Machine Protection for Synchrotron Light Sources

Louis Emery
Senior Physicist
Argonne National Laboratory
Using slides and texts from J. Dooling, M. Borland, J. Carter, U. Wienands, K. Ha (BNL)

Beam Loss and Machine Protection
United States Particle Accelerator School
Jan 30th – Feb 3rd, 2023

Overview

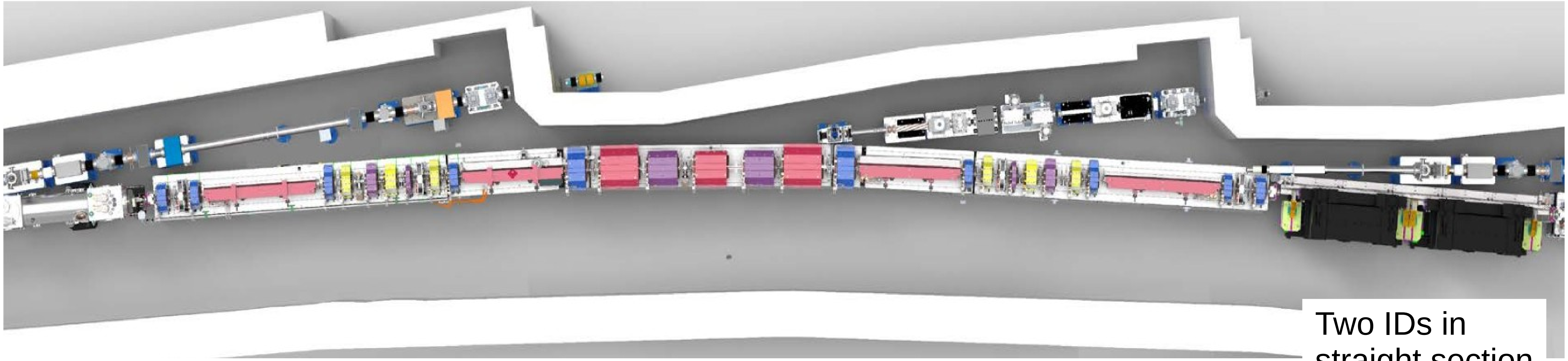
- Damage by electron beam
- Damage by photon beam (dipole fan and insertion devices)
- Passive protection from photon beam (absorbers)
- Passive protection from electron beam (collimators)
- Active protection from photon beam (orbit interlocks)
- Active protection from electron beam

  } Requires a beam abort
- Beam abort of stored electron beam (on demand or automatic)
- Beam dump design
- Slides emphasize design of APS-U (Installation in 2023 and commissioning in Jan 2024)

But first, light source overview

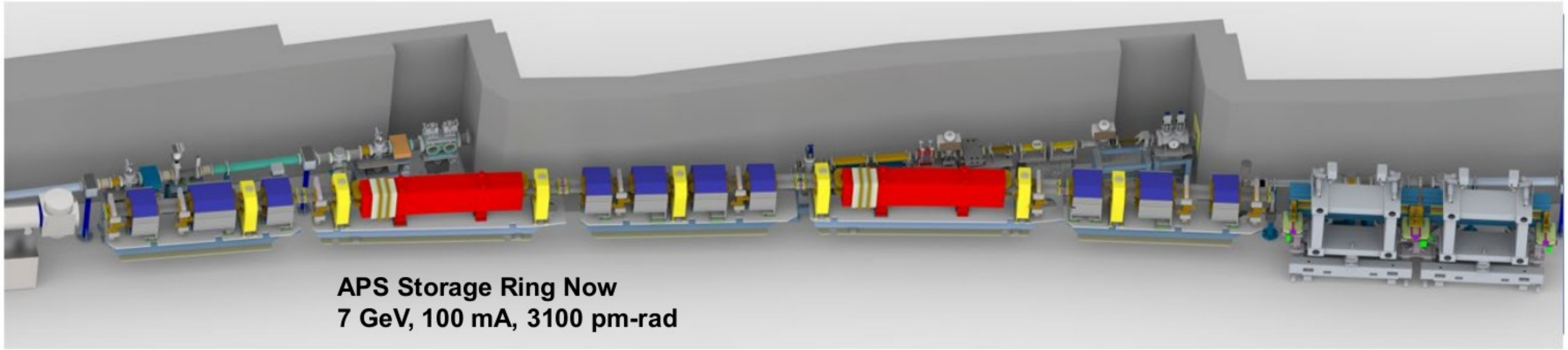
- More complex optics in one cell, repeated many times (10 to 48)
- Insertion devices (periodic magnetic field) for photon production
- Xray beams penetrate through sheilding wall and into sealed “hutches” (not shown)

APS Upgrade cell, 40 in number, two photon beamlines per cell

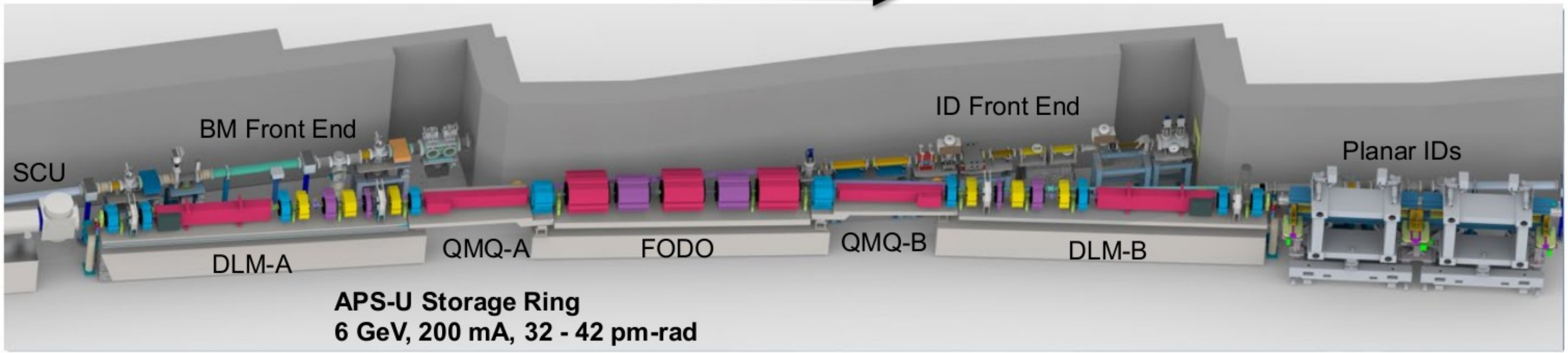


Two IDs in straight section

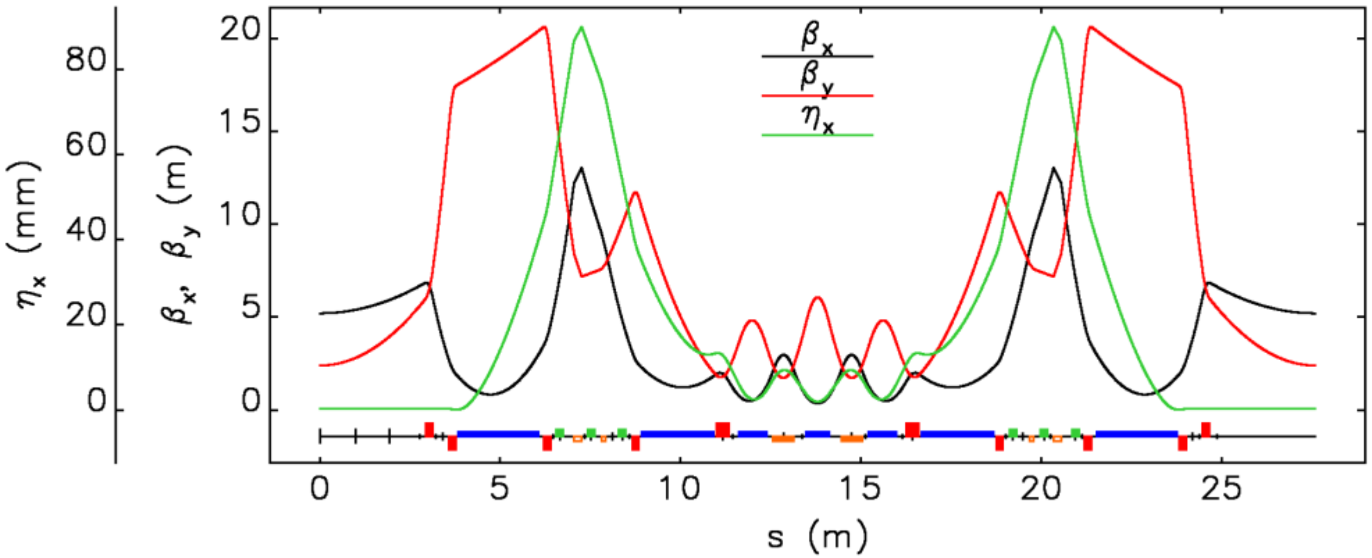
Upgrades worldwide to achieve high photon brightness using very low-emittance electron beams



Beam Direction



Light Source Upgrades



Chosen lattice is ESRF-inspired H7BA[1] with six reverse-direction dipoles[2,3] per cell.

Red: quadrupoles
Blue: main-direction dipoles
Orange: reverse direction dipoles
Green: sextupoles

Facility	E (GeV)	Circum. (m)	Current (mA)	ε_0 (pm)	σ_δ (%)	β_x (m)	β_y (m)	ETA User Ops
ESRF-EBS[4]	6	844	200	133	0.095	6.9	2.6	Operating
APS-U[5]	6	1104	200	42	0.13	5.2	2.4	Early 2024
HEPS[6]	6	1360	200	34	0.11	2.8	1.9	2025?
SPring8-II[7]	6	1435	100	140	?	5.5	3.0	Conceptual
PETRA IV[8]	6	2304	200	20 (DW)	0.09	2.2	2.2	Late 2028

1: L. Farvacque et al., IPAC13, 79.
2: J. Delahaye et al., PAC89, 1611.
3: A. Streun, NIM A **37**, 148 (2014).
4: N. Carmignani, private communication, 2013.
5: M. Borland et al., NAPAC16, 877.
6: Y. Jiao et al., JSR **25**, 1611 (2018).
7: H. Tanaka et al., IPAC16, 2867.
8: R. Bartolini et al., IPAC22, 1475.

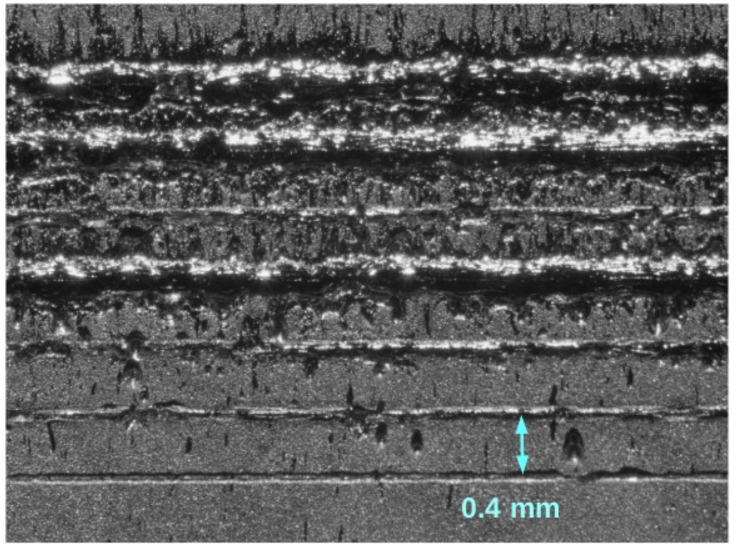
Pause

Damage by Electron Beam

Chamber damage a significant concern for APS-U

- In 2011, we discovered that the APS tungsten beam dump had significant damage due to beam strikes[1]
- With higher energy density, APS-U beam has potential to damage most materials used in accelerators
- Modeling[2] suggested aluminum as the best compromise material to reduce damage
  - Low Z
  - High thermal conductivity
  - High heat capacity
- APS experiments replicating APS-U conditions confirm that this is an issue[3]

Surface damage to APS aluminum beam dump struck w/APS-U-like energy density

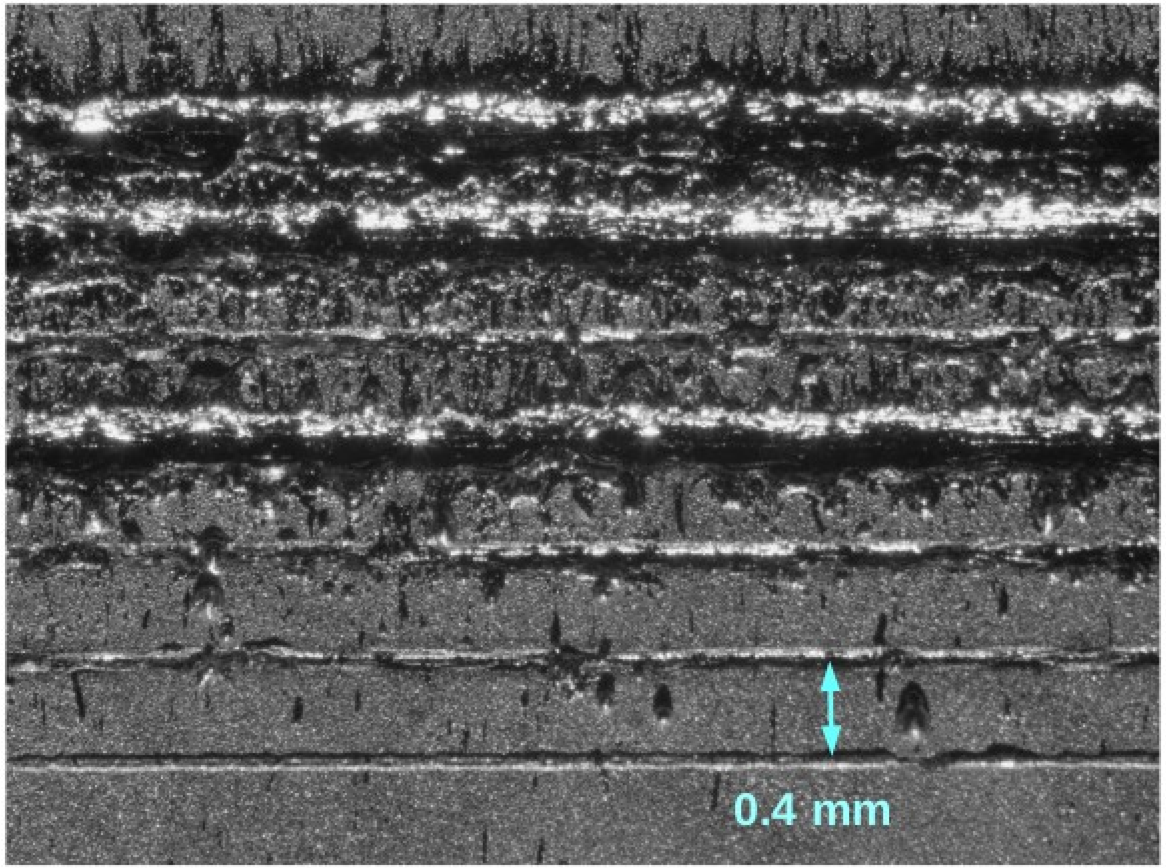


SN	I (mA)
10	202.1
09	201.2
06	100.0
08	202.0
03	99.1
02	69.4
01	34.6

1: J. Dooling et al., PAC13, 1361.
2: J. Dooling et al., AOP-TN-2018-025.
3: J. Dooling et al., PRAB **25**, 043001 (2022).

Damage by Electron Beam (Zoom in)

Surface damage to APS aluminum beam dump struck w/APS-U-like energy density



SN	I (mA)
10	202.1
09	201.2
06	100.0
08	202.0
03	99.1
02	69.4
01	34.6

Slow Damage by Electron Beam

- Need to reduce long-term radiation damage on components
- Demagnetization of permanent magnet insertion devices from long-term dose of neutrons (1990s APS – at smallest vacuum chamber aperture over a few years). Also a few 10s deg C temperature pulse can reduce magnetization locally as well.
  - Local demagnetization of few percent can reduce brightness (coherence) of photon beam, in particular higher harmonics.
  - Replace NdFeB materials with SmCo, which is radiation harder material (E. Moog)

*Neutrons are produced by bremmstrahlung of > 10 MeV electrons

Damage by Photon Beam from Power Emitted

Instantaneous power $\sim E^2 B^2$

$$P_\gamma [\text{GeV/sec}] = \frac{c\, C_\gamma}{2\pi} \frac{E^4 [\text{GeV}]}{\rho^2}$$

$$C_\gamma = \frac{4\pi}{3} \frac{r_e}{(mc^2)^3} = 8.85 \times 10^{-5}\ \text{m/GeV}^4$$

What is C_γ for protons? The power goes as $(\text{mass})^{-4}$

Loss per turn

$$U[\text{MeV}] = 0.088 \frac{E^4 [\text{GeV}^4]}{\rho [\text{m}]}$$

Power

$$P[\text{MW}] = 0.088 \frac{E^4 [\text{GeV}^4]}{\rho [\text{m}]} I[\text{A}]$$

APS: E = 7 GeV, ρ = 40 m, and U = 5.5 MeV, P = 0.545 MW

LEP (1990-2000): E = 104 GeV, ρ = 3100 m, and U = 3300 MeV

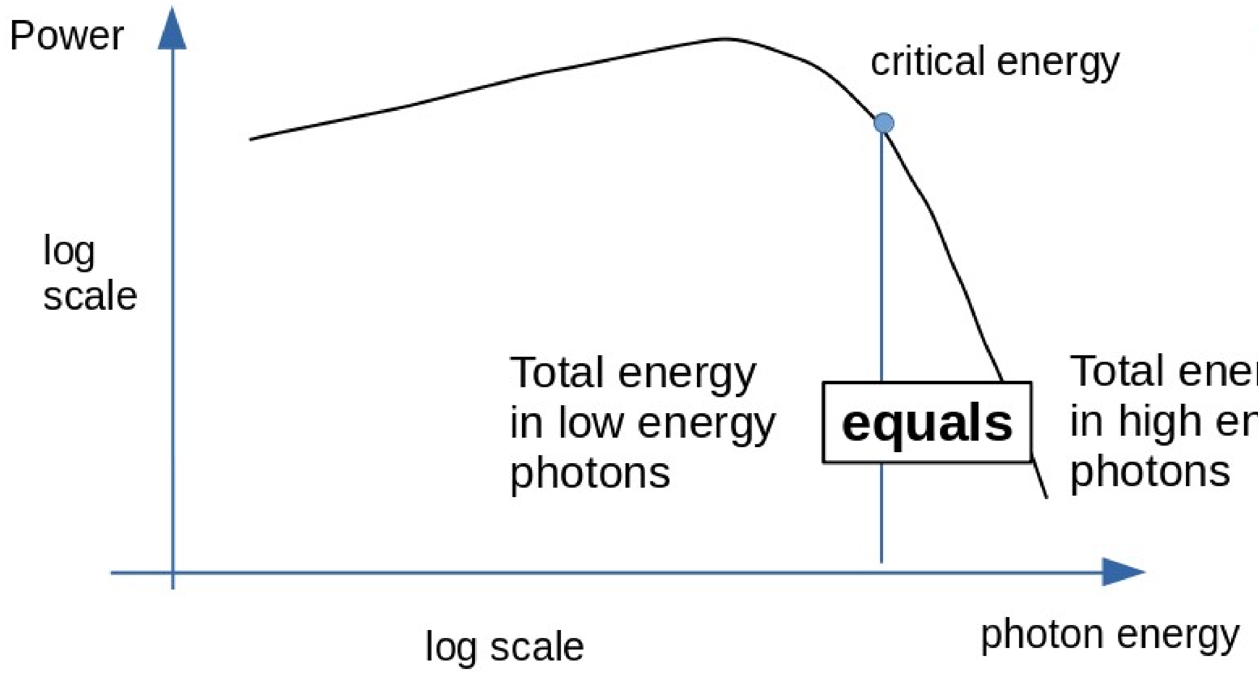
Damage by Photon Beam from ...

Bending Magnet Spectrum

$$u_c = \frac{3}{2}\frac{\hbar c}{\rho}\gamma^3$$

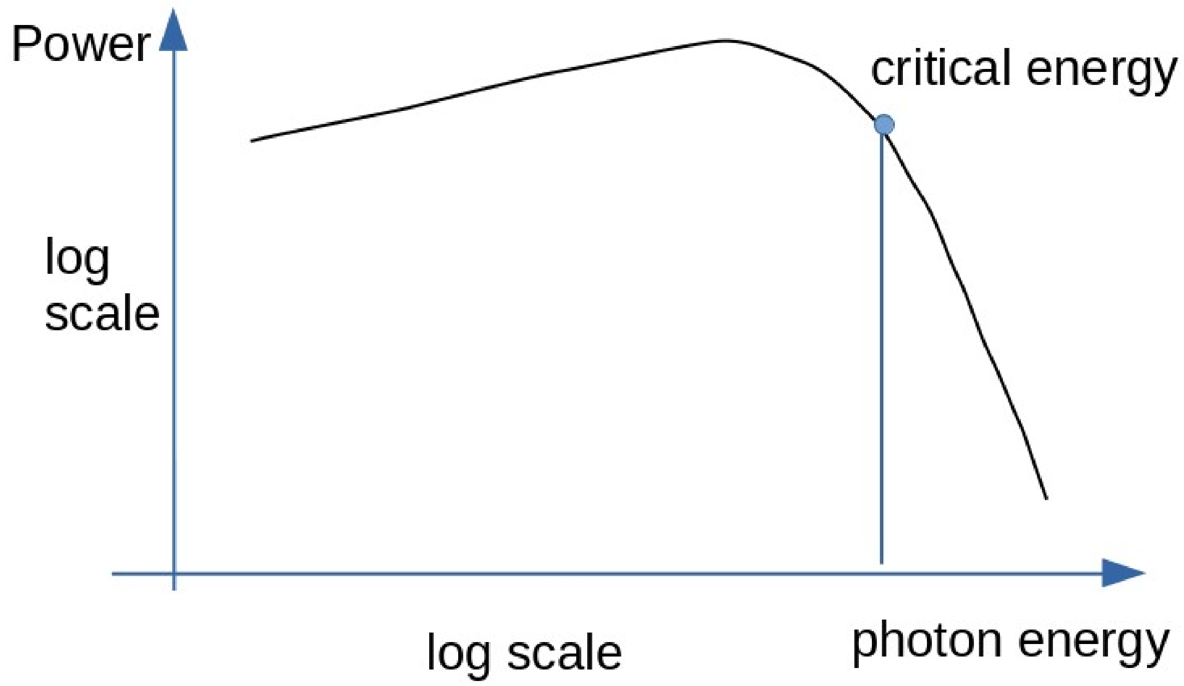
$$u_c\,[\mathrm{keV}] = 0.66\,E^2\,[\mathrm{GeV}]\,B\,[\mathrm{T}]$$

APS: 7GeV, 0.6T u_c = 20 keV, useful for research using x-rays



Damage by Photon Beam from ...

Bending Magnet Opening Angle



photons are highly directional above the critical energy. Opening angle is

$$\phi_y \approx \frac{1}{\gamma}$$

Good for making highly-collimated x-ray beams for research

APS: $1/\gamma$ = 73 μrad

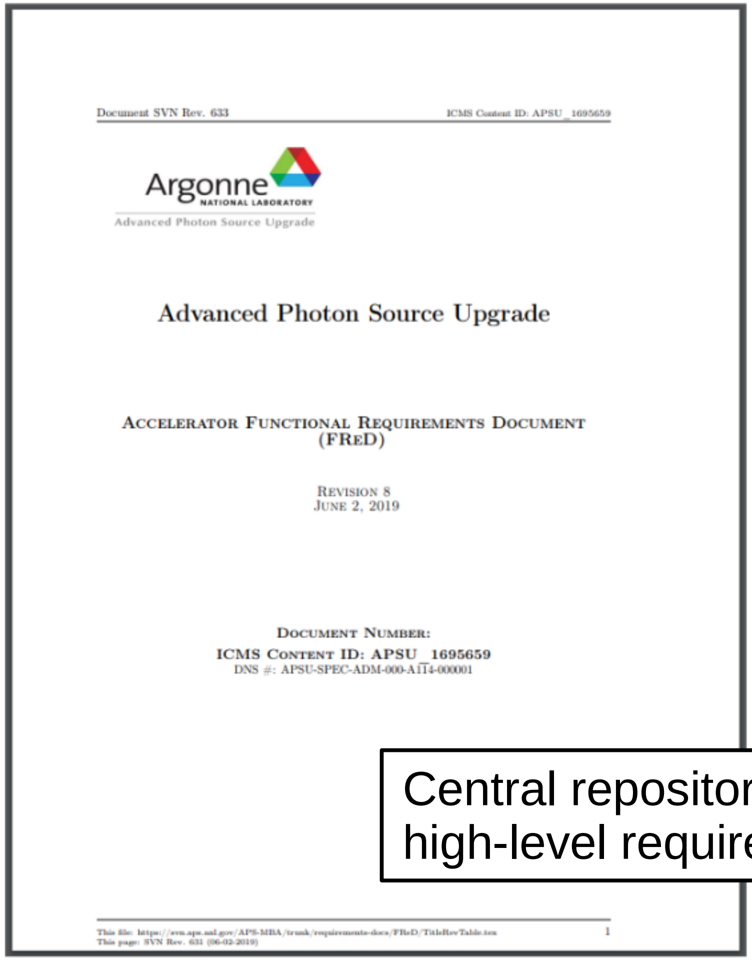
Damage by Photon Beam

- Relatively high power, with x-ray getting absorbed on surface (not bulk), with collimation in vertical plane
- Susceptible components: rf fingers (say from rf bpms assemblies), crotches where photon beam is directed outside the SR vacuum chamber
- Similarly with Insertion device (ID) beam, where additional collimation in horizontal plane
- XFELs suffer the same problem with possible errant ID radiation photon beam

Passive protection from photon beam

Design Requirements

- APS-U Accelerator FReD (Rev 8, June 2019)
  - 2.2.1 Aperture & 2.2.4 Impedance Requirements
    - Absorbers tips encroaching 22 mm ID, shape transition angles exceeding 5.7 degrees subject to accelerator physics group evaluation
    - Absorbers included in the impedance budget and modelling and are subject to approval by the beam-physics group.
      Continued dialogue with accelerator physics about absorber needs vs impedance issues
  - 2.2.3 Heat absorption and masking
    - Shadow all areas sensitive to synchrotron radiation including joints, bellows and their rf shields, BPM modules, flanges, kickers and other machine elements.
    - Absorbers shall be thermally monitored by suitable means, providing an analog value.
      Past efforts to monitor APS absorber water temperatures weren't satisfying.
      Pressure monitoring at nearby ion pumps found to be an adequate diagnostic.
  - 2.2.5 X-ray beam extraction
    - ID source: +/- 0.67 mrads vertical, +/- 1.67 mrads horizontal
    - BM source: +/- 0.40 mrads vertical, +/- 2.70 mrads horizontal
      More details on this point to come


Document SVN Rev. 633 ICMS Content ID: APSU_1695659

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Advanced Photon Source Upgrade

Advanced Photon Source Upgrade

ACCELERATOR FUNCTIONAL REQUIREMENTS DOCUMENT (FREeD)

REVISION 8
JUNE 2, 2019

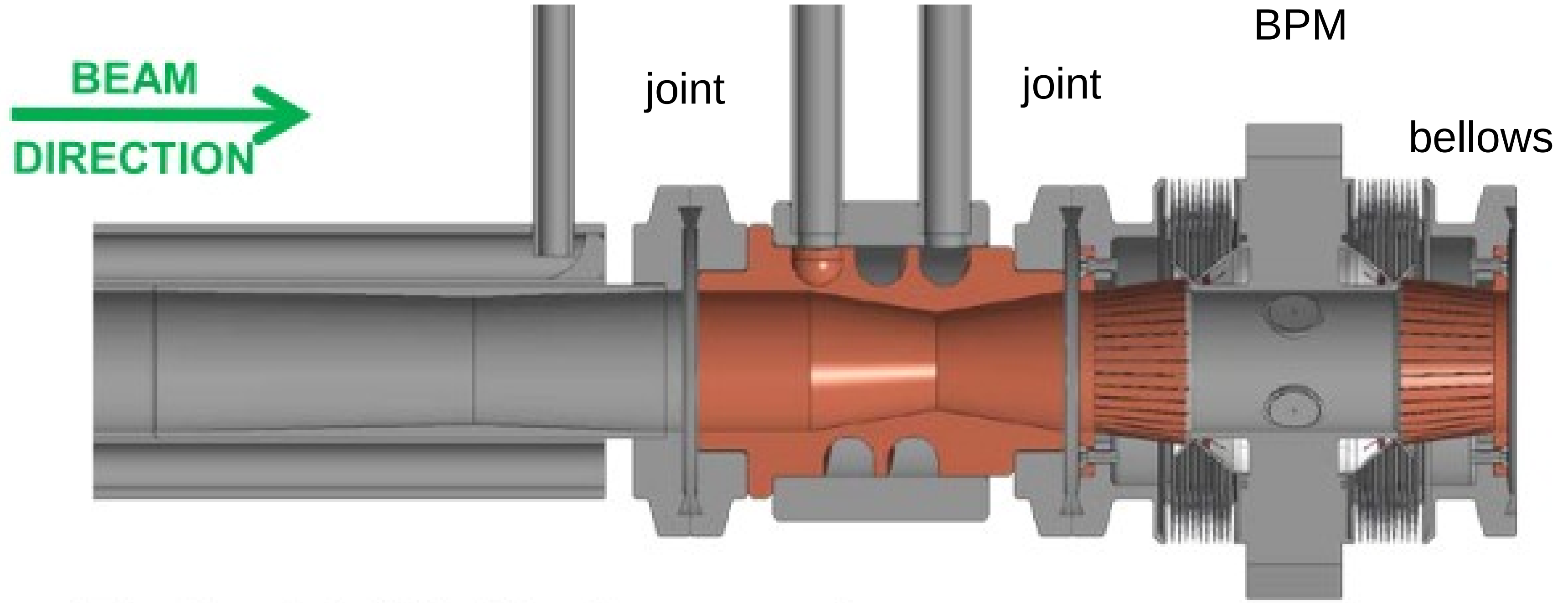
DOCUMENT NUMBER:
ICMS CONTENT ID: APSU_1695659
DNS #: APSU-SPEC-ADM-000-A114-000001

This file: https://svn.aps.anl.gov/APS-MBA/trunk/requirements-docs/FReD/TitleRevTable.tex 1
This page: SVN Rev. 631 (06-02-2019)

Central repository of high-level requirements

Argonne NATIONAL LABORATORY APS-U Storage Ring Vacuum Photon Absorbers - Final Design Review June 14, 2019 12

Passive protection from photon beam

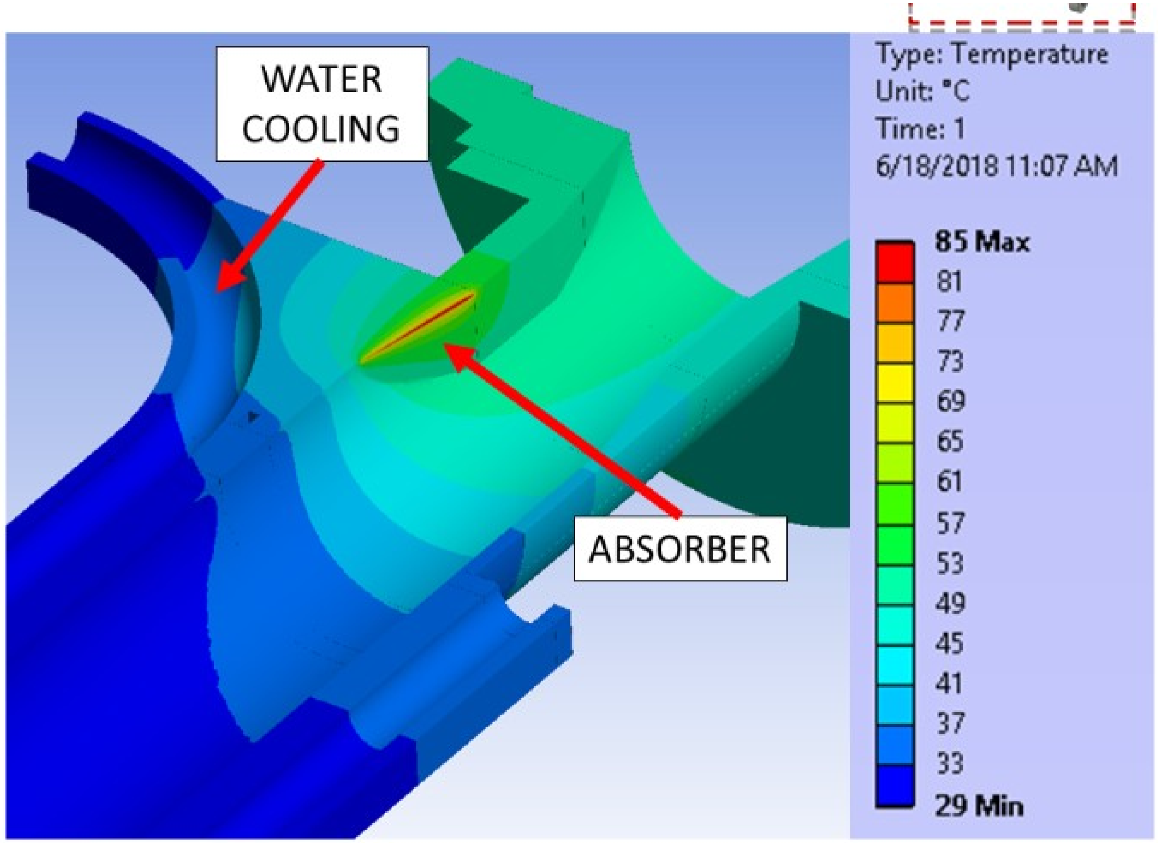


Typical APS-U storage ring vacuum sequence:
22 mm ID chamber protecting downstream flange joint,
inline absorber protecting length of downstream BPM

Passive protection from photon beam

- Absorbers for dipole fan, need to handle power expected
  - Cool all surfaces indirectly with water channels
  - Use thermally conductive alloys
  - 3D engineering codes for equilibrium temperature estimate
  - Designed for beam with only a little misteering
  - Balance need of intrusion with need to reduce impedance (instabilities)
- Absorbers for Insertion device (ID) beam, in photon beamline much further distance and glancing angles
  - No absorber in storage ring because the intensity is too high

Chamber upstream of bpm with rf fingers to protect



Typical ANSYS thermal analysis of water-cooled APS-U chamber with inline absorber

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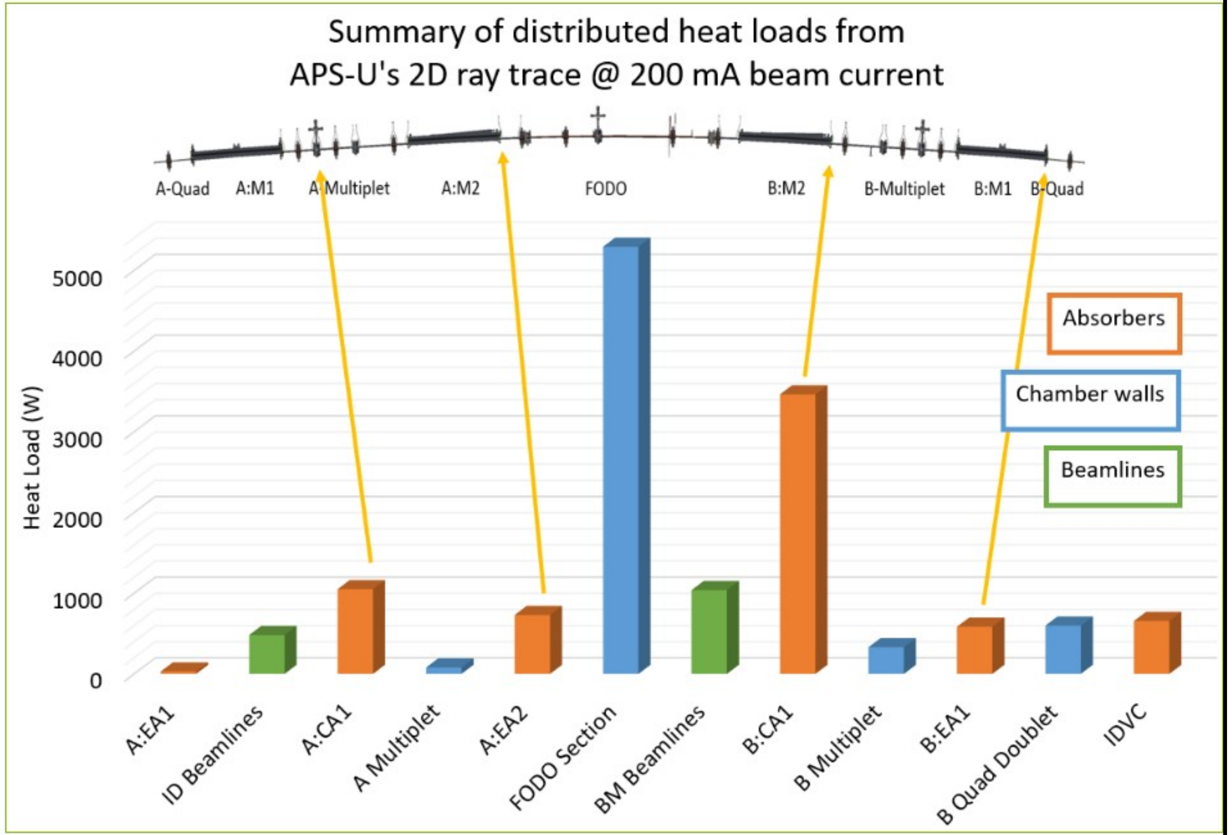
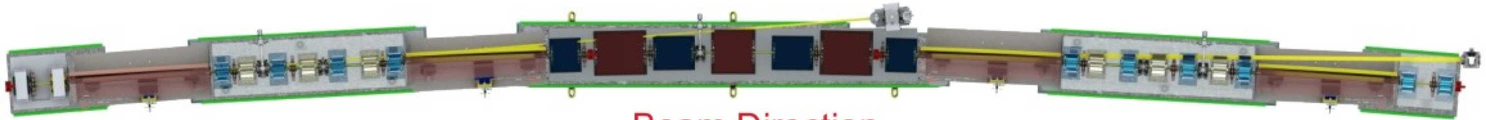
Passive protection from photon beam

Summary of APS-U storage ring ray tracing

- 2D Ray Tracing for APS-U
  - Rays strike 20 separate vacuum components per sector and breakdown requires a complex 2D CAD layout
  - 14.3 kW generated per sector @ 200 mA
    - 5.3 kW on FODO section chambers
    - 3.5 kW on B-side crotch absorber
    - 600 W in B Quad Doublet
- Ray tracing compared and verified using 3 separate tools:
  - 2D CAD layout
  - SynRad, CERN's 3D ray tracing code
  - New 3D MatLab program for studying beam missteering



Summary of APS-U's 2D ray trace



Beam Direction

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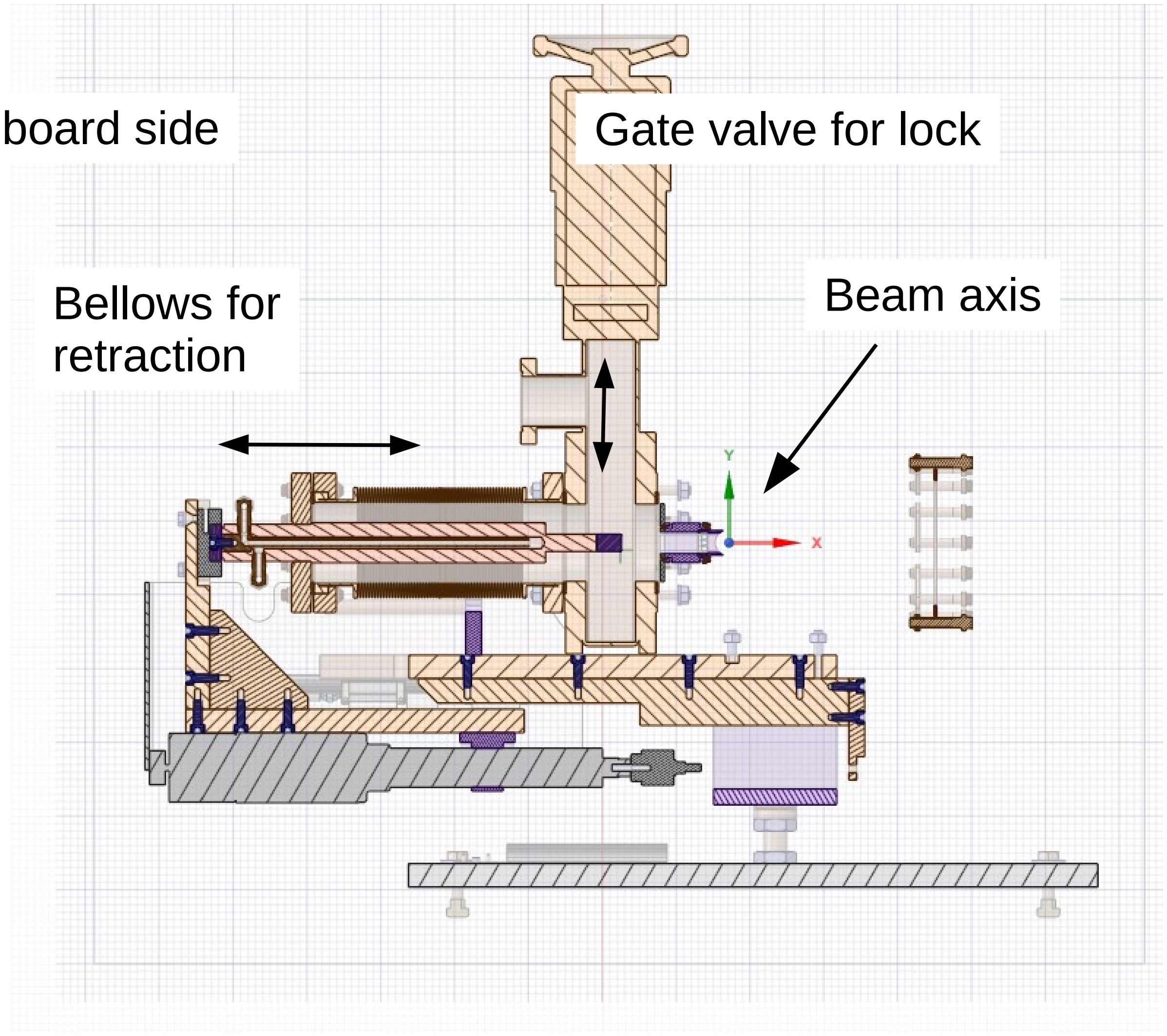
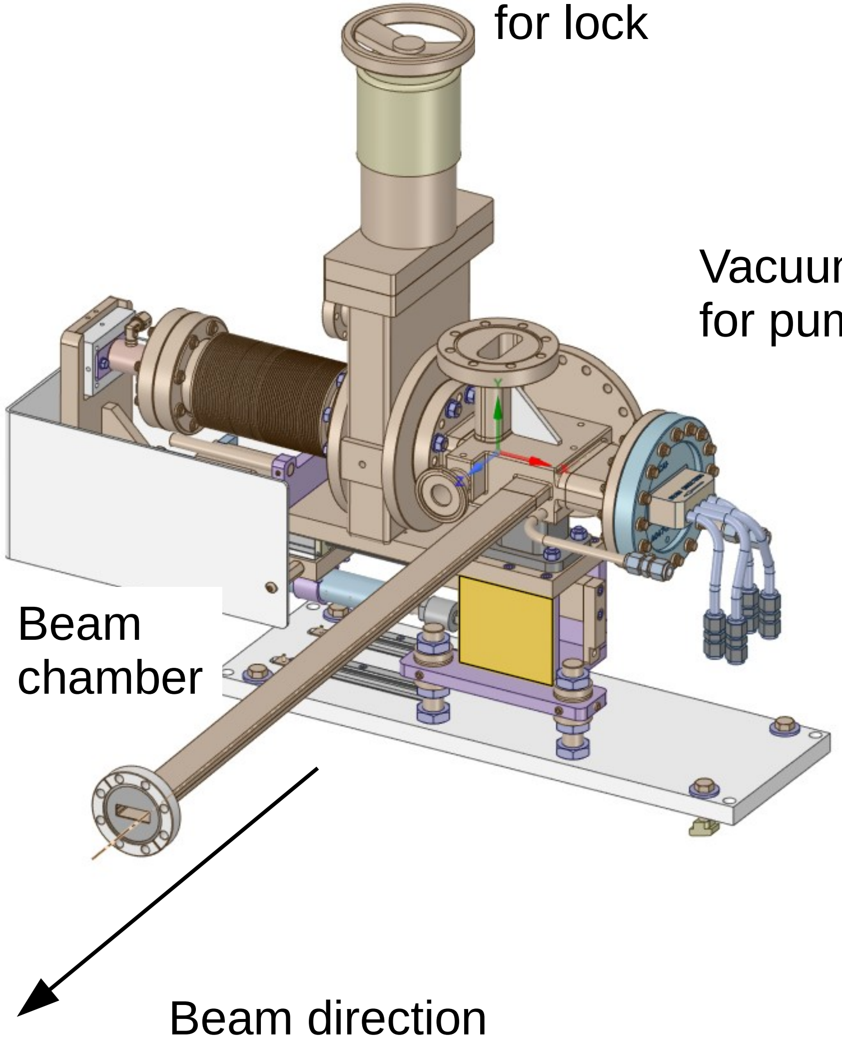
Passive protection from electron beam

- Touschek scattered particle can be mostly absorbed by collimators (say 80%)
- Vertical collimators at two locations inside dipole magnet
  - Two sided, fixed aperture of 4. 6 mm, optimized through particle tracking
  - One is modified to make a horizontal swap-out dump
- Horizontal collimators at dispersion locations in 5 sectors
  - To protect the following sectors of insertion devices
  - Number and locations optimized through tracking and robust against beam misalignments. Adjustable aperture.
  - Only one-sided because of synchrotron radiation.
  - Don’t have secondary collimators
  - These also serve as whole beam dumps. Thus replaceable target.

Horizontal collimator assembly with lock for replacing "target" during maintenance





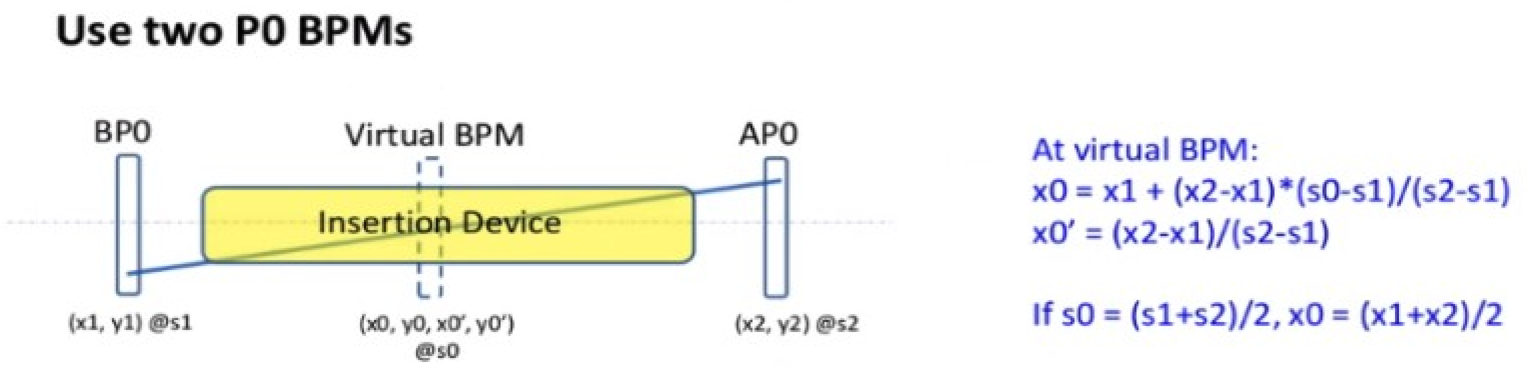
Pause

Active protection from photon beam

- Orbit Interlock at ID source points to protect against errant photon beam
  - electron positions near the source indicate the coordinates (position and angle) of the photon beam anywhere downstream
  - Global orbit feedback is suppose to prevent this, but it may have failed in some way
  - To prevent immediate melting on surface of VC or absorbers, command a fast beam abort (removal of whole beam) at some intermediate value of coordinates
  - Don’t use temperature sensors since they react too slowly
- Orbit interlock at BM source points and for general locations to reduce thermal load on absorbers (the passive protection) and to prevent water boiling in cooling channels
  - Only electron beam positions are used (no angles)

Define limits of source coordinates using nearby bpm turn-by-turn readings

Definition: Phase space is the (x,x') "coordinate system" use in beam optics. May be generalized to include (y,y') and energy and time.

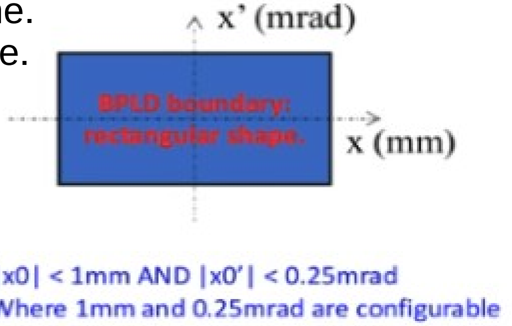


Position x
Angle x'

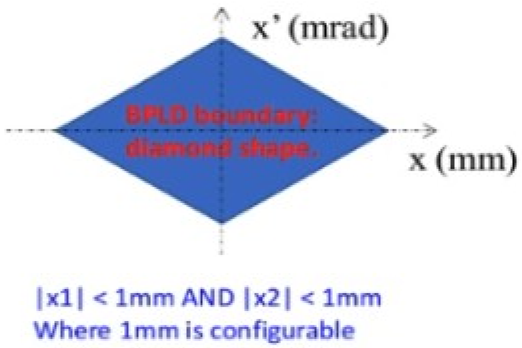
Definition: together x and x' are source coordinates

(x,x') used for H plane.
(y,y') used for V plane.

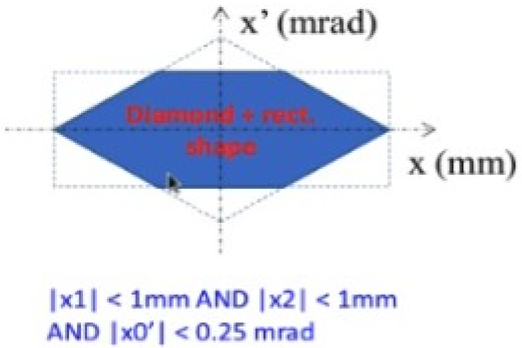
Rectangular boundary



Diamond boundary



Combined boundary

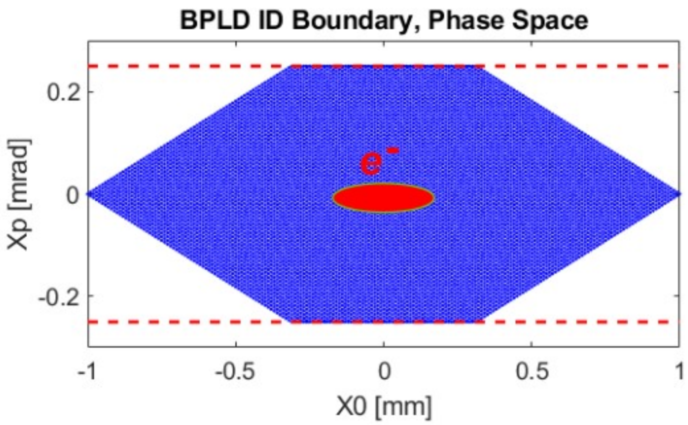


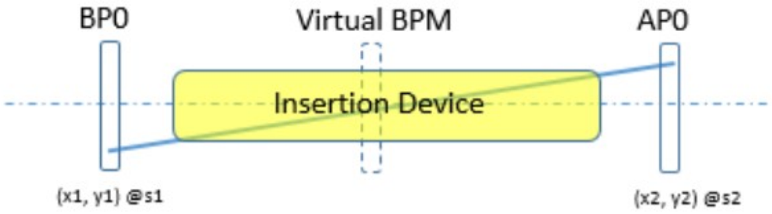
Note: x and x' represents both horizontal and vertical plane phase space

MPS local orbit interlock specification

Local BPLD/MPS Functions

- **BPLD - ID protection**
  - Over 2 mA and ID gap closed
  - Position/angle boundaries in phase space
  - Use two P0 BPMs, P1 BPMs as backup
  - Threshold current and boundaries configurable
- **BPLD - BM protection**
  - Over 25 mA
  - Position limits +/- 1.25 mm
  - Disable faulty BPMs
  - Threshold current and position limits configurable
- **Local MPS fault detection (see next slide)**
- **LB+ to Local Aurora communication**
  - 7 LB+ links; 6.25 Gbps; LB+ specified packet structure
- **Local to Main Aurora communication link**
  - 1 link; 3.125 Gbps; Custom packet structure





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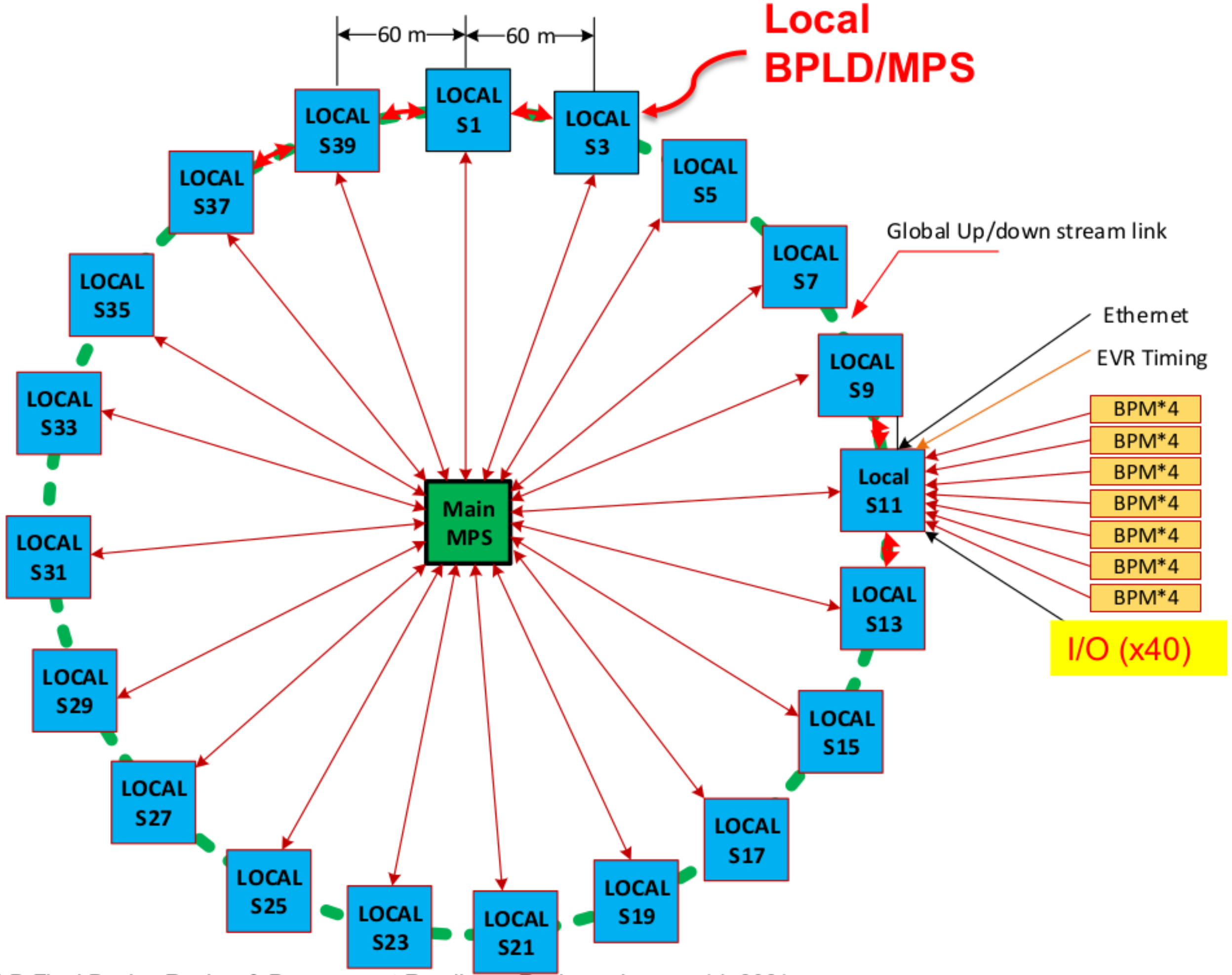
APS-U Storage Ring MPS/BPLD Final Design Review & Procurement Readiness Review - January 14, 2021

Pause

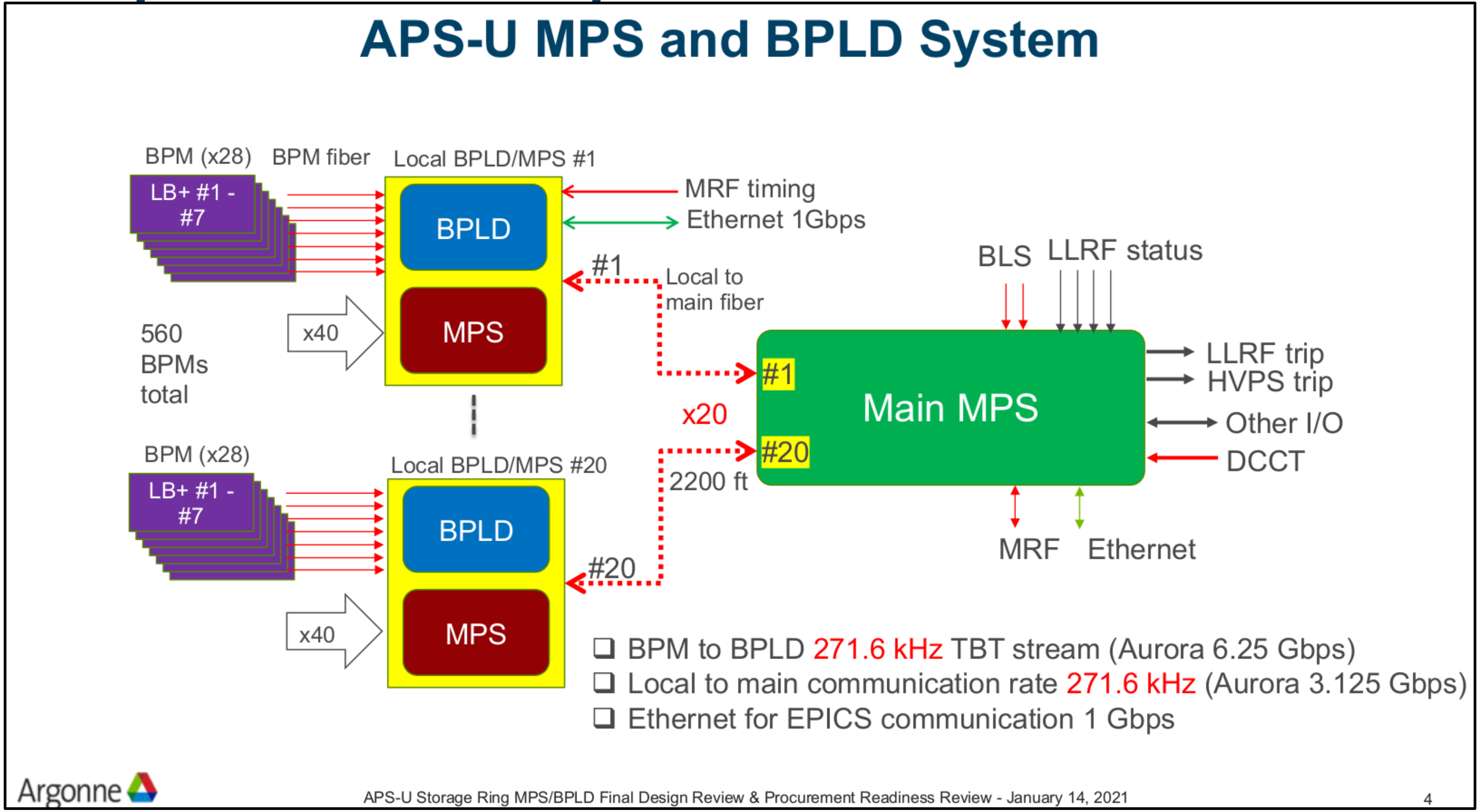
MPS topology

APS-U MPS and BPLD System

- Star connection topology
  - One main node (MPS)
  - 20 local nodes (MPS + BPLD)
  - Star topology and global bi-directional daisy-chain topology
- Local node
  - 28 BPMs per local node
  - 40 I/O for monitoring
  - EVR
- Main node
  - 30 I/O, DCCT, EVR etc.
- Fiber optics communication between main and local

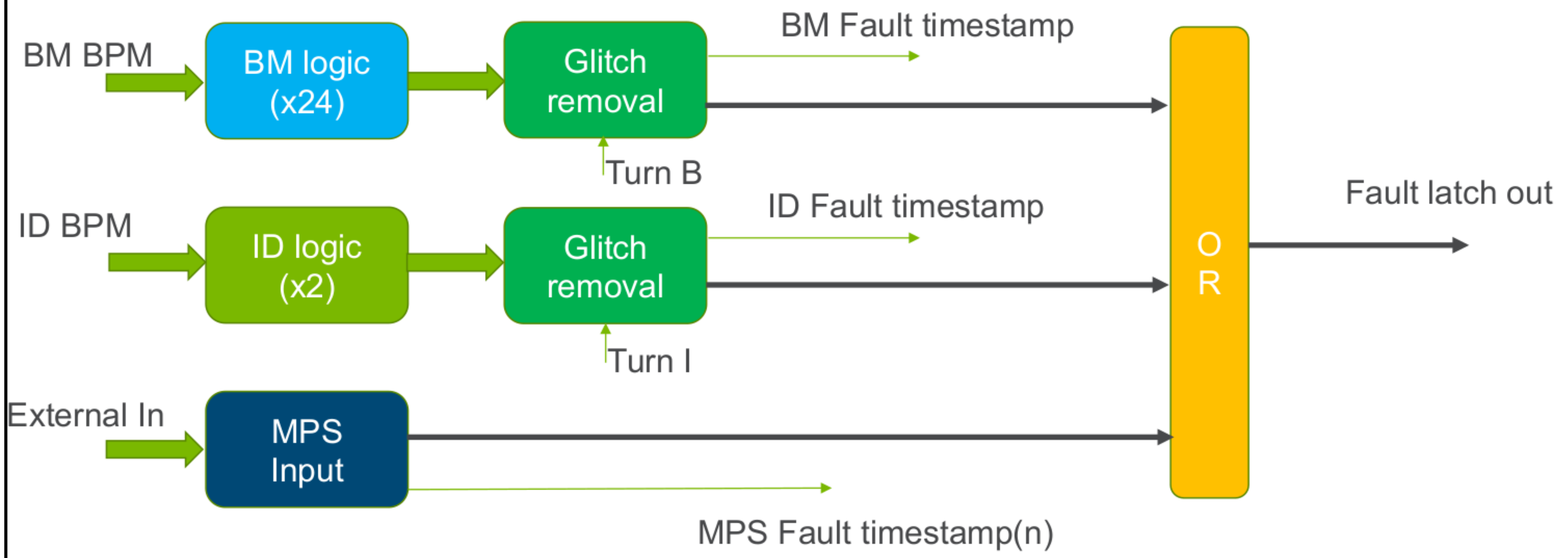


Active protection from photon beam



Active protection from photon beam

Local MPS/BPLD fault detection



- Fault condition with glitch removal: Beam out of boundary for more than B consecutive turns for BM (or I consecutive turns for ID)

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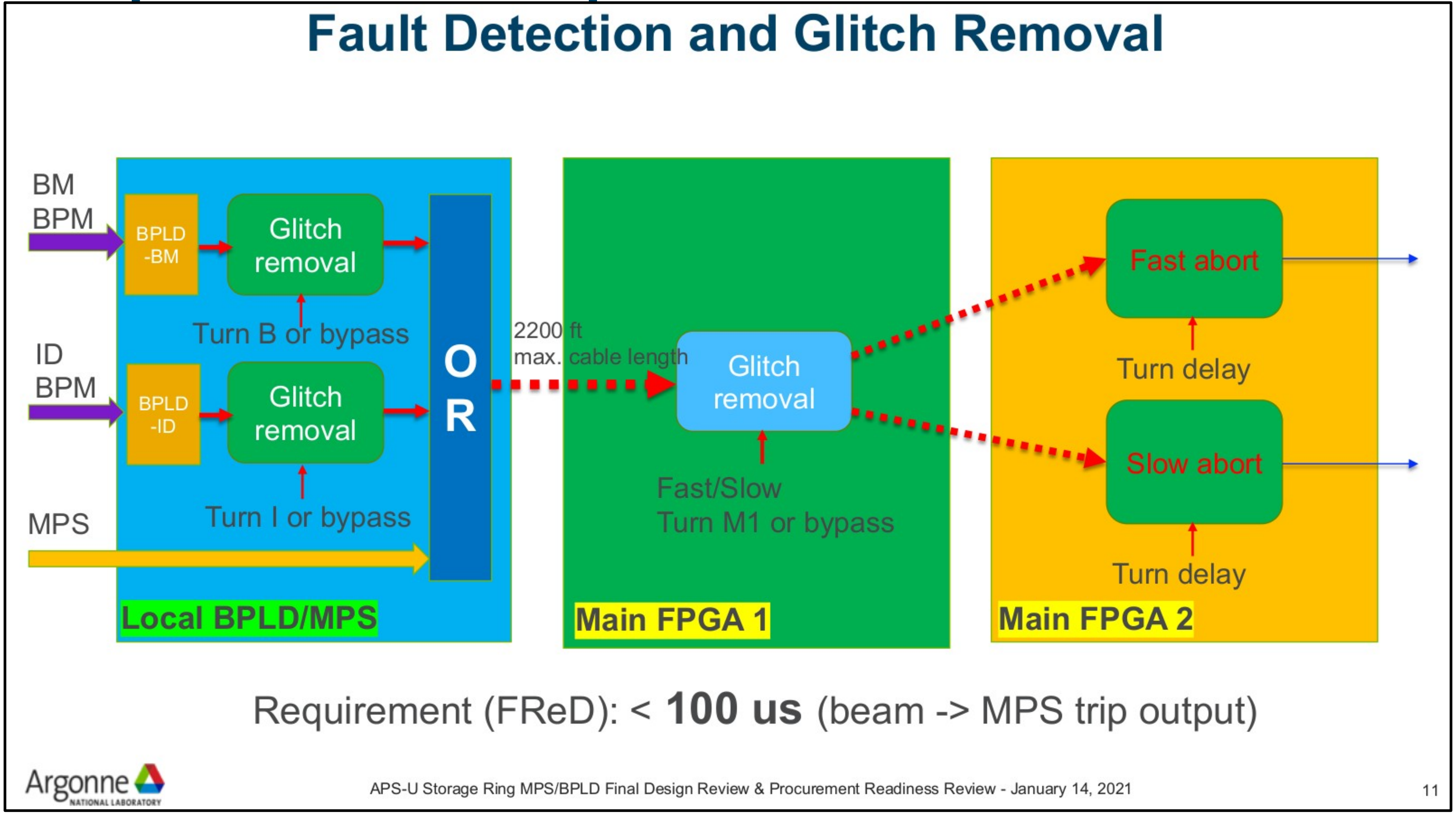
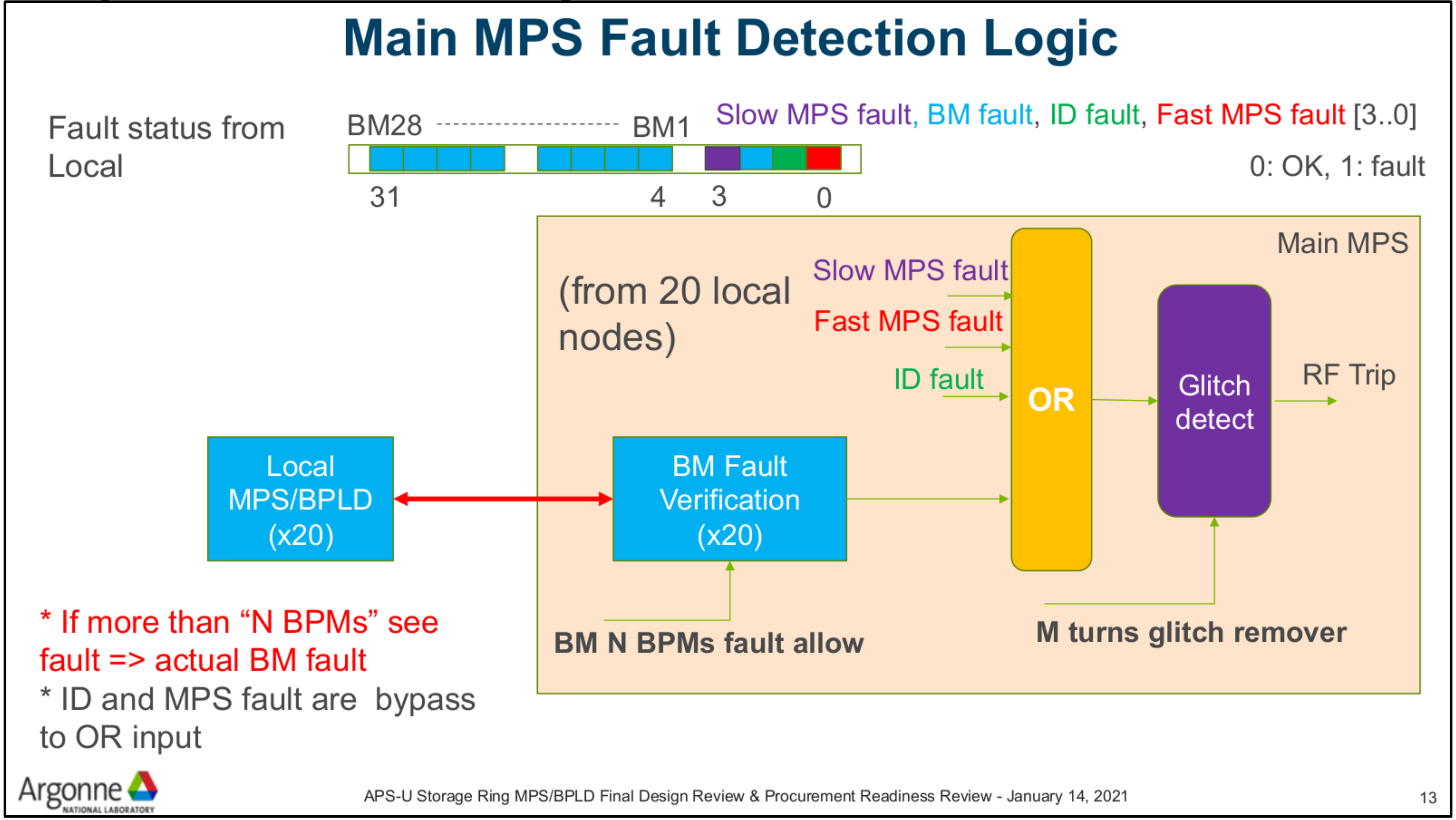
Active protection from photon beam



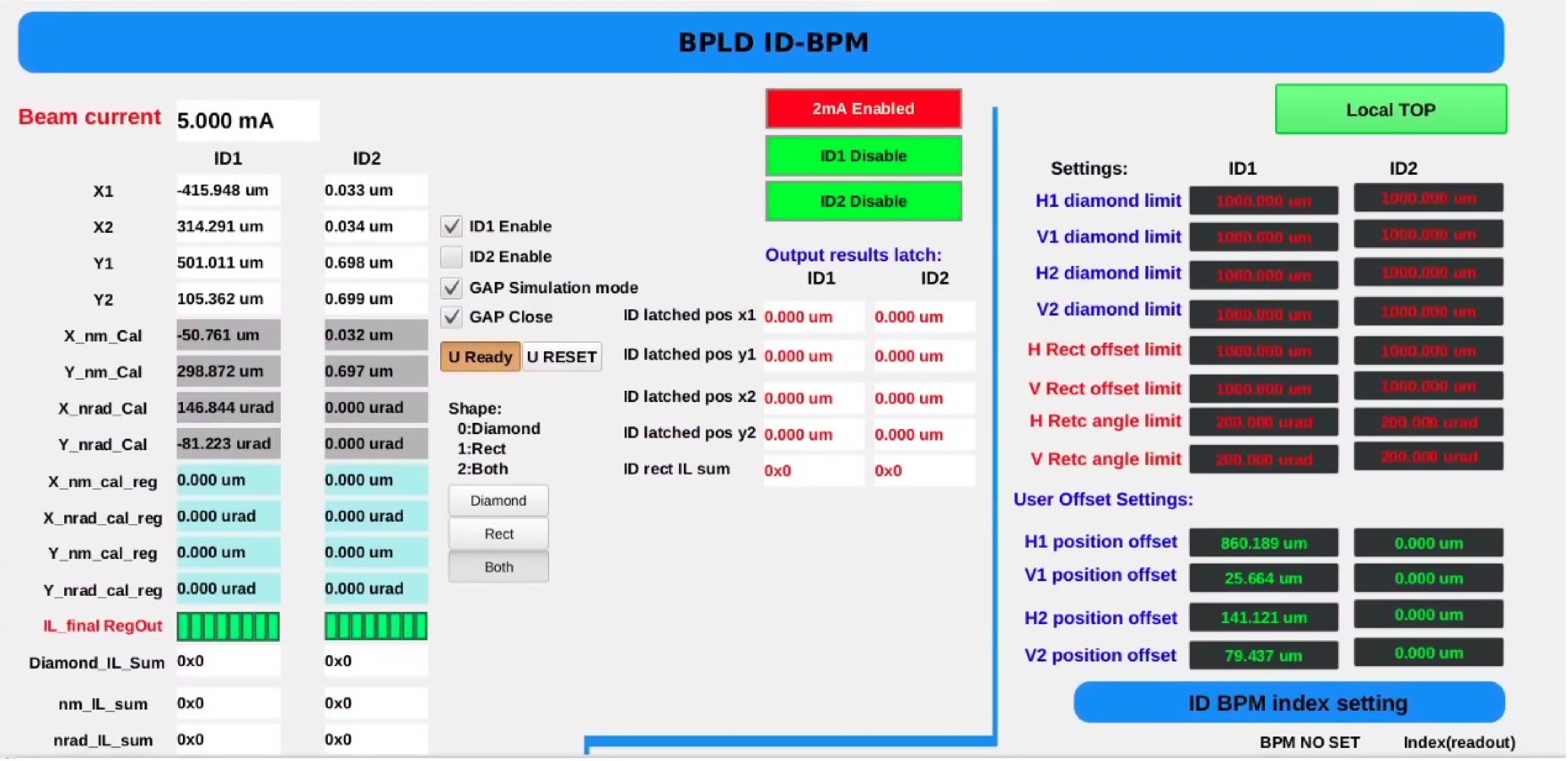
Active protection from photon beam



Pause

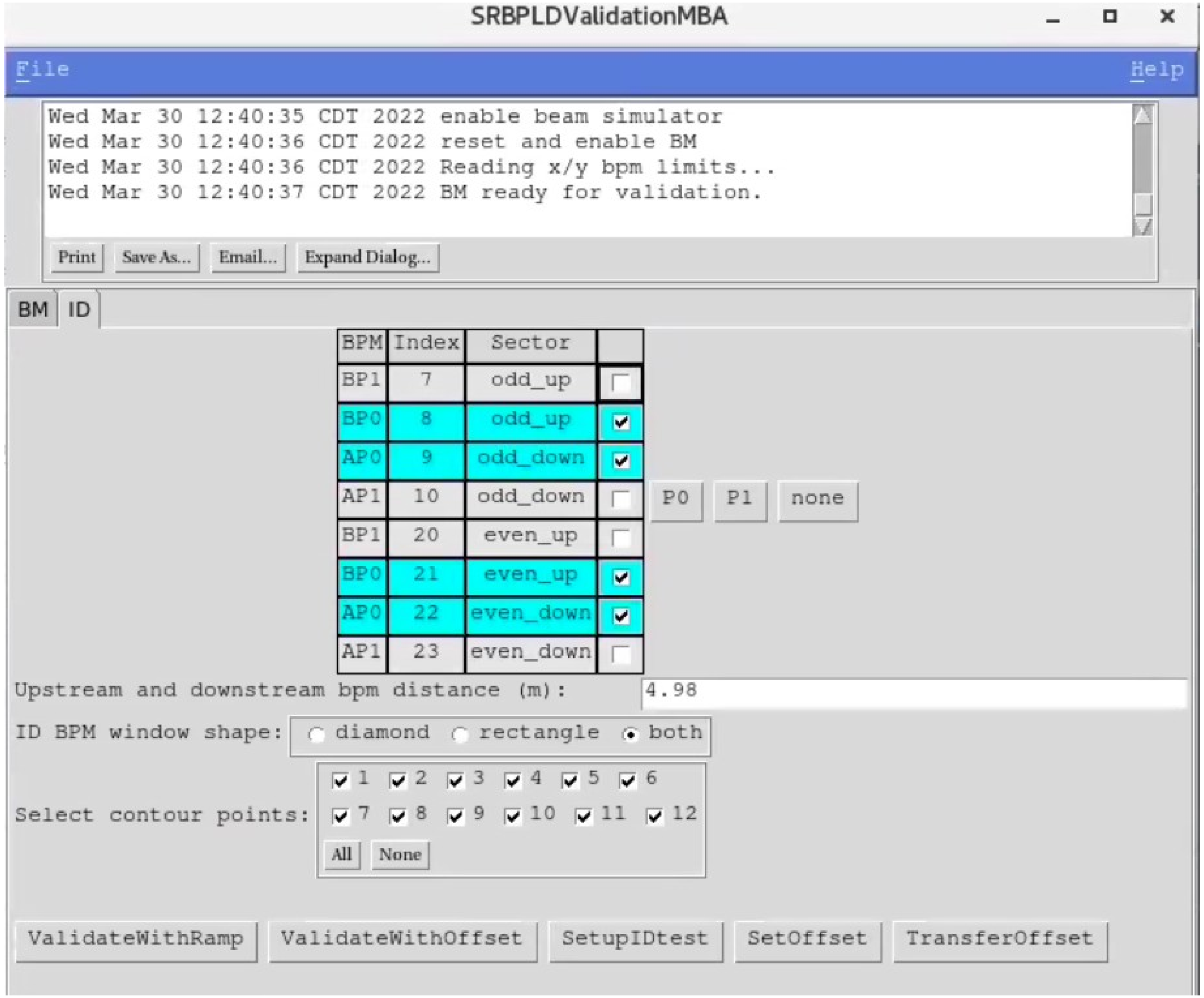
Orbit Interlock (for two sectors) configuration parameters

CSS interface. Sampled bpm readbacks, boundary limits, offsets

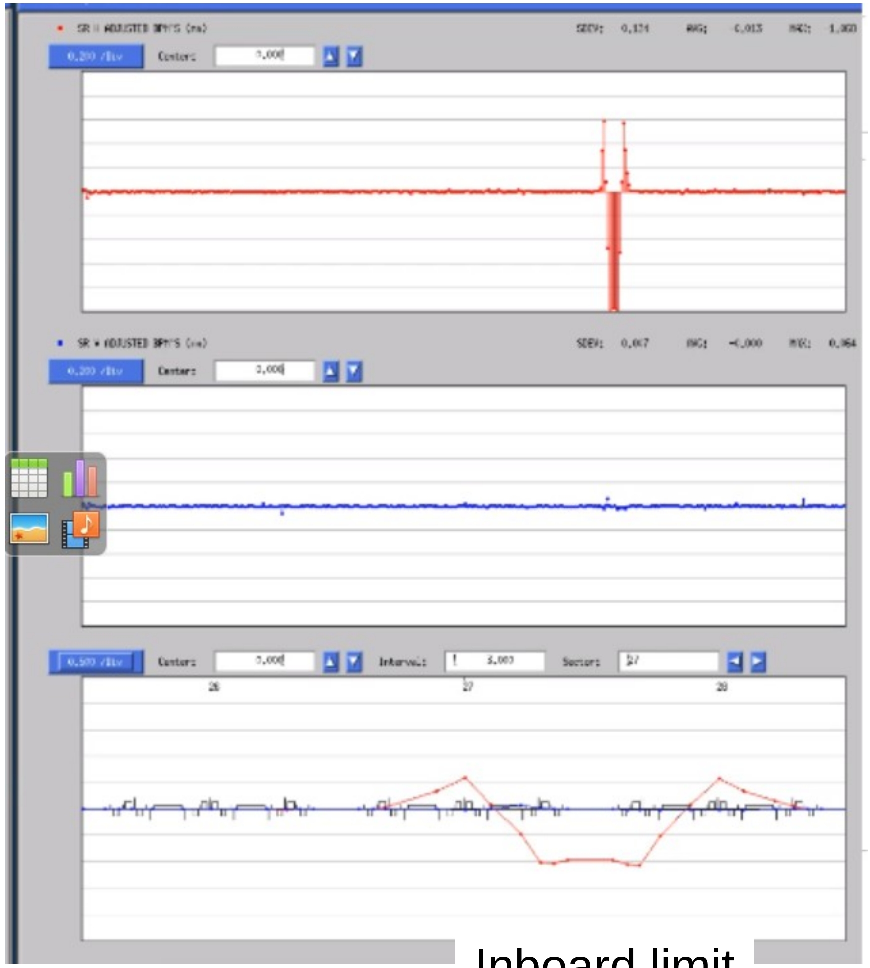


Orbit Interlock (BPLD) Validation GUI

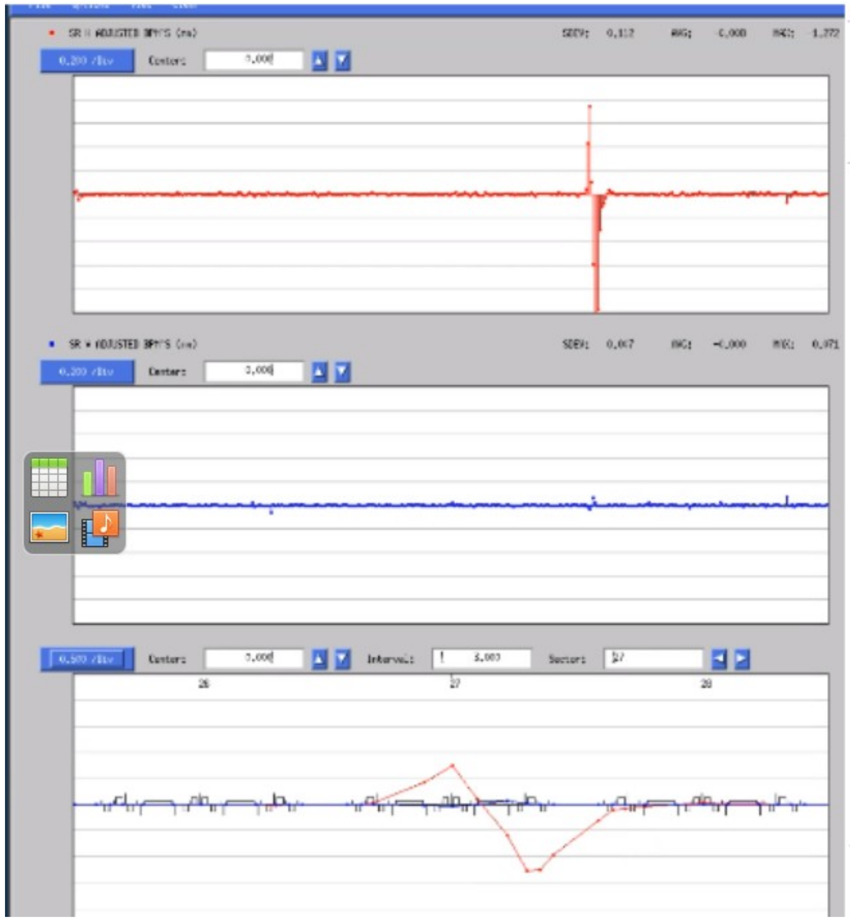
- Use global orbit correction to create local bumps which will cross the boundaries of safe phase space of source coordinates
- GUI can be written to move the beam systematically across many boundary edges, assess the status bits and give a report after finishing
- Example shows one prototype straight done at APS
- In actual upgrade all sectors (or a fraction of them) can be run in parallel.



APS-U Orbit Interlock Validation with orbit bumps on existing APS. Two cases.



Inboard limit



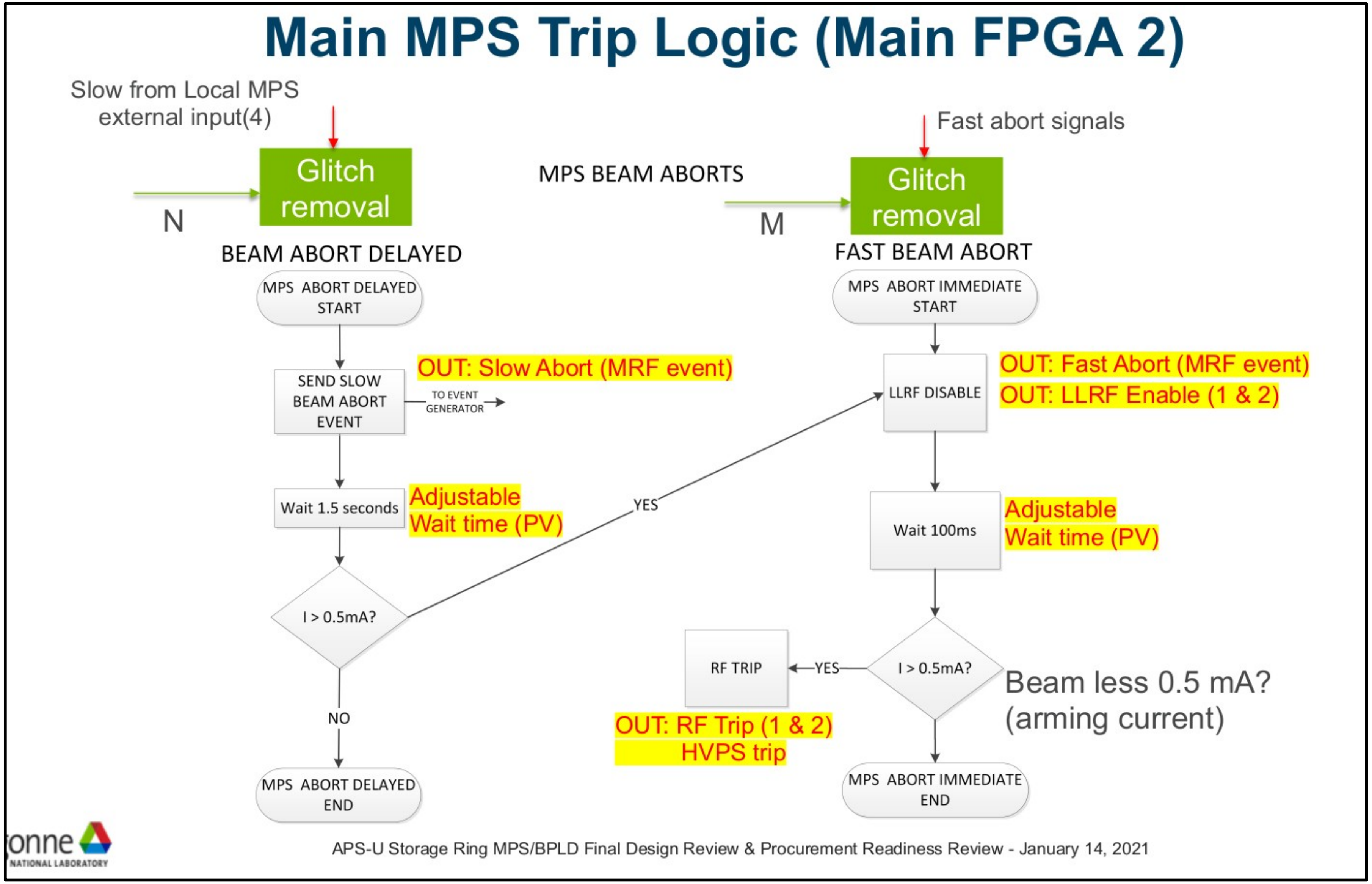
Edge of diamond limit, i.e. Coordinate x and slope

Active protection from electron beam

- Injection beam usually is safe from creating damage.
  - Large emittance (footprint), lower charge
  - Need to rationally limit losses to prevent excessive (but light) radiation dose outside the tunnel, where non-radiation worker (i.e. public) people are present.
  - ID radiation damage possible from bad injection for a long time (valuable lesson learned)
- Stored beam, after reaching equilibrium beam size, has very high density, thus beam must be prevented from hitting vacuum chamber and photon absorbers
  - Even with no photon production (ID gaps open – little B field on axis), orbit interlocks must be used to prevent a short-duration collision with vacuum chamber
  - Orbit interlock activate a spatially-controlled removal of beam
  - Obviously for beam aborts, we need to create special beam dumps into which beam is directed.

Pause

MPS: Slow and Fast Beam aborts



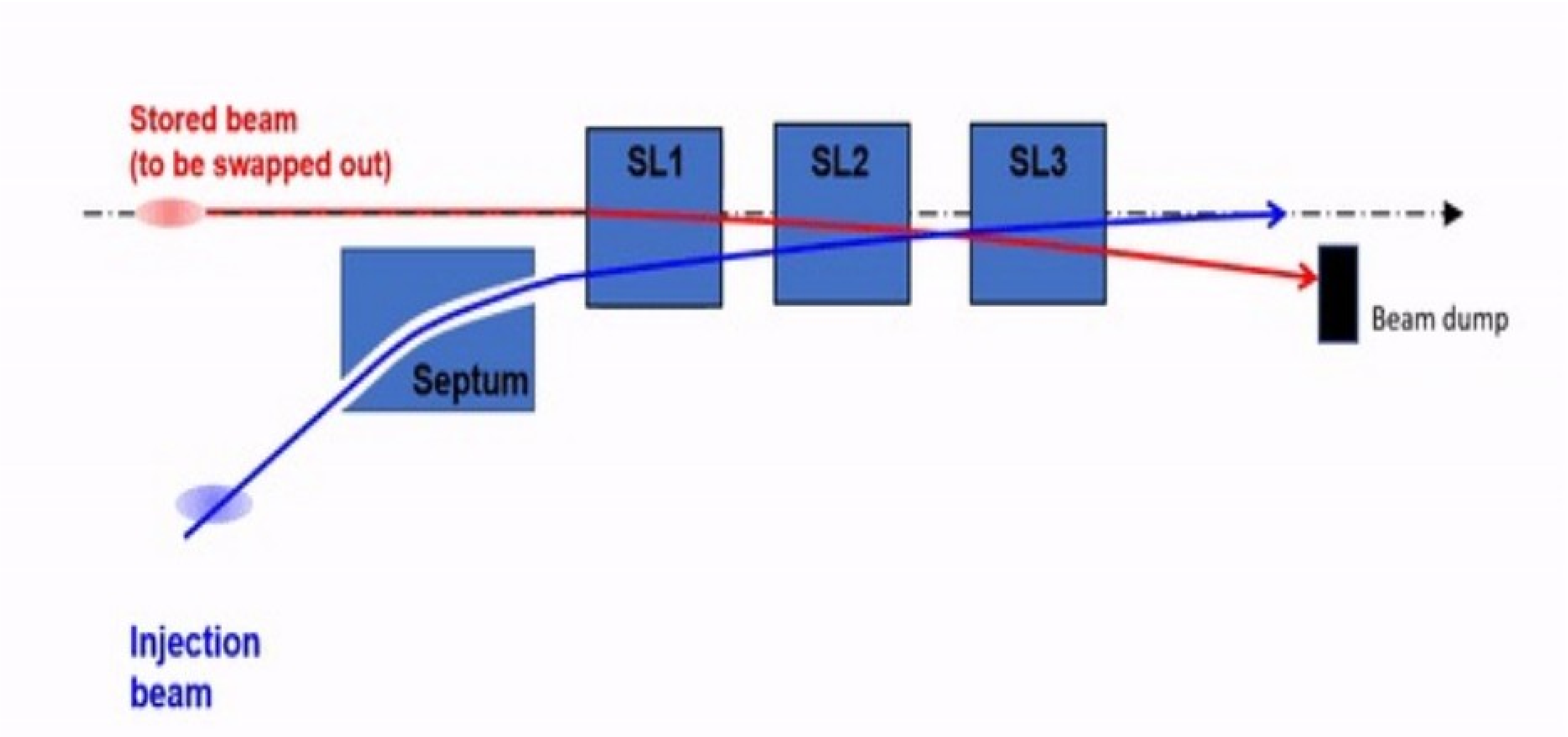
Swap out of single bunch of APS-U

- Definition: Swap-out injection is simultaneous removal of a single bunch and the injection of a new bunch
  - Can use separate kickers (for more flexibility) in different sectors or same kickers
  - APS-U uses same kickers
- Removed bunch is directed in a dump that can handle a damped, high density single bunch, “swap-out dump”
- APS-U uses horizontal kickers for injection, thus the dump is positioned inboard
- Difficult to make a dump that feeds new material, thus the dump material is meant to be permanent, and not damaged
- A decoherence vertical kicker is pulsed ~100 turns before to spread the bunch’s vertical emittance. Vertical kicker MUST be pulsed, other wise damage occurs at nominal bunch charge. Swap out is disabled within 100 turns is kicker output is not detected..

Swap out of single bunch of APS-U

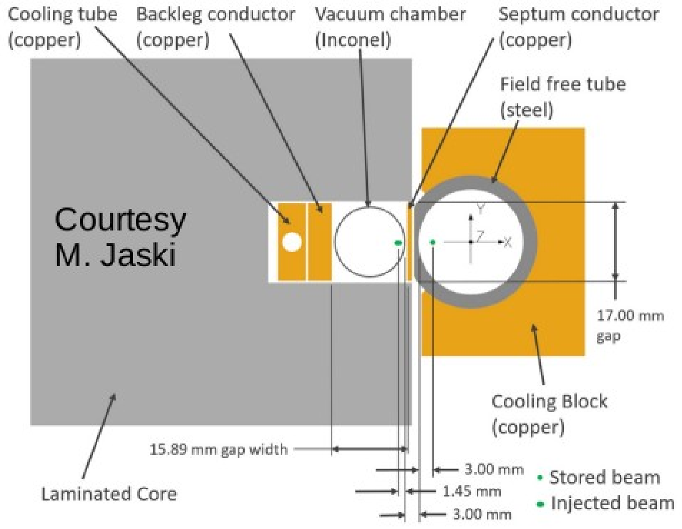
- To maintain a constant current with low lifetime, each bunch is replaced in turn by one of higher charge from the injectors
- Dynamic aperture is too small for accumulation method, plus other impedance effect causes problems with oscillating injected beam
- New normal mode of injection ?

Swap out of single bunch of APS-U



Injection scheme will have unique features

- Kickers fast enough to kick only one bunch in/out with 11-ns bunch spacing[1]
- x-y emittance exchange in transport line[2,3] reduces kicker strength requirements
- Septum bracketed by two AFG-driven leakage-field compensating magnets[4]



1: C. Yao et al., NAPAC16, 950.
2: M. Aiba et al., IPAC15, 1716
3: P. Kuske et al., IPAC16, 2028.
4: M. Borland et al., IPAC21, 245.

APS-U Beam Physics, M. Borland, 11 October 2022

Two Kinds of Beam Aborts of stored electron beam

- Definition of beam abort: remove all the bunches in some specially designed location (as opposed to just one bunch for swap-out)
- Manually or automatically commanded
- Fast (~100 usec), with RF "mute" and beam spiraling inwards from lack of energy recovery
  - Terminal location is the surface of a whole-beam dump, that may or may not suffer some minor damage, but can be replaced during shutdowns every 3 months.
  - There are 5 such whole-beam dumps (also called collimators) in consecutive sectors to ensure capture of particles.
- Slow (~1 second), bunch by bunch into (single-bunch) swap-out dump
  - we want to end the fill for reasons other that protection, or a slow thermal event that is about to happen

Two kinds of beam dumps for two kinds of beam aborts

- Thus APS-U has two beam dump designs, one for single bunch (swap-out and slow aborts), one for whole beam (fast aborts and halo collection).

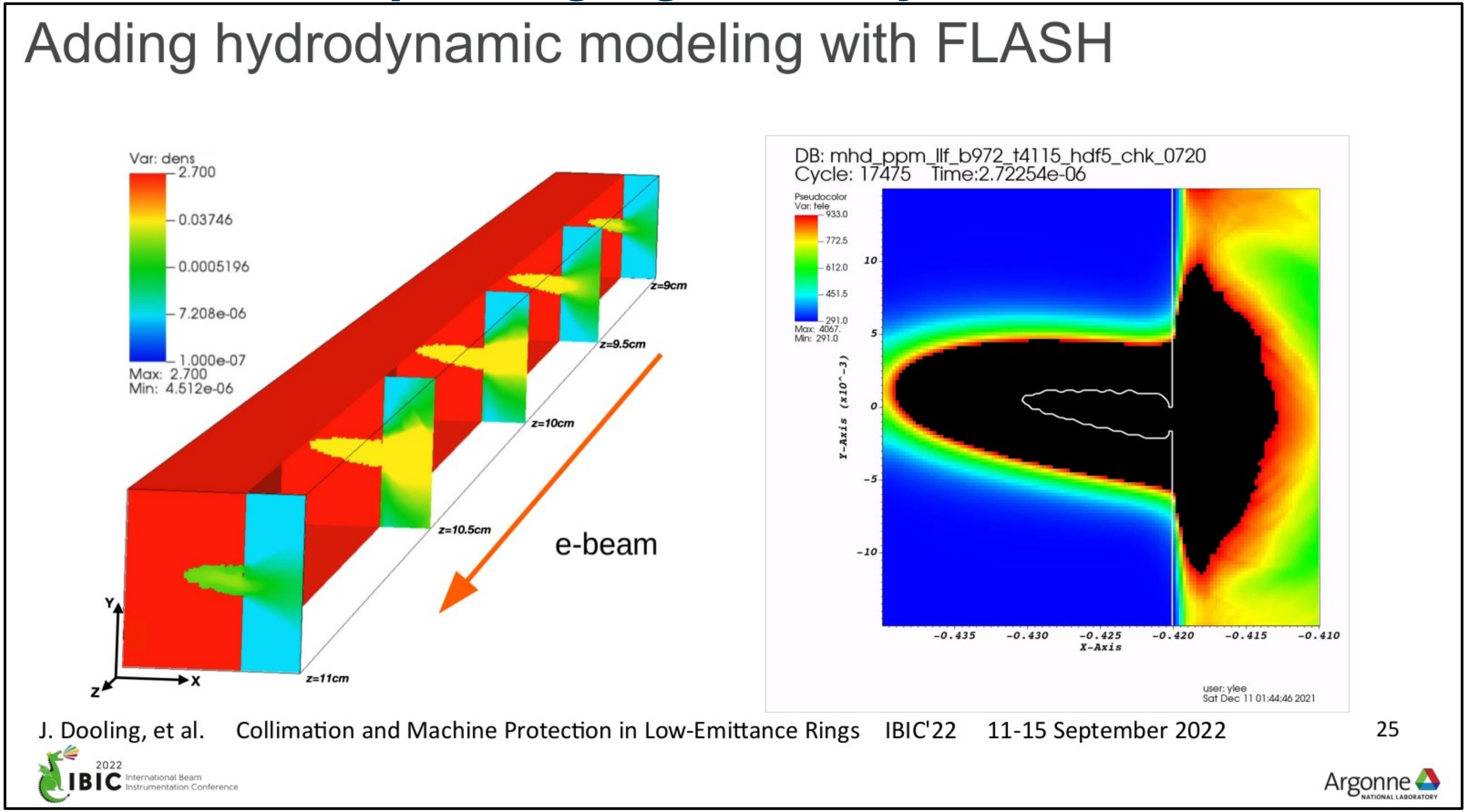
Whole beam dump

- Five locations at high dispersion
- Inserted from inside – it is also a collimator for Touschek scattered particles
- Vertical ferrite kicker with a 4 usec pulse (one turn) is used to spread the coordinates of individual bunches to increase effective footprint on dump
  - Necessary for I > 30 mA
- Each bunch still has low emittance and high density, but whole beam dump interacts each bunch over many turns, thus reducing the instantaneous temperature.
  - Temperature diffuses on a time scale shorter than revolution time.
  - Swap-out dump, on the other hand, receives charge of one bunch in one pass. Higher temperatures achieved.

Beam Dump Design

- Beams dumps need to be tolerant of high density electron beam. Where to begin?
- Simulations and Experiments guides the design for APS-U beam dumps
- Experiments at APS on collimator material Al, TiAl → Al is more tolerant

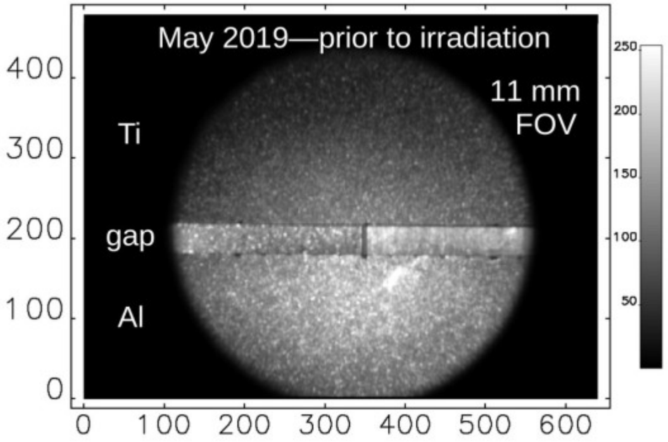
Whole beam dump design guided by simulation

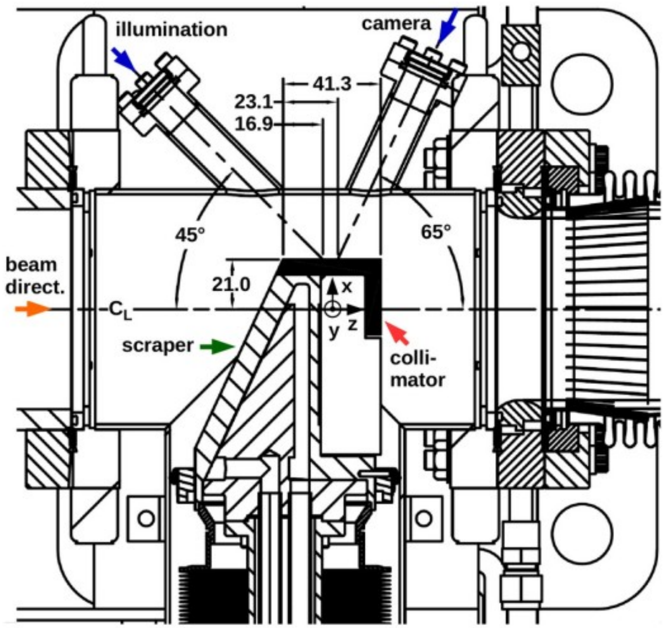


Beam dump design guided by experiments

Diagnostics

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





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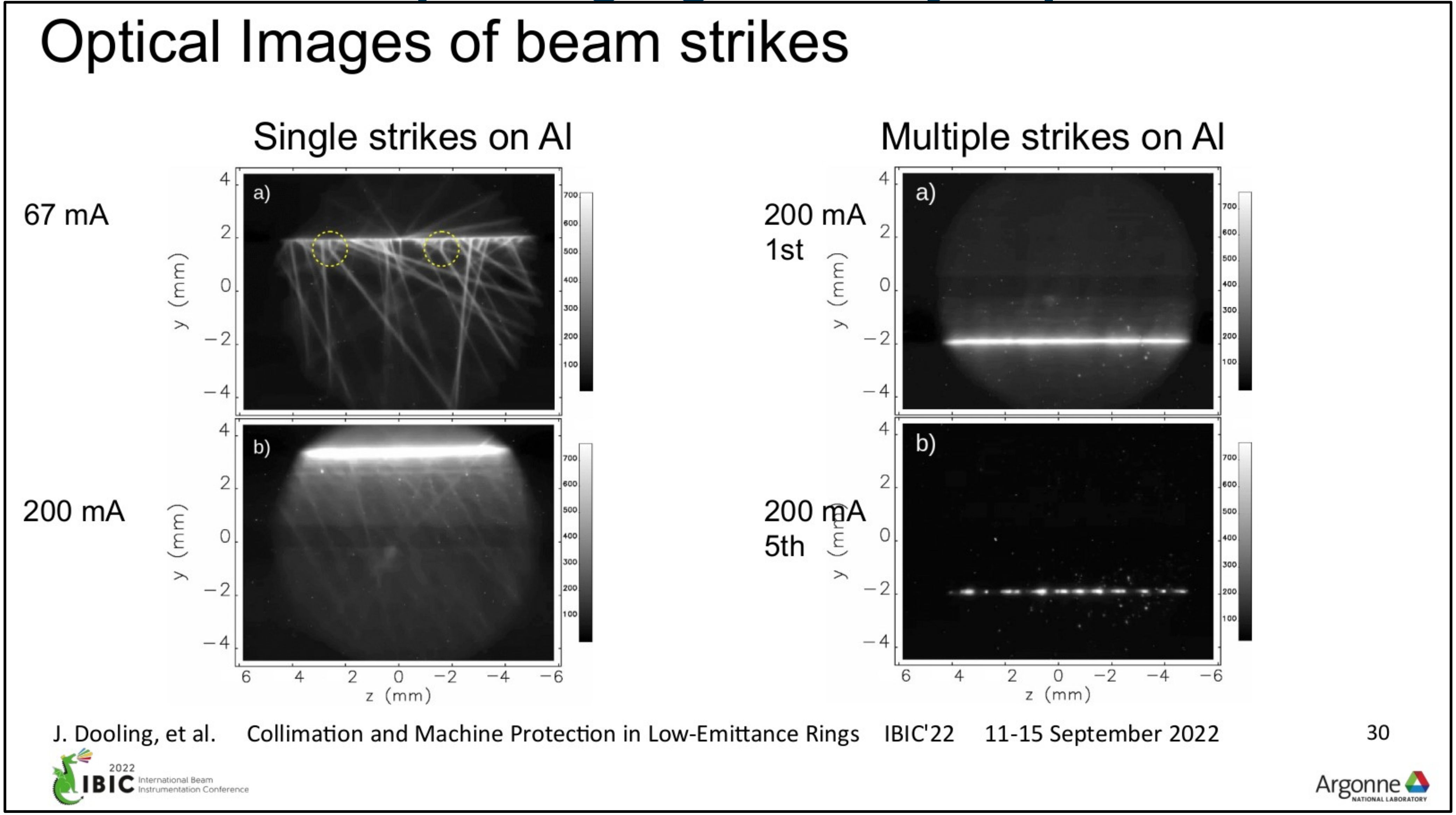
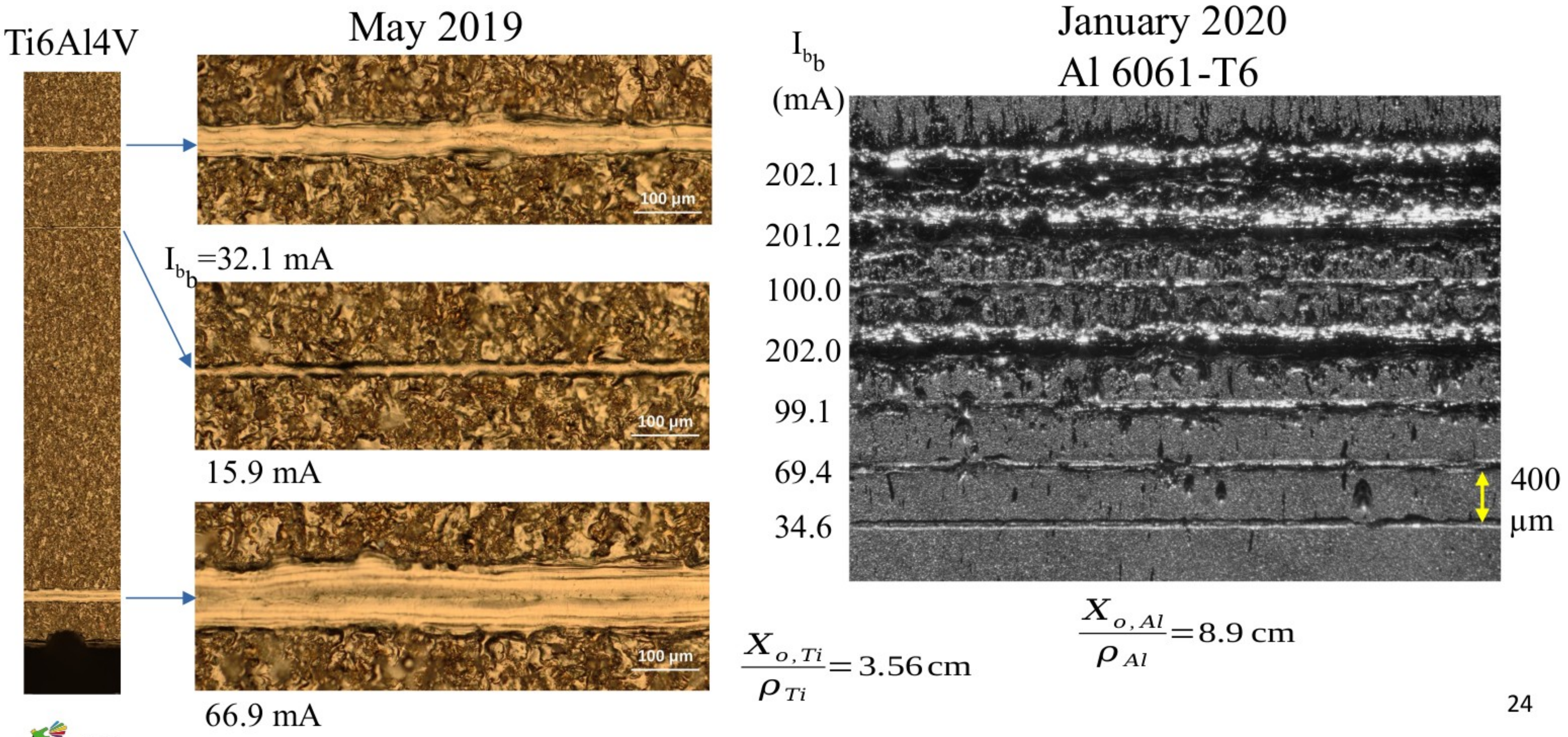
Whole beam dump design guided by experiments



Whole beam dump design guided by experiment

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



$$\frac{X_{o,Ti}}{\rho_{Ti}} = 3.56\,\text{cm} \qquad \frac{X_{o,Al}}{\rho_{Al}} = 8.9\,\text{cm}$$

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Beam losses summary

- Electrons being light particles have generally less impact than protons
- Storage rings have typically 500 nC of charge (APS operations 370 nC)
- Scattering losses to be minimized
  - Protection of permanent magnets of insertion devices
- Swap out of bunch
  - Vertical decoherence to protect swap-out beam dump
- Whole beam abort
  - Vertical bunch-by-bunch spreading to protect the beam dumps
- With typical light source equilibrium emittances the light-Z materials (e.g. Al) of the vacuum chamber are not harmed (until ultra-low emittance upgrades)
  - High-Z like Cu and W collimator were damaged (APS scraper/collimator, SSRL)
  - Low-Z material are presently used for dump (at APS this in an Al insertion device chamber. Recently we changed to injection straight section of combination Al and inconel to reduce heat-inducing showers in superconductor undulators)
- For APS-U stored (damped) single-bunch in single-pass loss is calculated to melt any material