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Material Selection of the Beam Profile Monitoring Devices at ESS Target Station

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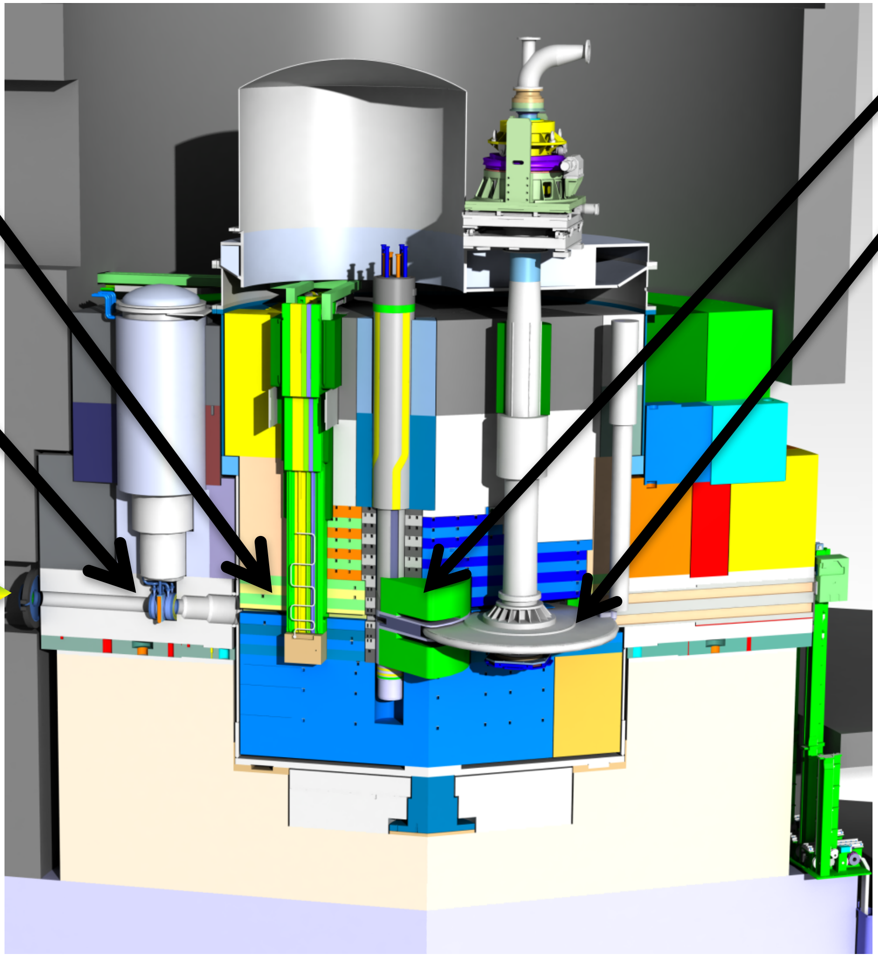
Need for beam profile monitoring (BPM)

- ESS beam parameters
  - 2 GeV, 5 MW proton beam
  - 4% duty factor
    - 14 Hz repetition rate
    - Pulse duration of 2.86 ms
    - 2.5 mA (5 MW) time averaged beam current
    - 62.5 mA (125 MW) beam current during pulse
- BPM is required to avoid a target systems failure due to an anomalous beam.
  - Beam current density
  - Beam halo distribution
  - Beam position

Target Monolith – Beam Diagnostics



Proton Beam Instrumentation Plug (PBIP)

Proton Beam Window (PBW)

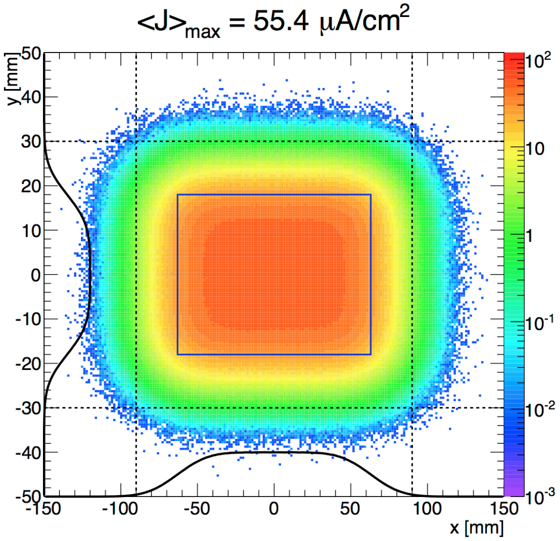
Proton beam:
2 GeV/5 MW

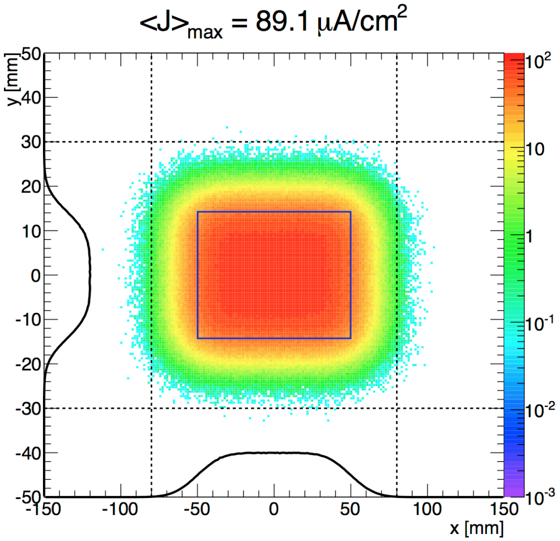
Moderator-Reflector Plug (MR Plug)

Target Wheel

Design Beam Profile on Target

- Beam on target requirements:
  - Beam footprint enclosing 97.5% beam fraction: 180 mm (H) × 60 mm (V)
  - Beam footprint enclosing 99.9% beam fraction: 200 mm (H) × 64 mm (V)
  - Nominal time-averaged peak current density: 56 µA/cm²
  - Maximum time-averaged peak current density: 81 µA/cm²
  - Max displacement of footprint from nominal position: ±5 mm (H), ±3 mm (H)
- Beam on PBW:
  - Higher beam current density, assuming linear optics.

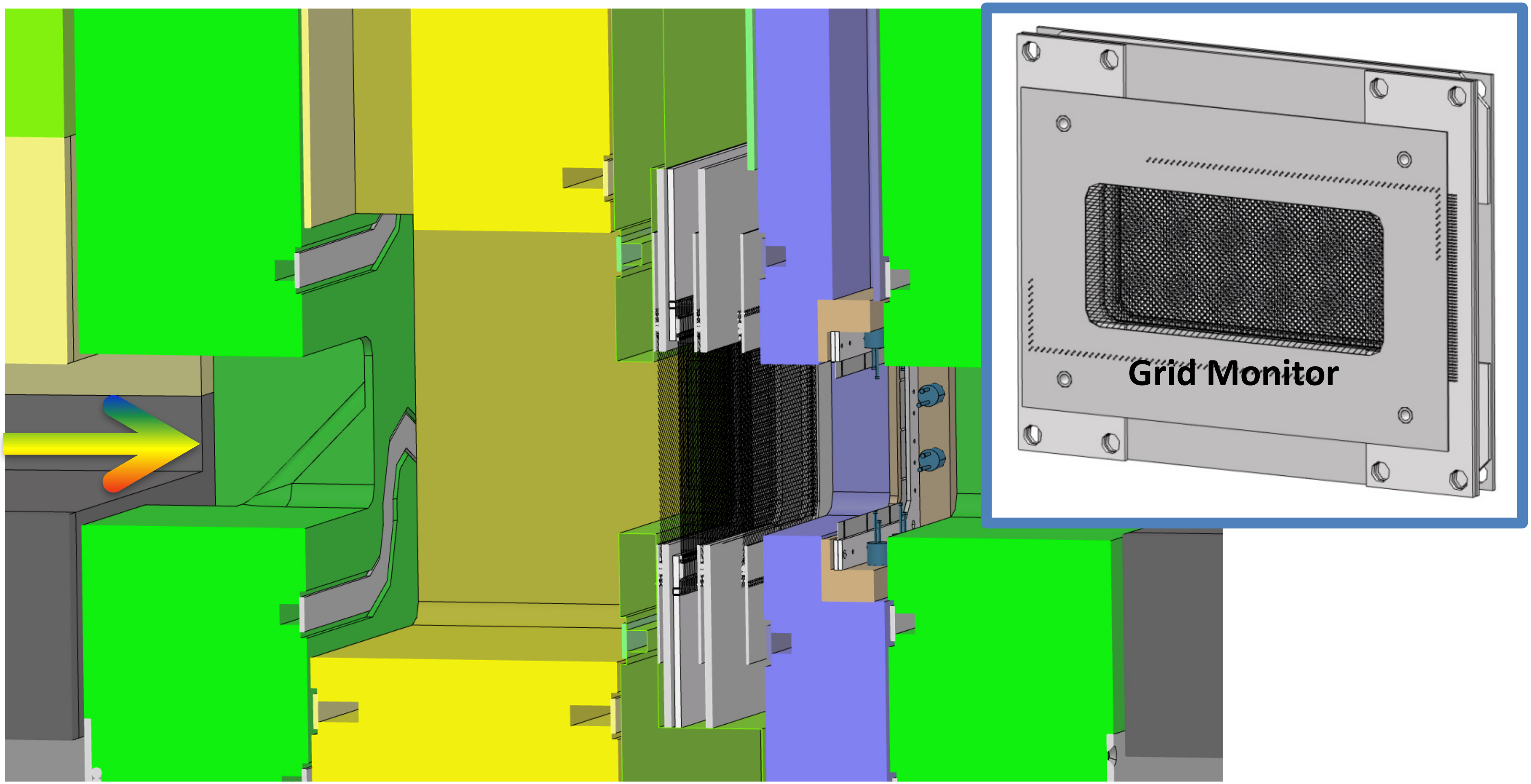




Beam Profile Monitoring Syatem

- All the BPM systems planned is based on beam-intersecting
  - High irradiation damage induced short service lifetime
  - High thermal load induced structural failure
- Baseline scope of the BPM Systems at the Target Station:
  - Multi-wire profile monitor (MWPM):
    - Set of conducting wires intersecting proton beam
  - Aperture monitor:
    - Set of thin metal blades intersecting the proton beam edge
  - Luminescent coating:
    - Proton beam window (PBW)
    - Beam entrance window (BEW) of the target wheel

Proton Beam Instrumentation Plug

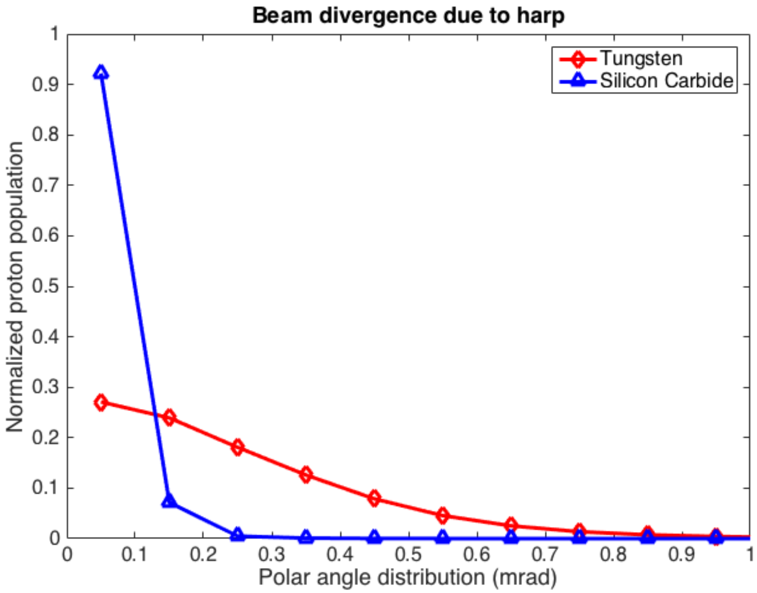


Material choice for harp

- Candidate Materials
  - Pure tungsten: SNS
  - Tungsten-Rhenium alloy: BLIP
  - SiC: JSNS, ISIS, LANSCE
- Material Selection Criteria
  - Disturbance to beam optics
  - Signal characteristics
  - Lifetime limited by radiation damage
  - Endurance to thermal and mechanical loads

Harp material: Disturbance to beam optics

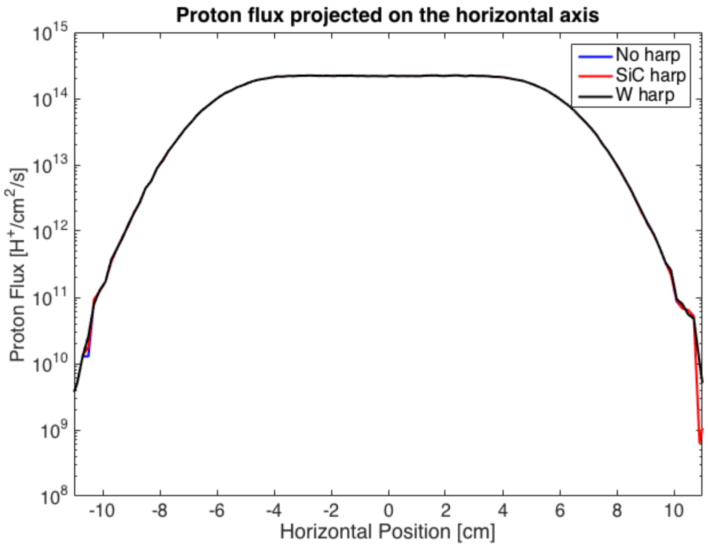
- There are five layers of harp made of 100 um thick wires with a pitch of 2 mm.
- For a pencil beam, the beam diverges with:
  - SiC harp: 0.06 mrad
  - W harp: 0.25 mrad

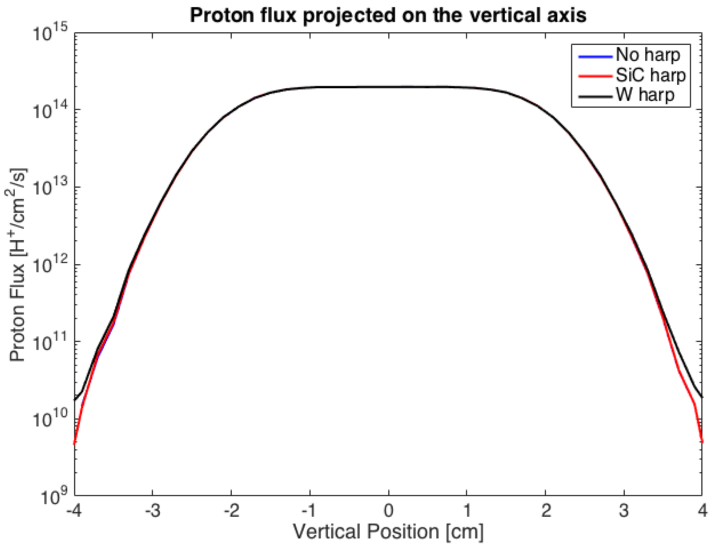


Effect of harps on beam-on-target requirement

Harp	Envelop 180 mm (H) × 60 mm (V)	Envelop 200 mm (H) × 64 mm (V)
No harp	99.38%	99.89%
SiC harps	99.37%	99.88%
W harps	99.33%	99.85%

- With the W harps, the beam shooting off the target is in an order of 1 kW compared to SiC harps.


Proton flux projected on the horizontal axis

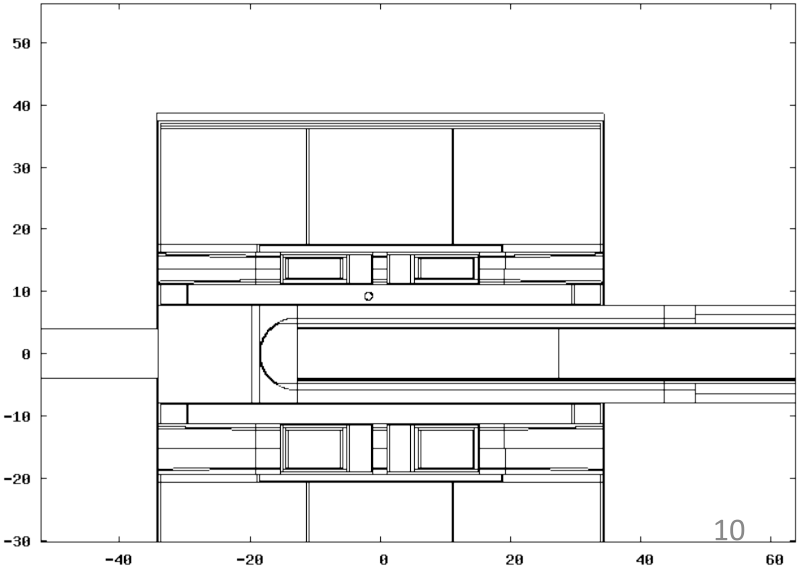

Proton flux projected on the vertical axis

Signal strength

- Negative charge deficiency
  - Secondary electron emission (SEE)
    - Ionization, diffusion of slow secondaries to the surface, subsequent escape of electrons
    - Secondary electron yield (SEY) is calculated by an empirical formula:

$$SEY = \frac{P \cdot d_s}{E^*} \frac{dE}{dz}$$

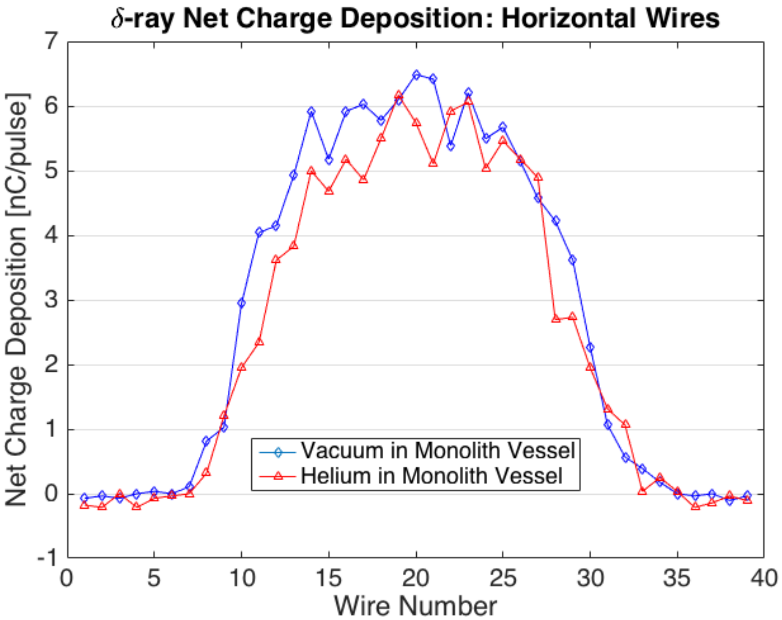
  - Recoiled delta ray electrons
    - Directly calculated by FLUKA

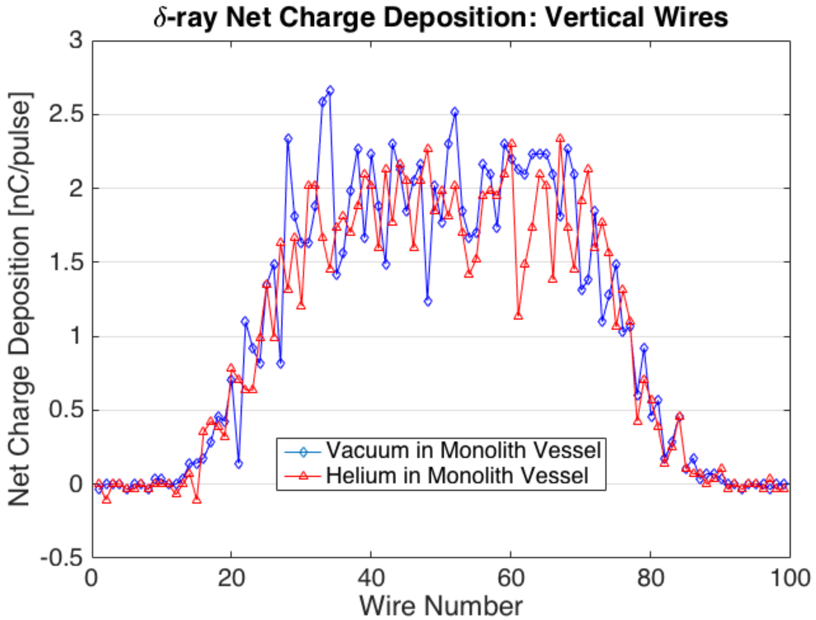


Signal Strength

Harp Material	dE/dz [MeV/cm]@2GeV-H^+	Secondary electron yield	Delta ray electron yield	Total Yield	Benchmark
W	24.4	0.049	0.026	0.075	0.07 SNS: 1 GeV-H^+
SiC	5.16	0.010	0.013	0.023	0.01 LANSCE: 0.8 GeV-H^+

- The signal from the tungsten harp is more than three times higher.





Radiation Damage

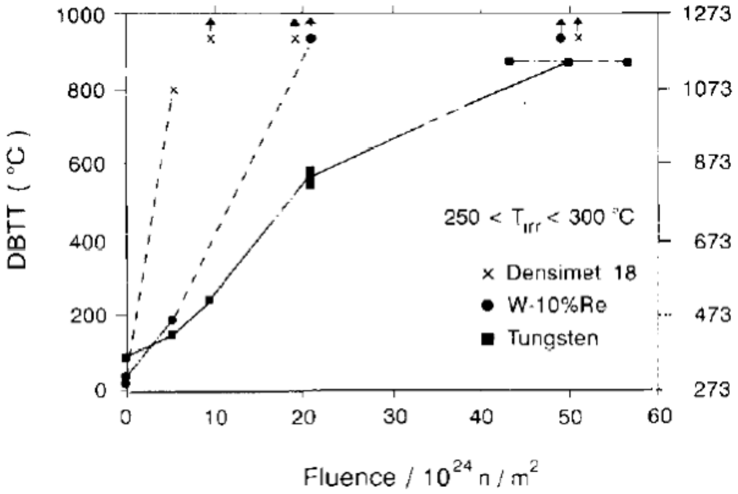
Harp Material	Max. DPA Rate [dpa/hour]	Annual Beam on Target Time	Max. DPA per Year
W	0.012	5400	64.8
SiC	0.001	5400	5.4

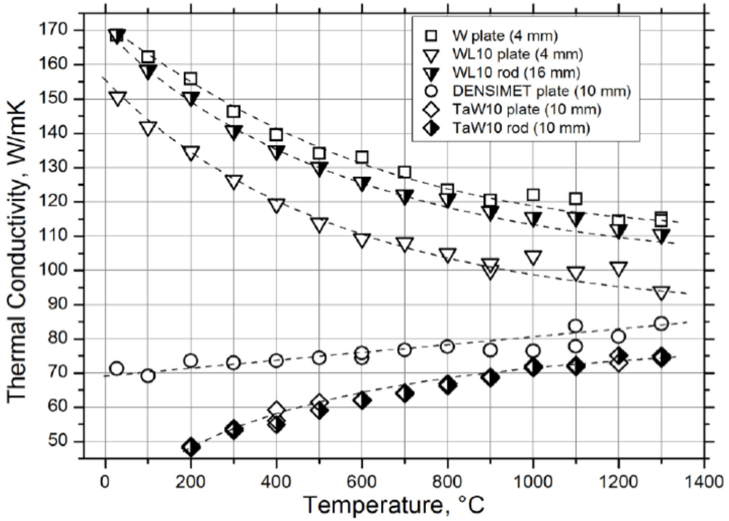
- The tungsten harp at SNS and the SiC harp at TS2 of ISIS have been operating without failure since its commissioning of the facilities.
- The accumulated damage dose on the harp in both facilities is roughly equivalent to one year dose at ESS.

Benchmarking Institution	Harp Material	Total Beam Energy/Charge	Accumulated Max. DPA
ORNL-SNS	W	32000 MWh	70
ISIS-TS2	SiC	1.5 Ah	3

Early failure of W-Re Harp at BLIP

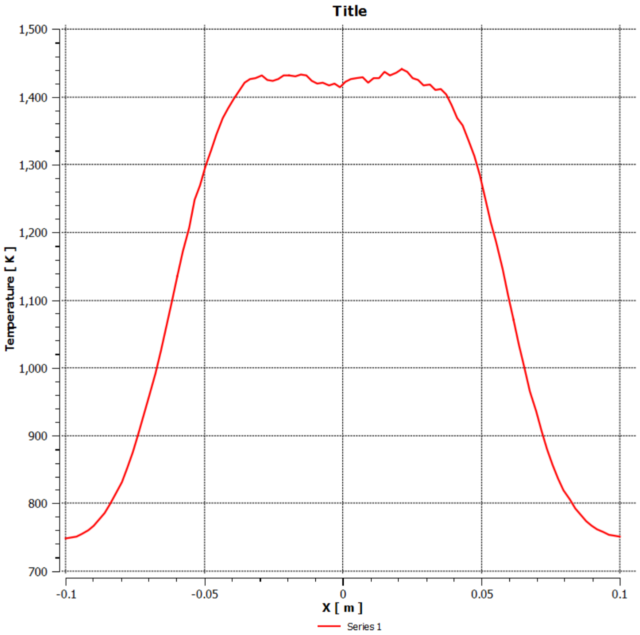
- The DBTT of W-Re alloy gets higher than pure tungsten after irradiation [H. Ullmaier, F. Carsughi, NIM-B 101, 1995]
- The thermal conductivity of W-Re alloy is lower than pure tungsten, which should lead to a higher thermo-mechanical stress and fatigue stress amplitude [M. Rieth et al, Tech- Rep.-KIT]

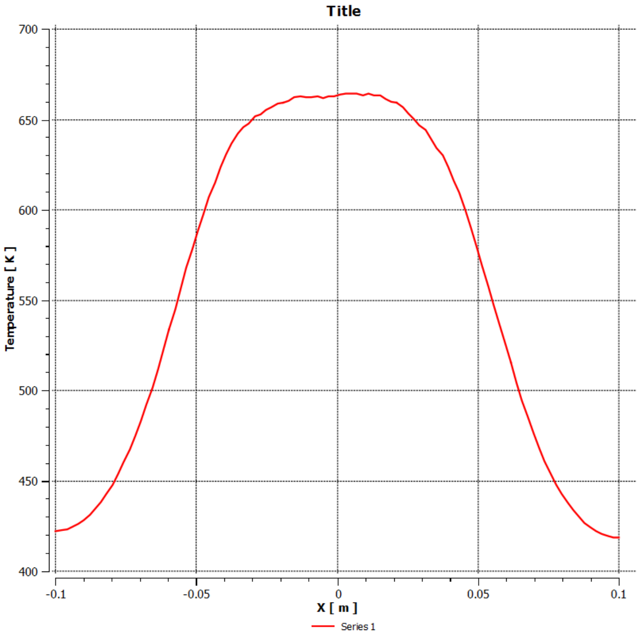




Thermal and mechanical properties

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



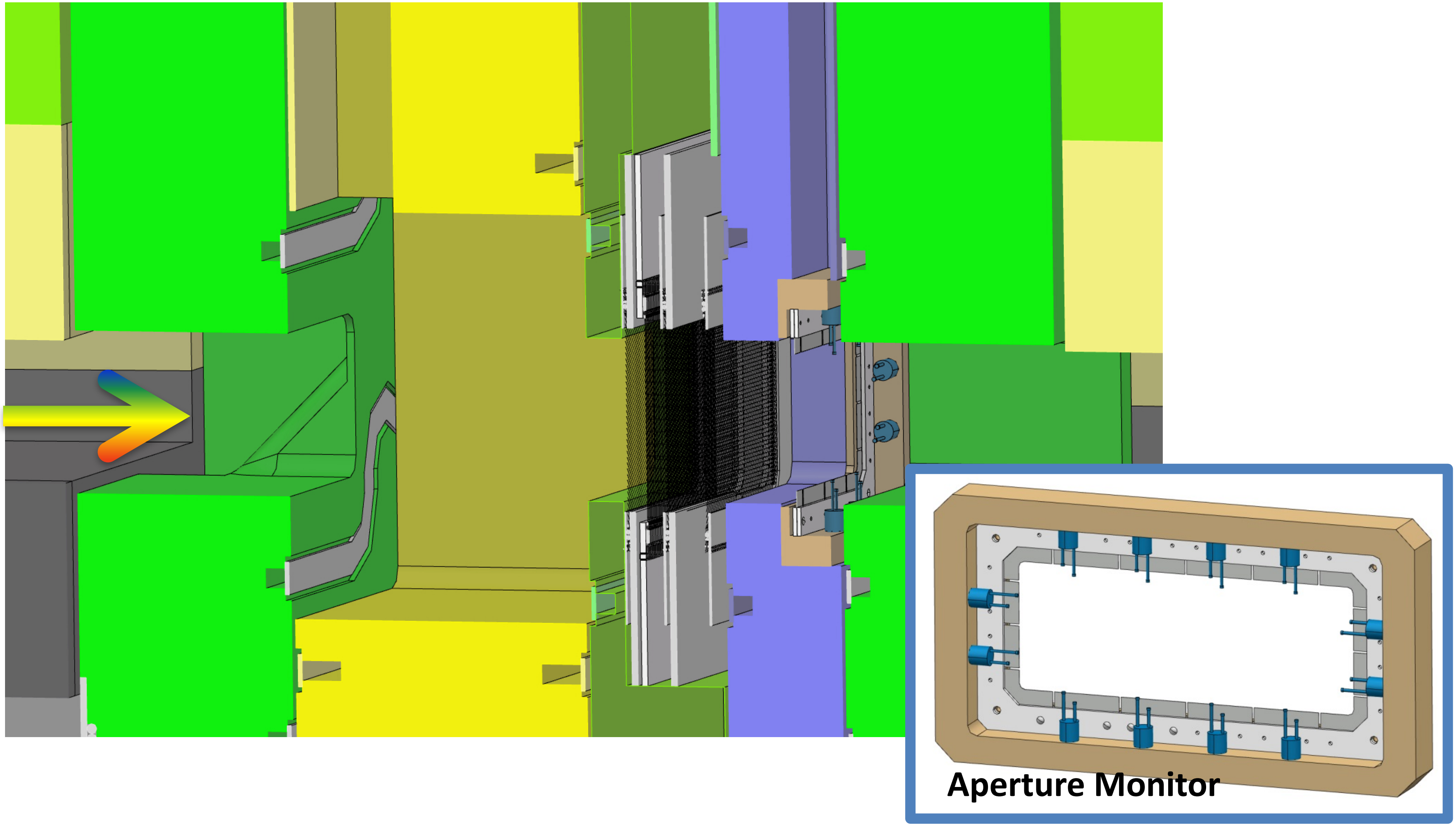


Tungsten vs. SiC

Properties	Tungsten	SiC
Beam optics disturbance	-	o
Δ-ray production	--	-
Radiation damage limit	1 year@5 MW	1 year@5 MW
Signal strength	+	-
Surface corrosion	-	+
Operation temperature	High	Medium
Mechanical load during operation	High	Low

- Silicon Carbide is preferred for the ESS application

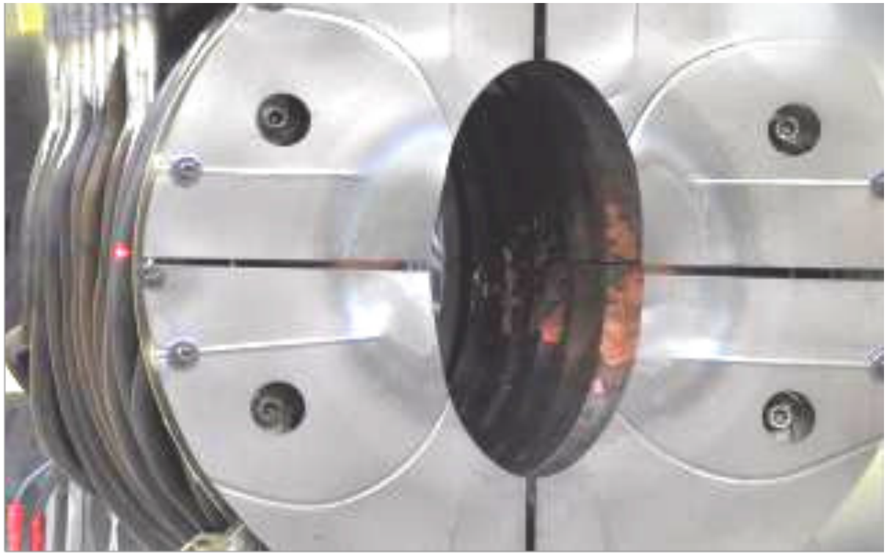
Proton Beam Instrumentation Plug

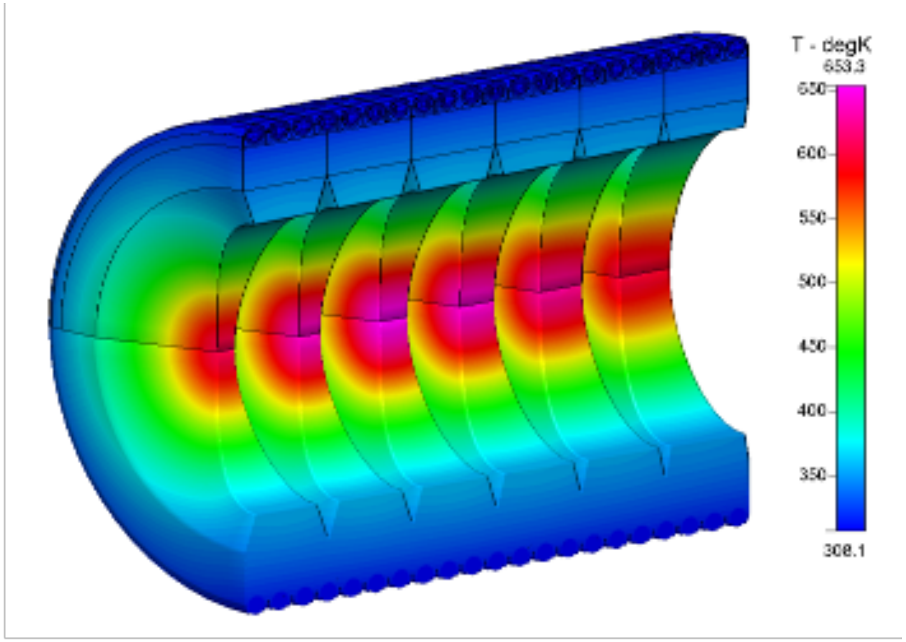


Aperture Monitor

Aperture Monitor

- Material Selection: Nickel
  - The halo monitor mounted at the direct beam upstream of KHE-2 is made of 100 um thick nickel membrane.

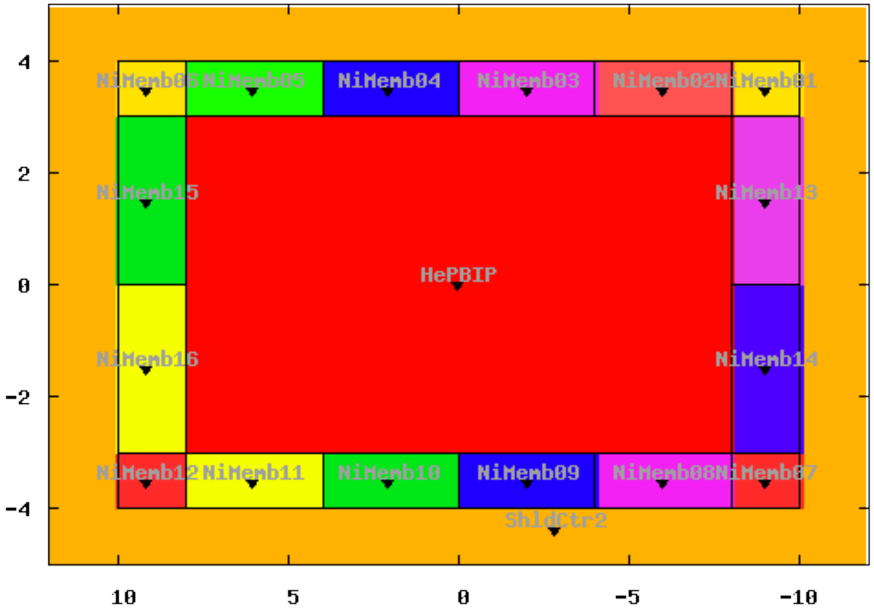


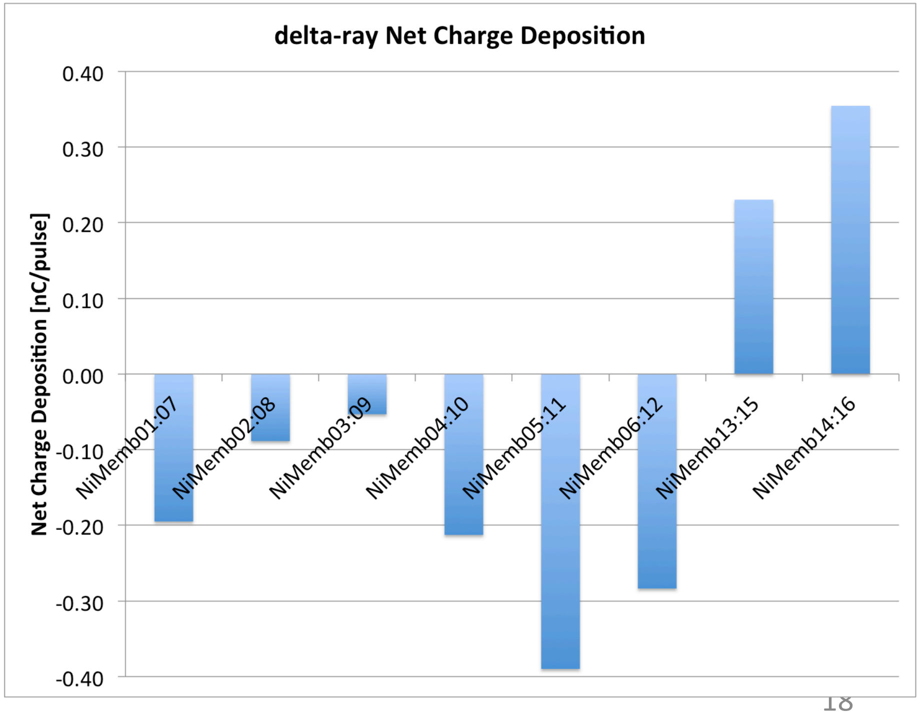


A. Strinning, et. al. HB2010

Signal Strength: 100 um thin Ni-Diaphram

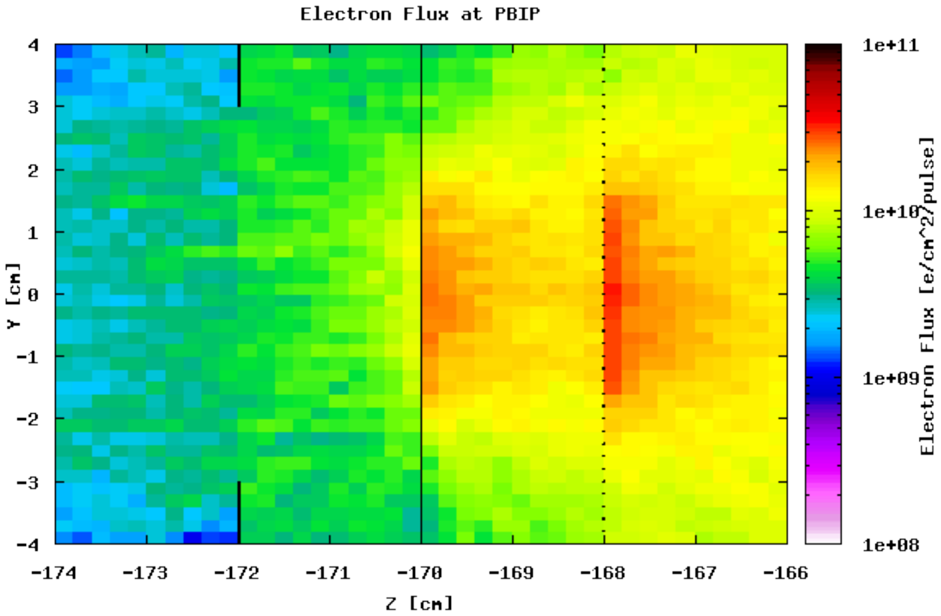
Facility	dE/dz [MeV/cm]	Secondary Electron Yield	δ-Ray Yield	Total Yield
PSI	16.7	0.033	0.023	0.056
ESS	13.6	0.027	0.019	0.046

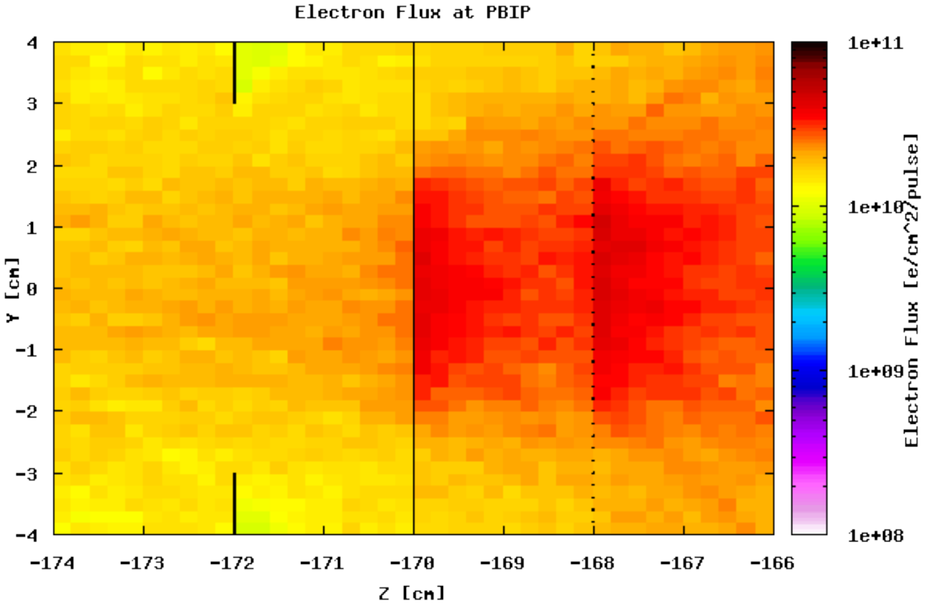




Negative Net-Charge Deposition

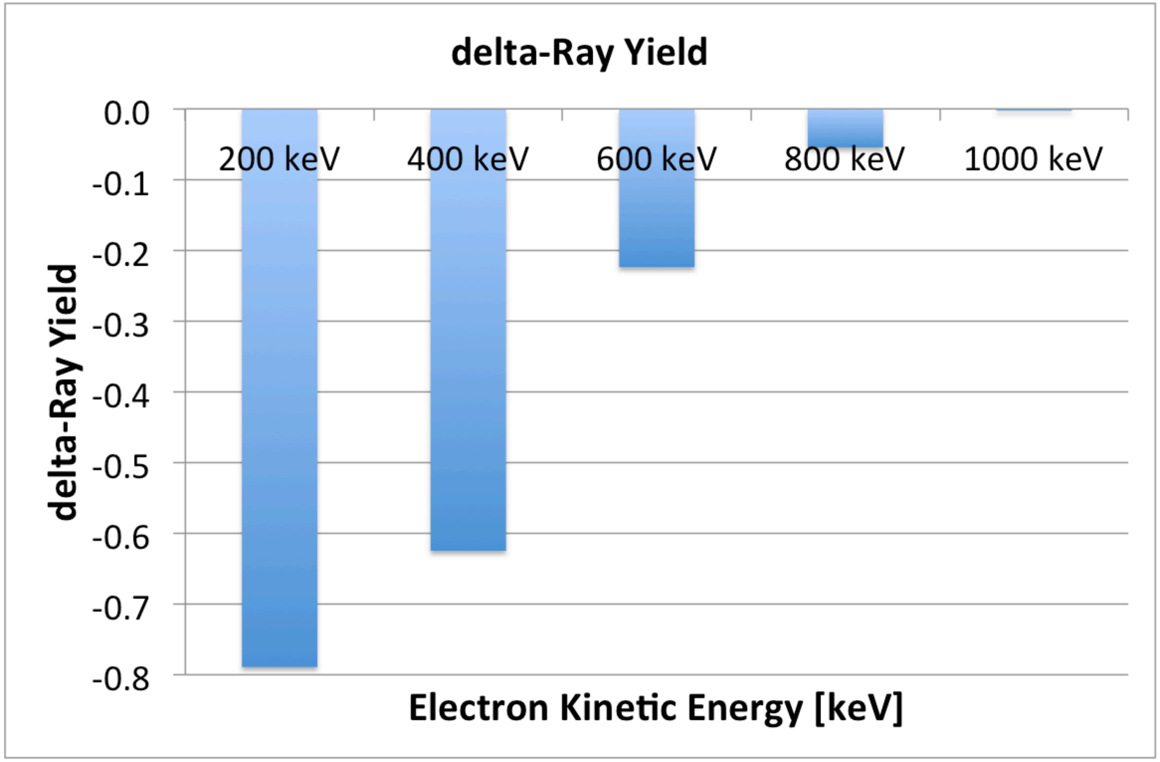
- Δ-rays from harp and helium atmosphere





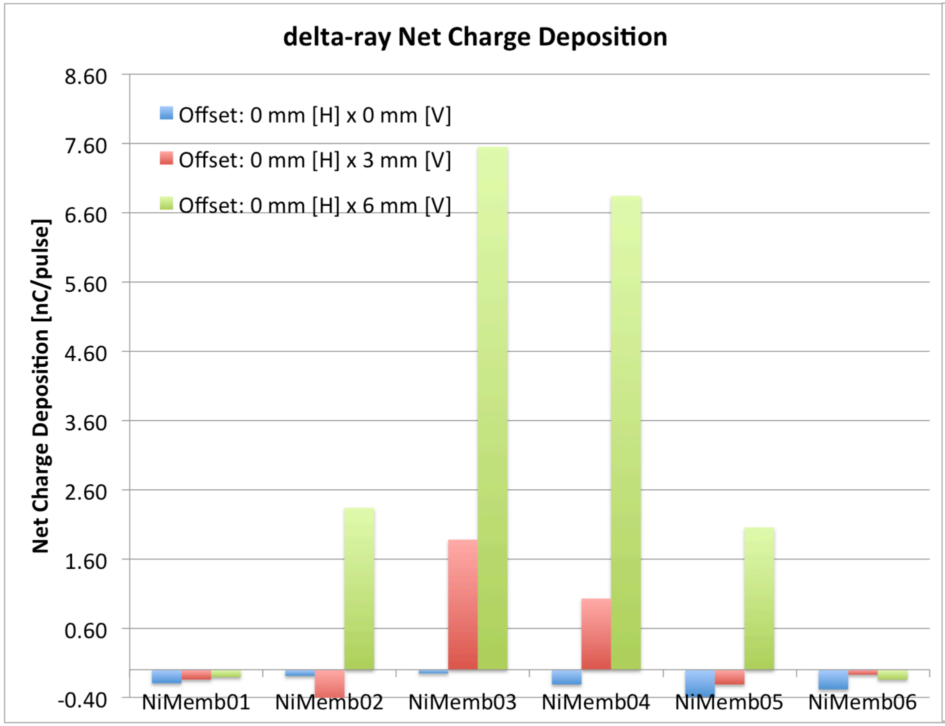
Δ-ray yield due to impinging δ-ray electrons

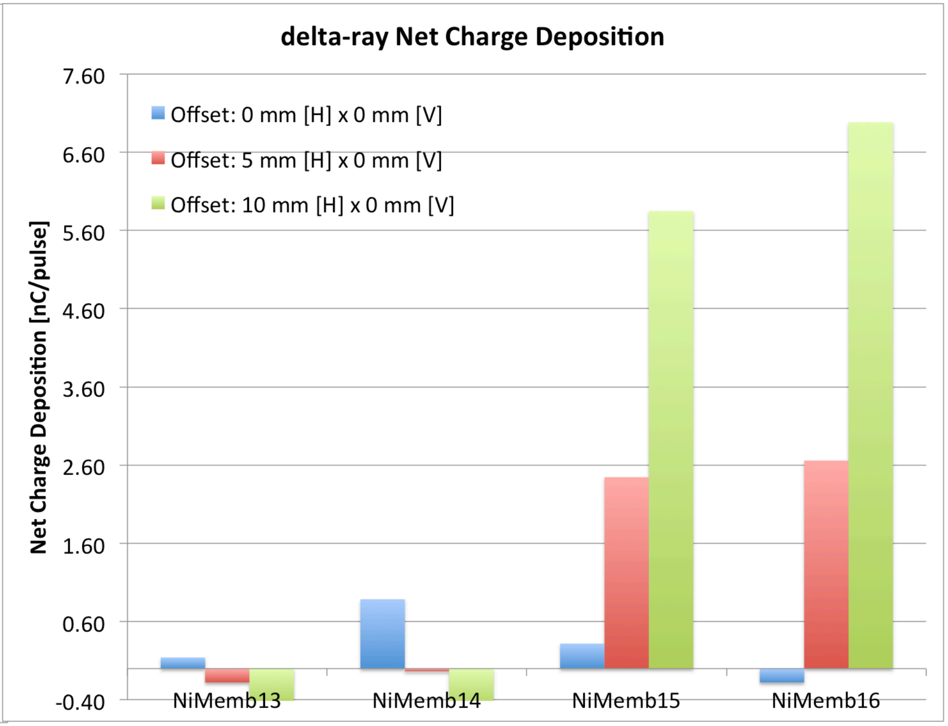
- The calculated δ-rays are in the energy range between 10 keV and 1 MeV
- Low energy δ-rays are stopped within the 100 um thickness of the Ni-diaphragm, creating negative net charge deposition.



Beam offset and δ-ray yield

- As there are more protons bombarding the blade, the net charge yield turns to “positive”



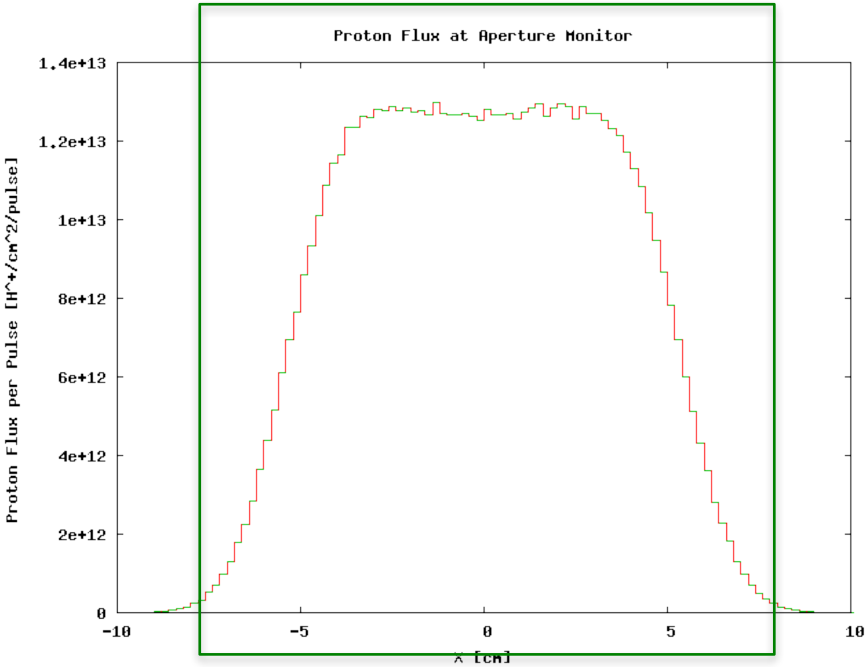


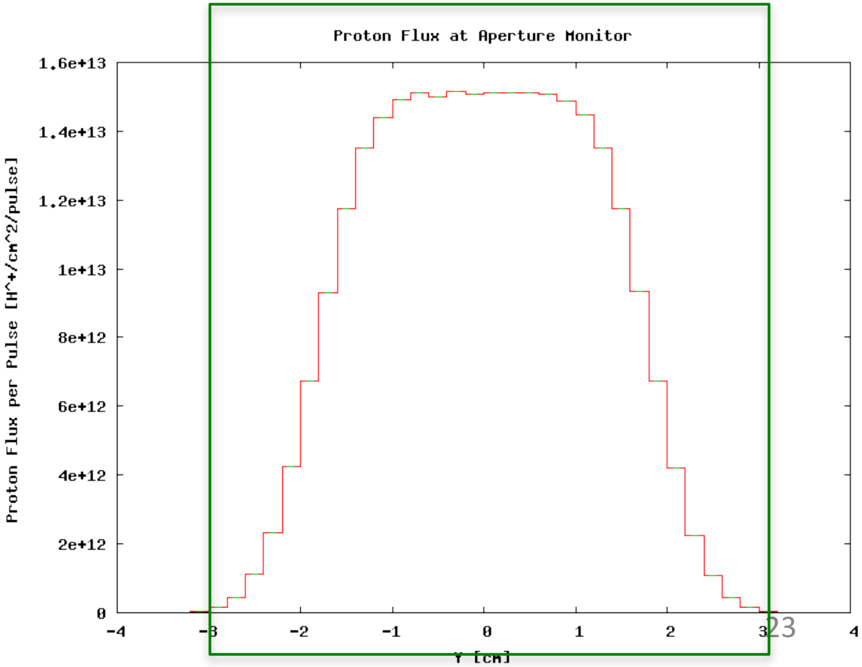
Radiation Damage and Lifetime

- Benchmarking: PSI
  - Integrated beam charge up to 2010: 120 Ah
  - Maximum integrated DPA: 100
- Aperture monitor at ESS
  - Maximum damage rate: < 10 dpa/year for 27000 MWh/y
  - The lifetime of the aperture monitor is conservatively estimated to be 10 years

Temperature at Aperture Monitor

- The maximum volumetric energy density per pulse is 1 J/cm^3/pulse.
- The dynamic temperature amplitude per pulse is less than 1 ^{o}C.
  - A small beam offset will increase the maximum temperature amplitude per pulse rapidly.



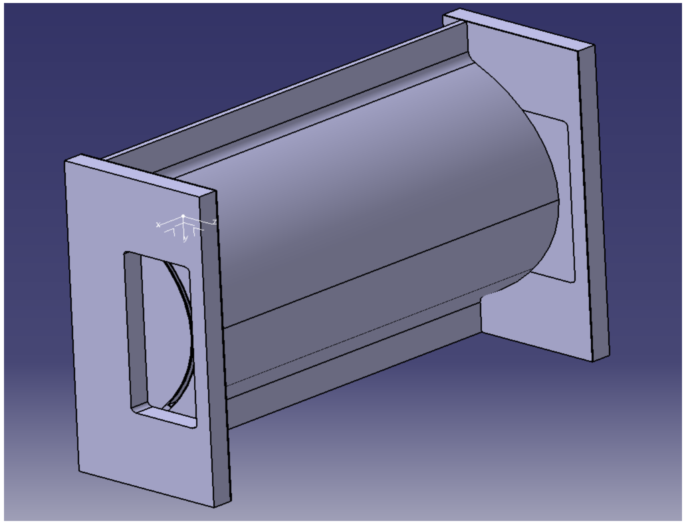


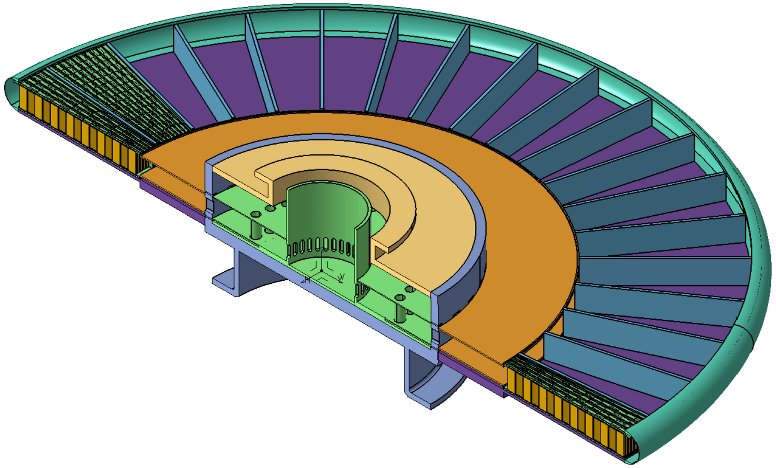
Halo monitoring and δ-ray

- Δ-ray introduces negative charge deposition in the aperture monitor intersecting halo
  - During normal operation, the aperture monitor expects to produce noise signal.
  - In case of beam offset, more protons will be intersected by nickel diaphragms, producing "positive net charge deposition."

Luminescent coating

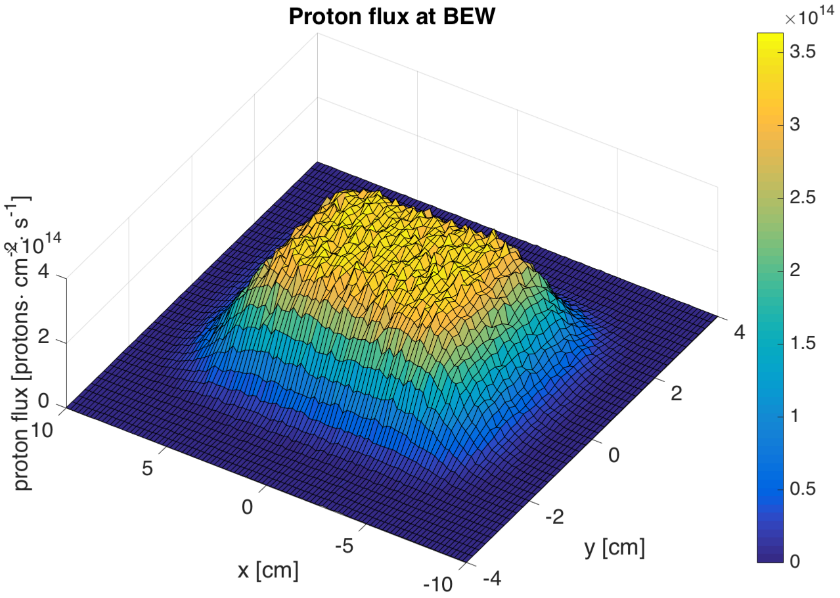
- Luminescent coatings on PBW and target for the beam profile imaging
- Baseline material:
  - Benchmarking SNS
  - Cr (1%) doped alumina (Al_2O_3)

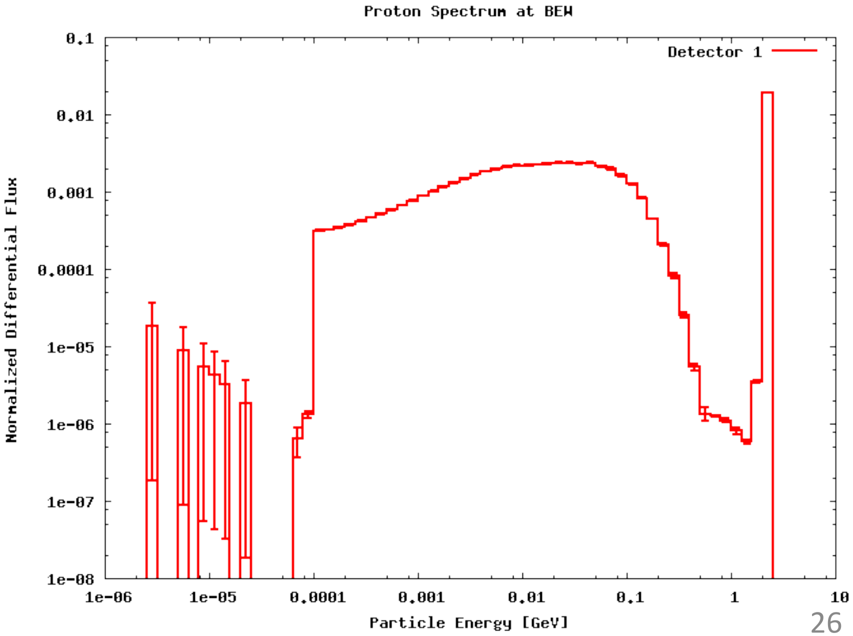




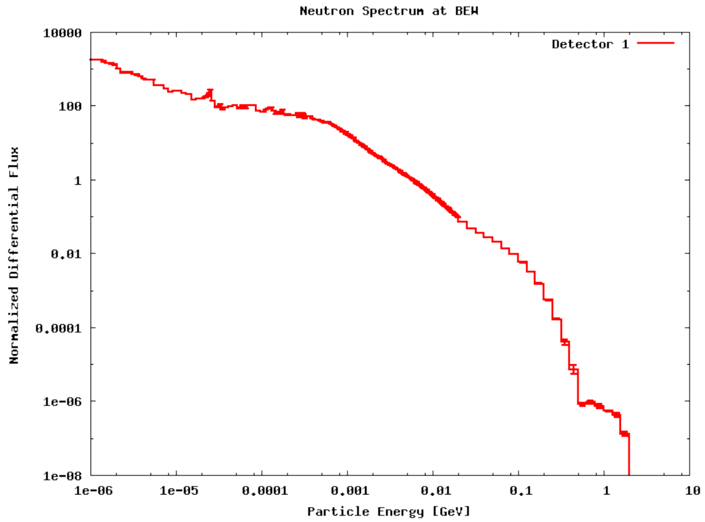
Proton flux at BEW

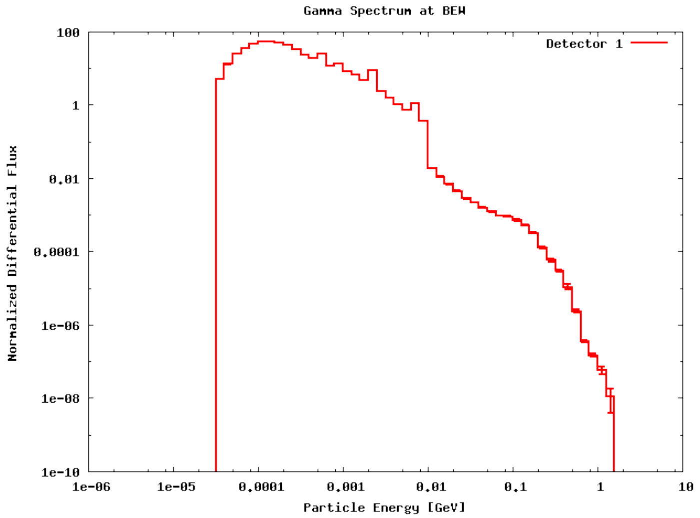
- Secondary protons from the harp

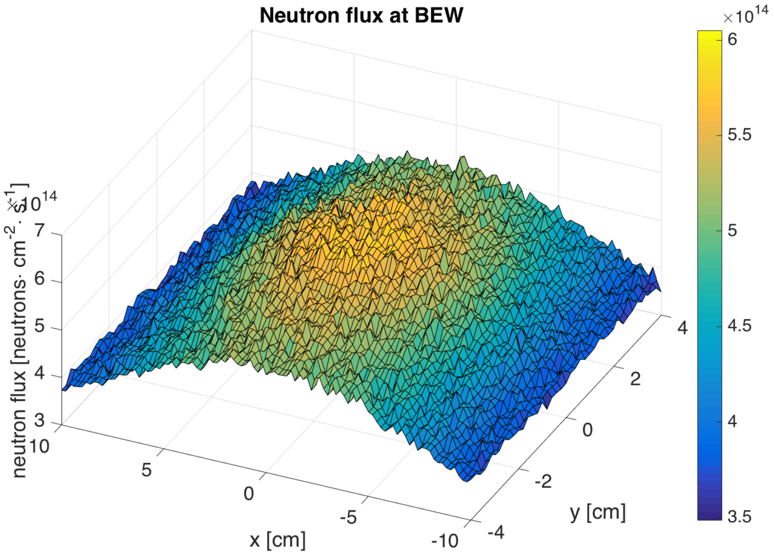


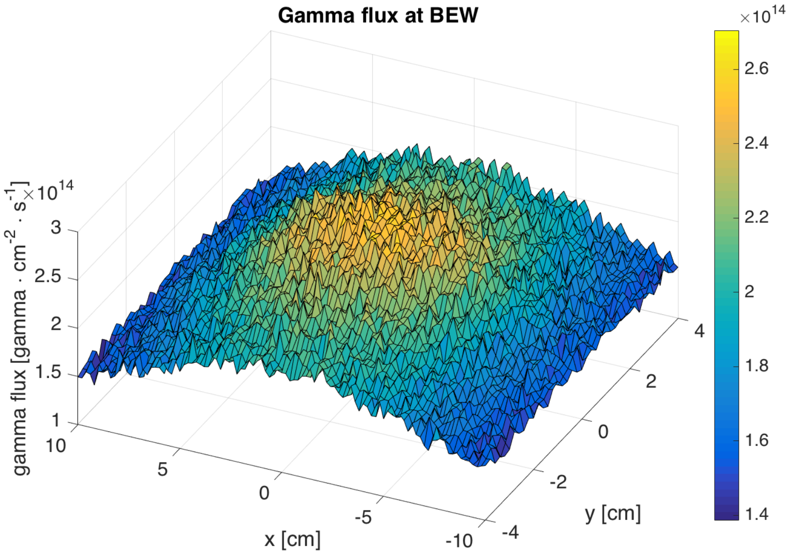


Neutron and gamma flux at BEW



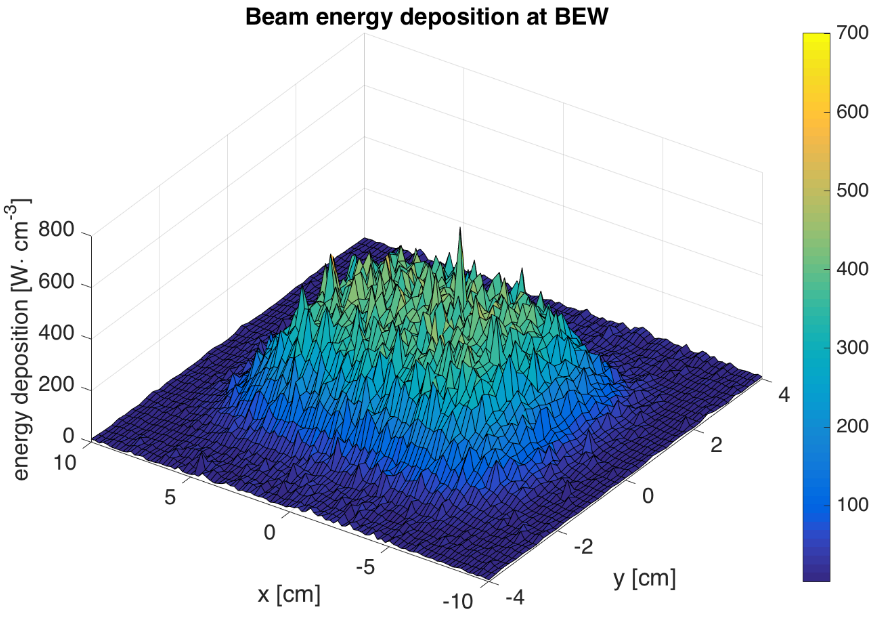




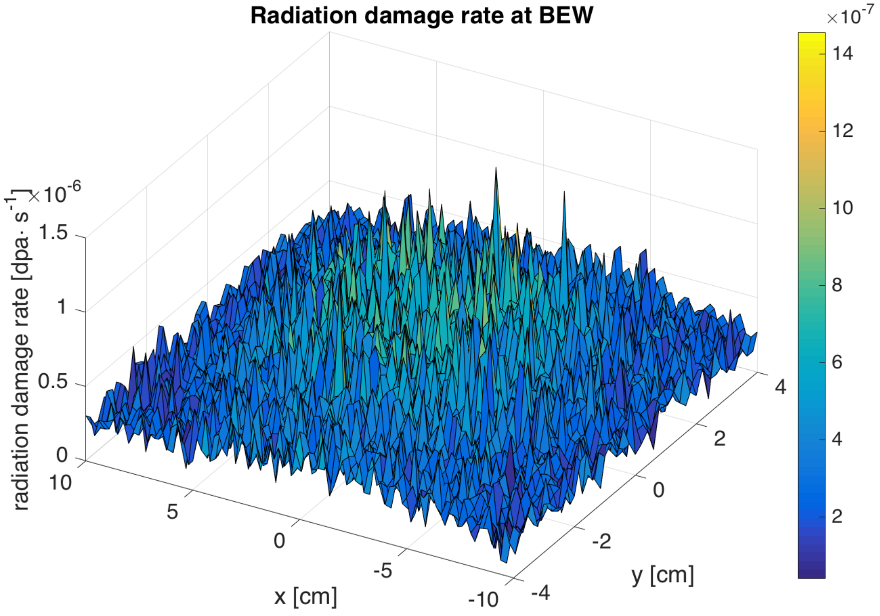


Energy deposition and radiation damage at BEW

- The radiation damage doesn't follow the proton beam profile



Beam energy deposition at BEW



Radiation damage rate at BEW

Issues in luminescent coating

- Radiation induced luminosity degradation
- Excit
- Etc. .

Thomas Shea et al., *"Luminescent materials development for beam-on-target imaging at the European Spallation Source."*

Summary

- The SiC is chosen to be the baseline material for the harp
- The Ni-diaphragm for halo monitoring will generate noises during normal beam operation, due to δ-rays from the harp and upstream components. But, it should be able to detect the anomalous beam position offset.
- There is on-going research on the luminescent coating material. Currently, baseline material is Cr:Al_2O_3 as at SNS.

Thank you!