Introduction to MPEX

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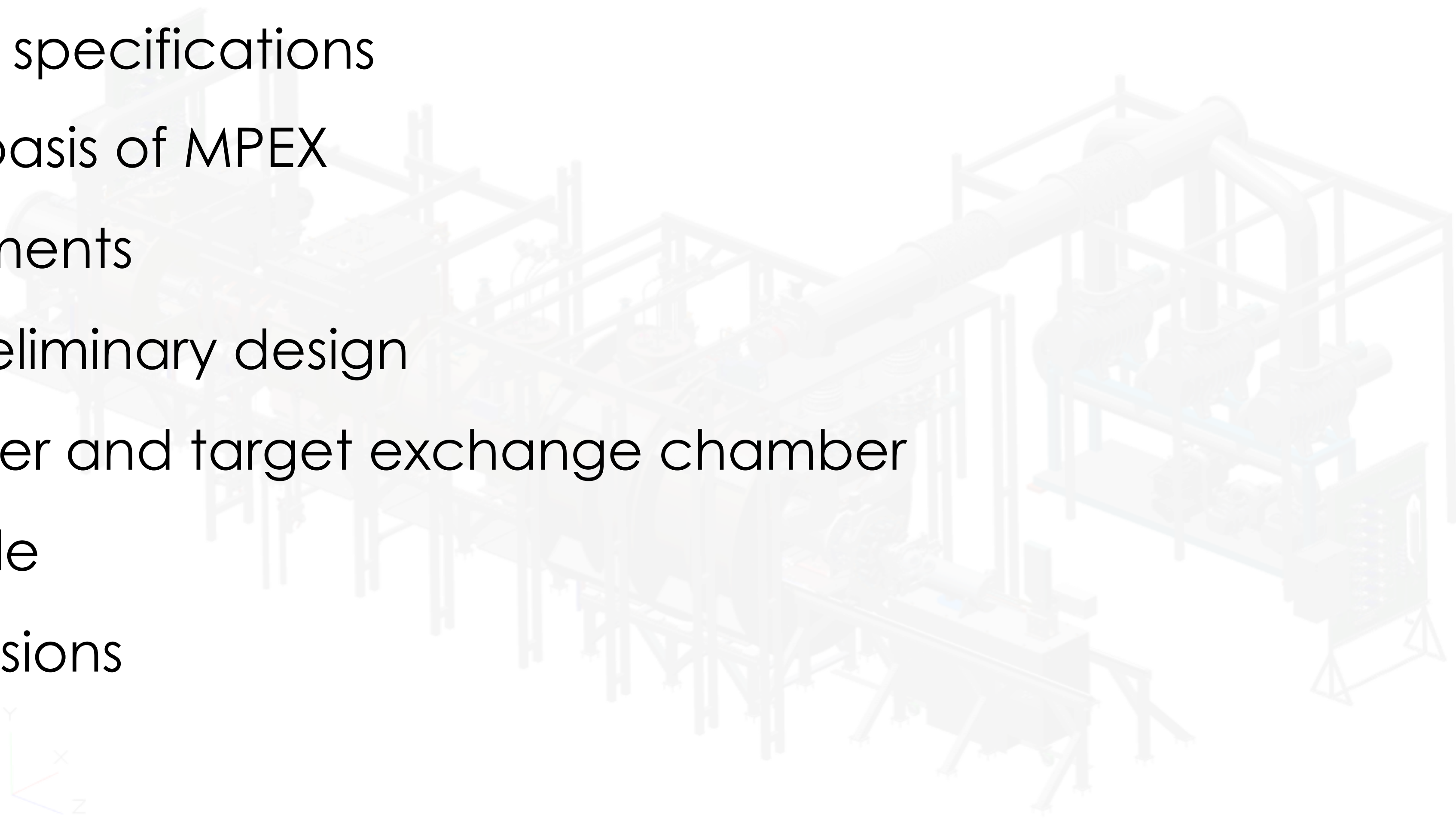
ORNL is managed by UT-Battelle, LLC for the US Department of Energy

Agenda

- Scope of this meeting
- Introduction to MPEX, specifications
- Overview of physics basis of MPEX
- Some design requirements
- Overview of MPEX preliminary design
- Design of PMI chamber and target exchange chamber
- MPEX project schedule
- Summary and conclusions



Scope of the meeting

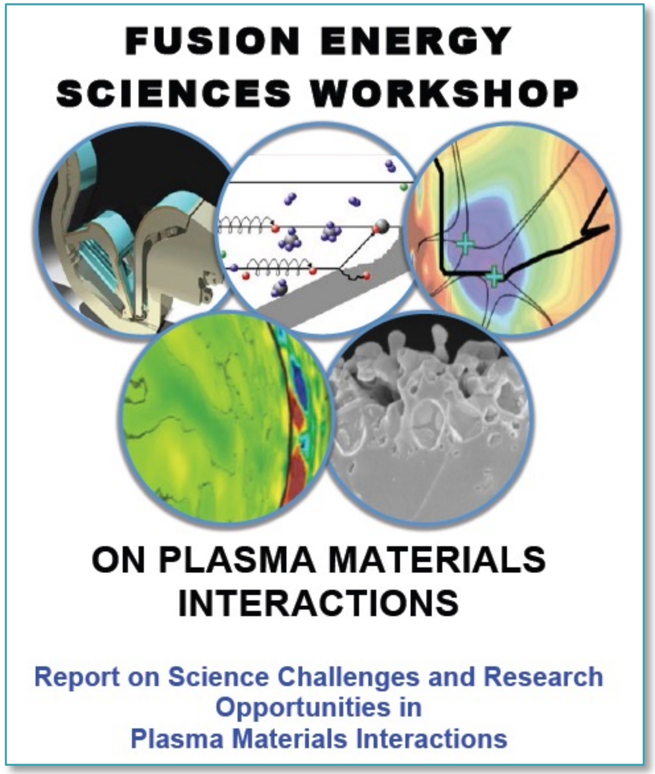
Community input into the definition of the MPEX research program for the first 5 years.

Need for prioritized Research Questions that are appropriate for and make use of unique capabilities of MPEX.

- Early exploitation in parallel to high level commissioning which could lead to a possible re-prioritization of the commissioning program, if necessary.
- Identification of improvements for the next generation target holder assembly.
- Identification/prioritization of diagnostics needs beyond device commissioning.
- Identification of potential material targets to be tested, reference materials throughout the phases of high-level commissioning.
- Identification of first batch of irradiated materials to be tested.

Furthermore, we want to identify collaborations with confinement facilities that would leverage MPEX operation or generate unique synergies in identifying, testing, or validating candidate materials for future fusion systems.

ORNL response to U.S. community needs: increased capabilities with MPEX

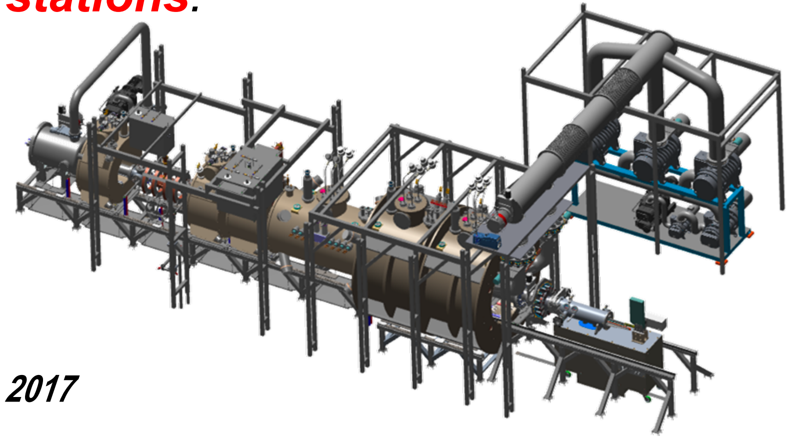


FUSION ENERGY SCIENCES WORKSHOP

ON PLASMA MATERIALS INTERACTIONS

Report on Science Challenges and Research Opportunities in Plasma Materials Interactions

> *“The development of steady state operation will require mastering plasma-materials interactions science to develop plasma facing components with strong erosion resistance . . . Development of world-leading capability* ***requires a new high fluence, linear divertor simulator with flexible target stations****.”*



J. Rapp et al. Nucl. Fusion 2017

MPEX Goals and Ultimate Performance Parameters

Steady-state magnetic field at target [T]	1
Steady-state high power flux to target [MW/m^2]	> 10
Steady-state high power plasma flux on tilted (5 degree) target [MW/m^2]	**3**
Target T_e, T_i [eV]	1 - **15**
Target n_e [m^{-3}]	10^{21} - 10^{19}
Target ion flux [$m^{-2}s^{-1}$]	10^{24}
Annual fluence	**10^{31}**
Hazardous materials like neutron irradiated samples and liquid metals	**Y**
Target ambient temperature [^oC]	600
Plasma diameter [cm]	10
Test of divertor component mock-ups	Y

Plasma source parameters requirement to meet MPEX goals

Hierarchy of analysis tools have been developed and used to set source parameter requirement from target plasma requirements

- Conduction limited 2-point model $\left(n_{target} \propto n_{source}^{3} q_{||}^{-8/7} L^{6/7}\right)$
- 1-D fluid/2-D kinetic model
- 2-D B2-EIRENE model
- 3-D EMC3-EIRENE (tilted targets)

Parameters	**MPEX goals**
n_e source	Up to $9\text{x}10^{19}$ m^{-3}
T_e source	Up to 25 eV
T_i source	Up to 30 eV
Length (heating to target)	~ 5 m
heat flux at target	> 10 MW/m^2

J. Rapp et al. J. Nucl. Mater 2015, L. Owen et al. Phys. Plasmas 2017

Plasma diameter requirements

Plasma Scenario	A: high n_e	B: high P_e	C: high T_e	D: low n_e
n_e target (m^{-3})	2×10^{21}	5×10^{20}	2×10^{20}	1×10^{19}
T_e target (eV)	2	7	10	15
T_i target (eV)	2	7	12	20
B target (T)	1	1	1	0.35
Parallel ion flux ($m^{-2}s^{-1}$)	1.4×10^{25}	6.5×10^{24}	3.3×10^{24}	2.1×10^{23}
$q_{//}$ (MW/m^2)	31.1	40.0	36.4	3.5
Ionization MFP of D (cm)	2.0	**2.4**	**1.0**	**12.0**
MFP of diffusive D (cm)	0.49	2.0	0.75	10.1
Ionization MFP of CH_4 (cm)	**2.5**	0.096	0.047	0.48
Ionization MFP of W (cm)	0.025	0.027	7.8×10^{-3}	0.13
W gyroradius (cm)	0.27	0.74	1.9	2.4
D gyroradius (cm)	0.028	0.076	0.19	0.25
Magnetic presheath length (cm)	0.069	0.19	0.48	0.62

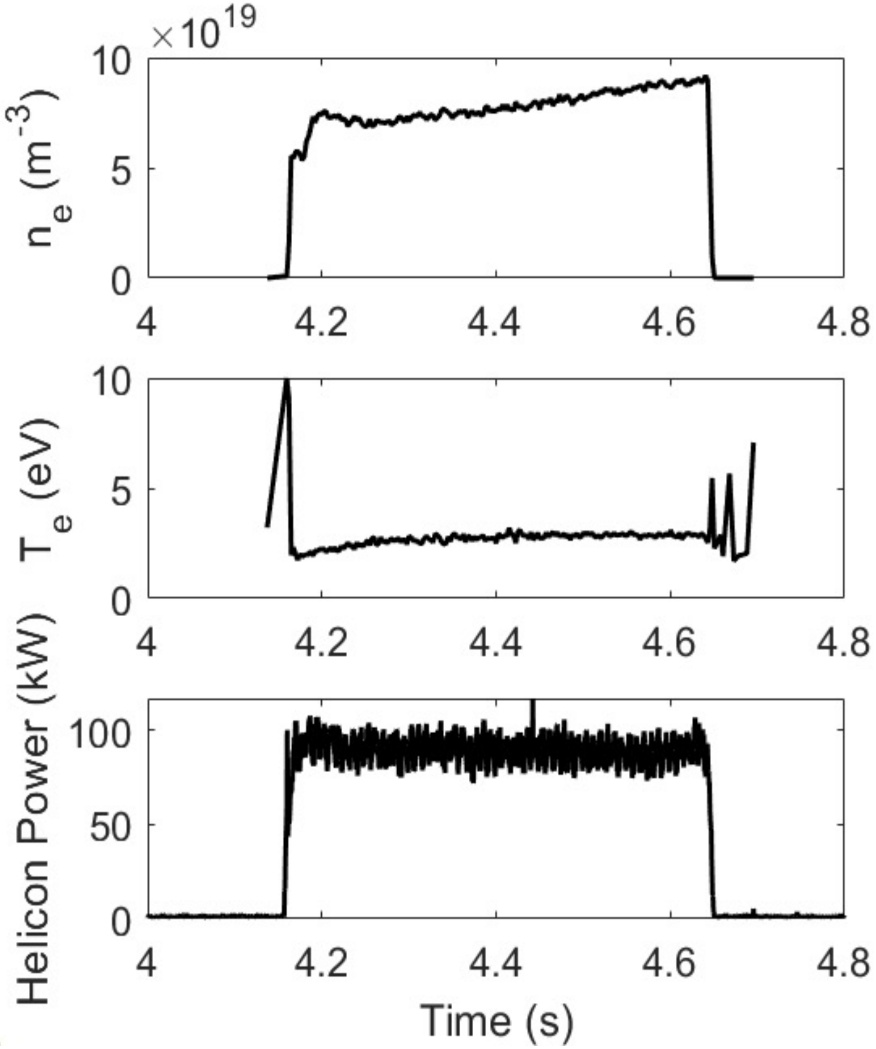
Plasma diameter needs to be larger than 3 cm for plasma scenarios A, B and C and it needs to be about 10 cm for low density scenarios

MPEX system goals and achieved performance in Proto-MPEX

Parameter	**MPEX Goal**	**Achieved in Proto-MPEX**	**Comments**
n_e source	4 - 9 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 30 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	up 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

Proto-MPEX has demonstrated needed density with 100 kW injected helicon power

- Helicon sources are widely used around the world for density production
- Achieved source density at ~ 8-9x10^{19} m^{-3}
- **200 kW** helicon conservatively planned for possible higher densities on MPEX

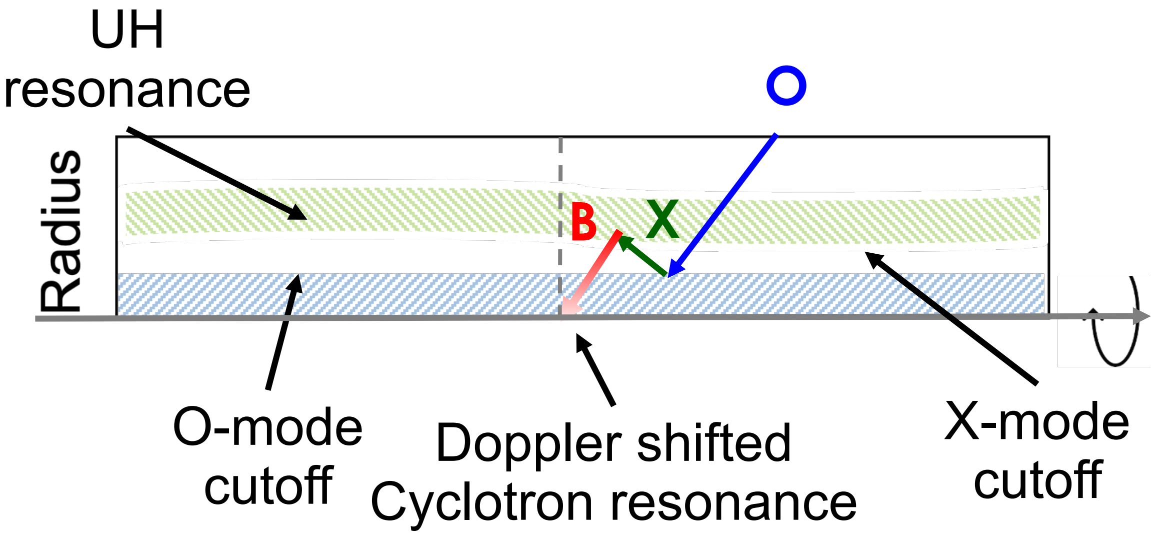


R. Goulding et al. Fus Sci Technol 2017, P. Piotrowicz et al. Plasma Sources Sci. Technol. 2018, P. Piotrowicz et al. Phys. Plasmas 2018, N. Kafle et al. Phys. Plasmas 2018

O-X-B Electron Bernstein Wave heating is proposed baseline ECH electron heating scheme

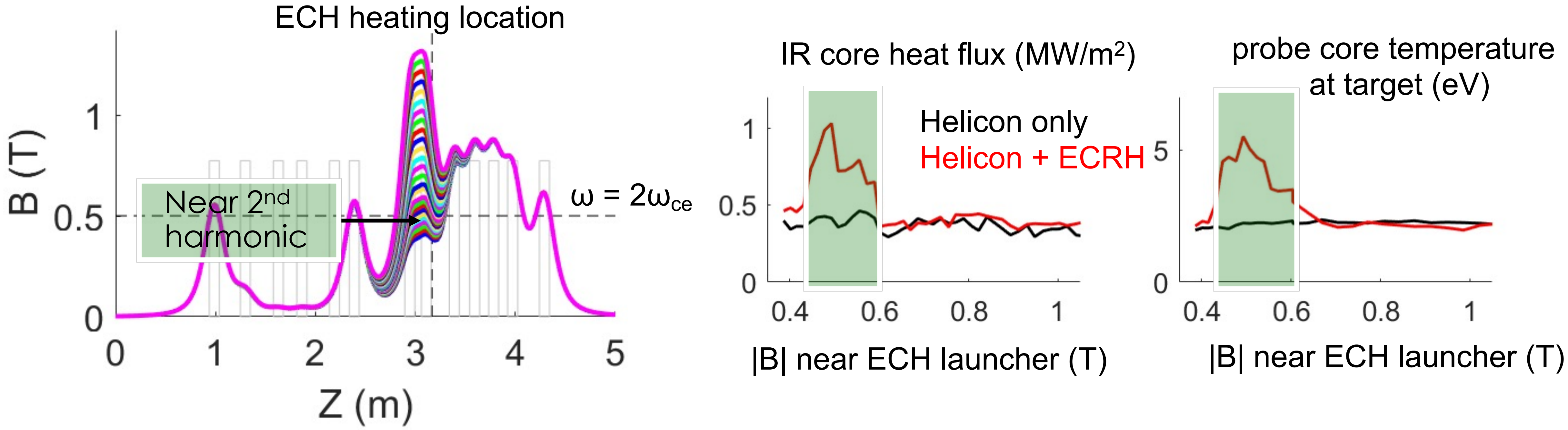
- Proto-MPEX currently uses O-X-B EBW heating scheme with an installed 200 kW, 28 GHz gyrotron into plasmas
  - Electron heating depends on many parameters such as density, magnetic field, frequency
  - O-X-B EBW has a minimum density requirement (O-mode cutoff density and upper hybrid resonance layer needs to be in the plasma)

- Other heating schemes include upper-hybrid, second harmonic ECH, and whistler for low density scenarios



S. Diem et al., Phys. Plasmas 2018, C. Lau et al. Phys. Plasmas 2019

Electron heating was observed in overdense plasma conditions (EBW) at 2nd harmonic for 28 GHz launch

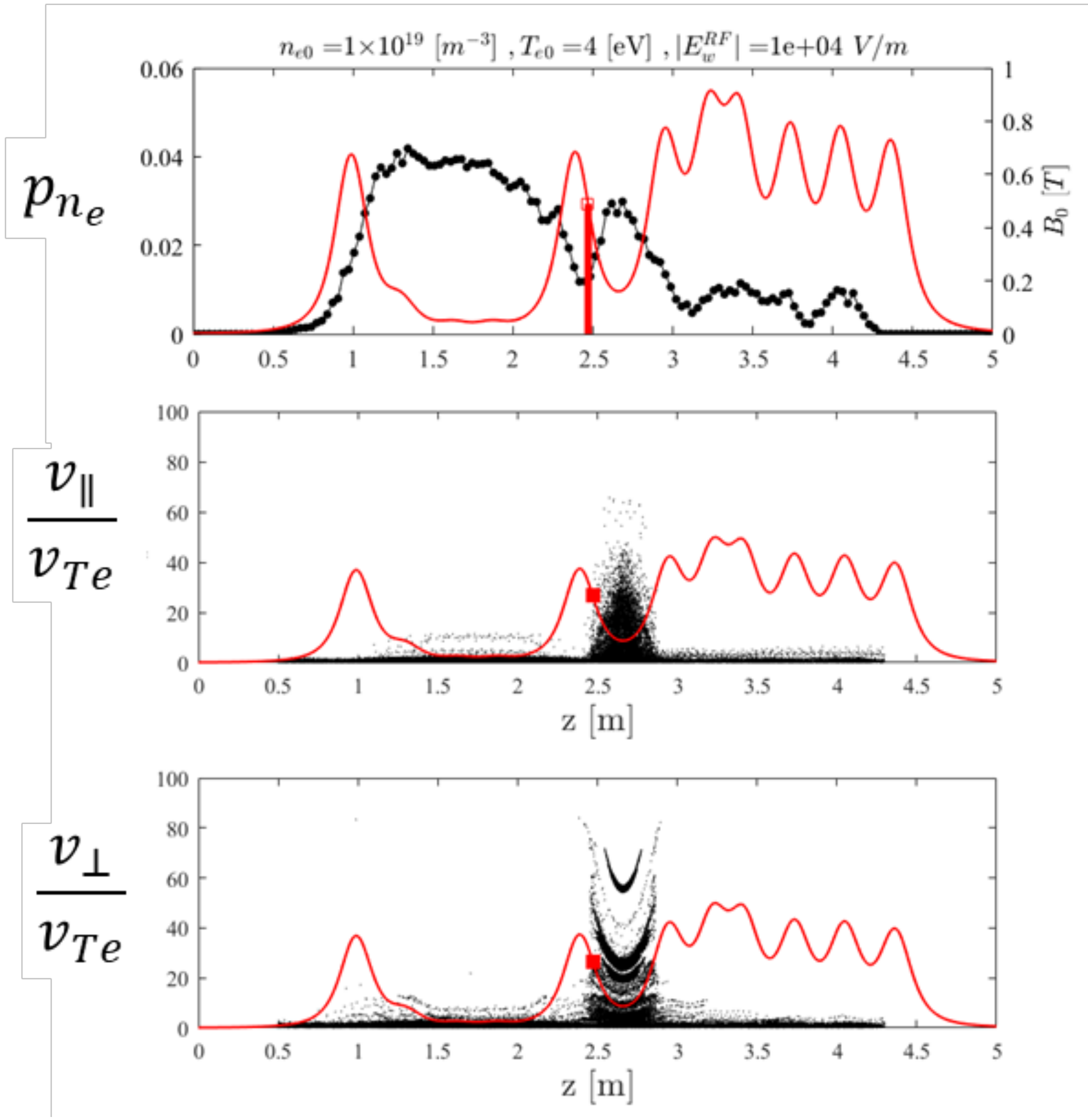


- ECH power ~ 25 kW
- core electron heating on LP correlates with core heating on IR camera
- ECH heating only occurs near 2nd harmonic (0.5 T) for 28 GHz launch

T. Biewer et al. Phys. Plasmas 2019

Downhill magnetic field is preferred

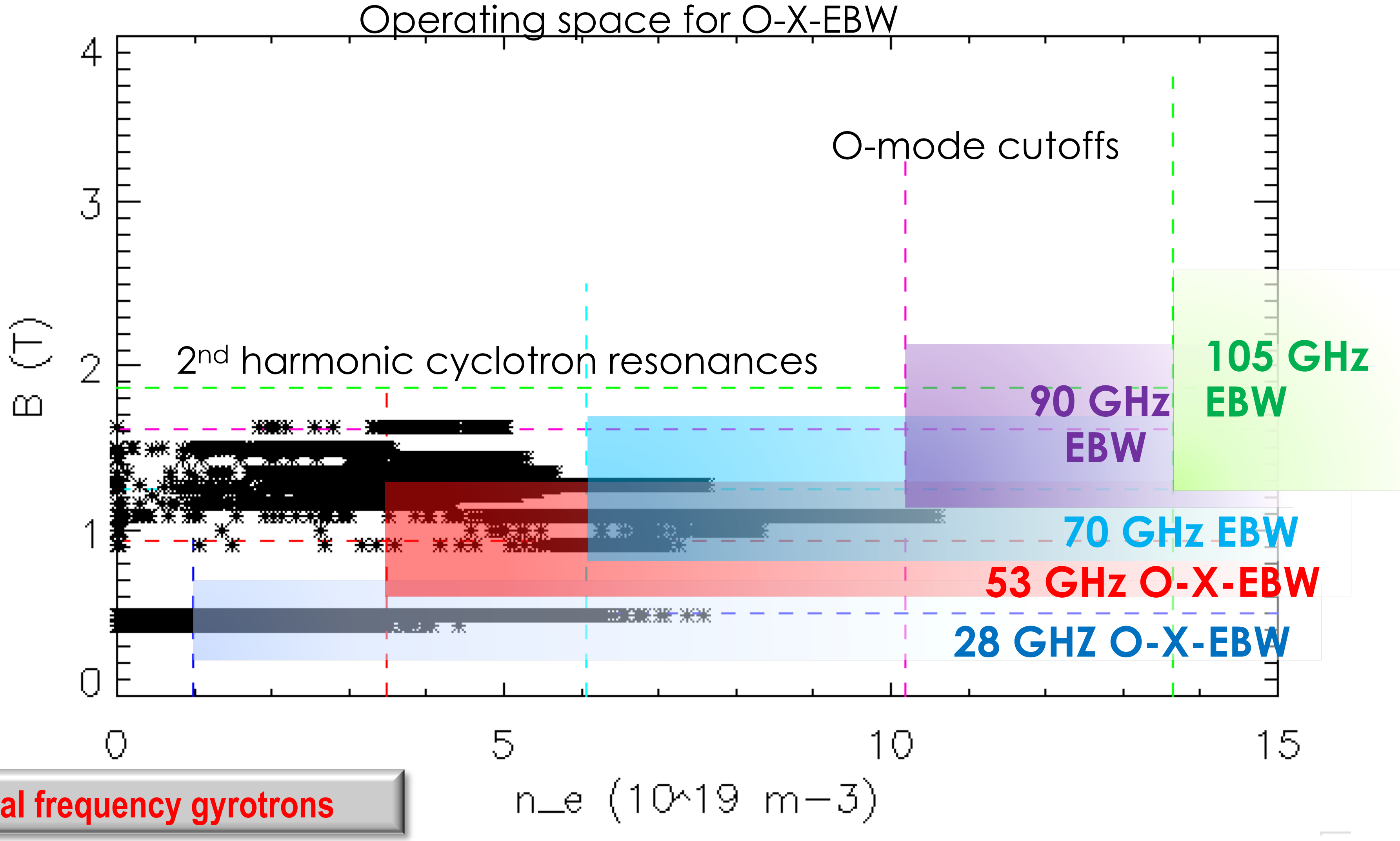
- Magnetic field need to be optimized for plasma source/heating and as well as transport to target
- Test particle Monte Carlo code has been developed and applied to understand source/heating mechanisms and their interactions with collisional and kinetic trapping
- Asymmetric well or “downhill” operation and minimal magnetic ripples are suggested for both simulation and experiment
- **$B_{ECH} > B_{ICH}$, $B_{ICH} > B_{target}$, $B_{hel} <$ B elsewhere with appropriate magnetic mirrors**



J. Caneses et al. Plasma Phys. Control. Fusion 2020

70 GHz Electron Bernstein Wave heating is the primary heating scheme for MPEX

- Operating frequency > 56 GHz for 2nd harmonic EBW to satisfy 1 T requirement at target
- **70 GHz and 1.25 T** is preferred baseline operation
- Other options:
  - 70 GHz Upper Hybrid
  - 70 GHz O-mode whistler wave heating
  - 105 GHz EBW
  - 105 GHz 2nd harmonic ECH

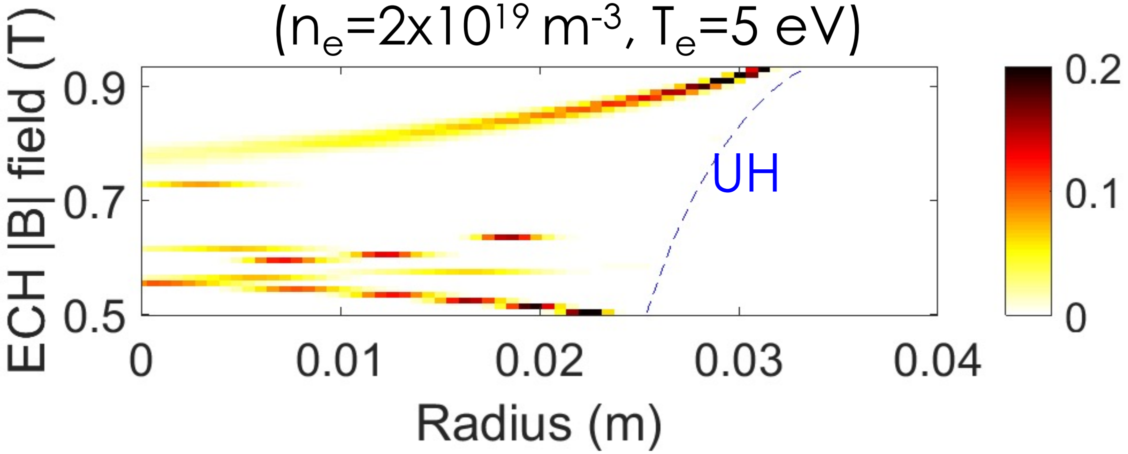


MPEX will use 70/105 GHz dual frequency gyrotrons

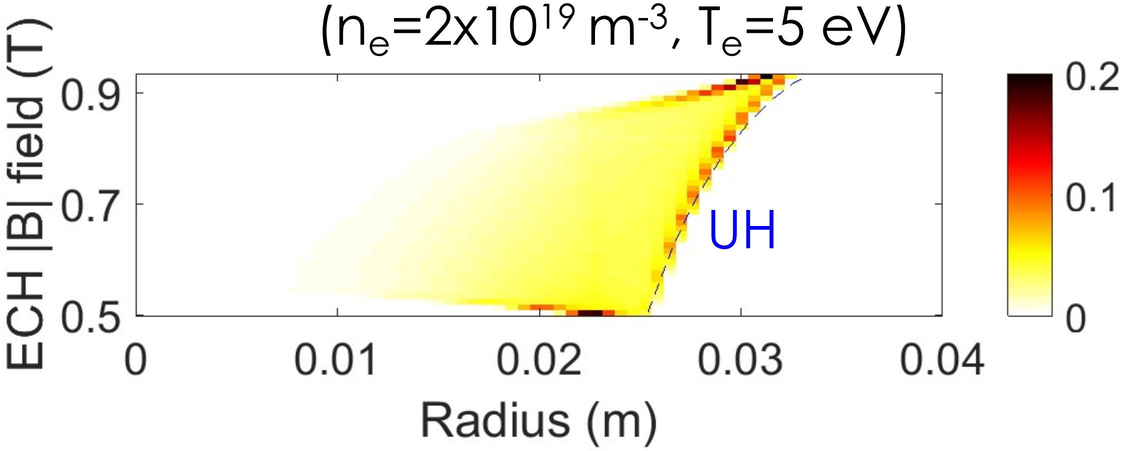
T. Biewer et al. Phys. Plasmas 2019

Neutral pressure needs to be low for heating sections

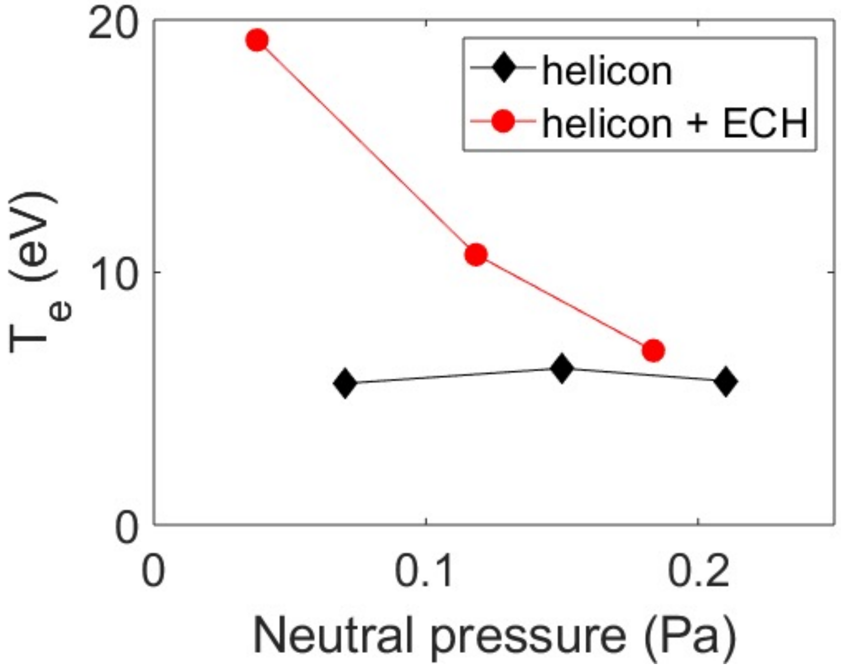
Fractional power absorption **without collisions** (n_e=2x10^{19} m^{-3}, T_e=5 eV)



Fractional power absorption **with collisions** (n_e=2x10^{19} m^{-3}, T_e=5 eV)



- GENRAY-C simulations and Thomson scattering experiments in 2017 show that neutral pressure for ECH section **~ 0.01 Pa**
- Similar calculation for charge exchange in ICH section **~ 0.01 Pa**

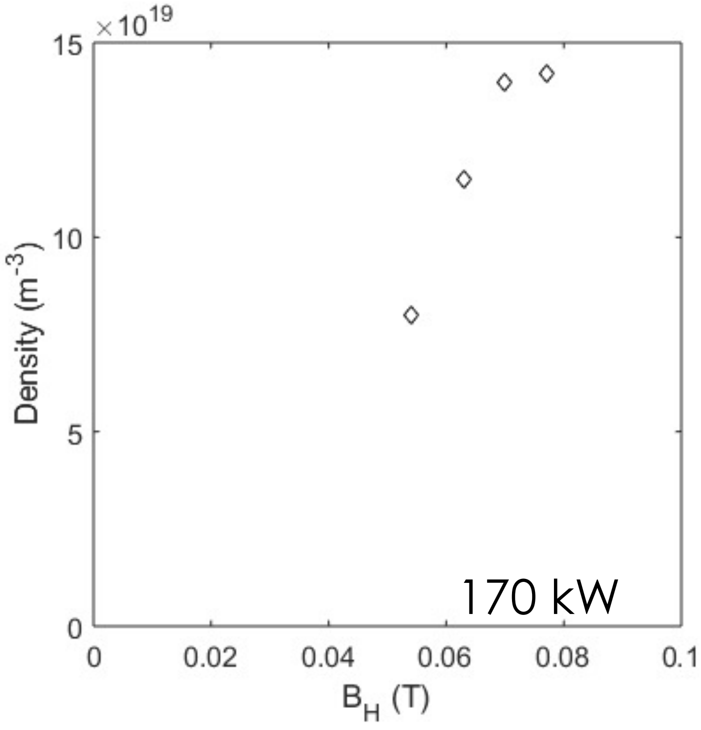


T. Biewer et al. Phys. Plasmas 2018, J. Caneses et al. Phys. Plasmas 2018, S. Diem et al. Phys. Plasmas 2018

Heating power requirements

Helicon

200 kW

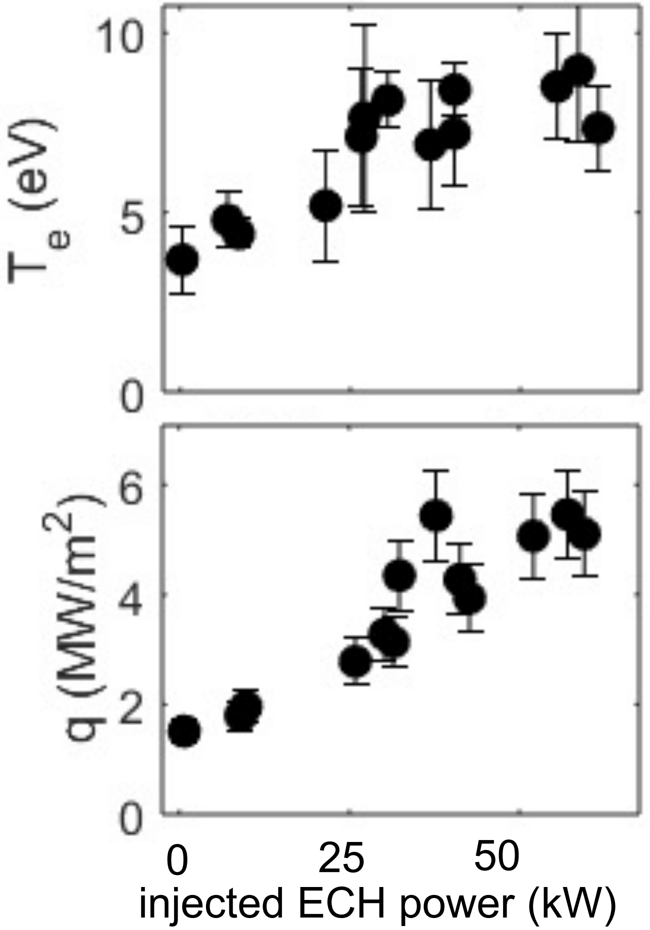


170 kW

Extrapolated heat fluxes for MPEX magnetic field configuration and total heating power of 1 MW: 37 MW/m^2

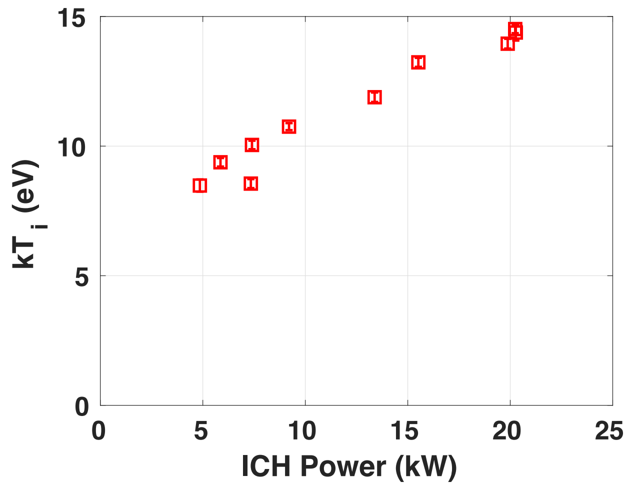
Electron heating

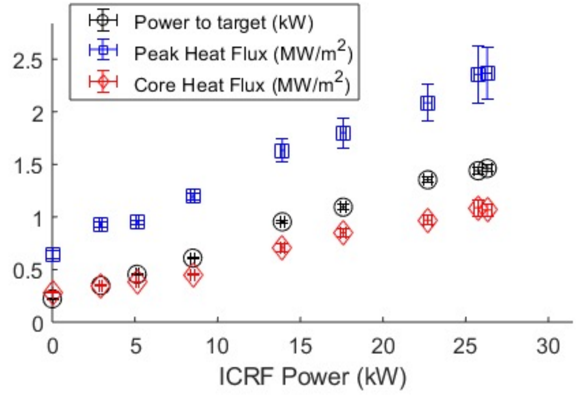
250 - 350 kW



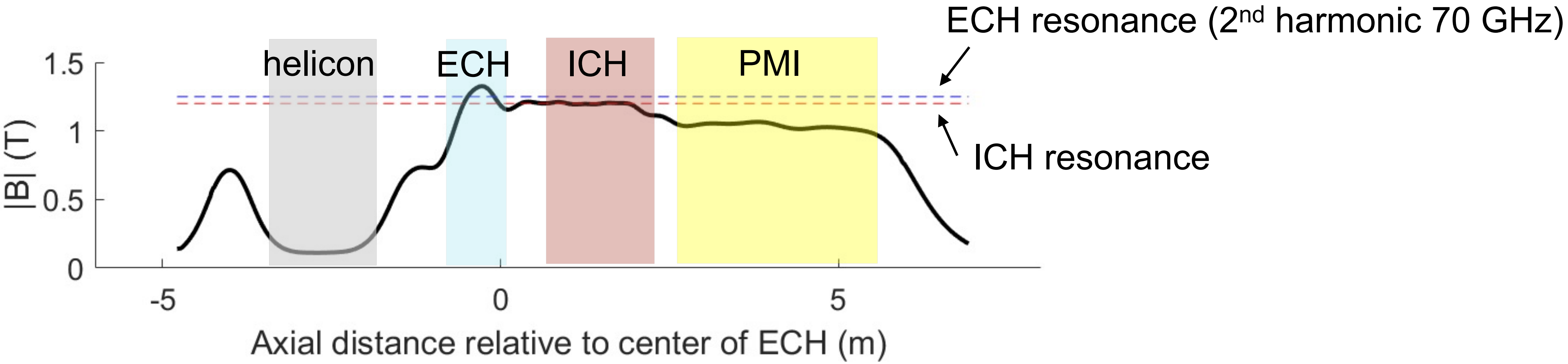
Ion heating

150 - 300 kW





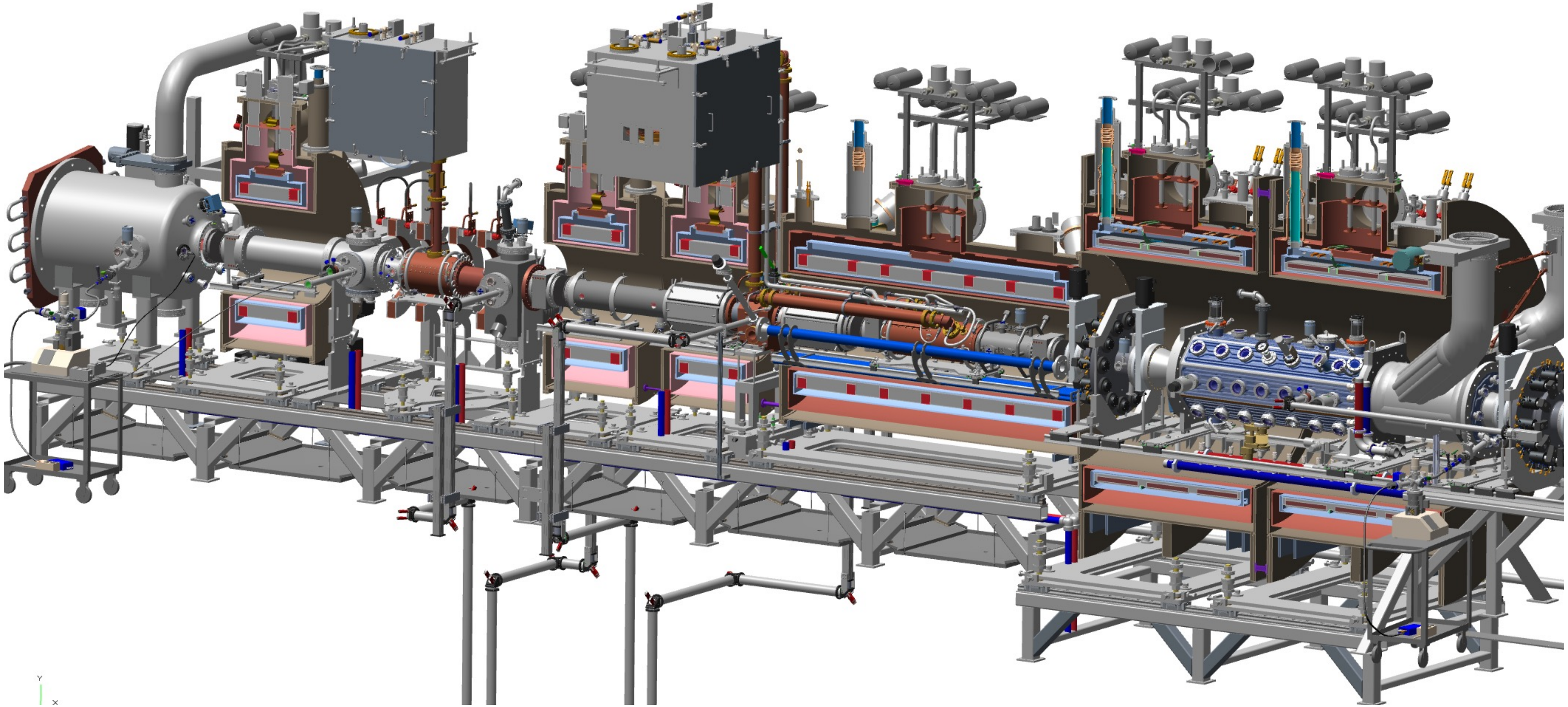
Physics basis for system requirements



Loads	Helicon	ECH	ICH	PMI
Magnetic field	• $B_{hel} < 0.2$ T	• $B_{ECH} \sim 1.25$ T	• $B_{ICH} \sim 1.1\text{-}1.2$ T	• $B_{tar} \sim 1$ T
RF power	• 200 kW	• up to 400 kW	• up to 400 kW	
RF frequency	• 13.56 MHz	• 70/105 GHz	• 4-9 MHz	
Neutral pressure	• 1-10 Pa	• 0.01 Pa	• 0.01 Pa	• 1-10 Pa

MPEX project status

MPEX has passed CD-1 and PDR for most systems, Magnets and Gyrotrons were ordered already.

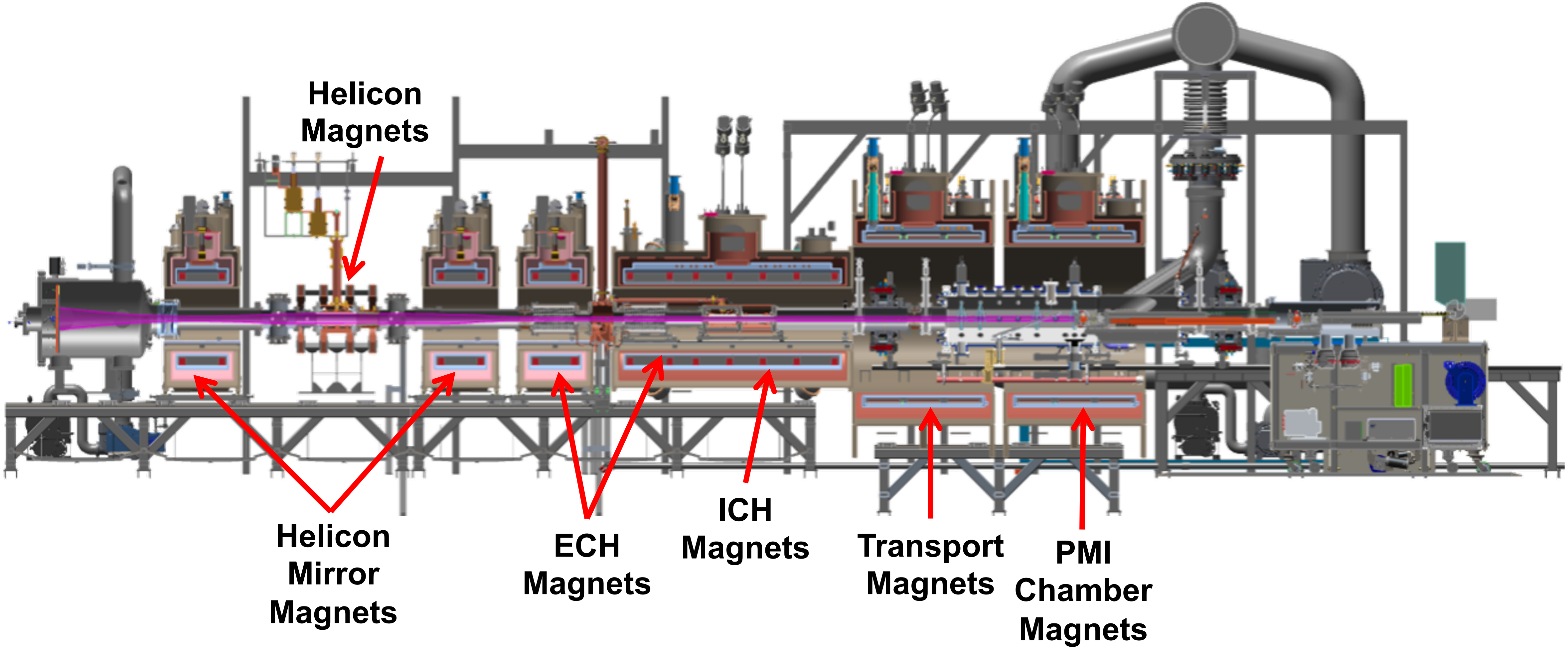


MPEX functional requirements

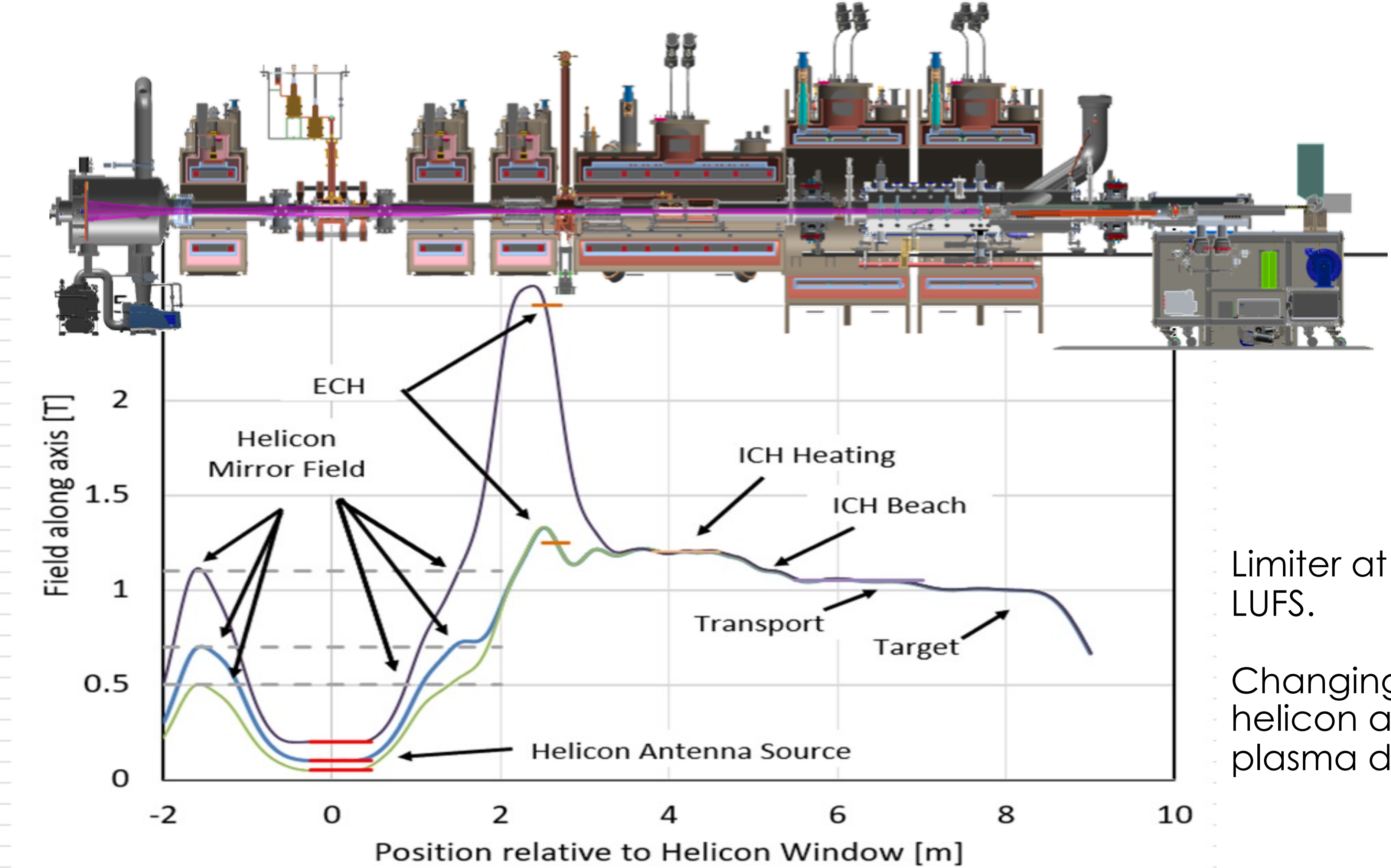
- Steady-state magnetic fields up to **2.5 T** (-> superconducting coils NbTi technology)
- Steady-state operation of up to **10^6 sec**
- Ability to expose radioactive and hazardous materials such as a-priori **neutron irradiated materials** (irradiated up to 50 dpa) and **liquid metals**
- Ability 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^o 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

MPEX Systems – Magnets

19 superconducting coils (NbTi) in 6 cryostats
4 room temperature coils (helicon magnets)



MPEX Systems – magnet “flexibility”



B field in ECH region allows for various heating schemes:

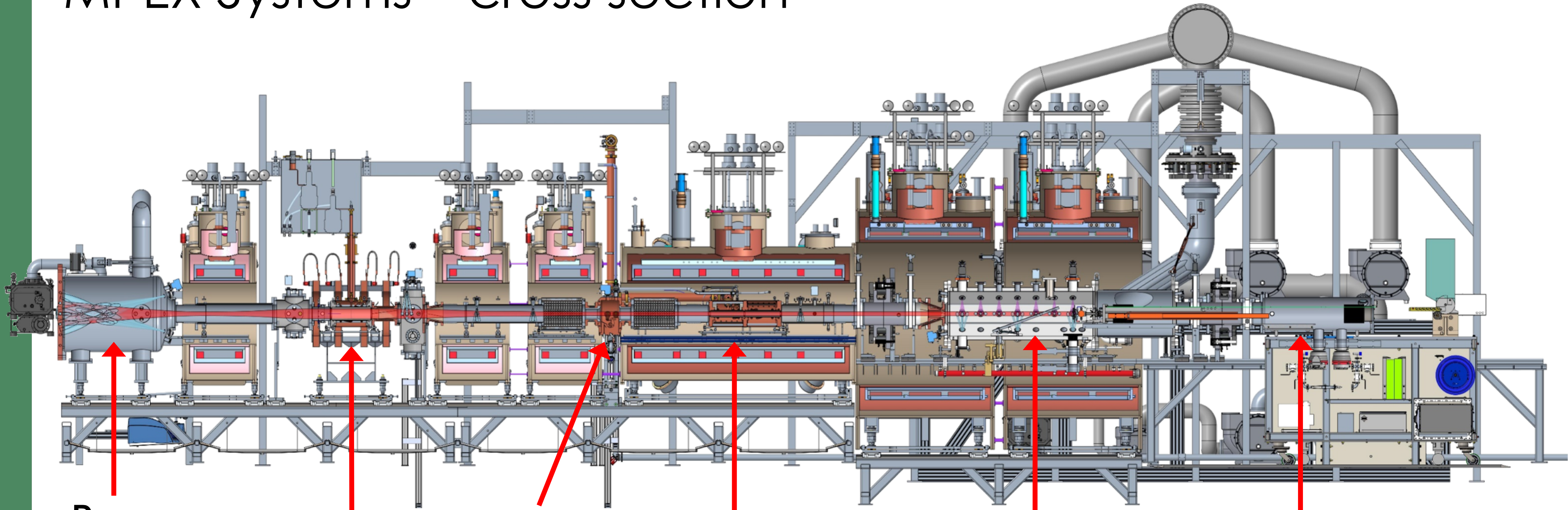
- 2^{nd} har 70 GHz EBW
- 2^{nd} har 70 GHz UH
- 2^{nd} har 105 GHz ECH
- fund 70 GHz Whistler

Limiter at helicon determines LUFS.

Changing B field ratio between helicon and target determines plasma diameter at target.

LUFS: last uninterrupted flux surface

MPEX Systems – cross section



Dump Chamber
plasma terminates upstream

Helicon Source
13.56 MHz
170 kW launched

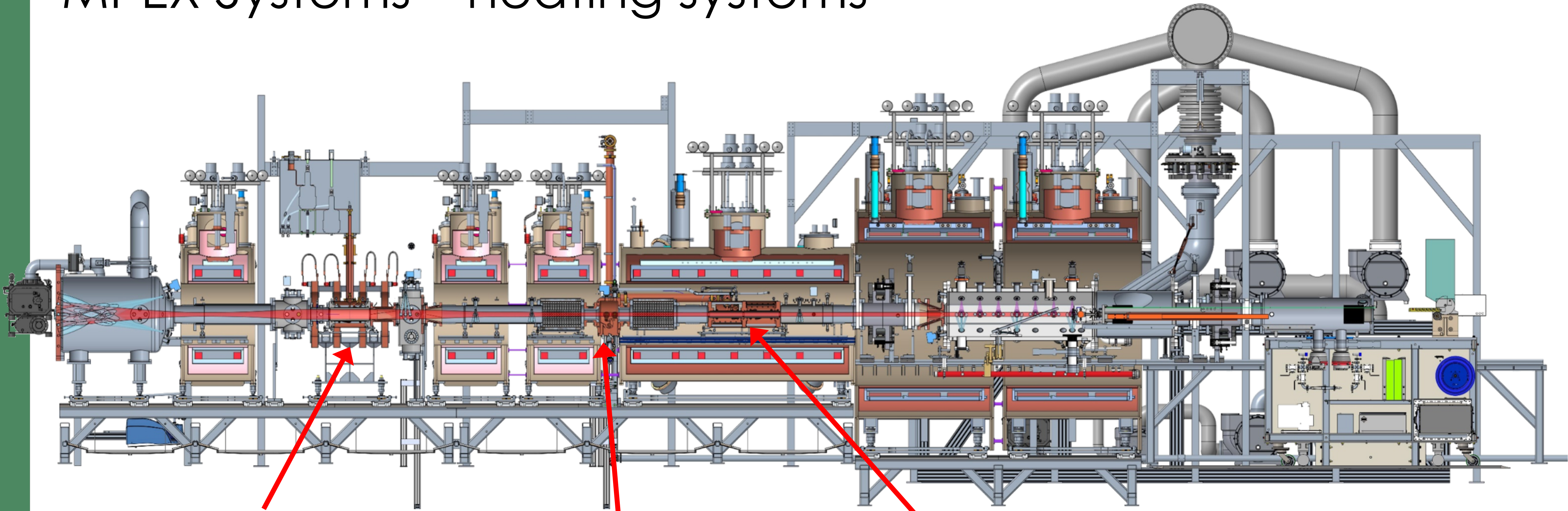
EC Heating
70/105 GHz
400 kW launched

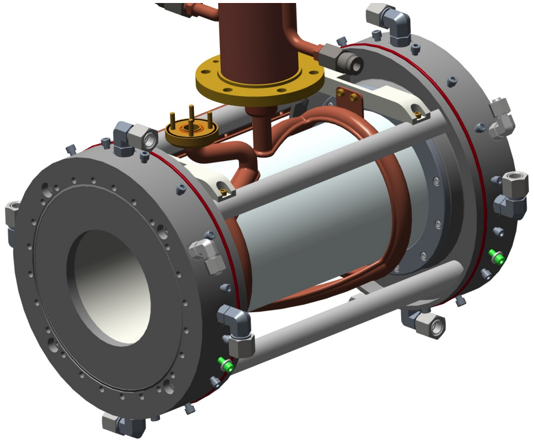
IC Heating
4-9 MHz
310 kW launched

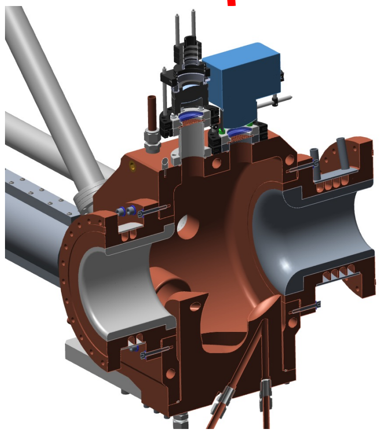
PMI Chamber
plasma terminates downstream

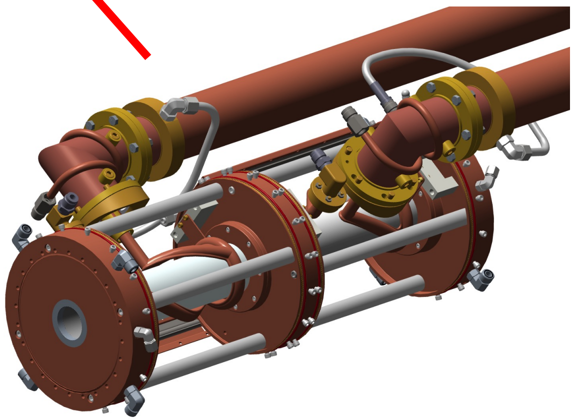
Target Exchange Chamber
transports target

MPEX Systems – heating systems

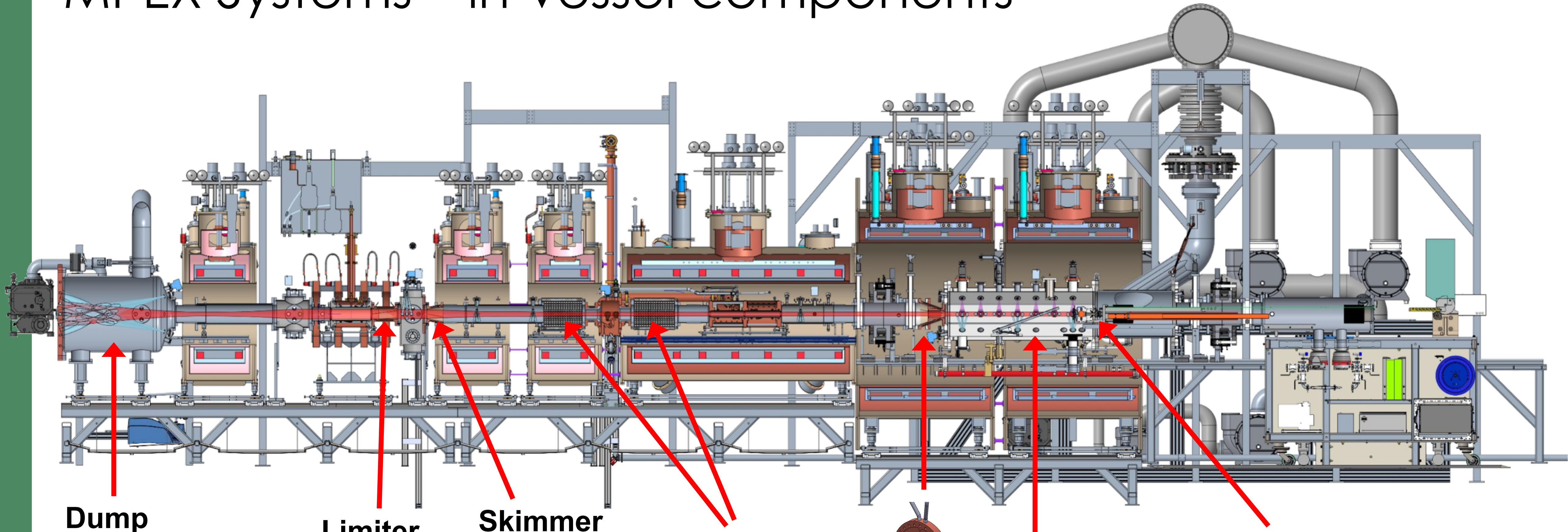




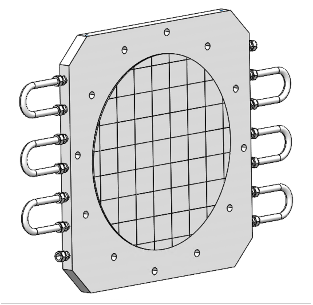




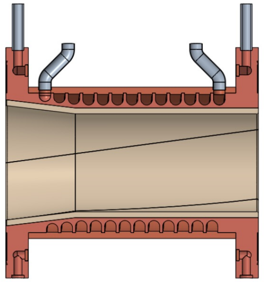
MPEX Systems – in-vessel components



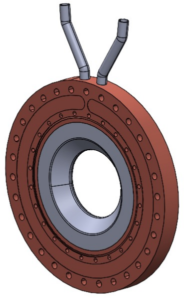
Dump



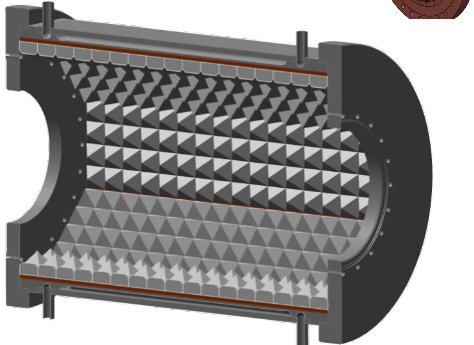
Limiter defines LUFS

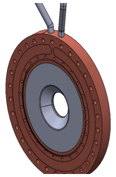


Skimmer



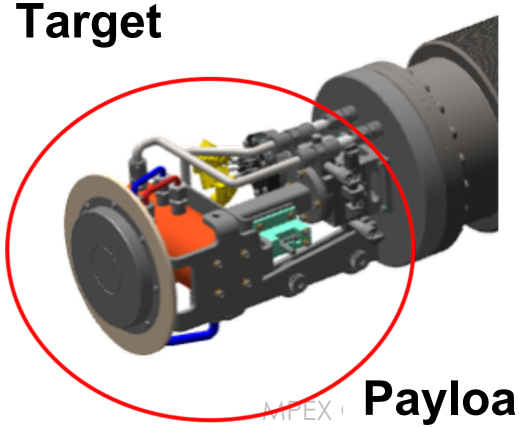
Microwave absorber





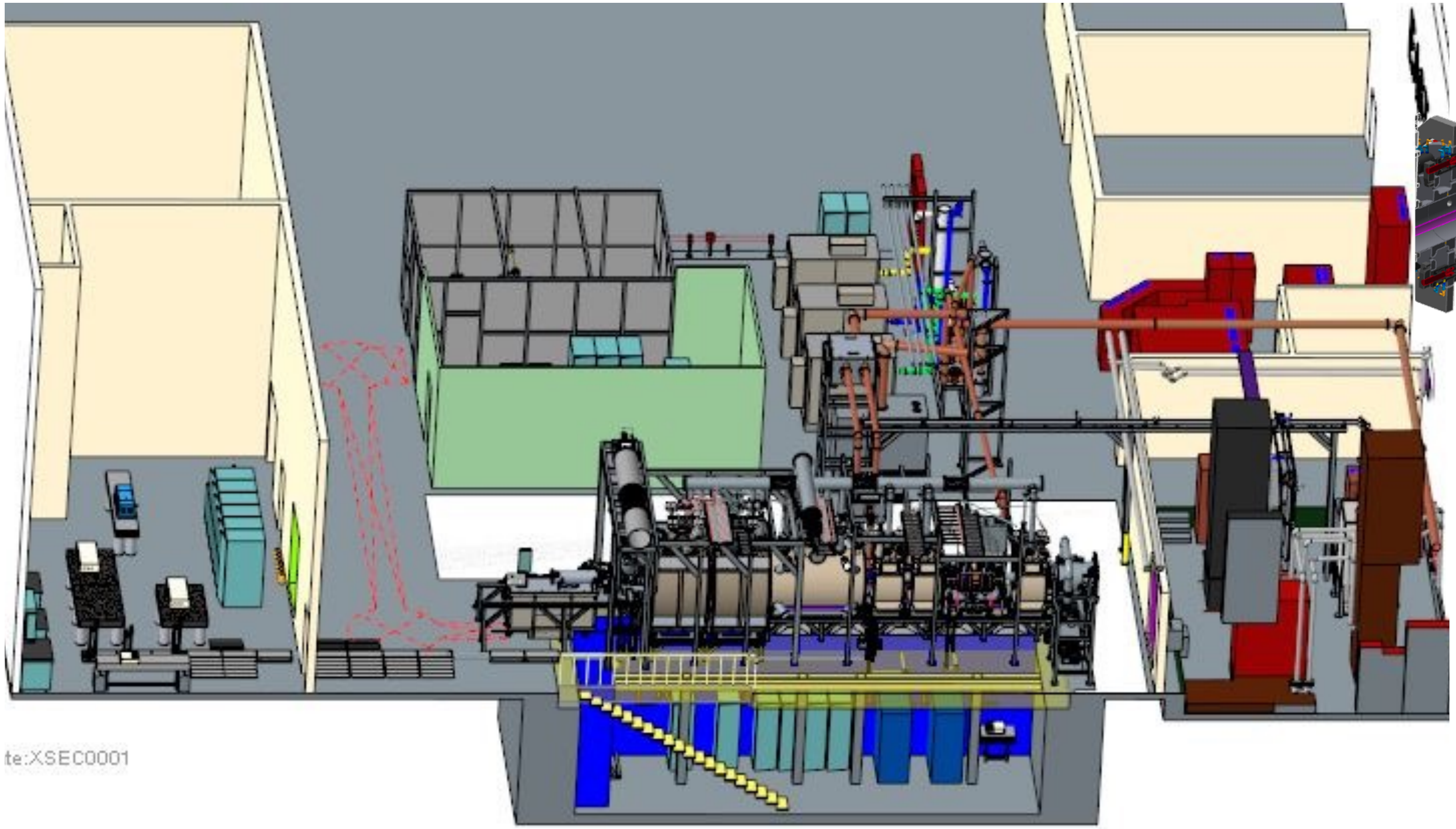
Target dump

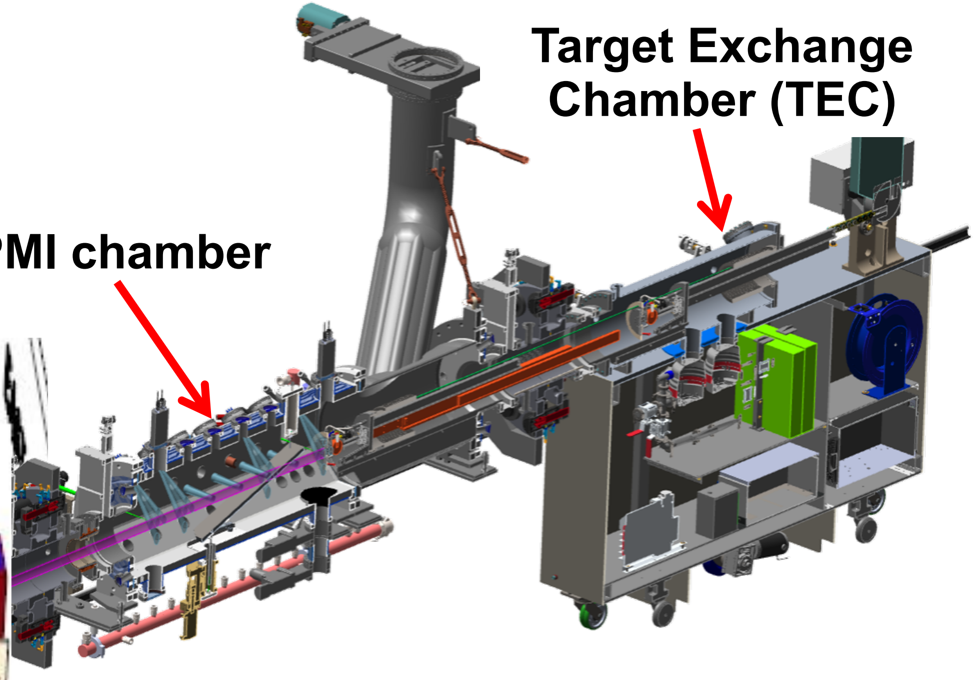
Target



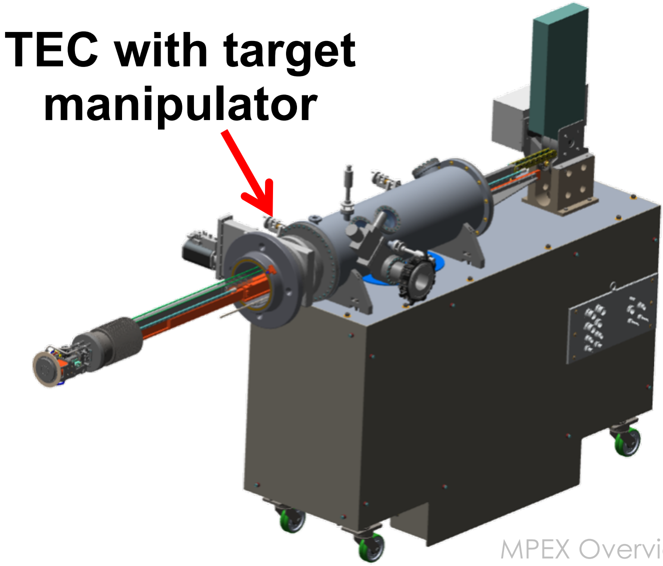
Payload

MPEX Systems – target handling

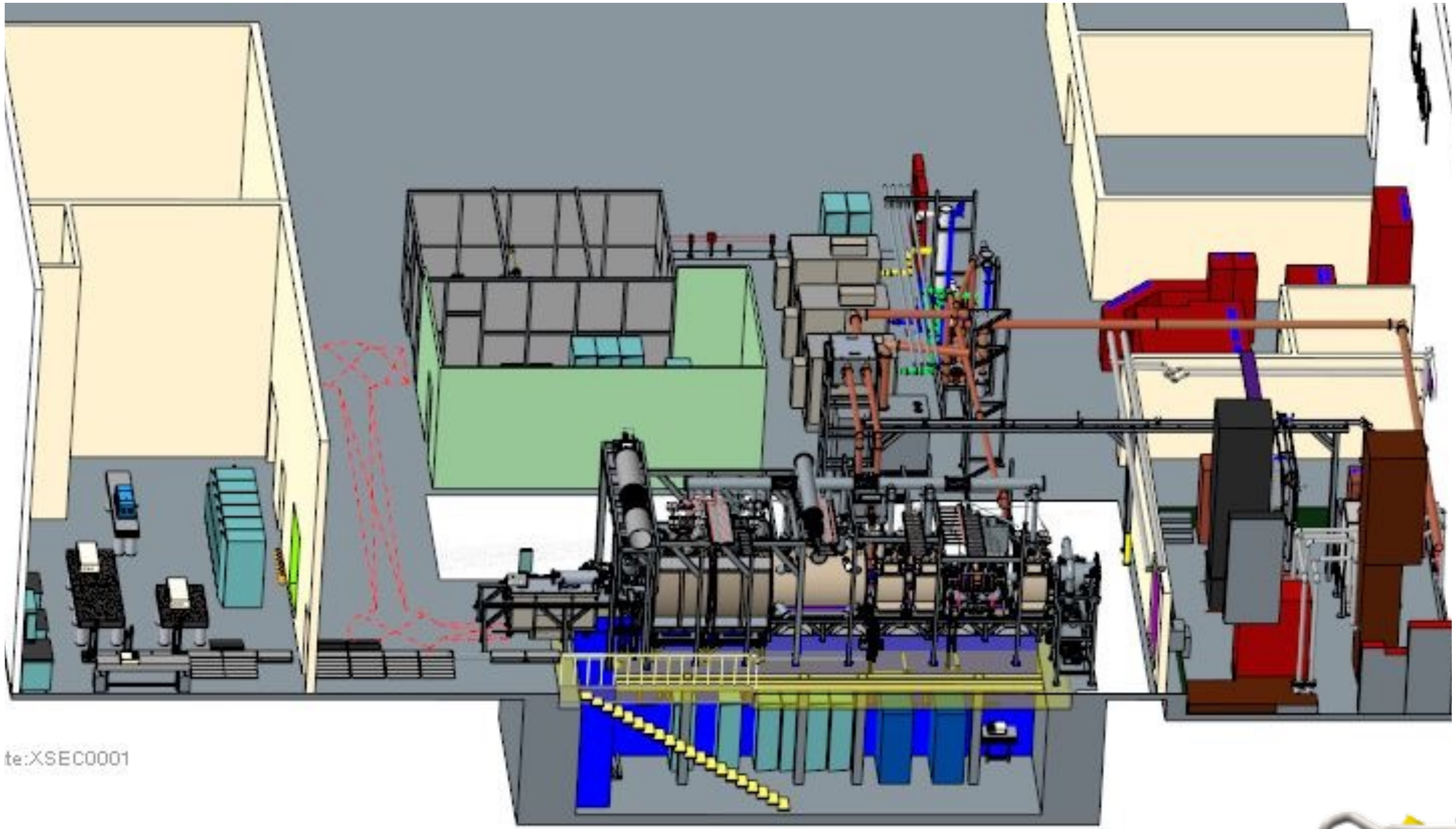



PMI chamber

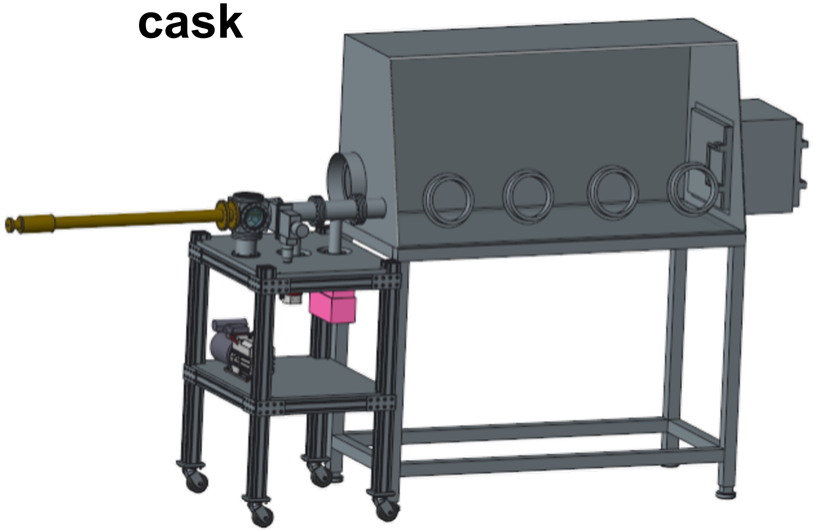
Target Exchange Chamber (TEC)


TEC with target manipulator

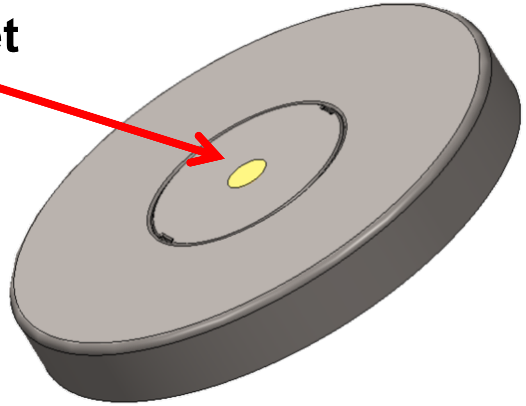
MPEX Systems – target handling

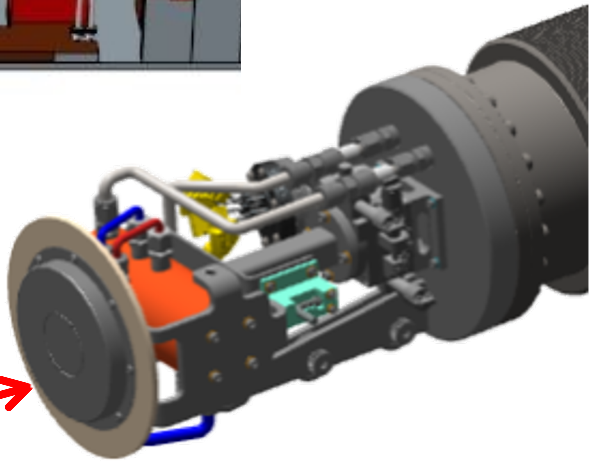


Inert gas glove box with target transfer cask



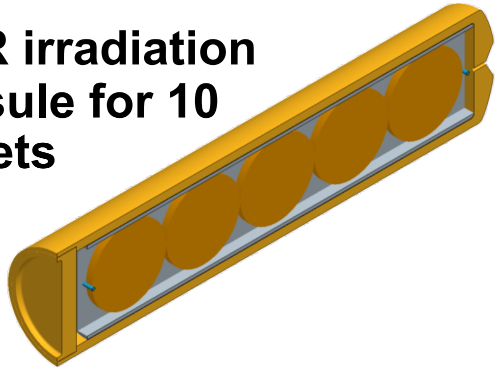
Target





Target

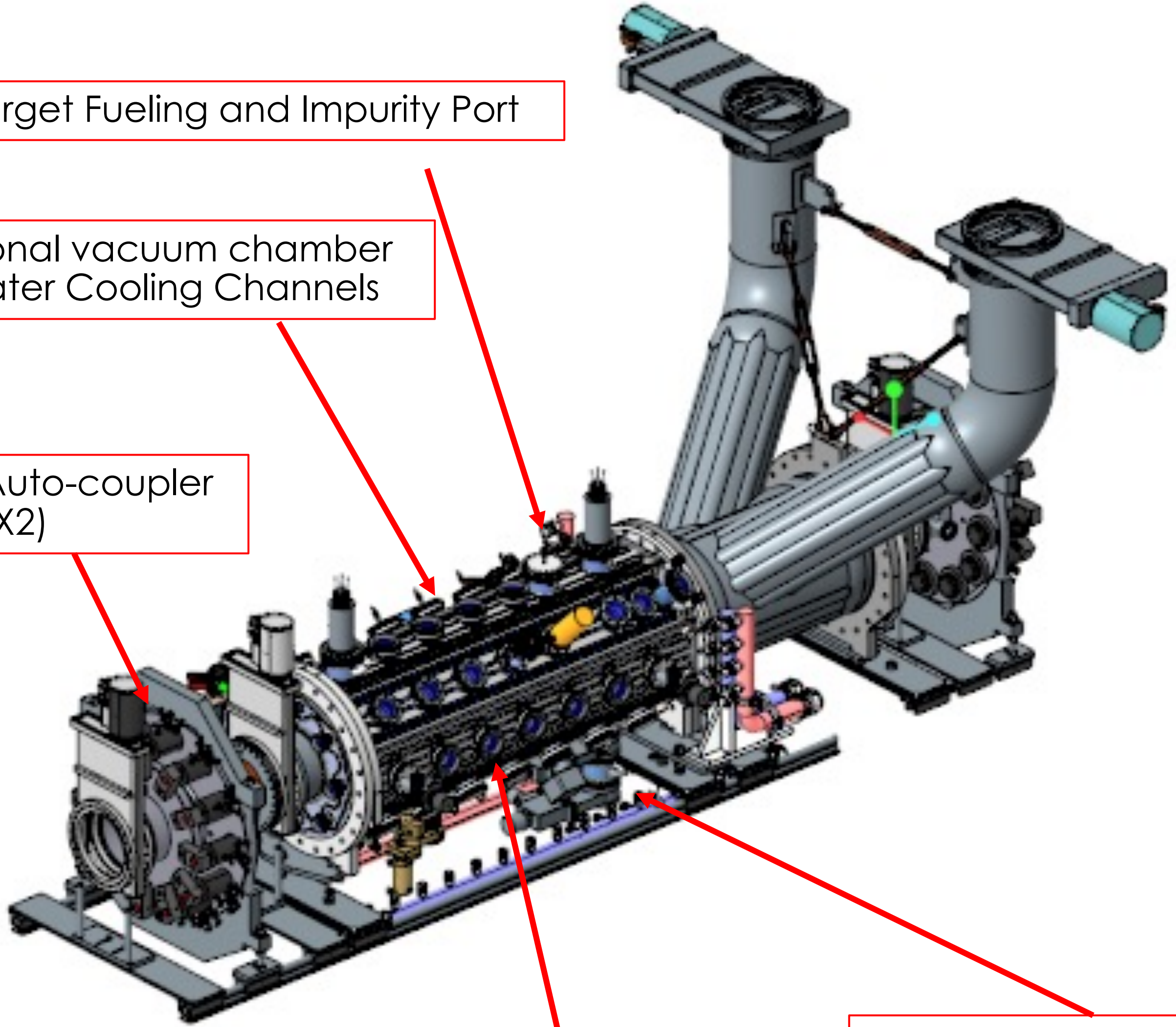
HFIR irradiation capsule for 10 targets



PMI Chamber

PMI chamber can be withdrawn from PMI magnet on rail system for maintenance purposes.

For this purpose, PMI chamber can be disconnected from main plasma generator with auto-coupler.



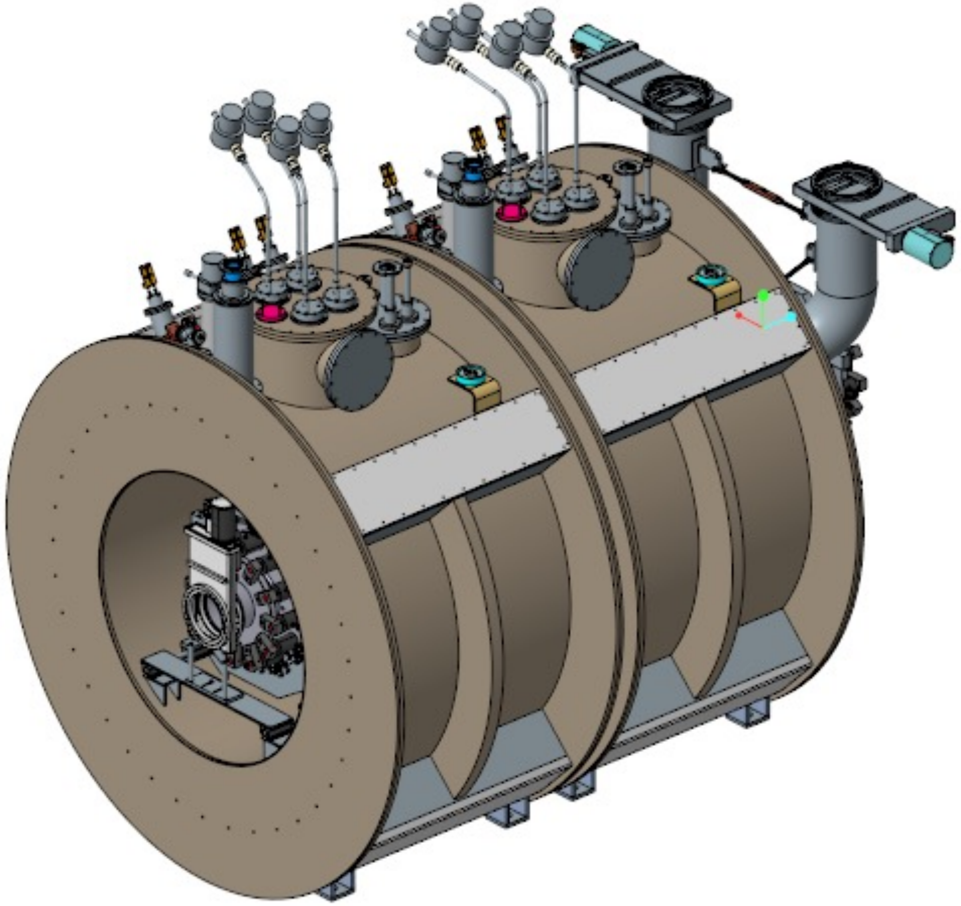
Target Fueling and Impurity Port

Octagonal vacuum chamber with Water Cooling Channels

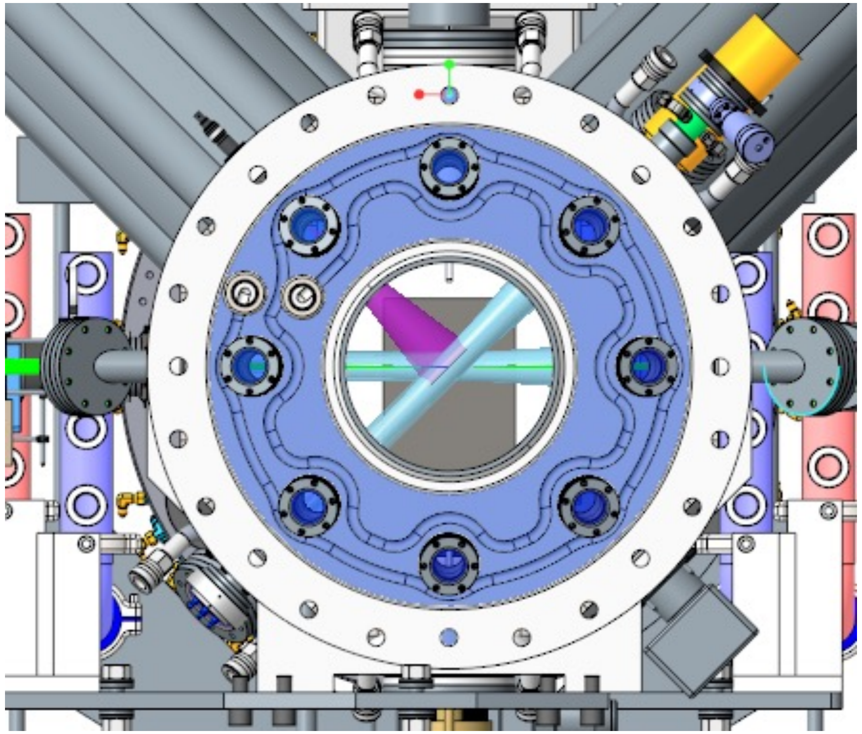
Auto-coupler (X2)

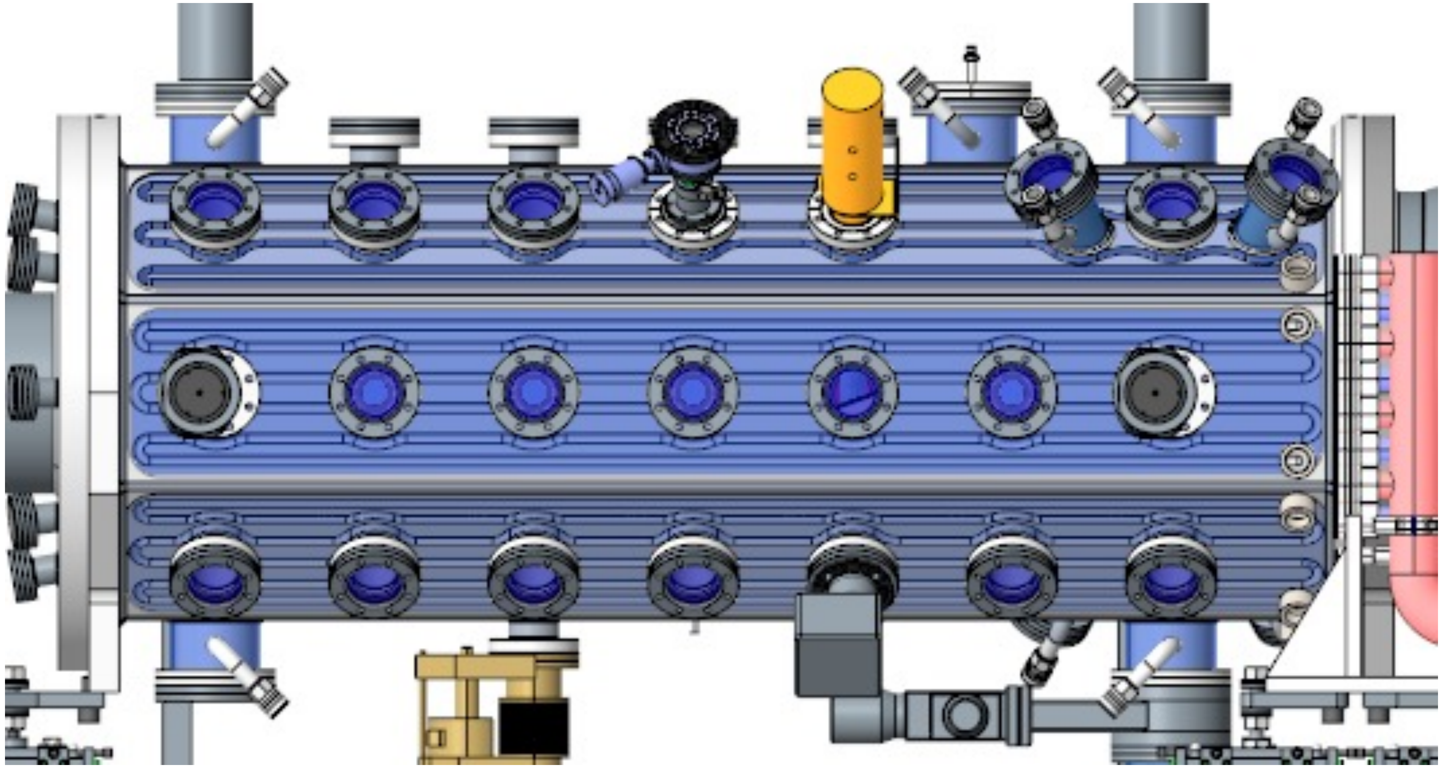
Diagnostic ports (x51)

Irradiated Material Recovery System



PMI chamber – ports



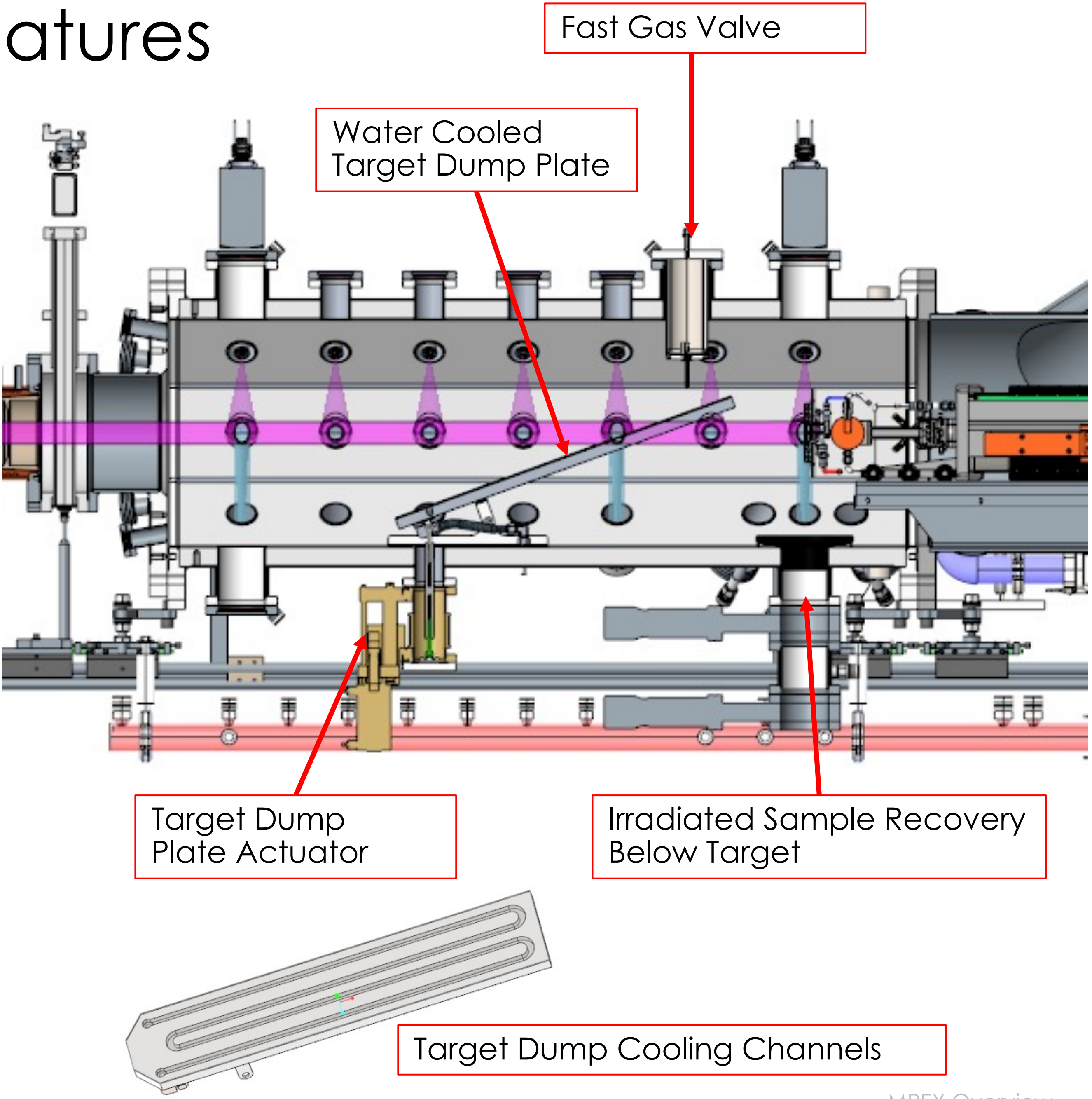


- PMI chamber 68 ports
- Currently planned diagnostics and other systems occupy 29 ports.

➢ **Good news: 39 ports are still available for other diagnostics !**

PMI Chamber – Internal Features

- Target is protected during plasma start-up by target dump.
- Gas fueling close to target is possible.
- Disintegrating samples and dust can be recovered by dedicated recovery system.
- Most ports are perpendicular to plasma and perhaps mirrors or periscopes need to be deployed to allow for best optical path.



Fast Gas Valve

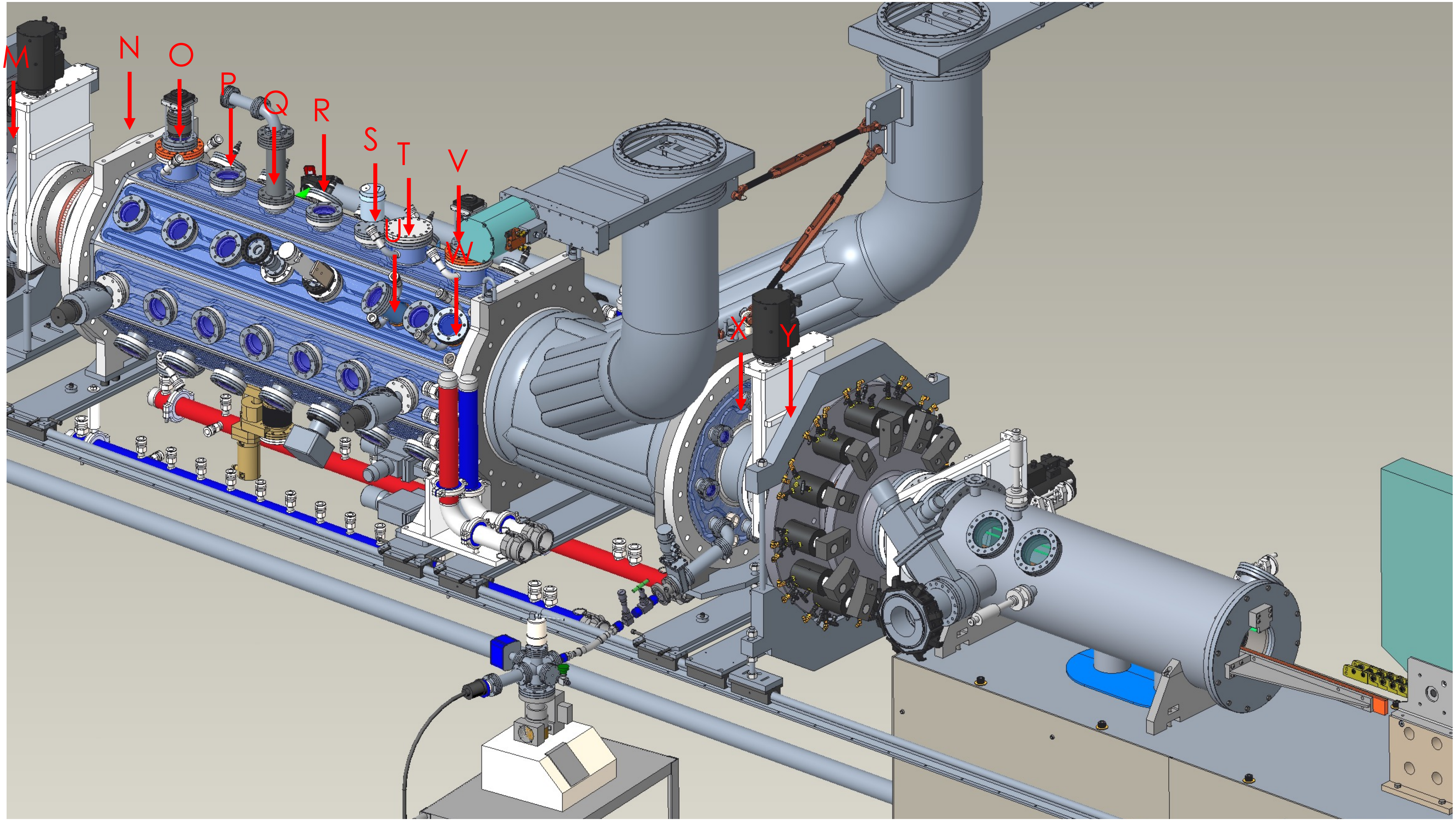
Water Cooled Target Dump Plate

Target Dump Plate Actuator

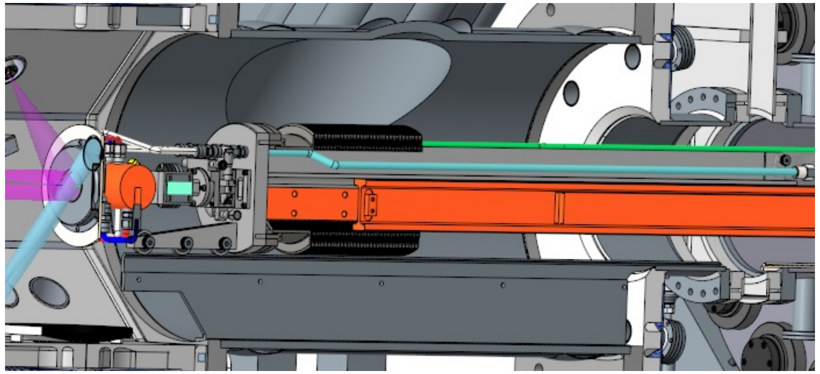
Irradiated Sample Recovery Below Target

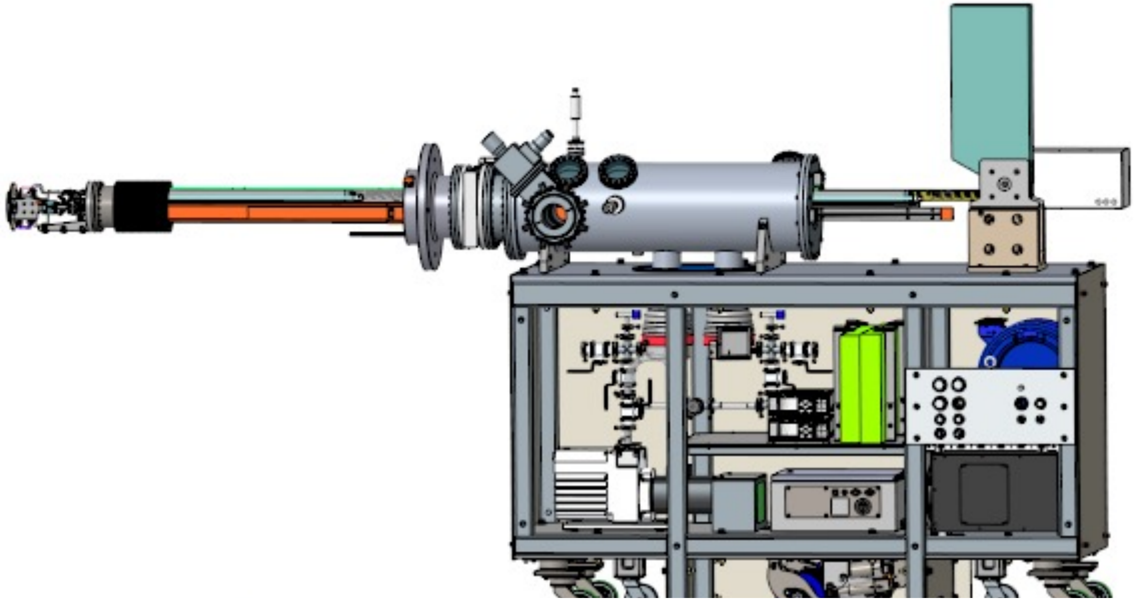
Target Dump Cooling Channels

MPEX PMI region

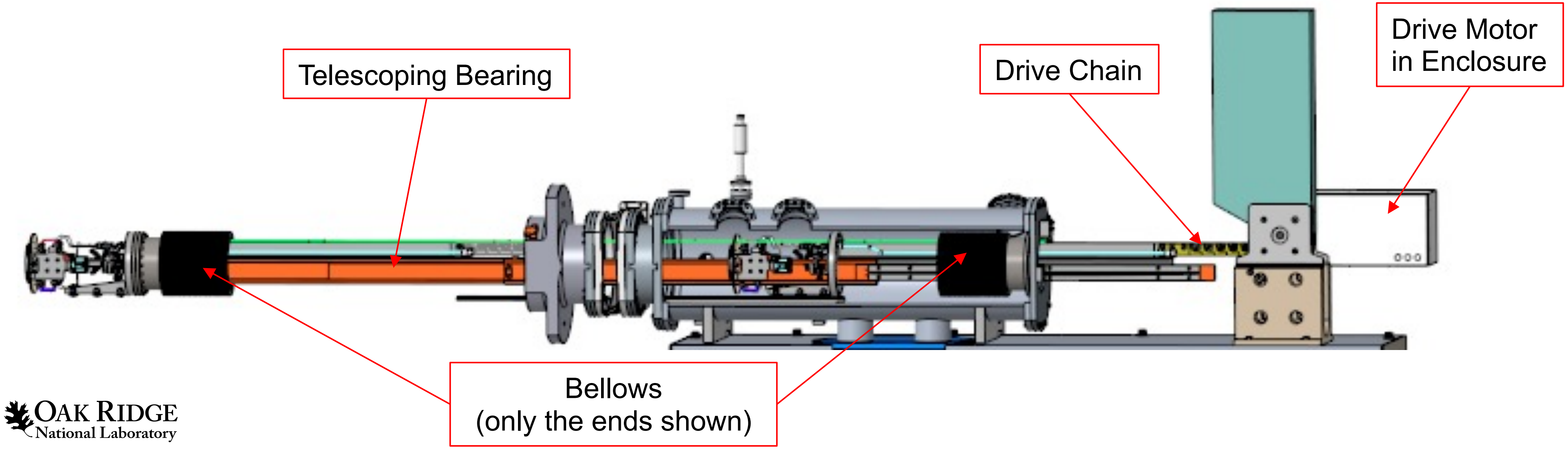


Target Exchange Chamber (TEC)





- Compact target exchange chamber allows for target analysis on a surface analysis station during plasma intermittences.
- Telescoping arm is crucial to make this concept compact.



Alkali metal targets < 3.45 moles in-vessel

3.45 moles is equivalent to:

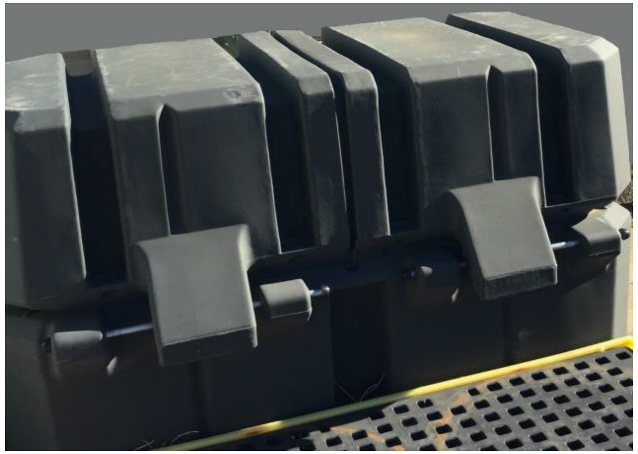
24 g	Li	-> 45 cm^3
79 g	Na	-> 81 cm^3
134 g	K	-> 155 cm^3
295 g	Rb	-> 181 cm^3
459 g	Cs	-> 244 cm^3

45 cm^3 of lithium equivalent to about 3 1" cubes

A standard 12-mm-DIA MPEX target 1 mm thick of pure lithium would weigh 204 mg

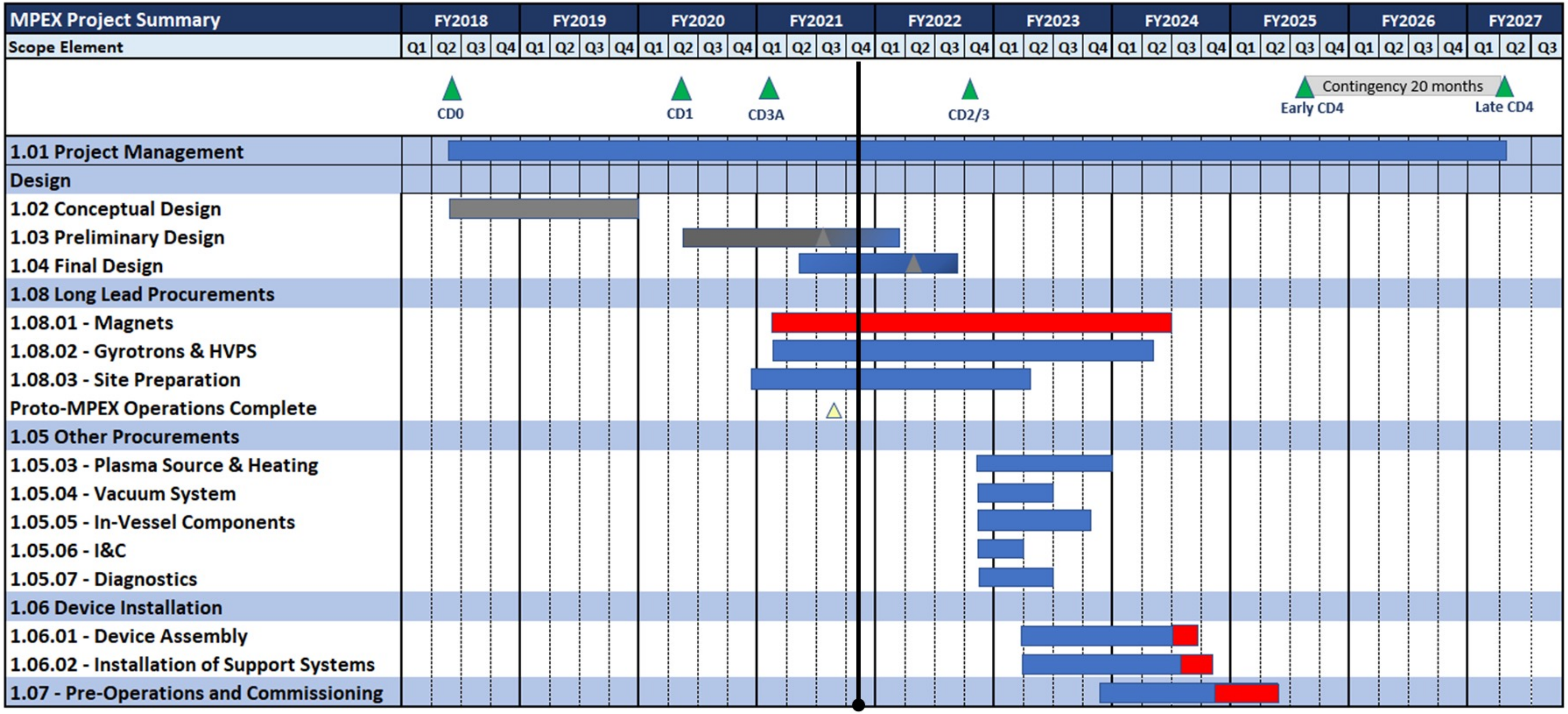
Storage if > 2.3 kg

- Must adhere to NFPA 484 Standard for Combustible Metals (ALL OF IT –you can't pick and choose. It's extensive!)
- Store alkali metals in fireproof metal cabinets or steel drums



Fast-flowing Liquid Alkali Metal Targets > 3.45 moles are not supported by MPEX design

MPEX project schedule



Summary and conclusions

- MPEX is a project to address U.S. community needs.
- The physics basis of MPEX has been developed on Proto-MPEX.
- The preliminary design of MPEX has been completed.
- On the current schedule MPEX is expected to have first plasma in 2025.

Back-up slides