Beam-material issues for instrumentation in a 5 MW monolith

M.A. Hartl, Y. Lee, C. Thomas, J. Habainy, T. Shea (ESS, Sweden)
David Wragg, Erik Adli, Håvard Gjersdal (University of Oslo, Finnland)
W. Blokland (Spallation Neutron Source, USA)
M. Jura (ISIS, Rutherford labs, England)
M. Tomut & group (GSI, Germany)

HB2016, Malmö

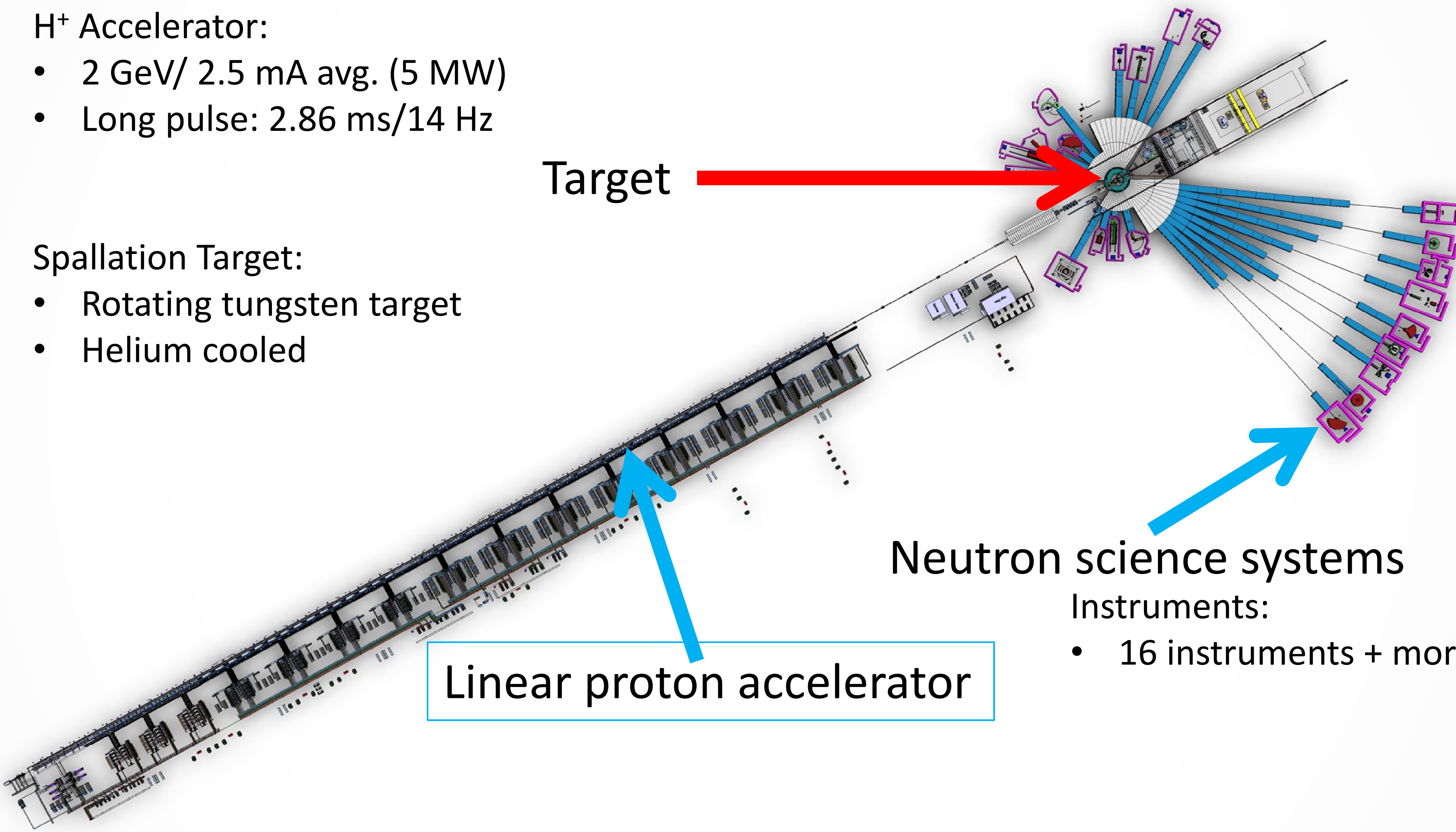
The ESS facility layout

H+ Accelerator:

- 2 GeV/ 2.5 mA avg. (5 MW)
- Long pulse: 2.86 ms/14 Hz

Spallation Target:

- Rotating tungsten target
- Helium cooled

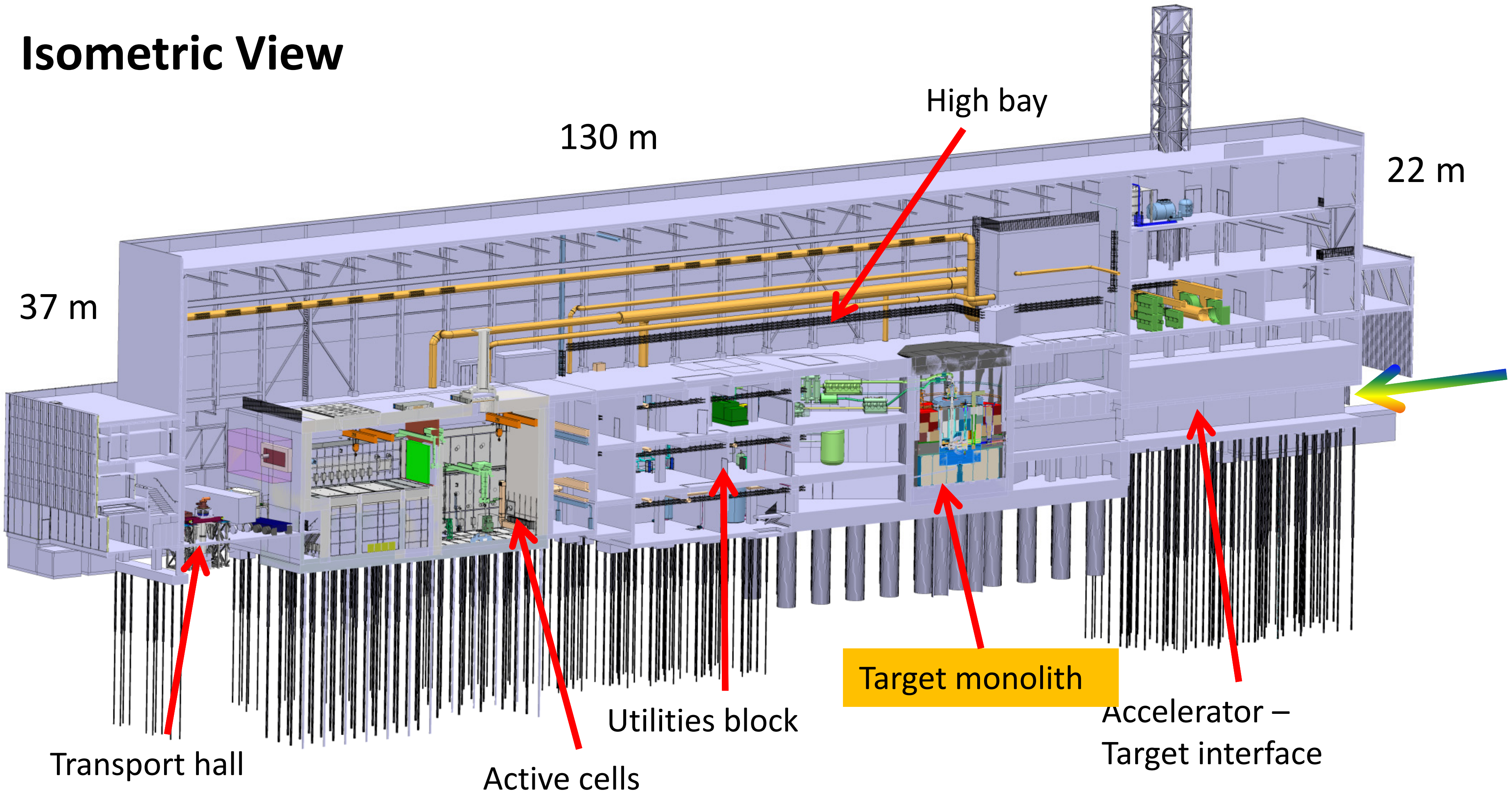


Instruments:

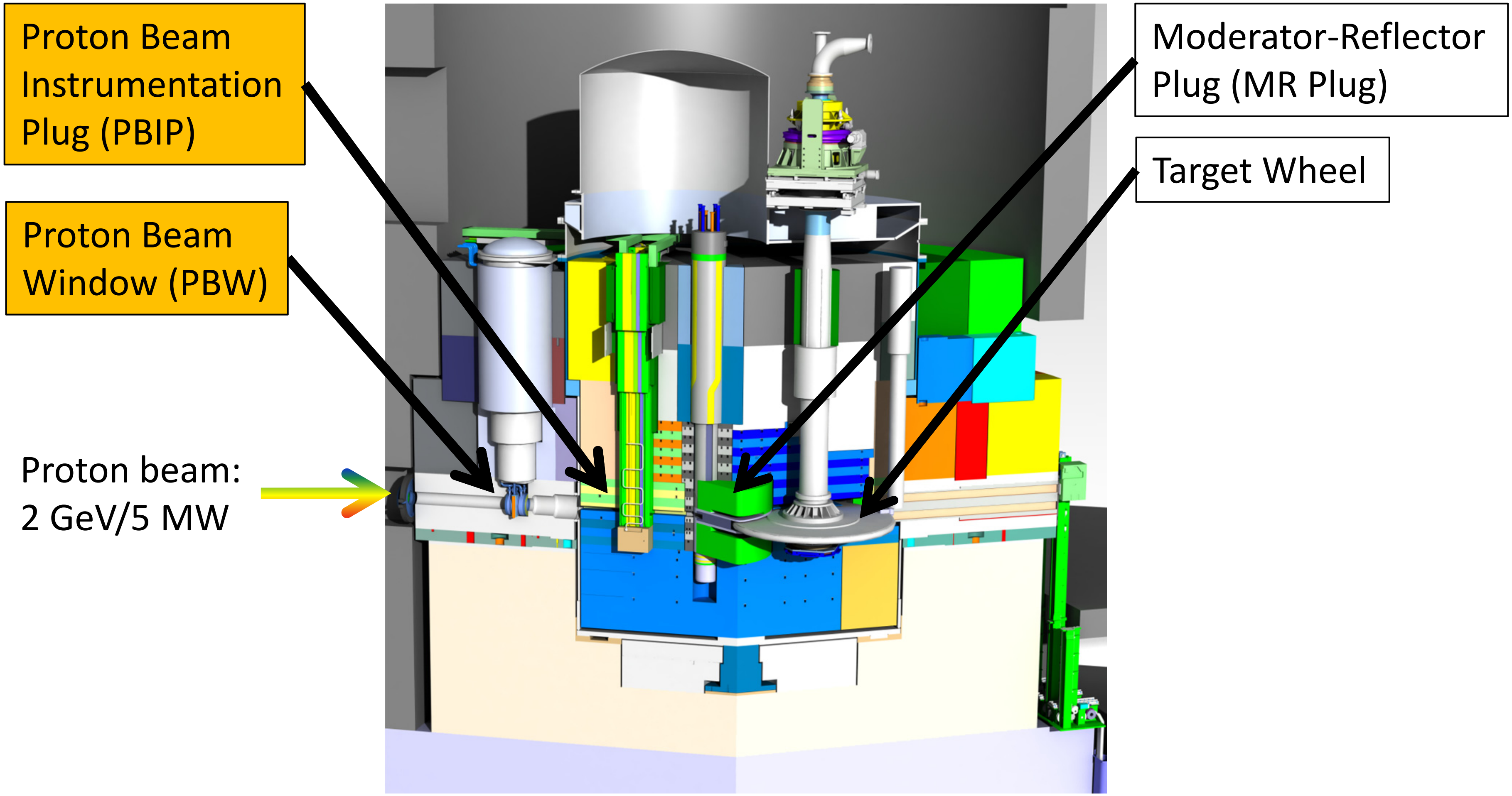
- 16 instruments + more

The ESS Target Station Layout

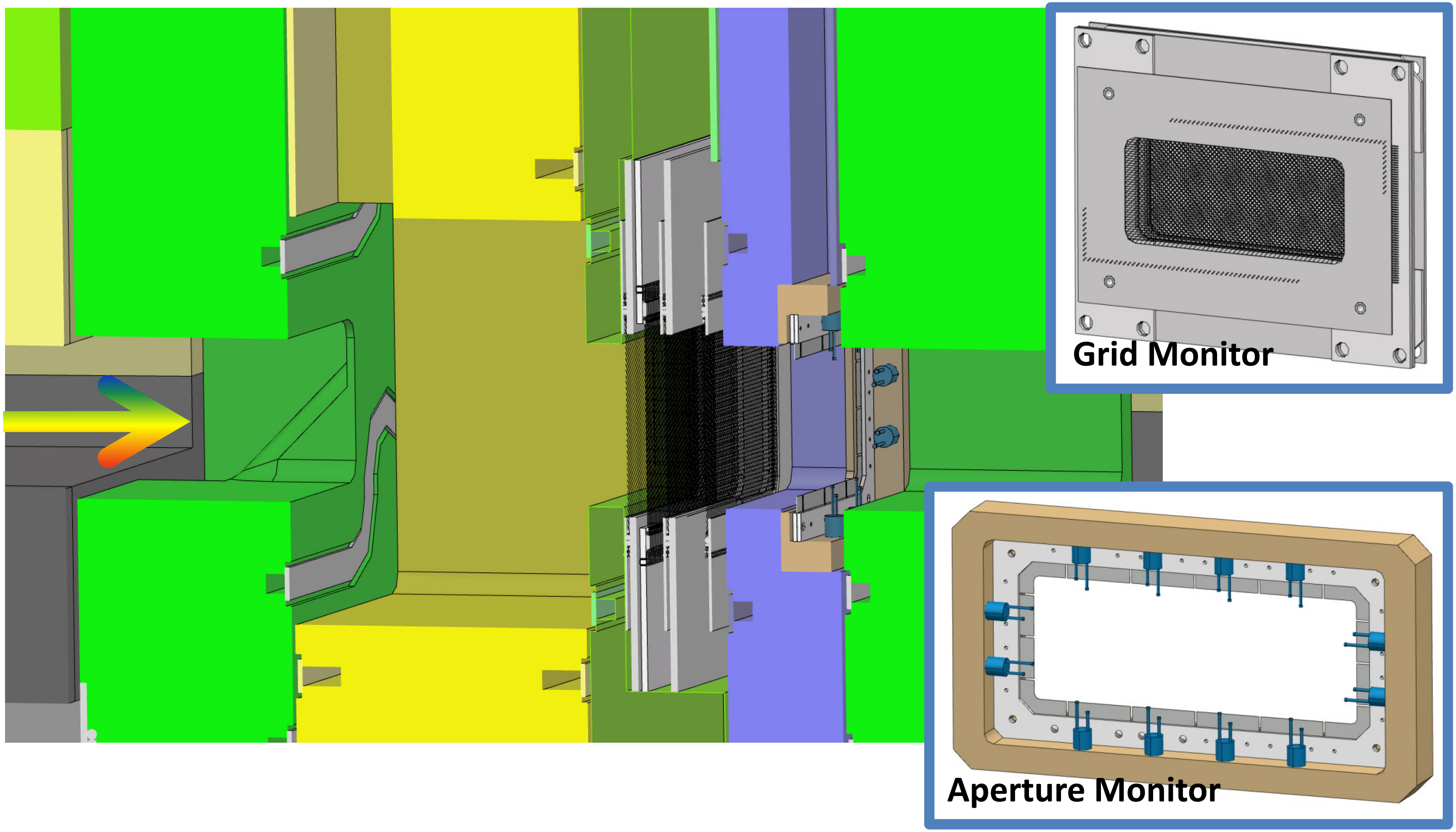
Isometric View



Target Monolith – Beam Diagnostics



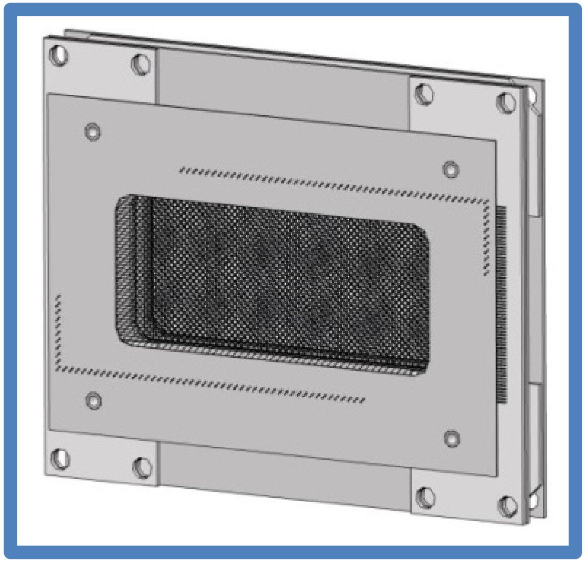
Proton Beam Instrumentation Plug



Multi-wire Beam Profile Monitor (Grid) "Harp"

EUROPEAN SPALLATION SOURCE

- Used for beam profile monitoring
- 5 layers of horiz./vert./diag. wires
- ESS Material:
  - W (SNS) or SiC (JSNS, ISIS, LANSCE)
- Thickness: 100 μm



- Method: secondary electron emission:
  - SEY: low energy (<1 keV)- Sternglass theory
  - DEY: enough energy to escape and produce further ionization (10 keV-1 MeV, "δ-rays") ➔ calculated by particle transport (FLUKA)

Secondary Electron yield at 2 GeV H^+ Sternglass formula (SEY) / FLUKA (DEY)

EUROPEAN SPALLATION SOURCE

- P: probability of e^- emittance = 0.5 (Bethe-Bohr equipart.)
- d_S: average depth for e^- emittance = $1*10^{-9}$ m
- E': average kin. energy lost = 25 eV (solid)
- dE/dz: proton stopping power of wire

Sternglass:

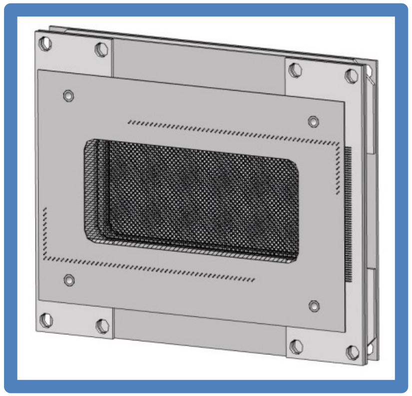
$$SEY = \frac{P * d_s}{E'} \frac{dE}{dz}$$

$E_k < 1$keV

FLUKA: DEY

larger E

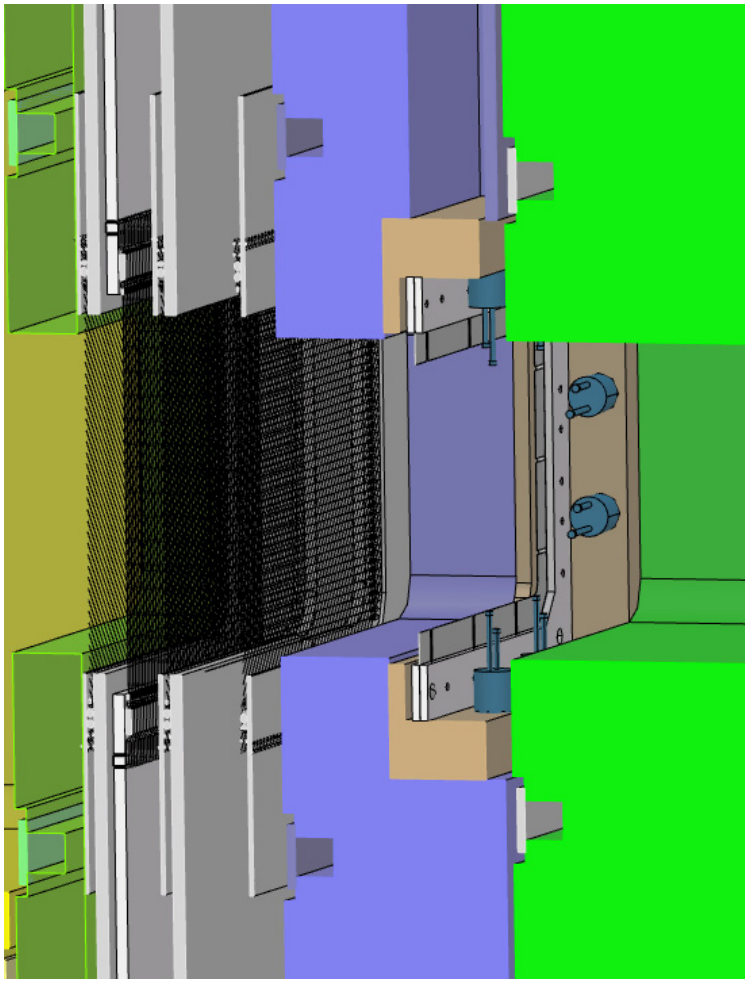
Wire Material	dE/dz [MeV/cm]	SEY $E_k<1$keV	DEY $E_k>10$keV	Total Yield
Tungsten	24.4	0.049	0.026	0.075
SiC	5.16	0.010	0.013	0.023



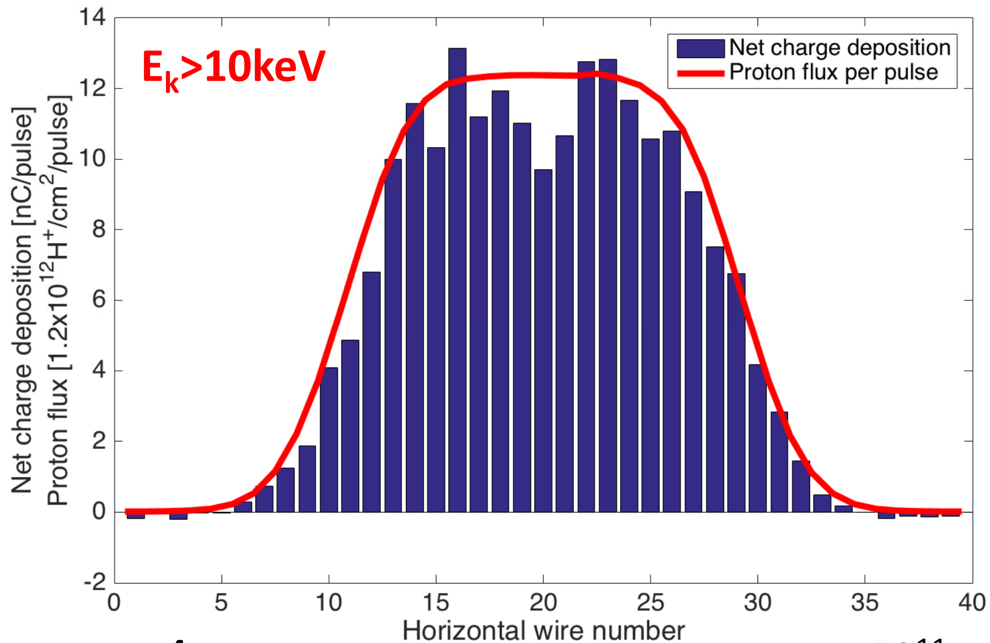
- Benchmark with SNS/LANSCE reasonable

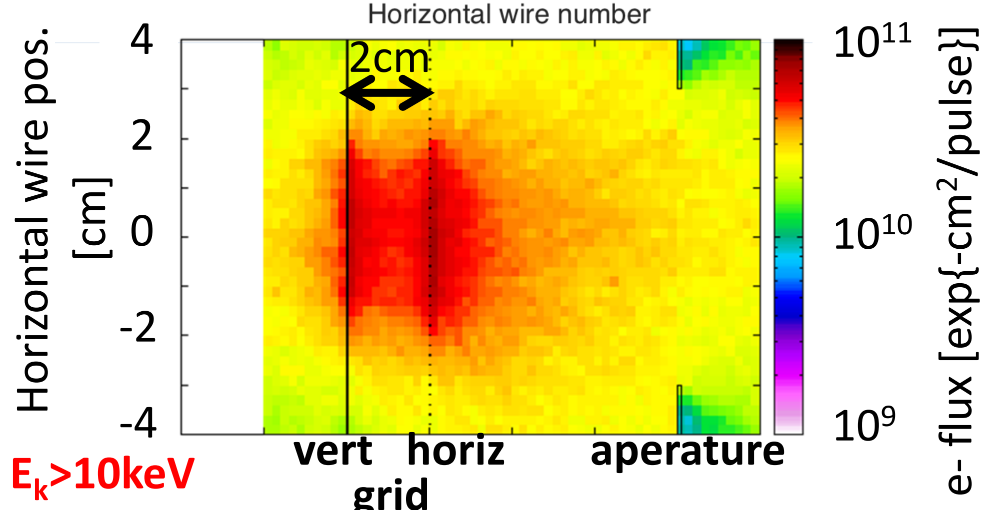
Charge Deposition and Electron Flux at the Harp (FLUKA)

EUROPEAN SPALLATION SOURCE



39 wires (2mm pitch)



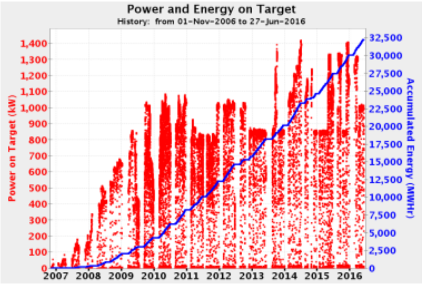


Radiation Damage & Life time of Harp wires

- Maximum displacement per atom (dpa) at 5 MW H^+ :

Wire Material	Max. dpa Rate [dpa/h]	Annual Operation Time	Max.dpa Rate per Year
Tungsten	0.012	5400	64.8
SiC	0.001	5400	5.4

- SiC wire: JSNS (3GeV, SiC, 0.25 dpa), ISIS (0.8 GeV, SiC, 3 dpa)
  - JSNS/ISIS dpa lower than expected @ ESS (5.2 dpa/year)
  - LANSCE reported failure of one/two wires within 1 year
- W-wire: SNS (1GeV, W harp 70 dpa)
  - ESS current >> SNS current
    => max. rad damage 70 dpa safe
    (see beam current density/accumulated beam)



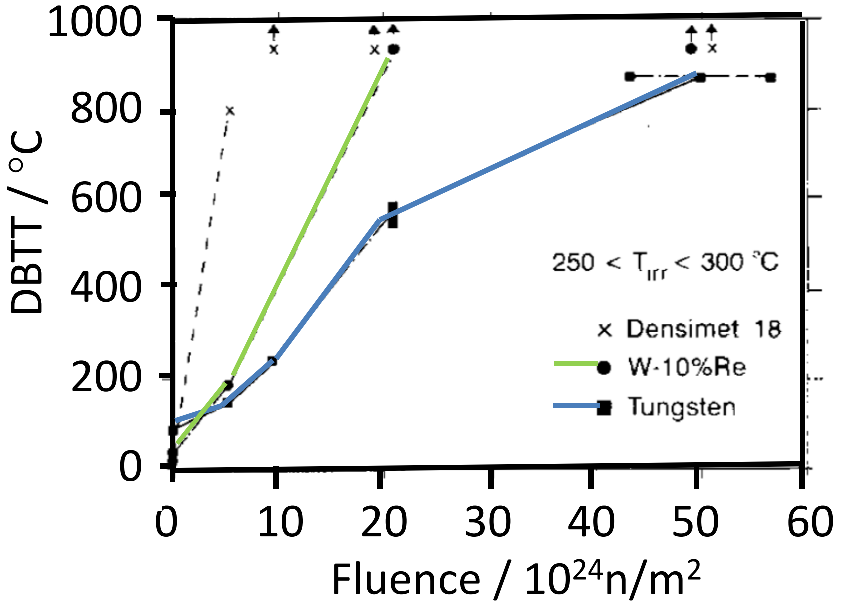
No use of W alloys for harp wires @ ESS

- W-wire:
  - **D**uctile-to-**B**rittle-**T**ransition-**T**emperature (DBTT) increases with rad. damage
  - higher operation T: W can self-anneal? W/Re not
  - W alloys: reduced life time (BLIP/CERN)

- DBTT (W) << DBTT (W-10% Re)

  for DPA>0.3

[H. Ullmaier, F. Carsughi, NIMB 101 (1995)]

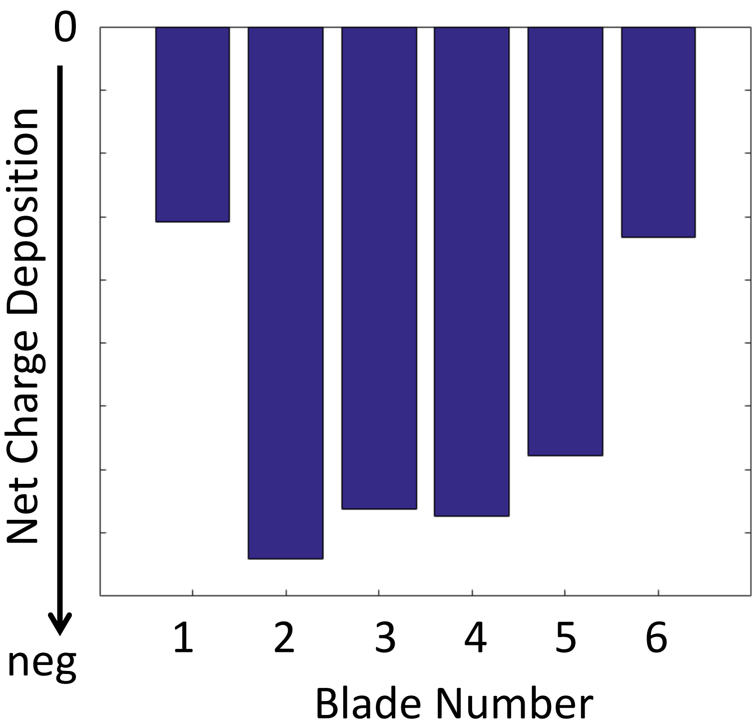


alloys W/Re are excluded for ESS

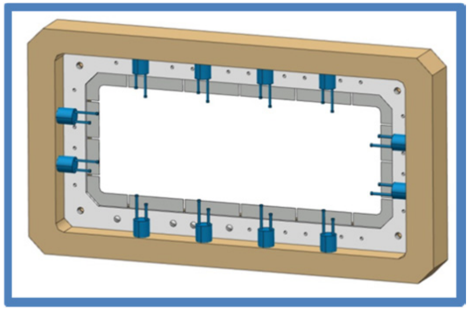
Aperture Monitor

- Material: Nickel, thickness 100 μm (PSI (0.575 GeV) has operated more than 2 decades without failure)
- Electron yields:

Facility	dE/dz [MeV/cm]	SEY E_k<1keV	DEY E_k>10keV	Total Yield
PSI	16.7	0.033	0.023	0.056
ESS	13.6	0.027	0.019	0.046



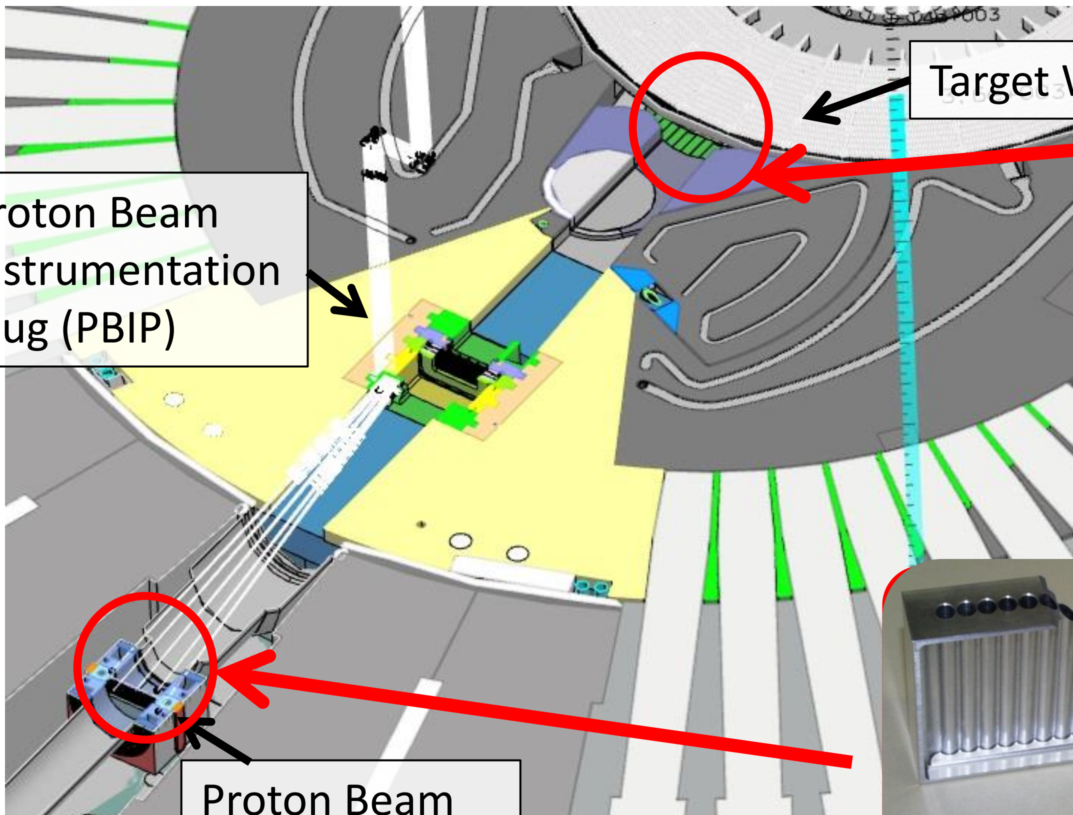
6 Ni sheets covering horizontal range (20 cm)

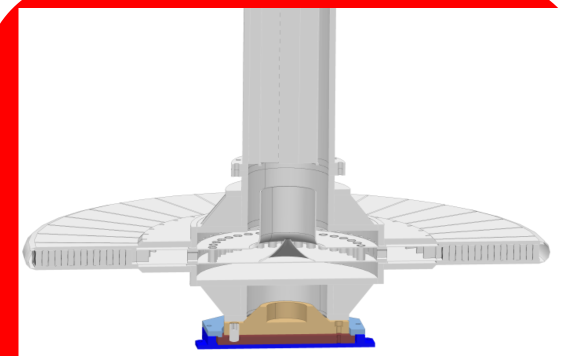


Net Charge Deposition is negative: incoming, fast e- are stopped in Ni blades (instead of only H+), need to change position of monitor

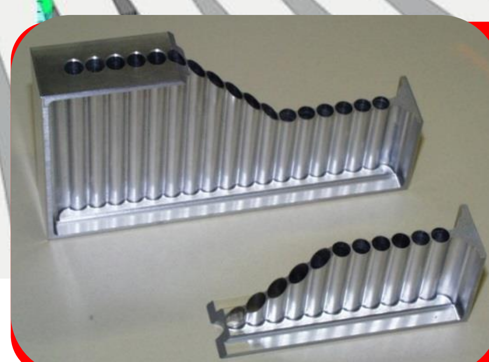
Beam imaging system:
Luminescence Coating On Target and PBW

Optical pathway (only one shown)





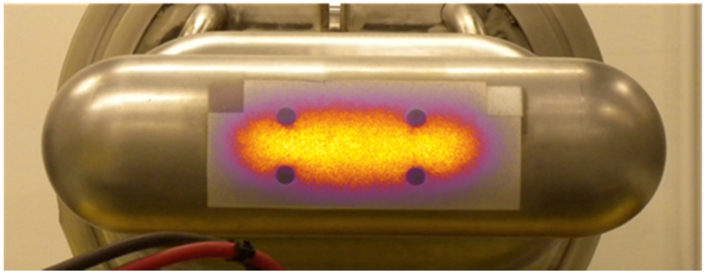
Coated steel samples

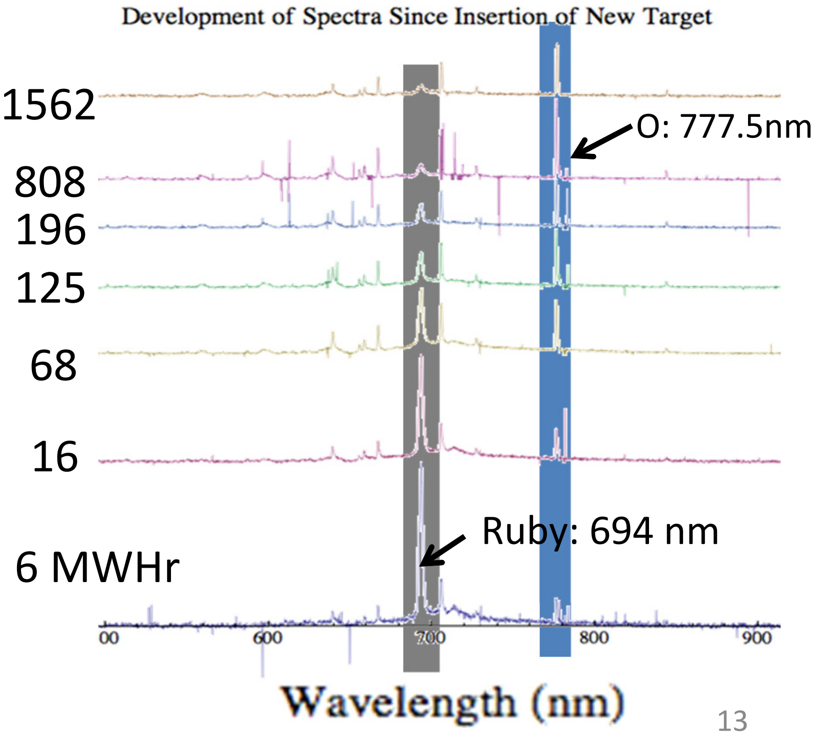


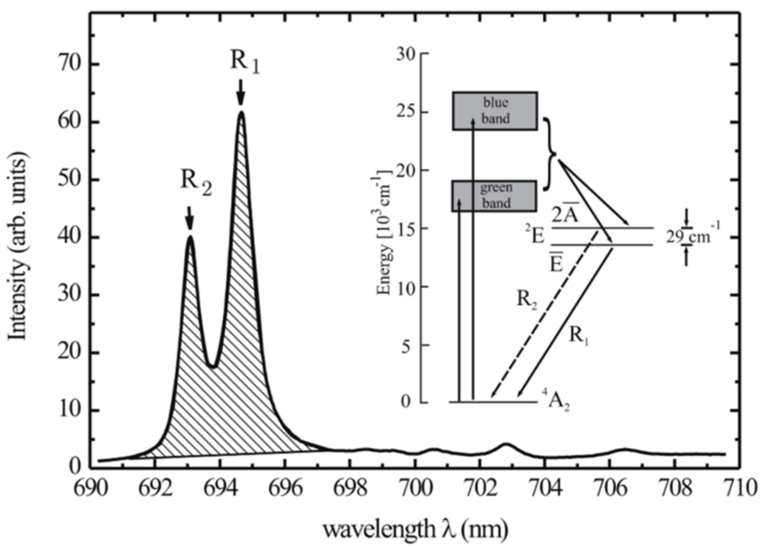
Coated Aluminum surface samples (Jülich, Stony Brook).

Luminescence coating: Cr-doped Alumina at SNS

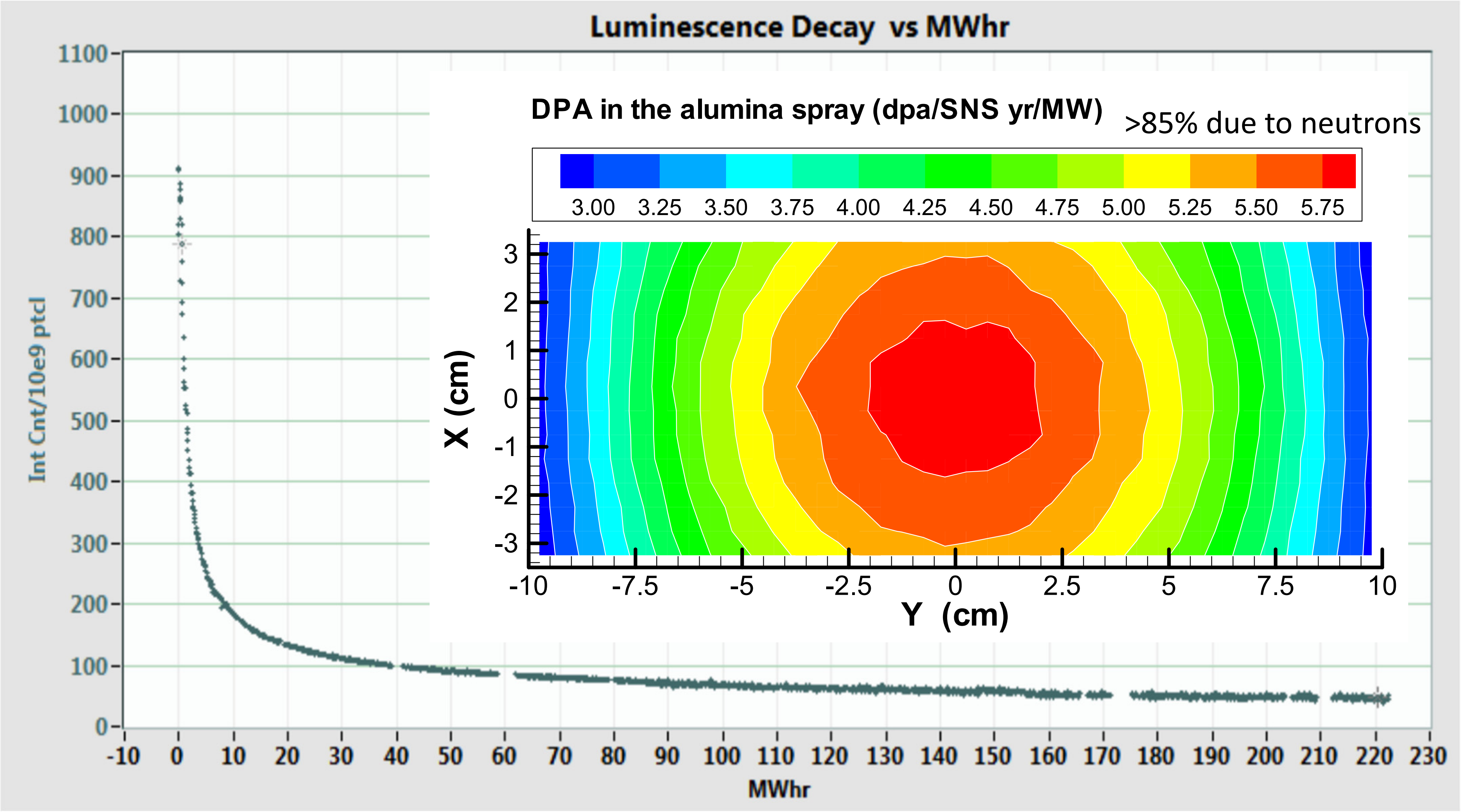
- SNS target coating material => Cr^{3+} doped Al_2O_3 sprayed on target,
  - Achieved 2D map of beam!
  - Material degrades in the radiation field within days to <10% luminescence.
  - Oxygen lines appear, ruby lines decrease





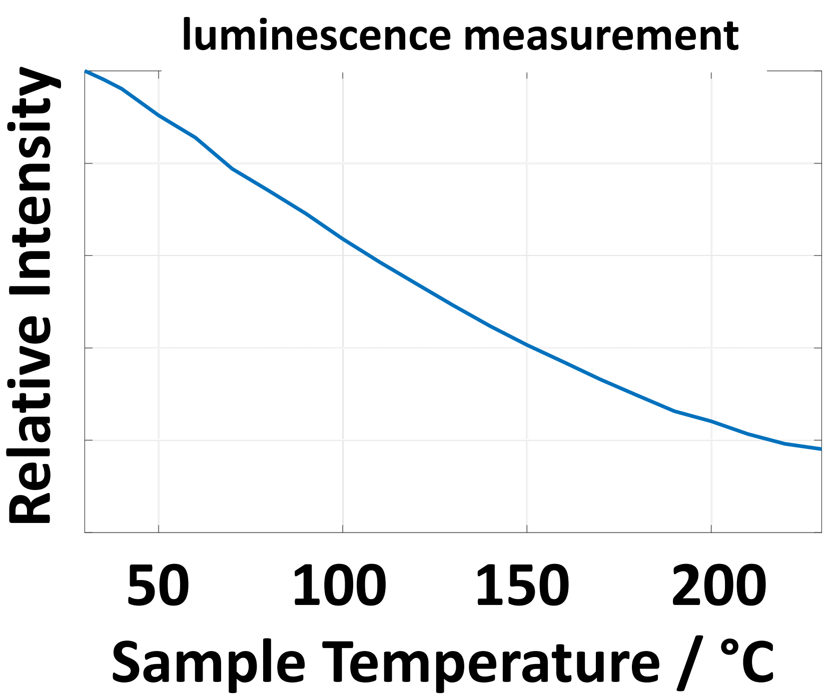


Decrease in luminescent efficiency with irradiation



Luminescence coating for ESS: Cr-doped Alumina?

- Start point: SNS target coating material
  - Material degrades in the radiation field over time
  - Contamination from particles emanating from the target (similar to SNS)
  - No more pre-cursor powder available !? (maybe new supplier)



ESS

- higher neutron flux than SNS
- ESS target change only every 5 years or so (SNS every 8 months)
- **Quenching of luminescence at higher temperature (~200 deg. C) due to He cooling of W**

Planned & performed characterization of luminescence material

- **What is special about the pre-cursor material for the luminescent screen?**
  - chemical & structural characterization (XRD, ND, N-PDF, NVS, XAFS) **VOODOO?**

- **Degradation due to radiation ?**
  - irradiation of coated PBW samples at BNL's BLIP facility
  - looking for partners for post-irradiation examination (LANL, ORNL, ..)
  - Ongoing Work with SNS on in-situ luminescence screen
  - heavy ion irradiation (GSI: June 2016), further measurements

Voodoo – or not?

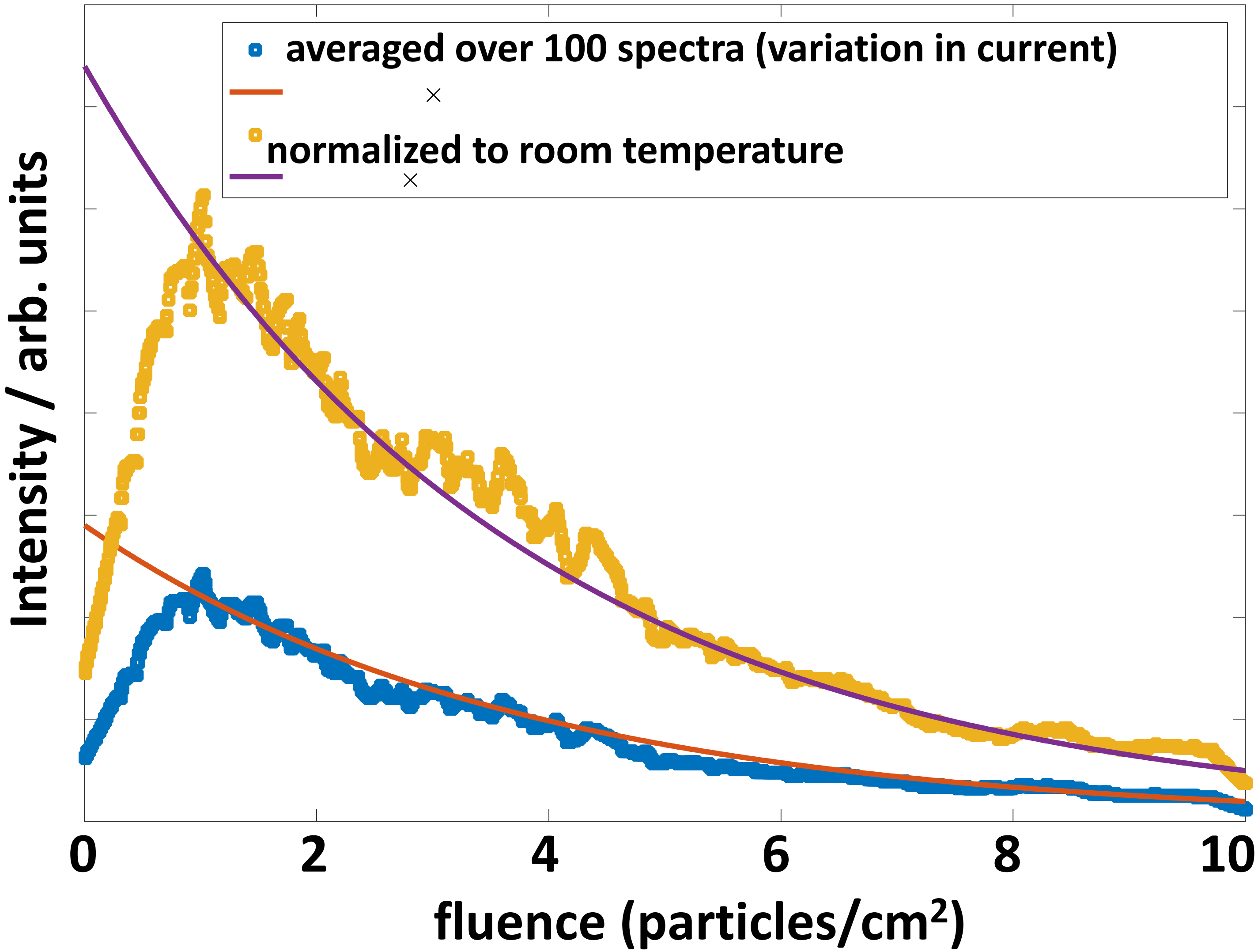
- X-ray Fluorescence (no standard)

Pre-cursor Voodoo powder	Sprayed powder
Al_2O_3 95.2%	Currently being measured
Cr_2O_3 3.8 %	
P_2O_5 0.6	
Ag_2O 0.2 %	

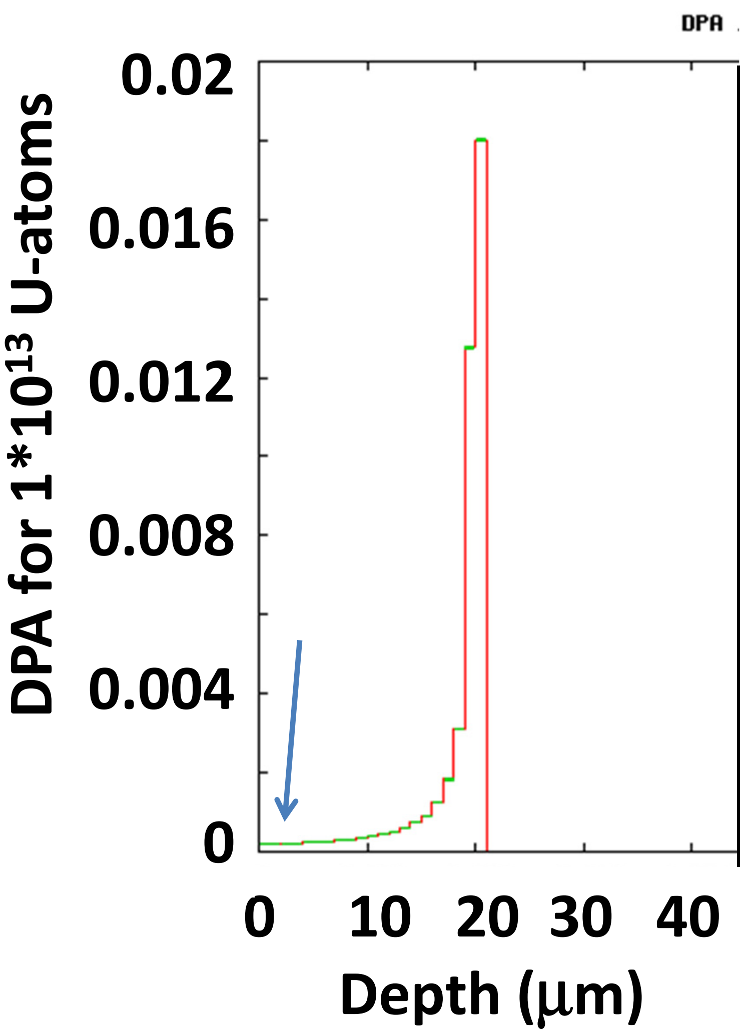
- Nuclear Magnetic Resonance (NMR):
  - No organic substances found.
- XRD (will be compared to neutron diffraction &PDF)

Pre-cursor Voodoo powder	Sprayed powder
Al_2O_3 99.5% (corundum)	Cr-substituted Corundum (ruby) (Al1.926 Cr0.074 O3) 39.8%
Cr_2O_3 0.5%	ε- Al-oxide (Al_2O_3) 60.1%

Luminescence measurementa under heavy-ion bombardment (^{238}U)



Displacement per atom in 1%Cr-Al_2O_3



The damage rate in the coating at 5MW beam power is **$8*10^{-5}$ dpa/h**

GSI beamtime:

Accumulated total fluence of

$1*10^{12}$ U/cm^2.

This translates to total dpa of:

$1.8*10^{-3}$ dpa at 20 μm

1d at 5 MW

$1.8*10^{-5}$ dpa at 1 μm

15 min at 5 MW

Testing of potential candidates for luminescence screen

EUROPEAN SPALLATION SOURCE

- Optimizing the established material
  - Cr-content
  - spray conditions
  - (choice of starting material)
- Understanding why the material works
  - VOODOO pre-cursor works - other “identical” materials do not
  - further characterization of Voodoo material and resulting sprayed material
- Understanding why the material degrades in the radiation field and what the mechanism is:
  - Oxygen lines due to reduction of Cr^{3+} when the proton beam hits?
  - Local areas of elemental Cr and O_2?
  - Characterization/ comparison before/after irradiation.
- Development of “new”, radiation-resistant materials:
  - yttria, zirconia, YAG,…

Thank you...

EUROPEAN SPALLATION SOURCE

SNS
SPALLATION NEUTRON SOURCE

GSI

EUROPEAN SPALLATION SOURCE

Science & Technology Facilities Council
ISIS

MAX IV
LABORATORY