Collimators for low-emittance whole-beam aborts

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Outline

- Introduction
- Recent Experiments
- Collimators in the APS-U Storage Ring
- Simulation Effort
- Mitigation/Machine Protection
- Summary

Introduction

- Ultra-low emittance, high-intensity electron beams in Fourth Generation storage rings (4GSR) are capable of causing high-energy-density (HED) conditions in components such as collimators or vacuum chamber walls.

- HED is defined as energy densities equal to or above 10^{11} J/m^3. (Warm-dense matter (WDM) regime.)[1]

- Dose is defined as absorbed energy per unit mass, therefore we can write $E_a = D/\rho$, in aluminum this represents an acute dose of 37 MGy, 11.2 MGy in copper, and 5.2 MGy in tungsten. During our experimental collimator studies, we reached peak dose values of 30-35 MGy. Significant damage was observed. In APS-U, peak total dose may exceed 100 MGy over 3 turns[2].

Introduction, cont'd

- Acute implies the duration of the deposition is short[3]. A useful rule-of-thumb is to compare the duration with a thermal diffusion time defined from the heat equation as $\tau = L^2/\alpha$, where L is a characteristic scale length of the absorbed energy distribution and α is the diffusivity.
- For example, in aluminum, α = 64 μm^2/μs. With L=10 μm, τ=1.56 μs. This is roughly ½ turn (T_0=3.68 μs), short compared to the loss period (3 turns at 200 mA, 972 bunches), but long compared to the bunch duration time (100 ps, rms).
- Goal: Simulate the effects of HED conditions in the accelerator environment and develop a widely-usable framework for beam strike modeling. This effort is intimately connected to having good experimental data.

Experiments in the APS SR

Collimator irradiation studies were conducted in 2019 and 2020[4,5].

Recommendation from October 2022 MAC review: "Continue to improve the modeling as well as measurements to validate modeling improvements."

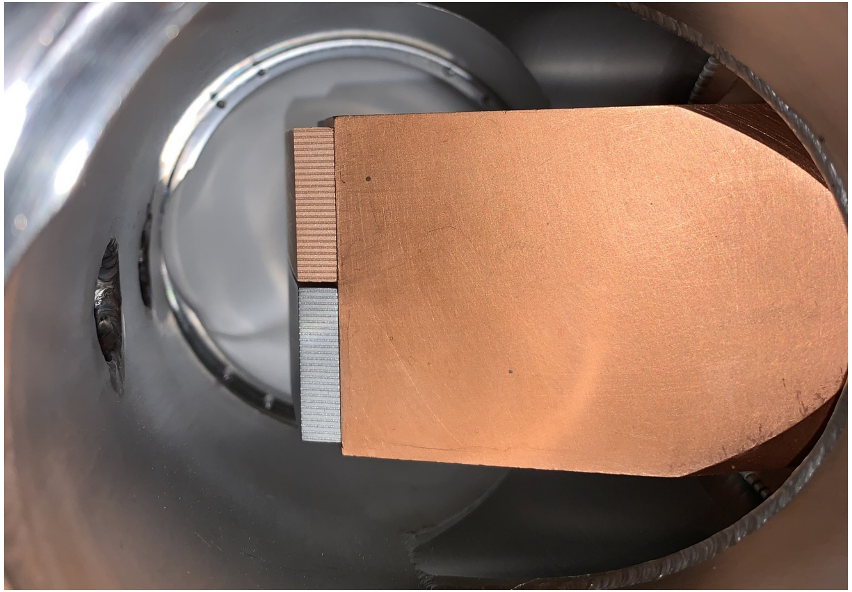
A third collimator irradiation experiment was carried out in April 2023 during the final Machine Studies period in the now-retired storage ring (SR) for the following purposes:

- Conduct 200-mA beam aborts in Cu and Al collimator test-pieces
- Test the effectiveness of a vertically deflecting fan-out kicker (FOK) for protecting collimator surfaces
- Determine if Cu can safely be used as a collimator material with an FOK
- Provide additional data for benchmarking simulations
- Explore wakefield effects

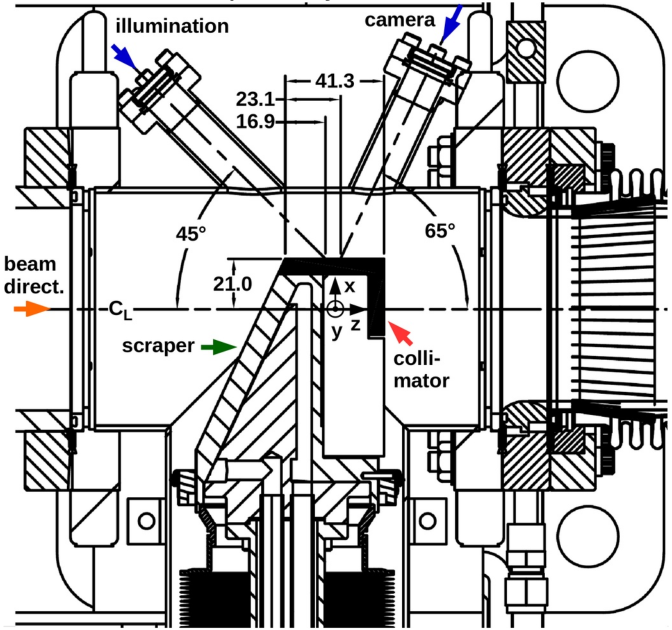
Third Collimator Experiment

Mounted collimator test pieces on the fully inserted scraper—Cu top, Al bottom

Downstream view



midplane, y=0



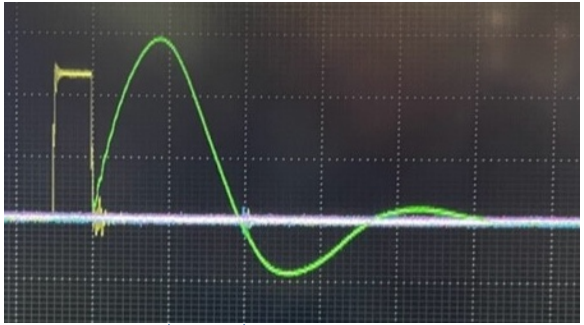
dimensions in mm

For injection, the collimator apex is withdrawn to x=-2 mm.

Mitigation/Machine Protection

Measurements and Simulations

- Fan-out kicker (FOK)
- Wakefield effects
- Slow beam abort system*



FOK current waveform

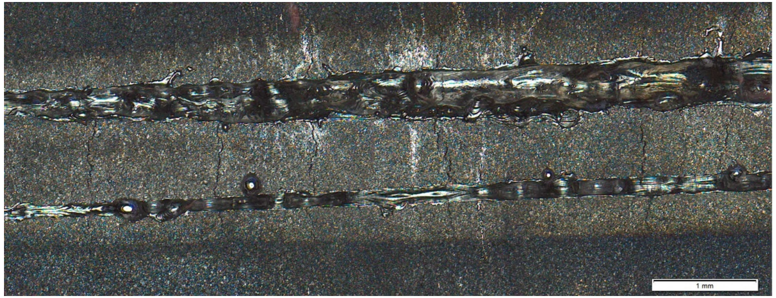
2 µs

*The slow beam abort system is employed to dissipate the stored current using the decoherence and extraction kickers one bunch at a time; for example, at the end of a study or end of a run cycle. Beam will be extinguished in 0.1-1.0 sec.

Machine Protection vis-a-vis EBS-ESRF

- EBS-ESRF uses a technique similar to the APS-U FOK called the Collimator Protection System Shaker
- Sine wave around the betatron frequency lasting for 150 turns (425 μs)—this would be too long for APS-U, unless muting of the rf was delayed. Beam strikes collimators in APS-U in 20 turns (74 μs).
- EBS also use tungsten collimators; we thought these would be too easily damaged due to W's short radiation length (3.5 mm).

W scraper surface in APS SR after 100 mA beam aborts (2-3 MGy)



3rd Irradiation Study—Six Cases, Varying FOK V, y-offset

Table 1: Beam Abort Case List Parameters.

Case No.	Vertical Offset (mm)	Mat'l	FOK Voltage (kV)	Vert. defl. angle, y' (μrad)
0	+1.5	Cu	2	245.0
1	-1.5	Al	2	245.0
2	-2.0	Al	1	122.5
3	+3.0	Cu	0	0
4	-3.0	Al	0	0
5	+2.0	Cu	3	367.5

V-bumps, elegant

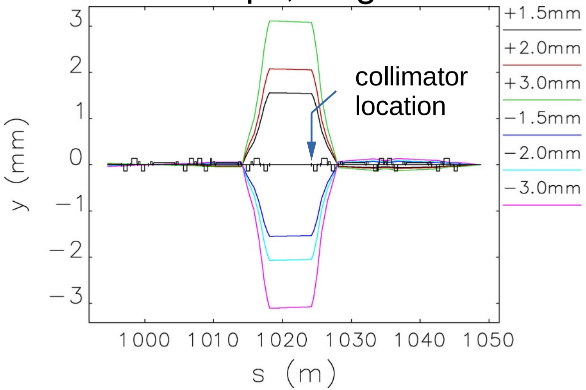
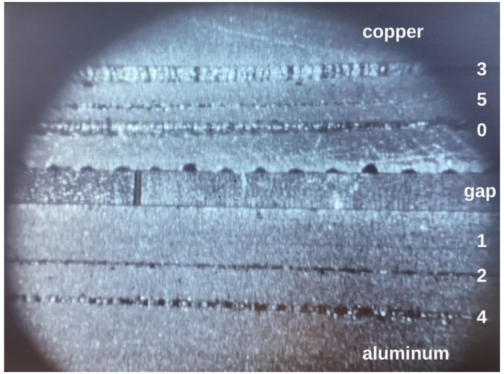


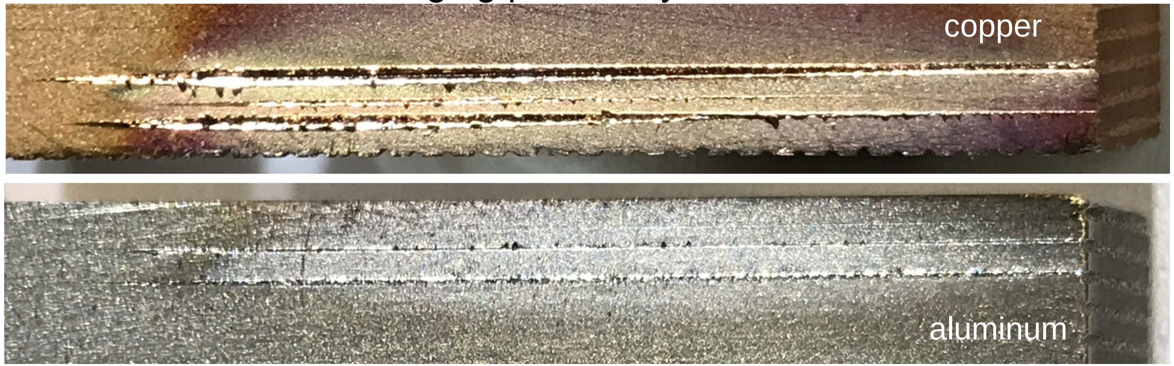
Table 2: Beam Parameters and Peak Dose during Beam Aborts. At 6 GeV, S_{pc} = 2.153 MeV-cm^2/g for Al and 1.959 MeV-cm^2/g for Cu. β_x = 3.96 nm/rad, β_y = 6.35 pm/rad, η_x = 0.0584 m

C. N.	I_b (mA)	ϵ_x (nm-rad)	ϵ_y (pm-rad)	σ_x (μm)	σ_y (μm)	D_G (MGy)
0	199.5	2.102	17.13	108.3	10.43	20.28
1	199.1	2.245	14.15	110.9	9.48	23.90
2	199.8	2.166	22.69	109.5	12.00	19.19
3	199.7	1.844	50.88	103.5	17.97	12.32
4	199.6	2.086	40.33	108.0	16.00	14.58
5	199.9	2.029	27.50	107.0	13.22	16.22

Diagnostic imaging camera



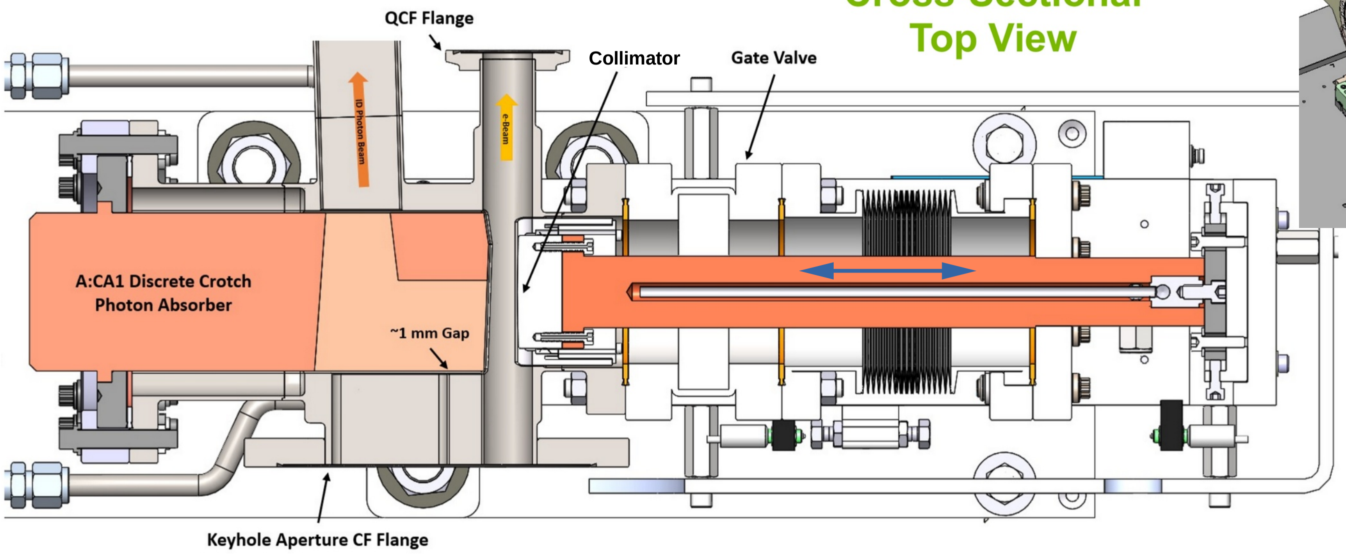
Imaging post study



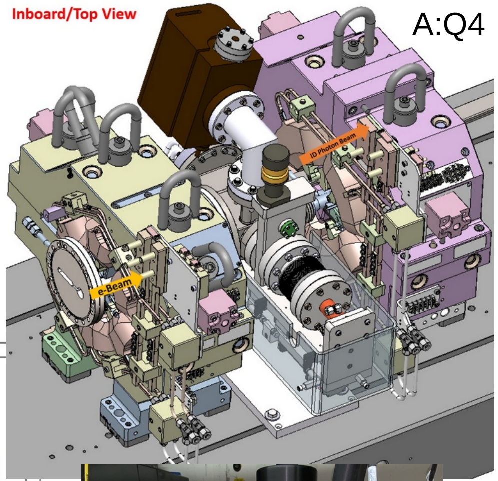
In all cases, Cu was damaged; Al survived at 2 kV.

APS-U SR Collimator Design

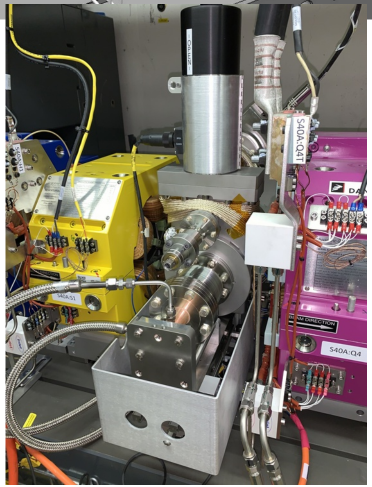
- Five total
- Located in sectors 37, 38, 39, 40, and 1



A:S1

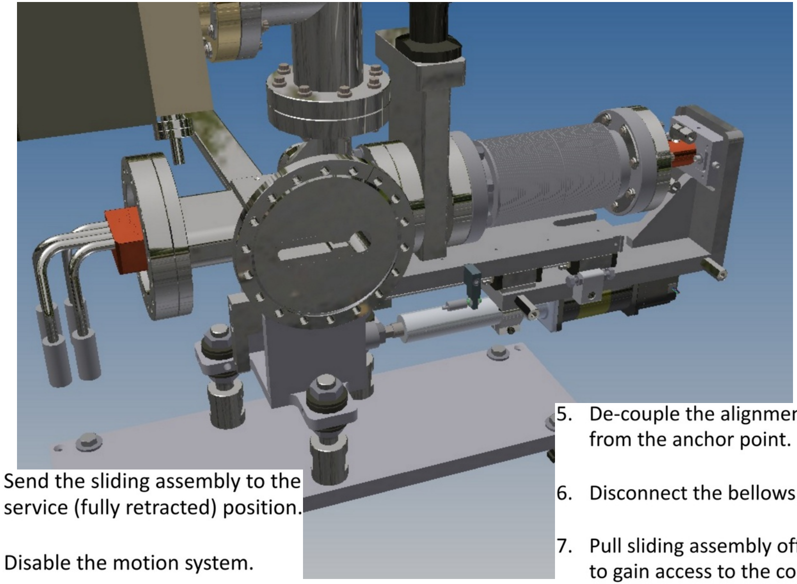


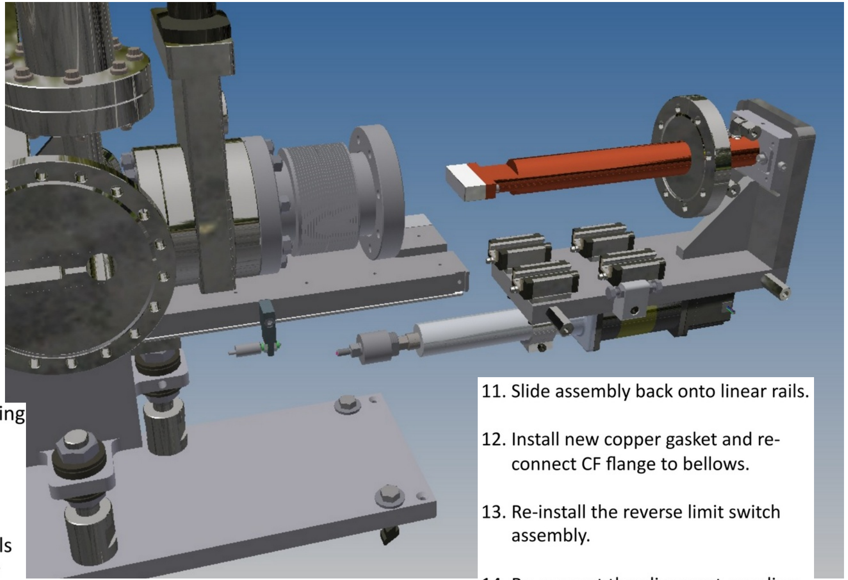
A:Q4



Possible diagnostic: Fast Beam Loss Monitor

Collimator Design—Servicing





1. Send the sliding assembly to the service (fully retracted) position.
2. Disable the motion system.
3. Close the manual gate valve and bleed up the vacuum on the bellows side.
4. Remove the reverse limit switch assembly.
5. De-couple the alignment coupling from the anchor point.
6. Disconnect the bellows joint.
7. Pull sliding assembly off the rails to gain access to the collimator jaw.
8. Liberate the collimator jaw by removing (2) vented screws.
9. Safely secure used collimator jaw (health physics procedure).
10. Install new collimator jaw.
11. Slide assembly back onto linear rails.
12. Install new copper gasket and re-connect CF flange to bellows.
13. Re-install the reverse limit switch assembly.
14. Re-connect the alignment coupling to anchor point.
15. Pump down vacuum on bellows side.
16. Open manual gate valve.
17. Re-activate motion system.
18. Re-position collimator to operational position.

—B. Kosciuk, BNL

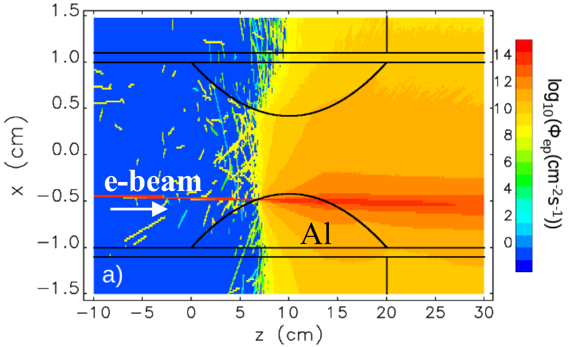
Simulation Effort—Code Couping

- Initial modeling with elegant and MARS
- Dose maps for FLASH
- Code coupling
- Wakefield effects

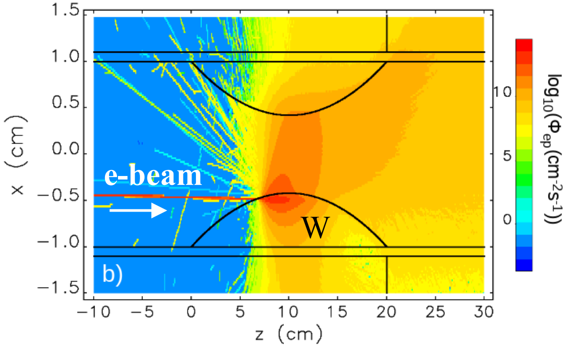
Early APS-U Collimator Simulations with `elegant` & MARS

e/p flux, single bunch (15.3 nC) in a 48-bunch, 200-mA fill pattern at 6 GeV.

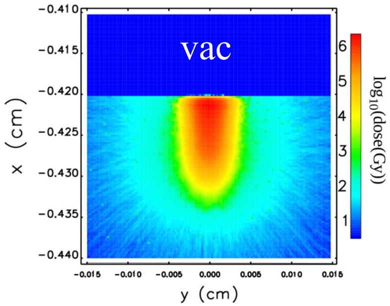
Al



W



Al apex dose map



$$q_v(x) = \int_{T_1}^{T_2} \rho(x,T)\, c_p(T)\, dT$$

$$T_{2,max} \approx \frac{q_v(x_{max})}{\rho(x_{max})\,\bar{c}_p} + T_1 = \frac{D_{max} A_w}{C_m} + T_1$$

1 bunch of 48 (timing mode)

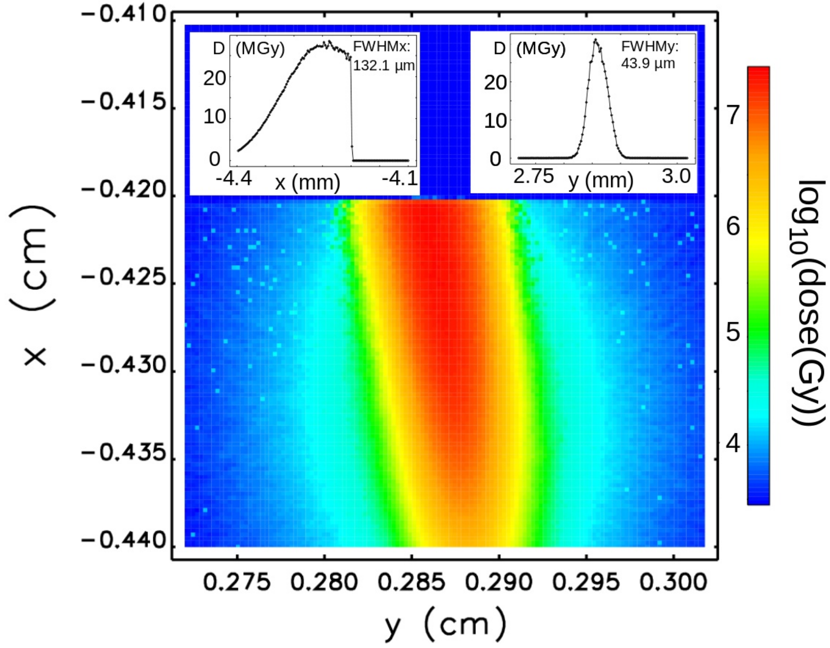
T_1=293 K

Mat'l	D_{max}	A_w	C_m	T_m	T_v	$T_{2,max}$
	(MGy)	(g/mole)	(J/kg-mole)	(K)	(K)	(K)
Al	1.96	26.98	24.20	933	2743	2285
Ti	3.03	47.87	25.06	1941	3560	5830
Cu	2.94	63.55	24.44	1358	2835	7650
W	2.53	183.84	24.27	3695	6203	19,300

Damage to scraper Cu & W material has been observed when $T_2 > T_m$

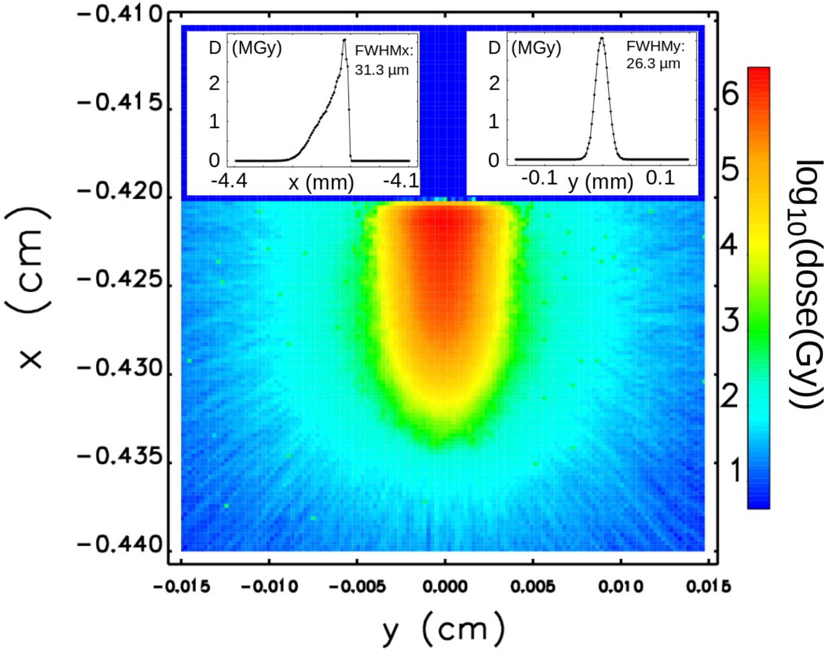
Deposition Models

Deposition of full 200-mA beam derived from expt.



Peak dose: 35 MGy

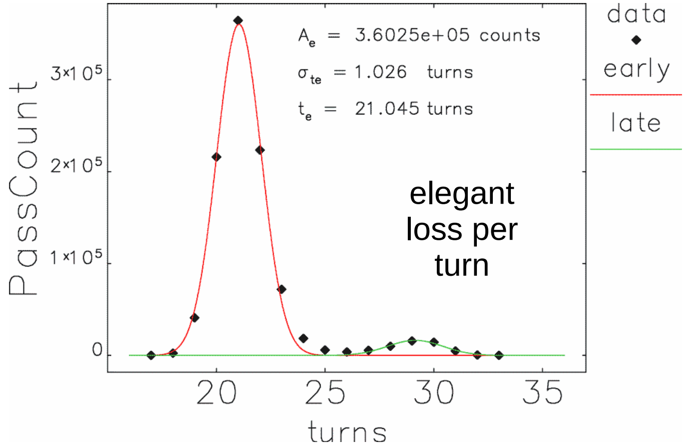
APS-U model of full 200-mA beam, from 1 of 48 bunches

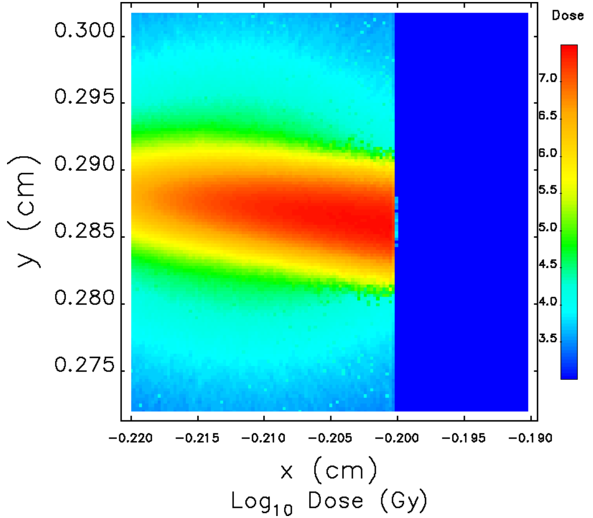


Peak dose: 150 MGy

Simulations

- Initially assumed the same dose distribution over 3-5 turns
- Next moved to include time variation of dose per turn
- Dose profiles based on measured emittance from January 2020
- 6 GeV in a 972-bunch, 200-mA fill pattern
- 5 turns, release condition: 4115 K (1.5T_{vap} in Al)

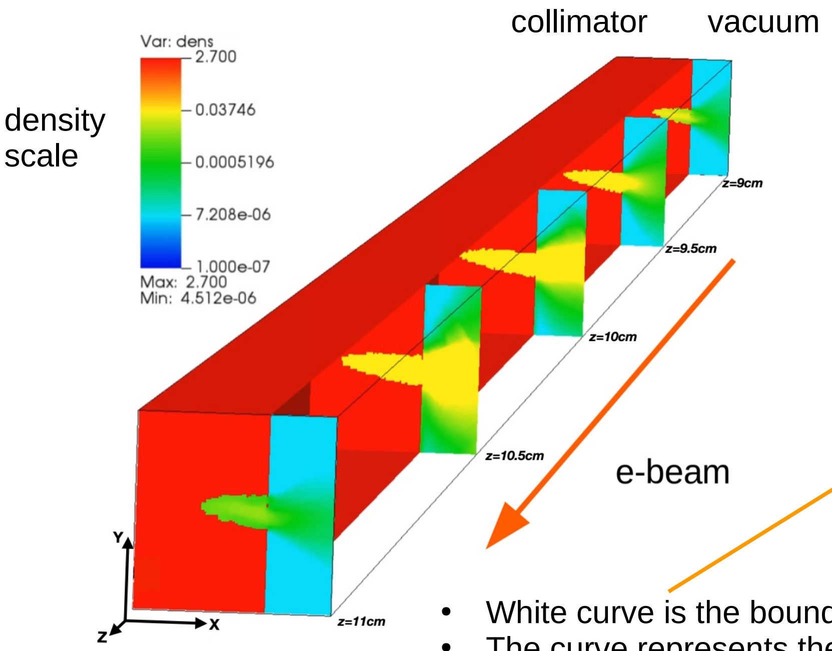




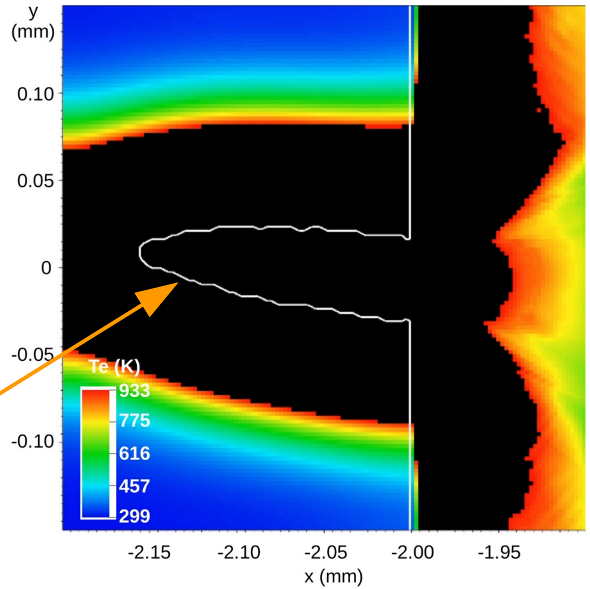
Dose from sum of all turns

Hydrodynamic Modeling using Measured Emittances

3-D simulation



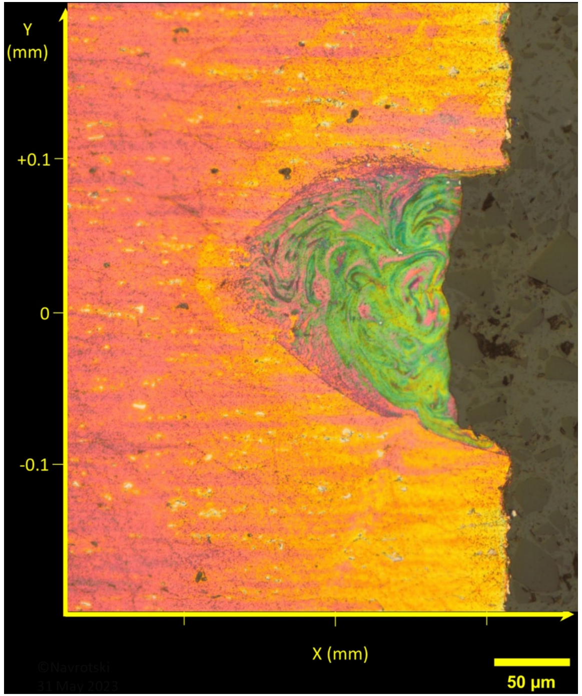
2-D simulation



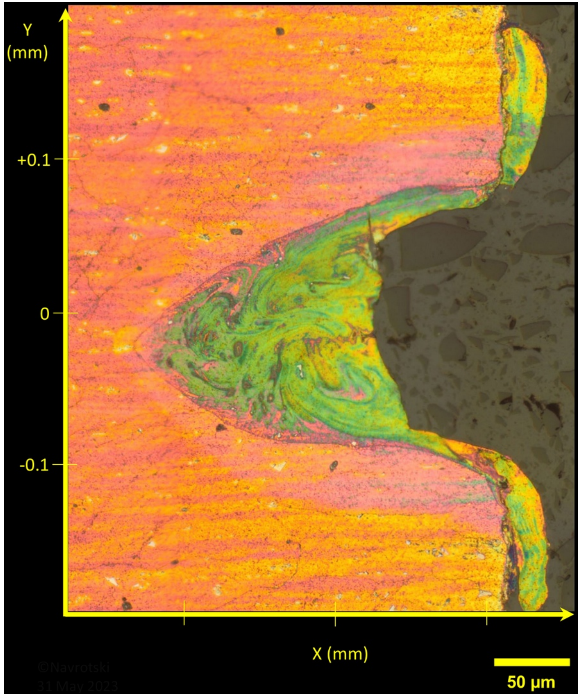
- White curve is the boundary between solid and plasma (bdry_var)
- The curve represents the “release condition” in FLASH
- Melt temp in Al: 933 K, black region indicates areas of melt

Metallurgical Analysis from Jan. 2020 samples (Al)

single 200-mA, 6-GeV strike location



double 200-mA, 6-GeV strike location



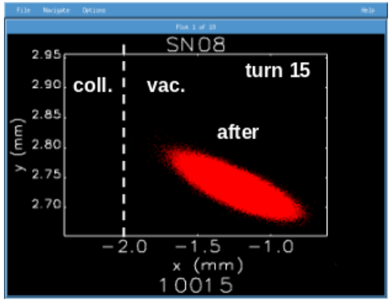
We have begun to model the liquid phase in FLASH, first for Cu and then for Al.

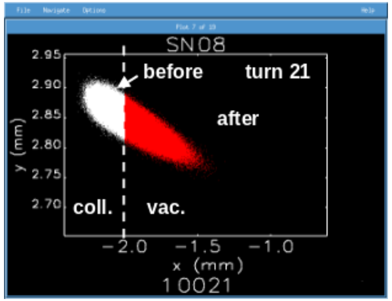
The first implementation will focus on more accurately modeling the density, thermal conductivity, and specific heat of liquid phase.

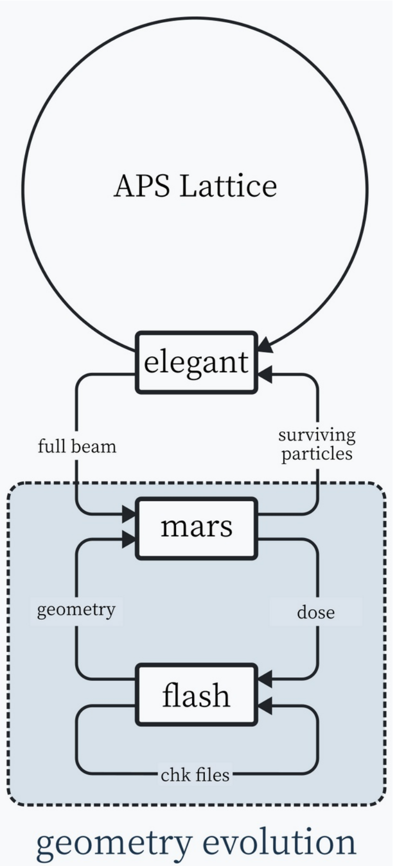
Under polarized lighting, the melt regions generally have a green tint highlighting turbulent mixing present during the rapid melting and solidification process.

Code Coupling[6,7]—Flow Diagram

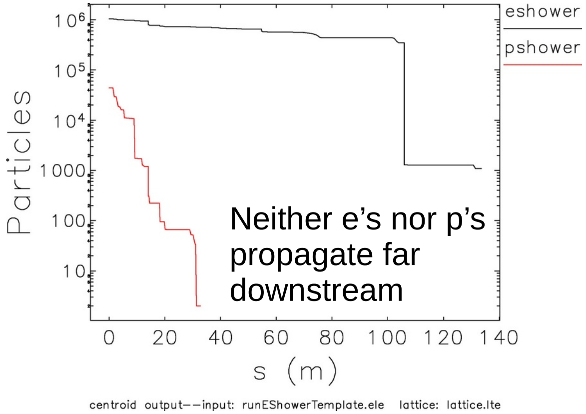
Have been using the "before" collimator distribution. Instead use the full distribution.





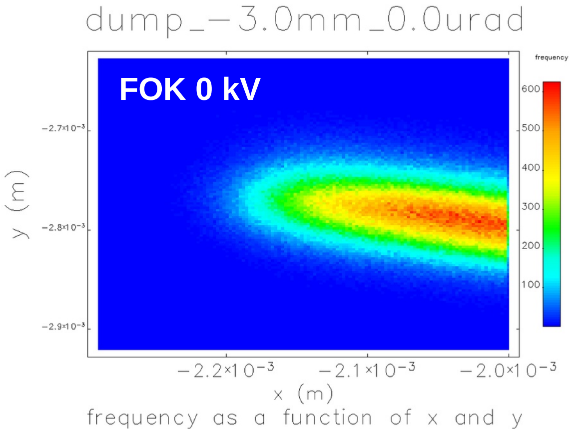


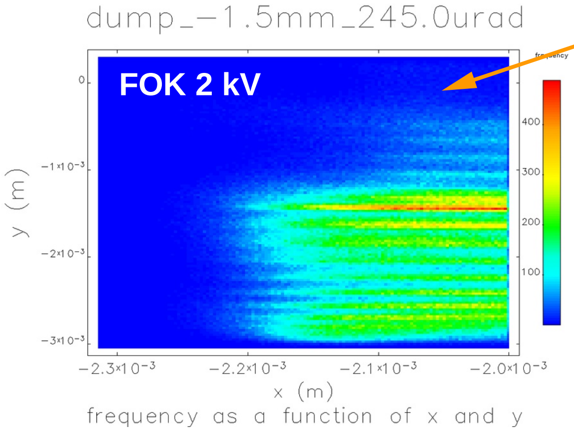
Downstream shower propagation of electrons and positrons **after** striking the collimator.



Let MARS and FLASH determine the interacting (before) and passing (after) distributions. The latter back to elegant

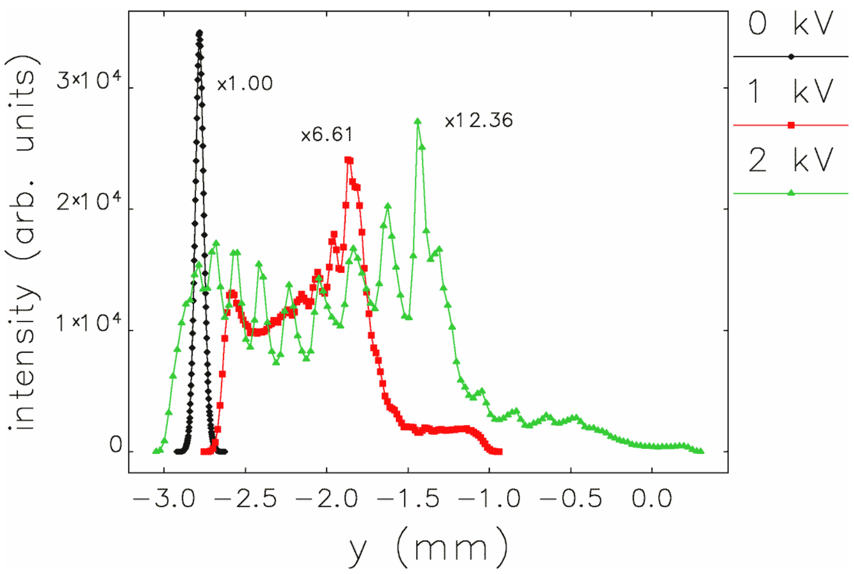
elegant loss distributions with variable FOK voltages—Al



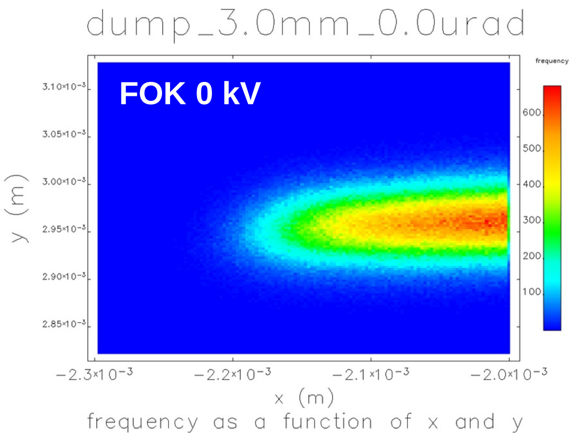


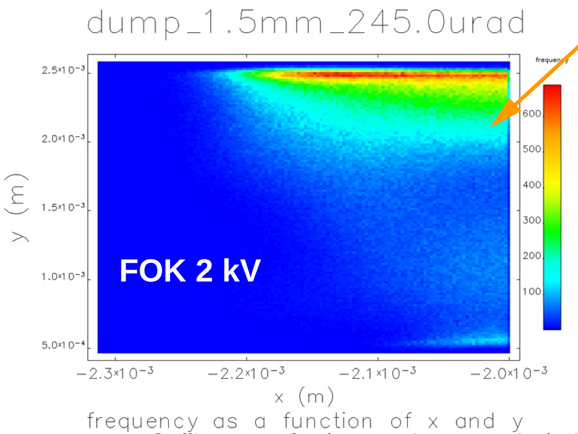
y-pixel dimension much larger

x- and t-integrated, y-profiles at 0, 1, and 2 kV on the FOK



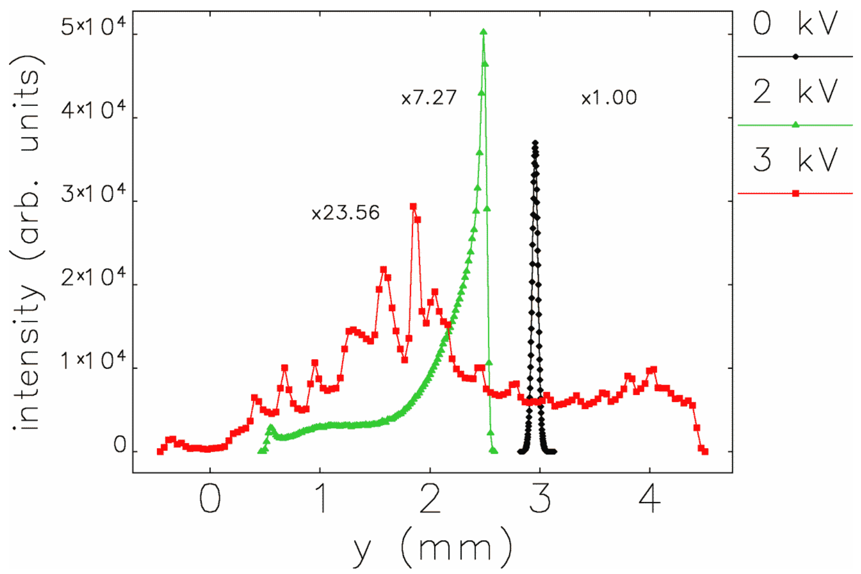
elegant loss distributions with variable FOK voltages—Cu

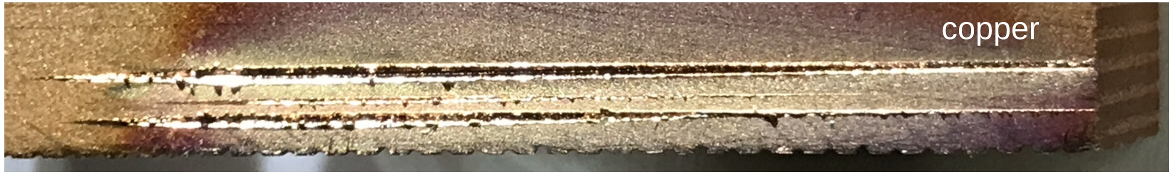




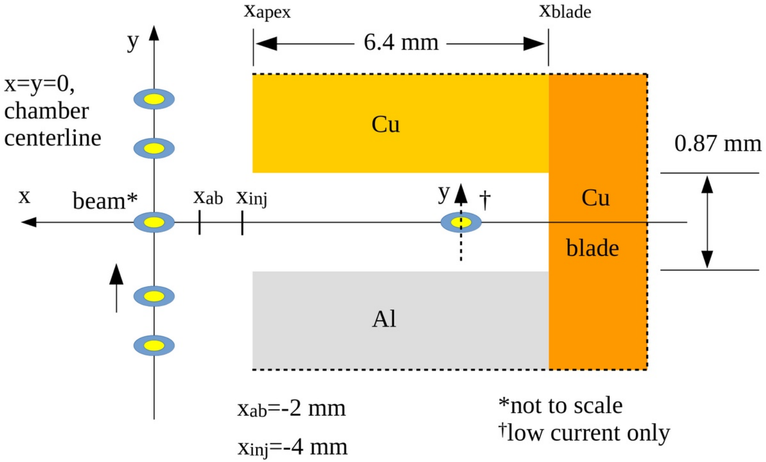
y-pixel dimension much larger

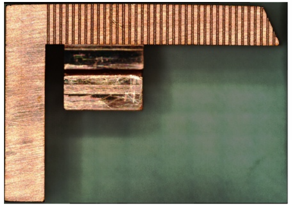
x- and t-integrated, y-profiles at 0, 1, and 2 kV on the FOK

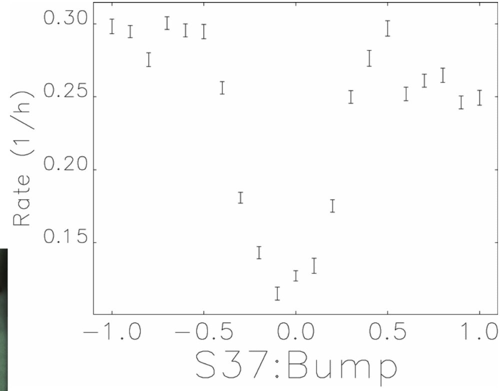




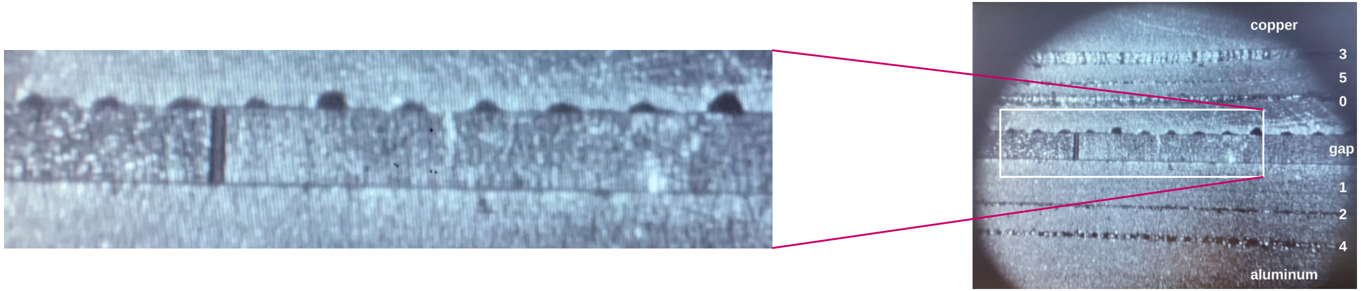
Possible Mitigation Technique—Wakefields







Lifetime measure-ments identify the gap center, y=0 via wakefield effects

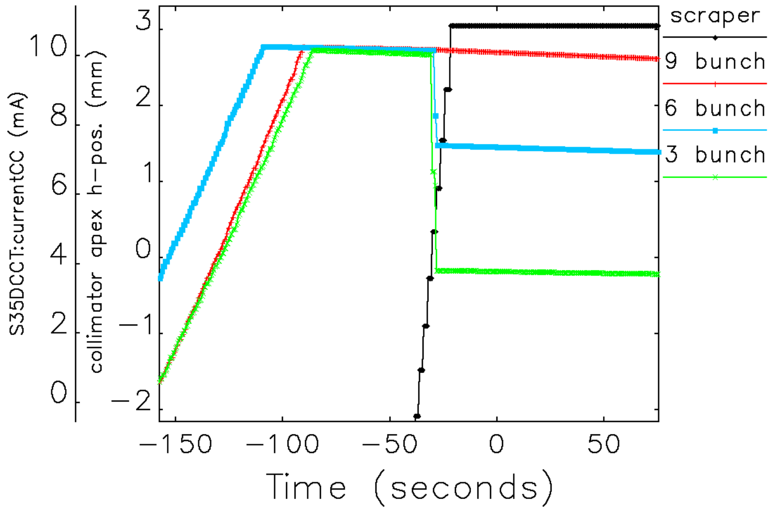


De-coherence kicker (works on one bunch at a time for slow beam aborts only)

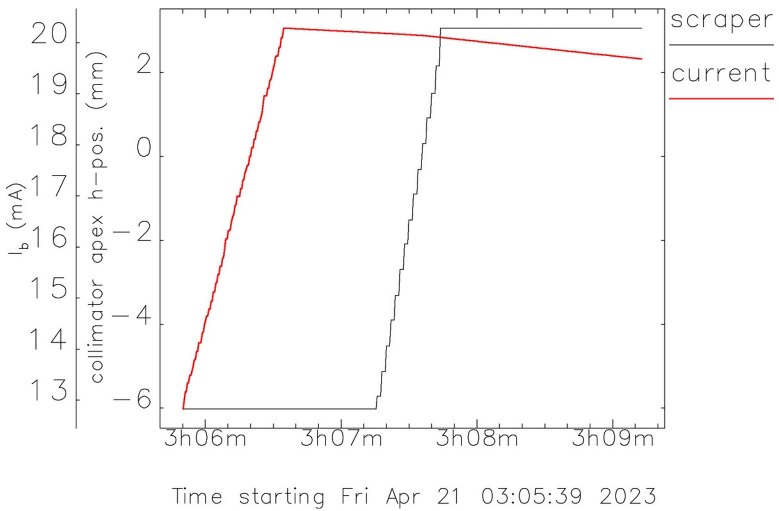
Wakefield effects: Beam current as collimator gap is moved over beam

—Can structures be built to make the machine self protecting?

10 mA, 3, 6, and 9 bunches



20 mA, 18 bunches



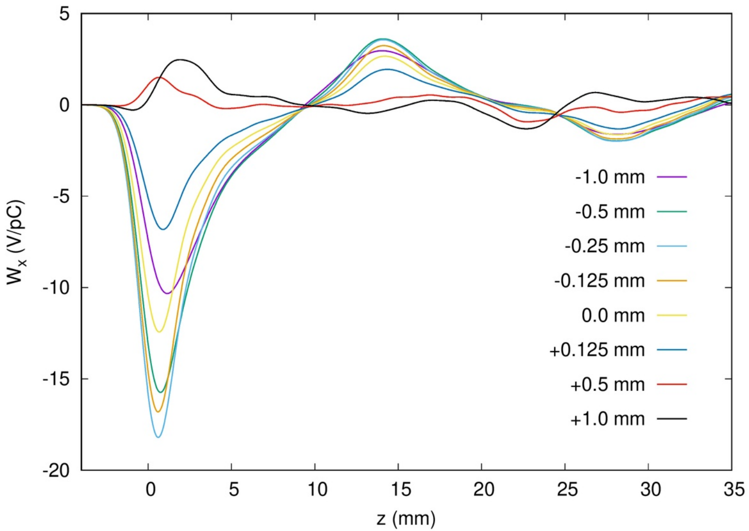
…maybe!

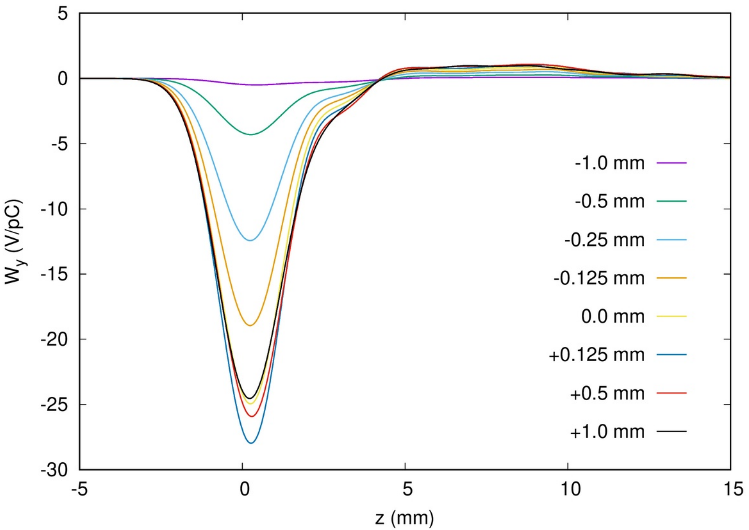
10 mA / 3 bunches * 3.68 nC/mA = 11.04 nC/bunch ➡ relevant in timing mode.

Simulation effort underway to model this effect.

Simulated Wakefields using GdfidL

vertical and horizontal wakefields driven by a 1 mm bunch along the axis





The plots show how the wakefields vary with position of the bunch with respect to the scraper channel. '0 mm' is when the bunch is even with the scraper face, +1 mm means 1 mm into the channel, while -1 mm means 1 mm from the channel. The kick factor:

—R. Lindberg

$$\kappa_{x,y}(\sigma)=\int_{-\infty}^{\infty} W_{x,y}(\tau)\lambda(\tau)d\tau=\int_{0}^{\infty} G_{x,y}(t)S(t)dt,$$

where λ is the longitudinal charge distribution, $G_{x,y}$ is the transverse Green's function, and $S(t)$ is the autocorrelation function.

Summary

- A third whole-beam-abort experiment was conducted to study whether a vertical FOK could be utilized to protect the horizontal collimators planned for the APS-U SR.
- Tests carried out on both aluminum and copper targets. In the case of aluminum, a FOK voltage of 2 kV was sufficient to protect the target; however, for copper even a 3 kV kick was not enough to prevent damage.
- For both targets, damage was reduced as FOK voltage was increased.
- The data collected provides useful information for benchmarking our coupled-code simulation effort modeling the effects of whole-beam loss events in 4GSR light sources.
- Working on coupling—challenges but progress being made
- Still to do: Include MHD effects in FLASH; include synchrotron radiation effects

Acknowledgments

- Thanks to APS colleagues H. Bui and M. Smith on MPS
- Analysis support: Hairong Shang and Robert Soliday

Thank you for your attention!

References

1. R. P. Drake, High-Energy-Density Physics, Foundation of Inertial Fusion and Experimental Astrophysics, Second Edition, Berlin, Germany, Springer, 2018.

2. J. Dooling et al., “Collimator irradiation studies in the Argonne Advanced Photon Source at energy densities expected in next-generation storage ring light sources”, Phys. Rev. Accel. Beams, vol. 25, no. 4, p. 043001, Apr. 2022. doi:10.1103/PhysRevAccelBeams.25.043001

3. A. Bertarelli, Beam-induced damage mechanisms and their calculation, edited by R. Schmidt, in Proceedings of the Joint International Accelerator School: Beam Loss and Accelerator Protection, pp. 159–227, (CERN, Geneva, 2016), Vol. CERN-2016-002, https://cds.cern.ch/record/1641418/files/CERN-2016-002.pdf

4. J. C. Dooling et al., “Studies of Beam Dumps in Candidate Horizontal Collimator Materials for the Advanced Photon Source Upgrade Storage Ring”, doi:10.18429/JACoW-NAPAC2019-MOPLM14

5. J. Dooling et al., “Diagnostics for Collimator Irradiation Studies in the Advanced Photon Source Storage Ring,” doi:10.18429/JACoW-IBIC2020-TUAO02

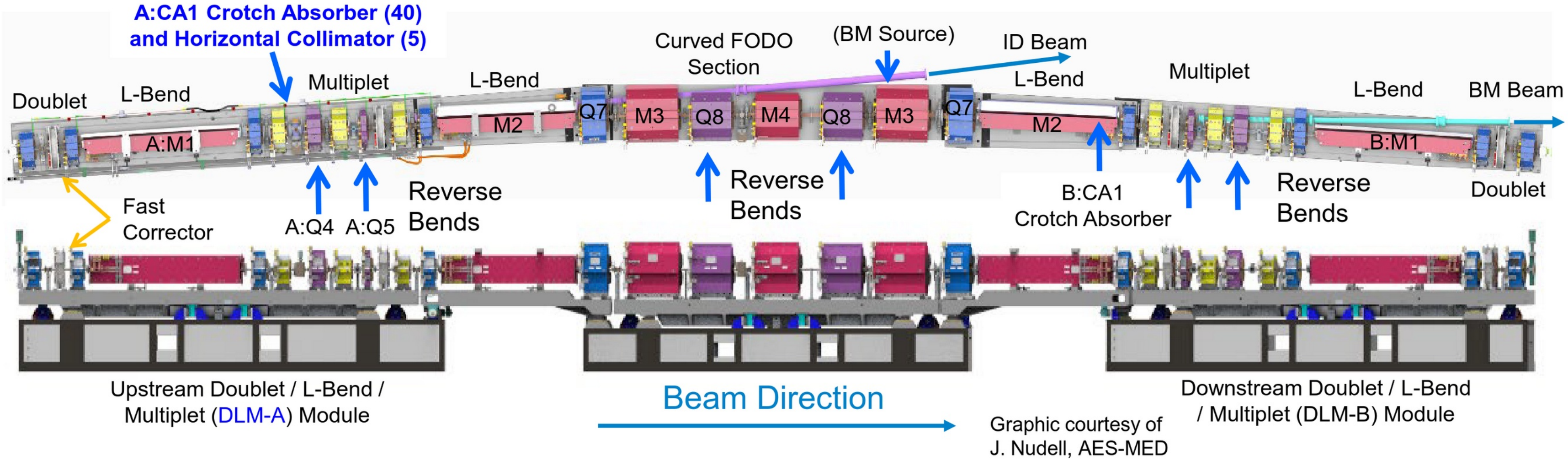
6. D. C. Wilson, R. P. Godwin, J. C. Goldstein, N. V. Mokhov, and C. A. Wingate, “Hydrodynamic calculations of 20-TeV beam interactions with the SSC beam dump,” https://accelconf.web.cern.ch/p93/PDF/PAC1993_3090.PDF.

7. Y. Nie et al., “Simulation of hydrodynamic tunneling induced by high-energy proton beam in copper by coupling computer codes, https://doi.org/10.1103/PhysRevAccelBeams.22.014501

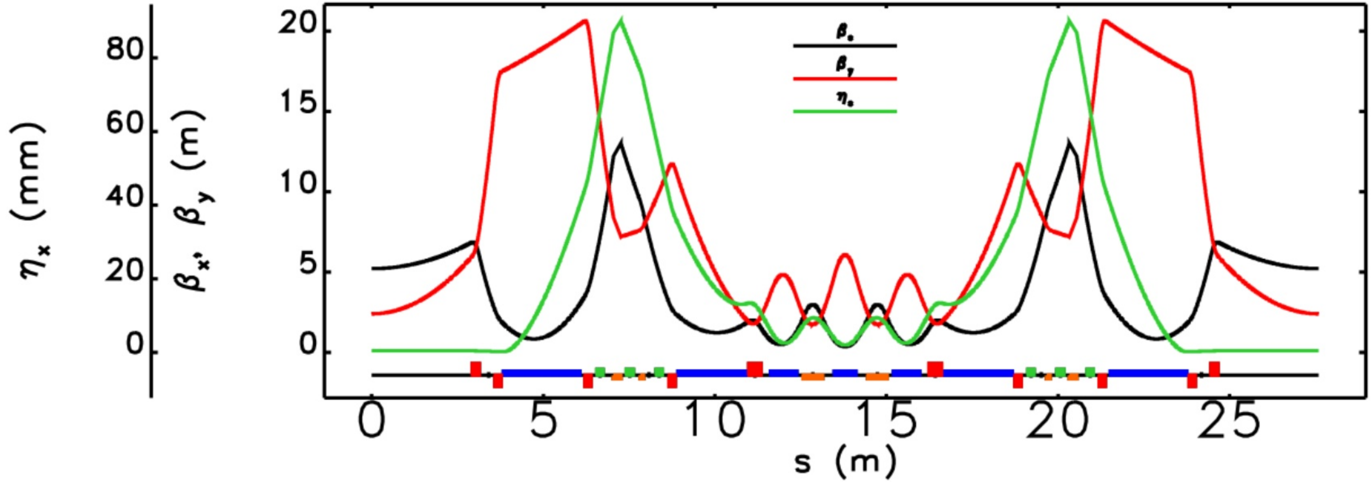
Backup Slides

APS-U Storage Ring

- Storage ring consists of 40 Sectors. Each with 33 arc magnets; 27.6 meters / sector.
- Sector arcs consist of five modules, mounted upon three large plinth assemblies.
- Vacuum systems integrated with magnets, supports, insertion devices, front ends.
- 5 Straight sections in Zone F
  – Injection/extraction hardware, RF accelerating cavities, bunch lengthening system, collimators



APS-U Lattice Functions—From the APS-U FDR

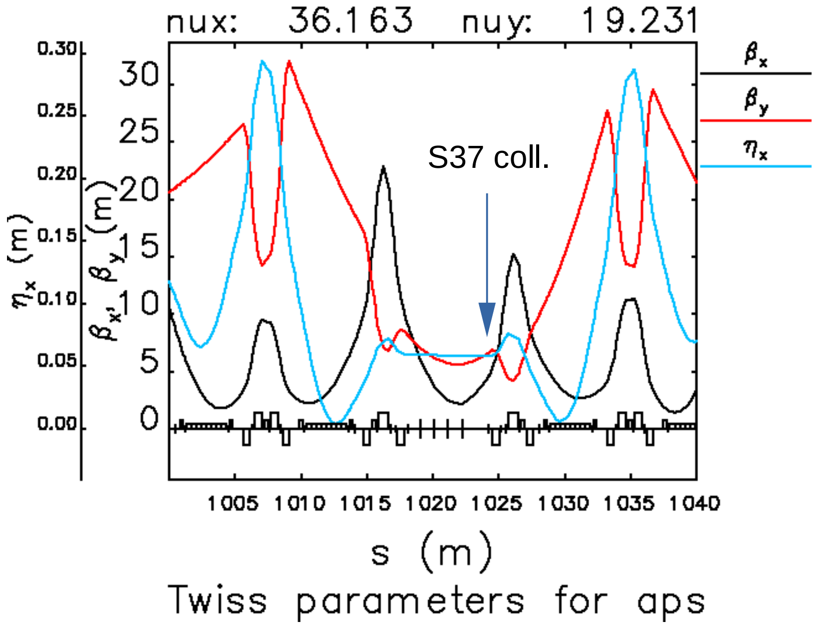


All M3s and M4s

Beam pipe offset 1.28 cm inboard (beam into page)

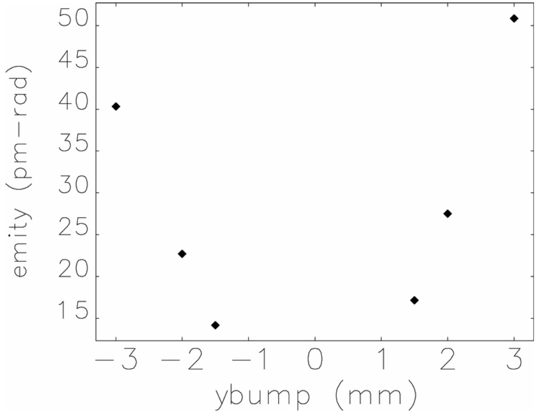
7BA (MBA) lattice with reverse bends for the APS. The natural emittance is 42 pm. Blue blocks represent normal-direction dipoles, orange blocks represent reverse-direction dipoles, red blocks represent quadrupoles and green blocks represent sextupoles.

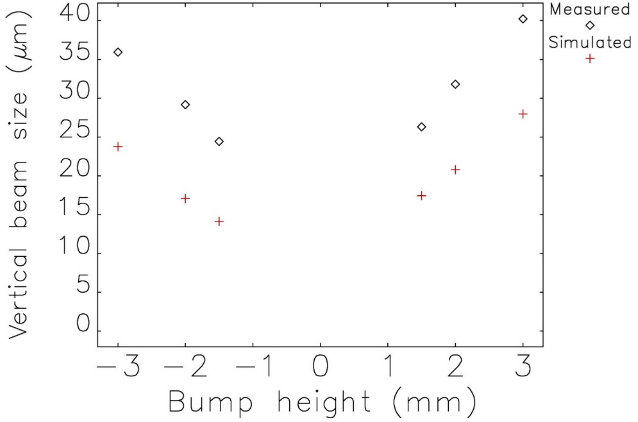
RHB Lattice Functions Beam Size and Emittance during 3rd study



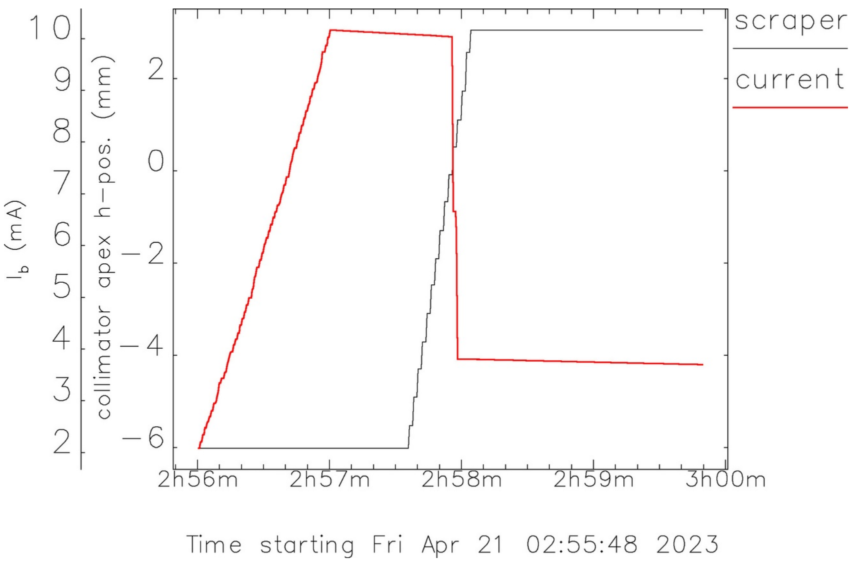
Neglected to recognize sextupoles within bump were left on

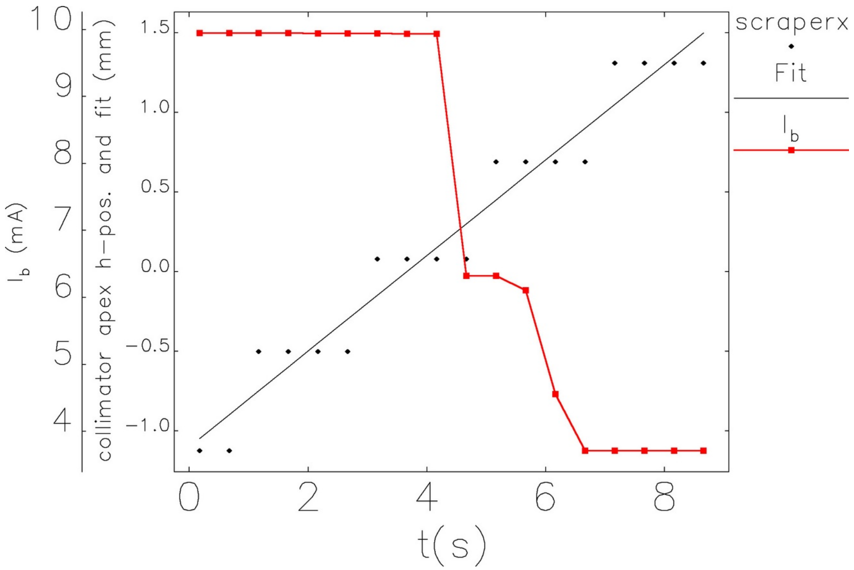
—led to blow up in ε_y and σ_y



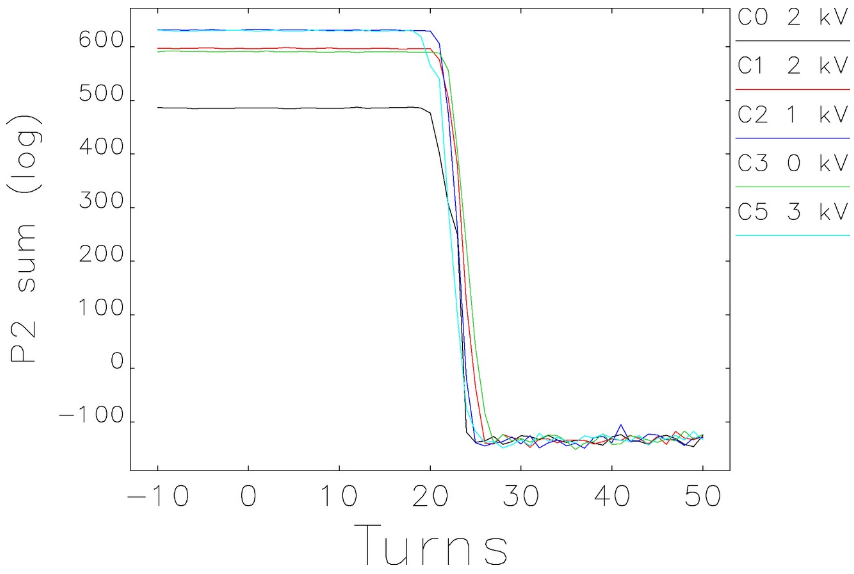


High-Charge Wakefield Measurement, Zooming In

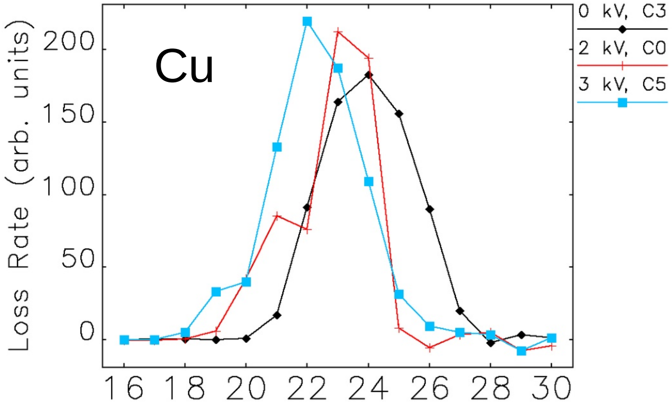


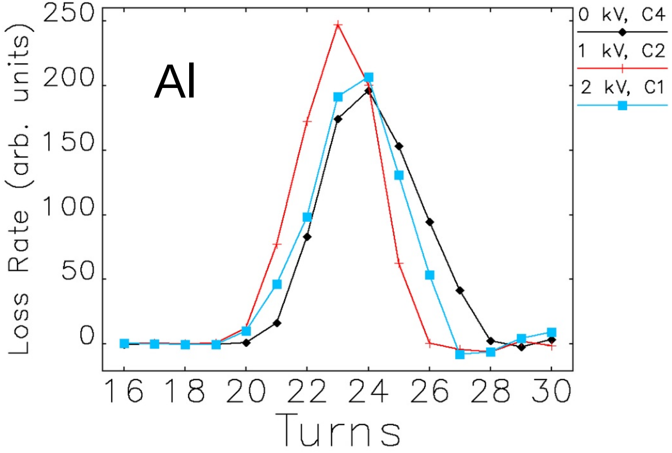


Turn-by-Turn BPM Data 2023



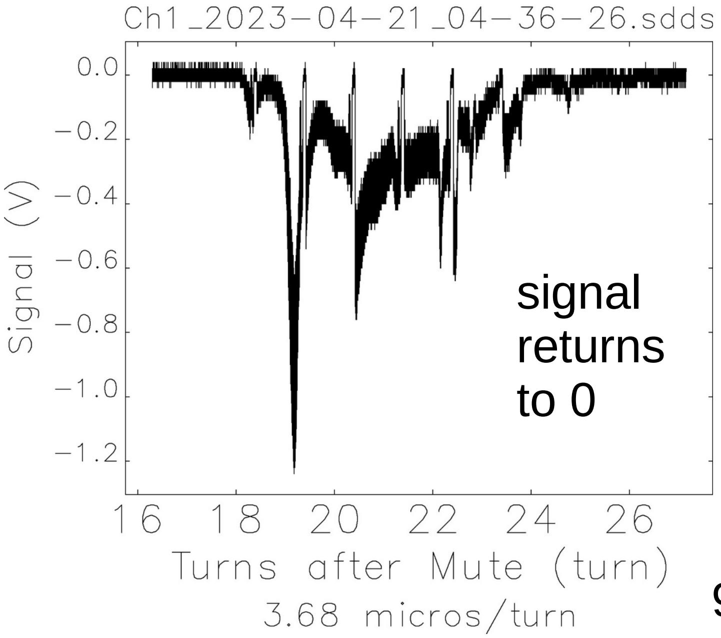
RF muting occurs at Turn 0





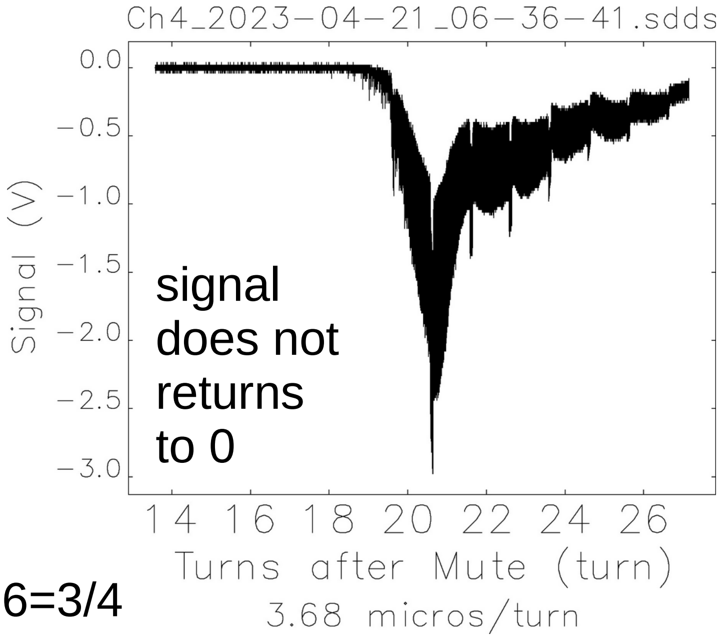
Fast Beam Loss Data in ID1 (1st und. vac. chamber)

FOK: 2 kV, +1.5 mm



972 minus a few, 200 mA

FOK: 0 kV, -3.0 mm

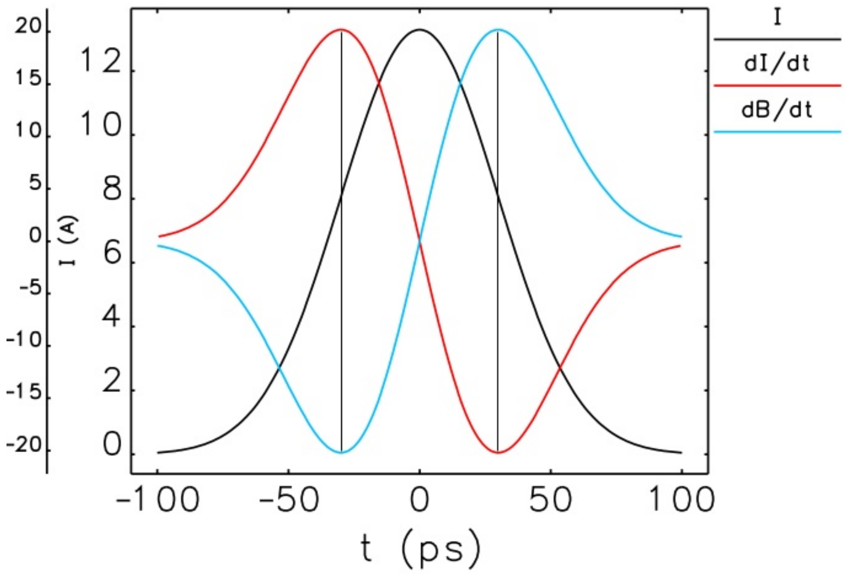


972 plus a few, 200 mA

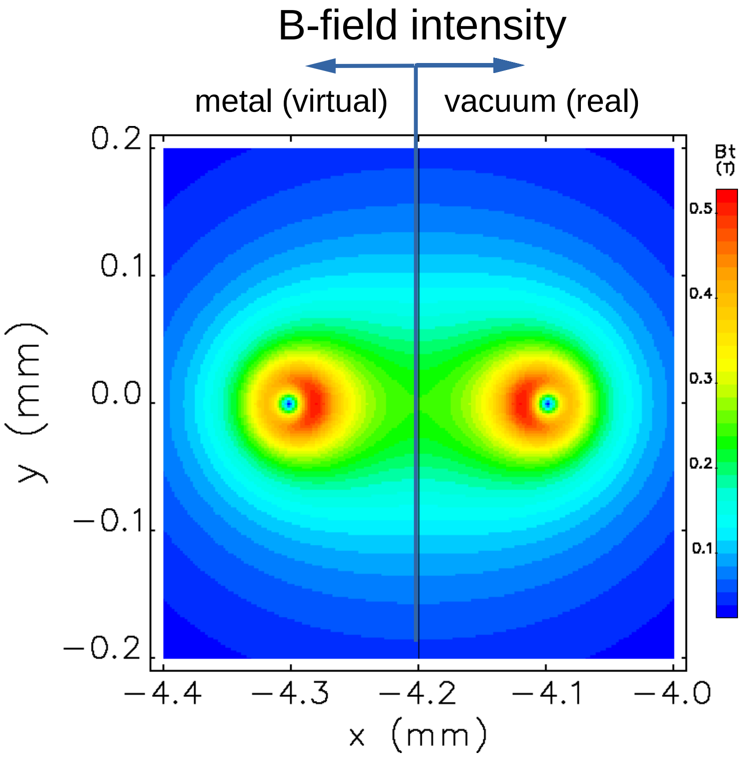
972/1296=3/4

MHD Effects—Starting Point

—15.3 nC, Gaussian σ_t=20 ps



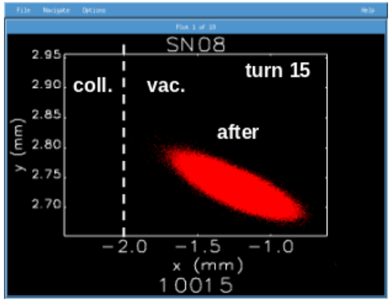
Temporal waveform and 1st derivative

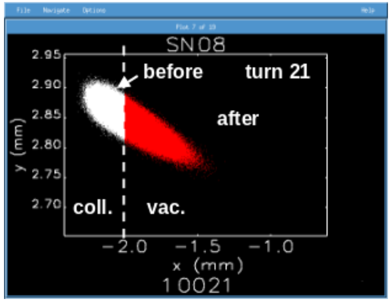


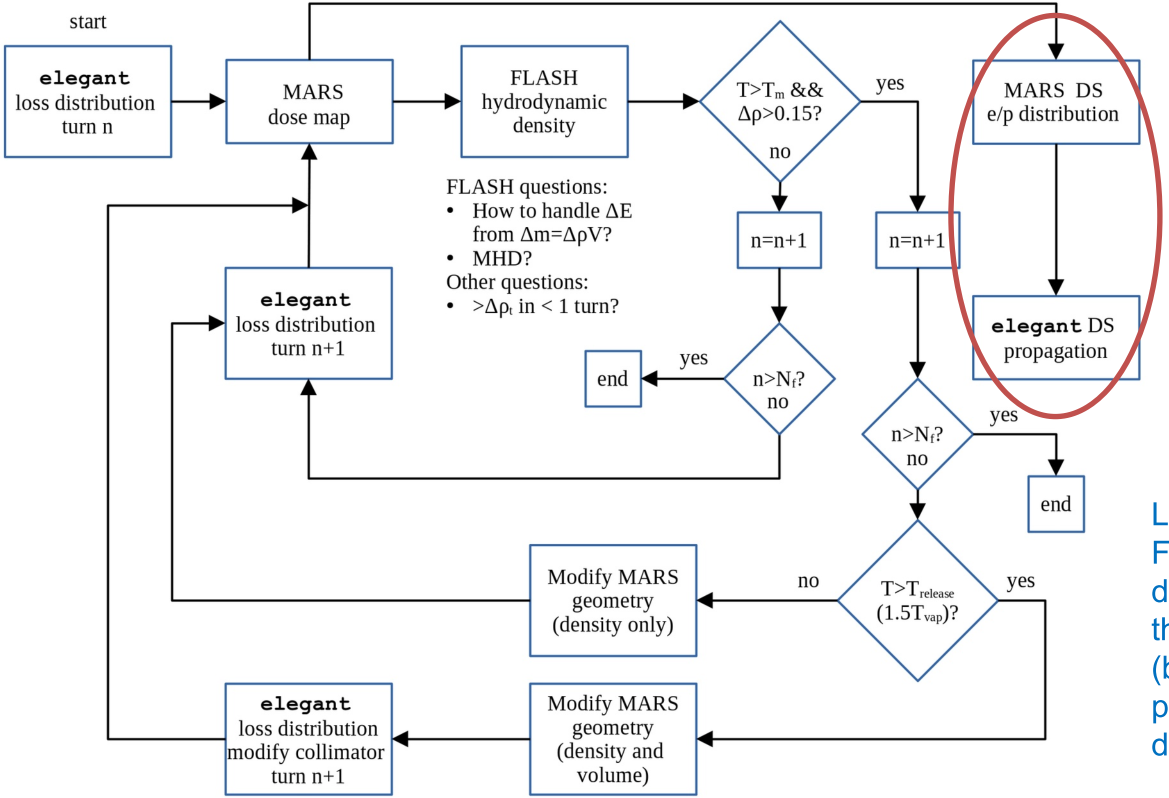
Current filament, 0.1 mm above surface and image current

Code Coupling—Flow Diagram in Greater Detail

Have been using the "before" collimator distribution. Instead use the full distribution.





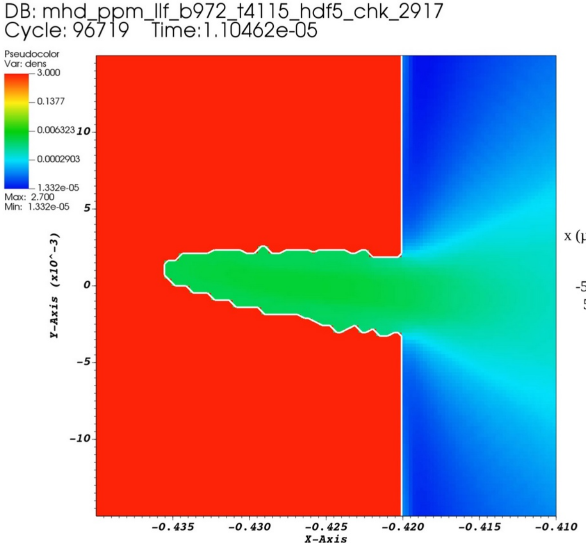


Can be run separately

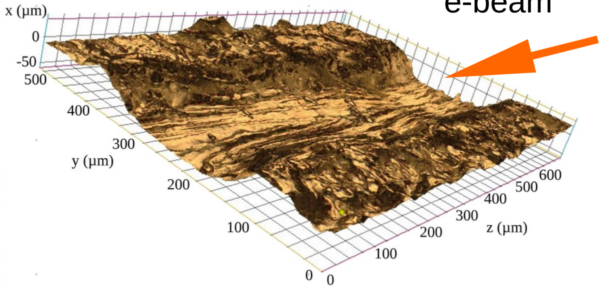
Let MARS and FLASH determine the interacting (before) and passing (after) distributions.

Release modification in FLASH—filling the gap

After last deposition, bdry_var is stepped from $1.5T_{vap}$ to $1.0T_{vap}$



For mechanical integrity want to know the depth of the plastic/melt region



Microscopy image from 200-mA beam strike on Al (Jan 2020). See slide 8