Enabling Technologies – VLT Town Hall

Nuclear Reactor Compatibility Issues

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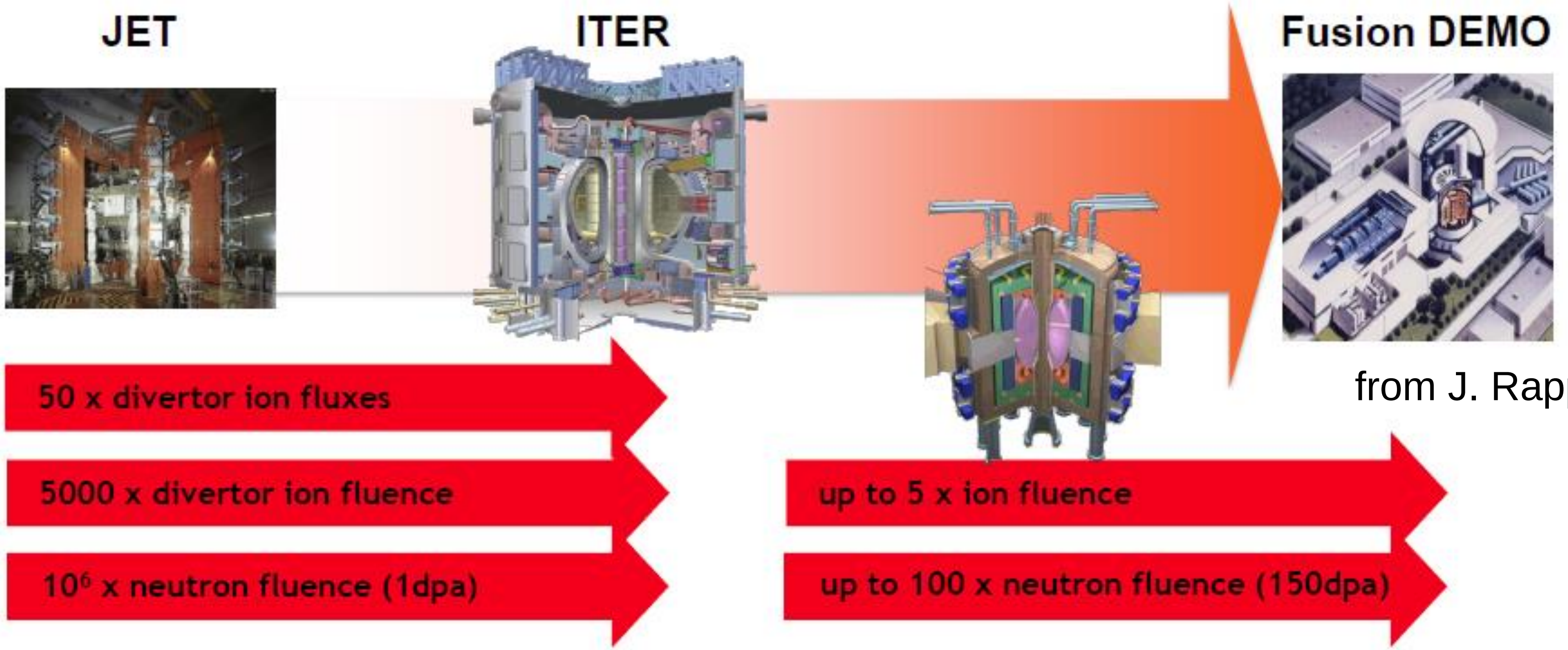
June 04, 2019

Outline

- Objectives/Requirements for a nuclear reactor (compact pilot plant)
- Major Critical Issues including Gap Metrics for a Nuclear Reactor
  - Magnets
  - Heating
  - Fueling
  - PFCs and IVCs
  - Blankets and Power Conversion (covered by C. Kessel)
  - Remote Handling
- Potential Next Step Initiatives
- Q&A with audience

Pilot plant means long pulse, compact, high density, DT and blanket operations



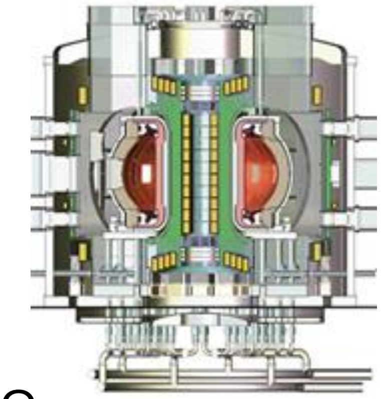
from J. Rapp

The goal of such a device would be to provide fusion-relevant neutron wall loading W_n $1MW/m^2$, neutron uence $6MW$-yr/m^2, component testing area of 5-10m^2, and continuous on-time (i.e. steady-state operation)for durations in the range of 10^6s

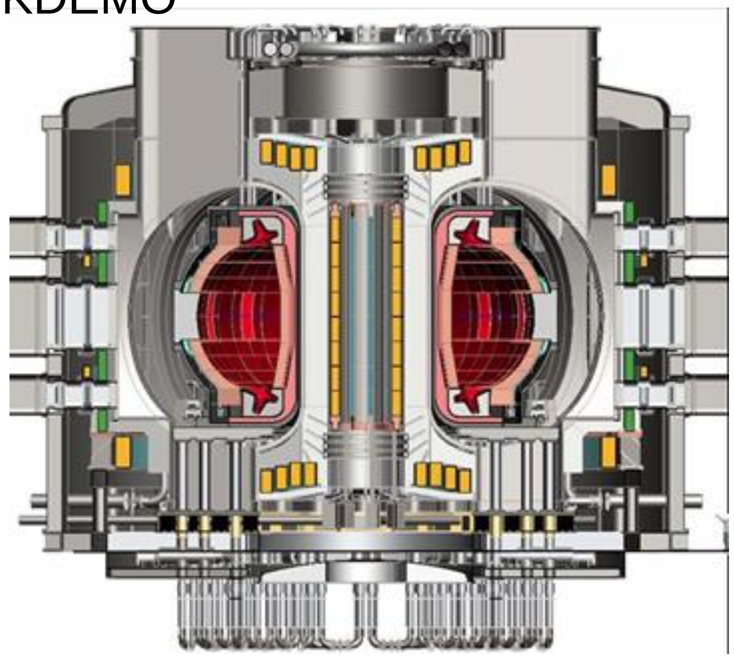
International DEMO Concept Requirements

	EU DEMO	JA DEMO	K-DEMO	CFETR (Phase I)
Mission	Net electricity (Qeng > 1) Tritium self-sufficiency	Net electricity (Qeng > 1) Tritium self-sufficiency	Net electricity (Qeng > 1) Tritium self-sufficiency Materials and component testing in fusion environment	Materials & component testing in fusion environment Full tritium fuel cycle
Pfus	2000 MW	1,500 MW	≥ 300 MW	50–200 MW
TBR	> 1.0	> 1.05	> 1.0	≥ 1.0
Pulse length	2 hr	2 hr to steady state	Steady state	1000 s to steady state
Duty factor	~ 70%			30–50%
Pelec	500 MW	200-300 MW (net)	≥ 150 MW (net)	N/A
Tritium breeding	To be determined – solid and PbLi breeder under consideration	Solid breeder, PWR technology	Solid breeder, PWR technology	Solid breeder, PWR technology, close tritium cycle at ~ 1/10 DEMO scale
Magnetic configuration	Tokamak	Tokamak	Tokamak	Tokamak
Maintenance	Remote handling	Remote handling	Remote handling	Remote handling

PILOT PLANT



KDEMO



Source: Kamendje, Richard et al, International Energy Agency's Fusion Power Coordinating Committee, Paris, France, 2016.

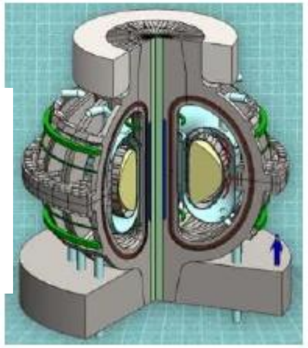
HTS as an enabling technology for high field fusion magnets

Progress has been made in conductor & cable concepts for high field magnets

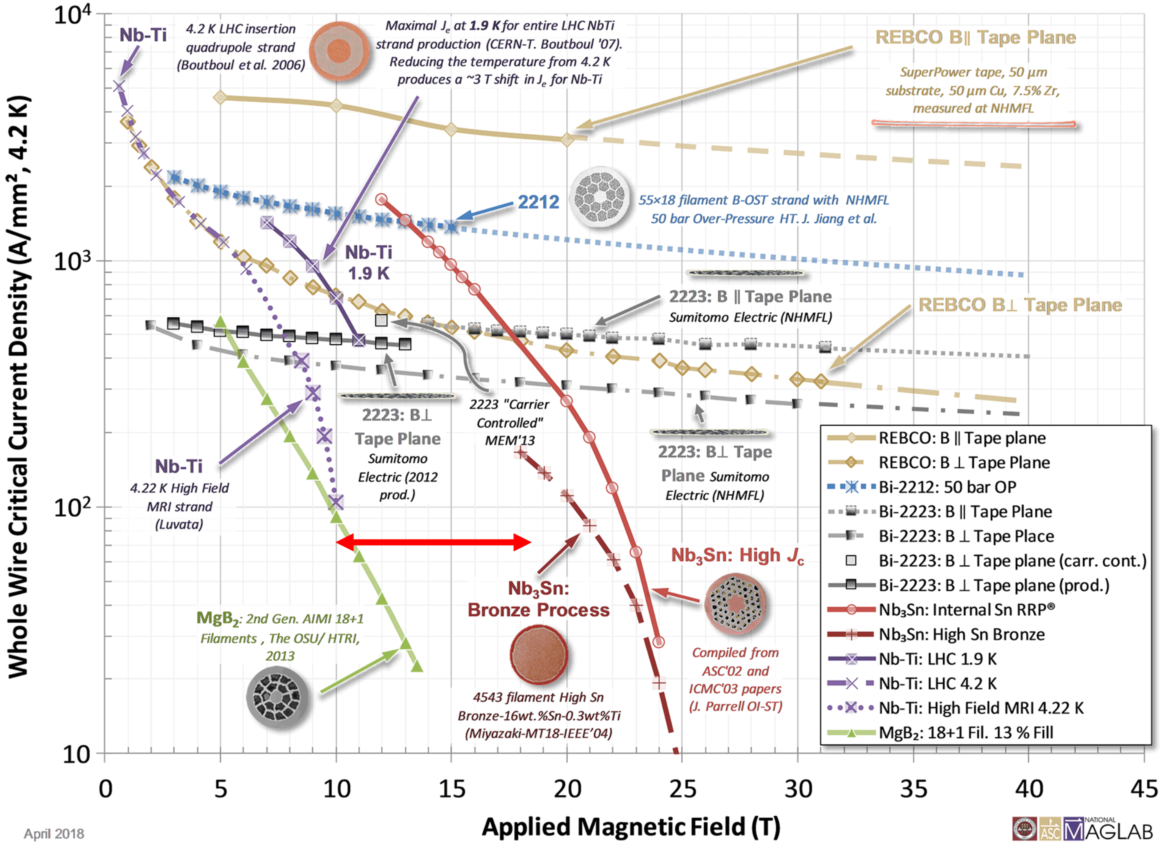
- Driven primarily by high energy physics community in US but significant efforts
- Focus particular in the field range of 10 T – 20 T were REBCO and Bi-2212 are advantageous

Two private venture fusion efforts are pursuing this enabling technology for their concepts

- But many other national and international labs / universities are pursuing HTS for fusion & high field magnets



Mumgaard NAS comments 2018



Peter Lee, ASC/NHMFL

Path to fusion magnets over the next ten years could be interesting

Issues to consider

Conductor supply and cost?

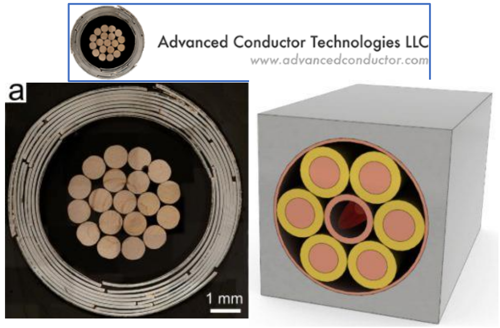
Conductor and cable piece lengths

Cable Stability and Quench Protections

Radiation Degradation

Prototype Large Coils

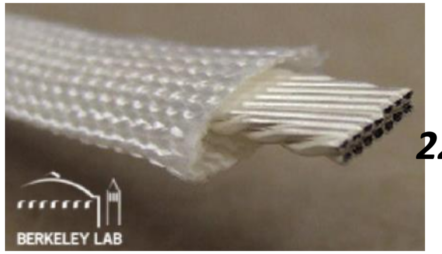
Cryogenic Cooling (SCHe, H_2, LN_2?)



400 A/mm², 4.2 K, 20 T

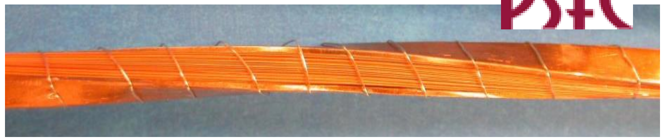
80 kA, 4.2 K, 10.9 T

60 kA, 4.2 K 12 T



BSCCO-2212 Rutherford cable

2212 Strand 1000 A/mm² 4.2 K 27 T



TSTC-Twisted Stacked-Tape Cable

6 kA 17 T 4.2 K

What the appropriate performance metrics?

2000's DOE Superconductivity Program

$25/kA-m @ 77 K

Fusion

Depends on who you ask and the final applications

Current / Current Density (B,T)

50 -100 kA

1000 A/mm² (CS ITER)

4.2 K, 20 K

10 T to 20 T

Strategic investments could enable growth in fusion and other high field areas

Prototype Cable Test Facility

Access to cable testing in general is limited by no. of facilities and time available

SULTAN – split solenoid

11T – 1% over 300 mm, 100 kA

EDIPO – in repair

12 T – 1% over 1 m

NHMFL

14.5 T, 160 mm bore

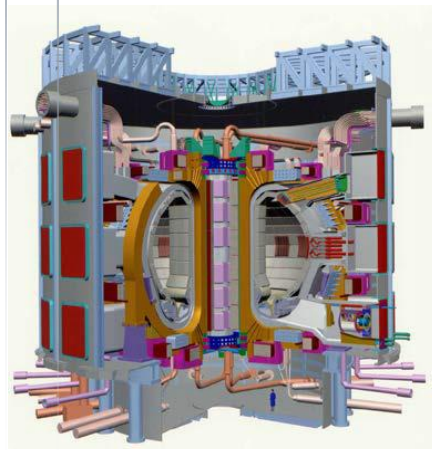
NIFS (Japan)

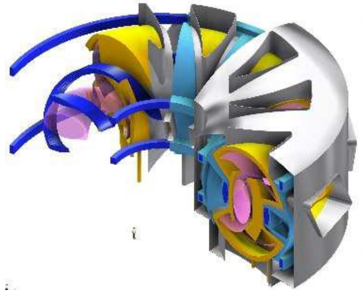
13 T, 700mm bore, 50 kA

Large Coil Demonstrations

Which geometry and when (3-5 years)?

TF PF CS Helical





NIFS-FFHR-d1

Multi-coil demo facility

NAS report suggested that perhaps an updated version of the 80's international Large Coil Test (LCT)

Six Coils, 8 T, 11 kA, NbTi

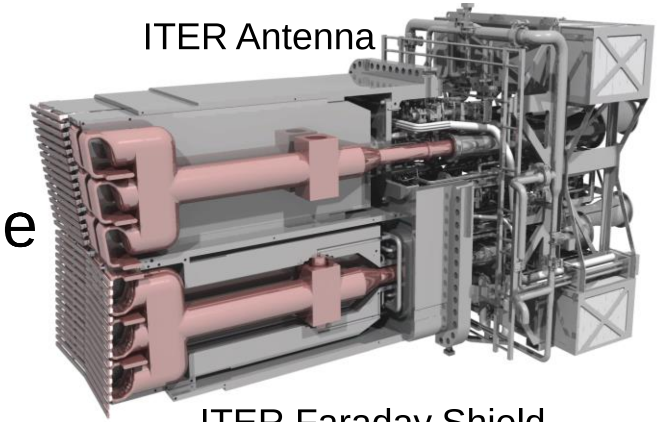
It should be thought about the process (time, funds) it took to get to LTS cables that are currently being used for current fusion magnets.

IEEE NPSS NUCLEAR & PLASMA SCIENCES SOCIETY

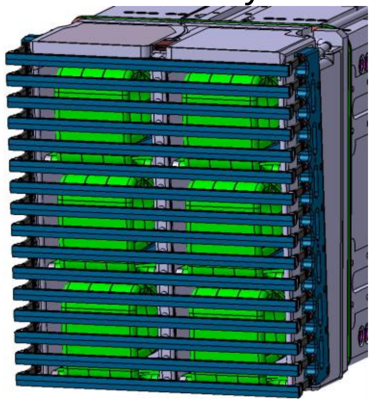
ICRF Issues and Gaps

- Plasma heating and current drive using the Ion Cyclotron Range of Frequencies (ICRF) are important elements for the success of fusion[1,2]
  - Most DEMO concepts identify ICRF as a main heating system
  - Launching structures for ICRH or LHCD must operate in a high radiation, high heat-flux environment
  - The exposed antenna surfaces must be resistive to high heat (1-10 MW/m^2) and neutron fluxes with acceptable levels of impurity production
  - Many reactor concepts will require operating at ~700 °C
- The issues and gaps with creating reliable ICRF operation cut across the disciplines of plasma theory and simulation, RF technology, materials, diagnostics, and reactor engineering (reliability and maintenance)

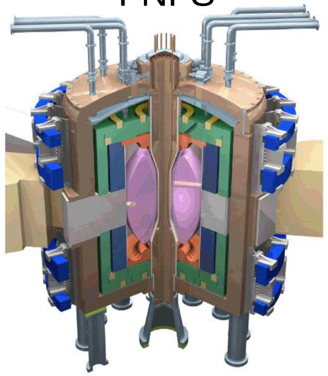
ITER Antenna



ITER Faraday Shield



FNFS

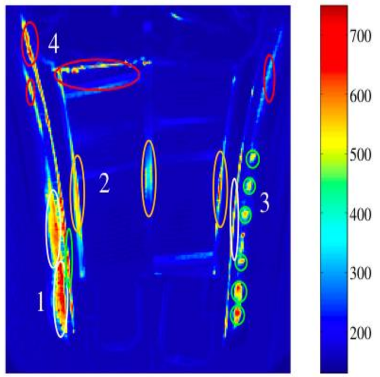


[1]Greenwald Panel FESAC Report (http://science.energy.gov/~/media/fes/fesac/pdf/2007/Fesac_planning_report.pdf)
[2]Research Needs for Magnetic Fusion Energy Sciences Final Report (https://www.burningplasma.org/web/ReNeW/ReNeW.report.press1.pdf)

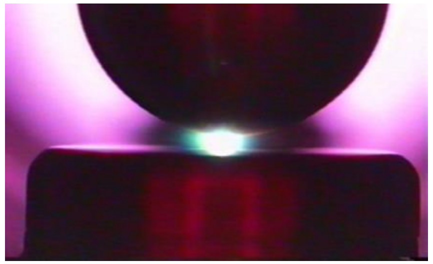
Antennas operate in a harsh environment

- Physics issues: antenna near-field interactions with the plasma in the scrape off layer (SOL) are not well understood:
  - The formation of the RF plasma sheath: enhanced particle and energy fluxes on the antenna and on surfaces intersected by the magnetic field lines connected to/near the antenna
  - The parasitic RF losses in SOL region
  - RF breakdown/arcing, which is one of the main power-limiting issues operating in the plasma environment
- Material issues: antenna-compatible materials operating in a CW high heat/neutron flux environment are not validated:
  - Thermal and neutron-induced stresses at joints/grain boundaries (antenna structural stability)
  - Cracking due to void formation (possible arc initiation)
  - Erosion of coatings and dust production (possible arc initiation)
- Reliability issues: Long pulse operation of the antenna and source
- Solving these problems will likely require an approach that combines modeling/design with validation of the models on dedicated RF Coupling Experiments/Test Stands and Confinement Devices

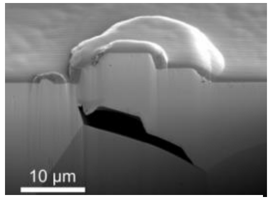
Hot spots on Tore Supra antenna



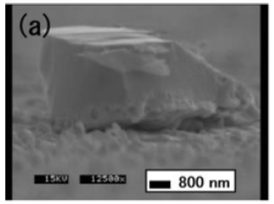
RF breakdown/arcing



Surface changes from PMI



S Lindig et al., T145 (2011) 014039

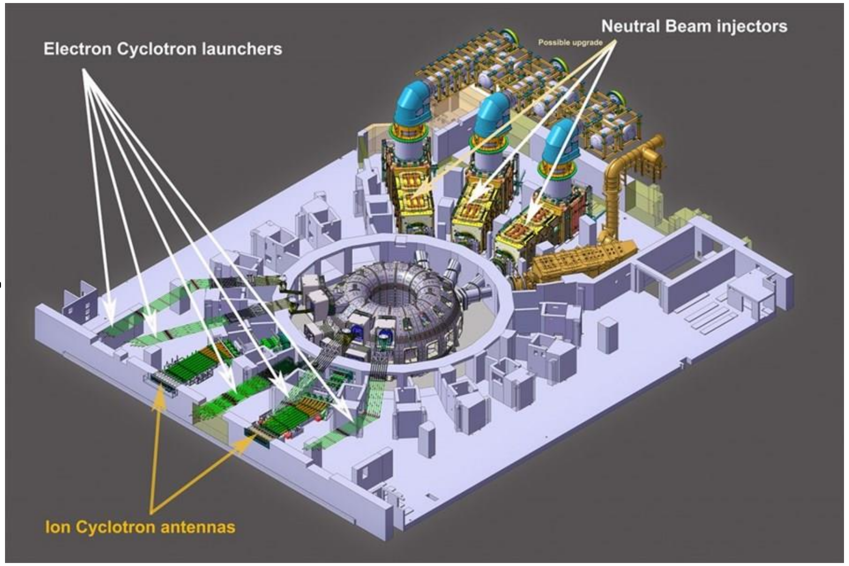


Y Ueda et al., Fus. Sci. Technol. 52 (2007) 513

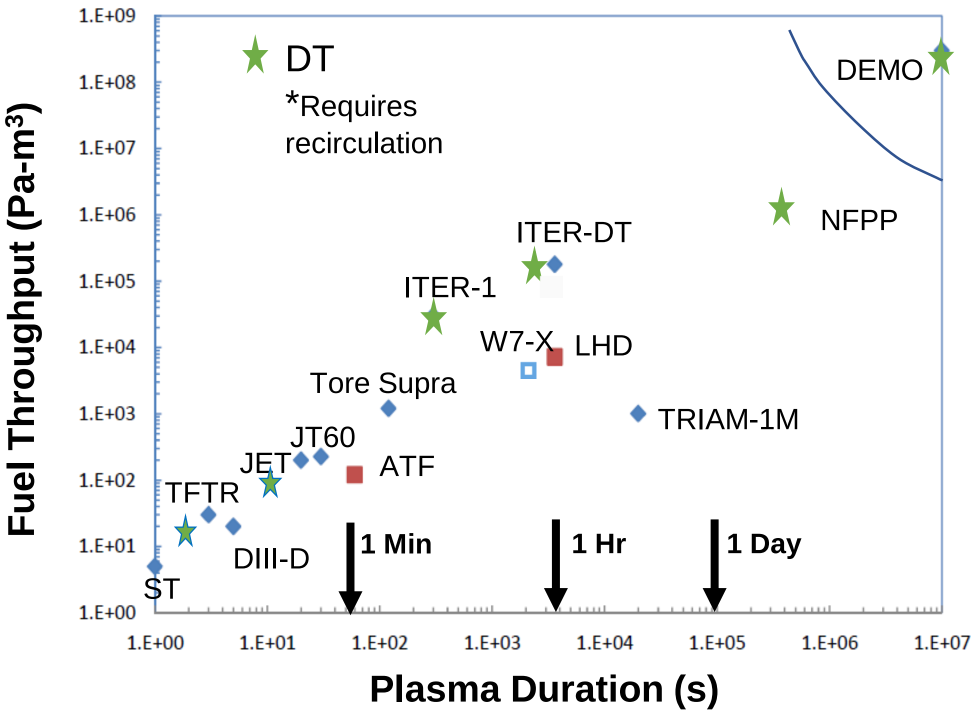
ECH challenges

- Steady state, 1 MW+ gyrotrons, high frequencies and lifetimes
- Cooled, high power miter bends, switches and polarizers
- Window development
- Neutron damage to mirrors
- HFS launch, integration of antennas and WGs into blankets necessary for a nuclear facility.

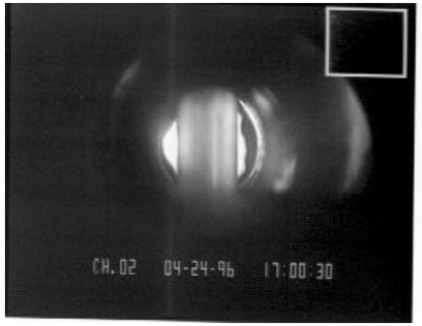
Problem: too many ports!

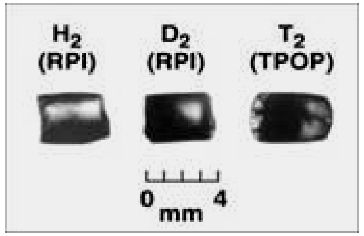


Fuel Throughput in Fusion Plasmas
Needs Dramatic Extension from Previous Experiments



Pure Tritium Extrusion



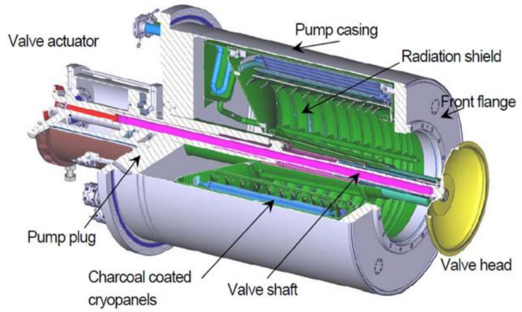


Hydrogen, Deuterium and Tritium Pellets

- DT fuel throughput for ITER and beyond is well beyond what has been achieved in previous devices. Recirculation of DT within the pellet system makes the design much more complicated.

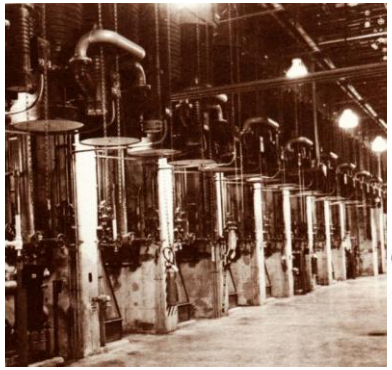
Fusion Exhaust Pumping Schemes

Efficient tritium compatible pumping is needed to remove the exhaust gases from the plasma (transport losses and burn byproducts).



ITER

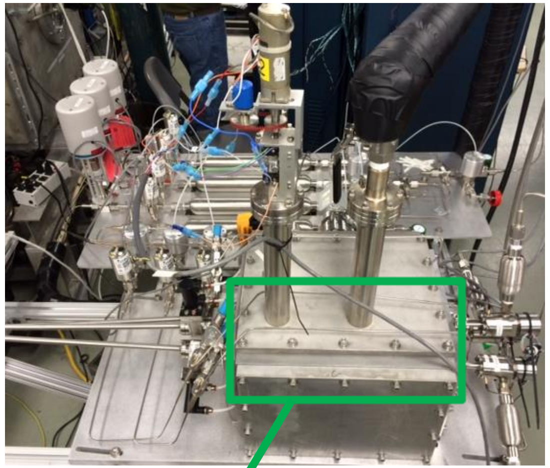
- Batch Cryopumps – **ITER Method** T_2 inventory, Deflagration limit, Thermal cycling, Valve cycling, He pumping
- Continuous Cryopump – Snail pump prototype developed and tested by Foster at ORNL
  - Mechanical scraper
  - Cryo separation
  - Helium compression for conventional pumping
  - Pellet formation from exhaust concept tested
- Liquid Metal Pumps (KIT): – Diffusion pump and liquid metal ring roughing pump
  - Needs separation of impurities and helium to provide direct recirculation to fueling system
  - Super permeable membrane separation?



Transient Mitigation using Pellet Technology

- Disruption Mitigation
  - Shattered pellet injector (SPI) experiments on DIII-D deliver deep penetration and assimilation to maximize dispersal of plasma energy into radiation to spread out the heat over greatest area possible
  - Large High-Z (Ar, Ne) pellets developed for thermal mitigation and runaway electron dissipation
  - SPI experiments on JET and KSTAR are planned in support of ITER DMS
- ELM Pacing
  - Experiments on DIII-D demonstrated peak heat flux deposited in the divertor per ELM decreases with increasing injection frequency

SPI-II with Gas Manifold



Three cryogenically cooled barrels inside the guard vacuum

Plasma Facing Components

New challenges in a nuclear facility:

- Higher q” and temperatures from compact plasmas
- Long pulse or steady state operation
- Active cooling required (high pressure, high temperature, chemistry). Water is <u>not</u> coolant of choice.
- Corrosion, transport and fouling (crud activation)
- Modularity compatible with blanket and divertor concepts – (affects manifolds, RH, shielding, ports, part count, connections, bake-out)
- <u>Integral</u> FW/blanket and advanced divertors
- Manifolding and welding
- Remote handling and repair
- EM loads particularly during disruptions
- Joining and additive mfg.
- Engineering Diagnostics, Performance monitoring & RAMI
- Neutron irradiation -> activation
- Tritium absorption and permeation
- Disruption/ELM melting
- Erosion and dust formation

*A nuclear reactor cannot be a versatile plasma research platform

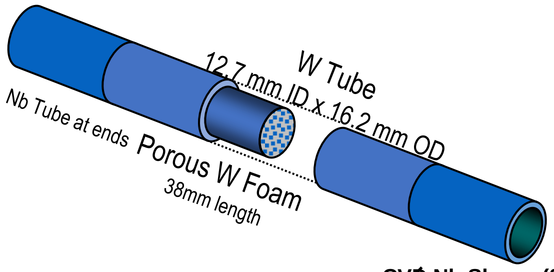
PFC development path from PMI Workshop Report

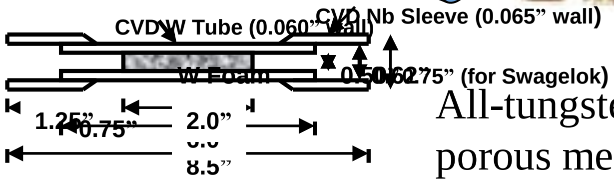
actively cooled

- armor
- heatsink
- coolant

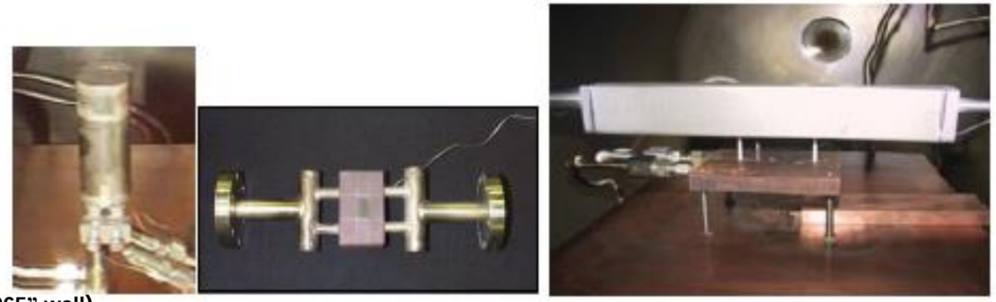
- multi-channel
- manifolding
- mounts
- diagnostics

	component design	material qualification	joining techniques	mockups	neutron irradiation	prototype
divertor	monoblocks flat tiles (macrobrush)	armour: C~~f~~C and W heat sink: DS-Cu CuCrZr	CFC/Cu: laser texturing AMC* e-beam HT-brazing HIPing W/Cu: casting e-beam HT-brazing HIPing	approx. 100 small scale components qualification: ultrasonic thermography HHF-testing: ≥ 20 MWm^{-2}, ≥ 1000 cycles	materials and components T_{irr}: 200 – 700°C fluence: 0.1 – 1 dpa (PIE plus in-pile testing)	medium scale VT full scale VT full scale dome
first wall	flat tiles (shield block design with poloidal coolant channels)	W & RAFM beryllium heat sink: DS-Cu CuCrZr	~~Be~~/DS-Cu: HT-HIPing HT-brazing ~~Be~~/CuCrZr: LT-HIPing fast brazing DS-Cu/SS, CuCrZr/SS: HAT-HIPing	approx. 50 small scale components qualification: ultrasonic HHF-testing: ≥ 2.5 MWm^{-2}, ≥ 30.000 cycles	materials and components T_{irr}: up to 700°C fluence: 0.3 – 1.0 dpa (PIE plus in-pile testing in preparation)	several full scale primary first wall components





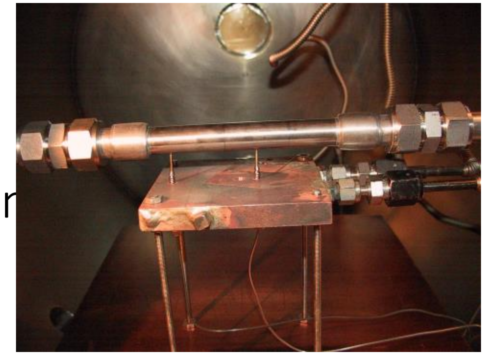
TRL2

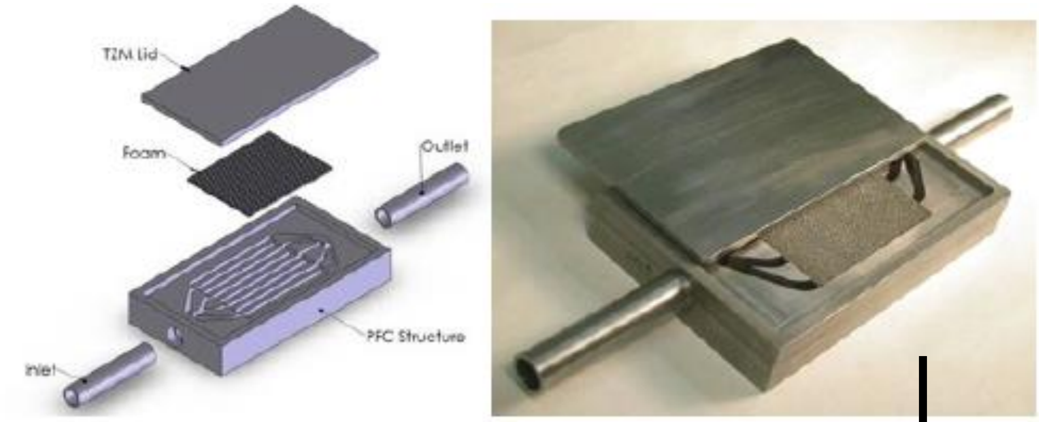


TRL3

All-tungsten porous media heat sink (left), all-copper porous media heat sink (middle), all-moly porous foam tee-tube heat sink (right)

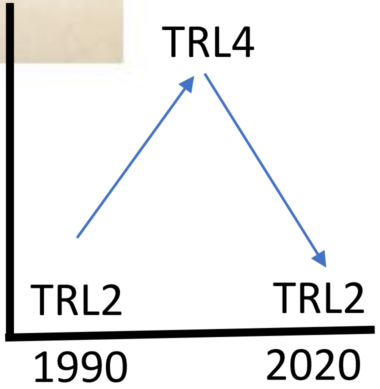
U.S. can r





TRL4

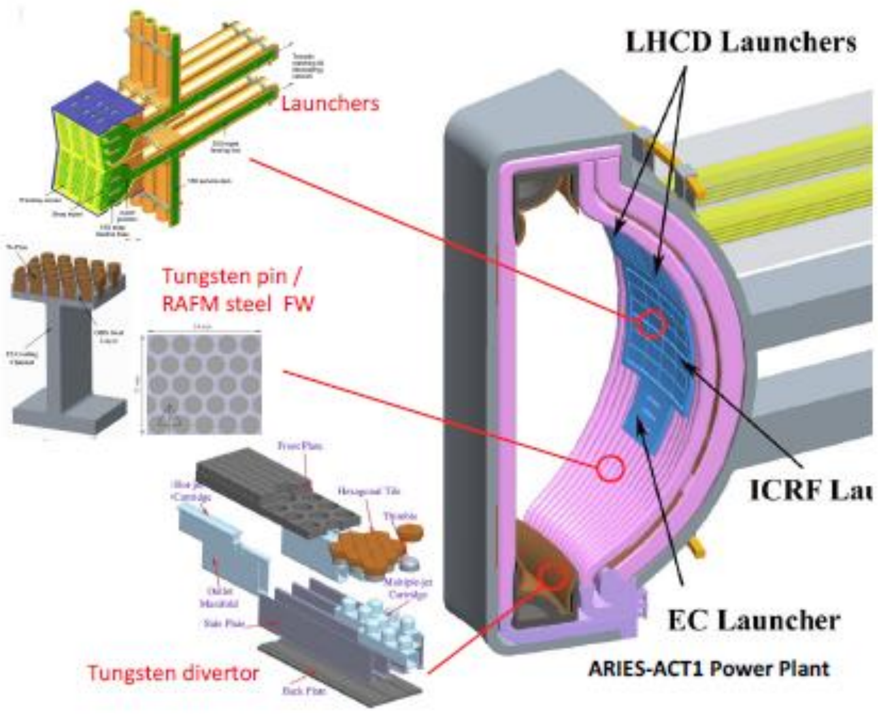
Multi-channel helium-cooled TZM/Moly heat sink with moly foam: 3D CAD (left panel) and fabricated test device (right panel)



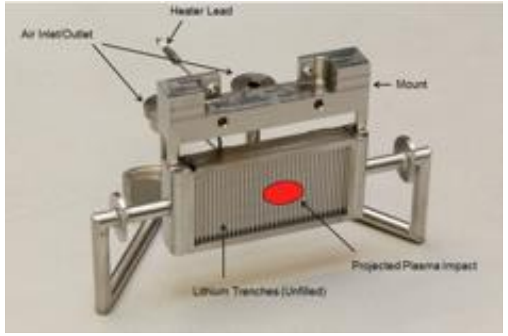
New Initiative in Advanced Helium Cooling

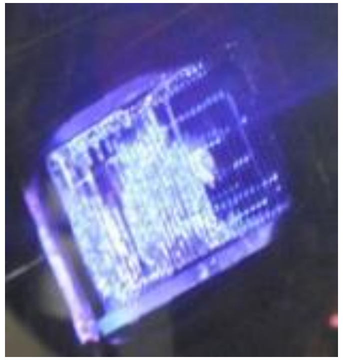
- Helium cooling for FW/Blanket and divertor
  - PFCs and power conversion HXs
- RAFM and W materials – additive manufacturing
- Manifold development
- Closed helium flow loop, 10 MPa, 1 kg/s
- E-beam HHF facility with microwave and induction heating

In-vessel Components



LM PFCs

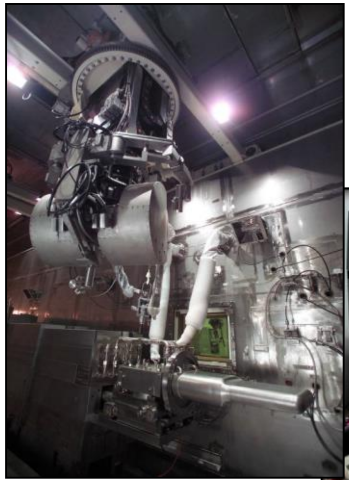




Remote Handling Technology

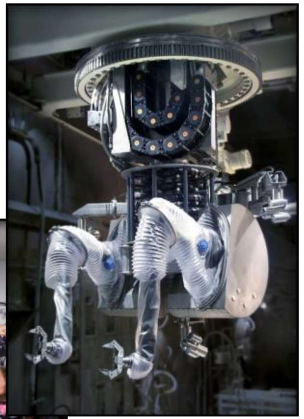
- Reactor systems must incorporate RH designs from the very beginning
- Large Hot Cell repair bays and shielded transport systems are required
- Large component assembly/disassembly with precision
- Sealing of large faces to maintain vacuum – how many making and breaking can a surface take? Are there better methods for sealing components to ensure vacuum?
- For large component replacement with very high radiation (Tritium and other airborne contamination), how to design an effective hot cell? Is an overhead bridge crane system still the best option?
- What is the best design for an airlock that enables robotic transfers?

Advanced Human–Machine Interfaces



Target

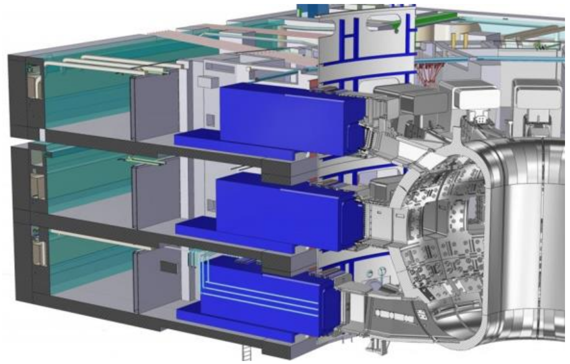
Remote Controlled Servomanipulator



Remote Handling Control Room

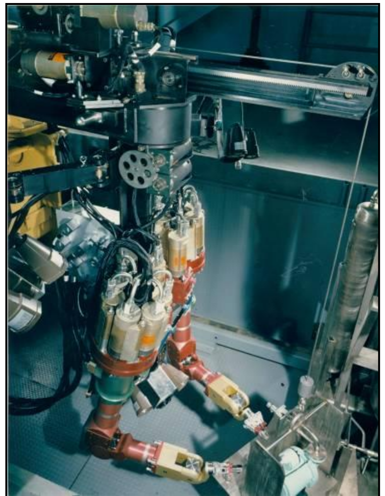
Remote Handling Sensor/Actuators

- How to disconnect and reconnect myriads of fluid and vacuum lines? Are there better ways than cutting and welding?
- Develop radiation tolerant cameras that can withstand radiation levels of $>10^7$ Gy. Vacuum tube (Vidicon & Chalnicon) cameras can withstand 10^6 Gy, but have poor resolution. Rad resistant fiber optics.
- Do LiDAR and ultrasonic offer possibilities for some areas of diagnostics? Need improved synthetic vision and VR simulation.
- Do electronics need to go to vacuum tubes or can CMOS with shielding still be a viable option? What about GaAs rad hard chips?
- Large component placement – hydraulic, air, or electric actuation. Non organic based hydraulic system?



ITER casks

Cassette manipulators



Some New Initiatives:

- Advanced helium cooling for PFCs & HHF test facility
  - could be part of a larger blanket test facility
- RH as part of FESS system studies
- HTSC joint development – SC magnet test stand
- HFS launch RF heating initiative
- Steady-state pellet fueling

Q&A