FFAG ACCELERATORS

M.K.Craddock

Department of Physics and Astronomy,
University of British Columbia
& TRIUMF

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Workshop on Hadron Beam Therapy for Cancer, Erice, 24-30 April, 2009

OUTLINE

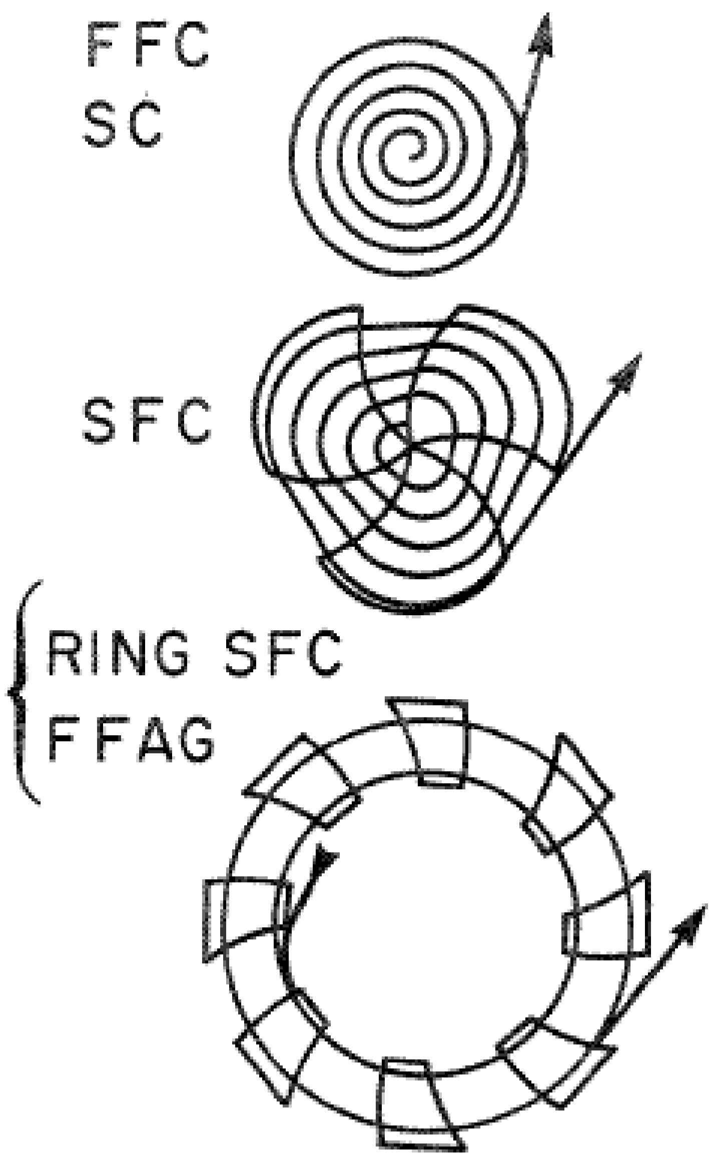
1. What are Fixed-Field Alternating-Gradient Accelerators (FFAGs)? How do they differ from cyclotrons and synchrotrons?

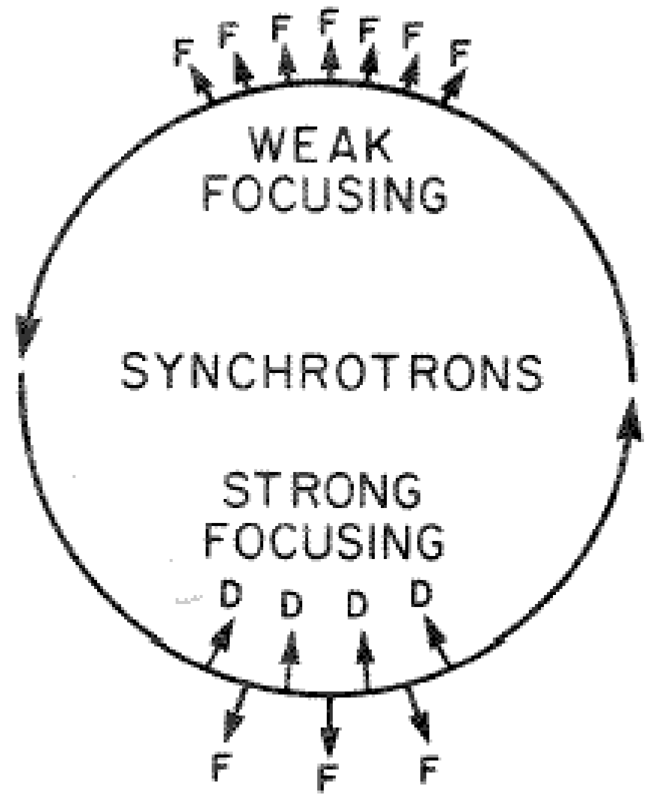
2. What distinguishes scaling from non-scaling FFAGs?

3. Brief overview of proposed FFAG designs for cancer therapy.

4. Advantages and disadvantages of FFAGs.

THE CYCLOTRON AND SYNCHROTRON FAMILIES





FFC = fixed frequency cyclotron

SC = synchrocyclotron

SFC = sector-focused/isochronous cyclotron

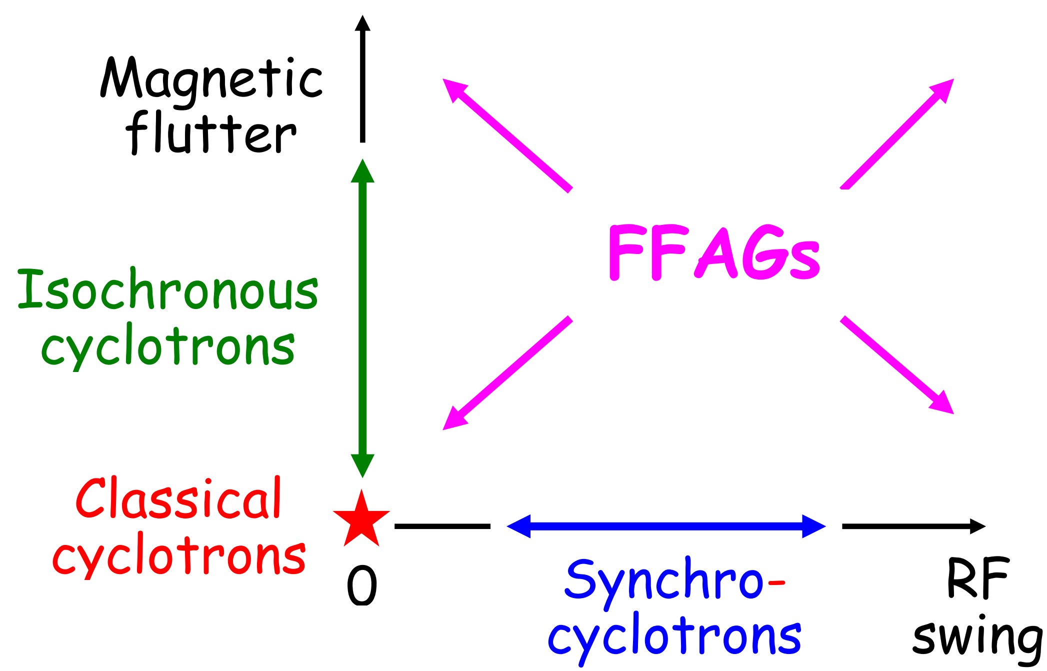
FFAG = fixed field alternating gradient

FFAGs – Fixed Field Alternating Gradient accelerators

Fixed Magnetic Field – members of the CYCLOTRON family[1]

Magnetic field variation B(θ)	Fixed Frequency (CW beam)	Frequency-modulated (Pulsed beam)
Uniform	Classical	Synchro-
Alternating	Isochronous	FFAG

But FFAG enthusiasts sometimes express an alternative view:
– cyclotrons are just special cases of the FFAG!



1. E.M. McMillan, *Particle Accelerators*, in *Experimental Nuclear Physics*, **III**, 639-786 (1959)

BRIEF HISTORY

FFAGs were **proposed** by **Ohkawa, Kolomensky, Symon** and **Kerst**, (1953-5)

- and **studied** intensively at **MURA** in the 1950s and 1960s
- several **electron models** were **built** and **operated** successfully
- but no **proton FFAG** until **Mori's** at **KEK** (1 MeV 2000, 150 MeV 2003)

Now there's an explosion of interest!

- **6 more are now operating (for p, e, α)** and **3 more (e) are being built**
- **~20 designs** under study:
  - for **protons, heavy ions, electrons** and **muons**
  - many of **novel "non-scaling" design**
- with **diverse applications:**
  - **cancer therapy**
  - **industrial irradiation**
  - **driving subcritical reactors**
  - **boosting high-energy proton intensity**
  - **producing neutrinos.**

FFAG Workshops since 1999:- Japan (x8), CERN, USA(x3), Canada, France, UK

BASIC CHARACTERISTICS OF FFAGs

are determined by their **FIXED MAGNETIC FIELD**

- Spiral orbits
  - needing wider magnets, rf cavities and vacuum chambers (compared to AG synchrotrons)
- Faster rep rates (up to kHz?) limited only by rf capabilities
  - not by magnet power supplies
- Large acceptances
- High beam current

The last 3 factors have fuelled interest in FFAGs over 50 years!

Good reading:

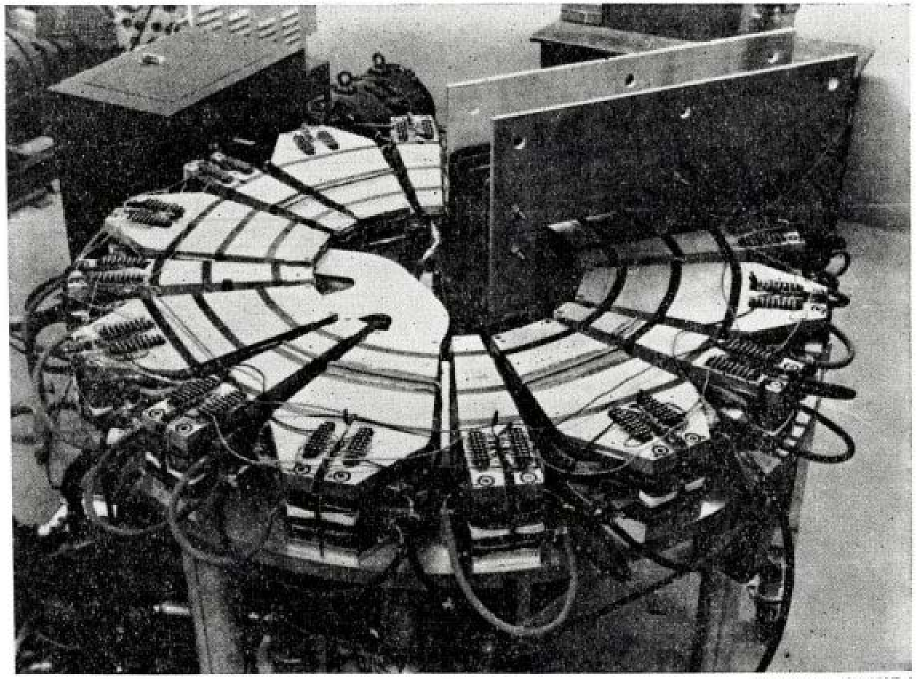
- K.R. Symon, D.W. Kerst, *et al.*, *Phys. Rev.* **103**, 1837 (1956)
- C.H Prior (ed.) *ICFA Beam Dynamics Newsletter* **43**, 19-133 (2007);
- FFAG Workshops – Web links at FFAG04 and FFAG 2007.

MURA Electron FFAGs

400keV radial sector →

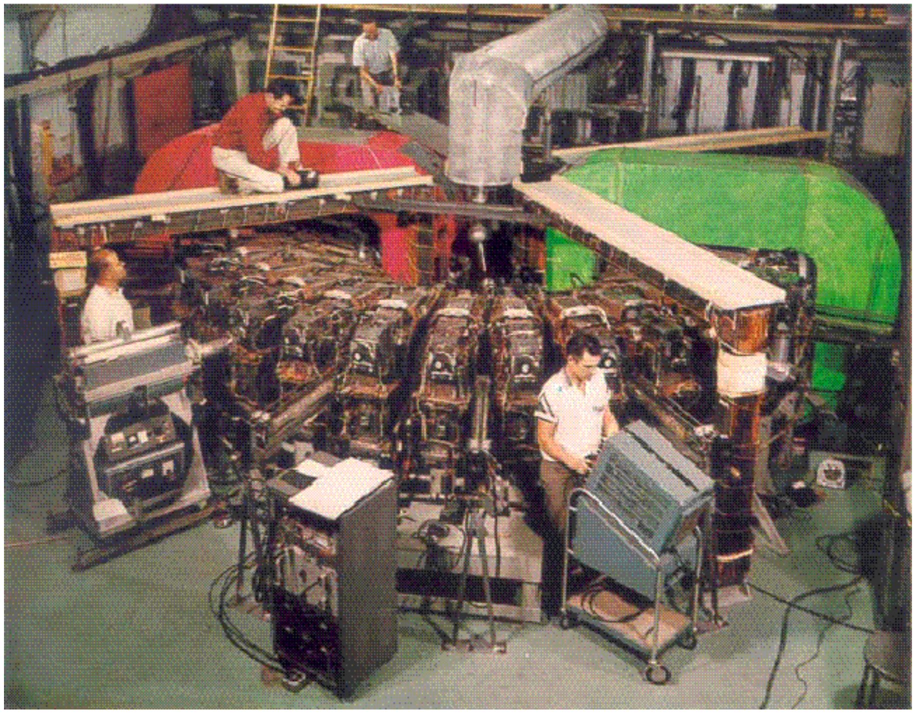
50 MeV radial sector ↘

120 keV spiral sector ↓



Courtesy of MURA

K.R. Symon, Proc PAC03, 452 (2003)



Courtesy of MURA

TRANSVERSE FOCUSING

In accelerators and beam transport systems, "focusing":

- does not generally refer to creation of a point focus;
- it means keeping a beam of neighbouring particles together by an E and/or M field distribution that provides restoring forces, leading to stable orbits.

Similarly, "defocusing" refers to situations with unstable orbits.

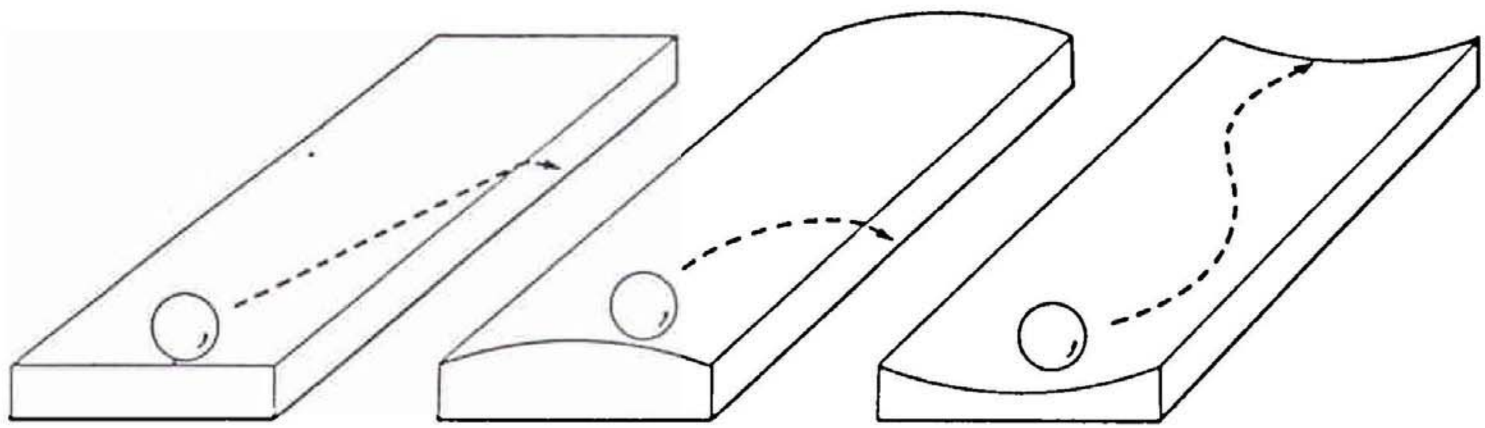


Fig. 2-1. Bowling alley analogy of systems of forces which produce neutral, unstable, or stable orbits.

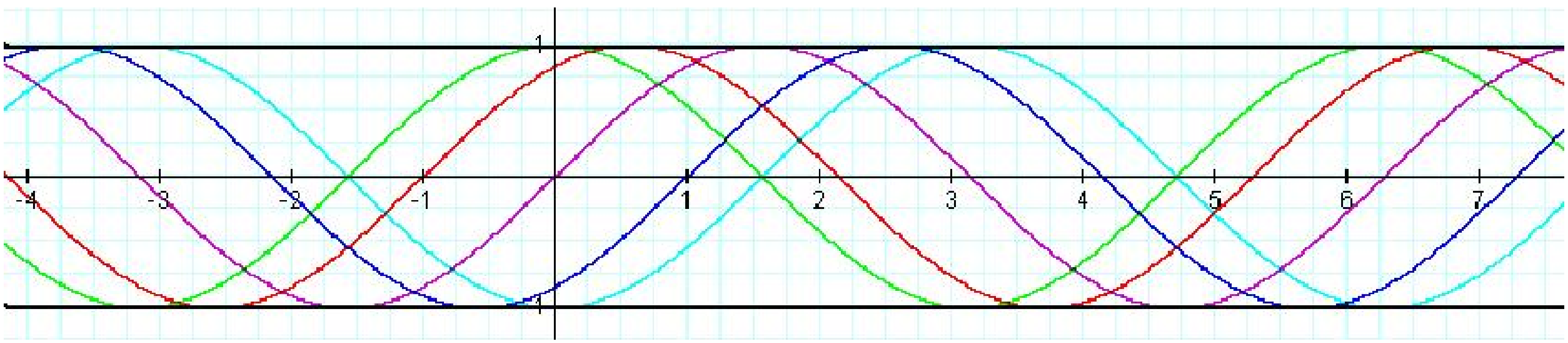
BETATRON OSCILLATIONS, TUNES & EMITTANCE

With uniform focusing, charged particles will follow sinusoidal paths with amplitude A_u and phase ϕ:

$$u = A_u \cos(\nu_u \theta + \phi)$$

Here u stands for transverse x or y and the '<u>tune</u>' ν (or Q in Europe) = number of oscillations per turn.

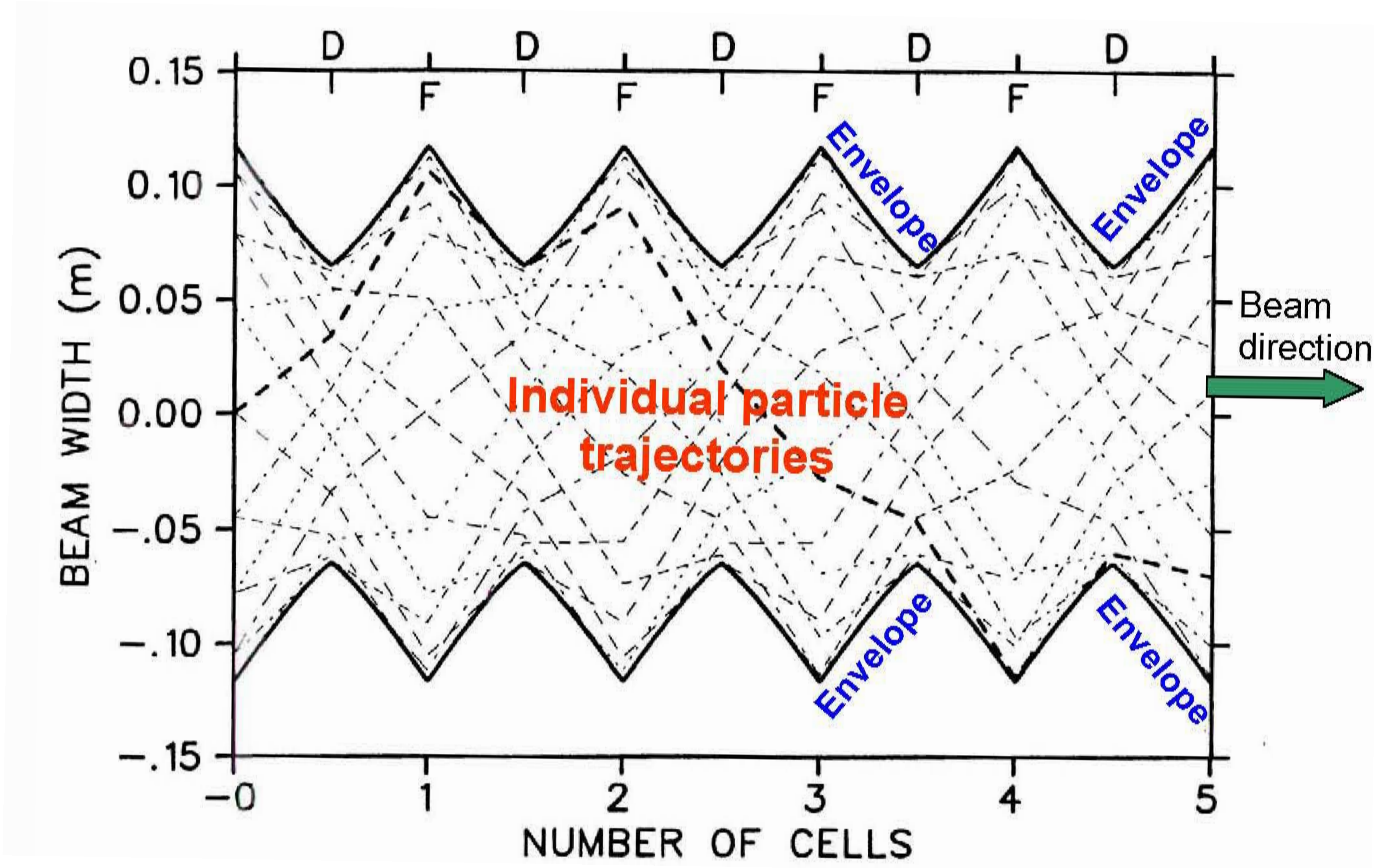
An aperture of half-height A can therefore accommodate a beam of particles with any phase ϕ and all amplitudes $A_u \leq A$, oscillating within a uniform envelope. [N.B. only max<u>m</u> amplitude orbits are shown in the sketch.]



A useful measure of beam size is '<u>emittance</u>' $\propto$ diameter × divergence.

The complementary quantity for an aperture/channel is its '<u>acceptance</u>' = the largest emittance that can pass through.

BETATRON OSCILLATIONS with ALTERNATING FOCUSING



With alternating F and D lenses, the envelope is no longer uniform.

SCALING DESIGNS - HORIZONTAL TUNE ν_r

Resonances were a worry in the 1950s, because of slow acceleration: if, at some energy, the betatron oscillation wavelength matches that of a harmonic component of the magnetic field, the ions may be driven into resonance, leading to loss of beam quality or intensity.

The general condition is $\boxed{\ell \nu_x \pm m \nu_y = n}$ where ℓ, m, n are integers.

So "**Scaling**" designs were used, with:

- the same orbit shape at all energies
- the same optics " " " " "
- the **same tunes** " " " " " $\Rightarrow$ no crossing of resonances!

To 1st order, the (radial tune)^2 $\nu_r^2 \approx 1 + k$ (even with sector magnets)

where the average field index $k(r) \equiv \dfrac{r}{B_{av}} \dfrac{dB_{av}}{dr}$ and $B_{av} = \langle B(\Theta) \rangle$

So large constant ν_r requires k = constant ≥ 0

$\Rightarrow$ $B_{av} = B_0 (r/r_0)^k$ and $p = p_0 (r/r_0)^{(k+1)}$

SCALING FFAGs - VERTICAL TUNE ν_z

In the vertical plane, with sector magnets and to 1st order,

$$\nu_z^2 \approx -k + F^2(1 + 2\tan^2\varepsilon)$$

where the 2nd term describes the Thomas and spiral edge focusing effects.

Note $k > 0 \Rightarrow$ vertical defocusing

$\therefore$ large constant, real ν_z requires large, constant $F^2(1 + 2\tan^2\varepsilon)$

MURA kept (1) magnetic flutter $F^2 \equiv \left\langle \left(\frac{B(\theta) - B_{av}}{B_{av}} \right)^2 \right\rangle$ = constant

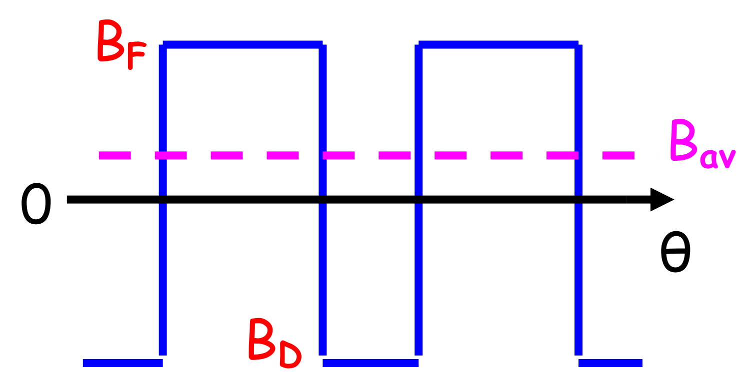
(most simply achieved by using constant profile $B(\Theta)/B_{av}$)

(2a) for spiral sectors,

spiral angle ε = constant (sector axis follows $R = R_0 e^{\Theta\cot\varepsilon}$)

(2b) for radial sectors,

$B_D = -B_F$ to boost F^2.



Note - reverse fields increase average radius:

$\Rightarrow$ >4.5x larger (Kerst & Symon '56 - no straights)

[Not so bad with straights: KEK 150-MeV FFAG has "circumference factor" 1.8]

In summary, scaling requires:-

- constant **field index**
- constant and high **flutter**, with opposing F and D fields (if radial)
- constant **spiral** angle (if spiral)

- meaning **complex wide-aperture sector magnets**

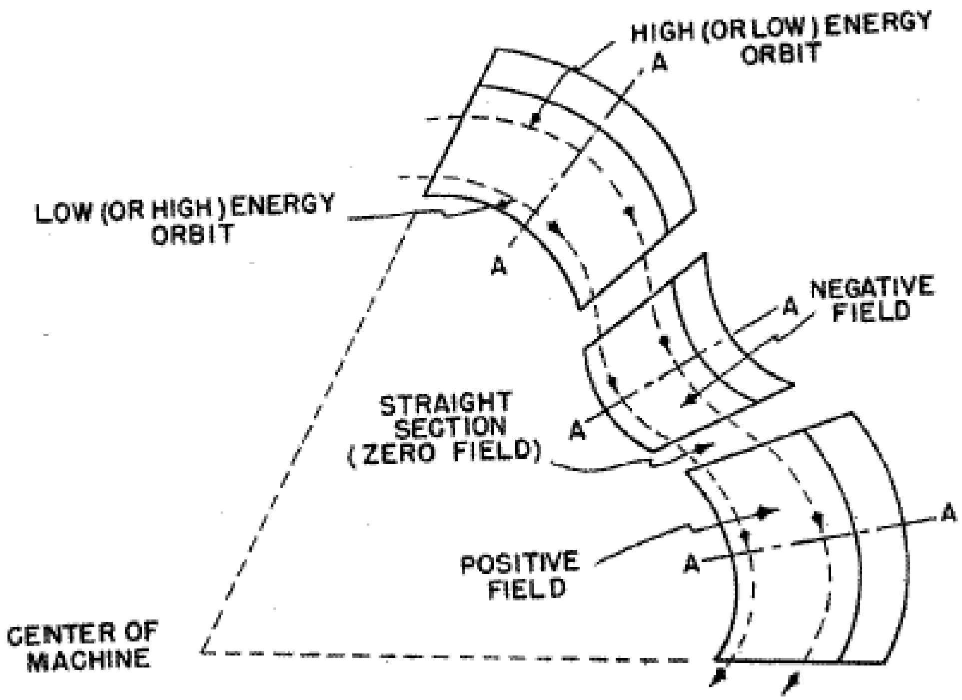


FIG. 2. Plan view of radial-sector magnets.

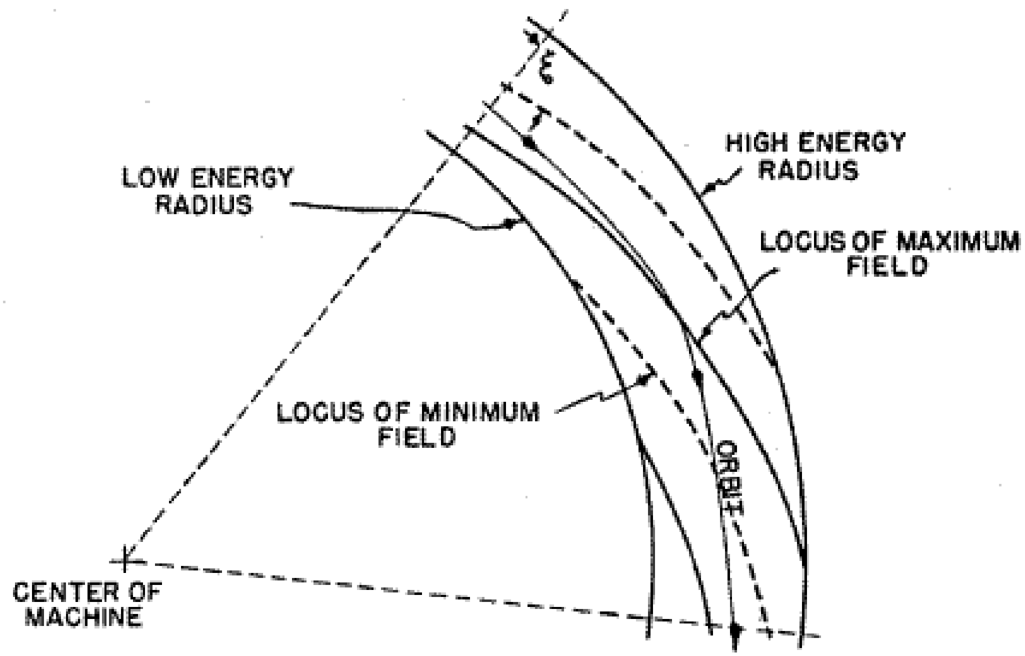
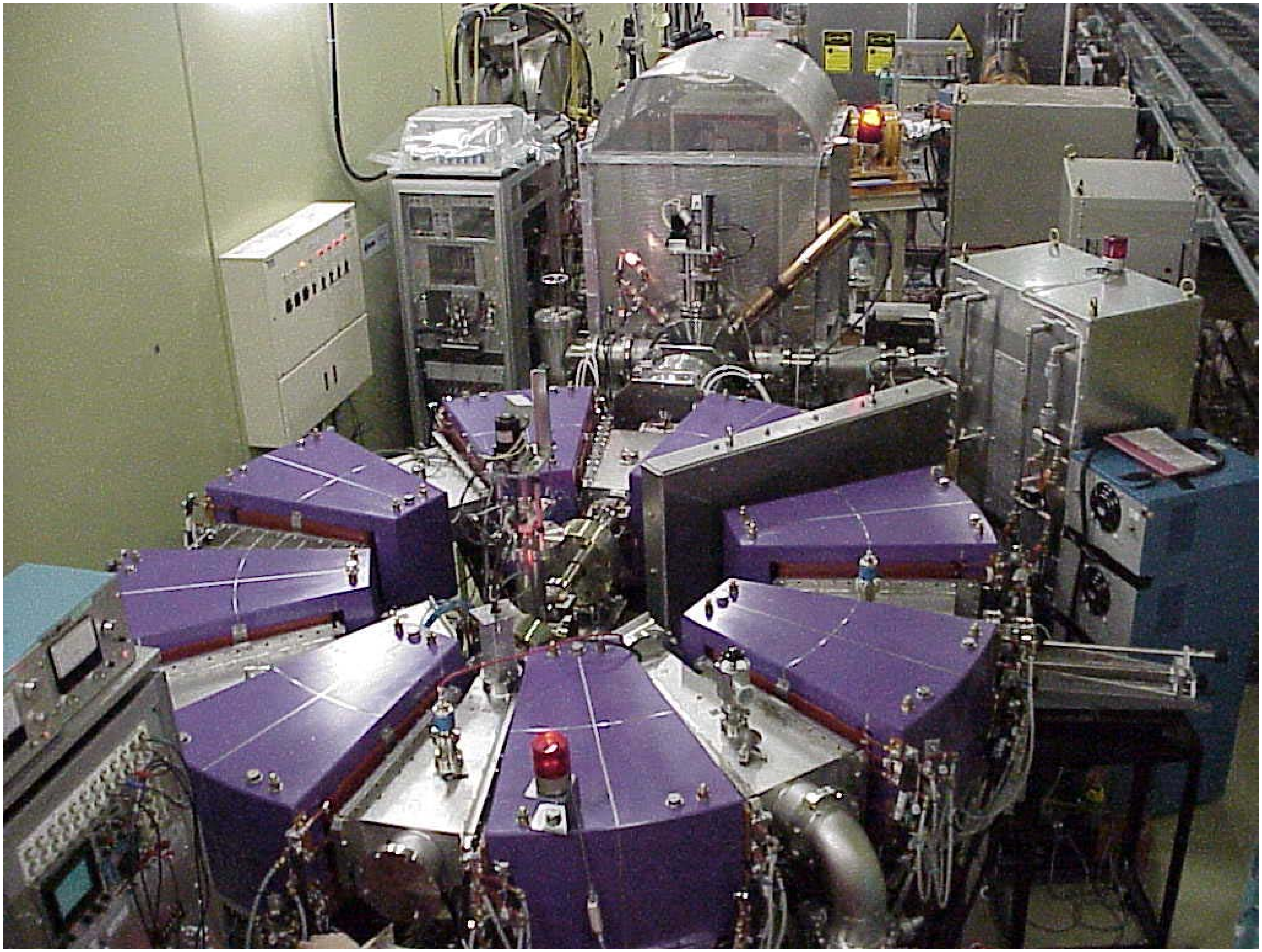


FIG. 3. Spiral-sector configuration.

K.R. Symon, D.W. Kerst, L.W. Jones, L.J. Laslett and K.M. Terwilliger, *Phys. Rev.* **103**, 1837 (1956)

KEK Proof-of-Principle 1 MeV proton FFAG



KEK 150-MeV 12-Sector Proton FFAG

INNOVATIONS AT KEK

Mori's 1 MeV (2000) and 150 MeV proton FFAGs introduced two important innovations:

1. **FINEMET metallic alloy tuners** allowing:
   - rf modulation at 250 Hz or more → high beam-pulse rep rates (remember the unreliable rotary capacitors on synchrocyclotrons, which operate in the same mode as FFAGs)
   - high permeability → short cavities with high effective fields
   - low Q (≅1) → broadband operation at a few MHz

2. **DFD triplet sector magnets:**
   - powered as a single unit
   - D acts as the return yoke, automatically providing reverse field
   - modern techniques enable accurate computation of the pole shape for constant field index *k*

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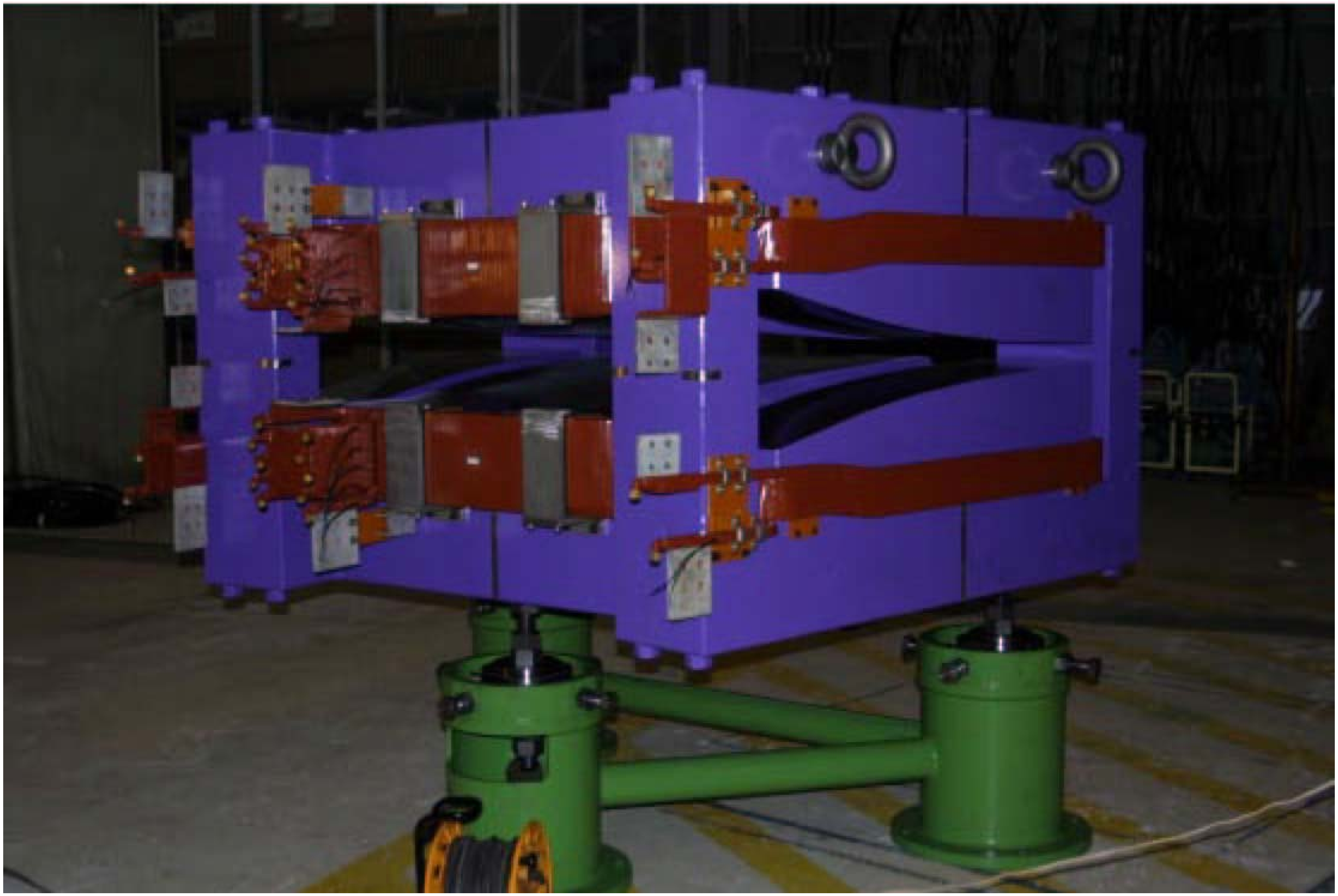
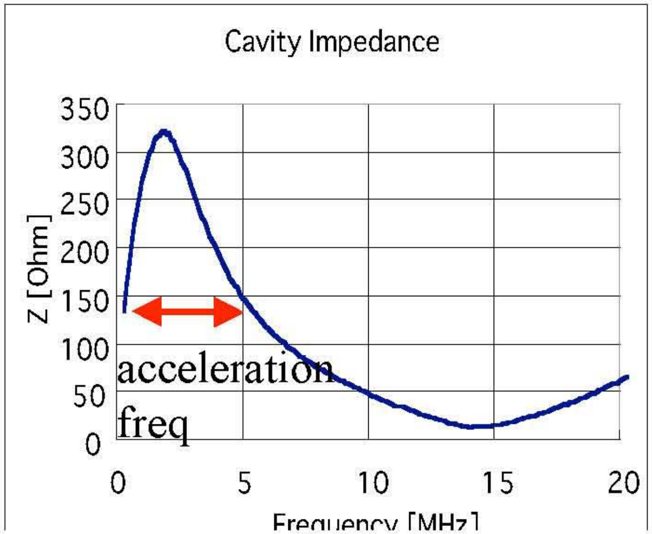
"Return-yoke-less" DFD Triplet for 150-MeV FFAG



RF system

Large Magnetic Alloy (FINEMET) Cavity

Number of core	4 pieces
Outer (Inner) size	1700x950mm(980x230mm)
Core thickness	25mm
RF frequency	1.5 – 4.6 MHz
RF voltage	9kV
RF output	55kW
Power density	1W/cm3
Cooling water	70 L/min



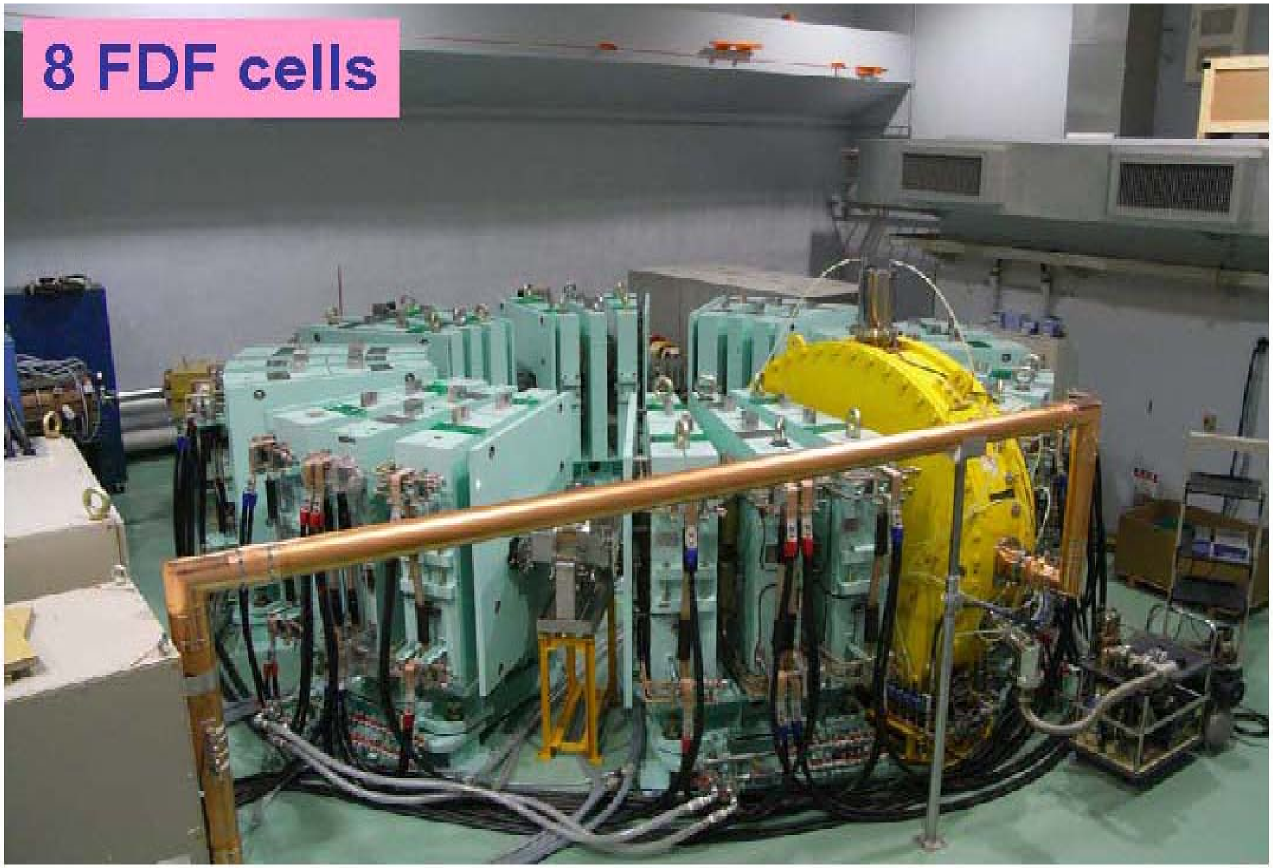
Measured Impedance

FFAG Complex at Kyoto University Research Reactor Inst.

- to test Accelerator-Driven Sub-critical Reactor (ADSR) operation

KURRI ERIT STORAGE RING FOR BNCT

(ERIT = Energy/Emittance Recovery Internal Target)



70-mA of circulating 11-MeV protons produce an intense neutron beam (>10^9/cm^2/s at the patient) via the Be(p,n) reaction.

V_{rf} = 250 kV plus large FFAG acceptances (>3000 mm-mrad, ±5% δp/p) allow ionization cooling to maintain stable beam over 1000 turns.

SCALING FFAGs

- IN OPERATION OR UNDER CONSTRUCTION -

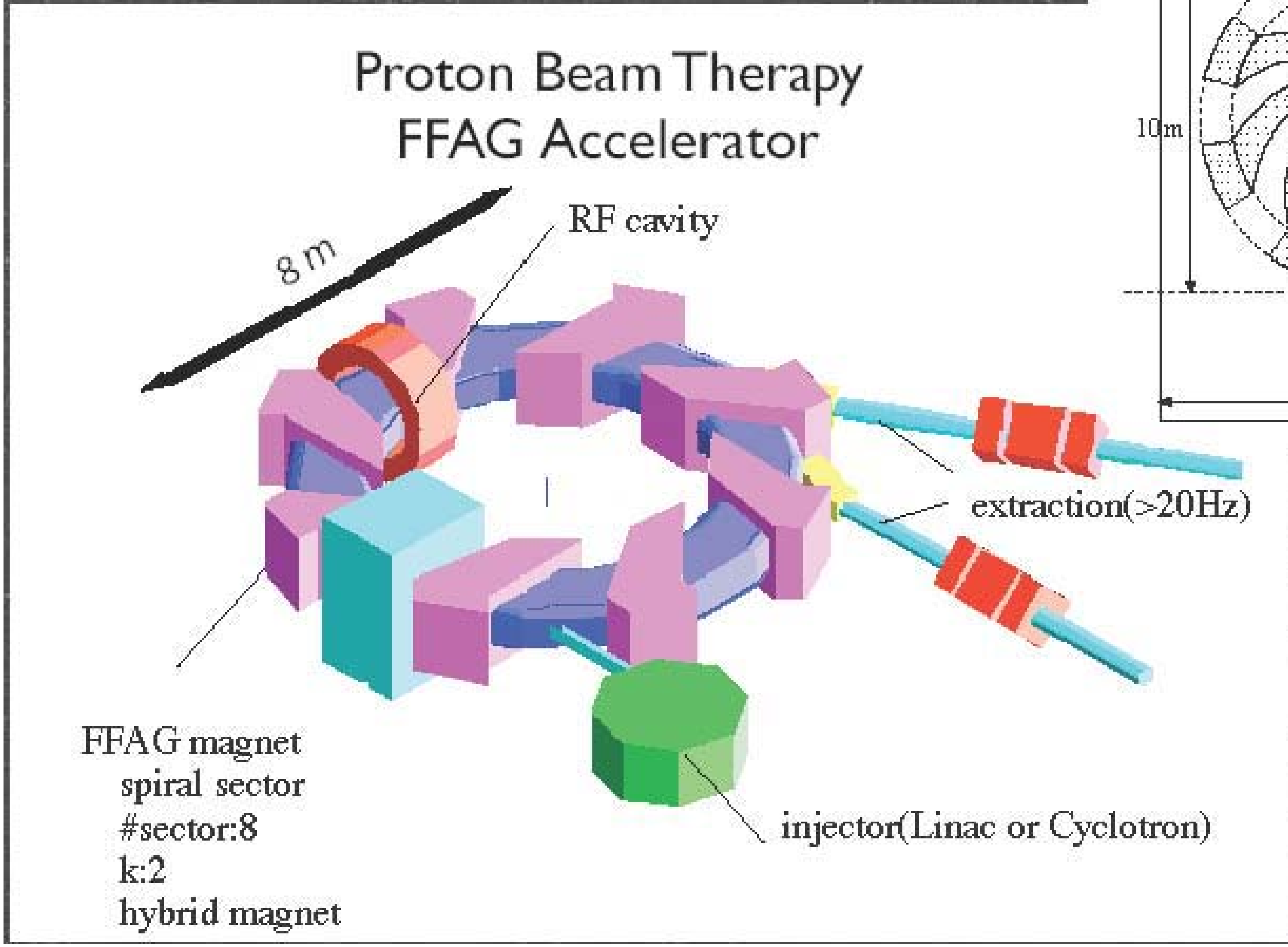
	Energy (MeV/u)	Ion	Cells	Spiral angle	Radius (m)	1st beam
KEK - POP	1	p	8	0°	0.8-1.1	2000
KEK	150	p	12	0°	4.5-5.2	2003
KURRI - ADSR	150	p	12	0°	4.5-5.1	2006
(Accelerator-Driven	20	p	8	0°	1.3-1.9	2006
Subcritical Reactor)	2.5	p	8	40°	0.6-1.0	2008
KURRI-ERIT (BNCT)	11	p	8	0°	2.35	2008
PRISM study	0.8	α	6	0°	3.3	2008
PRISM*	20	μ	10	0°	6.5	
NHV	0.5	e	6	30°	0.19-0.44	2008
RadiaBeam Radiatron	5	e	12	0°	0.3-0.7	(2009)

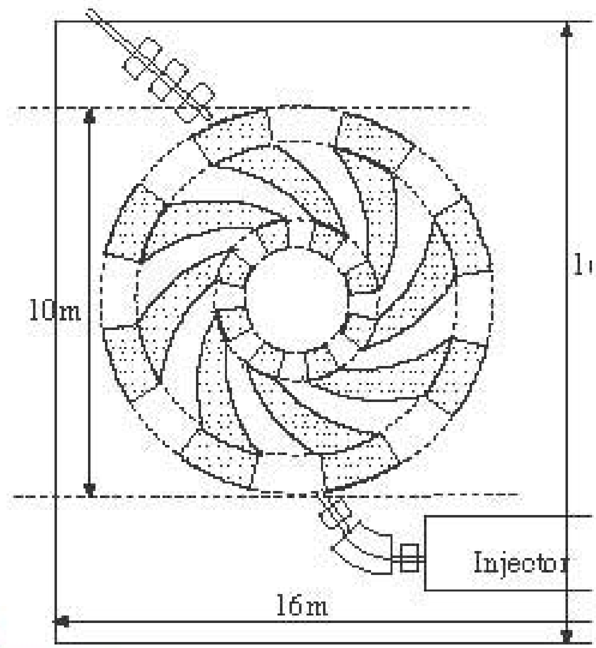
* storage ring for μ bunch rotation in phase space

SCALING FFAGs - DESIGN STUDIES

	Energy (MeV/u)	Ion	Cells	Spiral angle	Radius (m)	Rep rate (Hz)	Comments
MEICo - Laptop	1	e	5	35°	.023 -.028	1,000	Hybrid - Magnet built
eFFAG	10	e	8	47°	0.26 - 1.0	5,000	20-100 mA
LPSC RACCAM	180	p	10	54°	3.2 - 3.9	>20	Magnet sector 2008
Ibaraki Med.Acc.	230	p	8	50°	2.2 - 4.1	20	0.1 μA
MEICo - p Therapy	230	p	3	0°-60°	0 - 0.7	2,000	SC, Quasi-isochronous
MEICo - Ion Therapy	400	C^{6+}	16	64°	7.0 - 7.5	0.5	Hybrid (FFAG/synch^n)
(Mitsubishi Electric)	7	C^{4+}	8	0°	1.35 - 1.8	0.5	" " " "
NIRS Chiba	400	C^{6+}	12	0°	10.1 - 10.8	200	Compact
- Hadron	100	"	12	0°	5.9 - 6.7	"	radial
Therapy	7	C^{4+}	10	0°	2.1 - 2.9	"	sectors
Mu Cooling Ring	160	μ	12	0°	0.95 ± 0.08		Gas-filled
J-PARC	20,000	μ	120	0°	200		Δr = 0.5 m, ~10 turns.
Neutrino	10,000	"	64	0°	90		
Factory	3,000	"	32	0°	30		$Q \approx 1$ rf cavities allow
Accelerators	1,000	"	16	0°	10		broadband operation

IBARAKI MEDICAL FACILITY



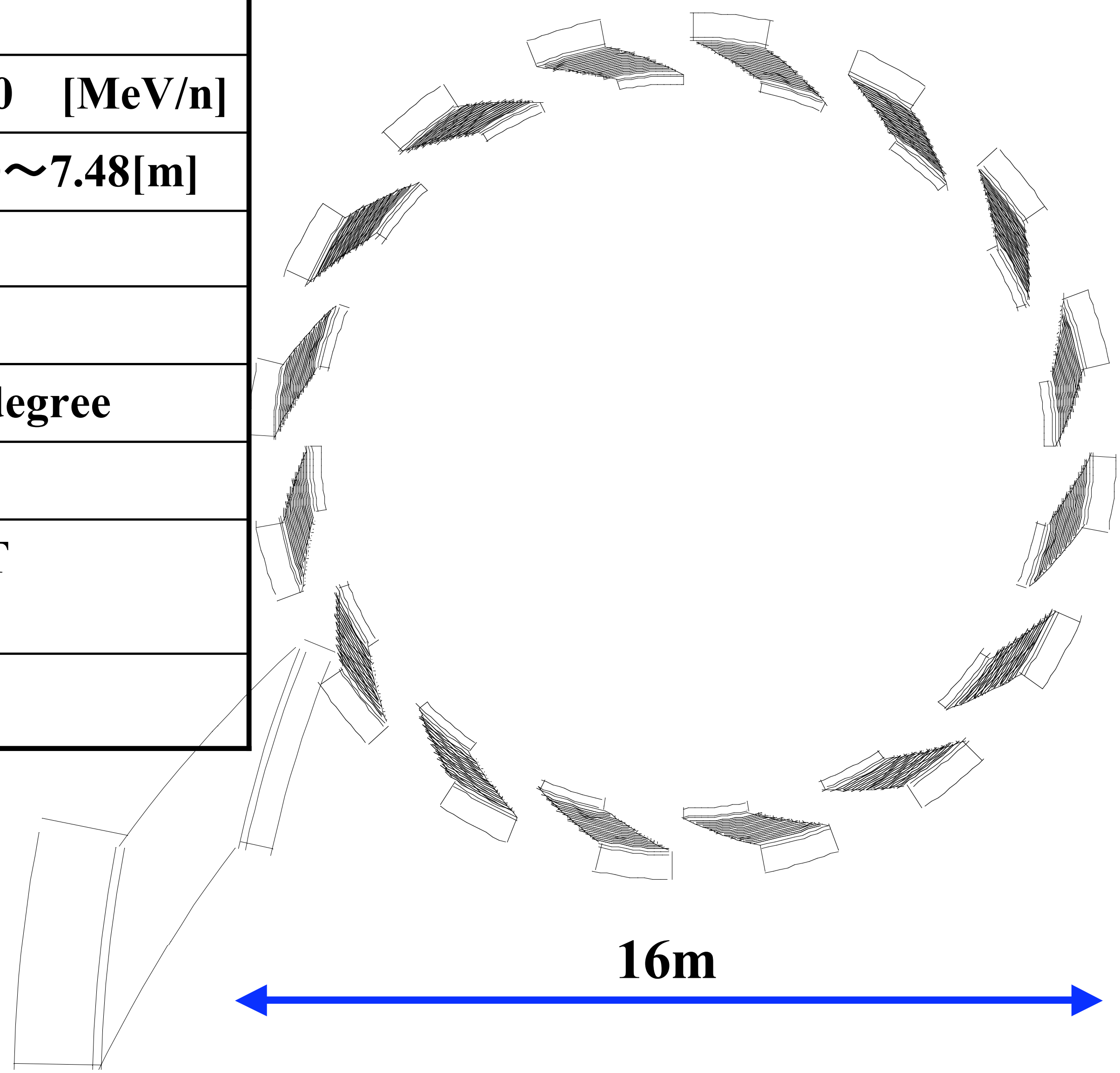


MITSUBISHI ELECTRIC

C6+400MeV/n Hybrid Accelerator

s for the Better

Particle	**C6+**
Energy	**4～400 [MeV/n]**
Radii	**7.00～7.48[m]**
Cell	**16**
K value	**12**
Spiral angle	**65 degree**
Packing F	**0.45**
Maximum Magnetic Strength	**1.9T**
Repetition	**0.5Hz**

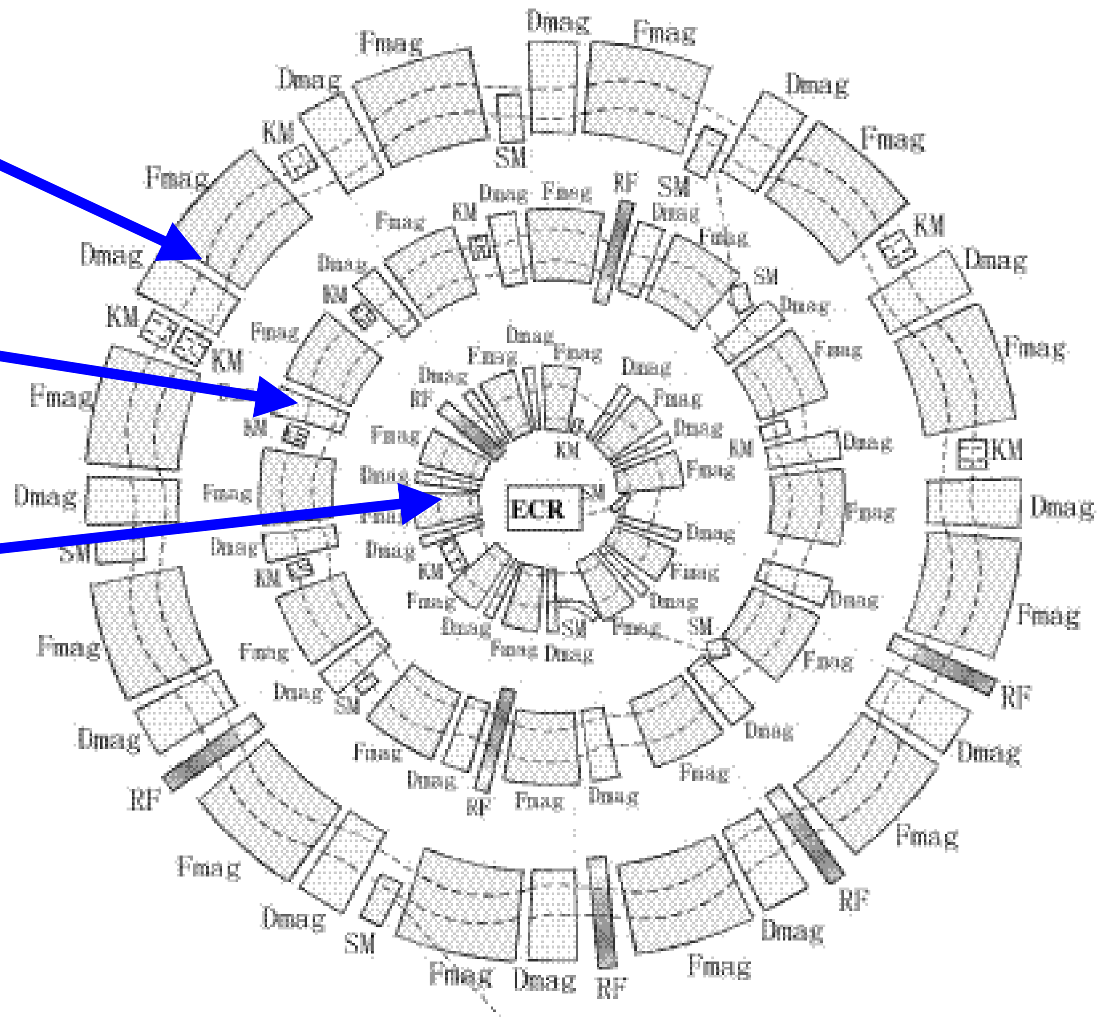


NIRS Chiba – Compact Hadron Therapy FFAG

400 MeV/u C^{6+}

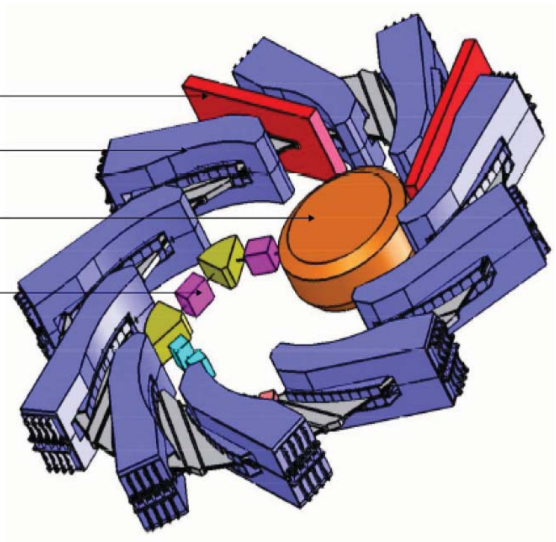
100 MeV/u C^{6+}

7 MeV/u C^{4+}



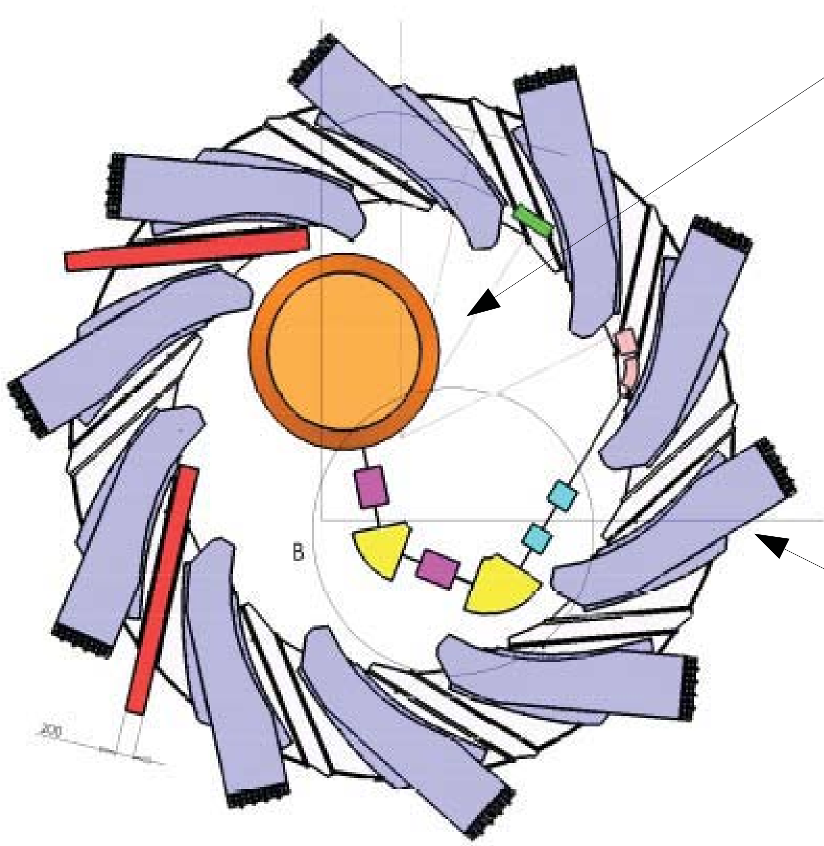
- FD0 lattices
- Radial sectors

Final parameters of the RACCAM 10 cell ring and magnet :



Extracion energy, variable	70 – 180 MeV
Injection energy	5.5 – 17 MeV
Nomentum ratio	3.62
Number of cells	10
Packing factor	0.34
Field index, k	5
Spiral angle	53.7 deg.
Qh / Qv	2.76 / 1.55~1.60
Radius on extraction/injection orbit : dR	3.46 m / 2.78 m / 0.67 m
Drift length, extraction/injection orbit	1.42 m / 1.15 m
Frev, 15->180 MeV	3.03 -> 7.54 MHz
Frev, 5.5->70 MeV	1.86 -> 5.07 MHz

Principle of Energy Variability for RACCAM System



Variable extraction energy from
Injector – H^- cyclotron
(AIMA),
5.5-17 MeV

Allows variable extraction energy from
FFAG, 70-180 MeV,
i.e., 4 to 21 cm Bragg pic penetration

by varying FFAG rigidity

+
extraction kick
synchronised on turn #

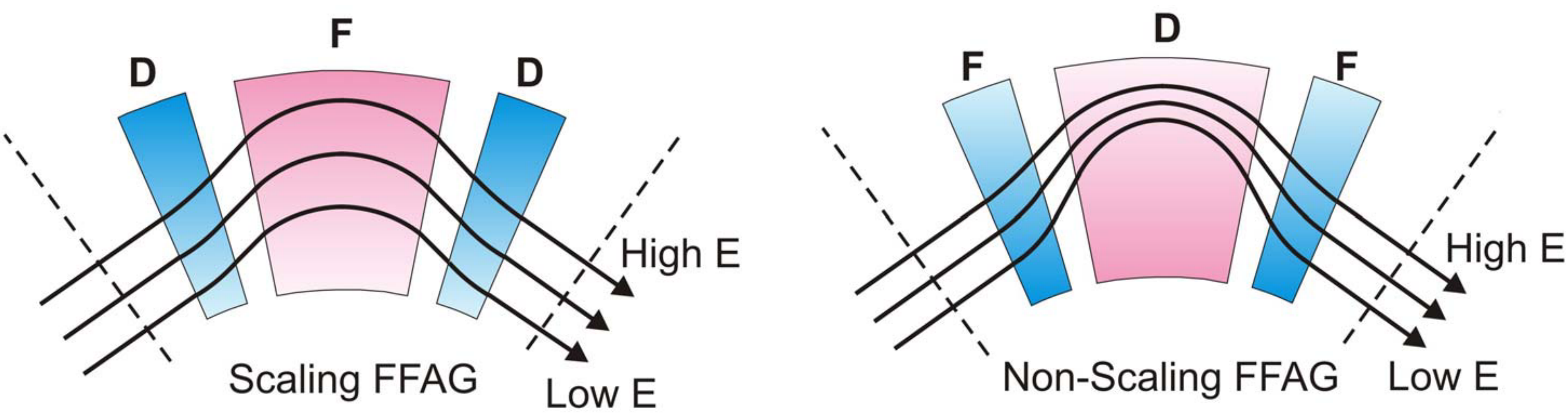
LINEAR NON-SCALING (LNS) FFAGs

FFAGs look attractive for accelerating muons in μ Colliders or ν Factories

- Large acceptance (in *r* & *p*) eliminates cooling & phase rotation stages
- Rapid acceleration (<20 turns) makes resonance crossing ignorable (Mills '97)
- Less expensive than recirculating linacs.

NON-SCALING approach first tried by Carol Johnstone (arc 1997, ring 1999)

- strong positive-bending Ds + negative Fs – i.e. negative field gradients!
- "LINEAR" constant-gradient magnets.



This leads to:

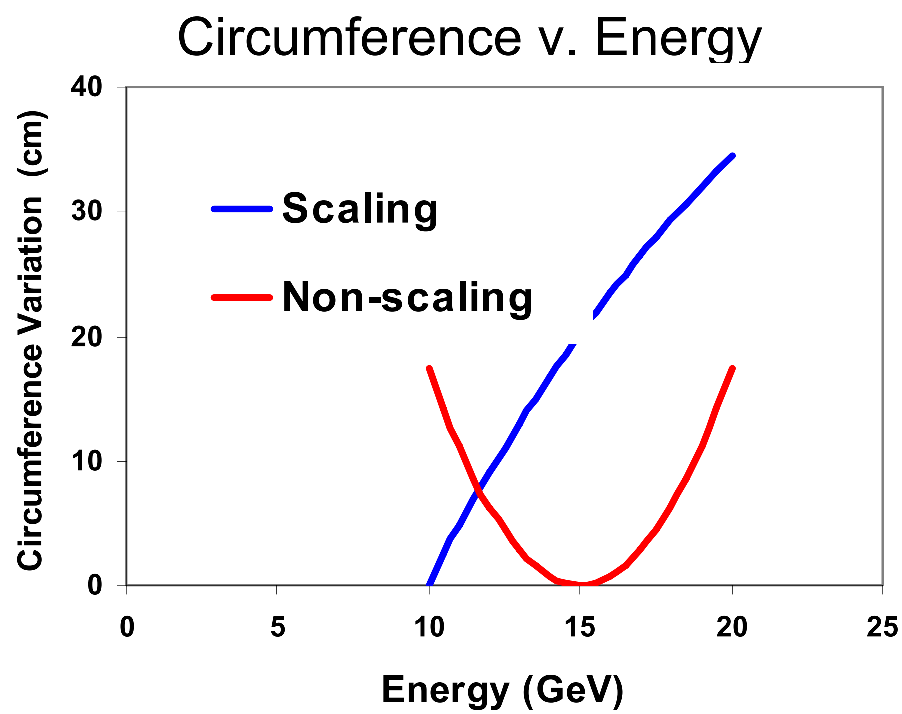
- Greater momentum compaction (& hence narrower radial apertures);
- No multipole field components to drive betatron resonances >1st order;
- Simpler construction ($B \propto r$ rather than r^k).

SCALING v. LINEAR NON-SCALING FFAGs

Note that for LNS-FFAGs, orbit circumference C varies quadratically with energy rather than rising monotonically:

$$C(p) = C(p_m) + \frac{12\pi^2}{e^2 q^2 N L_{FD}} (p - p_m)^2$$

So less variation in C and orbit period, enabling fixed rf frequency operation when $v \approx c$.

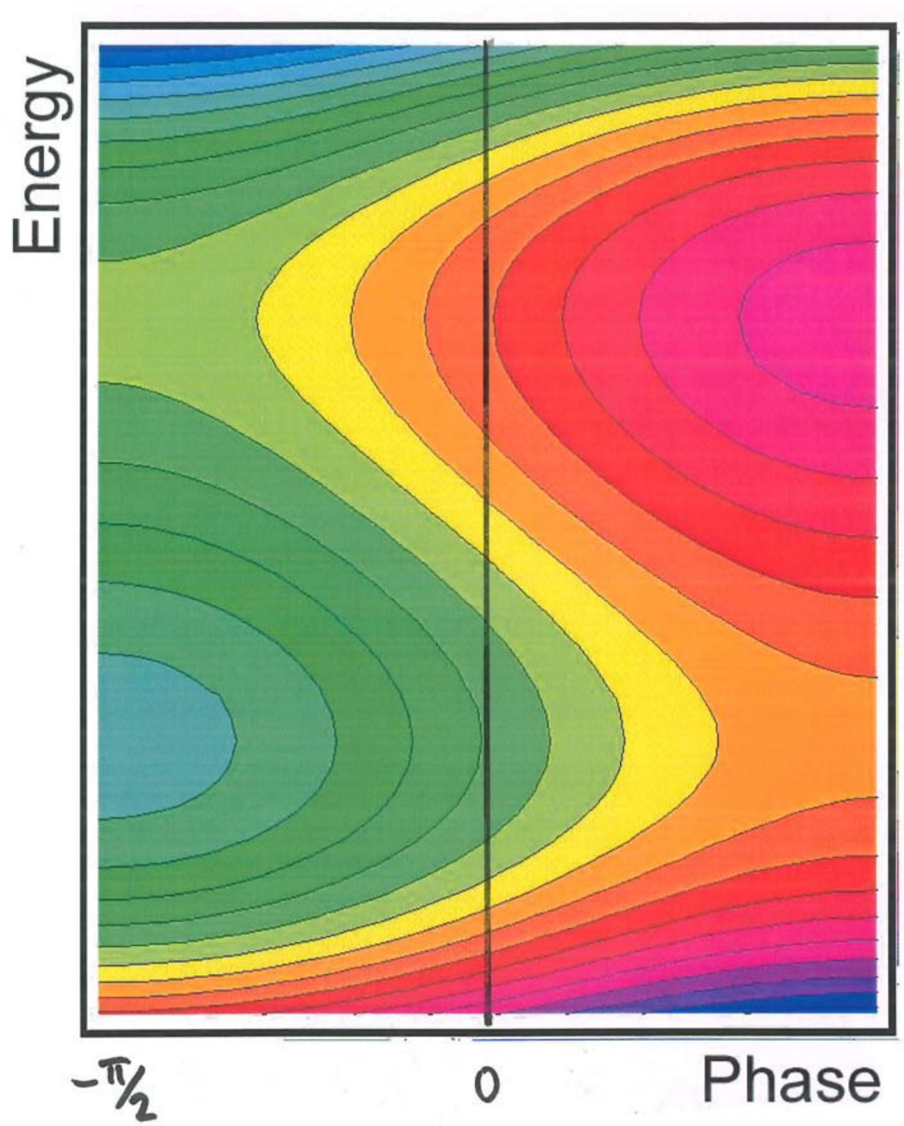


- The muons oscillate in phase across the rf voltage peak (3 crossings)
  - just as in a real, imperfectly isochronous, cyclotron!

The International Design Study for a Neutrino Factory chose LNS-FFAGs of 12.6-25 GeV and 25-50 GeV for the final stages of muon acceleration
- with designs developed by a consortium led by Johnstone (FNAL), Berg (BNL), and Koscielniak (TRIUMF).

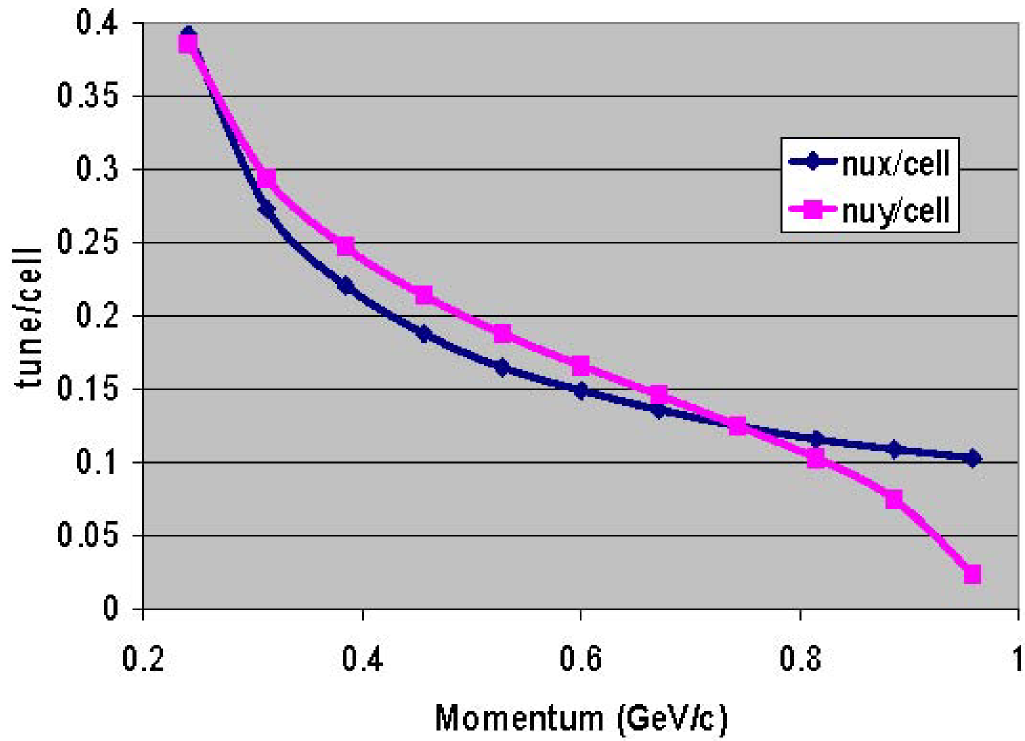
Non-linear NS-FFAGs are also being explored.

SERPENTINE ACCELERATION IN LNS-FFAGs



- Not within the buckets – but between them
- Follow the golden trail!

TUNES IN LNS-FFAGs



If the orbits cross the magnet ends perpendicularly:

- the tunes fall sharply with energy, crossing betatron resonances
- possibly leading to loss of beam quality/quantity
- danger lessened by rapid energy gain, but very expensive
- for muons (τ = 2 μs): expensive but essential anyhow
- for ions: just expensive

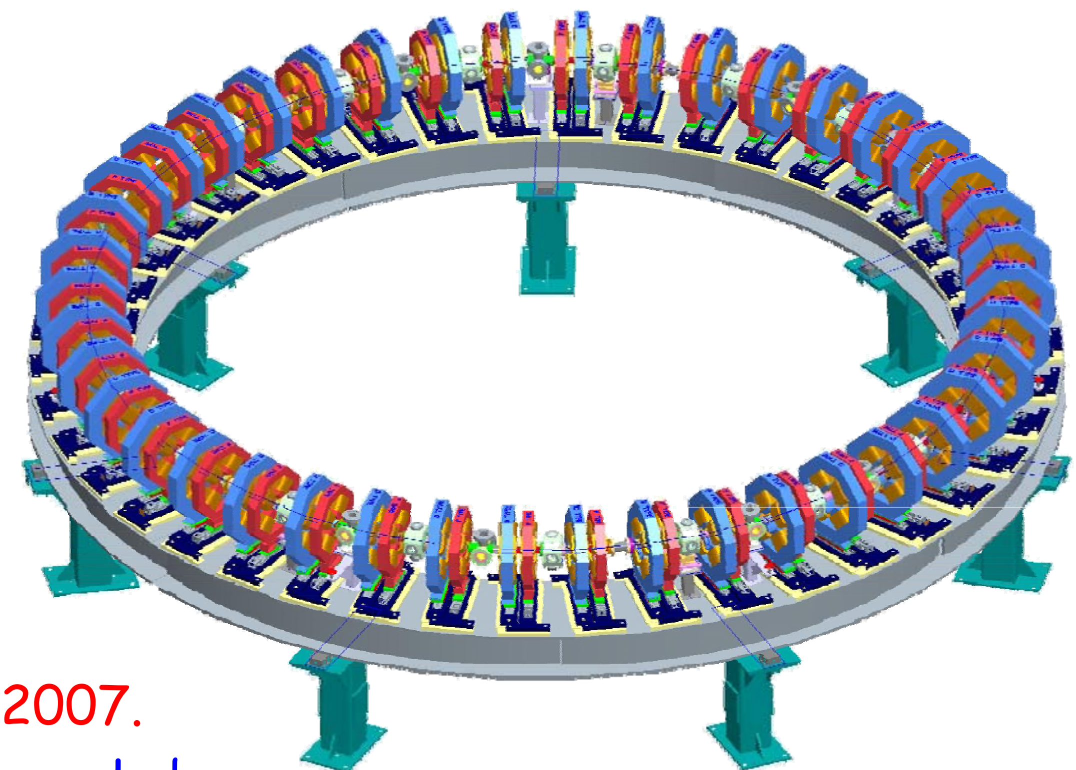
ELECTRON MODEL LNS-FFAG "EMMA"

A Proof of Principle machine for linear non-scaling FFAGs to demonstrate their two novel features:

- safe passage through many low-order structural resonances
- acceleration outside buckets.

EMMA has relativistic parameters similar to those of a 10-20 GeV muon FFAG, with a doublet lattice based on offset quadrupoles:

Energy	10-20 MeV
Circumference	16.57 m
Cells	42
N.T. Acceptance	3 mm
F quad length	5.88 cm
D quad length	7.57 cm
RF frequency	1.3 GHz
Cavities	19 x 120 kV
Injector	ALICE (7-35 MeV)



UK funding ($16M) started April 2007.

Construction under way at Daresbury Lab.

NON-SCALING LATTICES FOR HADRONS

To accelerate hadrons, where $v \ll c$, the wider range of speeds and orbit times τ requires either:

- frequency modulation, or broadband operation,
  - both requiring pulsed beam operation, or
- harmonic number jumping (HNJ) – as in microtrons
  - where the energy gain is adjusted to give $\Delta\tau$ = -integer × τ_{rf}
  - allowing cw fixed-frequency operation and higher beam intensity
  - but requiring precise variation of rf cavity voltage with radius.

With the small radial orbit spread, variable-energy extraction can be realized by timing the kicker pulse, even with fixed kicker and septum.

Three groups are actively designing NS-FFAGs for cancer treatment:

1. Keil (CERN), Trbojevic (BNL) and Sessler (LBNL)
2. Johnstone (FNAL) and Koscielniak (TRIUMF)
3. Yokoi, Peach et al. (Adams Inst.) and Machida (RAL).

Keil-Sessler-Trbojevic LNS-FFAG Therapy Complex

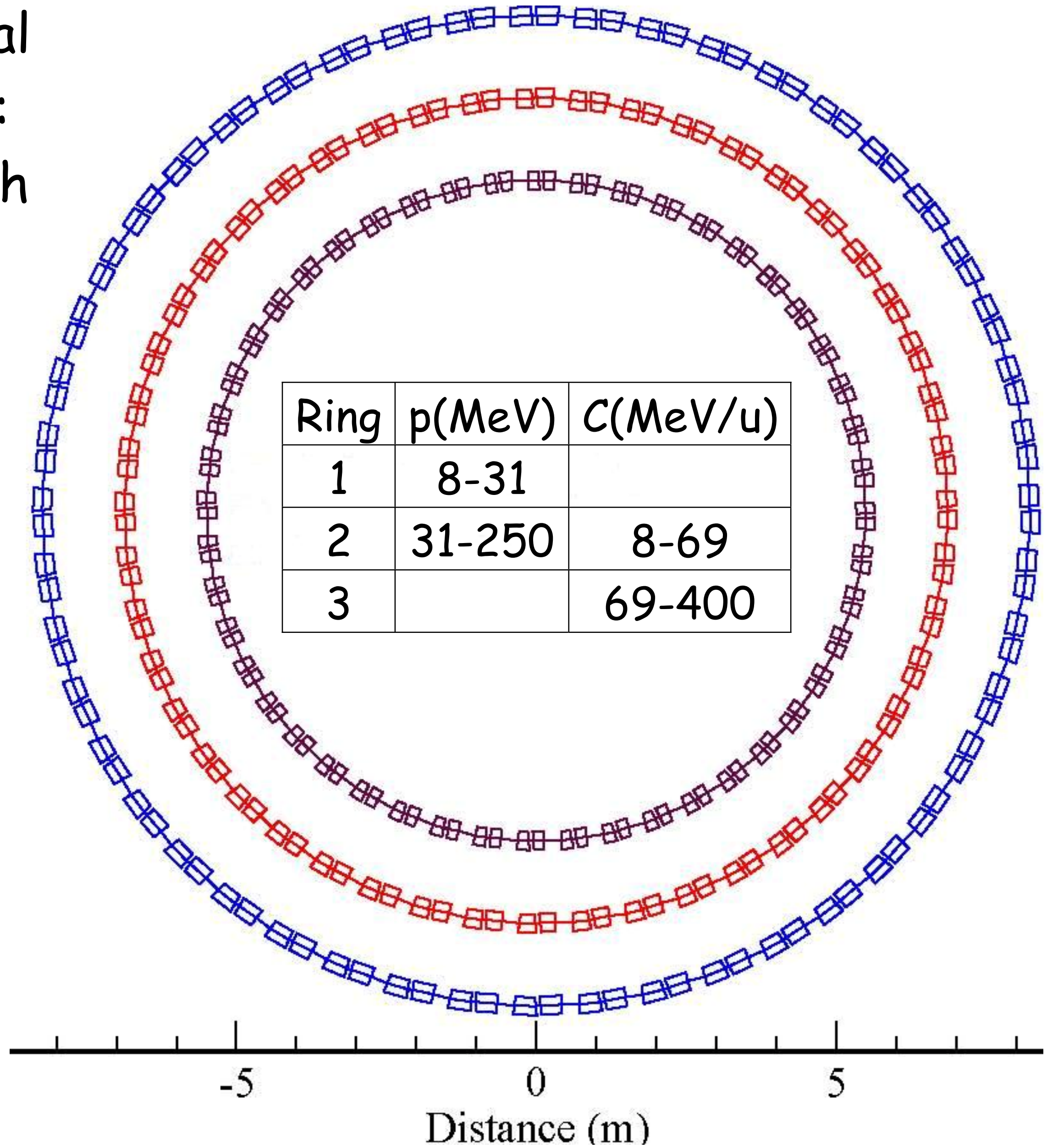
The first LNS-FFAG proposal for ion beam cancer therapy:
- three concentric rings, each of 48 doublet cells.

The tunes fall with energy, crossing several n & n/2 imperfection resonances - but no intrinsic resonances below 3rd order – so good beam quality is maintained.

RF is frequency-modulated (in the range 9-25 MHz).

Note the small magnets (cf. NIRS 3-ring S-FFAG).

Ring	p(MeV)	C(MeV/u)
1	8-31	
2	31-250	8-69
3		69-400



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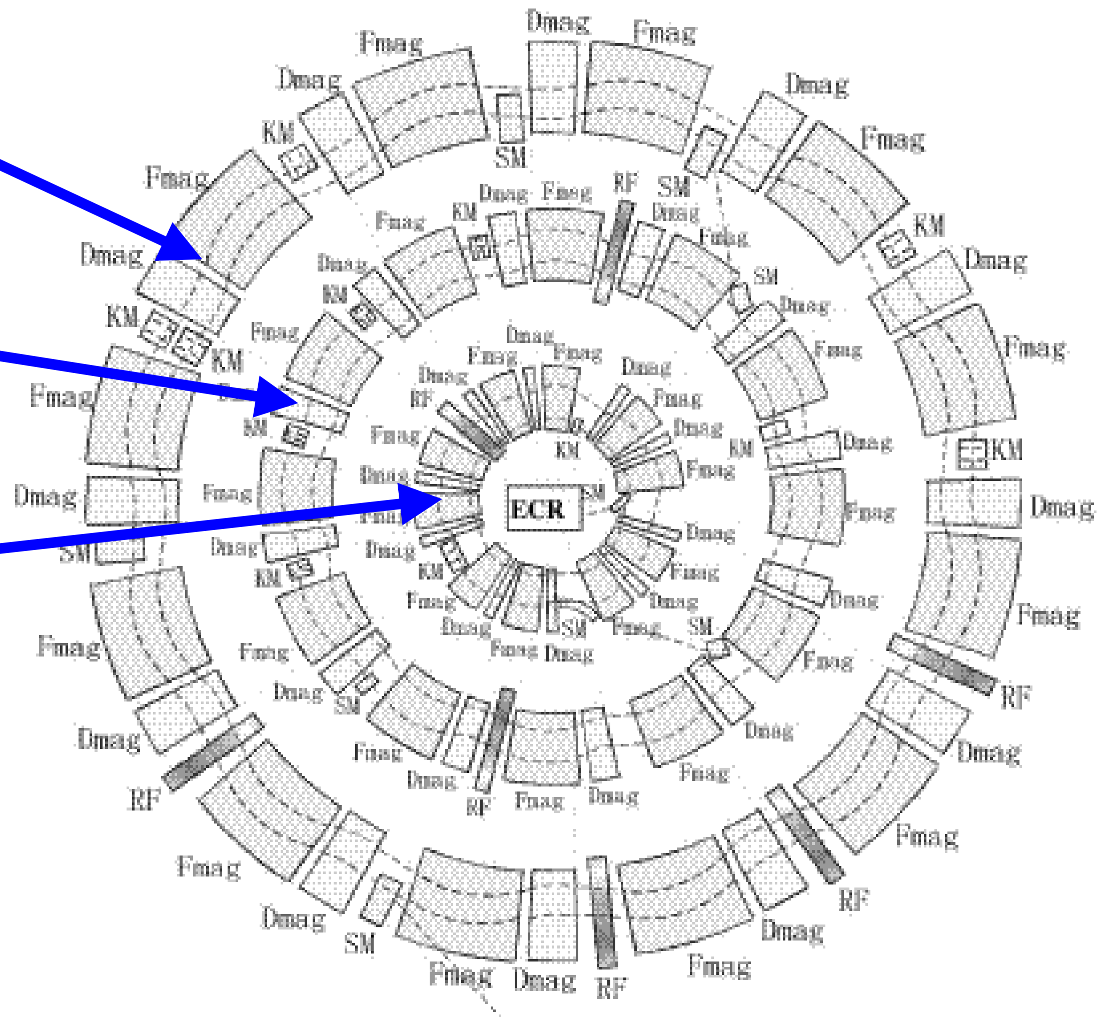
400 MeV/u C^{6+}

100 MeV/u C^{6+}

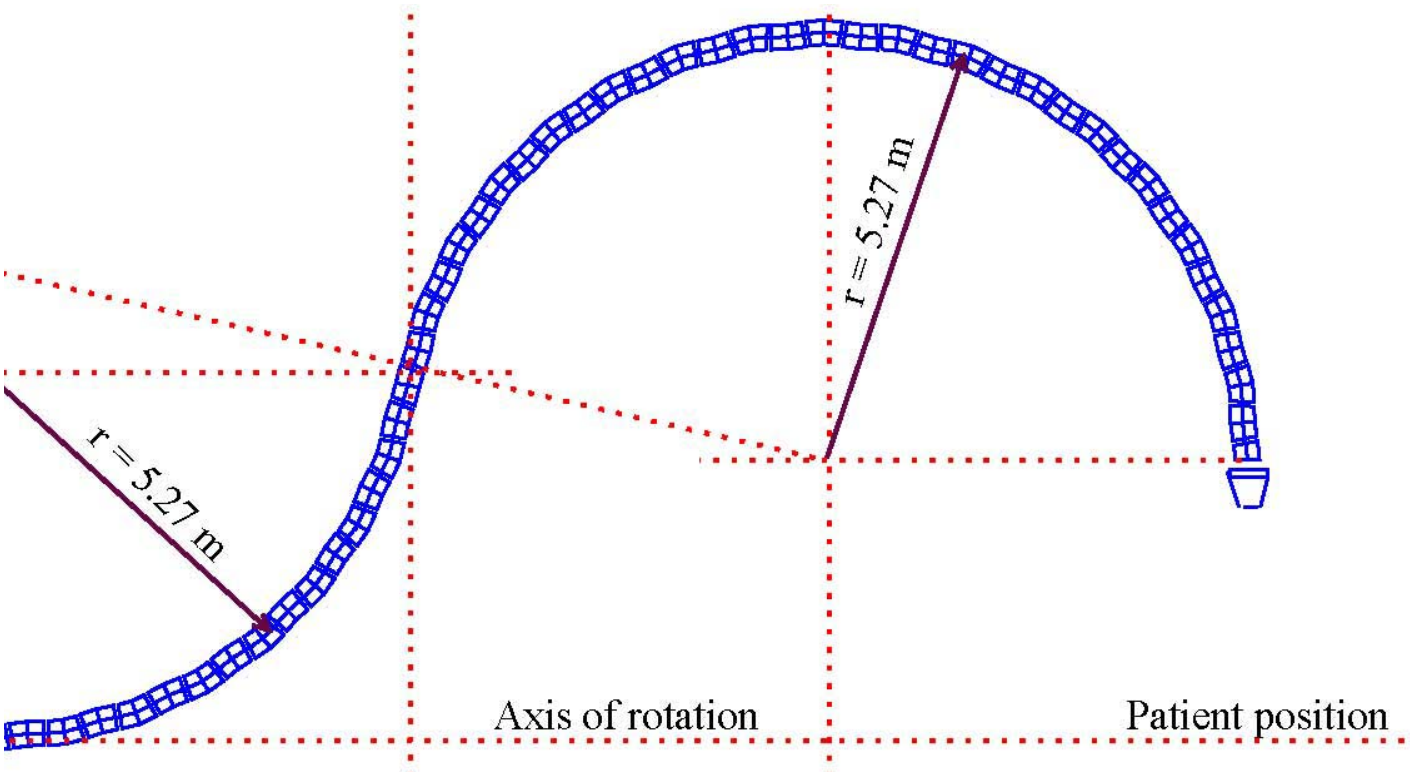
7 MeV/u C^{4+}



- FD0 lattices
- Radial sectors

Keil-Sessler-Trbojevic Lightweight FFAG Gantry

This group has also proposed a lightweight LNS-FFAG gantry, composed of superconducting magnets (either high-temperature or cryogenic) in a close-packed triplet lattice.



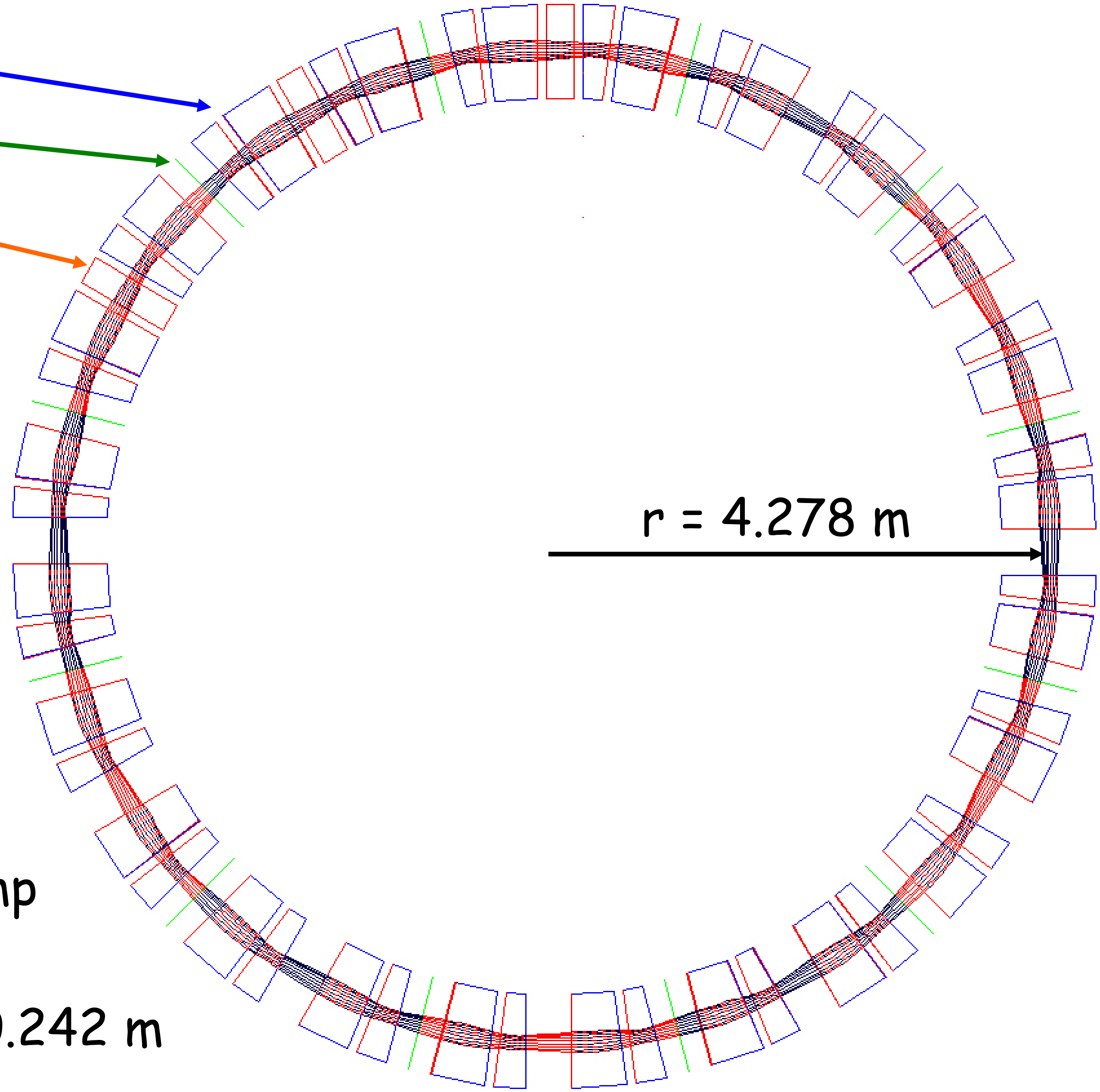
The acceptance is large enough to transmit C^{6+} ions of 150-400 MeV/u at one excitation, and protons of 90-250 MeV at another.

Dejan Trbojevic's 28-250 MeV proton LNS-FFAG

24 doublets

12 cavities

3 kickers

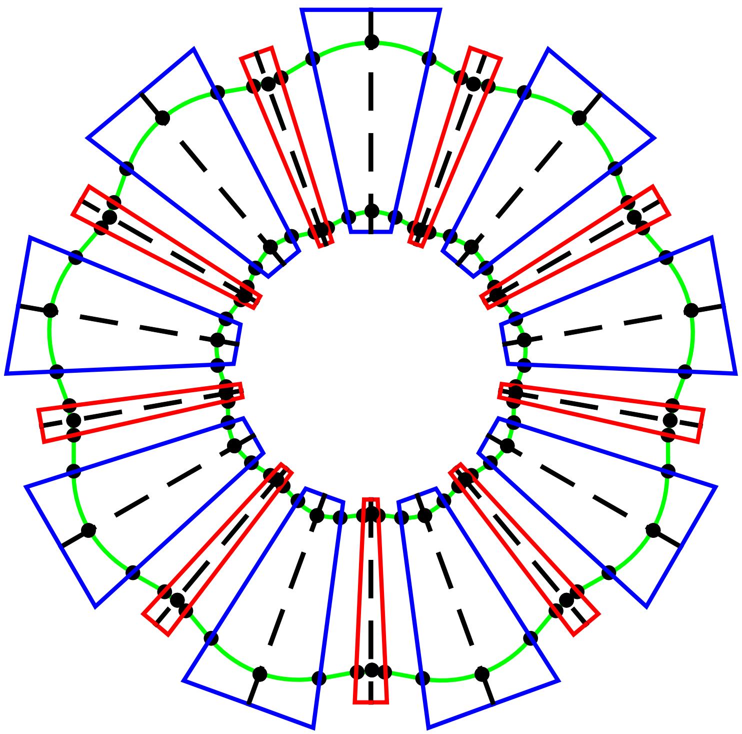


Acceleration by
harmonic number jump

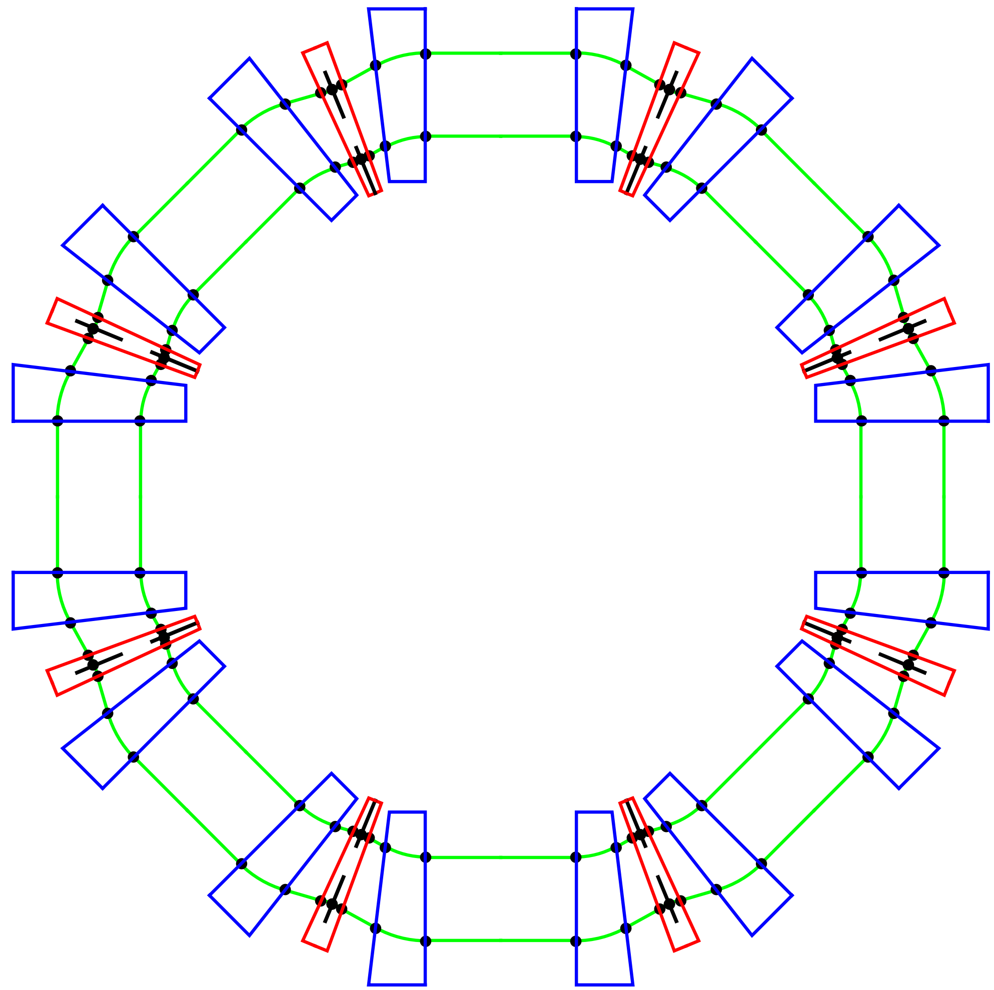
Radial orbit spread 0.242 m

Johnstone-Koscielniak Tune Stabilized NLNS-FFAGs (1)

Two designs are being considered for 30-250 MeV protons
- roughly to scale



9-cell FODO
Orbit radii 1.98-2.49 m

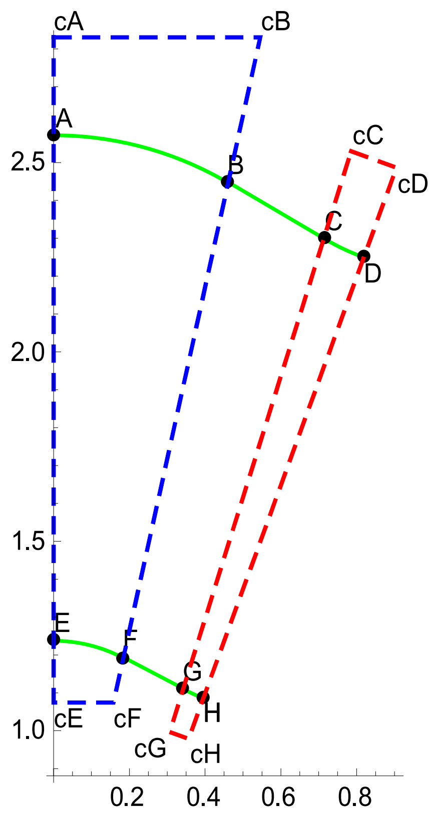


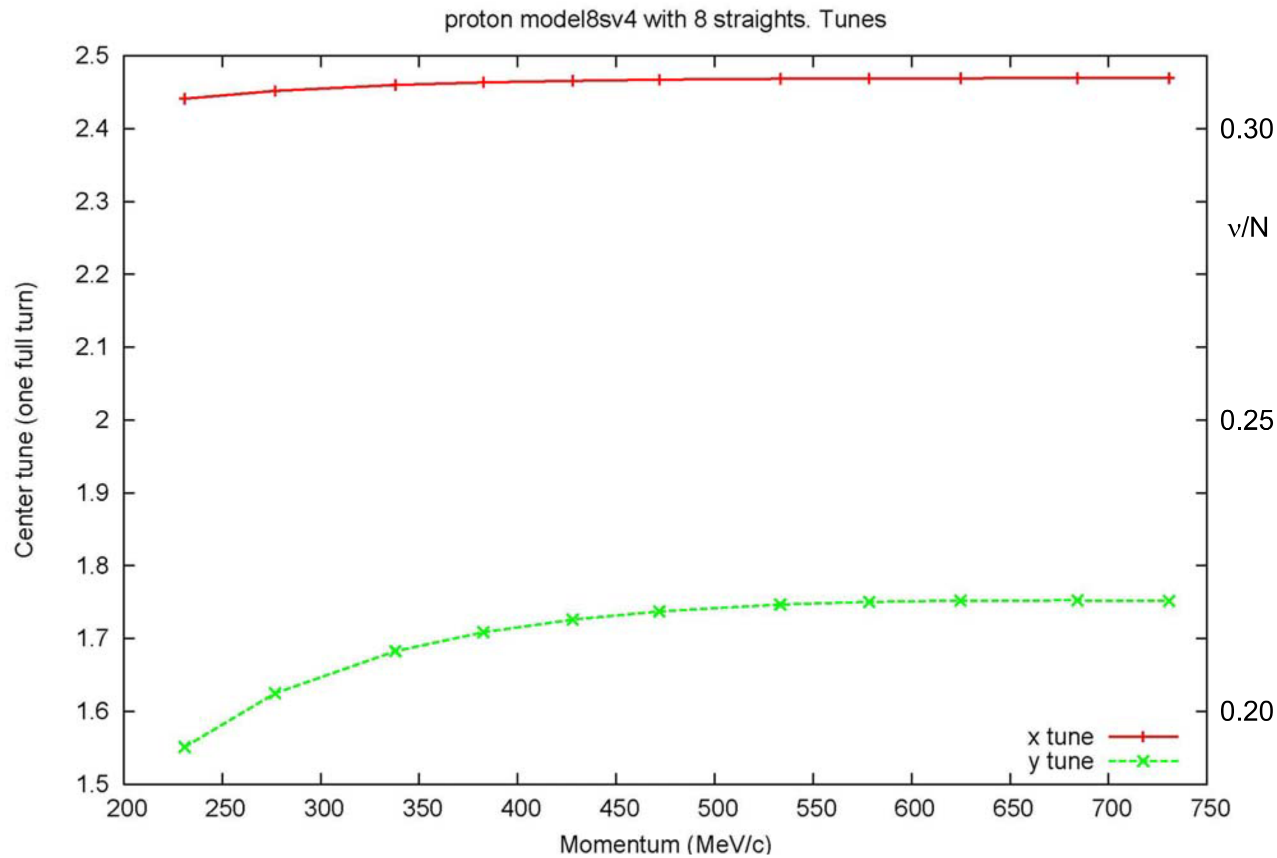
8-cell FDF Orbit radii 2.75-3.39 m

Tune Stabilized NLNS-FFAGs (2)

Tune drop-off with energy is avoided by:

- employing the "edge focusing" that occurs for non-perpendicular magnet entry/exit
- allowing a non-linear B(r) field variation

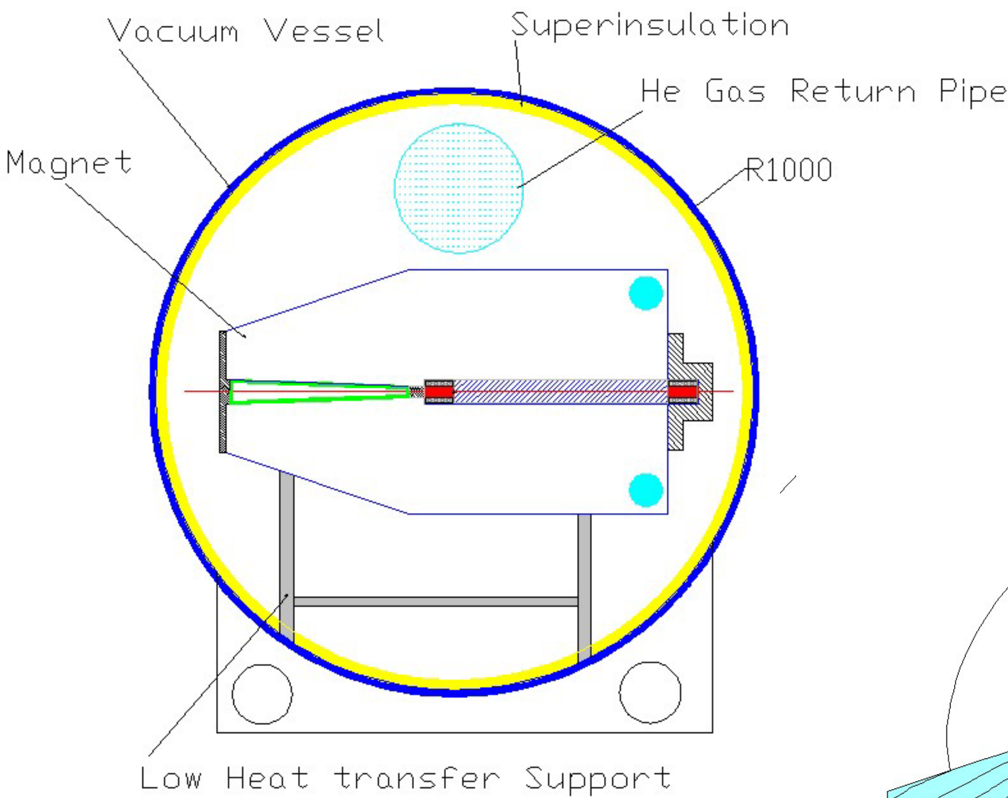


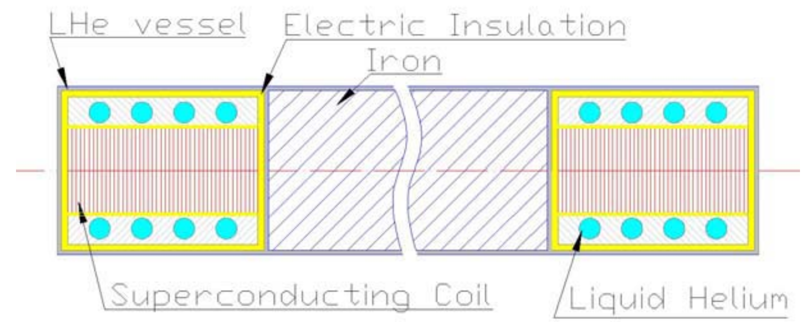


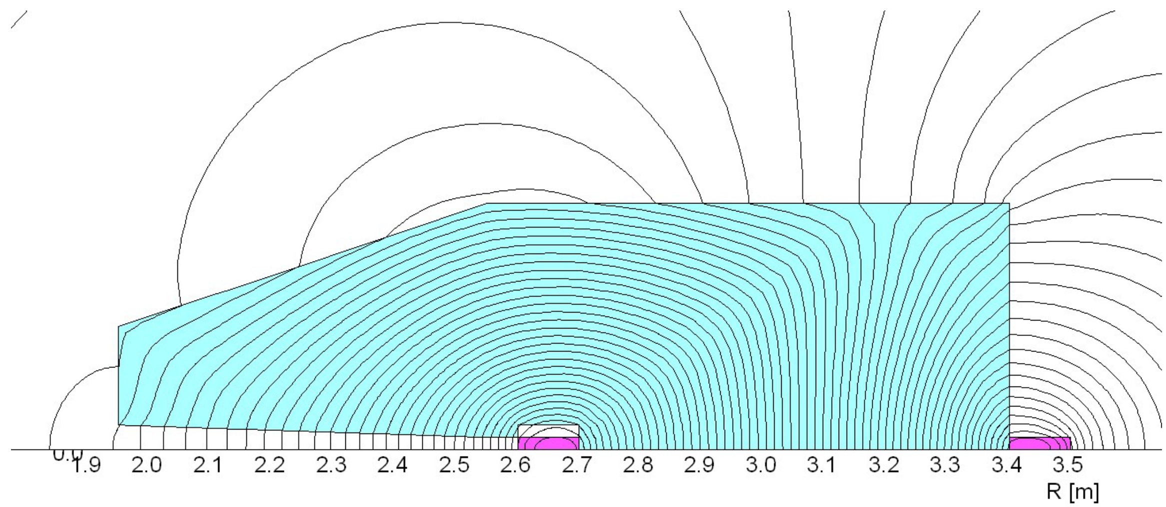
Nearly flat tunes are obtained, with large dynamic apertures.

Tune Stabilized NLNS-FFAGs (3)

4-T superconducting magnet designs have been prepared







For more details, see Carol Johnstone's poster.

PAMELA (Adams Inst. – Yokoi, Machida, Peach, *et al.*)

31 - 250 MeV protons

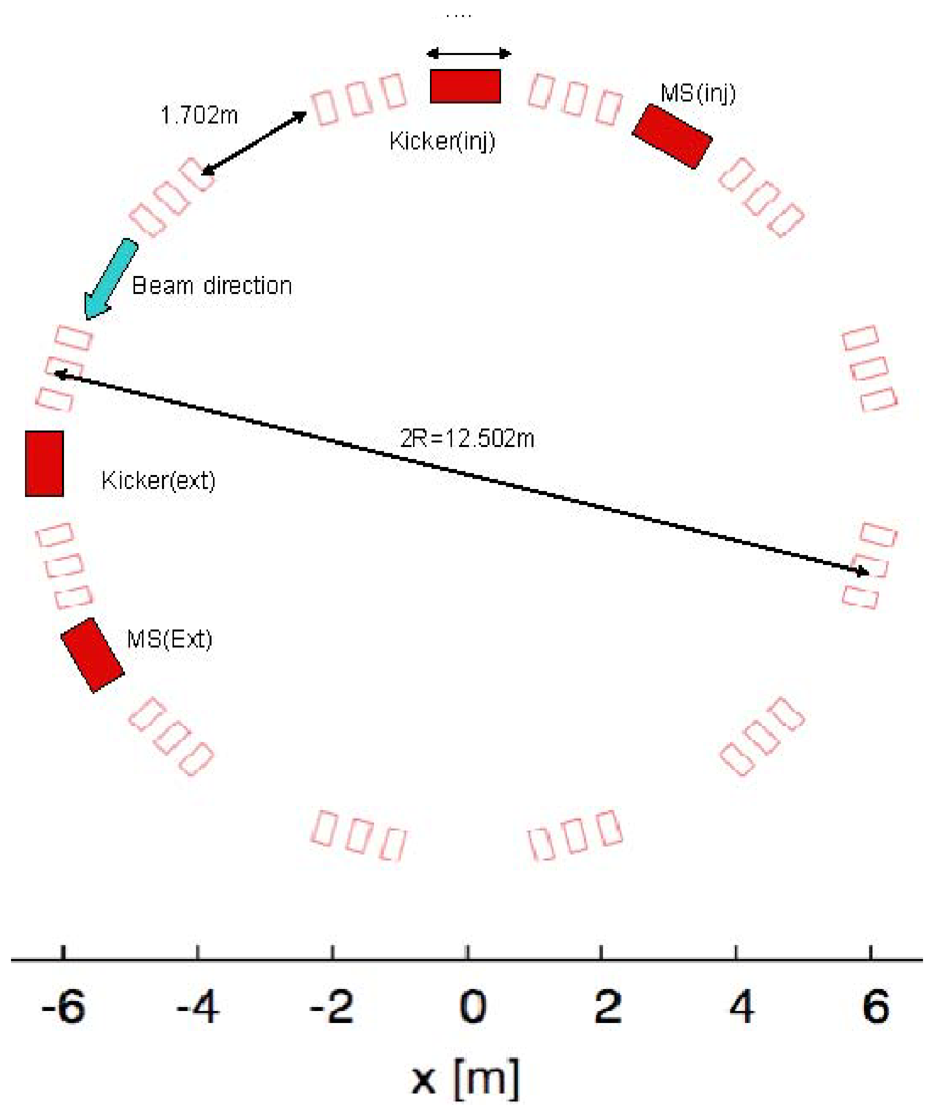
12-cell FDF

Radius ≈ 6.25 m

4-T magnets

Machida semi-scaling lattice

- High field index k (i.e. B ~ r^k) for small orbit excursions
- approximate r^k locally by $\Sigma b_n x^n$ with n = 0, 1, 2, 3 only
- flat tunes, good dynamic aperture



400-MeV/u C^+ version is being prepared

CURRENT FFAG CANCER THERAPY STUDIES

		Energy (MeV/u)	Ion	Cells	Spiral angle	Radius (m)	Pulse rep. rate (Hz)
SCALING							
KURRI: ERIT		11	p	8	0°	2.35	200
LPSC: RACCAM		17-180	p	10	54°	3.2-3.9	130
NON-SCALING							
Keil, Sessler & Trbojevic		8-31	p	48	0°	5.49-5.52	≲1000
		31-250	p	48	0°	6.86-6.95	≲1000
		8-69	C^{6+}				
		69-400	C^{6+}	48	0°	8.23-8.32	≲1000
Trbojevic		28-250	p	24	0°	4.18-4.42	cw (HNJ)
Johnstone *et al.*	FODO	30-250	p	9	0°	1.98-2.49	
	FDF			8	0°	2.75-3.39	
PAMELA (Machida lattice)		30-250	p	12	0°	≈6.25	≲1000 or cw (HNJ)
		7-450	C^{+}				

FFAGs versus SYNCHROTRONS

Advantages

Larger acceptance → Higher beam intensity, faster treatment

Higher pulse rep. rate → Higher beam intensity, faster treatment; Better compatibility with spot scanning

No magnetic field ramp

Disadvantages

Larger magnets, requiring high-quality field over a wider radial range.

FFAGs versus CYCLOTRONS

Advantages

Variable-energy beams

Flexible choice of ion (proton or heavier)

Multiple extracted beams

Less stringent magnetic field tolerances (10^{-3} cf. 10^{-5})

Disadvantages

Larger footprint & cost   (y' gets what y' pays for!)

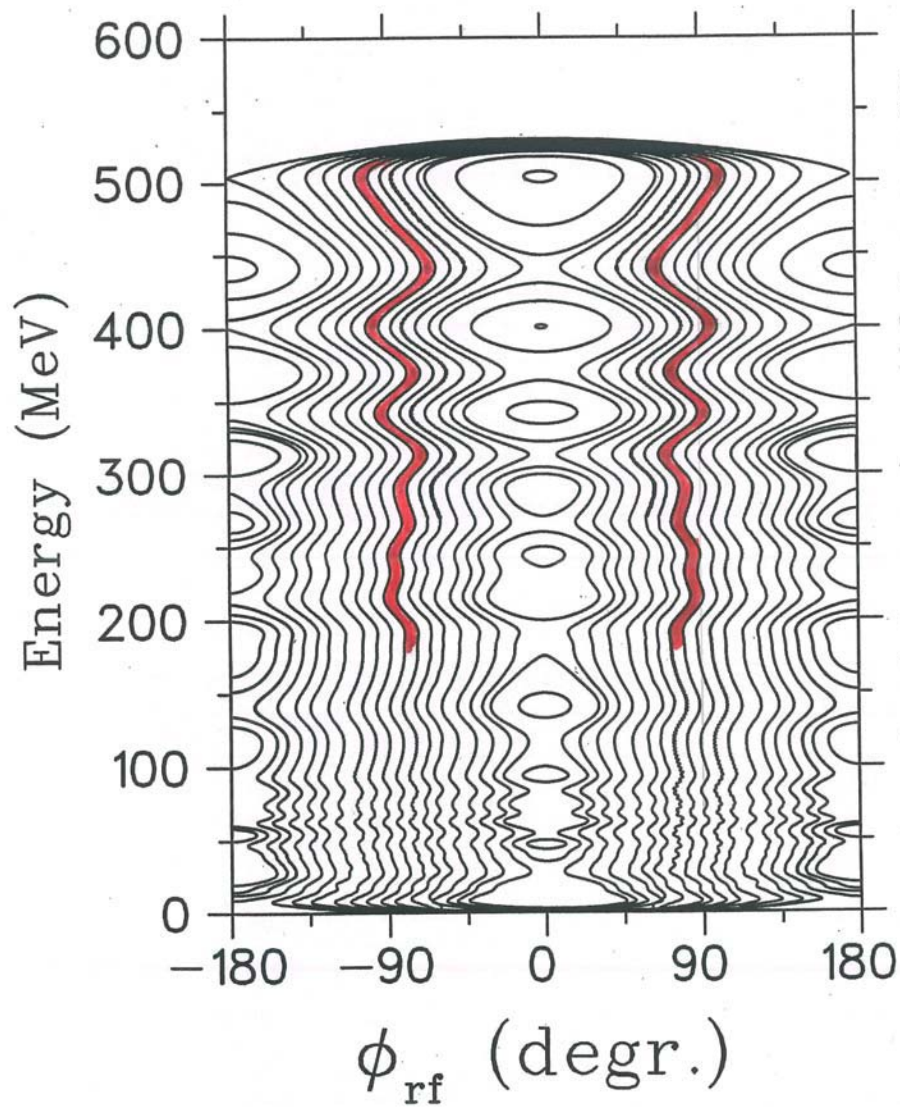
Limited momentum range requires an injector accelerator
(some early proposals involved 3 FFAG rings)

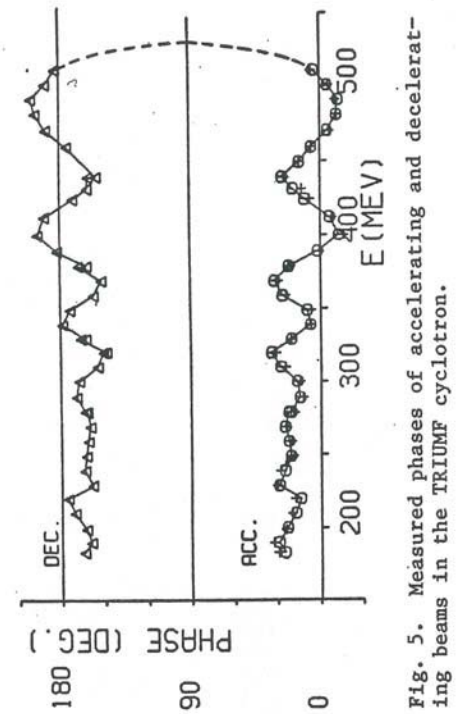
(Non-scaling FFAGs only)   High rf power

SUMMARY

- Last 10 years have seen rebirth of interest in FFAGs world-wide, prompted by the FFAG's unique characteristics:
  - high rep rate
  - high acceptance
- 8 built, 3 under way, ~20 designs proposed
- A whole new class of "non-scaling" FFAGs has been discovered
  - offering high momentum compaction
  - several varieties are being studied
- FFAGs offer advantages for cancer therapy:
  - high beam intensity
  - excellent compatibility with spot scanning
  - variable-energy beams
  - choice of ion
  - multiple extracted beams

SERPENTINE ACCELERATION IN CYCLOTRONS





Measured phase history in the TRIUMF cyclotron

- Real cyclotrons are only imperfectly isochronous
- Acceleration occurs along a serpentine path