Energy deposition in the S37 scraper

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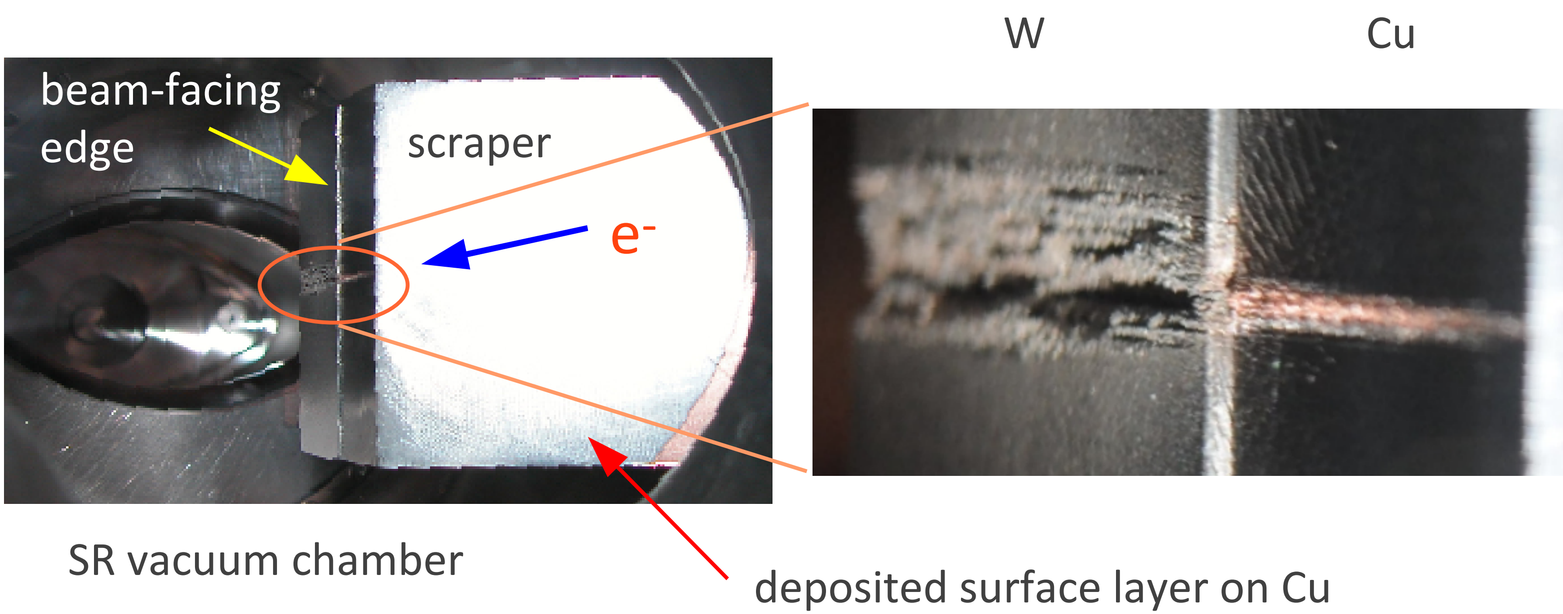
ASD Seminar
April 1, 2013

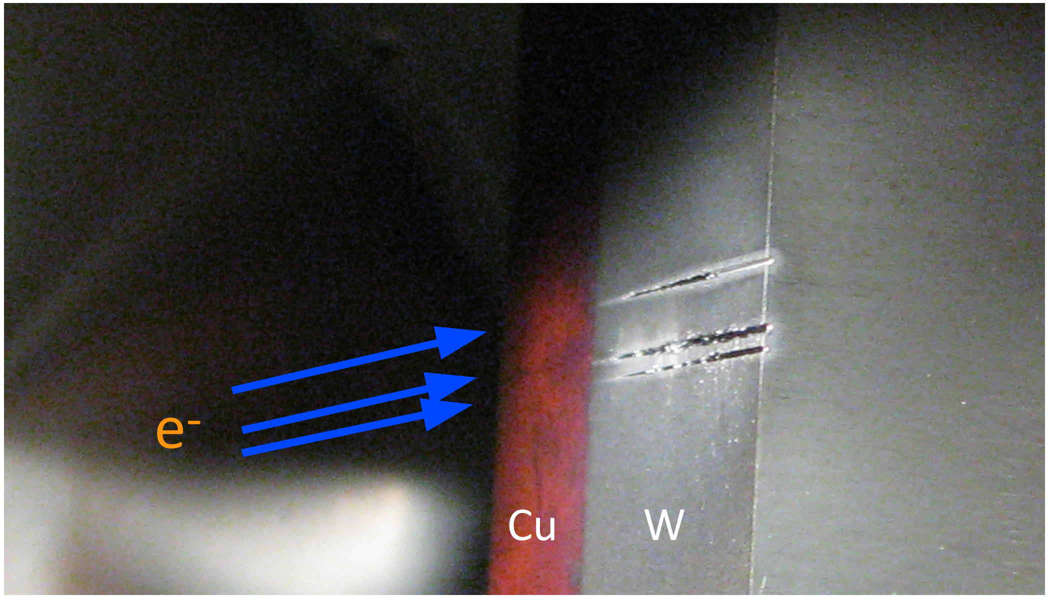
Motivation

At the end of Run-1 in April 2011, a pressure transient was noted in S37 during a high-current study. Subsequent investigation found that high-temperatures were occurring in this region and the S37 scraper had sustained damage on its beam facing surface.



Motivation, con't

- Refurbished scraper was installed in January 2012
- Beam dump testing was done at the end of that run on April 25
- several beam stores with 24-bunch and hybrid fill patterns were purposely dumped on the scraper
- The refurbished scraper was removed during April-May 2012



Address damage and determine the role of the scraper

- Model device with MARS, beam distribution from elegant
- Scraper, collimator, beam dump? Answer: yes
- new design?
- material evaluation—test and measurement with refurbished scraper

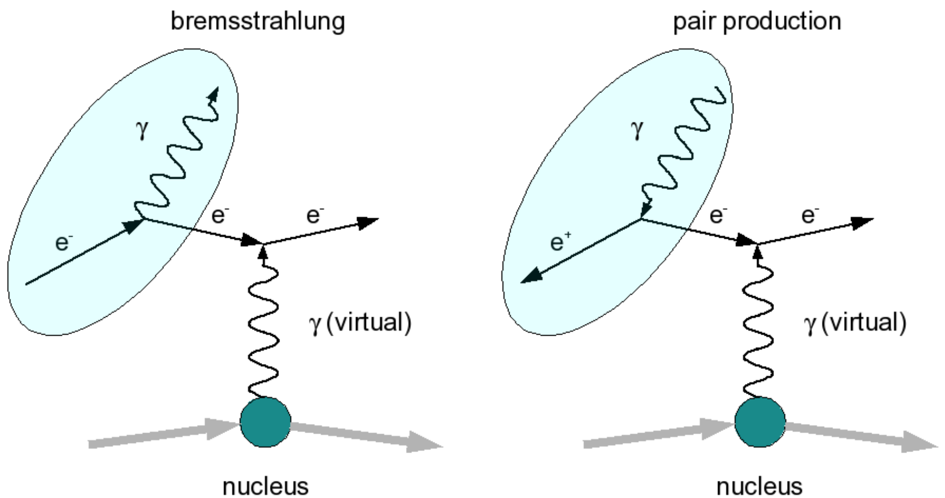
Radiative energy transfer is nonlocal

- Initial exchange of energy between electrons and matter is via bremsstrahlung and pair production
- At 7 GeV in Cu, collisional, radiative, and total stopping power:

  S_{pc}=1.97 MeVcm^2/g

  S_{pr}=542.0 MeVcm^2/g

  S_{pt}=543.9 MeVcm^2/g
- only 0.36% of the energy is locally deposited
- at E_{crit} collisional and radiative stopping powers are equal



Energy Deposition

- Instantaneous energy rise due to dose (energy per unit mass)--simplest approximation
- Assume a thin target
- Kinetic energy W, density ρ, radiation length X_o
- Fine structure constant α, classical electron radius r_e, atomic no. Z, atomic mass A, Avagadro's no. N_A
- Total charge N_Q (=368 nC at 100 mA)

Energy loss per unit length

$$\frac{dW}{dz} = W\frac{\rho}{X_o}$$

Radiation length given by Tsai:

$$\frac{1}{X_0} = 4\alpha r_e^2 \frac{N_A}{A}\left\{Z^2[L_{\text{rad}} - f(Z)] + Z\,L'_{\text{rad}}\right\}$$

Radiation length given by Nelson (used here):

$$X_o^{-1} = 4\alpha r_e^2 \frac{N_A}{A} Z\,(Z+1)\left[\ln\left(\frac{183}{Z^{\frac{1}{3}}}\right) + \frac{1}{18}\right]$$

$$W_L\,(z) = W_o\left(1 - \exp\left(-\frac{\rho}{X_o}z\right)\right)$$

$$W_L\,(z) \approx N_Q W_o \frac{\rho}{X_o} z$$

Simple Analysis—beam entry

- g, ratio of thermal stress to yield stress, σ_y
- Using electron stopping powers, S_{pc} and S_{pr}
- Young's modulus E_Y, thermal coefficient of expansion α, and molar heat capacity, $C_{mol}=C_V$

  where according to Dulong and Petite:

$$C_v = \frac{\partial}{\partial T}(3kTN_A) = 3kN_A$$

this value is 24.94 J/K/mole for most metals. In the present situation, not easily defined.

$$g = \frac{E_Y \alpha E_T A_w}{\sigma_y C_{mol} \rho V} = \frac{E_Y \alpha A_w}{\sigma_y C_{mol}} k_B S_{pc} \frac{N_e}{\pi r_b^2}$$

$$E_T \approx \frac{S_{pc}}{S_{pr}} N_e W_o \frac{\rho}{X_o} \Delta z$$

$$S_{pr} = \frac{W_o}{X_o}$$

The peak volume element from a distribution absorbs a dose

$$E_d = S_{pc} \Delta z \frac{N_Q}{V} \frac{N_{f,max}}{N_T}$$

$$\Delta T = E_d \frac{A_w}{C_v}$$

As the shower builds, this simple analysis is no longer valid

Material properties

Table 1: Materal properties and thermal to yield stress ratio.

Mat.	A_w $\left(\frac{\text{g}}{\text{mole}}\right)$	S_{pc} $\left(\frac{\text{MeV-cm}^2}{\text{g}}\right)$	E_Y (GPa)	$\alpha \times 10^6$ (K^{-1})	C_{mol} $\left(\frac{\text{J}}{\text{mole-K}}\right)$	σ_y (MPa)	g
Be	9.01	2.025	248	12.4	16.44	345	11.6
Pyr. Gr. (C)	12.0	2.264	20.7	0.5	8.28	82.7	0.48
PB1300 (C)	12.0	2.264	6.9	4	10.08	37.9	2.30
Al	26.98	2.165	69	25	24.20	310	15.8
Ti	47.87	2.031	116	8.5	25.06	951	4.72
Cu	63.55	1.970	110	16.5	24.44	220	49.6
W	183.84	1.698	345	14.4	24.27	1510	49.6

Might also add magnesium (Mg) to this list.

Material properties

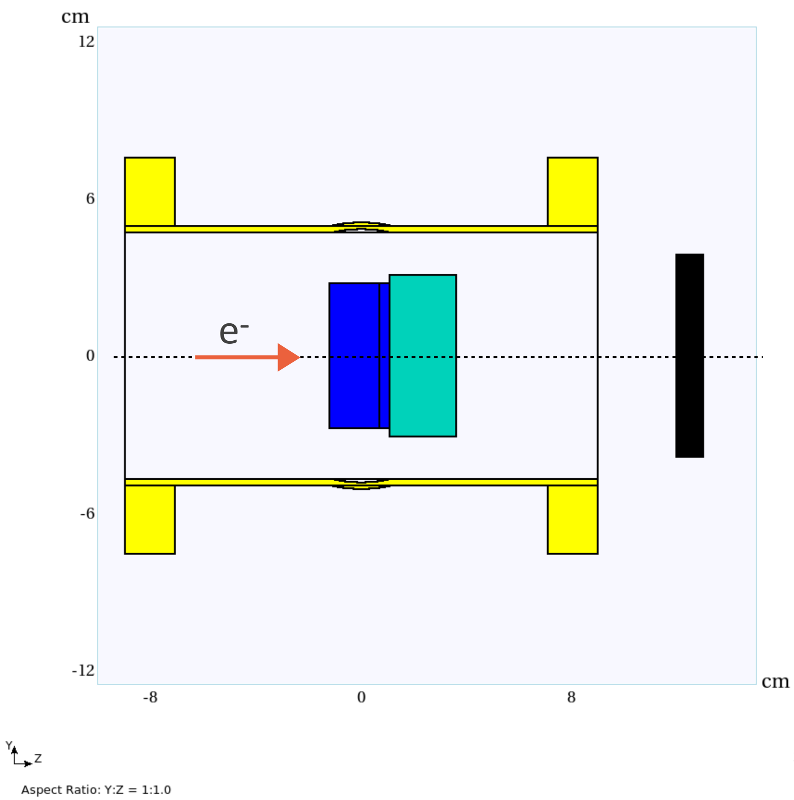
Table 2: Radiation Length.

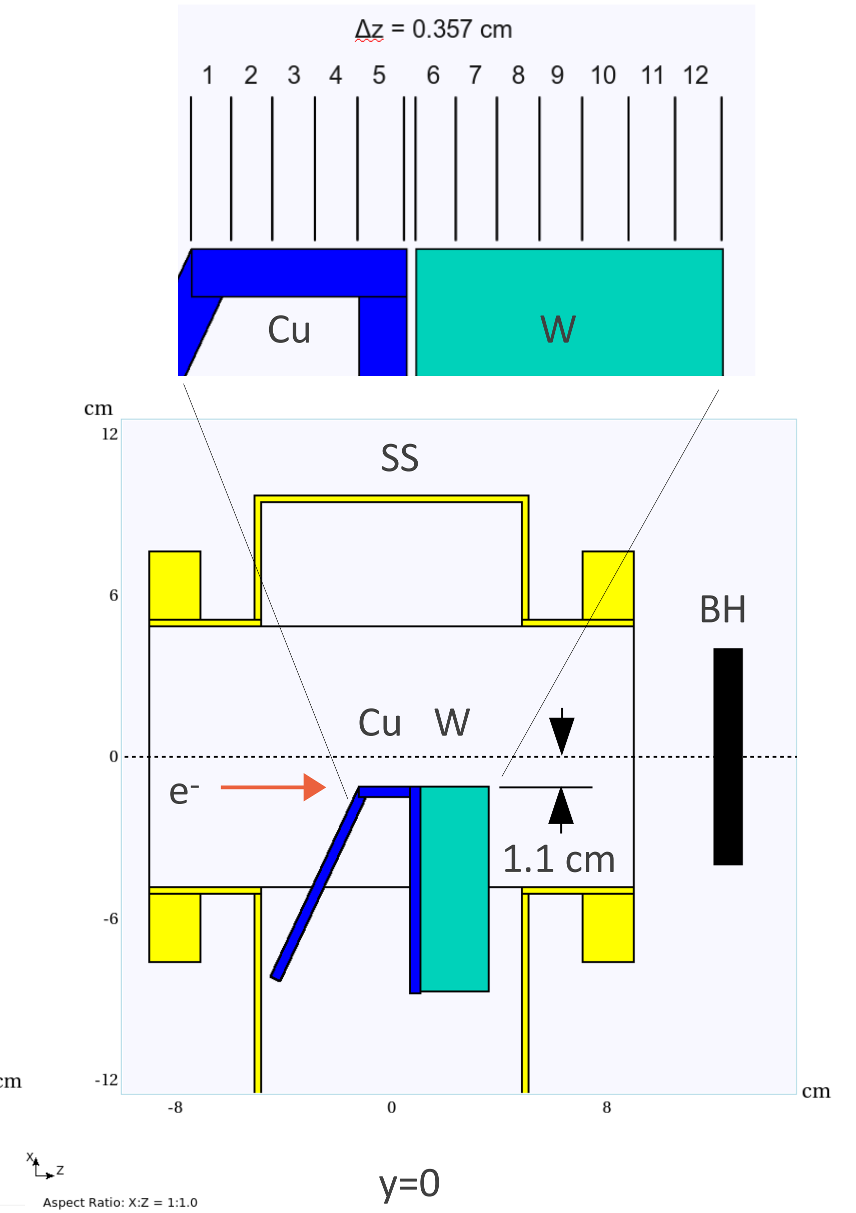
Mat.	X_o $\left(\frac{\text{g}}{\text{cm}^2}\right)$	ρ $\left(\frac{\text{g}}{\text{cm}^3}\right)$	$t = X_o/\rho$ (cm)
Be	65.2	1.85	35.2
Pyr. Gr. (C)	42.7	2.2	19.4
PB1300 (C)	42.7	2.2	19.4
Al	24.0	2.7	8.89
Ti	16.2	4.54	3.57
Cu	12.9	8.96	1.44
W	6.76	19.3	0.35

Want the spreader to be ~ 2t to intercept most of the charge

MARS models

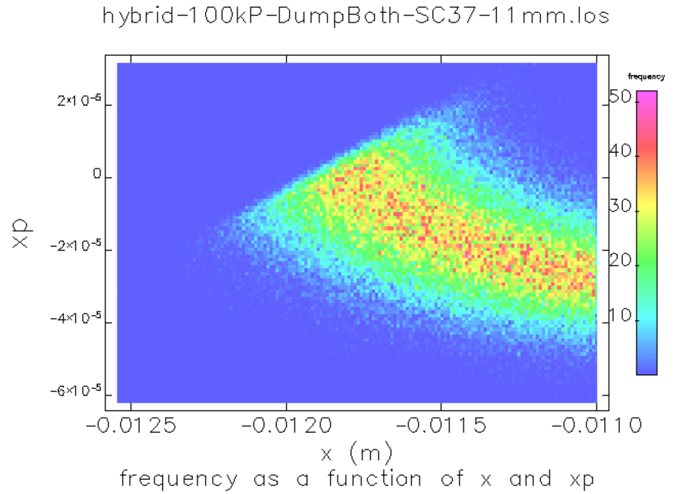
- baseline
- modified designs

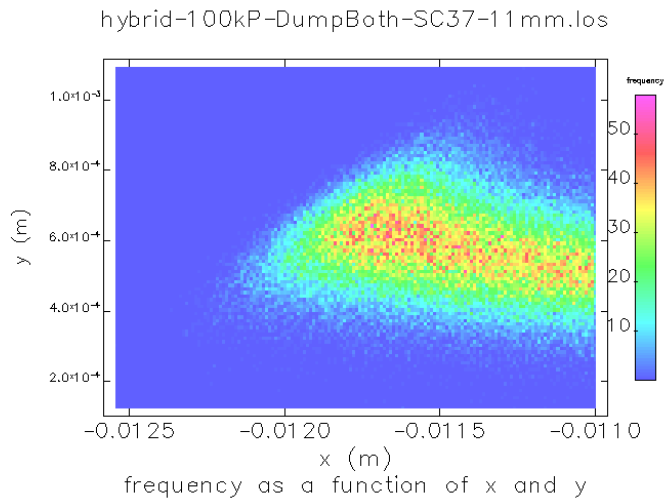


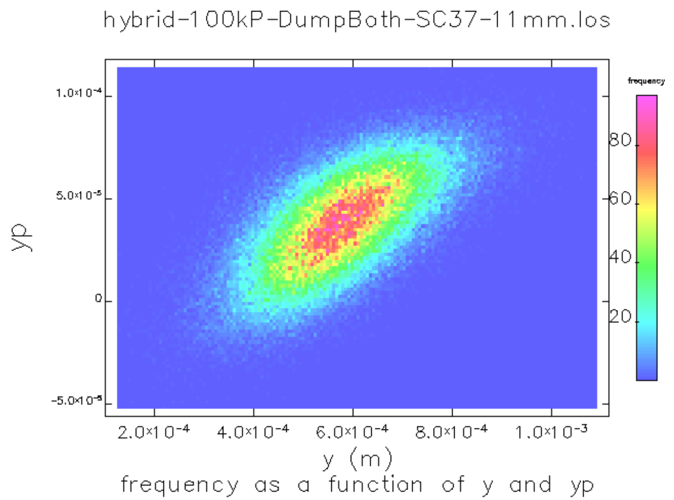


elegant provides input beam distribution for MARS

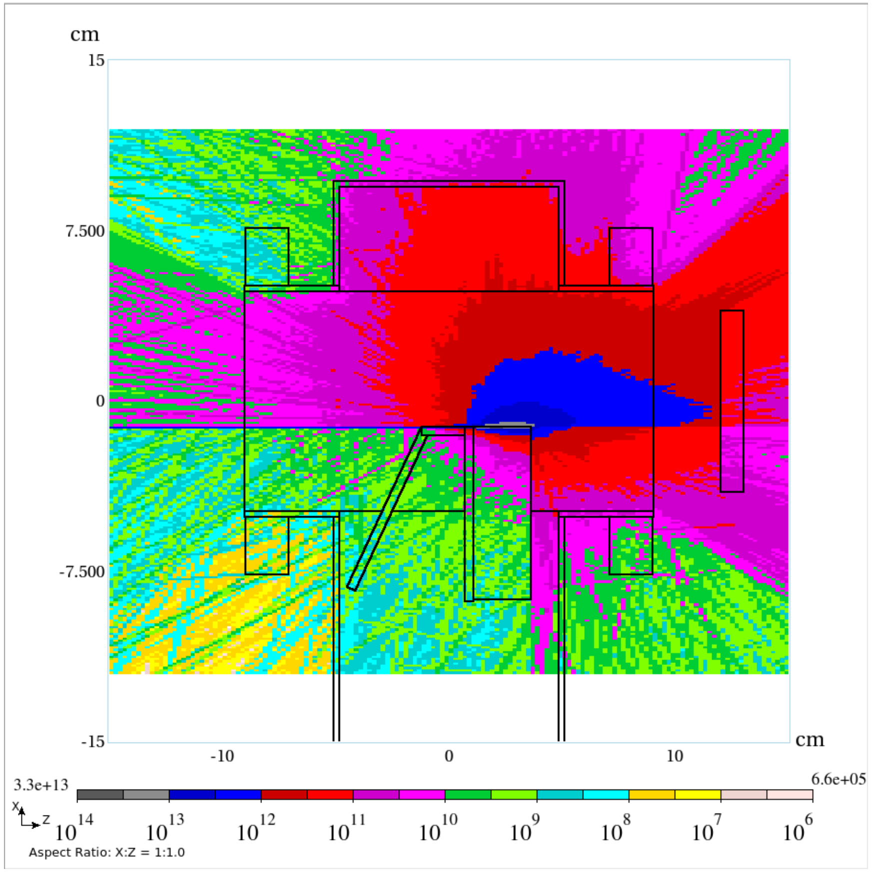
- beam spirals in after rf is muted
- can model one or both rf systems muted
- includes quantum fluctuations
- hybrid beam
- can include the effect of kicker firings

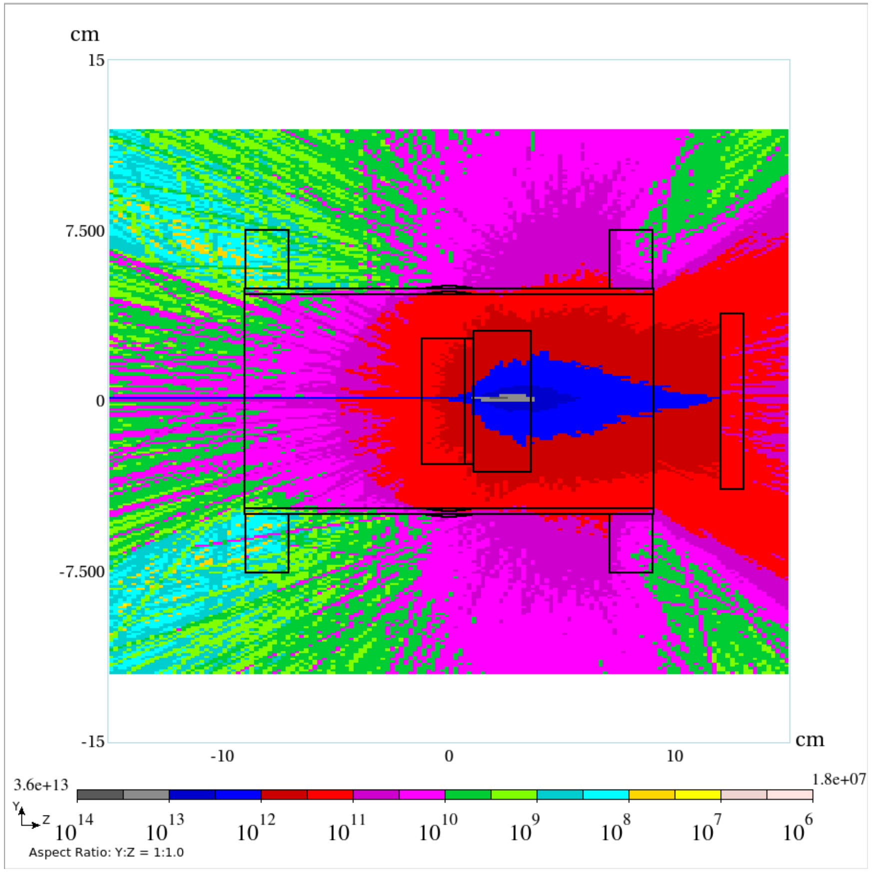






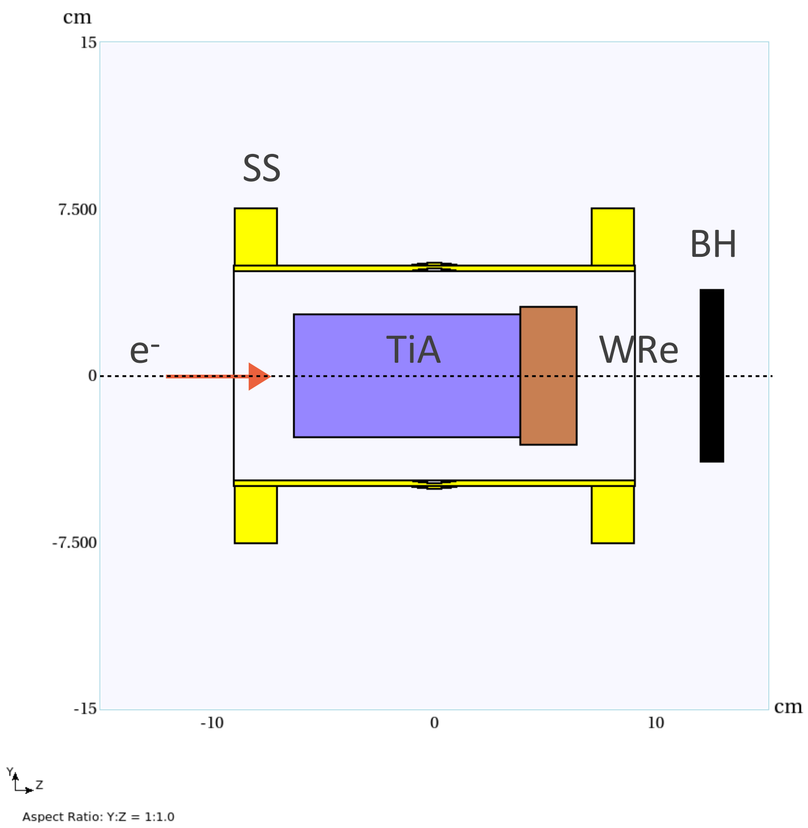
MARS electron positron fluence, baseline design

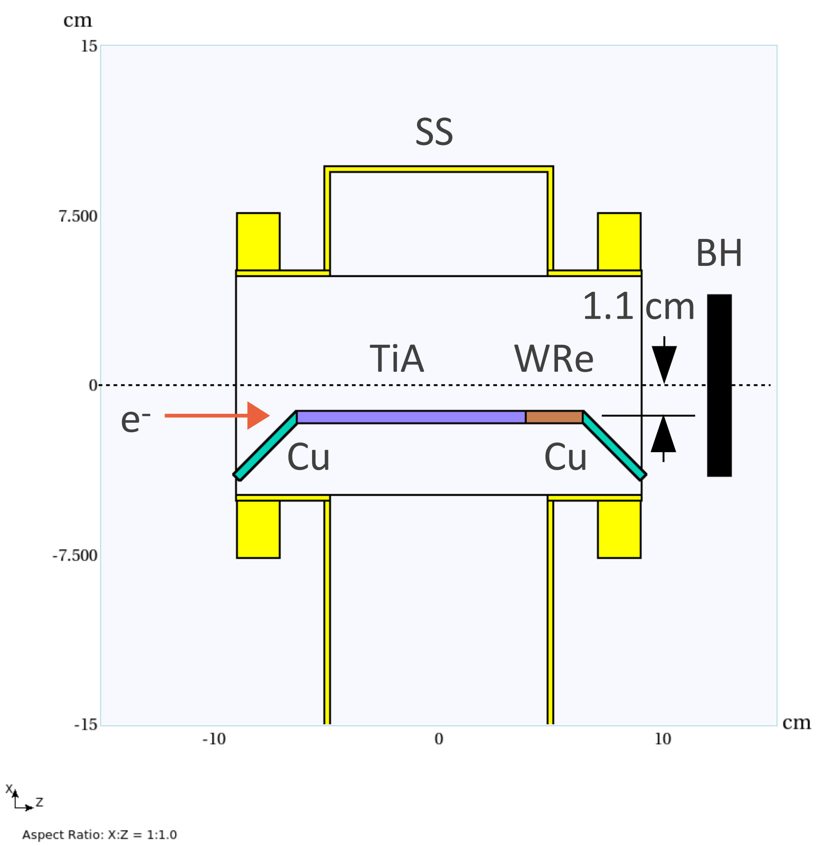




MARS modeling

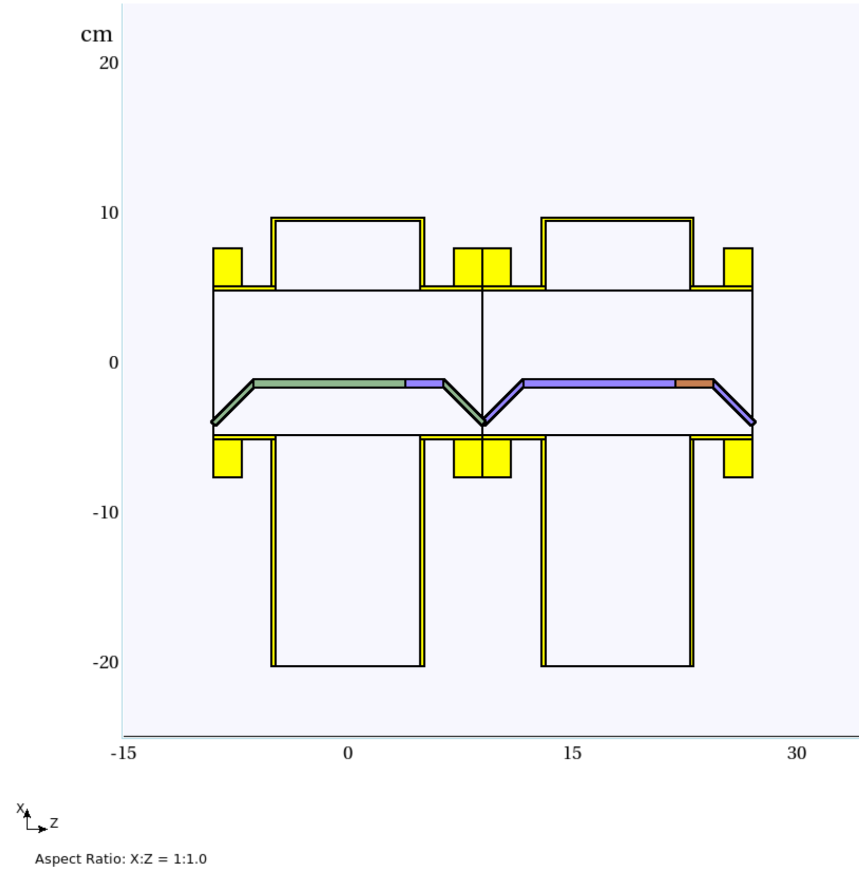
- modified designs—extended geometry, different materials
- better impedance matching



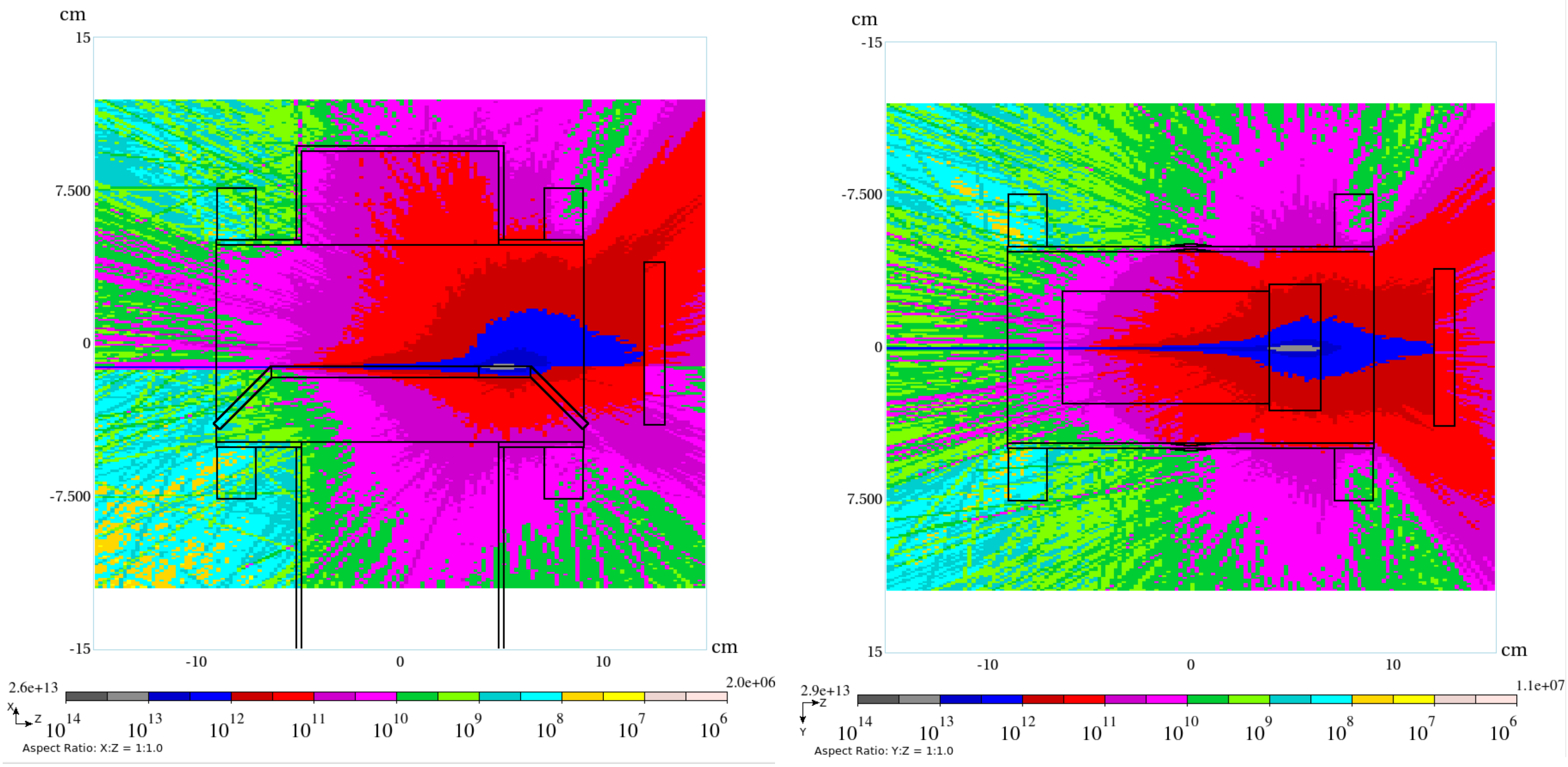


MARS modeling

- further extending the scraper length
- using Al to initially spread the beam
- actually build as one unit

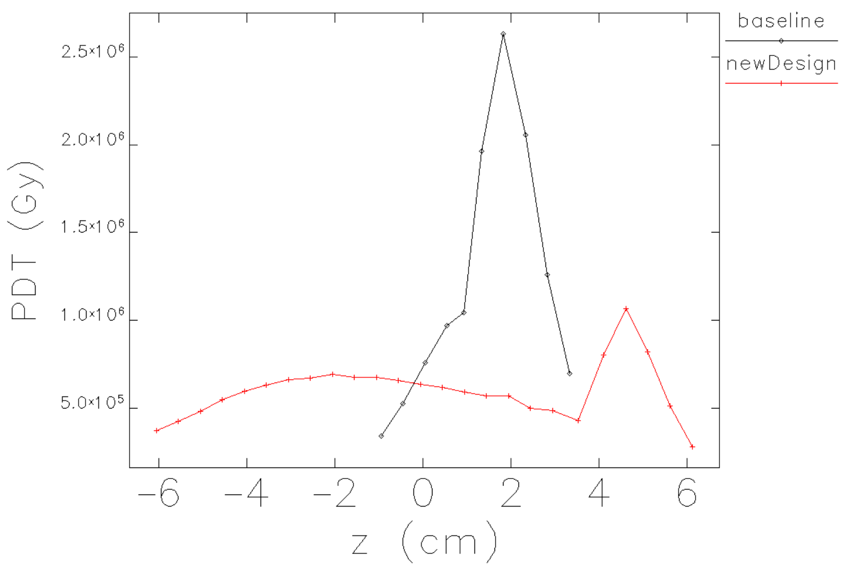


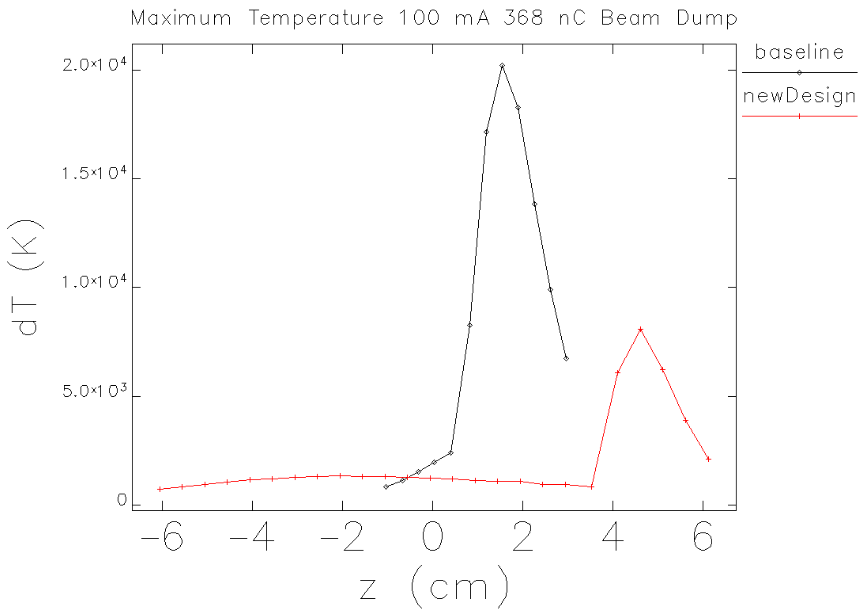
MARS electron positron fluence, extended design



Peak dose and temperature

- Comparing baseline and new design
- hybrid fill, dumping both rf systems
- no ping





Simulation results

$$E_T = \sum_i \sum_j (D_{i,j} \Delta V_j \rho_j)$$

Table 3: Peak dose and total deposited energy for baseline and new design geometries.

	baseline upstream (spreader)	baseline downstream (beam stop)	new design upstream (spreader)	new design downstream (beam stop)
D_{max} (MGy)	1.046	2.634	0.691	1.065
E_T (J)	46.34	709.0	182.3	730.6

$$E_e = N_e W_0 = 2.58\, kJ\, (100\, mA, 7\, GeV)$$

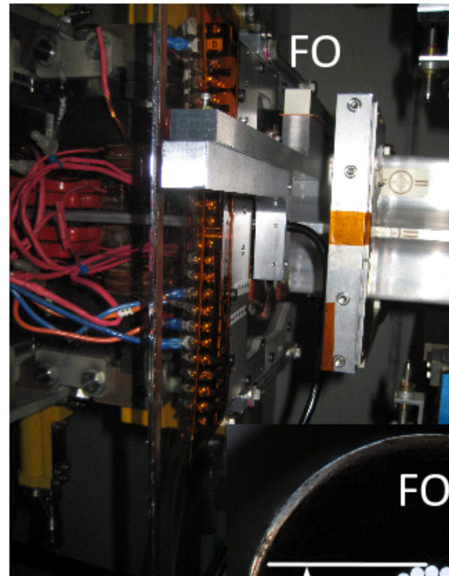
- Even with a substantially longer scraper/beam dump, less than half the total energy is absorbed
- However, all of the dumped beam has interacted and is spreading out

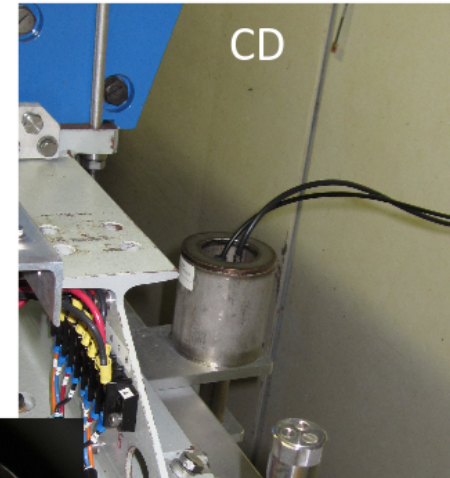
Beam dump sequence

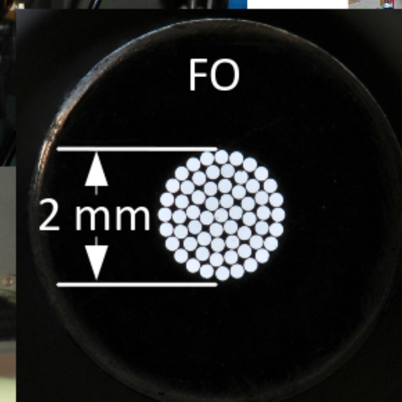
- when beam conditions dictate (e.g. BPLD limit) or an operator request occurs, the Machine Protection System (MPS) generates a trigger pulse
- the storage ring rf is muted
- beam spirals in to smaller radii as energy is lost
- beam facing scraper edge at x=-1.1 cm is first to receive the lost store
- depending on charge, beam strikes scraper after 10-20 turns
- when S37 scraper is absent, large fraction of beam is lost in ID4

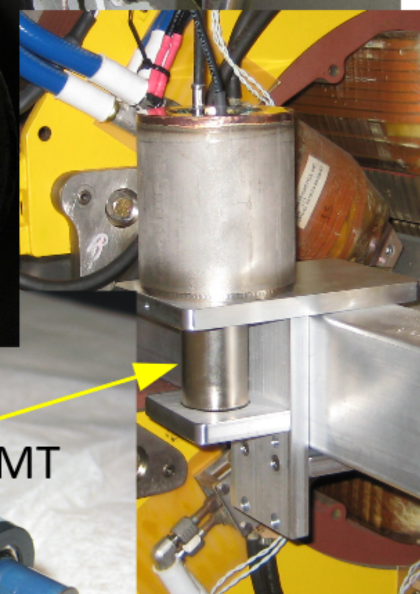
Fast beam dump detection

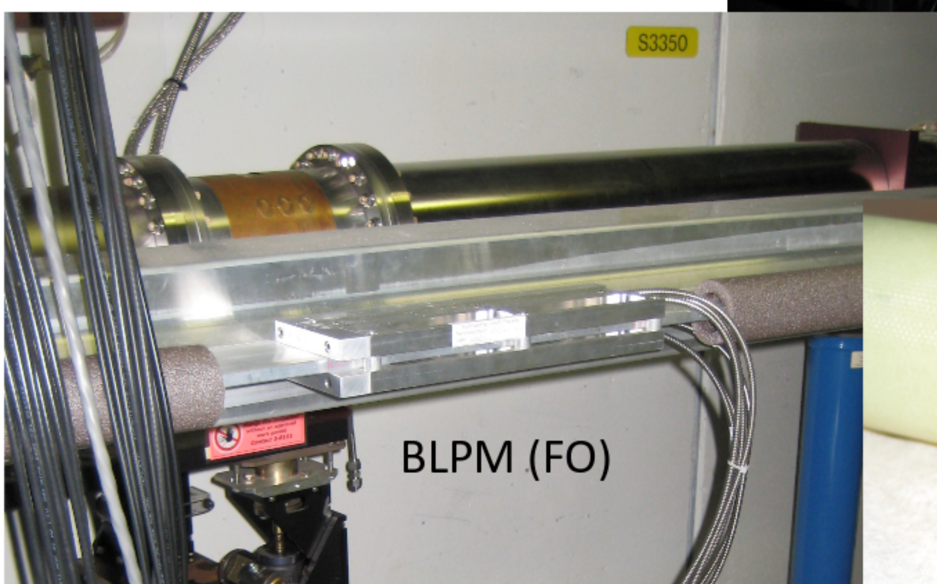
- Cerenkov radiation
- fused-silica radiators
  - minimum aspect cylinder
  - fiber optic bundles (FO)
- photomultiplier tubes (PMTs)
- standard Cerenkov Detector (CD) loss monitor electronics do not see beam dumps

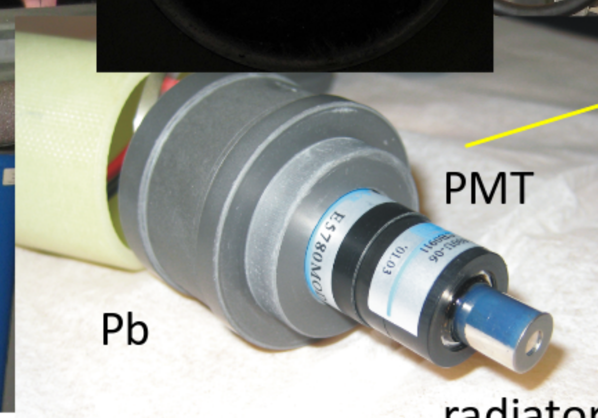








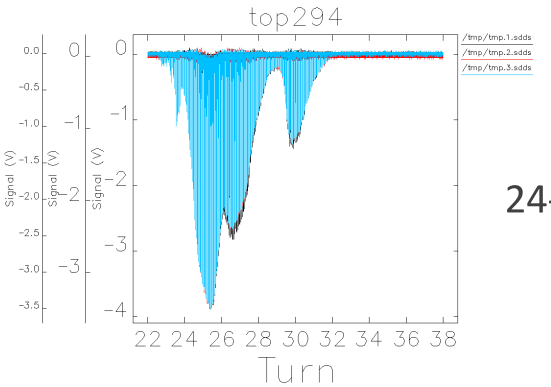




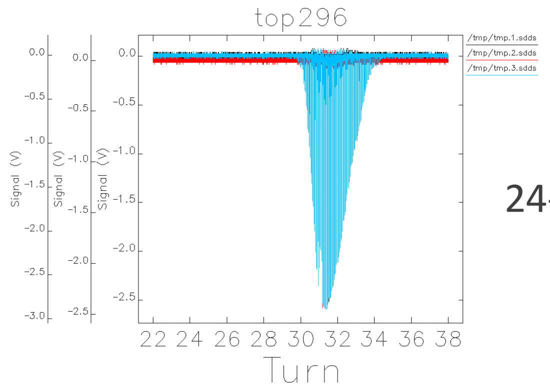
Beam dump temporal profiles

- Beam dumps come in all shapes and sizes and can be destructive
- Worst dumps tend to deposit beam energy most rapidly; 2600 J of stored energy at 100 mA and 7 GeV.
- Scripts are now in place to dump the beam slowly when called for (e.g., changing fill patterns during studies and commencement of studies)
- passive vs. active—ours was passive, but script provides more active control
- could also consider kicker abort into a dump; we have not gone this route

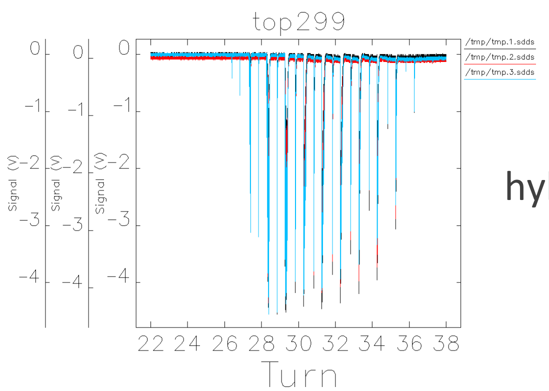
April 25, 2012



24-bunch

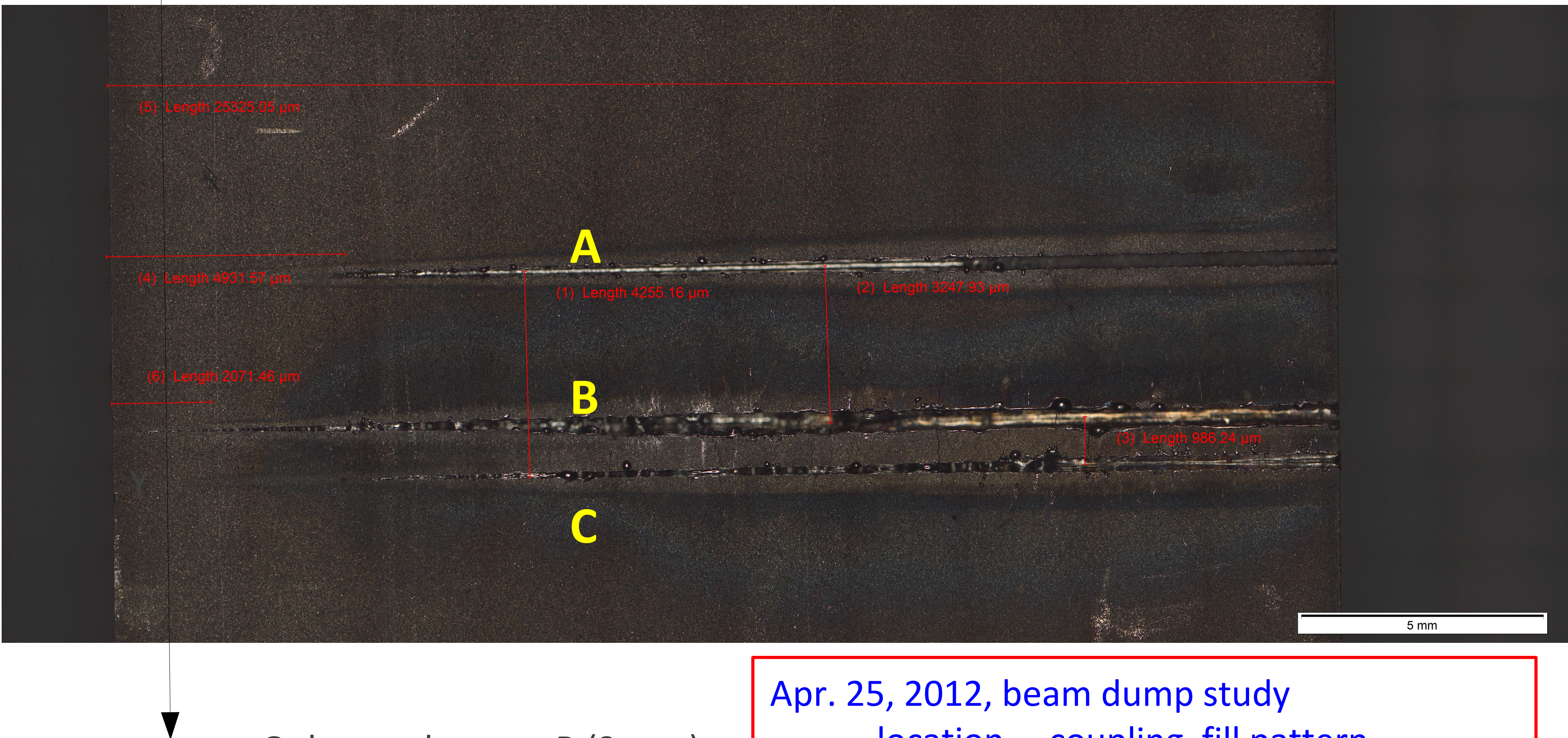


24-bunch



hybrid

April 25, beam dump study



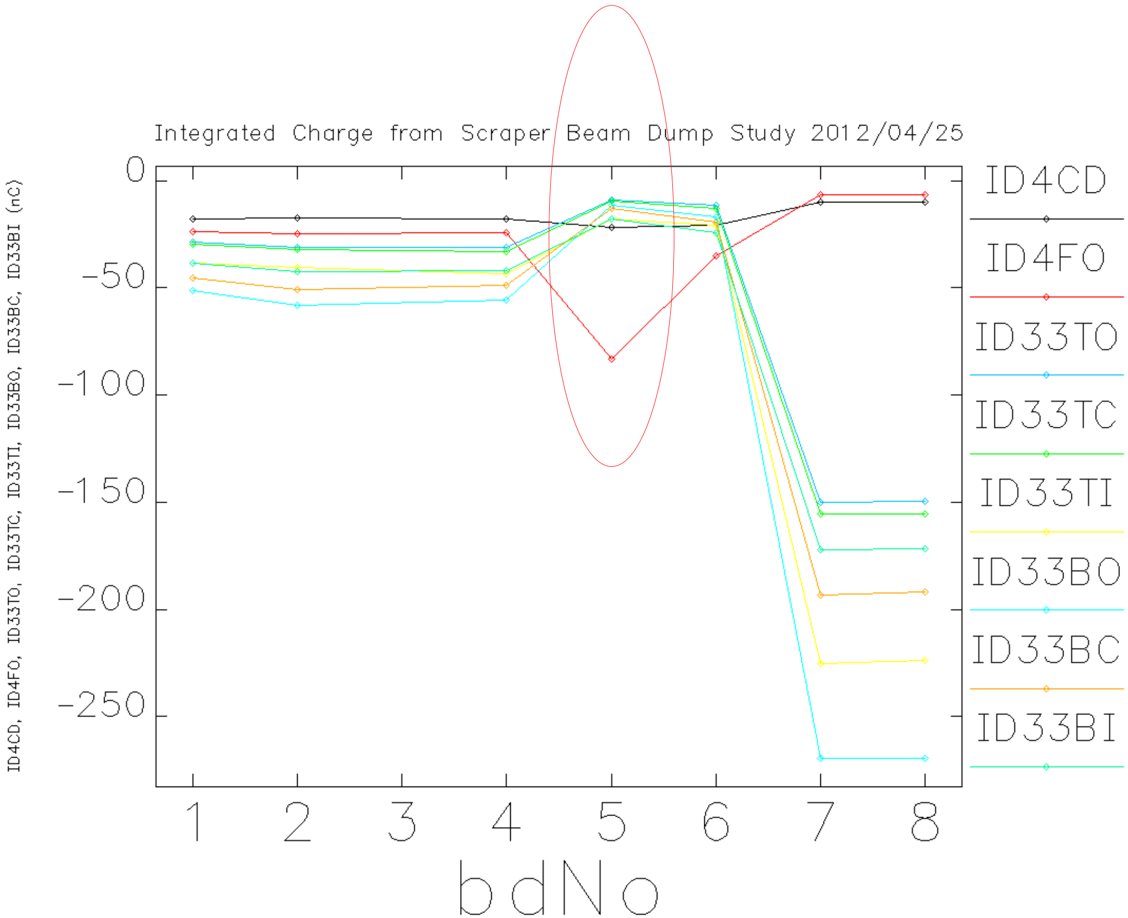
Only one dump at B (3 mm)
3 at C (4 mm)

Apr. 25, 2012, beam dump study

	location	coupling	fill pattern
D1-3	4 mm	6.6%	24
D4	0 mm	6.6%	24
D5	3/1.5 mm	16.2%	24
D6	0 mm	17%	hybrid (5 mA + 8x7)
D7-8	0 mm	5.7,5.8%	hybrid (5 mA + 8x7)

Summed Q-loss from April 25, 2012 study

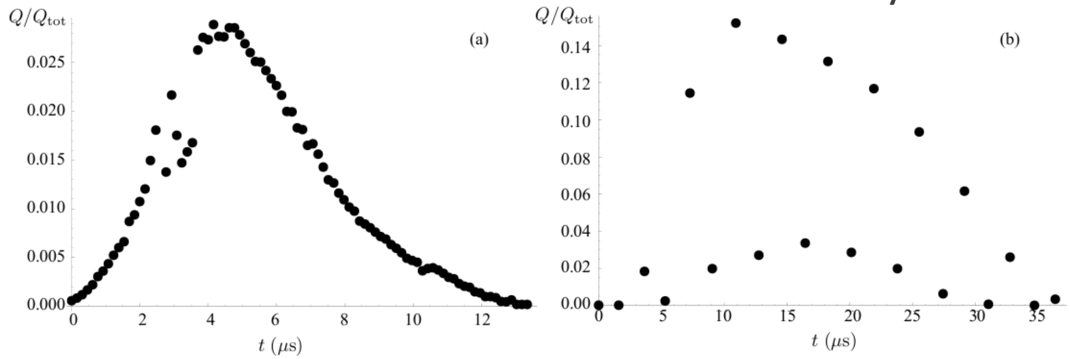
- Largest dump in ID4 in terms of integrated signal comes from the fifth and final 24-bunch.
- elegant simulations show significant loss in ID4 with beam dumps in S37



Heat Diffusion

Fast beam dump data

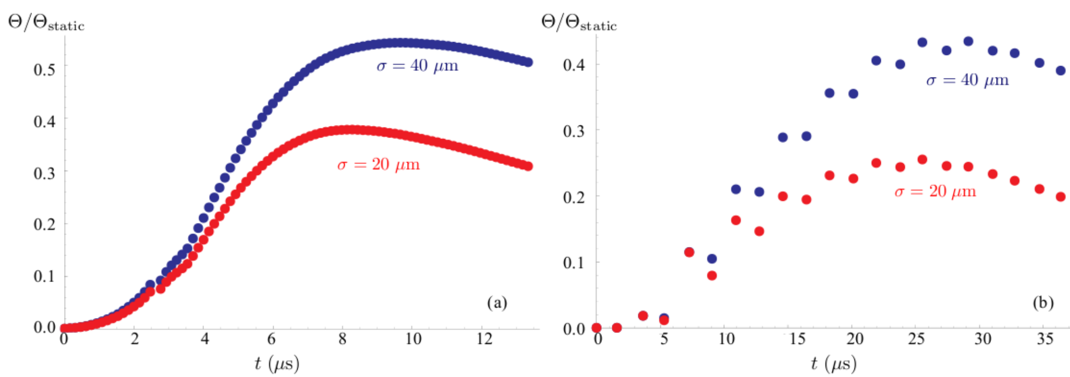
24-bunch   hybrid



Employing Green's fn. to calc. T evolution with diffusion

$$\Theta_{\rm rad}(r, t_N) = \Theta_N + \sum_{n=1}^{N-1} \Theta_n \int_0^r d\rho\, \frac{\rho\, e^{-\rho^2/2\sigma^2}}{4\pi\alpha(t_N - t_n)} \exp\left[-\frac{r^2+\rho^2}{4\alpha(t_N - t_n)}\right] I_0\left[\frac{r\rho}{2\alpha(t_N - t_n)}\right]$$

comparison of temperature ratio for differing beam sizes and fill patterns

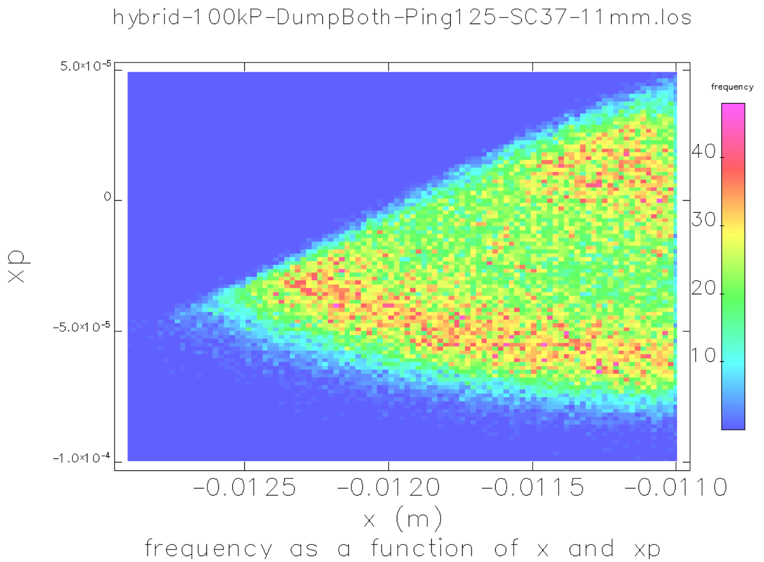


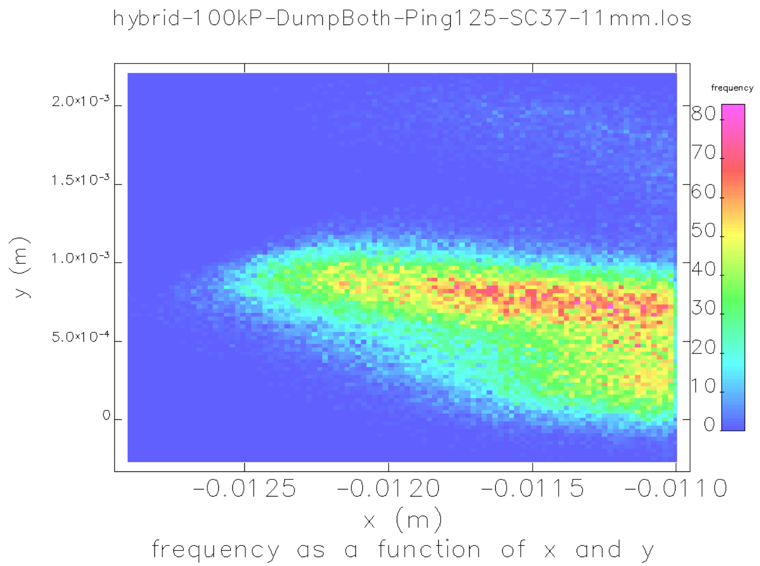
R. Lindberg, J. Dooling, AOP TN-2012-030

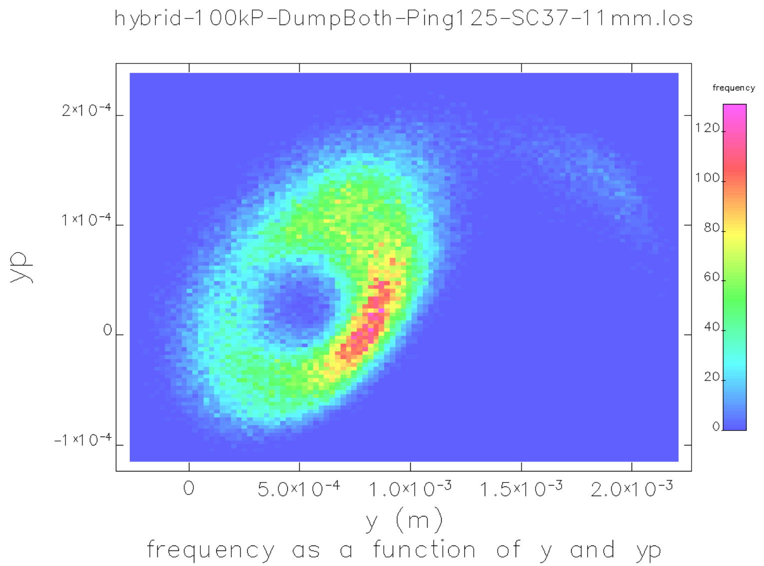
appears that the 24-bunch case produces the highest T

Including injection kicker ping

- elegant distributions

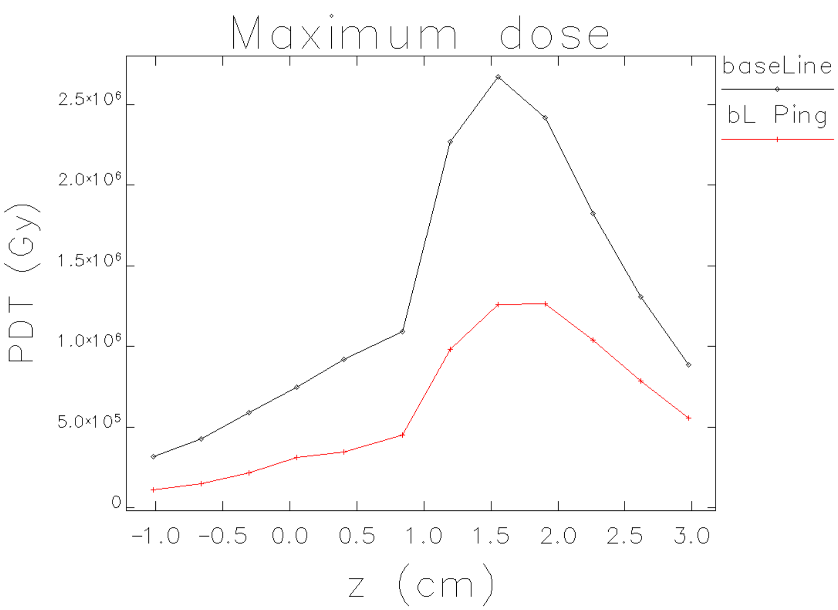


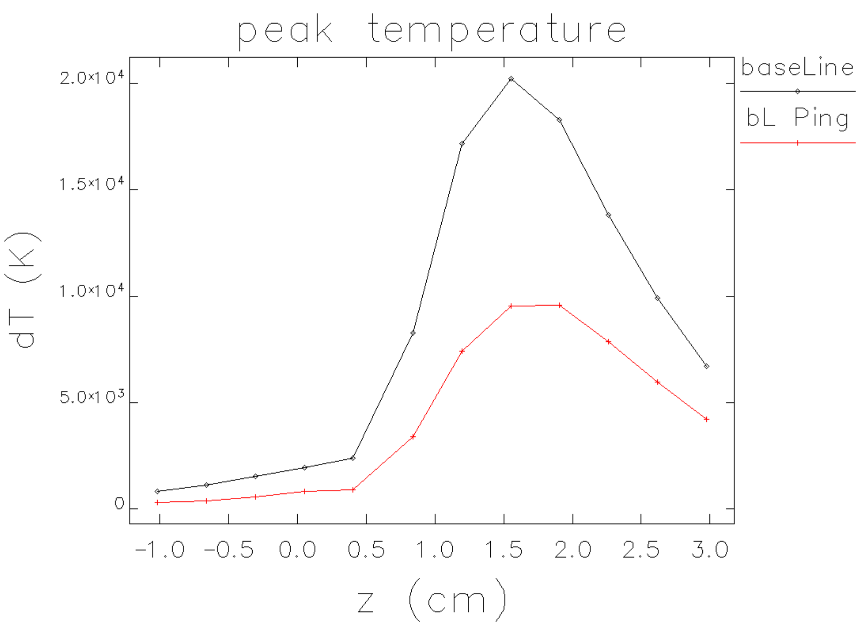




Comparing peak dose and temperature

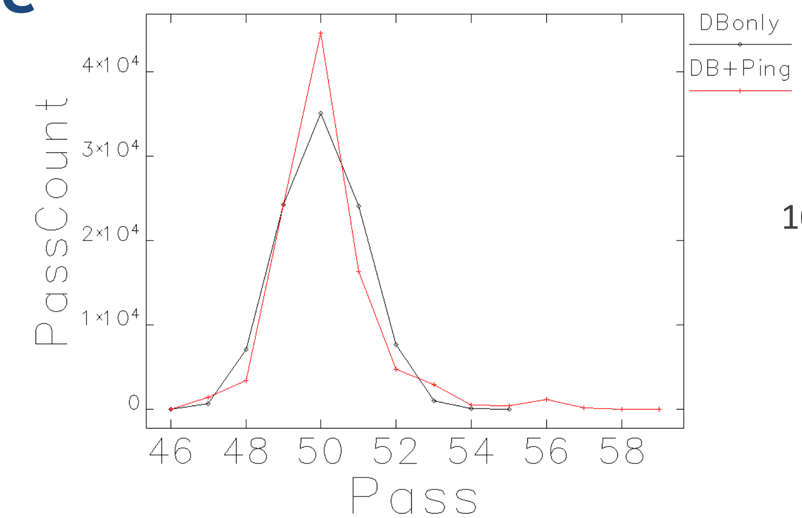
- ping in baseline model
- hybrid fill, dumping both rf systems





Pinged beam dump does not show a broader temporal profile

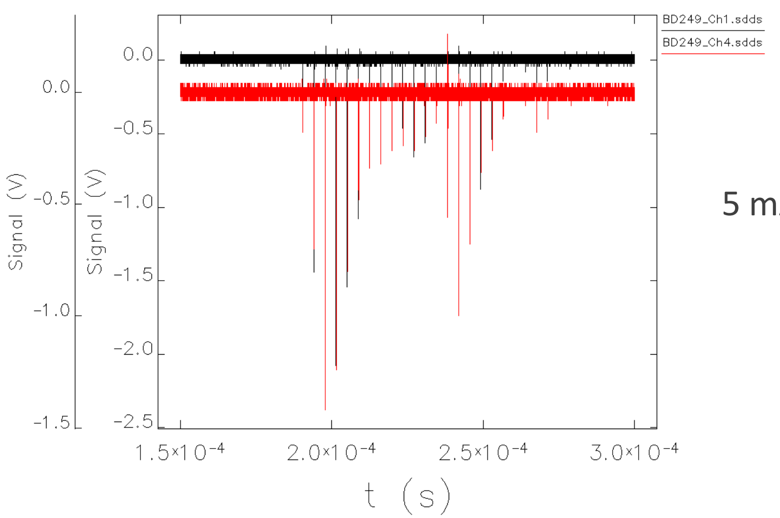
- measured loss distribution does not show a significant change
- transverse dist. matters



100 mA

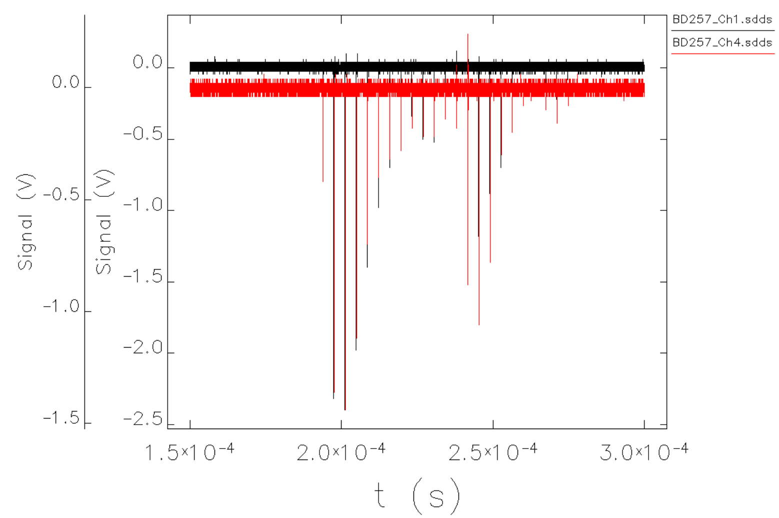
1 pass = 3.68 µs

PV=0.0 kV



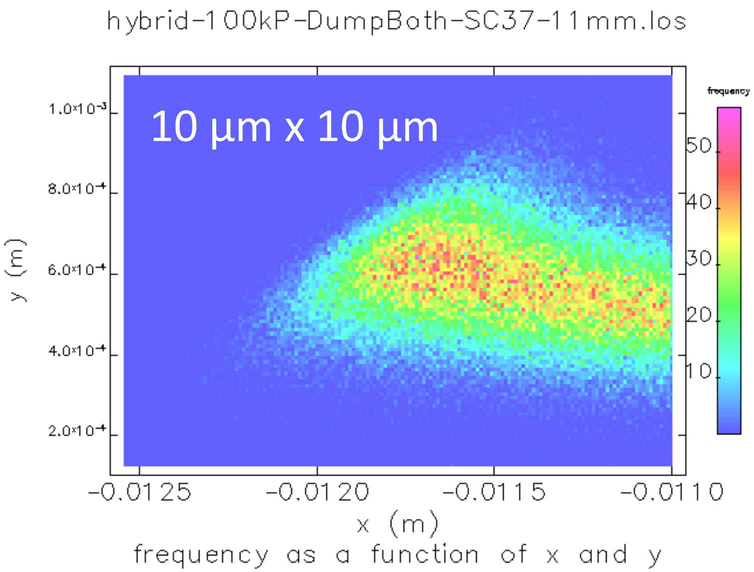
5 mA

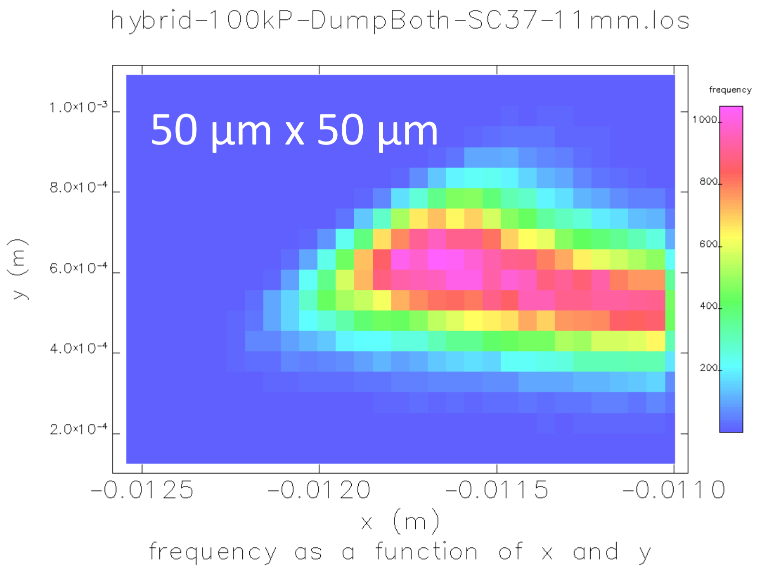
4.0 kV

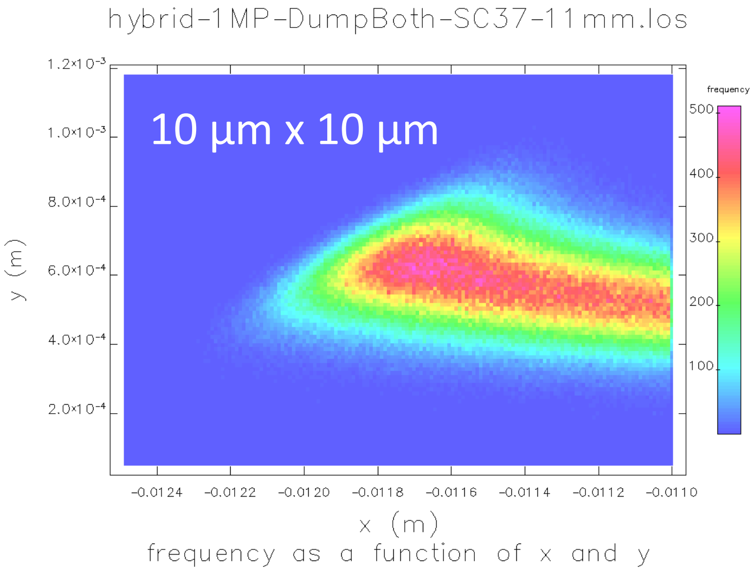


Simulation considerations

- Pixel size—want the pixel size to be smaller than the smallest "real" feature in the beam
- On the other hand, want the number of trajectories per pixel high; otherwise, peak temperature is overestimated
- Using 50 µm x 50 µm in MARS







Voxel size affects temperature calculations
—script *deposit1* for instantaneous temperature rise using *sddshist2d*

For 1E5—

deposit1 -input hybrid-100kP-DumpBoth-SC37-11mm.los -nx 156 -ny 98 -material Al

Printout for SDDS file stdin

xInterval	yInterval	frequencyMax	frequencySum	Ed	dT
m	m			J/g	K
9.958890e-06	9.951995e-06	5.800000e+01	1.000000e+05	4.242491e+02	4.589511e+02

deposit1 -input hybrid-100kP-DumpBoth-SC37-11mm.los -nx 31 -ny 20 -material Al

Printout for SDDS file stdin

xInterval	yInterval	frequencyMax	frequencySum	Ed	dT
m	m			J/g	K
5.145427e-05	5.080755e-05	1.053000e+03	1.000000e+05	2.920067e+02	3.158917e+02

Voxel size affects temperature calculations

—script *deposit1* for instantaneous temperature rise using *sddshist2d*

For 1E6—

deposit1 -input hybrid-1MP-DumpBoth-SC37-11mm.los -nx 150 -ny 114 -material Al

Printout for SDDS file stdin

xInterval	yInterval	frequencyMax	frequencySum	Ed	dT
m	m			J/g	K
9.999597e-06	1.001684e-05	4.540000e+02	1.000000e+06	3.285919e+02	3.554695e+02

deposit1 -input hybrid-1MP-DumpBoth-SC37-11mm.los -nx 31 -ny 24 -material Al

Printout for SDDS file stdin

xInterval	yInterval	frequencyMax	frequencySum	Ed	dT
m	m			J/g	K
4.966467e-05	4.921315e-05	9.891000e+03	1.000000e+06	2.933766e+02	3.173738e+02

Voxel size affects temperature calculations
—script *deposit1* for instantaneous temperature rise using *sddshist2d*

- Comparison of the maximum instantaneous temperature rise in aluminum assuming a beam dump of 100 mA (368 nC).

- Comparing loss distributions:
  - hybrid-100kP-DumpBoth-SC37-11mm.los (1E5 particles) and
  - hybrid-1MP-DumpBoth-SC37-11mm.los (1E6 particles)

Dist. size\Voxel size	10 μm x 10 μm	50 μm x 50 μm
1E5	459.0 K	315.9 K
1E6	355.5 K	317.4 K

Central limit theory, in the region of the maximum:

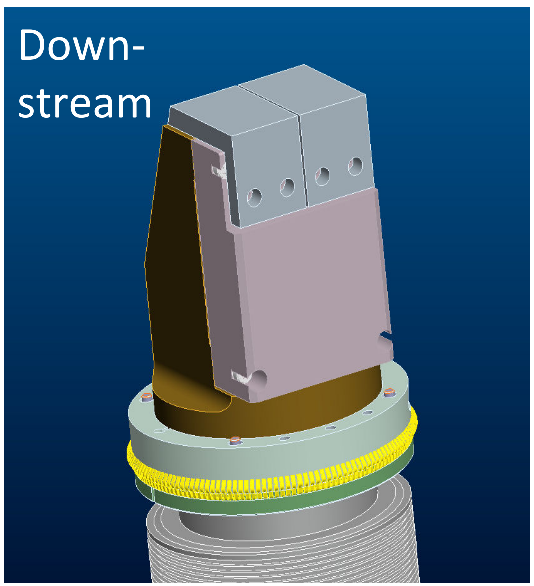
$$T_p = \langle T \rangle + \frac{\langle T \rangle}{\sqrt{N}}$$

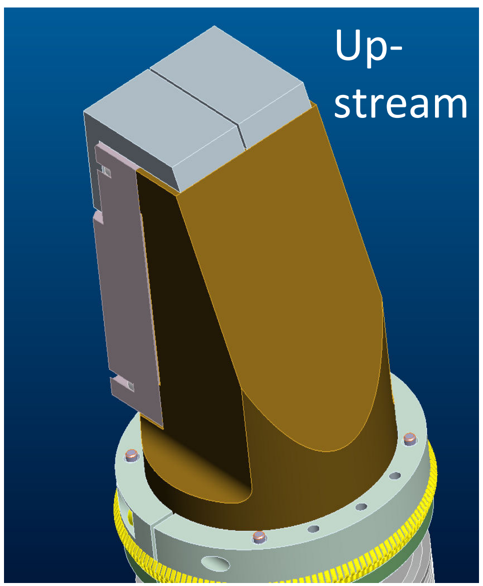
A 50 μm x 50 μm voxel size may be okay.

Note: melting temperature of pure aluminum is 933.47 K

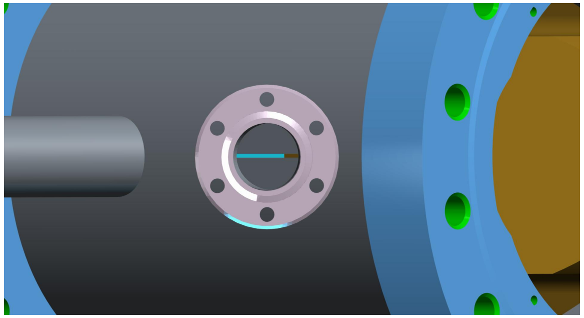
Discussion

- Specific heat is not easily defined; however, room temperature value gives a starting point
- Power density in beam very important; simulations with 24-bunch still to do.
- Material testing to start next run
- Viewport to see beam strike region





Upstream viewport



Acknowledgements

M. Borland, B. Brajuskovic, Y.-C. Chae, L. Emery, K. Harkay,
J. Hoyt, A. Gorski, R. Lindberg, L. Morrison,
A. Xiao, and A. Zholents contributed to this work.

Thank you.