



EUROPEAN
SPALLATION
SOURCE

THE BEAM CONDITIONS ON THE TARGET AND ITS OPERATIONAL IMPACTS ON BEAM INTERCEPTING DEVICES AT ESS

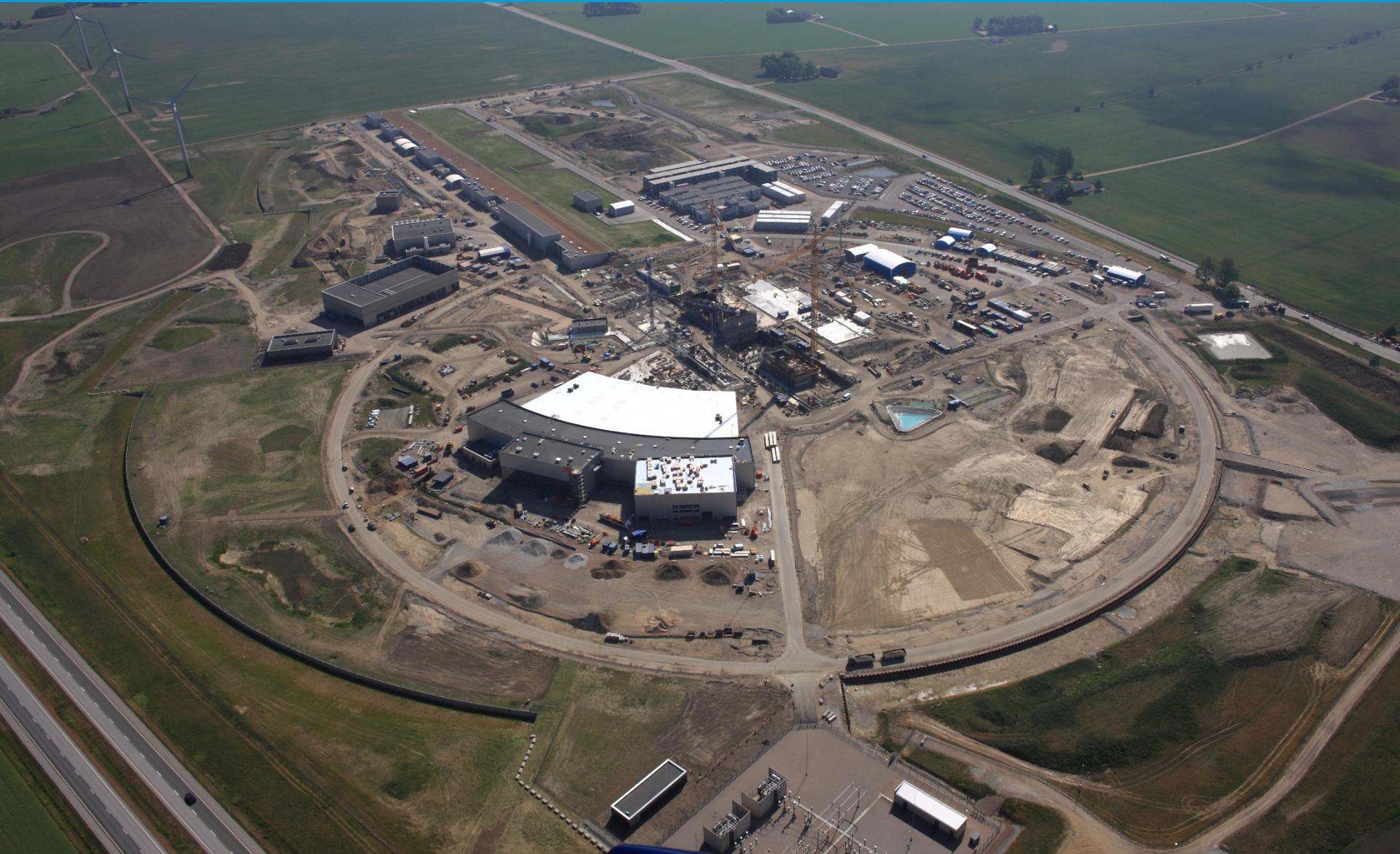
Yong Joong Lee (ESS)

Heine Dølrath Thomsen (Aarhus University)

Ryoichi Miyamoto (ESS)

Thomas Shea (ESS)

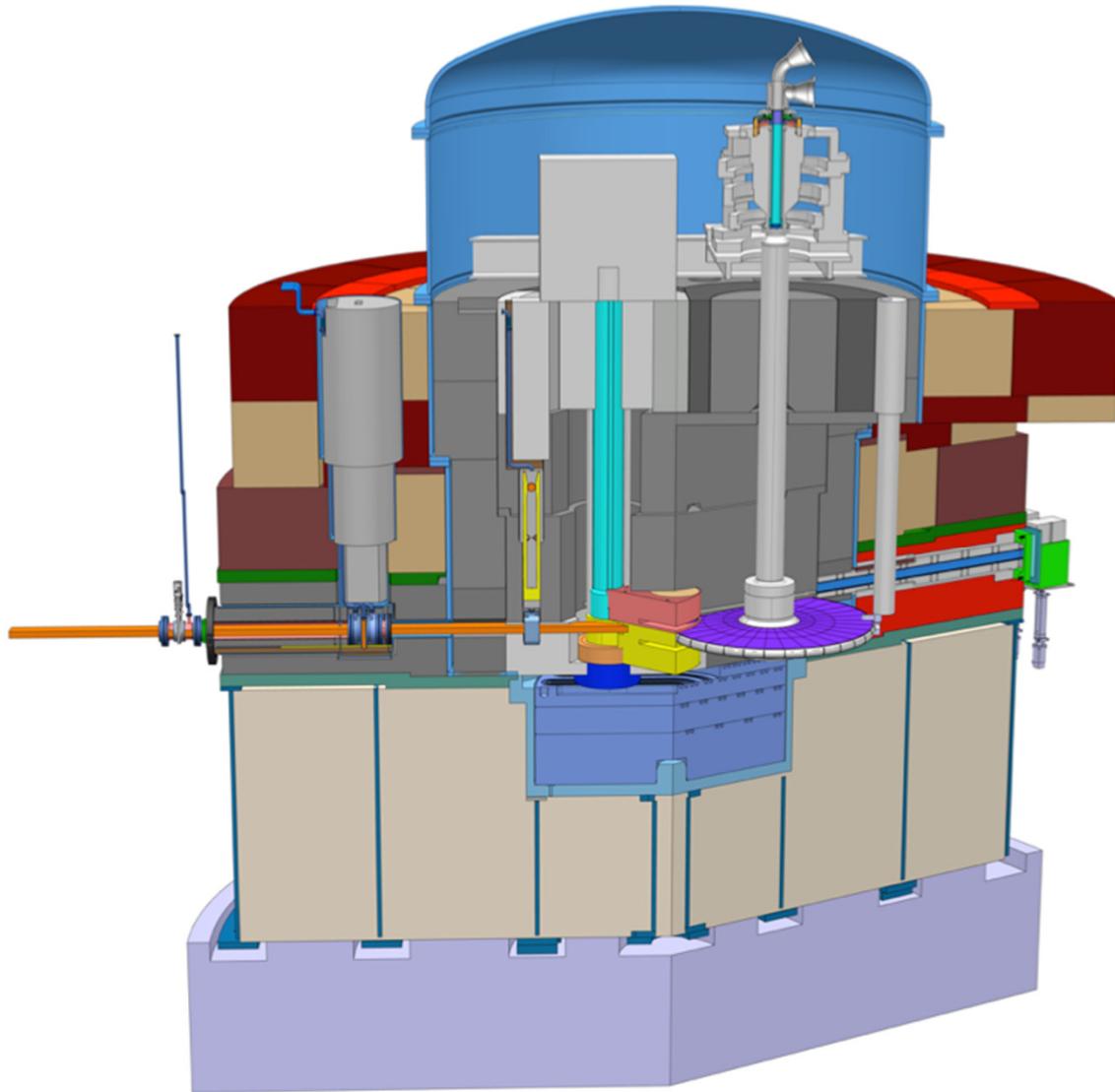
Building ESS: 45% Completion in June 2018



Target Station in June 2018

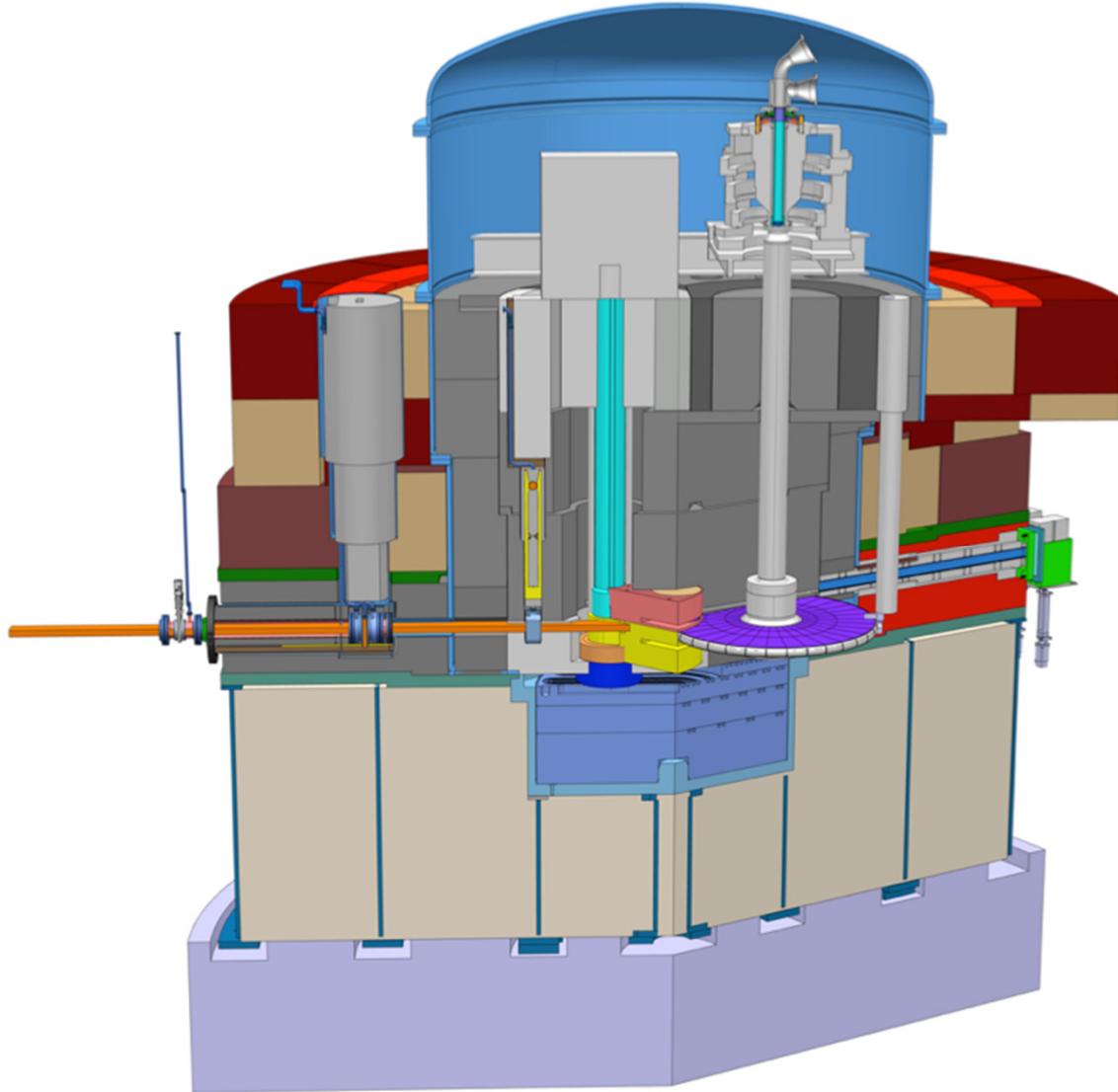


ESS Target Environment

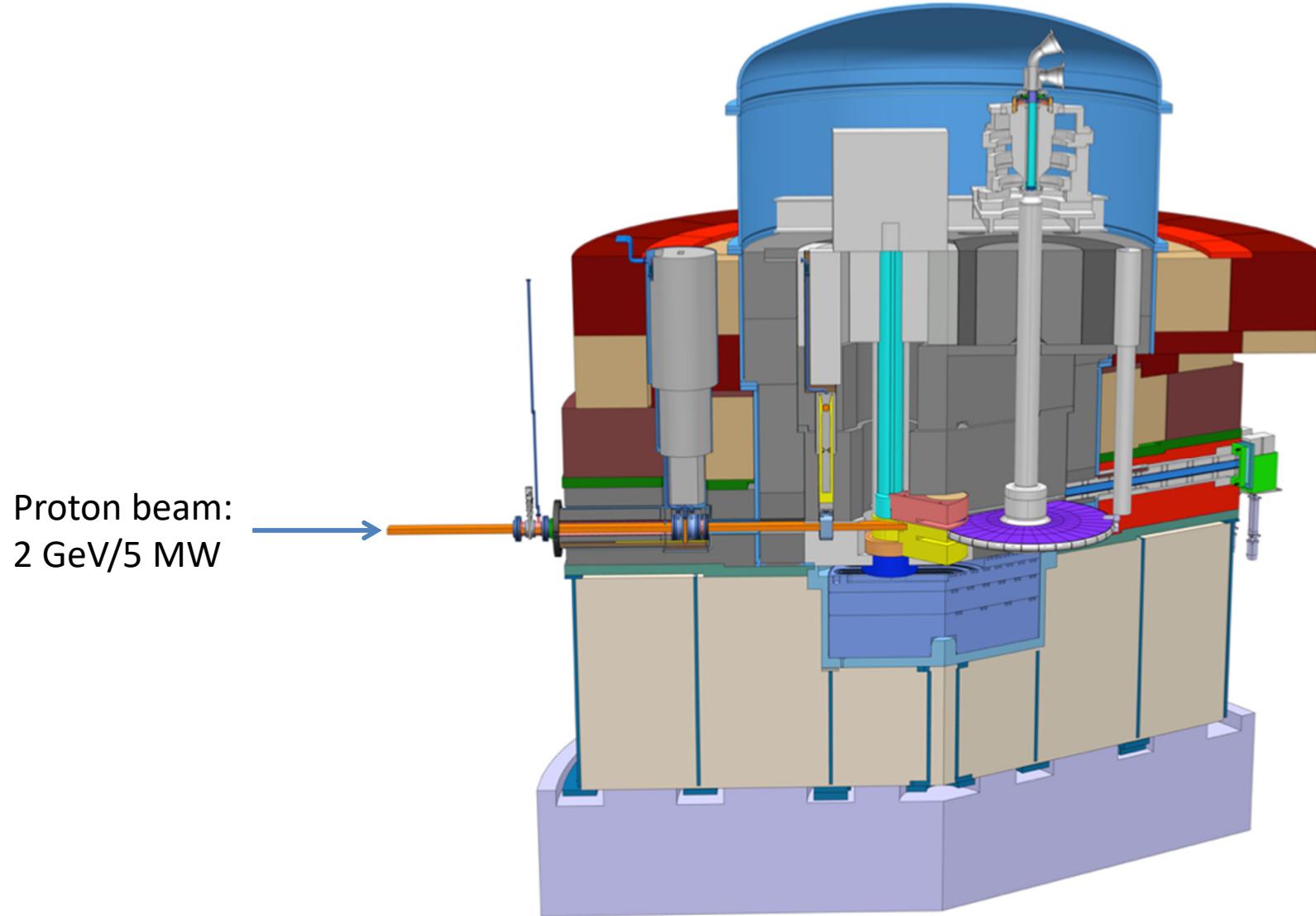


ESS Target Environment

Proton beam:
2 GeV/5 MW



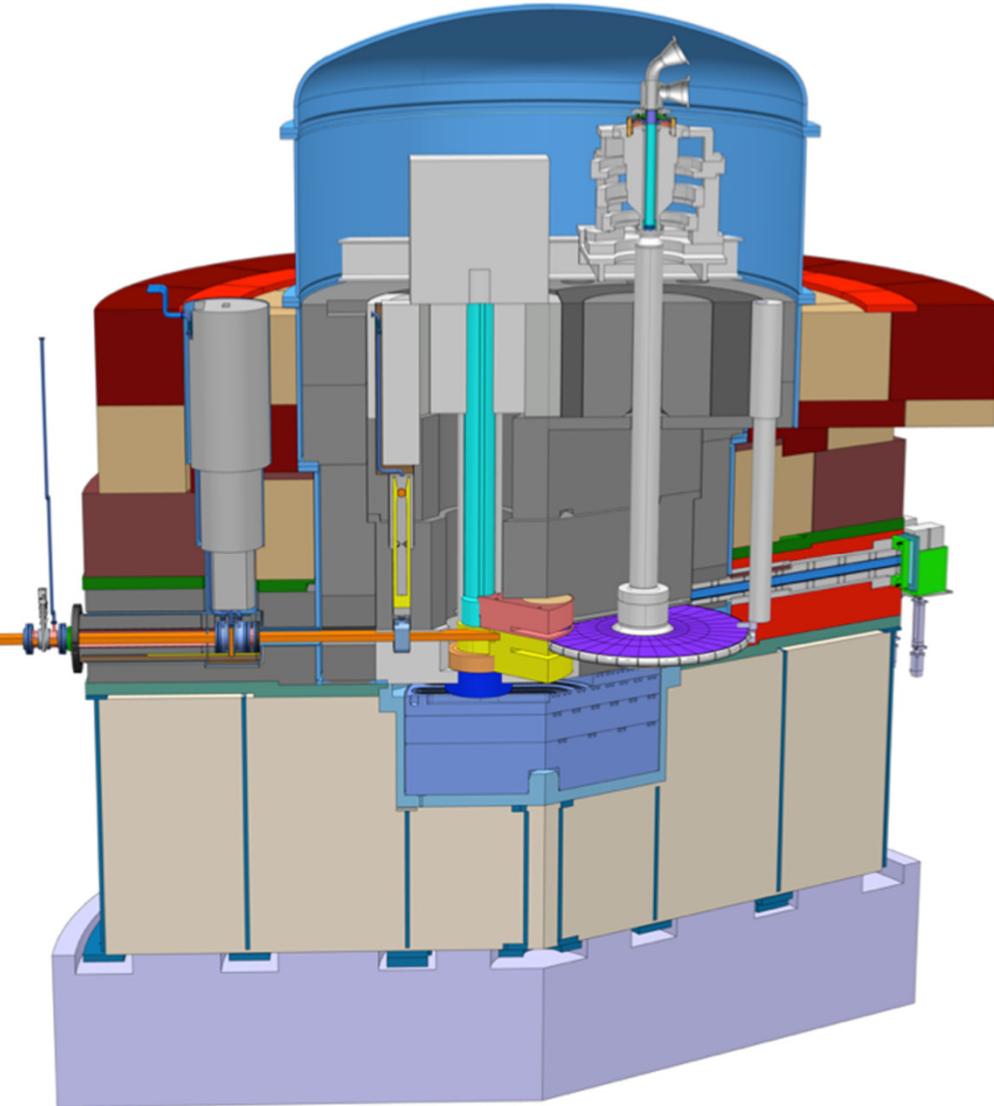
ESS Target Environment



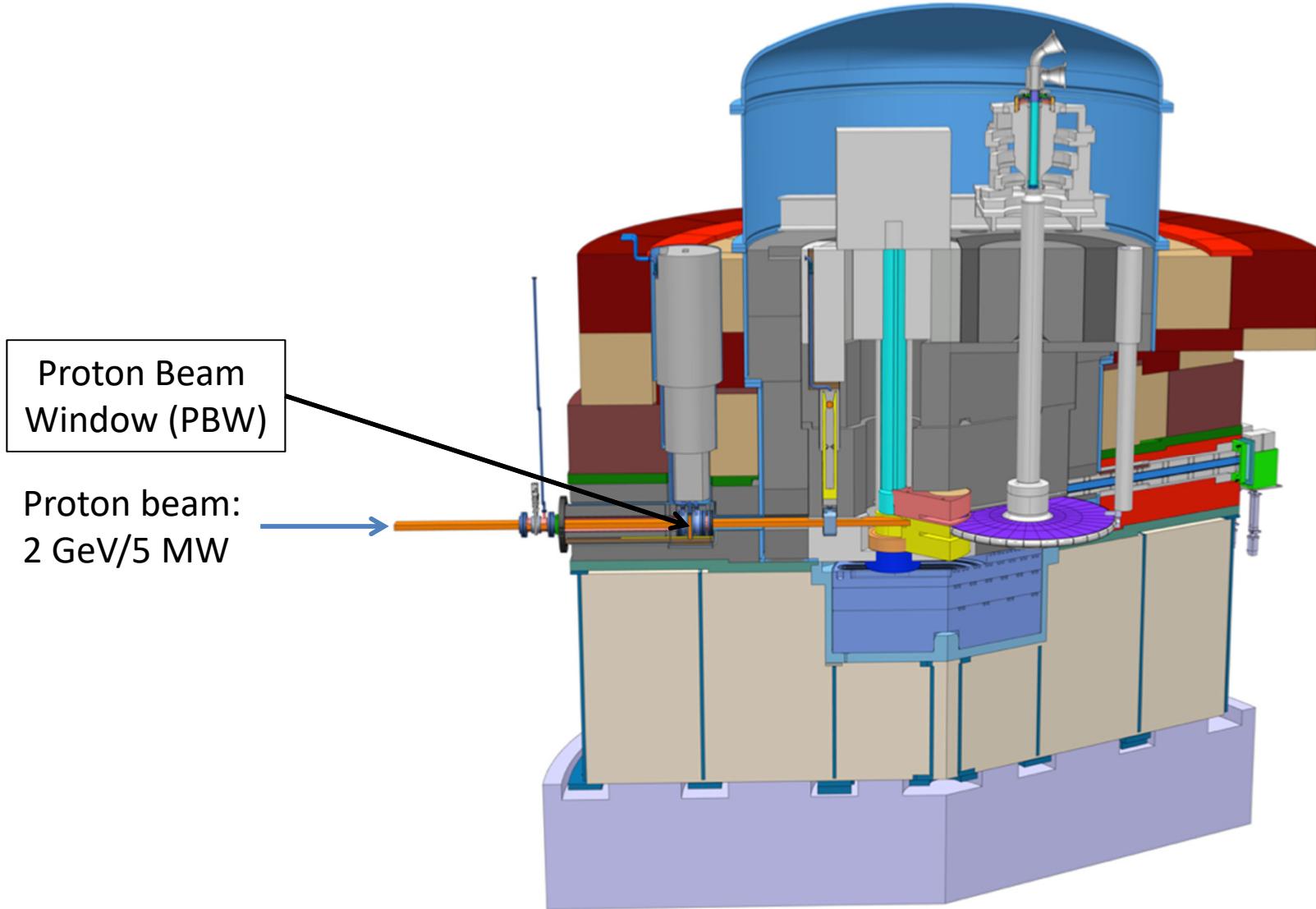
ESS Target Environment

Proton Beam
Window (PBW)

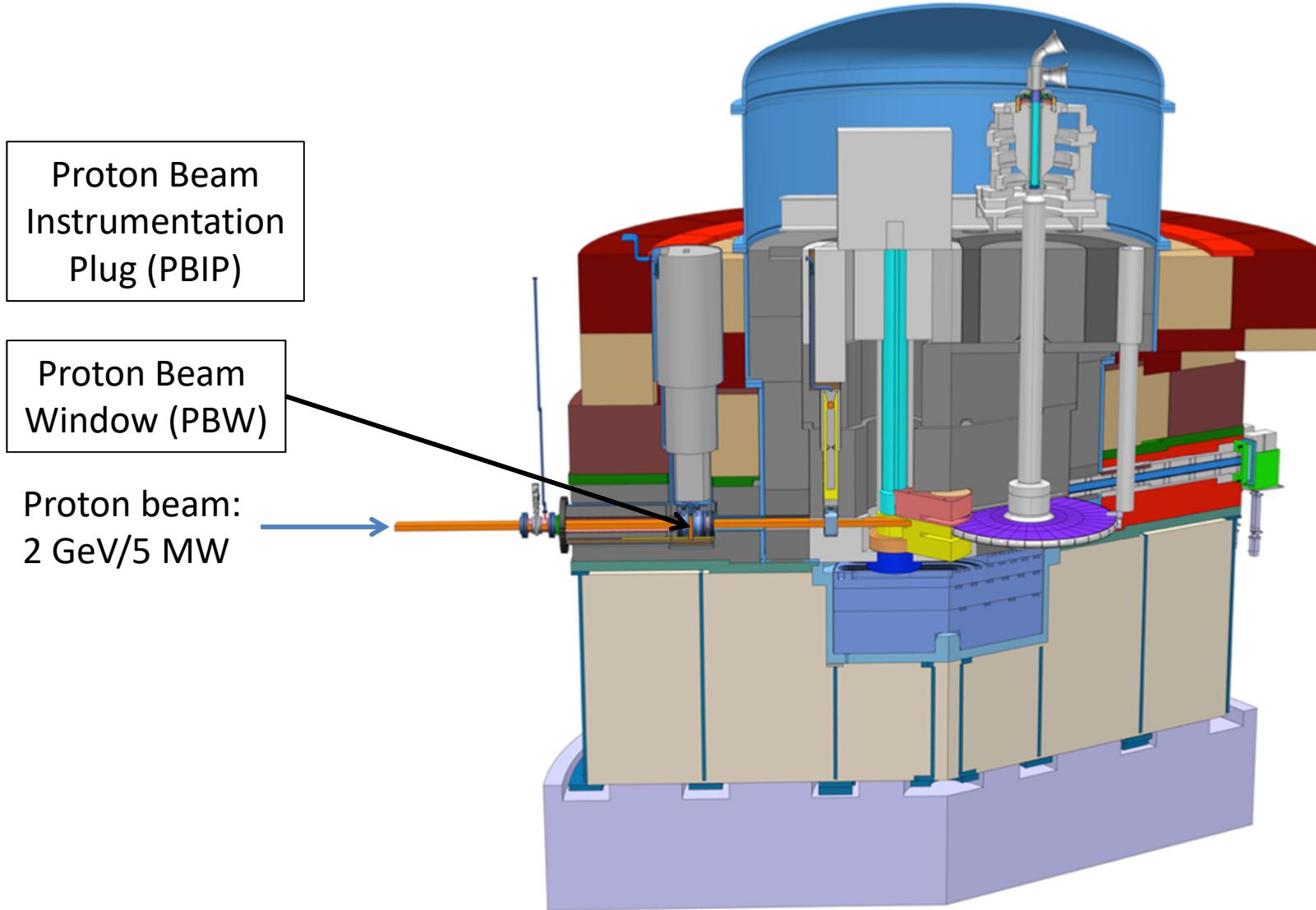
Proton beam:
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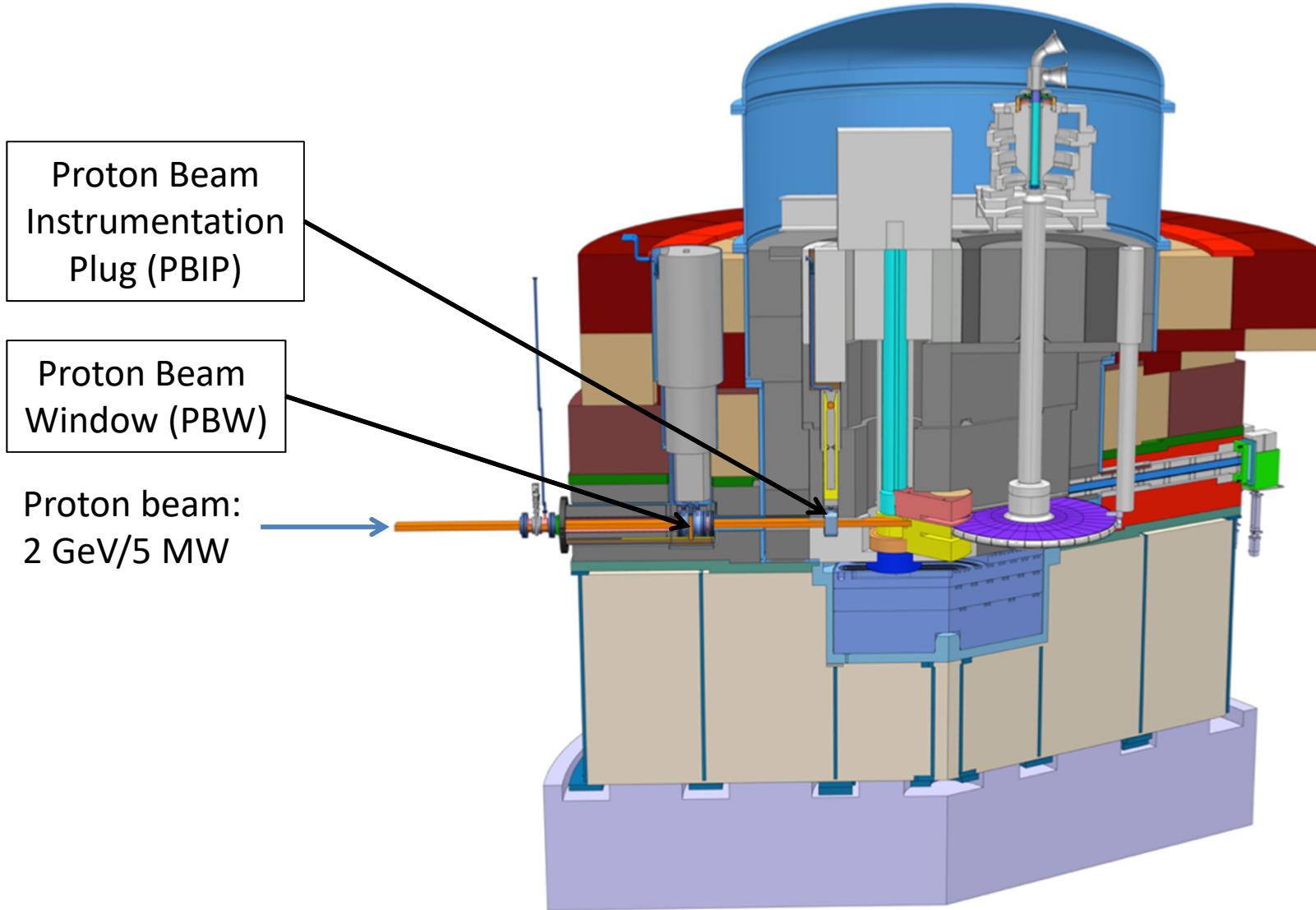
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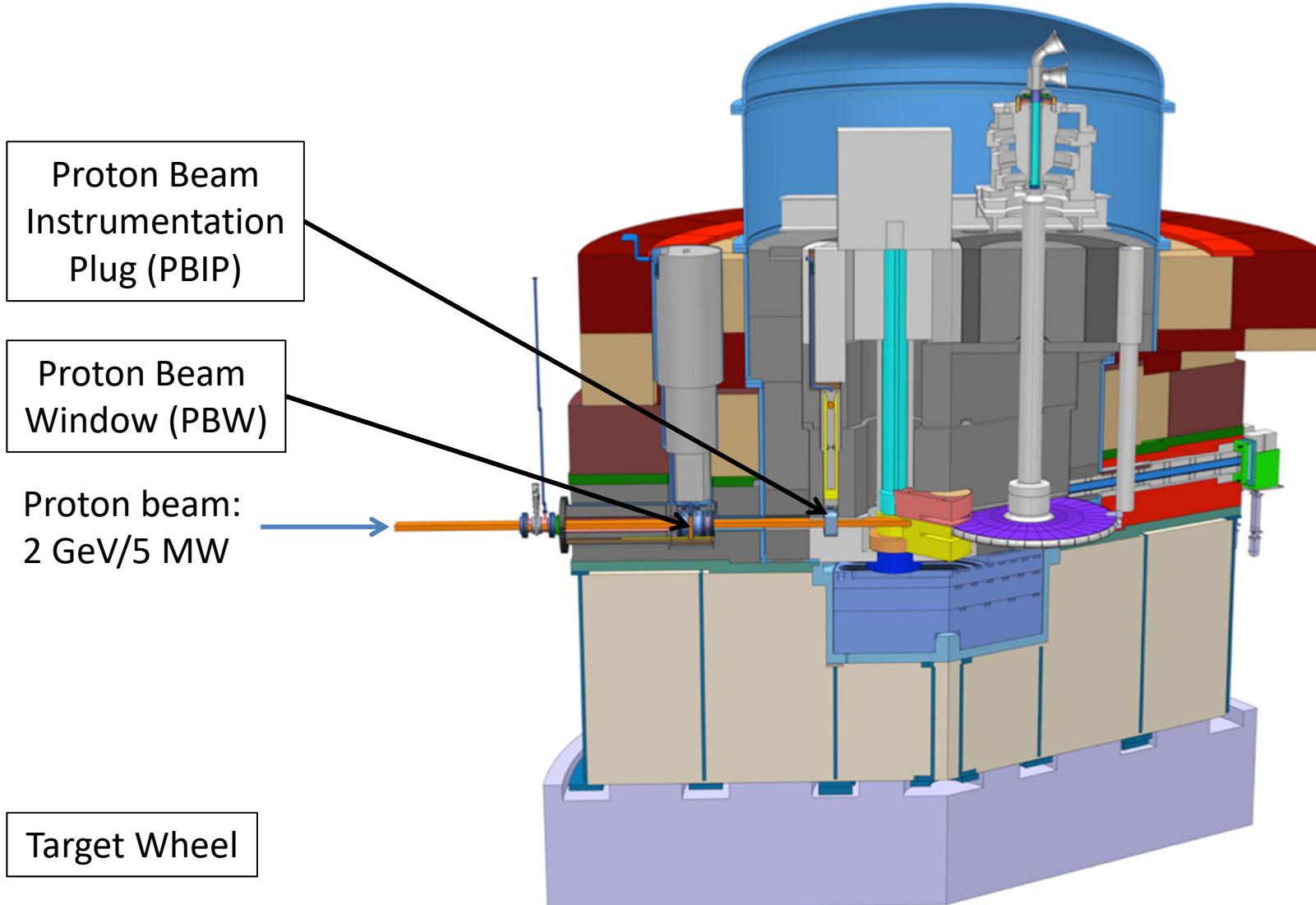
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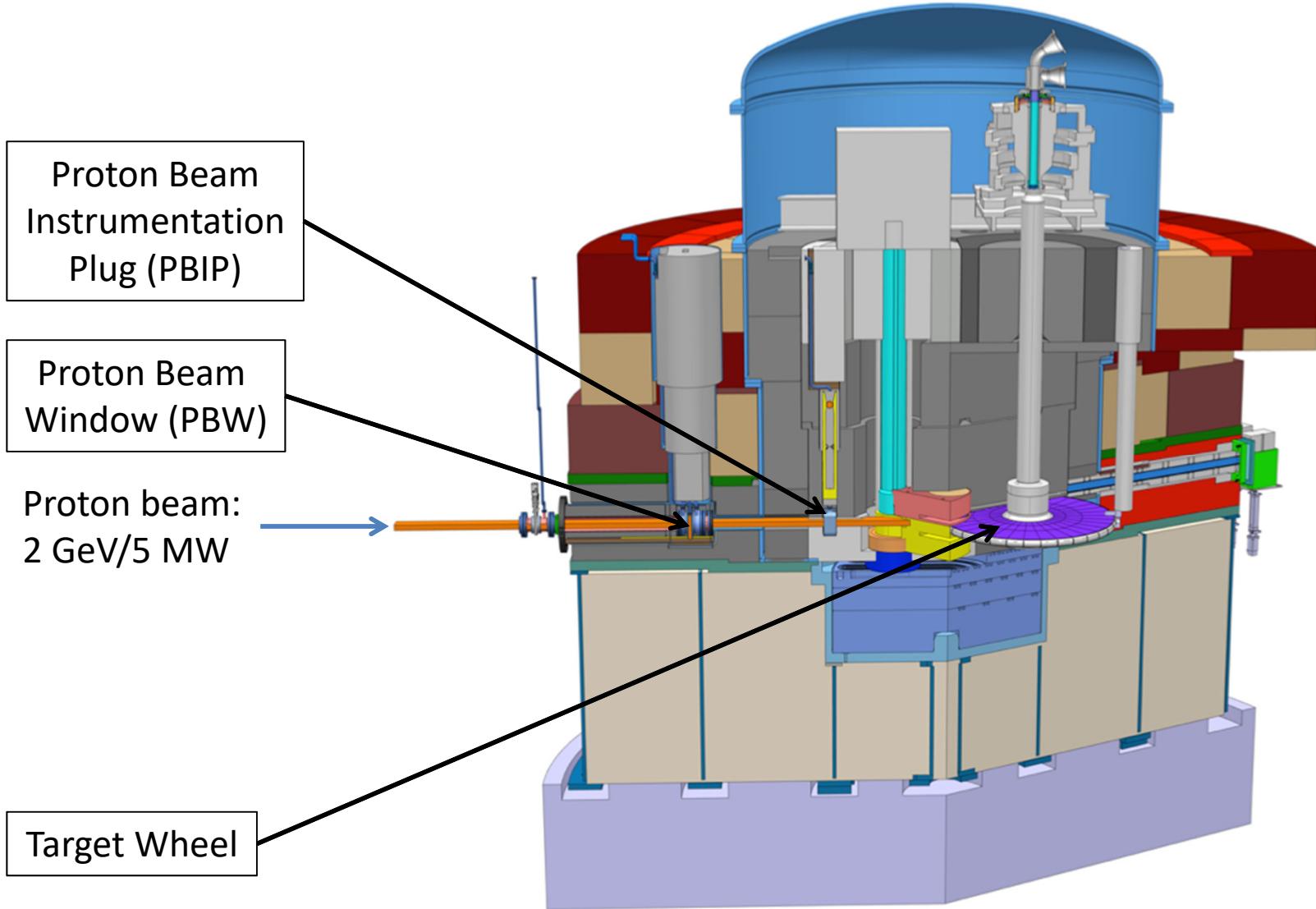
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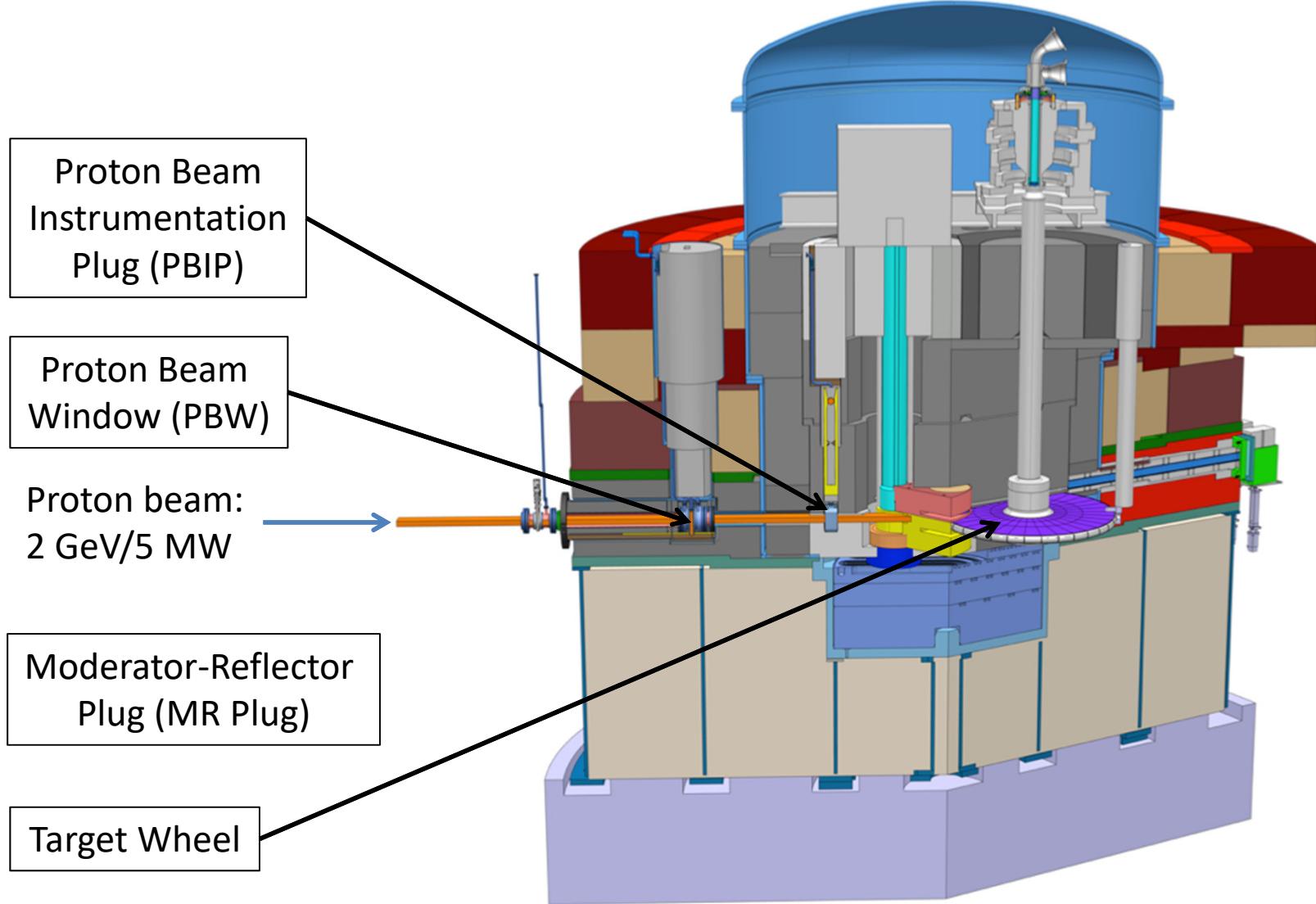
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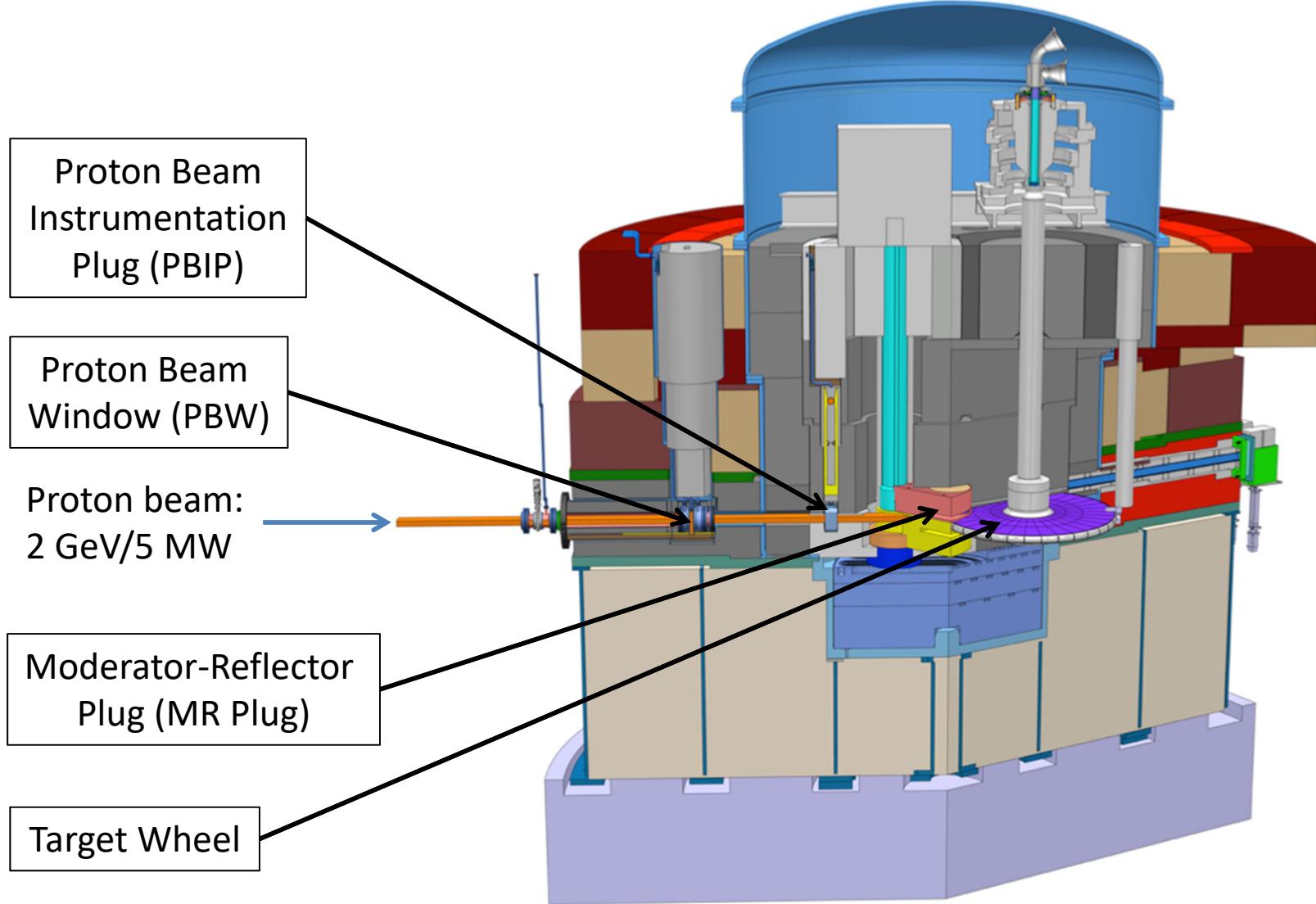
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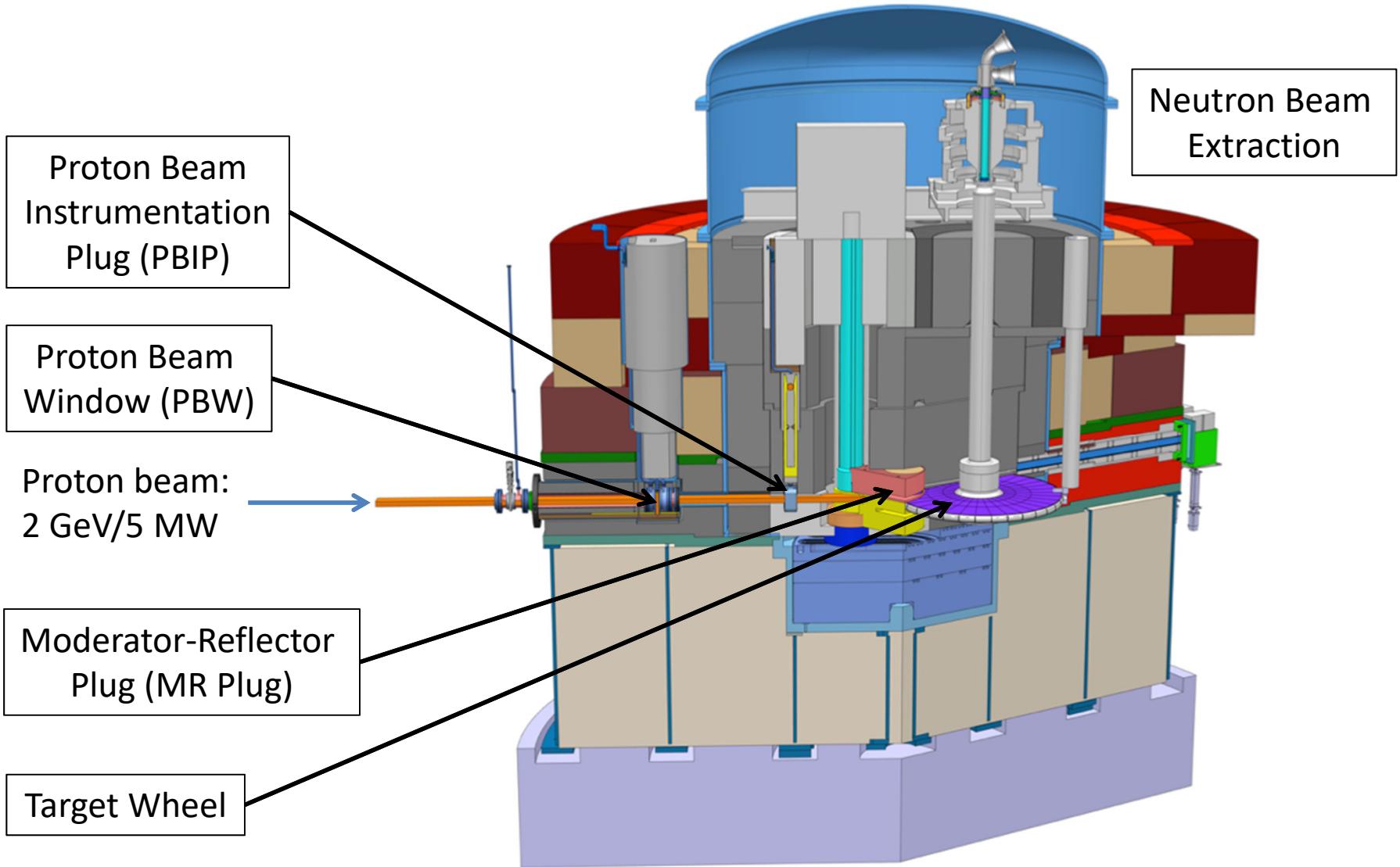
ESS Target Environment



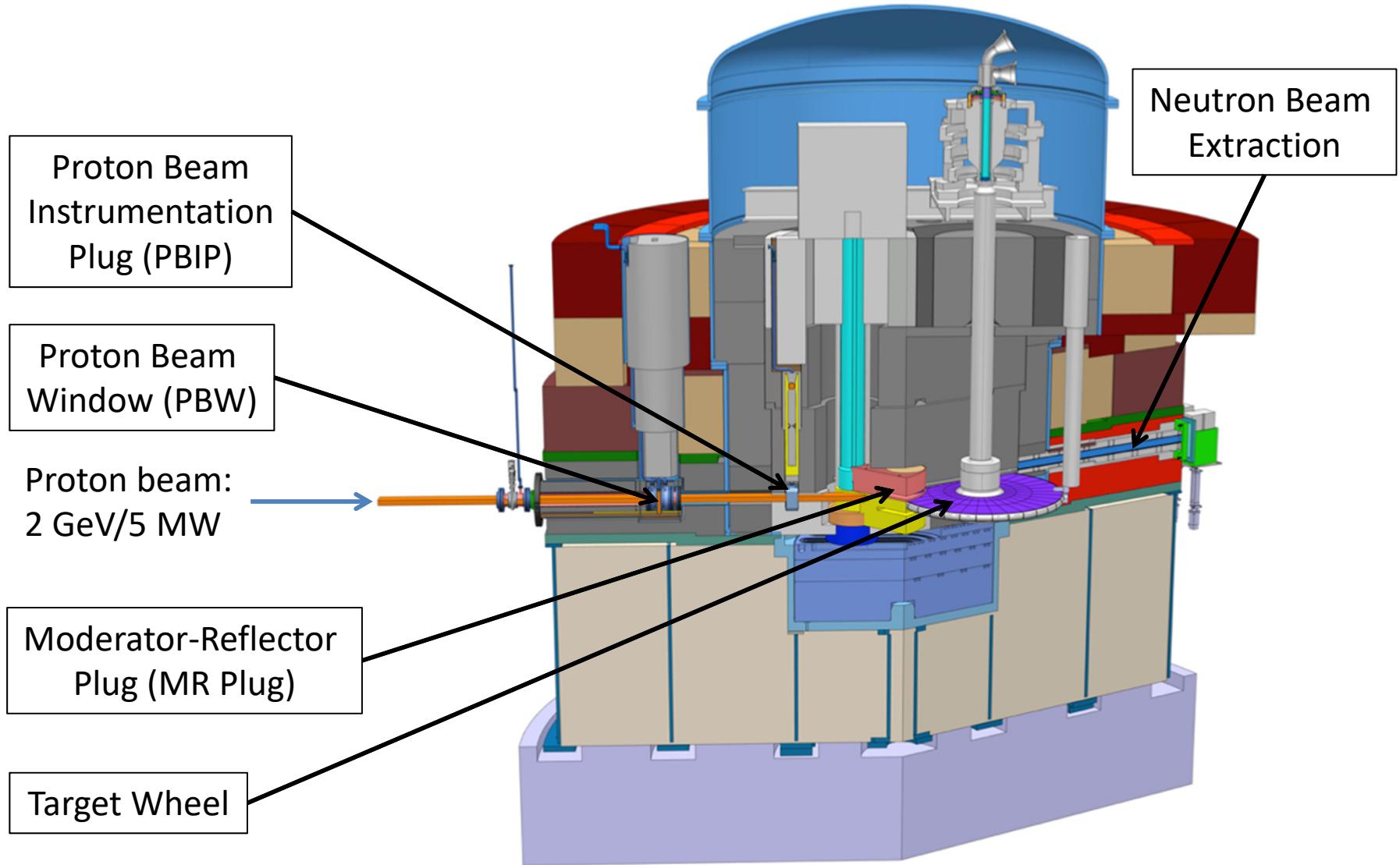
ESS Target Environment



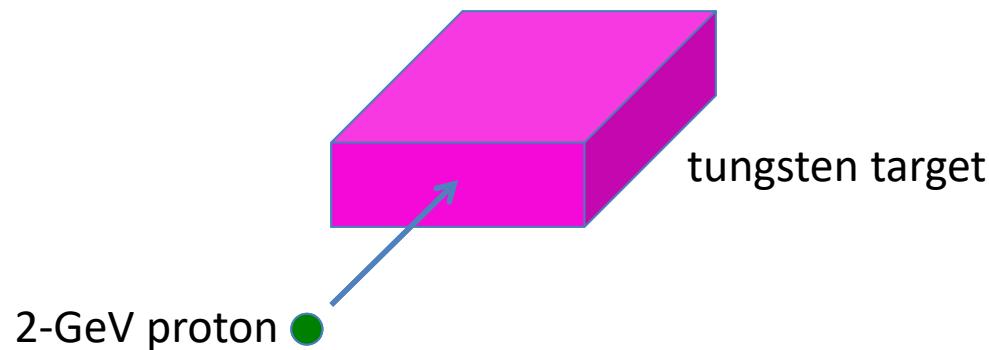
ESS Target Environment



ESS Target Environment

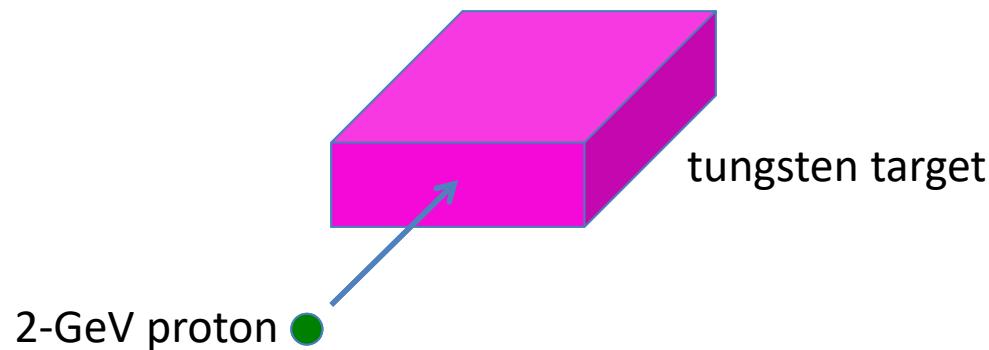


ESS Target Station: High Level Functions



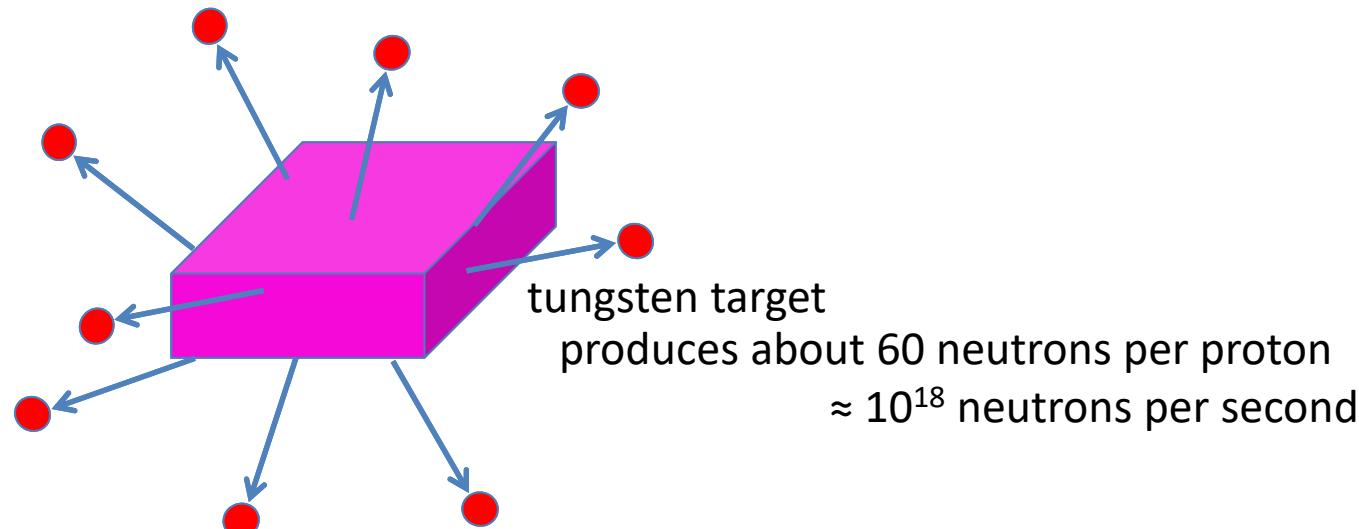
ESS Target Station: High Level Functions

Generate spallation neutrons



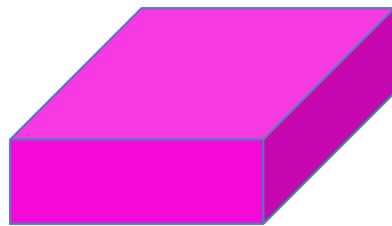
ESS Target Station: High Level Functions

Generate spallation neutrons



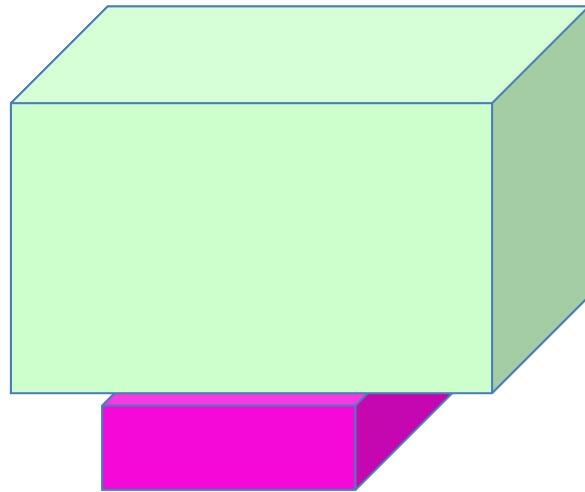
ESS Target Station: High Level Functions

Generate spallation neutrons

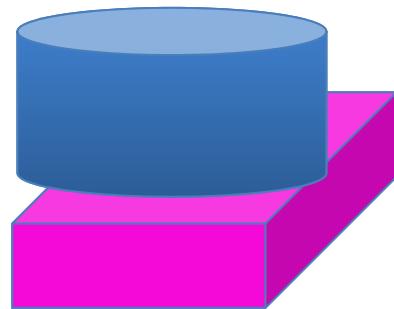


ESS Target Station: High Level Functions

Beryllium reflects neutrons that might otherwise escape, boosting performance by a factor of 5



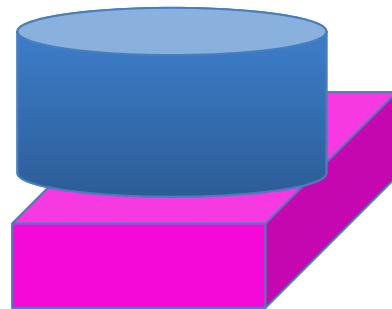
ESS Target Station: High Level Functions



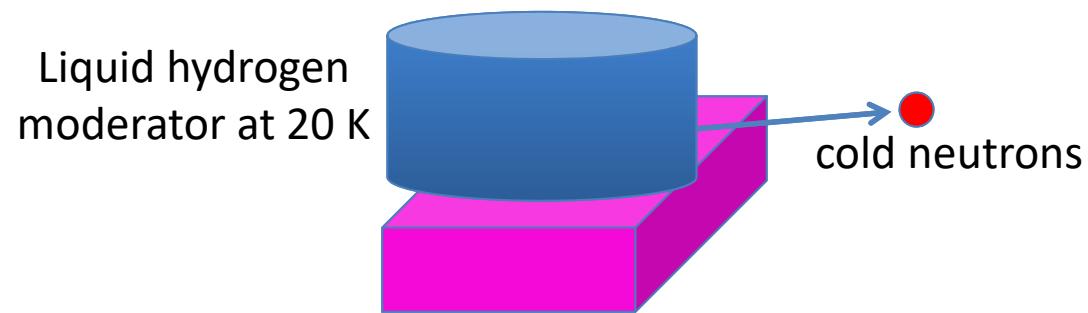
ESS Target Station: High Level Functions

Slow the neutrons to speeds useful for science

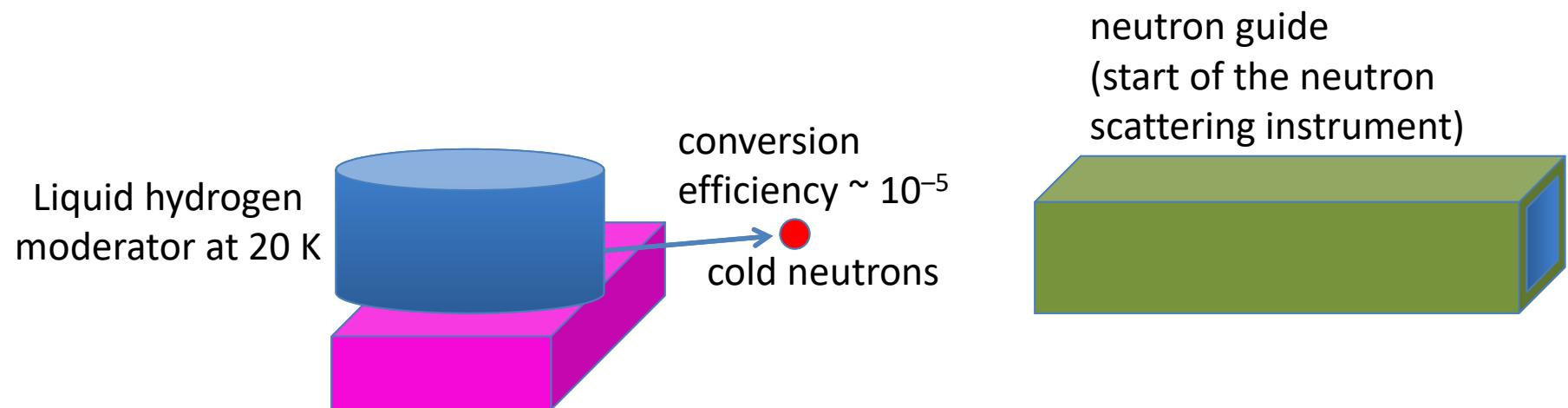
Liquid hydrogen
moderator at 20 K



ESS Target Station: High Level Functions

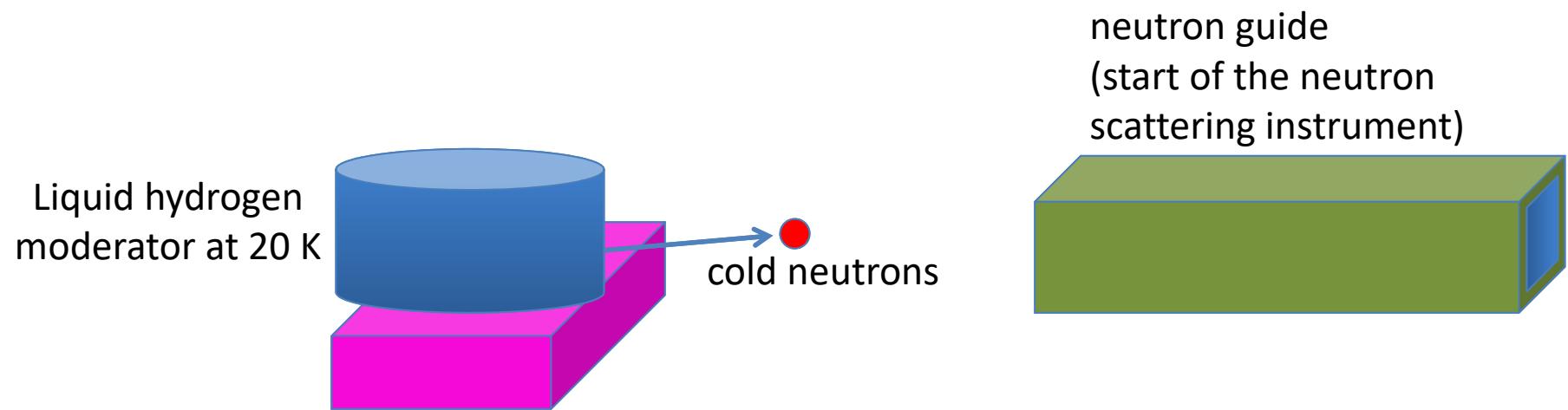


ESS Target Station: High Level Functions



Guide neutrons to neutron scattering instruments

ESS Target Station: High Level Functions



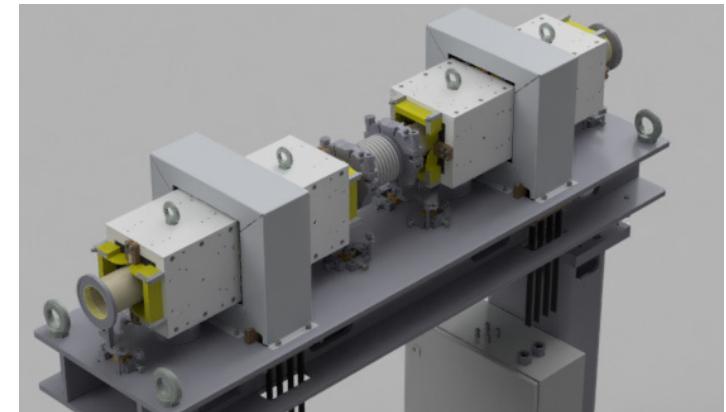
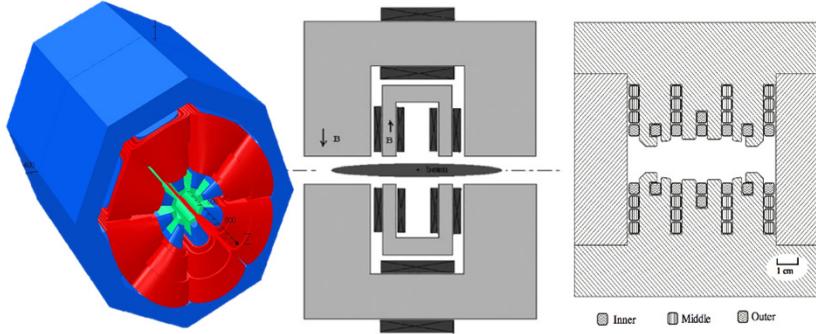
High Power Spallation Target

- The ESS target stops 5 MW beam
 - It's like stopping a Mercedes-Benz S-Class (2000 kg in weight) driving at 255 km/h every second.



Beam on Target

- Conflicting requirements:
 - **Uniform beam spot:** Lower damage rate and thermal load
 - **Minimum beam loss:** Higher neutron yield and lower heat deposition in target monolith structure
- Beam expander options:
 - **Nonlinear magnets:** relatively higher beam loss and risk of beam focusing via H-V coupling
 - **Raster scanning magnets:** introduces a time structure for CW or long-pulse beam



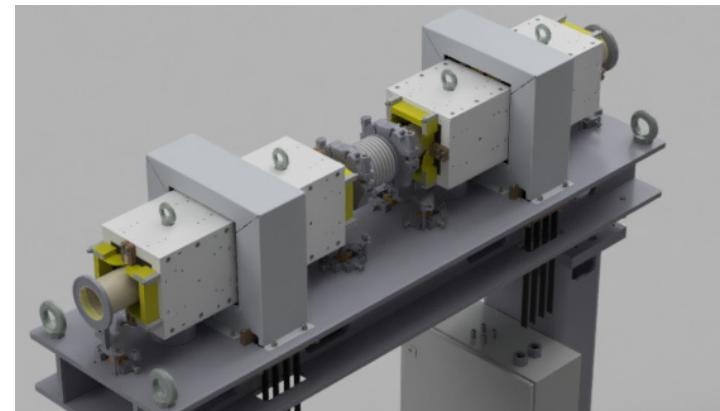
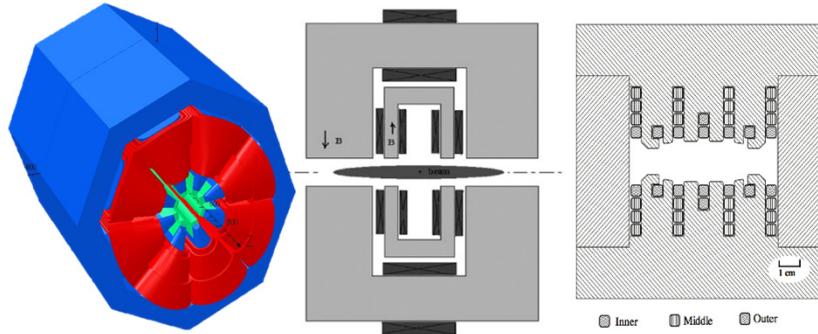
Beam on Target

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 - **Nonlinear magnets:** relatively higher beam loss and risk of losses focusing via H-V coupling
 - **Raster scanning magnets:** introduce a pulsed beam

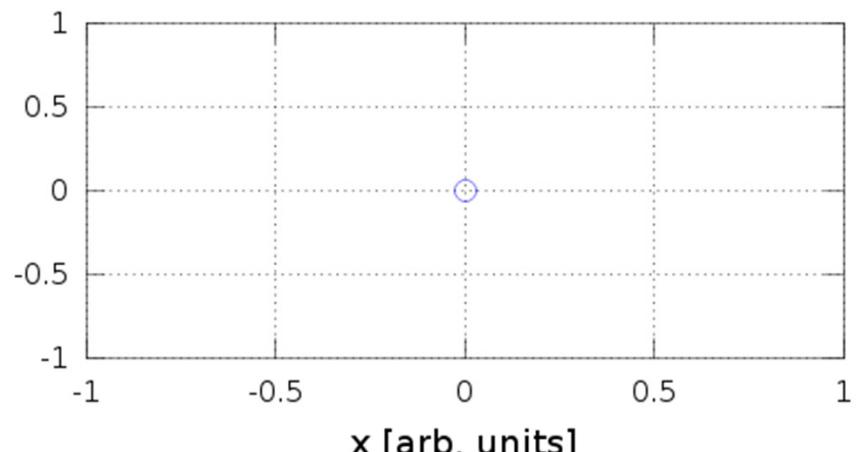
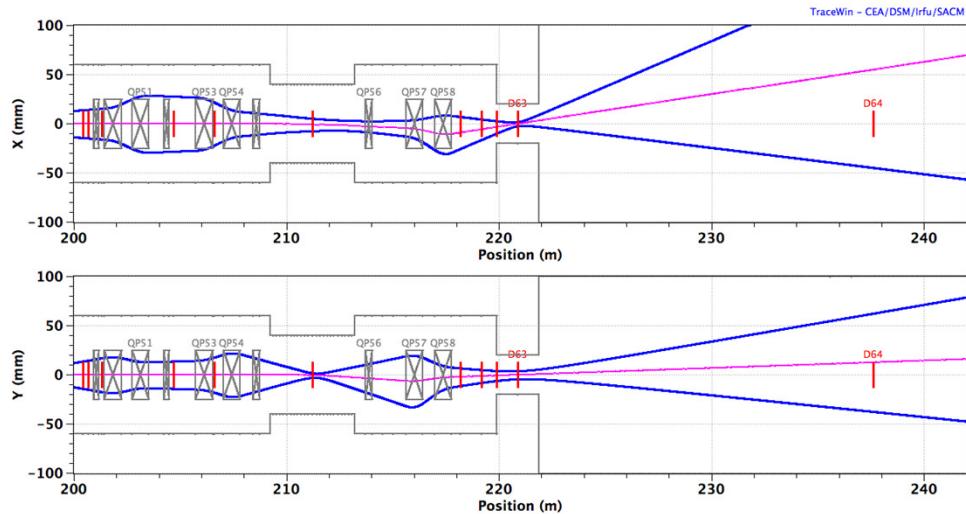
For more details on beam raster at ESS:

N. Milas, 14:00 Wed (WG-B)

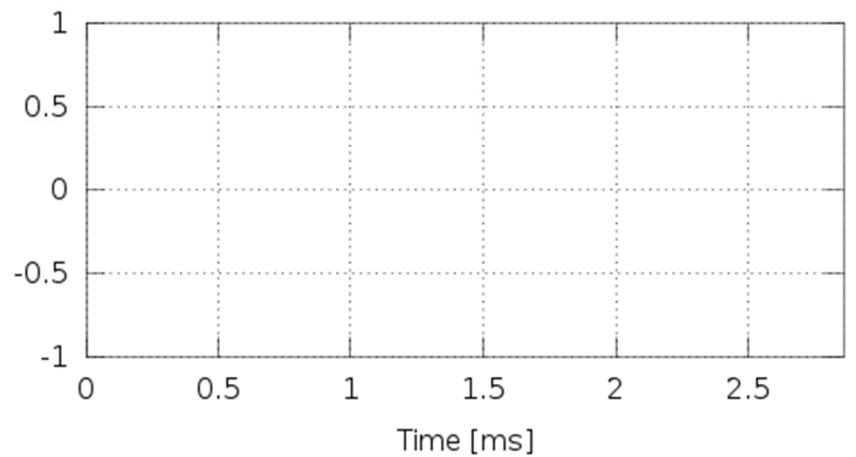
Beam Dynamics of the ESS linac



ESS Beam Raster

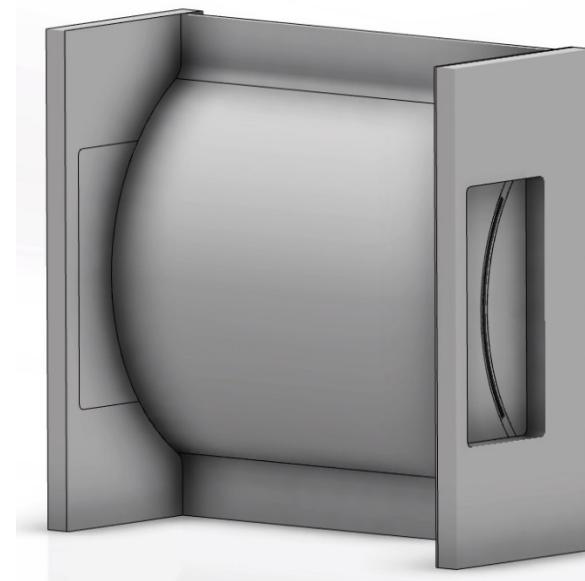
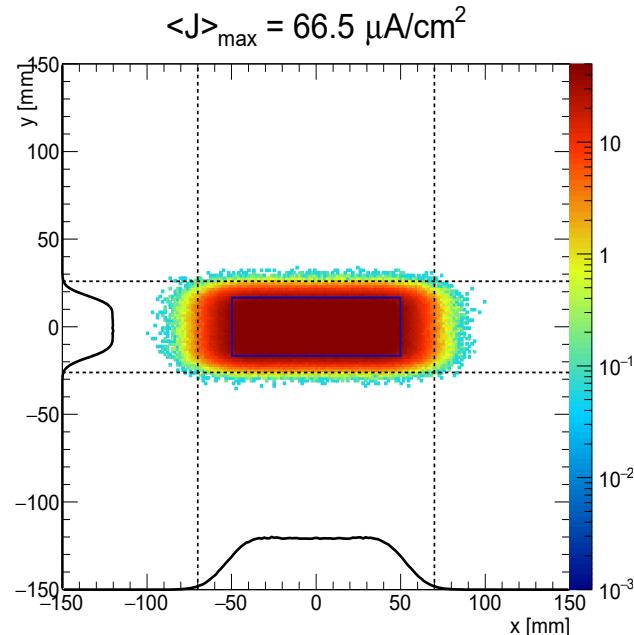


Parameter	Value
Beam pulse length	2.86 ms
Sweep frequency - horizontal	39.55 kHz
Sweep frequency - vertical	29.05 kHz



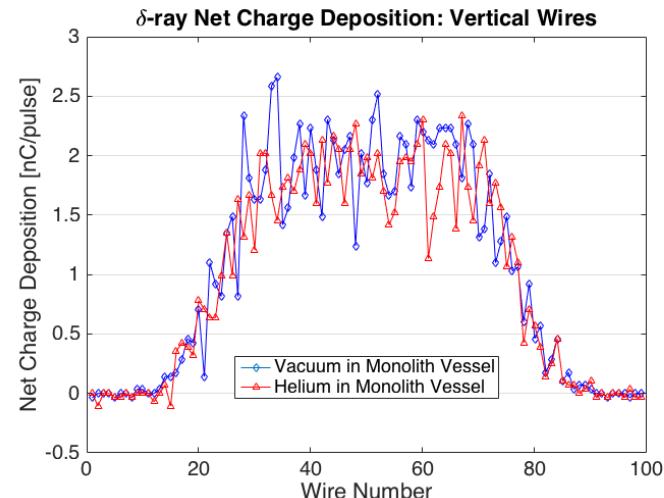
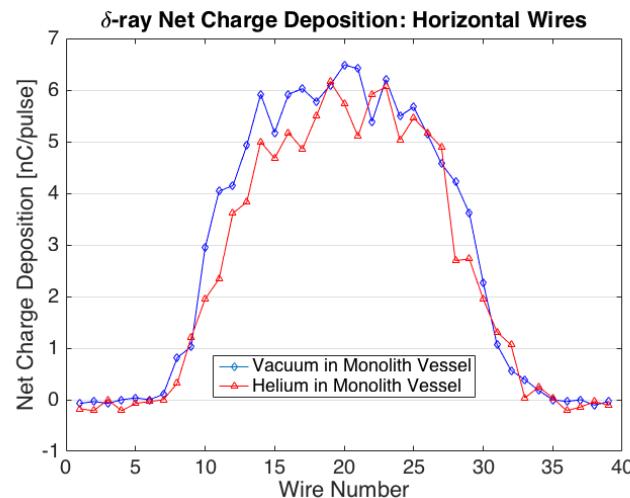
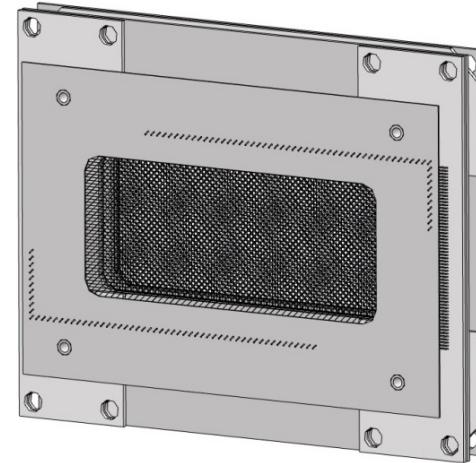
Proton Beam Window

Parameter	Unit	Value
Material		Al6061-T651
Raster deflection, horizontal	mm	47.4
Raster deflection, vertical	mm	15.8
Beamlet RMS, horizontal	mm	10.67
Beamlet RMS, vertical	mm	3.99
Peak current density	mA/cm ²	1.66



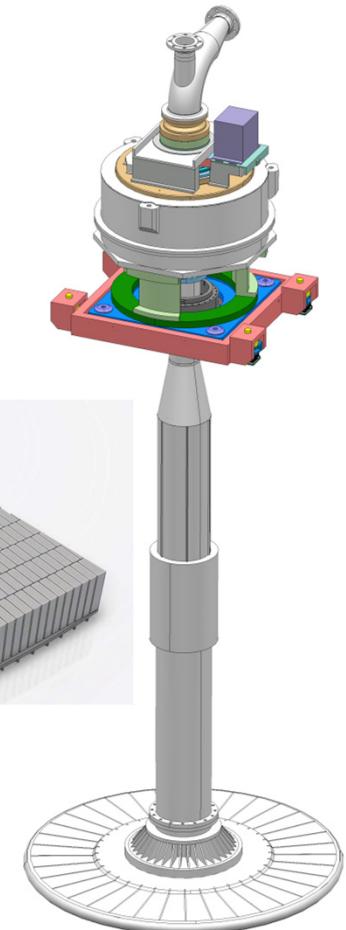
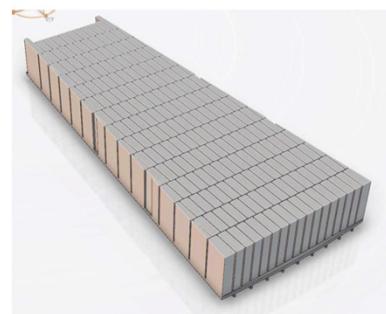
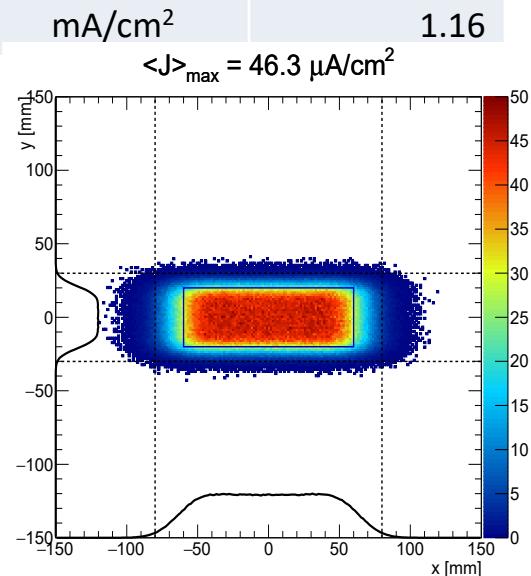
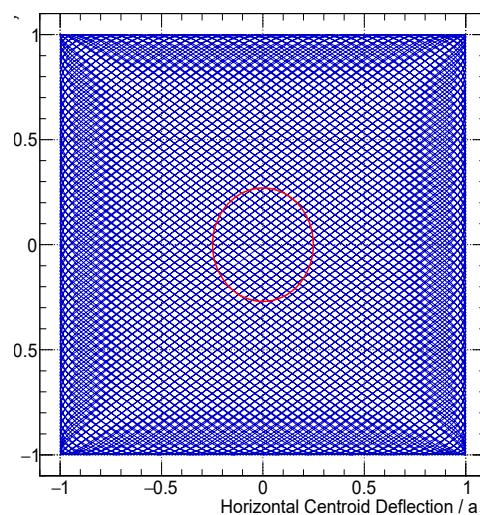
Multiwire Beam Profile Monitor

Parameter	Unit	Value
Material		SiC
Diameter	mm	0.1
Pitch	mm	2
Secondary electron yield	-	0.010
Delta-ray yield	-	0.013
Total electron yield	-	0.023



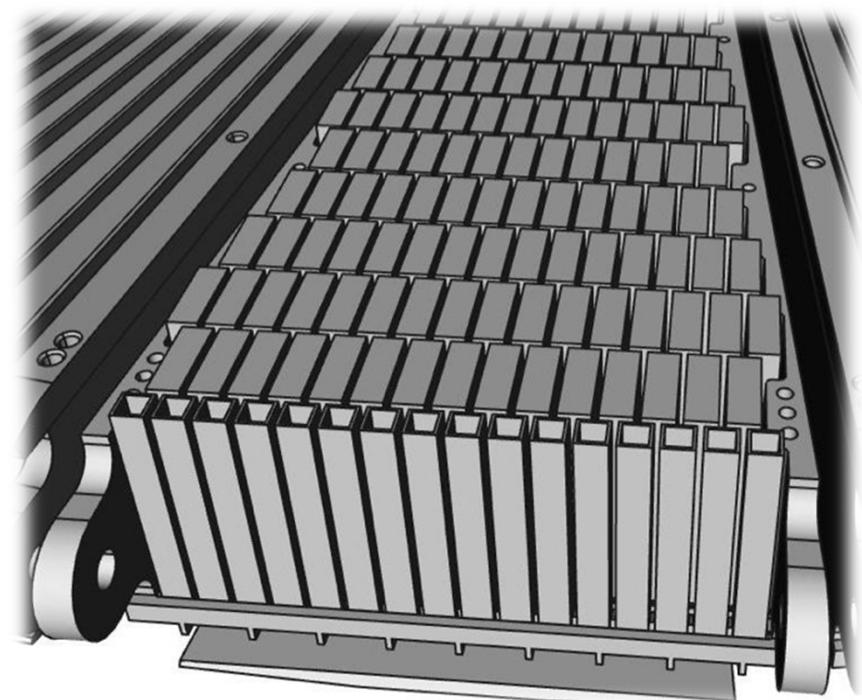
Spallation Target

Parameter	Unit	Value
Beam energy	GeV	2.0
Pulse length	ms	2.86
Repetition Rate	Hz	14
Raster deflection, horizontal	mm	60.0
Raster deflection, vertical	mm	20.0
Beamlet RMS, horizontal	mm	13.5
Beamlet RMS, vertical	mm	5.05
Peak current density	mA/cm^2	1.16



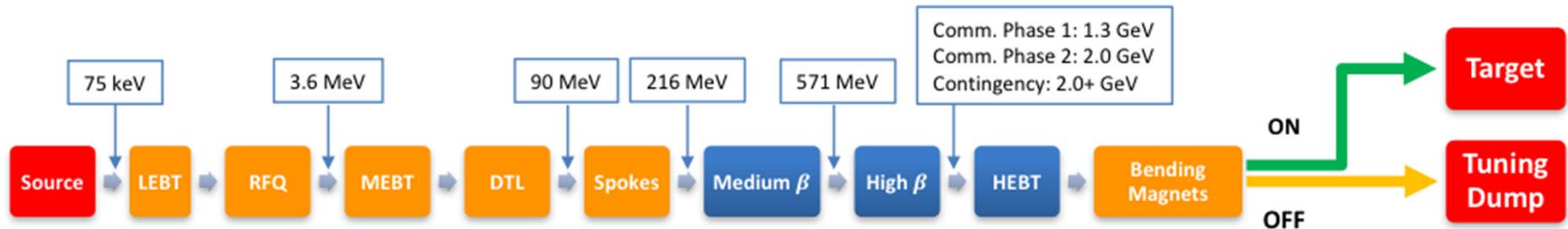
Beam on Target: Target Area Definition

- Proton beam shall not hit the structural part of the target vessel:
- Maximum cross section area of spallation volume: **190 x 70 mm²**.
- Maximum deviation of beam centroid:
 - Horizontal: ± 14.7 mm
 - Vertical: ± 3.0 mm
- Virtual target area: **160 x 64 mm²**



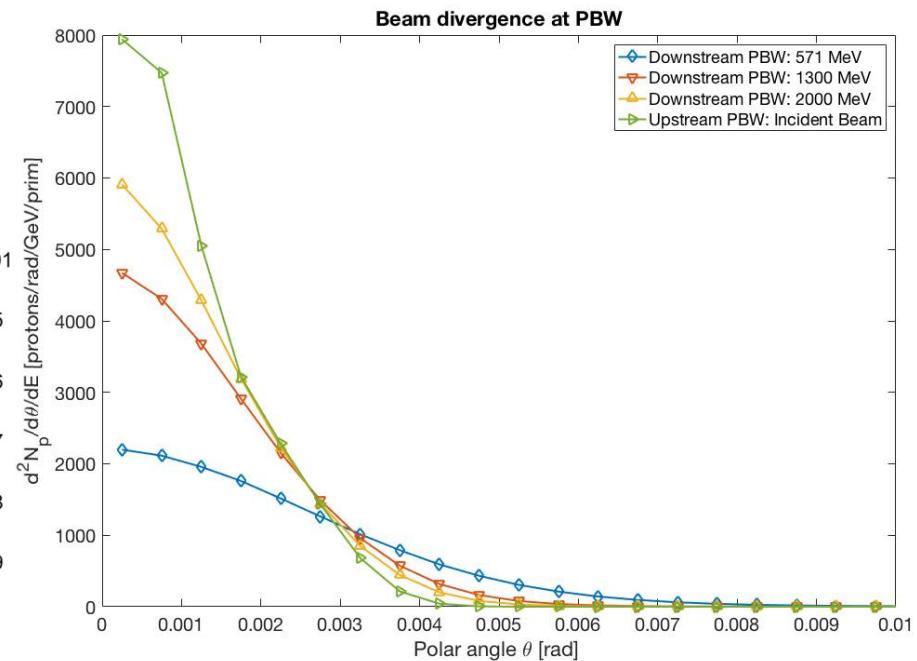
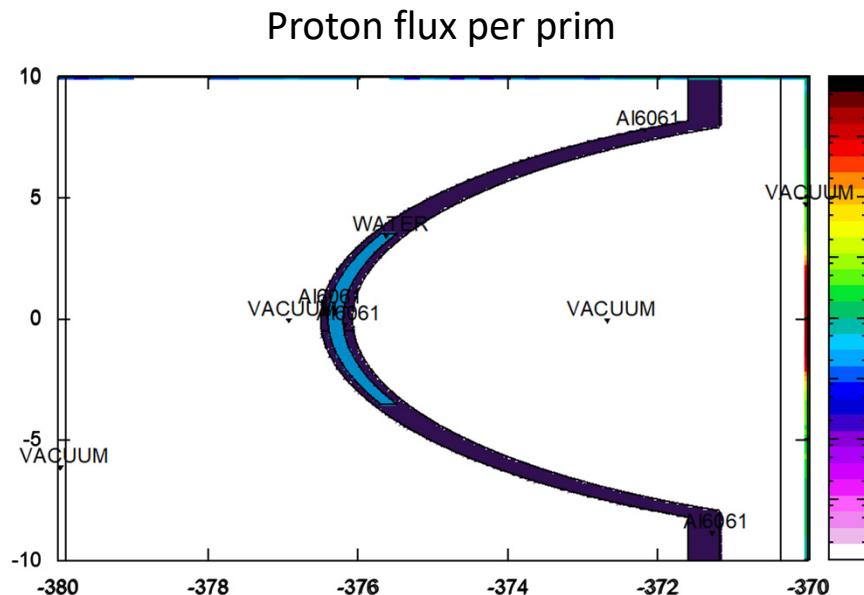
Stepwise Beam Commissioning at ESS

- Phase 0: 571 MeV on the dump and/or target
 - Commissioning up to the medium-beta cryo-modules
- Phase 1: 1.3 GeV on the target
 - Commissioning up to half of the high-beta cryo-modules
- Phase 2: 2.0 GeV on the target
 - Full commissioning



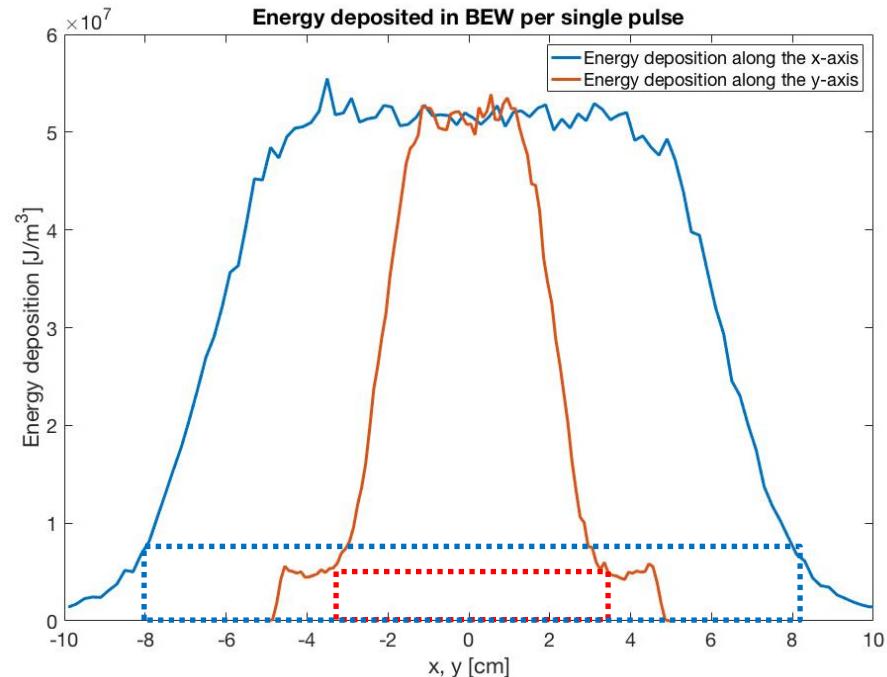
Proton Scattering at PBW

Beam Energy	Fraction landed on target area	Reference fraction on target area
571 MeV	0.885	0.961
1.3 GeV	0.928	0.961
2.0 GeV	0.965	0.988



Maximum Beam Offset and Thermal Stress in Target Vessel

- Steel structure receives maximum 10 MJ/m^3 for a $2 \text{ GeV}/62.5 \text{ mA}$ beam
- Additional stress of less than 10 MPa due to sudden thermal expansion
- **No risk** to structural integrity



Raster Failure and Beam Size

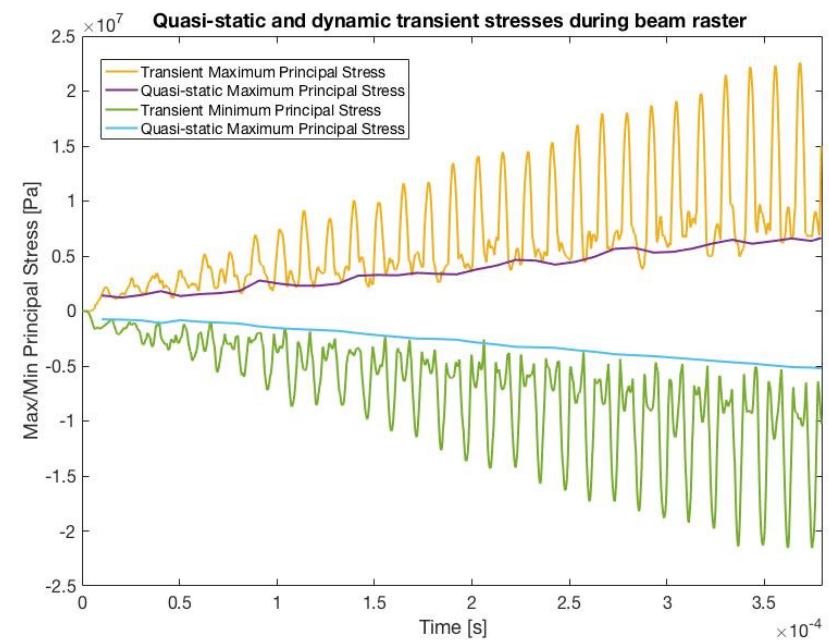
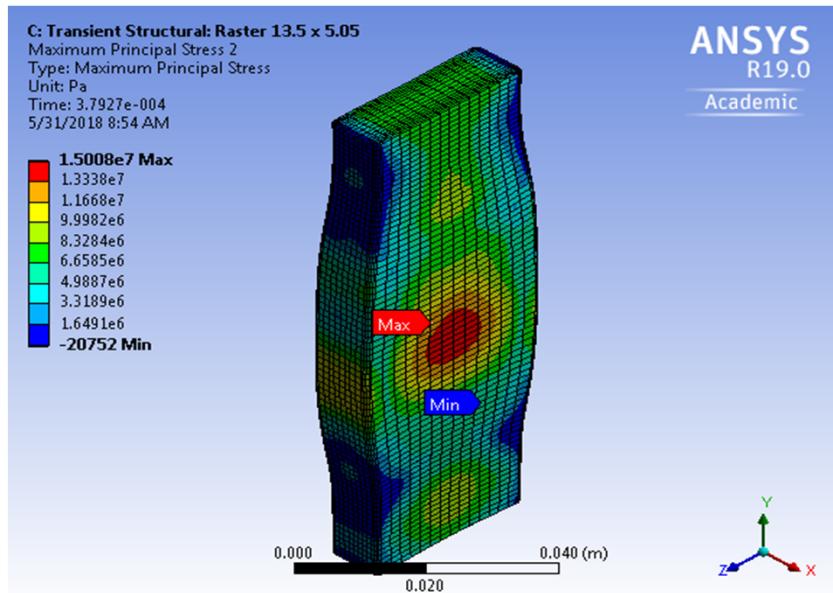
- The BEW and PBW shall not lose its mechanical properties during a full pulse in case of a total failure of beam raster.
 - SA SS-316L: Precipitation of chromium-rich carbides at grain boundaries at above 550 °C.
 - Al6061-T6: Thermal aging becomes an issue at the temperatures above 250 °C [RCC-MRx]

$$\Delta T_{\max} = \frac{\tau}{\rho C_p} \frac{i_{\text{total}}}{2\pi\sigma_x\sigma_y} \left. \frac{dE}{dz} \right|_{\max}$$

Component	Max. temperature operation	Temperature limit during pulse	Max. dE/dz [MeV/cm]	Min. allowed RMSx * RMSy
BEW	160 °C	550 °C	18.5	33.5 mm ²
PBW	60 °C	250 °C	5.3	32.6 mm ²

Dynamic Stress Wave in Tungsten Bricks

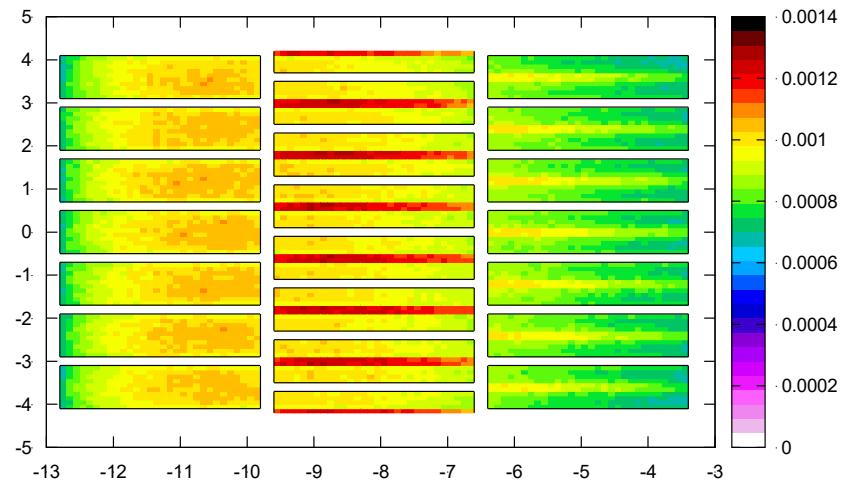
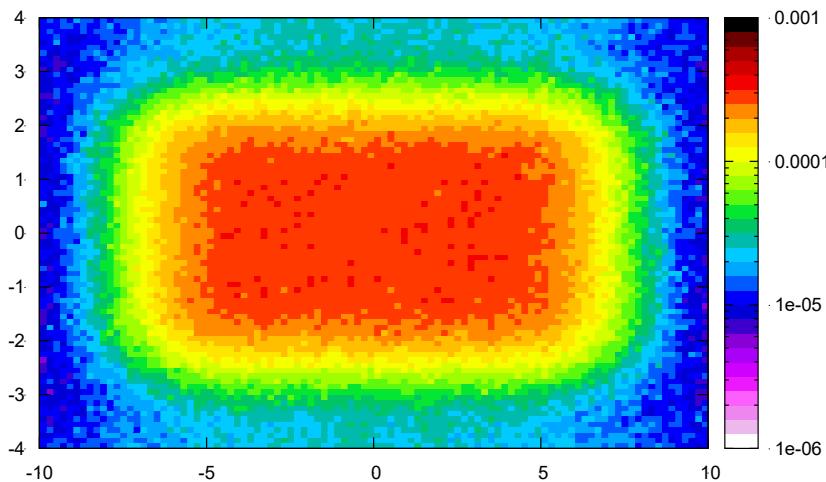
- 30 Raster sweeps (0.38 ms, 13% of single pulse) were simulated.
- Dynamic stress amplifies with time.
- Resonance mode identified at 41.2 kHz which is only 4% off from the horizontal raster frequency (39.55 kHz)
- The raster frequency will be tuned away from the band-width of the resonance mode.



Beam Energies and Nuclear Heat Deposition

Beam Energy	PBW	BEW	Tungsten (Max.)
571 MeV	1.41 MeV/proton	3.98 MeV/proton	8.1 MeV/proton
1.3 GeV	1.24 MeV/proton	4.38 MeV/proton	10.8 MeV/proton
2.0 GeV	1.22 MeV/proton	5.01 MeV/proton	14.5 MeV/proton

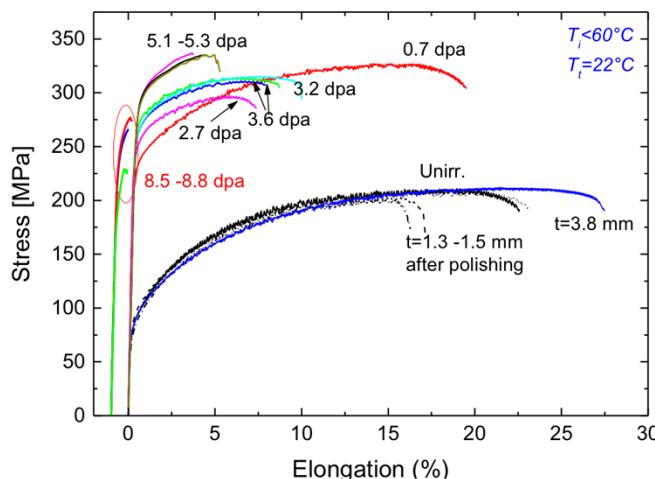
At an early linac commissioning phase with a lower energy beam, attention should be paid to the higher heat load and associated higher thermal stress in the PBW.



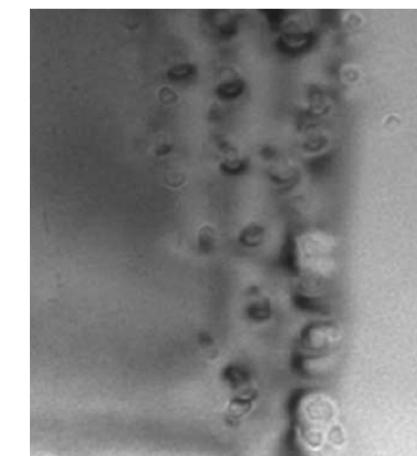
Radiation Damage and Lifetime: PBW

- Helium embrittlement determines the lifetime
 - The SINQ target window at PSI doesn't show much ductility at the accumulated helium production of 2400 appm.

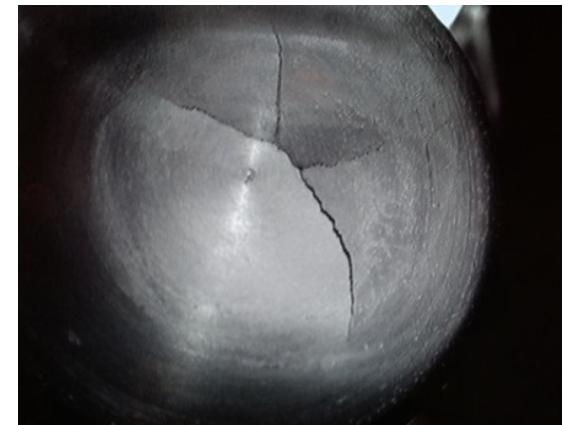
Beam energy	Lifetime at full beam current	Lifetime in accumulated beam power
571 MeV	5780 hours	8.25 GWh
1.3 GeV	4110 hours	13.3 GWh
2.0 GeV	3580 hours	17.9 GWh



SINQ safety hull made of AlMg3:
Picture courtesy by Y. Dai (PSI)



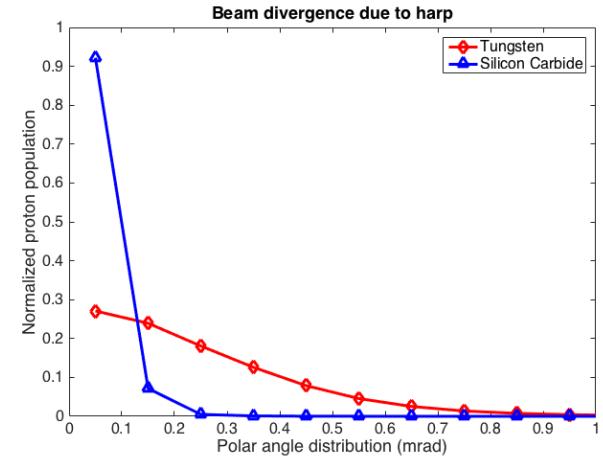
D. Hamaguchi and Y. Dai,
JNM 329-333 (2004) 958-962



ISIS- TS2 PBW:
Picture courtesy by D. B. Lopez (ISIS)

Radiation Damage and Lifetime: MWPM

- Both pure tungsten and SiC could be used for MWPM
- For a pencil beam, the beam diverges with:
 - SiC harp: 0.06 mrad => 0.01% of additional beam loss at the target
 - W harp: 0.25 mrad => 0.05% of additional beam loss at the target
- Radiation damage limited lifetime is 1 year at full beam current.



Material	Secondary electron yield	Delta ray electron yield	Total Yield
W	0.049	0.026	0.075
SiC	0.010	0.013	0.023

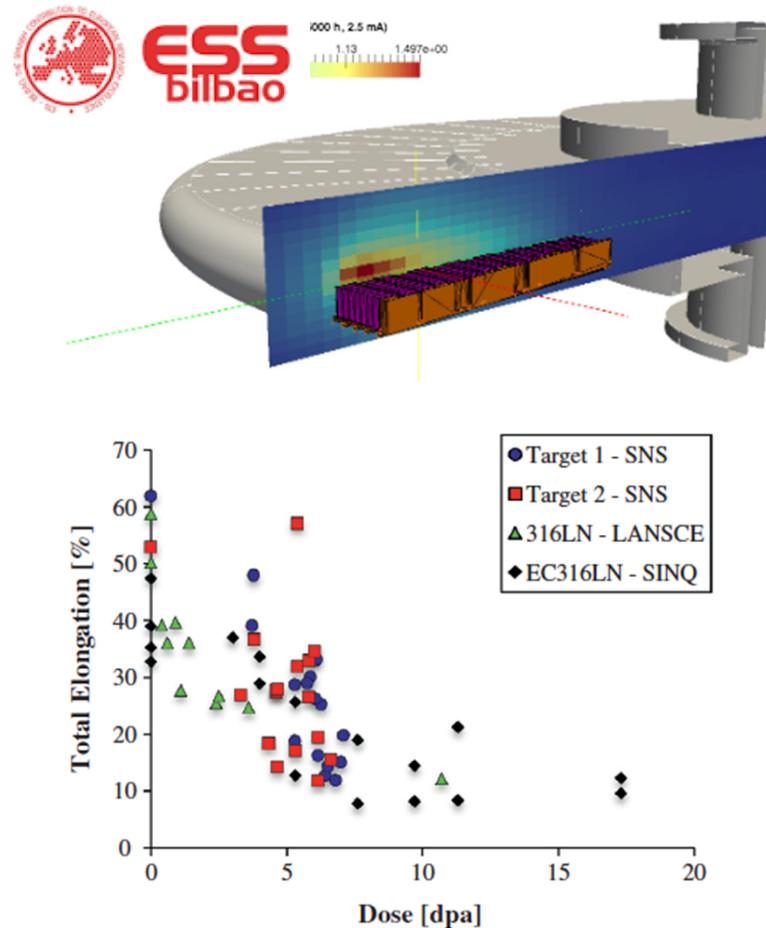
	Tungsten	SiC
Post-pulse max. temperature	1420 K	660 K
Post-pulse max. stress	77 MPa	76 MPa
Yield Stress/Flexural Strength	200 MPa	415 MPa

Material	Max. DPA per Year
W	64.8
SiC	5.4

Benchmark	Material	Total Beam Energy/Charge	Accumulated Max. DPA
ORNL-SNS	W	41000 MWh	90
ISIS-TS2	SiC	0.985 Ah	2

Radiation Damage and Lifetime: Target Vessel

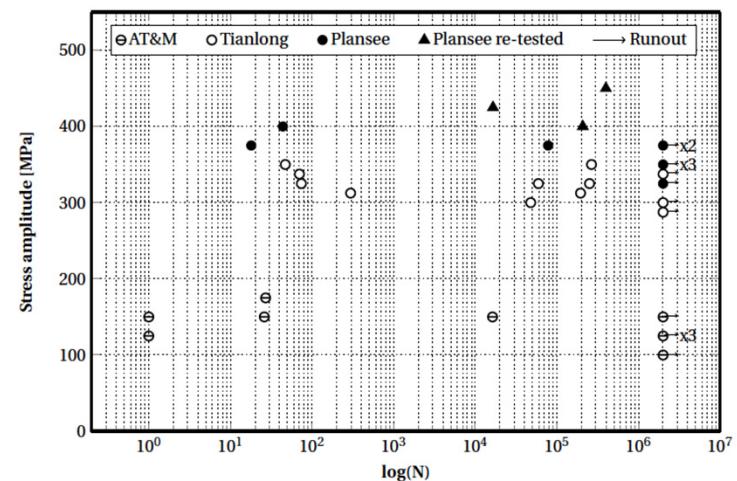
- Lifetime criteria: DPA
 - Decided maximum DPA dose limit: 8 DPA
 - Damage Rate: 1.6 DPA/ESS-year
 - Lifetime: 5 ESS-year
 - Conservatism is due to:
 - Different irradiation temperatures of STIP specimens and water cooled SNS beam entrance window
 - STIP specimen is SS 316 LN
 - Uncertainty in DPA estimates



D. A. McClintock et al.,
JNM 450 (2014) 130-140

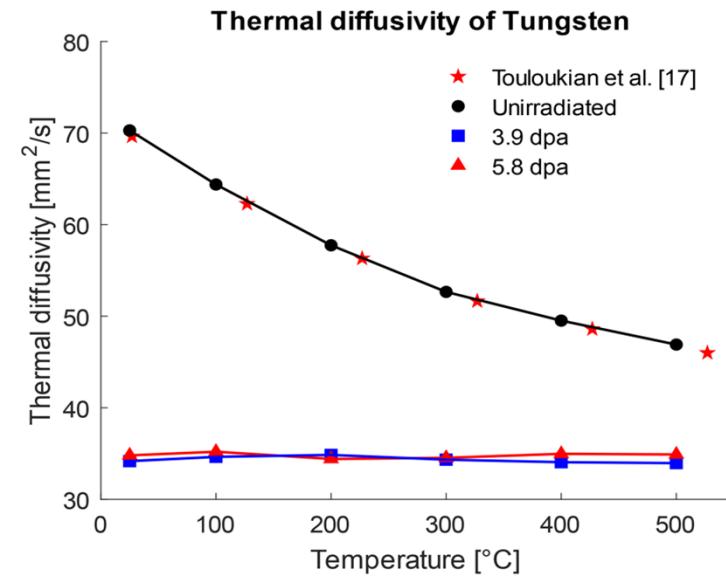
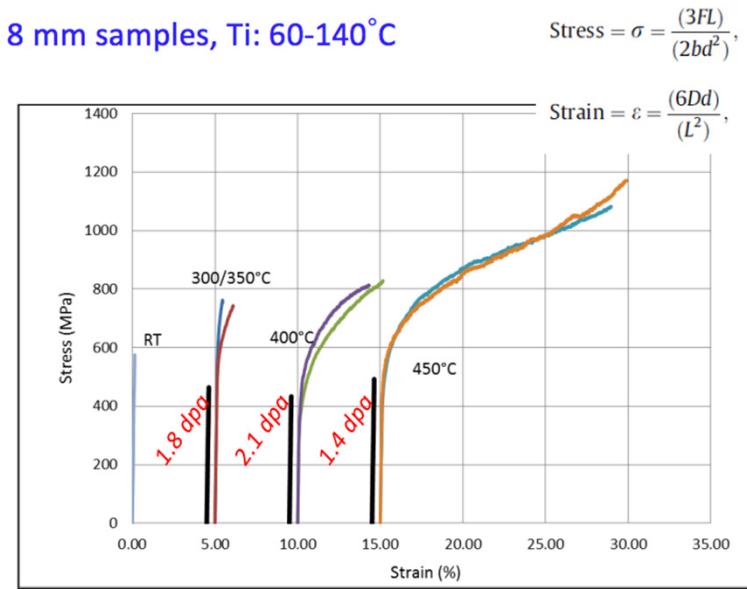
Dose Limited Lifetime: Tungsten Bricks

- Tungsten is not subject to dose limited lifetime
 - It doesn't carry structural load of target wheel
 - But, loss of mechanical integrity of tungsten bricks caused by thermal cycling could result in premature target failure
- Main concerns:
 - The radiation damage pushes the DBTT of tungsten bricks above the operation temperature of the ESS target
 - Uncertainty in setting fatigue limit for brittle materials



Tungsten Bricks: Radiation Damage

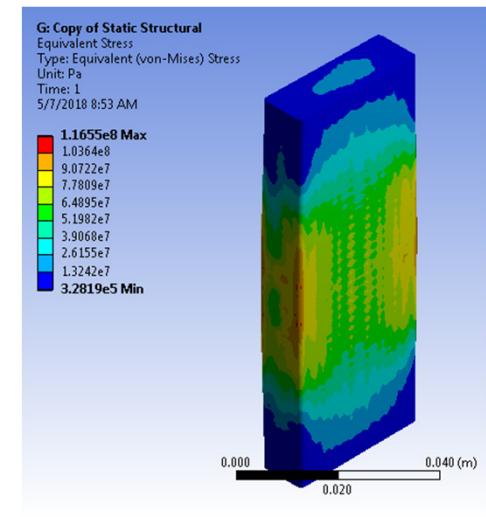
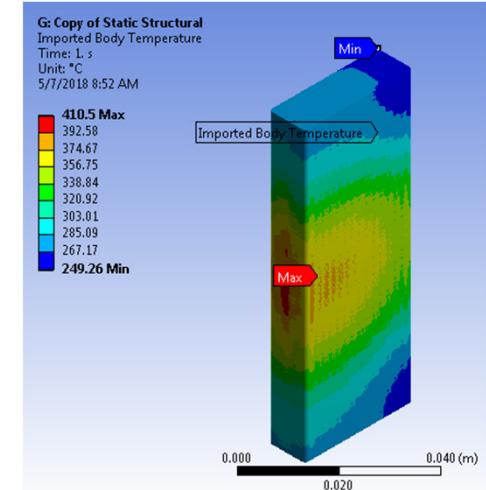
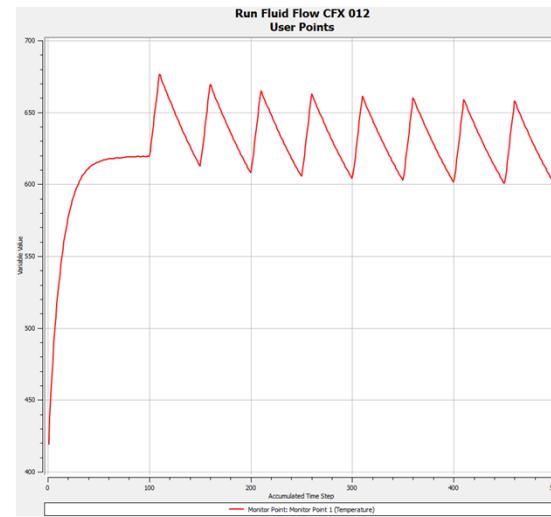
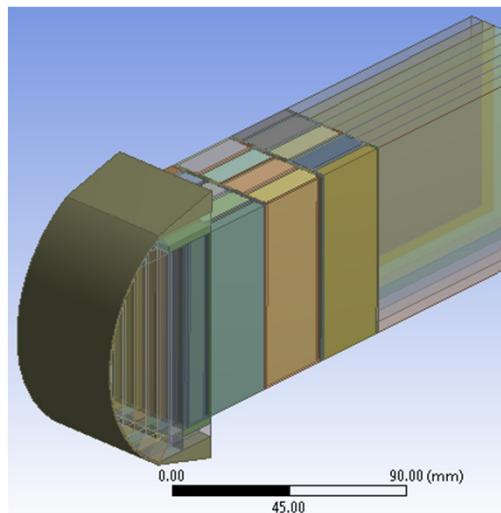
- Reduction of flexural stress => premature brittle failure
- Reduction of thermal conductivity => elevated thermal stress
- Increase of stiffness => elevated mechanical stress



Tungsten Bricks: Radiation Damage Effects

- Coupled CFD and Structural Analyses are made.
 - Thermal conductivity as irradiated was taken from recent STIP-V data [J. Habainy et al.].
 - Young's modulus as irradiated was taken to be 20% higher than un-irradiated one [J. Habainy et al.].

Parameter	Time	Un-irradiated	Irradiated
Maximum temperature	Pre-pulse	321 °C	337 °C
	Post-pulse	395 °C	411 °C
Maximum Quasi-static stress	Pre-pulse	27 MPa	50 MPa
	Post-pulse	83 MPa	117 MPa



Materials Research in Target Environment



Materials Research

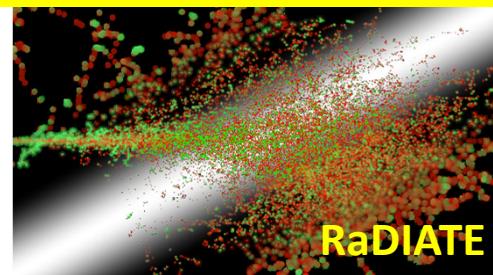
Spallation Materials



- Understanding beam and matter interaction is crucial for a reliable operation of the facility.
- Numerous Materials Research Program in Target Environments are in Progress.
- Acquired materials information is compiled in the ESS Materials Handbook.

Materials

Irradiation Module



Materials Research in Target Environment



Materials Research

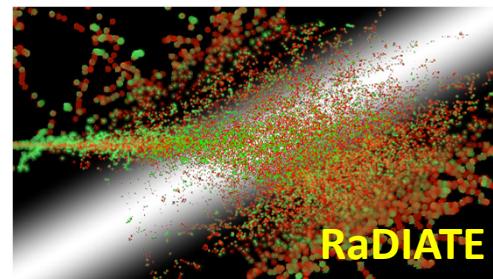
- Spallation Materials
- PBW Materials
- Polymers and Lubricants
- Moderator Materials
- Beam Imaging Materials
- Irradiation Module



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Technical University
of Denmark



Thank you!

