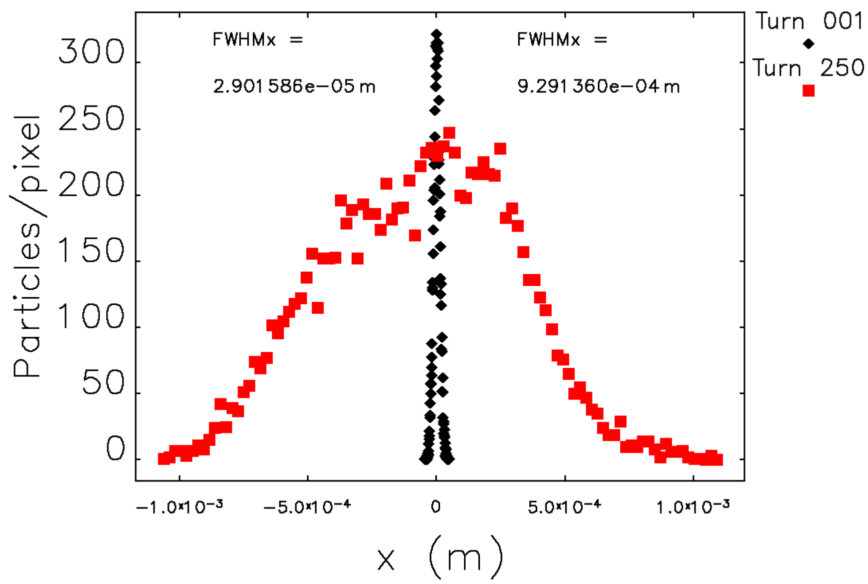
TECHNICAL WORKSHOP ON INJECTION AND INJECTION SYSTEMS
AUGUST 28-30, 2017 BERLIN GERMANY

ENERGY DEPOSITION IN THE APS-U SWAP-OUT DUMP AND DISCUSSION OF WHOLE BEAM LOSS



JEFF DOOLING
MICHAEL BORLAND

Advanced Photon Source
Argonne National Laboratory

OUTLINE

Injection into the APS-U Multibend Achromat (MBA) storage ring (SR)

- Background—The requirement for Swap-Out Injection
- Energy Density / Material Challenges
- Decoherence—Distributions modeled with ELEGANT[1]
- Loss Distributions from ELEGANT used as input to MARS[2]
- Whole Beam Dump Considerations
- Beam Damage Experience in the Present APS Storage Ring
- Discussion and Summary

Yesterday A. Xiao and L. Emery discussed model predictions for the "swapped-in" or "refreshed" bunch. Today we will talk about what happens to the "swapped-out" or "depleted" bunch, where it goes and what effects the charge could have on material it encounters.

[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)

BACKGROUND

Swap-Out injection takes place after a the charge of a particular bunch in the SR drops below 90% of its nominal value.

- Based on the present 2.9-hr lifetime estimate for a 48-bunch fill pattern, a bunch needs to be replaced once every 23 s.
- Injector beam loss power: 4 W
- Total charge with 200 mA circulating in the 1104-m circumference storage ring: 4.6×10^{12} $e^{-} \rightarrow$ 737 nC, representing 4420 J at 6 GeV
- 92 J in a single bunch
- MARS is used to model the energy density (dose) and fluences as the electrons interact with matter.
- The primary electron input distributions are provided by ELEGANT.
- In the case of swap-out, temperature excursions are determined with MARS by integrating enthalpy to include the variation of specific heat with temperature.
- This calculation works as long as final temperature is far from a phase transition.

TEMPERATURE EXCURSION

- Naïve calculation of temperature rise (mono-energetic beam, constant specific heat, ignoring phase transitions)

$$\Delta T = \frac{D A_w}{C_m}$$

  – $D \equiv$ dose (Gy or J/kg)
  – $A_w \equiv$ atomic weight (g/mole)
  – $C_m \equiv$ molar specific heat (J/K/mole)
- At the Swap-Out Dump, the beam cross section is elliptical, assume Gaussian
  – σ_x = 6.5 μm = $6.5\text{x}10^{-4}$ cm
  – σ_y = 12.5 μm = $12.5\text{x}10^{-4}$ cm
  – $A_b = 4\pi\sigma_x\sigma_y = 1.02\text{x}10^{-5}$ cm^2
- Candidate Swap-Out Dump materials
  – Aluminum
  – Titanium (alloy)
  – Copper
  – Tungsten
- Dose is the product of collisional stopping power and fluence, $D = Spc\left(\frac{N_e}{A_b}\right)$,
  – N_e = 15.3 nC /($1.602\text{x}10^{-10}$ nC/e) = $9.58\text{x}10^{10}$ e
  – $N_e/A_b = 9.38\text{x}10^{15}$ cm^{-2}

RADIATIVE AND ABSORBED (COLLISIONAL) STOPPING POWER

NIST e-star (https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html)

ALUMINUM

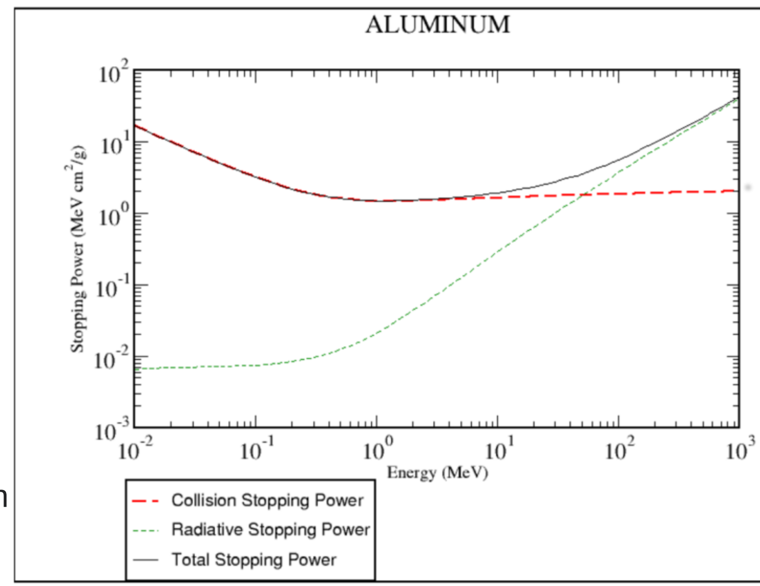
To download data in spreadsheet (array) form, choose a delimiter and use the che
save the output by using your browser's `Save As` feature.

Delimiter:
- ◉ space
- ○ | (vertical bar)
- ○ tab
- ○ newline

Download data | Reset

(required) Kinetic Energy (MeV)	Stopping Power (MeV cm²/g) Collision	Radiative	Total	Density Effect Parameter
1.000E-02	1.649E+01	6.559E-03	1.650E+01	3.534E-04
1.500E-02	1.220E+01	6.798E-03	1.221E+01	6.538E-04
2.000E-02	9.844E+00	6.926E-03	9.851E+00	1.031E-03
2.500E-02	8.338E+00	7.004E-03	8.345E+00	1.483E-03
3.000E-02	7.287E+00	7.059E-03	7.294E+00	2.005E-03
3.500E-02	6.509E+00	7.100E-03	6.516E+00	2.594E-03

3.000E+03	2.102E+00	1.228E+02	1.249E+02	1.312E+01
3.500E+03	2.113E+00	1.435E+02	1.456E+02	1.342E+01
4.000E+03	2.123E+00	1.641E+02	1.662E+02	1.369E+01
4.500E+03	2.132E+00	1.848E+02	1.869E+02	1.393E+01
5.000E+03	2.140E+00	2.054E+02	2.076E+02	1.414E+01
6.000E+03	2.153E+00	2.467E+02	2.489E+02	1.450E+01
7.000E+03	2.165E+00	2.880E+02	2.902E+02	1.481E+01
8.000E+03	2.174E+00	3.294E+02	3.315E+02	1.508E+01
9.000E+03	2.183E+00	3.707E+02	3.729E+02	1.531E+01
1.000E+04	2.191E+00	4.120E+02	4.142E+02	1.552E+01



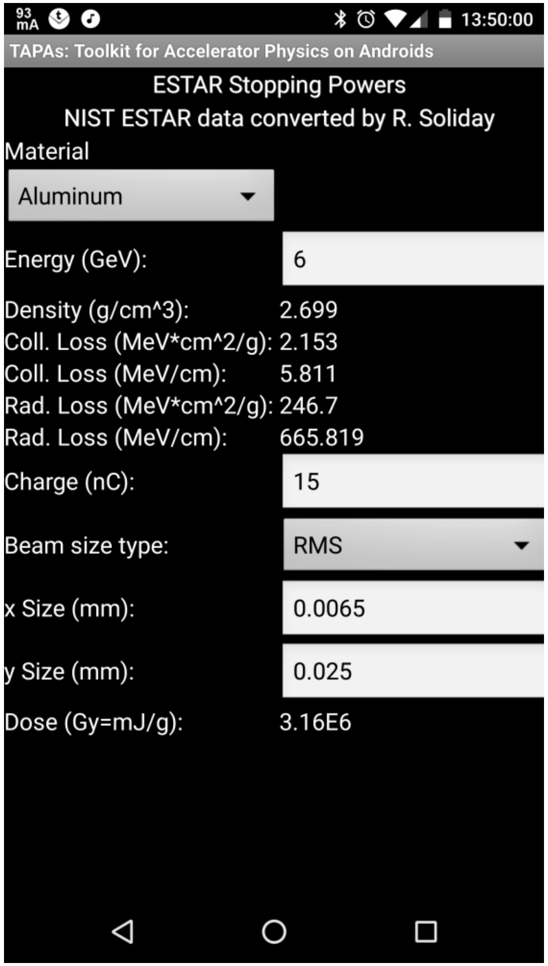
Most of the stopping power at 6 GeV is due to radiative loss (bremsstrahlung).

However, because of the high power densities, the absorbed dose from the collisional component leads to very high temperatures in all materials including carbon

TAPAS—TOOLKIT FOR ACCELERATOR PHYSICS ON ANDROIDS (SORRY IPHONE USERS)

Dose estimates for various metals (Al, Ti, Cu, W) and carbon (gr. & amorph.)

Z=13



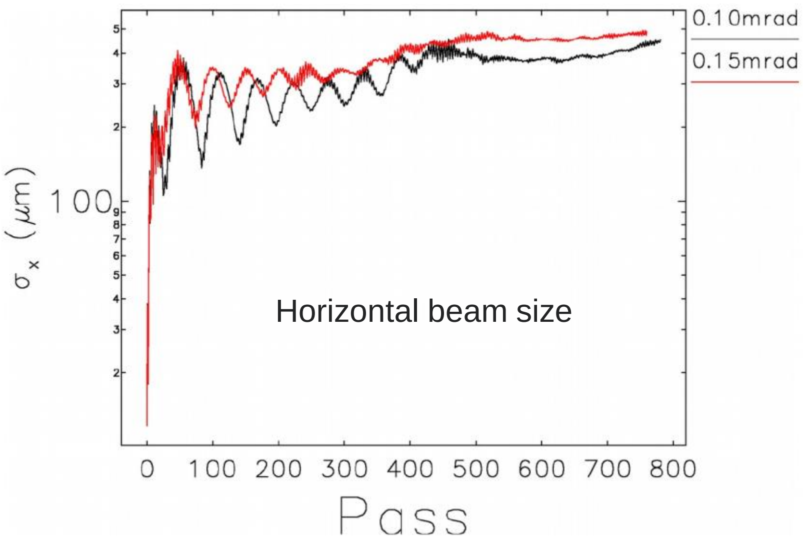
- Summarizing dose and ΔT

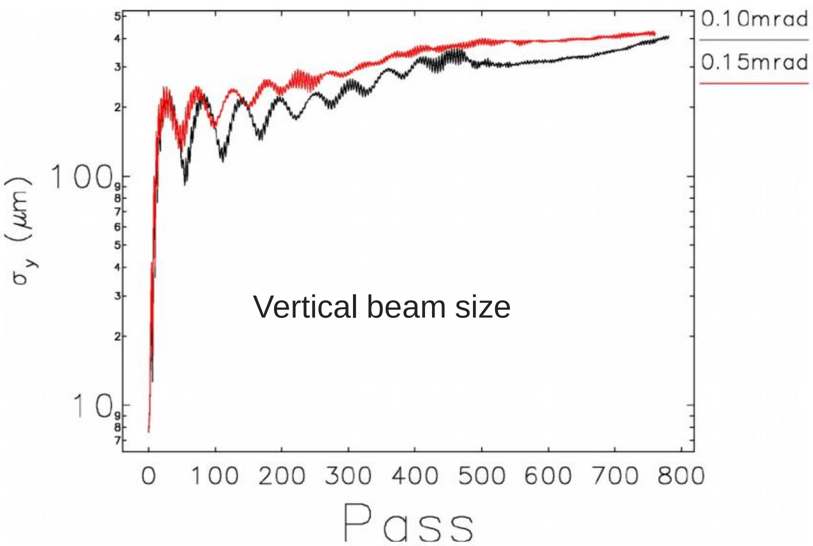
Material	Dose (Gy)	C_m (J/mole/K)	A_w (g/mole)	ΔT (K)
Carbon (gr.)	3.40×10^6	8.52	12.0	4794
Carbon (am.)	3.39×10^6	8.52	12.0	4768
Aluminum	3.16×10^6	24.2	26.98	3523
Titanium	2.97×10^6	24.89	47.87	5712
Copper	2.88×10^6	24.44	63.55	7489
Tungsten	2.48×10^6	24.27	183.84	18,785

- In all cases ΔT is above T_{mp}
- Empirically have found that temp. excursions above the MP lead to damage
- Need a way to reduce dose

DECOHERENCE OF SWAP OUT BUNCH BY A FAST KICKER WITH MODEST DEFLECTION—PROVIDES A METHOD TO REDUCE INTENSITY

ELEGANT modeling: several hundred turns are required to fully inflate the bunch at pre-kicker strengths of 100, 150, and 200 μrads —here we use the distribution after 250 turns. The result is a dramatically reduce energy density.

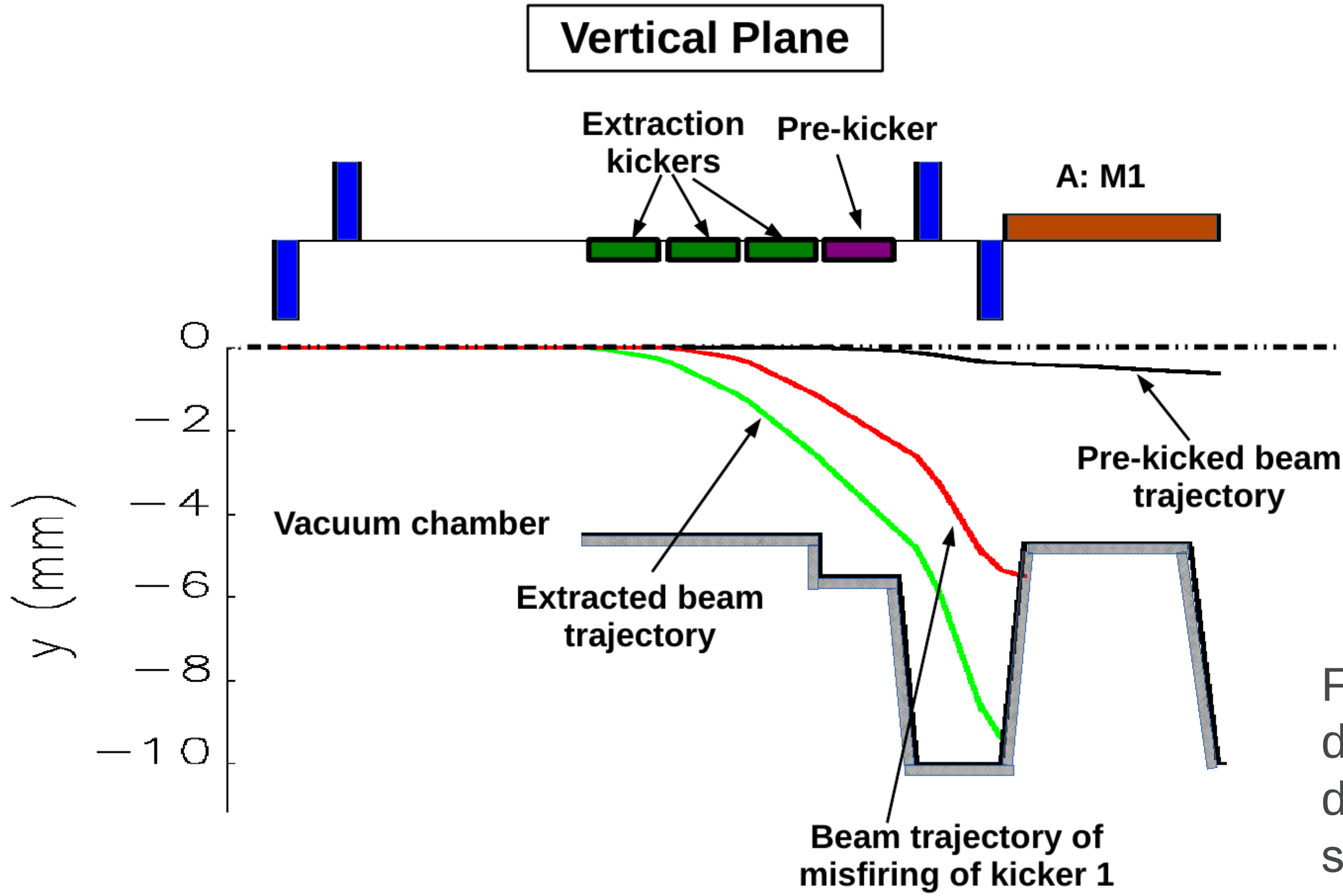




Pre-kicker strength is set to operate without beam loss

SWAP OUT EXTRACTION KICKER LAYOUT AND DUMPED BEAM TRAJECTORIES

Nominal operation and kicker 1 misfire

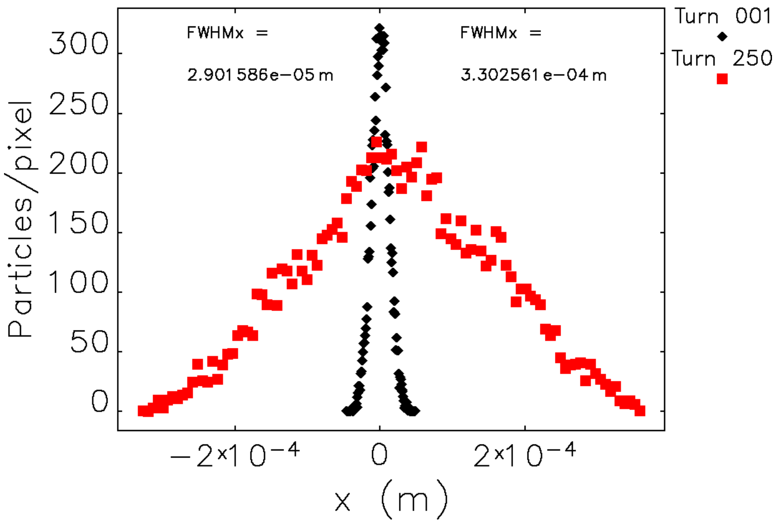


For a more detailed discussion, see A. Xiao's talk

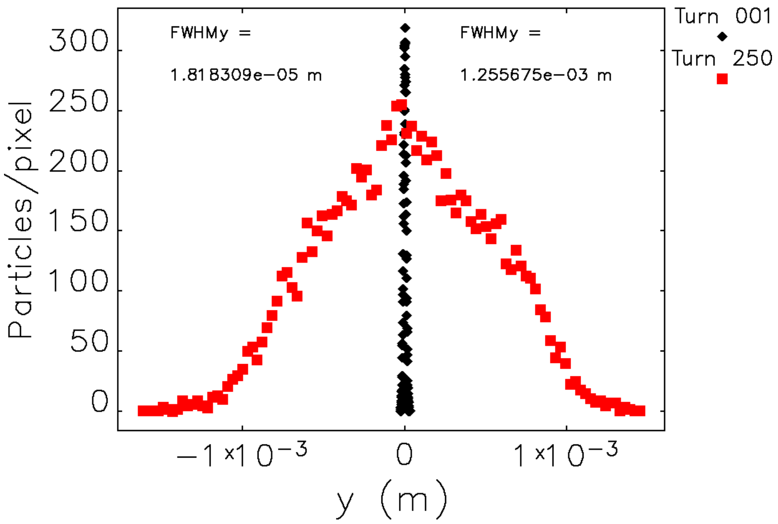
TRANSVERSE PROFILES WITH DECOHERENCE KICKS

Turn 1 and 250 profiles after decoherence kick of 0.2 mrad at turn 0

Horizontal profiles



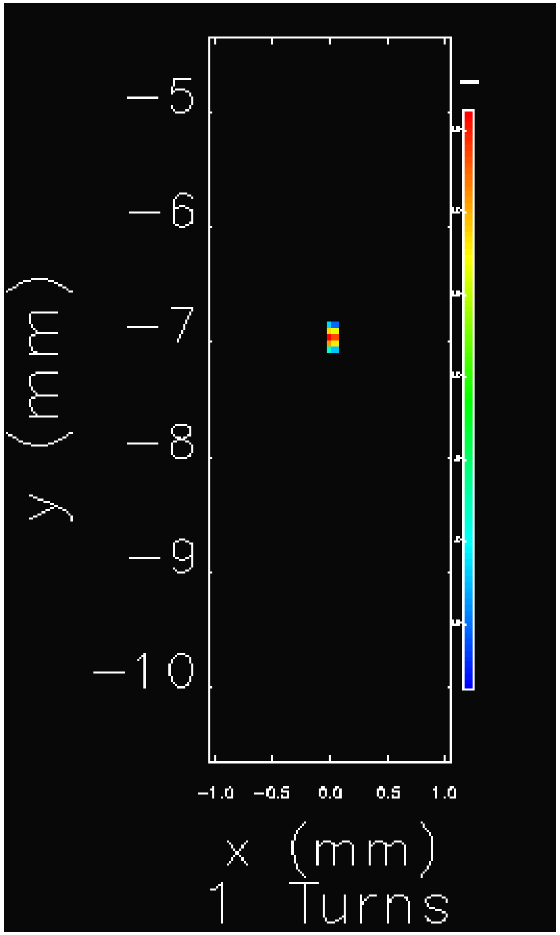
Vertical profiles



Pixel sizes change, total number of pixels same in all cases

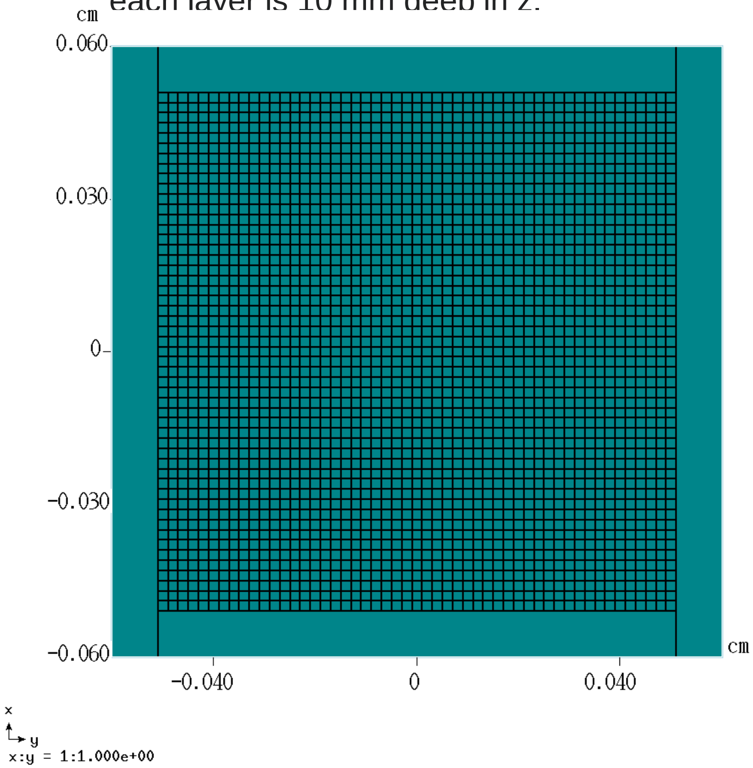
DECOHERENCE OF THE DEPLETED SWAP-OUT BUNCH

The bunch inflates more in the vertical direction, but both planes experience substantial growth

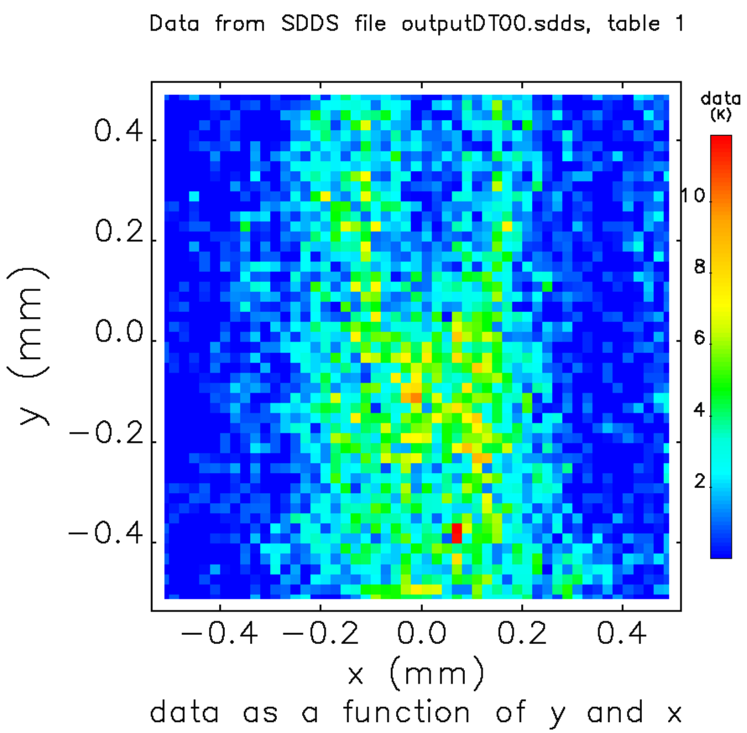


MARS GEOMETRY AND TRANSVERSE TEMPERATURE DISTRIBUTION (TURN 250)

X-Y view; voxels: 51x51, 20 μm x 20 μm; each layer is 10 mm deep in z.



200 μrad kick



Distribution near the peak intensity in an Aluminum collimator. Animation steps through the collimator in 1 cm increments; 12 steps in total.

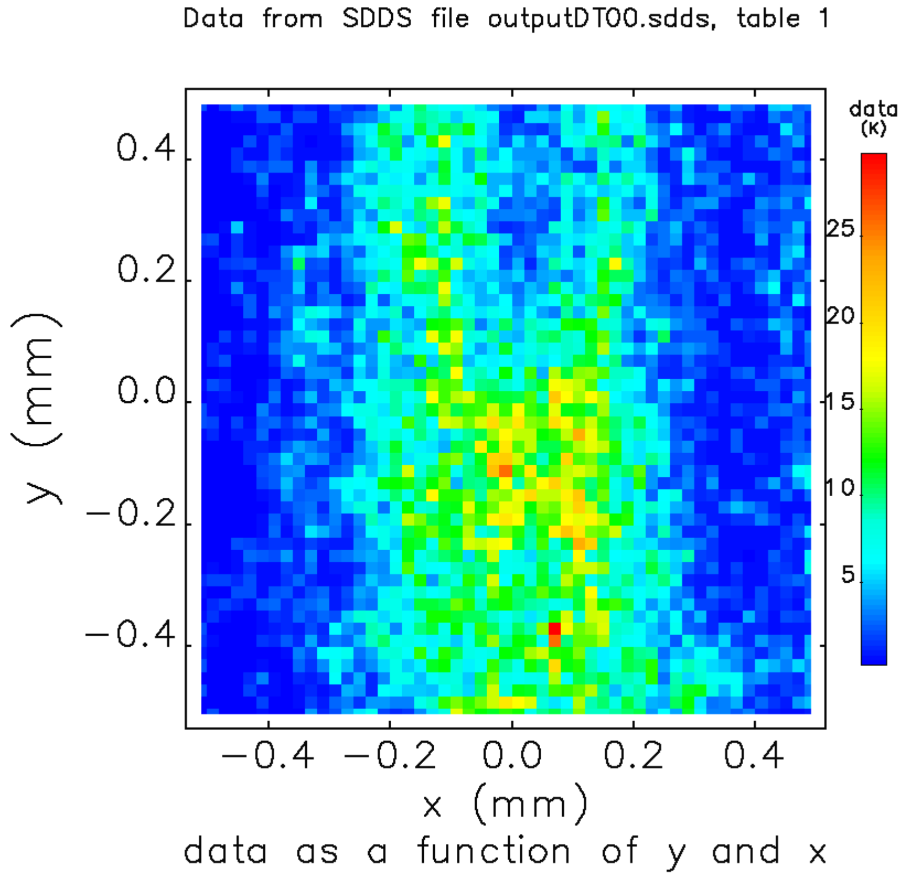
TEMPERATURE EXCURSION DISTRIBUTION IN AL

1-cm steps in the collimator—12 steps, frames 00, 06, and 11; aluminum

- frame 00, z=0-1 cm; distribution is noisy due to relatively low number of trajectories
- Will over-estimate peak temperature rise
- frame 05, z=5-6 cm; particle generation (showering) fills out the distribution
- frame 11, z=11-12 cm; distribution has filled in after 1.3 X_o/ρ.

TEMP. DIST. VS. DEPTH IN THE COLLIMATOR

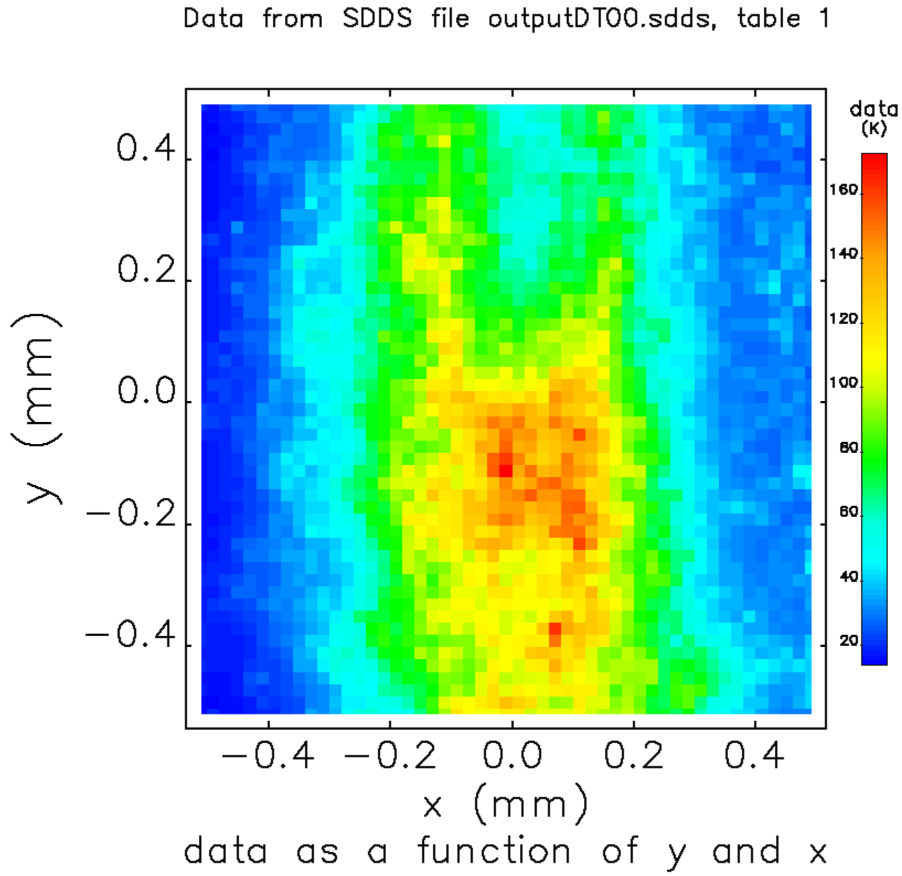
Copper



- Distribution in the 1st cm is noticeably smoothed
- frame 11 is 8 radiation lengths deep (centered at z=11.5 cm)

TEMP. DIST. VS. DEPTH IN THE COLLIMATOR

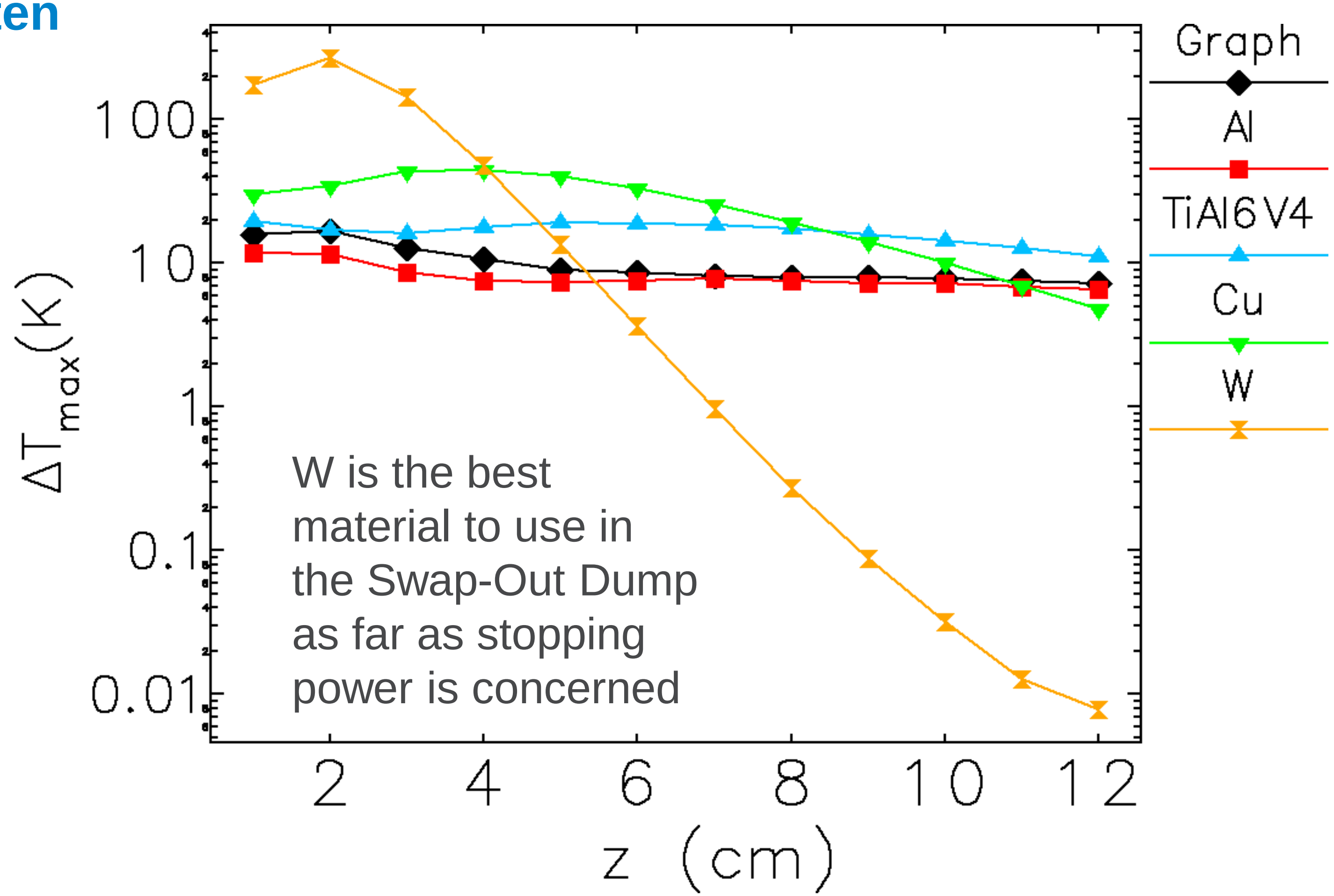
Tungsten



- Initial distribution is smoothed significantly in the 1st cm of W
- Beam energy almost fully dissipated by frame 11 (x: 11-12 cm)

PEAK TEMPERATURE DISTRIBUTION VS. DEPTH IN THE SWAP-OUT DUMP

Candidate materials: graphite, aluminum, titanium alloy, copper, tungsten



W is the best material to use in the Swap-Out Dump as far as stopping power is concerned

WHOLE BEAM DUMP CONSIDERATIONS

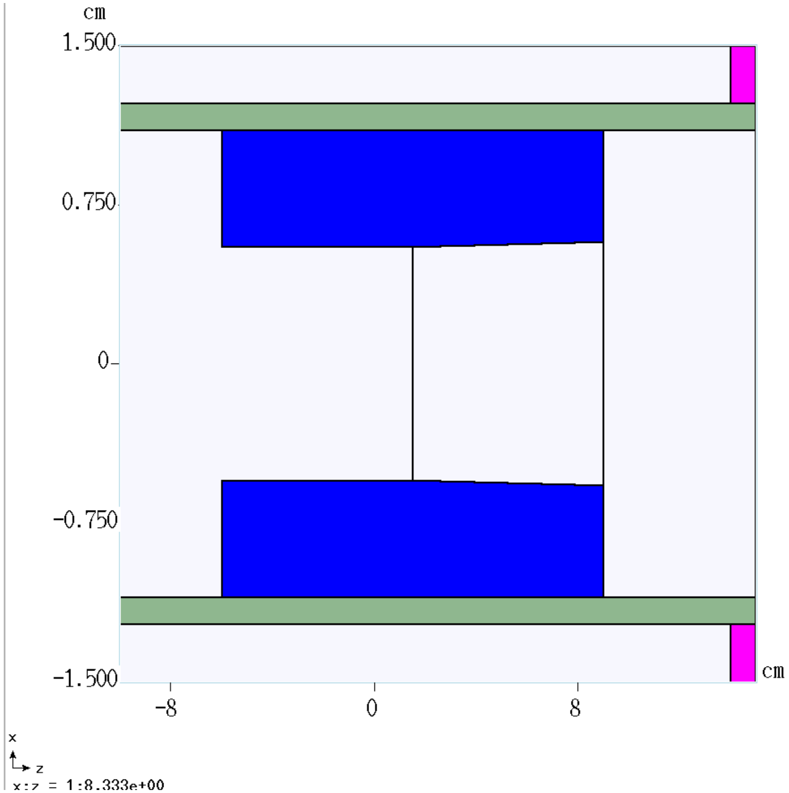
Collimators/Spoilers

- Collimators receive the primary beam but energy absorption is not local
- Initial energy densities reach into the hydrodynamic regime (>15 kJ/g or 15 MGy)
- Alternate codes required; N. Mokhov[3] mentions LANL codes, MESA and SPHINX (contact Doug Wilson)
- High power levels at SLAC were handled with water-cooled copper plates in a SS (316-L) vessel (D. R. Walz, et al.)[4]
- For higher power densities, lower Z material Walz recommended (Al or Ti)
- Collimators may be considered sacrificial and therefore must be moved after each whole beam dump

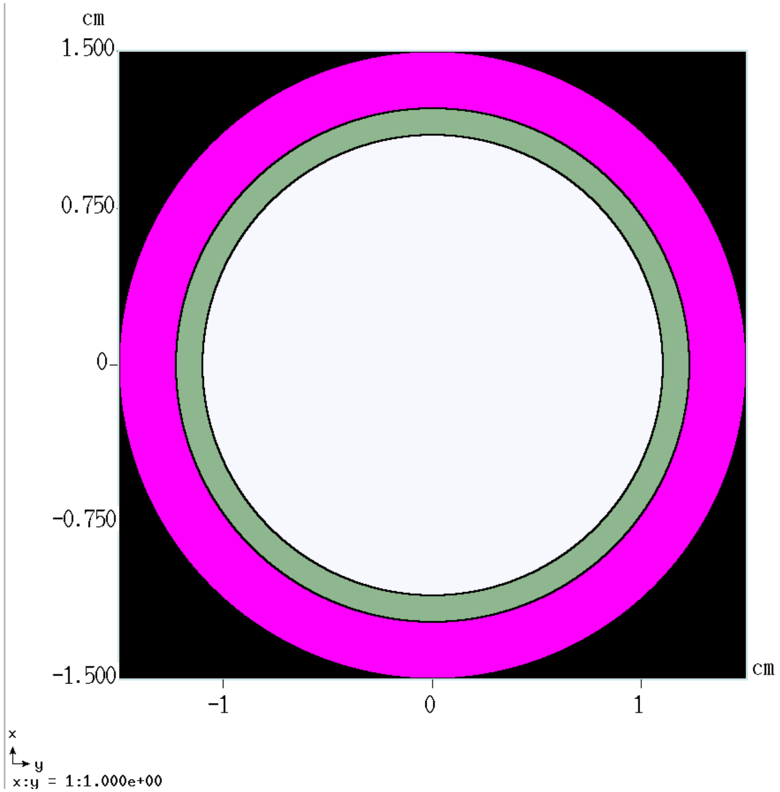
[3] N. Mokhov, “Beam-Materials Interactions,” In: Reviews of Accelerator Science and Technology **6** (2013), pp. 275–290.

[4] D. Walz et al. in. *The Stanford Two-Mile Accelerator*, R. B. Jeal, General Editor Stanford University 1968, W. A. Benjamin, Inc. New York, p.705.; http://www.slac.stanford.edu/library/2MileAccelerator/2mile.htm

SIMPLIFIED MARS GEOMETRY FOR COLLIMATOR AND NEARBY MAGNET



X-Z view

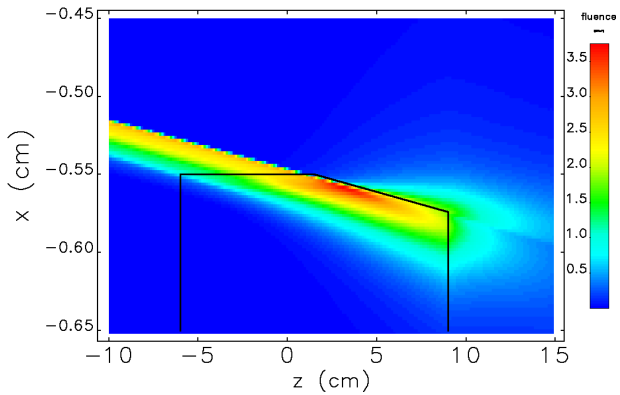


X-Y view

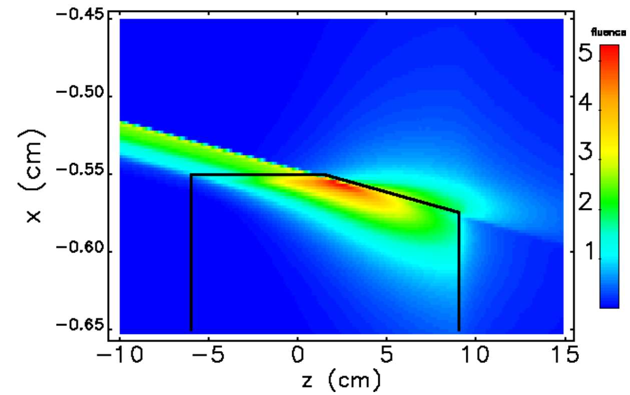
ELECTRON / POSITRON FLUENCE IN THE COLLIMATOR

Hydrodynamics will affect this

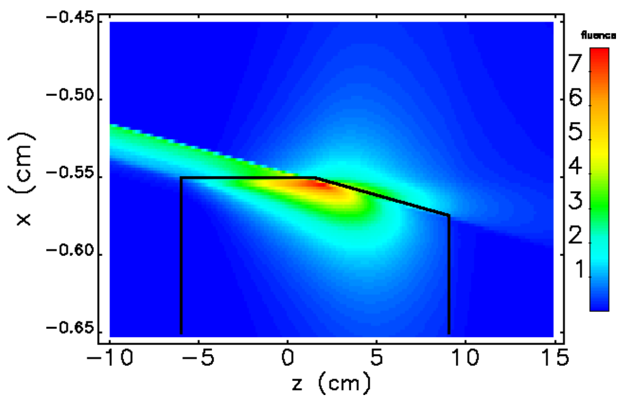
Aluminum



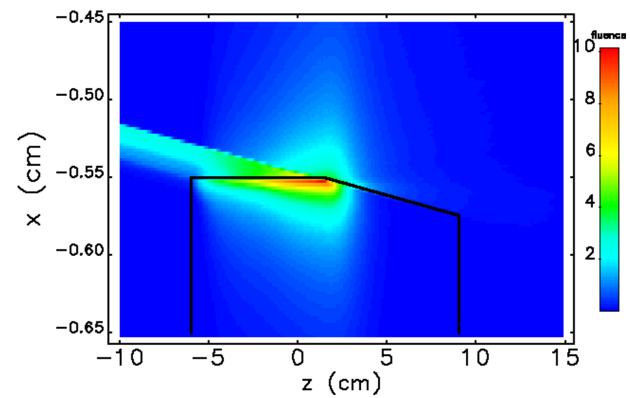
Titanium alloy



Copper

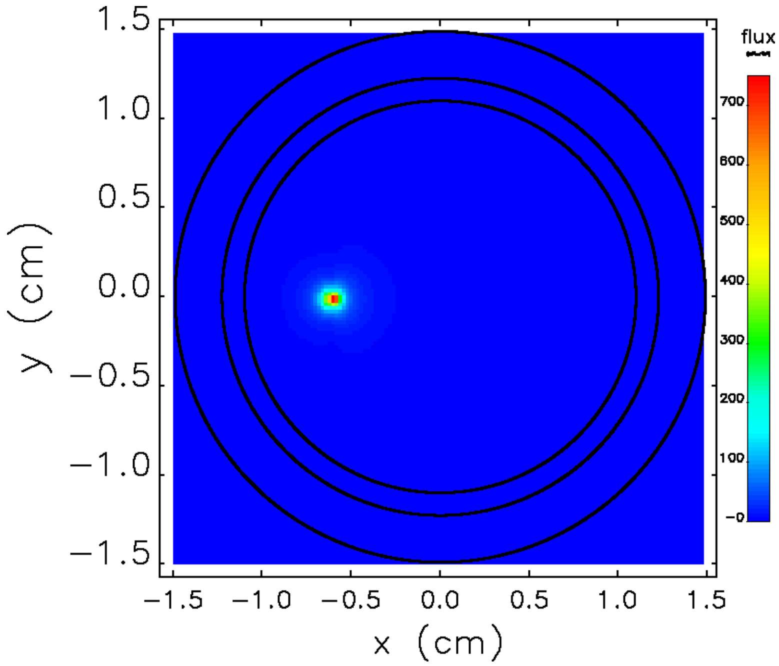


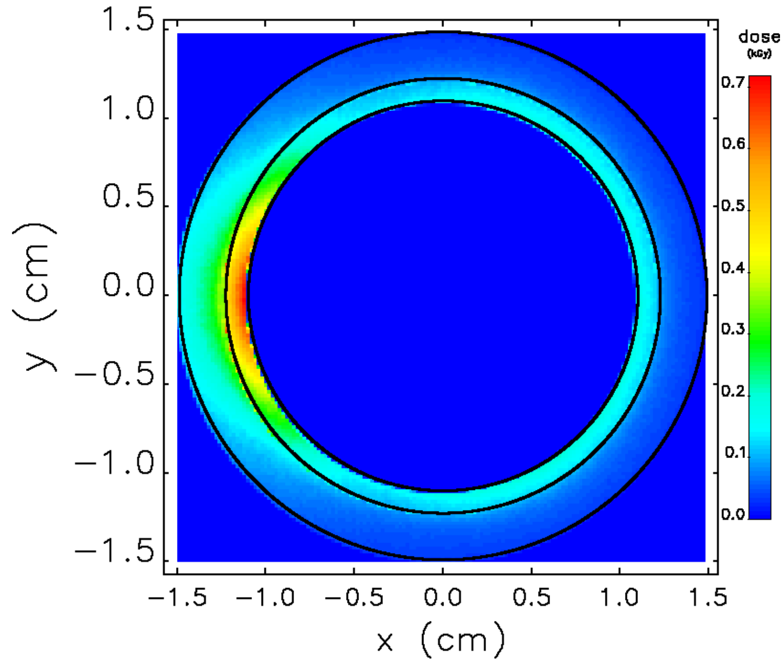
Tungsten



FLUENCE AND DOSE DOWNSTREAM OF COLLIMATOR

Aluminum collimator



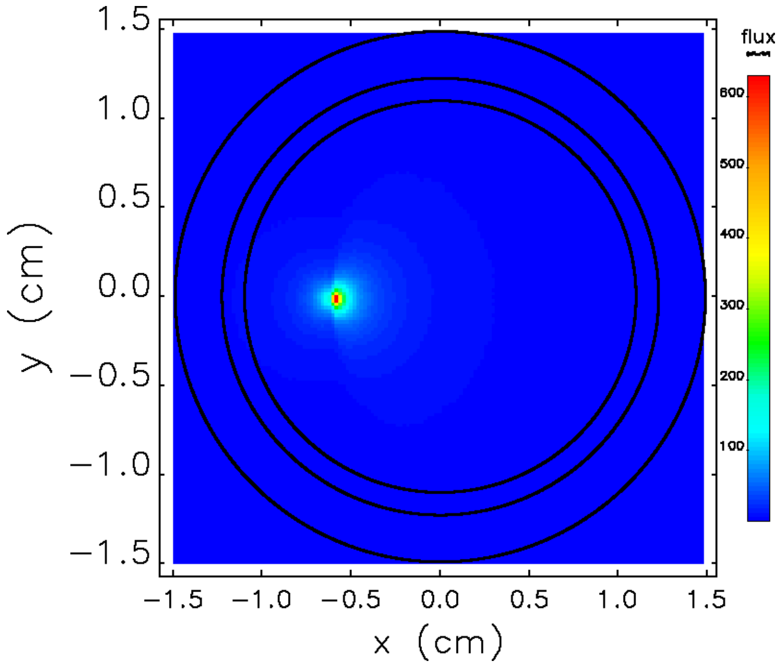


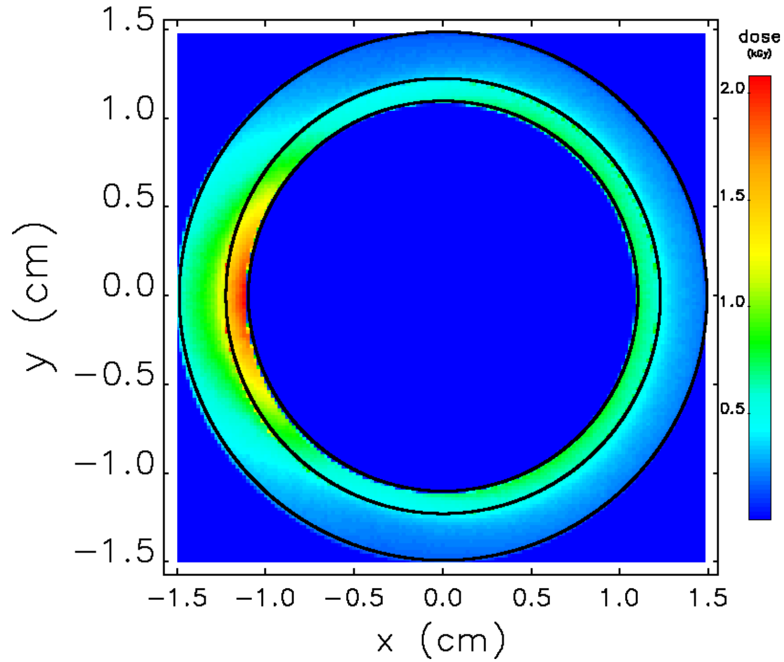
Peak fluence: 7.4×10^{14} cm^{-2}

Peak dose: 0.7 kGy

FLUENCE AND DOSE DOWNSTREAM OF COLLIMATOR

Titanium



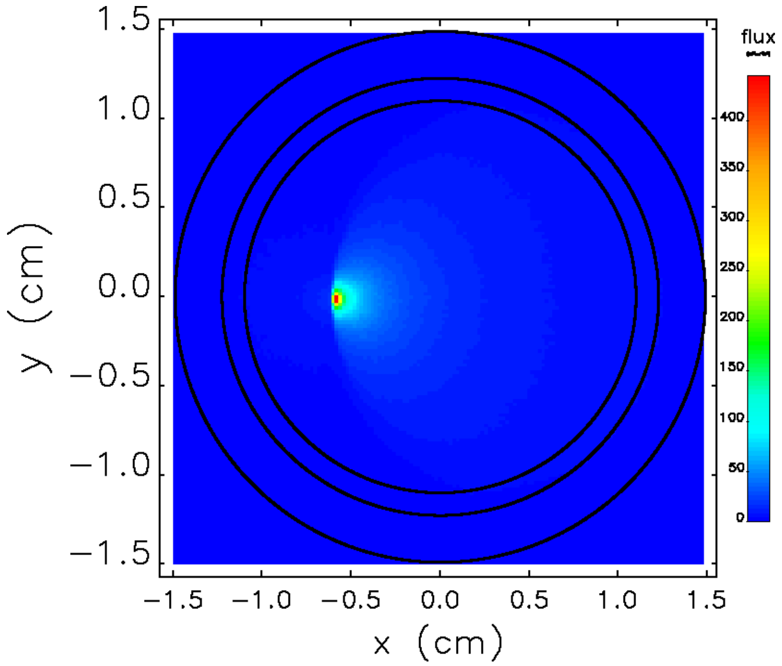


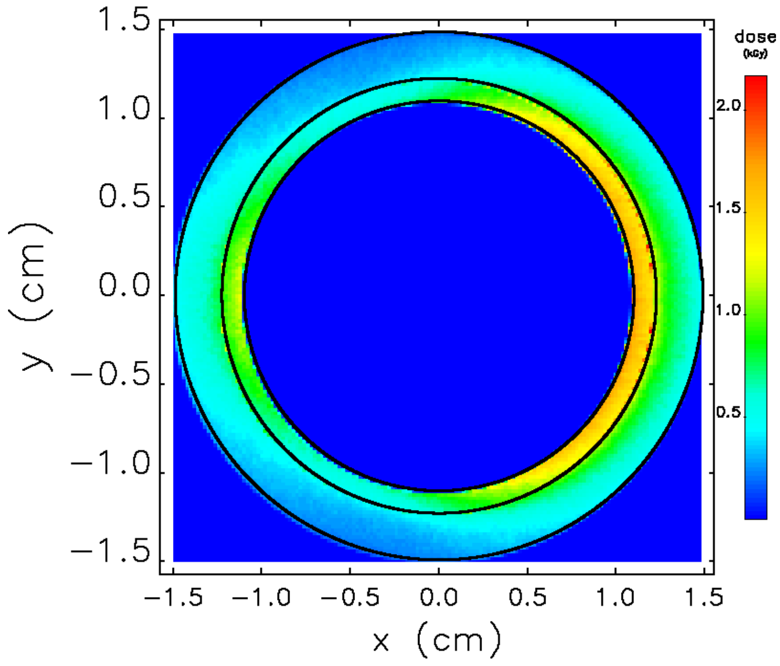
Peak fluence: $6.2\text{x}10^{14}$ cm^{-2}

Peak dose: 2.1 kGy

FLUENCE AND DOSE DOWNSTREAM OF COLLIMATOR

Copper



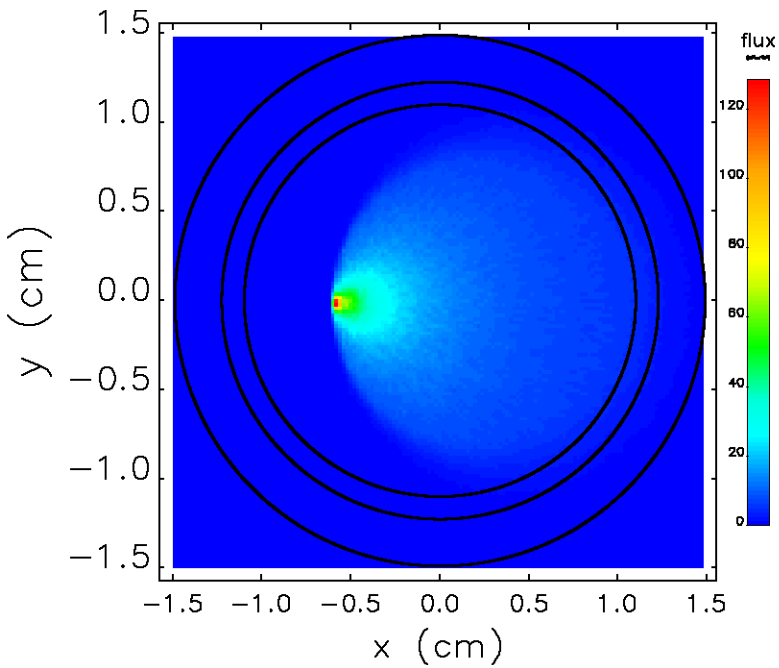


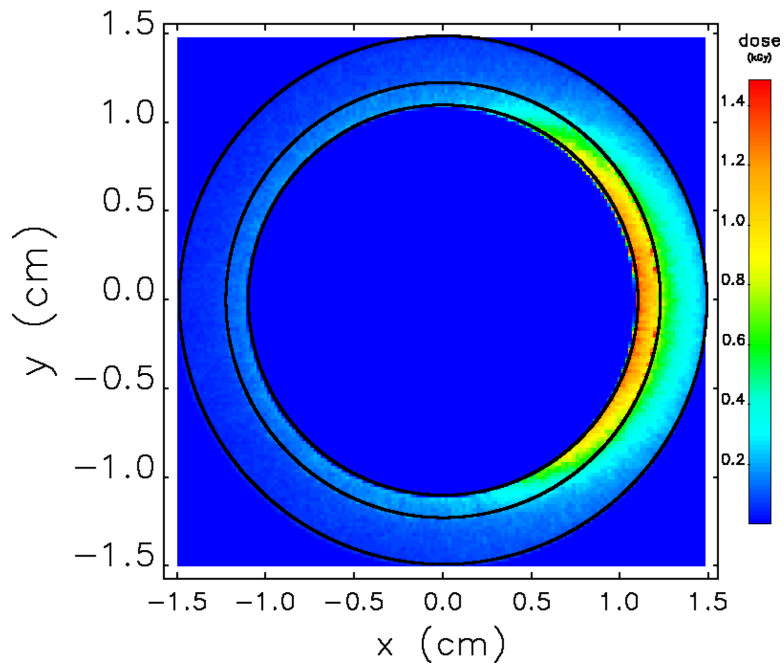
Peak fluence: 4.4x10^{14} cm^{-2}

Peak dose: 2.1 kGy

FLUENCE AND DOSE DOWNSTREAM OF COLLIMATOR

Tungsten



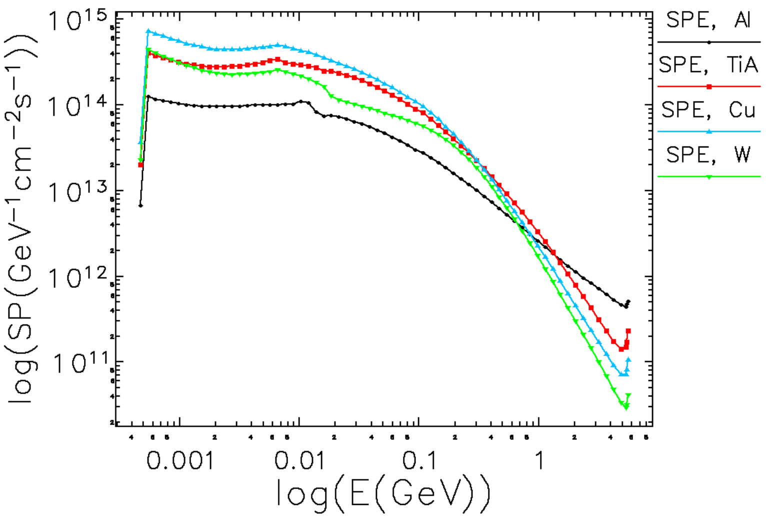


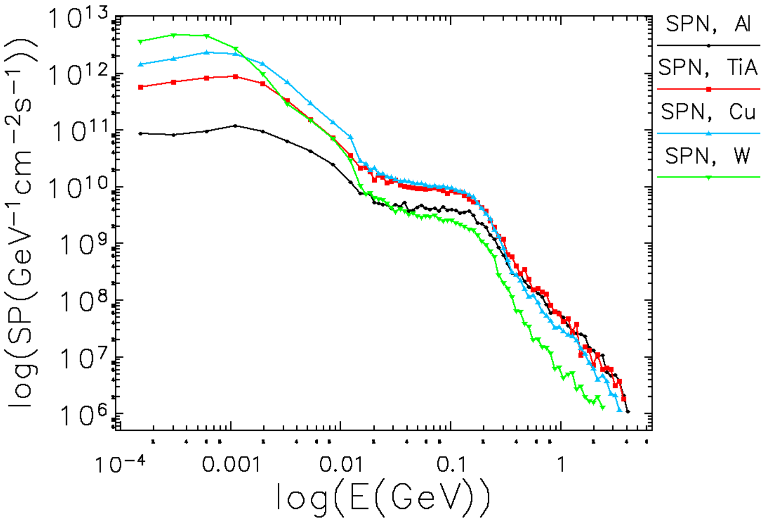
Peak fluence 1.26×10^{14} cm^{-2}

Peak dose: 1.45 kGy

SPECTRA DOWNSTREAM OF THE COLLIMATOR

Electron-positron and neutron



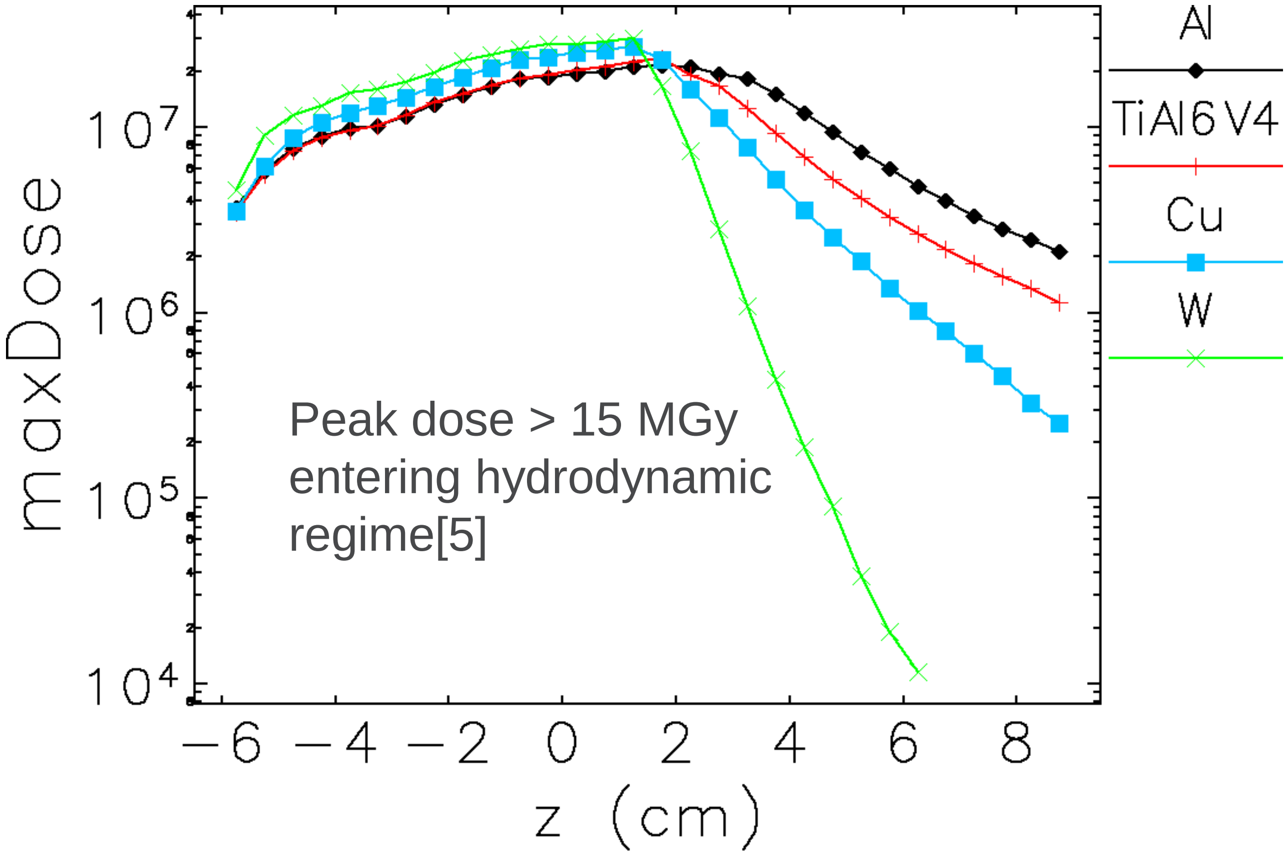


Sampled in the vacuum chanber near the magnet location

Aluminum acts more as a spoiler. Beam for the most part passes through the collimator, but is scattered.

NOMINAL MAXIMUM DOSE VS DEPTH IN AN EXTENDED COLLIMATOR

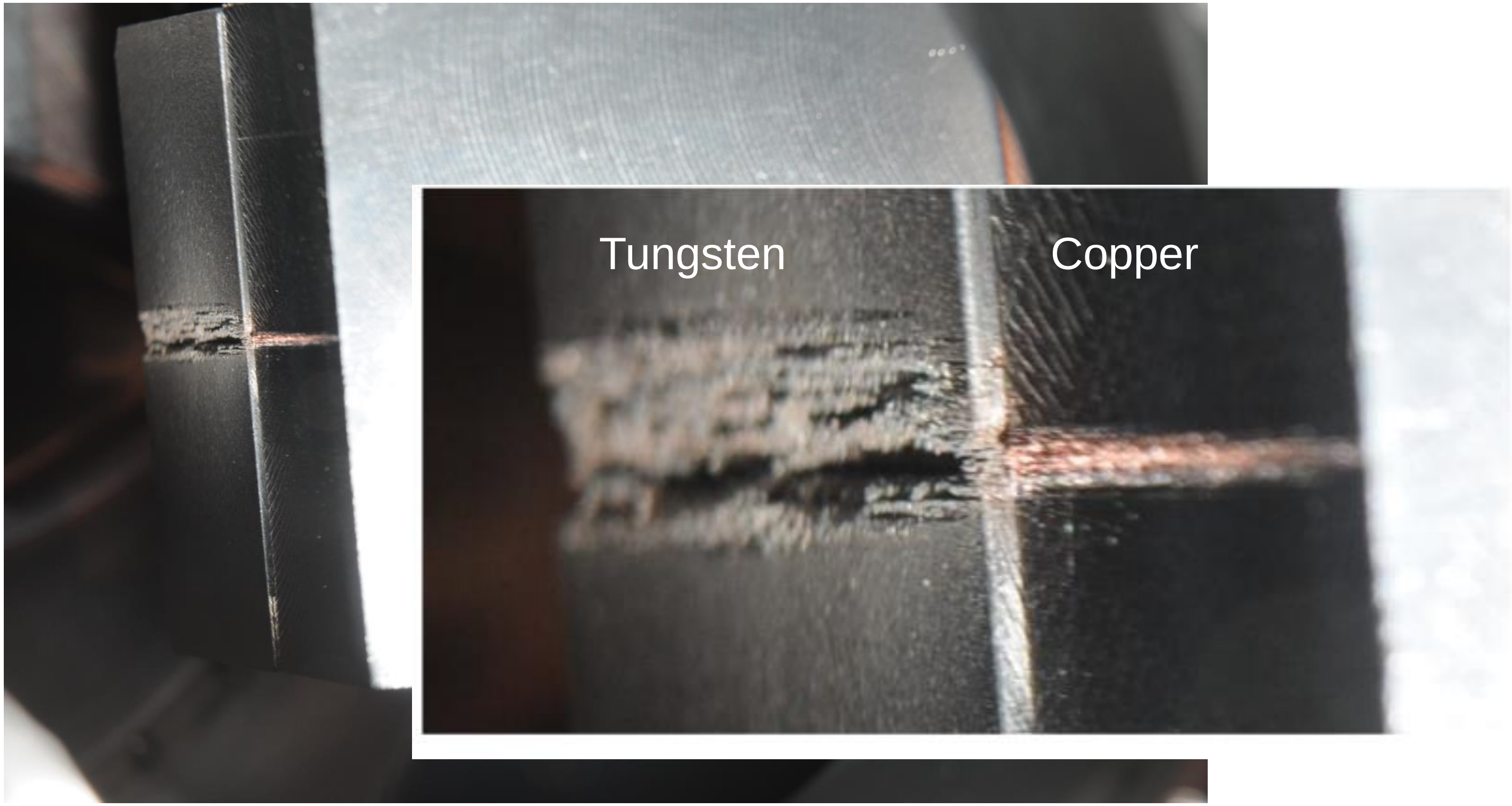
Dose in Gy



[5] N. Mokhov, ipid

BEAM DAMAGE EXPERIENCE IN THE PRESENT APS STORAGE RING

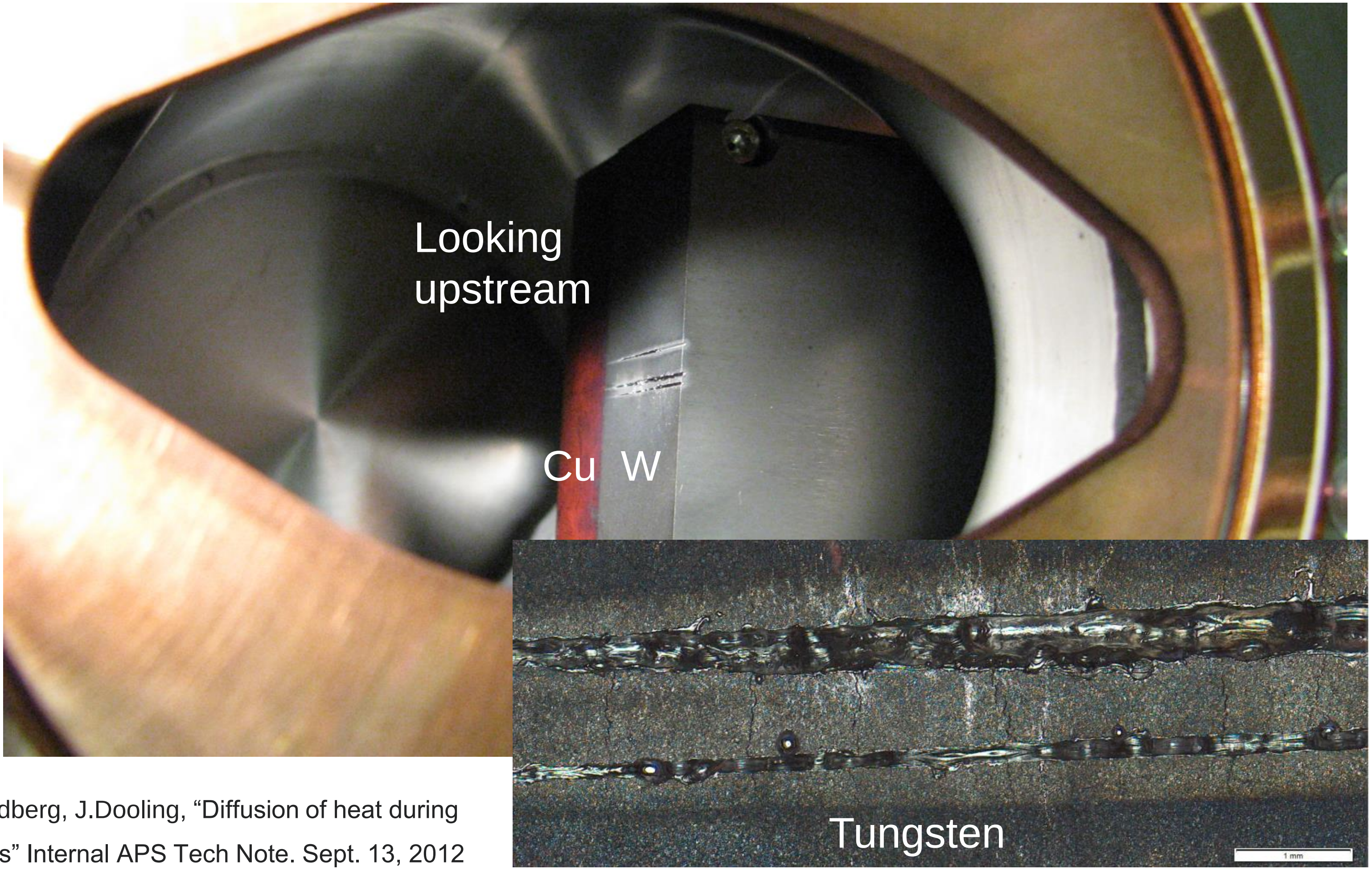
Copper/Tungsten scraper installed in the APS SR Sector 37



Dose Estimates: 1-2MGy

TEST SCRAPER INSTALLED IN S37

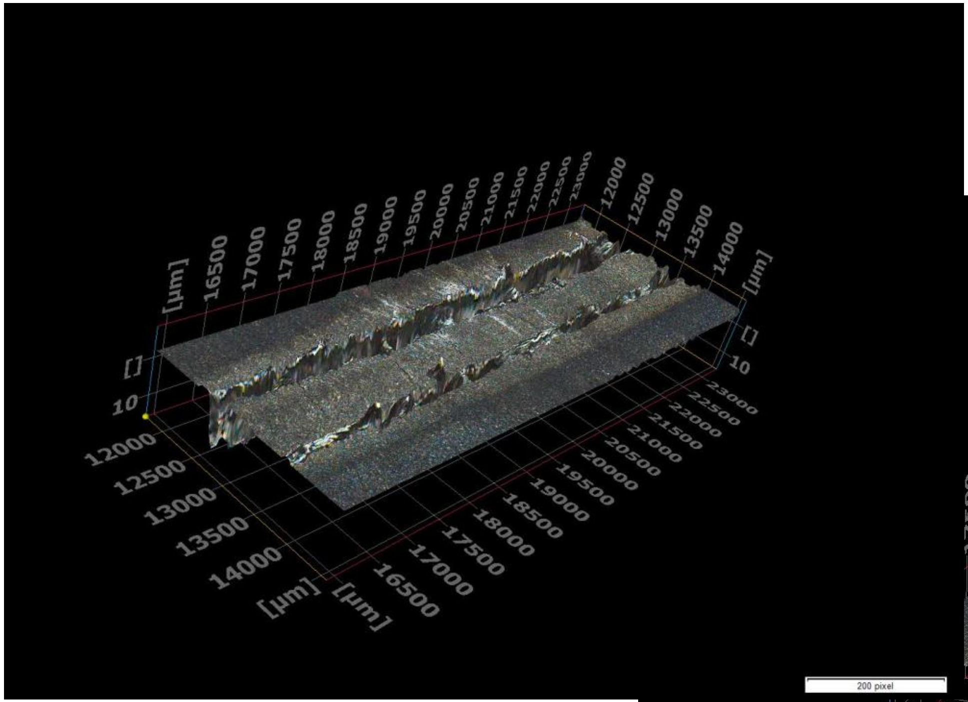
Also Copper-Tungsten design—experiment on final day of the run April 2012 empirically validated model and measurements[3]

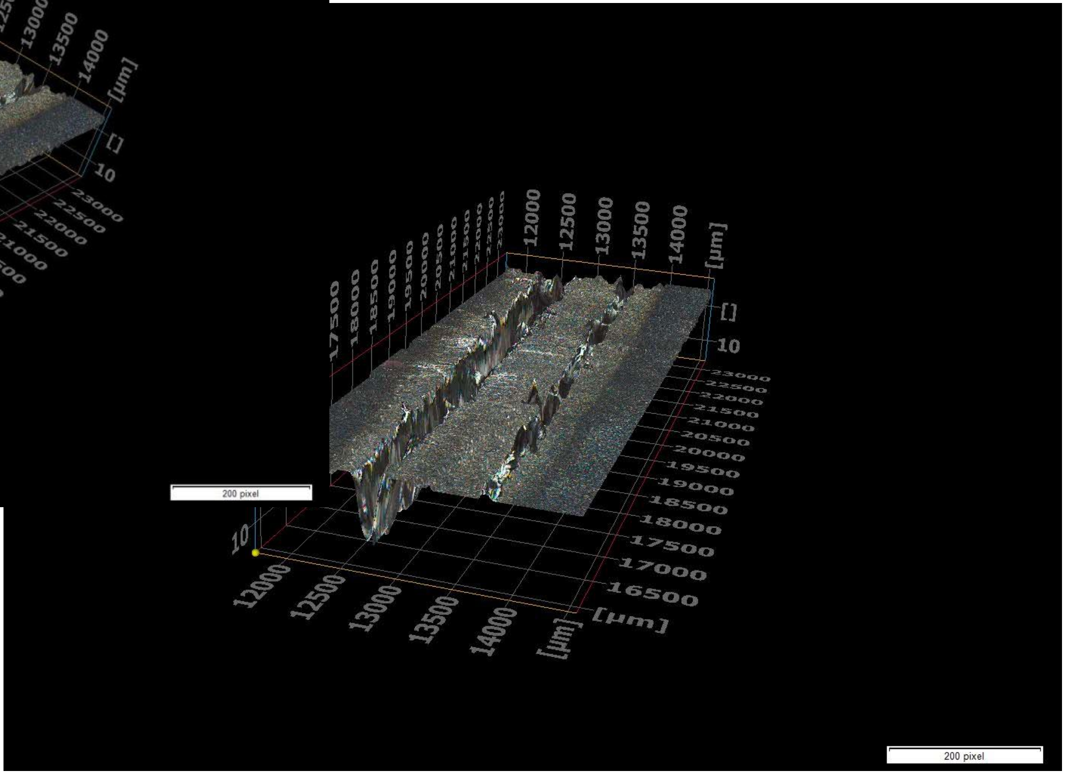


[3] R. Lindberg, J.Dooling, “Diffusion of heat during beam loss” Internal APS Tech Note. Sept. 13, 2012

BEAM DUMP SCRAPER DAMAGE

Damage consistent with ps-ns energy deposition rate—transition regime from hot electron to phonon mechanisms





SUMMARY (WORK IN PROGRESS)

Swap Out beam dump are managed, but whole beam dumps require additional work

- For the Swap-Out Dump, W is the best candidate, assuming the transverse beam size can be adequately inflated
- Decoherence can limit temperature excursions in the swap out dump to modest levels
- Whole-beam dump will be damaged by beam dump event
- Of the total beam energy (4600 J)
  - 23 J absorbed in Al
  - 260 J absorbed in Cu
  - 410 J absorbed in W
- Aluminum the best choice—spreads the beam downstream, absorbs the least energy and is compatible with the surrounding vacuum chamber
- Whole beam dump must be moved after each dump event—rotation seems the most natural

SUMMARY, CON'T

- Alternatively direct beam to a dedicated beam dump line
- Design of whole-beam dump engineering and evaluation system
- Includes diagnostics to evaluate collimators after beam loss
- Work in progress

ACKNOWLEDGMENT

Thanks to B. Soliday for assistance with analysis scripts.