Luminescent Materials Development for Beam-on-Target Imaging at the European Spallation Source

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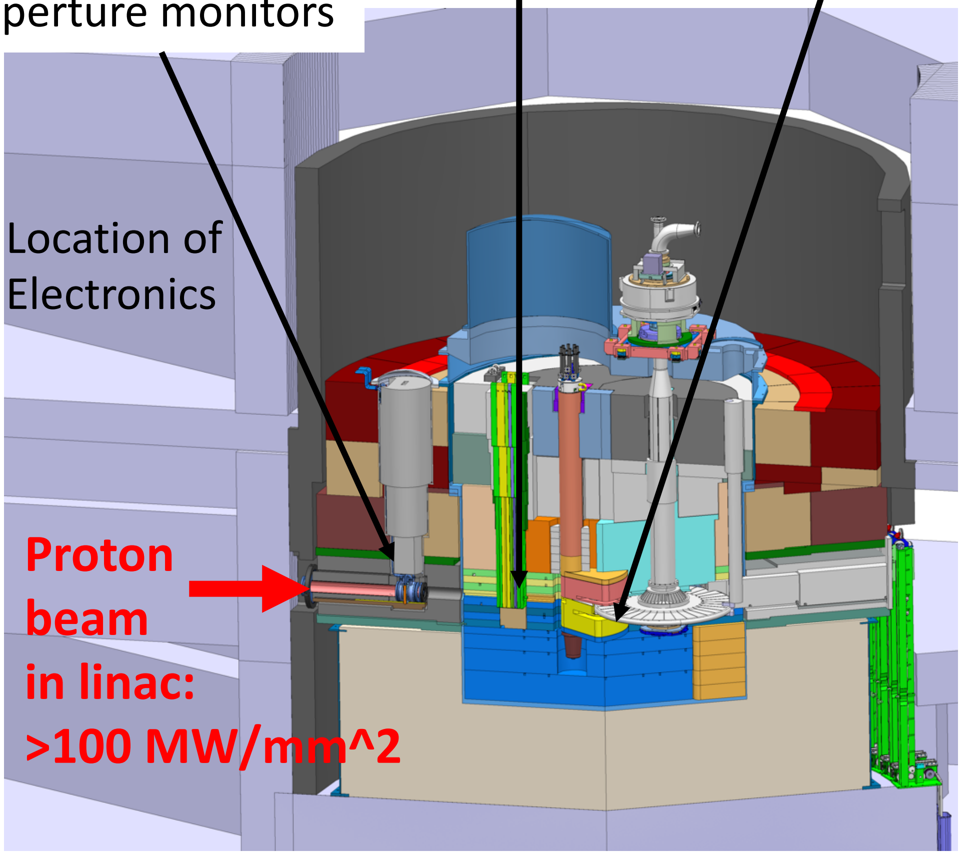
ESS Beam-on-Target Imaging

Proton beam window: luminescent coating, aperture monitors

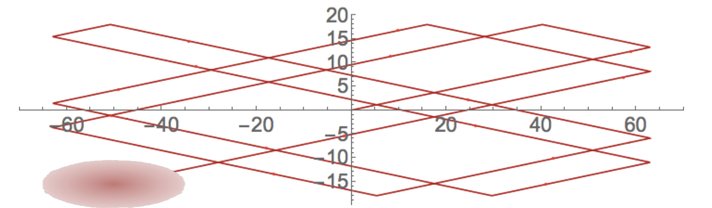
Proton beam instrument plug: wire grid, optics, aperture monitors

Target Wheel: luminescent coating

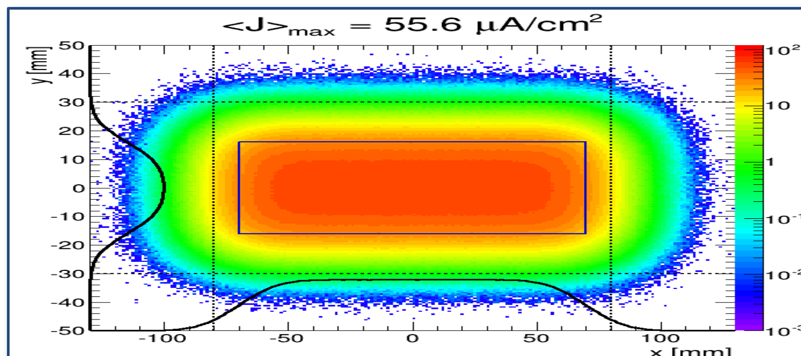


99% beam footprint	160 by 60 mm
Avg. current density	56 µA/cm^2

Beamlet Rastered on Sector of Target during 2.86 ms pulse (~10 mm/µs)



Imaging system should measure 2-D beam density map of each pulse



Luminescent Coating Development Goals

- **High photon yield:** Require adequate signal relative to background and noise. Example: 250 photons per proton (similar to SNS) results in 1e10 photons per pulse through optics and onto image sensor.
- **Appropriate emission spectrum:** Within range where imaging sensors are efficient (visible and nearby IR and UV bands), and selectable from He background.
- **Short luminescence lifetime:** Time between pulses ~70 ms. Target wheel moves 8 mm during pulse. Rastered beamlet scans at ~10 mm/µs.
- **High radiation tolerance:** 8.75E20 p/cm^2 lifetime proton fluence per sector, with most displacement damage due to spallation neutrons
- **Characterized (and moderate) temperature dependence:** Temperature up to ~200 C peak, with ~20 C increase during pulse. Non-uniform temperature distribution.
- **Characterized response to secondary particles:** Secondaries will also stimulate emission and distort image.
- **Compatibility with thermal spray process**. Sprayable without degrading properties of 316L or Al substrate.
- **Tolerance of gas environment:** Helium impurities or ~mbar vacuum pressure.

Also relevant for other ESS imaging applications: beam window and tuning dump

Downselection Process

- Material selection and evaluation of process compatibility
- Sample preparation: process refinement; factory floor testing
- Photoluminescence and low energy particle beams

Result at this stage: candidates for irradiation campaigns

- Irradiation with no or minimal activation*
- Irradiation with significant activation*
- Industrialization

Result: coating technology for target

* Pre- and Post-irradiation characterization
  - photon and proton stimulation
  - X-ray and neutron scattering

Candidate Materials

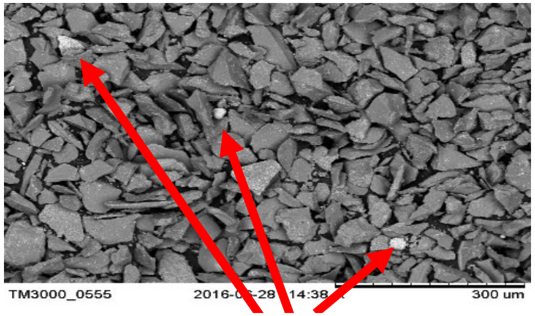
- Materials:
  - **Baseline**: Cr3+ doped Al2O3; developed for SNS; ruby; also shows O2 lines
  - Y2O3: radiation hard, broad luminescence signal
    - Can be doped to enhance some specific narrow band lines
  - Y_2WO_6 and doped $Ln_xY_{2-x}WO_6$ ($Ln=La^{3+}$, Dy^{3+}, …): according to literature will form easily O2 in defect positions, luminescence sharp and short-lived for certain doped materials.
  - Still adding to the list based on key criteria
- Luminescence properties:
  - High luminescent yield: greater than 250 photons/2GeV proton
  - Narrow band spectral lines: less than 10nm
  - Lifetime shorter than 1µs lifetime
- Radiation hardness:
  - material should survive in a high-radiation field for 5 years
  - material should when degrading provide alternate source of luminescence, e.g. "O_2" in defect positions

Activities

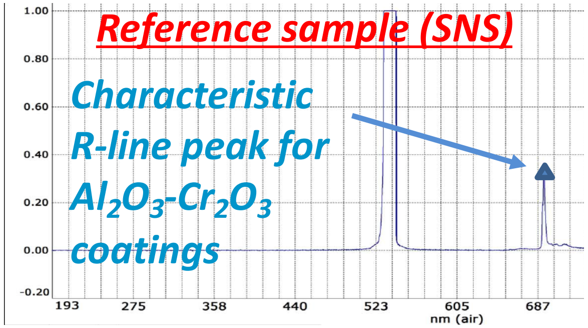
Sample Preparation

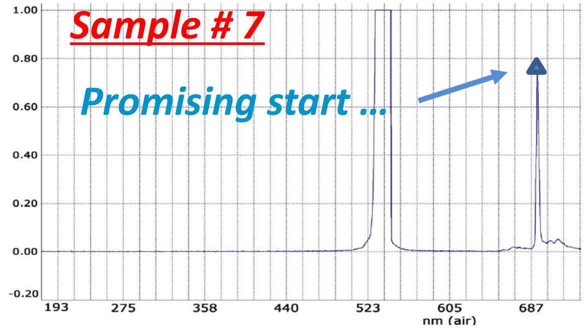
Samples: ~ 50 µm oxide coating on Al substrate

- Continuation thermal spray coating development done by Stony Brook University for SNS
- Short-term Goal: Spray deposition, testing of Al_2O_3-1.5 wt.% Cr_2O_3 coatings to replicate the SNS results.
- Previously used powder no longer in stock, so develop coating with currently available powder

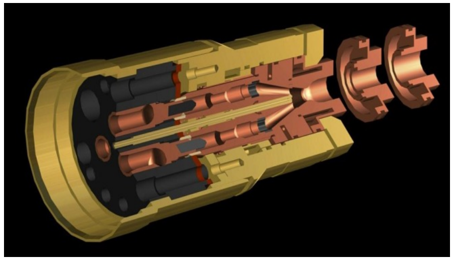


Cr_2O_3 particles





Thermal spray gun



- Looking ahead: Other promising chemistries being explored (e.g., Y2O3, YVO4, Y2WO6 with and without doping); these can be deposited by powder / suspension / solution-precursor plasma spraying

Photostimulated Luminescence

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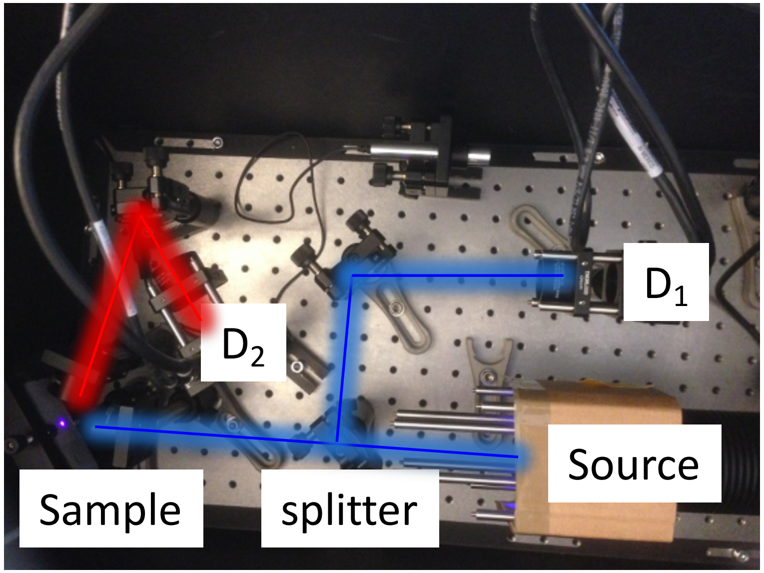
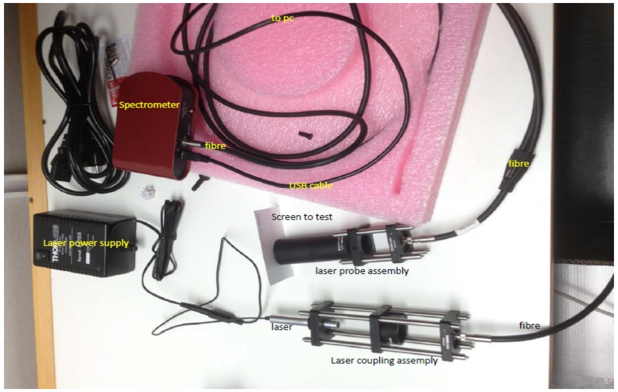
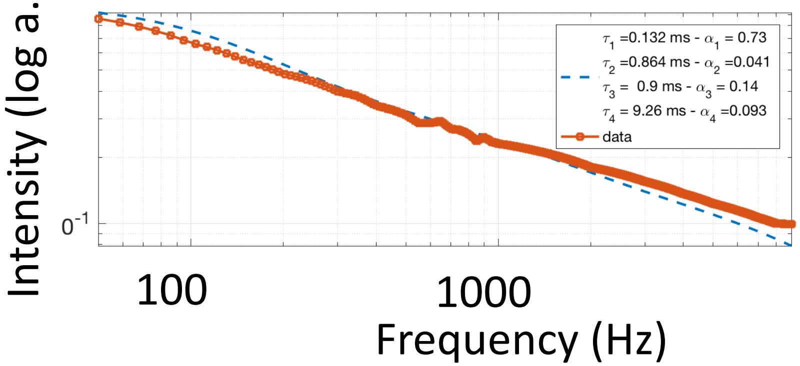


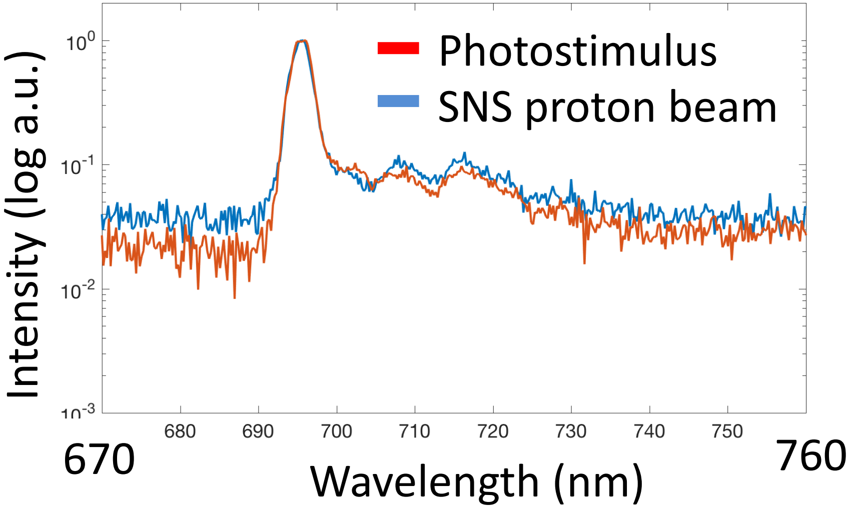
Factory floor inspection kit



Luminescence lifetime of SNS coupon: Al2O3:Cr(1%)



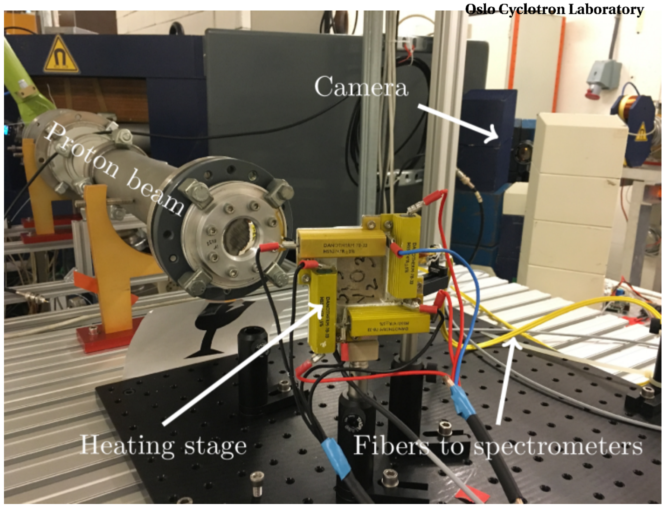
Comparison to SNS emission spectrum

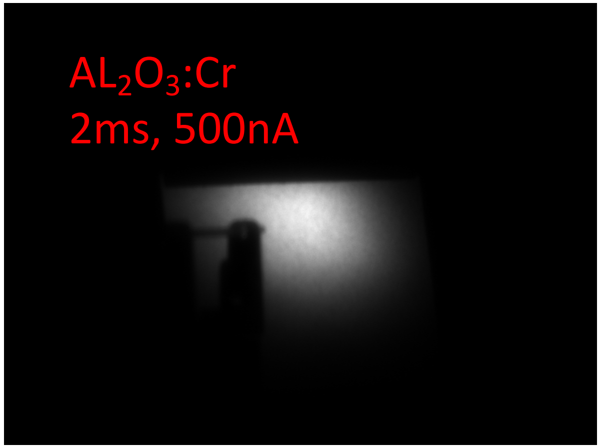


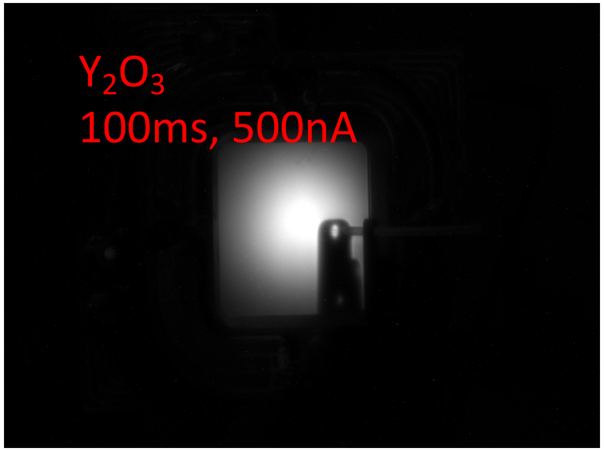
Low-energy proton beam

- SCANDITRONIX MC-35 Cyclotron at University of Oslo
- 16 MeV, 2-3μA, 1-2cm² beam size, continuous beam
- Semi-permanent setup, new materials can be tested quickly

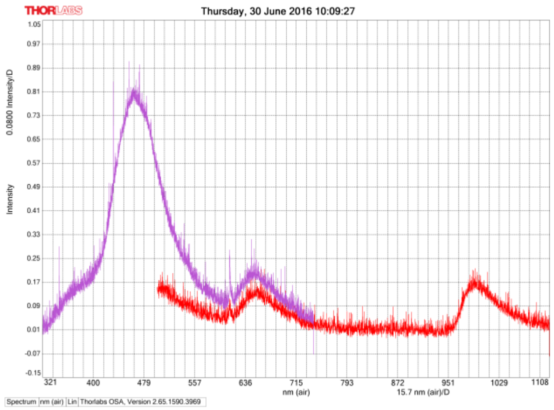
OCL
Oslo Cyclotron Laboratory



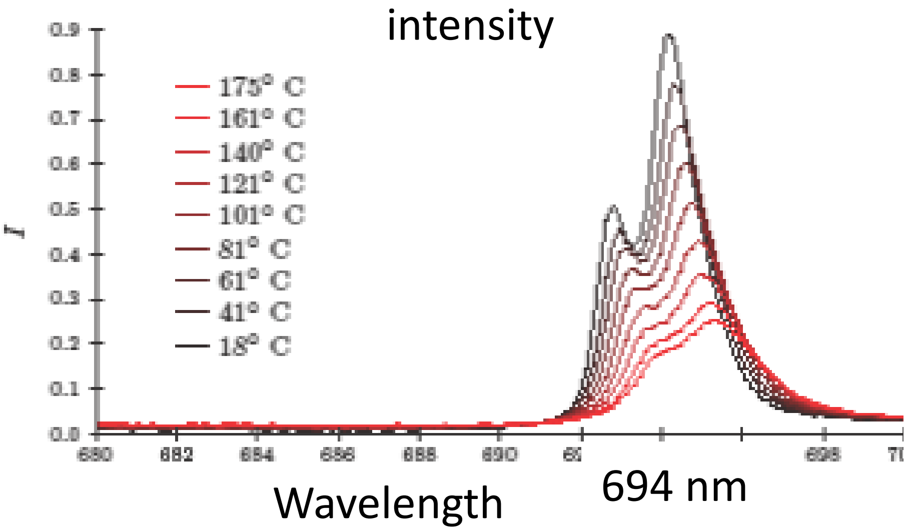


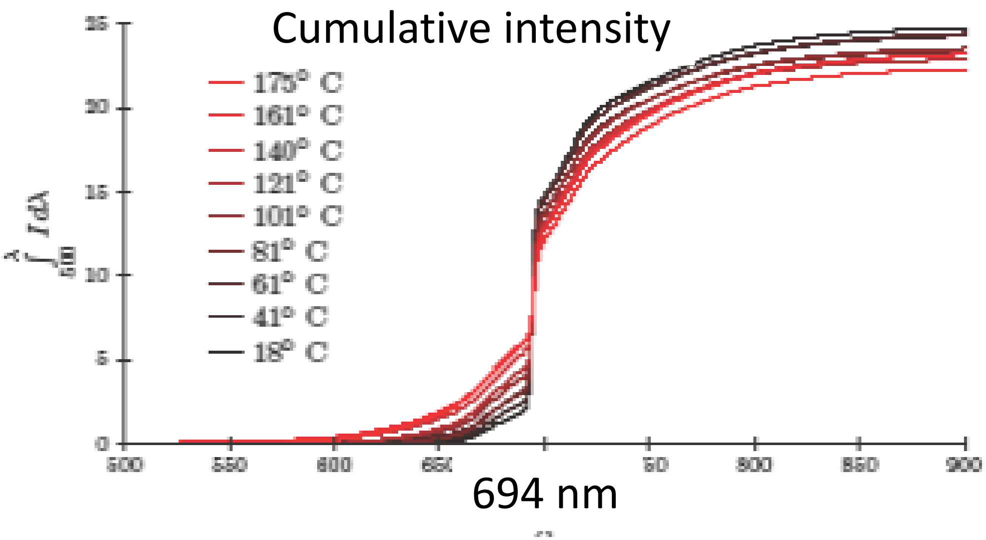


Broad Yttria spectrum



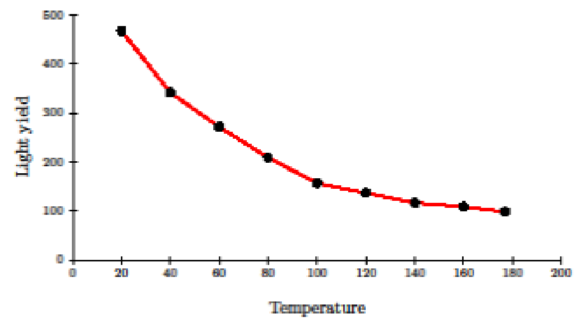
Temperature Dependence





- 18 to 175 C: R-lines lose amplitude with temperature
- Emission below the R-line increases with temperature
- Could also be a temperature diagnostic if characterized over irradiation lifetime

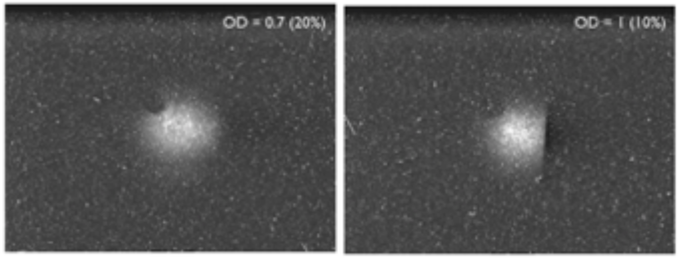
Emission from Yttria decreases with temperature:



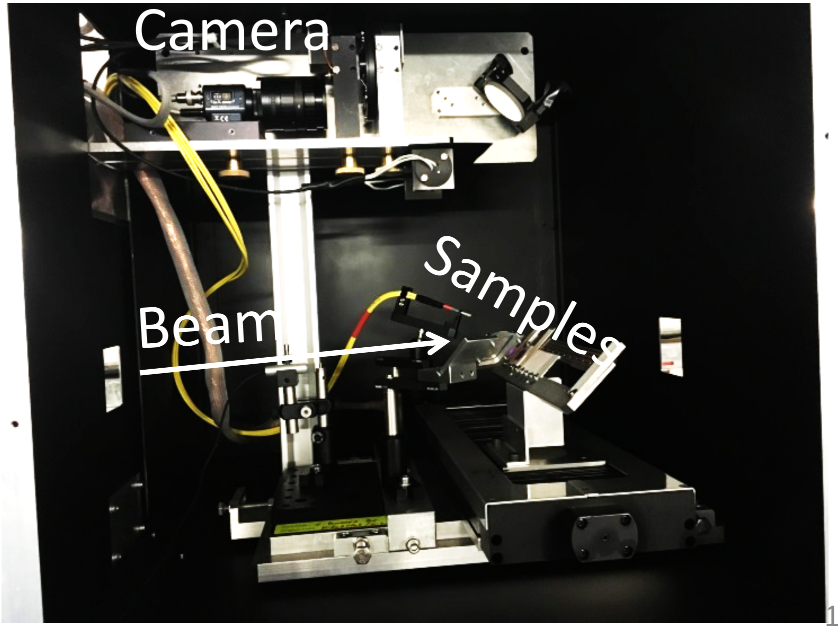
High Energy Protons

HiRadMat
High-Radiation to Materials

- High intensity, high energy proton beam from CERN SPS
- 10^{11} 440 GeV protons per pulse
- Limited access. A few hundred pulses once a year.
- Results to be published



Yttrium stabilized Zirconia in HiRadMat beam. GSI irradiated (left), non-irradiated (right).



SNS in-situ Measurements

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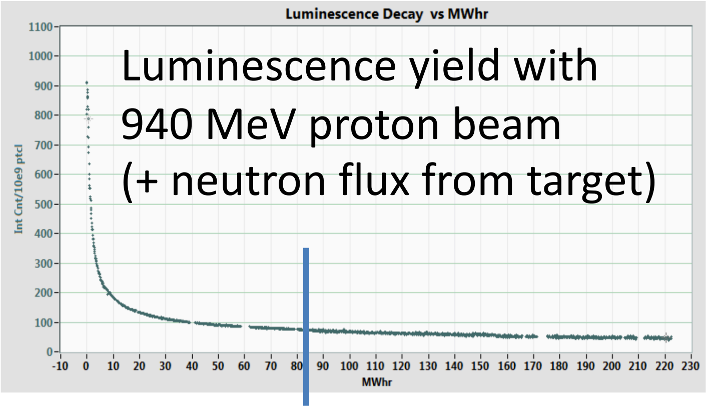
High energy proton beam, target radiation environment most similar to ESS

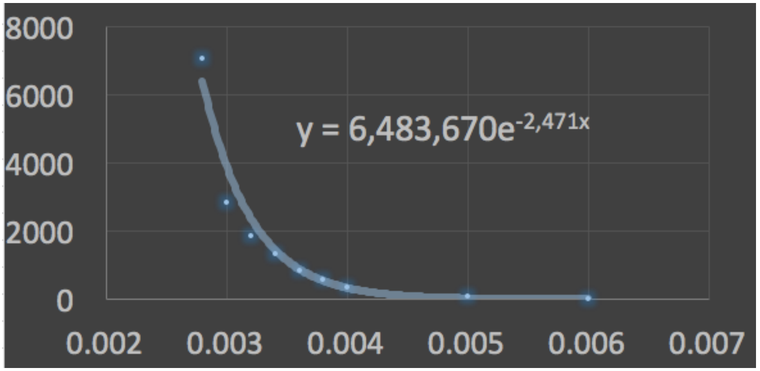
Example measurements:

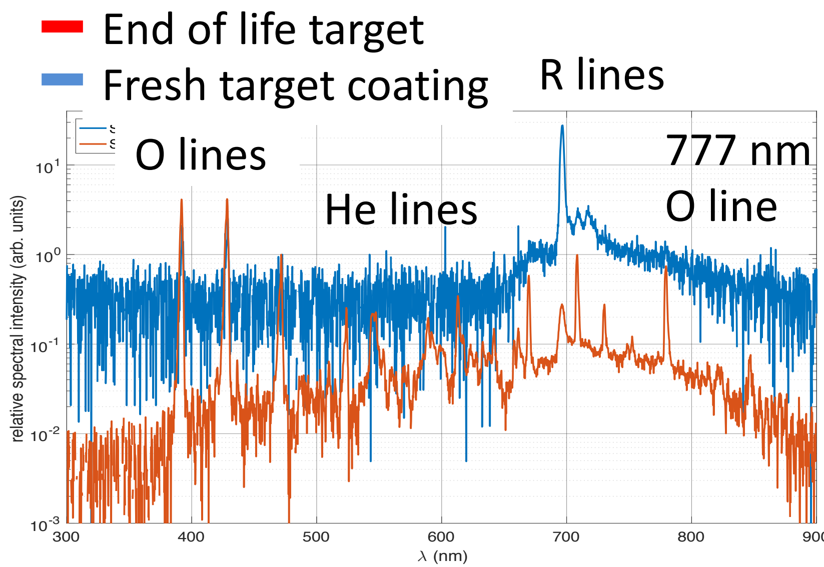
- Luminescence yield vs. dose
- Time resolved imaging
- Emission spectrum
  - In addition to R-lines from the Cr^{3+} doped Al_2O_3 and He lines: emission at 777nm and 426nm, <1µs lifetime, almost constant intensity after initial irradiation
  - Ruby and He lines imaged; O_2 lines not yet successfully imaged



~0.1 DPA in Alumina

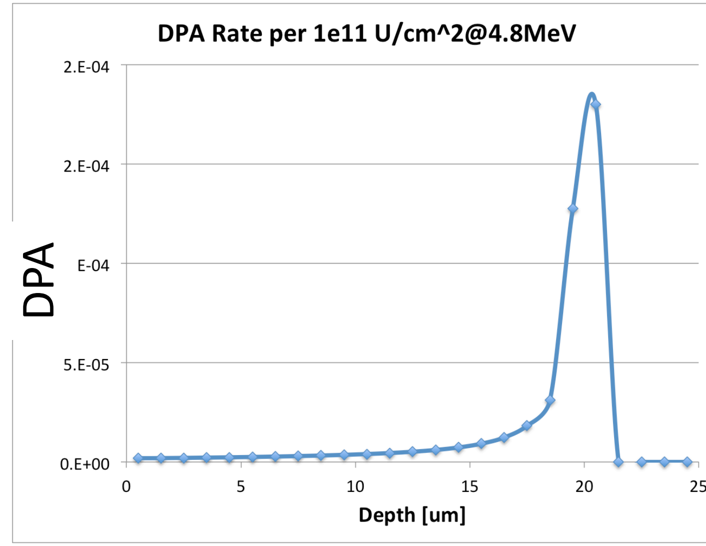
Luminescent intensity vs. time (s)

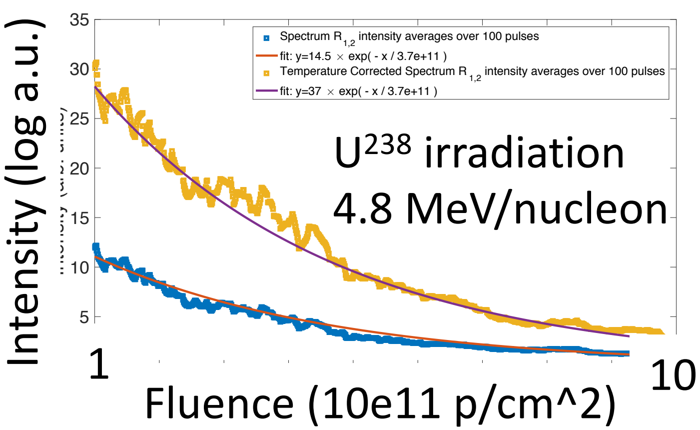


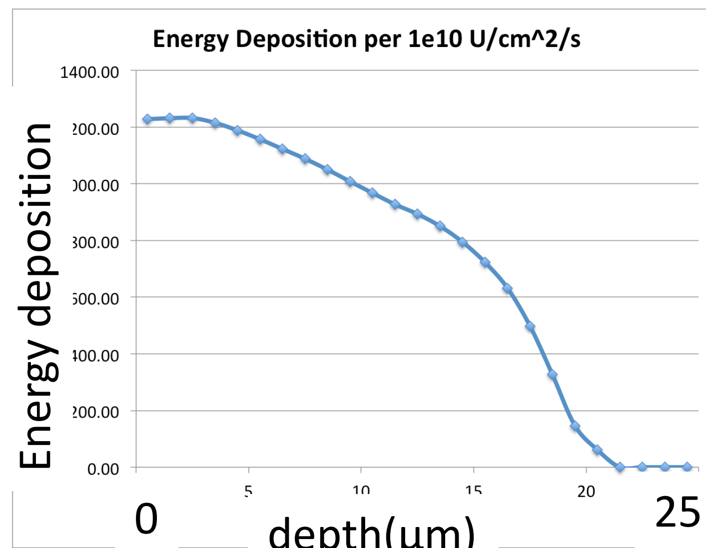


Heavy Ion Bombardment

- Radiation tolerance investigation with limited activation
- Example: Al_2O_3:Cr under (GSI) U^{238} Irradiation:
  - 4.8 MeV/nucleon U ($26e^+$), 1.0e10 U/cm^2
  - Accumulated total fluence: 10^12 U/cm2.
  - 1.8x10-3 DPA at 20 µm: 1 day at 5 MW ESS
  - 1.8*10-5 dpa at 1 µm







Host for GSI beamtime: Marilena Tomut

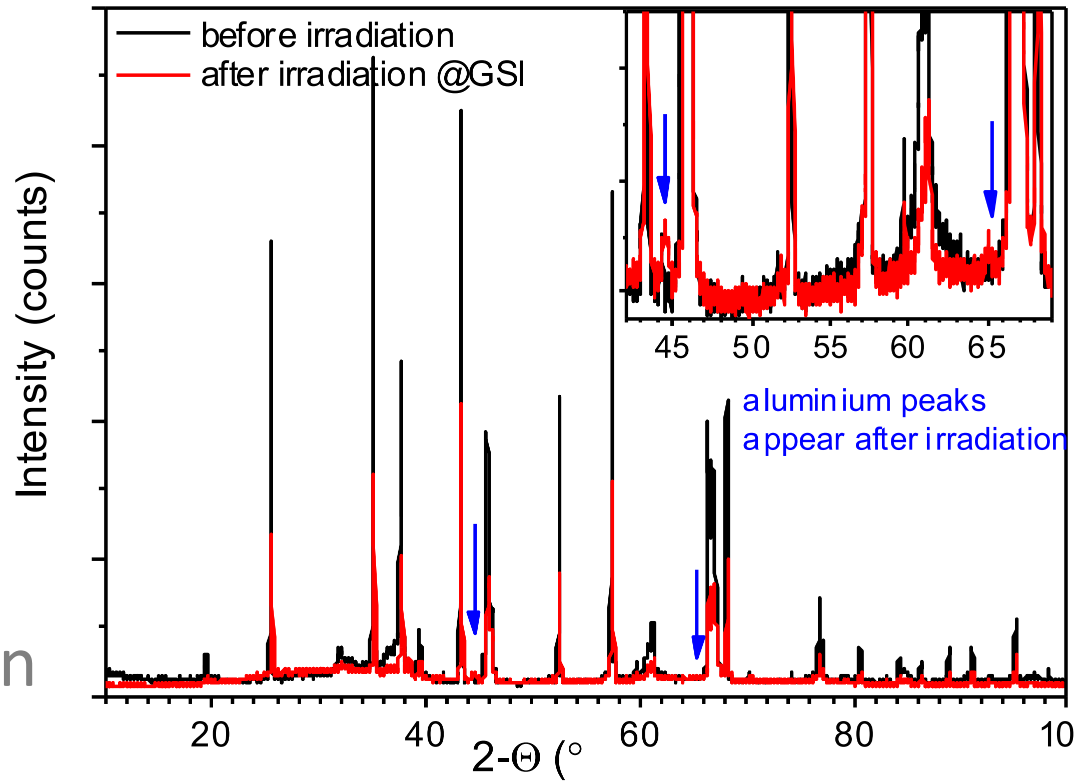
X-ray Diffraction

After irradiation @ GSI

- No uranium detectable
- decrease of η-Al_2O_3
- Aluminium reflections detected:

$$Al_2O_3 \rightarrow 2Al + 3/2\ O_2$$

Explanation for O_2 peaks in luminescence spectrum from SNS target?!



	corundum: α-Al_2O_3	η-Al_2O_3	Al
Before	40%	60 %	-
after	42 %	57 %	1 %

Additional X-ray and Neutron Characterization Techniques

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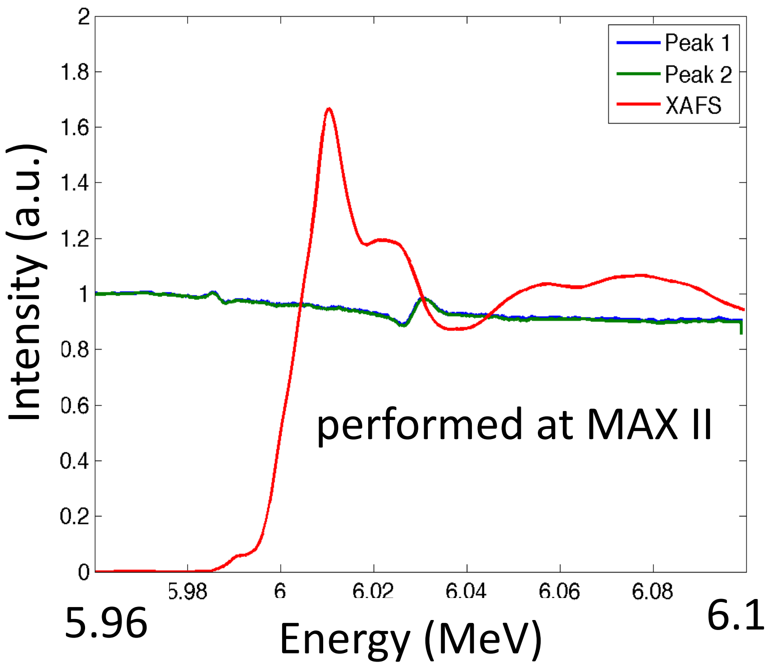
- XANES: oxidation state and surrounding of dopants in bulk materials, e.g. Cr^{3+} in Al_2O_3 or La^{3+} in Y_2WO_6
- Diffraction with X-rays and neutrons:
  - to determine structure and phase changes (powder diffraction)
  - to determine macroscopic structure (small angle diffraction)



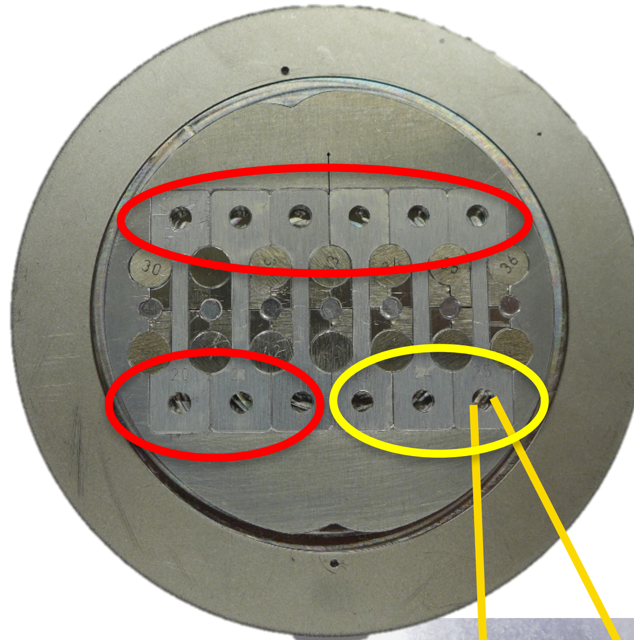
XAFS at MAX-II for SNS Cr^{3+} doped Al_2O_3:

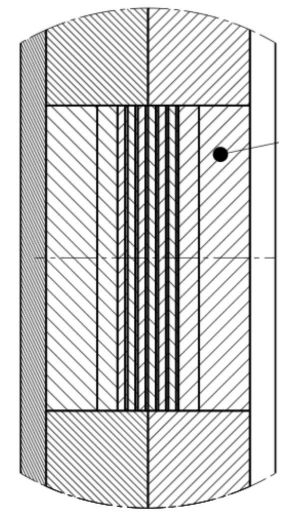
- As expected: Cr^{3+}
- Cr^{3+} is in octahedral surrounding (Al_2O_3 consists of Al(O)4 tetraehedra)

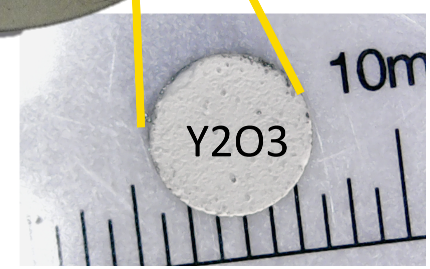
✓Tools in place for the determination of the structure and composition

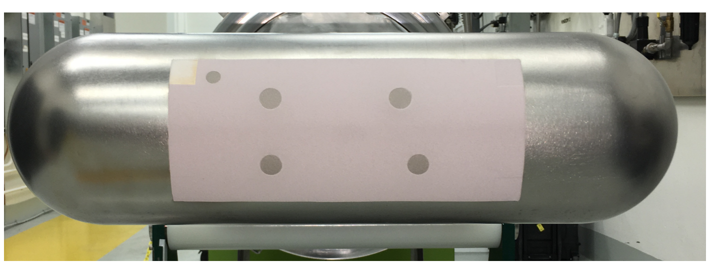
Irradiation Campaigns with Significant Activation

- BLIP, 2017
  - Sample list:
    - Al2O3:Cr (1% Cr) several plasma spray conditions
    - Y2O3 plasma sprayed
    - Y2WO6 pellet
  - 181 MeV, 165 uA
  - Temperature < 144 C
  - 0.85 DPA in Al after 12 weeks
- SNS target sample retrieval
  - Coating sample area in corners
  - Retrieve coating samples for PIE









- 3 mm diameter samples
- ~ 50 µm coating on 0.5 mm Al

BLIP capsule: Y. Bessler, F. Hanusch (FZ-Juelich)

Outlook

- Coming year
  - Decision on coating technology for 1st target coating opportunity: rim components in 2017.
  - BLIP/SNS/Ion irradiation and PIE
  - Identification of proton beam test site, neutron and X-ray instruments, and other PIE facilities
  - Monte Carlo and experimental verification of response to secondaries
- R&D program will continue
  - 2nd target coating opportunity: completed assembly in 2018.
  - Application to proton beam window, tuning dump line, next ESS target, SNS target and other facilities

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Thank you