High radiation beam instrumentation use and needs at SNS

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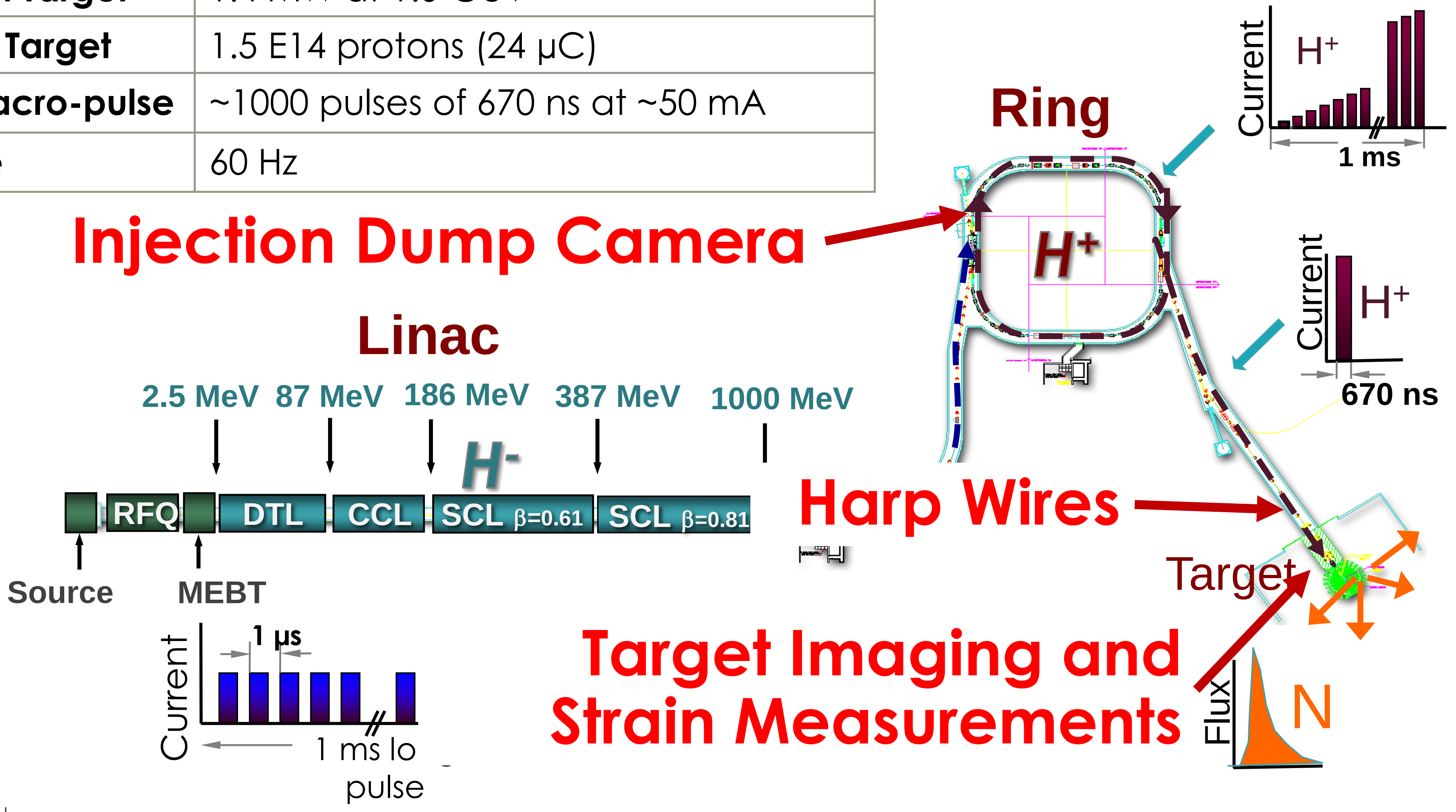
ORNL/SNS

ORNL is managed by UT-Battelle, LLC for the US Department of Energy

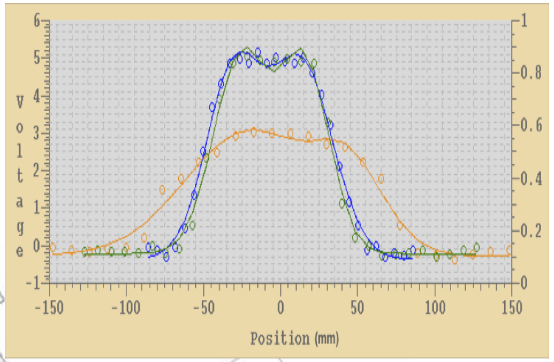
Spallation Neutron Source Complex

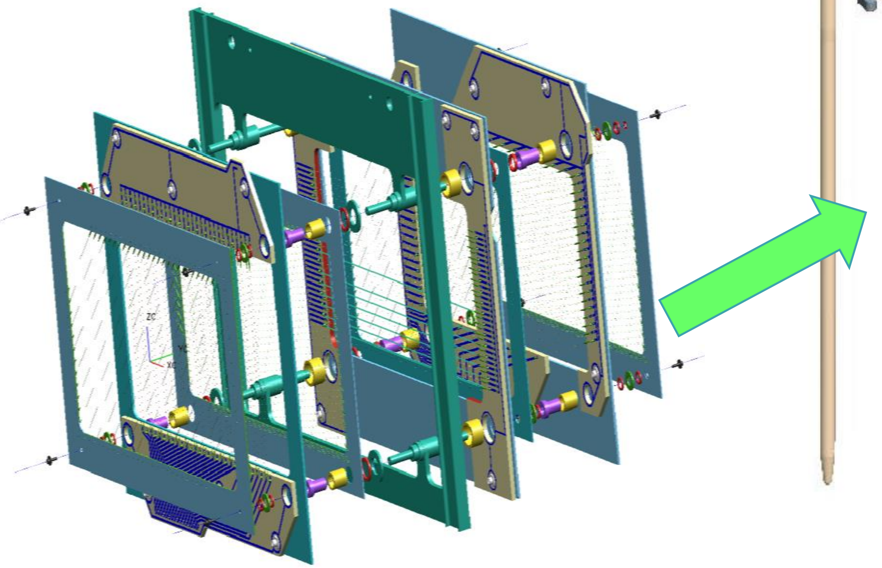
Power on Target	1.4 MW at 1.0 GeV
Pulse on Target	1.5 E14 protons (24 μC)
Linac macro-pulse	~1000 pulses of 670 ns at ~50 mA
Rep-rate	60 Hz

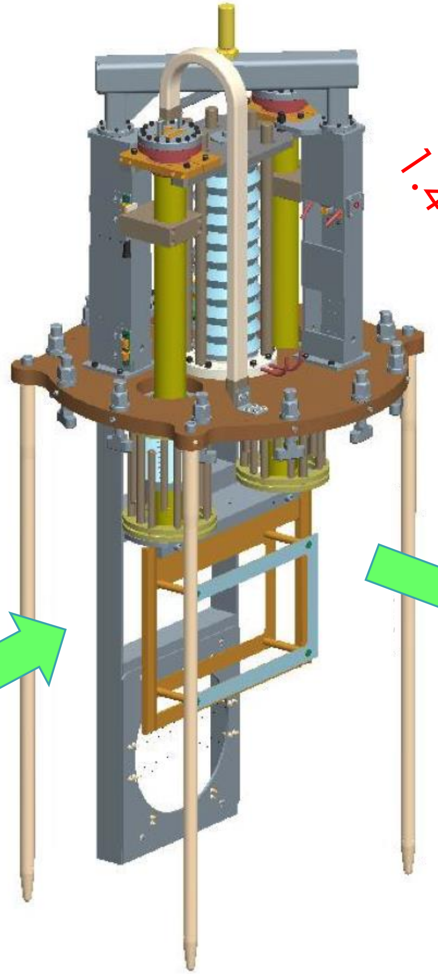


Harp for transverse profile measurements

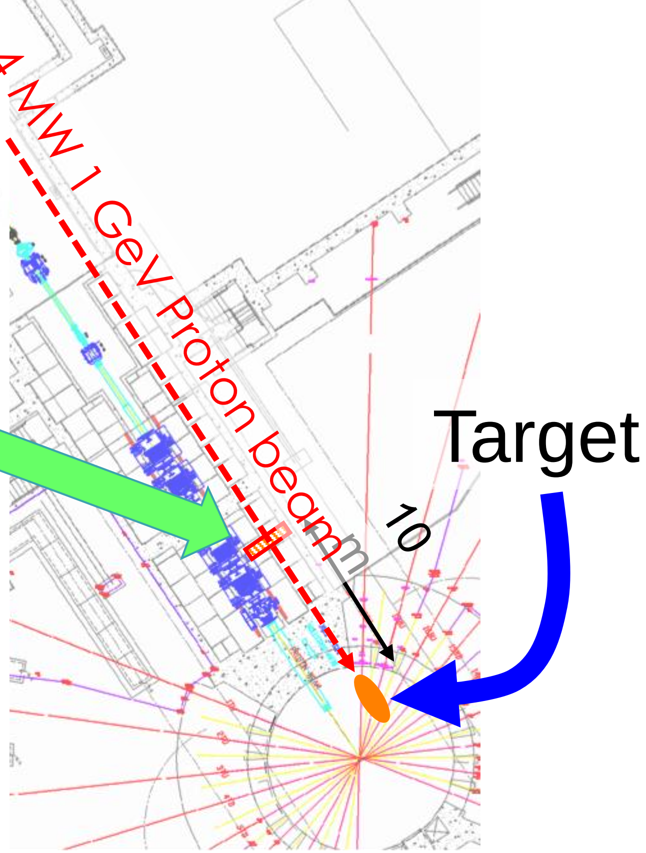
- The harp measures the proton beam's transverse profile
  - 3 planes of 30 tungsten wires of 100 µm
  - Always inserted as stage failed
- Needs:
  - What alloys are radiation hard: do not use Rhenium. Is there a vendor database?





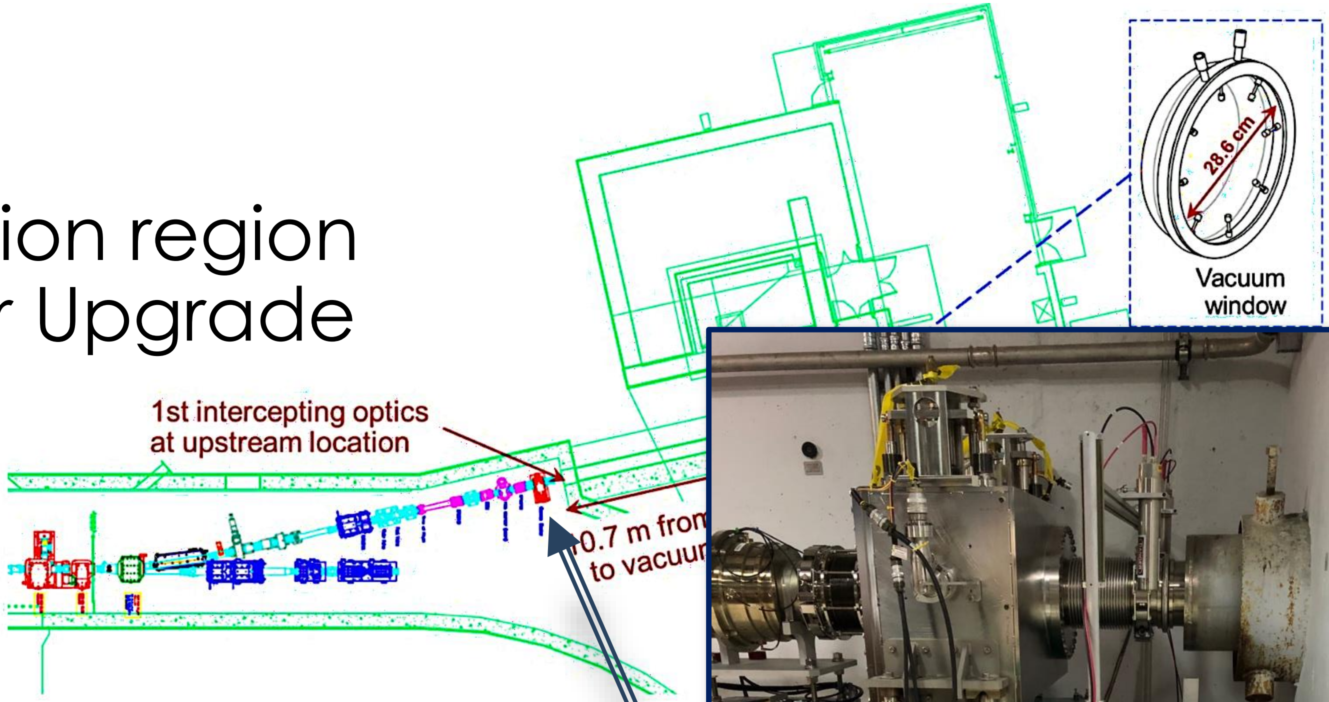


Harp layout



Injection Dump

- Charge exchange Injection region change for Proton Power Upgrade



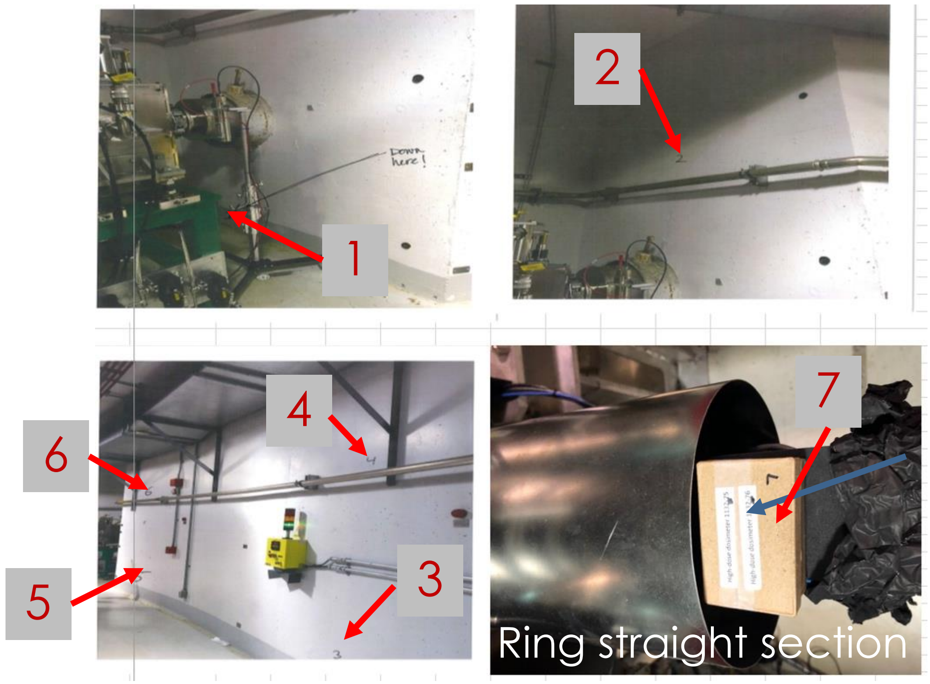
  - We need to know where the different proton species H^- and H^o land on the dump
    - H^- and H^o as defined as the particle between the first and second stripping foil
  - To reduce cost and installation time, we like to avoid expensive fiber bundles, or long optical paths through shielding structures

→ Testing a shielded non-radhard camera

HiRadMat camera radiation data

- Prediction of Injection Dump camera lifetime using HiRadMat data#:
  - Single Event : 1.5 E9 HEH/cm^2 (HEH = High Energy Hadrons)
  - Time To Death : 4.1-5.6 E11 HEH/cm^2 or 116 - 161 Gy

#From: S. Burger "Scintillation Screens and Optical Technology for transverse Profile Measurements", ARIES-ADA Topical Workshop, Krakow, Poland, April 1 to 3, 2019



Locations of measurements near injection dump and in ring straight section

This camera survives for years

*At 1.4 MW

Position	Time to Death* (HRS) (116 Gy)	MTBF* (HRS)	Gamma dose rate (Gy/MWHr)	Neutron dose rate (Gy/MWHr)
1	285	0.9	0.0738	0.2167
2	339	1.1	0.0784	0.1660
3	2246	7.2	0.0092	0.0277
4	1797	5.8	0.0184	0.0277
5	998	3.2	0.0277	0.0553
6	998	3.2	0.0323	0.0507
7	25674	82.3	0.0028	0.0005

Prediction based on local measured radiation without shielding and HiRadMat experiment

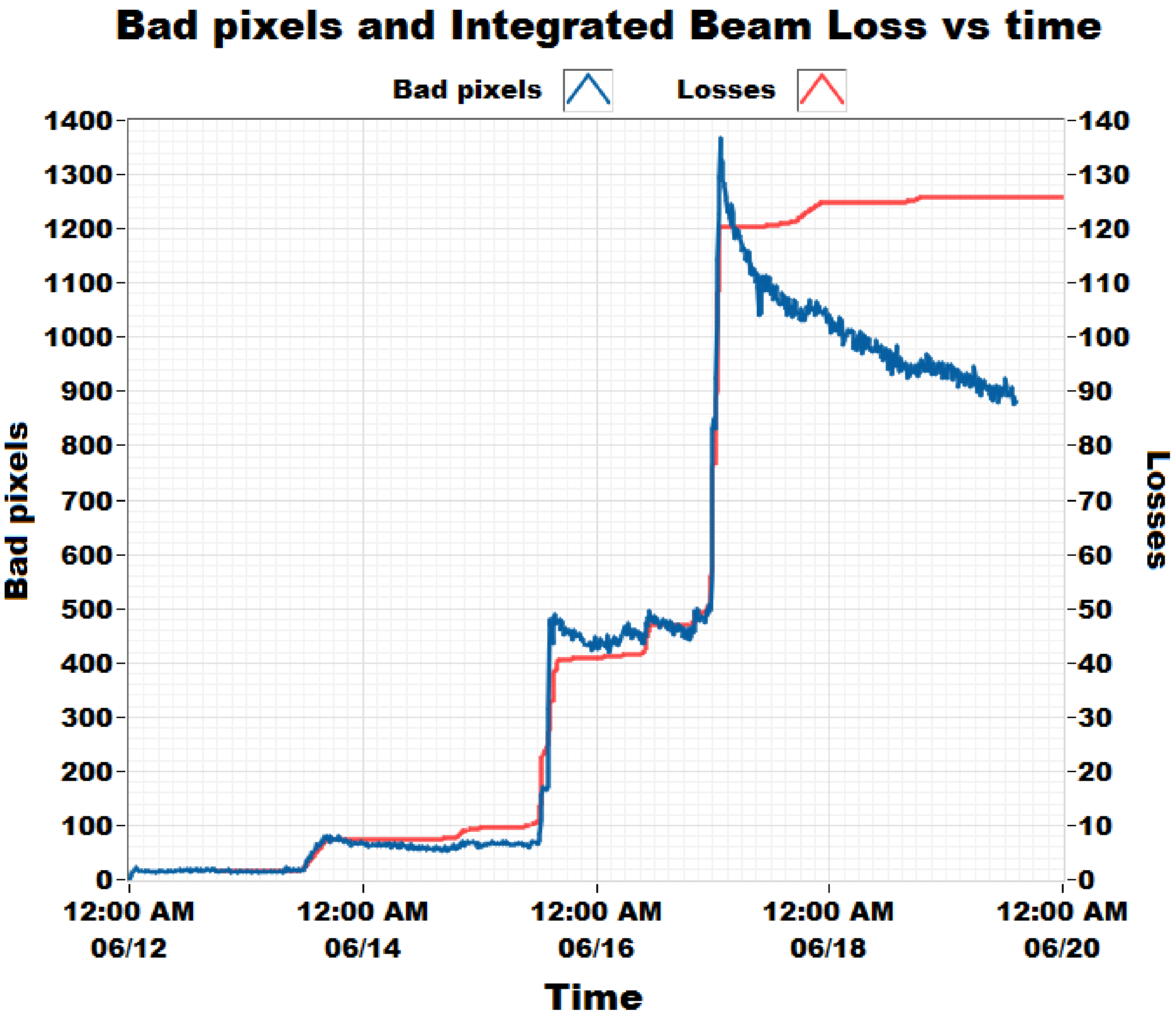
Camera Testing

Bad pixels are labeled with red numbers

Shielded camera in the dark during beam study before neutron production

Needs: Cameras

- Radiation resistant cameras
  - Commercially available rad-hard or regular cameras
  - Effect of radiation types: neutron/gamma/proton
    - Shielding optimization



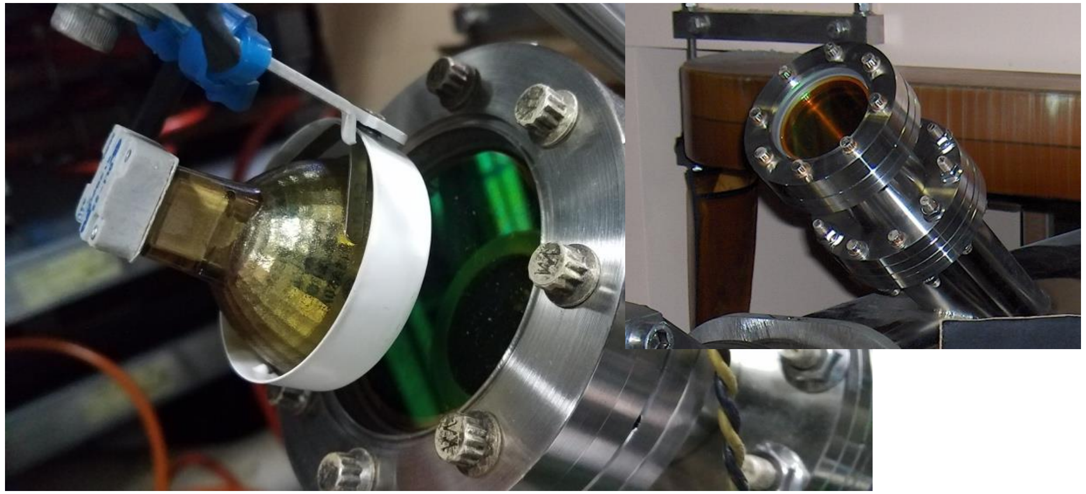
Ongoing test of shielded camera in Injection Dump: integrated loss during study is only about 1/60 of normal production

Inadvertent study of ZnSe vacuum window at stripper foil

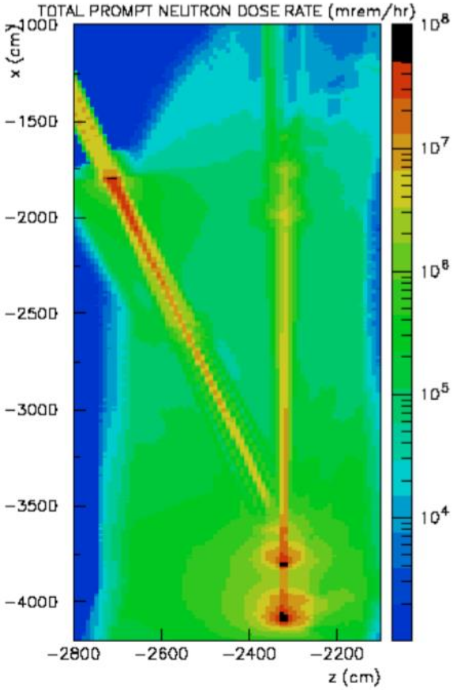
Prompt radiation dose:

- At 1.4 MW, we get 10^8 mRem/hr or about 10^7 mRad/hr or about 10 kRad/hr
- We have this window in place for ~9 years or about 36000 MWhr

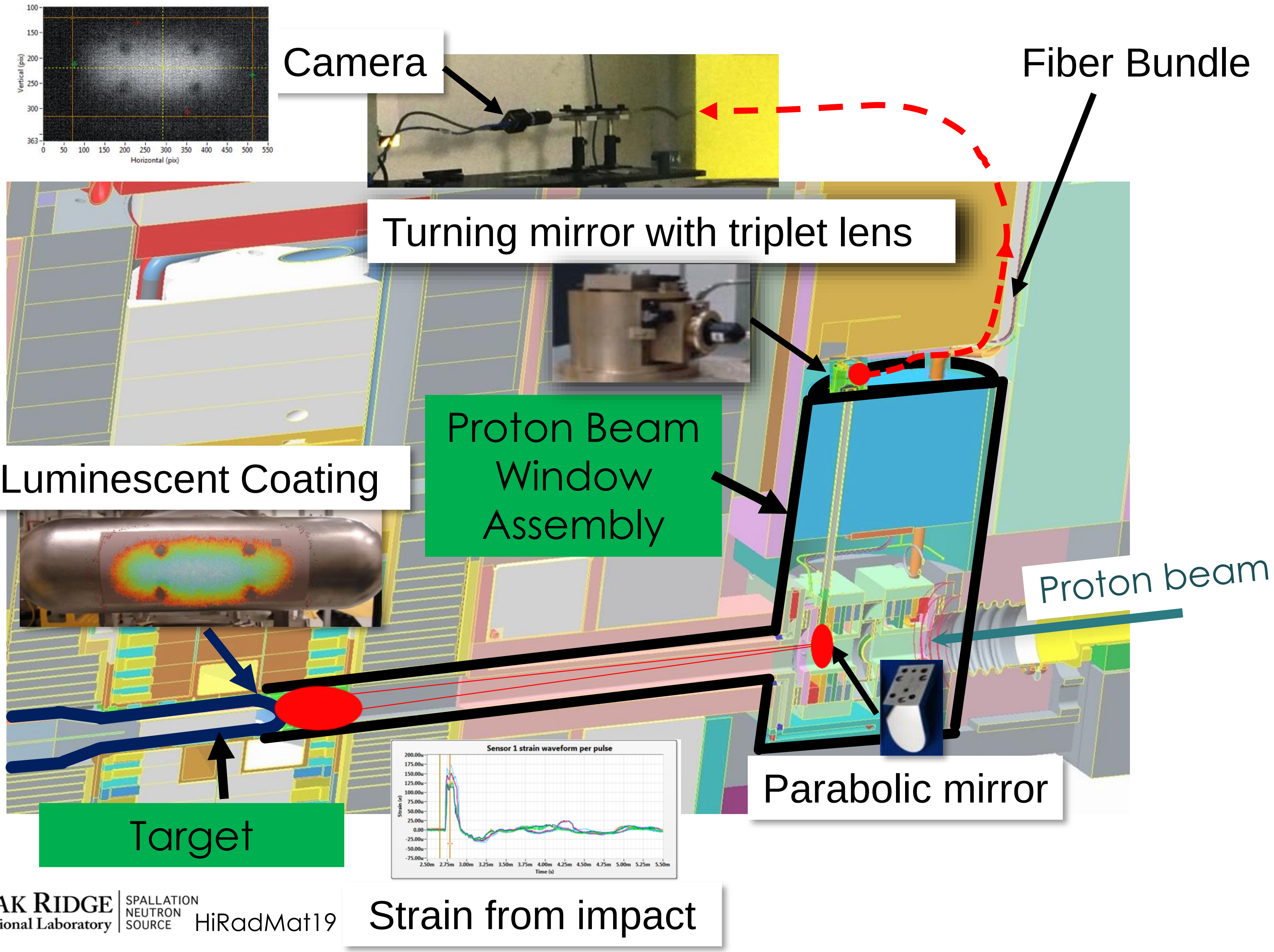
→ $36000 * 10^4 / 1.4 = 257$ MRad



Window is now green (coating damage?)

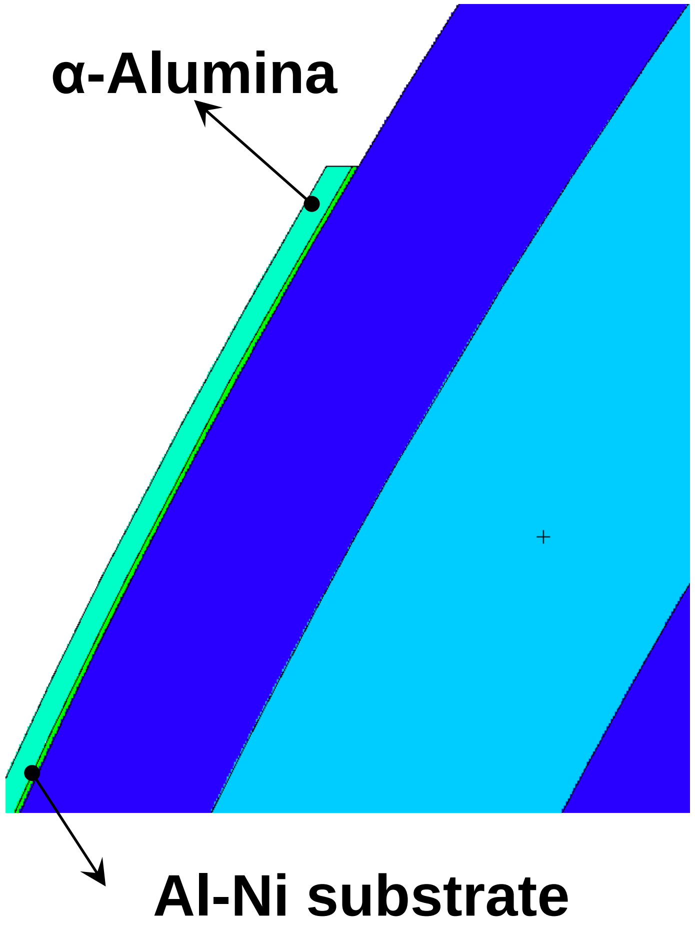


Target Imaging System



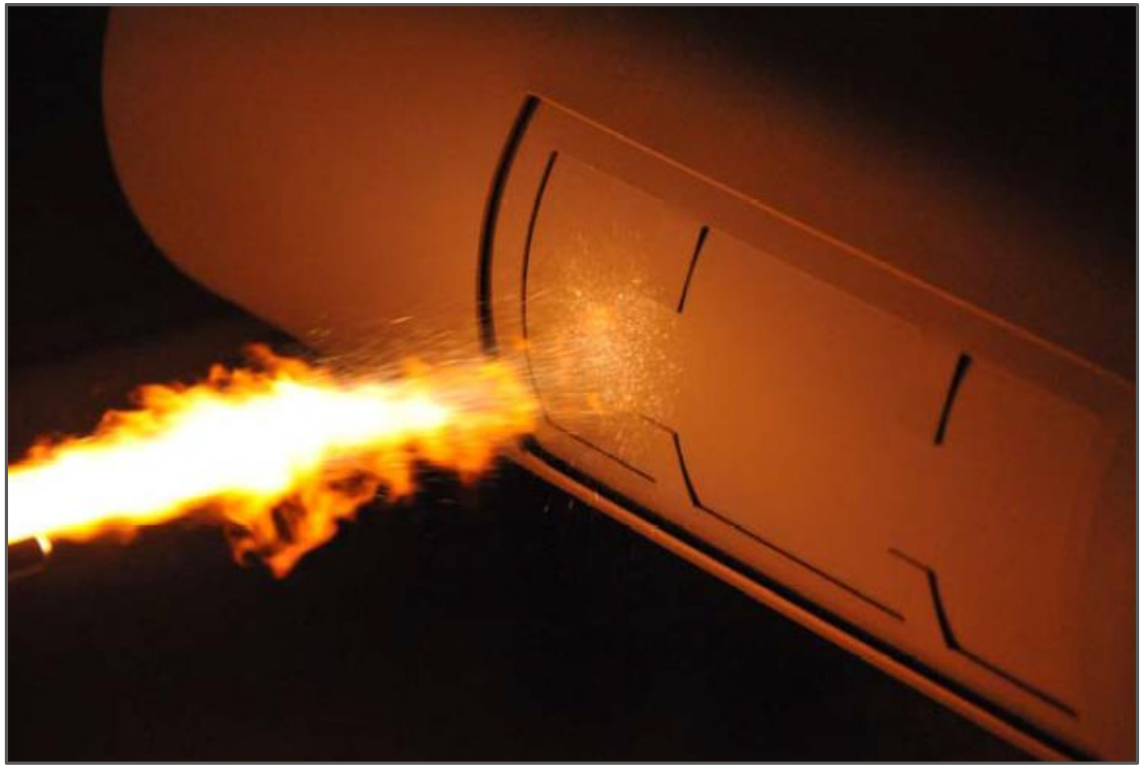
Specs	TIS/Beam
Light Flight Path to Imaging Optics (m)	2.1
Imaging Optics Aperture Diameter (mm)	25
Geometric (r^2) Efficiency	1.77×10^{-3}
Imaging Optics NA Efficiency	1.35
Reflectivity • Aluminum Mirrors • Silica Surfaces	 80.91 72.61
Imaging Fiber Transmission • Packing Fraction • Attenuation	 72.95 92.26
Total Light Collection Efficiency	9.46×10^{-6}
Number of Protons per Pulse at 1.4 MW/1.0 GeV	1.50×10^{14}
Number of Photons per Pulse at 694 nm‡	1.42×10^{8}
Peak Density (ppp/m^2)	2.7×10^{16}
Current Density (A/m^2)	0.26
x_{rms} (cm)	5
y_{rms} (cm)	1.75
DPA/year	10.5

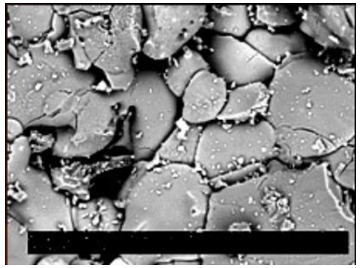
Alumina coating



- Alumina
  - 3.1 g/cm3
  - 0.0229 mm
  - 97.5 wt% Al_2O_3
  - 2.5 wt% Cr_2O_3
- Al-Ni substrate
  - 8.9 g/cm3
  - 0.0051 mm
  - 95 wt% Ni
  - 5 wt% Al

Coating of the target with Al-Ni for bonding

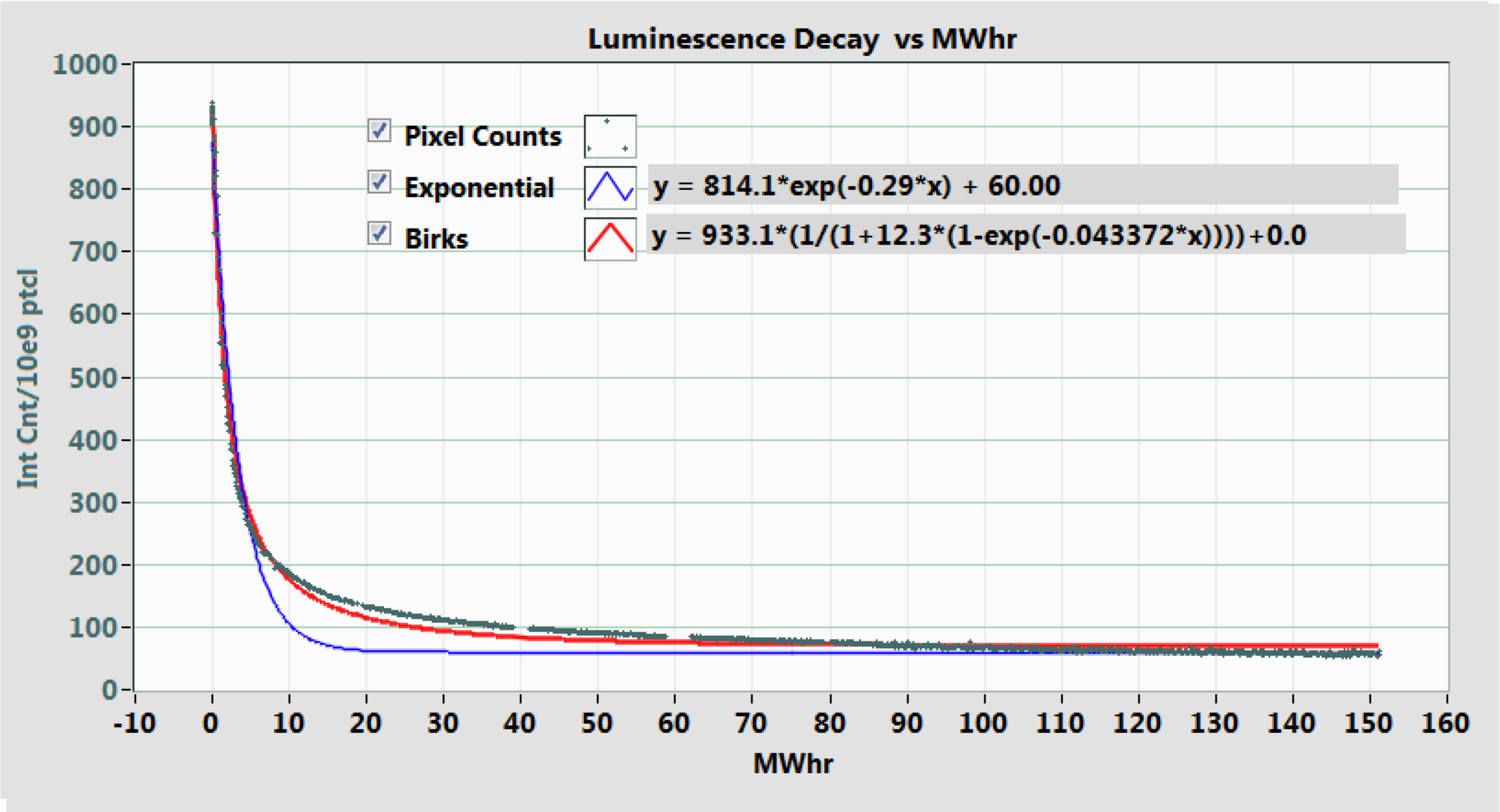




Spraying the cooled target nose without overheating to retain alpha phase alumina.

Decay of luminosity during neutron production

- Drop of about 93% in 100 MHrs (~ 3 Days)



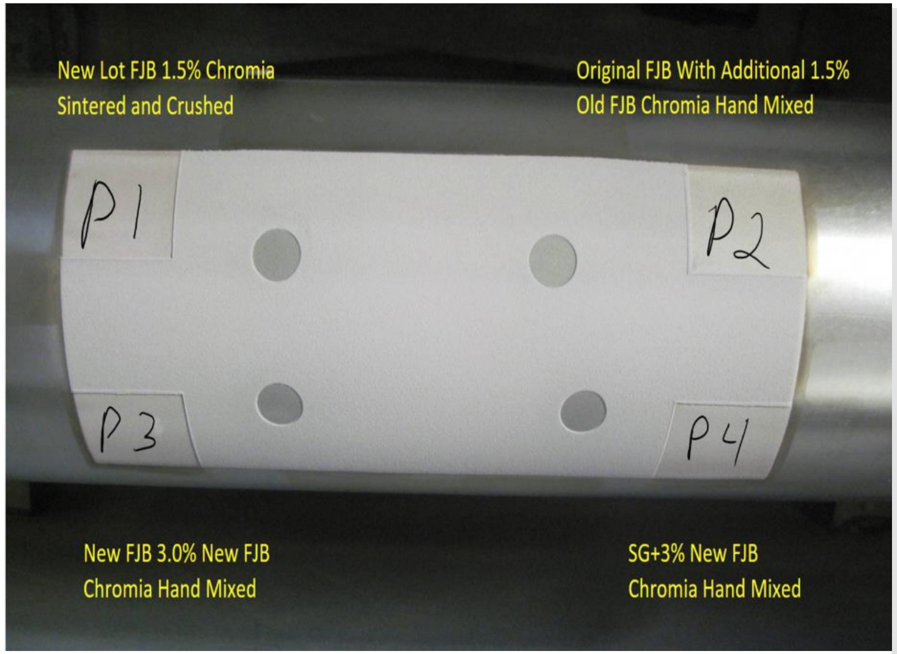
Not an exponential decay, Birks[#] is a better fit (with offset it fits even better)

[#]From: P. Forck "Radiation hardness investigations of Al2O3 for MeV/u ions at GSI", ARIES-ADA Topical Workshop, Krakow, Poland, April 1 to 3, 2019

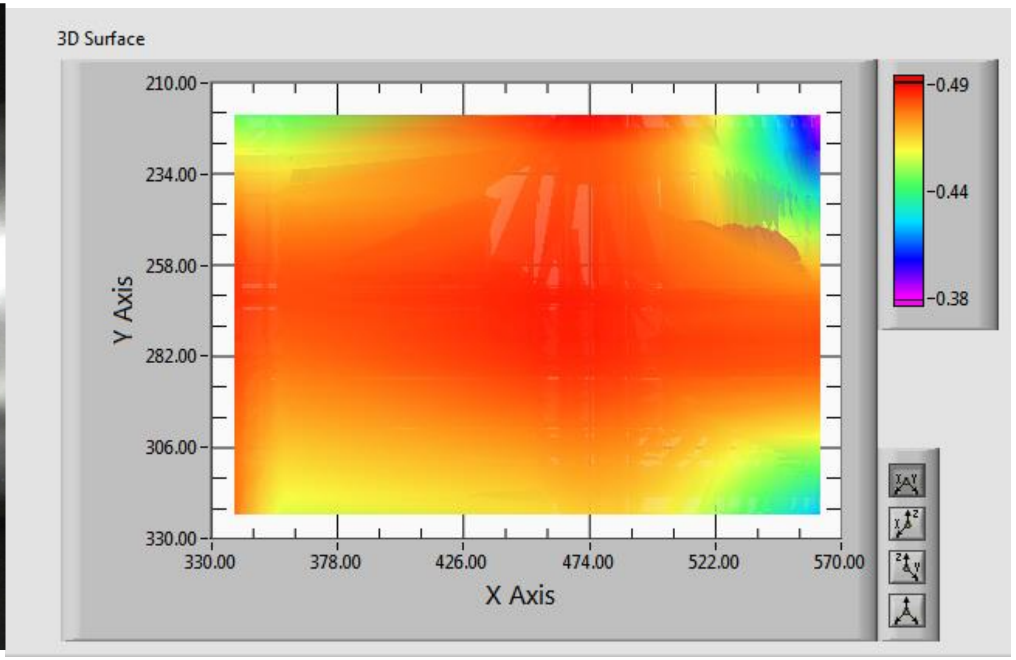
New coatings on the target

Try out different coatings in the corners

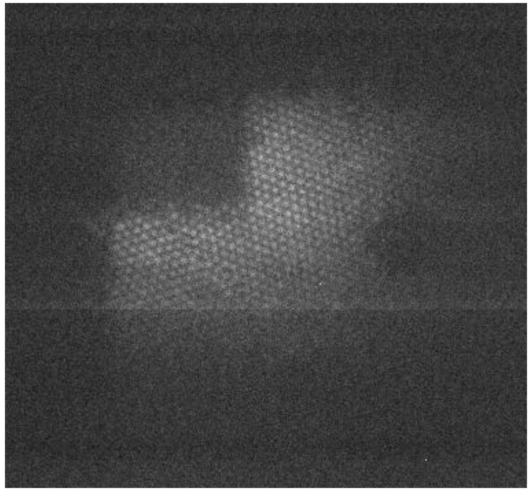
- P3 (3% Mix New FJB) and P1 (3% Mix New FJB) are the brightest
- Lost mirror due to water leak in core vessel before full beam on target data could be taken→ no more TIS



Target as coated



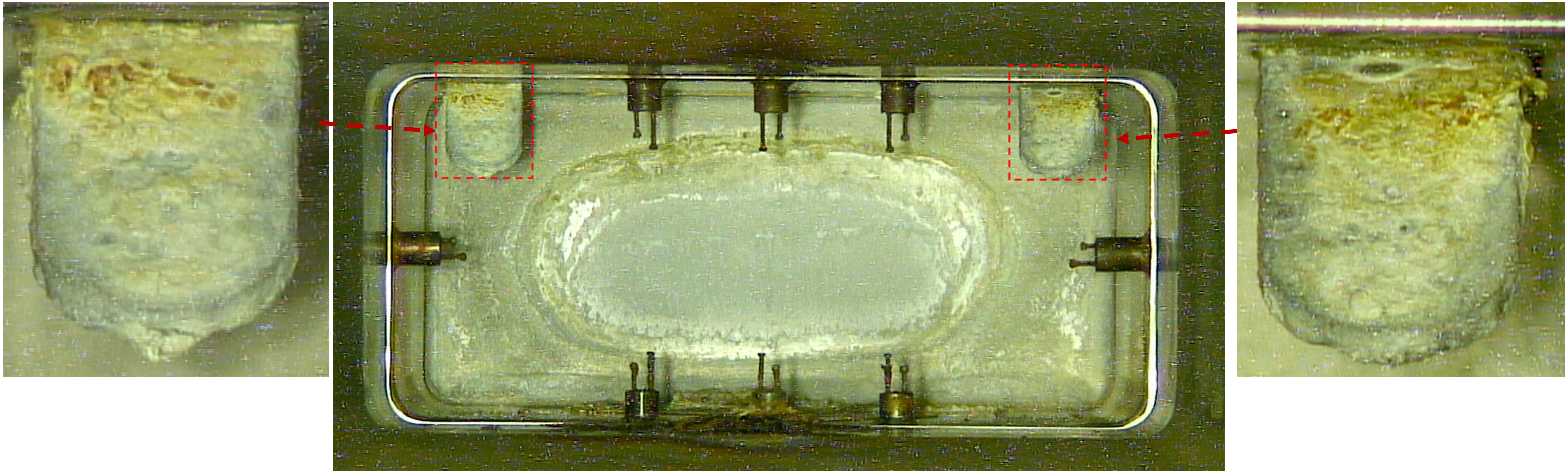
Interpolated surface plot from uniformity scan on fresh target



2000 MWHr test on ruby (2011) Initially higher, now lower.

Picture of proton beam window

- Eventually there are water leaks into the core vessel
  - Radiation mixes with water to create corrosion



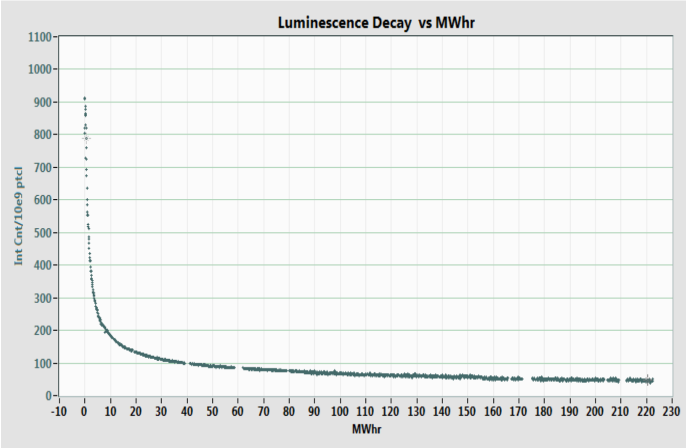
Corrosion on mirrors and Proton Beam Window

Needs: Target Imaging

- Corrosion test of different mirrors with water vapor and radiation
  - Planned test at Fermilab

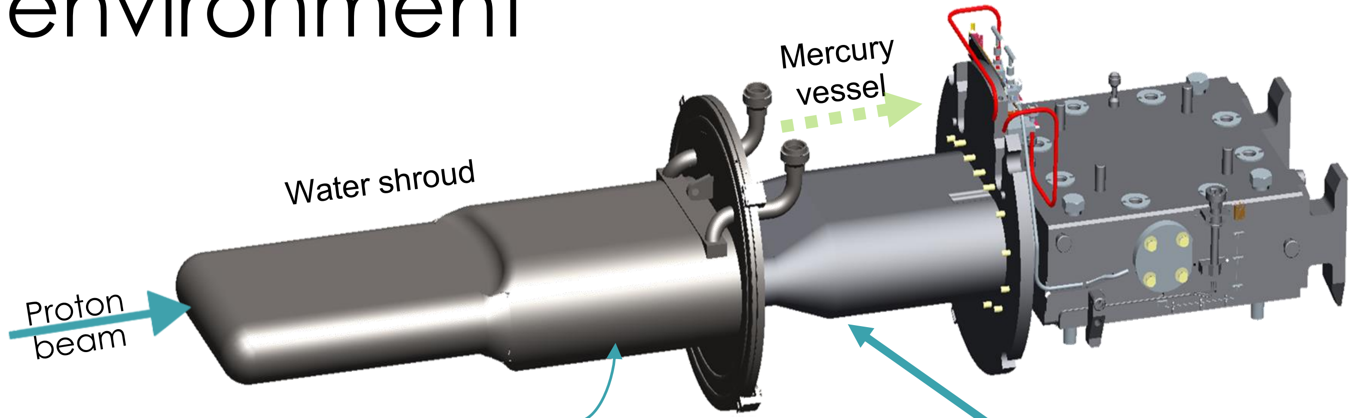
Mirrors with different reflective surfaces and protective coatings

- Understanding and testing of coating
  - Make Al_2O_3:Cr further radiation resistant
  - Test different compositions
  - Test different luminescent materials



Luminosity decay

Sensor environment

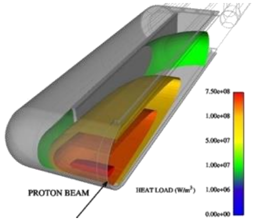


Installed sensors

This is where we place the sensors.

- Leak detector
  - Cannot affect detector → minimize introducing new materials
- Interstitial space
  - < 3 mm height
- Electrical noise
  - Beam pulse of ~24 μC in 600 ns, 50-100 A
  - Pumps and other equipment

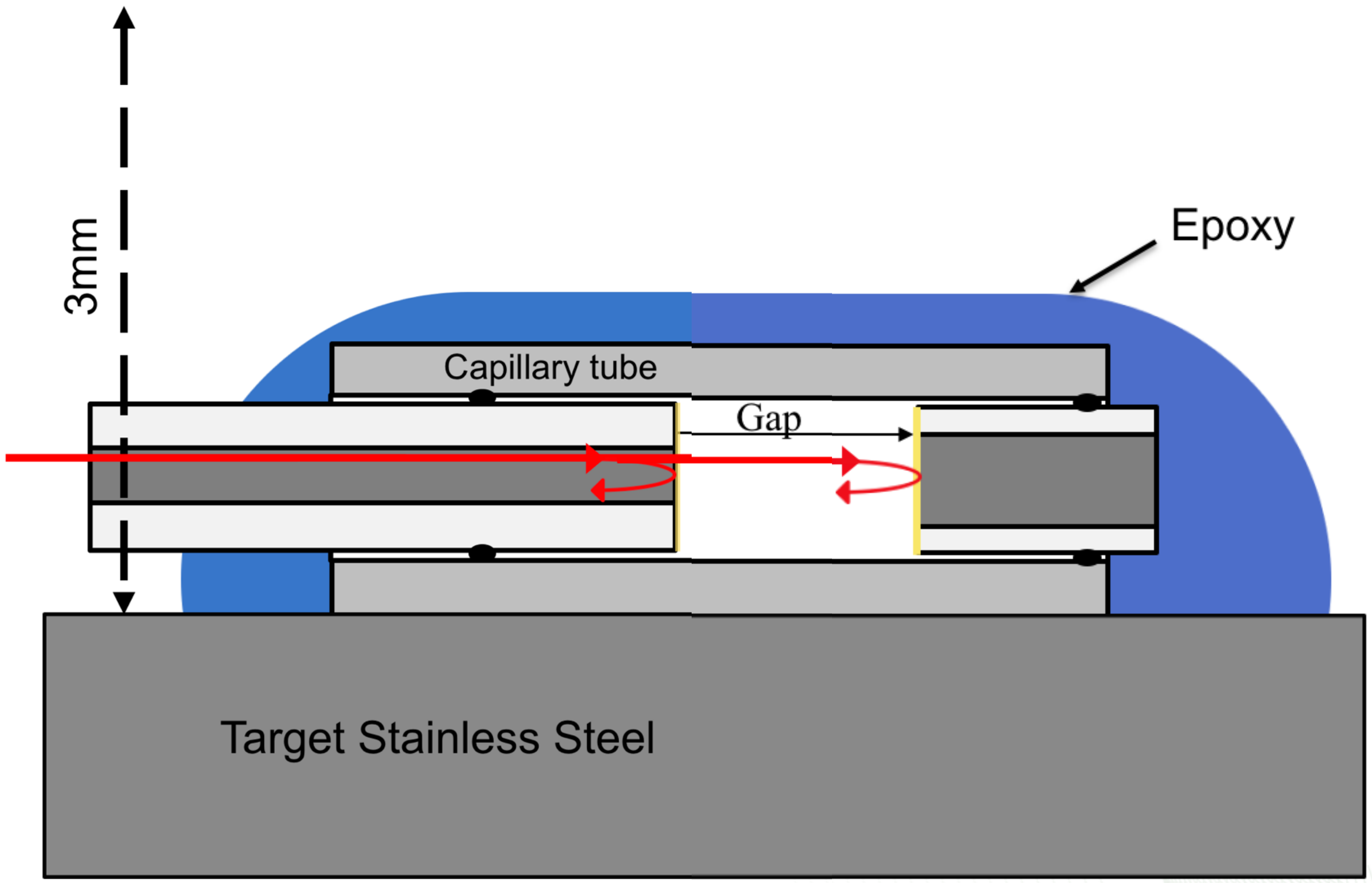
- Proton beam impact
  - ~60% of beam energy is deposited as heat in the target producing a shockwave
    → 10 - 500 με on wall
    → 25 -100 Celsius



- Radiation at sensor locations
  - During production: from 1 MRad/MWhr up to 2.5 GRad/MWhr

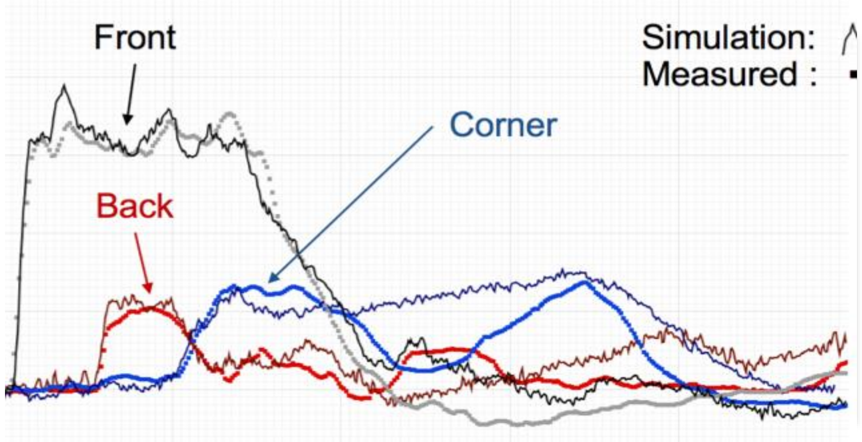
Fiber Optic Strain Gauges

- Sensors are thin (mounted in the ~3mm thick interstitial space between shroud and mercury vessel)
- Non-conductive and insensitive to electrical noise
- High directionality
- SNS prototype:
  - High bandwidth (>1 MHz) to measure fast pulse response
  - Single-mode is radhard
  - Noise: <1 με
  - One sensor per fiber

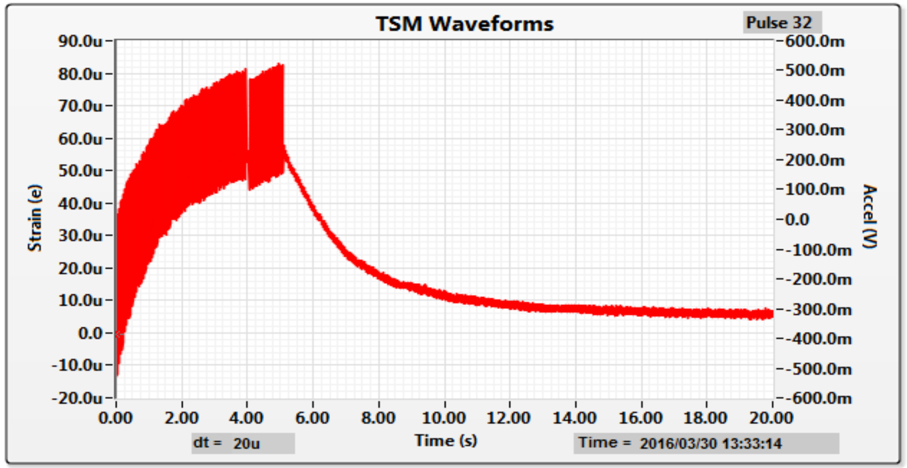


Strain Measurements

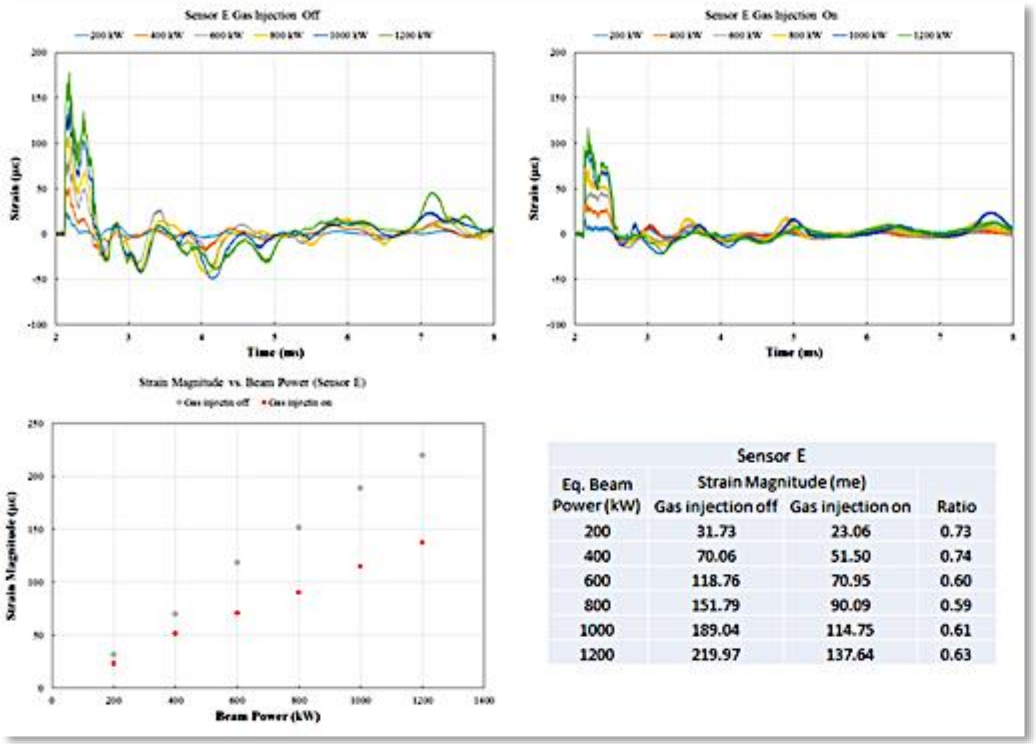
- Using strain measurements we can:
  - Compare to simulations
  - Check for resonances
  - Look for static strain build up
  - Study the effect of helium gas injection
  - Study linearity of strain vs beam power



Measured strain versus simulation



Slow strain buildup

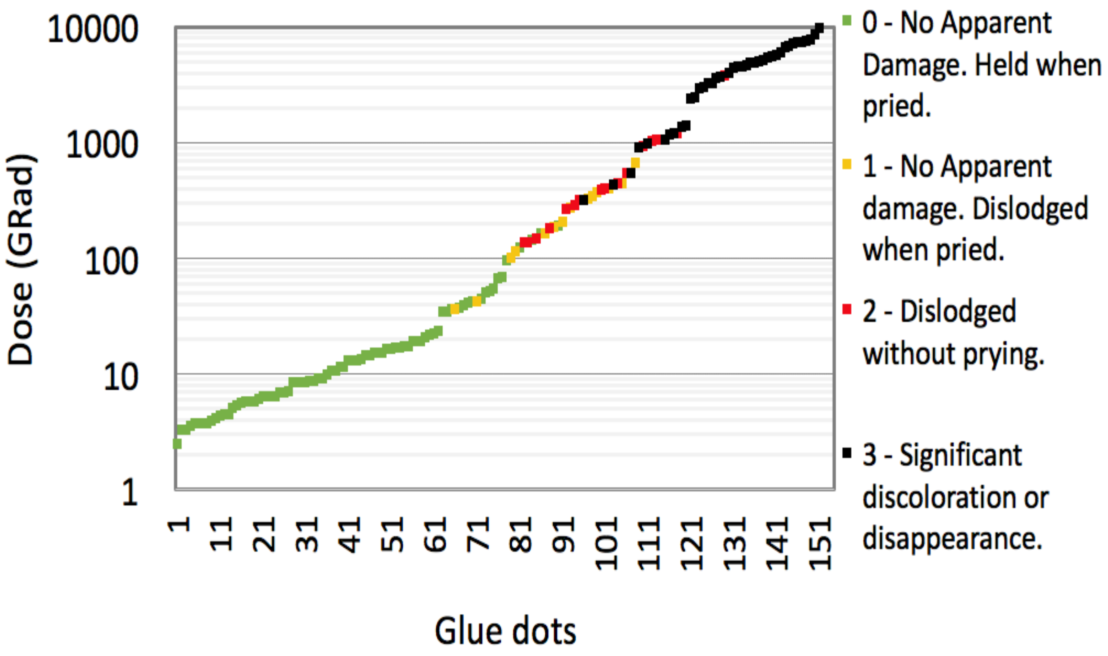


Sensor E			
Eq. Beam Power (kW)	Strain Magnitude (me) Gas injection off	Strain Magnitude (me) Gas injection on	Ratio
200	31.73	23.06	0.73
400	70.06	51.50	0.74
600	118.76	70.95	0.60
800	151.79	90.09	0.59
1000	189.04	114.75	0.61
1200	219.97	137.64	0.63

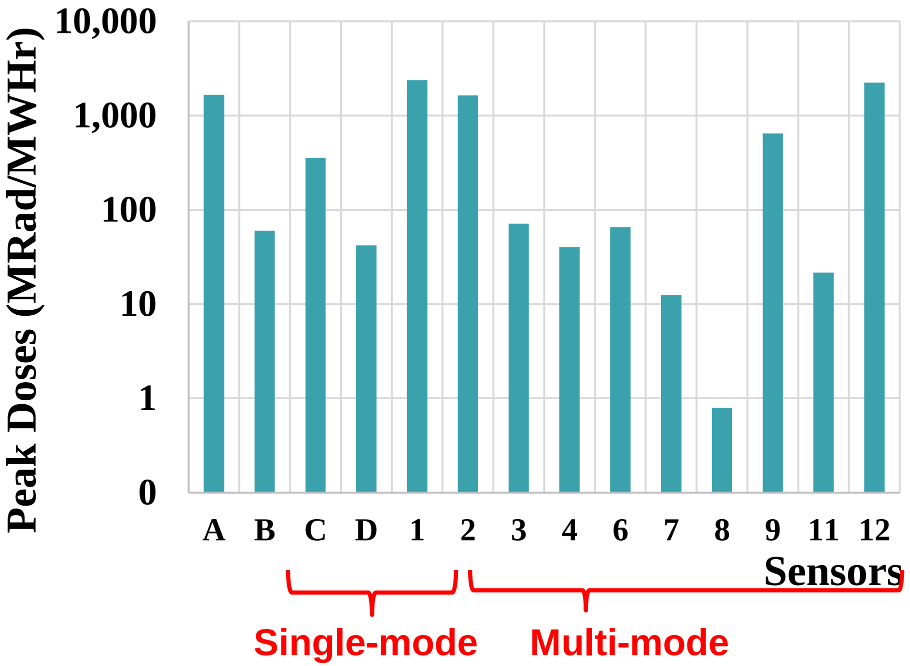
Dependency of strain reduction versus beam power and gas flow

Sensor radiation tolerance

- We performed rough evaluations of radiation hardness of the fiber and the glue



Target 13 total radiation dose per glue dot



Target 15 total radiation dose per sensor

Estimated Radiation tolerance

Radiation tolerance	GRad
High OH Multi-Mode fiber	3.5
Single-Mode	120
Stycast 2850FT	100

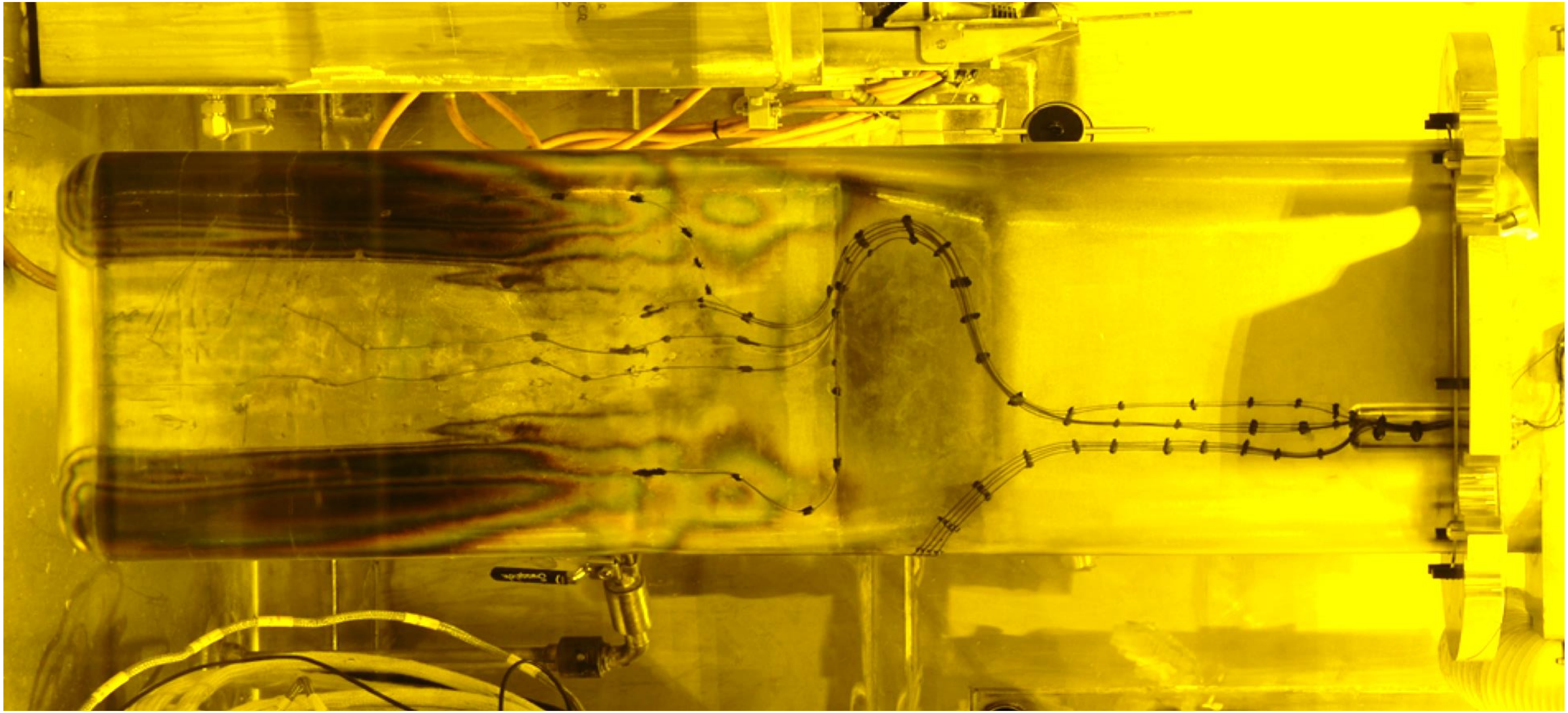
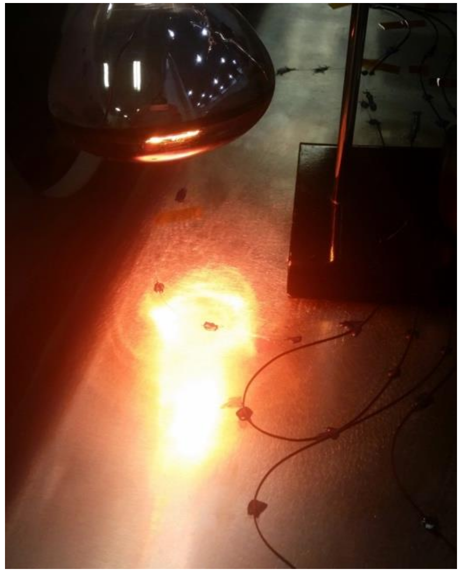


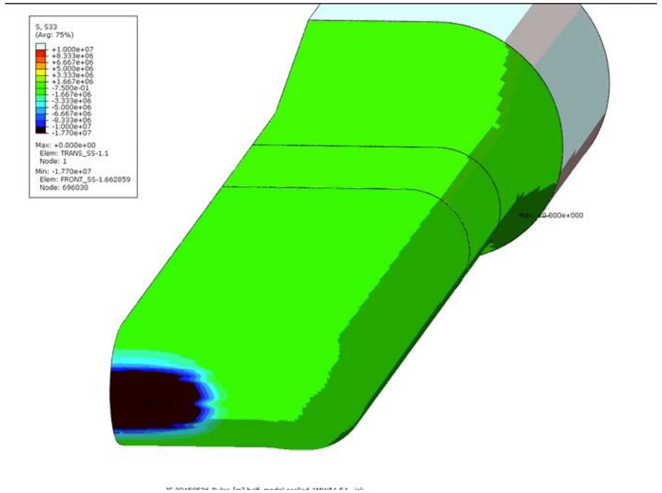
Image of the target mercury vessel after its production cycle

Target Strain Single-Mode Sensor

- At SNS we can only do one test per target or ~2x per year and we cannot visually inspect the sensors afterwards
- Needs:
  - Test radiation hardness of different suitable glues (fiber sensor must survive curing process)
  - Test the single-mode sensors for failure-modes after radiation
    - Optical inspections to determine glass weld failure or cracks in tube
  - Measure effect of radiation flash on glue and glass on strain measurement



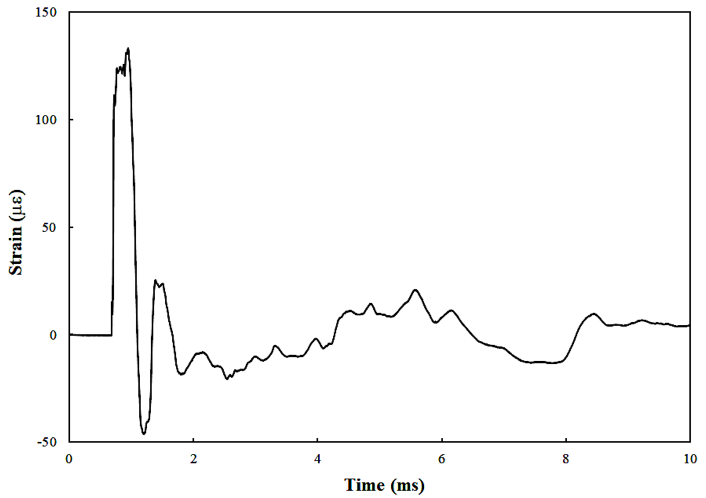
Curing of epoxy glue



Strain due to proton beam energy deposit

Summary

- At SNS we have high radiation resistant diagnostics but we do want to improve these and look for possible collaborations:
  - Find the best rad-hard camera for each application
  - Testing of materials: tungsten, glues and optical sensors
  - Understanding of luminescent coatings radiation damage
- We have a unique high bandwidth strain measurement system for use in very high radiation environments



Strain waveform

Optical processor modules