The ESS target design and beam raster system

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Outline

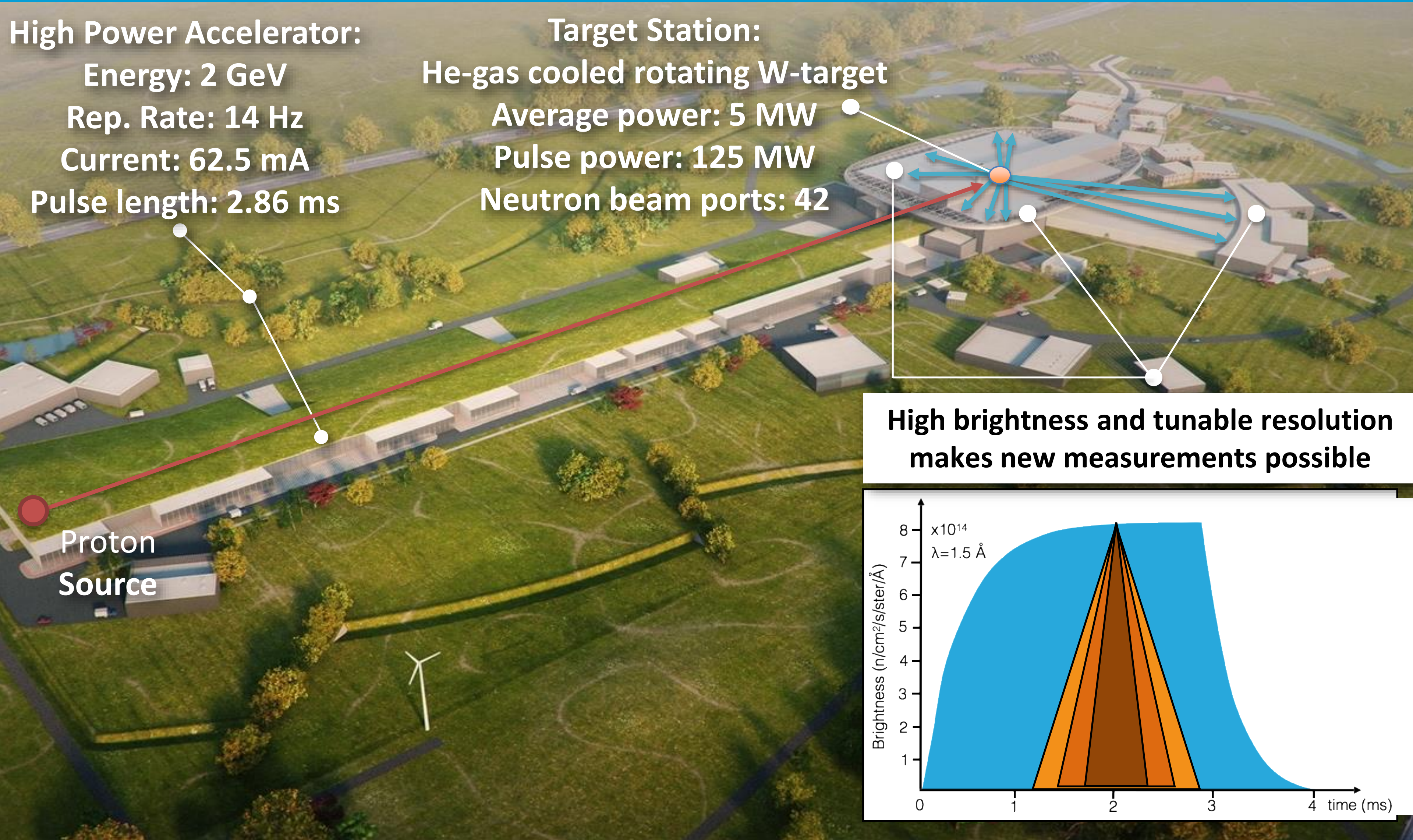
- Introduction to the European Spallation Source
- Technical design solutions
  - Rotating tungsten target
  - Target helium cooling
  - Proton beam expansion by raster scanning magnet system
- Raster scanning effects on neutron output
- Concluding remarks

Introduction to the European Spallation Source

European Spallation Source basics

High Power Accelerator:
Energy: 2 GeV
Rep. Rate: 14 Hz
Current: 62.5 mA
Pulse length: 2.86 ms

Target Station:
He-gas cooled rotating W-target
Average power: 5 MW
Pulse power: 125 MW
Neutron beam ports: 42

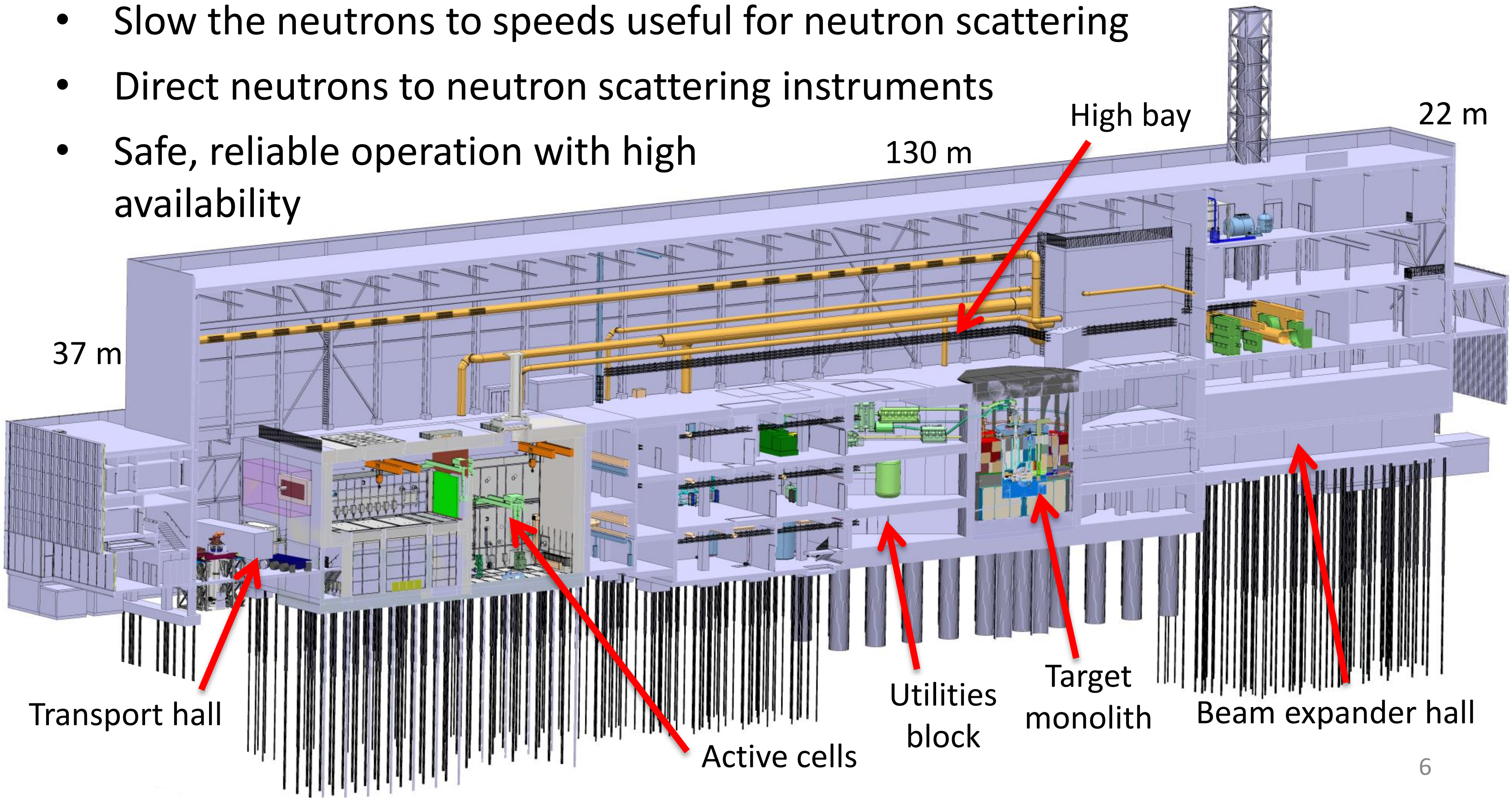


High brightness and tunable resolution makes new measurements possible

Construction site areal photo, Dec 2016

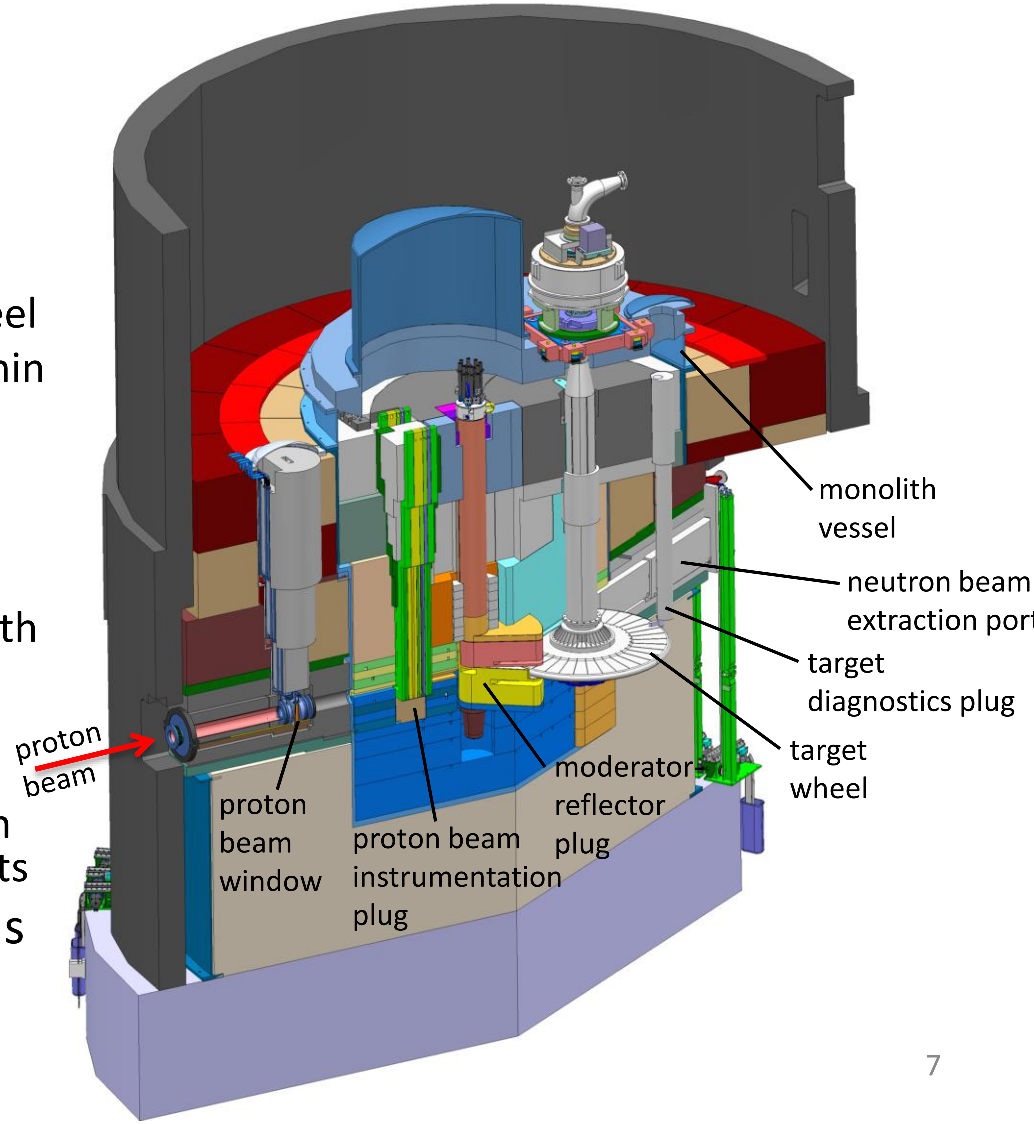
Target Station High Level Functions

- Generate neutrons via nuclear spallation using protons from the accelerator
- Slow the neutrons to speeds useful for neutron scattering
- Direct neutrons to neutron scattering instruments
- Safe, reliable operation with high availability



Target monolith and its internals

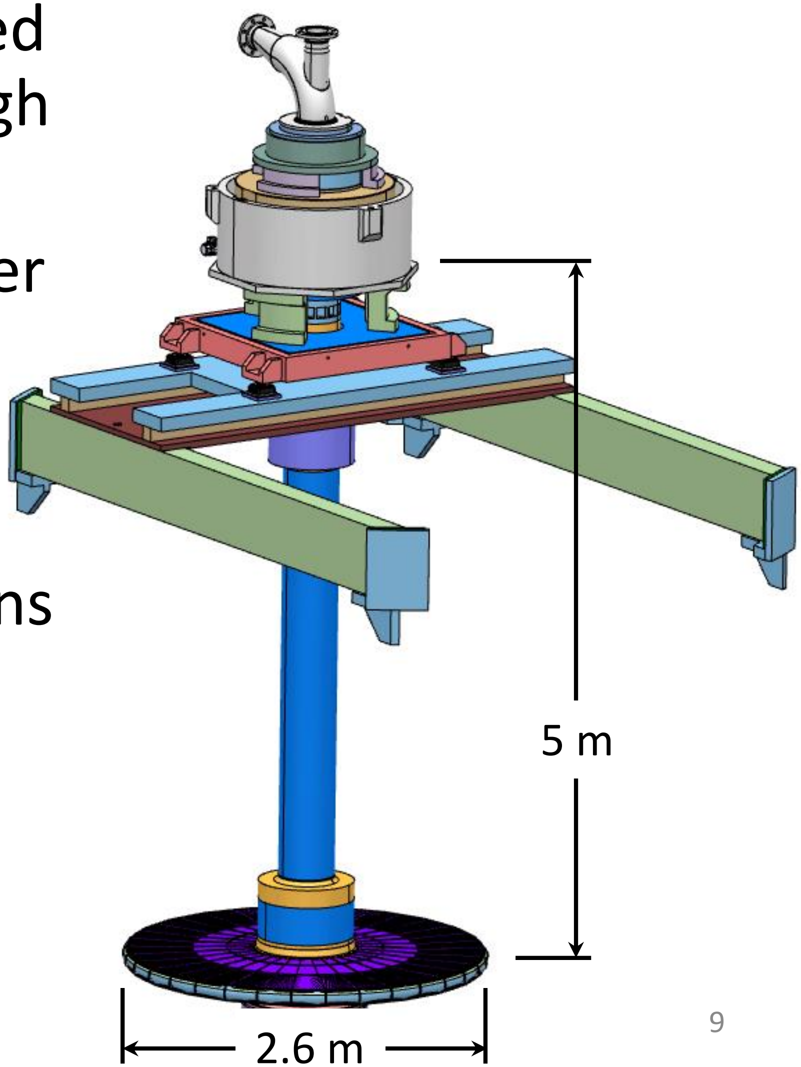
- The proton beam
  - Enters the monolith through a beam pipe
  - Passes through a proton beam window made of aluminum
  - Strikes the rim of the target wheel
  - Induces spallation reactions within the tungsten target material, producing copious neutrons
- The neutrons
  - Leak from the target wheel
  - Scatter into moderators filled with water and liquid hydrogen
  - Down-scatter to low energies
  - Leak through neutron beam extraction ports that direct them to neutron scattering instruments
- Monolith is filled with 3000 tons of steel to shield high-energy neutrons from escaping



Rotating tungsten target

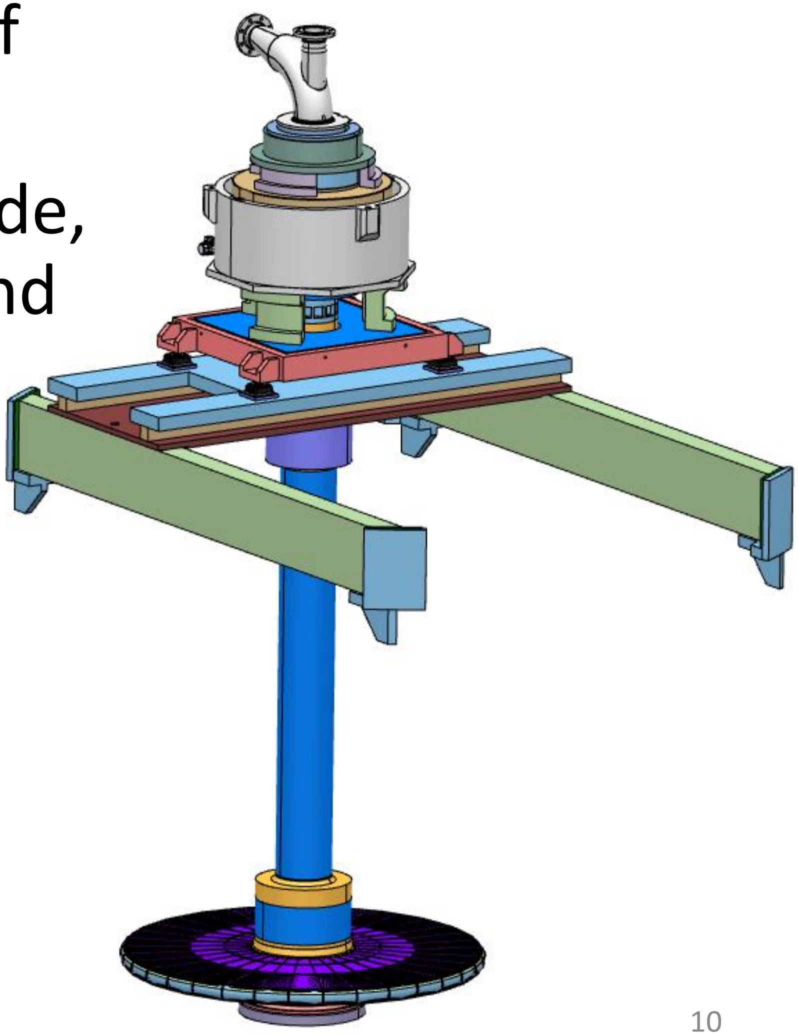
ESS will be the first spallation source to employ a helium-cooled rotating target

- Motor and bearings are mounted far away (5 meters) from the high radiation zone
- Wheel is suspended on a 6 meter long shaft
- Wheel contains 3 tons of tungsten
- Wheel+shaft total mass is 11 tons
- Helium removes 3 MW of heat deposited in the target by the 5-MW proton beam
- Expected lifetime of 5 years



Target wheel rotation scheme

- Target wheel has 36 sectors of 10° each
- The beam pulse is 2.86 ms wide, and pulses 14 times per second
- Wheel rotation is synchronized with the beam pulse
- Wheel rotational speed is 14 Hz/36 = 0.39 Hz, or 10° rotation between each pulse



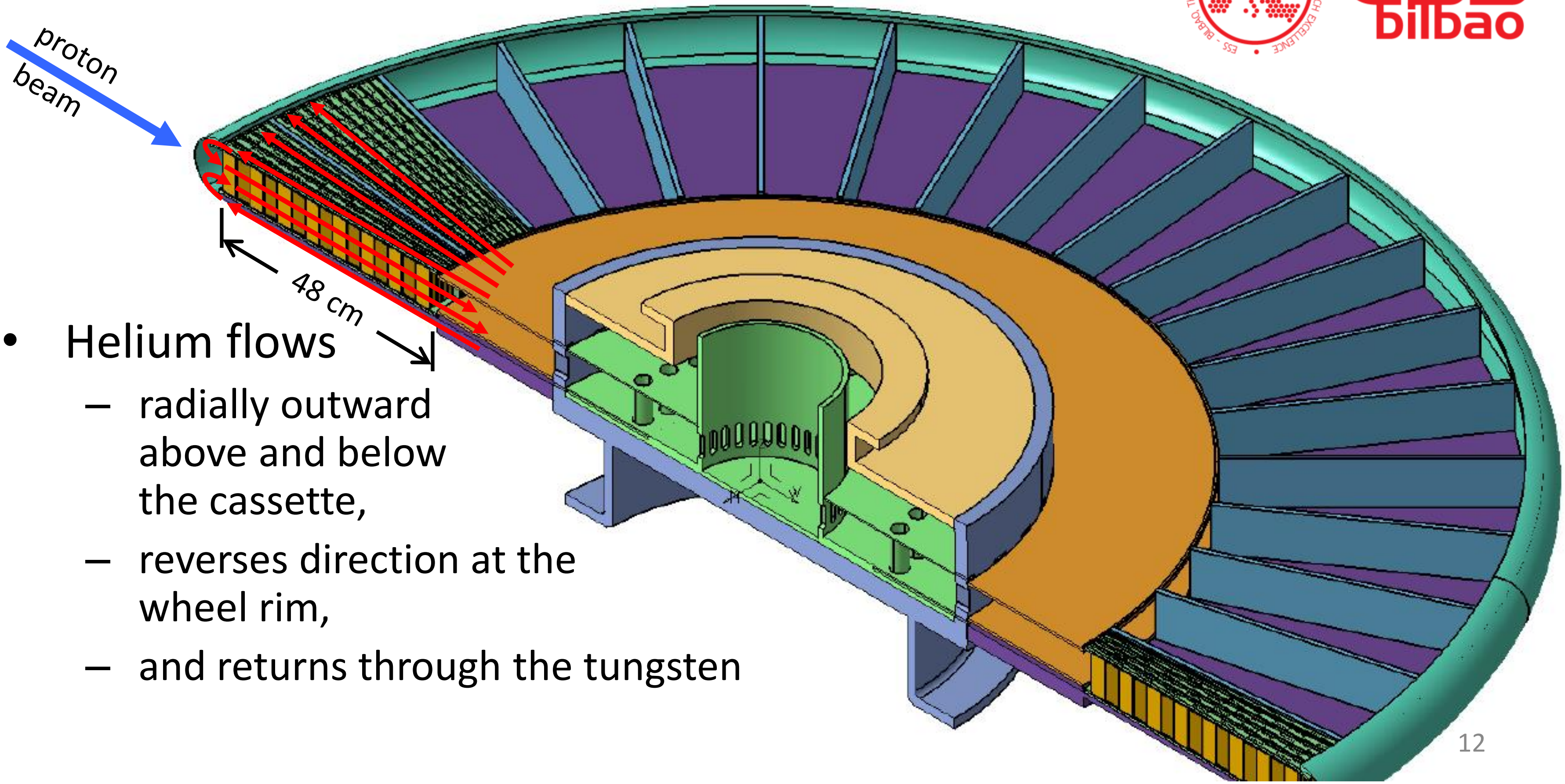
Rotating targets for spallation sources are not a new concept

- Main advantages:
  - Can accommodate high beam powers
  - If properly designed, decay heat can be removed passively
  - Long life
- Main drawbacks:
  - Large, heavy, expensive target
  - Components beneath the target wheel are difficult to extract

Prototype rotating target from the 1980s-era German SNQ project (Forschungszentrum Jülich)

Each 10° sector is loaded with a tungsten-filled cassette

- Tungsten depth in the proton beam direction is 45 cm
- The range of a 2-GeV proton in tungsten is 74 cm

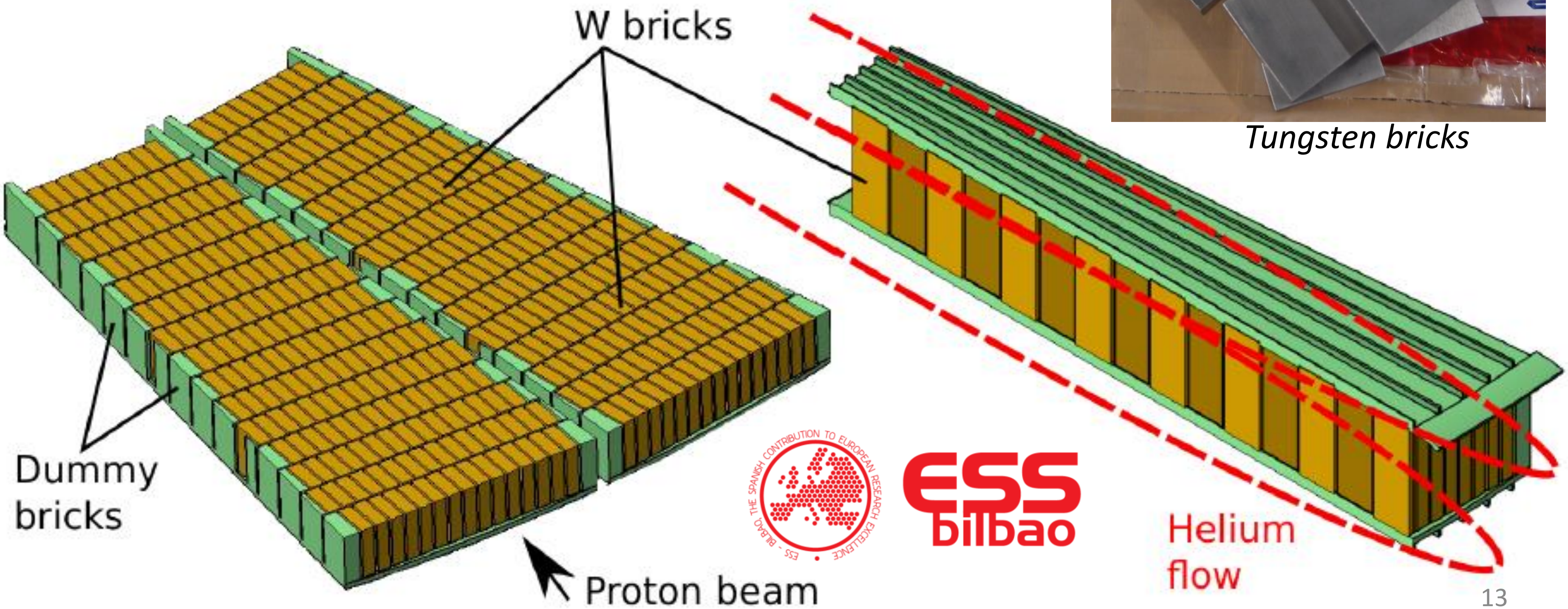


- Helium flows
  - radially outward above and below the cassette,
  - reverses direction at the wheel rim,
  - and returns through the tungsten

The target wheel is loaded with 3 tons of tungsten bricks

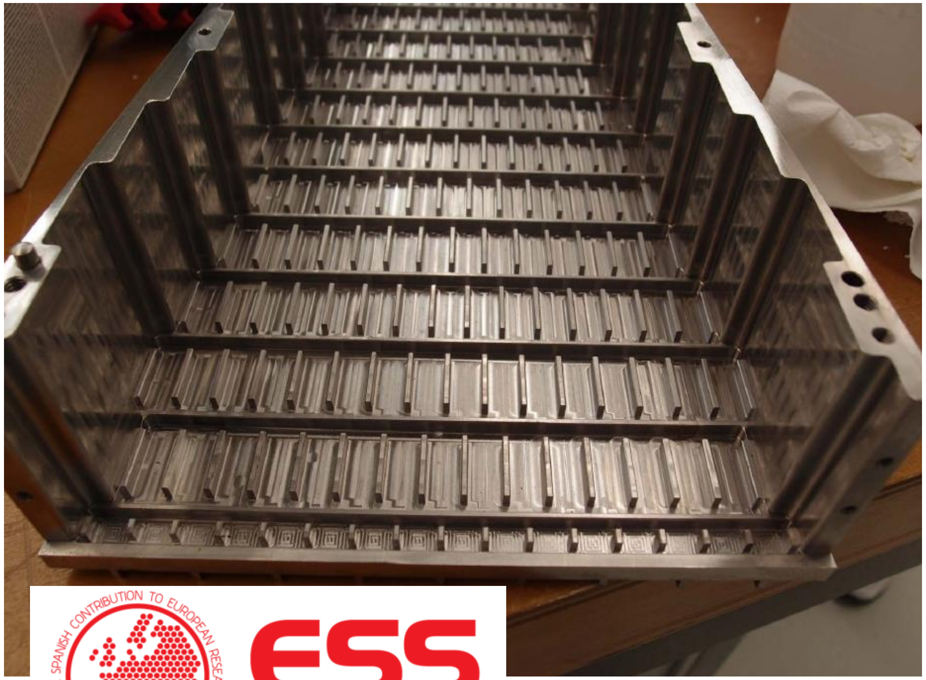
- Brick dimensions: 10 W x 30 D x 80 H mm^3
- 190 bricks per sector, 6840 bricks in total
- Manufacturing is straightforward

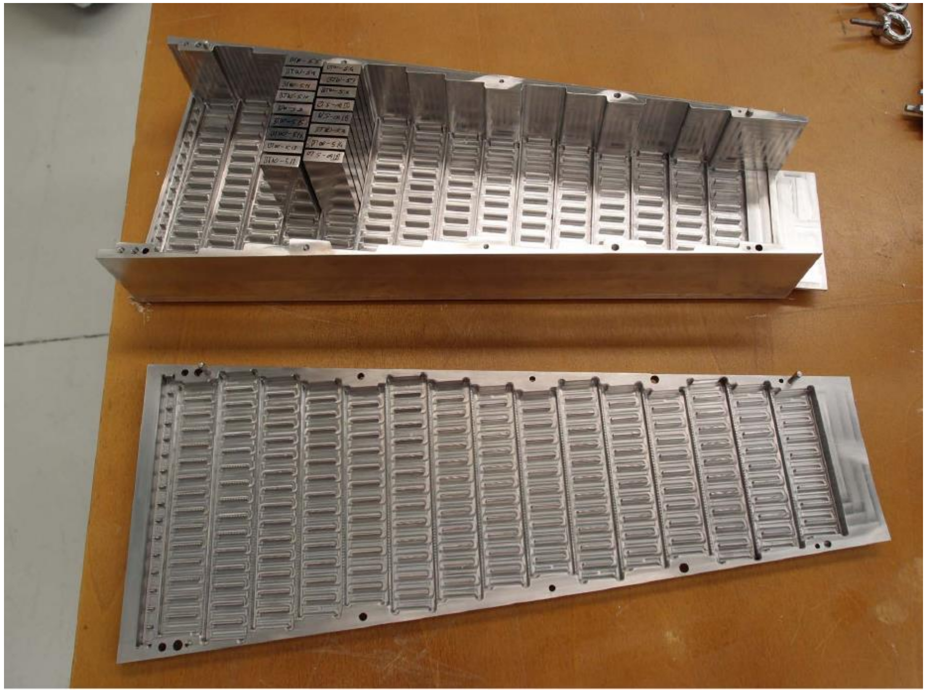
Tungsten bricks



Tungsten bricks are held in place by stainless steel 316L cassettes

- Tungsten is not bonded to the stainless steel
- Allows free thermal expansion in all three directions
- Cassettes maintain 2-mm coolant channels between bricks
- Chamfered ridges allow bricks to self-center, easing assembly



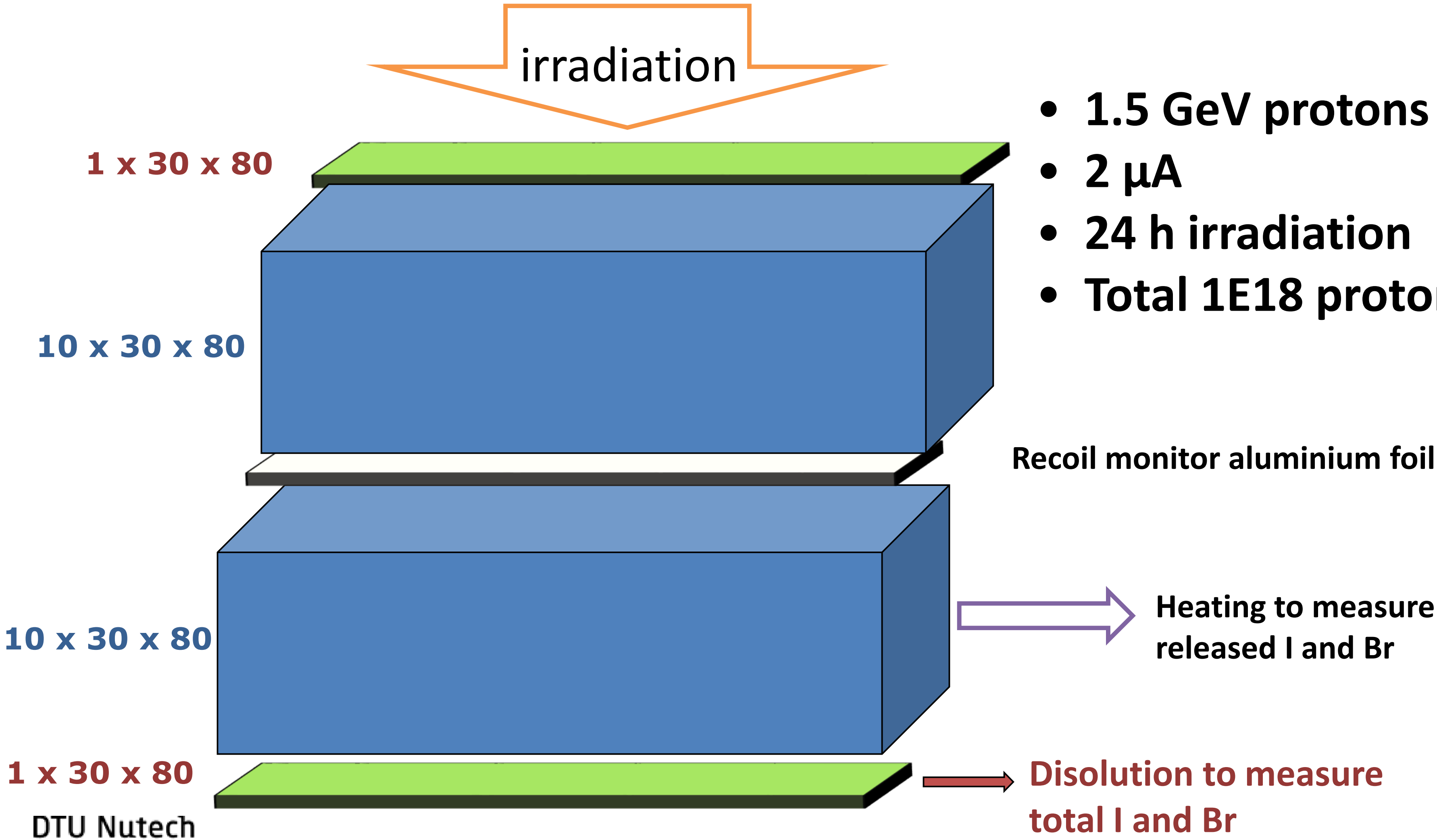


The biggest hazard to the public is the radionuclide inventory in the tungsten target

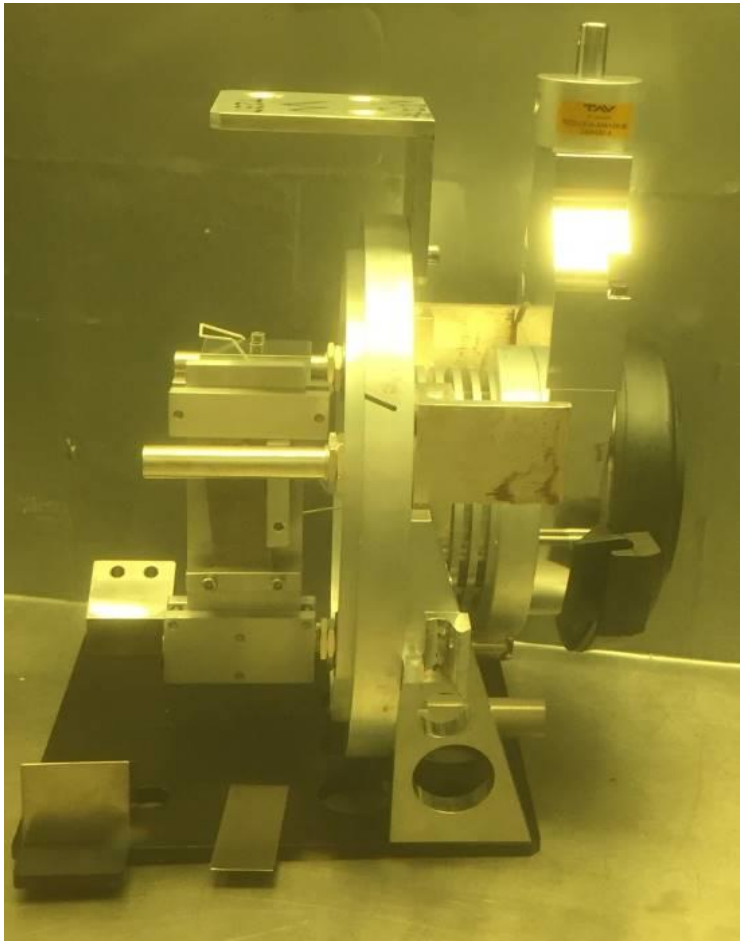
- If this inventory were released, the dose to the most exposed members of the public would exceed permissible limits
- Three energy sources can disperse this inventory:
  - Abnormal heating by the proton beam
    → *Addressed by a highly reliable Target Safety System*
  - Nearly 40 kW of decay heat in the target wheel
    → *Designed for completely passive decay heat removal*
  - Large inventory of liquid hydrogen next to the target
    → *Deflagration or detonation does not heat the target*

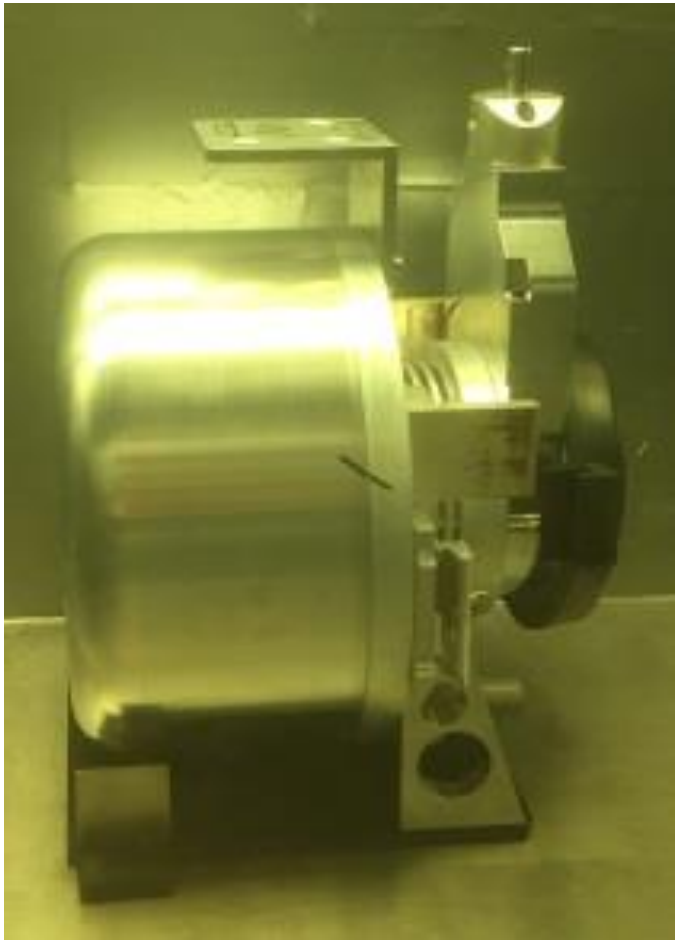
W bricks irradiated at ISOLDE used to measure release of volatile radionuclides

- **1.5 GeV protons**
- **2 µA**
- **24 h irradiation**
- **Total 1E18 protons**

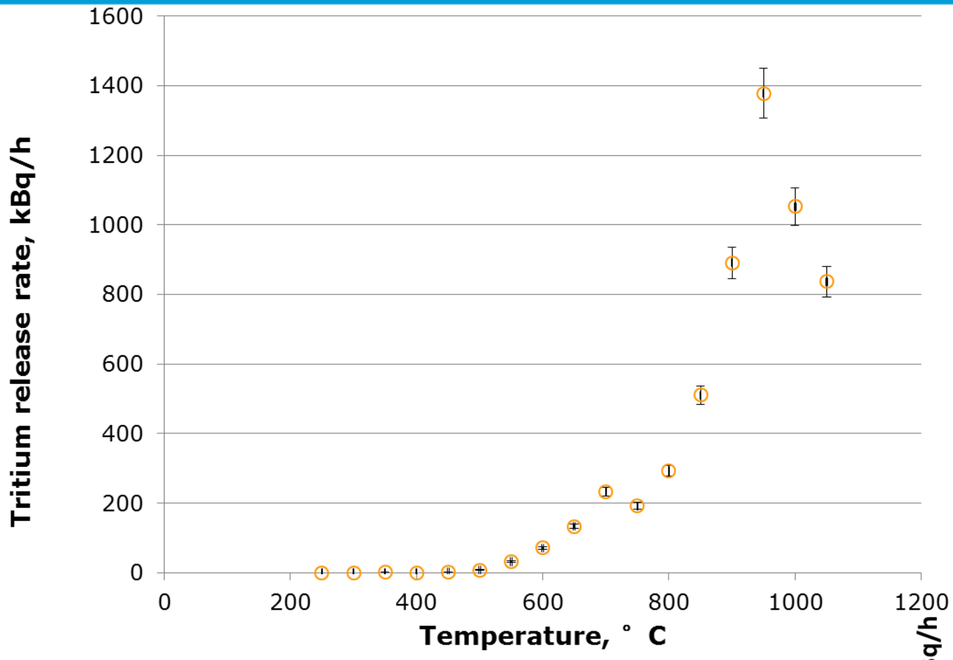


Chamber for proton irradiation of tungsten bricks at ISOLDE

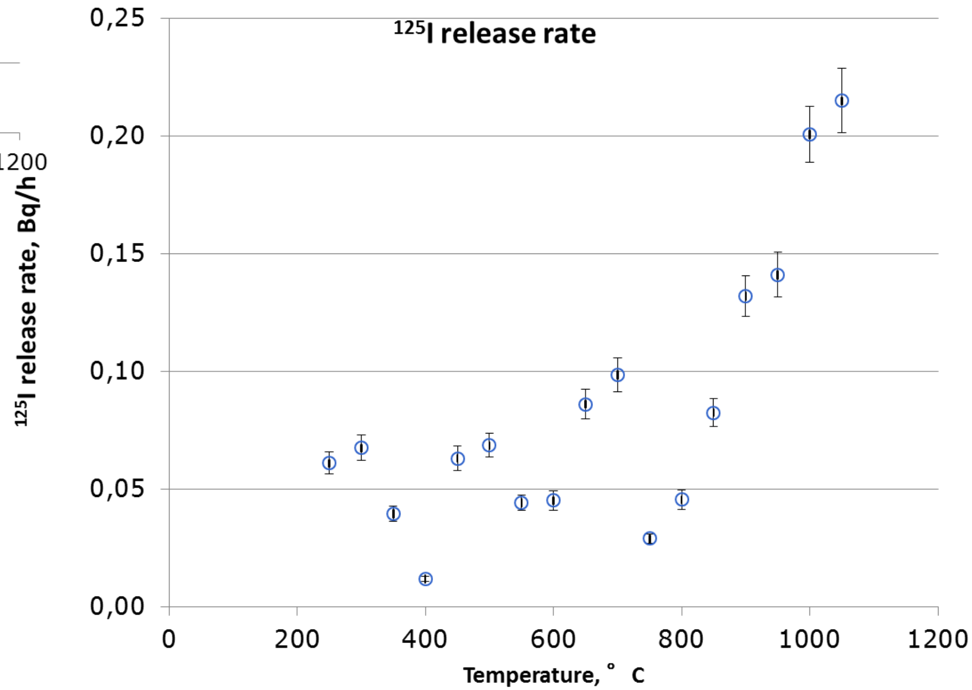




Tritium and ^{125}I releases during heating the irradiated tungsten block



- By heating, large amount of tritium was released from the irradiated tungsten, up to 1.8 MBq/h HTO was measured at 950 C.
- ^{125}I was released from the irradiated tungsten in a very small rate (<0.22 Bq/h) even at 1000 C.
- Analysis is ongoing



Courtesy of
Xiaolin Hou
Mikael Jensen
Sven P. Nielsen

DTU Nutech
Center for Nuclear Technologies

Target helium cooling

ESS will be the first high-power spallation target cooled by helium

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- 3 MW cooling capacity
- 30 kg helium inventory
- 3 kg/s flow rate
- 11 bar absolute pressure, 1.5 bar pressure drop
- 40°C inlet temperature, 240°C exit temperature
- Purification system removes contaminants
  - Full-flow filtration to 5 µm
  - 0.1% purification stream filtered to 0.5 µm
  - Getters in the purification stream remove hydrogen, halogens, and other trace elements
- Helium blowers will be oil-free turbo compressors

Rationale for the choice of helium as target coolant

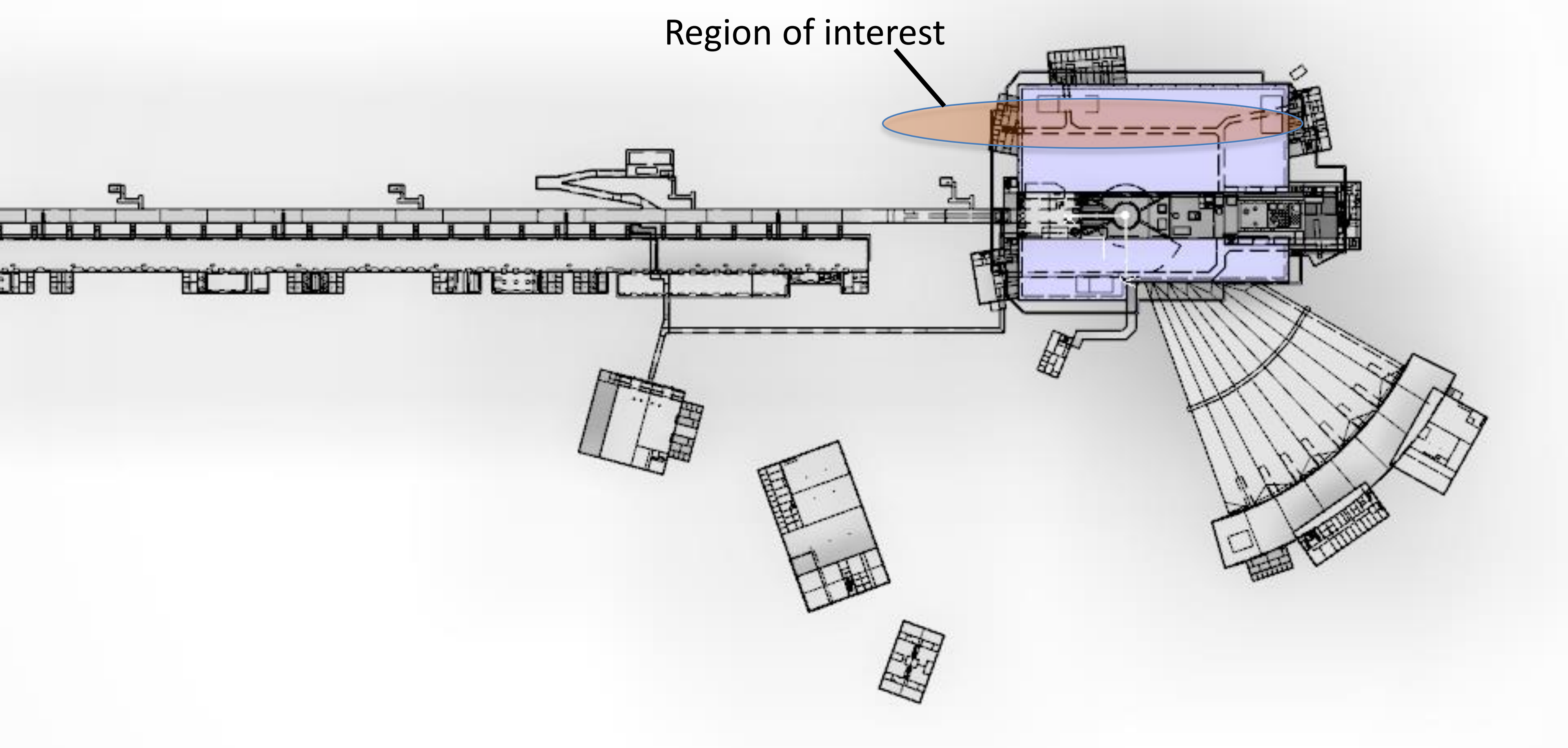
- Advantages
  - Chemically inert gas with minimal cross-section for particle irradiation
    - No need to clad the tungsten bricks
    - Minimal production of radioisotopes
    - Lower radioactivity in the loop components
    - Less dose to workers
  - No phase change issues
    - Avoiding cavitation
    - Less susceptible to over-heating and over-pressurization events
    - Much lower risk of tungsten-steam reactions
- Challenges
  - Leak-tightness
  - Design tradeoffs between operating pressure, pressure drop, system dimensions and power consumption
  - First of a kind application

Proton beam expansion by raster scanning magnet system

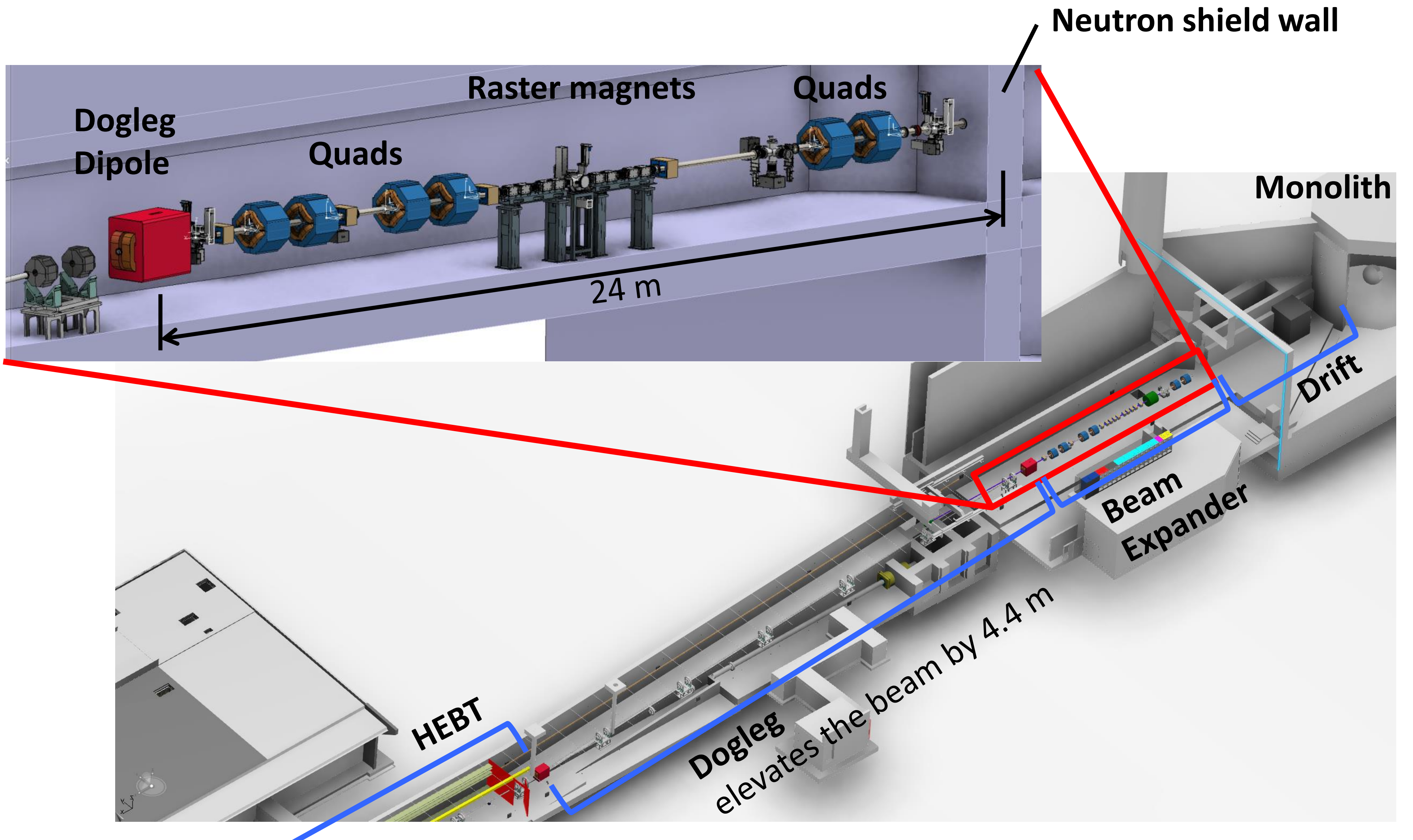
Issues to be addressed in the design of the accelerator-target interface

- Beam expansion and delivery to the target
- Potential activation of beamline components from neutrons coming from the target
- Assuring the beam delivered to the target is within allowable limits
- Shielding nearby rooms and hallways from prompt radiation

Accelerator-target interface

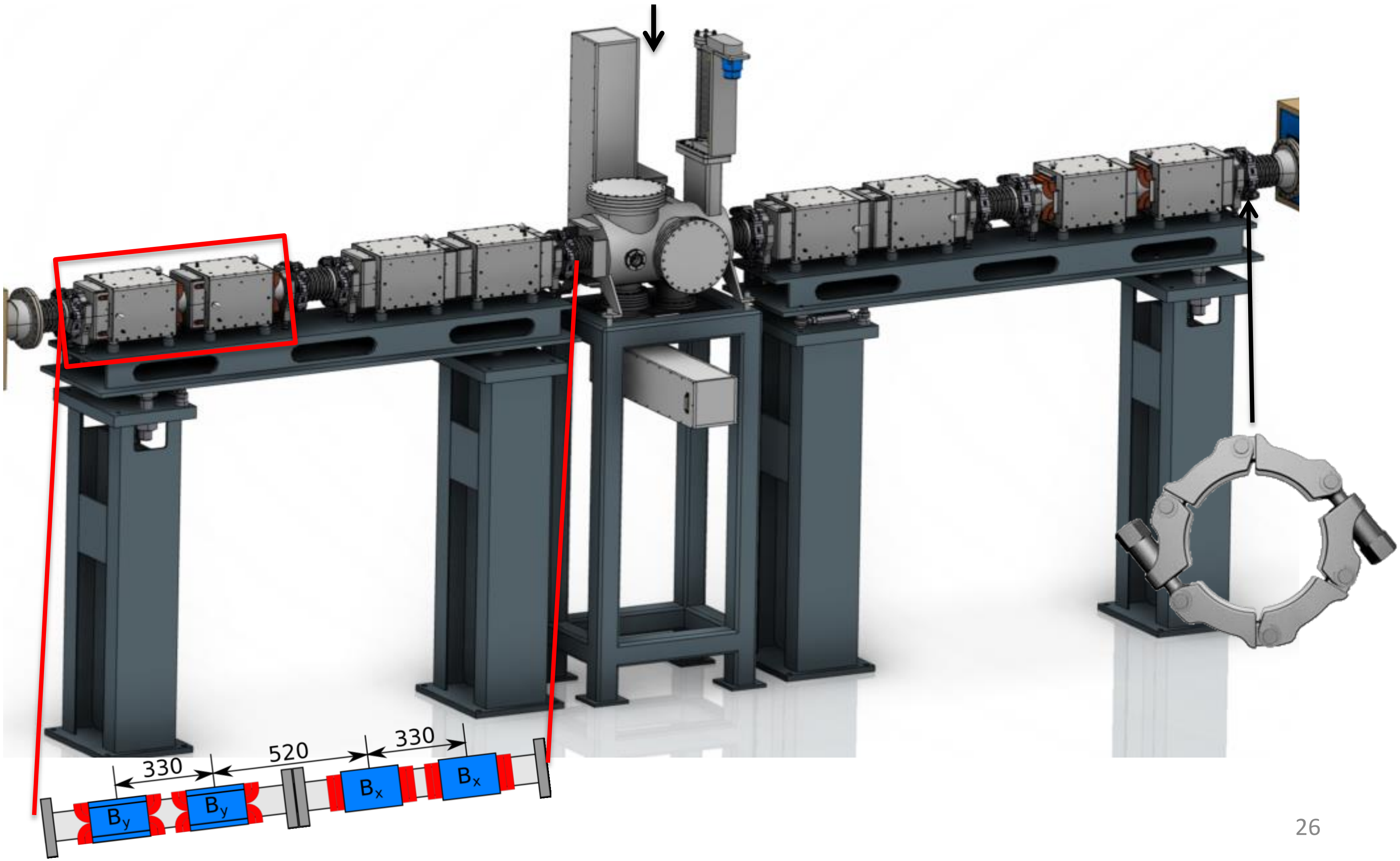


Beam transport configuration upstream of the target



Hardware: Magnets + Support

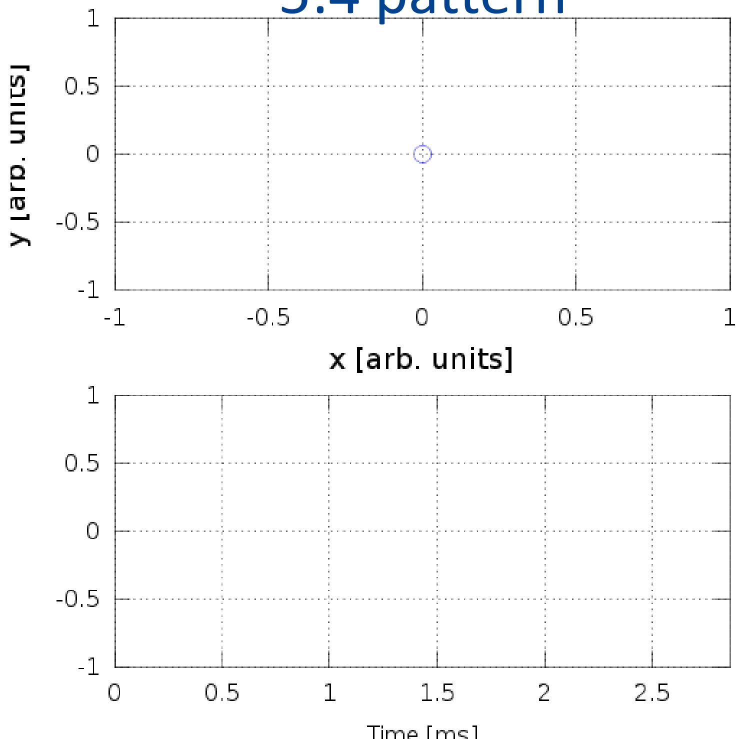
Profile monitor (wires + non-invasive)

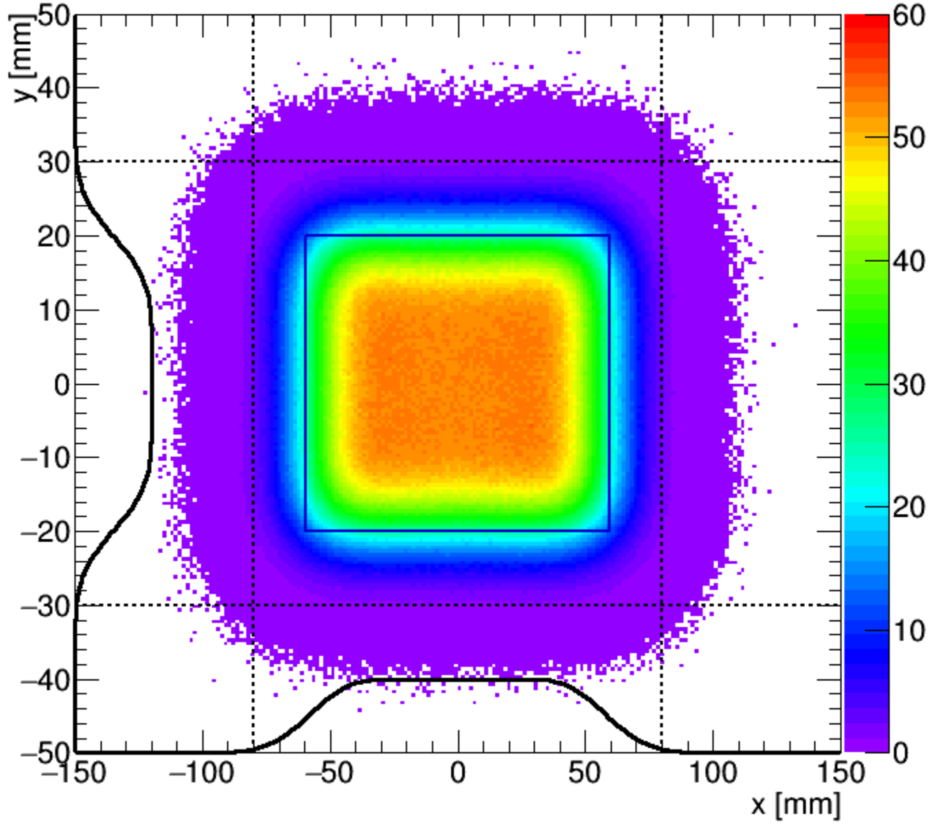


Concept of beam expansion by raster magnet system

- Raster system sweeping beam in 2D pattern @ target
- 8 colinear magnets, individually powered
- Crosshatch pattern (f_x/f_y, ϕ_{xy}, a_x, a_y) within 2.86 ms pulse

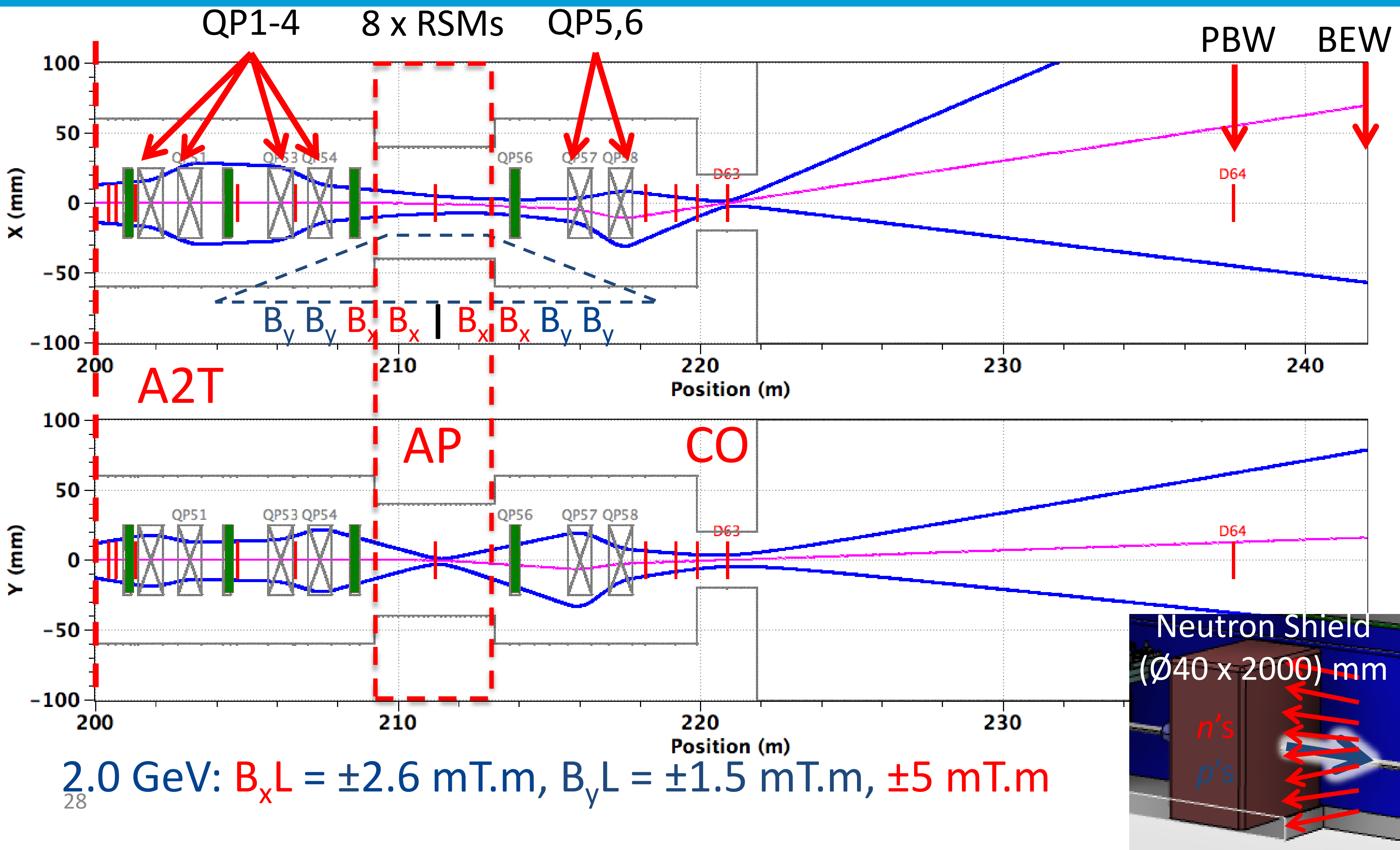
5:4 pattern





A2T Beam Optics

Centroid
10 x RMS beamlet



2.0 GeV: B_xL = ±2.6 mT.m, B_yL = ±1.5 mT.m, ±5 mT.m

Beam expander design exploits the high beam quality delivered by the linac

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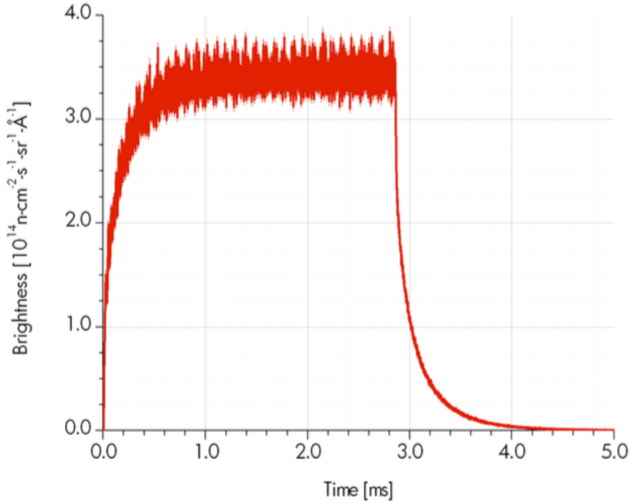
- Proton beam has very low transverse emittance
  - Delivered directly from the linac – no ring!
- Desirable features of raster beam expansion
  - Sharpness of the beam footprint on target is adjustable
  - Ability to incorporate a beam crossover where the beam is small
  - Long drift from the crossover to the target
  - Near uniform current density over a good fraction of the beam footprint on target
  - Beam size and distribution is relatively insensitive to the beam tune

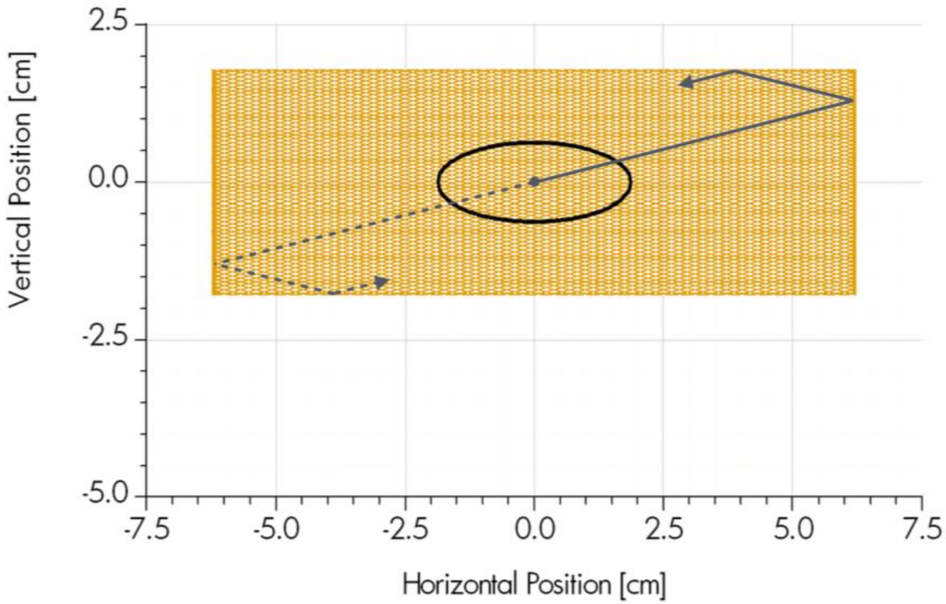
Raster scanning effects on neutron output

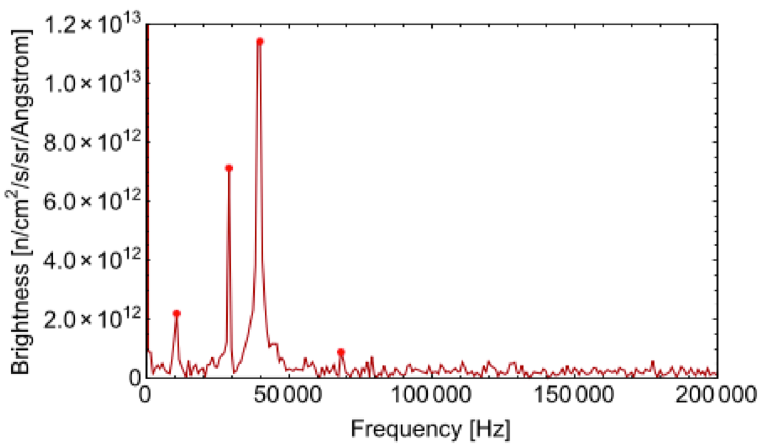
Raster Pulse: Alternating Parity

Shea et al, ICANS'15

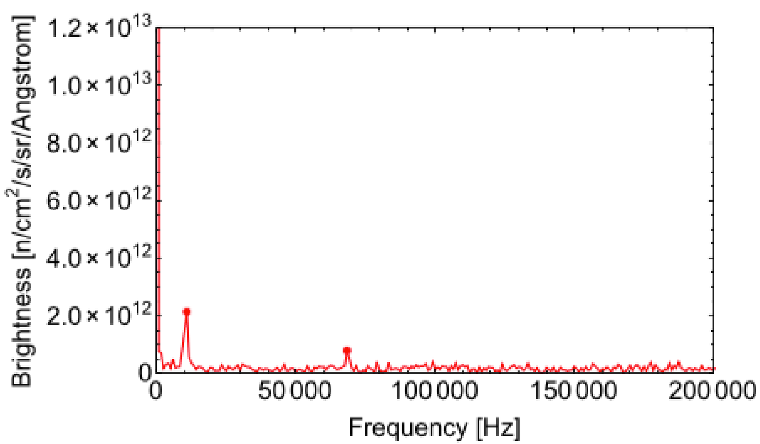


(a) 0.8 Å neutron pulse produced by thermal moderator from a single rastered pulse.





(a) From single neutron pulse.



(b) From average over direct and inverted pulse.

Concluding remarks

Concluding remarks

- Construction of ESS is well underway
- Key components and systems are currently designed and manufactured
  - High power rotating tungsten target
  - Target helium cooling system
  - Raster scanning magnet system for beam expansion
- In parallel to high performance goal priority is to make provisions for a safe, stable and reliable operation

Extra slides

Target safety becomes ever more important with increasing beam power

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- Radionuclide inventory in a 1-MW target is roughly on par with that of a 100-kW fission reactor
- Following beam shutdown, target decay heat removal must be robust and highly reliable
  - Passive decay heat removal is best
- Good practice: adopt the safety approach developed for nuclear facilities
  - Identify and assess the hazards
  - Those hazards with severe consequences and high frequency undergo detailed design basis accident (DBA) analysis
  - Controls identified to mitigate the likelihood or consequence of a DBA are deemed "credited controls," which must meet a higher standard in quality and pedigree

A “safety by design” philosophy should be adopted at an early stage of target design

- Safety of the public and of workers should be an important factor when making design choices
- Hierarchy:
  1. **Passive safety features**
     Easiest to defend to regulators
     Normally the least-cost option
  2. **Engineered controls**
     Active safety systems with an established pedigree
     Should be simple in concept, implementation and operation
  3. **Administrative controls**
     Relies on established processes and procedures
     Typically involves high operational overhead
     Subject to human error

RSM Failure?

Figure of merit:

- Peak current density (J_{max}) on target
- Beam outside nominal footprint regions