Oak Ridge National Laboratory

Screens for the SNS Target

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1. ORNL
2. SUNY-Stony Brook
3. CalTech
4. Dartmouth
5. ESS

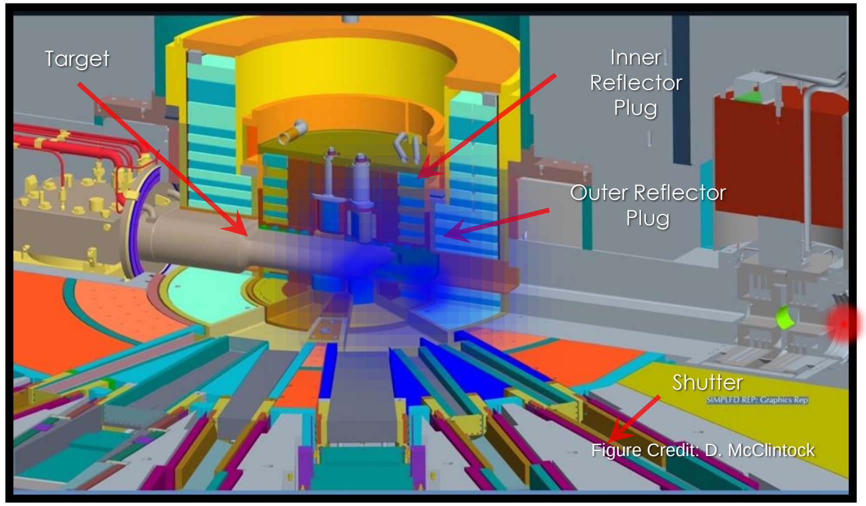
Scintillation Screens and Optical Technology for transverse Profile Measurements
ARIES-ADA Topical Workshop, Krakow, Poland, April 1 to 3, 2019

Introduction

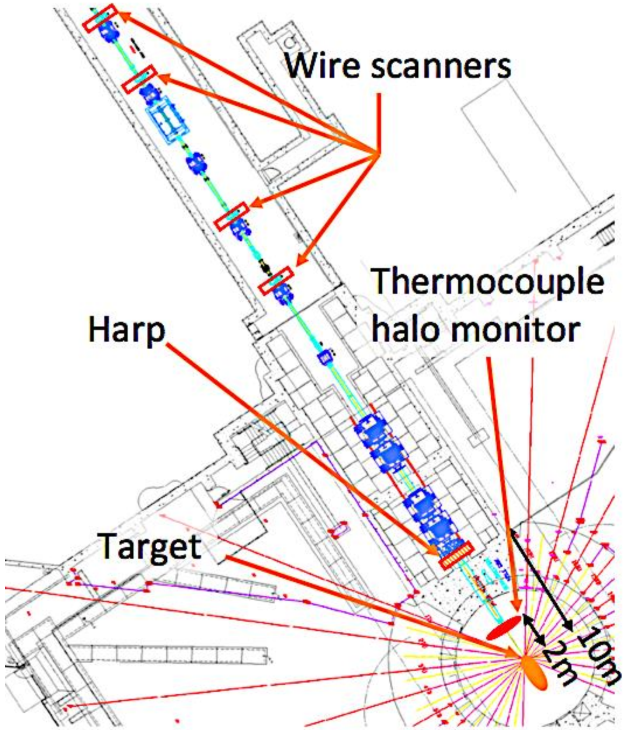
- This talk is about the development of and experience with the target luminescent coating and includes information from many other talks and publications as well as new data.
  - Development
    - Experimentation with $Cr:Al_2O_3$ composition, grain size, spraying, and more
  - Use during operations
    - Brightness per pulse drop due to DPA, uniformity, linear response, etc.
  - New developments
    - Use in SNS BTF at 2.5 MeV (H^-)
    - Running out of original coating powders

Target Imaging System

- Visualize the beam on the target:
  - Minimize target damage to off-centered beam
  - Verify upstream instrumentation at >10m
- Initially a ruby screen was placed in front of the target
  - Can’t handle high power
  - → target itself to be coated



Proton beam on target



Upstream instrumentation

Candidate Photon Sources

Source	Photon yield (photons/proton/steradian)
Screen ($Cr:Al_2O_3$)	$2*10^{+2}$ (used during low power commissioning)
Coating ($Cr:Al_2O_3$)	$2*10^{+1}$
Optical Transition Radiation	$3*10^{-4}$
Helium scintillation (1 m)	$3*10^{-1}$
Thermal Incandescence	Non-linear, long &wide wavelengths

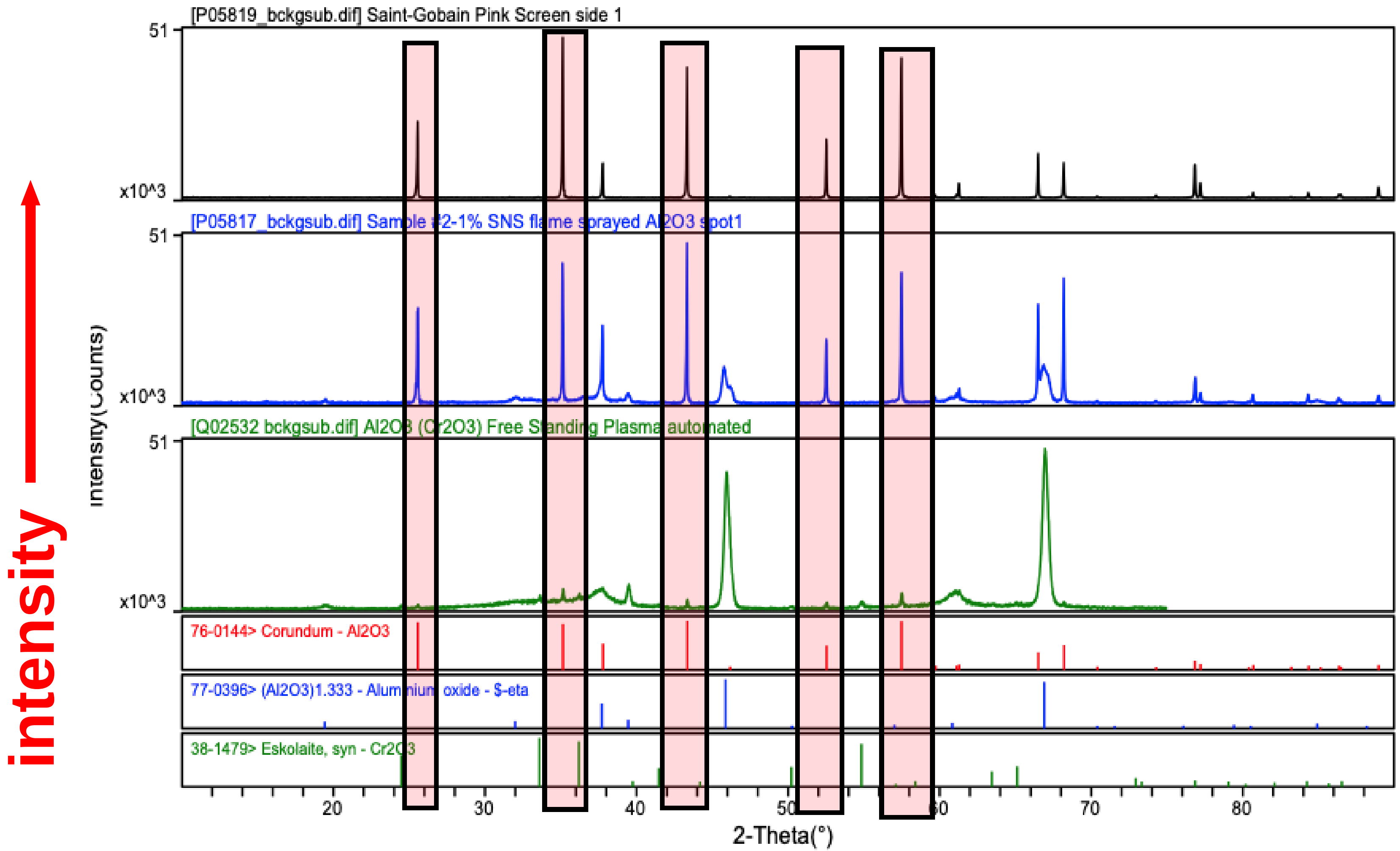
Fiorito et al, UMD

Target Coating with $Cr:Al_2O_3$ selected for development

- We are considering thermal incandescence for other projects

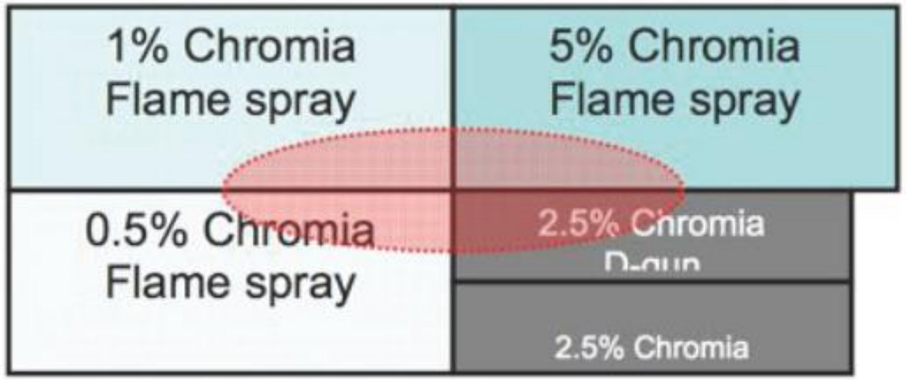
Testing of coating samples: XRD

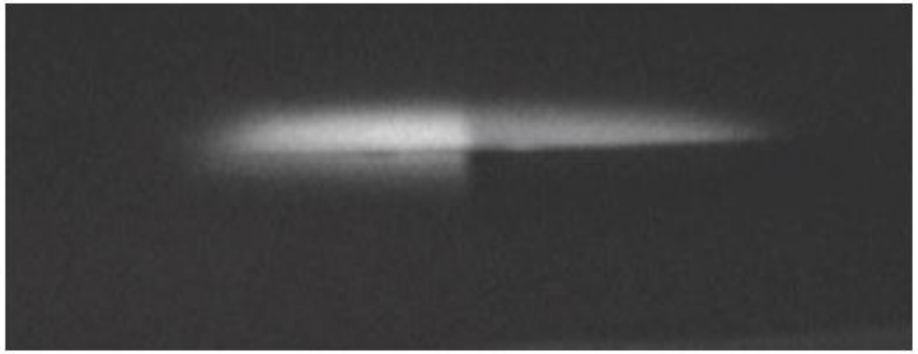
- The search for Alpha phase:



X-ray diffraction to identify % alpha phase alumina (strongest luminance)

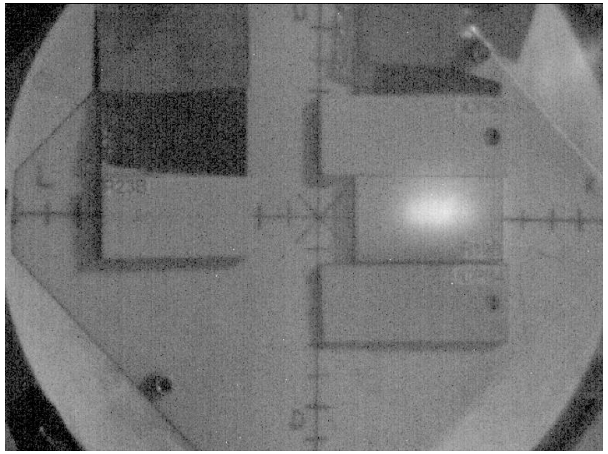
Testing response of coatings: proton and photon-stimulus



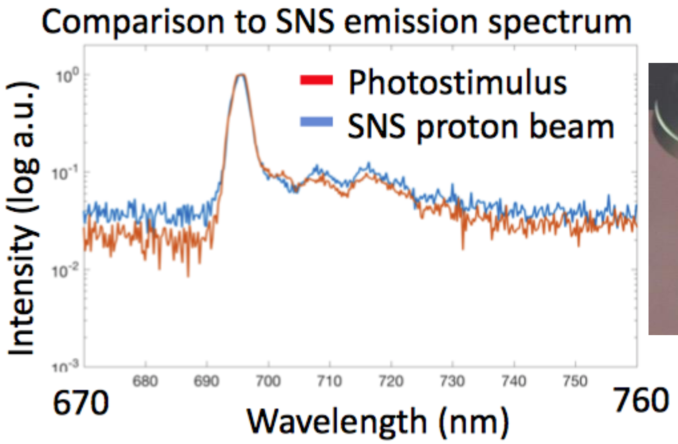


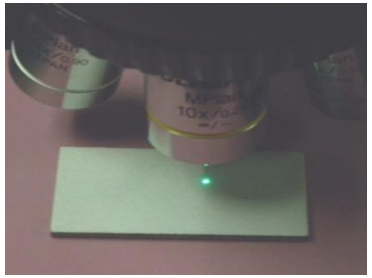
Test at LANL @ 800MeV protons. Lower right quadrant: D-gun coating. Other quadrants: lower temperature flame sprayed coatings.

(Samples coated by Tennessee Metalizing – Rick White)



In SNS linac at 1 GeV beam

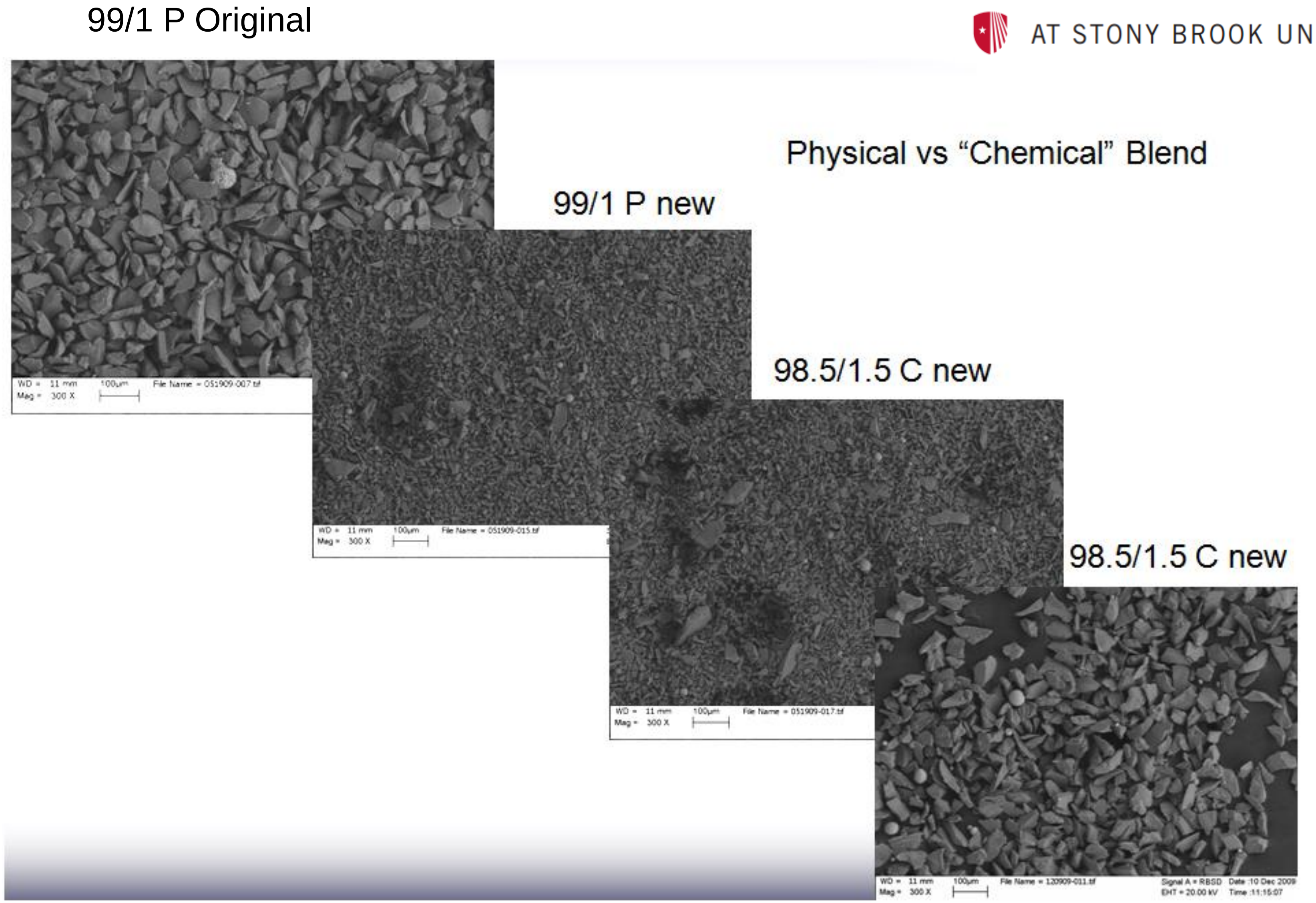




Photon Stimulated Luminescence vs Proton

Coating powders

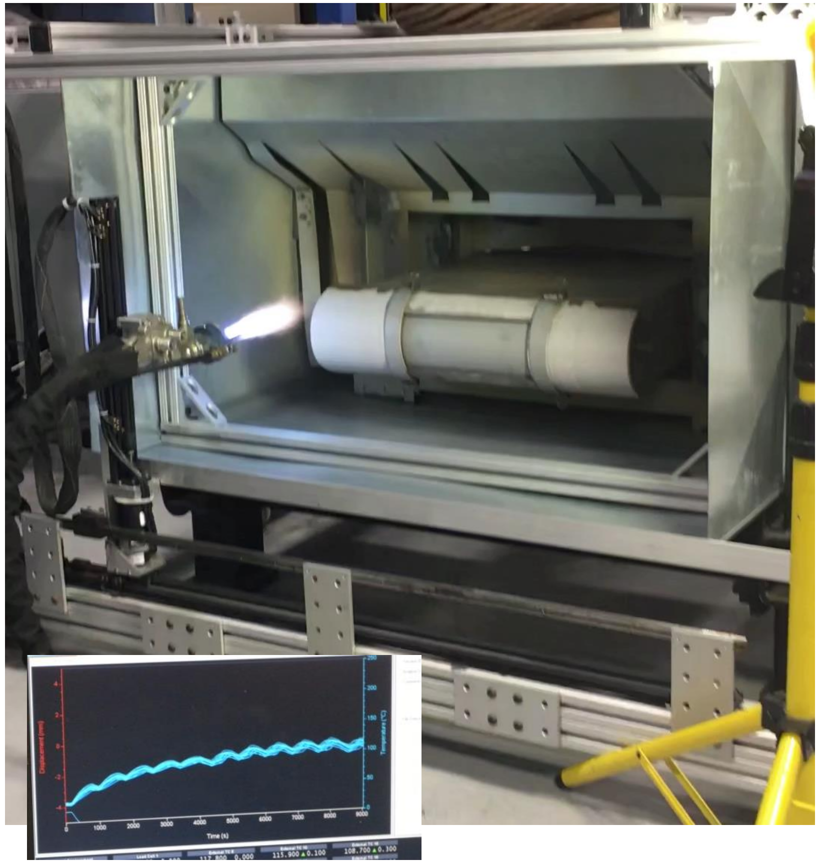
Center for Thermal Spray Research
AT STONY BROOK UNIVERSITY



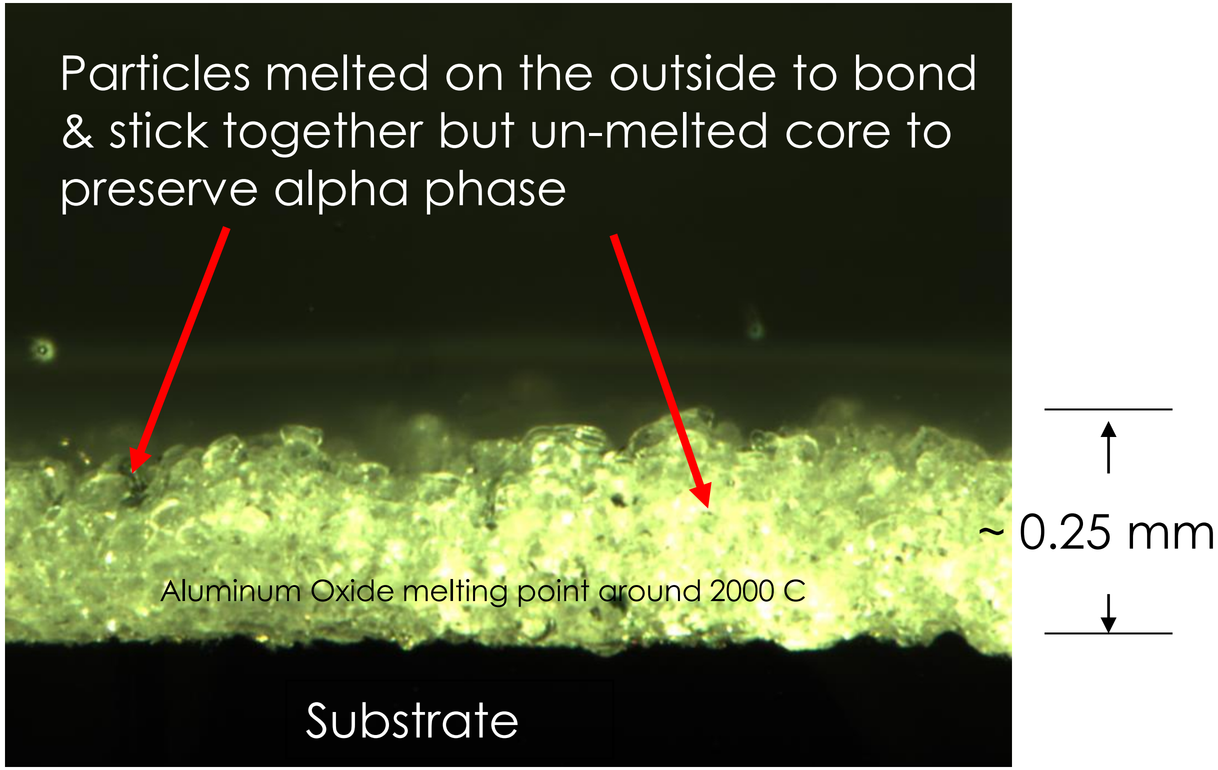
Finding the best composition of powders

Coating process

- Target is grit blasted to aid bonding, A pre-heat is done with 5 cycles of 20 passes
- Each pass is done at ~ 500 mm/s with a delay between passes
- A Nickel-Aluminum bond coat of ~ 0.002" is applied used one cycle of 20 passes.
- Aluminum Oxide with 1.5% chromium oxide is applied with multiple cycles (~ 20)

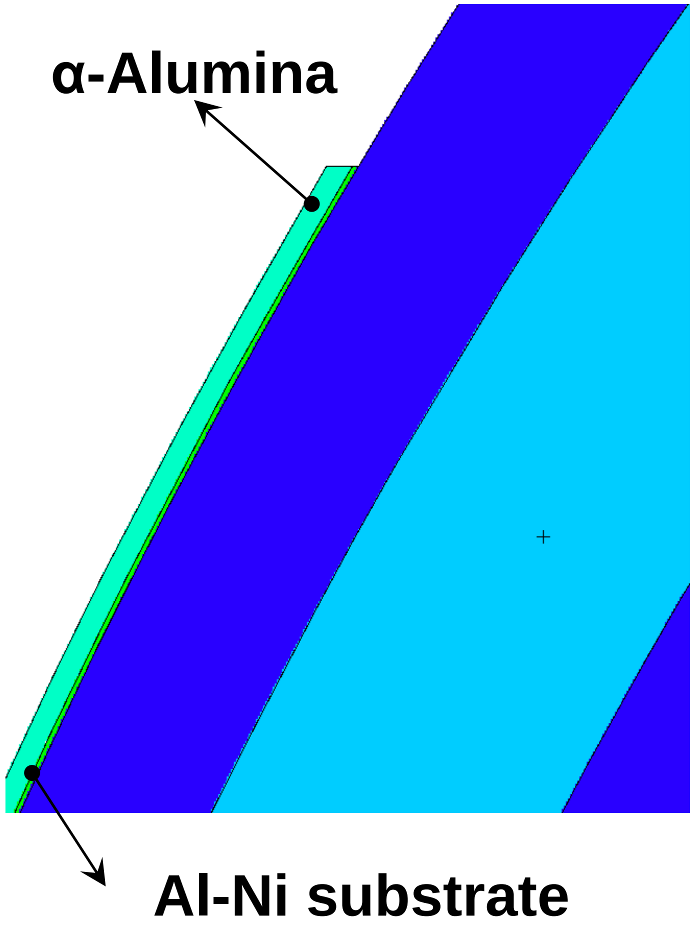


Spraying the target: target remains < 120 C



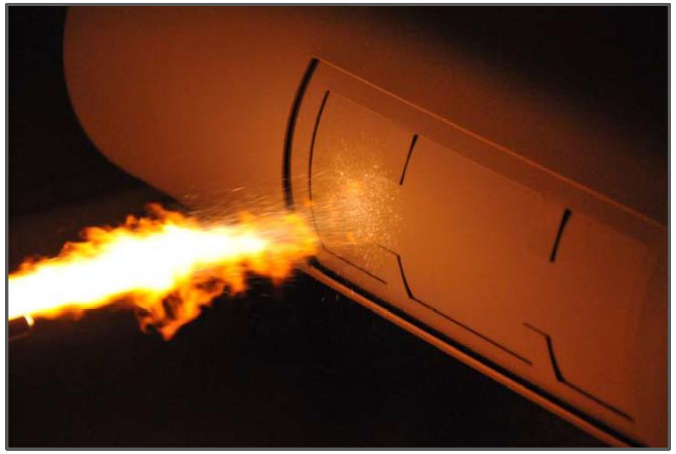
Cross section photo (Michael Lance, ORNL)

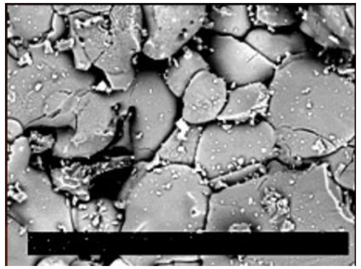
Alumina coating



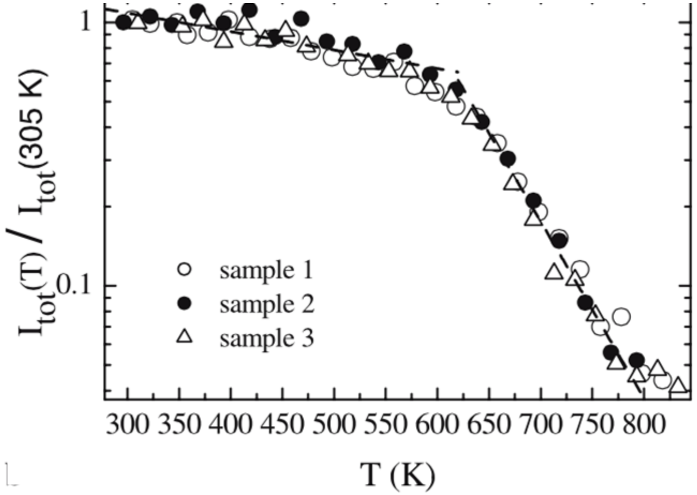
- Alumina
  - 3.1 g/cm3
  - 0.0229 mm
  - 97.5 wt% Al_2O_3
  - 2.5 wt% Cr_2O_3
- Al-Ni substrate
  - 8.9 g/cm3
  - 0.0051 mm
  - 95 wt% Ni
  - 5 wt% Al

Coating of the target with Al-Ni for bonding





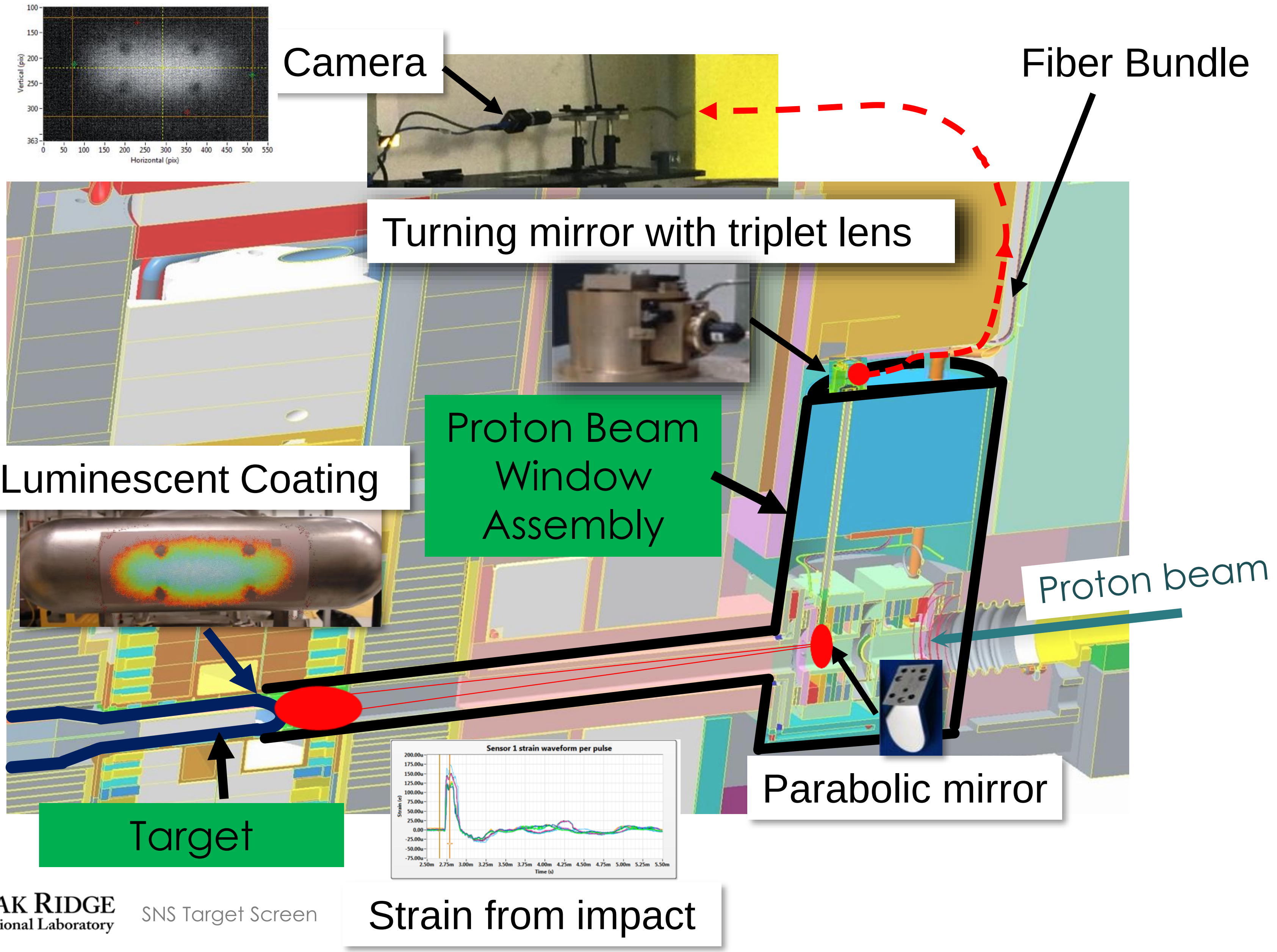
Spraying the cooled target nose without overheating to retain alpha phase alumina.



C. Pflitsch, *et al*, **Appl. Phys. A**, 90, 527–532, 2008

During full beam power at 1.4 MW, the coating can reach 150 C (425 K).

Target Imaging System Layout

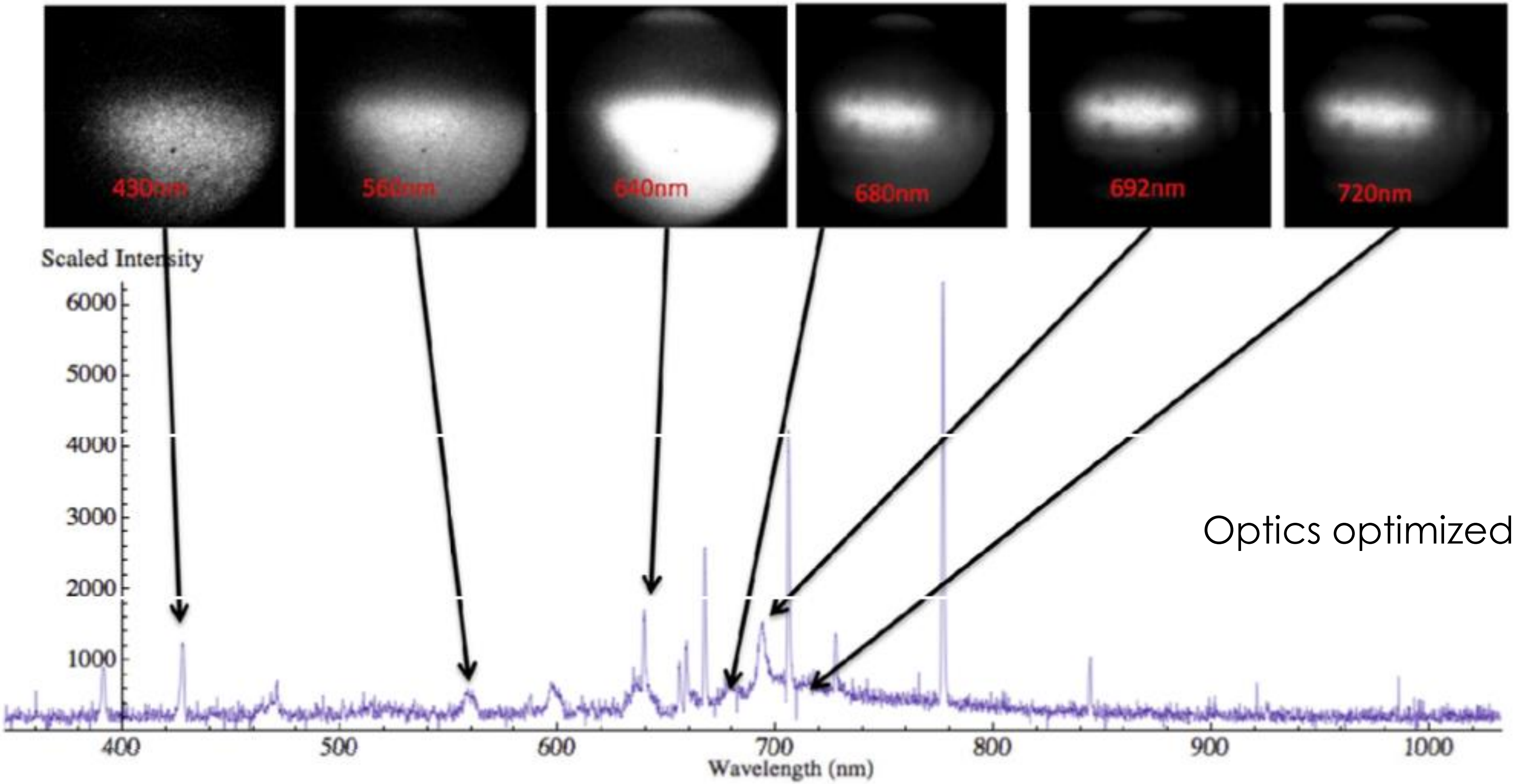


Specs	TIS/Beam
Light Flight Path to Imaging Optics (m)	2.1
Imaging Optics Aperture Diameter (mm)	25
Geometric (r^2) Efficiency	1.77×10^{-3}
Imaging Optics NA Efficiency	1.35
Reflectivity • Aluminum Mirrors • Silica Surfaces	 80.91 72.61
Imaging Fiber Transmission • Packing Fraction • Attenuation	 72.95 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

Luminescence During Operations

- Studies
  - Spectral response
  - Comparison with calculated beam parameters
  - Uniformity tests
  - Decay in Luminescence per MWHr
  - Effect of DPA on profile
  - Effect of DPA on spectrum
  - Linearity of luminescence vs beam pulse charge
  - Duration of luminescence pulse
  - Effect of secondary particles on luminescence

Spectral response



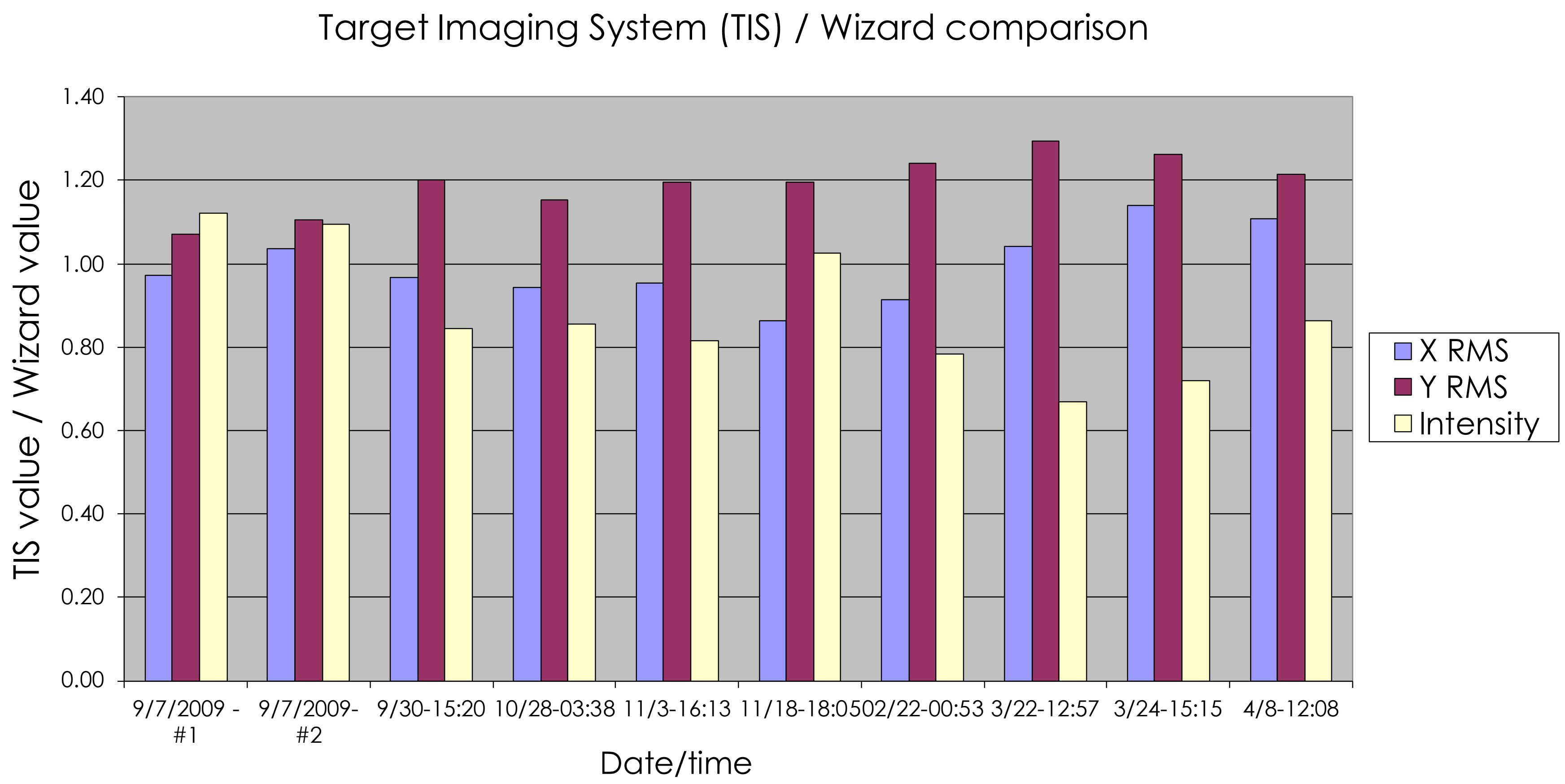
Optics optimized for 692 nm

Different spectra are present, most from gas scintillation and can be gated due to their short duration

SNS Target Imaging System Operation at ACCAPP 2011
T. McManamy[1], T. Shea[1] G. Bancke[2], W. Blokland[1], K. C. Goetz[1], C. Maxey[1], P. Rosenblad[1], S. Sampath[2] –

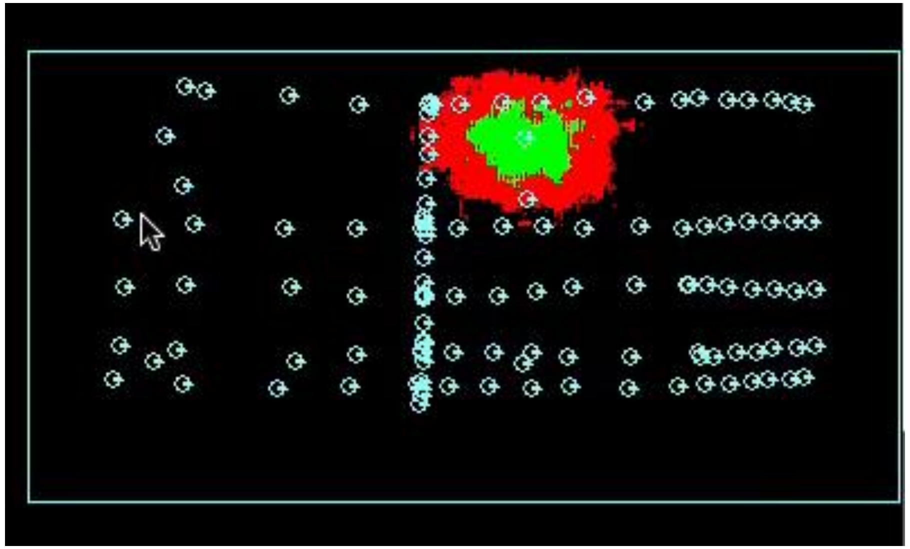
Comparison with calculated beam parameters

- We see an agreement ~20%: within expectation

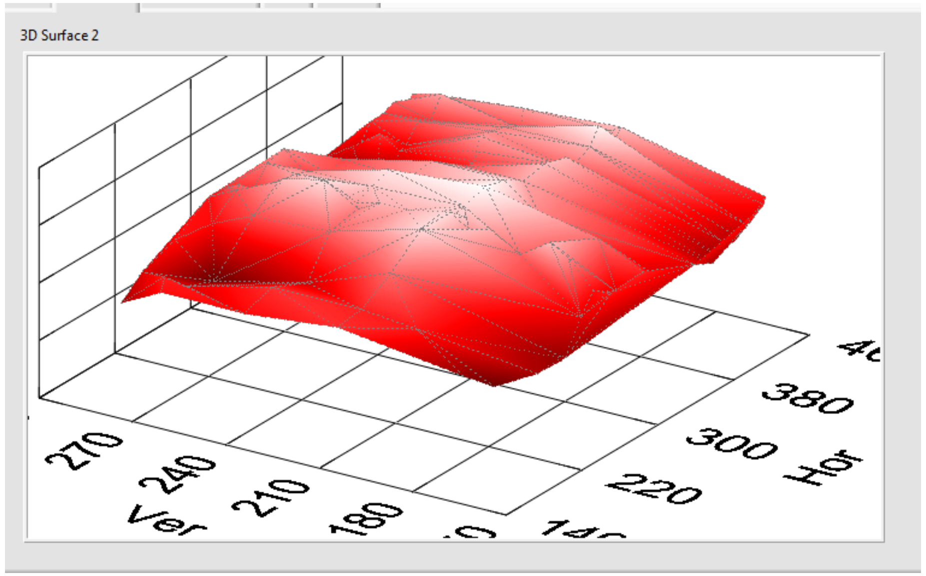


Measurements at different times

Uniformity Tests

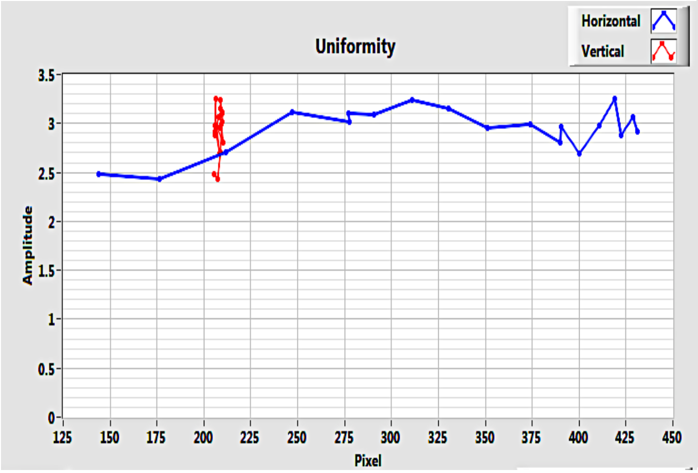


Smallest possible beam spot scans across the target

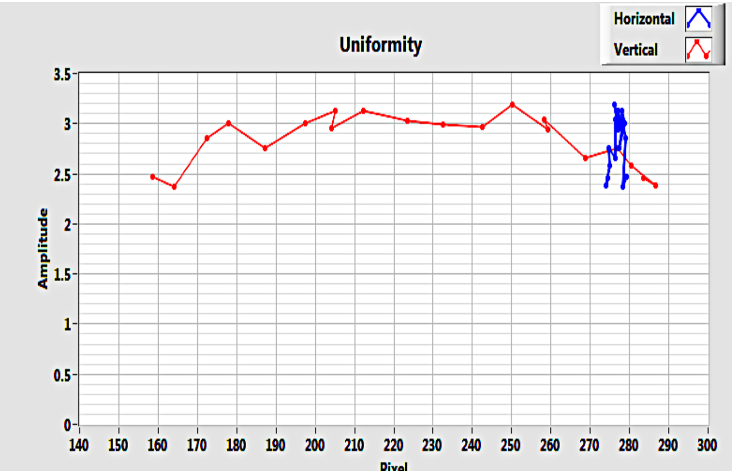


3D Surface plot of uniformity scan

About ±12.5 % variation measured but the amount of light is minimal (< 100 Watts per second or 100 Joule per pulse)



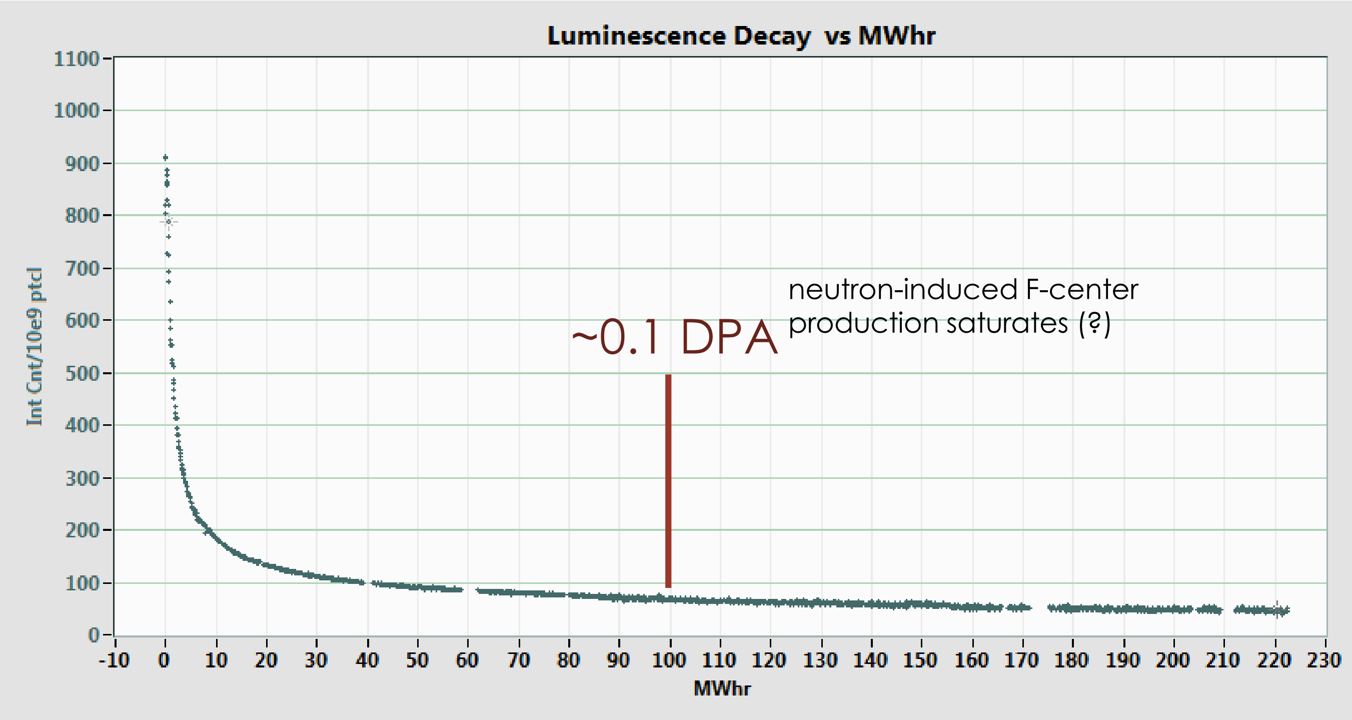
Horizontal Middle



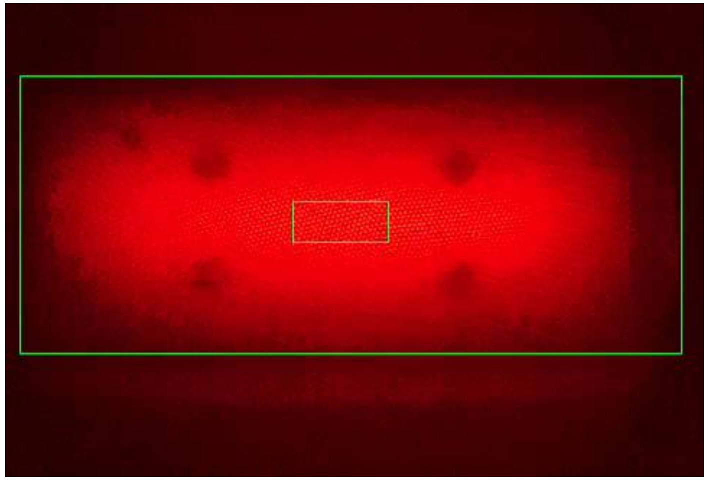
Vertical Middle

Decay of luminosity during neutron production

- Decay from October 15th to November 25
- Corrections were made to account to beam pulse charge and camera exposure changes
- 100 MW-hours is about ~0.1 dpa, estimated point at which neutron-induced F-center production saturates; now a slow intensity reduction



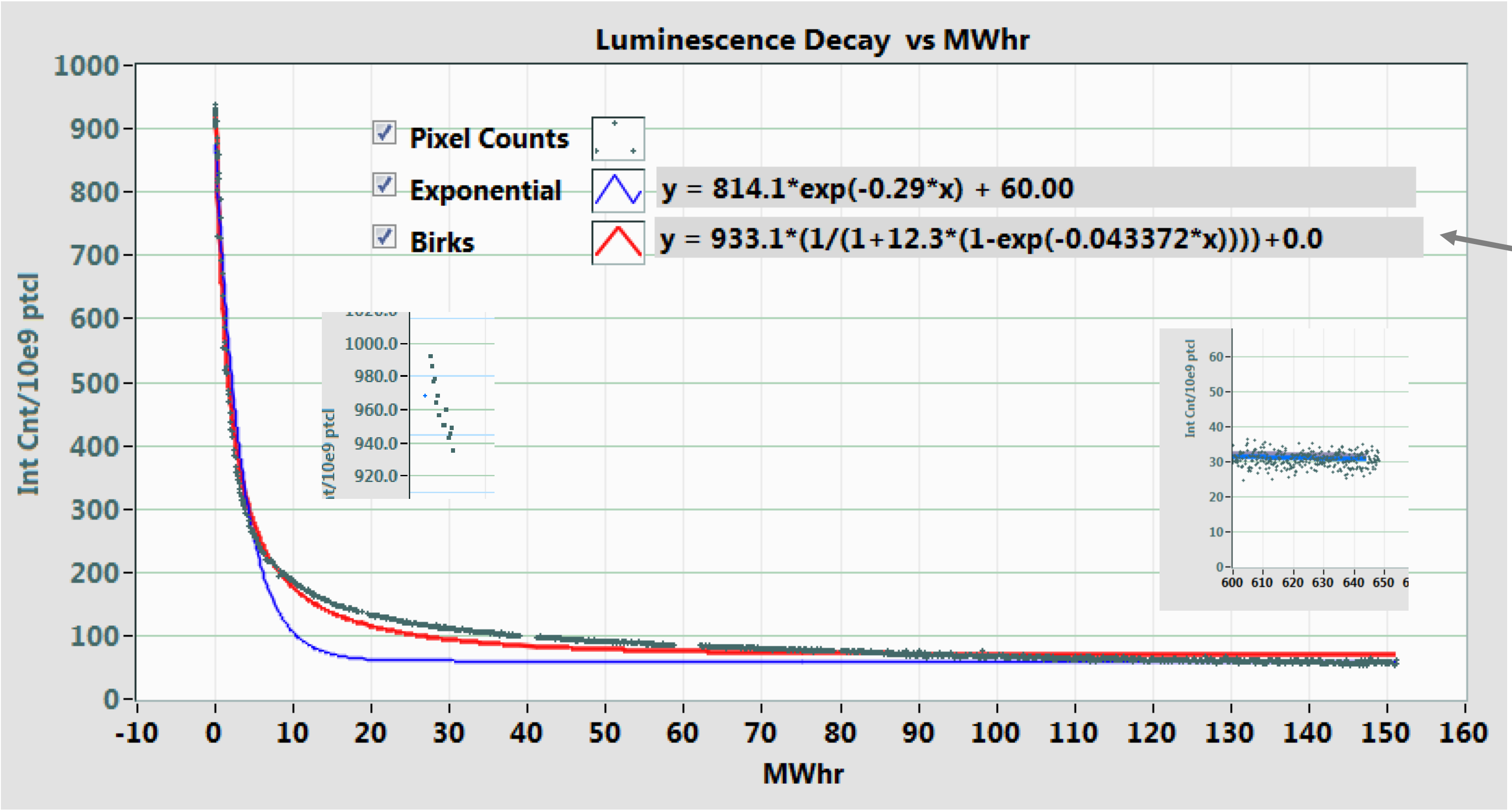
Decay due to protons (15%) and neutrons (85%)



Images during ramp-up and production.
(Jumps in intensity as opposed to gradual due adjusting camera parameters, e.g. to shorting exposure from 19ms to 4-8 ms)

Decay of luminosity during neutron production

- Drop of about 93% in 100 Mhrs (from ~1000 to ~65 cnts per 10^9)

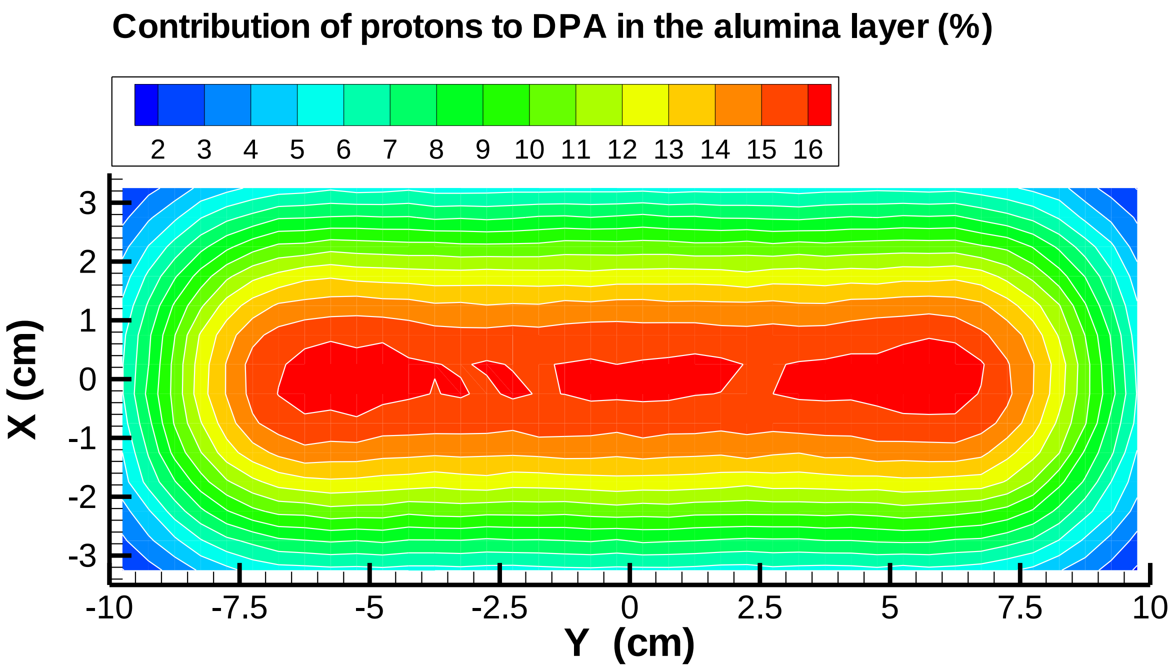


From P. Forck's talk

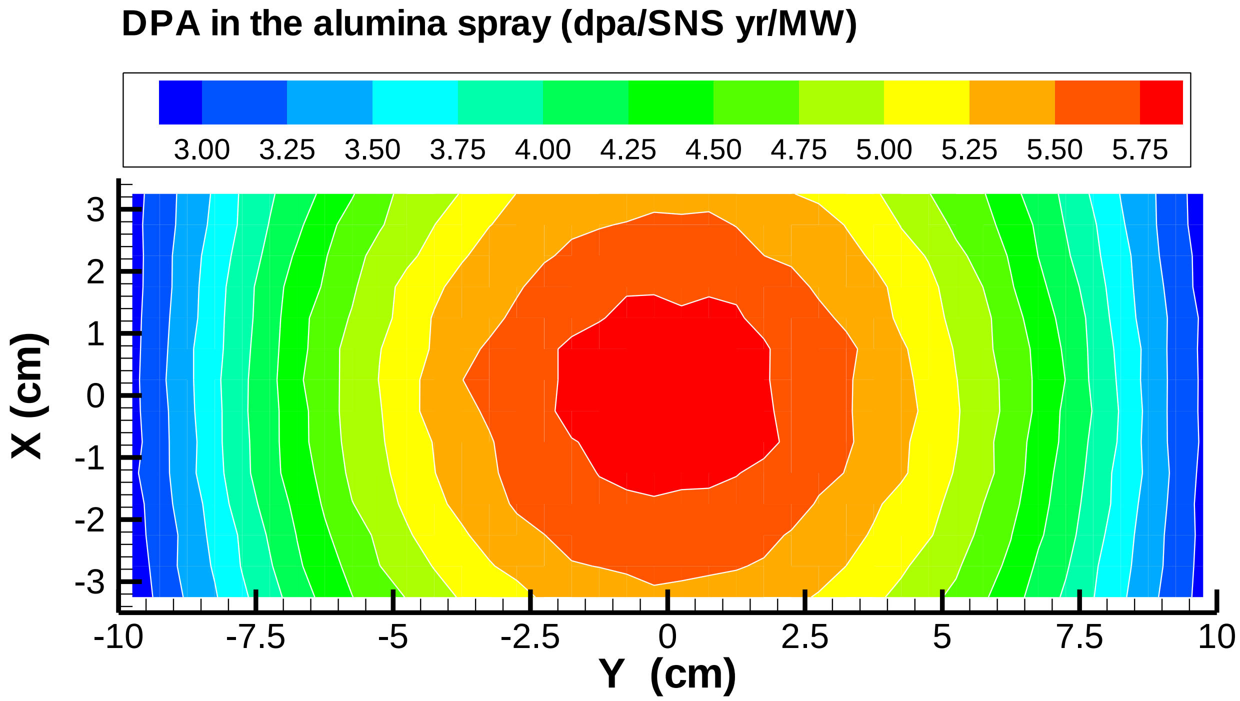
Not an exponential decay, Birks is a better fit (offset fits even better)

Effect of DPA: Distribution

- Given the distribution of the DPA in the coating, we would expect some change in the derived profiles of the beam



Calculated DPA percentage due to Protons



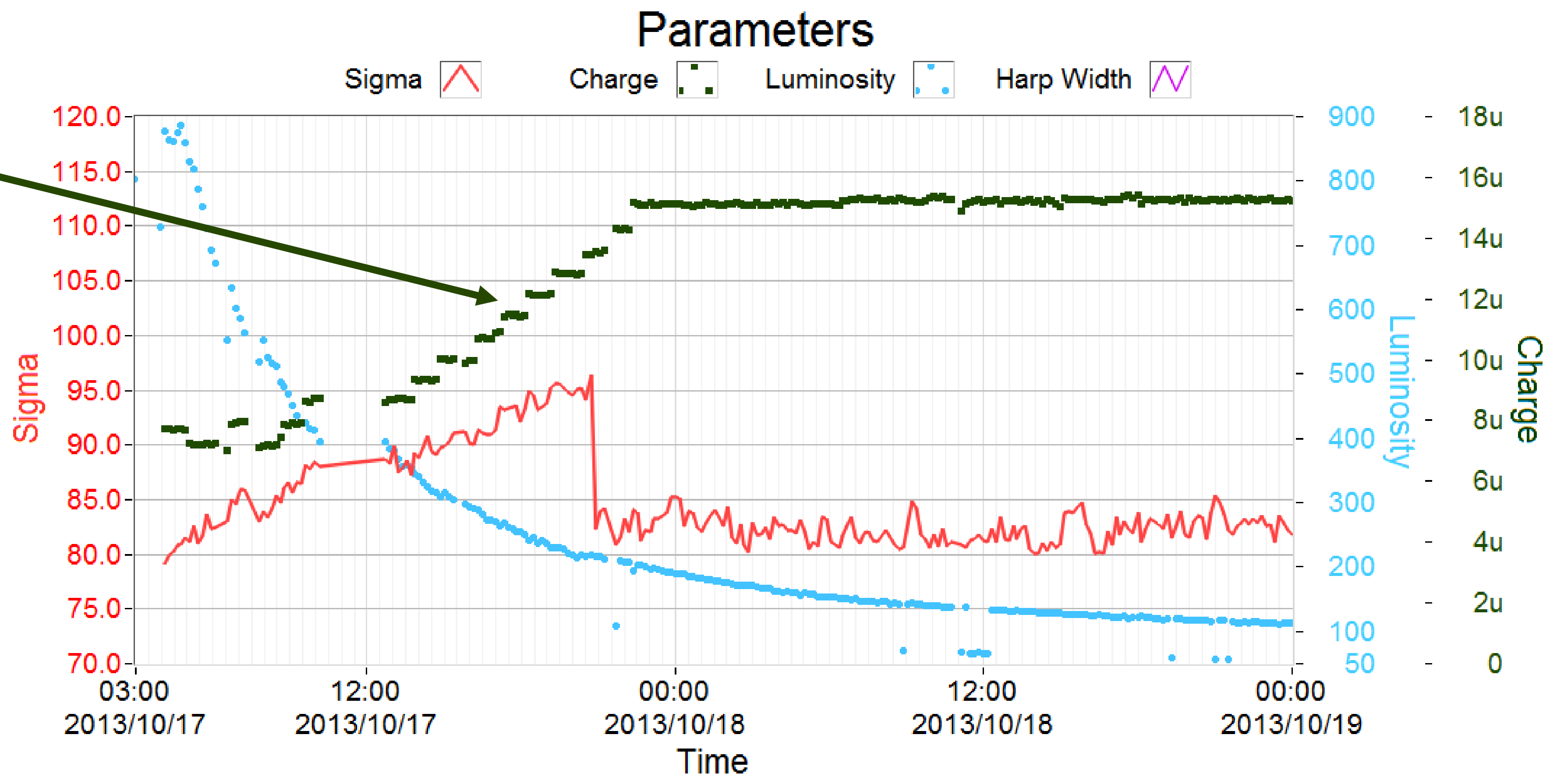
Calculated DPA due to Protons and Neutrons

Note: gamma distribution will be more homogenous

Effect of DPA on measurements during decay

- Measure during the first days

Keep in mind that the beam profile changes depending on the accumulated beam in the ring

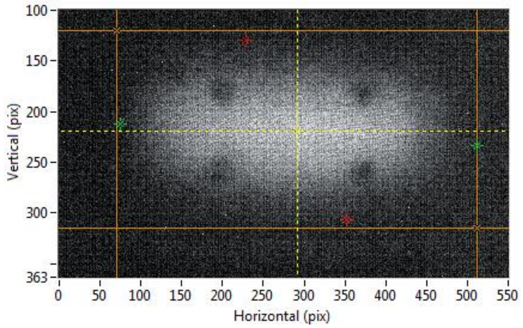


Estimated horizontal parameters vs luminosity

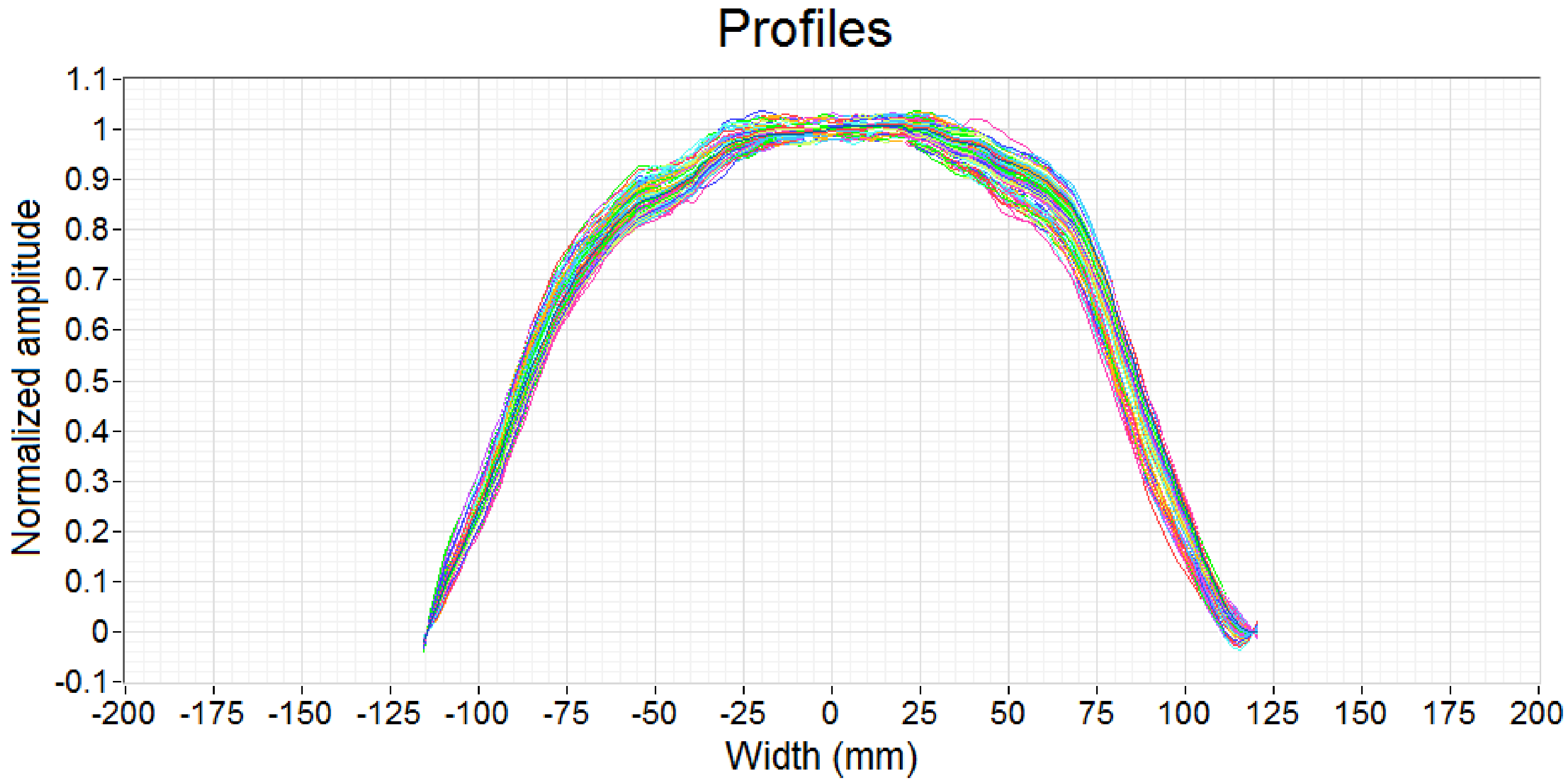
Effect of DPA on measurements during decay

- Excluding different beam pulse charges

→ Little effect on width despite intensity going down and background noise becoming more significant



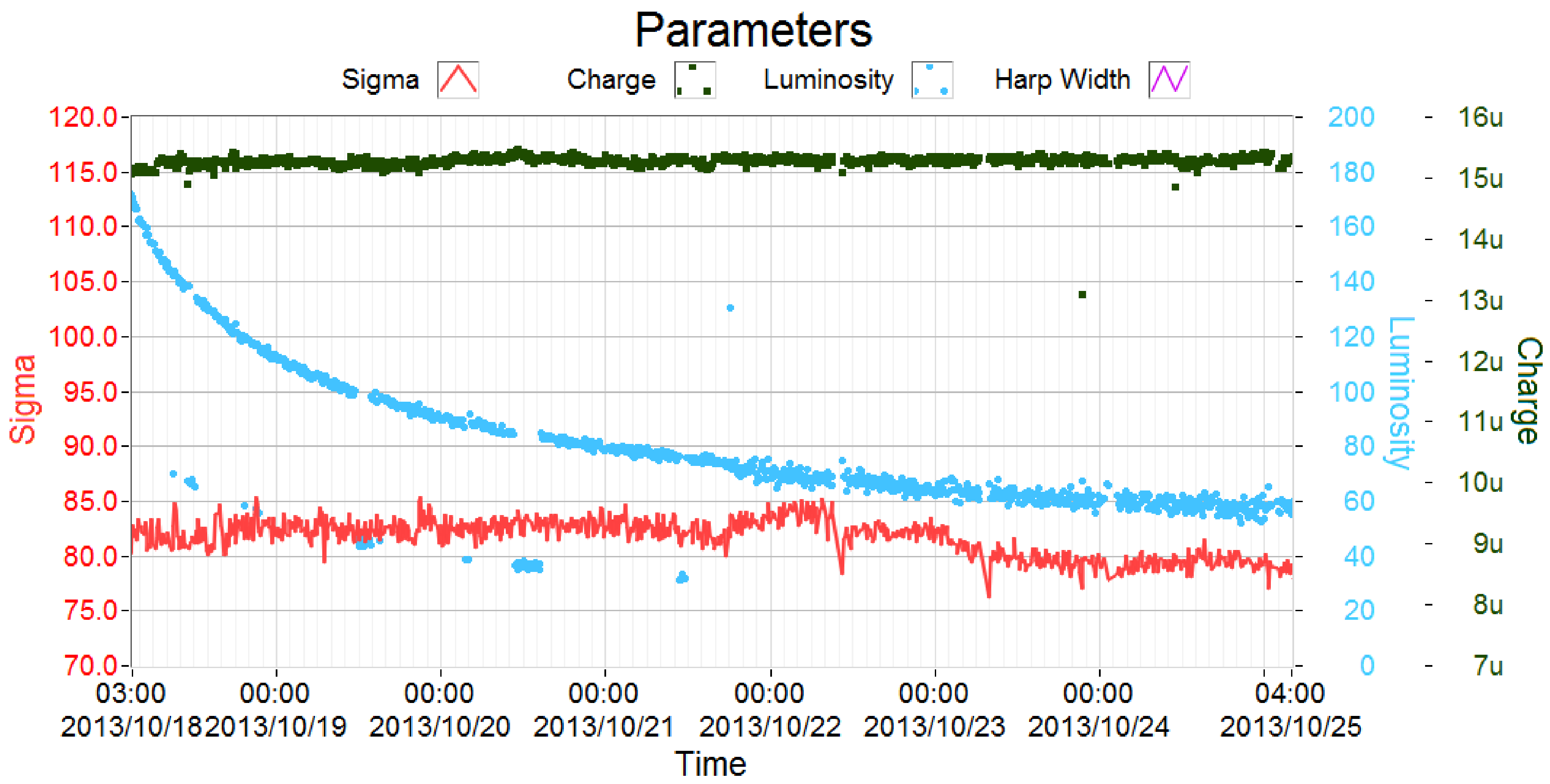
TIS Image at 15 μC



Normalized horizontal profiles of 15 μC beam pulses

Effect of DPA on measurements during decay

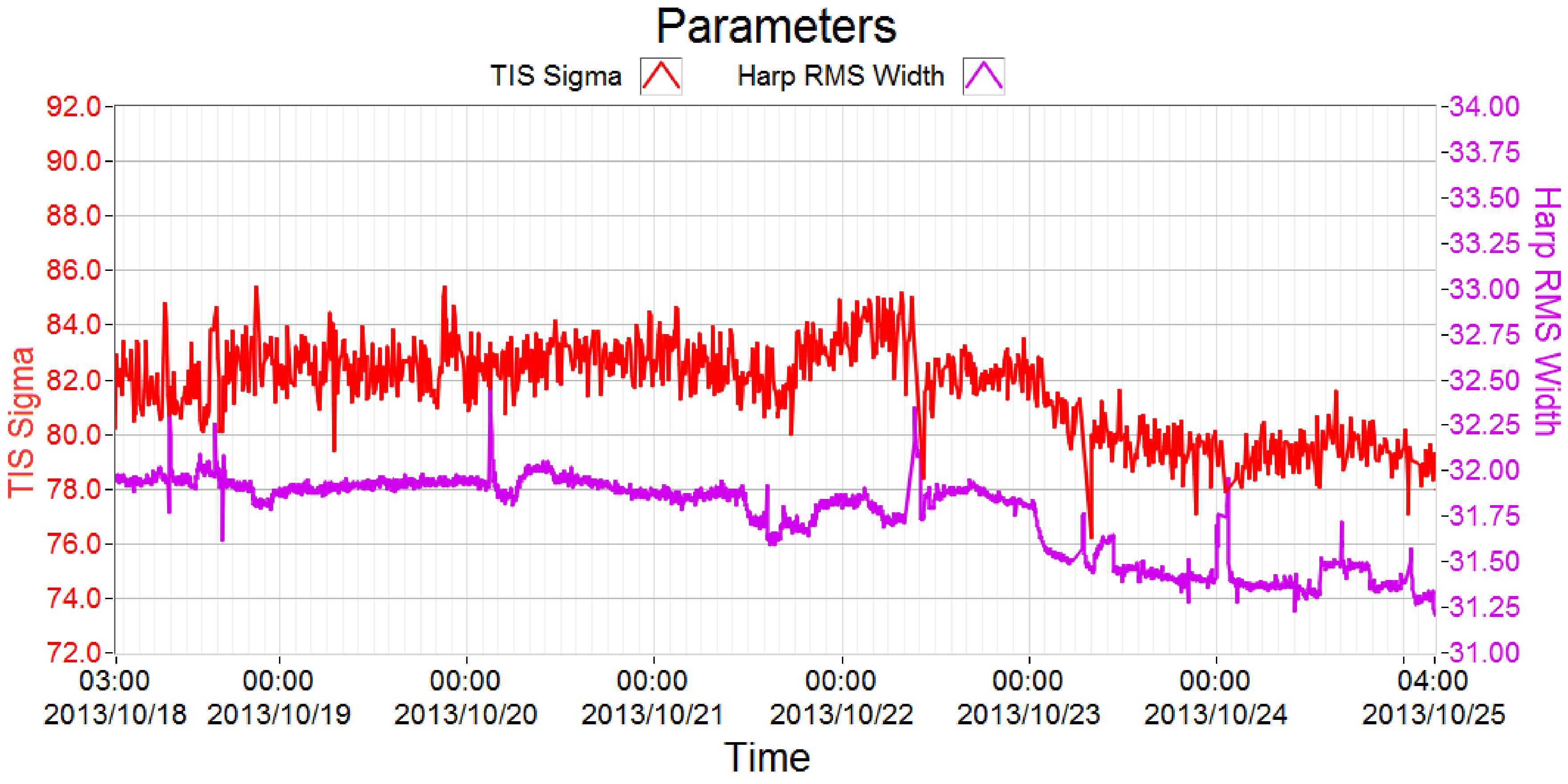
- We see some change in horizontal width



Estimated horizontal parameters vs luminosity

Effect of DPA on measurements during decay

- However, we see those changes in the upstream harp as well



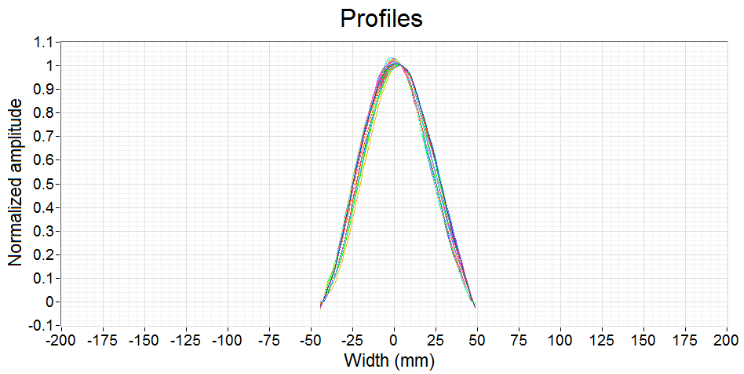
Horizontal widths as measured by the Harp and the TIS

Effect of DPA on measurements during decay

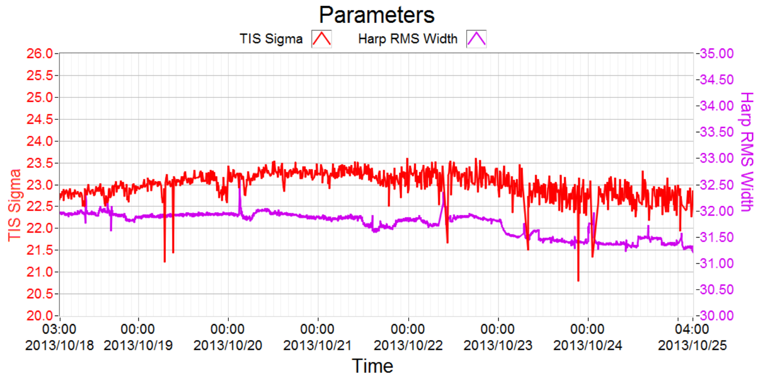
When excluding different beam pulse charges

→ no significant effect on width despite intensity going down and background noise becoming more significant

- Plans:
  - Uniformity scans during first 100 MWhrs
  - Simulate profile deformation based on DPA

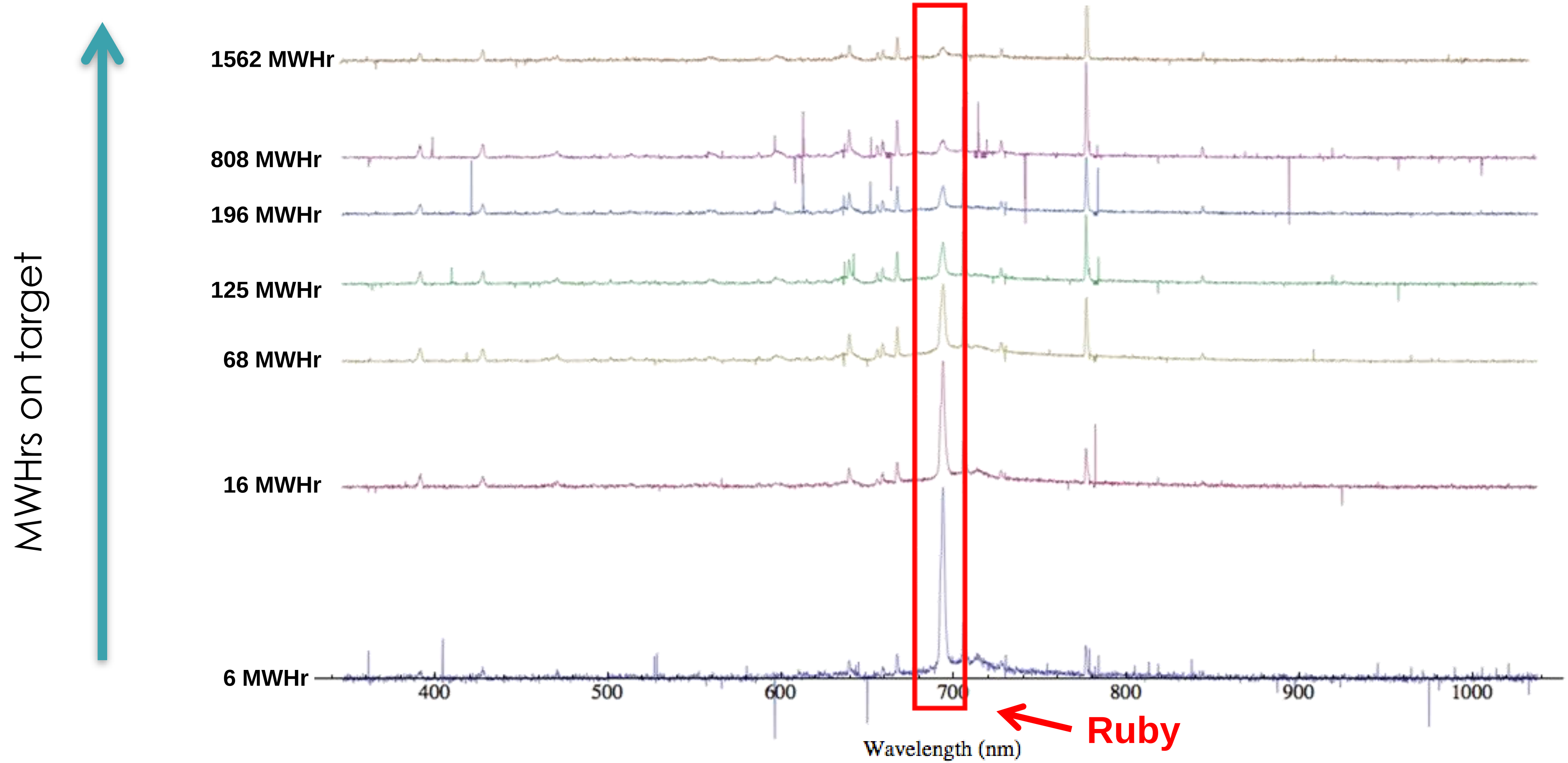


Smoothed TIS vertical profiles at 15 μC



Vertical profile widths of Harp and TIS

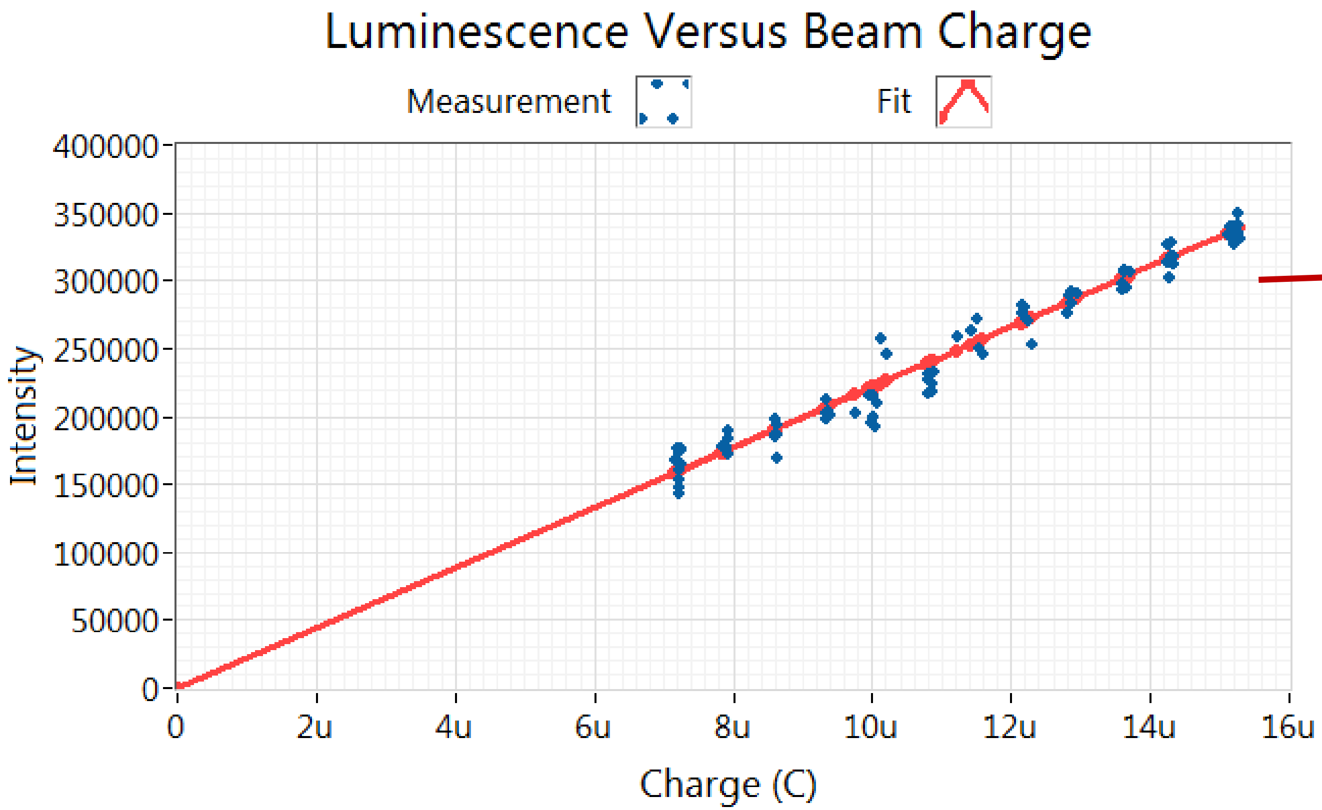
Effect of DPA on spectrum

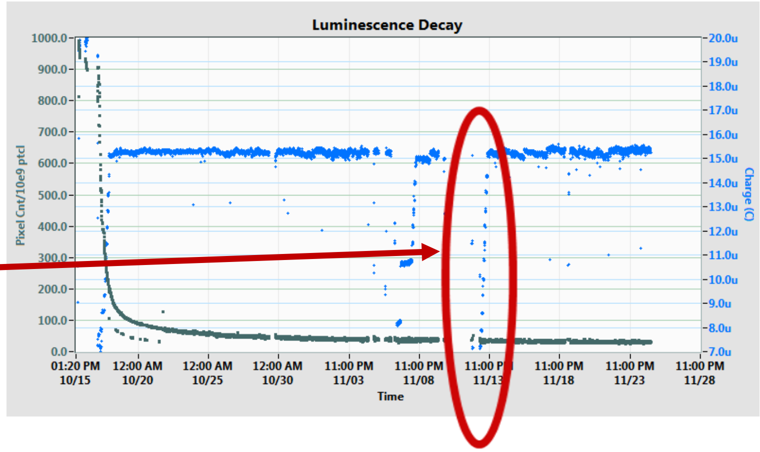


Development of spectra over time: Ruby line diminishes over time (target 3)

Coating Linearity

- The linearity after most of the drop in luminescence
  - Linear within the noise level up to 16 μC





Measurement during ramp up of beam

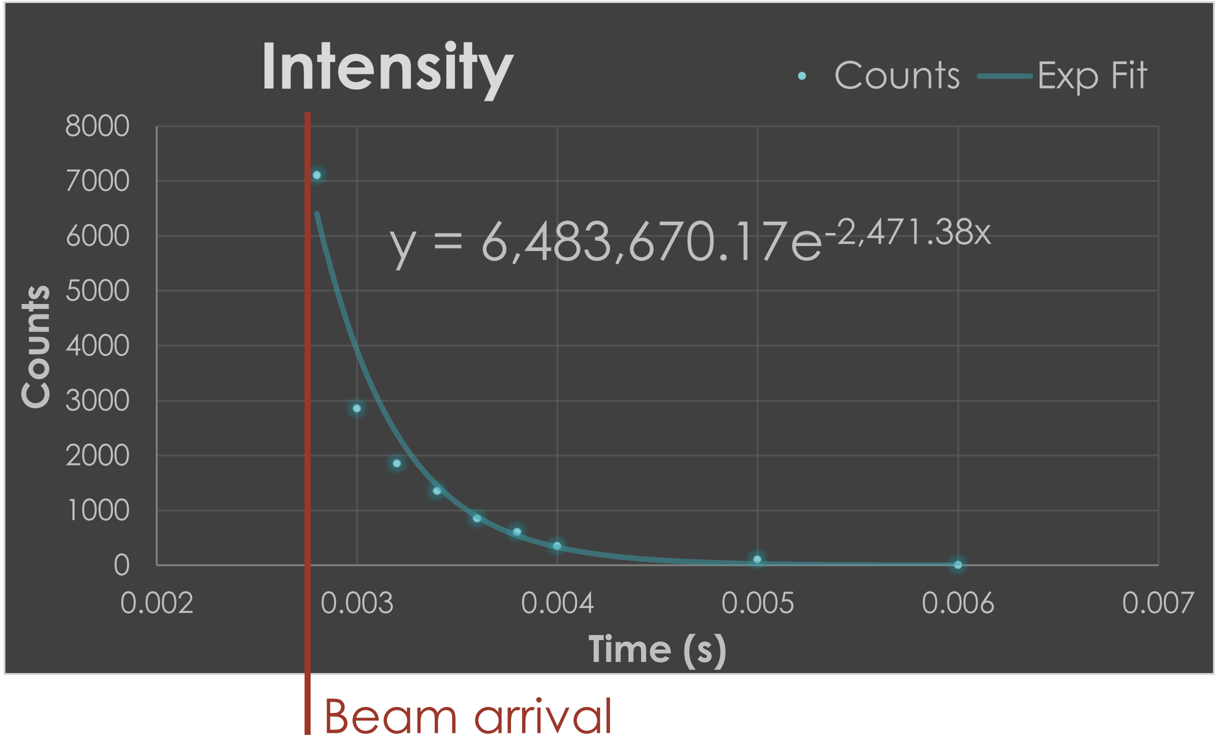
The response of the coating versus beam pulse charge. Fit forced to go through (0,0)

Prompt luminescence per proton pulse (650 ns)

We studied the time-constant of the coating using the camera:

- Short exposure with sliding delay
- Target about halfway lifetime
- Must avoid gas flash (few μs)

→ Tc around 400 μs



Comment	Tc
2.80 ms delay	410 us
2.80 ms but first sample excluded	410 us
2.73 ms delay	360 us
2.73 ms but first sample excluded	370 us

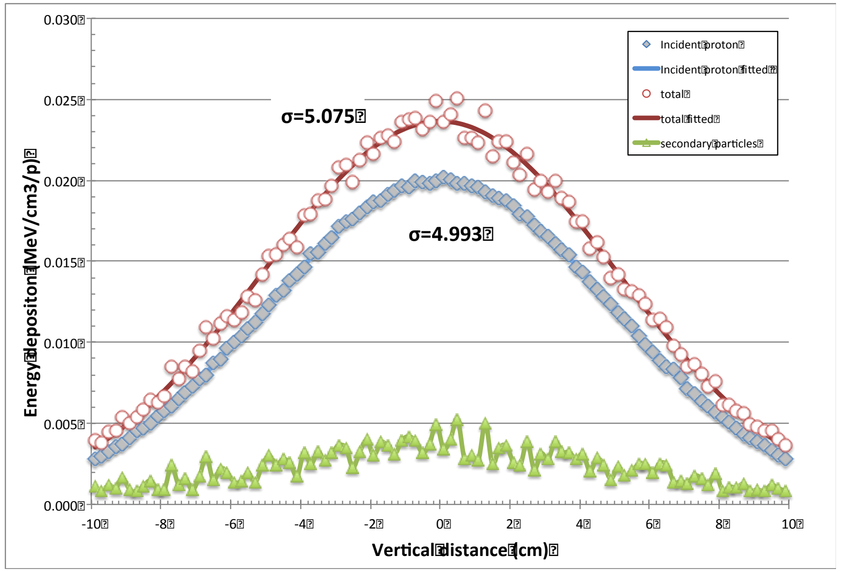
Calculated time-constant

Study August 30 2016 4pm	
SNS target	at 2123 MWHrs (MTX-010)
Beam	17.2 uC per pulse (1MW)
Camera G145B	200 us exposure, gain of 8, 2x2 binning

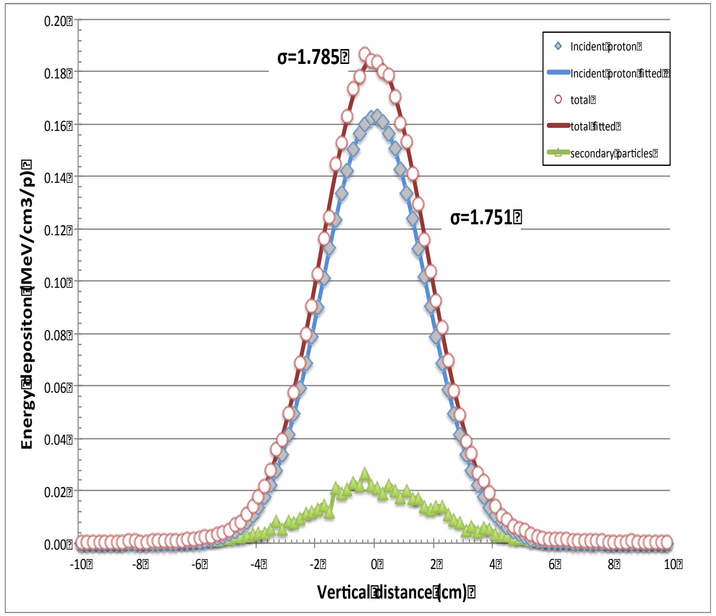
Counts versus time

Effect on profile due to secondary particles

- Secondary particles contribute ~20% (H) and 12% (V) at the center and increase to ~30% (H) and 99% (V) at the edge
- Distortion (measured by σ) of secondary particles is ~1.5% (H) and 2% (V)



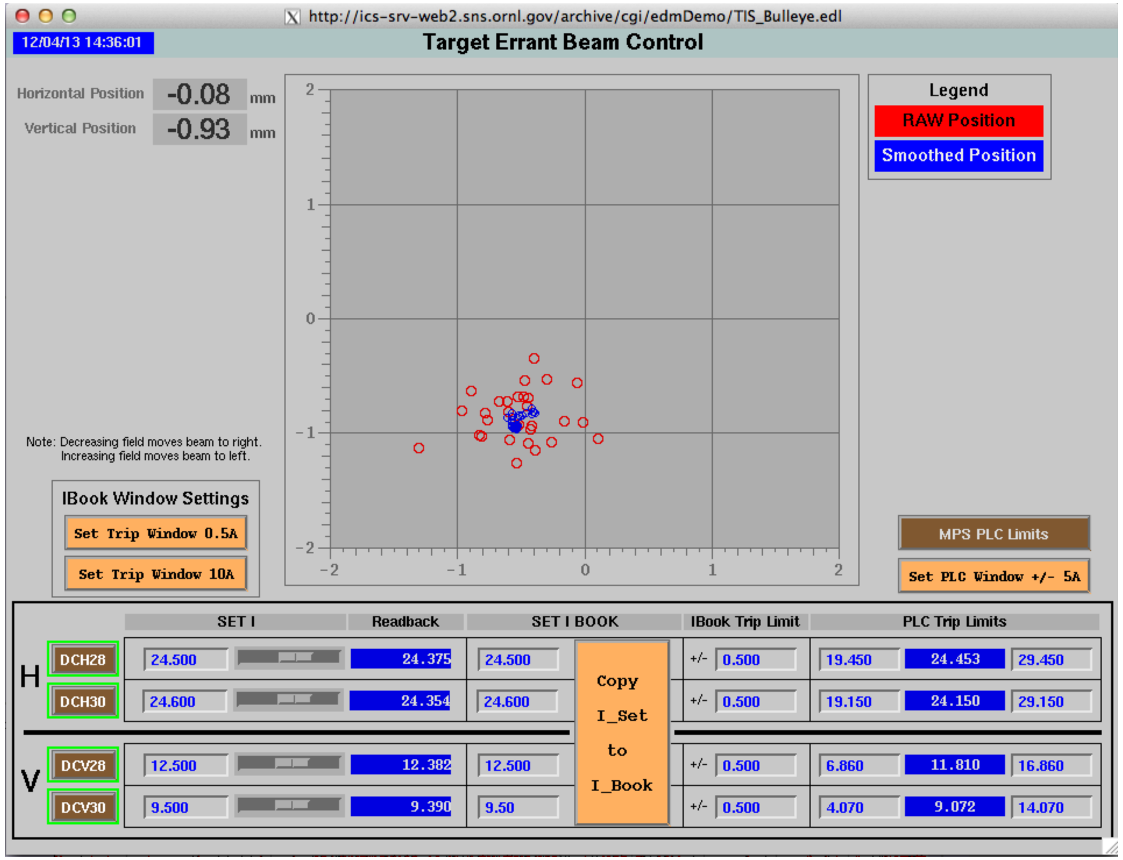
Results for horizontal beam with $\sigma_x=\sigma_y=5.0$ cm



Results for vertical beam with $\sigma_x=\sigma_y=1.75$ cm

Target Imaging Operation

- Main use is to center the beam on target
  - If there is a drift, the errant beam is re-centered
  - We can run without it but only because we verified the profile of the beam
  - Width (peak density) also in errant beam monitoring program
  - Overall system works very well



Target Errant Beam Control Screen

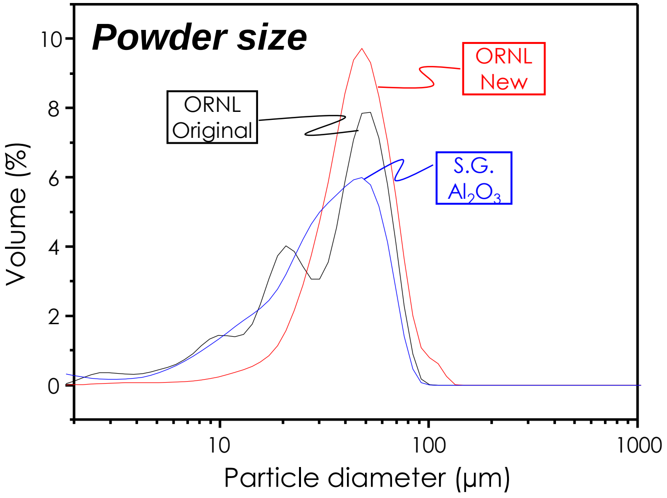
New Developments

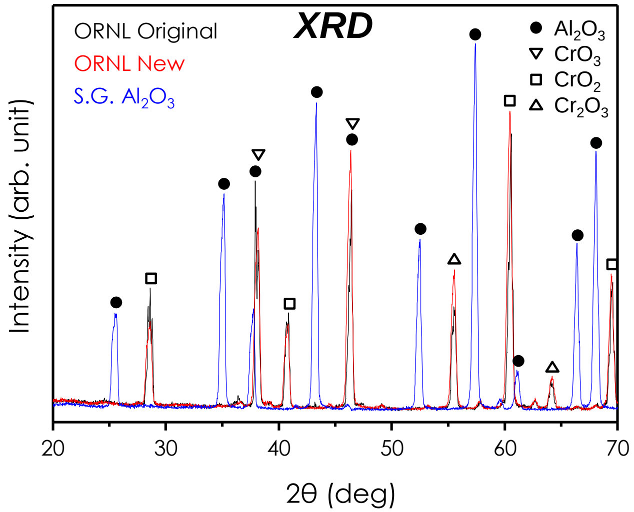
- Use in BTF at 2.5 MeV (H^-)
  - Very bright with small mA beam too bright and decay with full beam
- Running out of original coating powders
  - Testing new powders
    - In the lab
    - On target

New Developments

Starting again with analysis:

- Powder composition
- XRD
- Photon stimulation
- Proton response

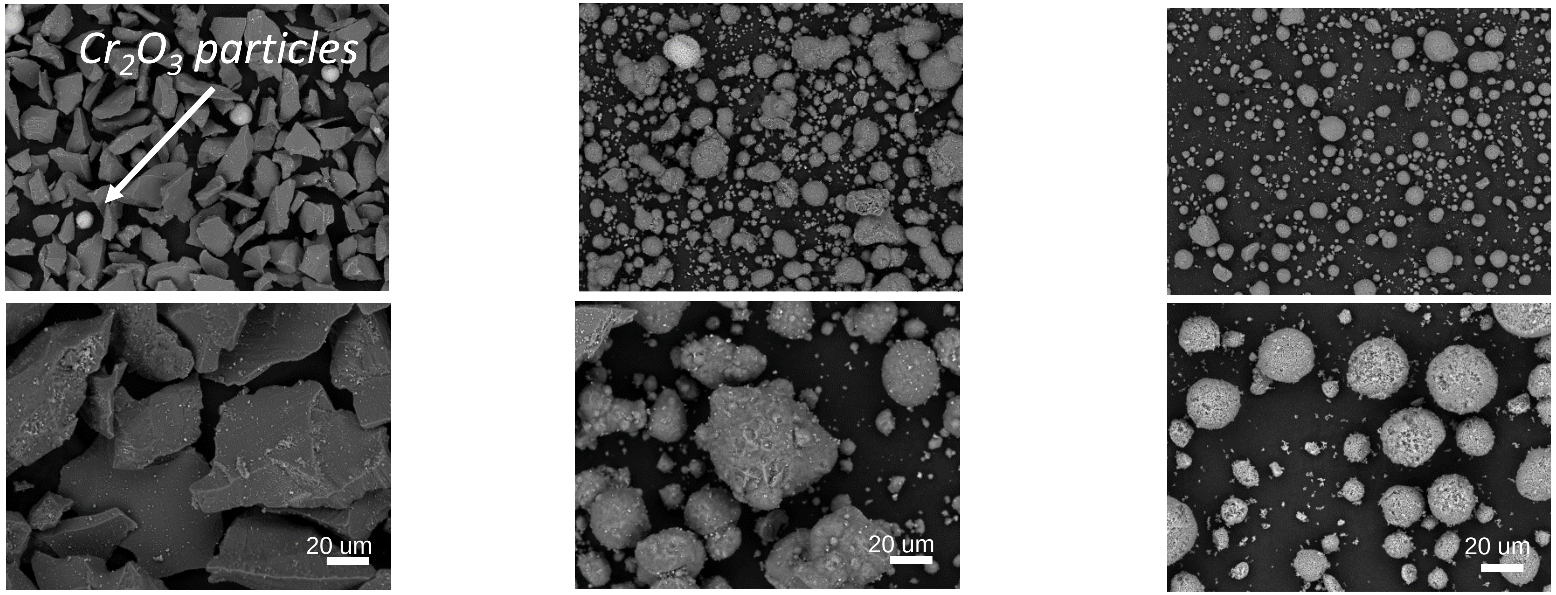




ORNL Original

ORNL New (Broadman)

Saint Gobain Al_2O_3



Studying new powders, sizes, XRD

Center for Thermal Spray Research

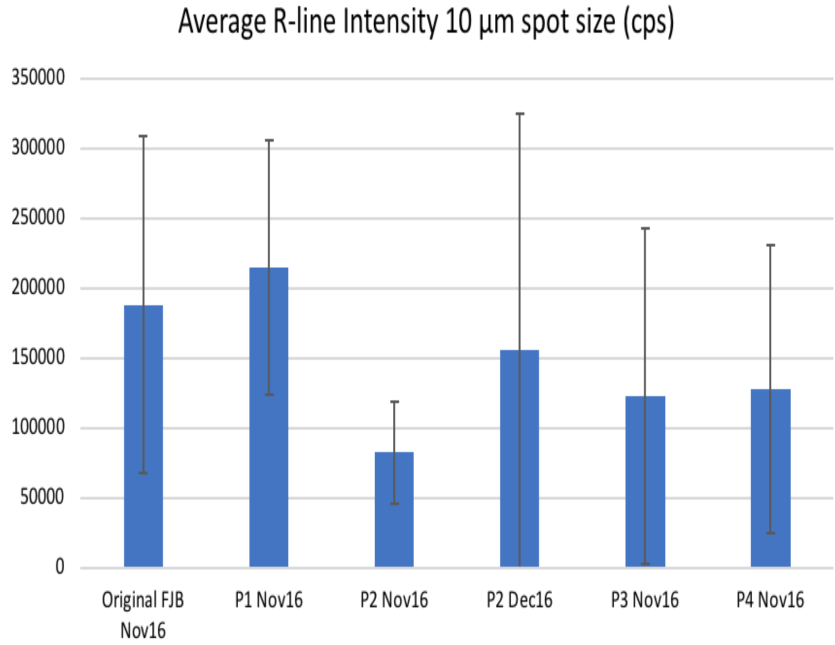
AT STONY BROOK UNIVERSITY

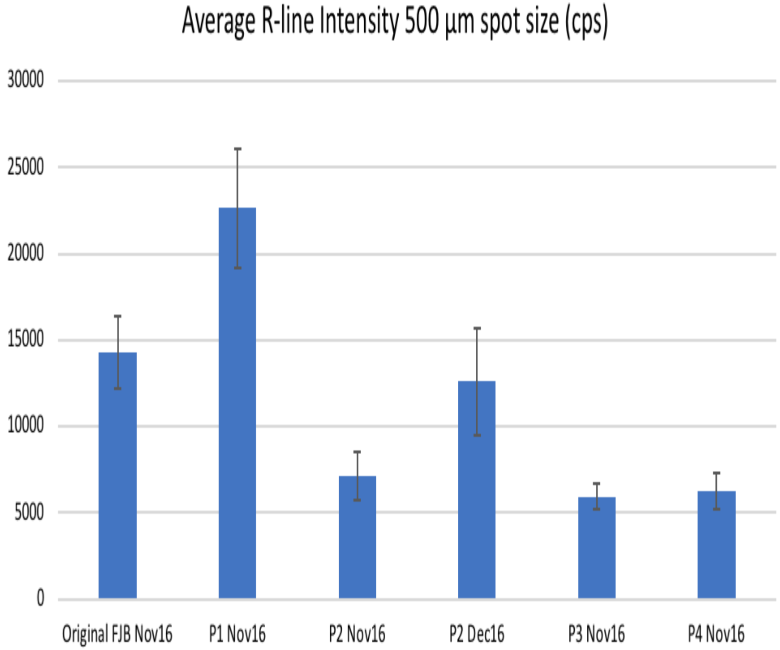
S. Sampath

Laser stimulation of new coatings

- With resolution related to grain

Samples





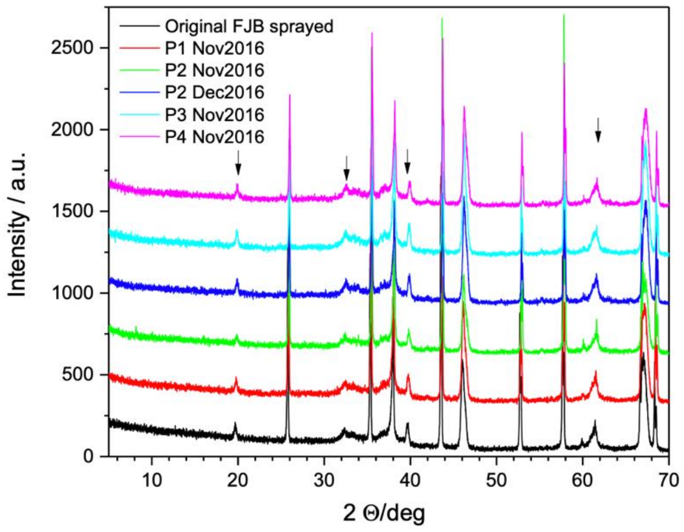
Name	Short name	Average R-line Intensity (cps)	StDev (cps)
Original FJB Alumina/Chromia 98.5%/1.5	Original FJB Nov16	188098	120501
New Lot FJB Alumina/Chromia 98.5%/1.5	P1 Nov16	214640	91465
3% mix Old FJB Al2O3/Cr2O3	P2 Nov16	82170	36282
3% mixed/fired SG Al2O3 with new FJB Cr2O3	P2 Dec16	155223	169636
3% Mix New FJB Al2O3/Cr2O3	P3 Nov16	122755	120327
3% Mix Sg Al2O3 with new FJB Cr2O3	P4 Nov16	127583	102780

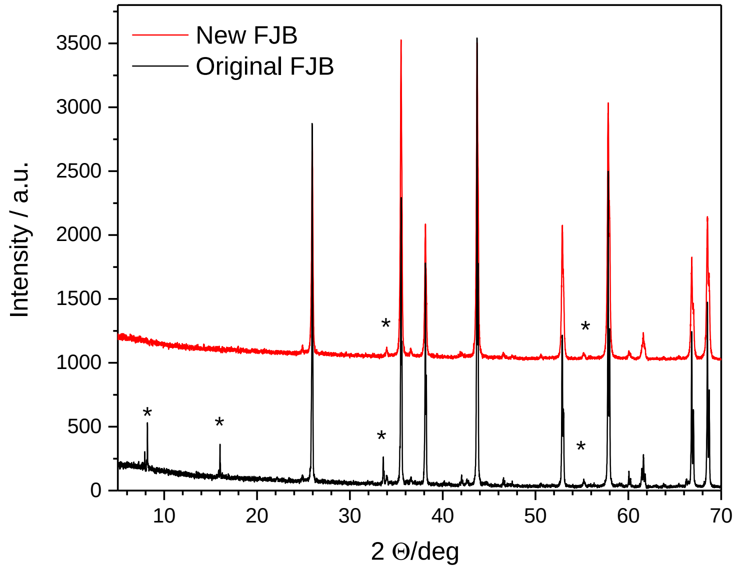
	Average R-line Intensity (cps)	StDev (cps)
	14313	2105
	22631	3457
	7107	1379
	12616	3093
	5937	777
	6245	1063

Results of laser stimulation by Michael Lance of ORNL

New coatings X-ray Diffraction

- At SNS in collaboration with ESS:
  - In progress: measure XRD on different coating powders
    - All compounds show alpha-Al2O3 structure however varying relative intensity (could be crystallinity or Cr present in alpha-Al2O3 structure)
    - There are extra reflections (arrows) -> second phase is present in all sprayed samples
    - XRD on old and new pre-cursors shows: Both show alpha Al2O3 composition. Both show extra reflections (*) indicating a second material in the sample however much less for the new pre-cursor. Non-crystalline sample present in new pre-cursor such as a hydroxide?
    - Thermogravimetric (TG) and Differential Scanning Calorimetry (DSC) on the pre-cursor compounds have been done
  - Our plan is to also measure exposed coatings



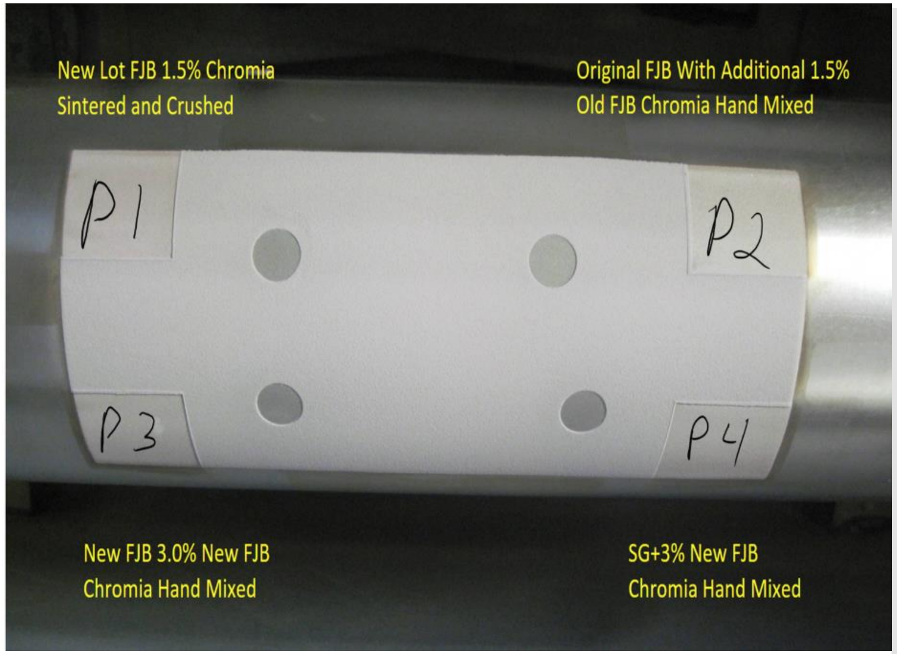


XRD on the different samples

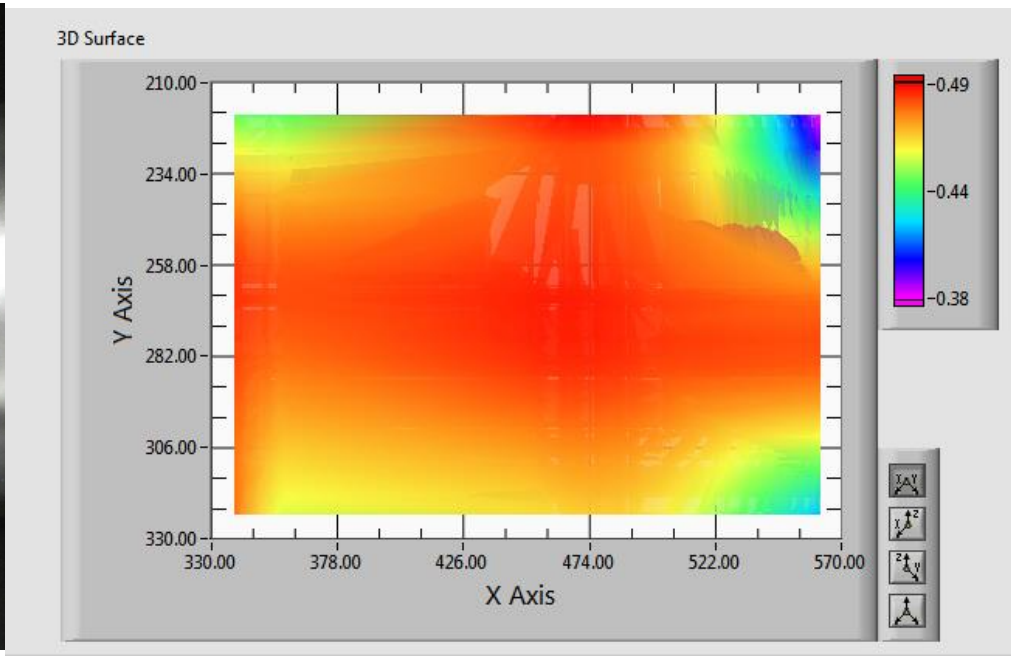
New coatings on the target

It is not a very accurate scan to begin with due low signal-to-noise

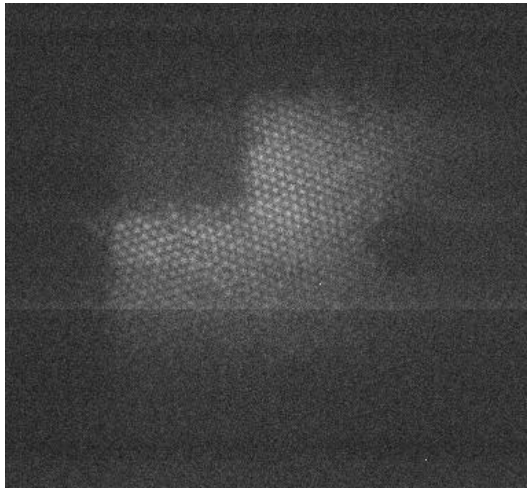
- P3 (3% Mix New FJB) and P1 (3% Mix New FJB) are the brightest
- Edges have drop in intensity when some of beam goes of coating
- Fiducials also affect measurements
- Lost mirror due to water leak in core vessel, no more TIS



Target as coated



Interpolated surface plot from uniformity scan on fresh target

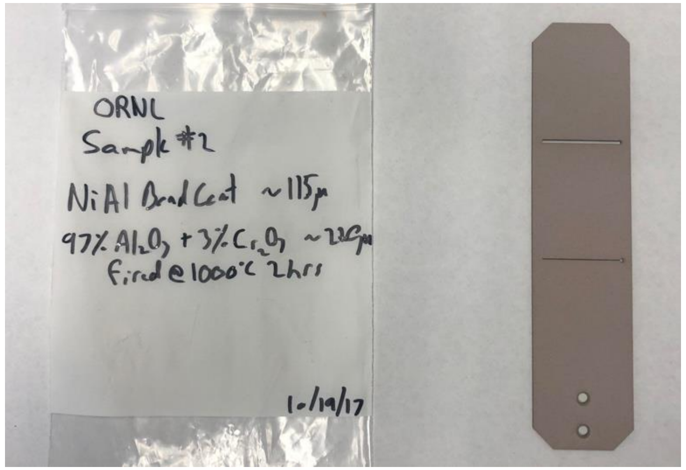


2000 MWHr test on ruby (2011) Initially higher, now lower.

New coatings for the target

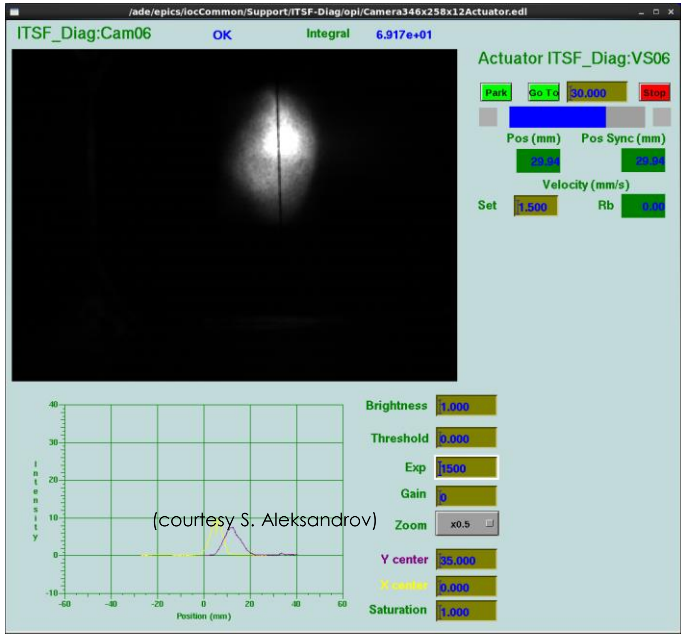
Used in Beam Test facility at SNS:

- If we take out the upstream slits, the beam current will increase to ~15mA and the screen will darken within a few seconds
  - Cr and Al have displacement production cross section of ~20,000 b at 2.5 MeV and ~790 b for Al and ~2200 b for Cr at 1 GeV. Due to the coulomb power, the charged particle at low energy has an order of magnitude higher displacement production cross section than at 1 GeV.



- NiAl bond coat thickness is ~115 μm
- 3% Cr_2O_3 with 97% Al_2O_3 @ thickness ~ 220 μm
- Fired at 1000 °C for 2 hrs for mixing
- Selected for higher resolution response

Metal strip coated by Stony Brook for SNS

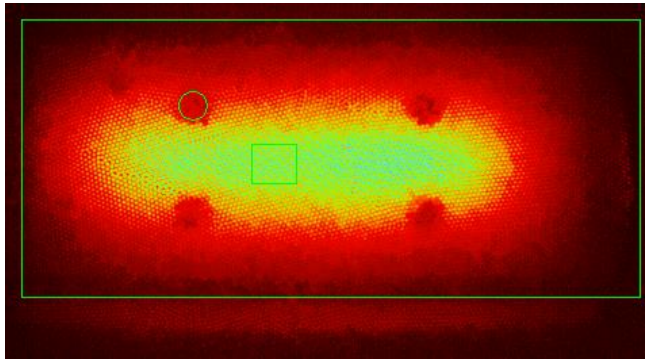


Beam spot

- Beam energy is 2.5 MeV, beam current to the screen is ~20 uA.
- Pulse length is 30 us.
- The vertical slit size on the image is 25mm.
- The camera is 500 mm away and is close to saturation with 100 us exposure time.

Future

- While the current luminescent coating works for SNS, we do want a longer lasting brightness of the coating:
  - Consider SNS Power Upgrade (PPU-> 2 MW on target) and Second Target Station (rotating disk)
  - Other imaging systems e.g. SNS Injection Dump
  - We are trying to understand the radiation effects on the coating
- Collaboration with ESS
  - Find longer lasting coatings
  - Different patches on the target
  - Analyze exposed coatings
- Some day, pull all data together and publish



TIS image

QUESTIONS/COMMENTS?

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2. T. Shea et al. "Installation and Initial Operation of an On-Line Target Imaging System for SNS*," NFDD Seminar, 4/20/2010, SNS, Oak Ridge, USA, 2010
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4. T. McManamyat al., "SNS Target Beam Profile Viewscreen Design and Operation", Proc. AccApp07, Pocatello, Idaho, (2007).
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11. W. Blokland and F. Garcia, "A Study of the Effect of Imperfections in the Optical Path of the SNS* Target Imaging System Using a Mock-up," Proc. of IBIC2017, Grand Rapids, MI, USA, 20-24 August, 978-3-95450-192-2, 10.18429/JACoW-IBIC2017-WEPCC14, http://jacow.org/ibic2017/papers/wepcc14.pdf
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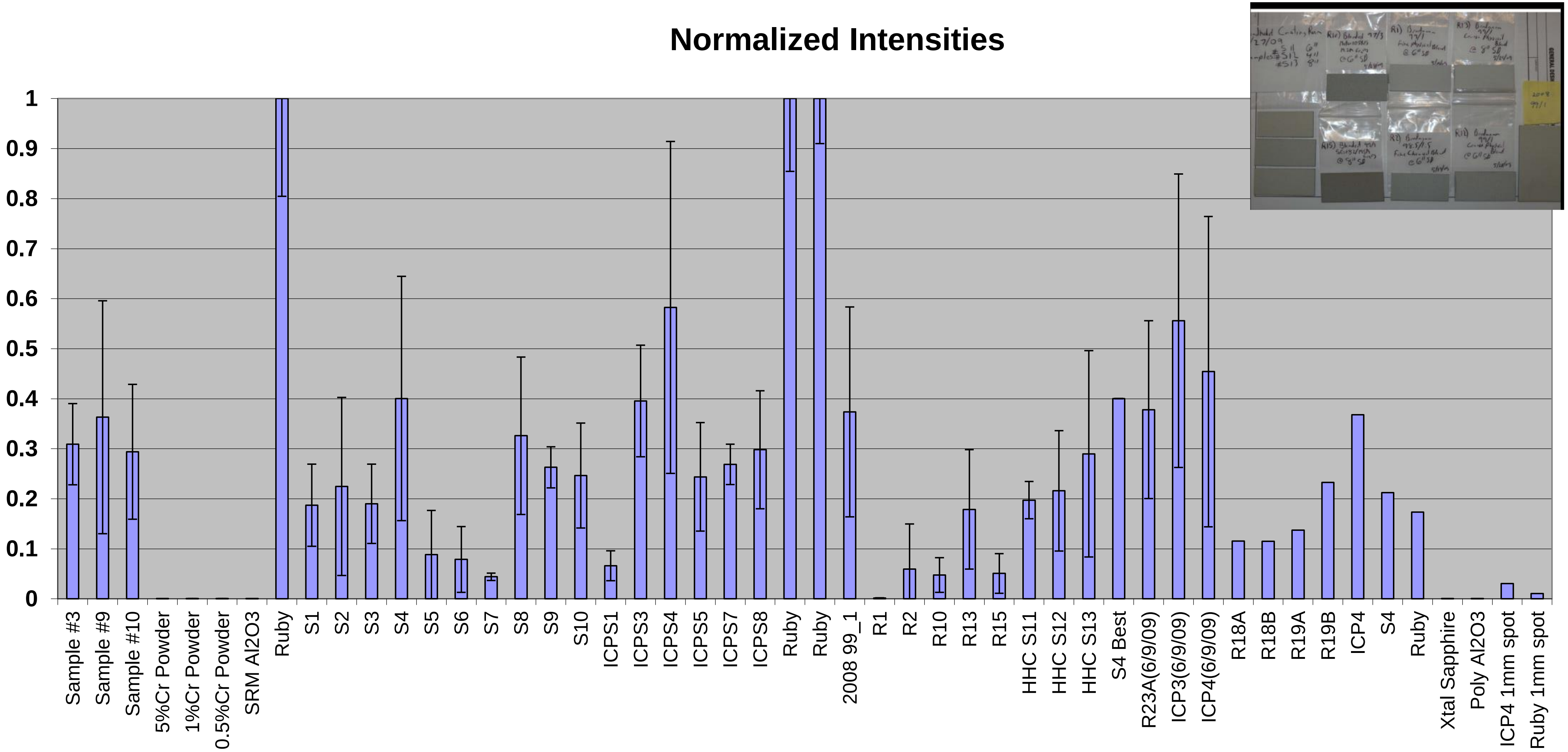
Extra Slides

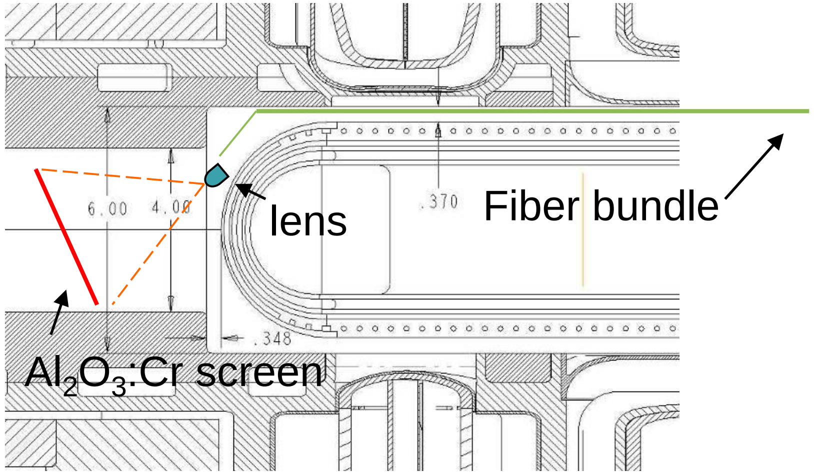
Spray parameters



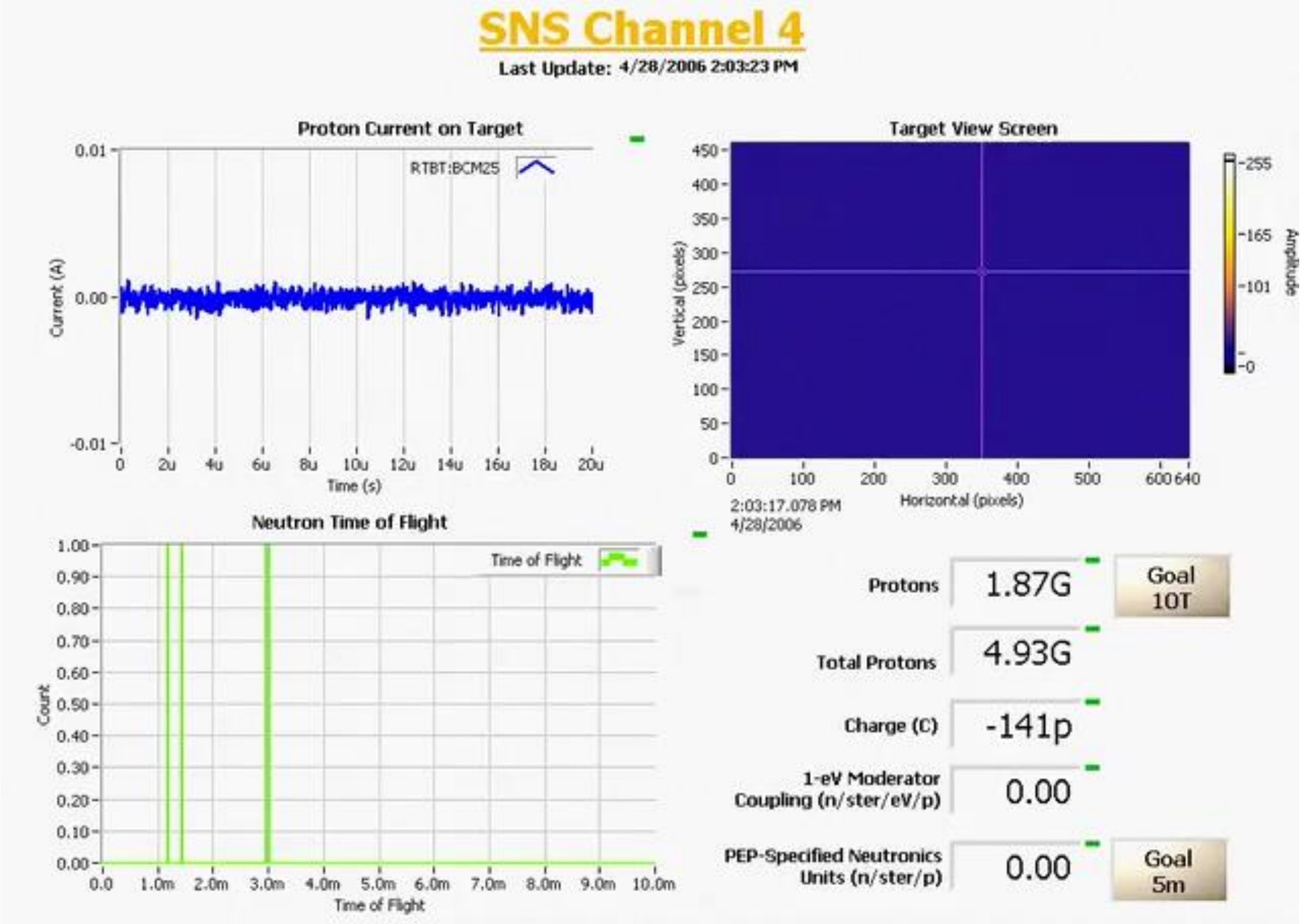
Select the sample with the highest photo induced luminescence

Initial system was a ruby plate

- But this plate can not handle the full SNS beam power at 1.4 MW

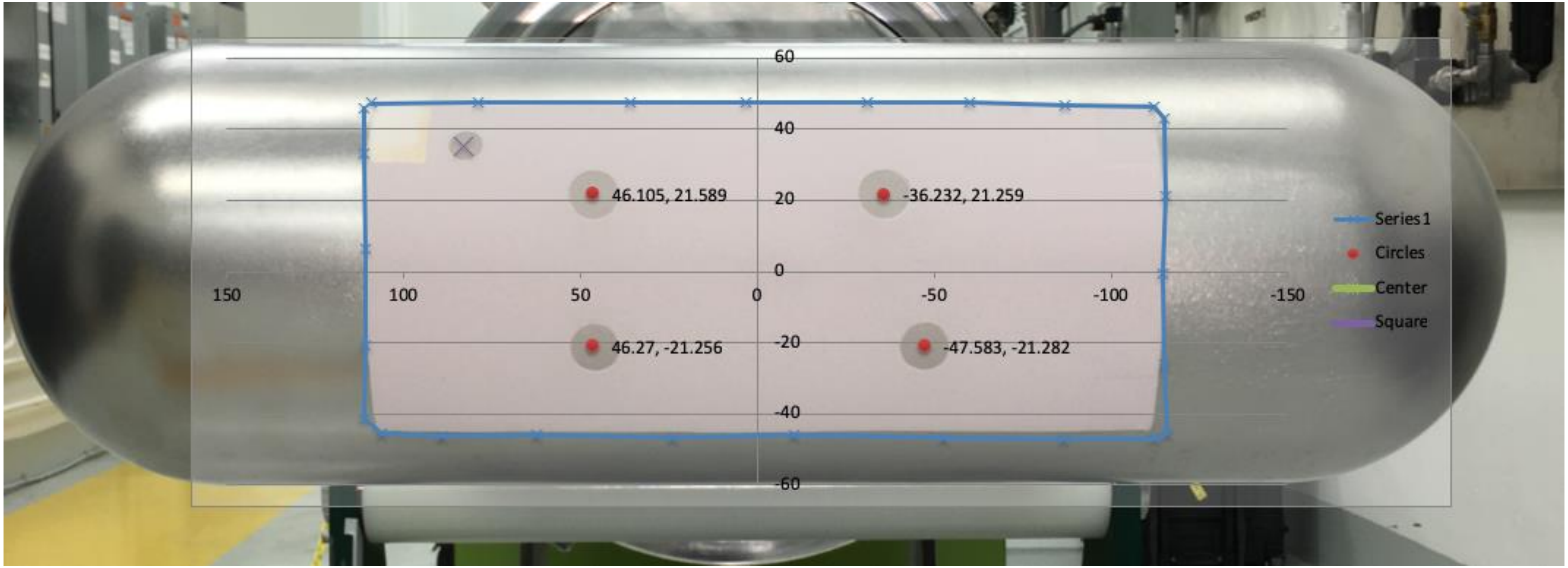


Installation



Very first beam on target

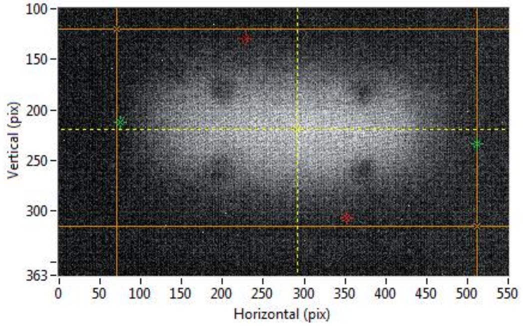
Target nose cone (water shroud)



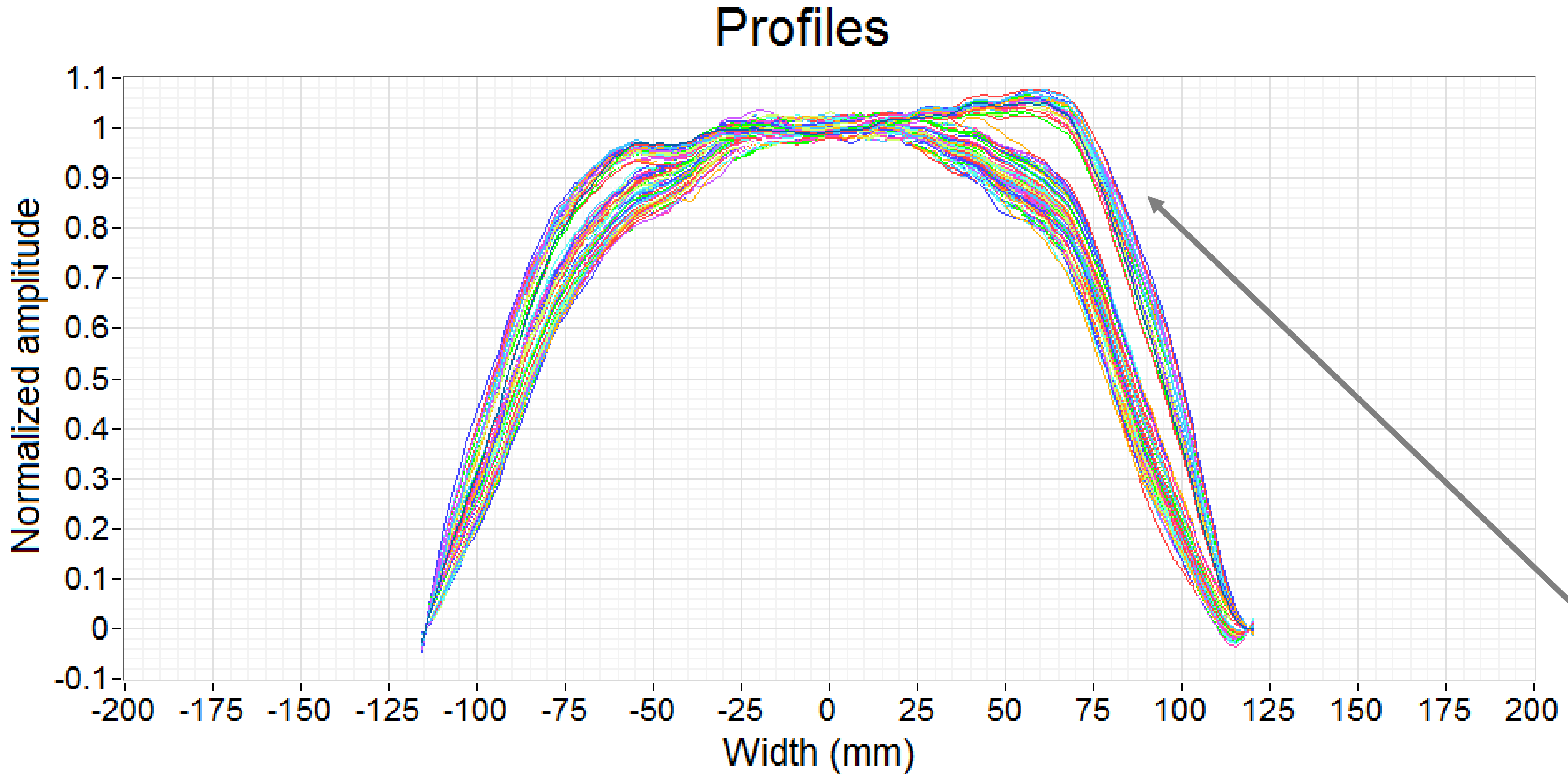
The target has fiducials so we can calibrate the image. The fiducials are round shapes without any coating

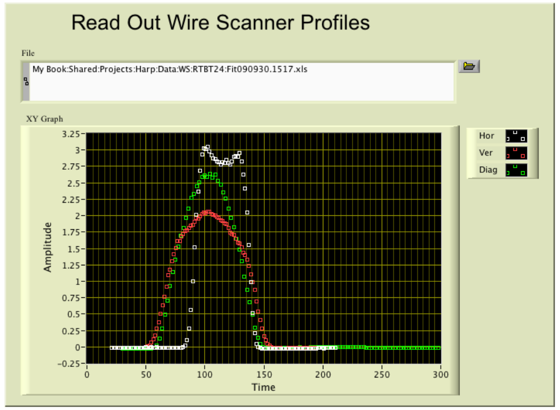
Effect of DPA on measurements during decay

- Looking at the normalized smoothed horizontal projections
- Includes different beam pulse charges



TIS Image at 15 μC





Uneven and different shapes at different beam charges also shows in wire scanner profiles. Different number of turns in the ring give different profiles due to painting scheme

Nc

Normalized horizontal profiles from beam pulses 10 to 15 μC

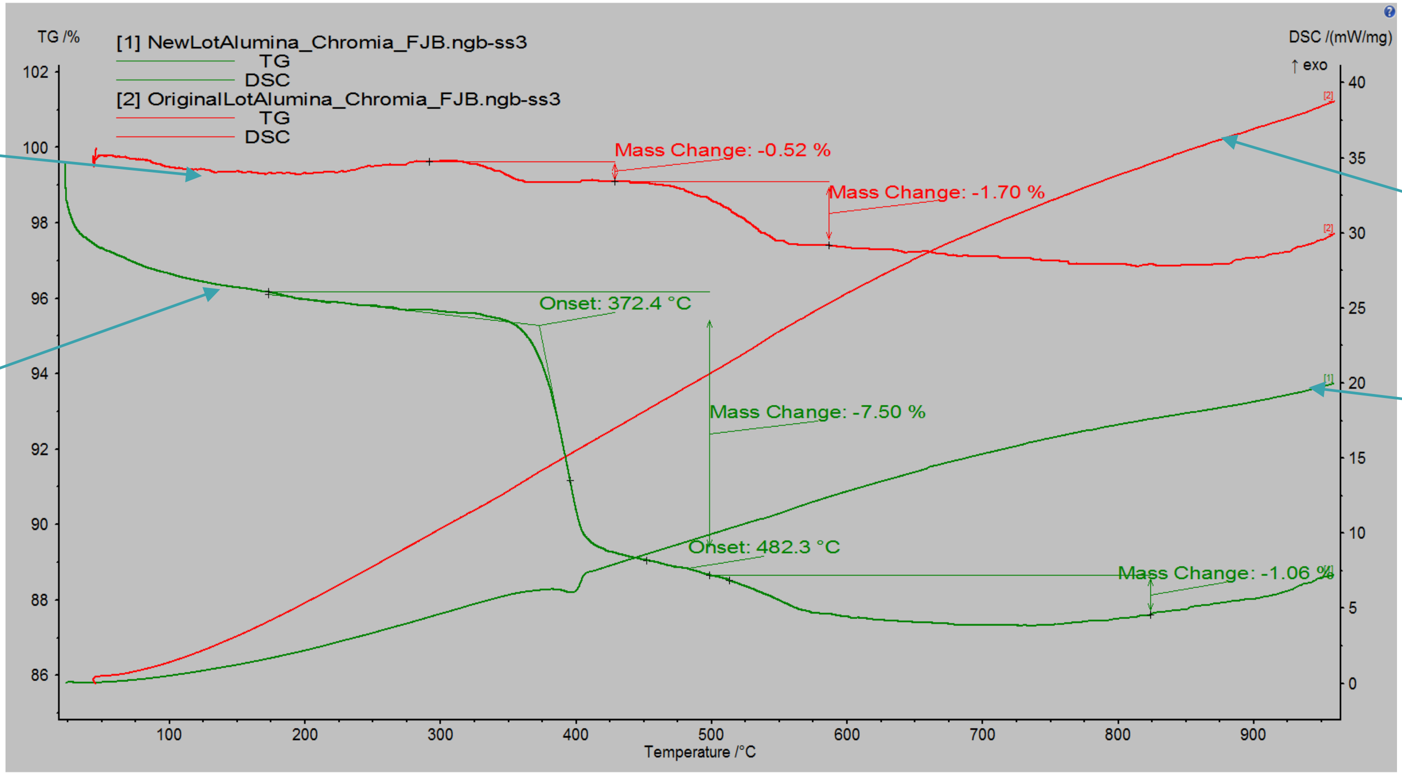
Thermogravimetric (TG) and Differential Scanning Calorimetry (DSC) on the pre-cursor compounds

TG analysis:

Original pre-cursor shows two mass losses:
@325 C 0.5% weight
@475 C 1.7% weight

New pre-cursor shows two mass losses:
@372 C 7.5% weight
@482 C 1.0%

-> second mass loss seems to be identical for both pre-cursors (i.e. same decomposition step)



Red line: Original Pre-Cursor
Green line: New Pre-cursor Lot

M. Hartl

DSC analysis:

Original pre-cursor shows two no phase transition (i.e. curve shows no minima/maxima)

New pre-cursor shows a phase transition at the first point of mass loss

-> the Cr-compound in the new substrate could be decomposing $2Cr(OH)_3 \rightarrow Cr_2O_3 + 3H_2O$???