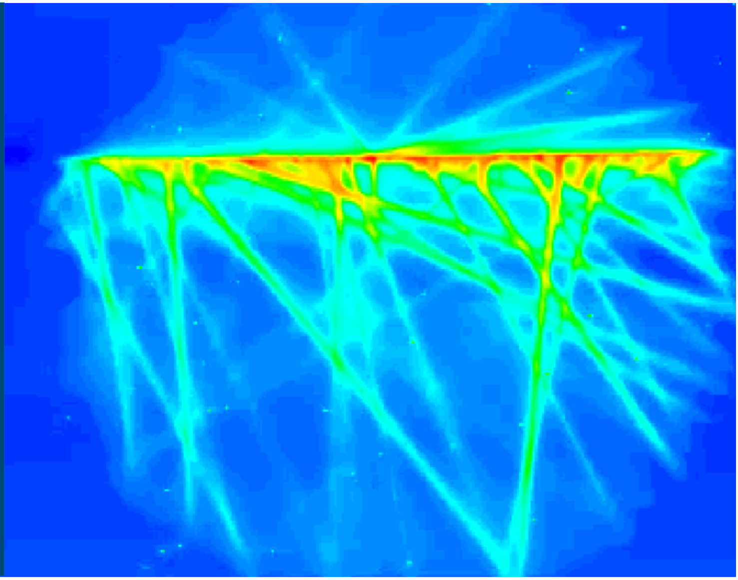
Diagnostics for Collimator Irradiation Studies in the Advanced Photon Source Storage Ring



J. Dooling, M. Borland, W. Berg, J. Calvey, L. Emery, A. Grannan, K. Harkay, R. Lindberg, A. Lumpkin, G. Navrotski, V. Sajaev, J. Stevens, Y-P. Sun, K. Wootton, A. Xiao

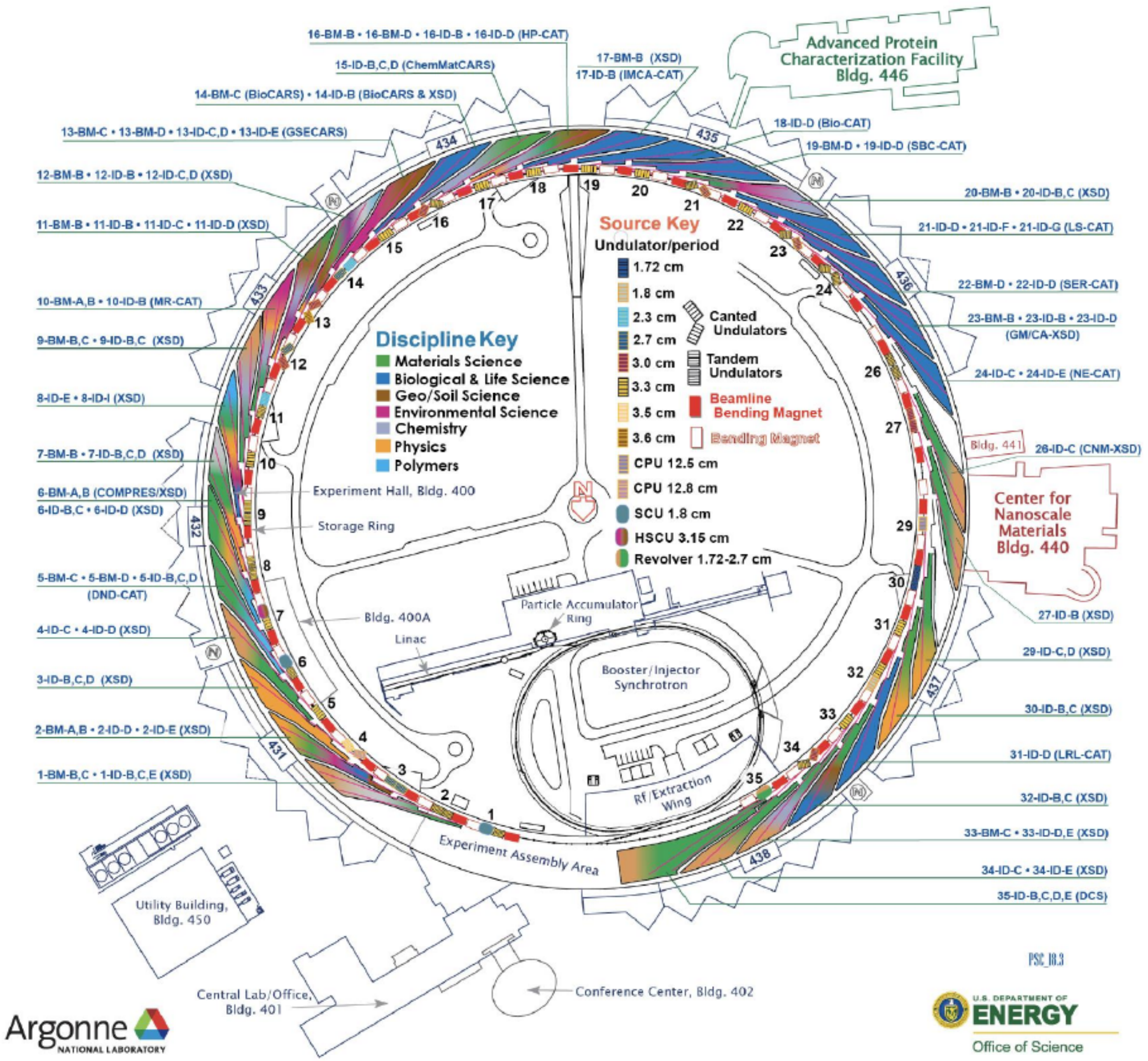
International Beam Instrumentation Conference 2020 (remote)
September 15, 2020

Outline

- Introduction
- Experiments
- Diagnostics
- Data Analysis (and Challenges)
- Discussion
- Summary

Introduction

- The Advanced Photon Source (APS): 7 GeV, 3rd generation storage-ring light source
- Planning to build a 4th generation SR (4GSR) light source
- Beam abort modeling with elegant[1] and MARS[2] indicated even low-Z, low-density material such as aluminum could be damaged as peak dose rates were expected to exceed 15 MGy.
- Had never observed beam damage in Al prior to running our experiments.
- This concern led to the studies we are discussing here to determine the validity of simulations.
- Good experiments require good diagnostics!



---

1. M. Borland. ANL/APS LS-287, (2000); Y. Wang et al. Proc. of PAC 2007, 3444–3446 (2007).

2. N.V. Mokhov, et al., “MARS15 code developments driven by the intensity frontier needs”, Prog. Nucl. Sci. Technol., 4, pp. 496-501 (2014)

Diagnostics—

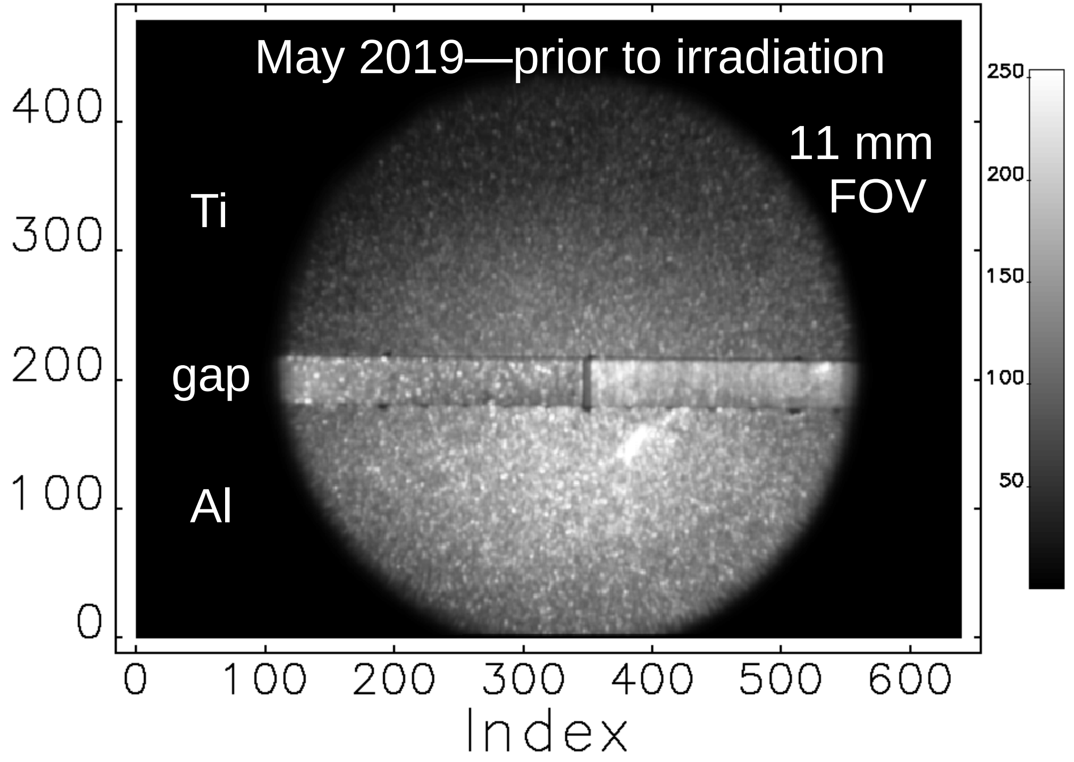
- Set-up and operations
  - BPMs for lattice and vertical positioning set-up
  - Linear Variable Differential Transformer (LVDT) for horizontal positioning of the scraper assembly
  - Diagnostic Camera and frame grabbers for pre-irradiation imaging
- Experiment
  - Turn-by-Turn (TBT) BPMs for beam position and orbit decay
  - Fast Beam Loss Monitors (BLMs) for loss intensity and timing
  - Pinhole Camera for spot size and beam emittance
  - Diagnostic Camera for collimator imaging after and during the beam strike
  - DCCT current reference
  - Pressure and temperature sensors—very important, especially during scraper conditioning
- Post experiment
  - Photography
  - Microscopy—a little tricky if pieces are activated
  - Metallurgy—almost impossible if pieces are activated!
  - Gamma spectroscopy—for activated pieces!!

Experiments—two thus far: May 2019 and January 2020

- Both studies were conducted at the beginning of a run cycle to have time to remove the collimator experiment prior to user operations. This posed challenges.
- In May 2019 [3], we were limited to <70 mA due to an obstruction in the SR beam chamber—unrelated to the collimator experiment—limiting our time.
- In January 2020, extra time was needed to condition the collimator and scraper assembly to 200 mA.

- Two collimator test pieces are mounted on a horizontal scraper assembly with ~1-mm gap between

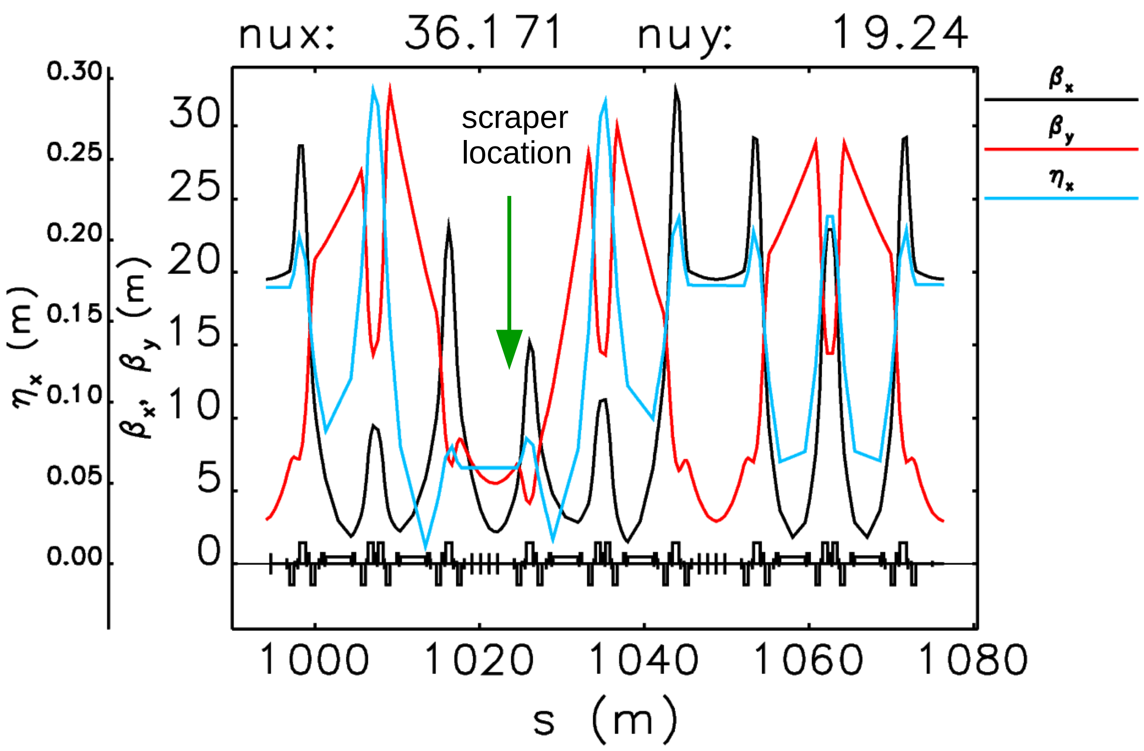
Diagnostic camera image



3. J. Dooling et al. NAPAC'19 MOPLM14

Experimental Setup—triple Reduced Horizontal Beamsize (RHB) Lattice [4-6]

Wish to make both σ_x and σ_y small to mimic APS-U conditions.



4. Yipeng Sun, AOP-TN-2018-090
5. V. Sajaev, AOP-TN-2019-022
6. Michael Borland, Yipeng Sun, Vadim Sajaev, AOP-TN-2019-024

Reference beam sizes taken with the S35 x-ray pinhole camera

$$\sigma_x^2 = \beta_x \epsilon_x + \left(\eta_x \frac{\Delta p}{p}\right)^2$$

$$\sigma_y^2 = \beta_y \epsilon_y$$

$$j_b = \frac{I_b}{2\pi\sigma_x\sigma_y}$$

with

$$\beta_x = 4 \text{ m}$$

$$\beta_y = 6 \text{ m}$$

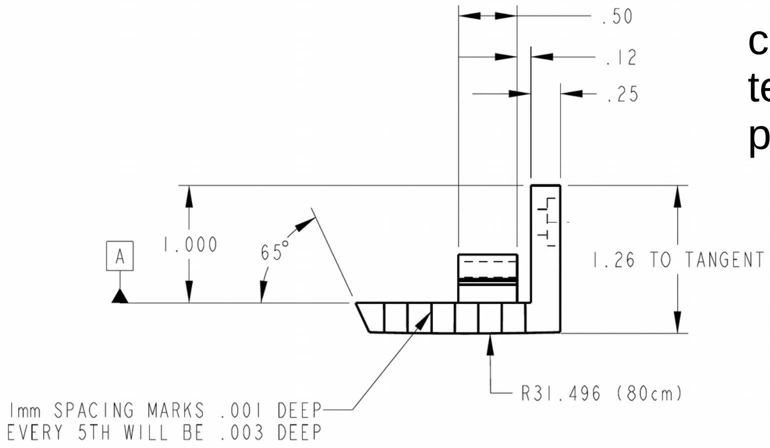
$$\eta_x = 0.059 \text{ m}$$

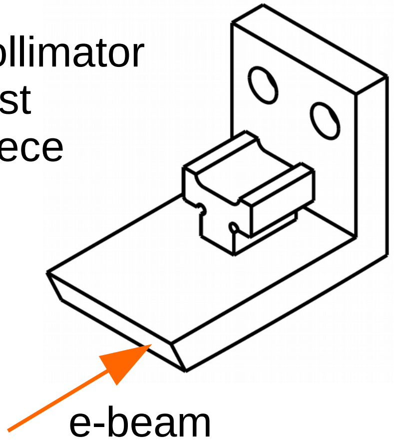
$$\eta_y = \eta'_x = \eta'_y = 0$$

$$\frac{\Delta p}{p} = 10^{-3}$$

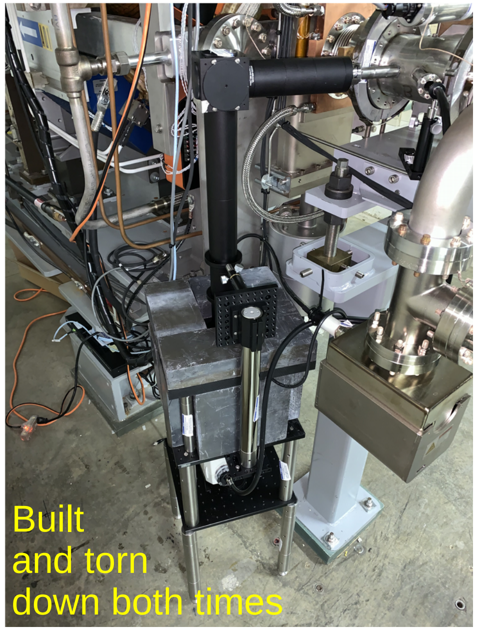
Experimental setup

- May 2019, collimator material tested: aluminum and titanium alloys
- January 2020: just aluminum—with reduced surface roughness
- Used a DVR to record images at 30 fps to observe collimators during the beam strike





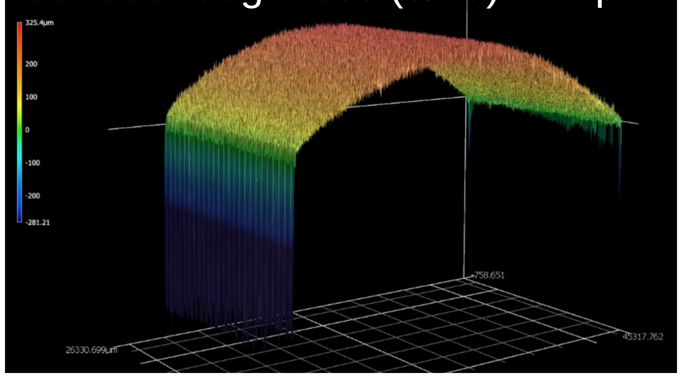
Two pieces are mounted side-by-side at the end of the scraper assembly

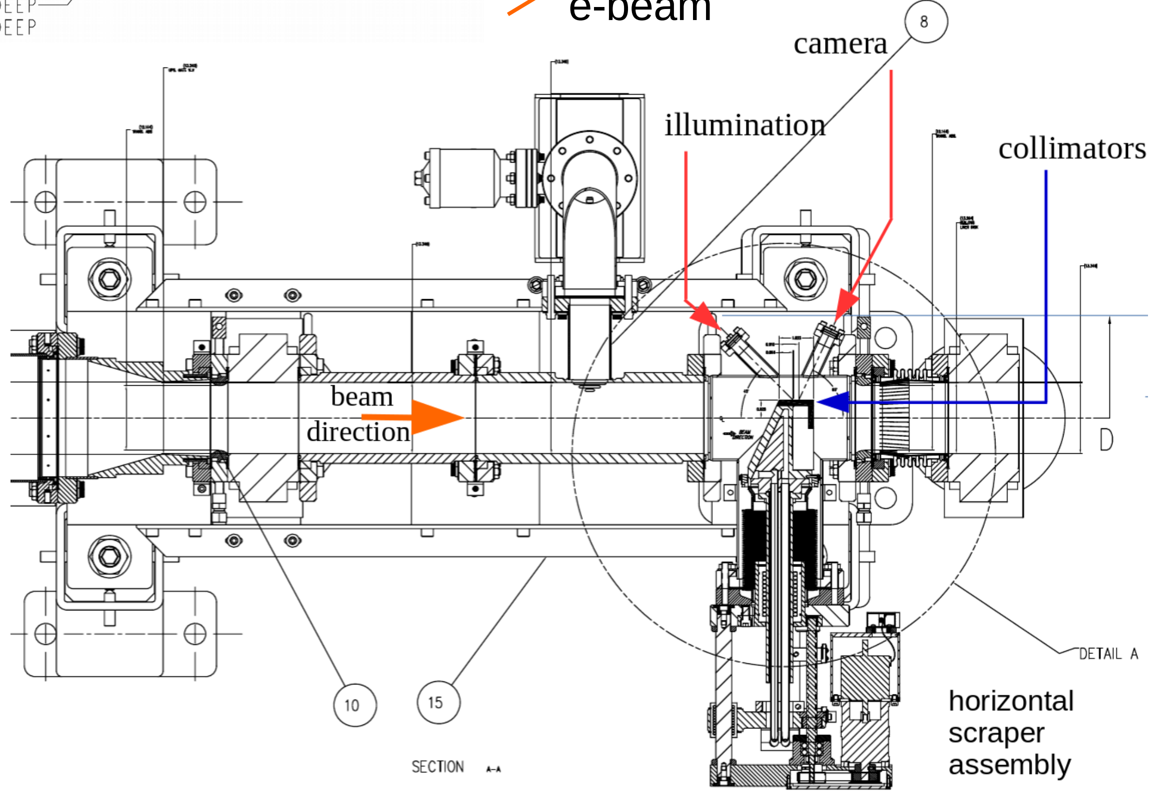


diagnostic camera

collimator surface radius 0.8 m

surface roughness (5/19): 2.7 μm



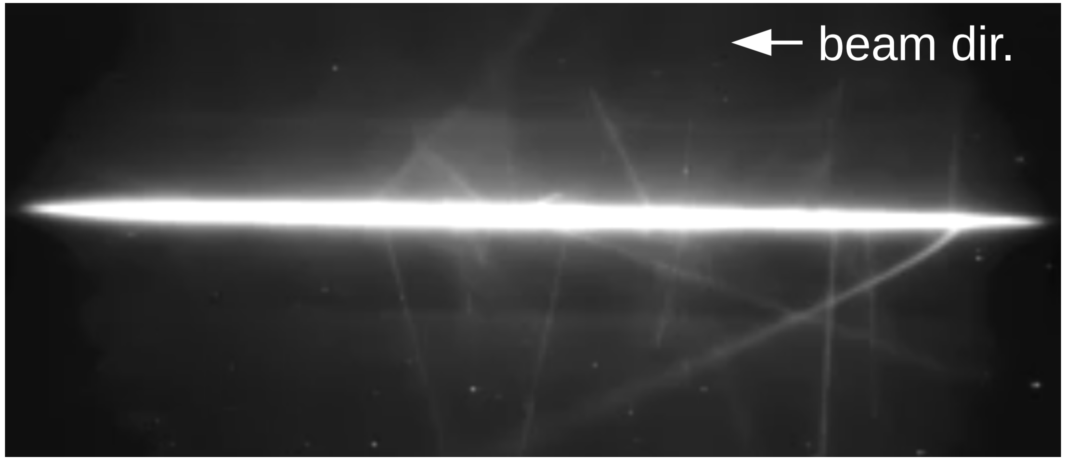


horizontal scraper assembly

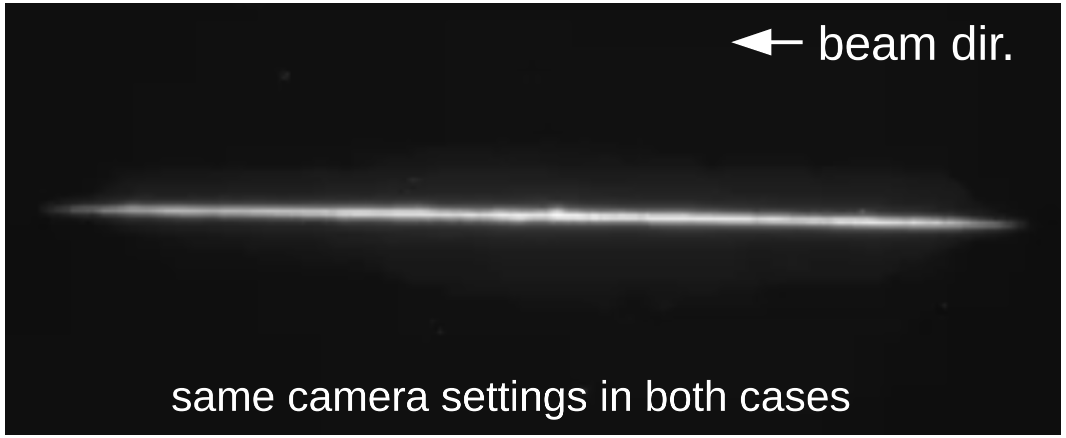
Experiment May 2019

Emission is observed only in a single frame

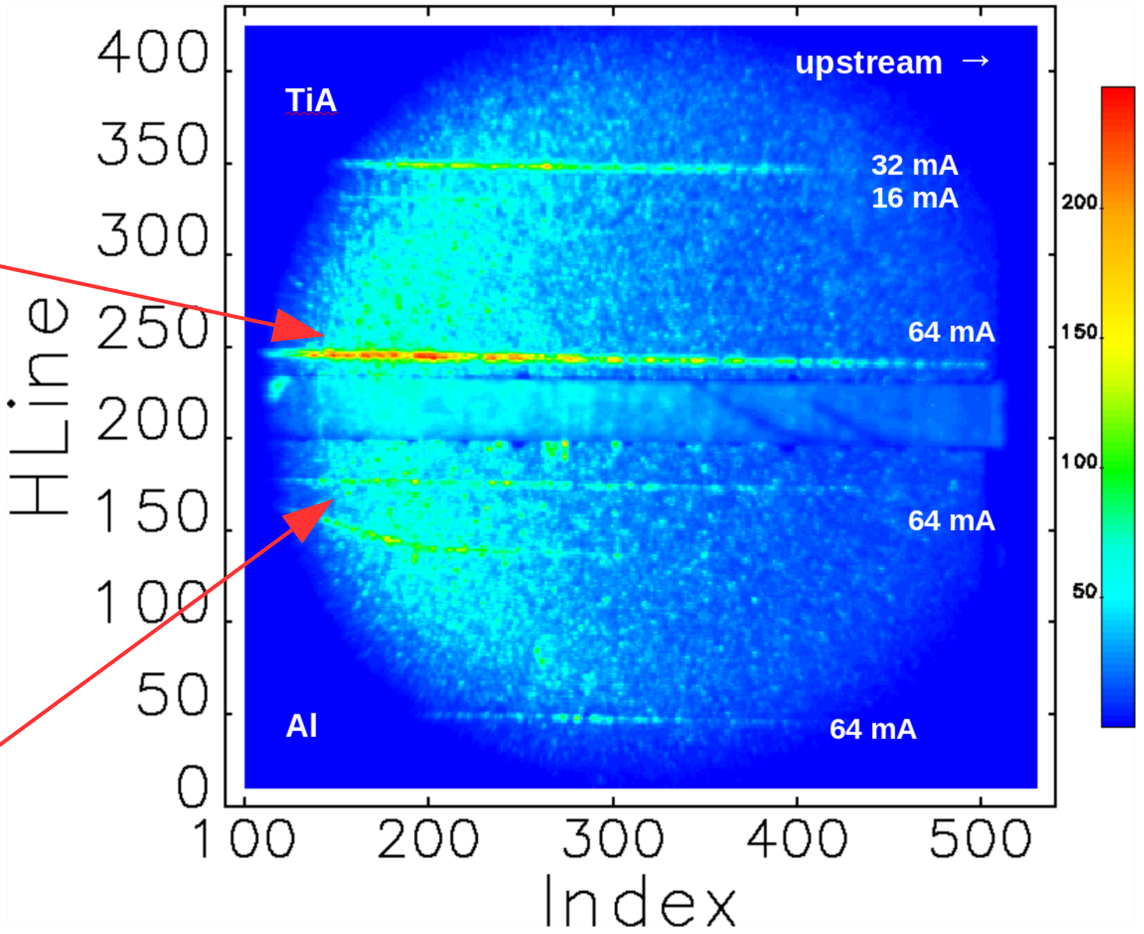
66.9 mA on titanium alloy Ti6Al4V



64.1 mA on aluminum alloy T6061



Post irradiation image

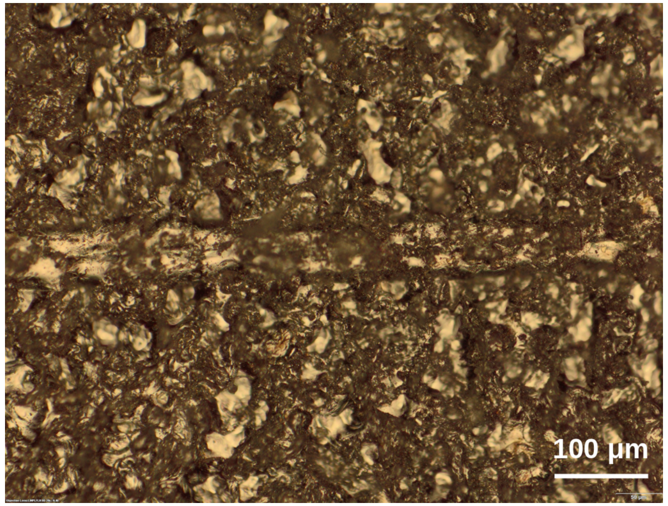


For the first time at APS, observe beam damage in Al

Experiment May 2019—Microscopy

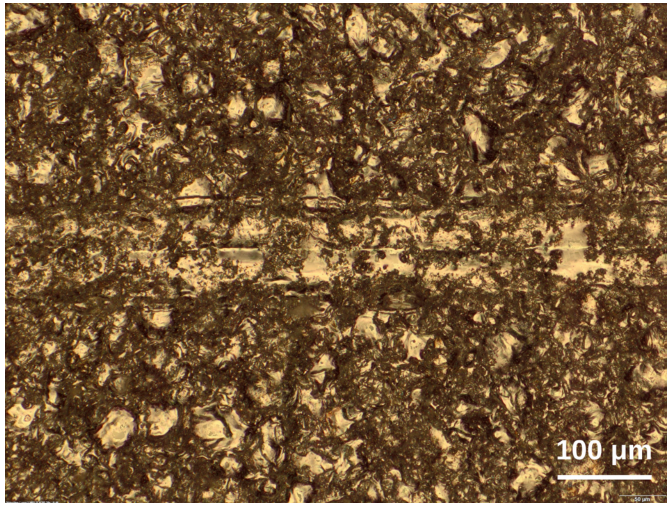
aluminum

33.1 mA



“double ridge”

64.1 mA



Surface features more highly modified in titanium Alloy

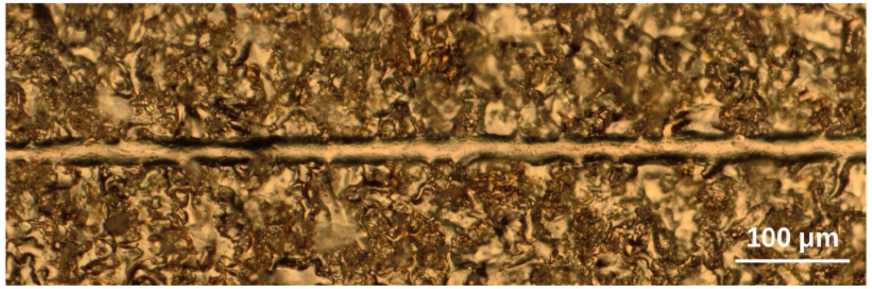
Melting temp:

AlT6061: 858 K
Al_2O_3: 2345 K

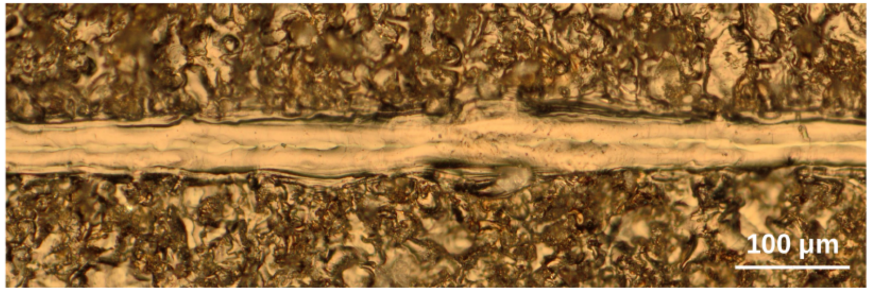
Ti6Al4V:1878 K
TiO_2: 2116 K

crude thermometry

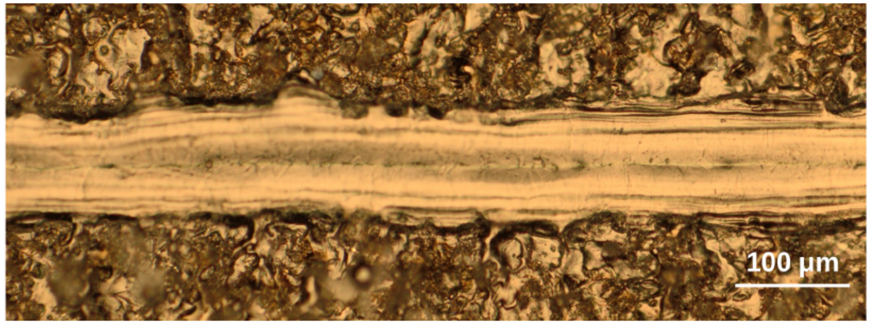
titanium alloy



15.9 mA



32.1 mA

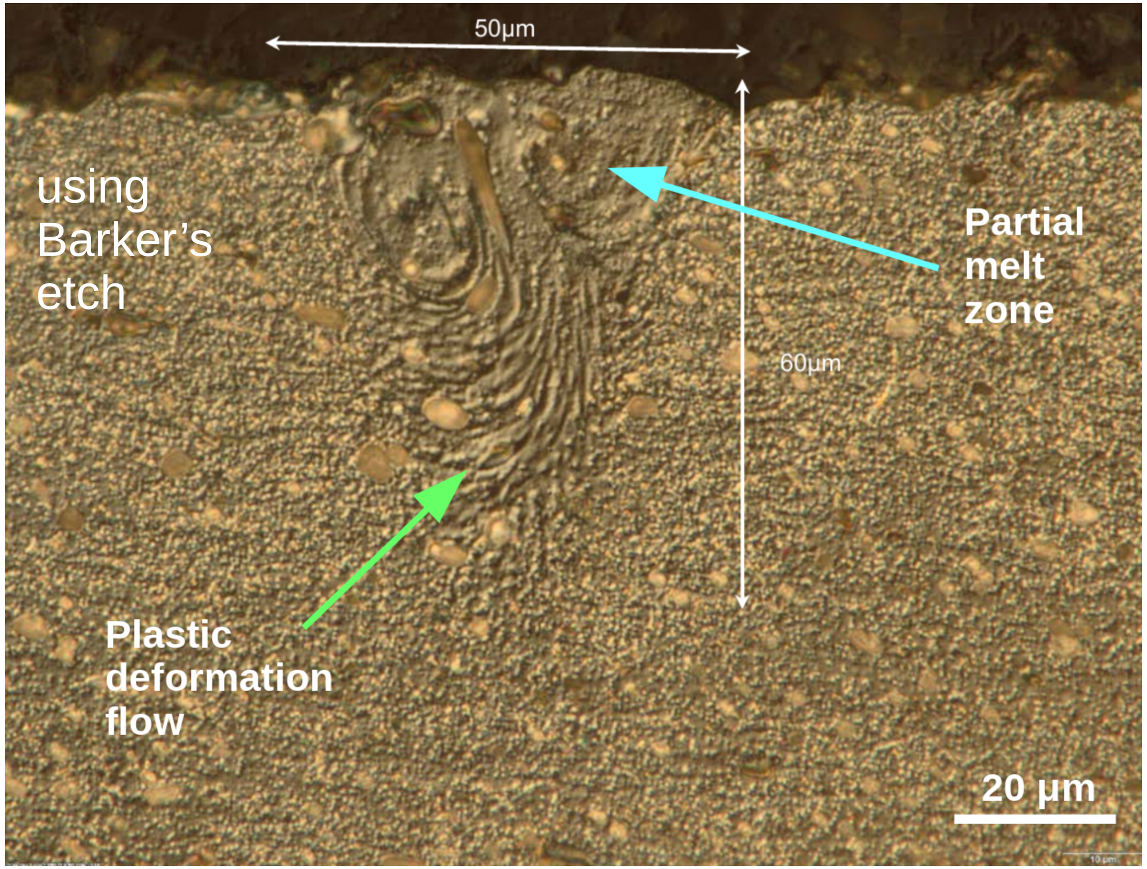


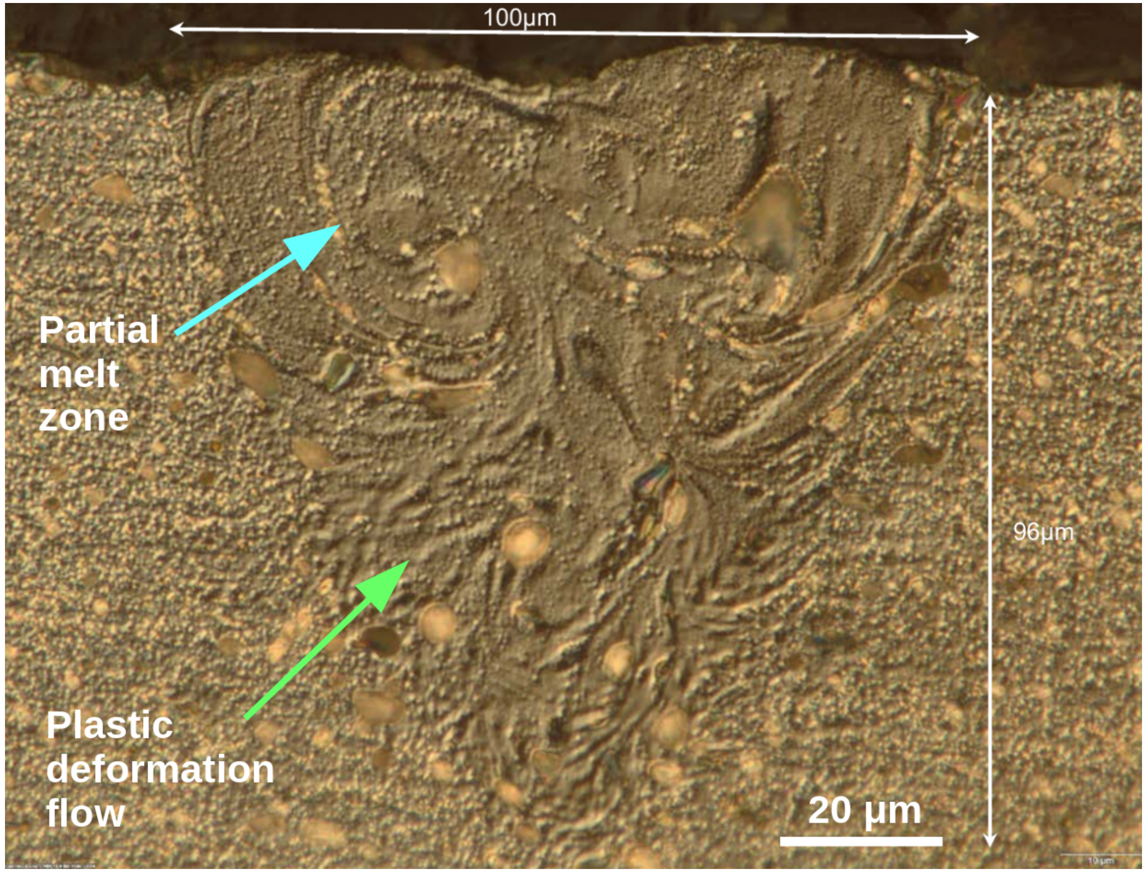
66.9 mA

May 2019—Metallurgy in aluminum only

—because of activation, cutting and polishing of the Ti-alloy piece was much more difficult

Beam direction is out of the page





33.1 mA

67.4 mA

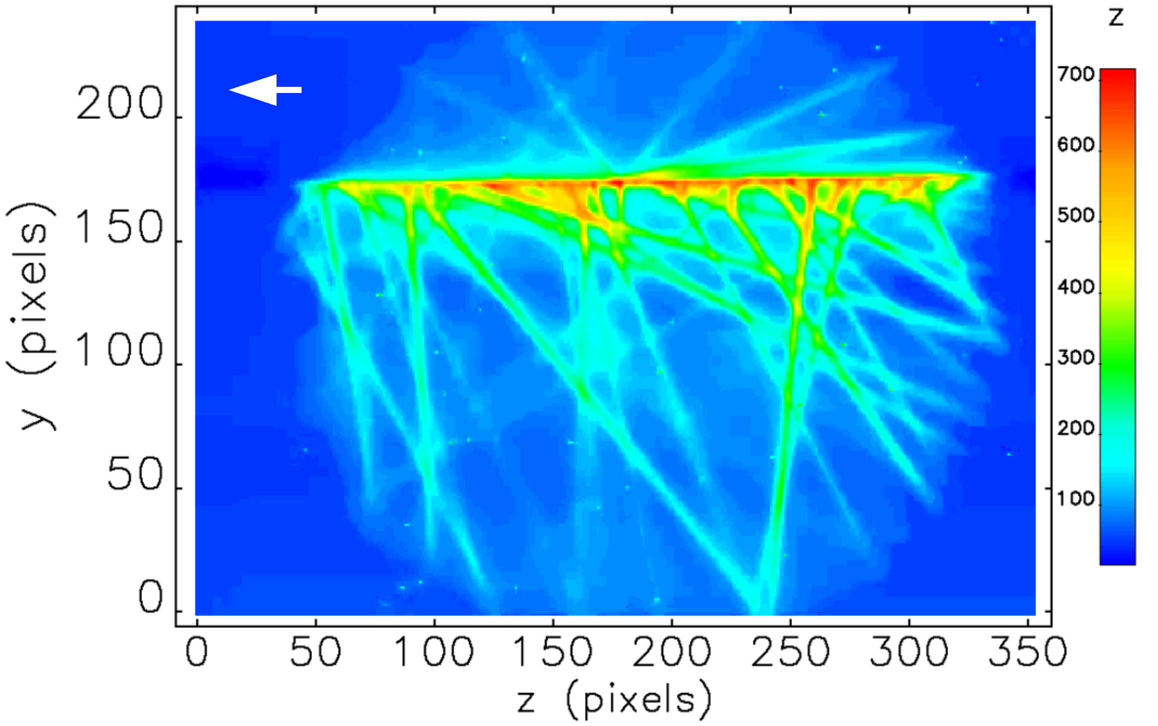
These are now seen as transitional conditions

January 2020 Collimator Experiment

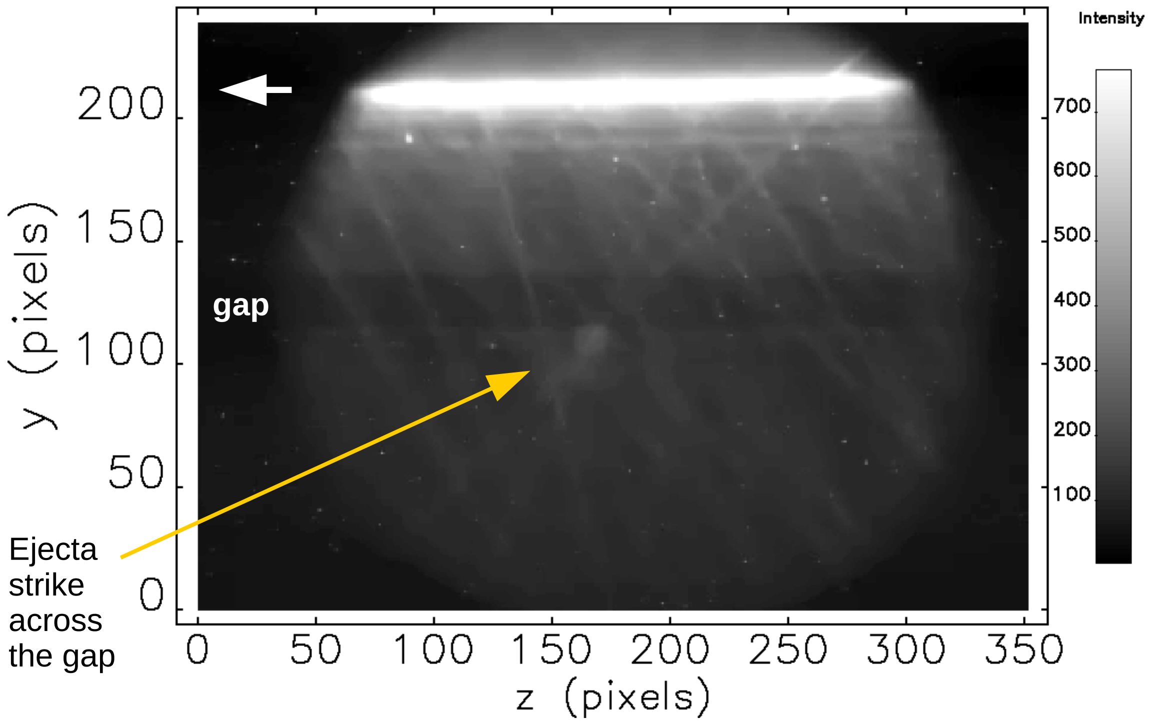
- Goal was to reach 200 mA—attained
- Vertical beam size was better controlled in this experiment
- Only Al collimator test pieces used: average surface roughness: 0.45 μm

Diagnostic camera images—beam moves from right to left

66 mA, false color



201 mA, BW

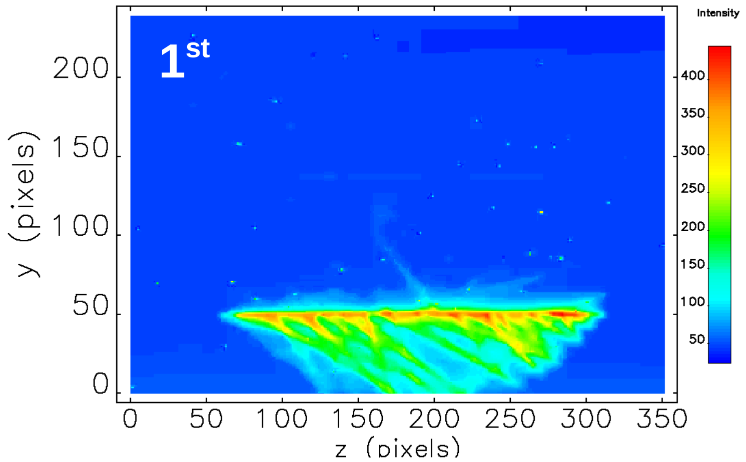


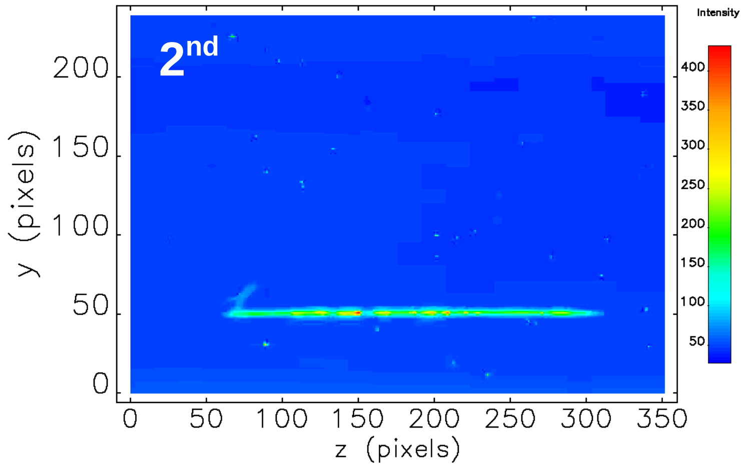
Multiple strike locations—emissions diminish with subsequent hits

64 mA

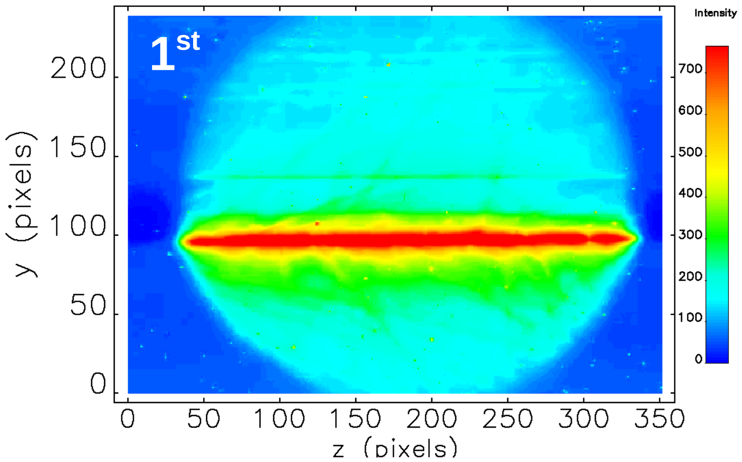
Beam direction right to left

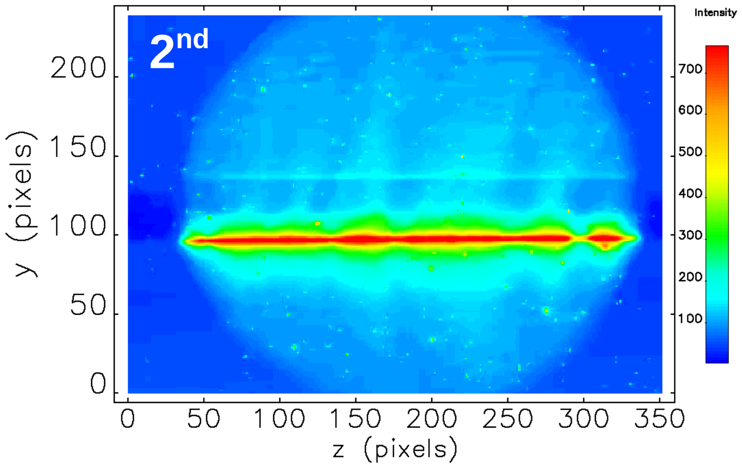
200 mA



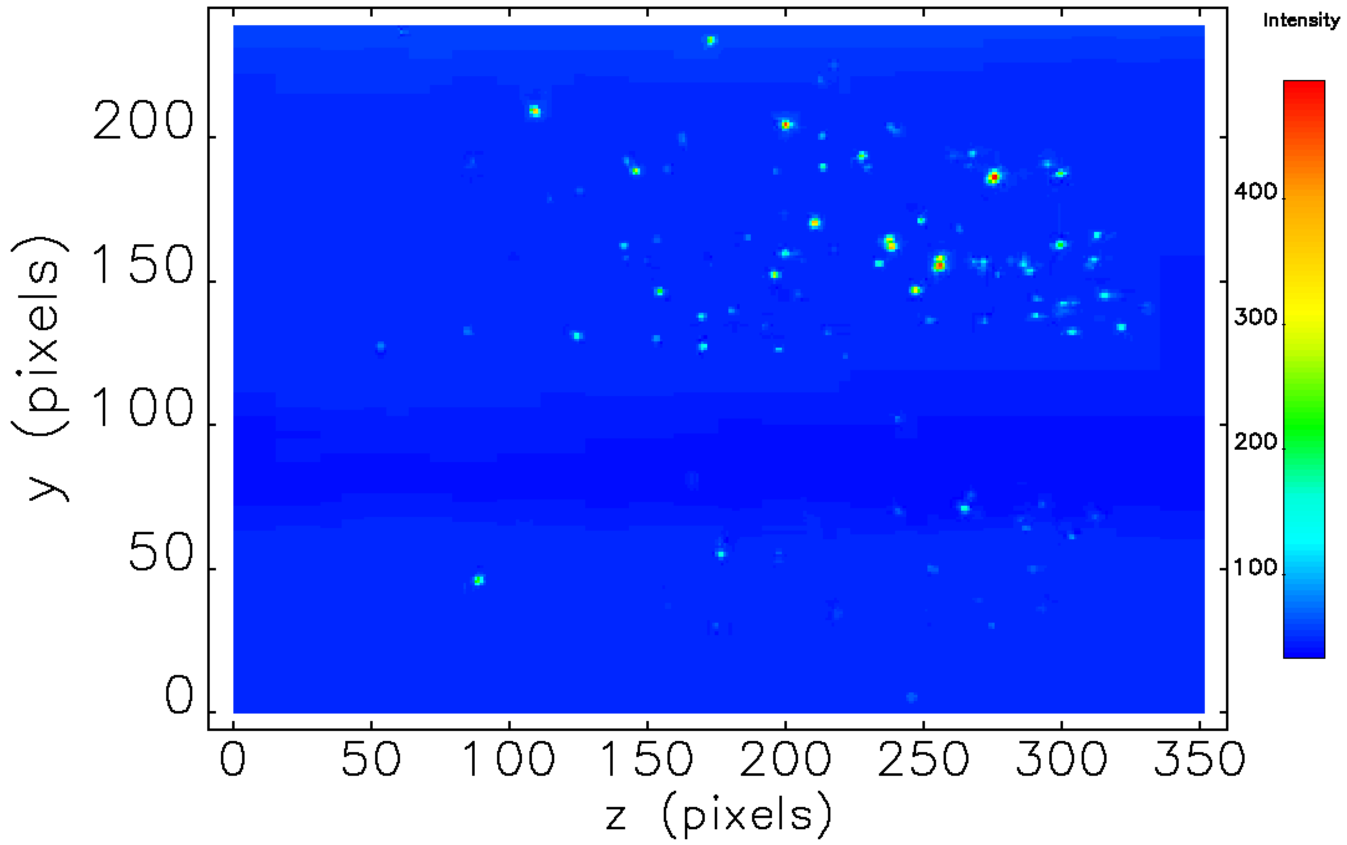


- Depth of field 2 mm
- Structures that remain in focus must be confined to this region
- Images are not high resolution (360x240) but still useful

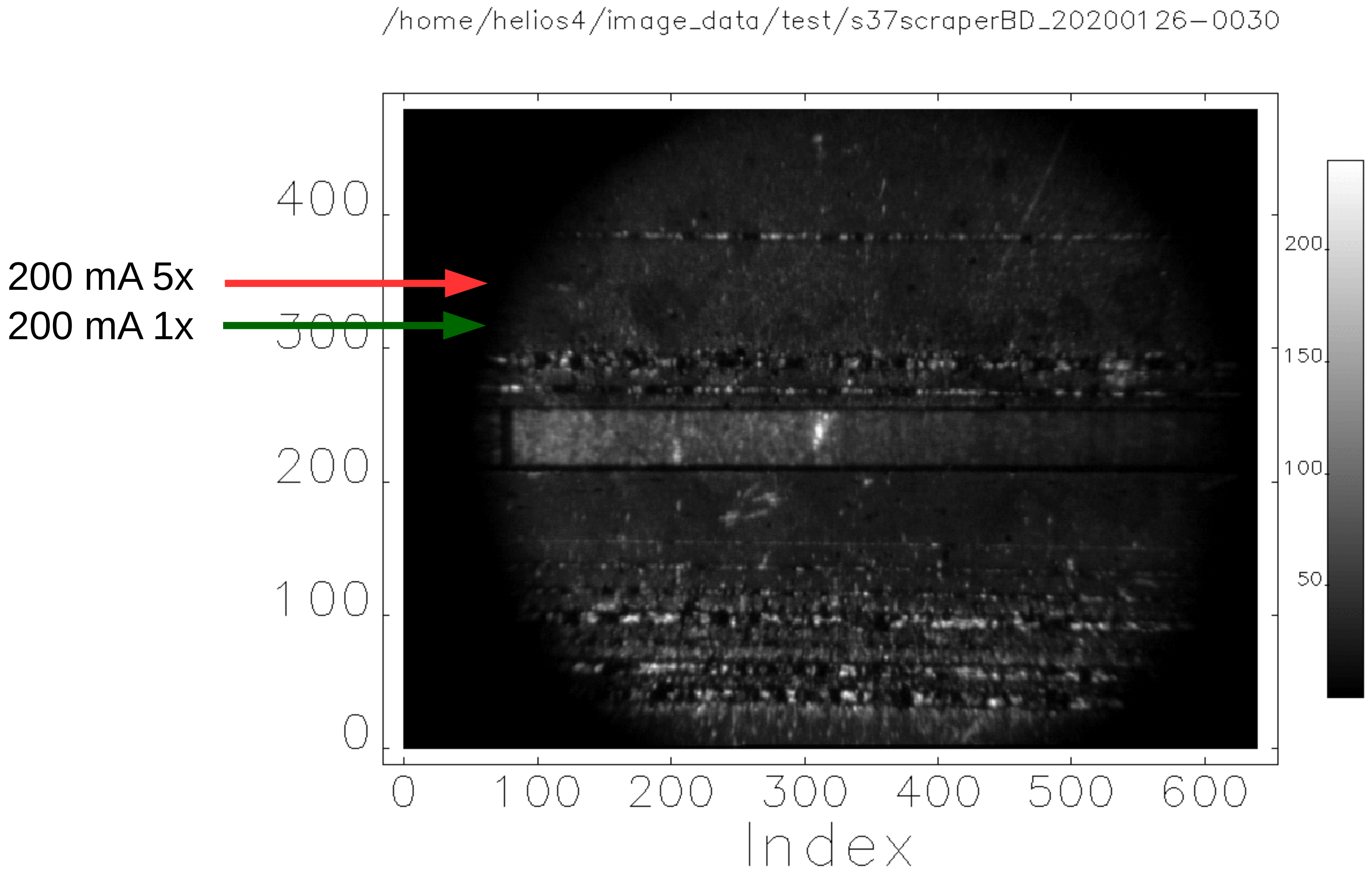




Five strike case at 200 mA—Emission



Five strike case at 200 mA—post-irradiation



January 2020 Experiment Results

- Collimators removed from the SR still on scraper body
- Using SLR camera; higher res., narrower depth of field
- 16 mA (18.1 mA)—no effect, damage starts at 32 mA (34.6 mA)
- To reduce wakefield heating, 200-mA cases were run with 972 bunches rather than 324.

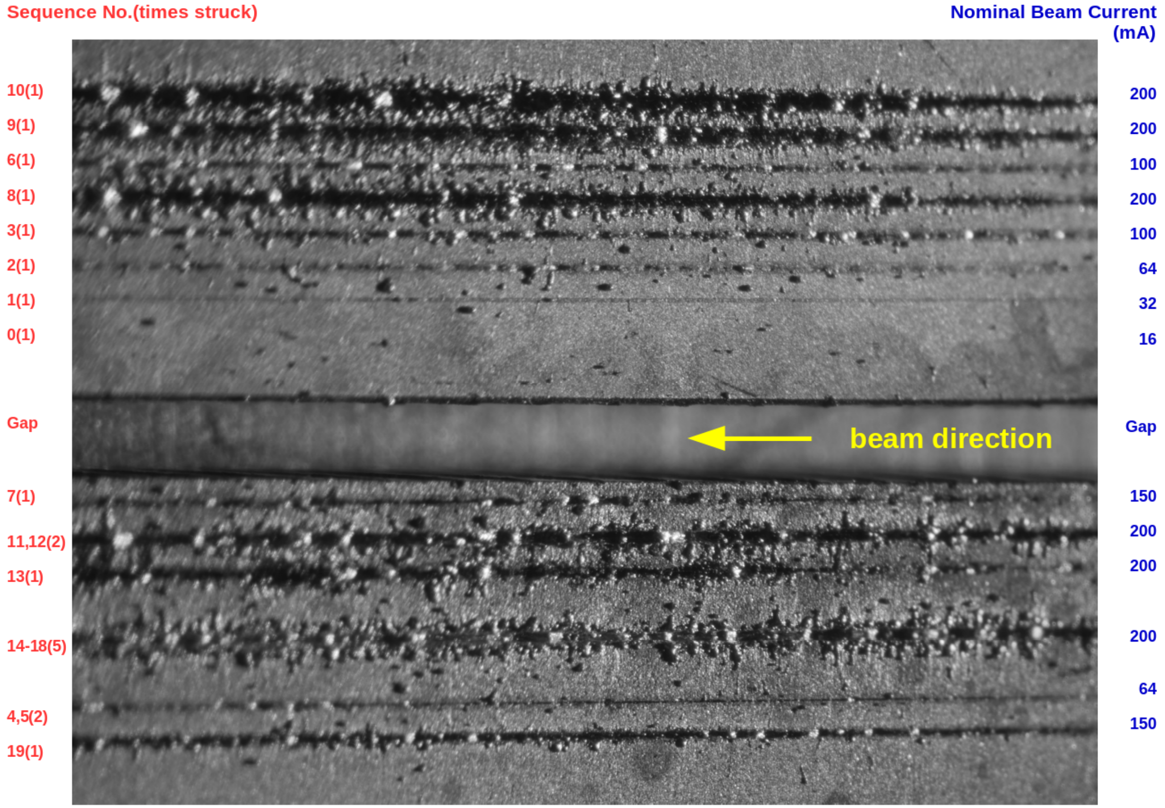


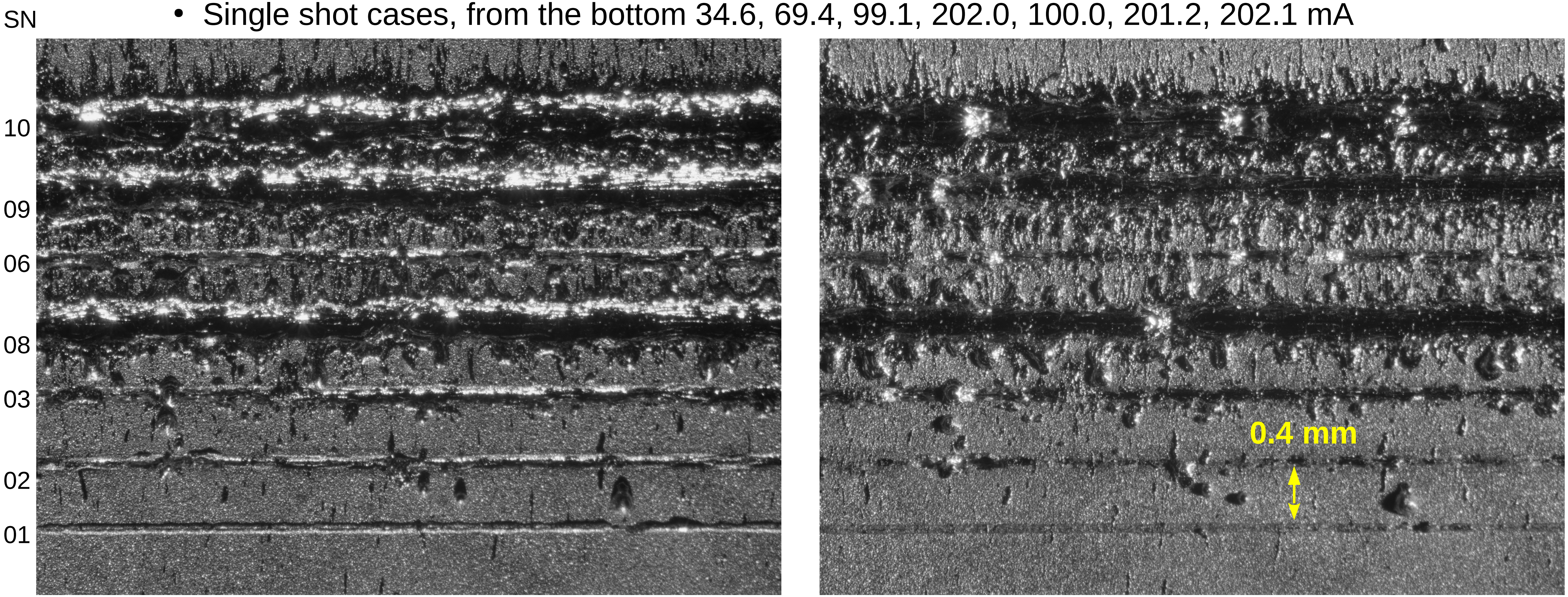
Table 1: Chronological sequence number, no. of bunches, current, charge per bunch, emittance, spot size, and dose during the January 2020 S37 collimator study. Gray backgrounds represent locations of repeated beam dumps.

SN	No. bun.	y-off. (mm)	I_b (mA)	Q_b (nC)	ϵ_x (nm)	ϵ_y (pm)	σ_x (mm)	σ_y (μm)	j_e ($\frac{A}{mm^2}$)	D (MGy)
0	27	1.0	18.1	2.18	1.831	6.00	0.1039	6.00	4.61	3.65
1	54	1.4	34.6	2.18	1.829	5.28	0.1039	5.63	9.42	7.47
2	108	1.8	69.4	2.18	1.972	7.58	0.1066	6.74	15.36	12.18
3	324	2.2	99.1	1.13	2.088	13.36	0.1088	8.95	16.20	12.84
4	108	-3.4	73.1	2.18	2.012	7.51	0.1074	6.71	16.14	12.80
5	108	-3.4	66.6	2.18	1.965	7.88	0.1065	6.88	14.47	11.47
6	324	3.0	100.0	1.13	2.023	13.74	0.1076	9.08	16.29	12.92
7	324	-1.0	166.8	1.7	2.120	9.58	0.1094	7.58	32.02	25.39
8	972	2.6	202.0	0.76	2.765	14.91	0.1206	9.46	28.18	22.35
9	972	3.4	201.2	0.76	2.094	17.85	0.1089	10.35	28.41	22.53
10	972	3.8	202.1	0.76	2.104	15.51	0.1091	9.65	30.56	24.23
11	972	-1.4	199.8	0.76	2.140	9.52	0.1097	7.56	38.33	30.39
12	972	-1.4	201.9	0.76	2.132	9.55	0.1096	7.57	38.74	30.71
13	972	-1.8	201.4	0.76	2.112	9.54	0.1092	7.57	38.79	30.76
14	972	-2.6	201.9	0.76	2.117	10.71	0.1093	8.02	36.68	29.08
15	972	-2.6	201.4	0.76	2.102	10.42	0.1090	7.91	37.18	29.48
16	972	-2.6	201.9	0.76	2.108	10.44	0.1091	7.92	37.19	29.49
17	972	-2.6	201.8	0.76	2.112	10.61	0.1092	7.98	36.86	29.22
18	972	-2.6	202.2	0.76	2.124	10.36	0.1094	7.88	37.31	29.58
19	324	-3.8	143.6	1.7	2.087	11.49	0.1088	8.30	25.32	20.07

→ Reached dose levels expected in APS-U

January 2020 Experiment Results—more photography

- Collimator pieces removed from scraper; surface ~ normal to FOV
- Single shot cases, from the bottom 34.6, 69.4, 99.1, 202.0, 100.0, 201.2, 202.1 mA



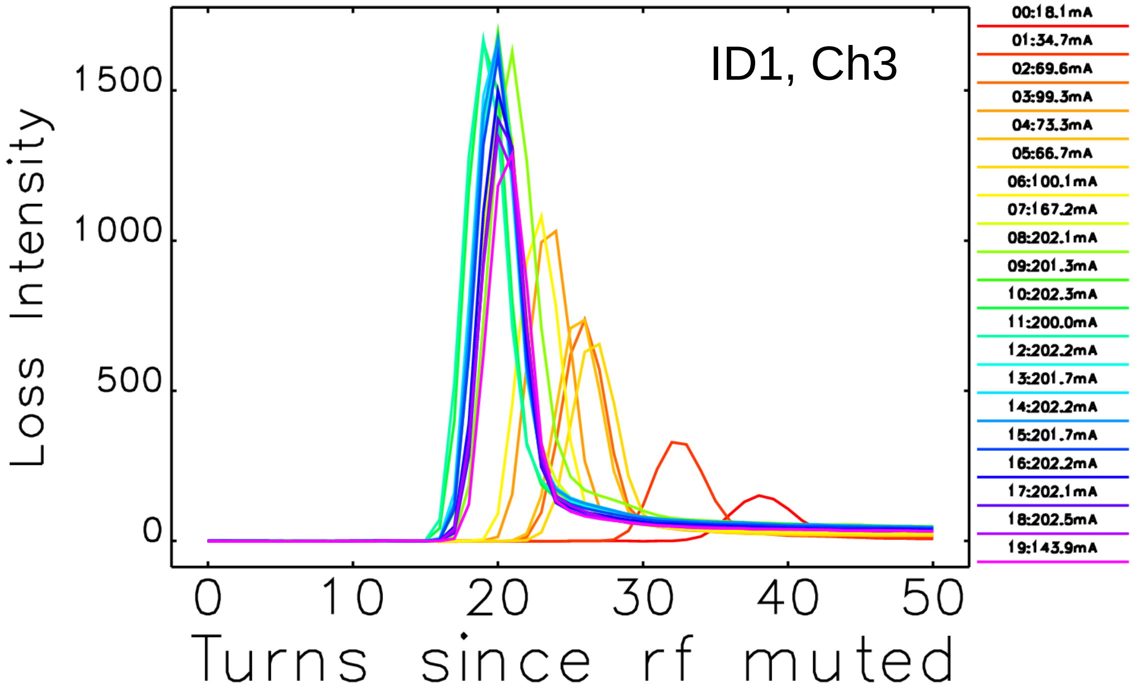
Illumination bottom

Illumination right

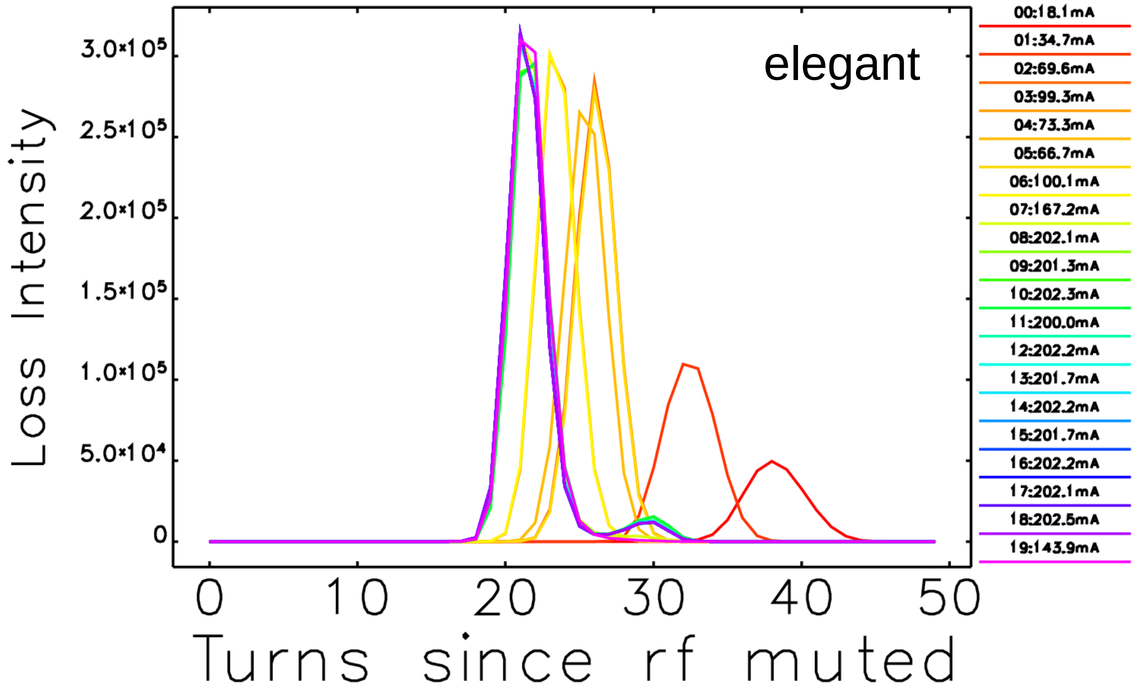
Damage crosses thresholds: from none to plastic to hydrodynamic

Experiment January 2020—Beam loss dynamics, typically loss is spread over several turns

Fast BLMs also show increasing current moves loss earlier. Shorter, more intense peaks.
Simulation with elegant [7] also shows this effect—due to beam loading



Fast FO BLM in ID1 cryostat

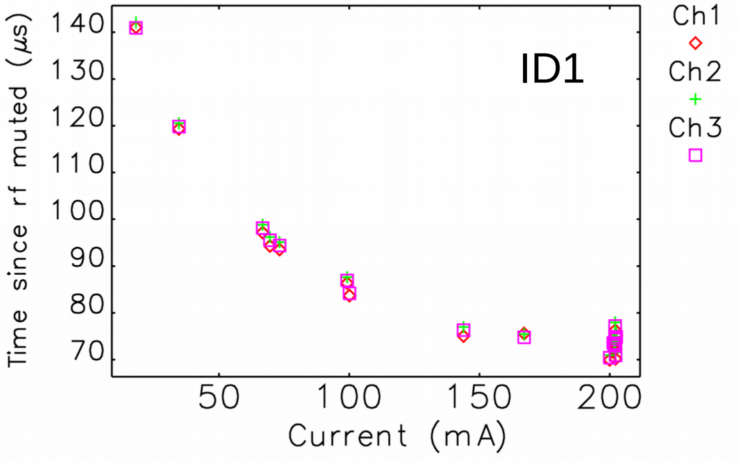


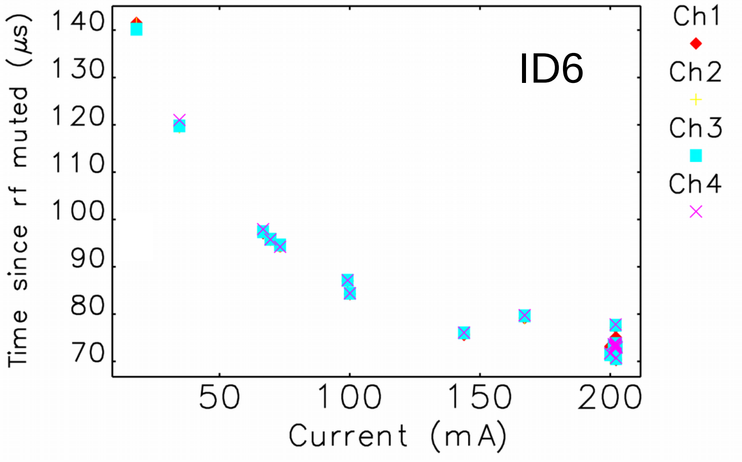
differentiating particles remaining

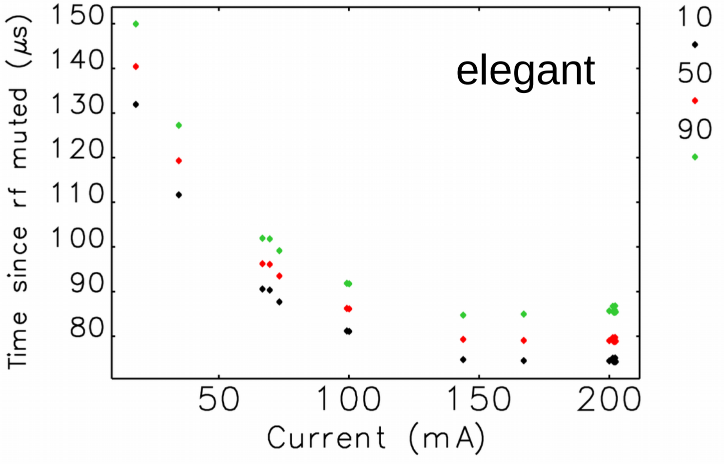
7. M. Borland, AOP-TN-2020-029

Experiment January 2020—Beam loss dynamics

—Spiral or arrival time of beam loss. Fast BLMs using center of the loss signal







- 110 m downstream of S37
- 2 fast BLMs in cryostat
- 1 fast BLMs external

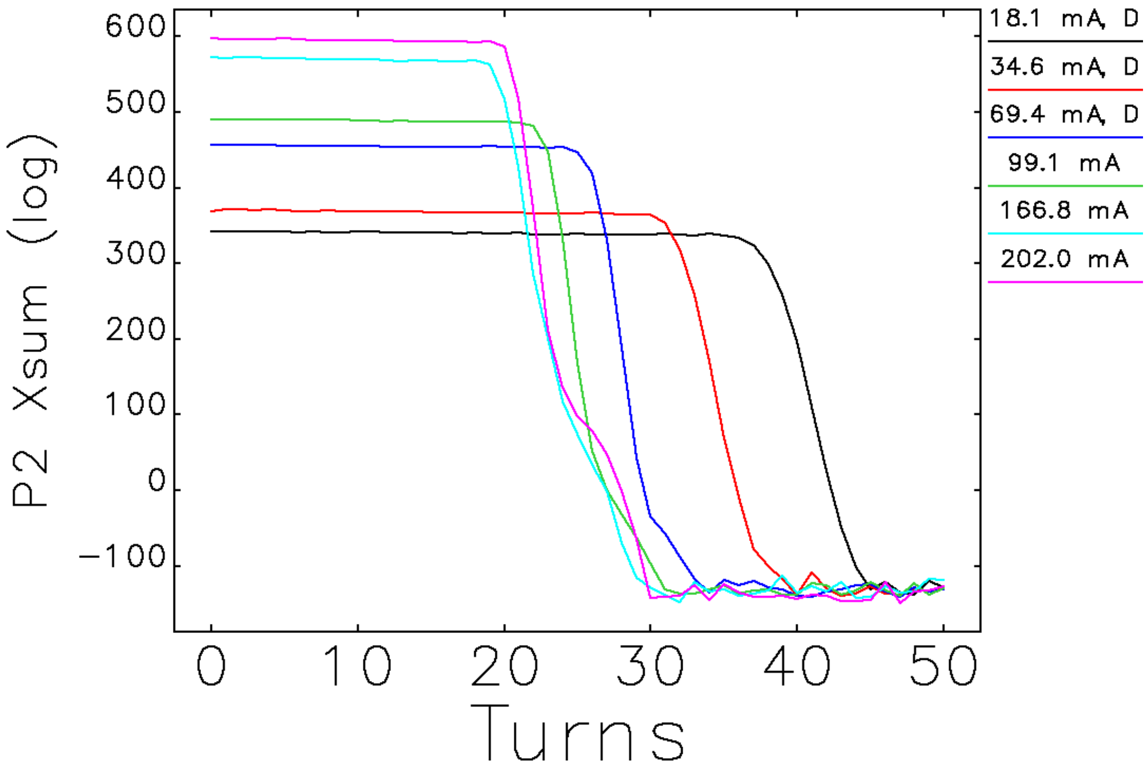
- 248 m downstream of S37
- 2 fast BLMs in cryostat
- 2 fast BLMs external
- Signals overall weaker here than in BLMs upstream

- Global
- Time to lose percentage of whole beam

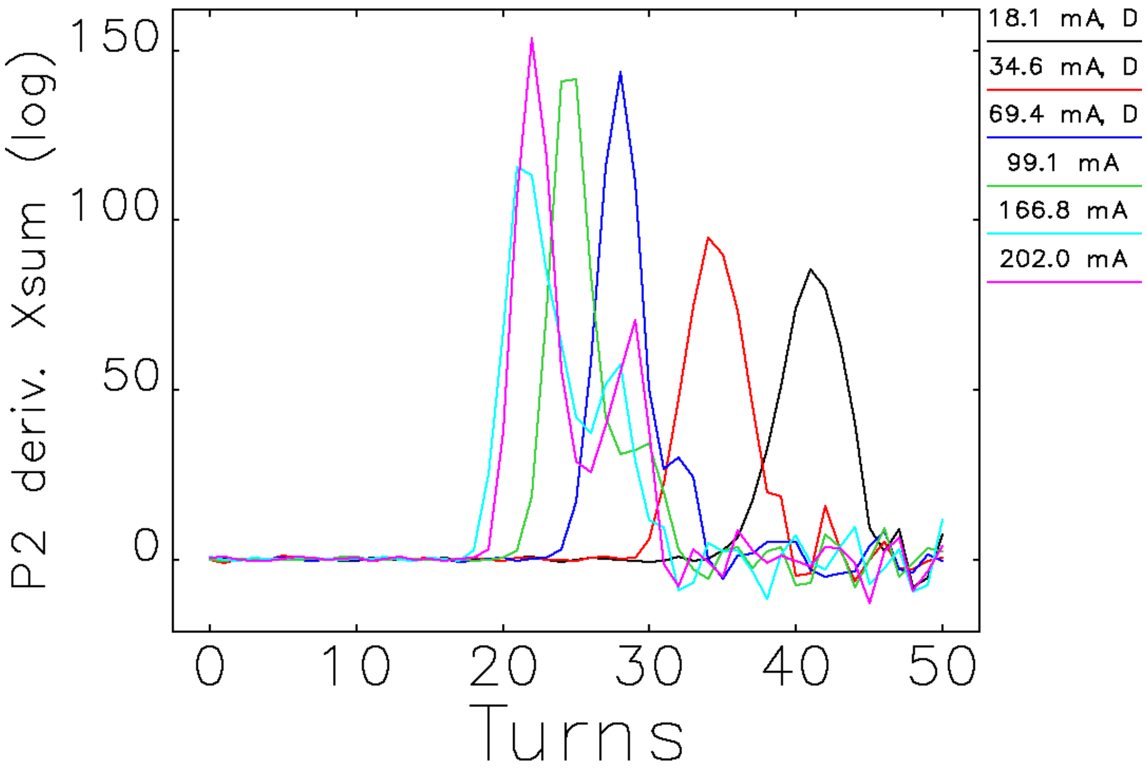
Overall an excellent agreement between measured arrival time and elegant 50% loss time

Turn-By-Turn (TBT) BPMs during selected beam dumps

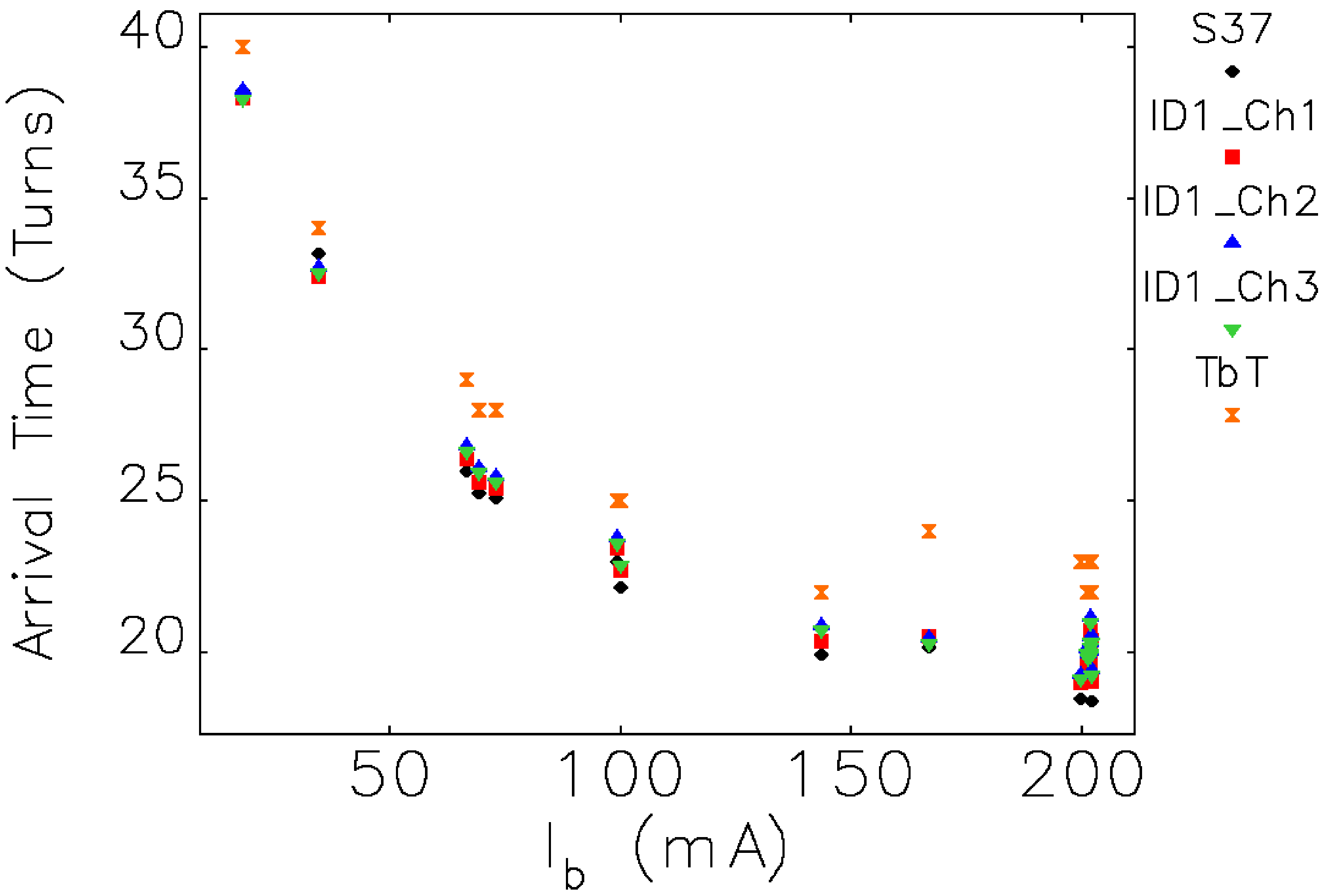
BPM TBT Sum signals (log scale)



derivative wrt turn



Comparison of TBT BPMs with fast BLMs



- Generally good agreement between fast BLMs and TBT BPMs in terms of arrival time (time since rf muted)
- Arrival Time defined by the peak of the distributions (no fitting)
- Systematic delay of TBT relative to the BLMs—log scaling of TBT may be part of the explanation

Experiment January 2020—Post irradiation analysis

- Significant surface damage is observed above 65 mA, fluid dynamic (hydrodynamic) behavior clearly evident at 200 mA
- Surface roughness appears to play a role possibly due to wakefields
  - Can this effect be used to disrupt the beam?
- Threshold for damage appears between 16 and 32 mA, similar to May 2019
- Both aluminum samples are now activated! Be-7 detected (53 day 1/2-life)
- This makes analysis difficult
  - Microscopy can be done after movement of samples or movement of microscope
  - Metallurgy may be possible at external locations (generation of “mixed waste” is the problem)—COVID has slowed this process

Whole beam dump / h-collimator modeling challenges

- Energy densities reach into the hydrodynamic regime (>15 kJ/g or 15 MGy)
- Hydrodynamic tunneling will take place[8], especially for higher-Z, higher-density materials
- Static simulations (e.g. MARS, FLUKA, MCNP) not reliable especially for high-Z, high-density—now must include aluminum in this group!
- Alternate codes required for coupling physics; Doug Wilson, LANL recommended FLASH[9]. Wilson did early coupling work with Nikolai Mokhov for the SSC[10].

---

8. N. Tahir et al., “Review of hydrodynamic tunneling issues in high power particle accelerators,” NIM-B, 427 (2018) 70-86.
9. http://flash.uchicago.edu/site/flashcode/user_support/
10. D. C. Wilson, R. P. Godwin, J. C. Goldstein, N. V. Mokhov, and C. A. Wingate, “Hydrodynamic Calculations of 20-TeV Beam Interactions with the SSC Beam Dump”, Proc. PAC'93, Washington D.C., USA, Mar. 1993, pp. 3090-3093.

Have started hydrodynamics modeling

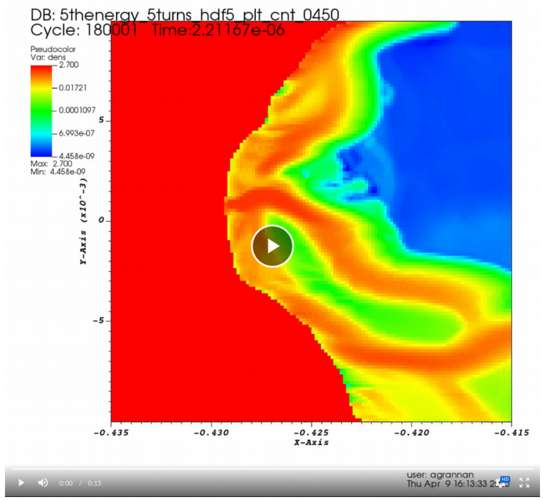
- Proposal to combine MARS, FLASH and elegant
- Preliminary results look promising
- Other labs are interested (SSRL, EIC/BNL, ESRF-EBS)
- Setting conditions for transitions from rigid to flowing matter is guided by our experimental data

FLASH Flow conditions:

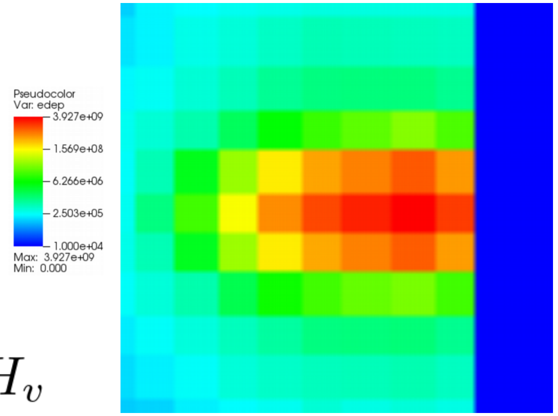
Melt: $$D_{ij} > C_{ps}(T_m - T_r) + \Delta H_m$$

Vapor.: $$D_{ij} > C_{ps}(T_m - T_r) + \Delta H_m + C_{pl}(T_b - T_m) + \Delta H_v$$

2-D FLASH model[11]—dose map from MARS



After bunch 28 of 48 in 1st turn of 5-turn loss

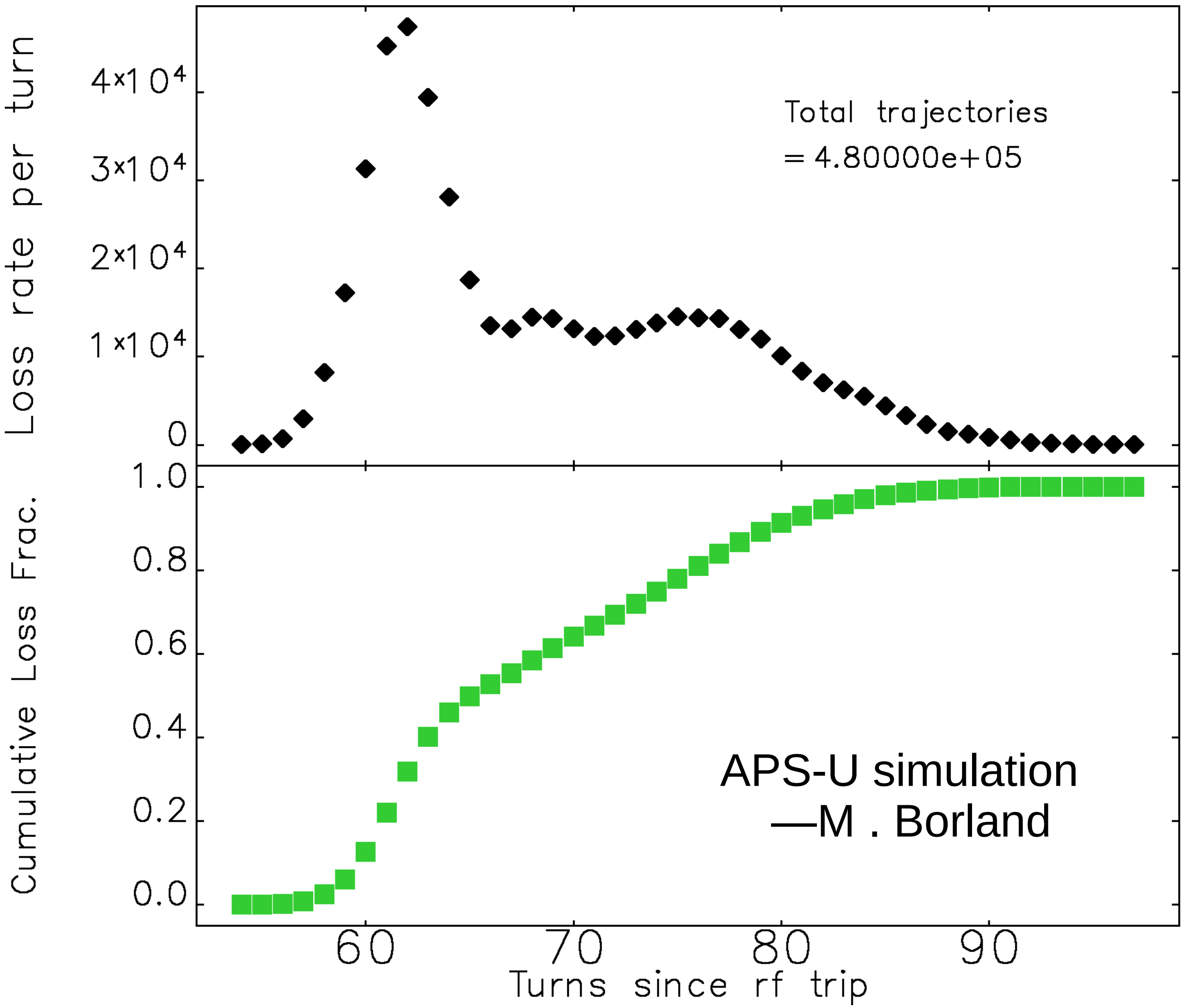


Max dose =1.6 MGy single bunch of 48

11. A. Grannan, J. Dooling, AOP-TN-2020-038

Developing coupled (multiphysics) modeling to guide MPS work

- elegant simulations indicate the temporal loss will be spread over many turns
- Complex temporal behavior:
  - FWHM bunch duration: 250 ps
  - time between bunches: 77 ns
  - one turn: 3.68 μs
- Model cannot account for all loss scenarios; therefore, need to be conservative
- Diagnostic data derived from experiments guide code development



Summary

- Two Whole-Beam Dump Collimator Experiments were conducted in the APS-SR
- In the first experiment, transitions from solid to plastic/partial-melt state in Al and Ti-alloy target collimators were observed
- In the second experiment, attained 200 mA on aluminum targets; transitions to a fully hydrodynamic behavior were observed
- elegant predictions of beam dynamics during aborts show good agreement with measurements
- Diagnostic camera installed to observe regions damaged AFTER beam strikes yielded fascinating and important data DURING beam strikes
- Fast loss monitors corroborate BPM data and provide high temporal resolution
- Good diagnostics are key for a successful experiment!
- We are presently involved in a effort to couple static and hydrodynamic modeling codes for MPS development—now have benchmark data from our array of diagnostics!

Acknowledgments

Thanks to—

- R. Soliday and H. Shang for assistance with analysis scripts
- J. Heckman of Simutech for work on LS-Dyna
- APS Technical Groups:
  - MOM Vacuum and Water
  - Diagnostics
  - Survey and Alignment
  - Controls