Simulation and Experimental Efforts to Develop Whole Beam Dump Collimators for the APS-U Storage-Ring

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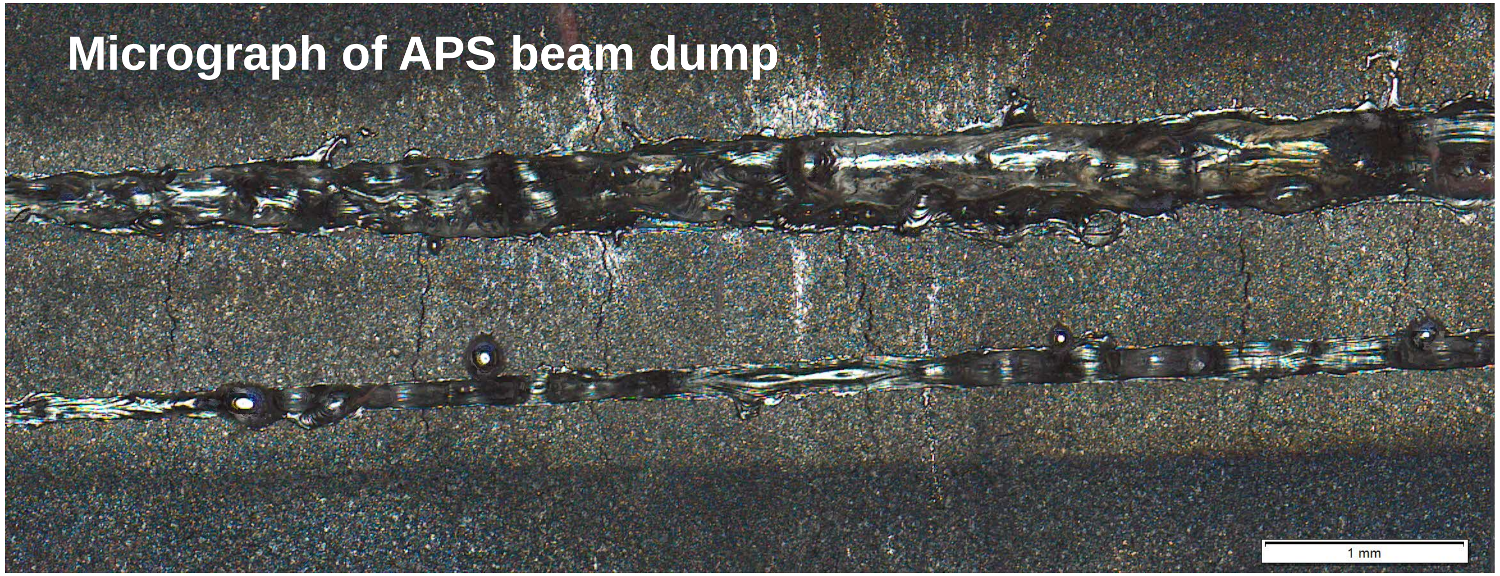
APS experience leads to concerns for APS-U beam dumps



- In 7-GeV Advanced Photon Source (APS), low-emittance beam has damaged both copper and tungsten beam dumps
- In ultra-low-emittance, 6-GeV APS Upgrade (APS-U), things get worse
  - Double the beam current (100 mA → 200 mA)
  - Horizontal emittance drops 100-fold (3.2 nm → 31 pm)
  - Vertical emittance about the same (40 pm → 31 pm)
- Simulations and experiments used to understand this issue

Outline

I. Introduction—Beam Dump Considerations

II. Simulations—integrated throughout this talk
  - A) Initial Dose Estimates (TAPAS/NIST)
  - B) Loss Distributions (ELEGANT[1])
    - 1) Longitudinal—Lattice function and Collimator location
    - 2) Transverse—Provide peak dose, input for MARS[2]
  - C) RHB lattice

III. Experiment
  - A) Overview
    - 1) Study Plan
    - 2) Injection and Data Collection Process
    - 3) Diagnostics and Alignment
  - B) Observations
    - 1) Charge and Position
    - 2) Visible light
  - C) Post Ops Examination
    - 1) Photography
    - 2) Microscopy
    - 3) Metallurgy

IV. Simulation Efforts
  - A) Hydrodynamic code development—coupling of codes
  - B) Wakefield Effects and Future experiments

V. Conclusion

Acknowledgments

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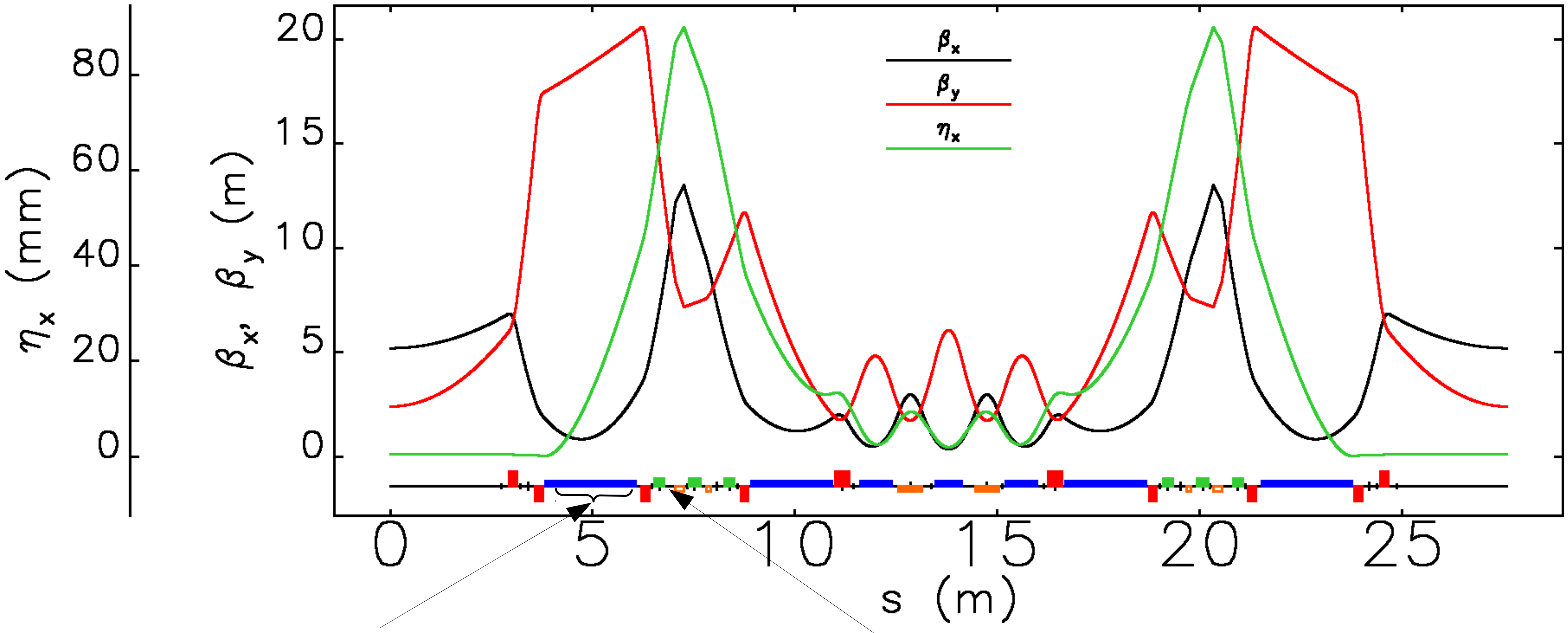
[1] M. Borland. ANL/APS LS-287, (2000); Y. Wang et al. Proc. of PAC 2007, 3444–3446 (2007).

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

APS-U Beam Dump Considerations

- Two types of beam dumps
  - Swap-out dumps used to extract single bunch prior to replacement and for “slow beam abort”
  - Whole-beam dumps used for fast beam aborts, may absorb entire store
- Swap-out dumps are protected by decoherence kicker
  - Targets a single bunch 250 turns prior to aborting the bunch
  - Provides 10-100-fold reduction in energy density
- No time for decoherence to protect whole-beam dumps
  - Beam abort initiated by machine protection system
  - Beam loss takes ~60 turns once started, insufficient time for decoherence of all bunches
  - Would need a 300-fold reduction in energy density
- We assume that whole-beam dumps will be damaged, but need to know
  - What’s the best material choice?
    - Limit the damage
    - Protecting downstream components
  - How bad will damage be (e.g., how large)?

APS-U collimator/dump locations take advantage of lattice functions



Vertical collimator or swap-out dump:

- Localizes injection and elastic scattering losses
- Two locations: S39A:M1, S01A:M1
- S39A:M1 is swap-out dump

Horizontal collimator and whole-beam dump

- Localizes Touschek and inelastic gas scattering losses
- Five locations (sectors 37, 38, 39, 40, 1) with existing enhanced shielding

Speedbump configuration chosen for whole-beam dumps

- Chose a “speedbump” configuration for whole-beam dumps
  - Beam interaction independent of the angle of approach
  - No sharp corners for beam to “clip”
  - Anticipate more consistent, predictable results
- Dumps not intended to fully absorb the beam
  - Much will be scattered, rendered relatively harmless
  - Simulations show that large radius of curvature improves localization of losses
- Expect dumps will be damaged, need to understand extent

Potential dose for APS-U exceeds 24 MGy

- Performed beam abort simulations for 100 “post-commissioning” error sets[1]
- Simulated losses are spread among five whole-beam dumps
- Estimated dose using collisional stopping power (Al)[2]

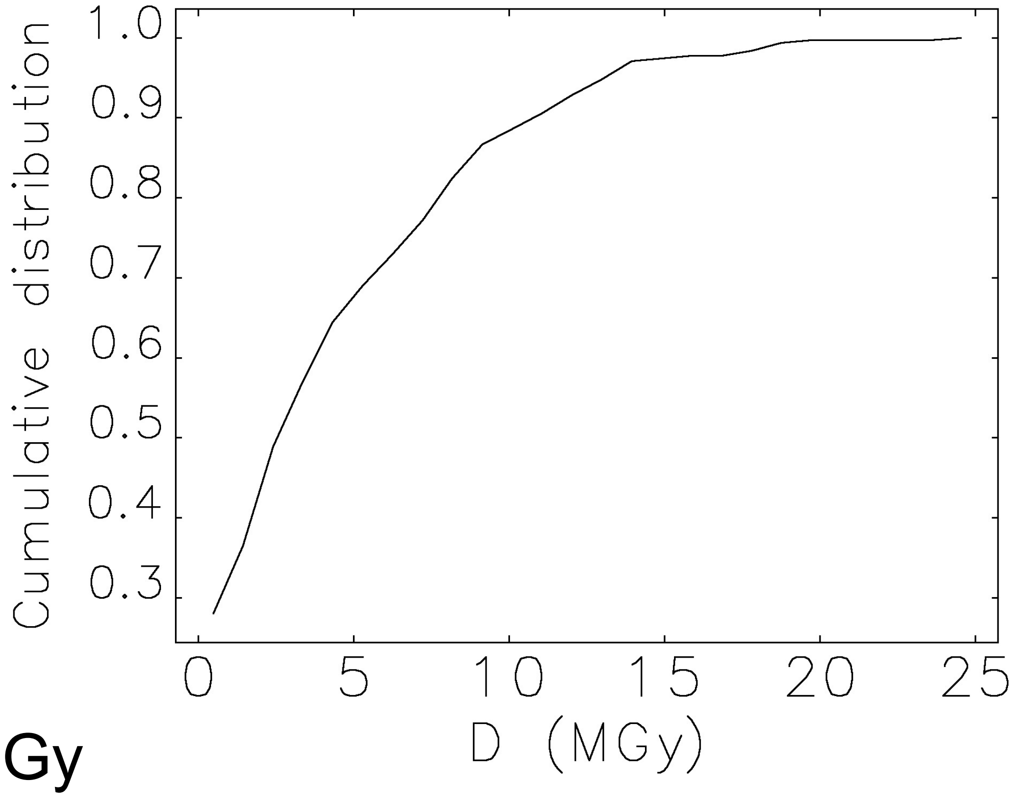
$$D[MGy] \approx 0.025 \frac{f}{\sigma_x[mm]\sigma_y[mm]}$$

where *f* is fraction of 200-mA beam lost at dump, $\sigma_{x,y}$ give loss footprint size

- Naive temperature rise estimate

$$\Delta T[K] = \frac{D[Gy]}{C_p[J/kG/K]}$$

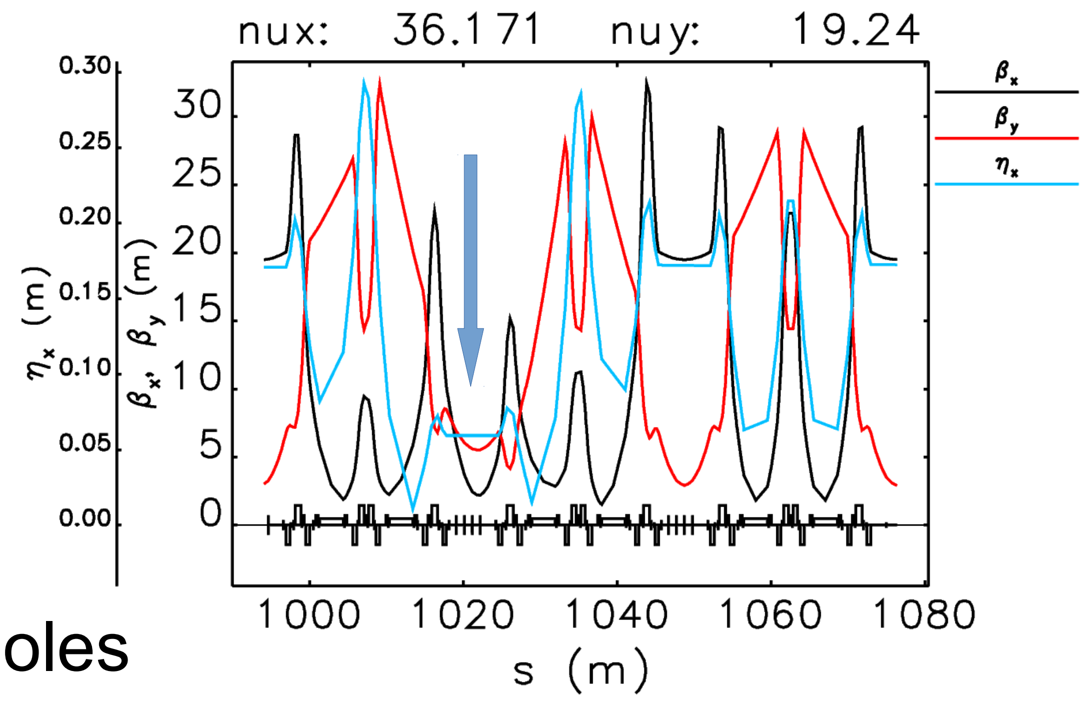
- Al, Cu, Ti, W predicted to melt at 0.4~0.9 MGy
- Worrisome even if estimate is naive



[1] V. Sajaev, Phys. Rev. Accel. Beams 22, 040102 (2019).
[2] physics.nist.gov/PhysRefData/Star/Text/ESTAR.html

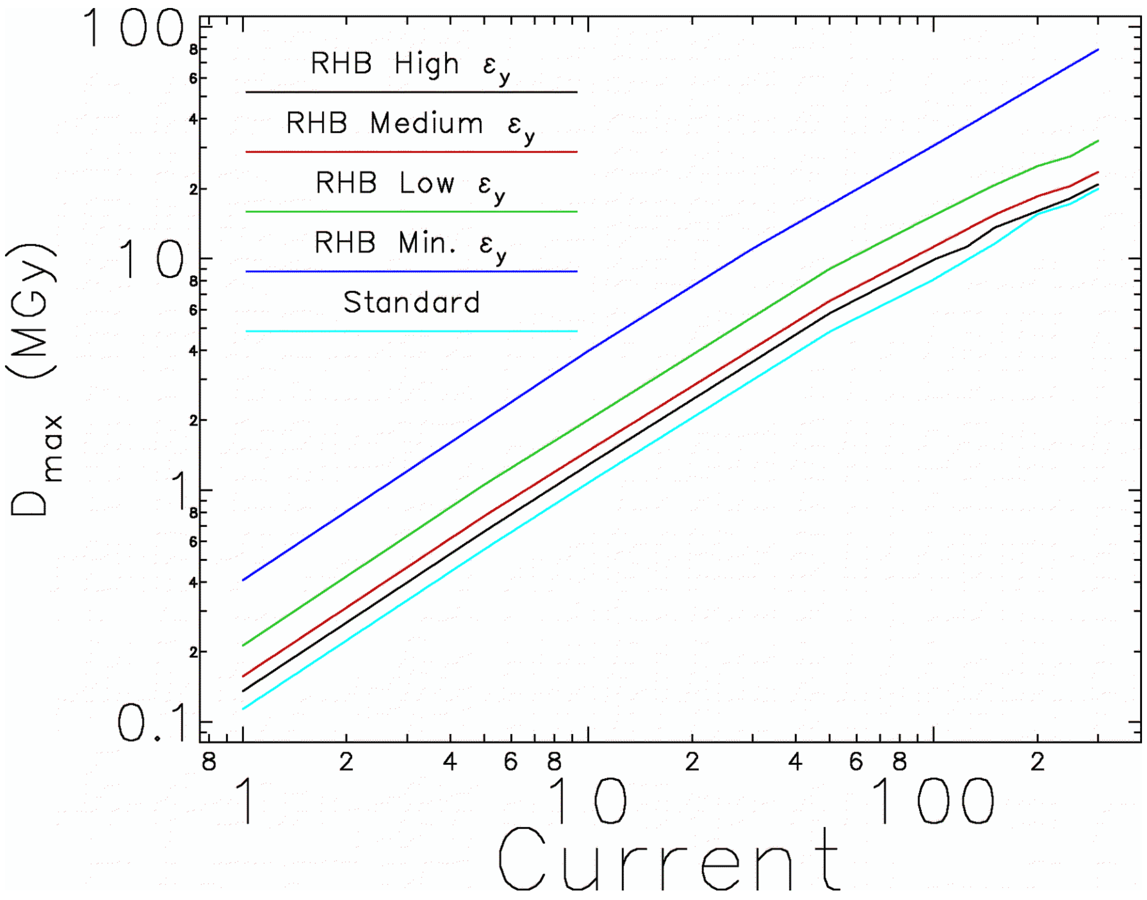
Lattice manipulations can provide higher dose in APS

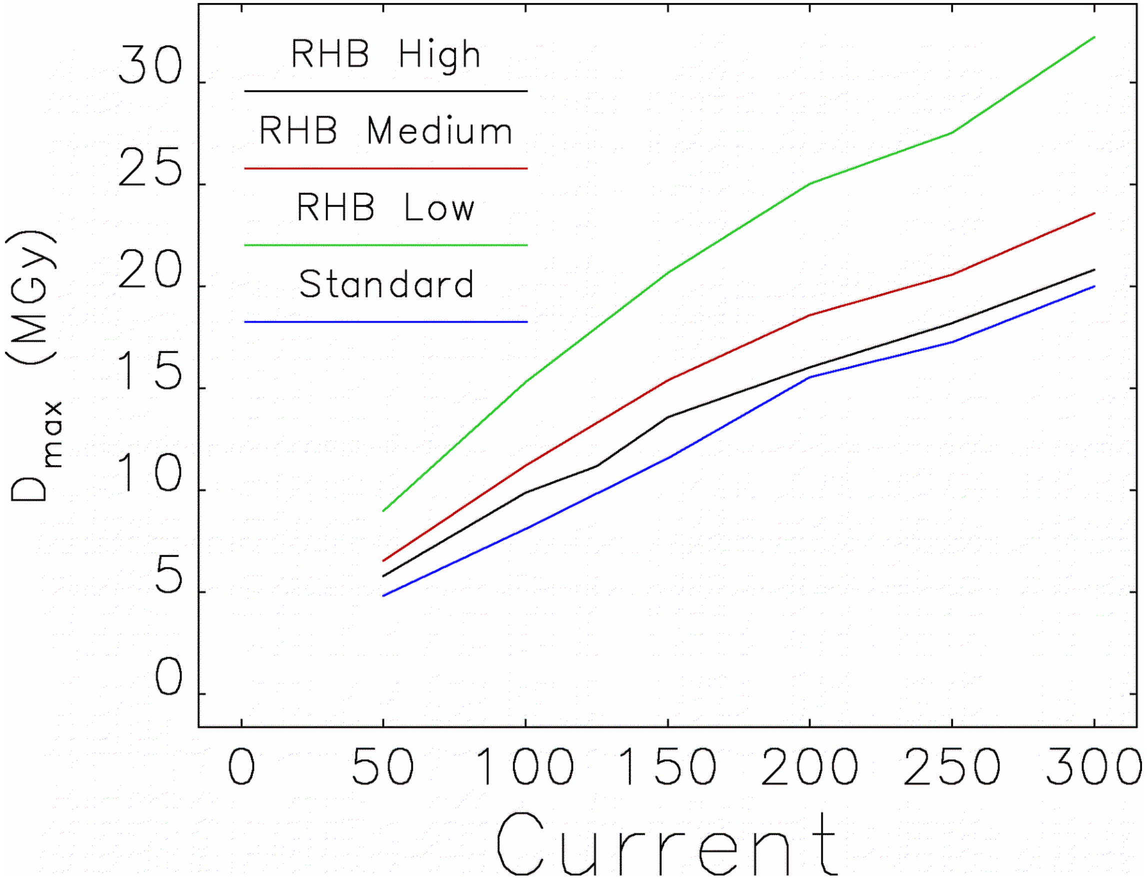
- Want to perform experiments in APS to approach APS-U dose levels
  - Higher current (up to 300 mA)
  - Lower vertical emittance
  - Reduce horizontal beamsize (RHB) through lattice manipulations
- APS has individually-powered quadrupoles so proved possible to manipulate the lattice functions at beam dump
  - The horizontal beta function is between 2.8-4.3 m, vertical beta function is between 5.8-6.4 m; Dx is 0.059m; Dxp is 0
- Emittance increased from 3.4nm to 3.5nm



Zoom-in of sector 37-39

Maximum Dose Estimates

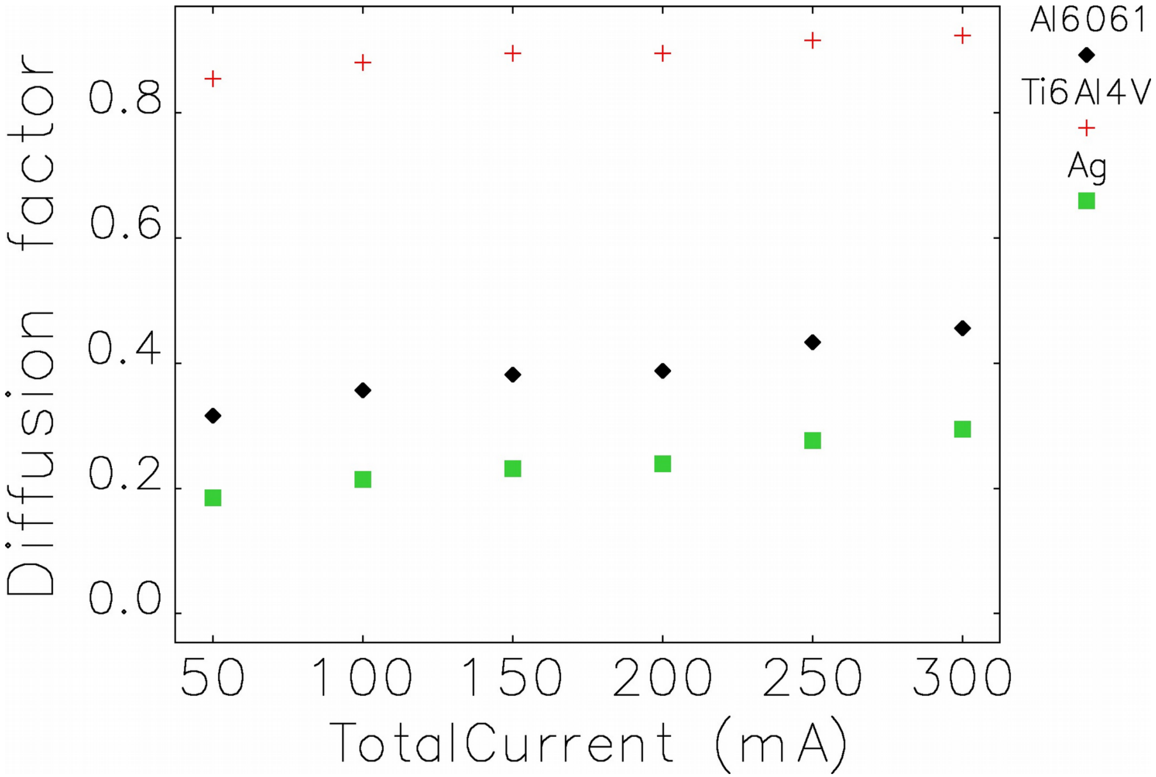




Thermal diffusion effects estimated with a simple model

- The effect of thermal diffusion becomes important when footprint (σ_x or σ_y) is small or loss interval (Δt) is long[1]

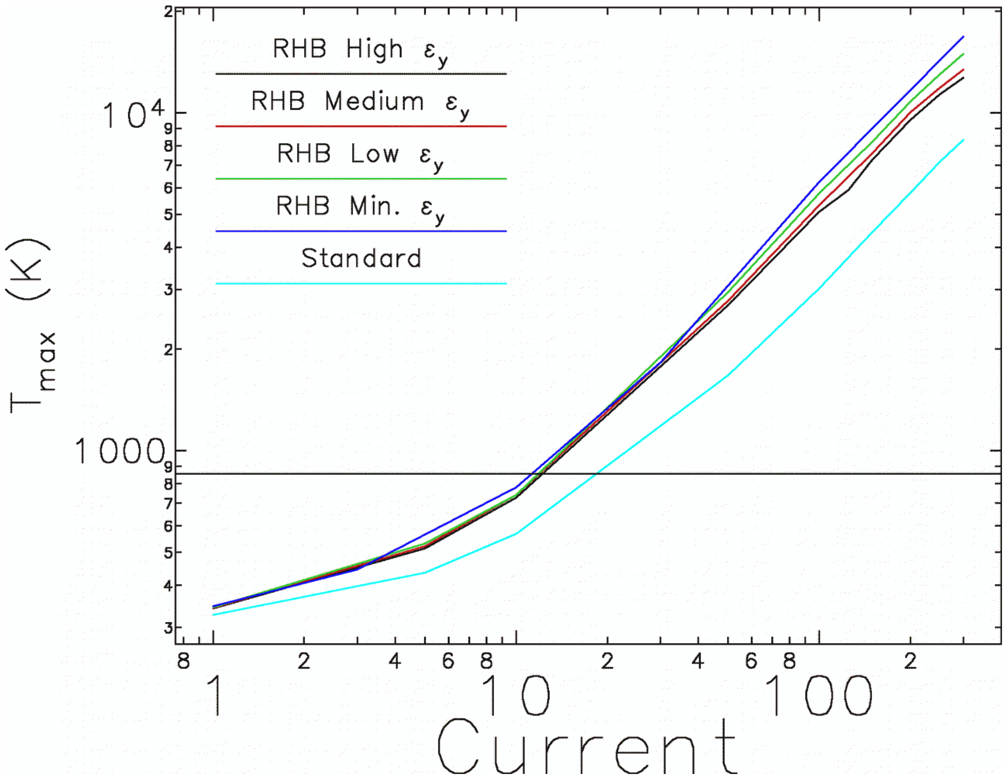
$$\frac{\Delta T}{\Delta T_{\text{static}}} \sim \sqrt{\frac{\sigma_x^2}{\sigma_x^2 + \alpha \Delta t}} \sqrt{\frac{\sigma_y^2}{\sigma_y^2 + \alpha \Delta t}}$$

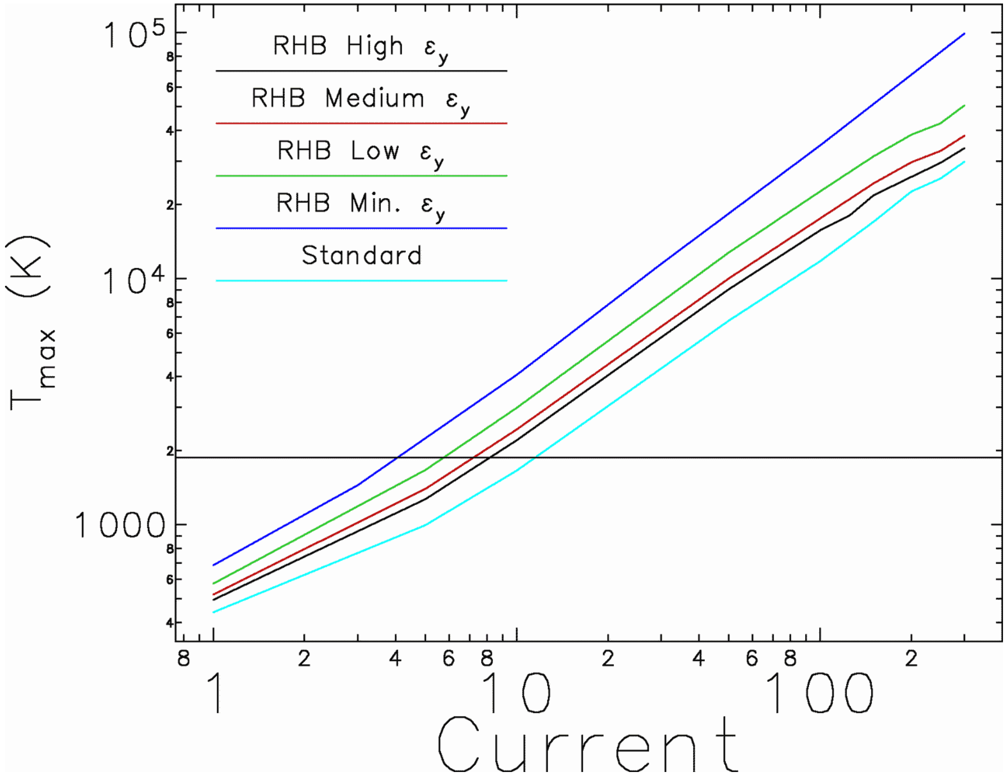


- Thermal diffusivity α is 64 μm²/μs for Al-6061, 3 μm²/μs for Ti6Al4V
- Should see significant benefit from diffusion in Al-6061, but not in Ti6Al4V
- Not enough to prevent melting, but may reduce extent of damage

[1] R.Lindberg, private communication.

Configuration can accentuate thermal diffusion effects



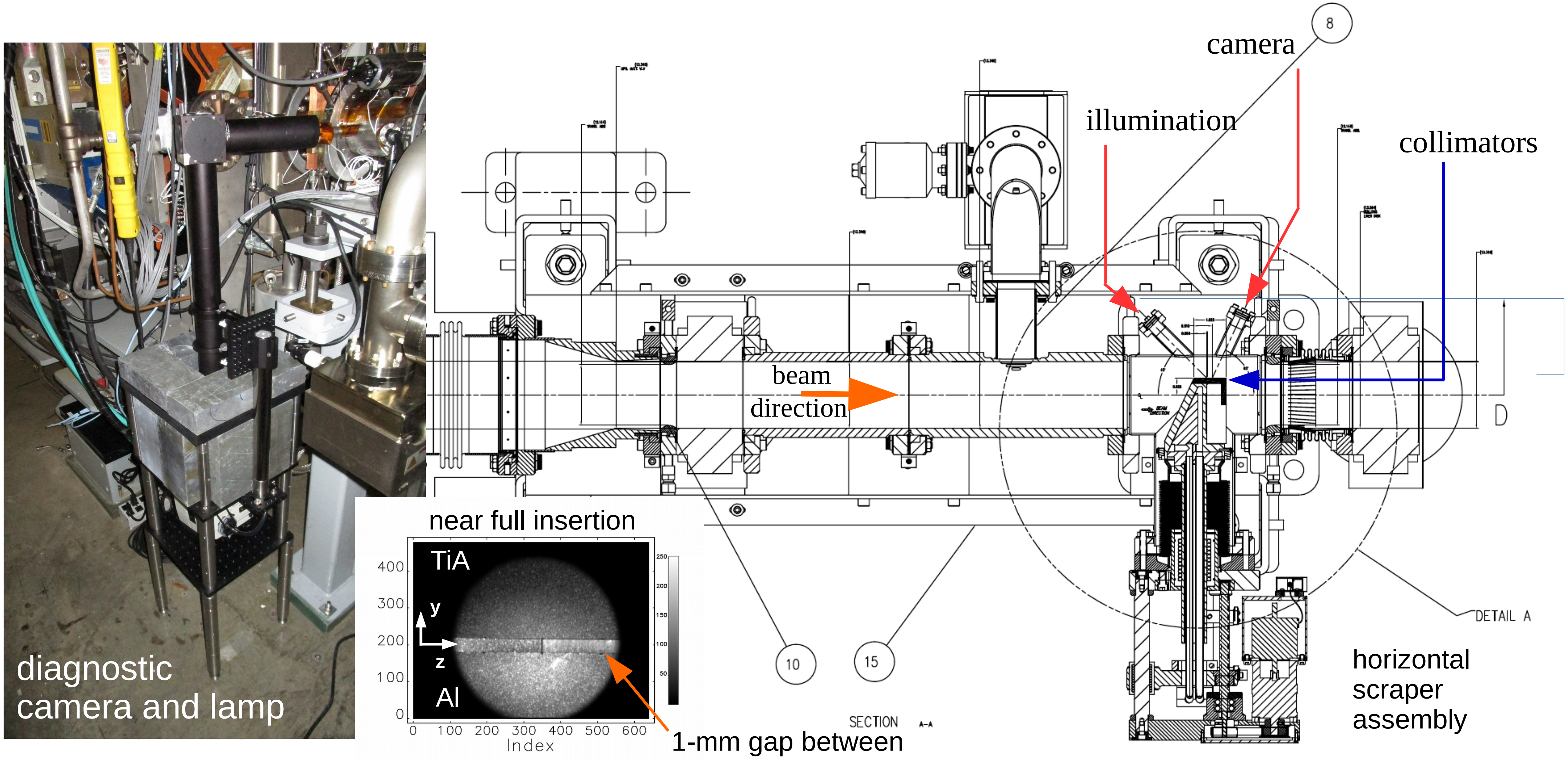


- Using “RHB” (Reduced Horizontal Beamsize) optics decreases predicted melting threshold in both Al-6061 (left) and Ti-6Al-4V (right)
- Low vertical emittance decreases threshold for Ti-6Al-4V, but not for Al-6061 due to high thermal diffusivity of latter

Overview of S37 beam dump experiments

- Movable dump/collimator installed in RHB section in Sector 37
  - Al-6061 (above midplane) and Ti-6A-4V (below midplane) targets
  - Targets have ~1m radius to match intended APS-U speedbump geometry
- Basic plan: abort beam of gradually increasing intensity (from ~1 mA to ~150 mA) into each material at different vertical positions
- Steps in plan
  - Vacuum chamber conditioning with beam (first beam after April-May 2019 maintenance period)
  - Exercise scraper (extend/retract) to reduce outgassing
  - At low current, use beam lifetime to find the edge of the dump and the gap between the materials
  - Perform beam abort tests
  - Time permitting: conduct wakefield experiment at low current
- Unplanned fun: vacuum chamber obstruction in Sector 5 due to unrelated maintenance
  - Worked around it but were limited to ~65 mA
  - Expected maximum dose is ~20 MGy

Mechanical arrangement of the S37 scraper (plan view)



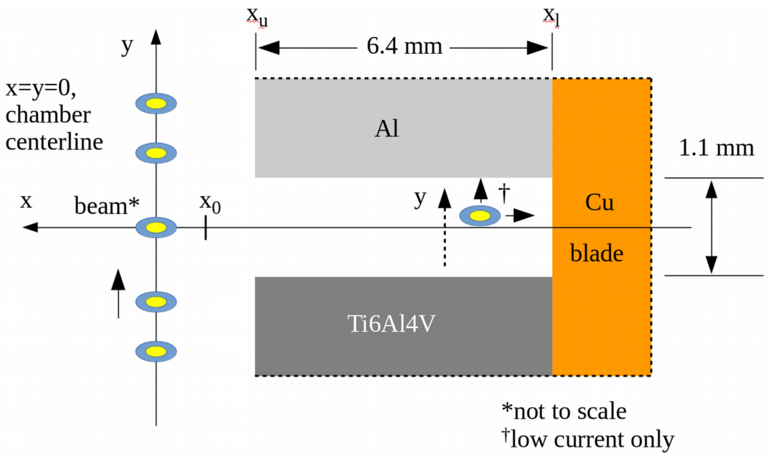
Injection and data collection process

- We require a range of total charges to dump on the two materials
- A low charge per bunch (1.2 nC) was injected in various uniform bunch patterns to cover total currents of 2 mA to 60 mA in roughly logarithmic steps
  - For low total current and low number of bunches, doublets of 1.2 nC were injected to improve rf bpm readings, e.g. 1.8 mA was reached with 2 doublets
- Written procedure (17 points) was followed to prevent accidental marking of the scraper material during injection. Roughly
  - Withdraw scraper
  - Configure injection GUI, and proceed with injection
  - Check uniformity of bunch pattern
  - Check orbit at 0-mm vertical bump
  - Move scraper “close”, i.e. 2 mm horizontally from beam
  - Apply vertical bump, and verify it
  - Abort beam and collect data from various instruments

Scraper alignment is checked using the beam

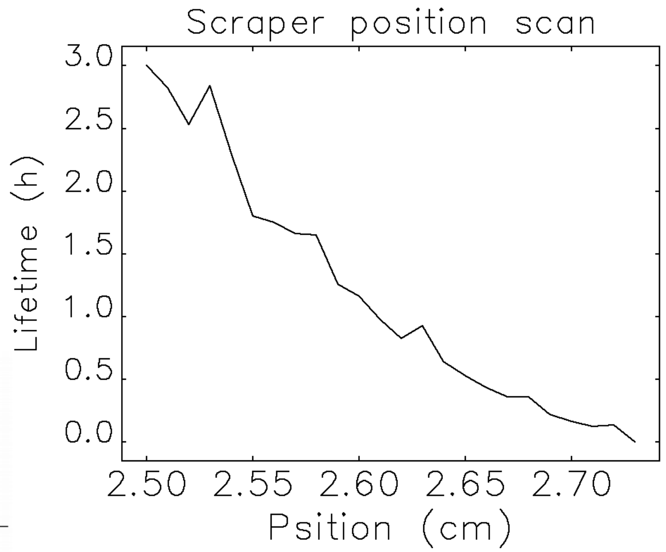
- First, scraper horizontal position is calibrated by measuring the lifetime as a function of the scraper position
  - Vertical orbit position is deliberately set high to avoid the gap between two scraper materials
  - A setting of 2.60 cm corresponds to beam-to-scraper distance of 2 mm
- Then, the orbit is moved vertically to find the position of the gap by measuring the beam lifetime
  - Simulations were performed prior to the experiment to test the concept
  - As expected, the lifetime measurement clearly showed the position of the gap

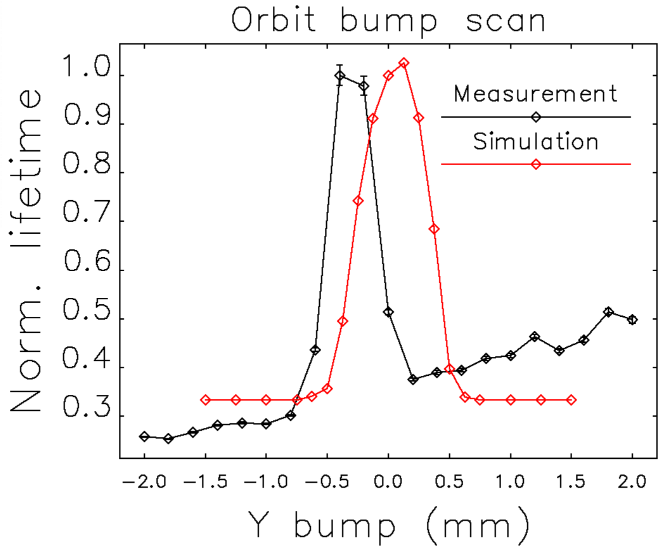
Section of the scraper assembly near the gap between collimator pieces —view downstream



*not to scale

†low current only

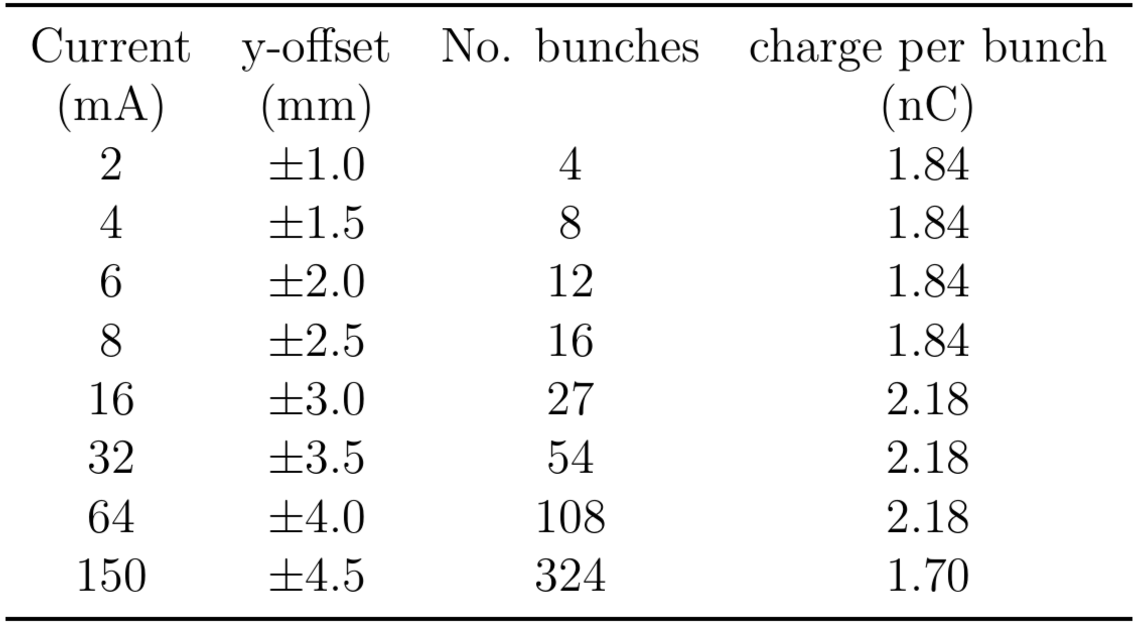




Planned and actual beam dumps during collimator irradiation studies

A partial blockage in ID5 shortened the time available for the experiment

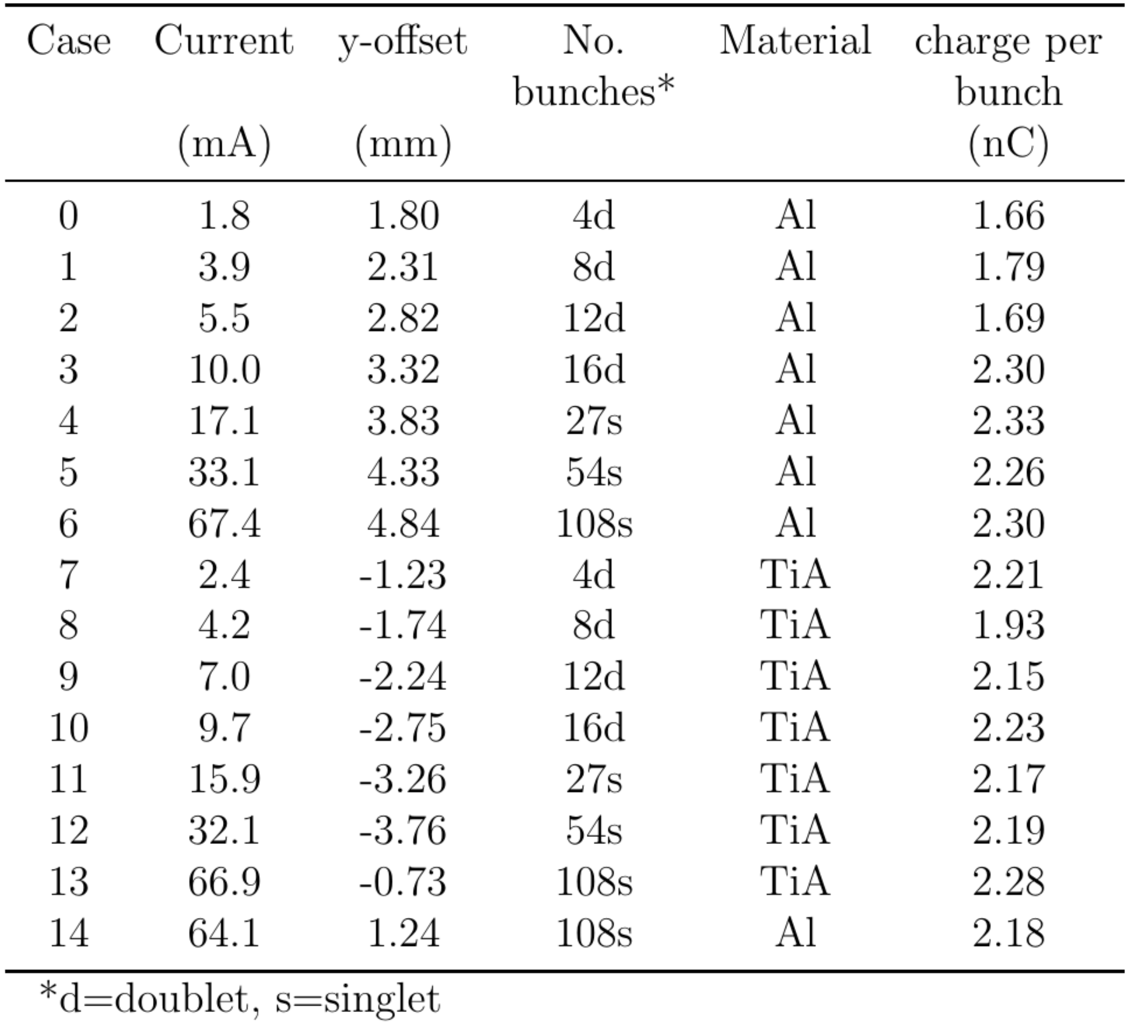
Planned beam dumps



Current (mA)	y-offset (mm)	No. bunches	charge per bunch (nC)
2	±1.0	4	1.84
4	±1.5	8	1.84
6	±2.0	12	1.84
8	±2.5	16	1.84
16	±3.0	27	2.18
32	±3.5	54	2.18
64	±4.0	108	2.18
150	±4.5	324	1.70

Positive y-values in Al (6061),
negative y in Ti-alloy (TiA=Ti6Al4V)

Actual beam dumps

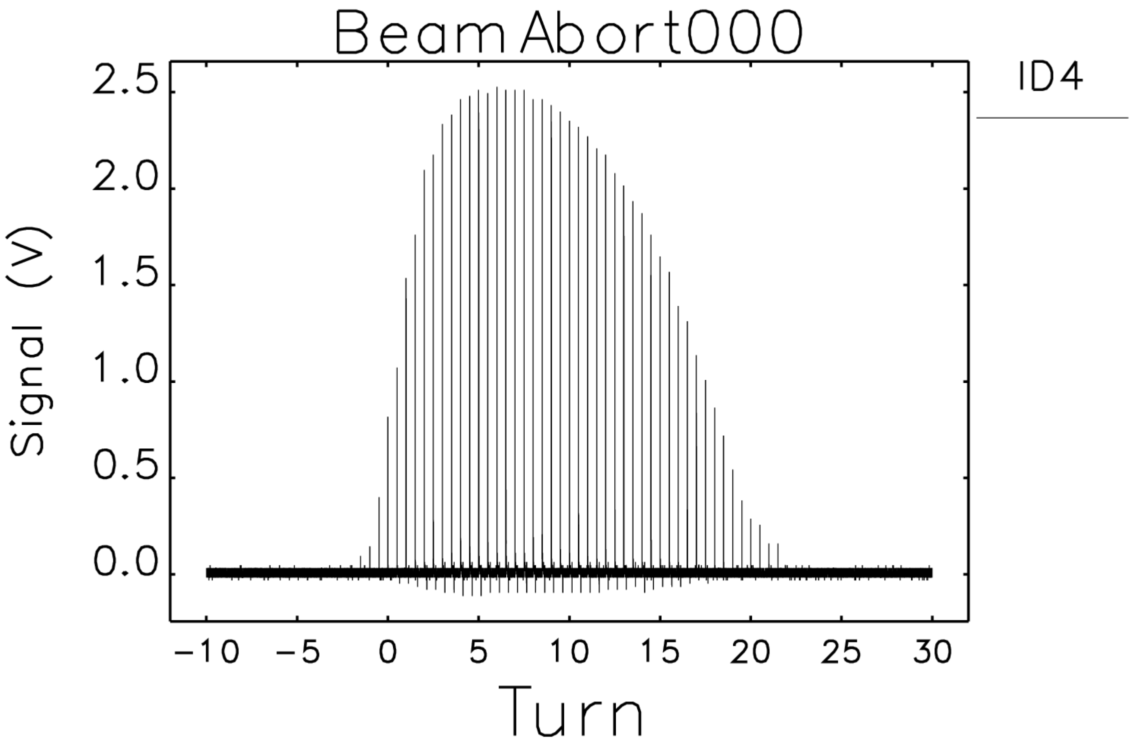


Case	Current (mA)	y-offset (mm)	No. bunches*	Material	charge per bunch (nC)
0	1.8	1.80	4d	Al	1.66
1	3.9	2.31	8d	Al	1.79
2	5.5	2.82	12d	Al	1.69
3	10.0	3.32	16d	Al	2.30
4	17.1	3.83	27s	Al	2.33
5	33.1	4.33	54s	Al	2.26
6	67.4	4.84	108s	Al	2.30
7	2.4	-1.23	4d	TiA	2.21
8	4.2	-1.74	8d	TiA	1.93
9	7.0	-2.24	12d	TiA	2.15
10	9.7	-2.75	16d	TiA	2.23
11	15.9	-3.26	27s	TiA	2.17
12	32.1	-3.76	54s	TiA	2.19
13	66.9	-0.73	108s	TiA	2.28
14	64.1	1.24	108s	Al	2.18

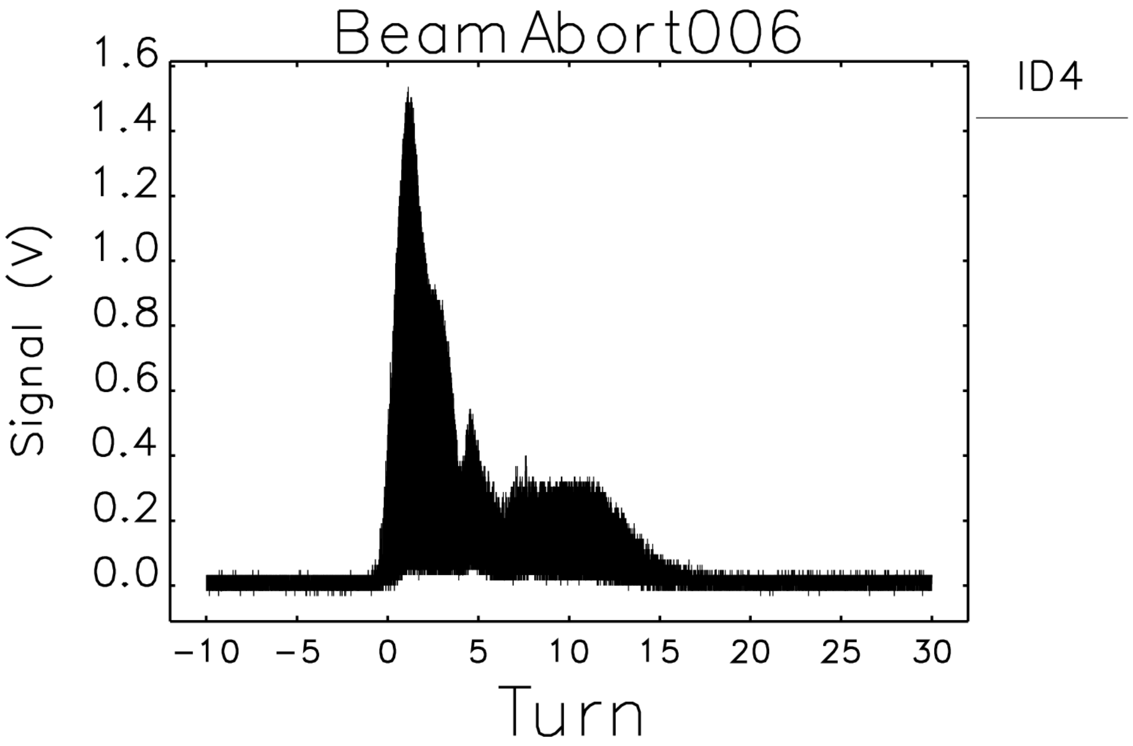
*d=doublet, s=singlet

Fast Beam Loss Monitor Diagnostics—Cerenkov Detector in ID4

4 doublet pulses (1.8 mA)



108 singlet pulses (64 mA)

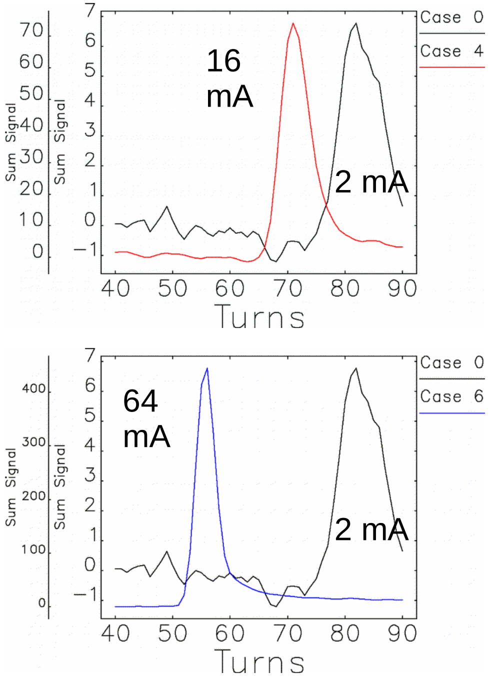


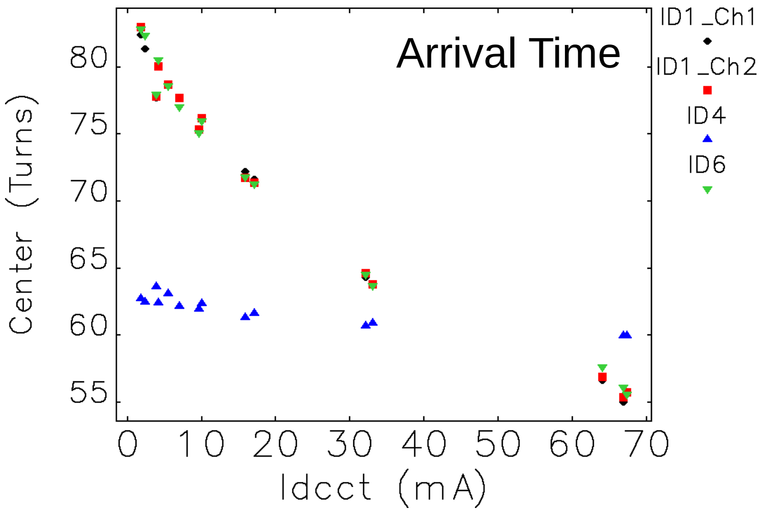
For bunch loss duration analysis, time data is divided into fast and slow axes and presented as a contour plot

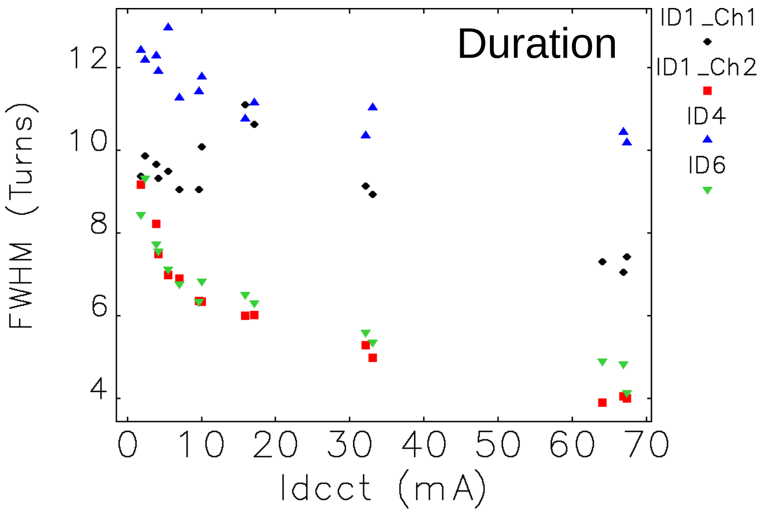
Fast Beam Loss Monitor Diagnostics

- Cerenkov/OTR light detection; located in S37, ID1, ID4, and ID6
- S37 weak but good signals at other locations; S37 and ID4 self-triggered
- Provides loss pulse duration and arrival time (AT—after rf mute; ID1 and ID6 only)
- Pulse duration observed to decrease with increasing current—mechanism unclear
- AT occurs earlier with increasing current—ohmic losses/resistive wall increase as I^2R
- Narrow-gap chamber in ID4 probably the clearest indication of pulse duration

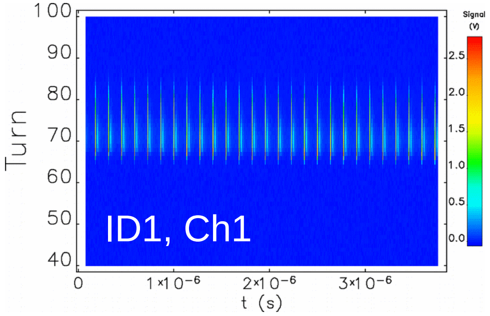
ID1, Ch2



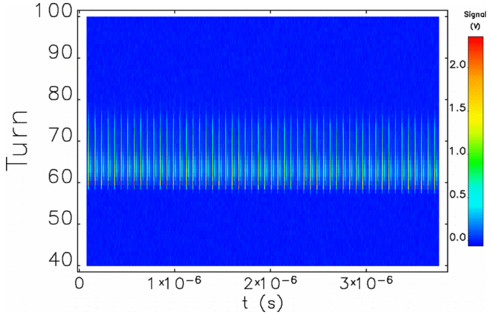




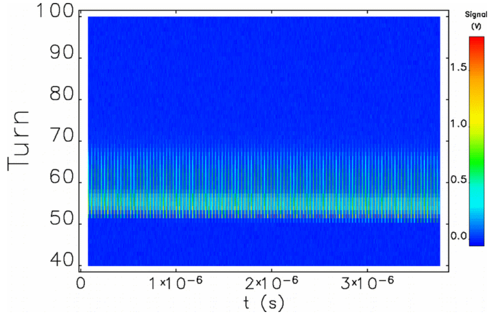
16 mA, 27 bunches



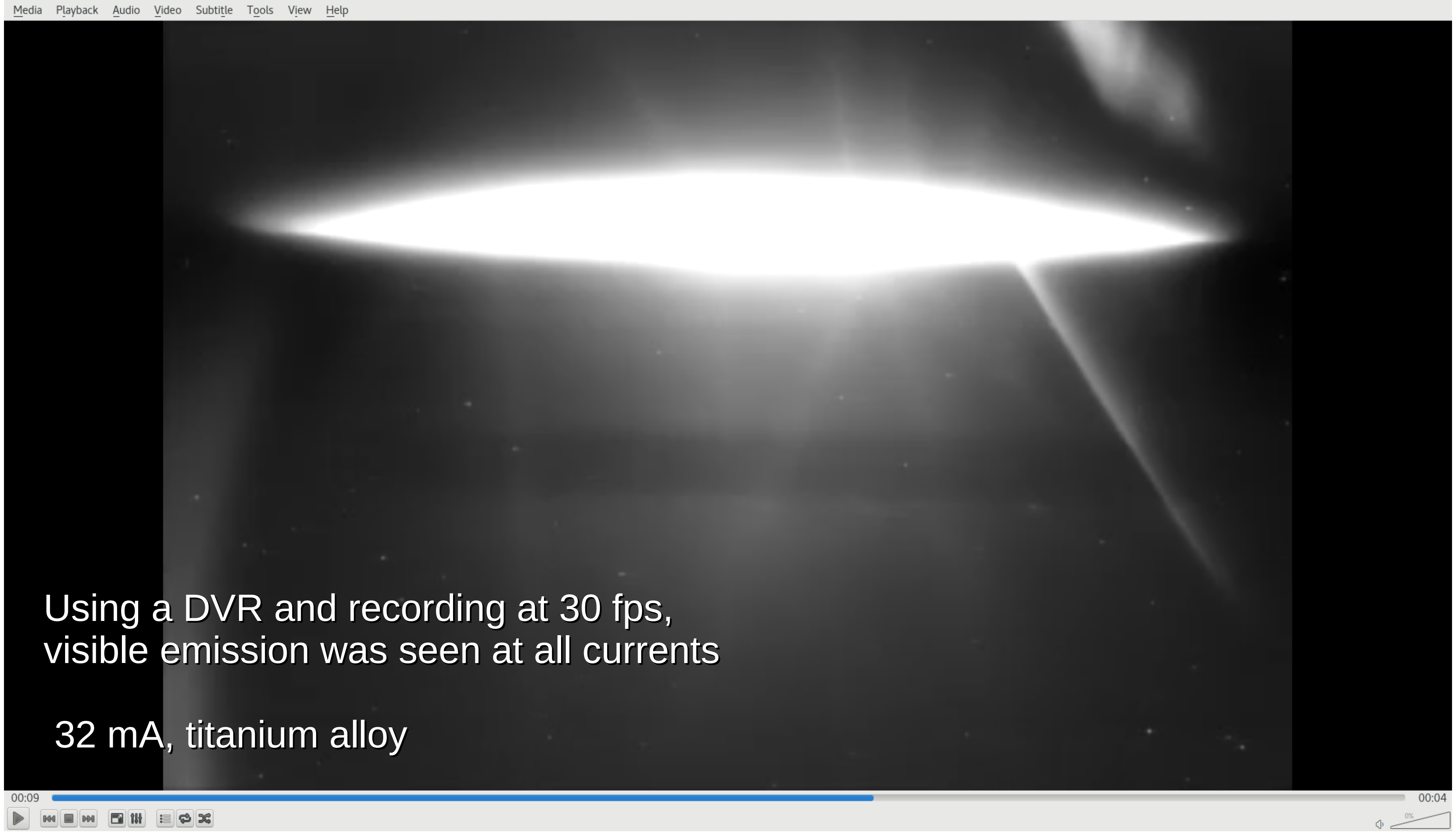
32 mA, 54 bunches



64 mA, 108 bunches



Visible light emission during collimator irradiation studies



Using a DVR and recording at 30 fps,
visible emission was seen at all currents

32 mA, titanium alloy

Visible light emission during collimator irradiation studies

64 mA, titanium alloy reduced iris

Streamers are likely heated ejecta

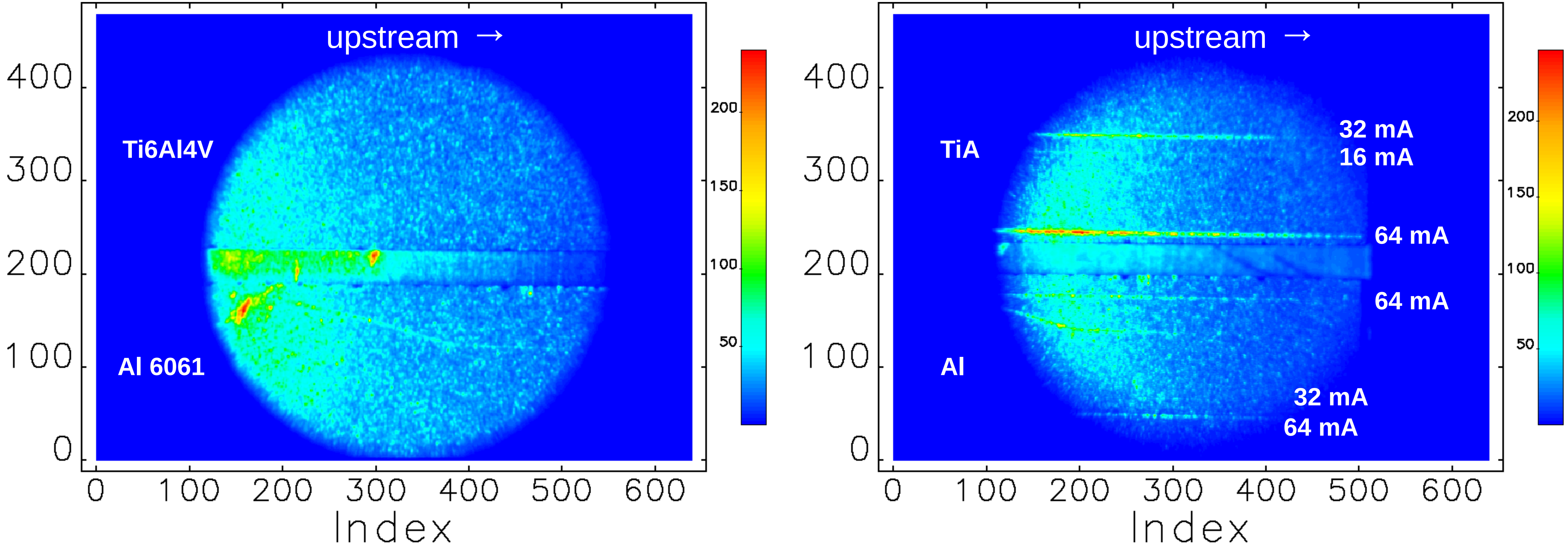
Visible light emission during collimator irradiation studies

Titanium alloy

Aluminum 6061

Emission at high current likely do to BB radiation

Diagnostic Camera Images Before and After Beam Dumps



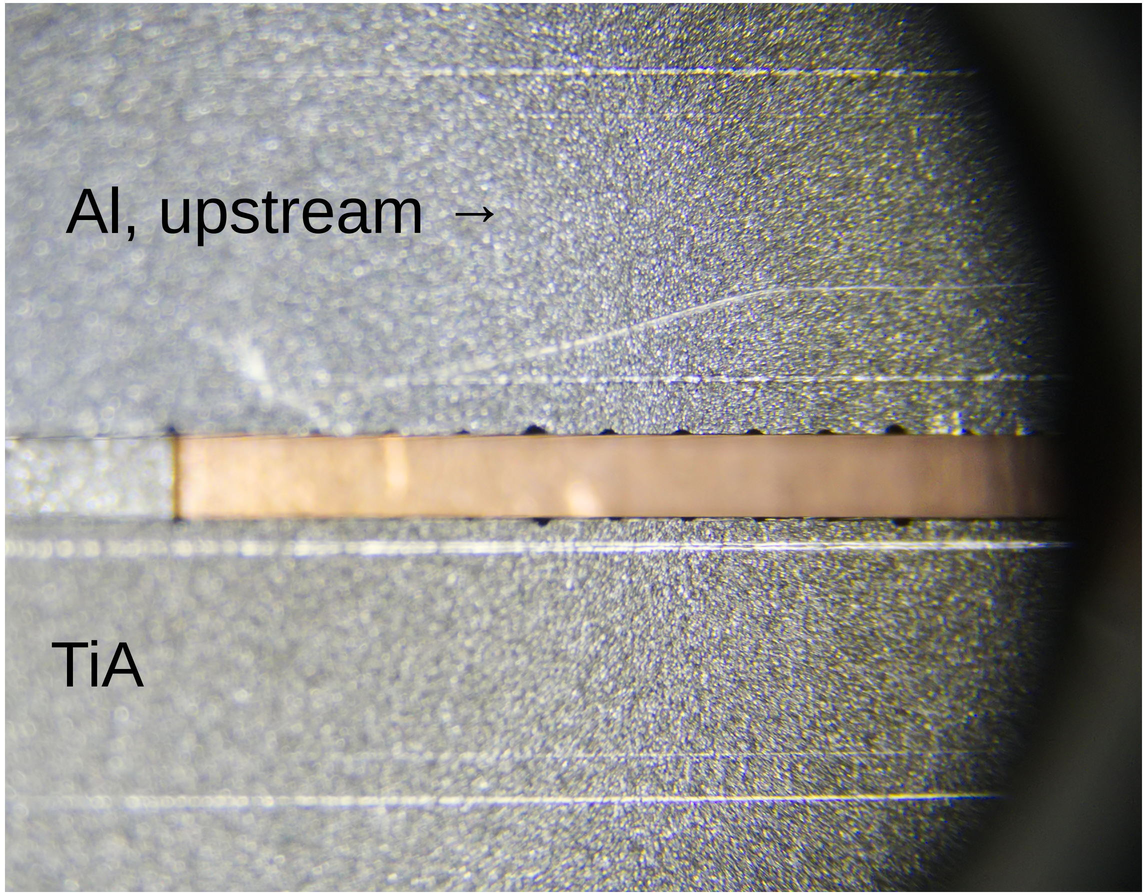
Before

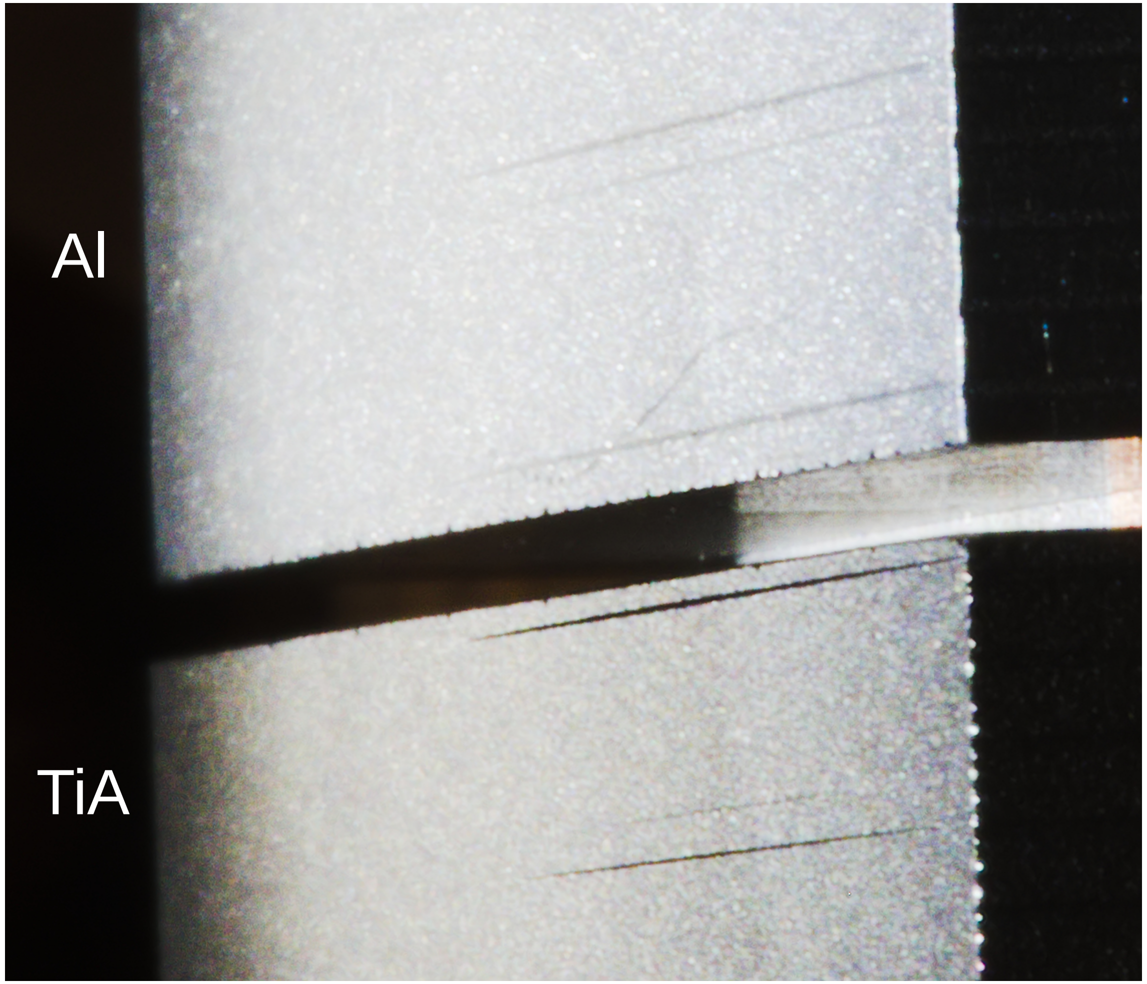
After

- Views are vertically flipped compared to actual installation
- Illumination grows stronger moving from right to left

Photography of collimator pieces after removal from SR—still mounted

Substantial differences in tracks observed between
Al and TiA at the same current

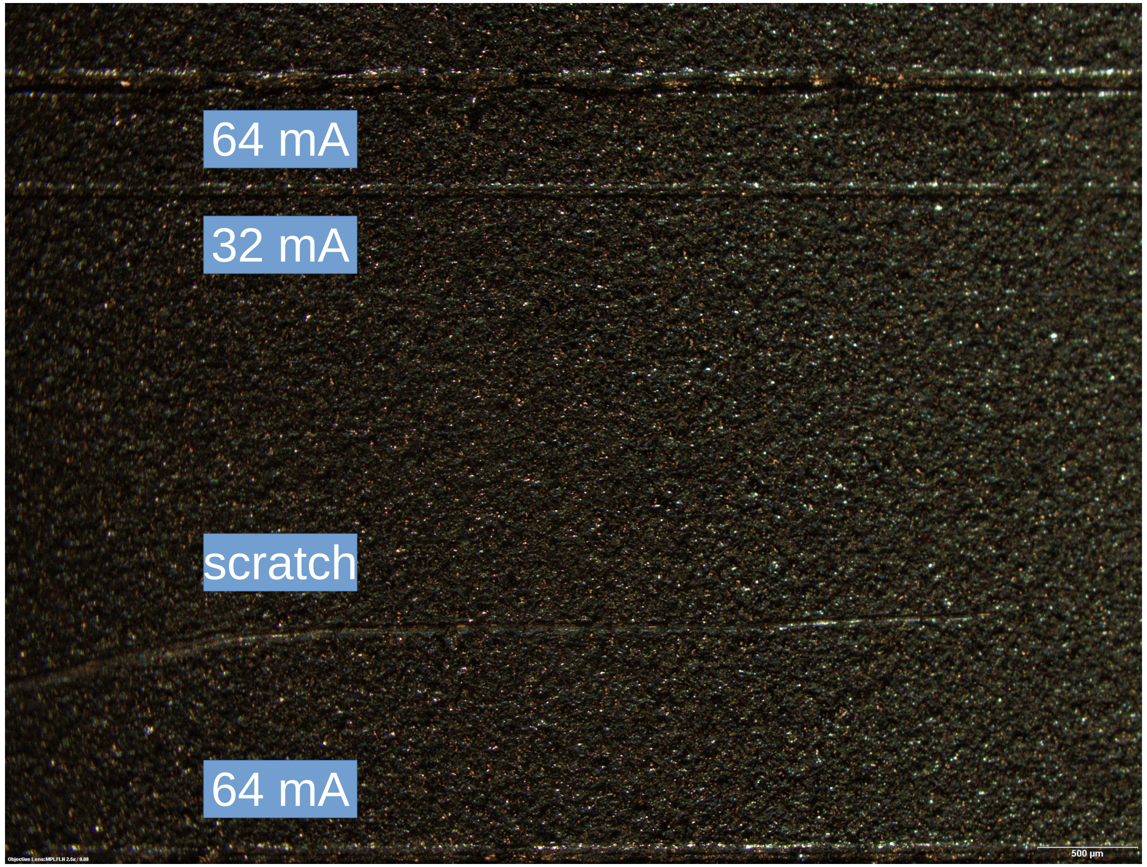




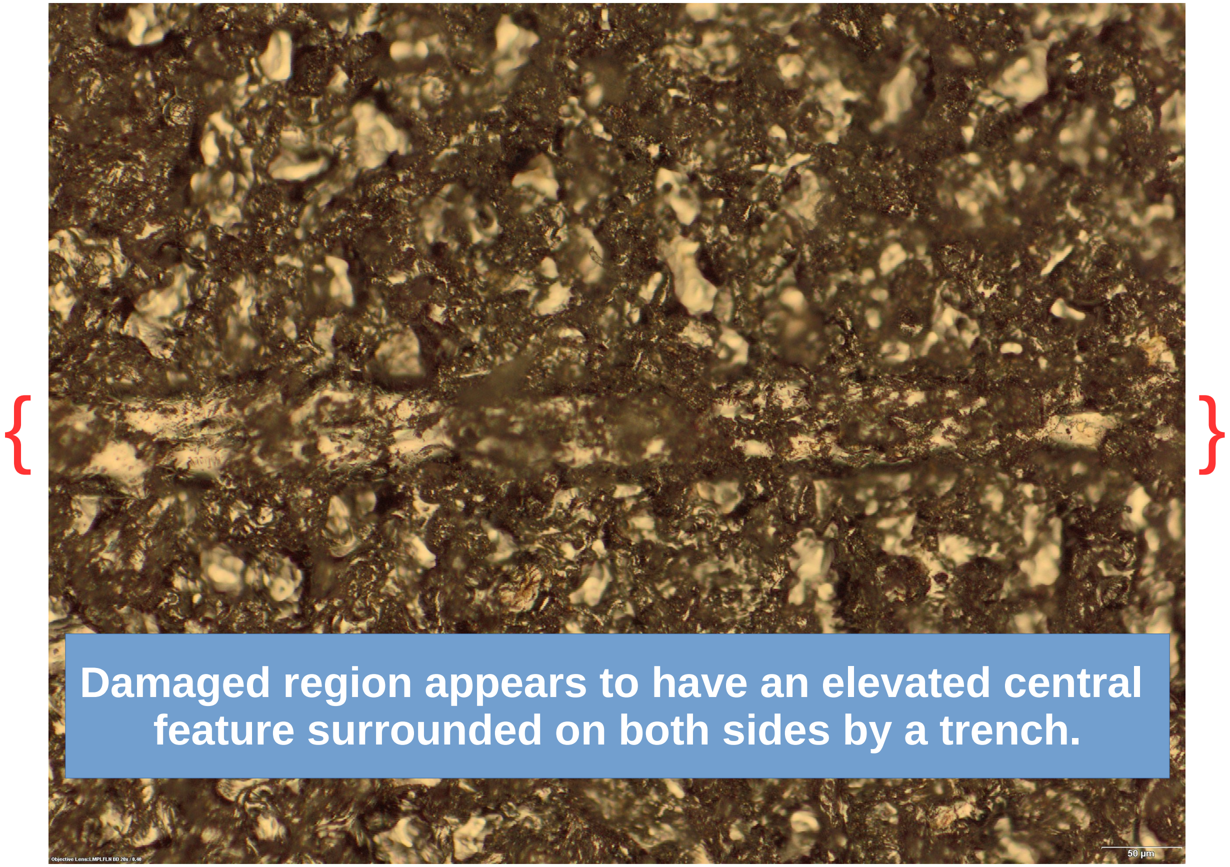
Microsopy—Aluminum collimator piece

Using an Olympus BX51M metallurgical microscope

Illumination from top (blue-white) and normal (orange)



32 mA, single source illumination

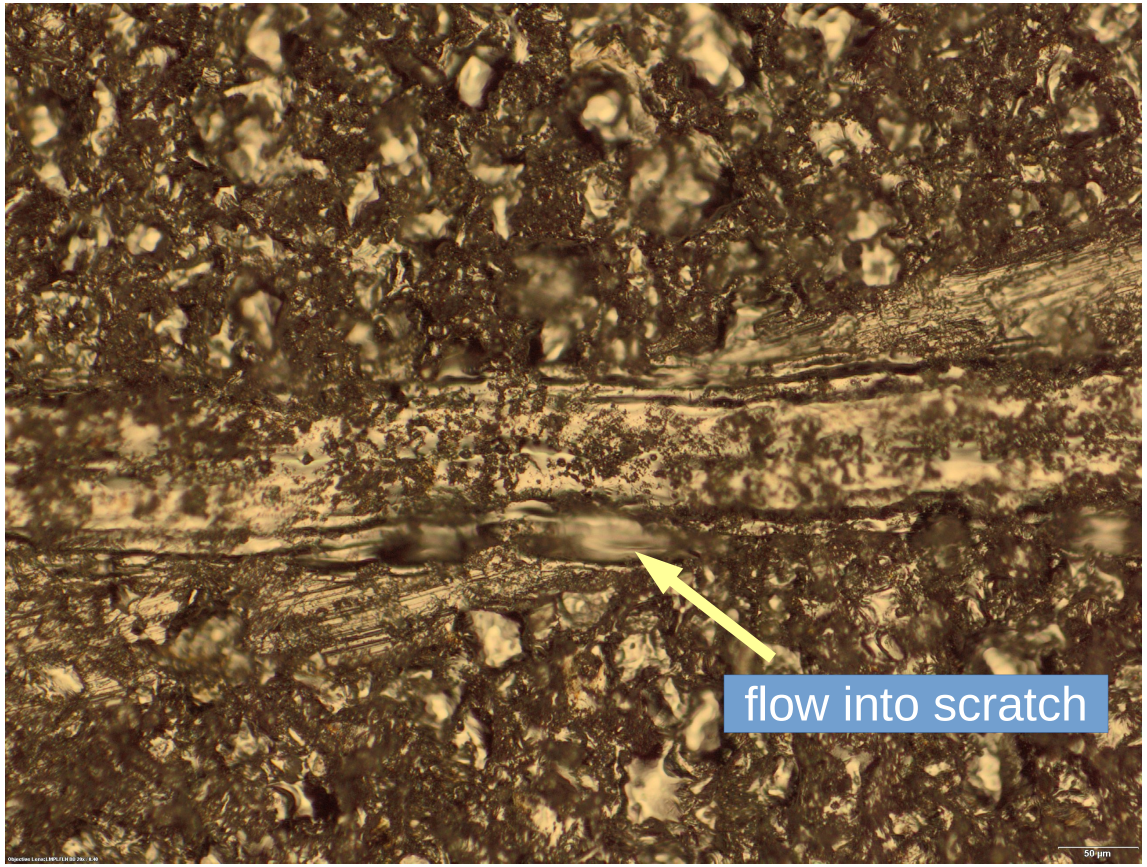


Damaged region appears to have an elevated central feature surrounded on both sides by a trench.

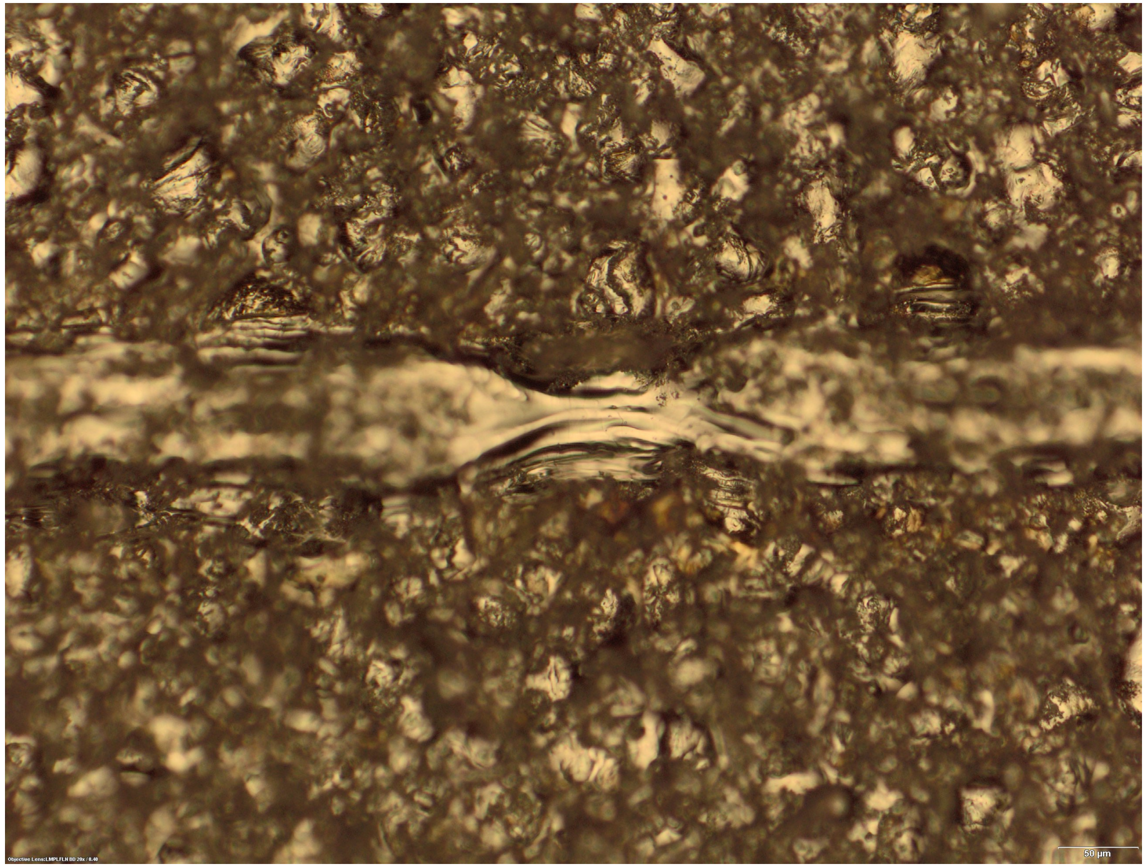
—microscope photographs courtesy of G. Navrotski

Al Microscopy, continued

64 mA, over scratch



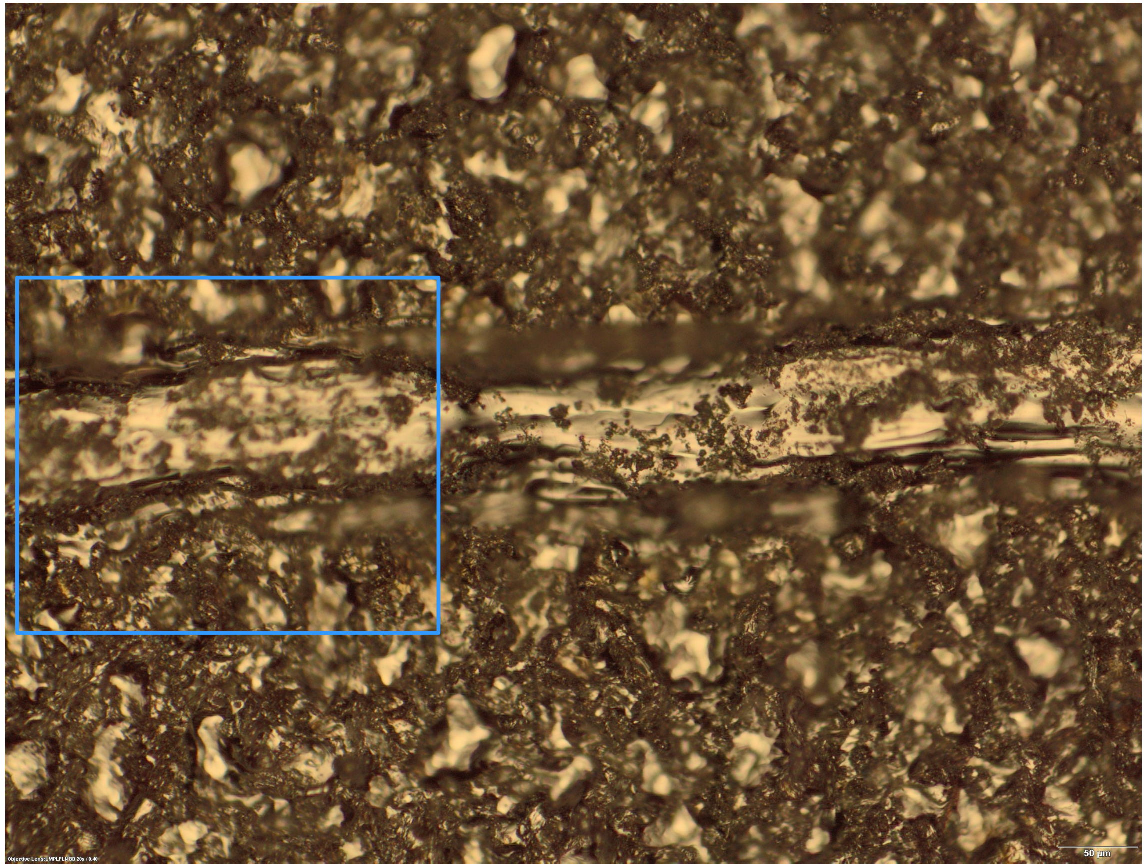
64 mA, neck



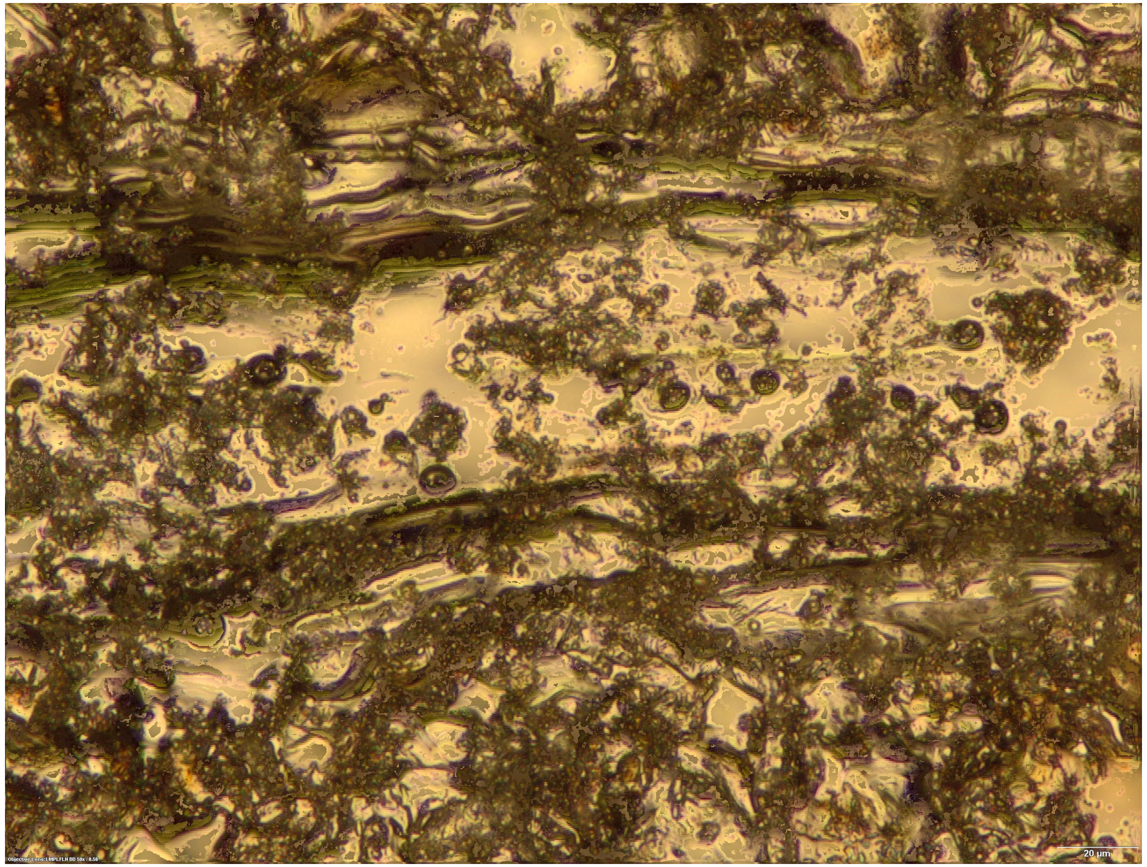
—microscope photographs courtesy of G. Navrotski

Al Microscopy, continued

64 mA, necking, narrow DOF



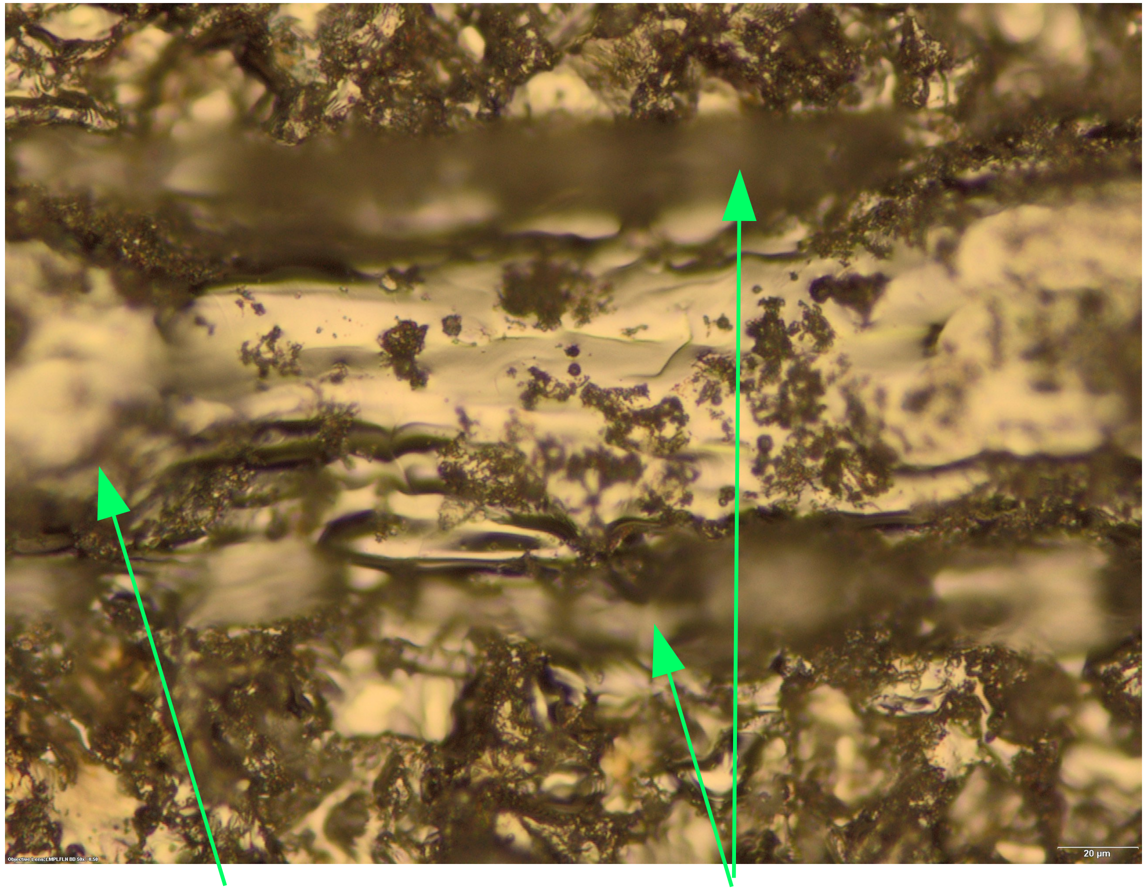
64 mA, zoom reconstruction



—microscope photographs courtesy of G. Navrotski

Al Microscopy, continued

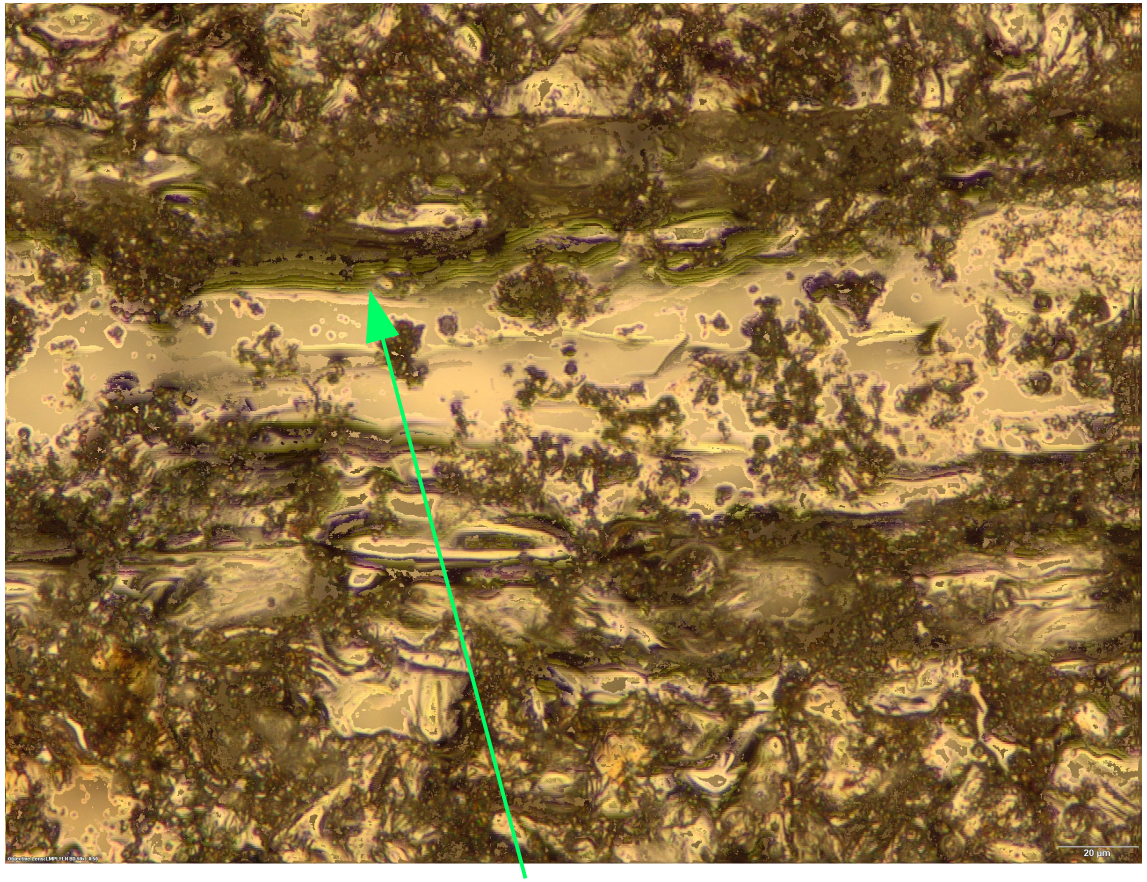
64 mA, necking, narrow DOF



Out of focus (high)

Out of focus (low)

64 mA, zoom reconstruction, 0.5 µm steps



“Terraced” regions

Metallugical Analysis

Underway to determine:

- Melting
- grain size & re-growth
- heat affected zone
- strength profile

Analysis conducted by G. Navrotski, ANL/XSD

Recent metallurgical examination of Al collimator sample

64 mA

32 mA

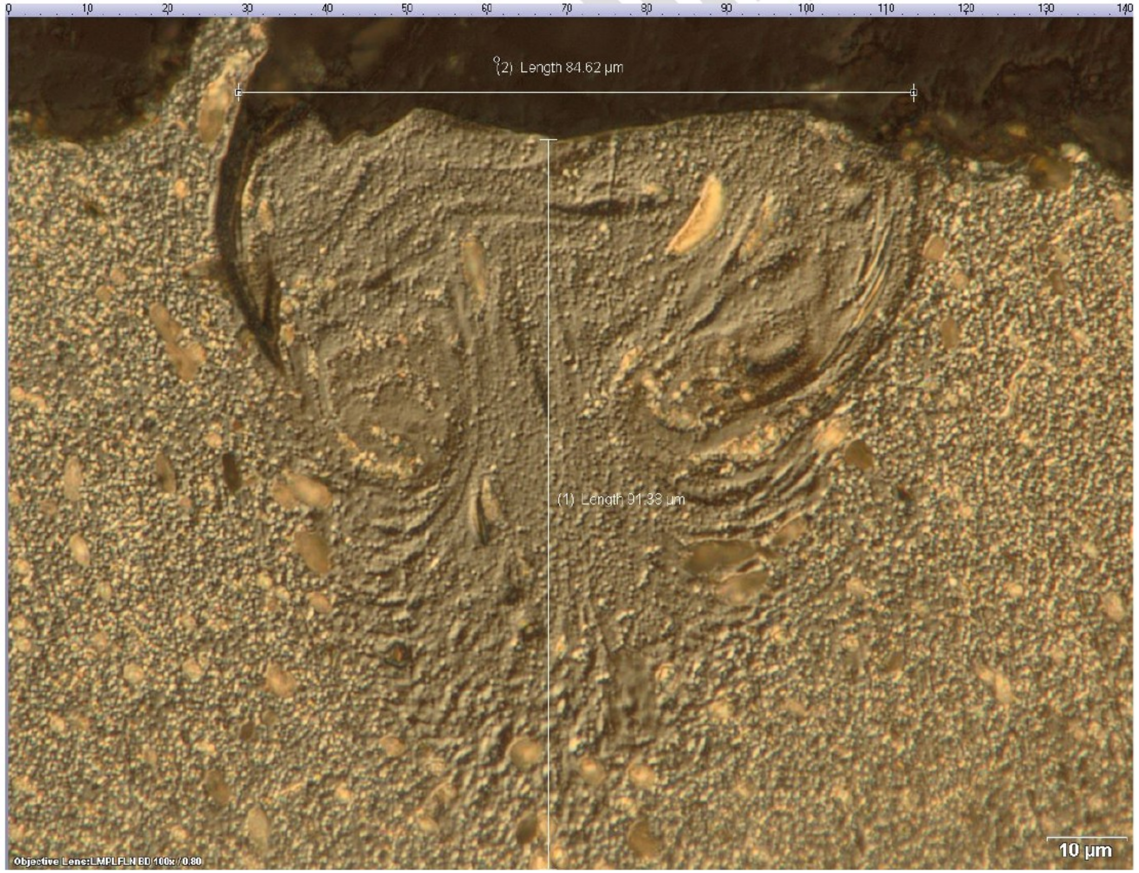


Figure 12: Highly magnified cross-section microstructure at RoI 1 under polarized indirect lighting. (Barker's etch)

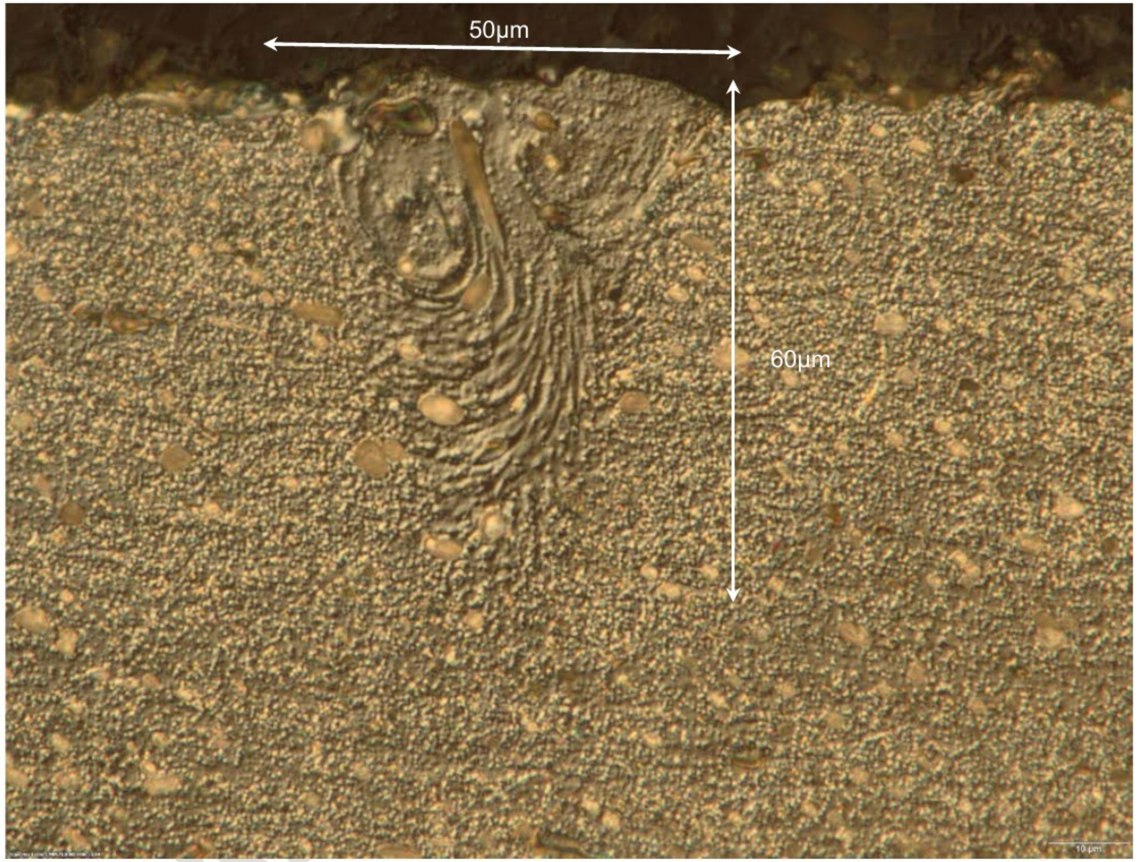
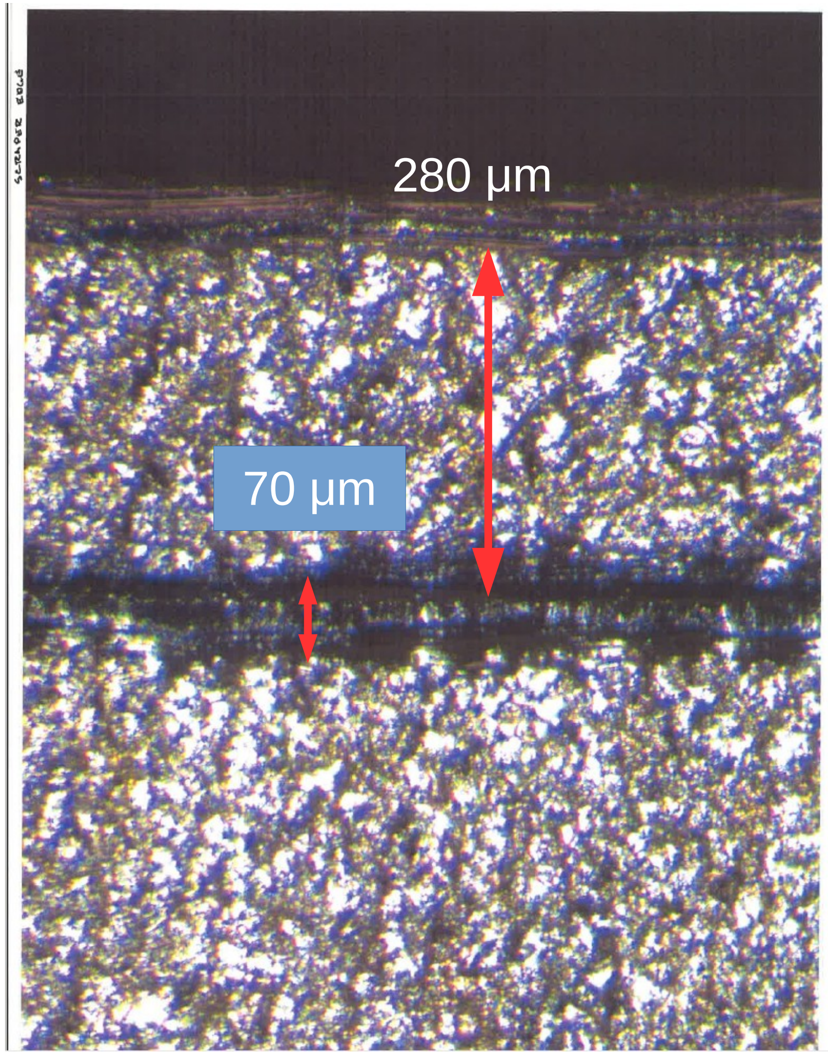


Figure 15: RoI 4 at the location of the 32 mA beam strike. (Barkers etch)

TiA Microscopy

64 mA

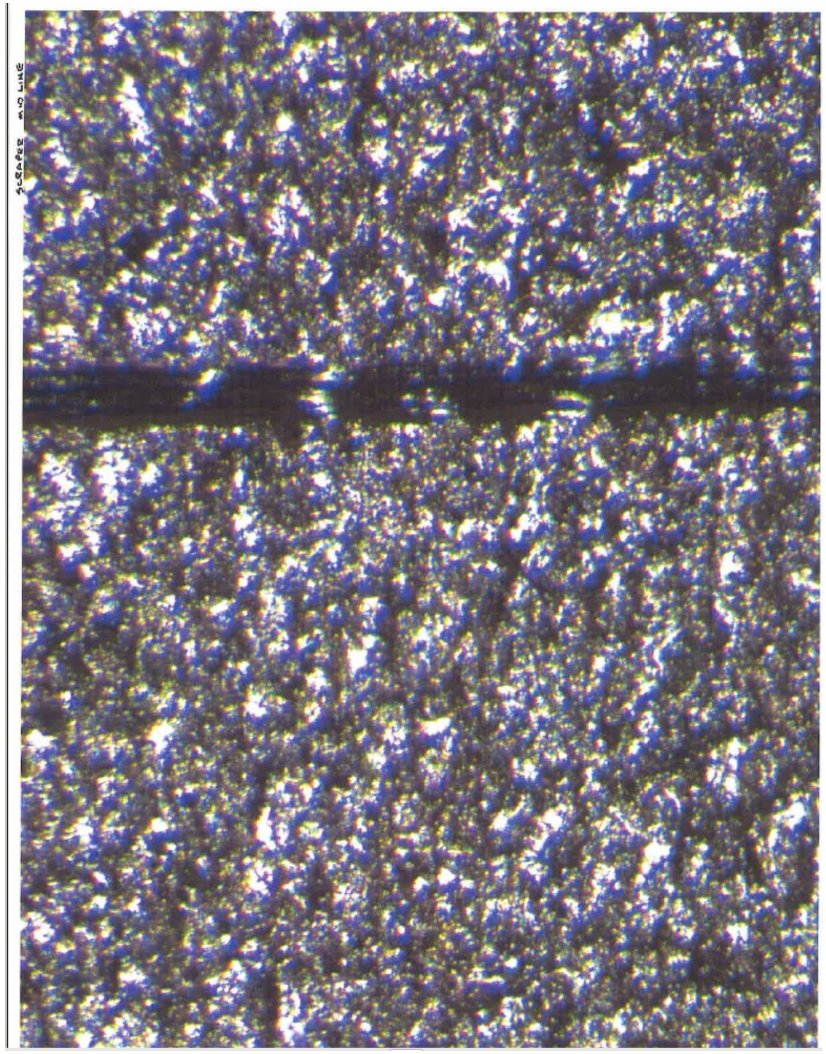


TiA piece is activated and cannot be viewed or examined with the same Instrumentation.

In the 64-mA case, the central region is now a trench.

32-mA case appears to be a combination of melt and trench.

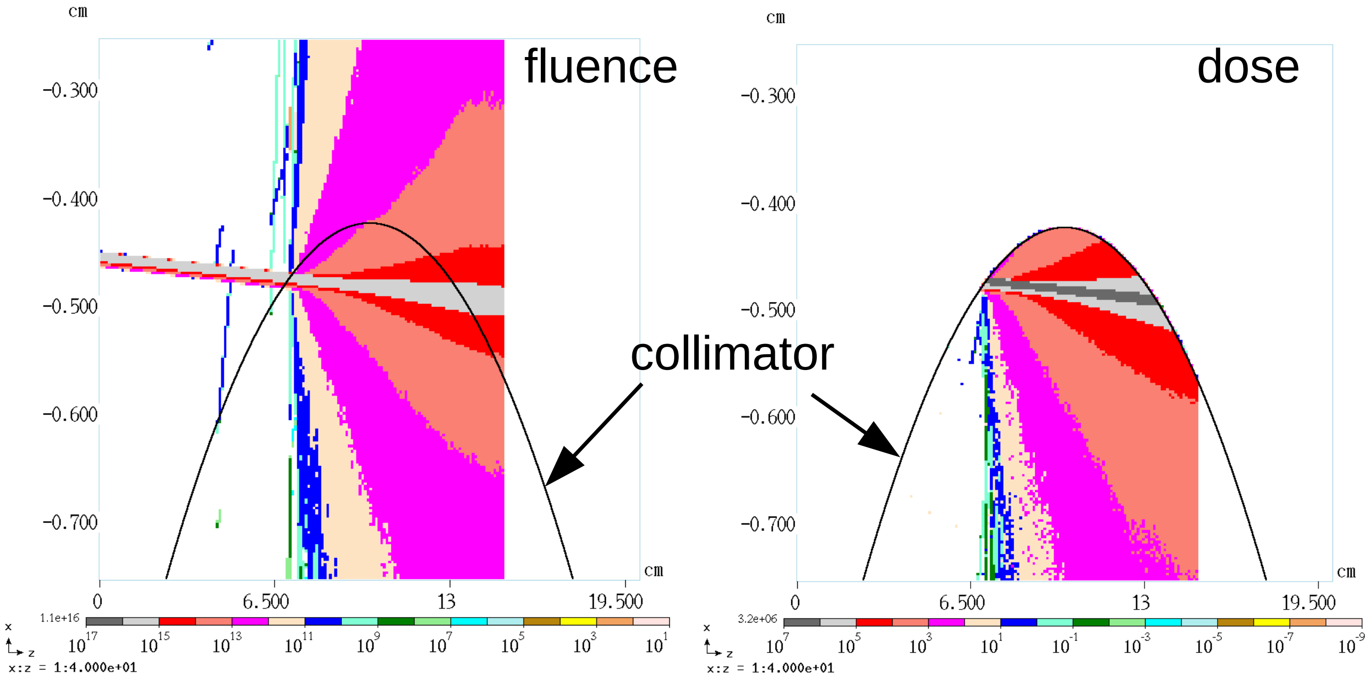
32 mA



Simulation efforts

- Seeking to couple MARS with a hydrodynamics code
  - FLASH (U. of Chicago)
  - LS-Dyna (LTSC, Simutech)
  - COMSOL—pseudo coupling
- For beam dynamics may also need to incorporate elegant
  - Loss duration
  - Transverse motion due to energy loss and local dispersion
- Need to handle phase transitions and shocks
  - Condensed matter→ Warm dense matter
  - EOS cold start in FLASH

Highly anamorphic x-z lateral views of electron-positron flueunce (left) and dose (right) interacting with the collimator (single 15.3 nC, 6 GeV bunch)



- Initially modeled beam striking below the apex
- In reality, beam strikes first at the apex and moves inboard due to local dispersion and energy loss: $\Delta x=\eta_x(\Delta p/p)$
- Must properly account for this motion

Coupling MARS with FLASH (U. of Chicago)

Parameter	eV/atom	kJ/mol
Per Bunch	2.79	279
48 Bunches	133.9	13390
L_f	0.11	11
L_v	2.84	284
L_s	3.26	326
1st Ioniz.	5.78	578
2nd Ioniz.	18.17	1817
3rd Ioniz.	27.45	2745
$\Delta T = 10K$	0.0025	0.25
$\Delta T = 100K$	0.025	2.5
$\Delta T = 1000K$	0.25	25
$\Delta T = 20000K$	5.00	500

Parameter	Temperature (K)	Density(g/cc)
Aluminum	$4 < T < 1.1 \times 10^5$	$4.48 \times 10^{-7} < \rho < 44.8$
Helium	$4 < T < 10^5$	$6.64 \times 10^{-7} < \rho < 6.64$

- L_f, L_v, L_s—fusion, vaporization, and sublimation energies
- LS Dyna uses Lagrangian mesh; FLASH uses Eulerian with adaptive mesh refinement (AMR)

—A. Grannan

Conclusions

- Must protect APS-U from whole beam dumps
  - Dump/collimator will be damaged—present plan: H-collimator sacrificial, move vertically after each beam dump
  - Use hydrodynamics code to assess hydro tunneling and actual DS dose
  - Low-Z metal (probably Al) is the best candidate for the dump/collimator
  - Assuming all loss in one location is conservative
- Have conducted first tests at APS with APS-U-relevant conditions
  - Qualitatively validates understanding of material choice, thermal diffusion
  - Al-6061 superior to Ti-6Al-4V in spite of low melting point
  - Quantitative analysis is on-going
- Hydrodynamic simulations should proceed cautiously to insure integrity of results
- Would like to conduct further experiments
  - Can wakefields be used to diffuse the beam prior to impact?
  - Are there better material choices?

Acknowledgments

- Many contributed to this effort (some could not be present at the study because they were attending IPAC19):

  K. Harkay, W. Berg, K. Wootton, J. Stevens, S. Shoaf, R. Diviero, K. Suthar, A. Grannan, G. Navrotski
- Also wish to thank AES MOM Group’s Mechanical, Vacuum, and Water teams; Survey and Alignment Group, and Health Physics personnel

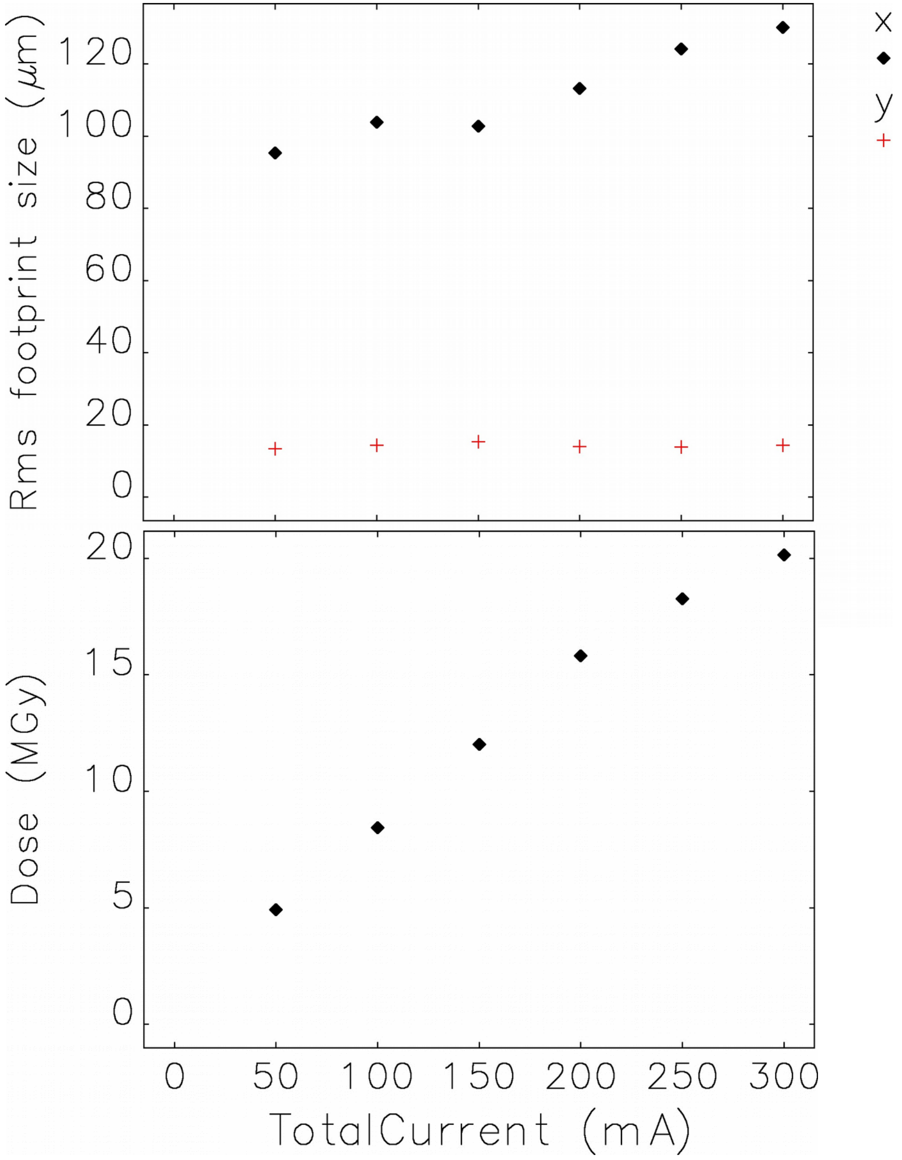
Backup Slides

Accelerator simulation methods are highly realistic

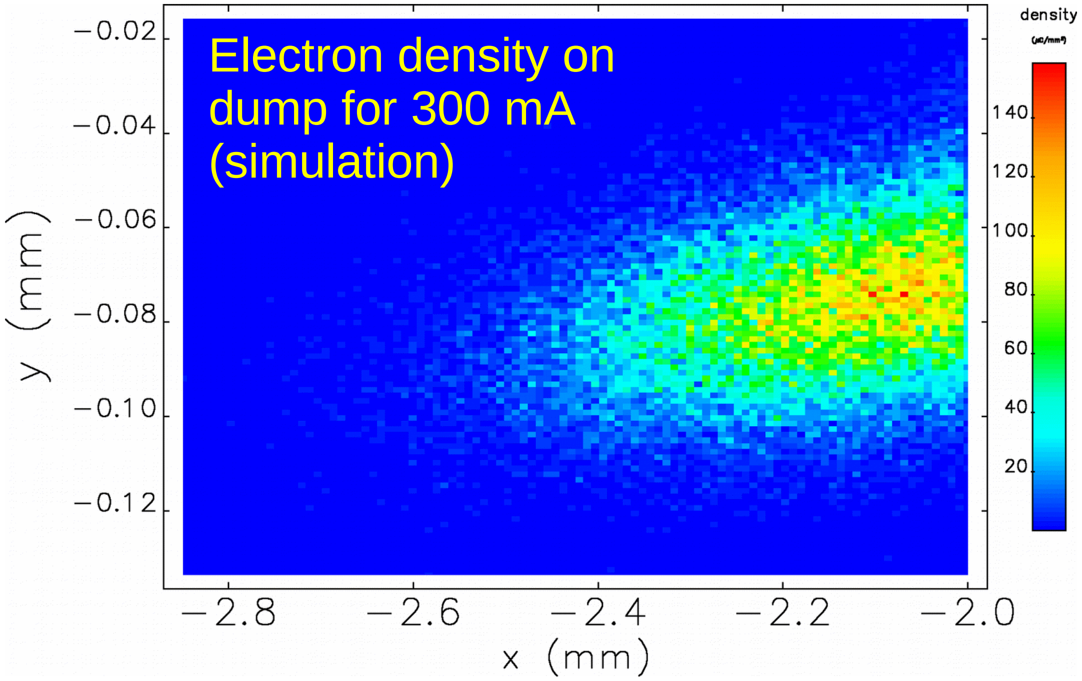
- Whole-beam aborts particularly concerning because of the amount of stored energy, lack of time to diffuse the beam
- Can be initiated without warning, e.g., by machine protection system
- Simulations use several features of the parallel tracking program Pelegant[1,2]
  - Symplectic integration with exact hard-edge Hamiltonian[3]
  - Element-by-element synchrotron radiation[3]
  - Beam-loaded rf systems with feedback[4]
  - Short-range impedance model[5,6,7]
  - Speed-bump collimators
- In simulations, beam is tracked to equilibrium, then rf drive is muted to initiate the abort

1: M. Borland, APS LS-287 (2000).
2: Y. Wang et al., AIP Conf. Proc. 877, 241 (2006).
3: M. Borland, ANL/APS/LS-356 (2019).
4: T. Berenc et al., IPAC15, 540 (2015).
5: Y. C. Chae et al., PAC07, 4336 (2007).
6: R. R. Lindberg et al., IPAC15, 1825 (2015).
7: R. R. Lindberg et al., IPAC15, 1822 (2015).

Dose for APS at 6 GeV is also potentially very high



- Want to explore this using existing APS
  - Have seen melting of W, Cu dumps by 100 mA beam abort in spite of “high” emittance[1]
- Dose from aborting 300 mA approaches 20 MGy
- Can increase dose further by adjusting lattice functions at dump location


Electron density on dump for 300 mA (simulation)

[1] J. Dooling et al., PAC13, 1361 (2013).

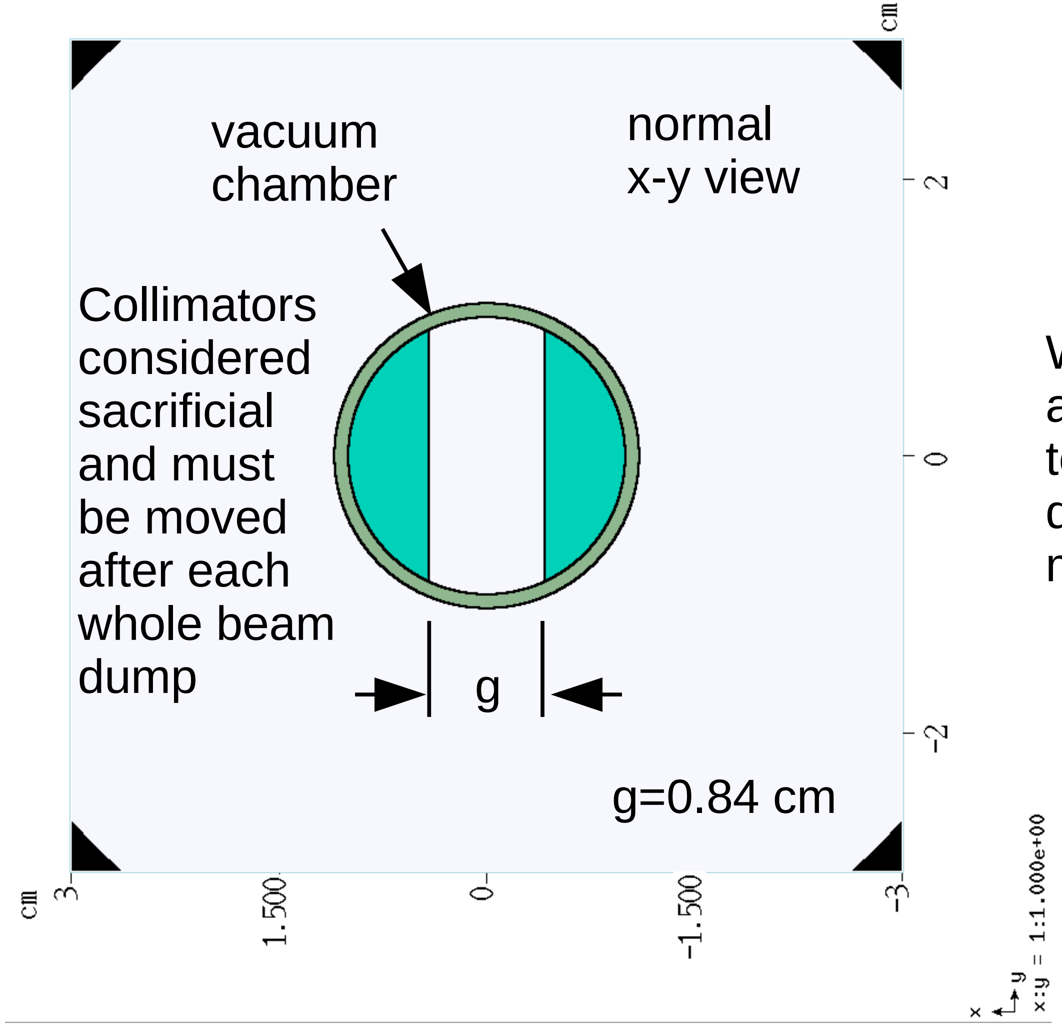
Triple RHB lattice developments*

- Procedure:
  - Verified from previous development of HSCU RHB lattice at ID-7
  - Change two local sectors (20 quads) first
  - Match Tunes to (36.205, 19.275)
  - Optics matching with various constraints: betatron tunes, emittance, dispersion & beta functions at ID, max beta/dispersion…
  - Change other ~20 sectors, Match Tunes to operational tunes of (36.17, 19.24)
- After obtaining linear lattice solution, optimize sextupoles (optional)
- Generate setpoints, apply to APS ring operation
- Measure tunes/coupling, lifetime, injection efficiency, response matrix

* Yipeng Sun, AOP-TN-2018-090, 2018.

Simplified Geometry in MARS for dump collimator and nearby magnet

Have settled on matched cylindrical surfaces to minimize impedance



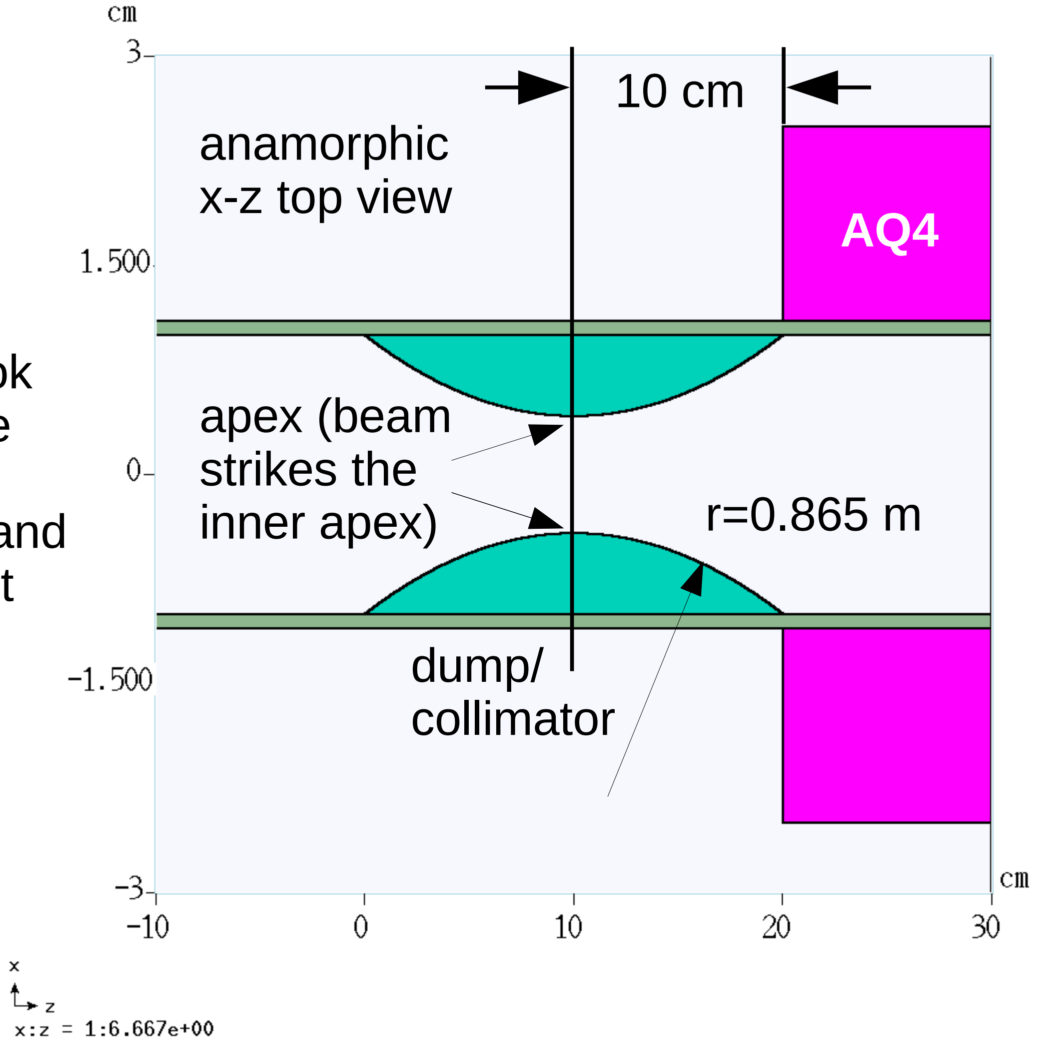
vacuum chamber

normal x-y view

Collimators considered sacrificial and must be moved after each whole beam dump

g=0.84 cm

Will look at dose to the dump and magnet



10 cm

anamorphic x-z top view

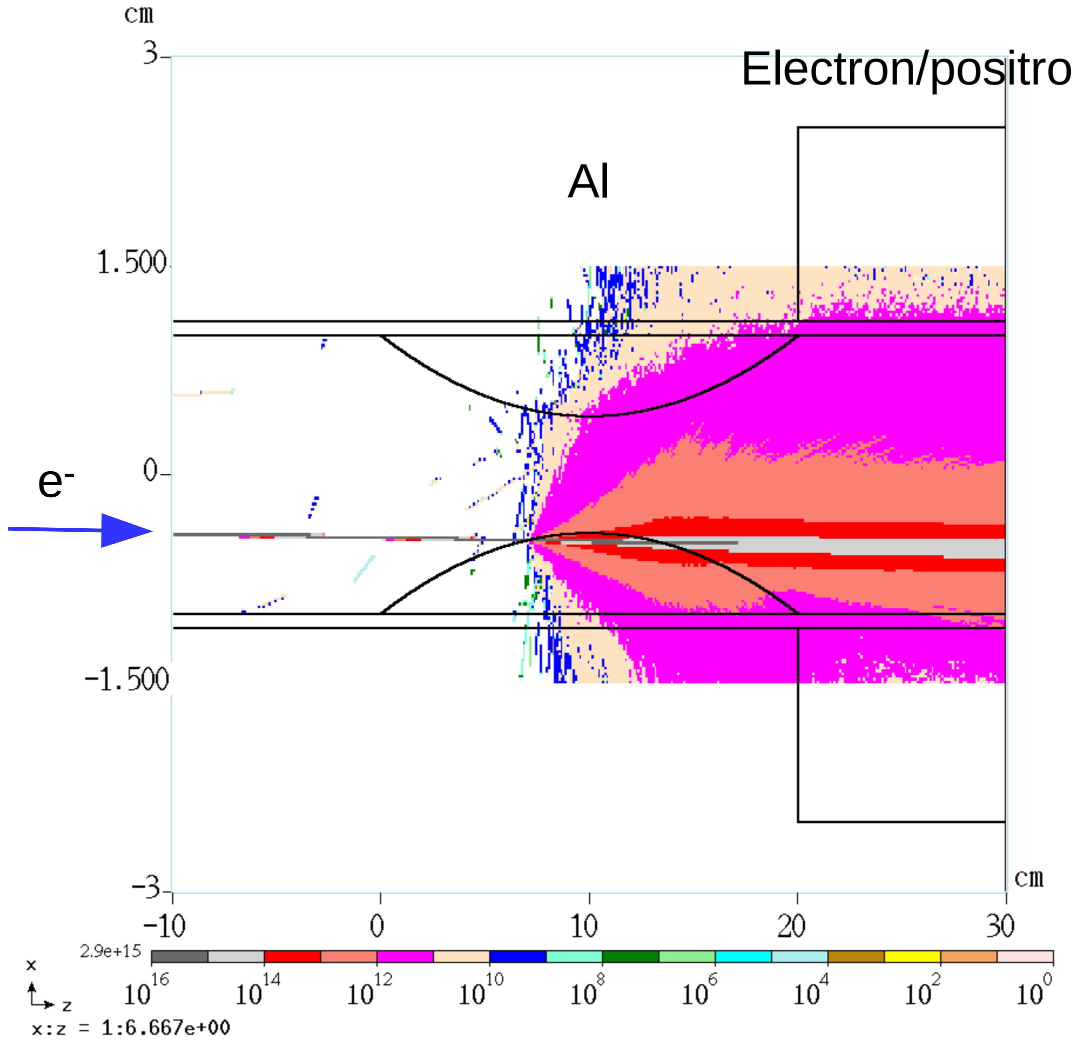
apex (beam strikes the inner apex)

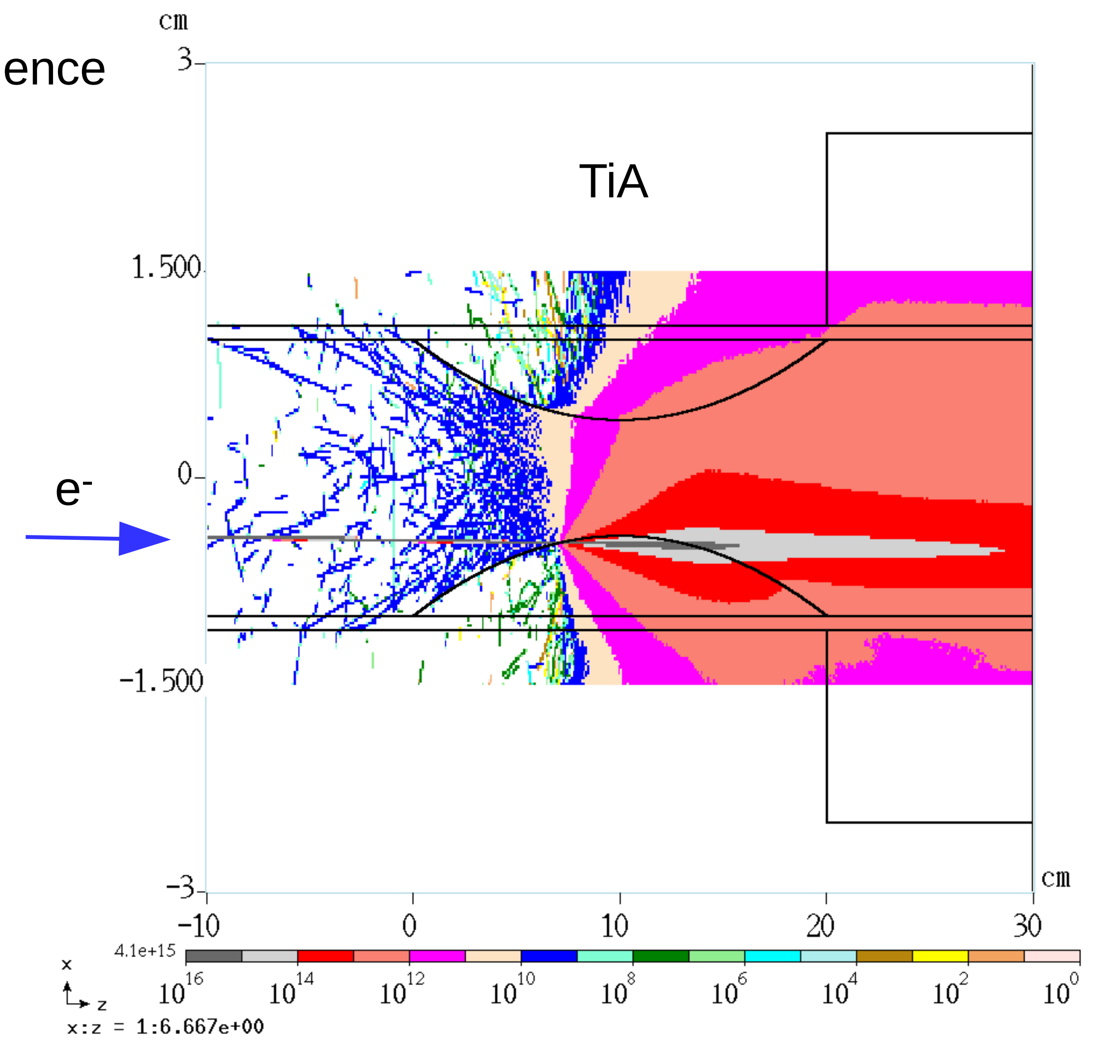
r=0.865 m

dump/ collimator

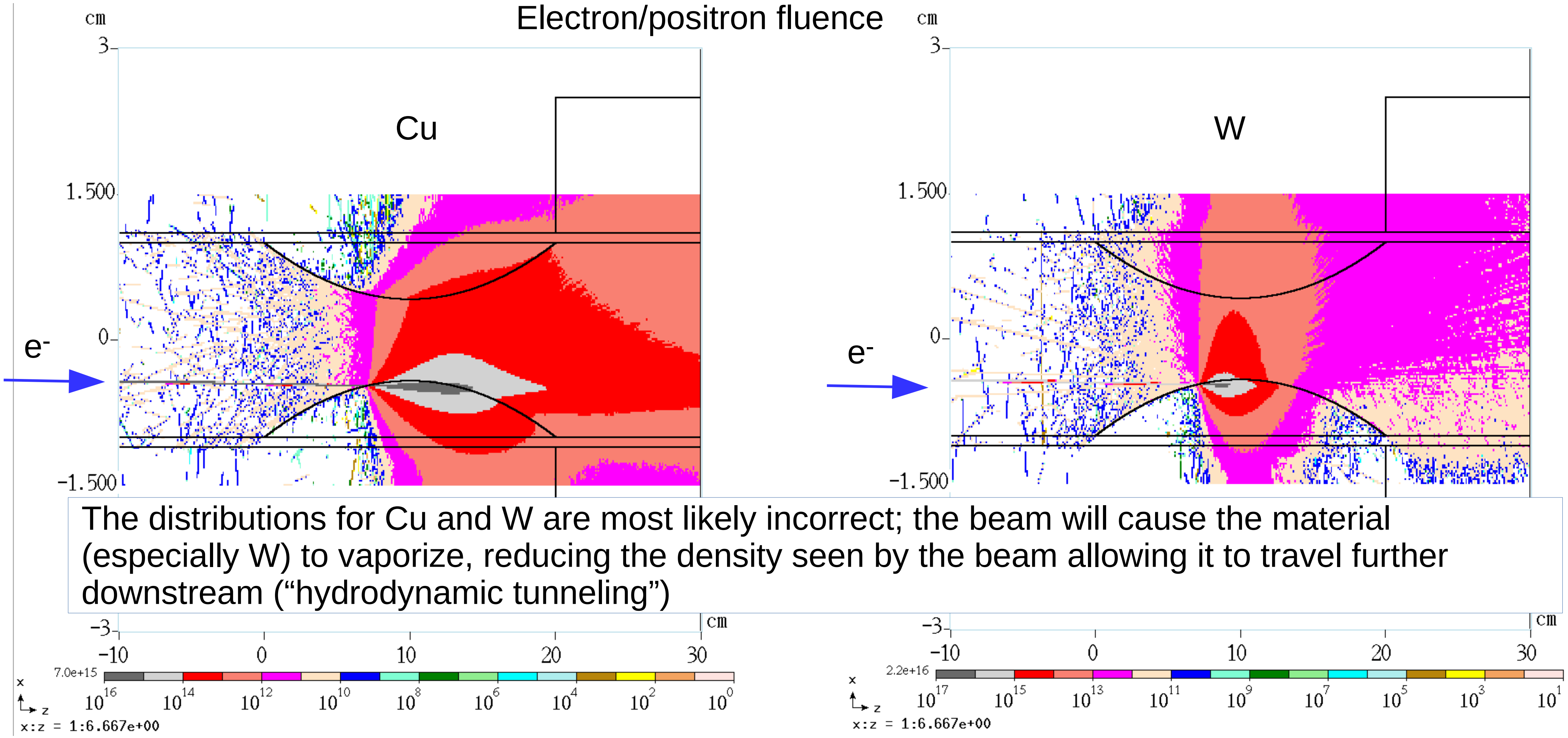
MARS simulations: Beam strike on the dump/collimator—4 candidate materials: aluminum, titanium alloy, copper, and tungsten

Electron/positron fluence





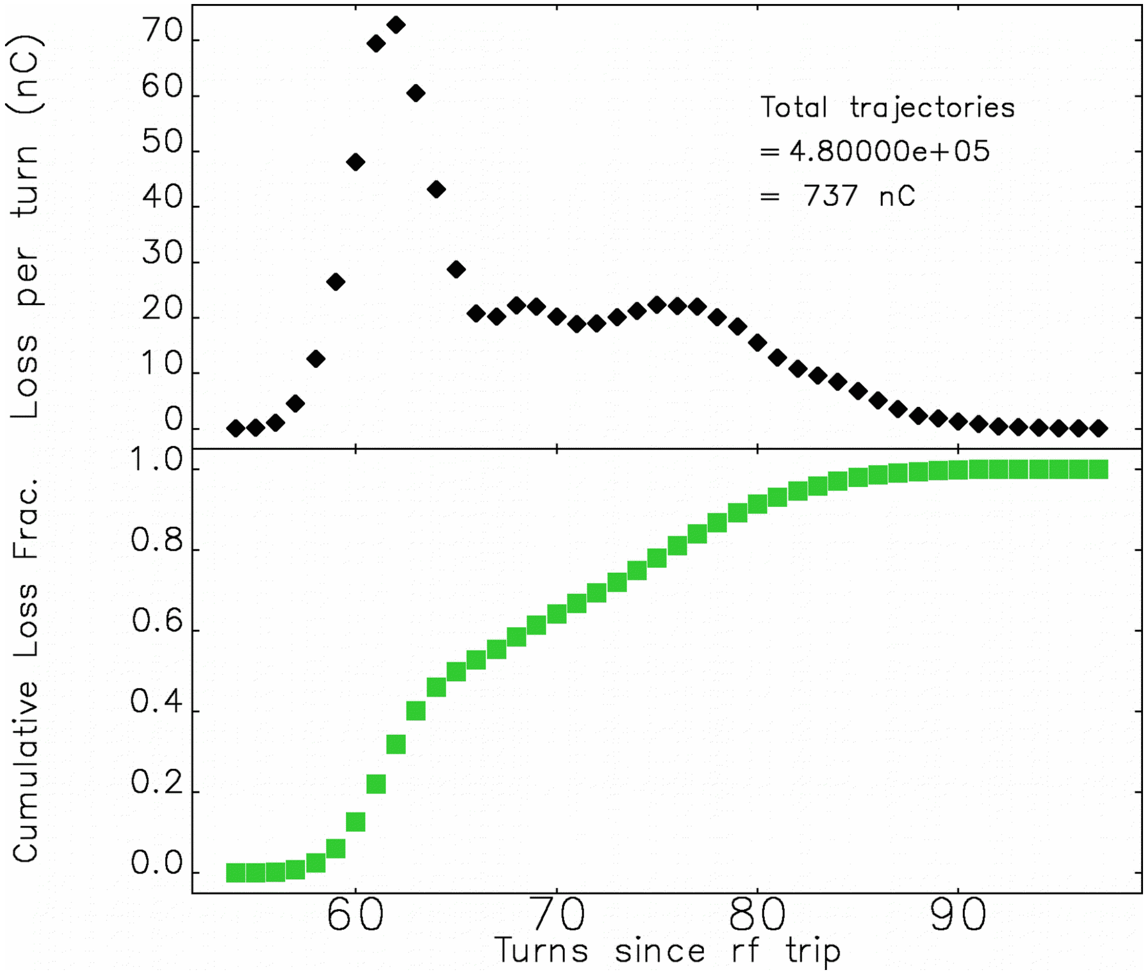
MARS simulations: Beam strike on the dump/collimator—4 candidate materials, continued



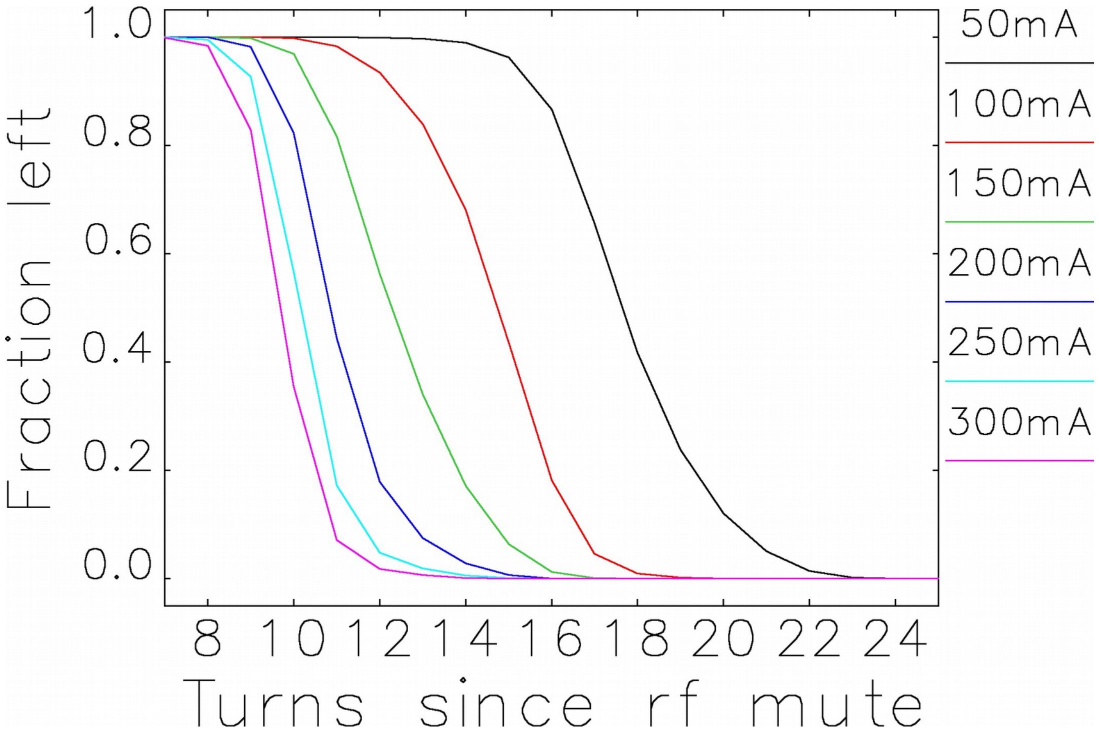
The distributions for Cu and W are most likely incorrect; the beam will cause the material (especially W) to vaporize, reducing the density seen by the beam allowing it to travel further downstream (“hydrodynamic tunneling”)

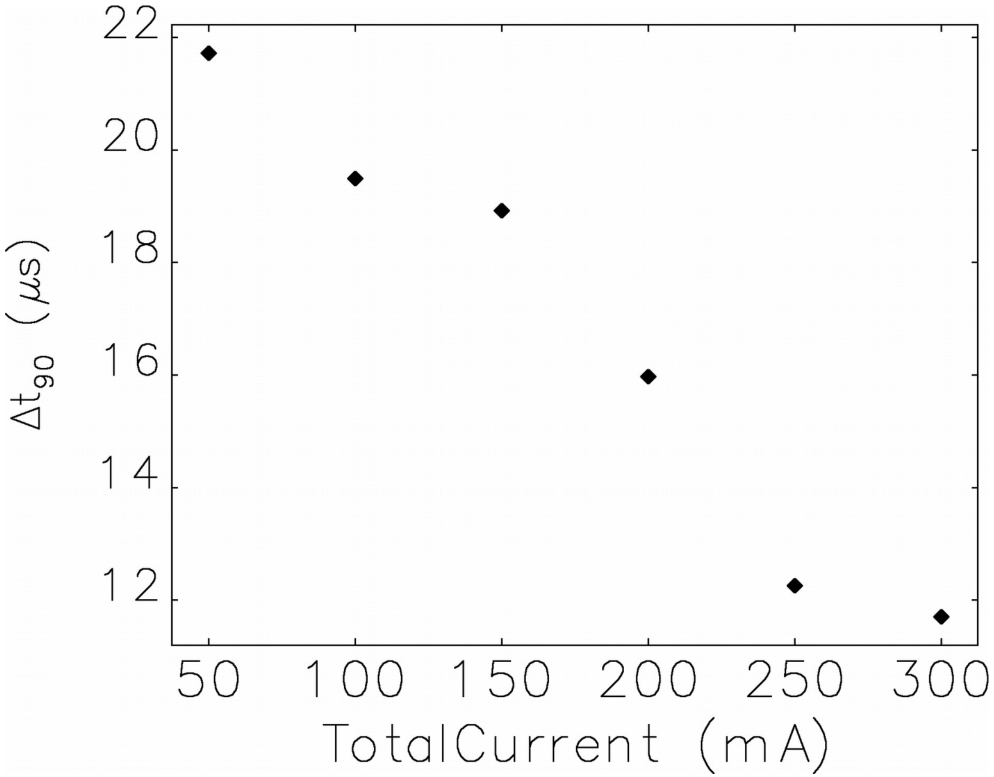
Elegant model of beam loss per pass (48 bunch mode)—whole beam, a complex electro-thermodynamic problem

- Simulations indicate the temporal loss will be spread over many turns
- Power densities will be reduced with respect to single-turn loss
- Beam will first strike the collimator apex at very low angles
- 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



Loss starts faster, takes less time, at higher current





- The time to lose 90% of the beam is as short as 12 µs
- It gets significantly longer at low current, due to reduction in beamloading

Observations from simulated beam strike on the dump/collimator

- Low-Z metals (e.g. aluminum) are probably the best choice for the dump/collimator (TiA second choice)
- Aluminum yields the smallest dose locally in wall and magnet; smallest temperature rise
- Al also generates the least activation[1]
- Al is the same material as surrounding vacuum chamber wall
- Need to examine the scattered beam downstream of the dump/collimator (i.e., beyond the geometry presented here)
- Temporal behavior and fill pattern important for thermal diffusion considerations[2]

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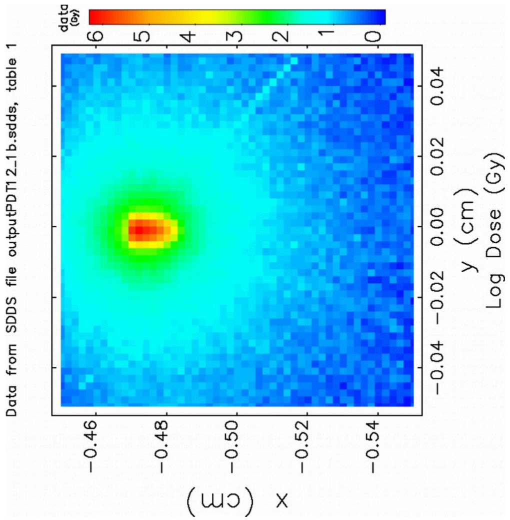
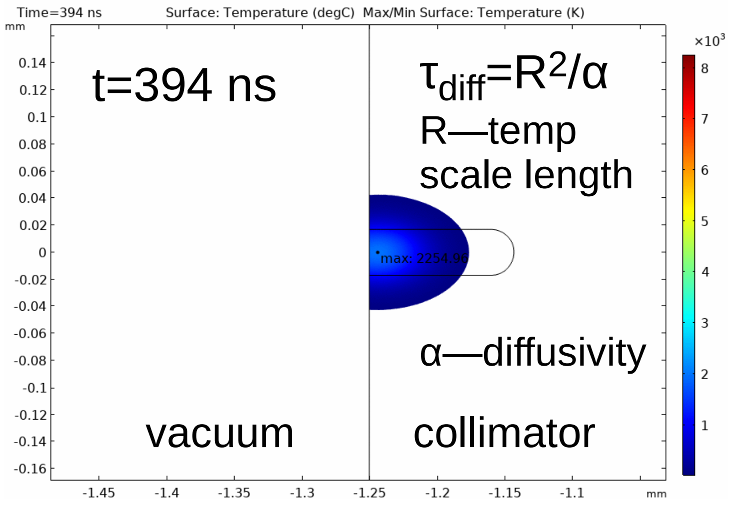
[1] J. Dooling, M. Borland Tech Note: AOP-TN-2018-017
[2] R. Lindberg, J. Dooling Tech Note: AOP-TN-2012-030

COMSOL Simulations: Beam moves into the collimator horizontally—48 bunch, 200 mA; thermal diffusion slows as heated region expands





t=394 ns

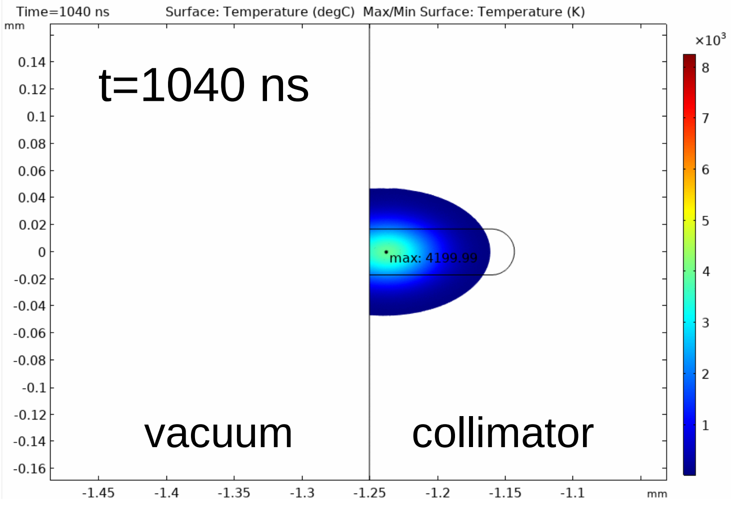
$\tau_{diff}=R^2/\alpha$

R—temp scale length

α—diffusivity

vacuum

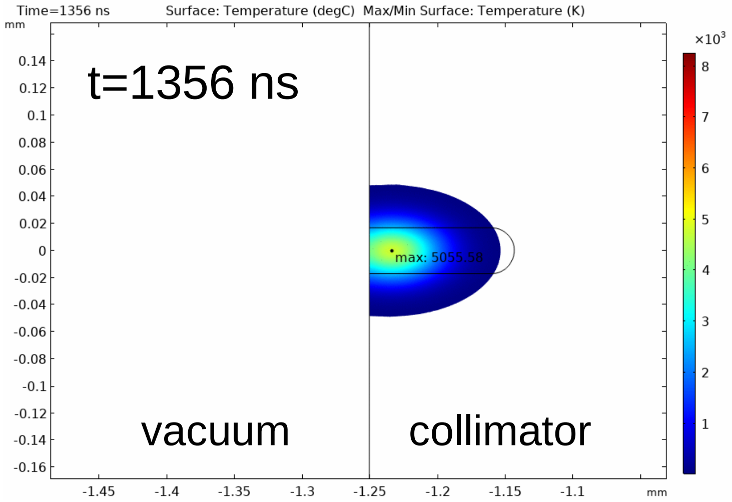
collimator



t=1040 ns

vacuum

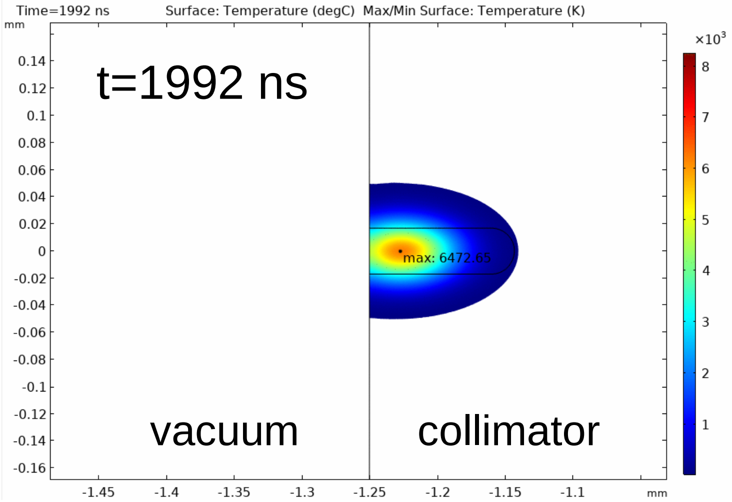
collimator



t=1356 ns

vacuum

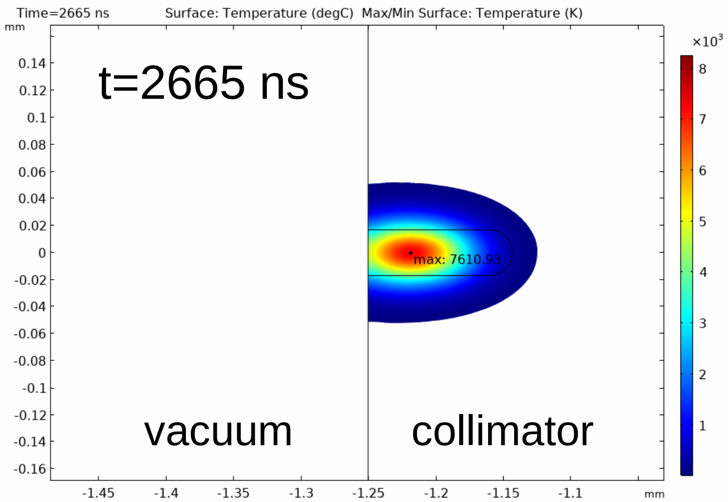
collimator



t=1992 ns

vacuum

collimator



t=2665 ns

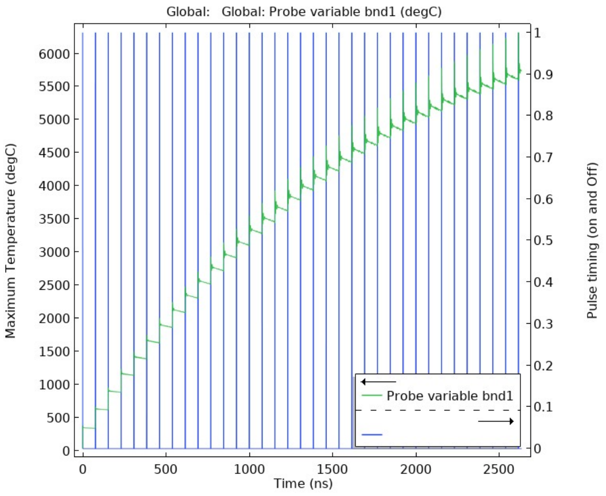
vacuum

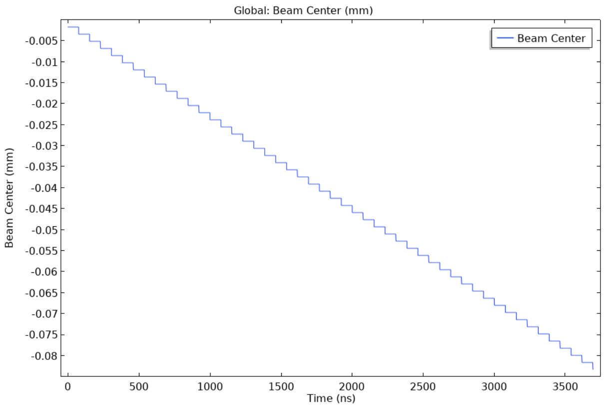
collimator

—K. Suthar

Simulations: COMSOL—provides thermal diffusion but no hydrodynamics

Al 6061





- From dispersion and energy loss, beam moves inboard at a rate of 80 μm/turn
- Simulations in Al were only able to run to 2600 ns
- Assume full energy deposition after one turn
- Temps appear to saturate as follows:
  T_{Ti}(1 turn)=8000°C
  T_{Al}(1 turn)=6000°C
- Total BB power: $P_{rad}=\sigma_{SB}T^4$
- Naively assuming T scales linearly with beam current, $P_{rad,Ti}=3.2P_{rad,Al}$

Ti6Al4V