# COLLIMATION AND MACHINE PROTECTION FOR LOW EMITTANCE RINGS

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# Outline

- Introduction—Paradigm shift in MPS for Fourth Generation Light Sources
- MPS examples
- Strategies for Protection of  APS-U Chambers and Collimators
- Coupled-Code Simulations and Loss Studies Data
- Summary

# Introduction

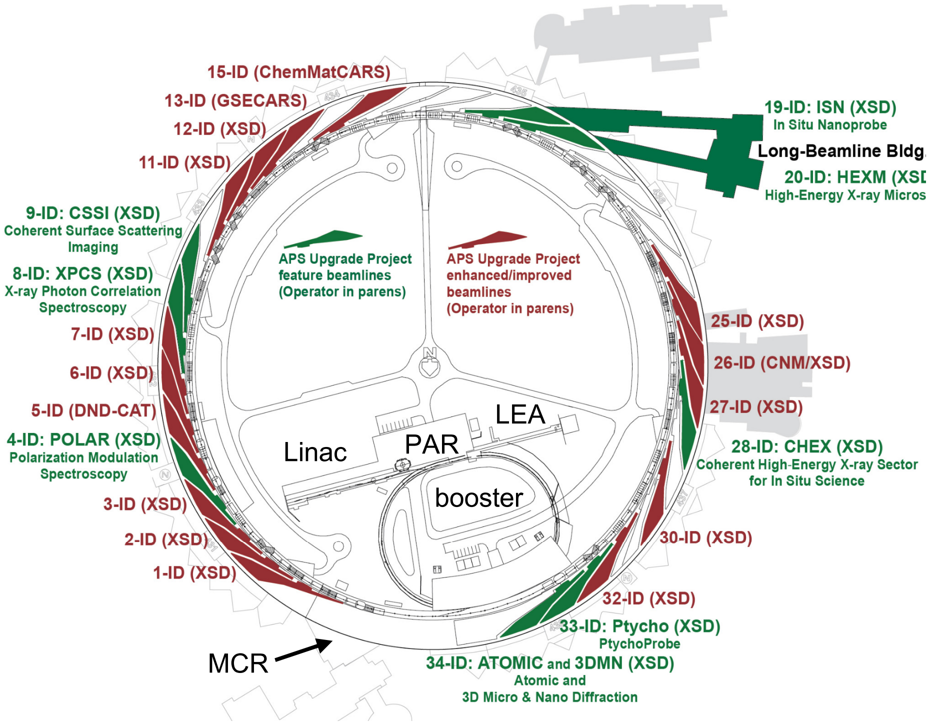
- The ultra-low emittance, high-intensity electron beams in Fourth Generation storage ring (4GSR) machines are capable of causing high-energy-density (HED) interactions on technical surfaces such as collimators or vacuum chamber walls.
- HED is defined as energy densities exceeding roughly $10^{11}$ J/m$^3$.
- Since dose is defined as absorbed energy per unit mass, $D = E_a/\rho$, in aluminum this represents an acute dose of 37 MGy, 11.2 MGy in copper, and 5.2 MGy in tungsten.
- The term "acute" is somewhat ambiguous; here it implies the duration of the deposition is short. Perhaps 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 $\alpha$ is the diffusivity.

# MPS Examples

- Advanced Photon Source Upgrade (APS-U)
- Electron-Ion Collider (EIC)
- Proton Improvement Plan-II (PIP-II)
- Spallation Neutron Source (SNS)

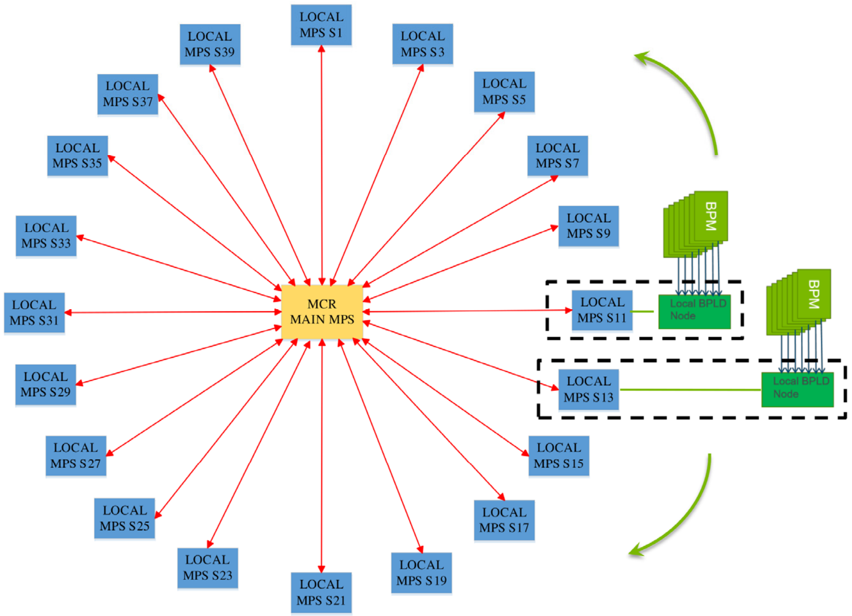
# APS-U MPS

## APS-U SR, 40 sectors




—E. Peoples-Evans

## MPS Topology




—M. Smith, H. Bui

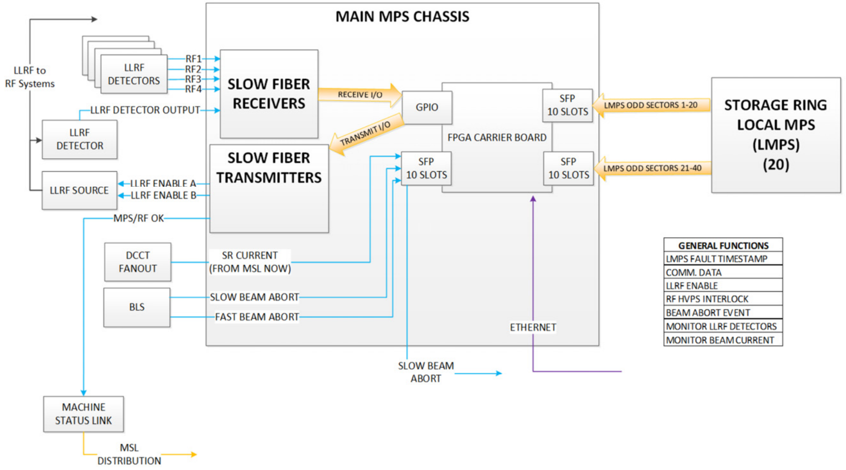
# APS-U MPS

## APS-U SR

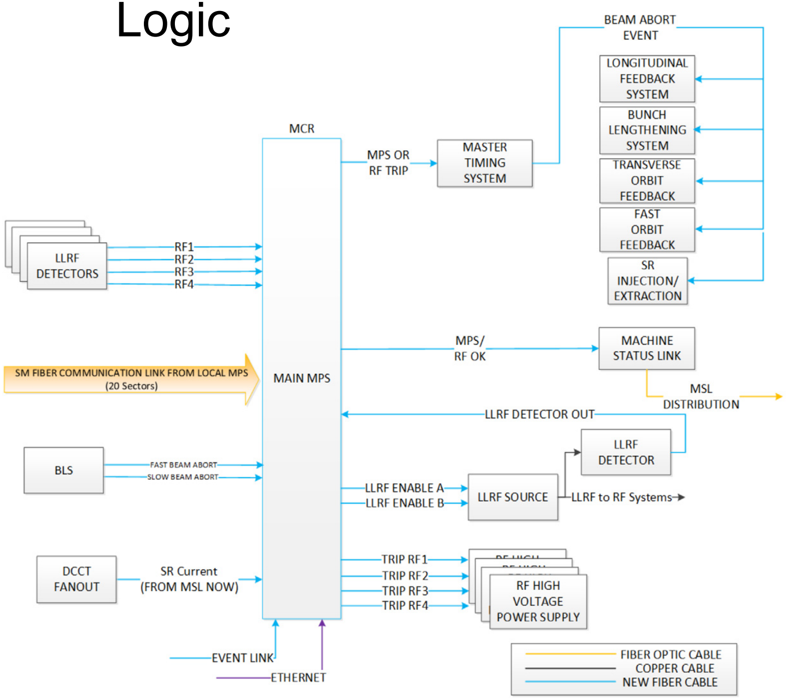
- Two fill patterns will primarily be used in the APS-U SR:
  - 48-bunch timing mode
  - 324-bunch brightness mode
- 200 mA, 6 GeV
- Machine circumference: 1104 m, T = 3.68 μs
- Stored energy: 4.4 kJ, average circulating power: 1.2 GW
- Power densities are also important and high—reaching peak levels of $7\times10^{13}$ W/mm$^2$ in loss study experiments

# APS-U MPS—Main

## Chassis



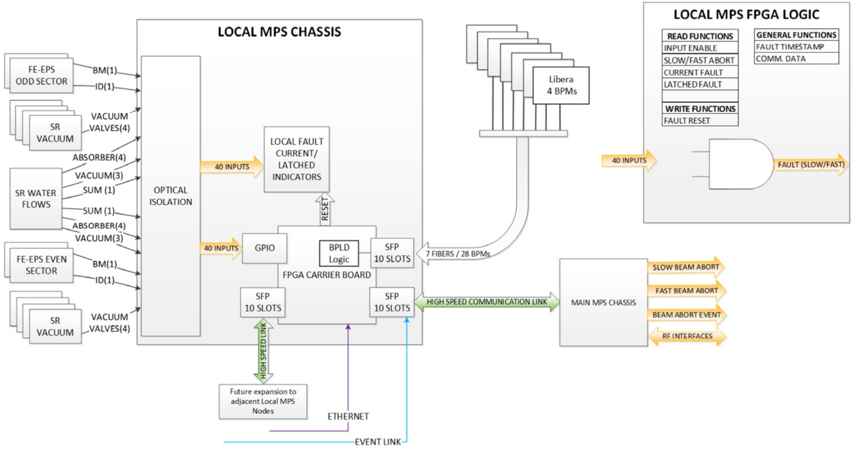

## Logic



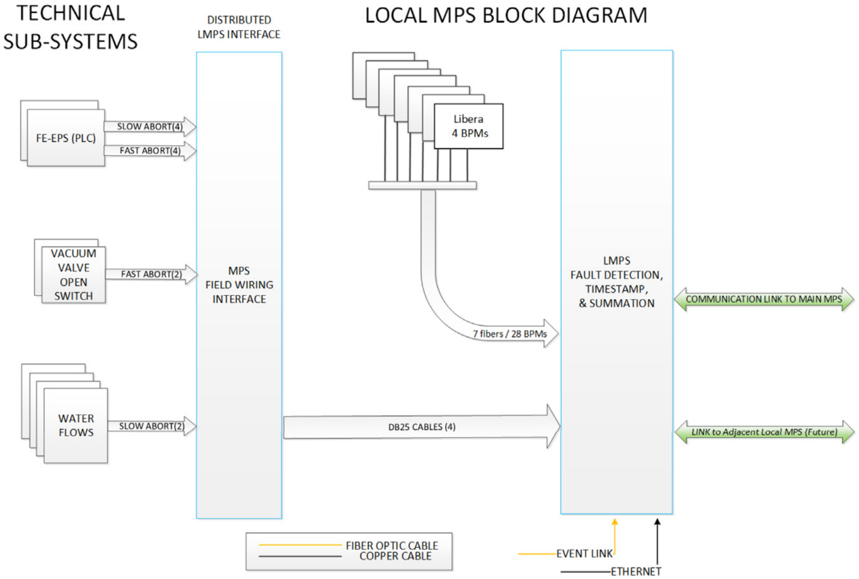

—M. Smith, H. Bui

# APS-U MPS—Local

## Chassis




## Logic

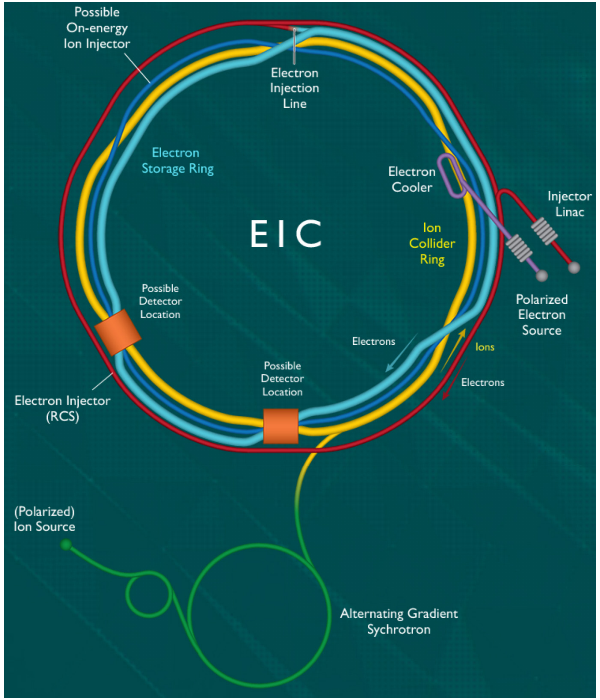



—M. Smith, H. Bui

# Electron-Ion Collider (EIC)

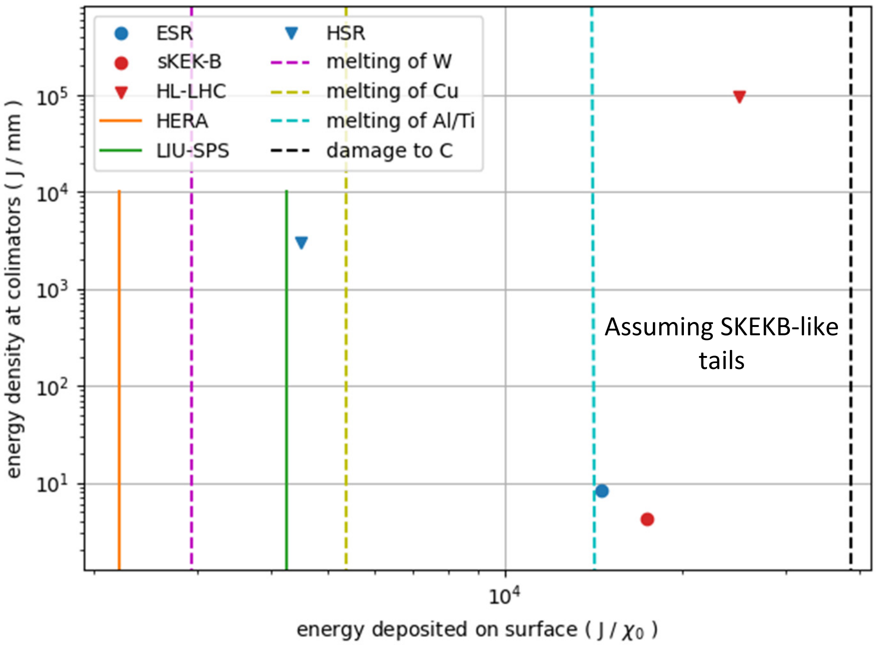
—Built inside the Relativistic Heavy Ion Collider Tunnel

- Will add an electron source including polarized electrons
- A rapidly cycling synchrotron (RCS) for electrons
- An electron storage ring (ESR)
- Presently 3 energies planned: 5, 10, and 18 GeV
- At 10 GeV, e-beam will circulate with the highest stored energy: 1160 27.5 nC bunches. Total stored E: 320 kJ; average circulating beam power: 24.9 GW



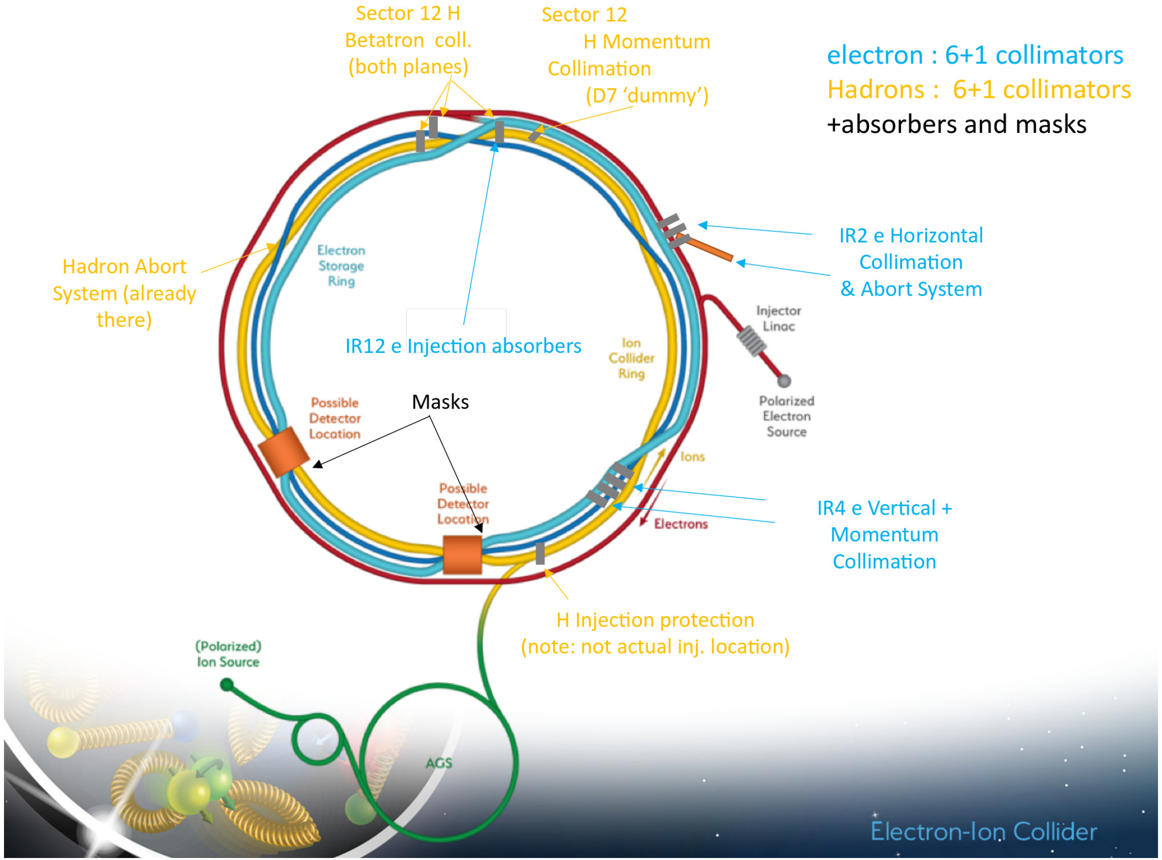
# EIC

- The $e^-$ bunches will be very dense ($0.5\ mm^2$) and melt metals in case of normal impact.
- The $p^+$ beam will have similar parameters as the post-LHC Injector Upgrade (LIU) SPS.
- Other complexes have reported issues limiting performance:
    - SuperKEK-B experienced instabilities causing collimator damage and limiting beam currents.
    - HL-LHC will switch to coated collimators (MoGr) to reduce impedance.




—A. Drees

# EIC Components

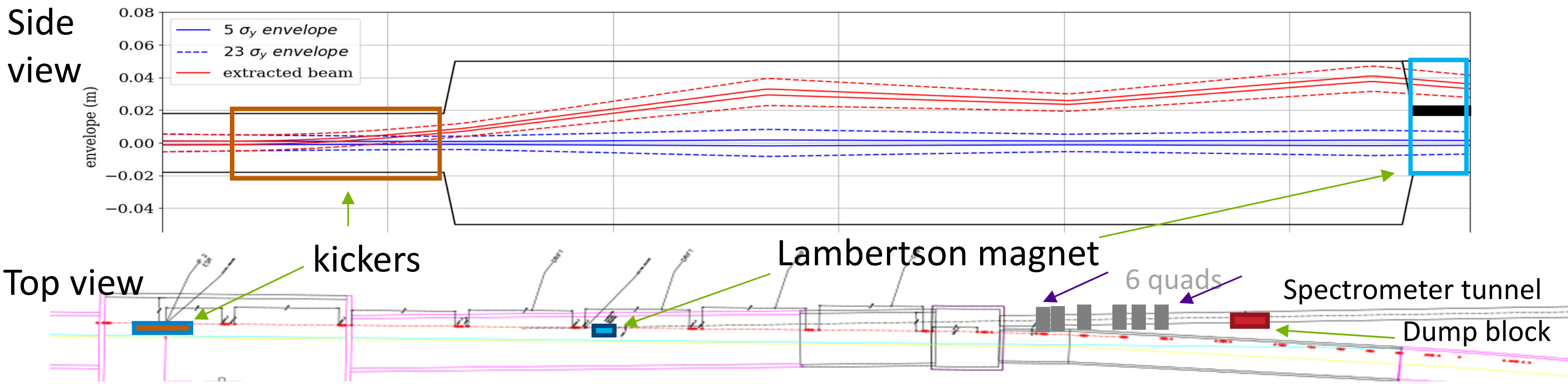



electron : 6+1 collimators
Hadrons :  6+1 collimators
+absorbers and masks

—A. Drees

# ESR abort in IR2

- IR2 features the unused spectrometer tunnel which will allow extracting the 300-kJ beam away from other IR2 users (e-cooling, ERL, RCS injection, …).
- A preliminary design requires 6 x 2-mrad vertical kickers, a 2° Lamberton magnet & a 50 m-long transfer line with 6 quads.




—A. Drees

# MPS logic

- The Hadron Storage Ring (HSR) will take ~35 minutes to fill +ramp.
- In case of an ESR abort the HSR beam can be kept while waiting for the ESR to be re-filled.
- The ESR will take 10 minutes to fill.
- The electrons will not survive the HSR ramp due to changing $f_{rev}$.
- The electrons need to be dumped in case of a hadron abort, to avoid short lifetimes.

  => One way coupling of the permits :

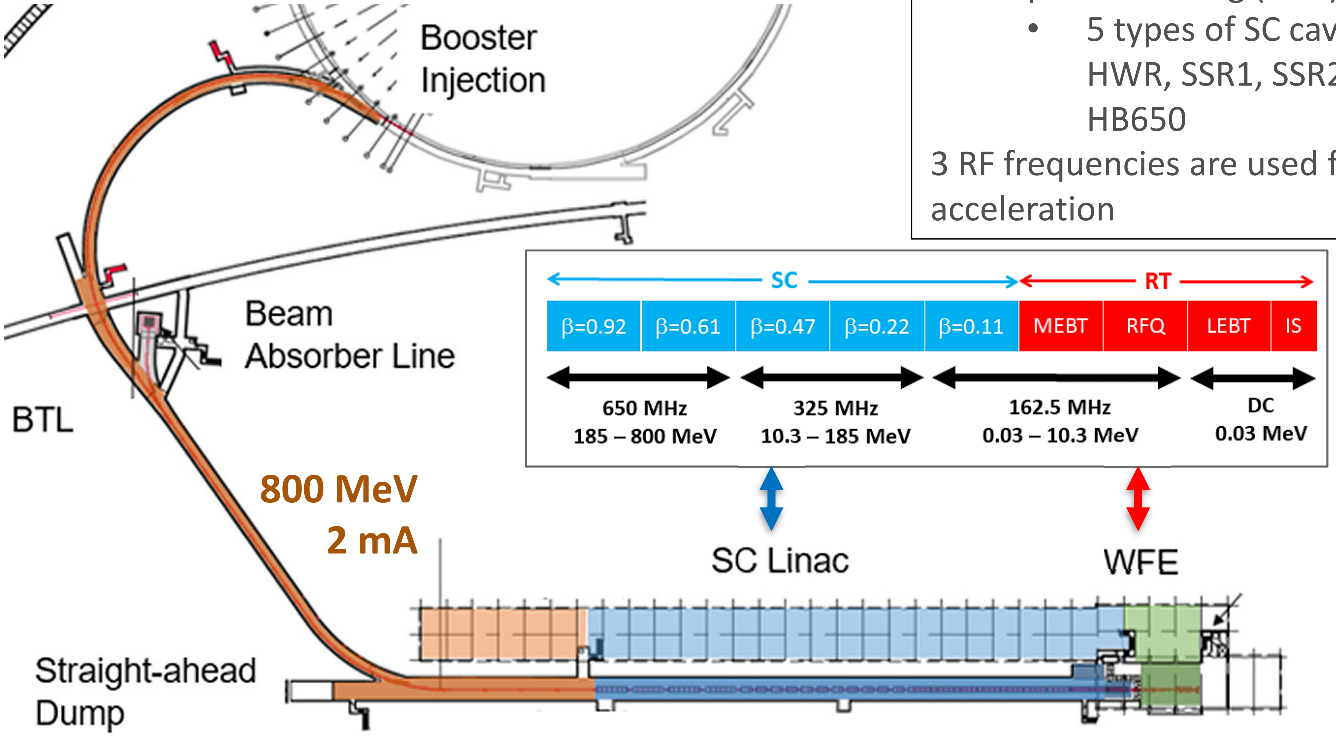
  HSR beam permit used as input for the ESR

—A. Drees

# PIP-II Linac and BTL Map

Linac consists of:
- Room temperature front end (up to 2.1 MeV)
- Superconducting (cold) linac
  - 5 types of SC cavities: HWR, SSR1, SSR2, LB650, HB650

3 RF frequencies are used for acceleration



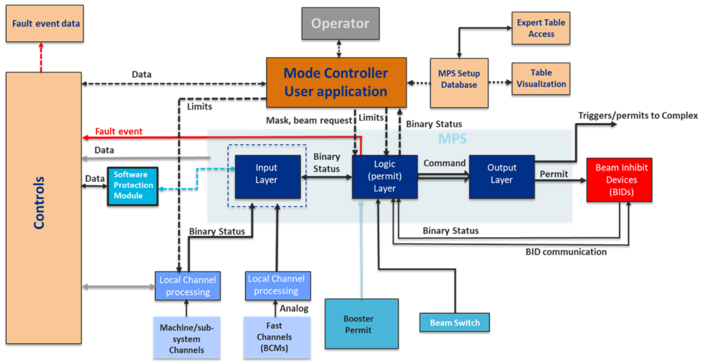
# Fermilab's PIP-II MPS Architecture, Scheme and Instrumentation Layout

General MPS Scheme:

- The main layer of protection is beam inhibiting by four devices, carefully tested and administratively controlled. All of them are upstream of the RFQ.
- The global protection of the linac is performed by comparison of signals from pairs of current-sensitive devices. These devices (4 pairs) are administratively controlled.
- The second layer of protection, the local protection, controlled the beam loss to multiple electrically isolated electrodes in the MEBT.
- The third level was the readiness signals from the subsystems (vacuum, RF etc.).
- Finally, the beam could be operated only at specific combinations of beam intensities and machine configurations defining how far the beam can propagate. Each combination had its own table of the MPS parameters to control.

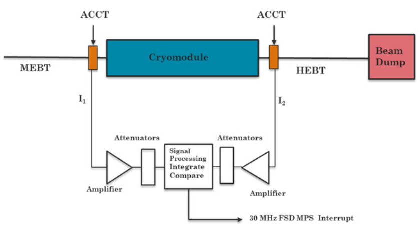
This hierarchy, on one hand, provided a robust protection, and, on the other hand, a significant flexibility in operation.

**General MPS Scheme**

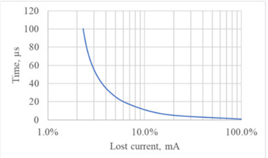



**General Scheme shows Controls and Instrumentation roles in MPS**

**Differential Beam current Monitoring (DBCM)**




$$Q_{th} < Q(T) = e^{\frac{-T}{\tau}} \int_0^T \Delta I(t) \cdot e^{\frac{t}{\tau}} dt$$




$Q_{th}$=2 mA·µs; $\tau$= 50 µs

- Allows losing 20% of the beam at 5 µs (for tuning) and limits to ~2% at >0.1 ms (for long-pulse operation)

Threshold limits were less restrictive in practice at PIP2IT (Qth =100mA . µs; t = 2000 µs)

**A continuous current integration system measures differential beam loss and set a threshold for losses**

# The purpose of the Machine Protection System (MPS) is to mitigate hazards that threaten accelerator components

- High beam power is inherently accompanied by potential hazards:
  - Uncontrolled energy release, failure of hardware systems, etc.
- Hazards pose a dual-threat to the accelerator components:
  - Physical damage & radio-activation
- The MPS mitigates hazards by turning off the beam at the front-end in the event of the following:
  - Equipment failure, beam loss, power supply trips, vacuum leaks, etc.
- The MPS is a high reliability system, but it is not a credited safety system.
  - The MPS does contribute to ALARA.

—A. Justice

# The purpose of this AIP is to modernize the FPS

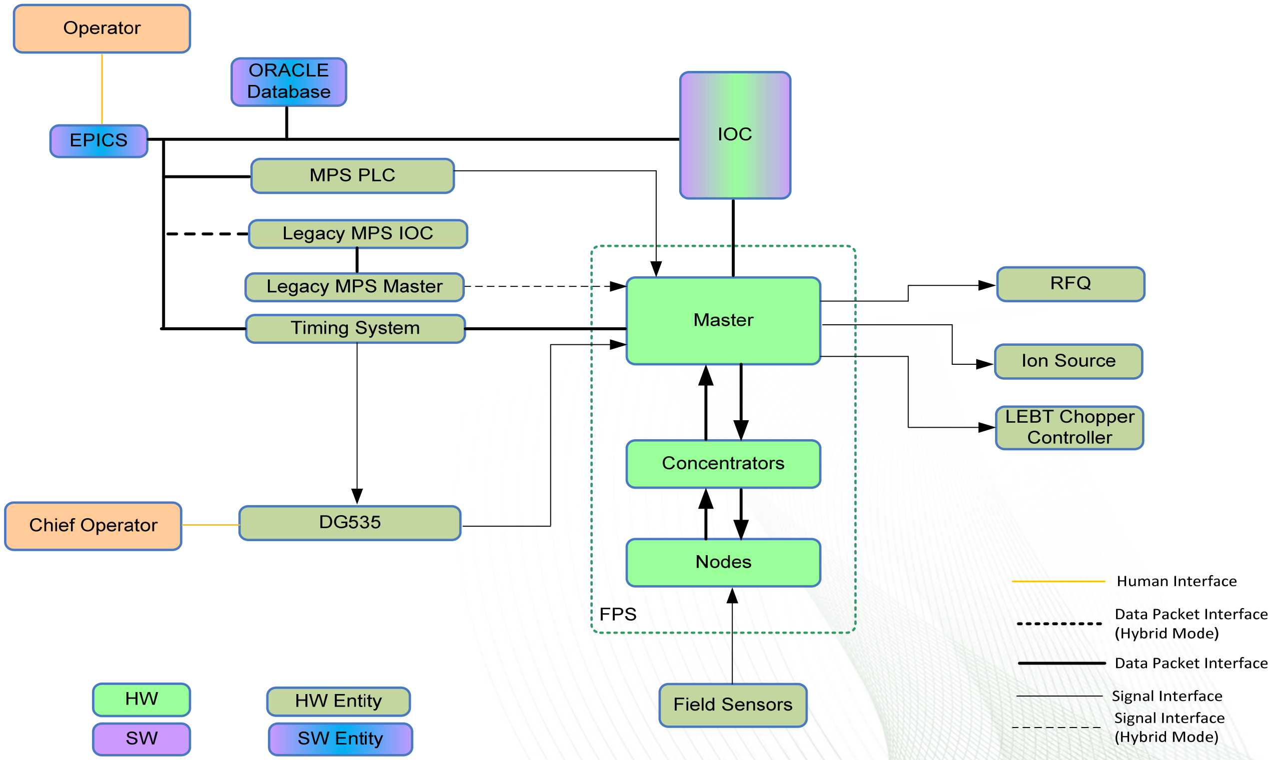
- Improve reliability significantly
  - Simplify the architecture
  - Increase integration => less "stuff" = fewer failure points
- Deploy scalable architecture:
  - Increase performance by decreasing system response time
  - viable path for major facility upgrades — PPU & STS
- Resolve the maintainability problem
  - Current system is mostly customized, obsolete hardware
  - Use "21$^{st}$ century" technology
    - Rely on industry standards where possible
    - Minimize custom hardware development
    - Utilize COTS solutions: hedge against future obsolescence

—A. Justice

# A New Fast Protection System has been designed for the MPS

"form, fit and function compatible" with legacy system interfaces

—A. Justice



# Strategies for Protection of APS-U Chambers and Collimators

# Strategies for Protection of APS-U Chambers and Collimators

Fan-out kicker

➢Vertically spreads the beam on the collimators (5) to reduce energy density and power density

➢Necessary above 30 mA

Slow aborts—swap out bunches one-by-one into the swap-out dump

Advanced Concept: Wakefields

➢Build structures (into collimators?) to disrupt the beam with head-tail kicks

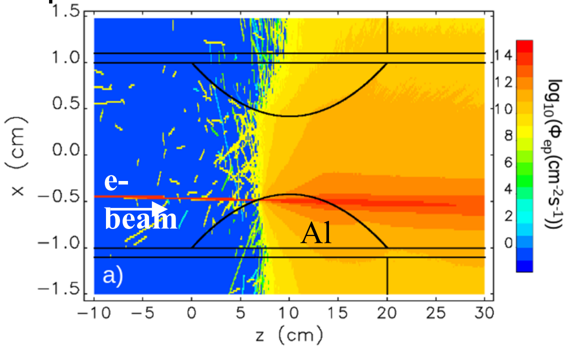
If all else fails, build a dedicated dump line—unlikely for APS-U

# Coupled-Code Simulations and Loss Studies Data

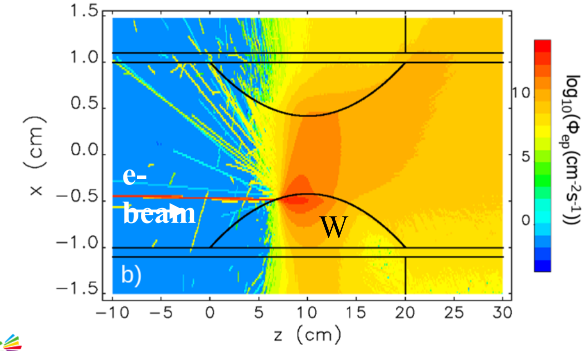
# Early APS-U Collimator Simulations with `elegant` & MARS

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

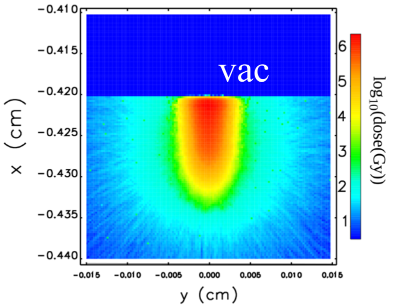
Al




W




Al apex dose




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

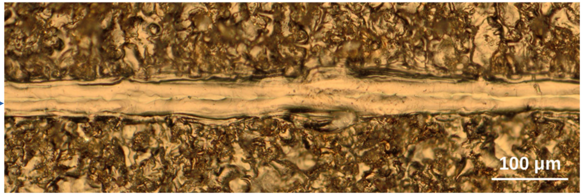
$$T_{2,max} \approx \frac{q_v(x_{max})}{\rho(x_{max})\bar{c}_p} + T_1 = \frac{D_{max}A_w}{C_m} + T_1$$

| Mat'l | $D_{max}$ | $A_w$ | Cp | $T_m$ | $T_v$ | $T_2$ |
|---|---|---|---|---|---|---|
| | (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 |

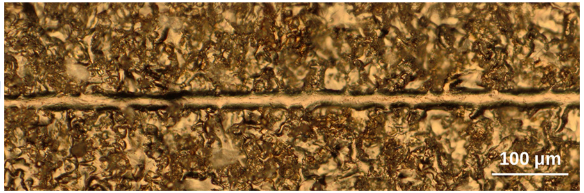
# Two experiments were conducted in the APS Storage Ring to approach APS-U conditions on possible collimator material

Ti6Al4V

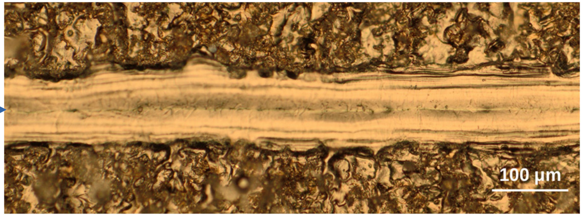
May 2019




$I_b$ =32.1 mA




15.9 mA




66.9 mA

$$\frac{X_{o,Ti}}{\rho_{Ti}} = 3.56\text{cm}$$

January 2020

Al 6061-T6

$I_b$ (mA)

202.1

201.2

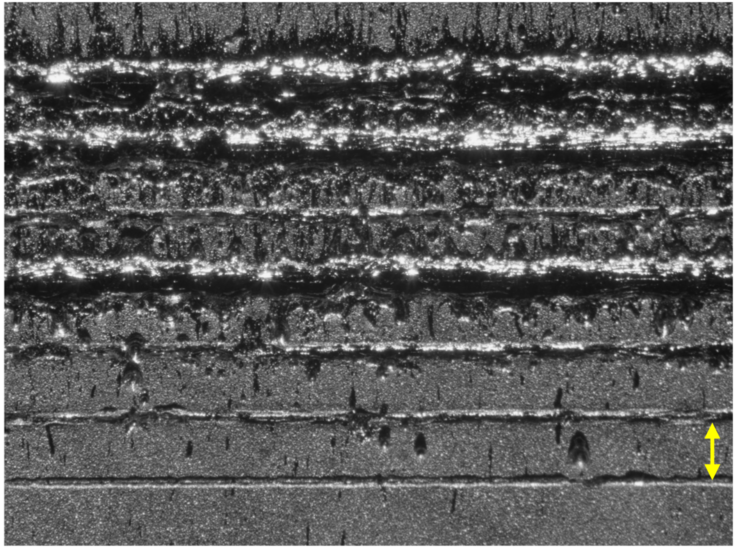
100.0

202.0

99.1

69.4

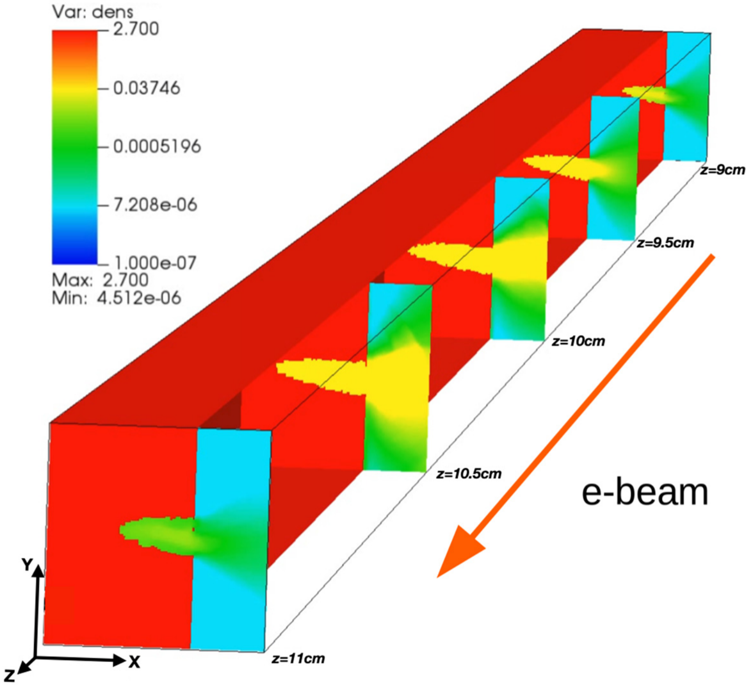
34.6

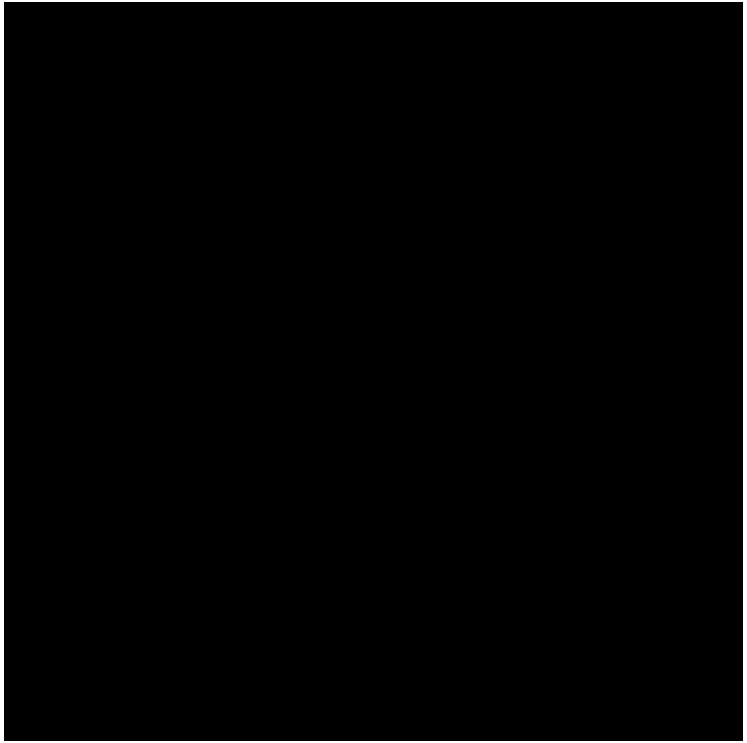


400 µm

$$\frac{X_{o,Al}}{\rho_{Al}} = 8.9\text{cm}$$

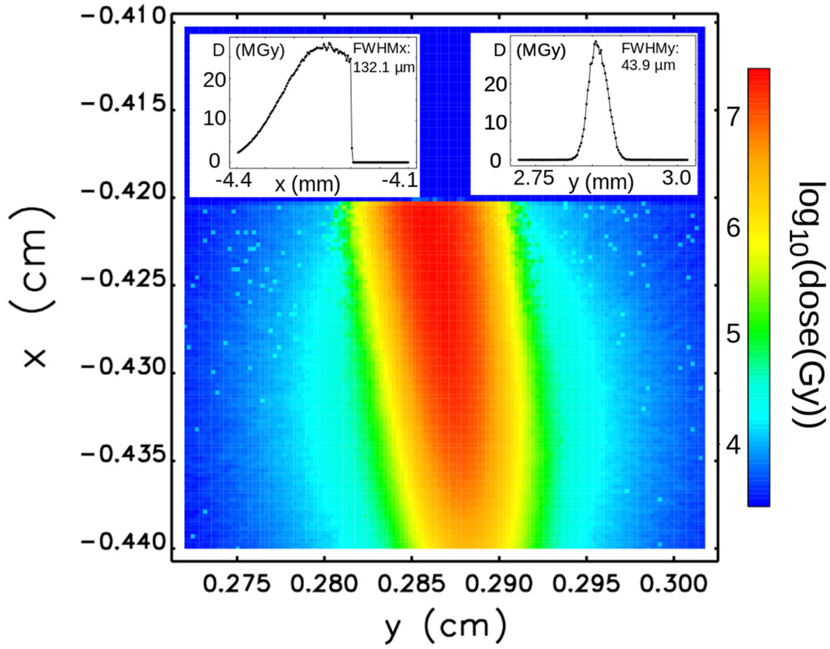
# Adding hydrodynamic modeling with FLASH



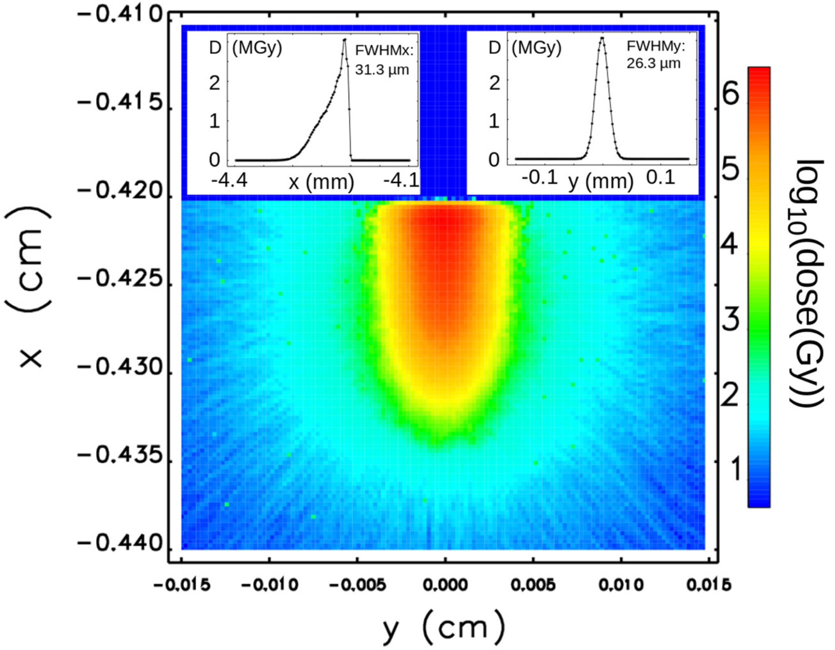



# Deposition Models

Deposition of full 200-mA beam dervied from expt.

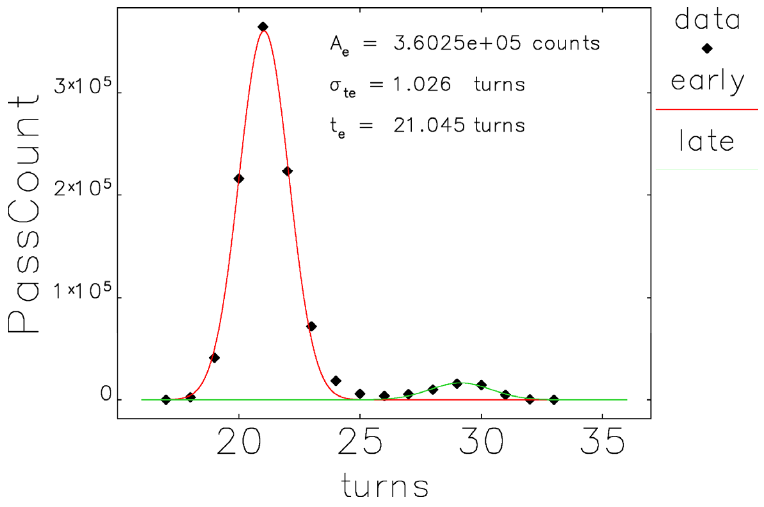



APS-U model of full 200-mA beam, from 1 of 48 bunches

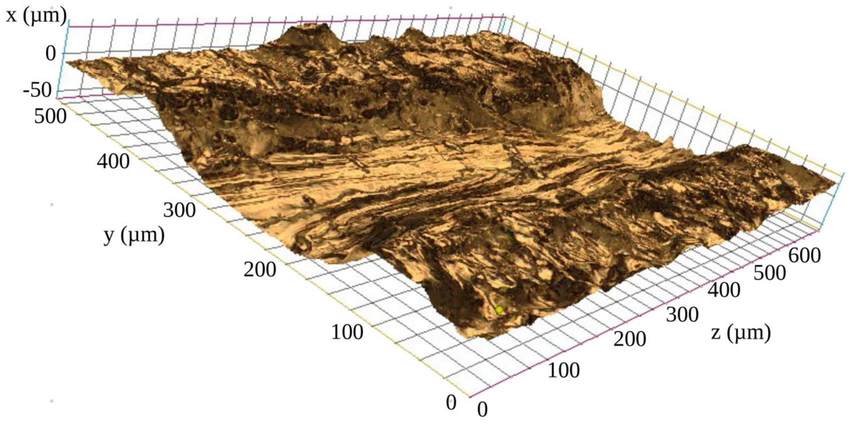


# Initially Assumed Uniform Irradiation

- However, when looking at time varying dose, observed transverse motion

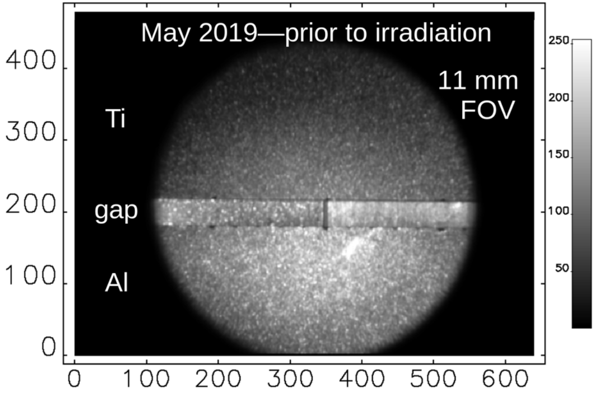


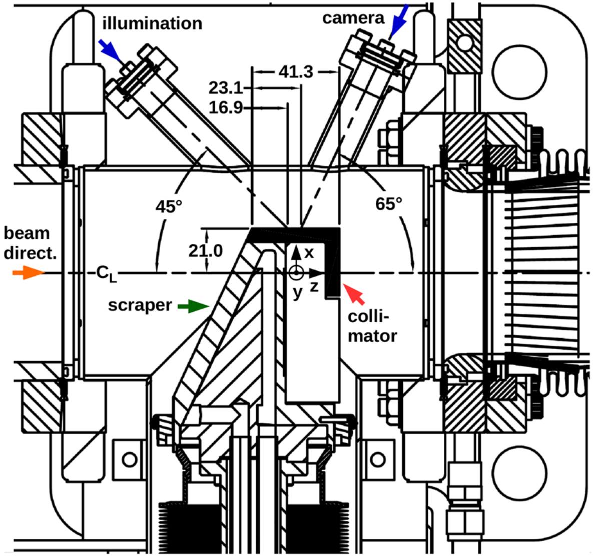

# Flow After Deposition



# Diagnostics

- Cameras
- Fast Beam Loss Monitors
- Turn-by-turn BPMs



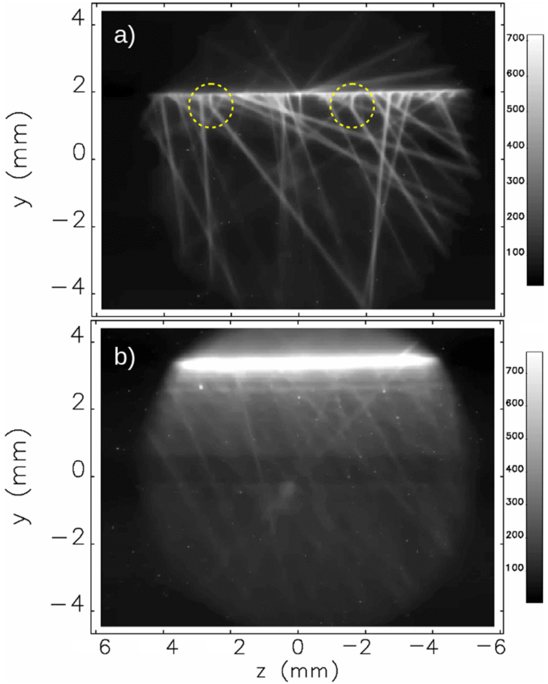




# Optical Images of beam strikes

## Single strikes on Al

67 mA

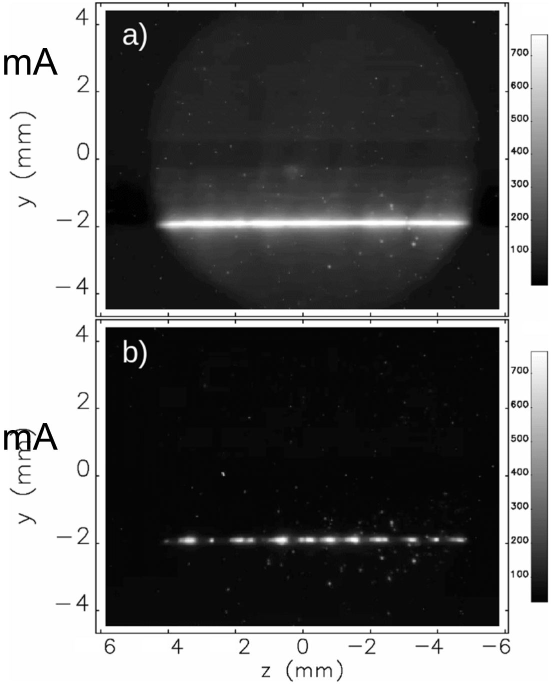
200 mA




## Multiple strikes on Al

200 mA
1st

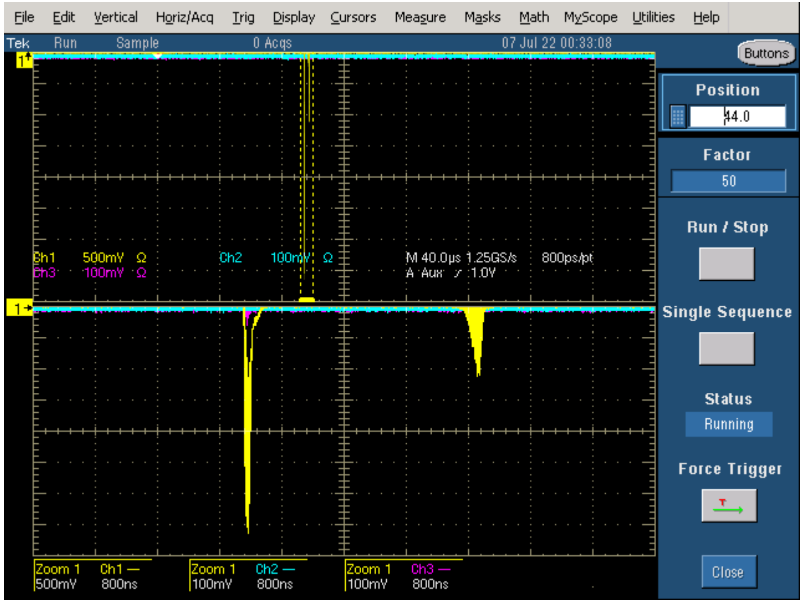
200 mA
5th



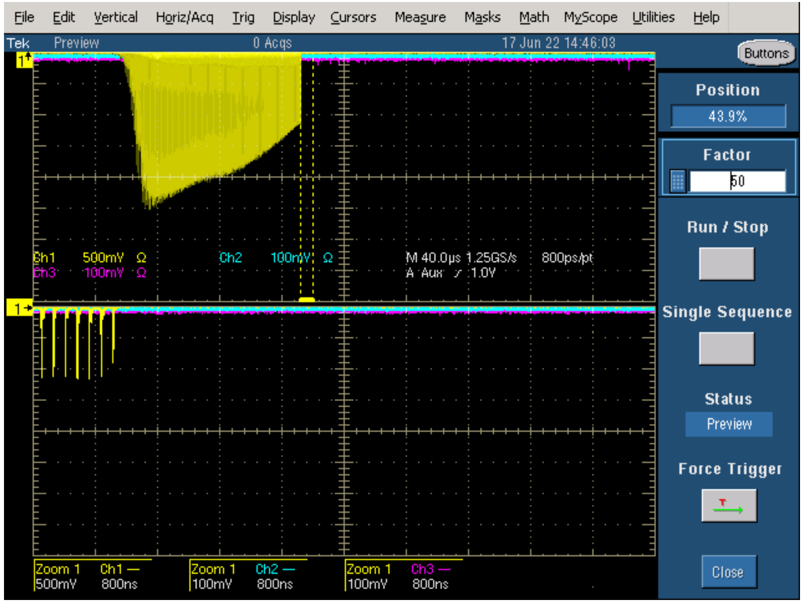
# Fast Beam Loss Monitors

Tells when things don’t go as planned

## Abort kicker fires properly

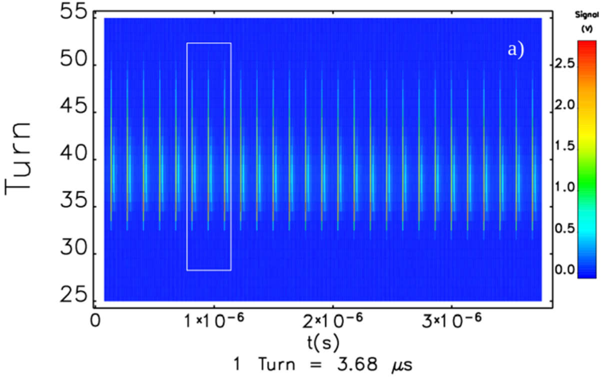


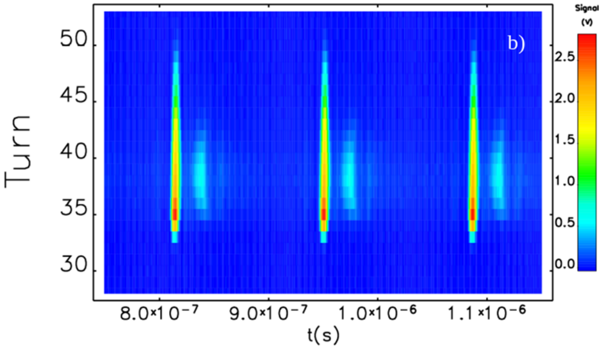

## Abort kicker fires late



# Fast BLMs Signals during Beam Dump Studies

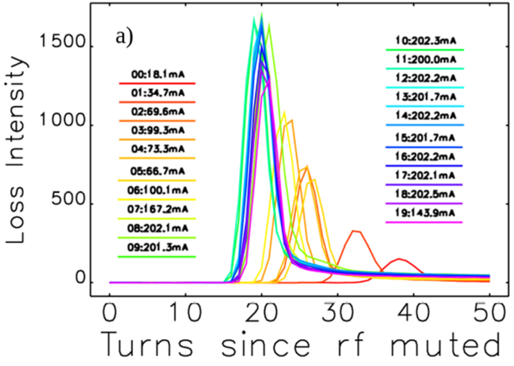
Fast BLM, 18 mA



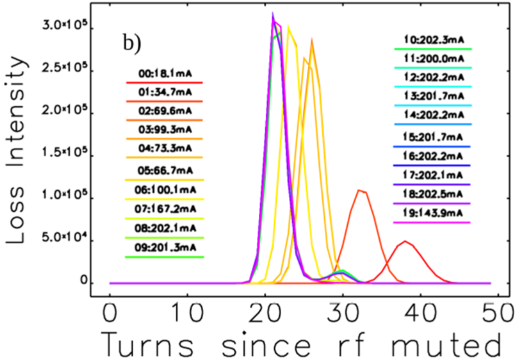




Fast BLM, all data

BLM



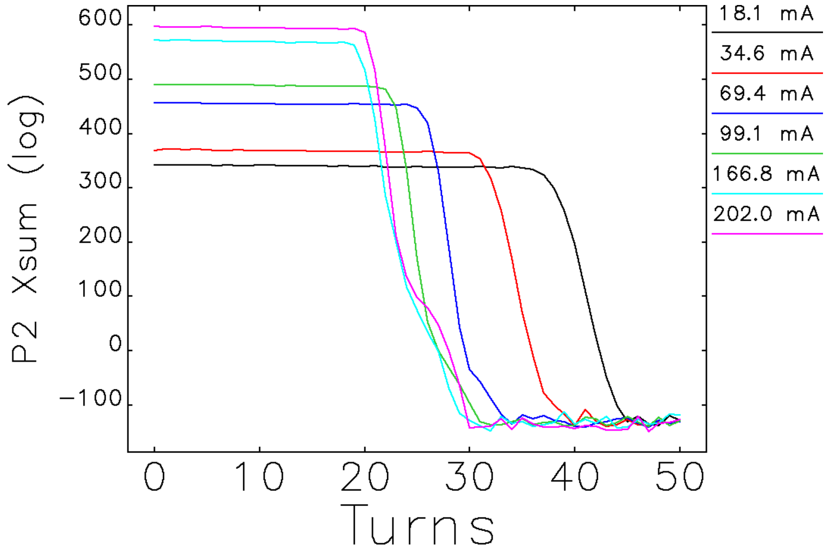

**elegant**

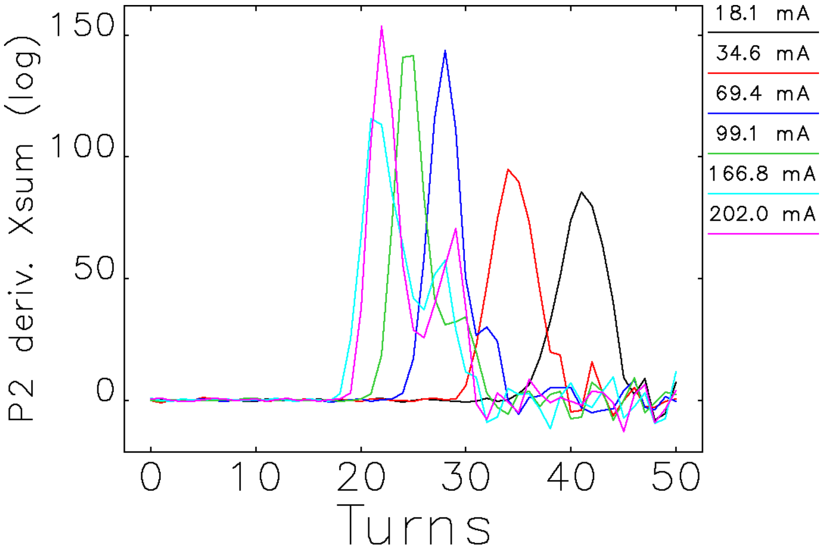


# Turn-by-turn BPMs

Select beam aborts during collimator irradiation (beam dump) studies

- Sum signal is depends on log current (non linear)
- Derivative of the sum during beam loss gived nonlinear loss intensity
- Can provide loss locations but not intra-turn signals



# Summary

- Present high-performance machines (light sources and linacs) require significant care and feeding
- New machines will be even higher performance and demand even more maintenance and machine protection
- 4GSR light sources must consider the threat from ultra-low emittance electron beams causing mechanical damage to high-value components and incorporate that into machine protection systems
- Simulations will help guide the effort to protect machine components exposed to the beam
- Diagnostics are a key component of MPS and necessary for benchmarking codes

# THANK YOU!

# QUESTIONS?