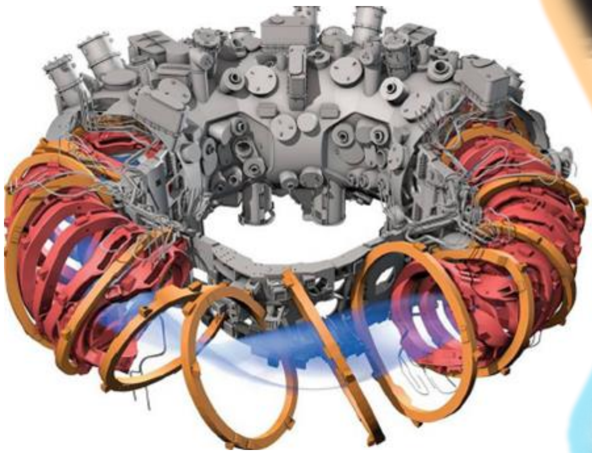
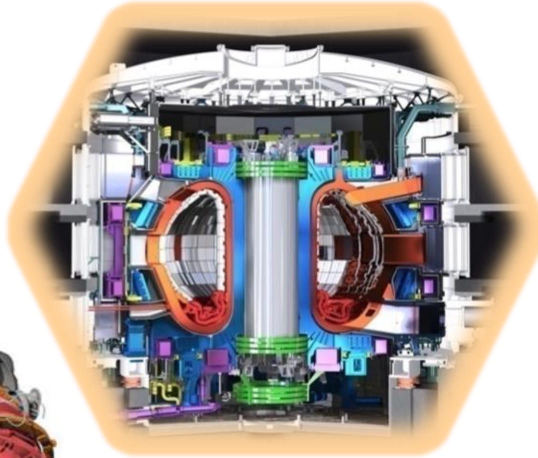
26th IAEA FEC





Summary of FIP, FNF, SEE and MPT

Jiangang Li

on behalf of all contributors

17–22 October 2016，Kyoto, Japan

Outline

- **Highlight**
- **Major Progresses**
  - **Fusion Engineering, Integration and Power Plant Design**
  - **Fusion Nuclear Physics and Technology**
  - **Safety, Environmental and Economic**
  - **Materials Physics and Technology**
- **Future Challenges**
- **Summary**

General Information

FIP - Fusion Engineering, Integration and Power Plant Design（116+25 OV）

FNS - Fusion Nuclear Physics and Technology（28）

SEE - Safety, Environmental and Economic （8）

MPT - Materials Physics and Technology（41）

Total： 218（28%）

Highlights

-Significant progresses have been made
Efforts have been focus towards fusion energy

- W7-X starts operation and C-Mode finished its mission
- ITER on the right track, all milestones have been met on schedule during past 15 month
- Next step device design is accelerating

  (EU DEMO, KDEMO, CFETR)
- Upgraded machines will address ITER key issues soon

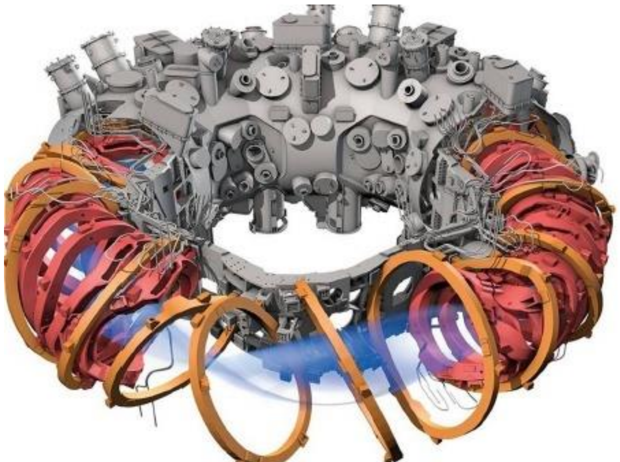
  (KSTAR, EAST, JT-60SA,WEST, NSTX-U, HL-2M, MAST-U)

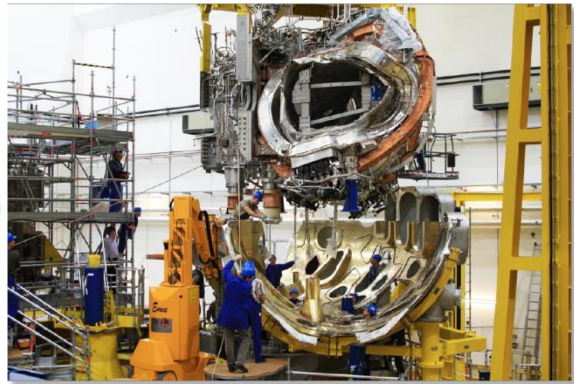
- New machines and new design

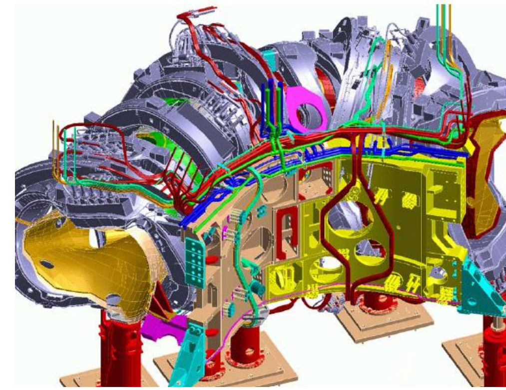
(KTX, ST40, T15, ARC, MEDUSA)
- Key technology development is continuing
- New approaches for DEMO material are on going
- New fusion neutron source R&D is moving forward (JP, EU,CN,KO)
- More work on SEE

W7-X Started Operation

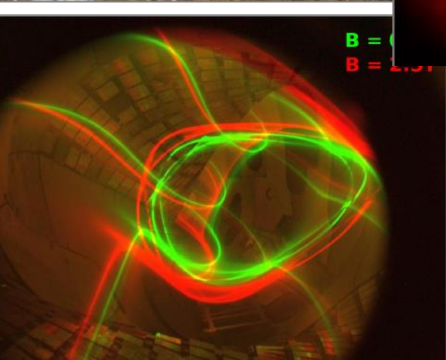
This beautiful piece of ART of technology demonstrates its merit







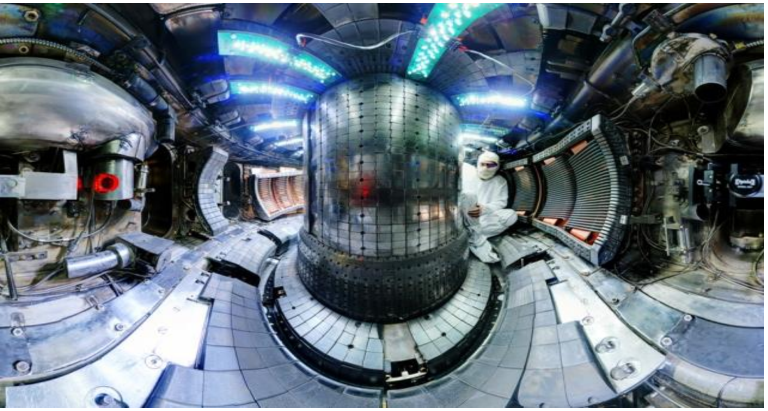
Key technologies for approaching steady state high performance plasma discharges have been developed



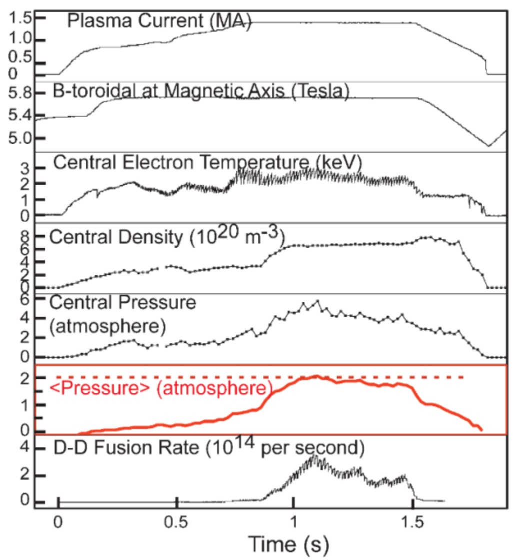
The first H/He operation shows its reliability

Next step for SS high performance will be exciting

C-Mod: Compact, ≤8 Tesla, 2 MA Divertor Tokamak



<P>= 2.05 Atm: achieved on last day of operation



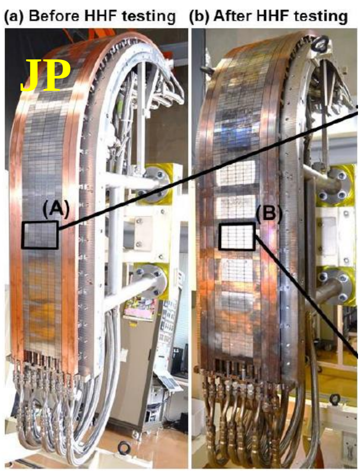
World's highest absolute plasma pressures

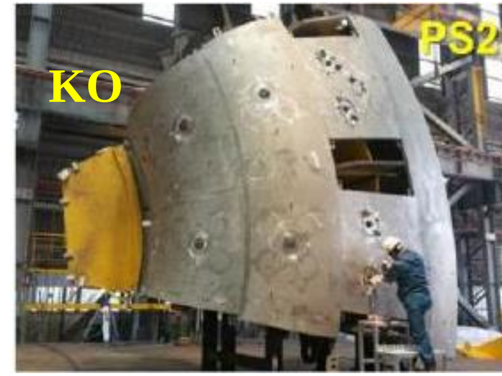
- **Unique design and operating parameters, produced wealth of new and important results since 1993**
- **Spearheaded development and optimization of vertical target divertor, always with high-Z metal PFC's (both adopted for ITER)**
- **Groundbreaking discoveries in divertor physics, PMI, critical role of cross-B SOL transport & edge flows**
- **Physics of the tokamak density limit**
- **Pioneered high-performance, ELM suppressed regimes: EDA-H and I-mode**
- **High power density technologies for LH and RF**
- **Direct experimental observation of ICRF mode-conversion & flow drive**
- **Fully non-inductive LHCD at ITER densities & fields**
- **First observations of non-axisymmetric disruption halo currents and non-axisymmetric radiation in mitigated disruptions**

1160930033

With courtesy to E.Marmar

ITER Technical Progress Has Been accelerated



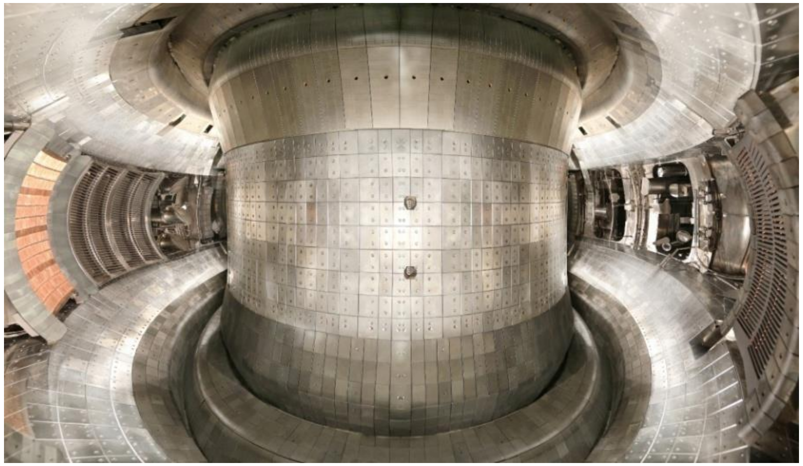


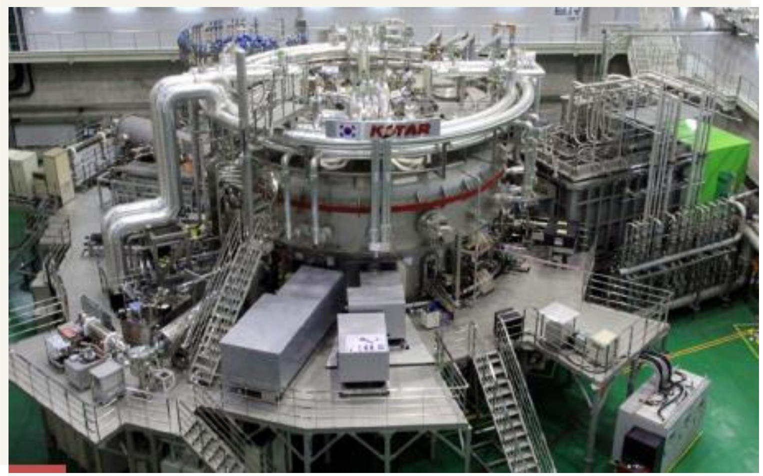
All milestones in past 15 month have been met

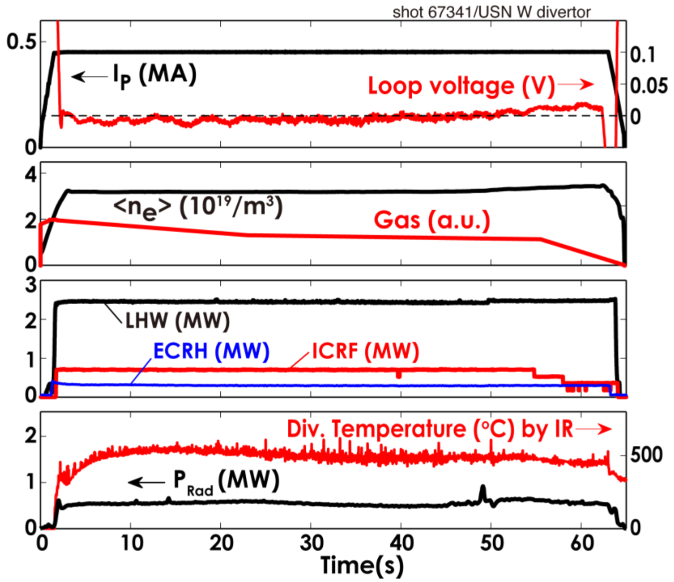
1st Plasma in Dec. 2025, DT in 2036

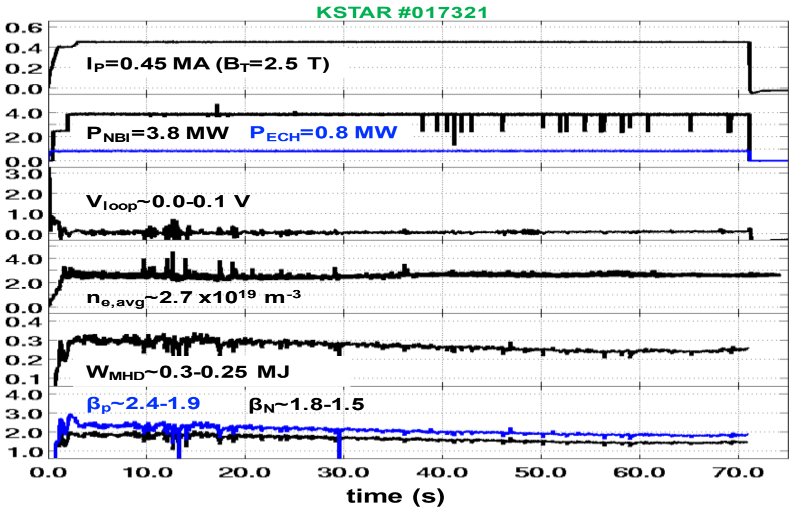
26 papers on ITER

KSTAR, EAST lead efforts for steady state high performance operation









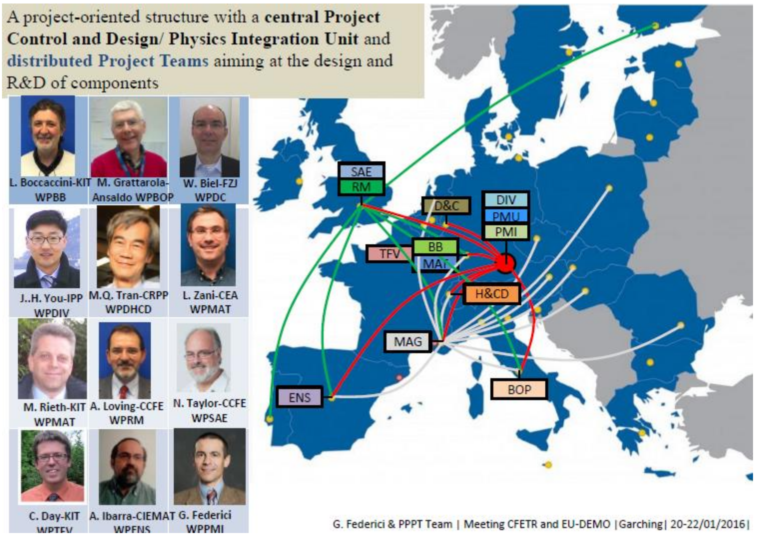
All actively cooled PFC&Diagnostics, CW H&CD

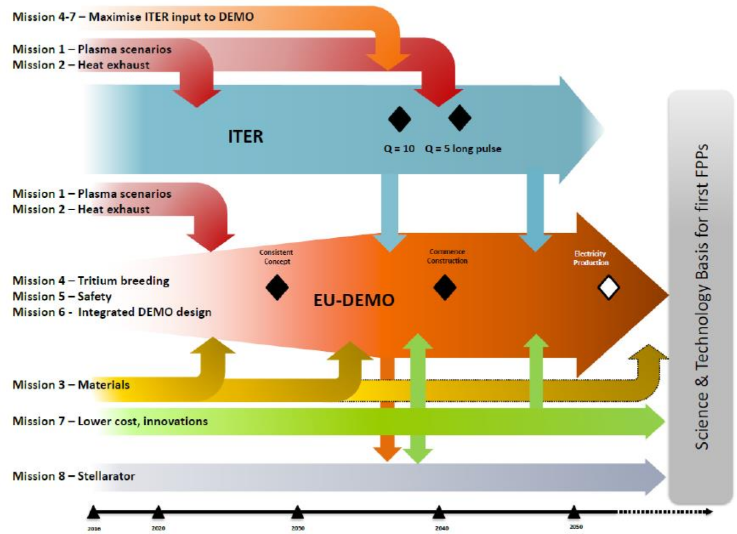
Long pulse NBI + ECRH+RMP coils

Y.Liang, A.Garofalo, G.N Luo

Y.K.Oh, H.S.Kim S.W Yoon

EU Fusion Roadmap to Fusion Power





Design features (near-term DEMO):

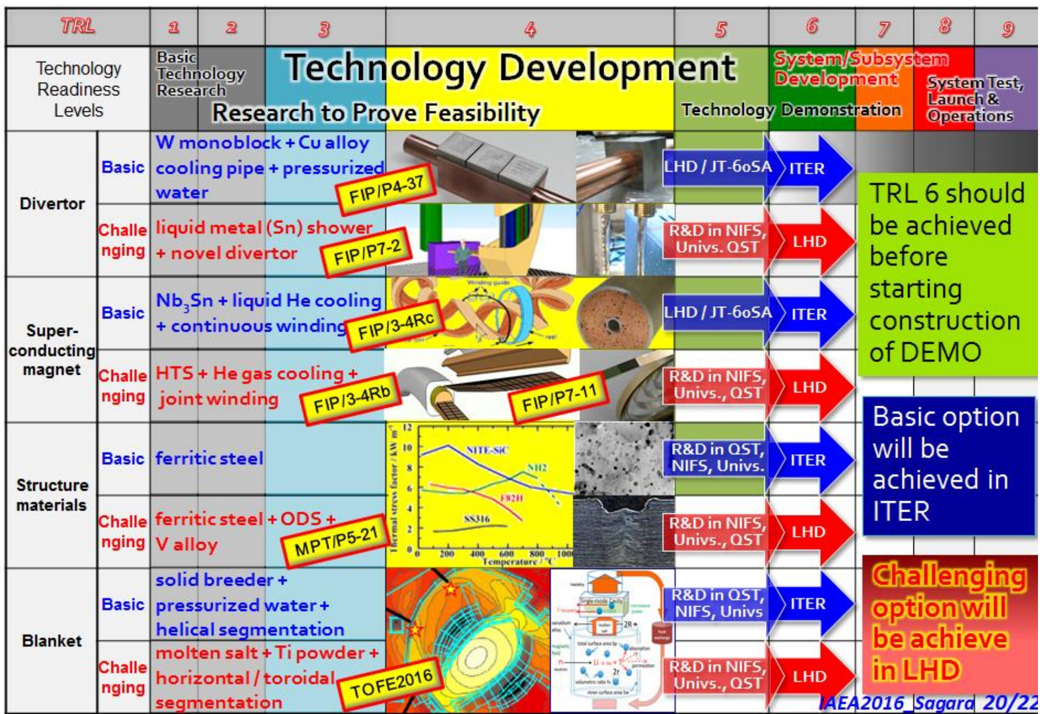
- 2000 MWth, ~500 Mwe
- Pulses > 2 hrs
- SN water cooled divertor
- PFC armor: W
- LTSC magnets Nb_3Sn (grading)
- B_{max} conductor ~12 T (depends on A)
- RAFM (EUROFER) as blanket structure
- VV made of AISI 316
- Blanket vertical RH / divertor cassettes
- Lifetime: first blanket: 20 dpa (200 appm He); 2nd blanket 50 dpa; divertor: 5 dpa (Cu)

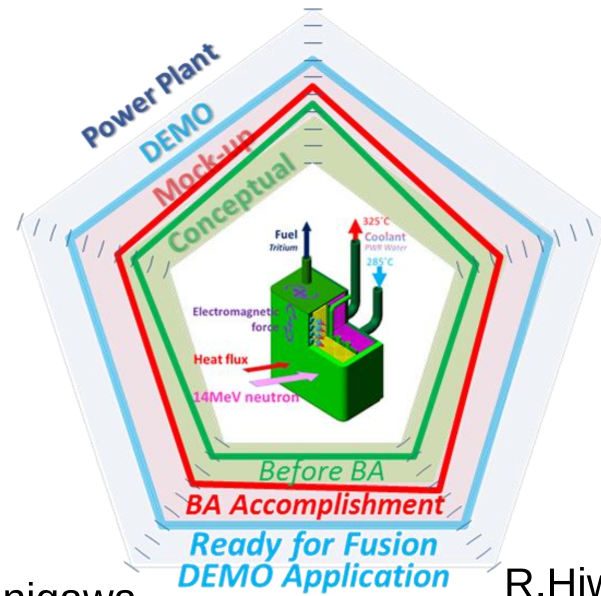
	ITER	DEMO1 (2015) A=3.1	DEMO2 (2015) A=2.6
R_0 / a (m)	6.2 / 2.0	9.1 / 2.9	7.5 / 2.9
K_{95} / δ_{95}	1.7 / 0.33	1.6 / 0.33	1.8 / 0.33
A (m^2)/ Vol (m^3)	683 / 831	1428 / 2502	1253 / 2217
H non-rad-corr / β_N (%)	1.0 / 2.0	1.0 / 2.6	1.2 / 3.8
P_{sep} (MW)	104	154	150
P_F (MW) / P_{NET} (MW)	500 / 0	2037 / 500	3255 / 953
I_p (MA) / f_{bs}	15 / 0.24	20 / 0.35	22 / 0.61
B at R_0 (T)	5.3	5.7	5.6
$B_{max, conductor}$ (T)	11.8	12.3	15.6
BB i/b / o/b (m)	0.45 / 0.45	1.1 / 2.1	1.0 / 1.9
Av NWL MW/m^2	0.5	1.1	1.9

With courtesy to G.Federici

DEMO activities in Japan

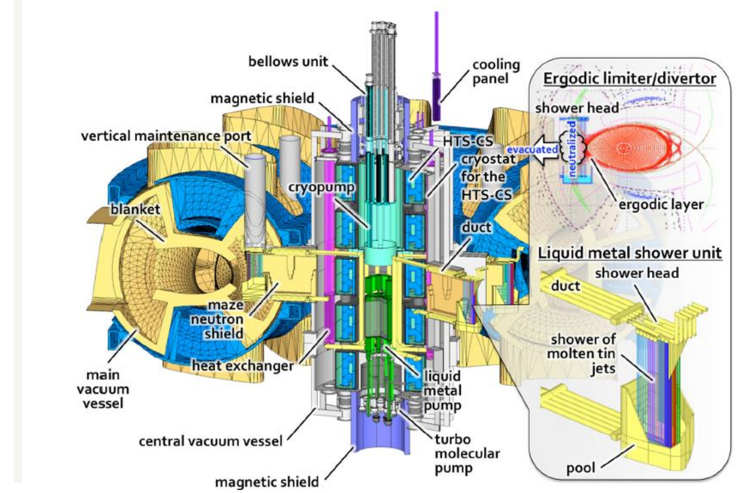
- A joint DEMO group has been form and stratagem plan has been proposed ender leadship of H.Yamada.
- Tokamak and Helical DEMO approaches.
- Very active activities in Helical approach in FEC26
- R&D Strategy Toward TRL 6 is proposed





H. Tanigawa

R.Hiwatari



FFHR-d1A **With courtesy to A. Sagara**

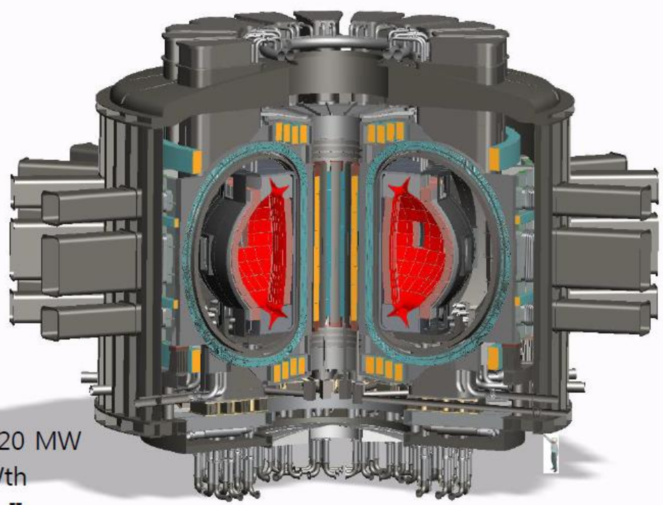
KDEMO

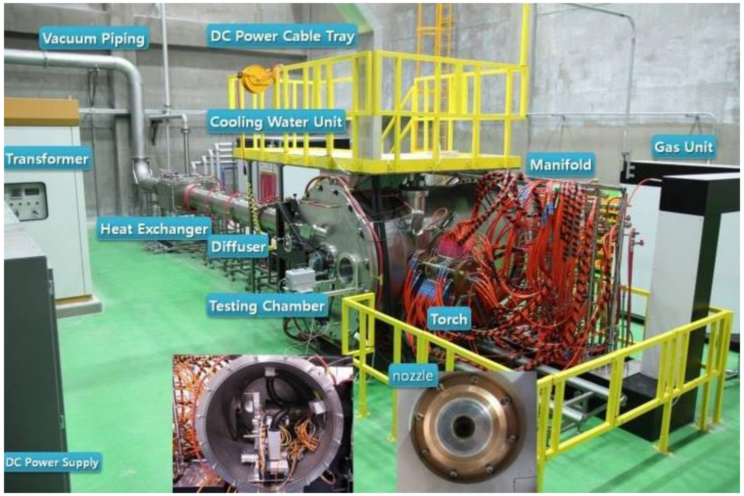
■ Main Parameters

- R = 6.8 m
- a = 2.1 m
- B-center = 7.0~7.4 T
- B-peak = 16 T
- κ_{95} = 1.8
- δ = 0.625
- Plasma Current > 12 MA
- Te > 20 keV

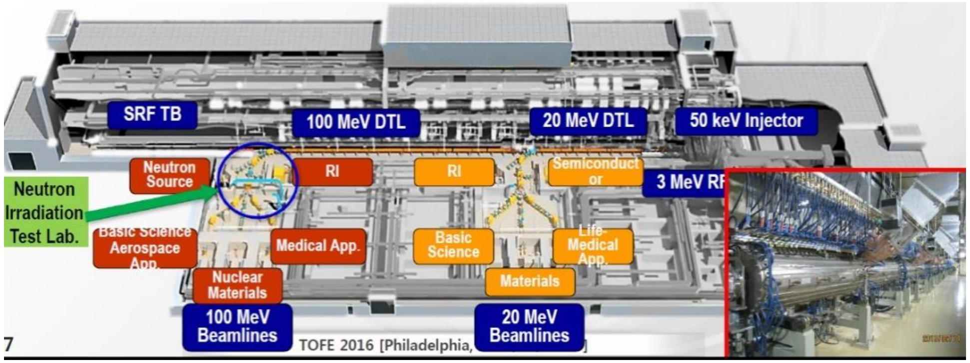
■ Other Feature

- Double Null Configuration
- Vertical Maintenance
- Total H&CD Power = 80~120 MW
- P-fusion = 2200~3000 MWth
- P-net > 400 MWe at Stage II
- Number of Coils : 16 TF, 8 CS, 12 PF





2.4 MW PSI Test Facility



20-100MV KOMEC proton Linac

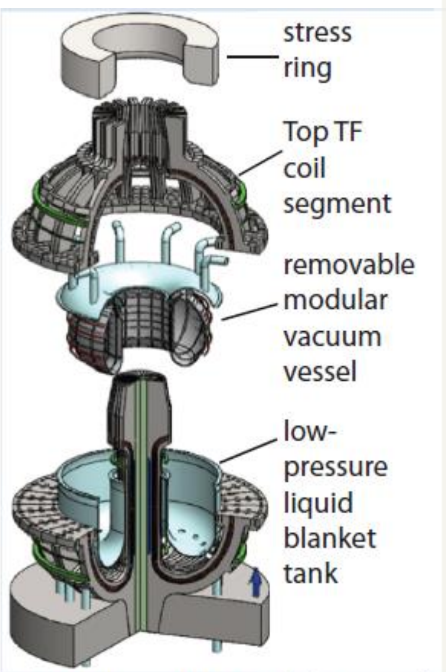
With courtesy to K.W.Kim

CFETR


1/32 VV
gyrotron
RH
Engineering design and large scale R&D will start soon
linac

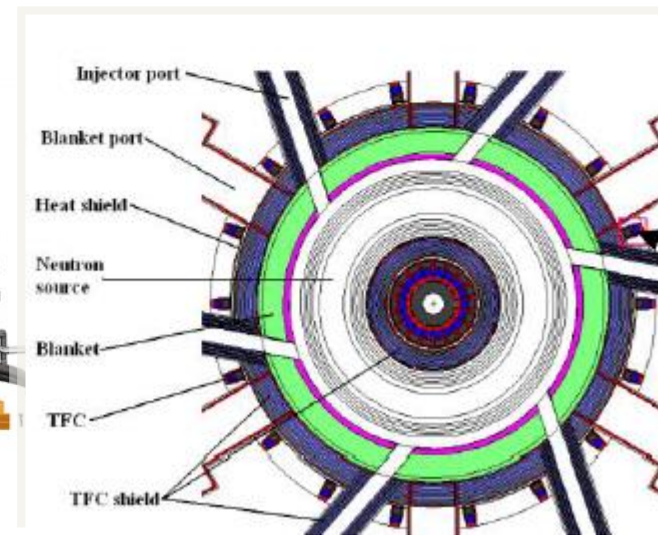
Compact Power Plant Design

- High field, compact and demountable FNF
- Fusion Fission Hybrid base on superconduction tokamak with molten salt coolant.



ARC D.White

T.Brown



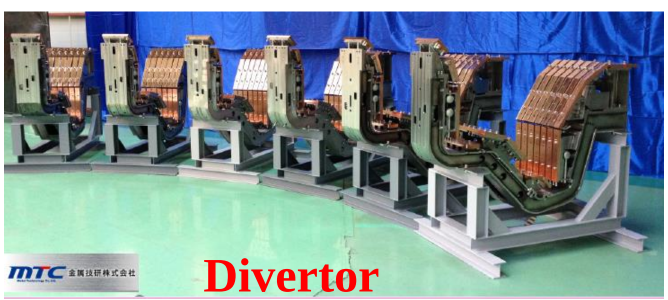
RU FNS-DEMO
B.V.Kuteev

Upgraded Machines Coming into Operation Soon

JT-60SA: 1st Plasma in 2019

On schedule, good cooperation

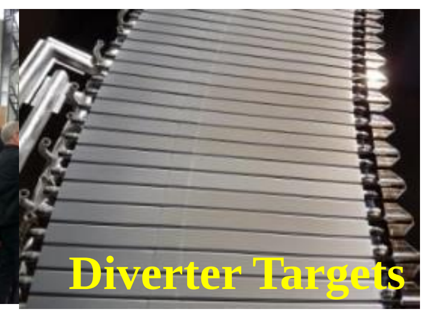
Satellite machines for ITER for advanced operation together with JET (DT, ITER like wall)



WEST: 1st Plasma, Nov. 2016

Key issues: SSO related technology

W divertor for >1000s



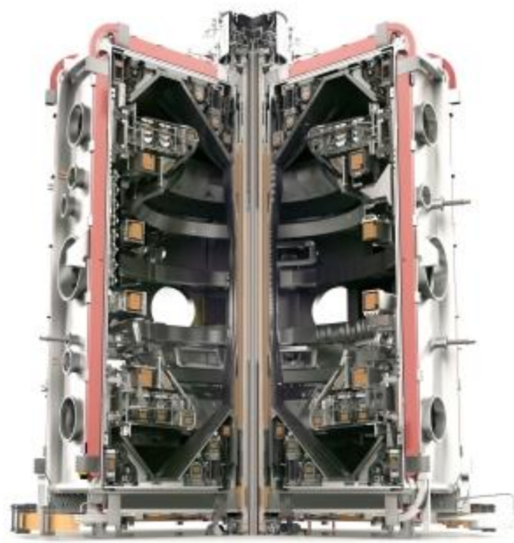
20MW/m^2 for 5000 cycles

Upgraded Machines Coming into Operation Soon

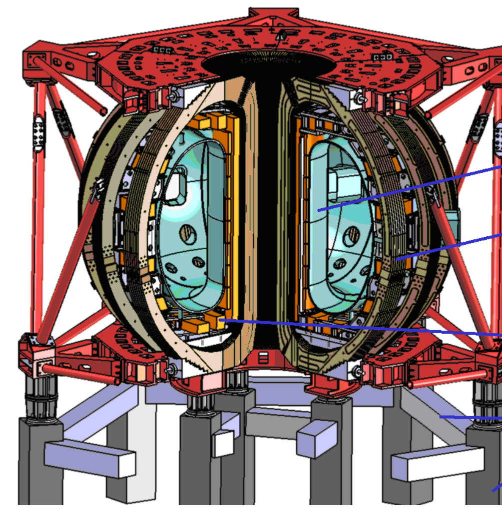
NSTX-U: The first test:
NBI ~4MW, I_P = 1MA, Wj~ 200kJ, β_N ~ 4,
κ ~ 2.2, τ_E > 50ms, τ_{pulse} ~ 1.7s,

full operation in 2017

Mast-U:2017.10

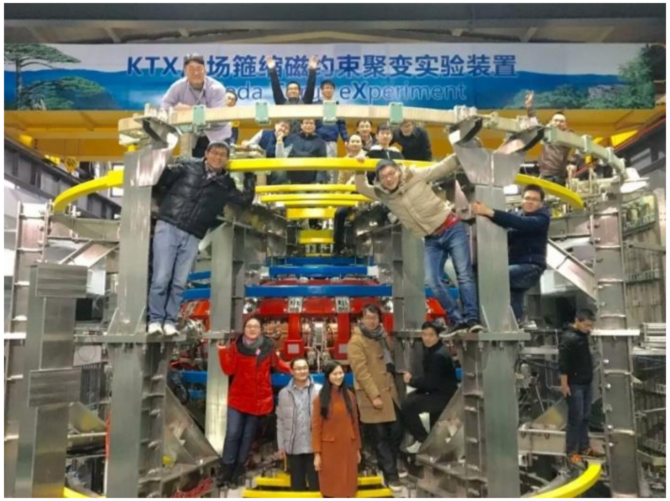


HL-2M:2018.12



- Advanced divertor configurations: Super-X, Snowflake,
- Heat and particle removal
- Edge turbulence and transport

New Devices



KTX, 2015

R=1.4m

a= 0.4m

Ip = 0.2-1.0MA, τ_{pulse} ~100ms

Ip ~ 200kA, τ_{pulse} ~20ms

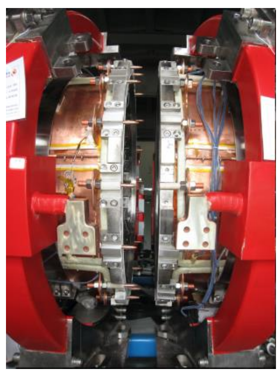
ne~$3x10^{19}m^{-3}$

20 Month construction

Double C structure

Separate Inductive baking system of VV

Terahertz solid state source interferometer



T15, 2018

R_0=0.4-0.6m, R/a=1.6-1.8, I_{pl}=2MA, B_t=3T, k=2.5, τ_{pulse} ~1-10sec, 2MW NBI

ST40 early 2017

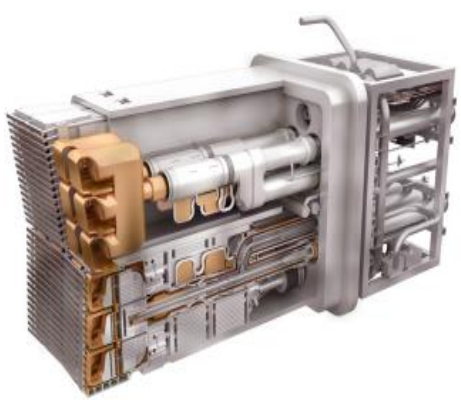
R_0=0.4-0.6m, I_{pl}=2MA, B_t=3T, k=2.5, τ_{pulse} ~1-10sec, 2MW NBI

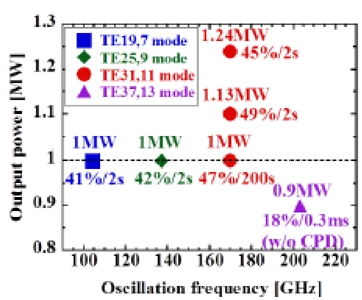
M Gryaznevich

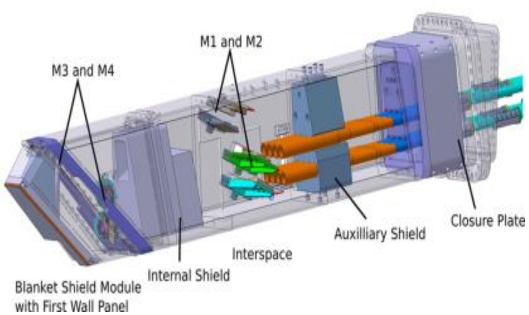
Key Technology Developments - IC, EC

ICRF (ITER)
20MW, 40-55MHz
for heating & conditioning
Sawtooth control, 1KHz modulation
Antenna is challenging
The rest is technically ready
DEMO
Concept of toroidally distributed antenna, low power density; Possibility to excite low $k_{//}$ to improve coupling

EC (ITER)
20MW, 170GHz
Heating & startup
NTM control, 4KHz modulation
Series production of gyrotron **is challenging**
The rest is technically ready
DEMO
Dual frequency (170 -204 GHz) 2 MW gyrotron
Advanced 240 GHz 2 MW coaxial gyrotron
Launcher using Remote Steering of RF beam



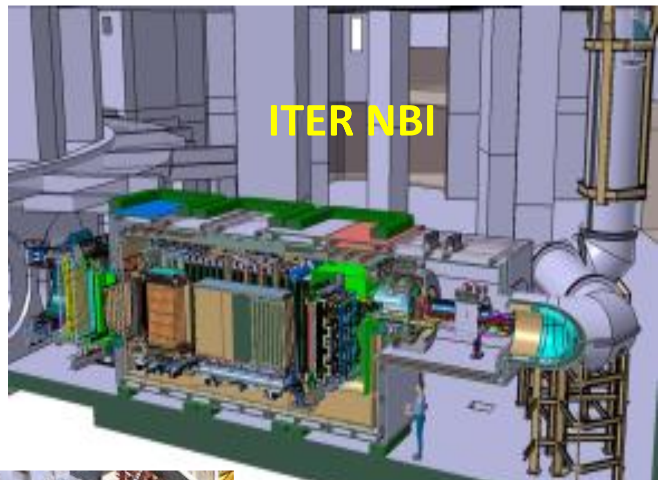


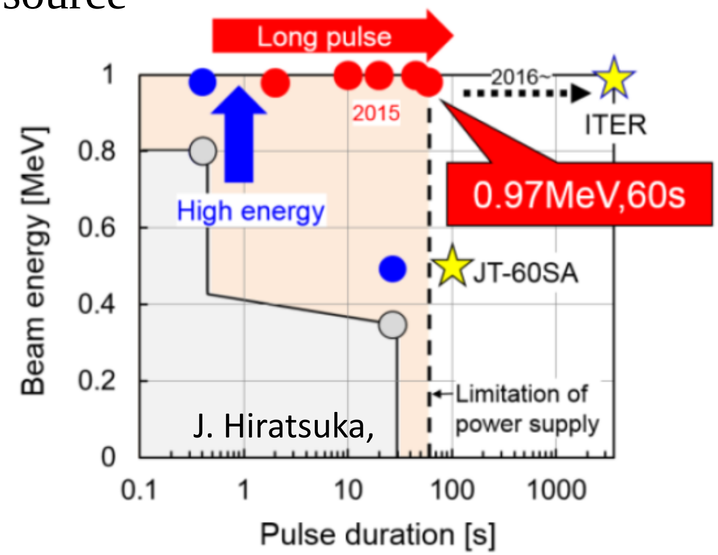


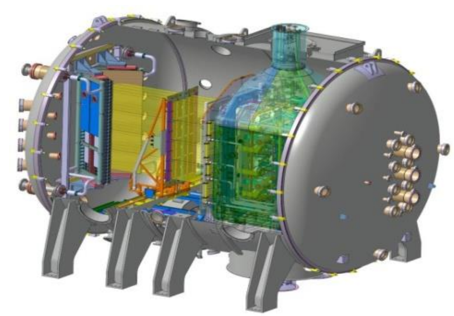
A. Mukherjee, A. Bader G. Granucci J-Noterdaeme M.Q. Tran G.Denisov, R. Ikeda,T.Kariya

Key Technology Developments - NBI

ITER: SS ion sources are progressing well. Integration of NBI system is challenging
The SPIDER first experimental phase will start in early 2018
DEMO: Advanced NBI system over 20MW /beam at an efficiency of 50% using photo neutralisation and on Cs free negative ion source





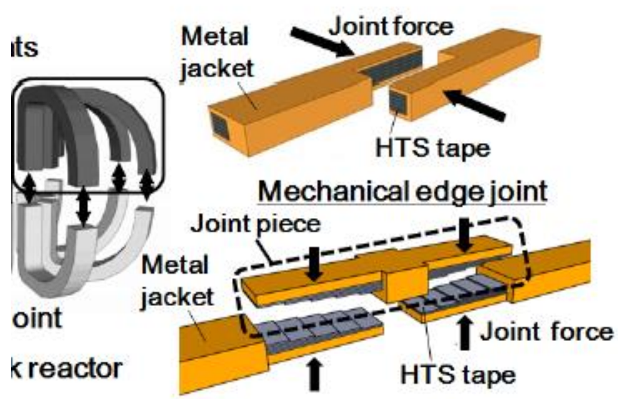


SPIDER Experiment

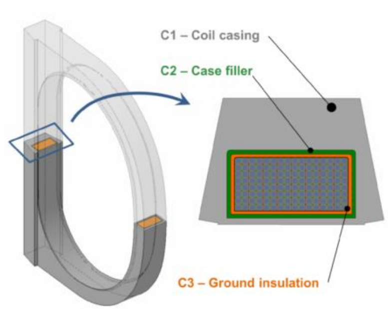
M.Kisaki, P. Sonato J.Hiratsuka, U. Fantz N. Umeda V. Toigo

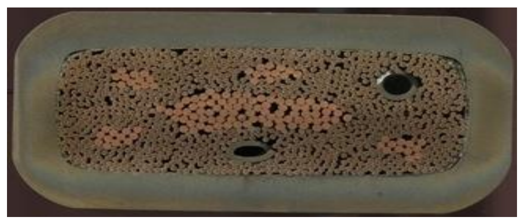
Key Technology Developments - Magnets

- New Design methods, analysis & design tools have been developed
- TF WP options were proposed and conductor samples were manufactured and one tested
- HTS conductors activity, substantial progresses were also made, 100kA HTc STARS conductor has been made

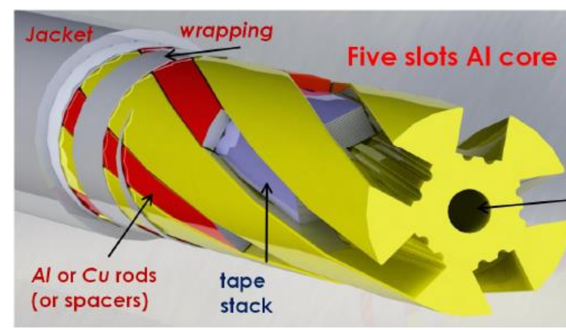


The "remountable" HTS magnets and the mechanical joints by H. Hashizhume



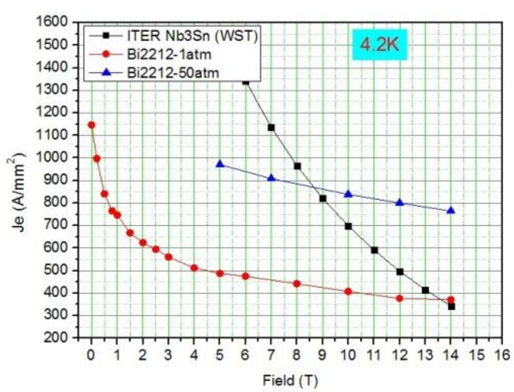


New Nb3Sn conductor



HTc tage-type conductor

2212 CICC conductor



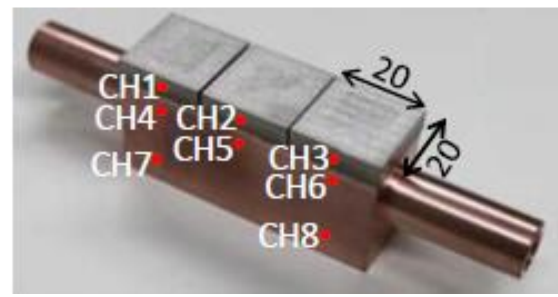
High Pa 2212 performance

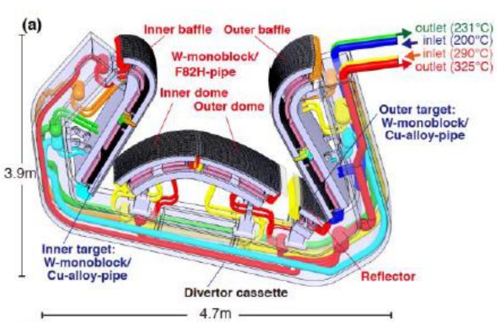
L. Zani N.Yanagi P. Bruzzone,

Key Technology Developments - Divertor

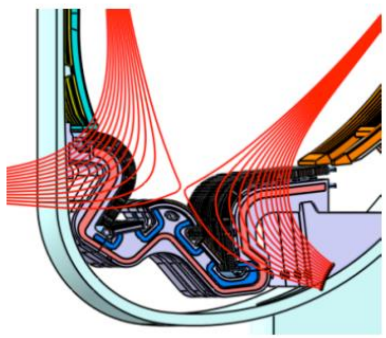
- Alternative demo divertor design being analysed: long, short legged SN and DN.
- Advanced divertor with new technical solution for over $20MW/m^2$
- HyperVapotrons (HVs) are considered highly robust and efficient heat exchangers at $10\text{-}20MW/m^2$

W as FW and water cooled ($20MW/m^2$)
ODS Cu （500C， 50dpa)
Cu alloy（550C， 100dpa)-base materials for Target heat sink;
Eurofer steel for Cassette body

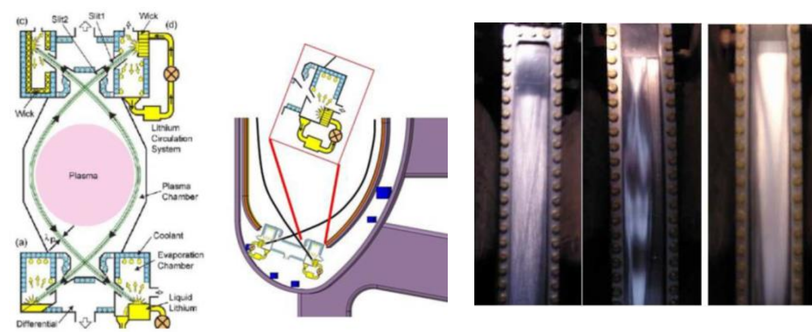




Neutronics analysis shows W/Cu-alloy heat sink can be applied at high heat flux and low n-flux area



DTT divertor design

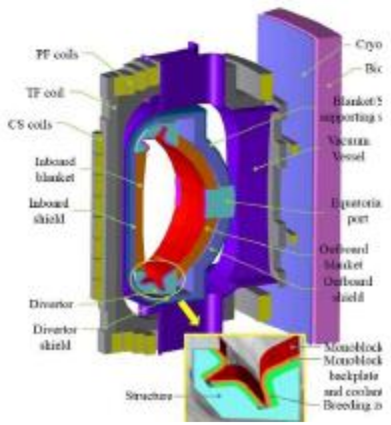


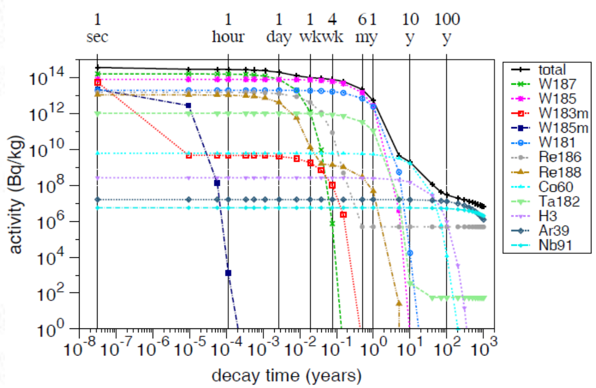
Flowing liquid metal divertor and R&D

N. Asakura A. Sergis F.Crisanti M. Tokitani R. Zanina M. Ono Zengyu XU

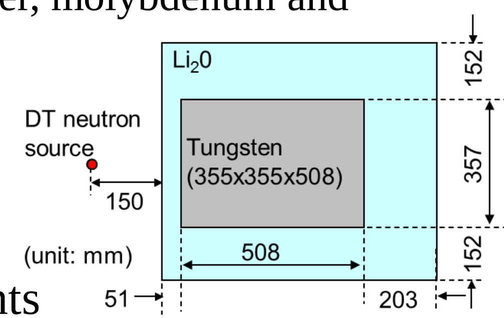
Fusion Nuclear Physics and Technology

- Advanced Neutronics Simulation Tools and Data
- Detail analysis and modeling for activation, decay heat, and waste classification for components:
  - Blanket, Divertor , VV, magnets
- 150KW, 15kW after one month, can be recycled after 100 years

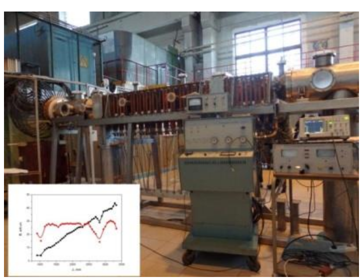




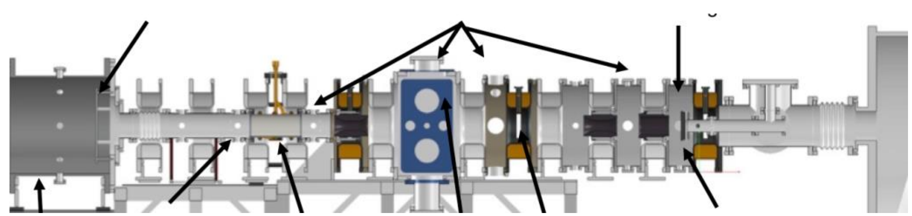
- New integrated experiments for a variety of fusion reactor materials with Fission and DT neutron source at (JA, EU)
- Nuclear analysis of structure damage and nuclear heating
- Nuclear data on tungsten and vanadium have no problems, while there are still concerns in the nuclear data on copper, molybdenum and titanium



New facilities for plasma material interaction and damage assessments



QSPA Plasma Accelerator

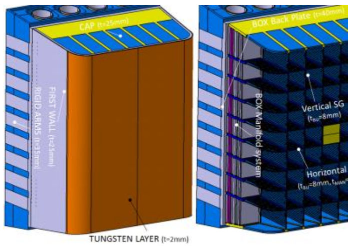


MPEX in ORNL

U. Fischer J Park M.Gilbert G. Stankunasa I.E. Garkusha J. Rapp Zhirkin A.V S. Sato

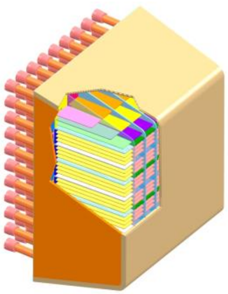
FNS-Blanket

ITER TBM design mainly focuses on licensing procedure, safety, investment protection, conventional control and impact of the integration of the TBS in the ITER environment . 16th TBM meetings and ITER TBM FDR could be held in 2021.

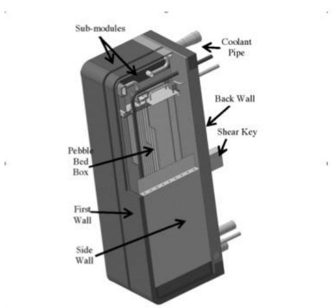


HCPB by EU

TBM Concept 1	TBM Concept 2
56-A1: HCLL (He-Cooled Lithium-Lead) **(TBM Leader: EU)**	**56-A2: HCPB** (He-Cooled Pebble Bed) **(TBM Leader: EU)**
56-B3: WCCB (Water-Cooled Ceramic Breeder) **(TBM Leader: JA)**	**56-B4: HCCR**(Helium-Cooled Ceramic Reflector) **(TBM Leader: KO)**
56-C5: HCCB (He-Cooled Ceramic Breeder) **(TBM Leader: CN)**	**56-C6: LLCB** (Lithium-Lead Ceramic Breeder) **(TBM Leader: IN)**

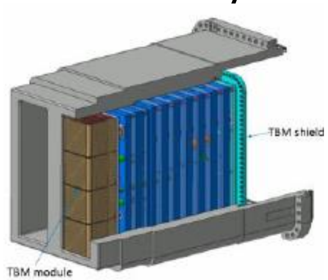


HCLL TBM by EU

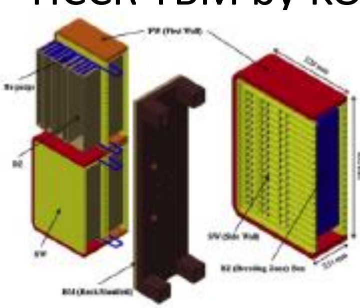


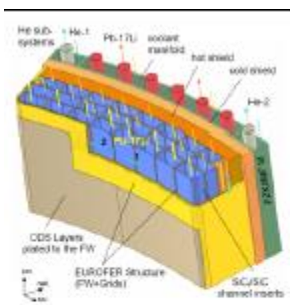
WCCB TBMby JA

HCCB TBM by CN



HCCR TBM by KO





LLCB TBM by IN

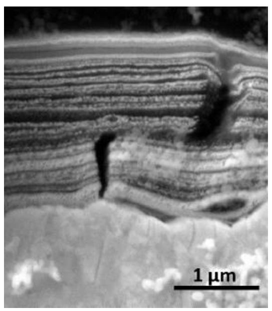
DEMO blanket designs are also under development with lesson learned from ITER TBM in EU(4), JA(1), CN(3), KO(1), US(2).

J.Ricapito, K.Feng, I.Palermo

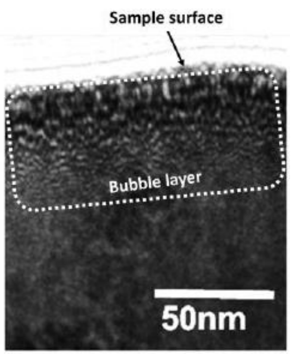
Materials Physics and Technology-FW

Validation of existing W performance:
Fuel retention on tokamak (LHD, JET, EAST..) and plasma facilities
D Retention and thermo-mechanical properties in beam damaged tungsten

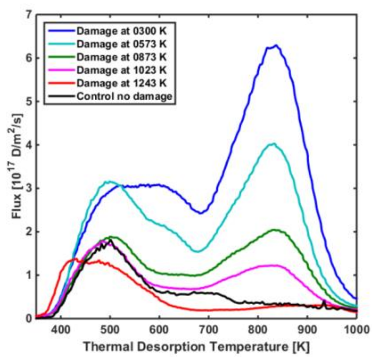
Advanced new W materials for anti-erosion, cracking are under development:
Nano W, W alloy, Wf/W and
smart W(Cr, Ti) alloys for intrinsic safety



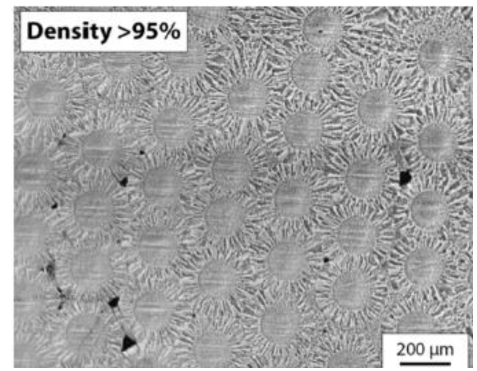
JET Fuel retention is still dominated by co-deposition

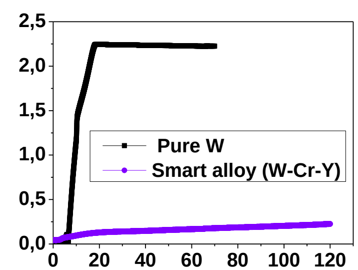


LHD sample for retension H~10^{17}



Tw is a key elements for D retention in damaged W





Mass change due to oxidation and evaporation, mg/cm^2 min.

M. Sakamoto **M. Oya** **R. S. Rawat** **G. Tynan** H.T. Lee

A.Widdowson **Y.Nobuta** H.-S. Zhou **J.W.Coenen** M. Wirtza G. -N. Luo **A. Litnovsky**

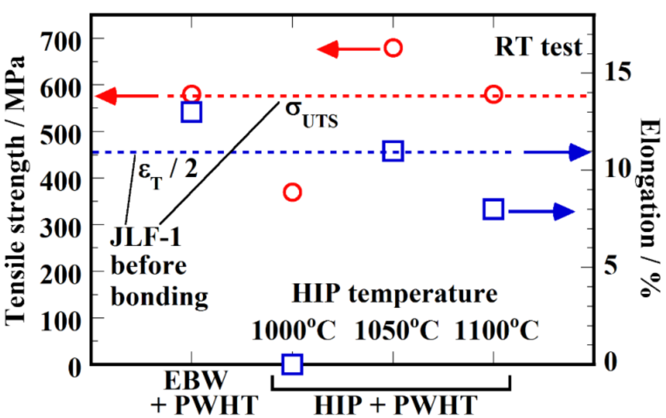
Materials Physics and Technology-SM

Advanced RAFM steels (EU, JA) for high temperature and water cooled applications
ODS steel: very active activities in many countries. Fabrication & demonstration of joint welding.
Experimental validation (fission reactor)

	RAF Steels (F82H)	ODS Steels (15Cr-ODSS)
Thermal Efficiency	Max. temp. allowable= 539 °C Max. stress allowable = 359 MPa (<3Sm) High Temp. Water 15 MPa, 309 °C	Max. temp. allowable=800 °C Max. stress allowable = 359 MPa (<3Sm) SCP Water 25 MPa, 502 °C
Lifetime Creep Corrosion Helium Irr. Embritt.	180 MPa, 550 °C, 10 khr 0.6 mm, 500 °C, 1 year < 600 appm (40 dpa) Large loss of elongation	180 MPa, 780 °C, 10 khr 0.003 mm, 500 °C, 1 year > 1000 appm (65 dpa) No loss of elongation

Table 1 Various ODS steels [1]

Country	Alloys (compositions)
Belgium	DT2906:Fe-13Cr-1.5Mo-2.9Ti-0.6Y_2O_3, DT2203Y05:Fe-13Cr-5Mo-2.2Ti-0.3O-0.5Y_2O_3)
China	K7:Fe-13Cr-1.1Ti-0.2Mo-2W-0.39Y_2O_3
Europe	ODS EUROFER:Fe-9Cr-1.1W-0.2V-0.14Ta -0.3 (0.5)Y_2O_3
Japan	Fe-9(12)Cr-0.12C-2W-0.2(0.3)Ti -0.35(0.23)Y_2O_3, 14-15Cr-2W-0.25Ti-0.35Y_2O_3
USA	MA957:Fe-14Cr-0.9Ti-0.3Mo-0.25Y_2O_3, 12CrY1:Fe-12.4Cr-.25Y_2O_3, 14CrYWTi:Fe-14.3Cr-3W-0.39Ti-0.25 Y_2O_3



Tensile properties of dissimilar-metals joint with various welding conditions

M. J. R. Sandim
A. Kimura
M. Nakajima
T. Nagasaka

Fusion Neutron Sources Development

IFMIF/EVEDA (2017) EDA phase was successfully accomplished on schedule between JA and EU

LIPAc installation is advancing in Rokkasho.

Ready for the construction of a Li(d,xn) fusion relevant neutron source

EU: **IFMIF/DONES**(*125 mA at 40 MeV)*

Small sample test standard is underway which may play an important role together with compact neutron sources for materials selection

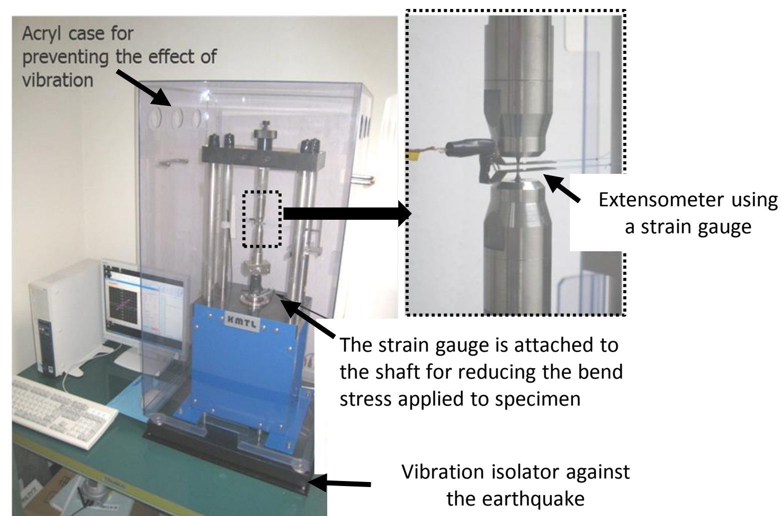
J.Knaster,

CCMIF: China Compact Fusion Neutron Sources is under construction:

2018.12 10^{14} /cm^2 s

2020. 12 10^{15}/cm^2 s

10mA 20MeV linac **Flowing Be target**



Safety, Environmental and Economics

Safety:

DEMO safety issues have been raised in terms of accidents, radioactive material release, occupational radiation exposure, and radioactive wastes, by comparison with existing Gen-II/PWRs, Gen-IV reactor designs, ITER and future DEMO systems

- To protect workers, the public and the environment from harm;
- To ensure that normal operation is controlled;
- To ensure that the likelihood of accidents is minimized and that their consequences are bounded;
- To minimize radioactive waste hazards and volumes and ensure that they are as low as reasonably achievable.

Confinement of radioactive inventories is the most important, and may lead to many systems, structures and components being classified as safety important

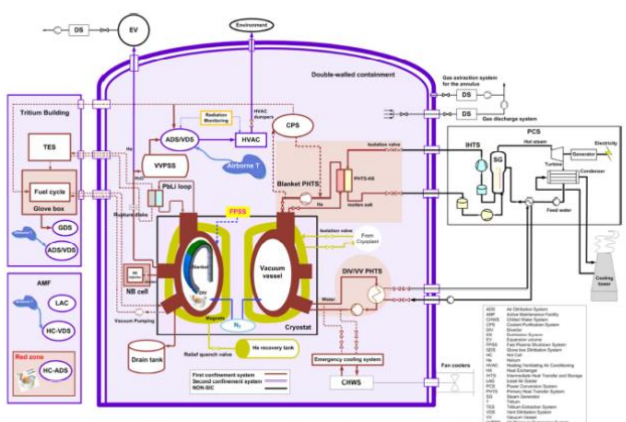
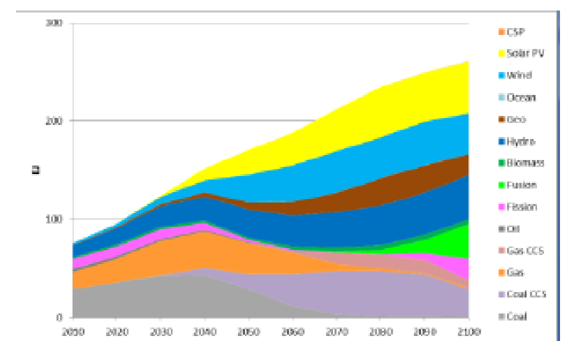


Fig. 1 Scheme of DEMO confinement for the HCLL blanket concept

Economics

Fusion may contribute to meet global environment target.
Technology costs are the key for fusion penetration.
Multi-function design could bring economic benefit.
Fusion deployment strategy with electricity storage systems.
It is still too early for economic estimation for fusion at present.



H. Cable X.Z.Jin Y.Someya K.Gi H. Cable S. Konish

Outline

- Highlight
- Major Progresses
  - Fusion Engineering, Integration and Power Plant Design
  - Fusion Nuclear Physics and Technology
  - Safety, Environmental and Economic
  - Materials Physics and Technology
- **Future Challenges**
- Summary

Future Challenges

Outstanding Technical Issues with Gaps beyond ITER

Tritium self-sufficiency

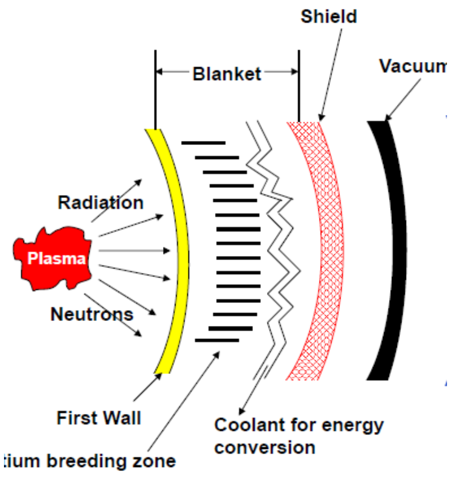
most novel part of DEMO
Very low burning rate(~1%)

start-up inventory may be too high

regulatory limit may not be achievable
TBR >1 marginally achievable but with
thin PFCs/few penetrations

fuel cycle is to support economic attractiveness
of the produced electric energy

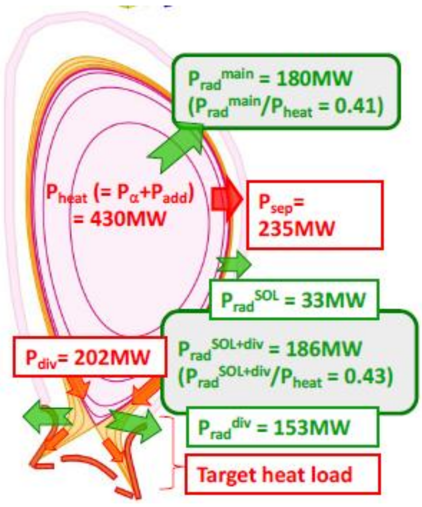
- Feasibility concerns
- Performance uncertainties for all concepts
- R&D needed
- Selection now is premature



Power Exhaust

Peak heat fluxes near technological limits (>20 MW/m^2)
ITER solution may be marginal for DEMO
Integration of DEMO working condition is very challenging

Need both new physical (advanced divertor +impurity seeding) and technical (new robust DEMO 20MW/m^2 target) solutions
Validation on long pulse tokamak experiments.



Future Challenges

Outstanding Technical Issues with Gaps beyond ITER

Remote Maintenance

- RH schemes affects plant design and layout
- Significant differences with ITER approach
- Should start from very beginning of DEMO design
- Large size Hot Cell required
- Service Joining Technology R&D is urgently needed.

Safety

Demonstrate that these characteristics lead to excellent safety and environmental performance

Radioactive inventory

Waste management

For requirement of licensing, safety considerations must be central to design activities from the beginning

Structural and HHF Materials

- Progressive blanket operation strategy (1st blanket 20 dpa; 2nd blanket 50 dpa)
- Embrittlement of RAFM steels and Cu-alloys at low temp. and loss of strength at ~ high temp.
- Need of structural design criteria and design codes
- Selection by Neutron Source(fission, fusion)
- Strong coupling between simulation and experimental validation

RAMI

Most novel part of DEMO
Very low for existing facility and too far towards DEMO
Need code and standard

ITER will play a key role

DEMO design activities from the beginning

Summary

- Significant technical progress has been made during past two years.
- W7-X starts operation, C-mode finished its mission which are outstanding milestones in fusion history, especially on technology achievements.
- Fusion is a century project which involves science, technology and engineering. Scientifically, we have to make targets more simple rather than more complicated. Technically, we have to make every component and system robust and reliable towards our final goal. Lets work on it.
- What will be the most exciting achievement within two years?