Closing gaps to CFETR Readiness

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Outline

- Introduction
- CFETR- Phase I gaps and possible solution
- CFETR-II gaps and possible solution
- Summary

CFETR Mission & Objectives

Mission: Bridge gaps between ITER and DEMO, realization of fusion energy application in China

➲ A good complementarities with ITER

- Demonstration of full cycle of fusion energy with P_f = 200MW
- Demonstration of full cycle of T self-sustained with TBR ≥ 1.0
- Long pulse or steady-state operation with duty cycle time ≥ 0.3 ~ 0.5
- Relay on the existing ITER physical （k~1.8, q>3, H~1) and technical (SC magnets, diagnostic, H&CD) bases
- Exploring options for DEMO blanket&divertor with a easy changeable core by RH
- Exploring the technical solution for licensing DEMO fusion plant
- With power plant potential by step by step approach.

Targets and Challenges

Physics:

- Creating predictable, high-performance steady-state plasmas
- Demonstrating and exploring the burning plasma state
- Taming the plasma-material interface
- Harnessing fusion power

Engineering:

- ➢Complete fusion energy cycle.
- ➢Complete T fuel cycle.
- ➢long pulse & SSO
- ➢Material Validation
- ➢Component Validation
- ➢RAMI for power plant
- ➢Necessary date for safety & licensing of power plant.

An integrated team for STE challenges from Uni., institutions, industries

Roadmap for Chinese MFE Development

PFPP

★ （˜2050）

1GWe, Power Plant Validation

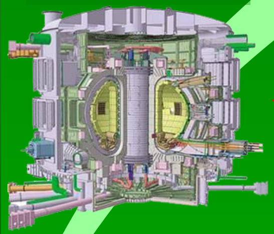
CFETR

★ （2030 start operation）

I： Q=1-5, steady state, TBR>1, ~200MW, 10dpa

II： DEMO validation, Q>10, CW, 1GW, 50dpa

ITER

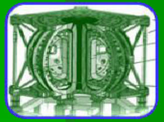


★ （˜2021）

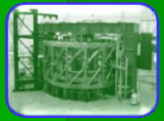
Phase I ： Q=10, 400s, 500MW, Hybrid burning plasma

Phase I I： Q=5, 3000s, 350MW, steady-state burning plasma

EAST Advance PFC, steady-state advanced operation



HL-2M Advanced divertor, high power H&CD, diagnostics

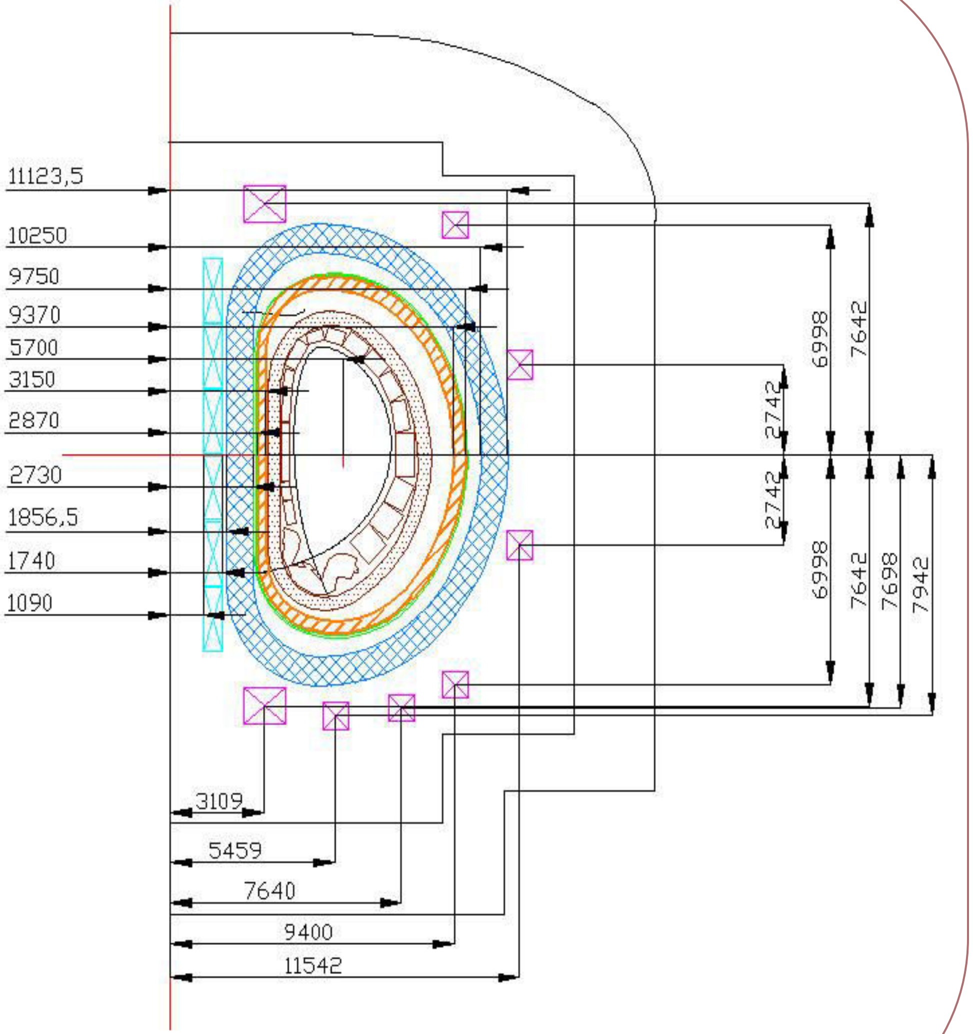


J-TEXT Disruption mitigation, basic plasma

2015 2020 2025 2030 2035 2040 2045 2050 2055 2060

CFETR Machine Configuration

- **B_t= 4.5 -5T;**
- **I_p= 8-10MA;**
- **R = 5.7m;**
- **a = 1.6m;**
- **К= a/b=1.8～2.0;**
- **β_N ～2.0 ; q_{95}≥3;**
- **Triangularity δ= 0.4-0.8;**
- **Single-null diverter;**
- **Neutron wall loading ≈0.5MW/m^2;**
- **Duty cycle time = 0.3-0.5;**
- **TBR >1.0**
- **Possible upgrade to R~6 m, a~2 m, B_t=7. 5T, I_p~14 MA**



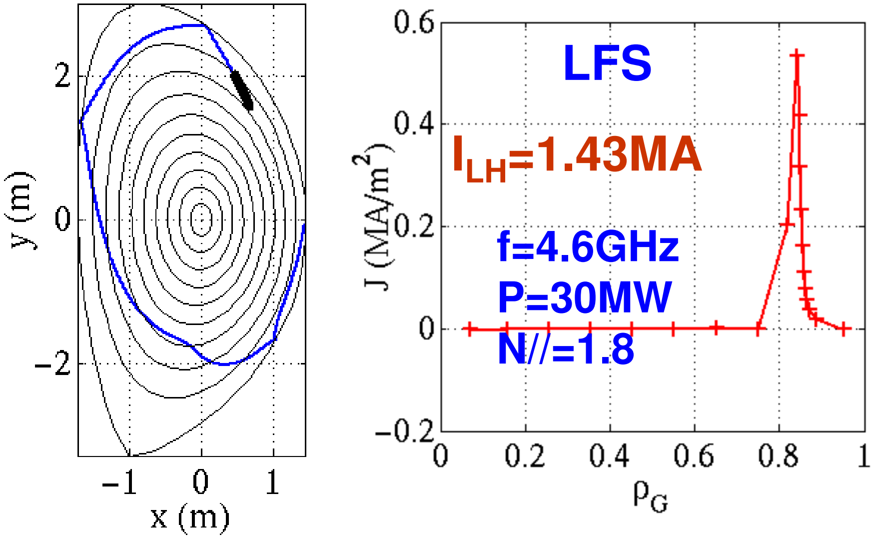
Gaps for CFETR-I

- Steady-state operation
- TBR > 1 & full cycle of T breeding
- High availability by RH
- Plasma –Wall interaction for W wall
- Ultra Low T retention under SSO

Key parameter investigation

Operation mode	A	B	C	D	E	ITER-SS	Upgrade
I_p(MA)	10	10	10	8	8	9	15
P_{aux}(MW)	65	65	65	65~70	65	59	65
q_{95}	3.9	3.9	3.9	4.9	4.9	5.2	3.9
W(MJ)	171~174	193	270~278	171	255	287	540
P_{Fus} (MW)	197~230	209	468~553	187~210	409	356	1000
Q_{pl}	3.0~3.5	3.2	7.2~8.5	2.7~3.2	6.3	6.0	15
T_{i0}(keV)	17.8~18.5	29	19.8~20.8	20.6~21	21	19	25
N_{el}($10^{20}/m^3$)	0.75	0.52	1.06	0.65	0.94		1
n_{GR}	0.6	0.42	0.85	0.65	0.95	0.82	0.85
β_N	1.59~1.62	1.8	2.51~2.59	2	2.97	3.0	2.7
β_T(%)	~2.0	2.3	3.1~3.25	2	2.97	2.8	4.2
f_{bs}(%)	31.7~32.3	35.8	50~51.5	50	73.9	48	47
τ_{98Y2}(s)	1.82~1.74	1.55	1.57~1.47	1.37	1.29	1.94	1.88
P_N/A(MW/m^2)	0.35~0.41	0.37	0.98	0.33~0.37	0.73	0.5	1.38
I_{CD}(MA)	3.0~3.1	7.0	2.45	4.0	2.76		3.0
H_{98}	1	1.3	1.2	1.2	1.5	1.57	1.2
$T_{burning}$(S)	1250	SS	2200	M/SS	SS		??

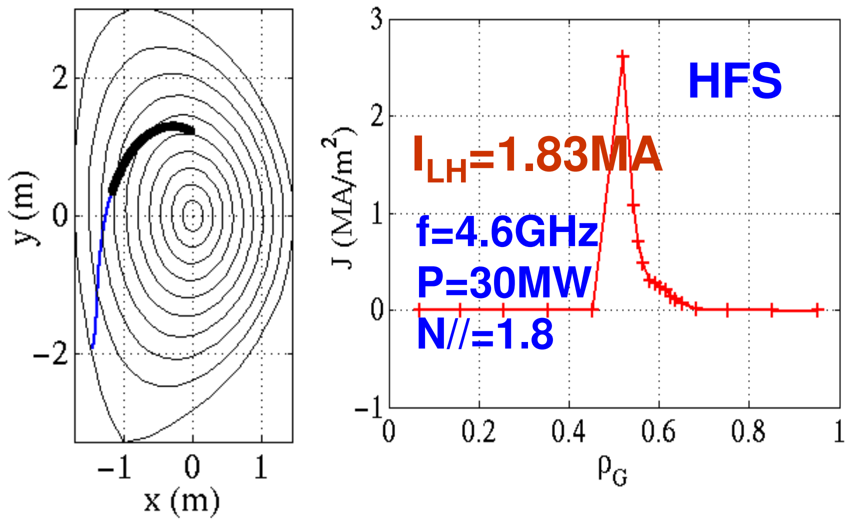
More effective current drive –HFS LHCD+Top ECCD



LFS

I_{LH}=1.43MA

f=4.6GHz
P=30MW
N//=1.8



HFS

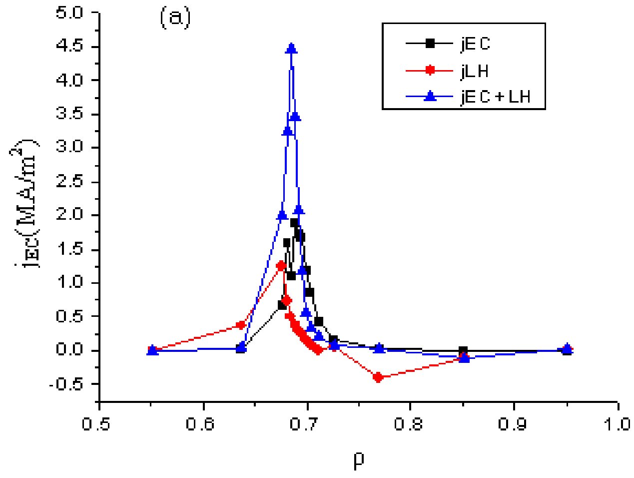
I_{LH}=1.83MA

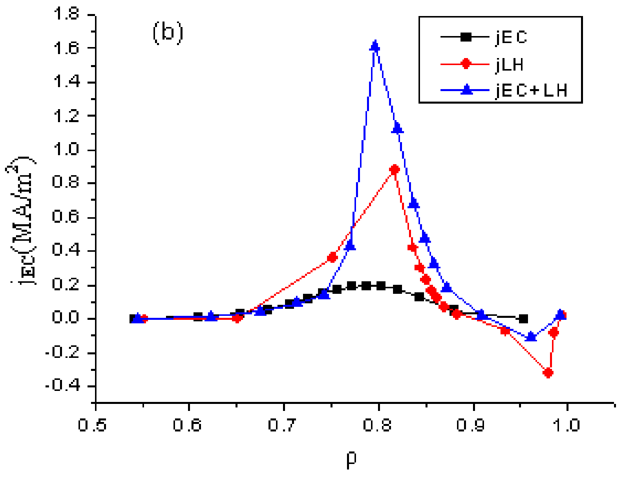
f=4.6GHz
P=30MW
N//=1.8

I_{EC}=0.975MA(Φ=205°, θ=110°)
I_{LH}=2.7305MA($N_{//}$=2.04)
I_{EC+LH}=4.0062MA
$\Delta I = I_{EC+LH} - I_{EC} - I_{LH}$=0.3007MA

I_{EC}=0.698MA(Φ=250°, θ=130°)
I_{LH}=1.45MA($N_{//}$=2.04)
I_{EC+LH}=2.4923MA
$\Delta I = I_{EC+LH} - I_{EC} - I_{LH}$=0.3443MA

HFS LHCD
TOP ECCD
ΔI = 0.3MA
I_{CD}=4.0MA

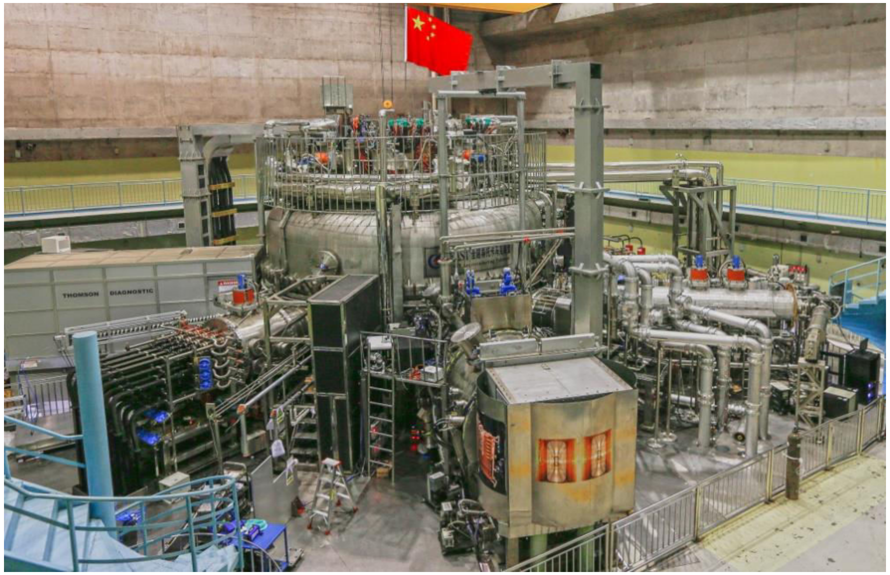


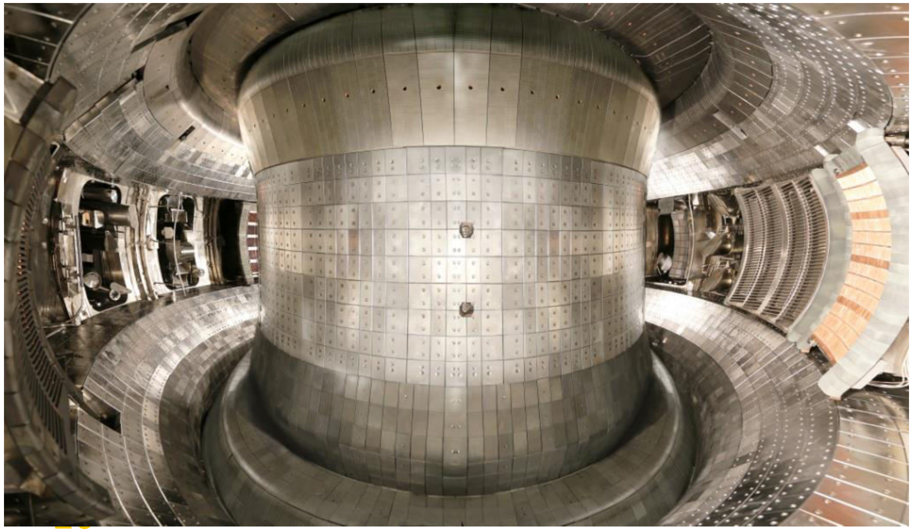


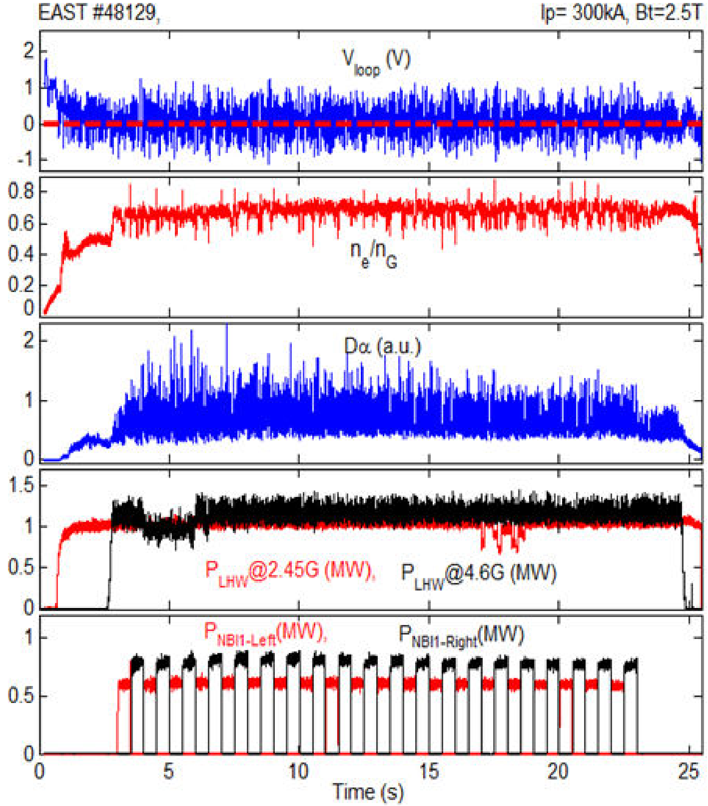
LFS LHCD
LFS ECCD
ΔI = 0.34MA
I_{CD}=2.49MA

EAST will be a good test bench for CFETR-I during next 5 years

Paut > 30MW CW, ~80 diagnostics, W-divertor, VS&ELM coils

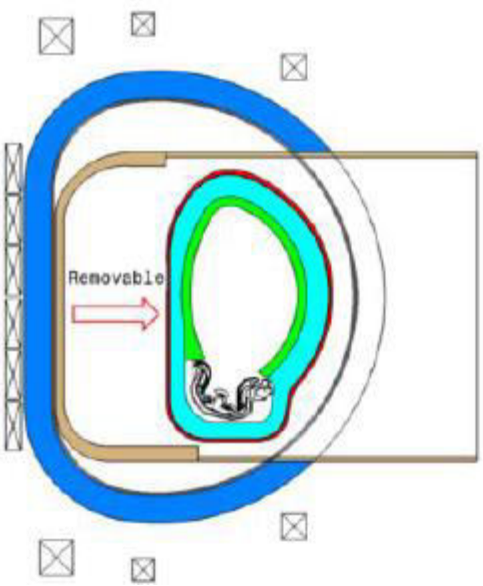


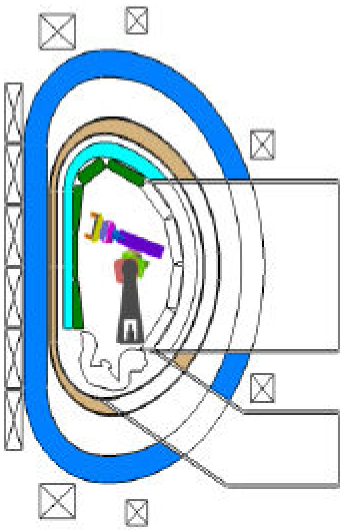


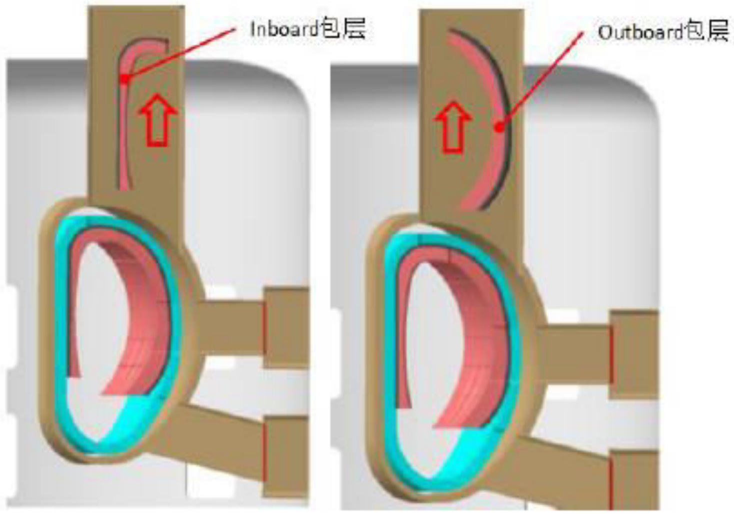


- ☐n_e/n_G ~0.7（0.65）, betaN~1.95（2）
- ☐Fbs~50%（50%）, H89~1.24（1.2）
- ☐V_{loop}~ 0V,T_d>20S, Small ELM & Controllable density
- ☐Need:t ~1000s-CW

Availability Concept validation



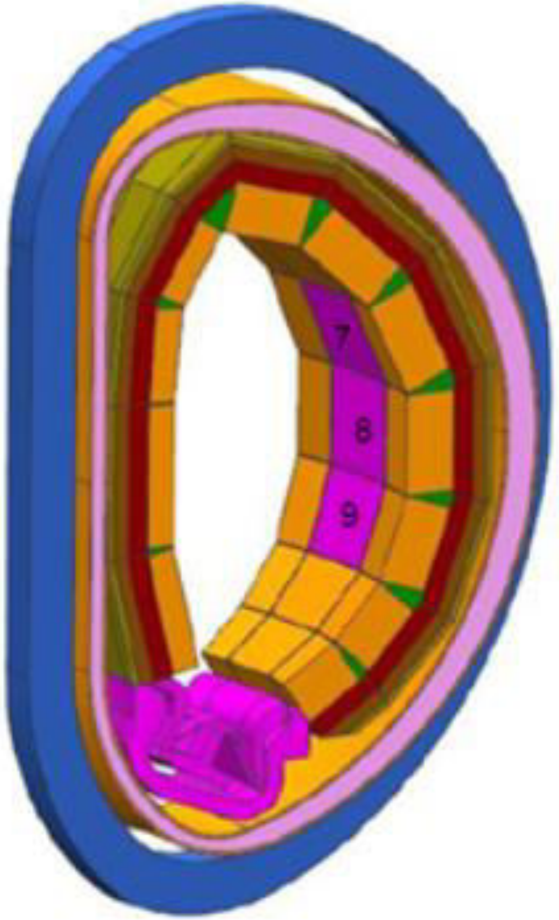




- Availability for change of components inside VV has been studied, 3 approaches have been carried out.
- Vertical remove has been selected as premier approach.

Key Components: Blanket

Three groups are working
on the concept design of CFETR blanket



Group I:

1) HC (8MPa, 300/500^{0}C),
Li$_4$SiO$_4$ (Li$_2$TiO$_3$), Be , RAFM

Group II :

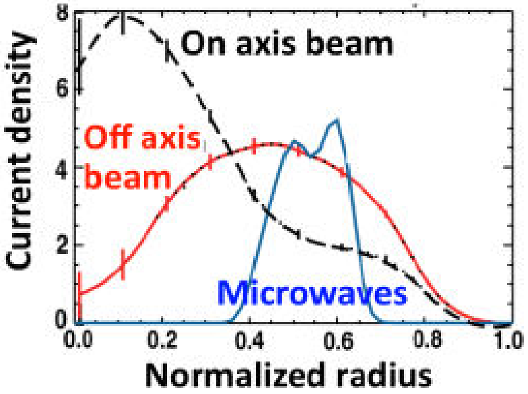
1) SLL (~150 ^{0} C) , CLAM
2) DLL(~700 ^{0}C), CLAM

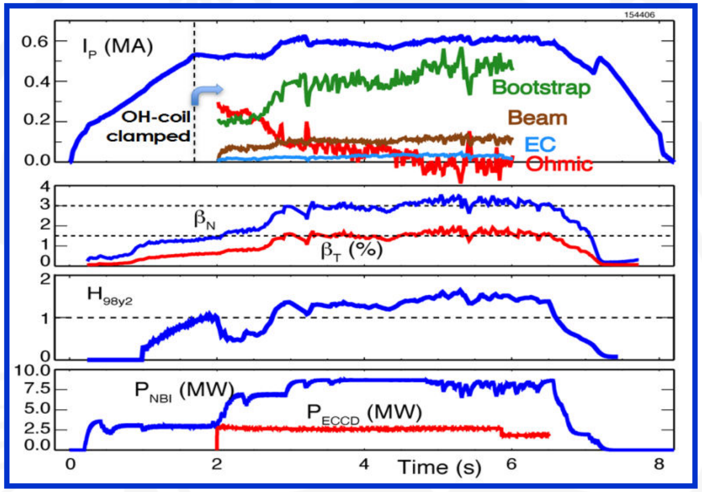
Group III :

1) HC, Li$_4$SiO$_4$, Be , RAFM
2) WC, Li$_2$TiO$_3$, Be$_{12}$Ti , RAFM

Phase II of CFETR: DEMO validation

- Phase 2: AT H-mode (DT-2, 10y)
- Ip=11-16MA； Bt=7.5T, BetaN=3.0
- R=6.0m, a=2.0m, K=2.0, Advanced TMB
- Advanced diagnostics (DEMO-relevant)
- Extension DIII-D AT(10s) to EAST(1000s)
- Explore possibility for higher Ini =1.0
- DEMO relevant H&CD
- Explore possibility for EC (H&CD) only

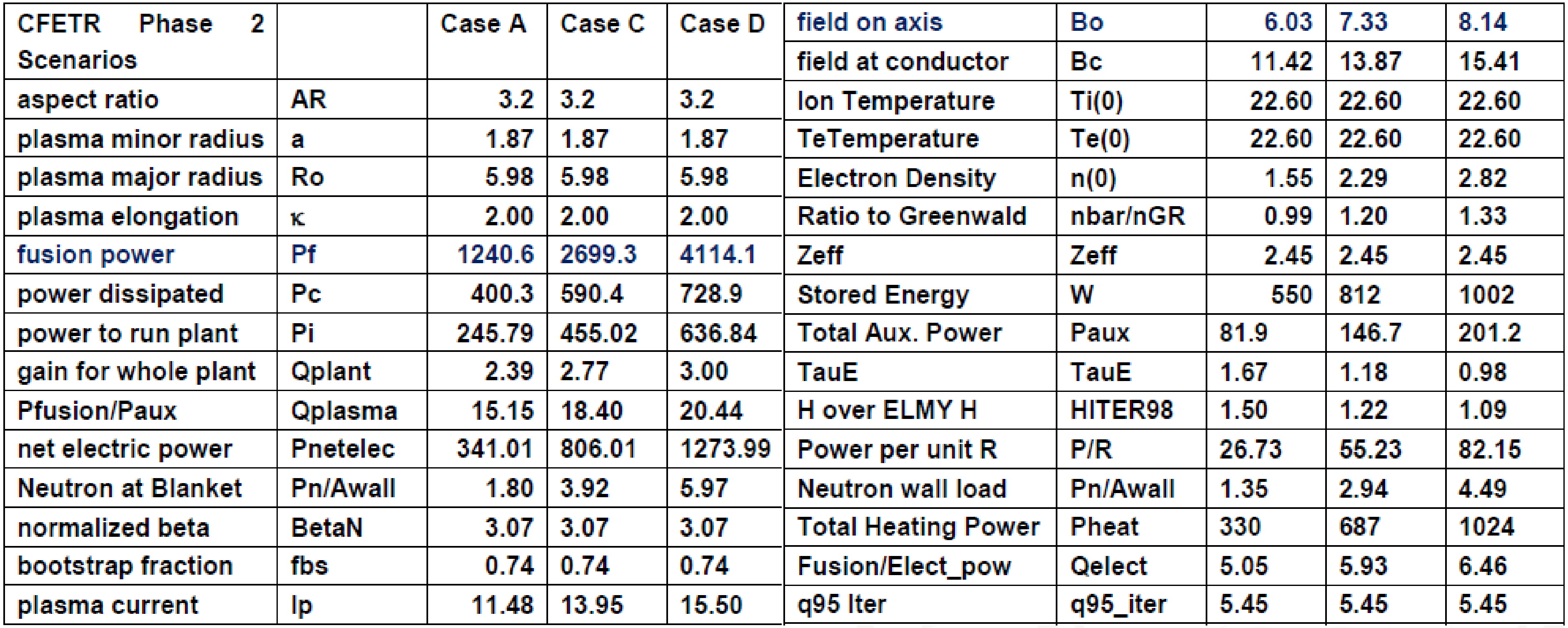




Joint DIII-D /EAST efforts at β_N ~ 3.5, f_{NI} ~ 1, ne_{GW}~0.8

Operation parameters with high B_T

A: B=6T, Ip=11.5MA, betaN=3， q_{95}=5.5, Q=15, P_{fusion}=1.24GW, Pnet =340MW



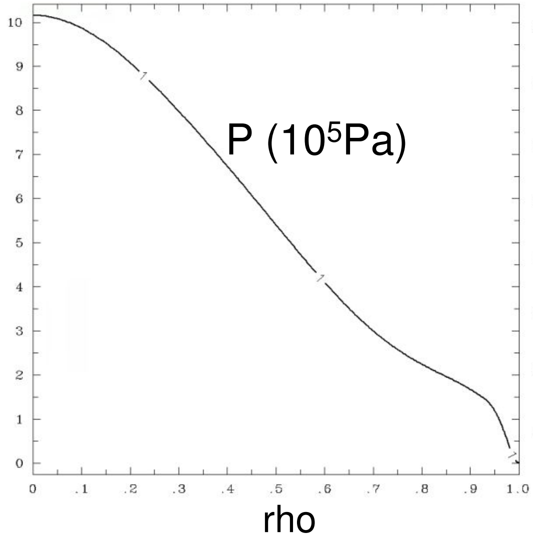
CFETR Phase 2 Scenarios		Case A	Case C	Case D
aspect ratio	AR	3.2	3.2	3.2
plasma minor radius	a	1.87	1.87	1.87
plasma major radius	Ro	5.98	5.98	5.98
plasma elongation	κ	2.00	2.00	2.00
fusion power	Pf	1240.6	2699.3	4114.1
power dissipated	Pc	400.3	590.4	728.9
power to run plant	Pi	245.79	455.02	636.84
gain for whole plant	Qplant	2.39	2.77	3.00
Pfusion/Paux	Qplasma	15.15	18.40	20.44
net electric power	Pnetelec	341.01	806.01	1273.99
Neutron at Blanket	Pn/Awall	1.80	3.92	5.97
normalized beta	BetaN	3.07	3.07	3.07
bootstrap fraction	fbs	0.74	0.74	0.74
plasma current	Ip	11.48	13.95	15.50

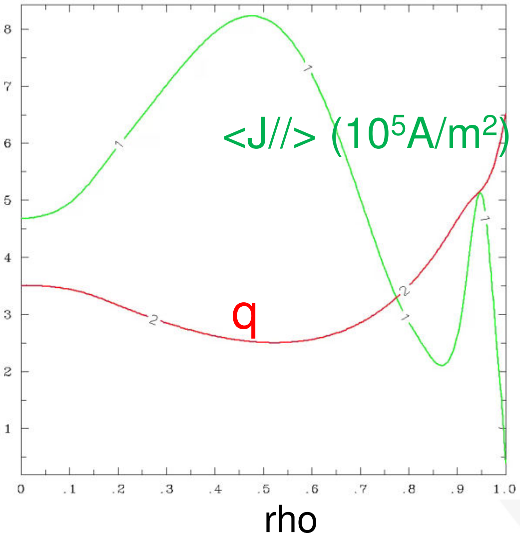
field on axis	Bo	6.03	7.33	8.14
field at conductor	Bc	11.42	13.87	15.41
Ion Temperature	Ti(0)	22.60	22.60	22.60
TeTemperature	Te(0)	22.60	22.60	22.60
Electron Density	n(0)	1.55	2.29	2.82
Ratio to Greenwald	nbar/nGR	0.99	1.20	1.33
Zeff	Zeff	2.45	2.45	2.45
Stored Energy	W	550	812	1002
Total Aux. Power	Paux	81.9	146.7	201.2
TauE	TauE	1.67	1.18	0.98
H over ELMY H	HITER98	1.50	1.22	1.09
Power per unit R	P/R	26.73	55.23	82.15
Neutron wall load	Pn/Awall	1.35	2.94	4.49
Total Heating Power	Pheat	330	687	1024
Fusion/Elect_pow	Qelect	5.05	5.93	6.46
q95 Iter	q95_iter	5.45	5.45	5.45

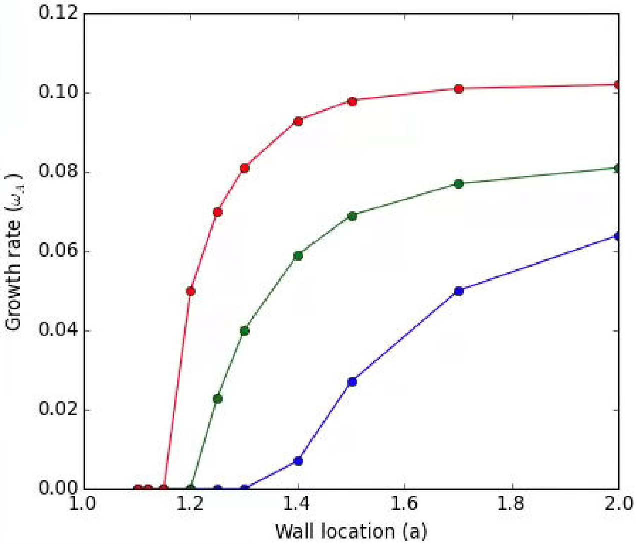
B: B=7.3T, Ip=14MA, betaN=3， q_{95}=5.5, Q=18.4, P_{fusion}=2.7GW, Pnet =800MW

MHD stability consideration of Phase II case A

- **Plasma parameters of phase II case A:**
  - **Bt0=6.0 T, BetaN=3.0, Ip=10.5 MA, q95=5.34, li(1)=0.72**
- **Reversed q profile with qmin~2.5, 2/1, 3/2 NTMs could be avoid**
- **The ideal wall at ~1.15a could stabilize the n=1,2,3 instabilities.**
- **CASE B， Reversed q profile with qmin~3.2, 2/1, 3/1，3/2 NTMs could be avoid**
- **Must find a way to stabilize the RWMs**







Key issues for CFETR-II

- Advanced steady-state operation scenario for maximum next electricity (Maximum Pfusion and minimum Pau)
- High Bt Magnets
- Self Consistent DEMO relevant H&CD
- Heat&Particle exhaust (Divertor, Cryo-pump)
- High available RH
- Advanced Blanket (TBR >1.1, high electricity gain)
- Materials

Present Activities

- **H&CD:**

off-aix NBI (0.5MeV) + ECRH(top， 170-230GHz）

LHCD（HF， 4.6、8.2GHz）+ECRH(top， 230GHz）

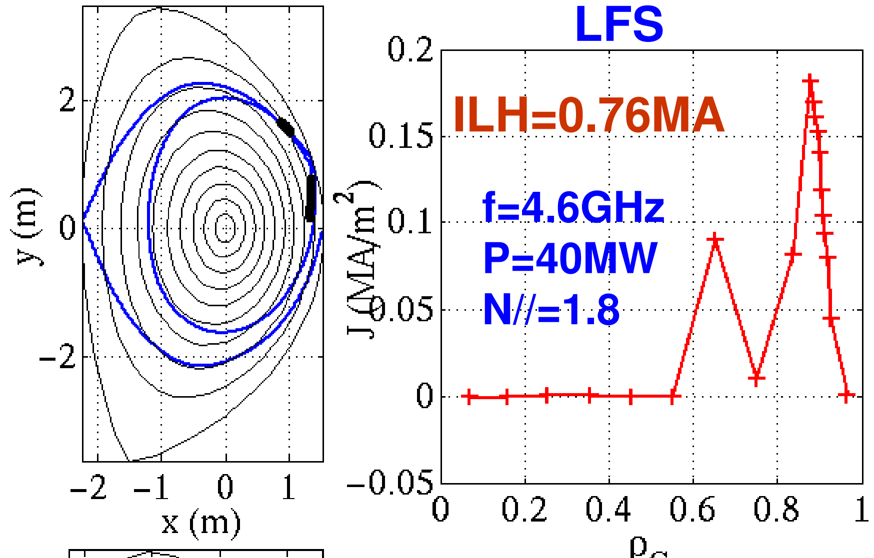
- **High BT （7.5-8 T）**

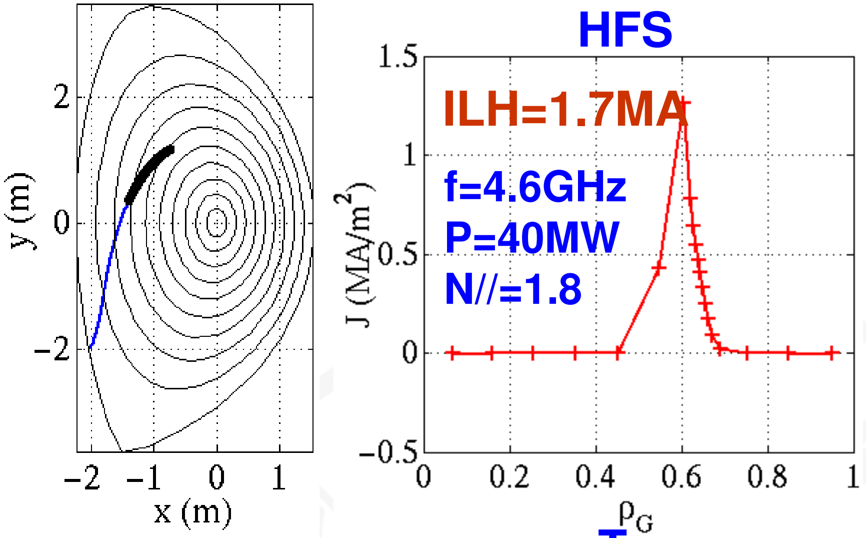
CS （2212 CICC， YBCO tape， Nb3Al)

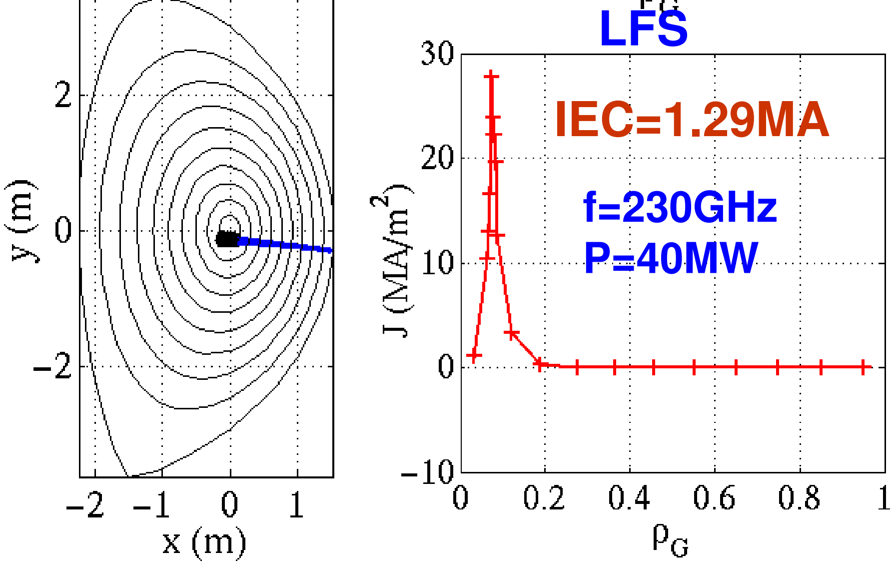
Hybrid TF (2212 CICC+Nb3Sb)

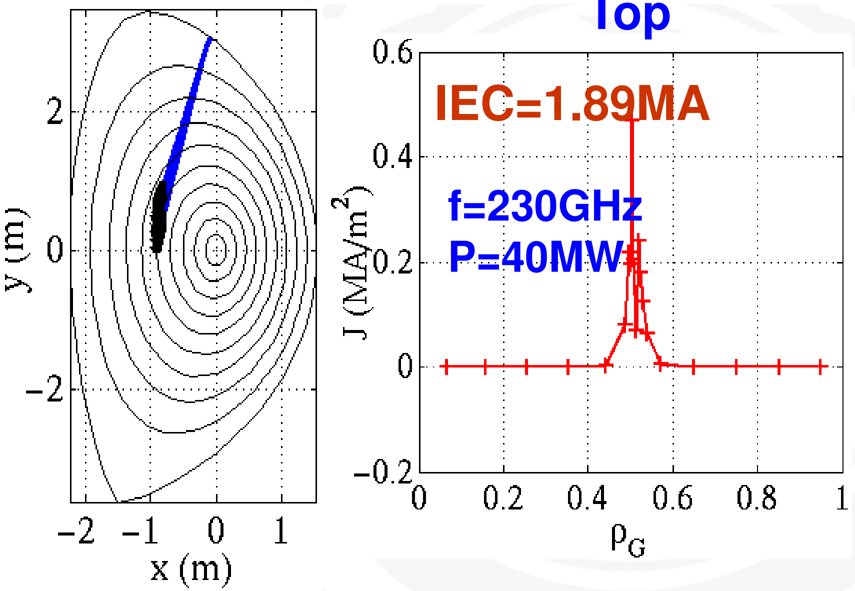
- **Heat exhaust (Divertor)**
- **Advanced Blanket**
- **T-Plant**
- **Materials**

HFS LHCD+Top ECCD(gaps for high Ip)









High Bt activities—YBCO Tape magnet

- **On IBAD substrate, 50 m YBCO film**

  I_c=780A/cm （77K,self-field)
- **I_c=200A/cm （77K,1.5T⊥C)**
- **100 m long YBCO tape, I_c=500 A/cm, I_c is uniform along the length**

Target: E=15kJ，I≥400A @20K

HTS tapes: YBCO (AMSC)

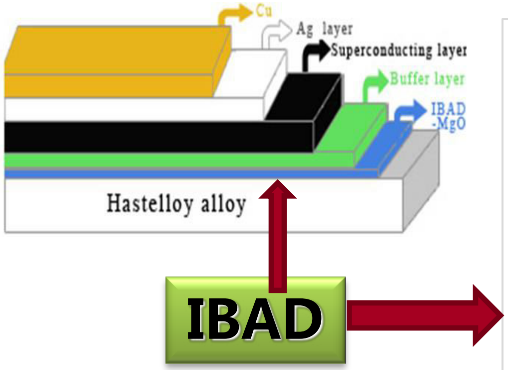
Cooling method: conduction cooling

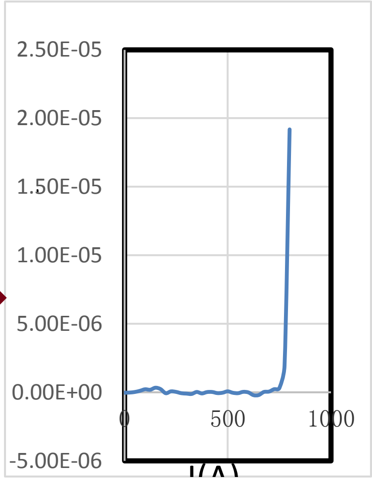
Operating temperature: 20K

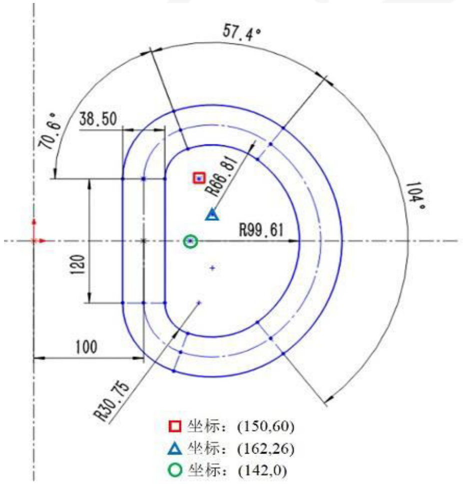
The No. of coils: 14 (D-shaped coils)

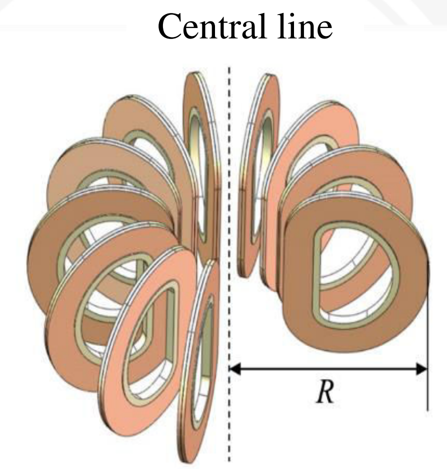
Total usage of tapes: 2100 m

Bt =0.75T at 20K

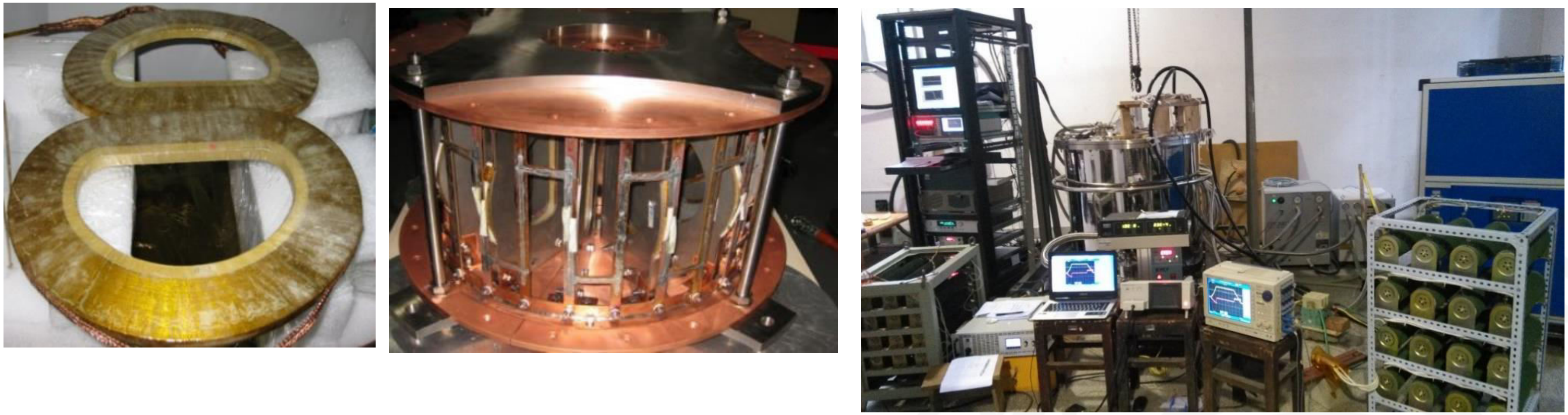








❑ MCF HTS Tokamak Oriented Researches

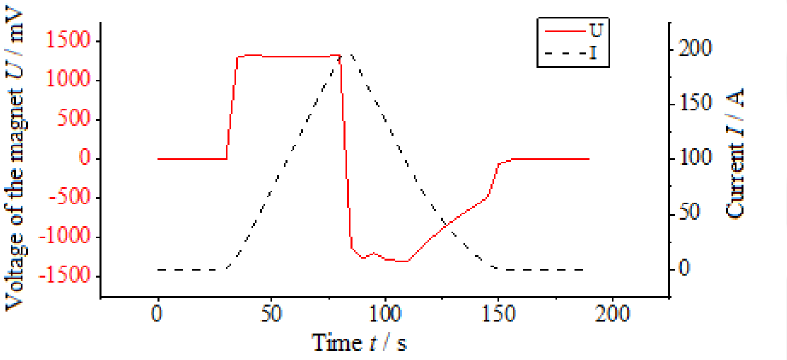


✓ Conclusions:

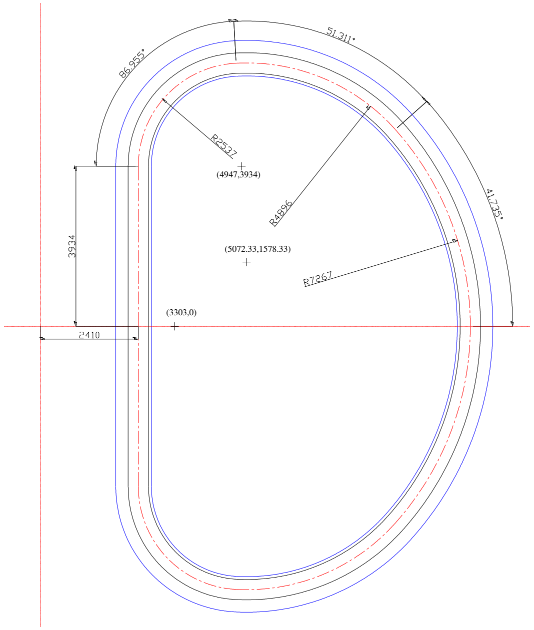
1）I_{max}=300A, E_{max}=15kJ, @ 20K

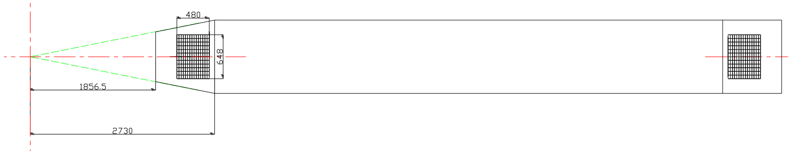
2）Magnetic field in the center of the coil is 0.75T

3）Temperature rise in various experiments is less than 0.3K



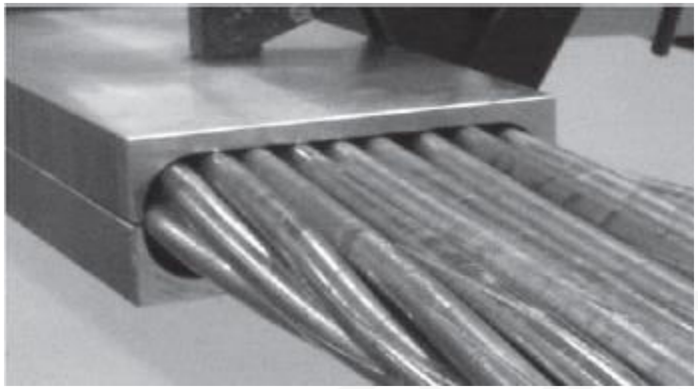
High B_T — HTC YBCO



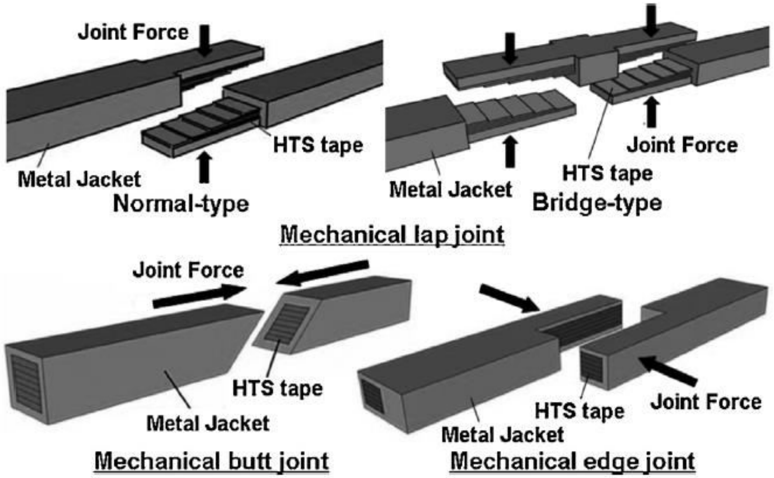



(a)


(b)



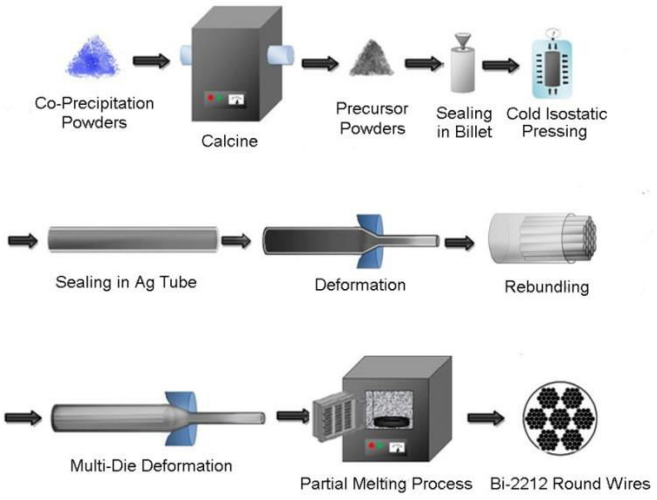
Bmax =18.7T, W =92GJ, F~1000MN

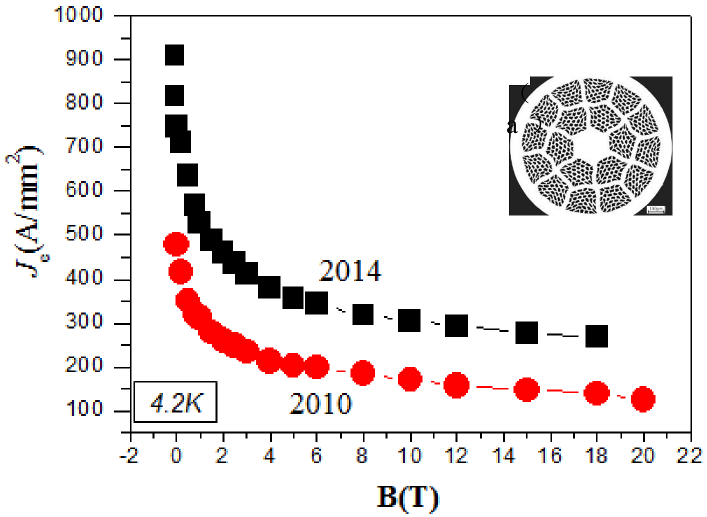


- Ic=750A @ 8T， Io =400A
- Joint is challenge

Development of Bi-2212 Superconducting Wires in NIN

PIT process for Bi-2212





Jce-B curves at 4.2 K

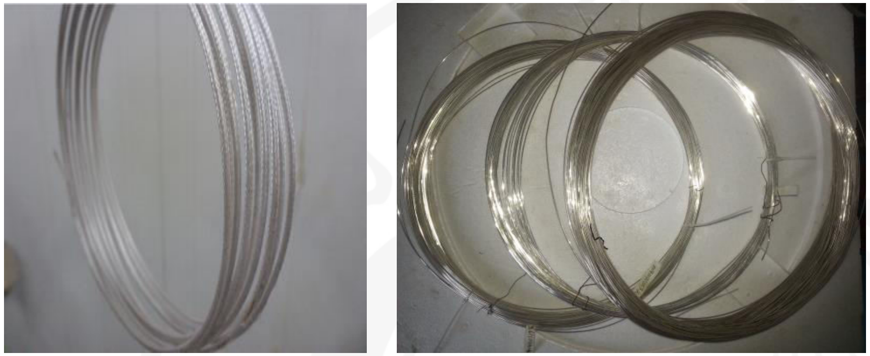
Batch production ability for 200-m long Φ1.0mm wires

4.2K, 0T: *Jce* > 920A/mm²，*Jc* ~ 4400A/mm²。

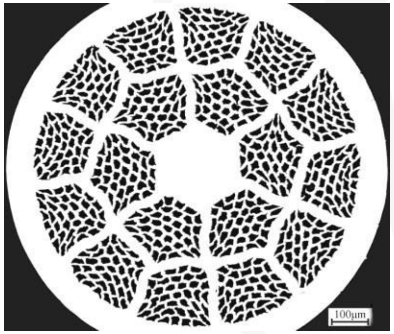
4.2K, 20T: *Jce* > 285A/mm²，*Jc* ~ 1200A/mm²。

Study of the **high pressure sintering process** is on the way, *Jc-B* property may be increased for 2~3 times.

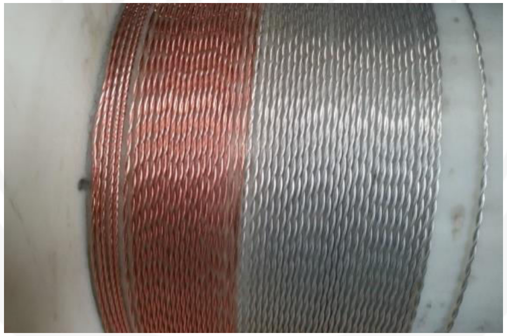
Target：long wires, 4.2K, 20T, Jce>600A/mm²



Bi-2212 wires

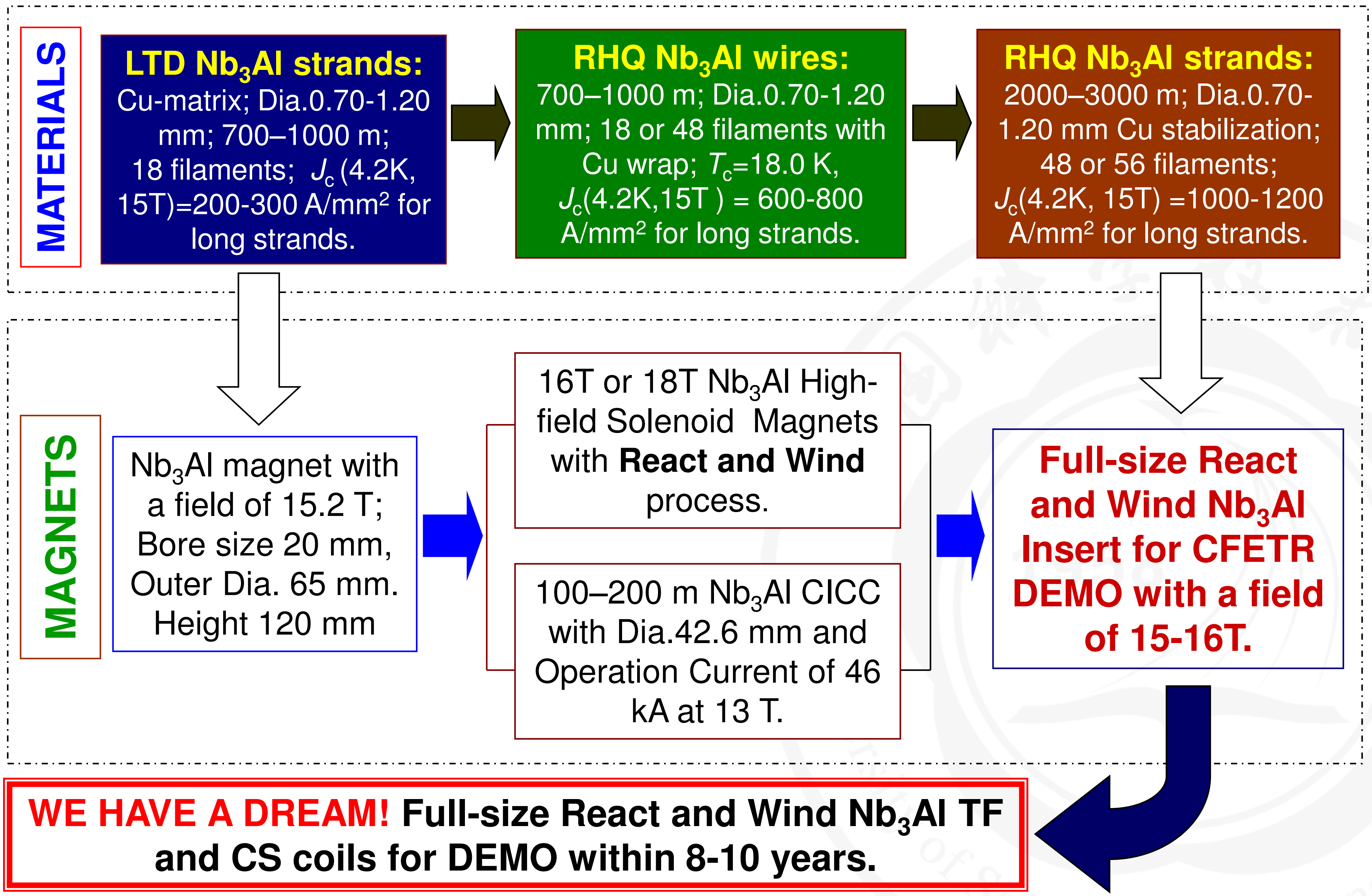


Cross section of wires



Bi-2212 cables

Present State and Future Plan for Nb_3Al Superconductor



Our Current Level | Aim within 3-5 years | Aim within 5-8 years

MATERIALS

LTD Nb_3Al strands: Cu-matrix; Dia.0.70-1.20 mm; 700–1000 m; 18 filaments; J_c (4.2K, 15T)=200-300 A/mm² for long strands.

RHQ Nb_3Al wires: 700–1000 m; Dia.0.70-1.20 mm; 18 or 48 filaments with Cu wrap; T_c=18.0 K, J_c(4.2K,15T) = 600-800 A/mm² for long strands.

RHQ Nb_3Al strands: 2000–3000 m; Dia.0.70-1.20 mm Cu stabilization; 48 or 56 filaments; J_c(4.2K, 15T) =1000-1200 A/mm² for long strands.

MAGNETS

Nb_3Al magnet with a field of 15.2 T; Bore size 20 mm, Outer Dia. 65 mm. Height 120 mm

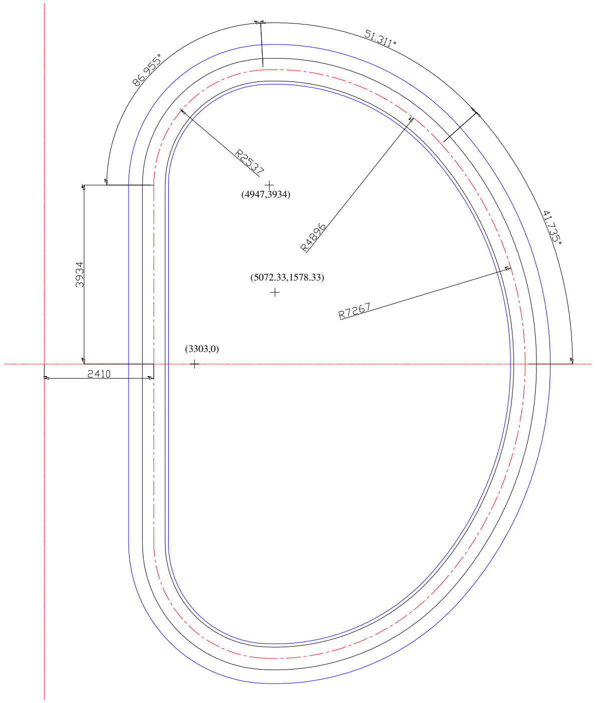
16T or 18T Nb_3Al High-field Solenoid Magnets with **React and Wind** process.

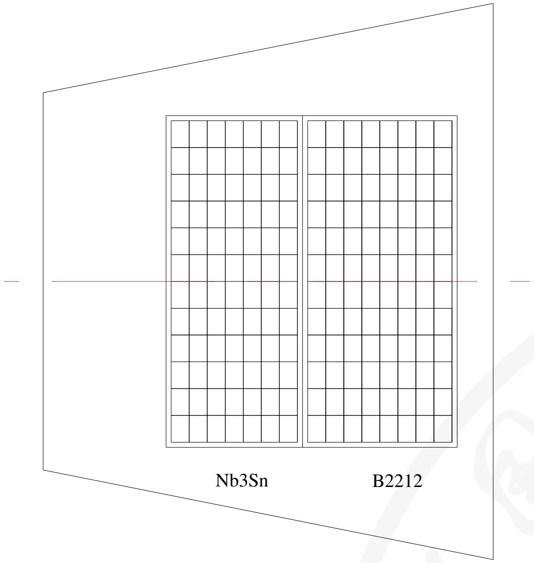
100–200 m Nb_3Al CICC with Dia.42.6 mm and Operation Current of 46 kA at 13 T.

Full-size React and Wind Nb_3Al Insert for CFETR DEMO with a field of 15-16T.

WE HAVE A DREAM! Full-size React and Wind Nb_3Al TF and CS coils for DEMO within 8-10 years.

High B_T – Hybrid (Nb_3Sn+2212) TF





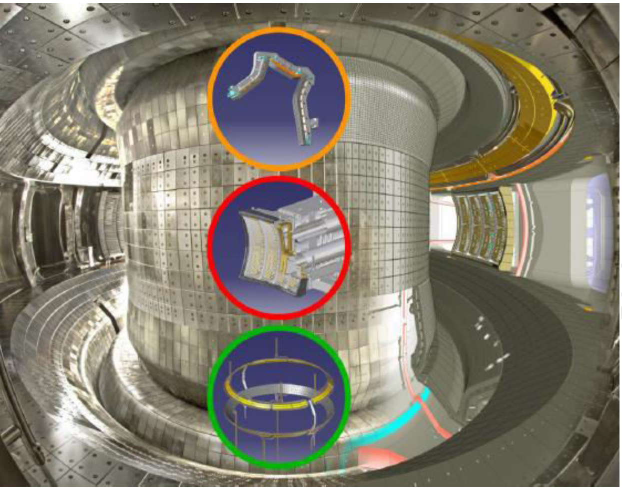
wire：ϕ=1.0mm
Cable：3×4×6×6=432
Porosity：30%
Cable size：15mm×32mm
Jacket thickness：8mm
conductor：31mm×48mm
Isolation thickness：2mm
Full size：35mm×52mm

Nb_3Sn or Nb_3Al :
Jce>1200A/mm² (Ic>942A)
Conductor I =190×432=82kA
245mm×624mm
Turn：7×12
Bmax=8.2T

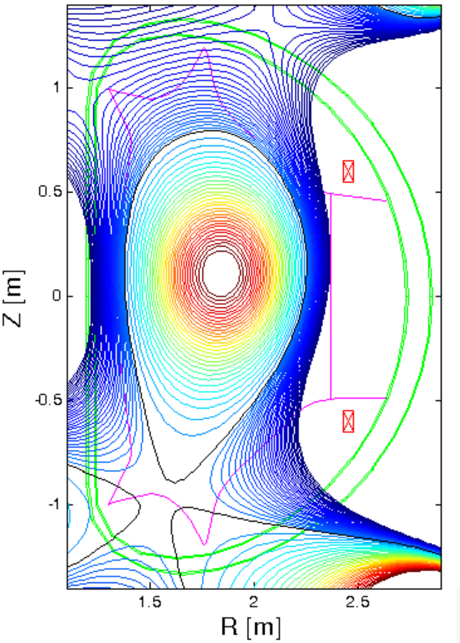
Bi2212:
Jce>380A/mm² (Ic>300A)
Conductor I =190×432=82kA
280mm×624mm
Turn： 8×12
Bmax=19.1

Maybe possible

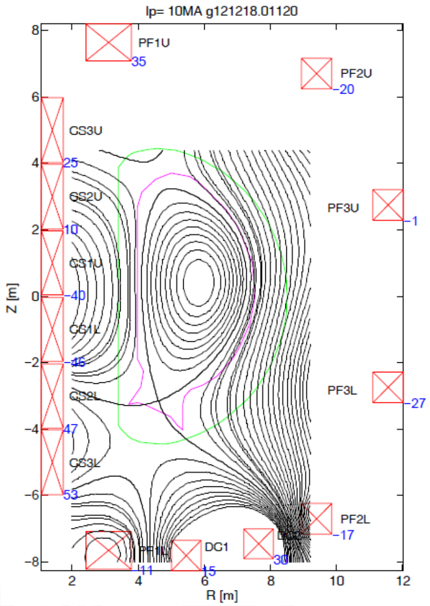
Divertor concept validation



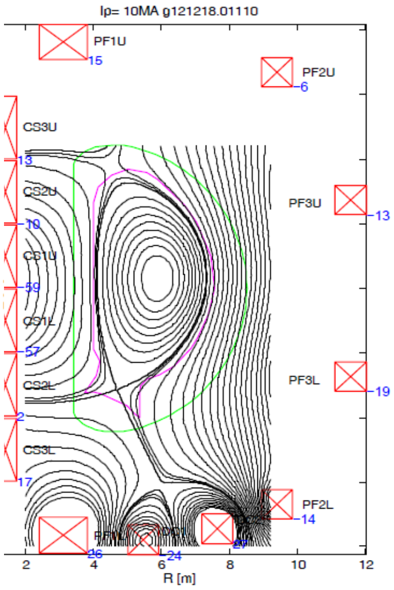
EAST 2015
Ptotal = 34 MW CW
ITER-like W divertor
>20MW/m2,



EAST- Snowflake



CFETR- Snowflake



CFETR- Super-X

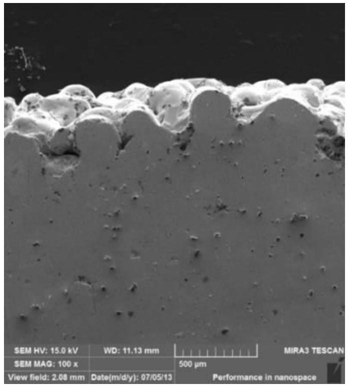
EAST: snowflake experiments Vs EFIT+TSC+B2, Radiation+detache
CFETR: Snowflake, Super-x, Snowflake+Super-x, adding D1+D2 coils new concept exploration

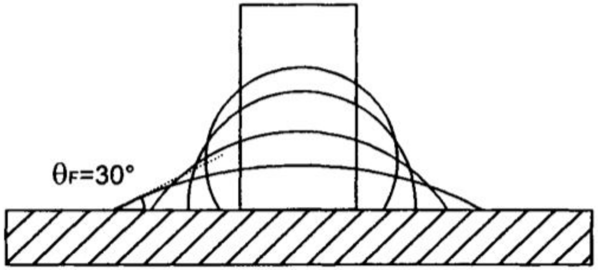
Efforts for closing the gaps for Phase II materials

Integrated efforts will be made under guidance of Roadmap

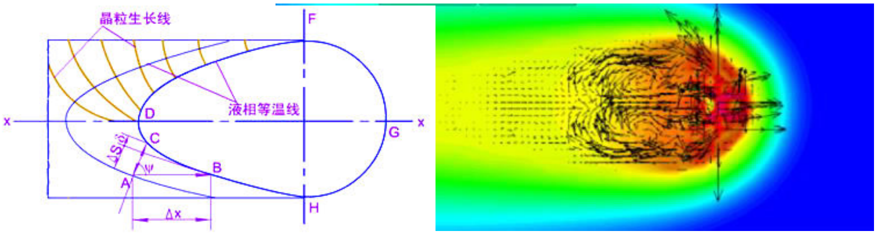
- **Code&simulation, Fabrication, validation (involve industry from very beginning)**
- **Multi-scale&integration, PFC&blanket, neutron sources**
- **Urgent: W for divertor (W alloy, nano scale, fib, 3D)**
- **Phase I: Divertor (water), blacked (water, He gas), T91**
- **Phase II: materials? SiC/SiC, ODS FS,**
- **neutron sources (two fission reactors + fusion source)**

Selective Laser Melting of Pure Tungsten

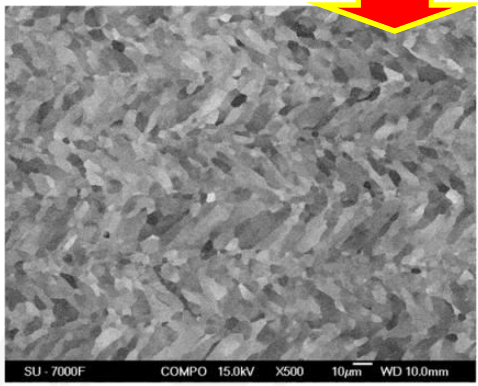




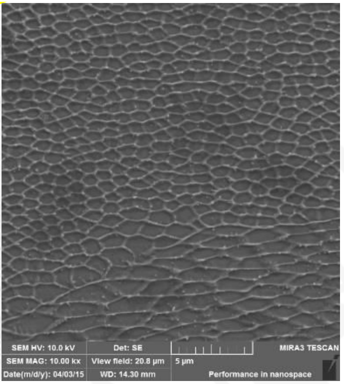
balling mechanism: the competitive processes of spreading and solidification



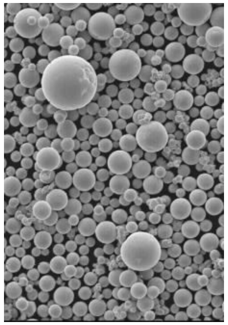
Heat,mass and momentum transfer in turbulence melt flow, homogenization

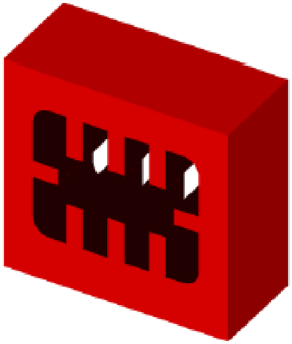


Surface texture



Sub-grain Cell

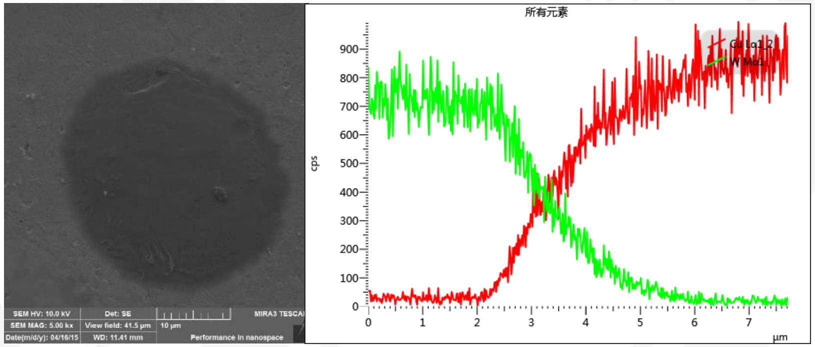




Target: 4-5 years DEMO full W block

30MW/m²Tmax: 1700C

水流速 m/s	20MW/m²	30MW/m²
8	1130℃	1680℃
10	1070℃	1600℃
12	1040℃	1540℃



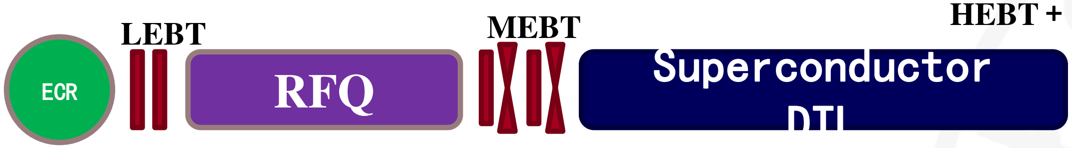
W-Cu dissimilar welding Inter-diffusion

CMIF: Compact Neutron Source

The Materials Irradiation Facility in China(CMIF)	
Target	**High Neutron Flux** **Low Neutron Yield** **Small Sample Size** **~1MW granular Be/C Target**
Beam	**50~100MeV@(5~30)mA (CW)**
Cost	**Low**

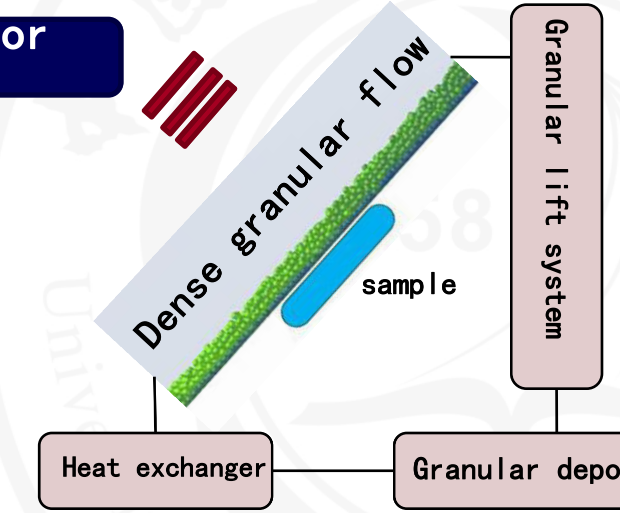
	energy（MeV）	**20**	**50**
I	**Flux(D+Be)** Y ($n\cdot cm^{-2}\cdot mA^{-1}\cdot s^{-1}$)	**3.6*10^{13}** *5 mA	**2*10^{14}** *10 mA
II	**Flux(D+Be)** Y ($n\cdot cm^{-2}\cdot mA^{-1}\cdot s^{-1}$)	**9.81*10^{14}** *20mA	**2*10^{15}** *30 mA

Superconductor LINPAC



Granular Targe

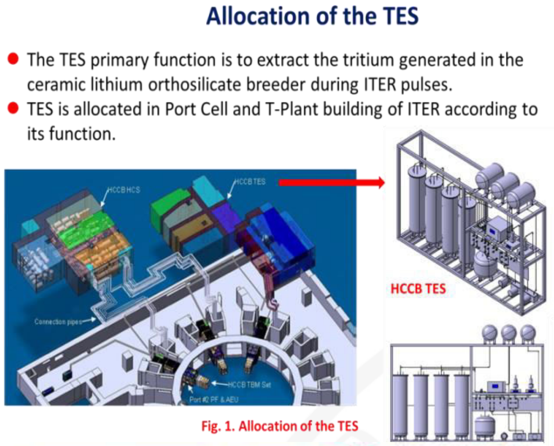
HEBT + scanning + Vacuum differential



Tritium cycling technologies

- **Tritium extraction/ determination systems developed for China helium cooled tritium breeding test blanket module (CN HCCB-TBM) to be tested in ITER machine (Cadarache, France).**

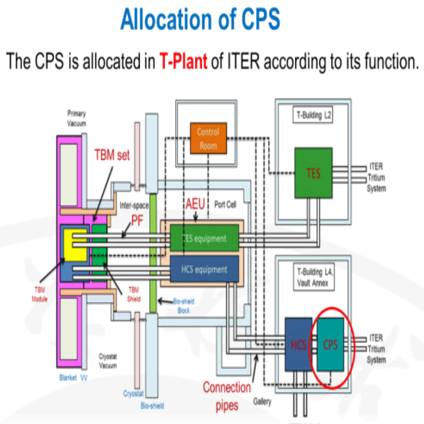
- **Tritium plants design for China fusion test engineering reactor (CFETR):**
  - Conceptual design of tritium fuel cycling and tritium safely handling systems (T-plant) for China next generation of fusion reactor
  - Key technologies on large scale of tritium handling like tritium isotopic separation (Cryogenic GC) and tritium recovery were developed



Allocation of the TES

- The TES primary function is to extract the tritium generated in the ceramic lithium orthosilicate breeder during ITER pulses.
- TES is allocated in Port Cell and T-Plant building of ITER according to its function.

Fig. 1. Allocation of the TES

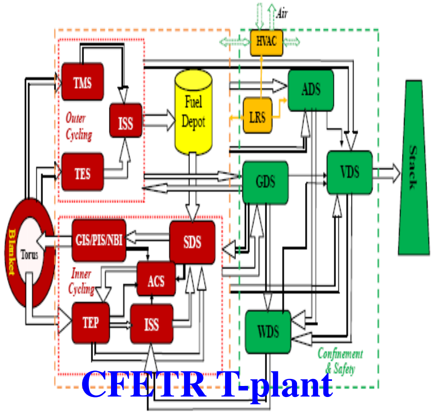


Allocation of CPS

The CPS is allocated in **T-Plant** of ITER according to its function.

Tritium extraction system For HCCB-TBM

Coolant purification system for HCCB-TBM



CFETR T-plant

Tritium storage and delivery system

Tritium separation system

Summary

- **Integrated Design and R&D of CFETR are in progress**
- **CFETR is moving towards Phase II design with emphasis for high BT option**
- **There are gaps to CFETR Readiness, especially for phase II.**
- **Challenges and risks are remained which need tremendous joint efforts, your helps are valuable.**
- **Moving forward is important.**
- **Learning by failures**