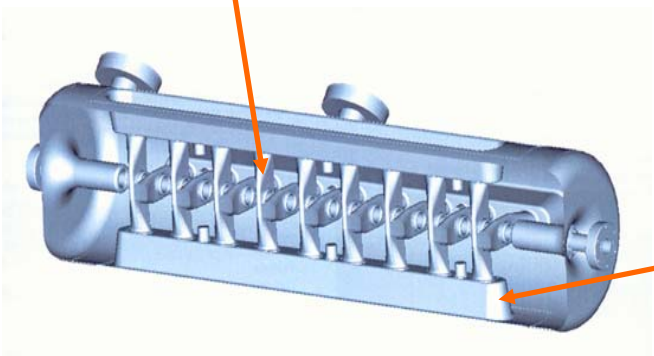


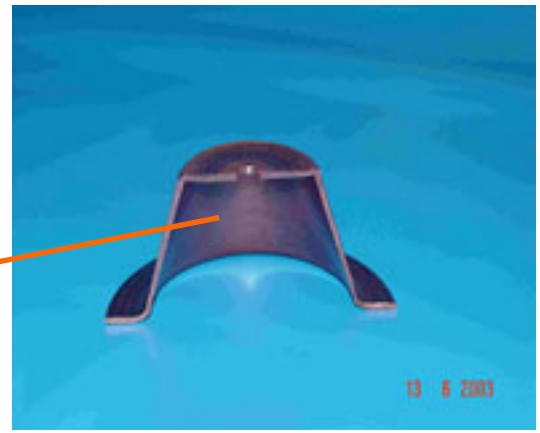

Required tube and gap length



# Manufacturing of Prototype Components at ACCEL Company




Status : Components ready for $e^-$ - beam welding

# Layout of the superconducting CH – DTL section

Due to the following experimental requirements :

- Variation of the output energy, 3.8 – 7.5 MeV/u
- Final energy spread < ± 3 keV/u

the following layout resulted :

- 7 CH tanks

| | | | |
|---|---|---|---|
| 1.4-1.85 MeV/u | -> 2.5 MeV/u | ->3.35 MeV/u | -> 4.25 MeV/u |

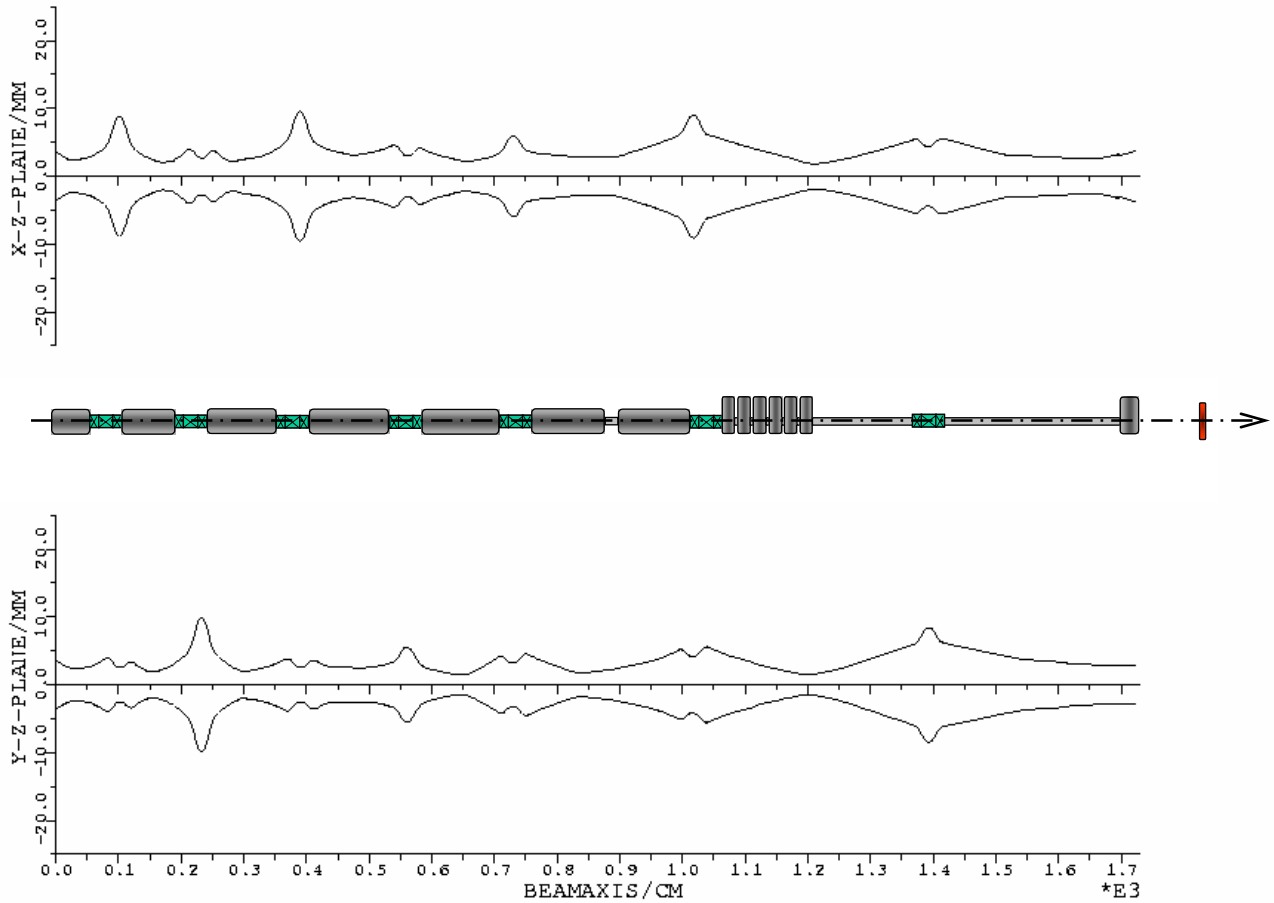
| | | |
|---|---|---|
| -> 5.25 MeV/u | -> 6.15 MeV/u | -> 7.15 MeV/u |

- An ‘energy modulator’ (2 gap resonators)

| |
|---|
| +/- 0.5 MeV/u |

- A 4 gap debuncher cavity (after a 5 m drift space) for the final longitudinal beam shaping.

# Beam dynamics for the CH – DTL (transverse beam envelopes)



# Parameters of the CH-DTL Section

| Resonator | Gaps | Res. Length | $E_{acc}$ |
|---|---|---|---|
| | | | |
| CH 1 | 24 | 625 mm | 5.0 MV/m |
| CH 2 | 28 | 850 mm | 5.4 MV/m |
| CH 3 | 32 | 1130 mm | 5.3 MV/m |
| CH 4 | 32 | 1290 mm | 5.0 MV/m |
| CH 5 | 28 | 1260 mm | 5.4 MV/m |
| CH 6 | 24 | 1180 mm | 5.2 MV/m |
| CH 7 | 22 | 1150 mm | 5.6 MV/m |
| | | | |
| | | | |
| QWR 1-6 | 2 | $E_{syn}$=5.6 MeV/u | |
| | | | |
| Debuncher (RT) | 4 | $E_{syn}$=5.6 MeV/u | |

# Parameters of the SC Quadrupole Lenses

| Quadrupole-triplet | Aperture | Gradient | | eff. Length | |
|---|---|---|---|---|---|
| | | Q1 & Q3 | Q2 | Q1 & Q3 | Q2 |
| | | | | | |
| QT 1 | 30 mm | 59 T/m | 56 T/m | 120 mm | 200 mm |
| QT 2 | 30 mm | 70 T/m | 66 T/m | 120 mm | 200 mm |
| QT 3 | 30 mm | 70 T/m | 68 T/m | 120 mm | 200 mm |
| QT 4 | 30 mm | 64 T/m | 70 T/m | 120 mm | 200 mm |
| QT 5 | 30 mm | 73 T/m | 73 T/m | 120 mm | 200 mm |
| QT 6 | 30 mm | 56 T/m | 62 T/m | 120 mm | 200 mm |
| | | | | | |
| | | | | | |
| QT 7 (RT) | 30 mm | 52 T/m | 59 T/m | 120 mm | 200 mm |

# Conclusions

- Improvements of beam intensities from Unilac by factors 10 (metals) to 100 (gases) for SHIP seem feasible:
  - 28 GHz ECR source.
  - Duty factor upgrade to 50 %.

- An optimized synchrotron injector Unilac together with a new cw linac offer attractive long term capabilities:
  - Rebuilt of the Unilac post stripper section as a pulsed high current linac (emittance growth reduction, higher beam energy and SIS current limit, factors ~ 2).
  - New cw linac with independent beam time schedule.

- Two main options for the cw linac:
  - Small solution $A/q \leq 5$, $3.8 < W < 6$ *AMeV*, room temperature IH linac with 4 s.c. quarter wave cavities (two cryostats) for energy variation.
  - Big solution $A/q \leq 7$, $3.8 < W < 7.5$ *AMeV*, 108 *MHz* HLI (1.4 *AMeV*) & s.c. 324 *MHz* CH linac & energy modulator (2 gap, $\lambda/4$).

# Attachment F

## Most relevant publications based on SHIP experiments

G. Münzenberg et al.
**Identification of element 107 by α correlation chains**
Z. Phys. A300, 107-108, 1981

Münzenberg et al.
**Observation of one correlated α-decay in the reaction $^{58}$Fe on $^{209}$Bi → $^{267}$109**
Z. Phys., A309, 89-90, 1982

S. Hofmann et al.
**Proton radioactivity of $^{151}$Lu**
Z. Phys., A305, 111-123, 1982

J.G. Keller et al.
**Observation of radiative capture in the reaction $^{90}$Zr + $^{90}$Zr**
Z. Phys. A311, 243-244, 1983

G. Münzenberg et al.
**The identification of element 108**
Z. Phys., A317, 235-236, 1984

P. Armbruster et al.
**Attempts to produce superheavy elements by fusion of $^{48}$Ca with $^{248}$Cm in the bombarding energy range of 4.5-5.2 MeV/u**
Phys. Rev. Lett., 54, 406-409, 1985

W. Reisdorf
**Heavy-ion reactions close to the Coulomb barrier**
J. Phys. G: Nucl. Part. Phys., 20, 1297-1353, 1994

S. Hofmann et al.
**Production and Decay of $^{269}$110**
Z. Phys. A350, 277, 1995

S. Hofmann et al.
**The New Element 111**
Z. Phys. A350, 281-282, 1995

S. Hofmann et al.
**The new element 112**
Z. Phys., A354, 229-230, 1996

G. Münzenberg
**Discoveries of the heaviest elements**
J. Phys., G25, 717, 1999

S. Hofmann and G. Münzenberg
**The discovery of the heaviest elements**
Rev. Mod. Phys., 72, 733-767, 2000

A.N. Andreyev et al.
**A triplet of differently shaped spin-zero states in the atomic nucleus $^{186}$Pb**
Nature 405, 430-433, 2000

S. Hofmann et al.
**The new isotope $^{270}$110 and its decay products $^{266}$Hs and $^{262}$Sg**
Eur. Phys. J., A10, 5-10, 2001

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**On Beyond Uranium: Journey to the End of the Periodic Table**
Taylor and Francis, London, 2002, 224 pp.

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S. Hofmann et al.
**New Results on elements 111 and 112**
Eur. Phys. J. A, 14, 147-157, 2002

S. Hofmann
**On Beyond Uranium: Journey to the End of the Periodic Table**
Taylor and Francis, London, 2002, 224 pp.

# Attachment G

## Most relevant publications based on chemical experiments and theory

### * *Covering chemical aspects*

M. Schädel et al.
**Chemical properties of element 106 (seaborgium)**
Nature **388,** 55-57 (1997).

M. Schädel et al.
**Aqueous Chemistry of Seaborgium (Z=106)**
Radiochim. Acta **83**, 163-165 (1998).

A. Türler et al.
**First Measurement of a Thermochemical Property of a Seaborgium Compound**
Angew. Chem. Int. Ed. **38**, 2212-2213 (1999).

W. Paulus et al.
**Chemical Properties of Element 105 in Aqueous Solution: Extraction of the Fluoride, Chloride and Bromide Complexes of the Group5 Elements into Aliphatic Amines**
Radiochim. Acta **84**, 69-77 (1999).

R. Eichler et al.
**Chemical characterization of bohrium (element107)**
Nature **407**, 63-65 (2000).

E. Strub et al.
**Fluoride complexation of rutherfordium (Rf, element 104)**
Radiochim. Acta **88**, 265-271 (2000).

S. Hübener et al.
**Physico-chemical characterization of seaborgium as oxide hydoxide**
Radiochim. Acta **89**, 737-741 (2001).

V. Pershina et al.
**Electronic Structure and Volatility of Group 8 Oxides $MO_4$, where M = Ru, Os, and Element 108, Hs the 108**
J. Chem. Phys. **115**, 792-799 (2001).

Ch. E. Düllmann
**Chemical investigation of hassium (element 108)**
Nature **418**, 859-862 (2002).

V. Pershina et al.
**Intermetallic compounds of the heaviest elements: the electronic structure and bonding of dimers of element 112 and its homolog Hg**
Chem. Phys. Lett. **365**, 176-183 (2002).

V. Pershina
**Theoretical treatment of the complexation of element 106, Sg, in HF solutions**
Radiochim. Acta **92**, 455-462 (2004).

H. Haba et al.
**Fluoride Complexation of Element 104, Rutherfordium**
J. Am. Chem. Soc. 126, 5219-5224 (2004).

## * ***Covering nuclear aspects***

A. Türler et al.
**Decay Properties of $^{265}$Sg (Z=106) and $^{266}$Sg (Z=106)**
Phys. Rev. **C 57**, 1648-1655 (1998).

A. Türler et al.
**On the decay properties of $^{269}$Hs and indications for the new nuclide $^{270}$Hs**
Eur. Phys. J. **A 17**, 505–508 (2003).

J.V. Kratz et al.
**An EC-branch in the decay of 27-s $^{263}$Db: Evidence for the isotope $^{263}$Rf**
Radiochim. Acta **91**, 59-62 (2003).

## * ***Reviews and books***

V. Pershina
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Chem. Rev. **96**, 1977-2010 (1996).

M. Schädel
**Aqueous Chemistry of Transactinides**
Radiochim. Acta, **89**, 721-728 (2001).

M. Schädel
**The Chemistry of Transactinide Elements -- Experimental Achievements and Perspectives**
J. Nucl. Radiochem. Sci. **3**, 113-120 (2002).

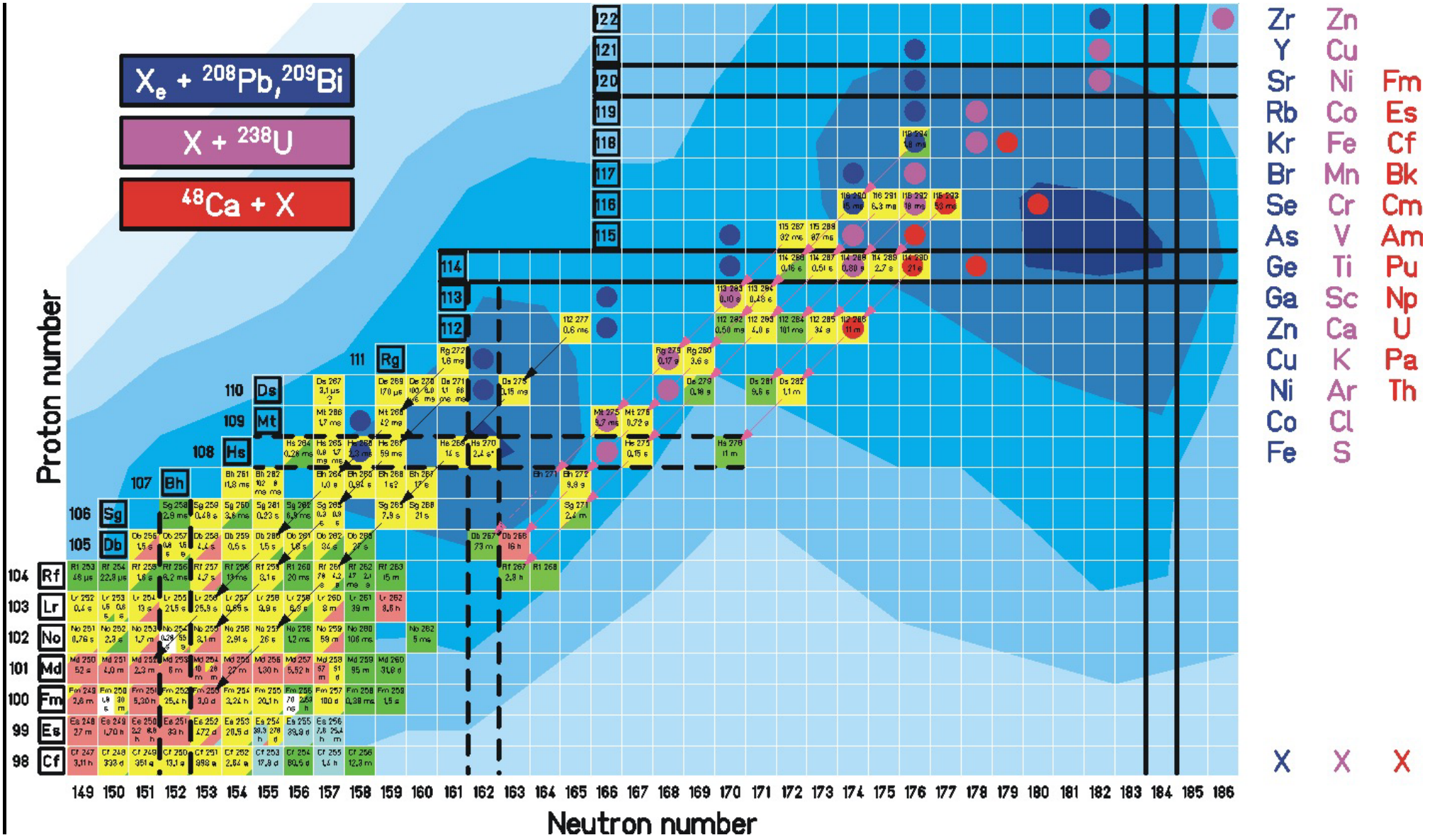
M. Schädel (Ed.)
**The Chemistry of Superheavy Elements**
Kluwer Academic Publishers, Dordrecht, 2003.
("This book is the first to treat the chemistry of superheavy elements, ... , as a self contained topic")

M. Schädel
**The Chemistry of Superheavy Elements**
Acta Phys. Polonica **34**, 1701-1728 (2003).

V. Pershina
**Theoretical Chemistry of the Heaviest Elements**
In: *The Chemistry of Superheavy Elements*, M. Schädel (Ed.), Kluwer, Dordrecht, 2003, p. 31- 94.

V. Pershina,
**The Chemistry of the Superheavy Elements and Relativistic Effects**
In: *Relativistic Electronic Structure Theory*, *Part 2: Applications*, Theoretical and Computational Chemistry, P. Schwerdtfeger (Ed.), Vol. 14, 2004, Elsevier B. V., p. 1-80.

# Attachment H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$^{48}$Ca + X
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Neutron number
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Y Cu
Sr Ni Fm
Rb Co Es
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As V Am
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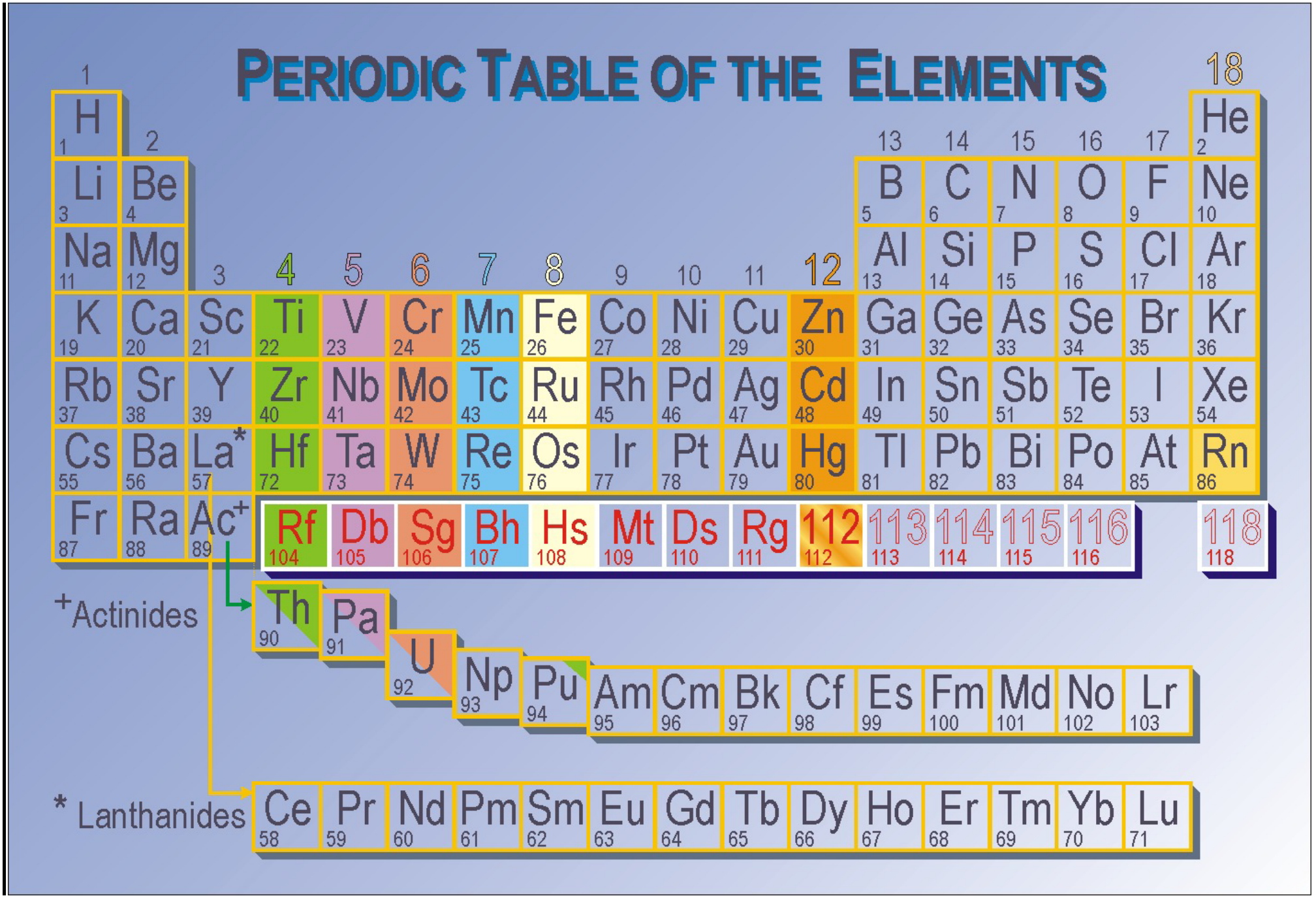
Zn Ca U
Cu K Pa
Ni Ar Th
Co Cl
Fe S
X X X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B 5
C 6
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O 8
F 9
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Na 11
Mg 12
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Si 14
P 15
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Cl 17
Ar 18
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Ga 31
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As 33
Se 34
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Rb 37
Sr 38
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Zr 40
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Tc 43
Ru 44
Rh 45
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I 53
Xe 54
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Ba 56
La* 57
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Re 75
Os 76
Ir 77
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Au 79
Hg 80
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Pb 82
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Rn 86
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Ra 88
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Yb 70
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