The U.S. approach to address plasma-material interactions and fusion nuclear science with linear plasma devices

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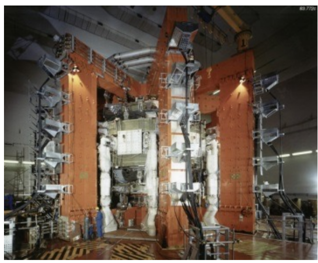
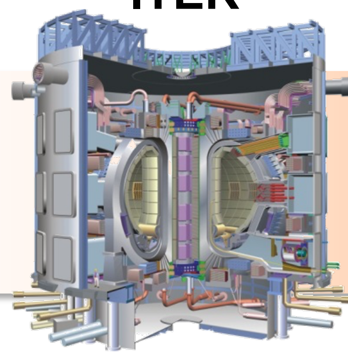
Challenges for divertor: fluxes, fluence and temperatures

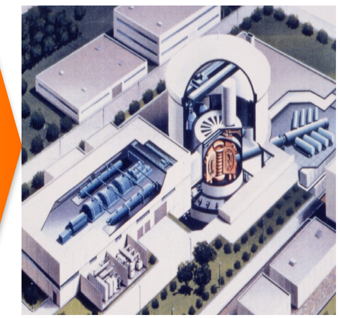
JET



ITER



Fusion Reactor



50 x divertor ion fluxes

5000 x divertor ion fluence

10^6 x neutron fluence (1dpa)

up to 5 x ion fluence

up to 100 x neutron fluence (150dpa)

Materials need to be developed and tested under fusion prototypic conditions:
High fluxes, high ion fluence, high neutron fluence

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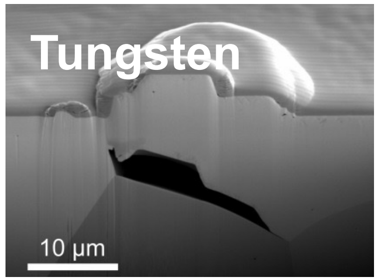
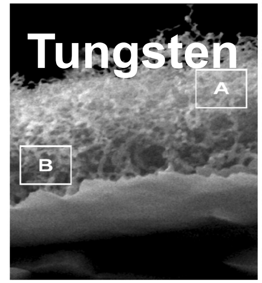
Fusion reactor like plasmas will change material erosion processes

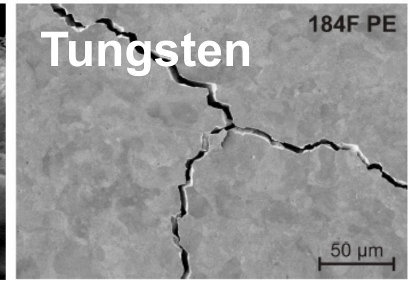
T Loewenhoff et al., Nucl. Fusion 55 (2015) 123004



S Lindig et al., Phys. Scr. T145 (2011) 014039



MJ Baldwin et al., Nucl. Fusion 48 (2008) 035001



M Wirtz et al., J. Nucl. Mater. 420 (2012) 218

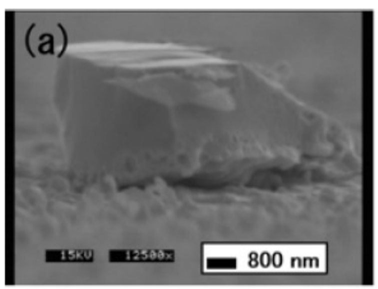
High energy density plasma changes:

Surface area; Surface roughness

Surface potential (unipolar arcing may occur)

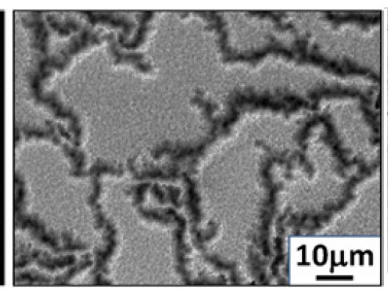
Surface temperature (loosely bound layers, He bubbles)

Surface chemical activity



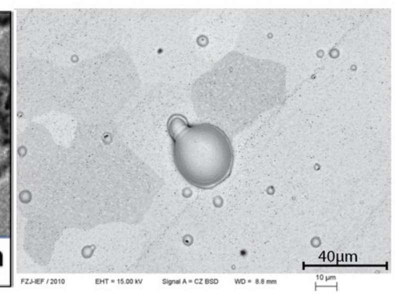
Y Ueda et al., Fus. Sci. Technol. 52 (2007) 513

Whole grain ejection can cause macroscopic erosion



M Tokitani et al., Nucl. Fusion 51 (2011) 102001

Unipolar arcing, can possibly create W dust of nm size



J Coenen et al., Nucl. Fusion 51 (2011) 083008

Meltlayer splashing creates W dust of µm size

Consequences:

Chemical and physical erosion yield

Relation between gross erosion and net erosion

Dust production might occur due to macroscopic erosion of surface structure and meltlayer splashing

Neutron irradiation will likely enhance macroscopic erosion

Neutron – PMI interplay dictates key PFM phenomena

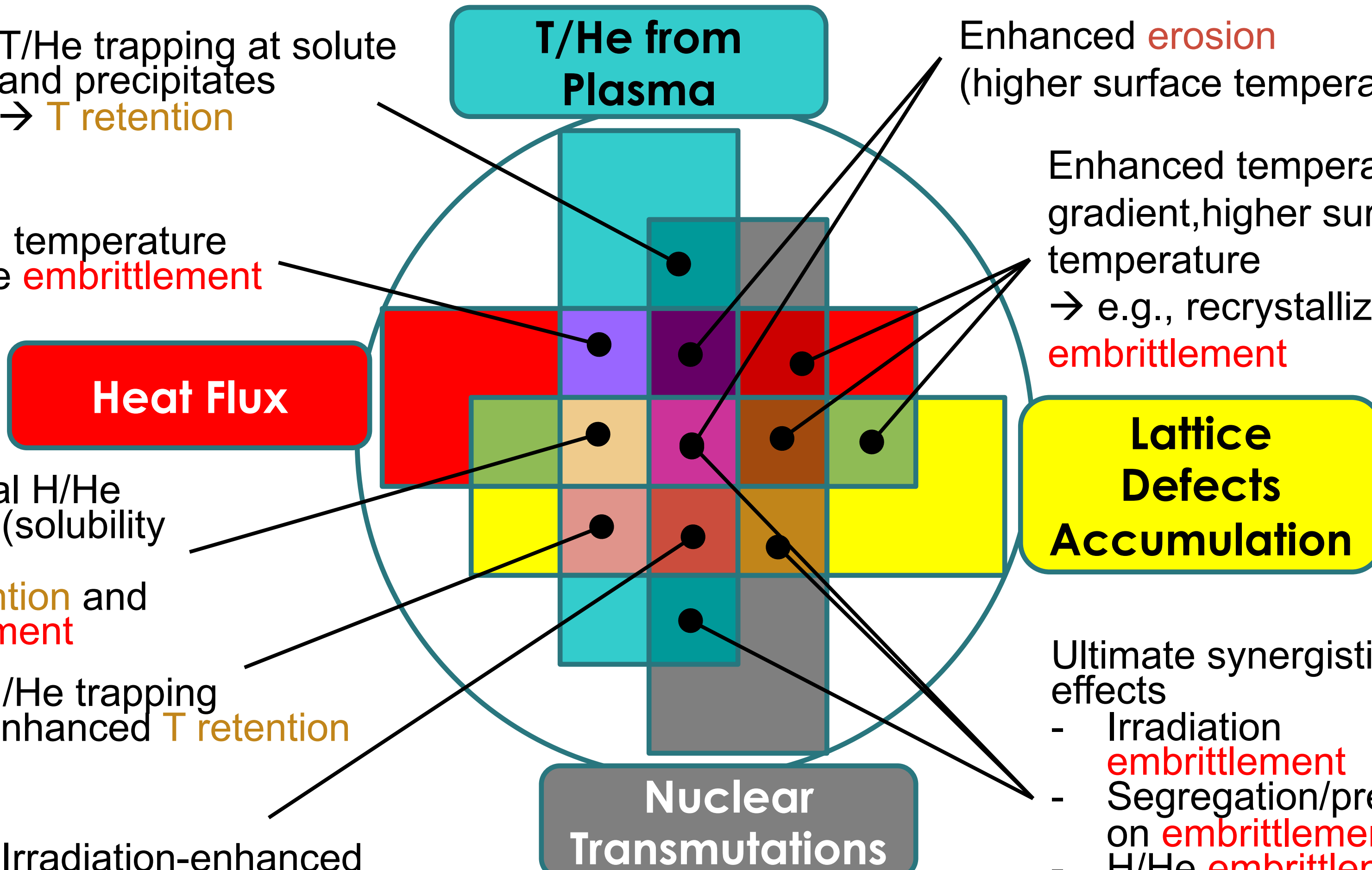
T/He trapping at solute and precipitates
→ T retention

High temperature
H/He embrittlement

Directional H/He transport (solubility gradient)
→ T retention and embrittlement

H/He trapping
Enhanced T retention

Irradiation-enhanced segregation & precipitation
→ enhanced embrittlement



Enhanced erosion
(higher surface temperature)

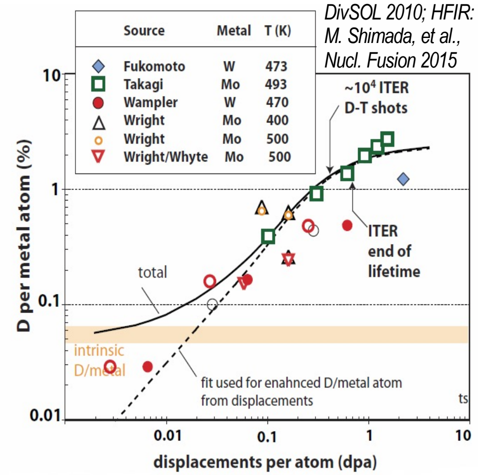
Enhanced temperature gradient,higher surface temperature
→ e.g., recrystallization embrittlement

Ultimate synergistic effects
- Irradiation embrittlement
- Segregation/precipitation embrittlement
- H/He embrittlement
- Enhanced T retention and transport

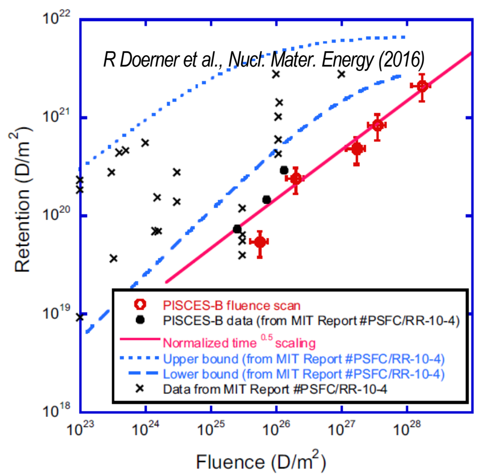
D-retention in tungsten and impact of irradiation

Retention vs dpa (ion irrad.)

Lipschultz, ITPA DivSOL 2010; HFIR: M. Shimada, et al., Nucl. Fusion 2015

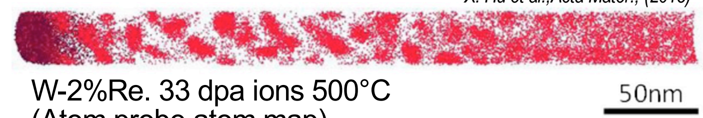


Retention vs fluence (ion irrad.)



Effect of neutron irradiation on transmutation

X. Hu et al.,Acta Mater., (2015)



W-2%Re. 33 dpa ions 500°C
(Atom probe atom map)

P. Edmondson, Nucl. Fusion 60 (2020) 126013

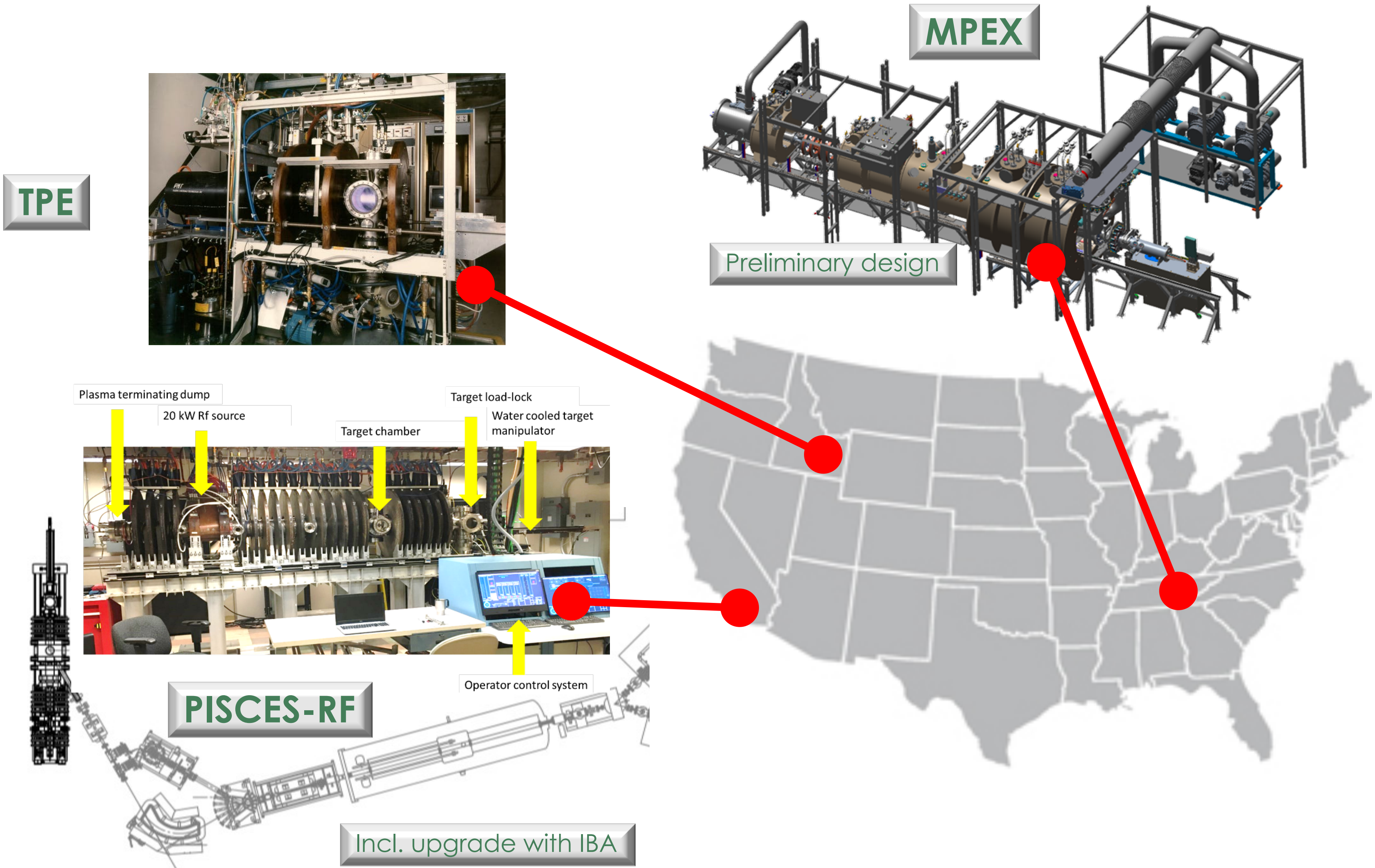
Pure W (99.9+%), 2.2 dpa HFIR 750°C
Now 5%Re-7%Os bulk, intermetallic interconnected ribbons (Atom probe isodensity surface)

How will tritium, helium, heat, etc., permeate this structure?

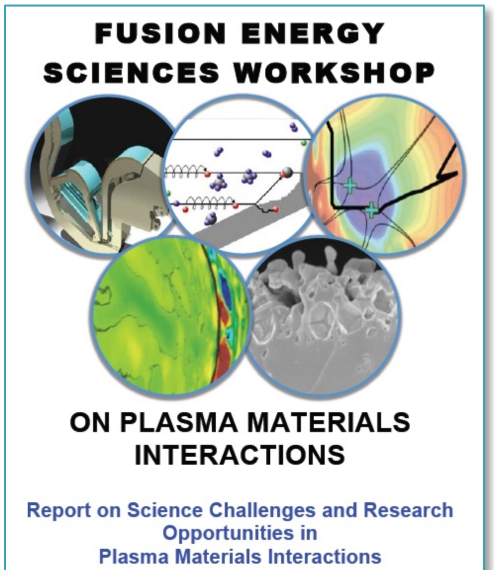
Gaps in data:

- Synergistic effects of simultaneous irradiation and plasma exposure
- Data at higher plasma fluxes and fluence (10^{31} m^{-2})
- Data of neutron irradiated materials at higher dpa with relevant He/dpa ratio
- Effect of impurities from plasma and from transmutation

U.S. linear plasma devices



Increased capabilities of U.S. linear plasma devices in response to U.S. community needs



- PISCES-RF upgrade to higher fluxes, added in-operando high energy ion irradiation capability and in-situ PMI diagnostics
- TPE upgrade to higher fluxes
- New build of MPEX to expose neutron irradiated materials to fusion reactor relevant plasmas

Can plasma inhibit vacancy-interstitial recombination?

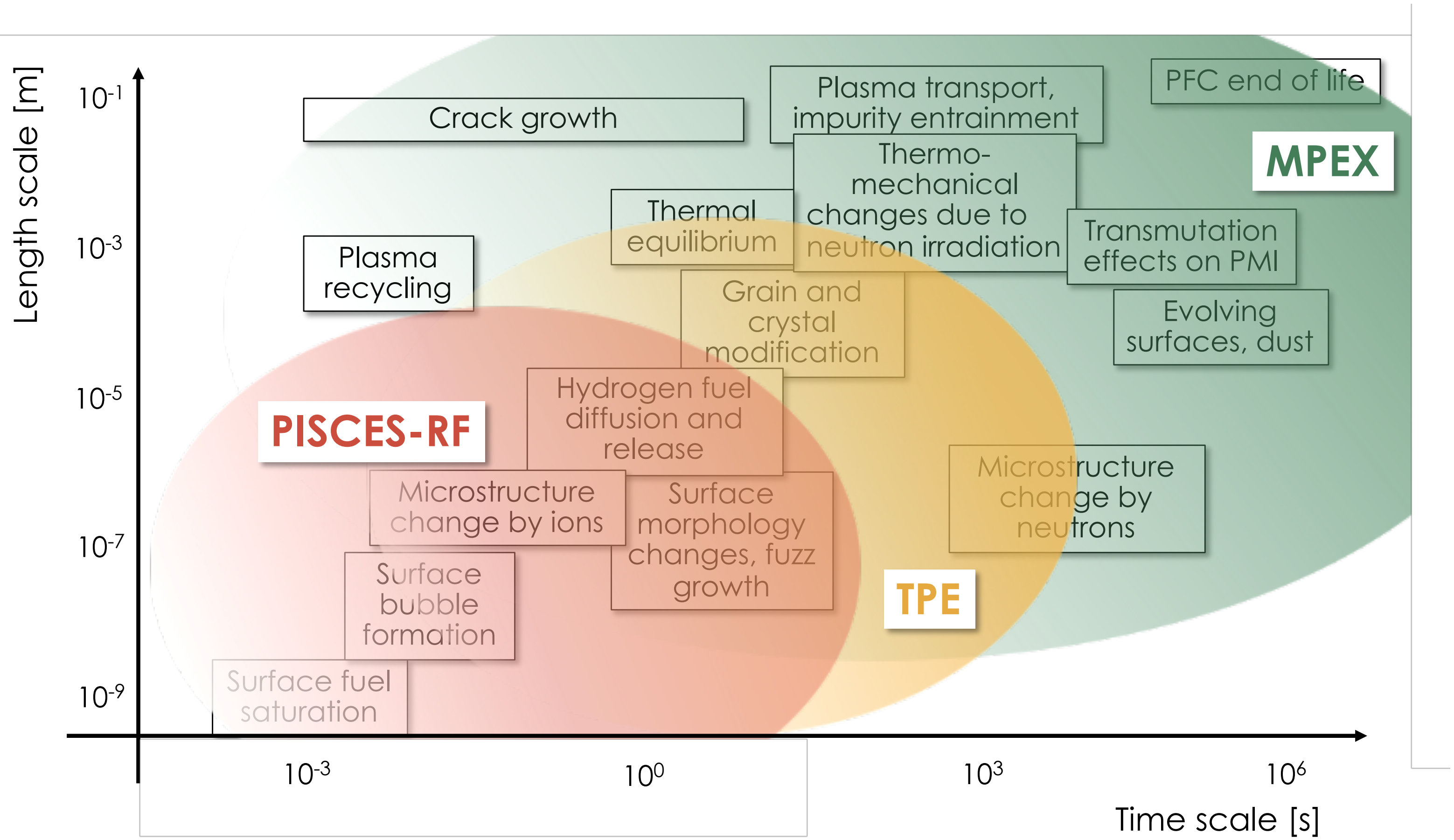
What is the long-term and long-range T-permeation through PFMs and PFCs?

What determines the physics of strongly evolving surfaces and the end-of-life of PFMs and PFCs?

US linear devices

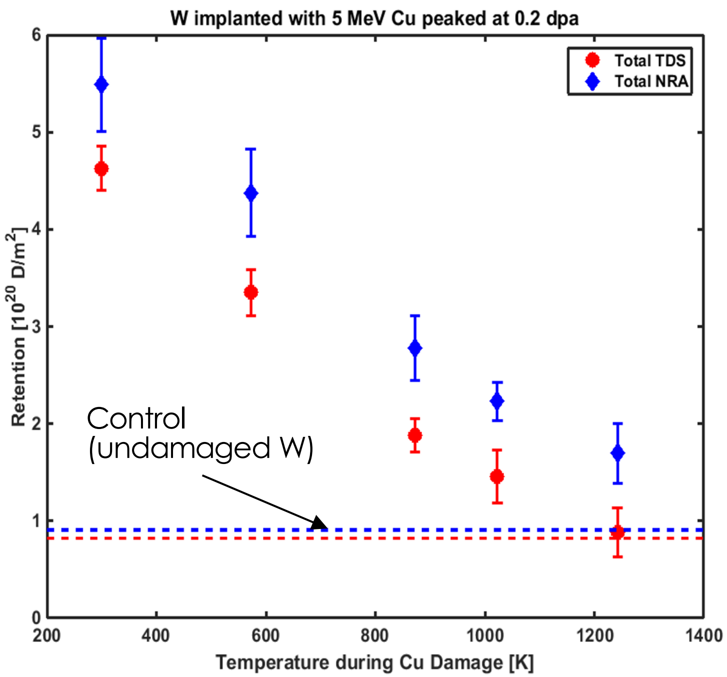
Parameter	TPE	PISCES RF	MPEX
n_e target	0.5 $\times 10^{19}$ m^{-3}	2×10^{19} m^{-3}	10^{21} m^{-3}
T_e target	5-10 eV	5-6 eV	15 eV
T_i target	<1 eV	1 eV	20 eV
B target	0.1 T	0.1 T	1 T
Plasma diameter	5 cm	5 cm	3 to 10 cm
Γ_I target	5 x 10^{22} $m^{-2}s^{-1}$	2 x 10^{23} $m^{-2}s^{-1}$	> 10^{24} $m^{-2}s^{-1}$
Min angle of B to target	normal	normal	5 degrees
P target, parallel	1 MW/m^2	1.5 MW/m^2	40 MW/m^2
P target, perpendicular	1 MW/m^2	1.5 MW/m^2	10 MW/m^2
Total ion fluence / plasma duration	10^{27} m^{-2}	>10^{28} m^{-2}	10^{31} m^{-2}
Irradiation tests	Pre-exposed neutrons	Ions/in-operando	Pre-exposed neutrons
Surface diagnostics	In vacuo TDS	In-situ LIBS, LIDS, OES, TGS Ex-situ FIB/TEM, SEM/EDX, SIMS, AES	In situ LIBS In-vacuo FIB/SEM/EDX

PMI challenges and how US facilities address these

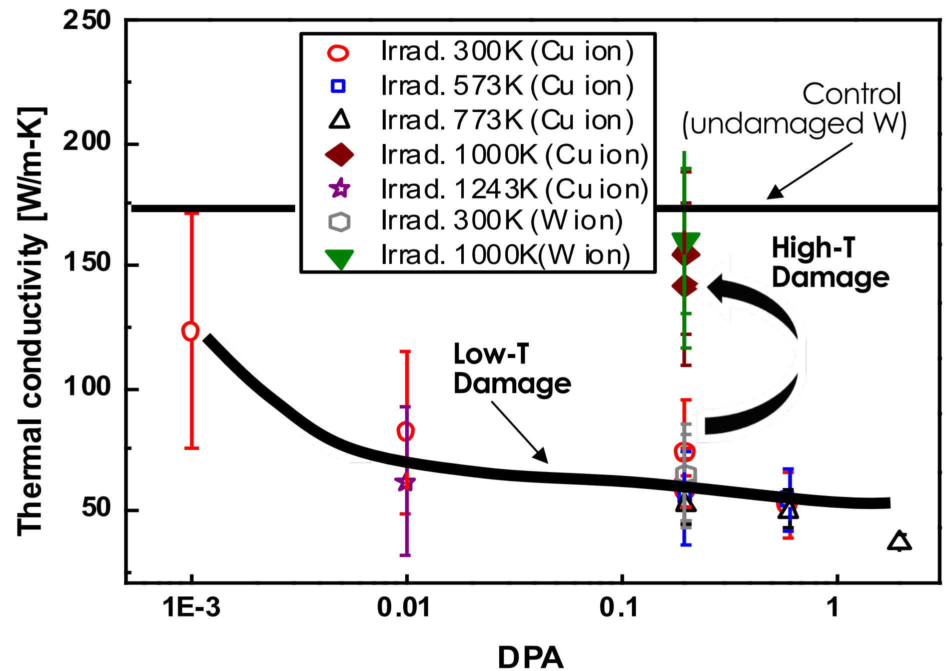


PISCES results

Annealing of D retention when Rad-damaged at high temperature



Rad-damaged thermal conductivity degradation anneals when operating at high temperature



Q: Will annealing survive in simultaneous plasma + damage exposures?

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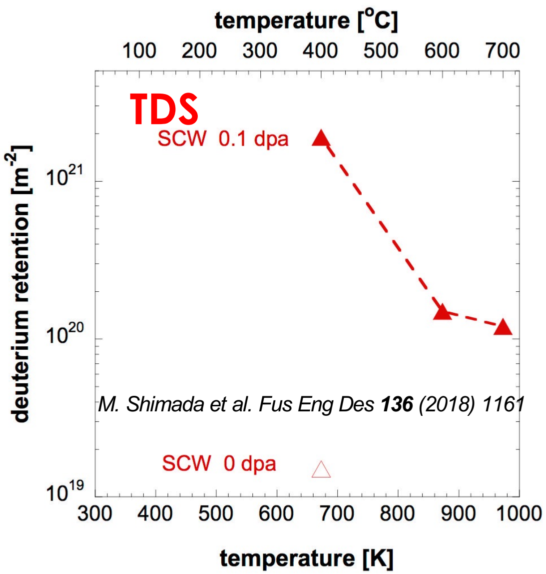
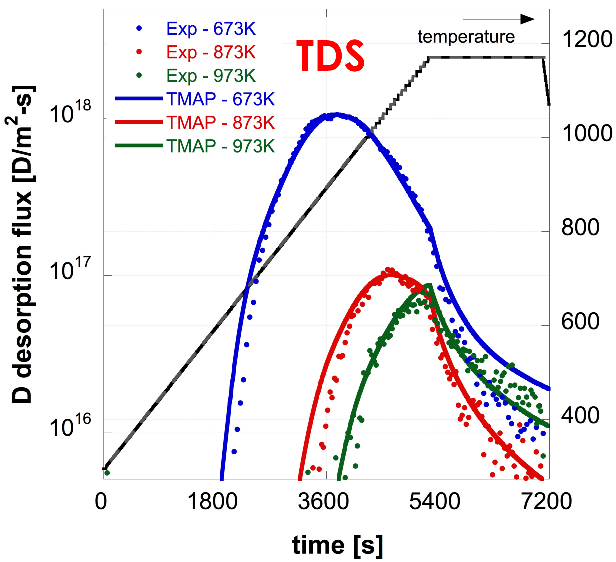
TPE results

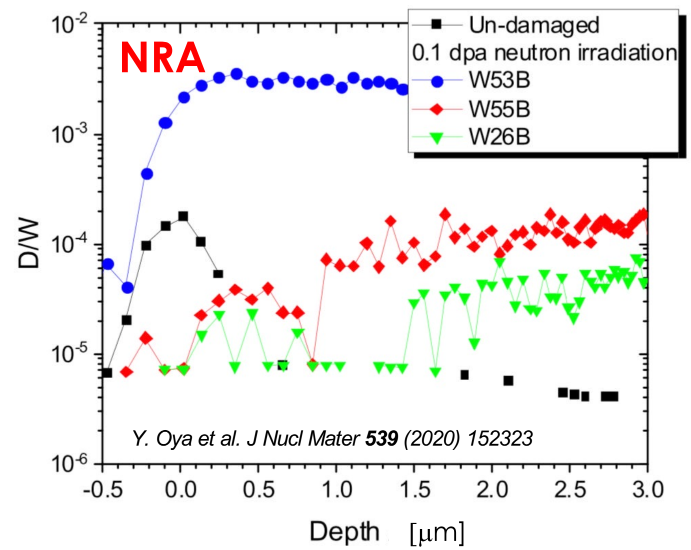
D retention from 0.1 dpa SCW was x100 higher than 0 dpa SCW

A broad D desorption indicated deep migration/trapping of D

Deep migration/trapping of D in 0.1 dpa neutron-irradiated SCW





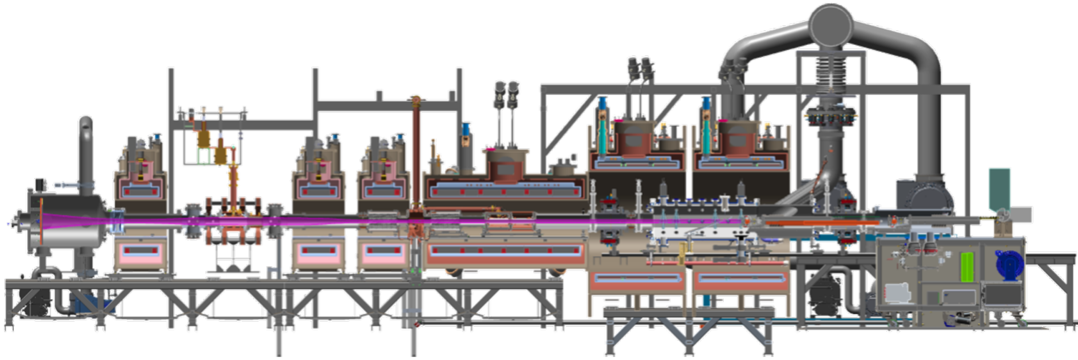


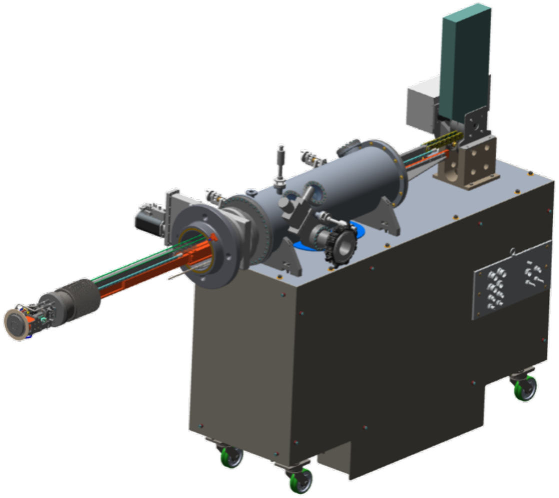
Q: Can D still be trapped in radiation damages created at elevated temperature?

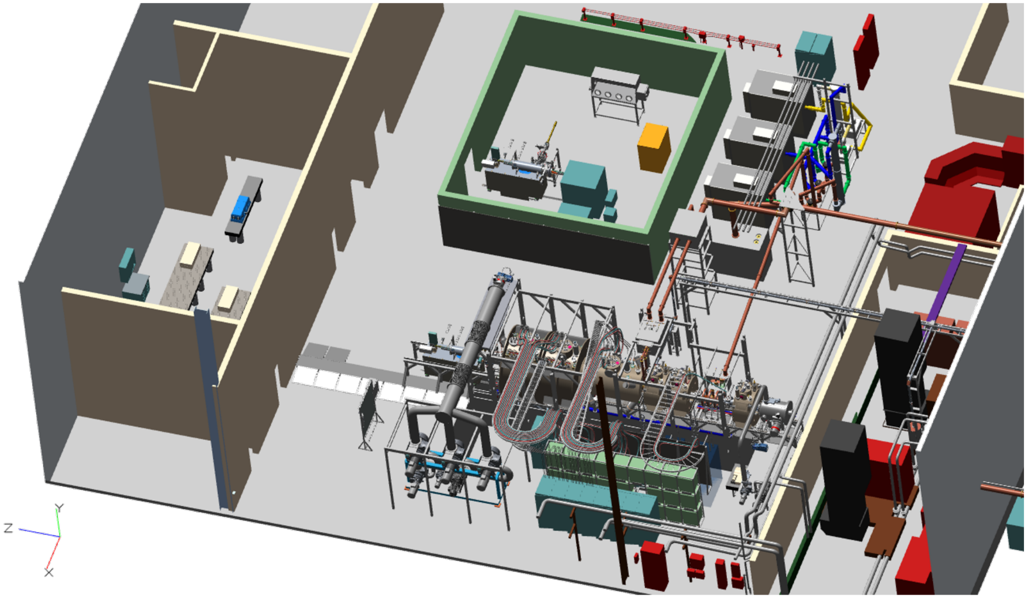
A: Although the near-surface D concentrations decreased at elevated temperatures, the deep migration and trapping of D resulted in non-negligible D retention in 0.1 dpa neutron-irradiated W due to D trapping in vacancy clusters and voids (trap energies 1.8 – 2.6 eV)

MPEX project status

New plasma source concept (Helicon, ECH, ICH) for independent control of T_e and T_i for entire divertor plasma parameter range.







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MPEX functional requirements

- Steady-state magnetic fields up to **2.5 T** (-> superconducting coils NbTi technology)
- Steady-state operation of up to **10^6 sec**
- Ability to expose radioactive and hazardous materials such as a-priori **neutron irradiated materials** (irradiated up to 50 dpa) and **liquid metals**
- Ability to expose large plasma facing components **(~60 x 600 mm)**
- Ability to expose targets at an angle as low as **5 degrees**
- Ability to monitor evolution of surface during high fluence exposures with variety of surface diagnostics including electron microscopy (in-situ or in-vacuo)
- Ability to actively control material temperature to some degree independent of incident heat flux and ability to reach reactor relevant temperature ranges (greater than **600° C**)
- Ability to study PMI at reactor relevant divertor plasma conditions and target inclination **without target biasing**
- Ability to control T_e and T_i independently

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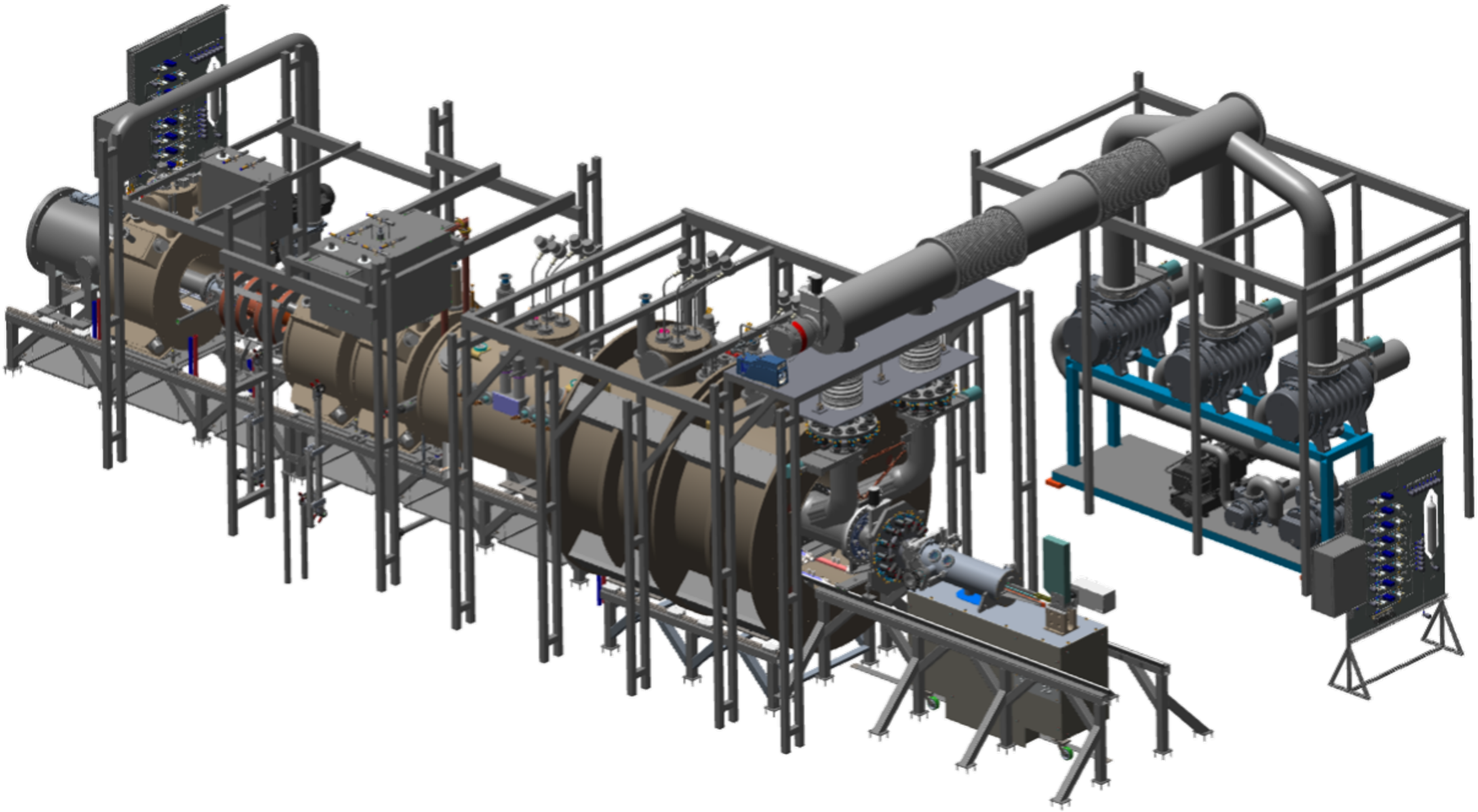
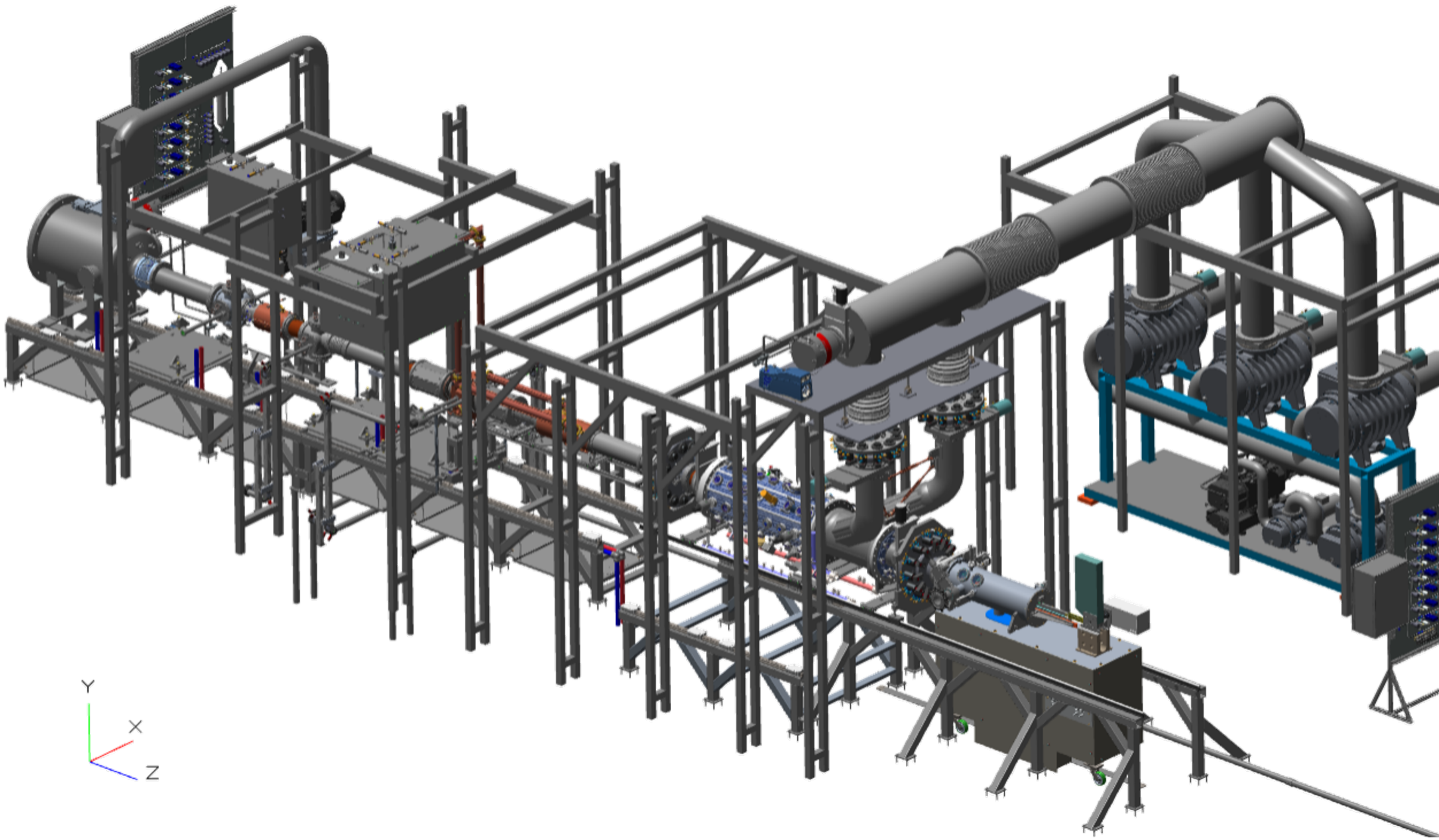
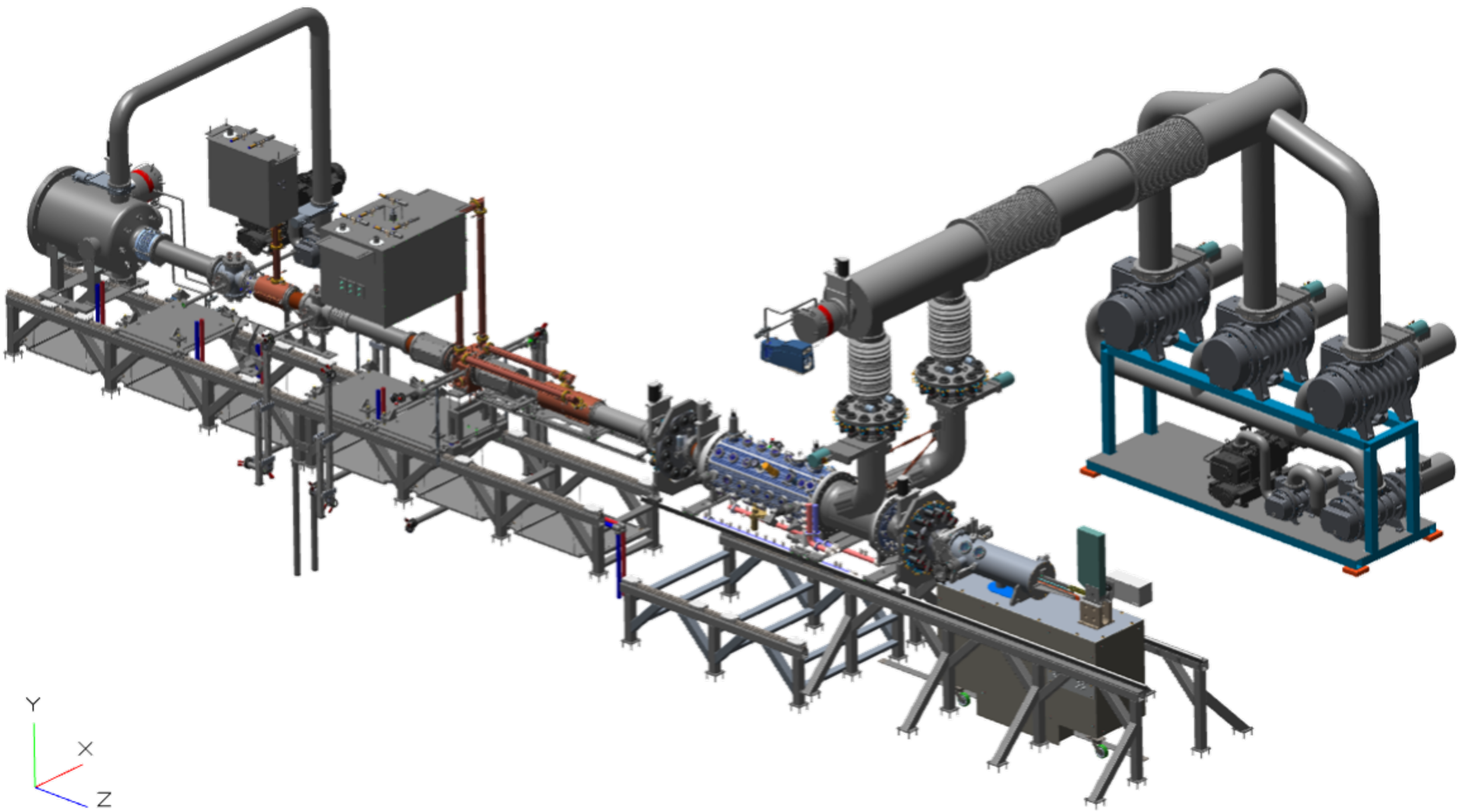
MPEX preliminary design




Y
X
Z



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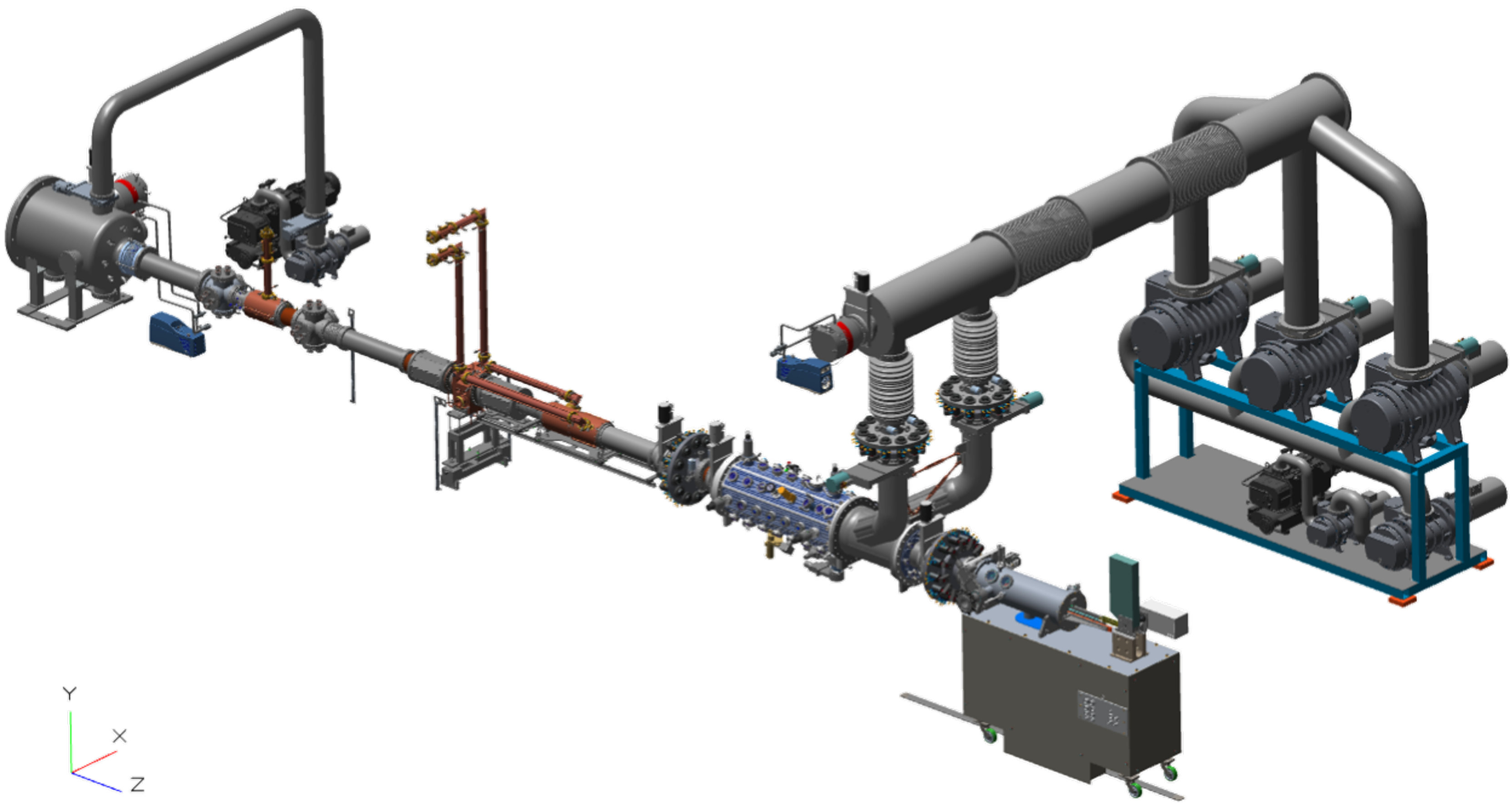
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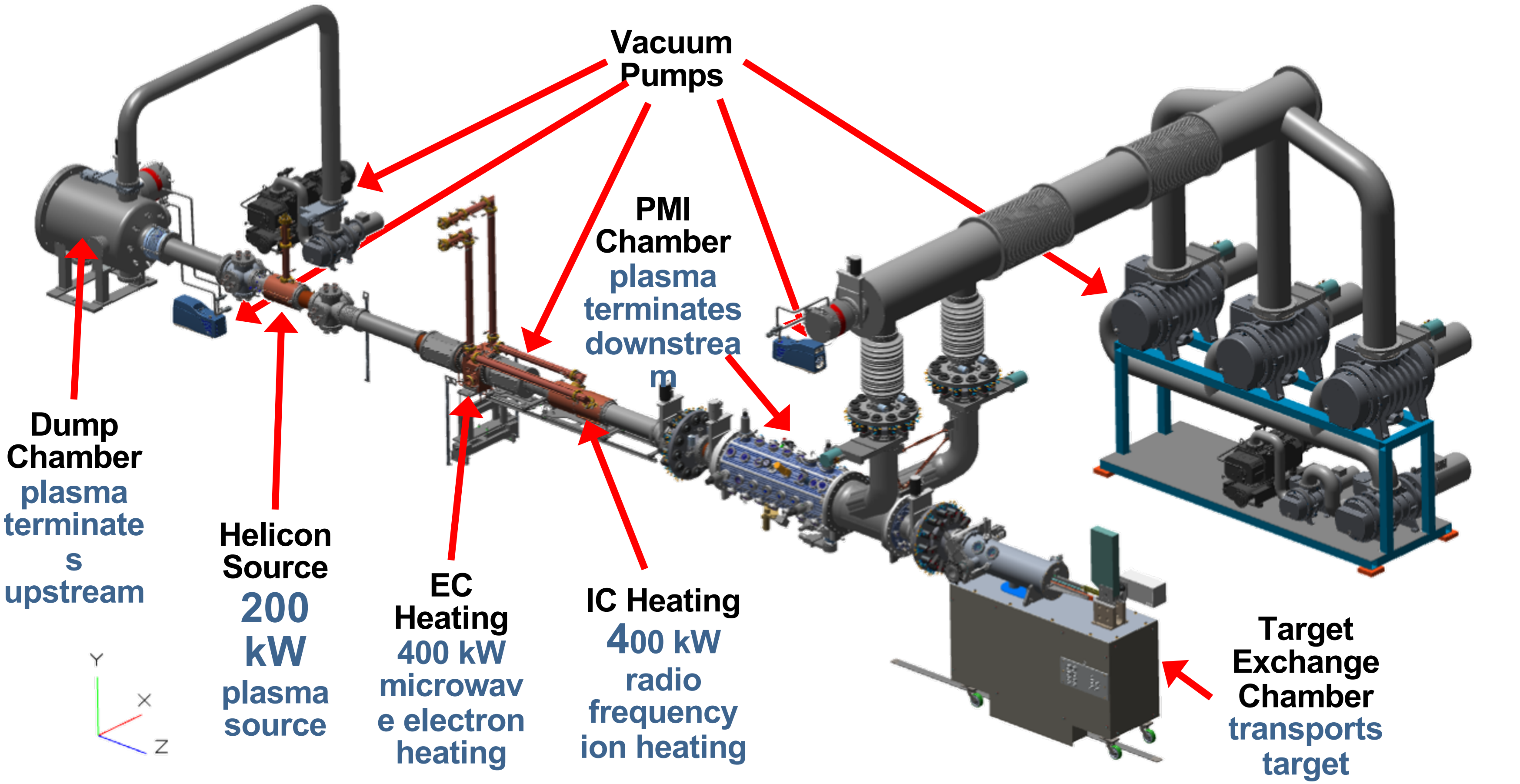

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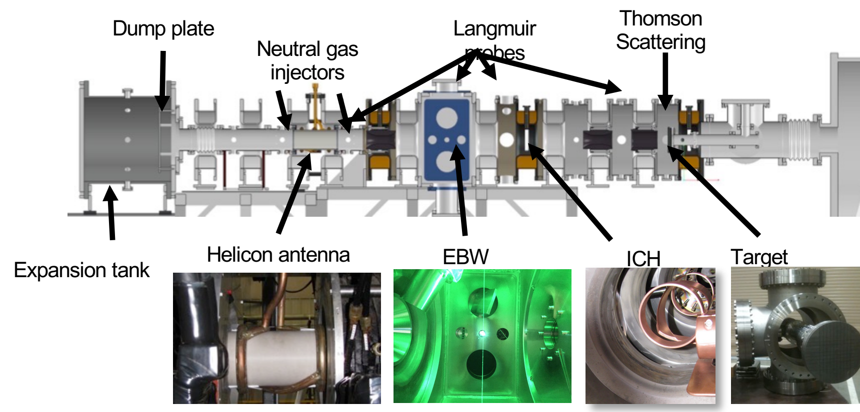
Proto-MPEX demonstrated almost all MPEX parameters within a factor 2



Parameter	MPEX Goal	Achieved in Proto-MPEX	Comments
n_e source	4 - 6 x 10^{19} m^{-3}	1.1 x 10^{20} m^{-3}	
n_e target	up to 10^{21} m^{-3}	1.8 x 10^{20} m^{-3}	2 cm in front of target
T_e source	up to 25 eV	21 eV	In overdense plasmas
T_e target	up to 15 eV	12 eV	In overdense plasmas
T_i source	up to 25 eV	16 eV	Measured on Ar-II
T_i target	up to 20 eV	11 eV	Measured on Ar-II
B target	1 T	1 T	
Plasma diameter	4 to 10 cm	4.5 cm / 8 cm	For B target: 1.0 T / 0.3 T
Γ_I target	> 10^{24} $m^{-2}s^{-1}$	~ 10^{24} m^{-2} s^{-1}	
Min angle of B to target	5 degrees	90 degrees	
P target, parallel	up to 40 MW/m^2	20 MW/m^2	at high n_e
P target, perpendicular	10 MW/m^2	20 MW/m^2	at high n_e

Summary and conclusions

- Upgraded and new linear plasma devices in the U.S. will address outstanding gaps in PMI for fusion reactors, in particular the fusion nuclear science.
- All three linear devices are complimentary to each other with unique capabilities.
- Capabilities will enable research to elucidate the vast length – and time scales of the PMI processes from fast synergistic effects of irradiation damage and plasma exposure close to the surface to bulk property changes and strongly evolving surfaces over lifetime of a PFC.
- Each device will have diagnostic suites to measure the PMI processes in-operando, in-situ and in-vacuo for first-of-a-kind measurements.
- All three devices will be (are) embedded in international collaborative networks to maximize their impact and productivity.