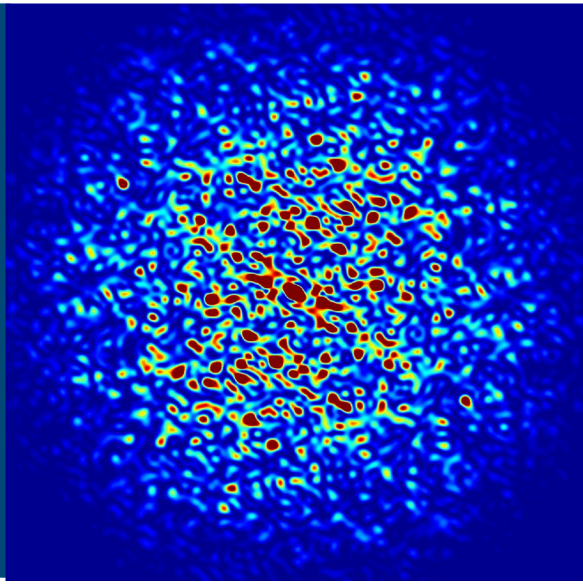
Use of solid xenon as a beam dump material for 4th-generation storage rings



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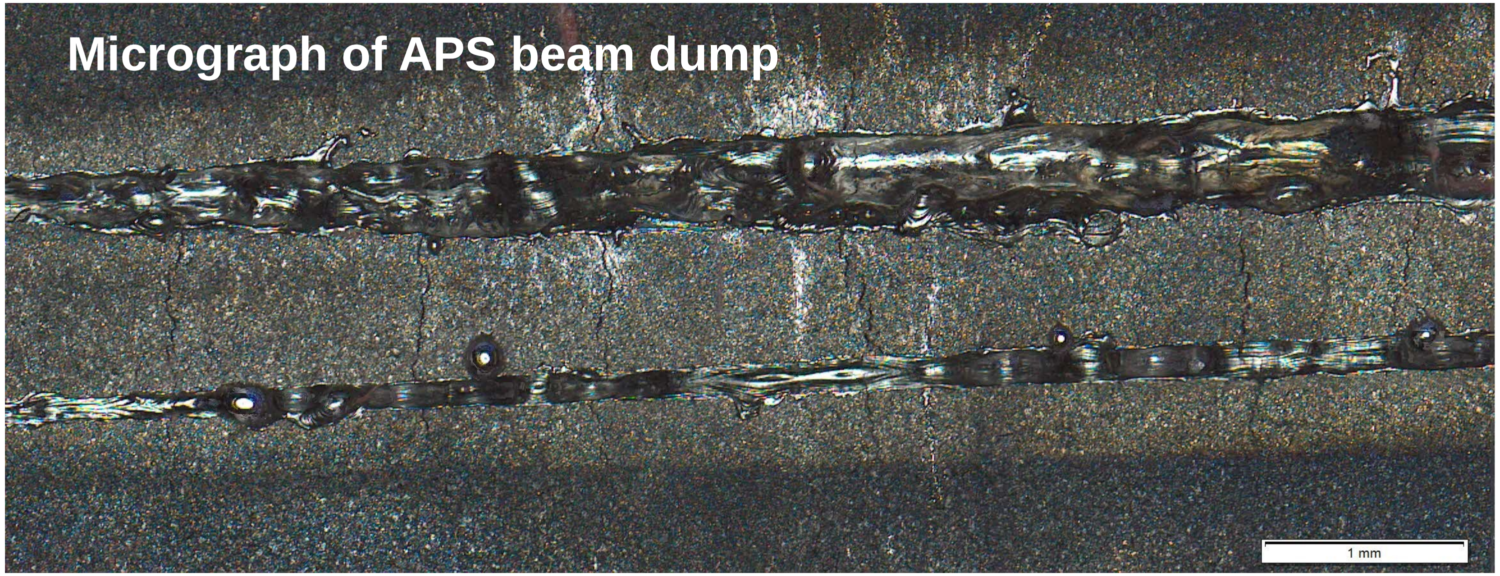
APS experience leads to concerns for APS-U beam dumps



- In 7-GeV Advanced Photon Source (APS), beam has damaged copper and tungsten beam dumps
- In APS Upgrade (APS-U[2]), 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 or less)
- Worry that erosion of beam dumps will lead to beam strikes on other chambers
  - Recent experiments confirm that aluminum and titanium will be damaged by beam strikes[3]

1: J. C. Dooling et al., PAC13, 1361.
2: M. Borland et al., IPAC18, 1494.
3: J. C. Dooling et al., NAPAC19, MOPLM14.

Damage threshold can be roughly estimated

- In APS and APS-U, damage occurs due to collisional losses
  - Build-up of E/M shower not required
- Dose from collisional losses roughly related to charge *Q*, specific dose *d*, and rms footprint sizes $\Phi_{x,y}$

$$D = \frac{Qd}{2\pi\Phi_x\Phi_y} \qquad d \sim 30\,\mathrm{Gy\,mm^2/nC}$$

- Melting occurs temperature is raised to melting point and heat of fusion supplied

$$D > C_p(T_m - 298) + \Delta H_m$$

- 0.3-1.1 MGy will melt metals commonly used in accelerators
- Doses in APS-U beam dump are ~35 MGy

Use of solid xenon as a beam dump material for 4th-generation storage rings, M. Borland et al., NAPAC19

Unplanned beam aborts are biggest concern

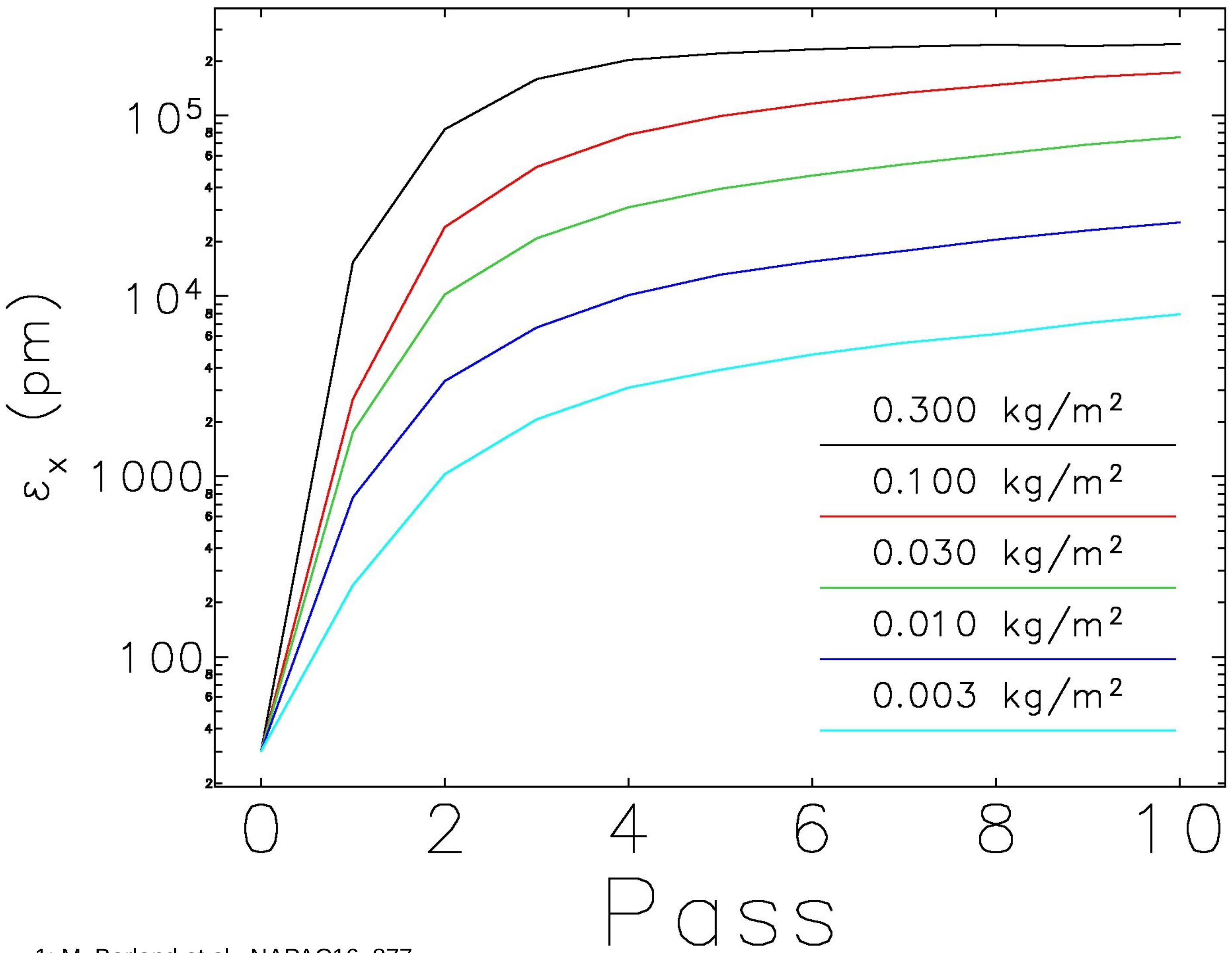
- Planned beam aborts can be handled without damage, e.g.,
  - Kick bunches one-by-one into a dump
    - Fire weak “prekicker”
    - Wait for decoherence to inflate the emittances
    - Kick bunch into dump
- In urgent cases (personnel and machine protection), can’t wait
  - Rf systems are tripped to abort the beam ASAP
  - This can also happen spontaneously
- In APS-U, have 0.2 ms (~55 turns) before beam touches the dump
  - We don’t have time for sufficient decoherence
  - Even if we did, such a system may fail when needed

Using a gas jet has many positive features

- A gas jet would have several advantages
  - No metal splatter
  - No erosion of dump surface
  - No periodic replacement of dump surface
- Xenon attractive
  - Inert
  - High Z
  - Good thermal and vacuum properties
- Can understand requirements by modeling a short gas column that suddenly appears in chamber
  - Use elegant’s MATTER element for this simulation[1]

1: M. Borland, APS LS-287, 2000.

Emittance inflated quickly and dramatically

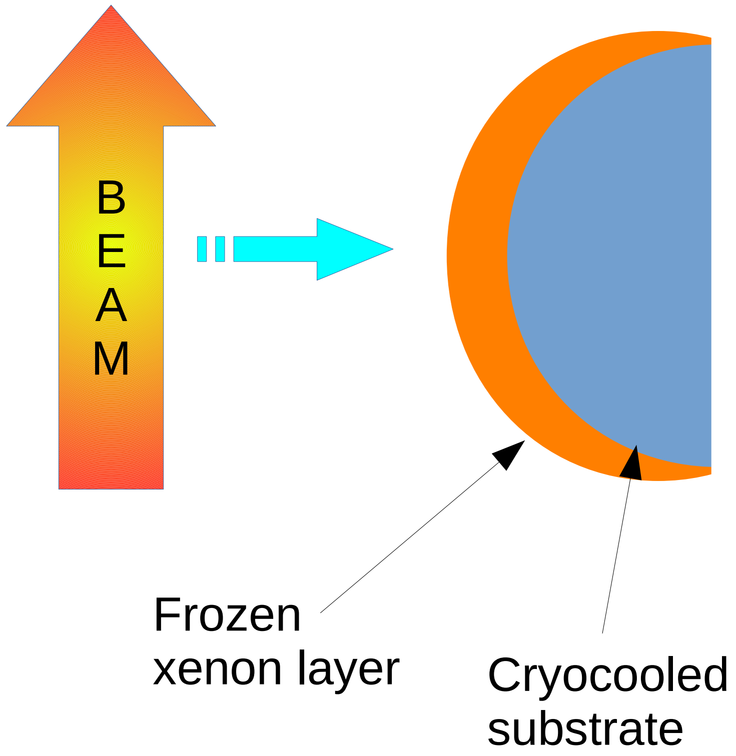


- Started with nominal APS-U parameters: 30 pm emittances, 0.13% momentum spread[1]
- Need to inflate emittances ~300-fold
- Get ~10^3 inflation of emittances from
  - Two passes through xenon with d=0.10 kg/m^2
  - Three passes through xenon with d=0.03 kg/m^2
- A 10-mm column of xenon at STP gives an areal density d=0.059 kg/m^2

1: M. Borland et al., NAPAC16, 877.

Jet is not trivial to make, or is it?

- Simulations assumed that jet “somehow” enveloped the beam instantaneously
- Can possibly make a jet using the electron beam itself
  - Put solid xenon block in place of an ordinary beam dump
  - Tails of beam vaporize xenon as the beam spirals in following rf trip
  - Vaporized xenon scatters the bulk of the beam, which is of necessity just outside the dump

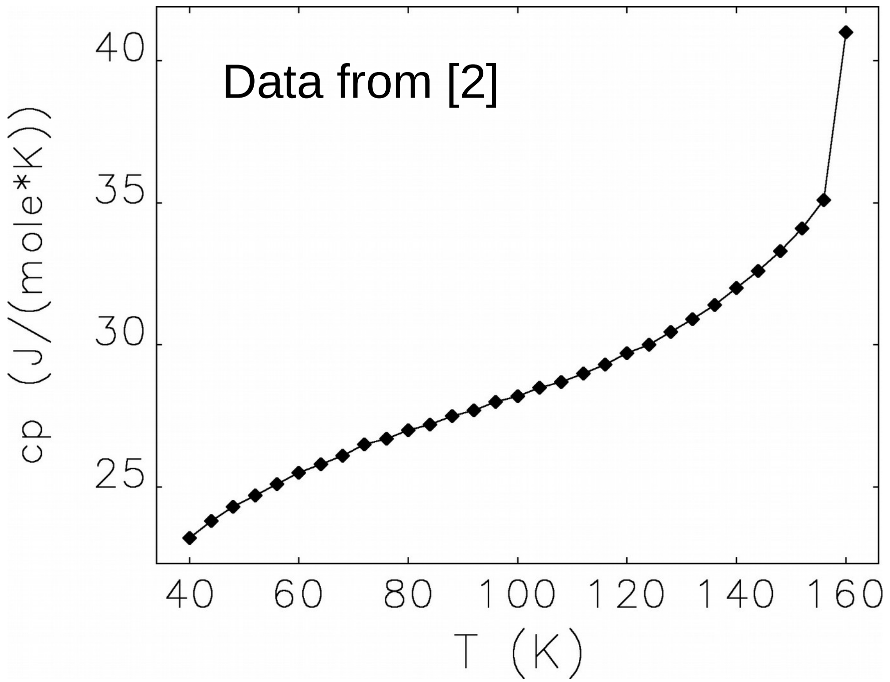


- Solid xenon at 44 K has low (0.1 nT) vapor pressure[1]

1: R. E. Honig et al., RCA Review, Sept. 1960.

Solid xenon is easily vaporized

- Liquify
  - 44K ⇒ 160K: 25.5 kGy
  - Heat of melting [1]: 17.3 kGy
- Vaporize
  - 160K ⇒ 165K [3]: 1.0 kGy
  - Heat of vaporization [1]: 96.0 kGy
- Total dose to go from 44K to vapor: 139.8 kGy
  - Beam dump sees dose of ~100 kGy/nC
  - APS-U stored beam contains 736 nC
- After vaporization, specific heat capacity of xenon gas is ~0.16 kGy/K

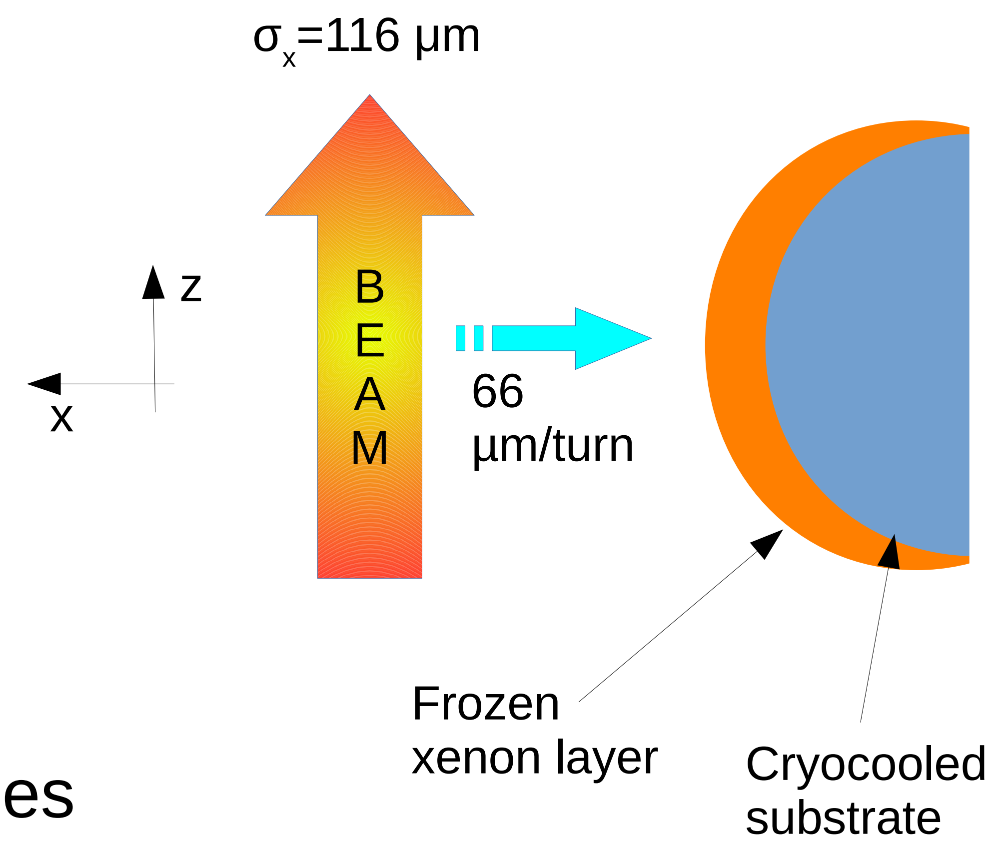


1: Wikipedia entry on Xenon
2: J. U. Trefny, Journal of Low Temperature Physics, 1(3), 1969.
3: P. Dashora et al., Indian Journal of Low Temperature Physics, 41, 438-442 (2003).

Note: 1 kGy = 1 J/g

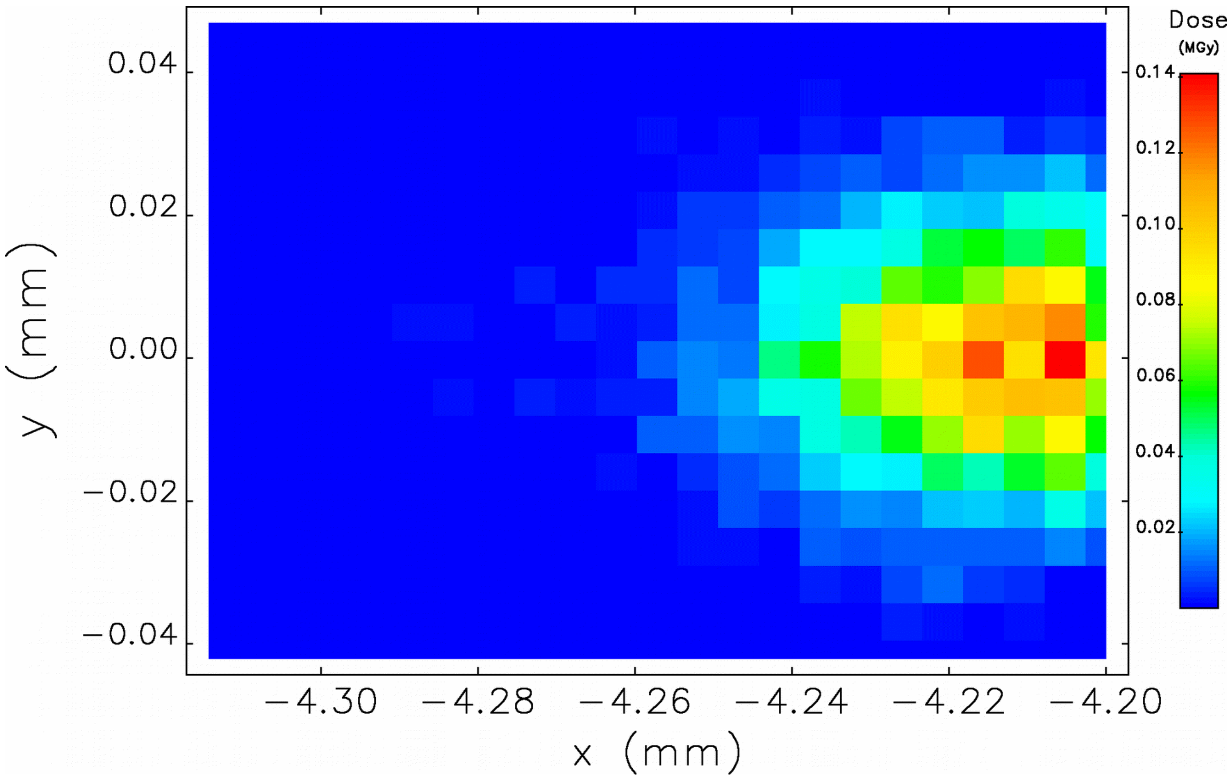
Simulation of the beam abort performed in detail

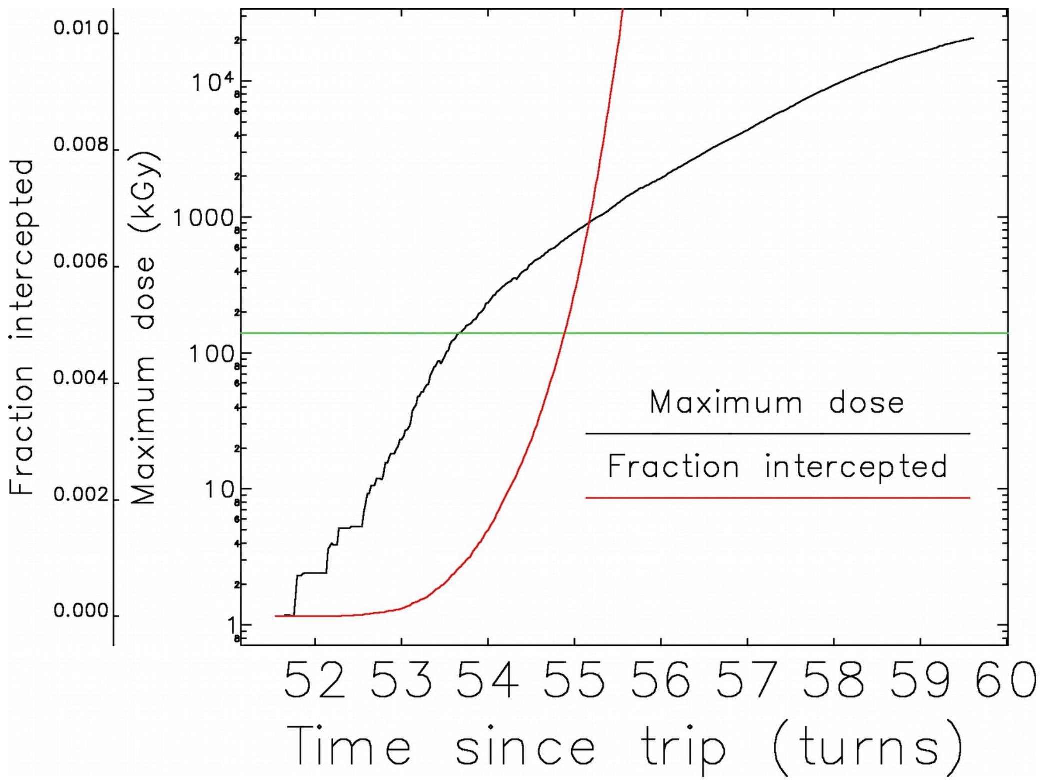
- Simulated a beam abort in APS-U using the parallel version of elegant[1]
  - Used 200 mA in 48 bunches
  - Included element-by-element tracking, synchrotron radiation, and beam-loaded rf cavities
  - Muted the rf generator to allow beam to spiral into dump
- At dump location (high dispersion point), beam spirals in at $0.6\sigma_x$/turn
  - Result of synchrotron radiation losses and energy dumped into the 12 rf cavities
- Simulation records coordinates of particles hitting the dump



1: Y. Wang et al., AIP Conf. Proc.877:241 (2006).

Maximum dose in xenon climbs rapidly





- Dose computed in 5 μm x 5 μm pixels using collisional stopping power[1,2]
- Vaporization of xenon begins on turn 53.7, when only ~0.08% of beam has been intercepted
- Beam centroid is ~3.15σ_x from the dump surface

1: NIST E-STAR database, nist.gov
2: M. Borland, NAPAC13, 1364.

Size, density of xenon cloud can be roughly estimated

- Dose above 139.8 kGy raises the temperature of the gas

$$T[K] = (D[kGy] - 139.8)/C_p + 165$$

- Rms velocity of the gas is related to the temperature

$$v_{rms} = \sqrt{3kT/m}$$

- Radius of the cloud given by the time integral of the velocity

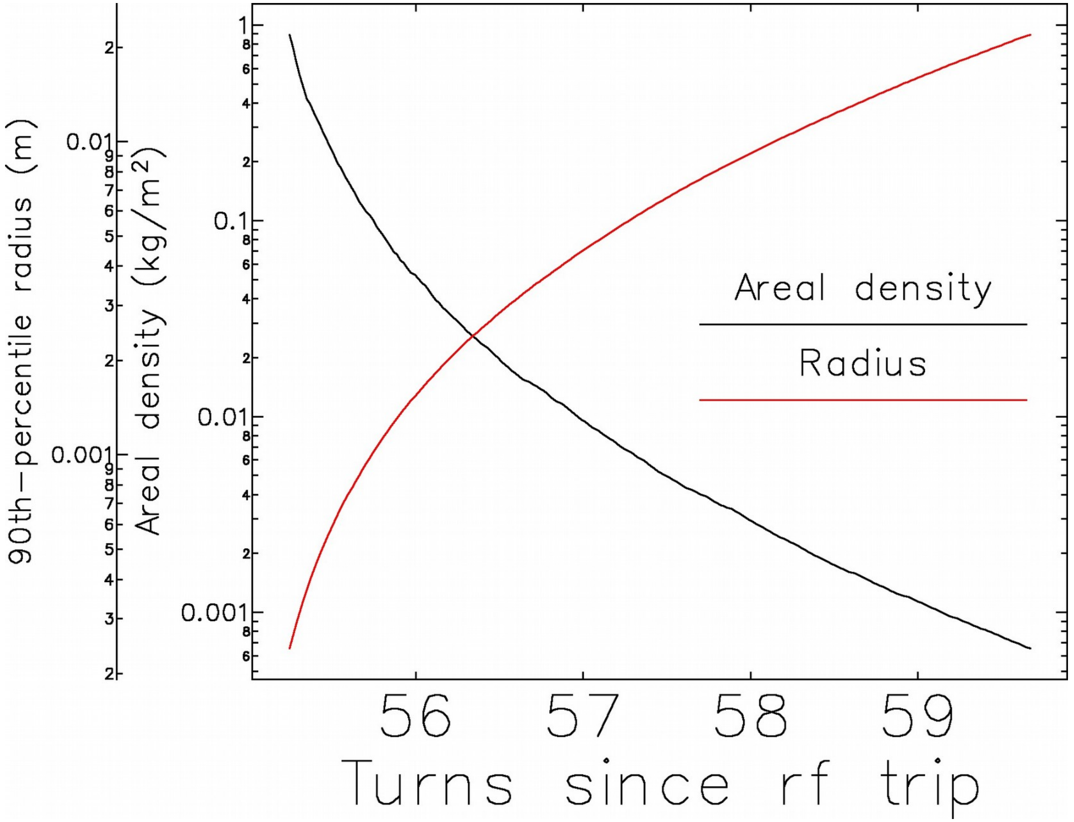
$$R_{90}(T) = \int_0^T (v_{rms})_{90} dt$$

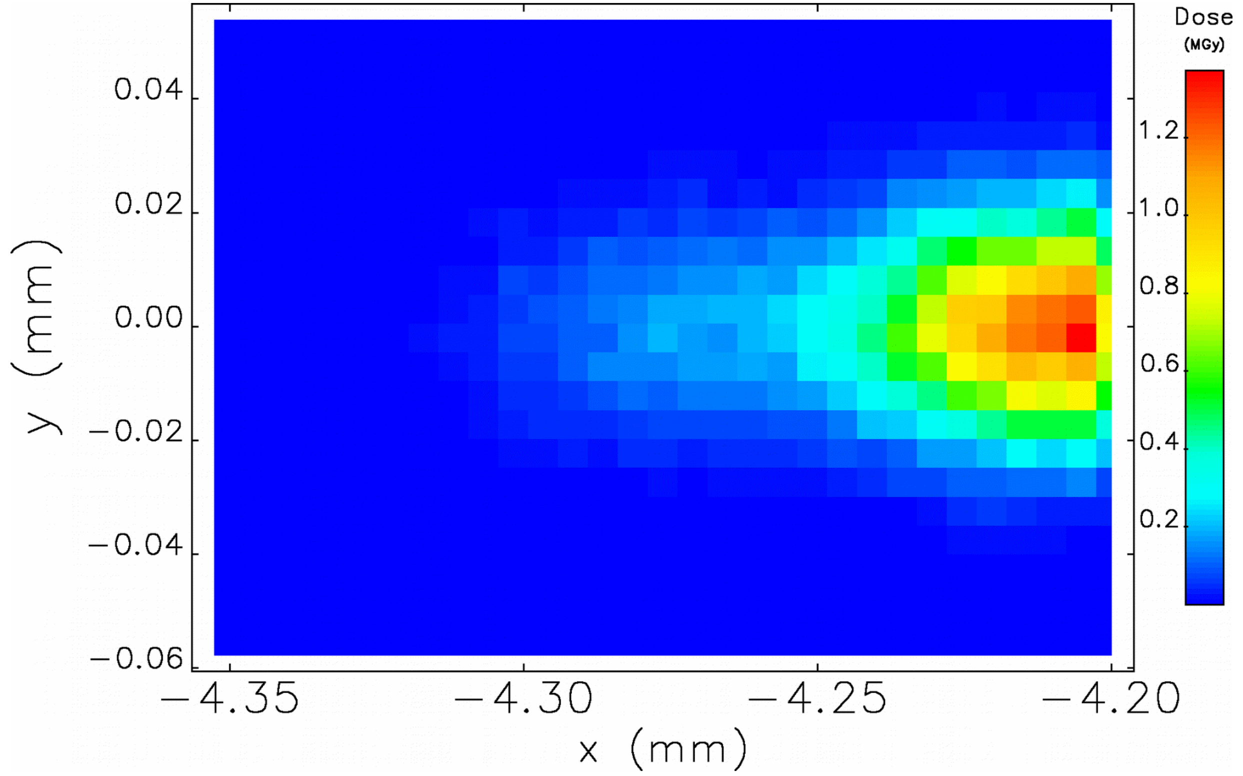
- Areal mass density of the cloud is related to the cloud radius, volume vaporized V, and solid density

$$a = \frac{2V\rho_s}{\pi R_{90}^2}$$

- Gas initially moves into region of higher beam density, so doses and velocities are underestimated

Dense xenon cloud expands rapidly





- 56.6 turns after trip, cloud should envelop 99% of electron beam
- Areal density at this time is ~0.2 kg/m^2
- This will inflate emittances 1000-fold in less than two turns!

Conclusions

- Appears a jet from a solid xenon dump can diffuse APS-U beam before it does damage
- Features and advantages
  - Xenon recondenses on the substrate
  - No metal splatter
  - No periodic breaking of vacuum for service
  - Resurface dump on maintenance days
- Challenges include
  - Rf seal around the substrate to prevent wakefield heating
  - Collimation to localize loss of the diffused beam
  - Avoiding losses of injected beam that might trigger a jet
  - Detailed simulations of gas cloud formation, interaction with beam
  - Convincing management that this isn't too crazy to try