Beam Instrumentation for Machine Protection

Tom Shea (ESS)

Material includes direct contibutions as well as portions of past presentations by many people in the accelerator community, particularly: P. Forck, M. Plum, T. Schilcher, K. Wittenburg, U. Raich, W. Blokland, C. Thomas, M. Werner, B. Cheymol, S. Lidia, J. Musson, K. Thompsen, S. Meigo, G. Decker, R. Gobin, L. Tchelidze, M. Minty, R.L. Witkover, D. Gassner

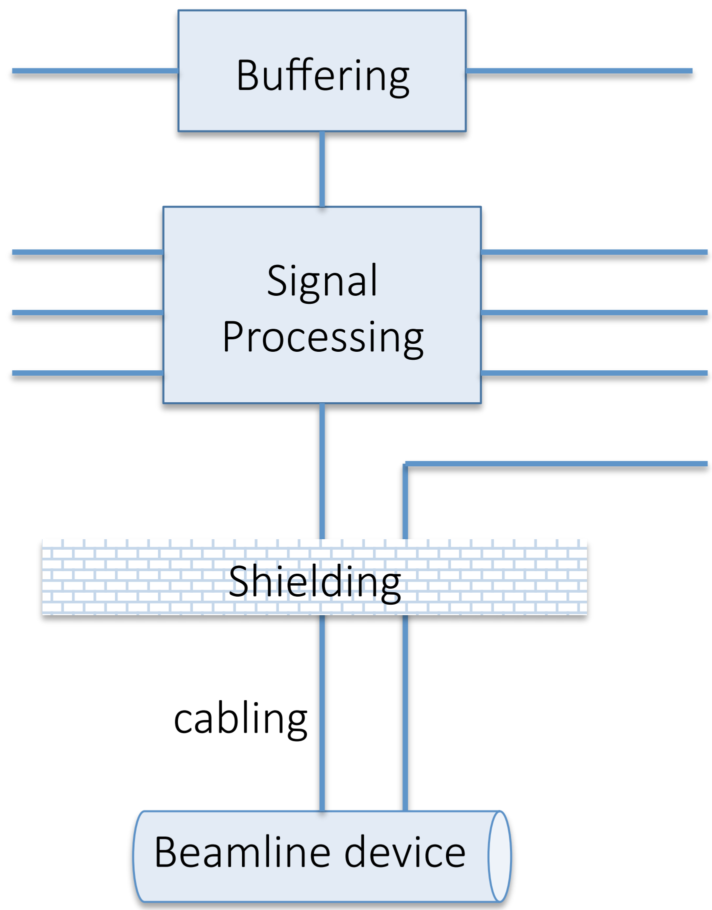
Topics

- The generic beam instrumentation system
- Where does Beam Instrumentation fit in the MPS Landscape?
- Types of beam instrumentation relevant for MPS
- A tour of some applications

Beam Instrumentation System

Accelerator Interfaces:

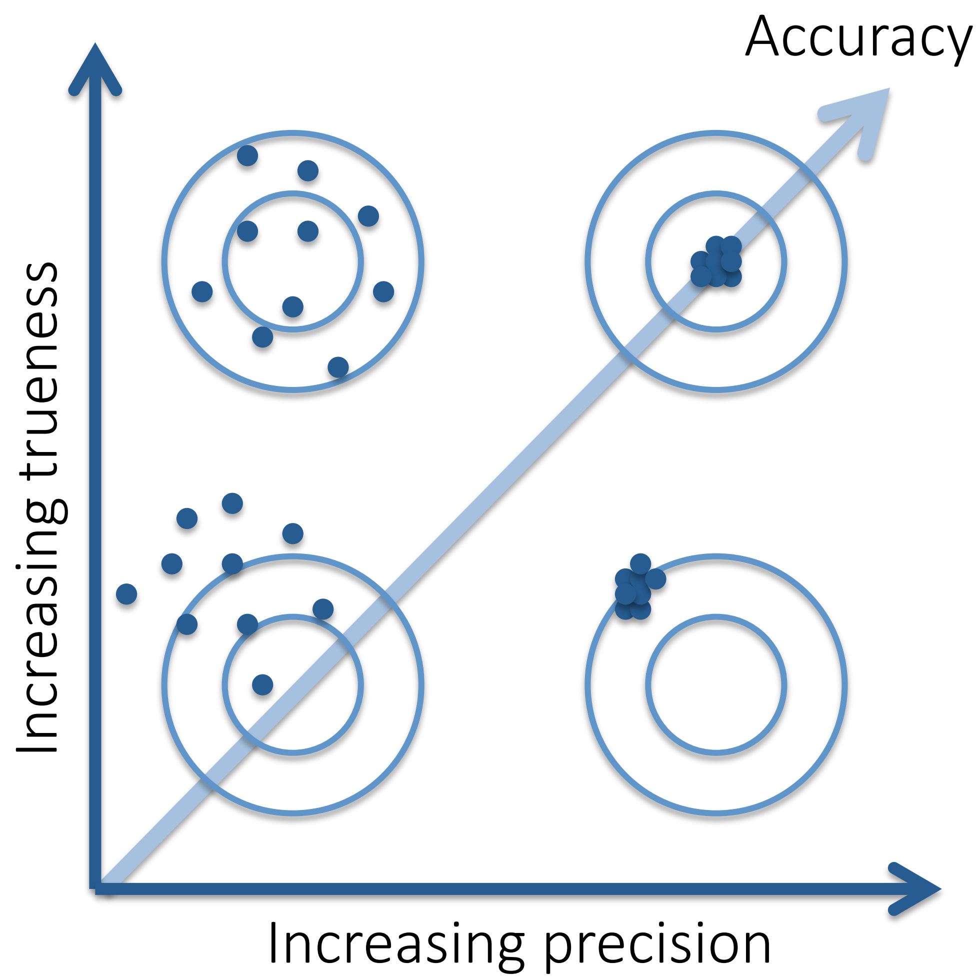
Machine Protection System Interfaces:



Functional Interfaces are shown. Some could be implemented over common physical interfaces.

Measurement Performance

- Precision, accuracy, bandwidth
- Latency between errant beam condition and interlock
- Other Functional Requirements
  - Health monitoring and self test
  - Dependence on timing system



ISO 1575

Measurement Performance Precision

Most relevant for MPS

	Repeatability	Intermediate Precision	Reproducibility
Facility	Same	Same	Different
Operator	Same	Different	Different
Equipment	Same	Could be Different	Different
Time	Short	Extended	Not Specified

Intermediate precision conditions

- Specify what is held constant and what changes
- The changes can include new calibrations, calibrators, operators, measuring systems, as well as environmental conditions like temperature, interference, ...
- For beam instrumentation, include a range for the orthogonal beam parameters (canonical list: charge per pulse, average current, position, size, ...)

ISO 1575

Where does Beam Instrumentation Fit?

Beam Instrumentation supports several activities:

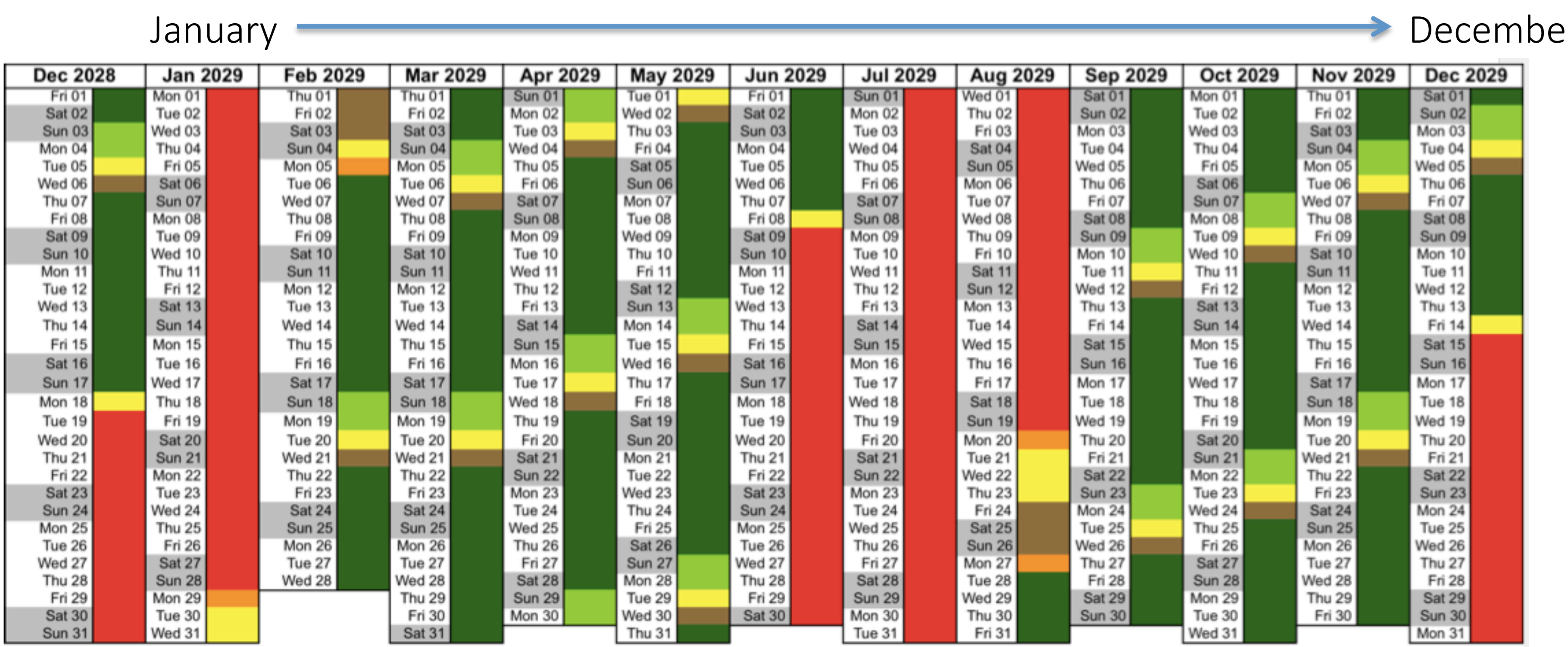
- Configuration
- Tuning and Setup
- Verification
- Qualification
- Performance ramp
- Nominal operation
- Errant conditions

Philosophy for all activities: as protected as reasonably achievable (APARA??)

- Redundancy: when one system is under test, protection still provided by others
- Designed for activities other than nominal operation: minimize dependence on administrative controls (beyond simple mode switches: "full protection"/"full cowboy")

Annual Schedule

- Instrumentation maintenance – could determine timescale for intermediate precision condition (red and small part of light green)
- Nominal operations (dark green)
- Other activities with beam (all else)

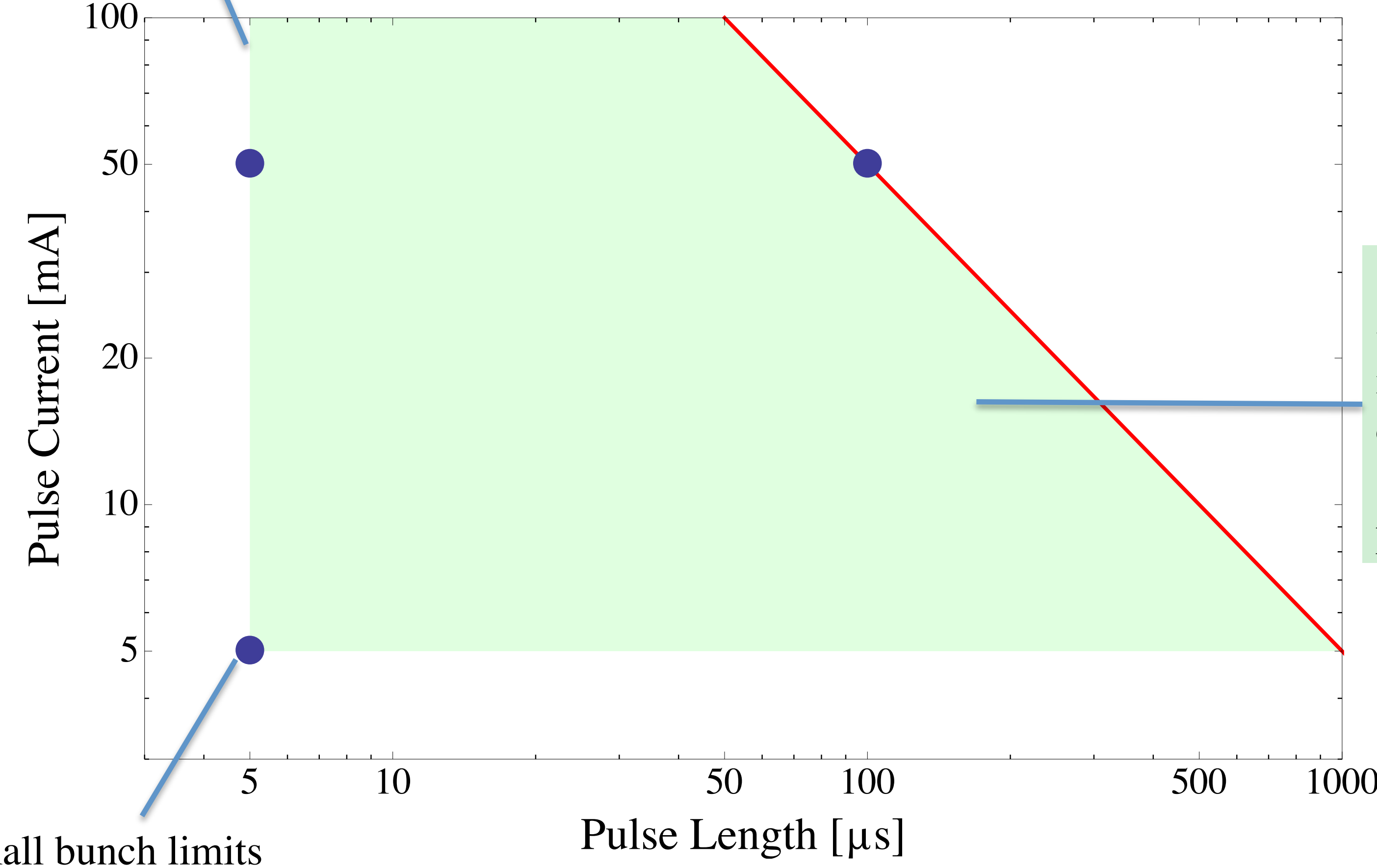


Configuration

- Report state of invasive devices
- Set interlock parameters: scalar thresholds, waveform templates, etc
- Interlock parameters could depend on time and mode of operation (e.g. 20 μA allowed to radiation effects facility, 2 mA allowed to neutrino target), and/or change from pulse to pulse.
- Verification of parameters
- Communication options
  - Through standard control system facilities
  - Through out-of-band path dedication to MPS

Example Beam Modes: Single Pulse

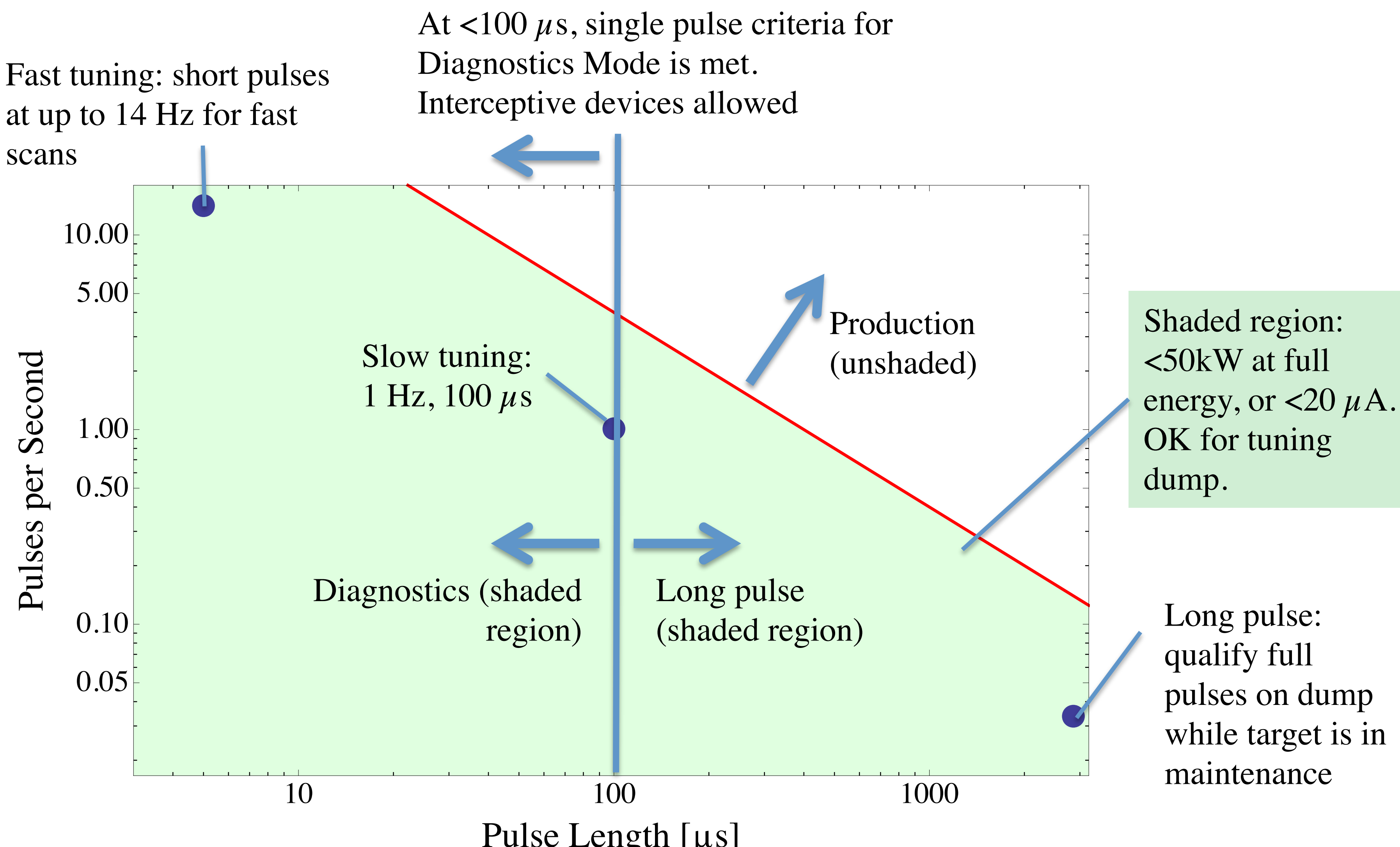
Neutralization time in LEBT is ~10 μs, so require MEBT chopper for short pulses



Shaded region: < 5 μcoulombs, invasive diagnostics survive one pulse

Small bunch limits activation and damage during startup and studies

Example Beam Modes: Long Timescale



Assumes full peak current within pulse.

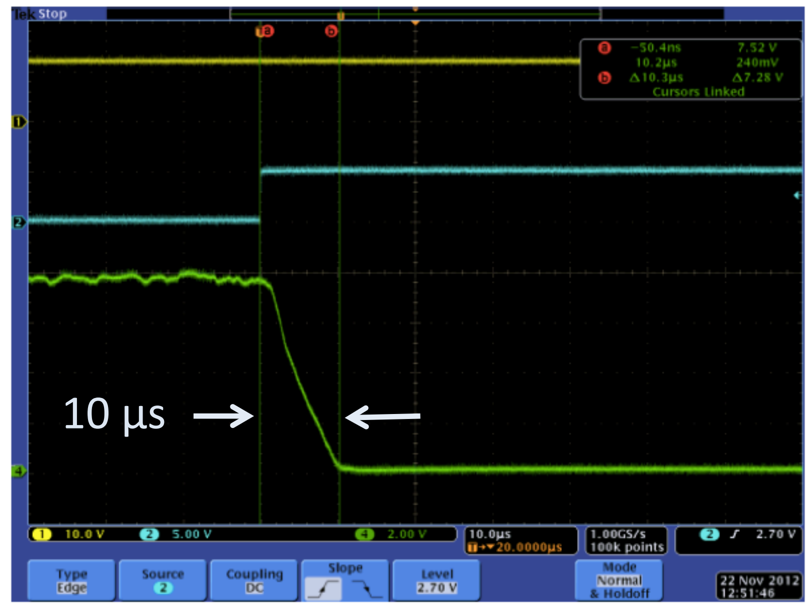
Tuning and Setup

- With beam, tune for better performance and prepare for operations
- Use full suite of beam instrumentation, many that are not available during full performance operations and therefore, not always available for MPS
- Unusual beam conditions for limited periods – would be considered errant during full performance operations.

Verification

- Vertical: Built-in self test and calibration
- Horizontal: Integrated testing, end-to-end interlock tests
- Fault studies
  - Verify models with beam
  - Example: controlled spill (of non-damaging beam) to calibrate instrumentation systems and verify Monte Carlo models

Verification of fast beam turn off via switch on ion source magnetron



Blue: Fast Interlock at ground level
Green: Beam Stopper current

R. Gobin

Qualification

Final check with beam before beginning ramp to full operation

- Non-damaging pilot beam/bunch
- Could be between runs, between cycles, between pulses, or first part of a long pulse
- Instrumentation Challenge: Beam could be significantly less intense and duration much shorter than during full performance operations
  - Dynamic range
  - Bandwidth

Performance Ramp

- Monitor changes and trends with changing beam parameters
- Detailed measurements at plateaus to demonstrate readiness for continued ramp
- Acquisition and archival of pre-determined data sets
  - Demonstrate that operations envelope is met
  - Some measurements may be reportable to licensing authorities

Nominal Operation

- About 90% of beam operations, >90% of irradiation
- For high performance accelerators, often running near engineering limits
- Beam accounting
- Loss and activation management
- Errant conditions:
  - Drifts in beam properties
  - Intermittent anomalies

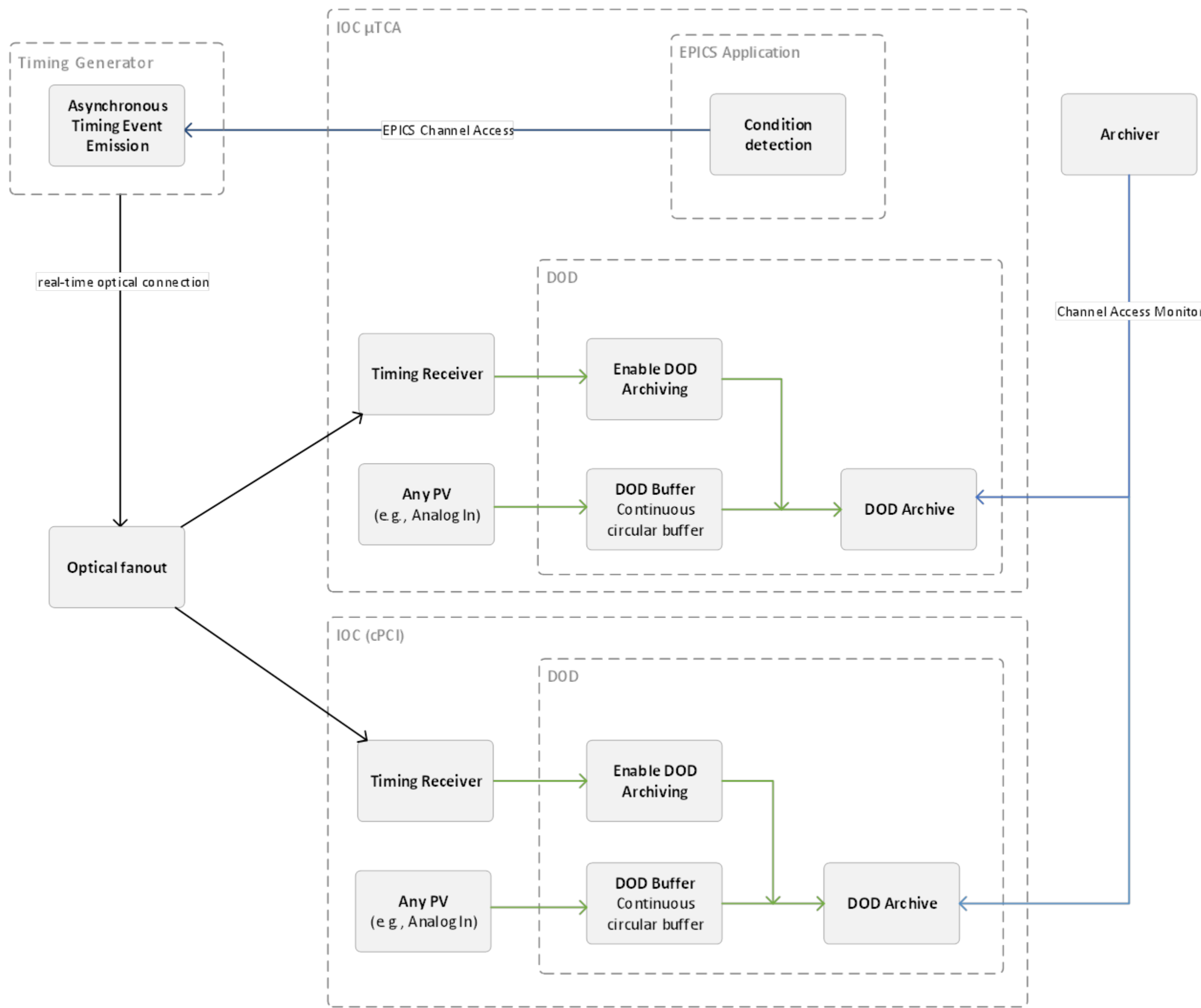
Errant Conditions

- Raise alarms
- Record near misses: triggered data acquisition
- Trip beam interlock system if threshold is violated
- Capture post mortem data
- Don't necessarily stop acquisition – simply copy requested data to a buffer for eventual transmission.
  - Option to continue operations with pilot beam and return to full operations after verification
  - Instrumentation systems must support this mode switch (switch interlock parameters, gains, data acquisition mode, etc)

Data Capture

- Instrumentation systems buffer measurements results and report them upon receipt of a trigger.
- Trigger communicated by timing/event system
  - Can be produced when a condition is met during a measurement
  - Can be produced by beam interlock system to capture post mortem data

ESS "Data on Demand" demonstration:



Where does Beam Instrumentation Fit?
Time Sequence of a Fault

Passage of Time

- Confirm configuration*
- Detect equipment problem*
- **Detect errant beam conditions**
- Protect by passive mitigation
- Onset of damage to victim
- Safety-significant shutdown

What happened???

Bold: Primary roles
*: Secondary roles

What Could Possibly Go Wrong?

- Initiating event
  - Cavity spark
  - Chopper failure
  - Dipole wrong
  - Quad wrong
  - Invasive device drawn in
- Produces errant beam condition
  - Off energy
  - Pulse too long
  - Mis-steered
  - Too diverging
- Through a transfer function
  - Drift
  - FODO lattice
  - Dispersive section

What we must measure:

1. Results in errant observable
   - Radiation produced
   - Too much charge
   - Current pulse at wrong time
   - Beam off center
   - Beam tails extend too far
   - Beam spot too small
2. With certain timescales for damage (required detection time is shorter):
   - Demagnetize undulator over years
   - Overwhelm bulk cooling system in minutes
   - Damage window in one pulse

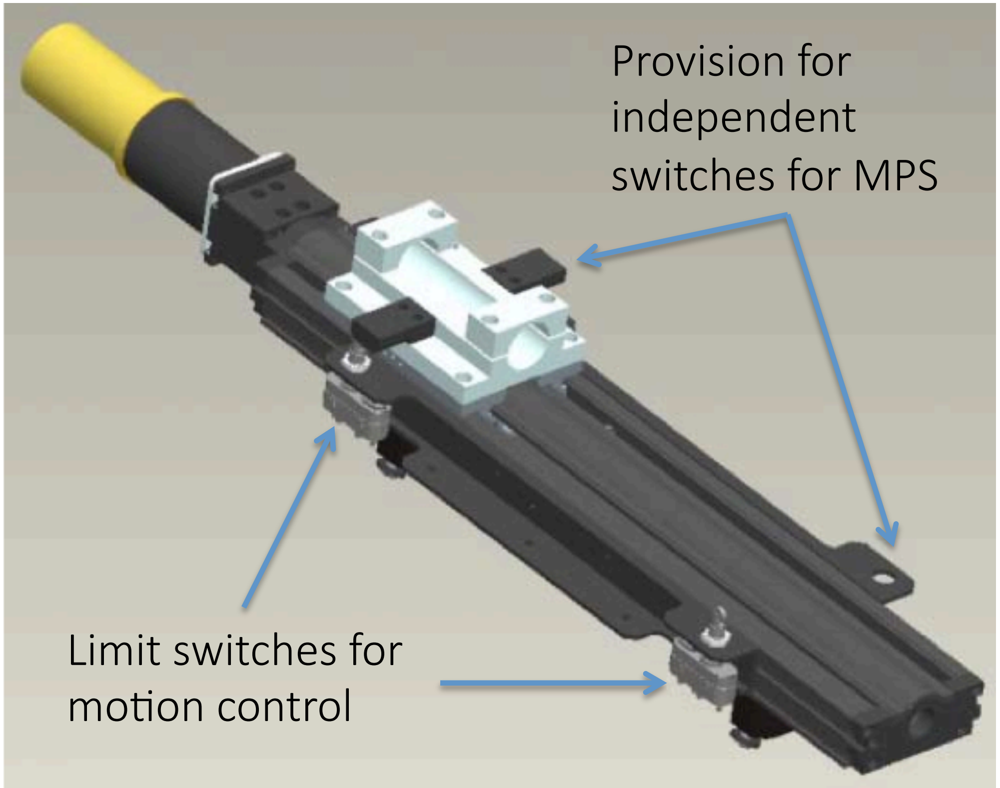
Now we have instrumentation requirements

1. Precision
2. Latency

Invasive devices

- Devices
  - Wire scanners
  - Faraday cups
  - Emittance slits
  - Thick luminescent screens
- Initiating events:
  - Errant configuration
  - Device failure (drawn in by pressure difference)
  - Events leading to too much beam
- Protect by:
  - Redundant limit switches for beam interlock system
  - Threshold on signal
  - Threshold on beam loss

Typical actuator

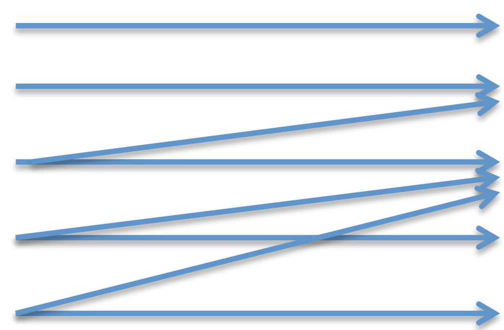


Observables and Instrumentation

Focus on non-invasive devices most relevant for machine protection (continuous monitoring over all modes of operation)

Instrumentation Systems:

- Beam Loss Monitor (BLM)
- Beam Current Monitor (BCM)
- Beam Position Monitor (BPM)
- Profile Monitors
- Aperture Monitors



Direct Observables:

- Radiation
- Current
- Position
- Profile
- Halo

- These observables can be combined or used with a model to produce beam measurements that are also used for machine protection
  - Loss (quantified in terms of primary particles or current)
  - Velocity and energy
  - Position inferred from halo measurement
- Pairs of current monitors produce a more direct measurement of beam loss than do beam loss monitors

BLM

BLM Layout

- Same tools used to predict machine damage due to beam loss are also used to support BLM system design
- Monte Carlo simulation to optimize layout
- Layout optimization
    - Diagnostics: geographic resolution
    - MPS: geographic coverage

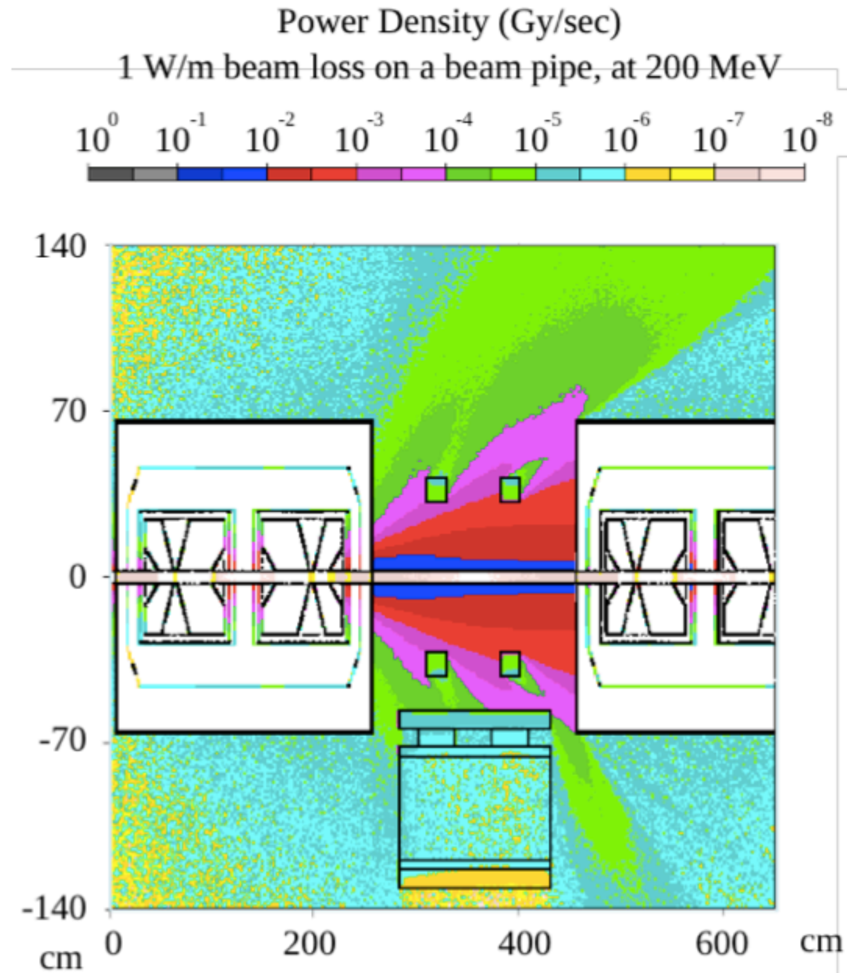
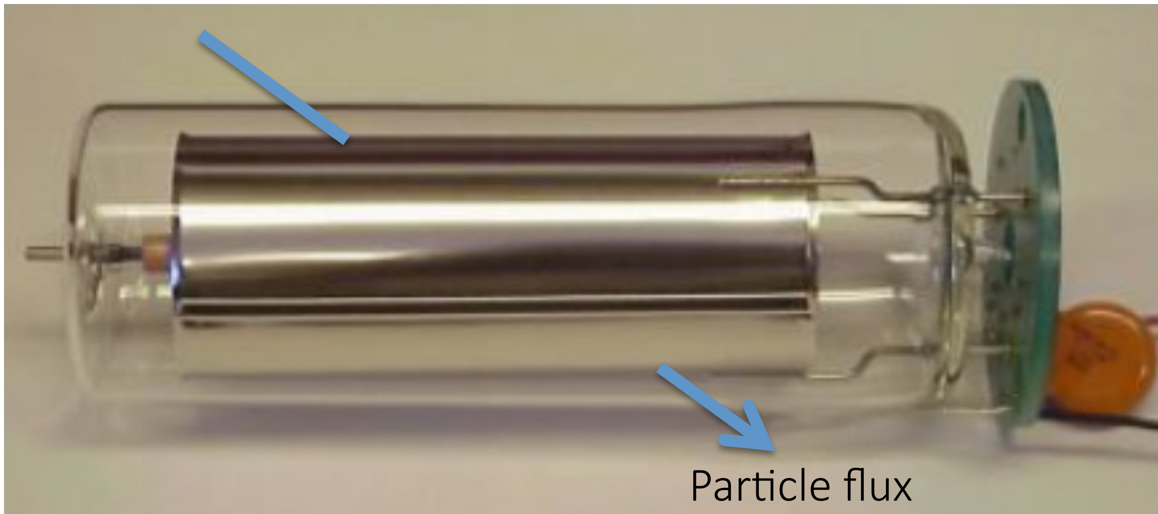
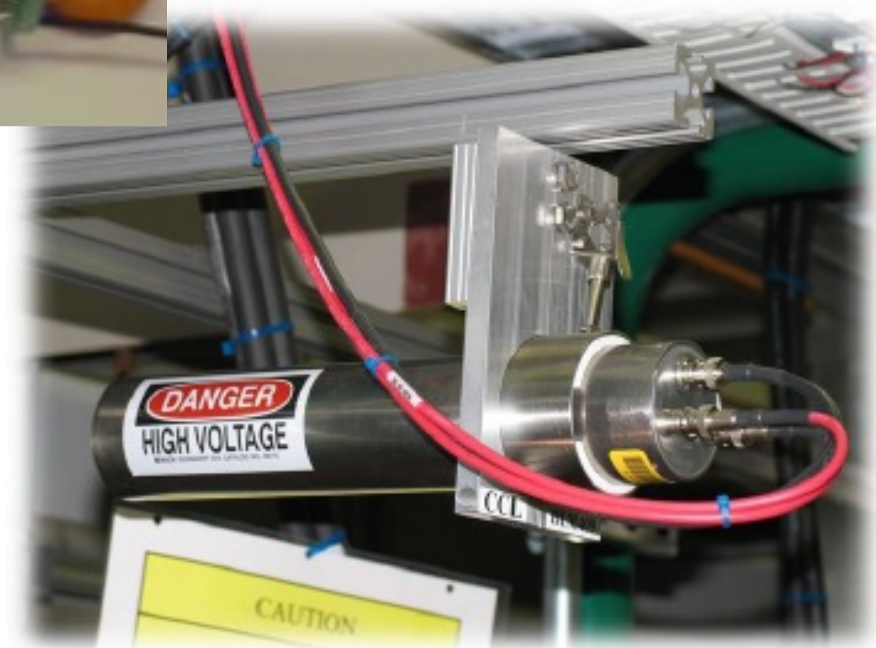


Figure 1: Power density, in Gy/sec, for 1 W/m distributed beam loss on a beam pipe, at 200 MeV.

Tchelidze

Ionization Chambers



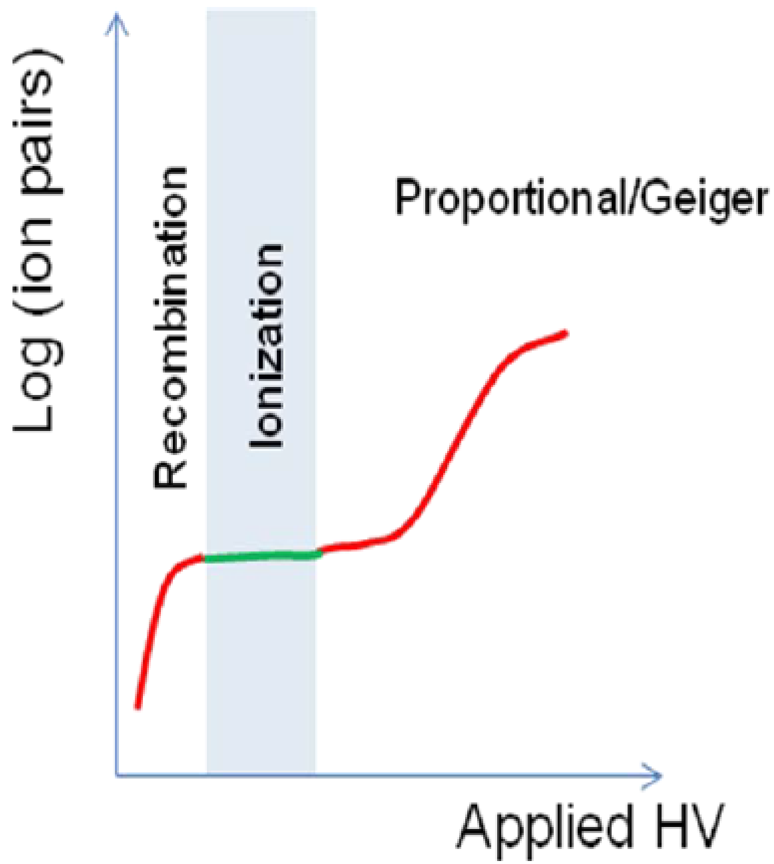


- Tevatron/RHIC/SNS-type: 133 cm^3 Ar gas
- Typical bias 1 kV
- Sensitivity 70 nC/rad
- Response time ~1-2 ms (electrons)
- Test with HV step

R.L. Witkover, D. Gassner

Ionization Chambers

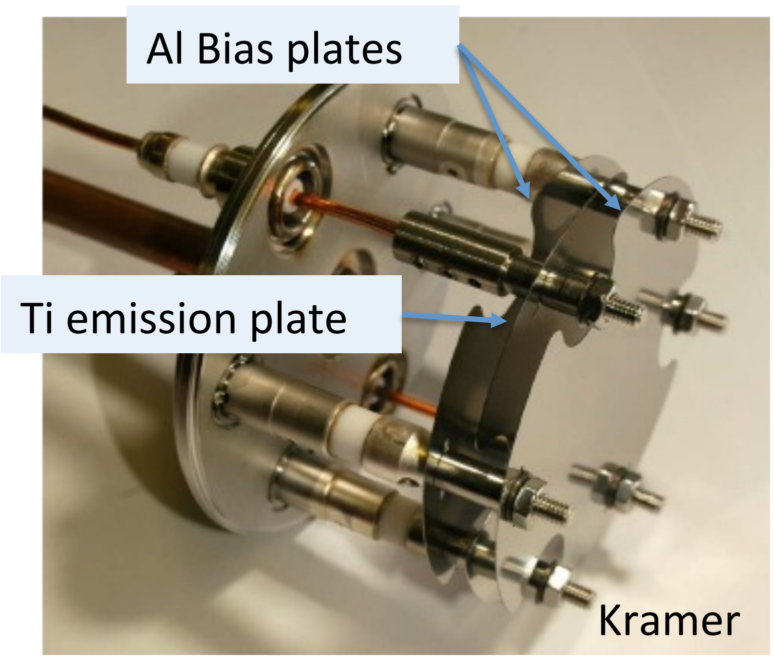
- Ionization chambers are the main type of loss monitors used in hadron machines.
- Gas-filled chambers containing an electrode pair with biasing high voltage.
- Operated in 'ionization' mode, the detector is insensitive to HV fluctuations.
- Small chambers are installed along specific components and provide adequate spatial resolution.
- Long chambers (LIONs, PLICs) provide wide coverage but lack spatial resolution (except for some pulsed machine applications)

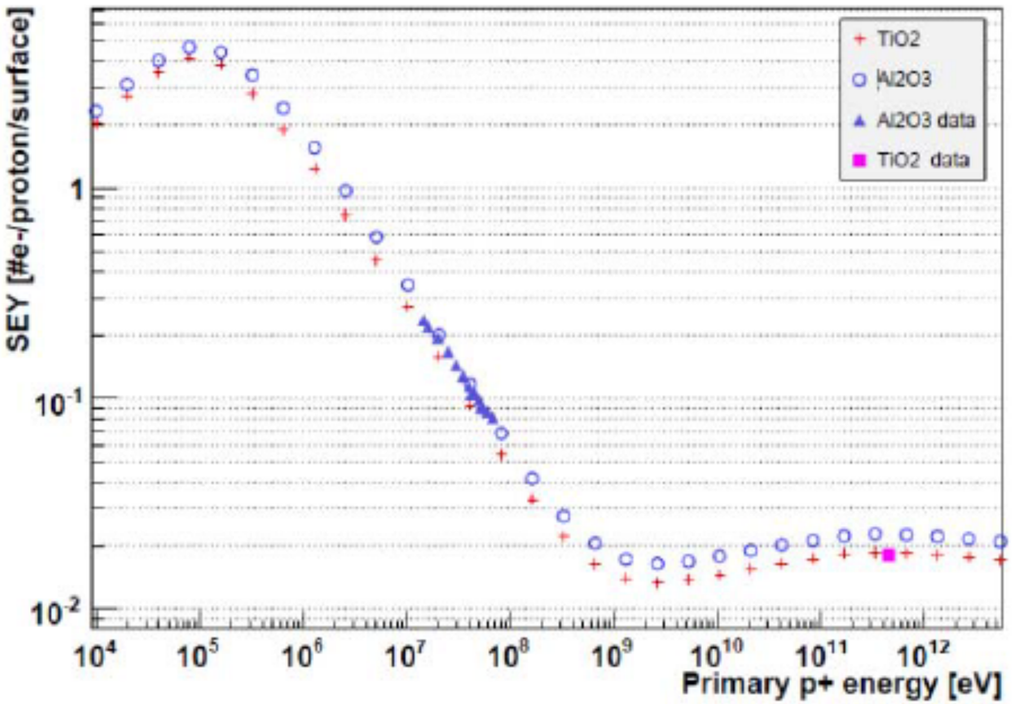


(Zhukov)

Secondary emission monitors (SEM)

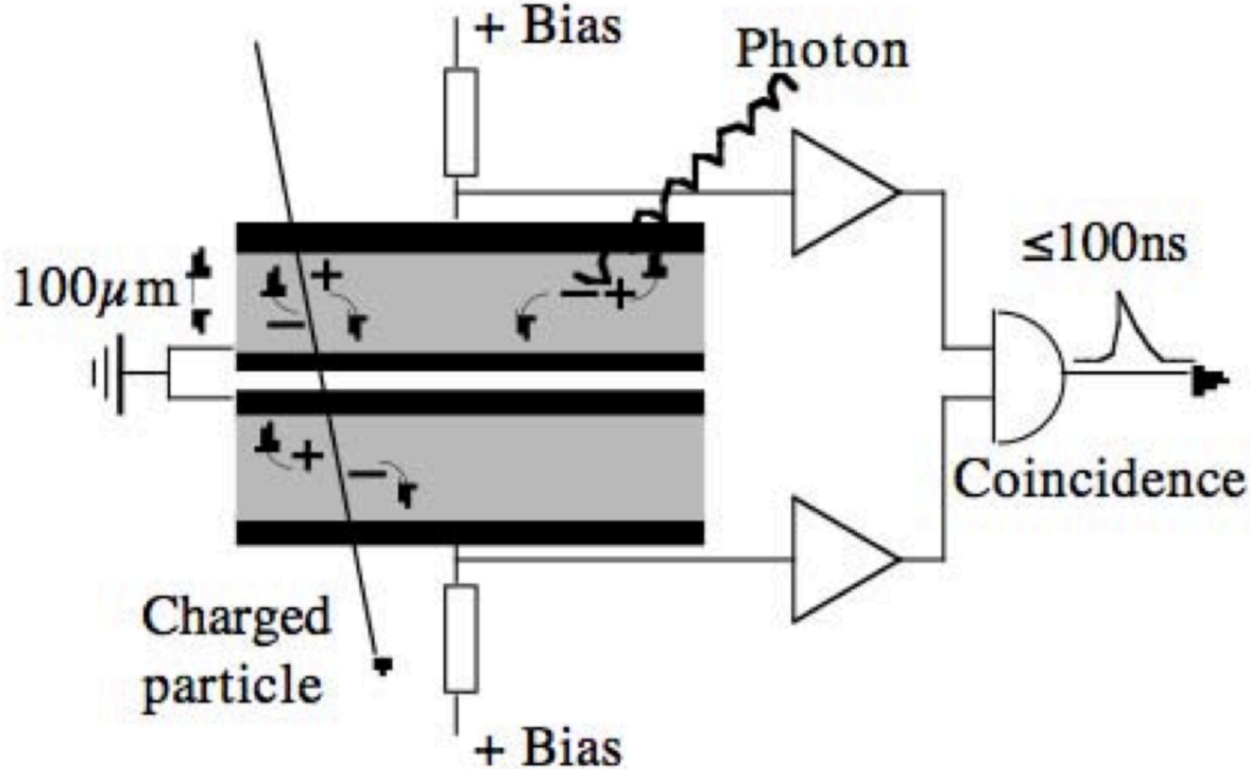
- Less sensitive than IC's to gammas
- Radiation tolerant (Ti SEY shows excellent linearity over integrated dose range)
- Complement high sensitivity monitor to extend dynamic range near critical devices



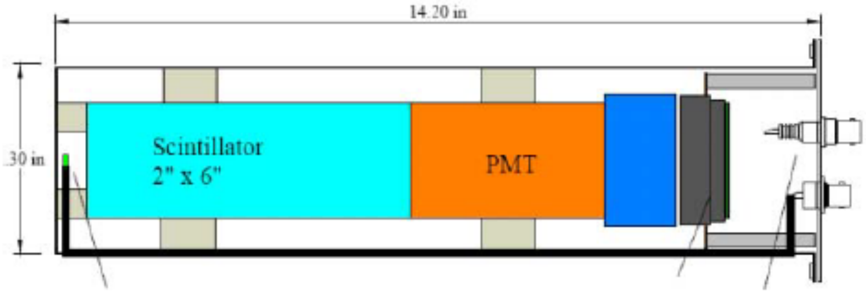


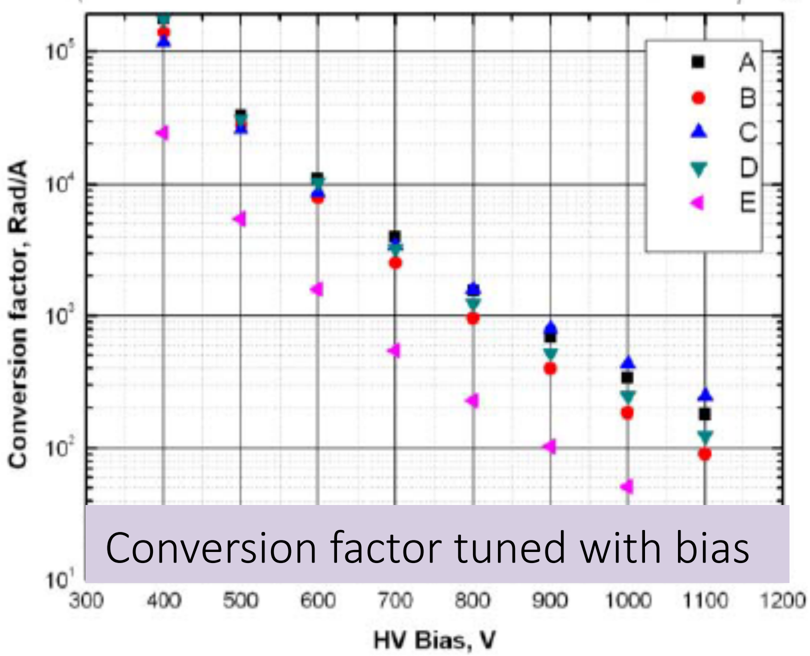
Solid State Detectors (and Coincidence Technique)

- Counting mode; rate >10 MHz
- Coincidence technique reduces background from low energy photons



Scintillation (and Cherenkov) Detectors

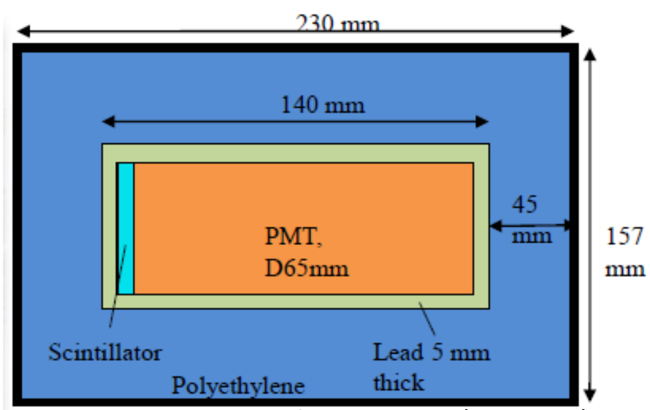




Conversion factor tuned with bias

SNS Fast Detector

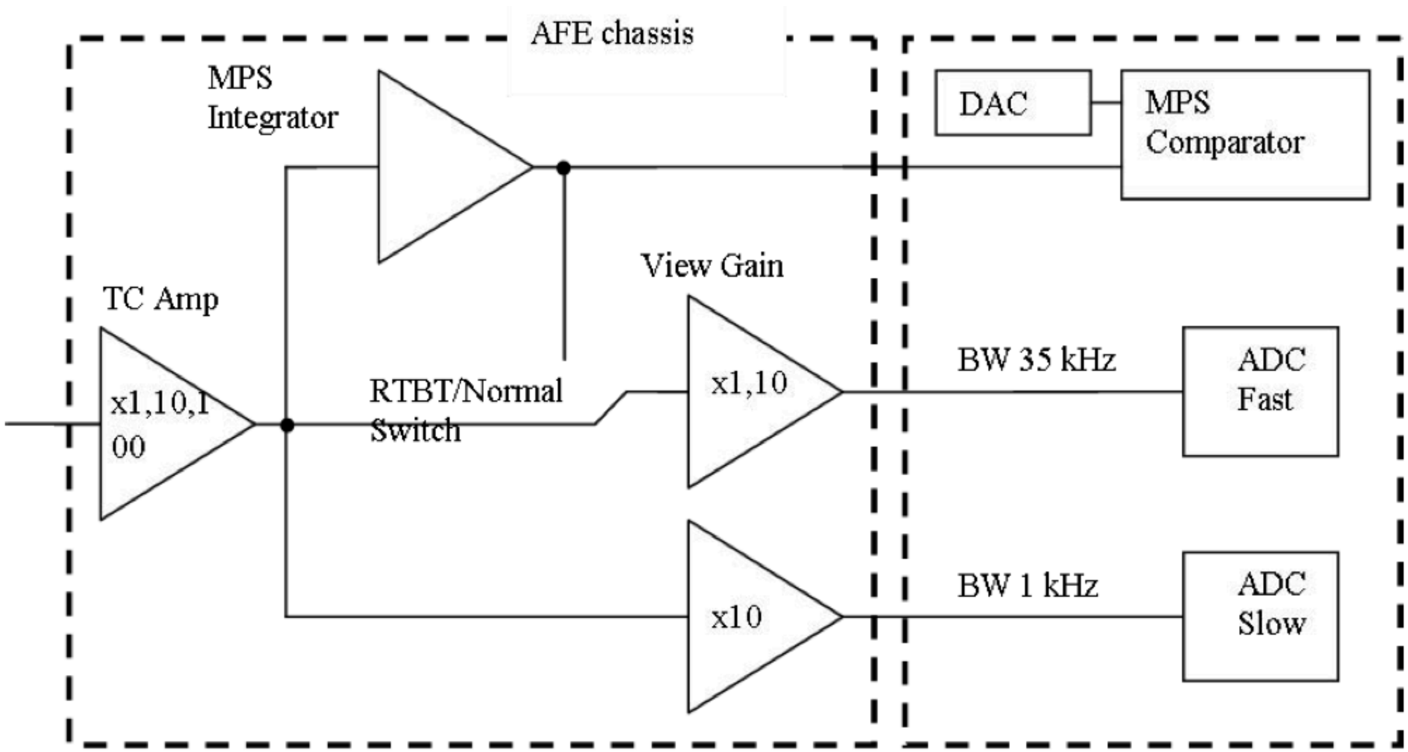
- Typically employ photomultiplier tubes for high gain (10^5-10^8) with applied HV
- Many types of scintillators respond to gamma and charged particle bombardment (fibers also)
- Cherenkov option for velocity selection
- Li- or B- doped plastic scintillators respond to neutrons
  - Additional moderation increases sensitivity at the expense of time response (~100 µs).



SNS Neutron detector (SBLM)

BLM Electronics

- If dynamic range requirement can be met, some processing and threshold comparison can be moved to digital section
- Can apply filtering that mimics thermal response of protected components
- 2 modes: current (simple), event (supports particle discrimination)

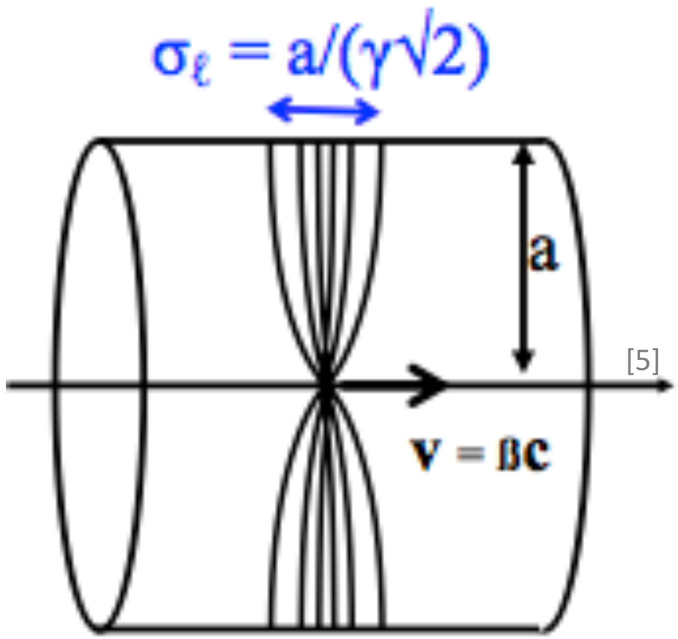


Overgeneralization for MPS: For ~μs latency, use current mode. For ~100 μs latency, could also consider counting mode and still get adequate statistics

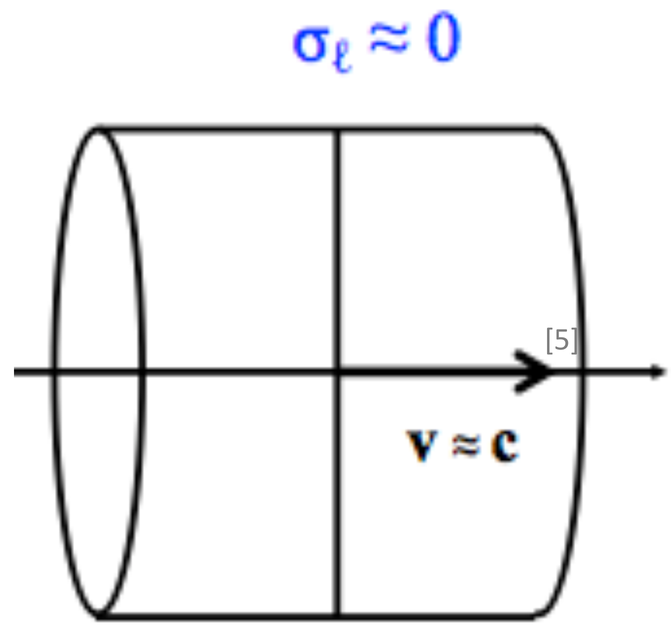
BCM and BPM

More focus here since are not based upon beam-material interactions presented by others

Beam Image currents



Approximation for non-relativistic moving charge



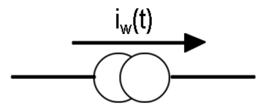
Approximation for relativistic moving charge

induced wall current $i_w(t)$ has opposite sign of beam current $i_b(t)$: $i_b(t) = -i_w(t)$

Using the Image Currents

Detection of charged particle beams – beam detectors:

i_w is a current source



with infinite output impedance, i_w will flow through any impedance placed in its path

many "classical" beam detectors consist of a modification of the walls through which the currents will flow

Sensitivity of beam detectors:

beam charge:

$$S(\omega) = \frac{V(\omega)}{I_w(\omega)}$$

(in Ω)
= ratio of signal size developed $V(\omega)$ to the wall current $I_w(\omega)$

beam position:

$$S(\omega) = \frac{V(\omega)}{D(\omega)}$$

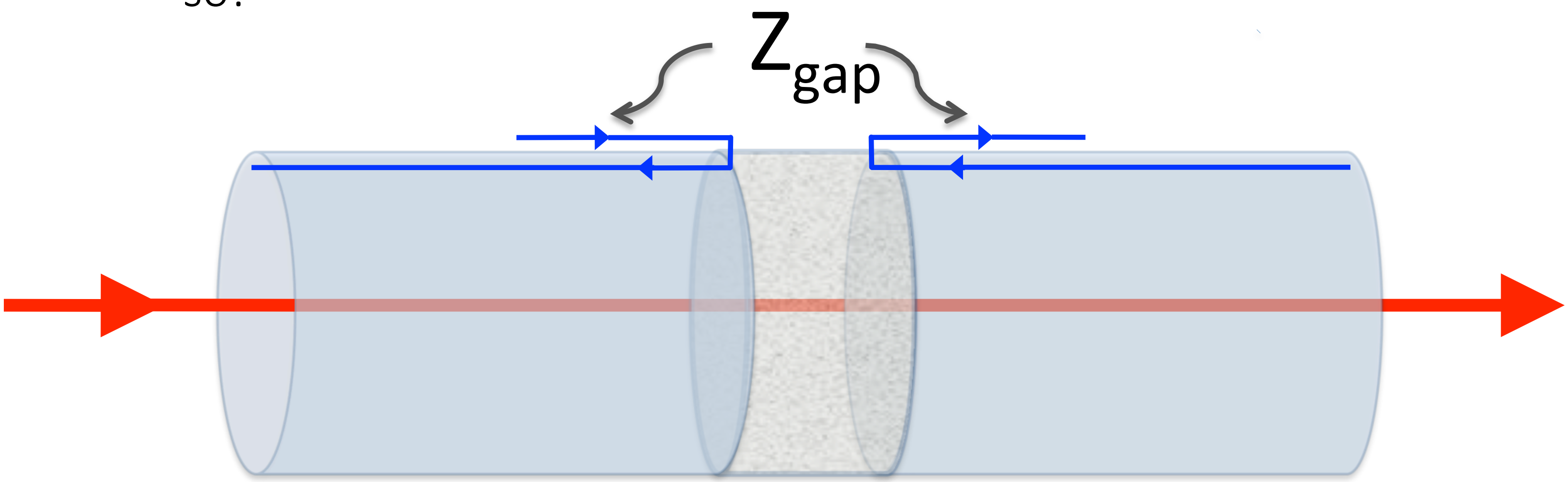
(in Ω/m)
= ratio of signal size developed /dipole mode of the distribution, given by $D(\omega)=I_w(\omega)\, z$, where $z = x$ (horizontal) or $z = y$ (vertical)

Byrd

Beam Pipe Break

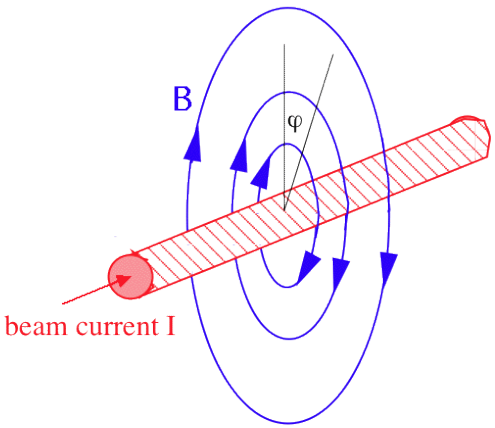
No field outside of beam pipe

- install detector inside beam pipe
  - Inside beam pipe means installation in vacuum
- use a ceramic break
  - Ceramic break forces image current to find another path and it will do so!



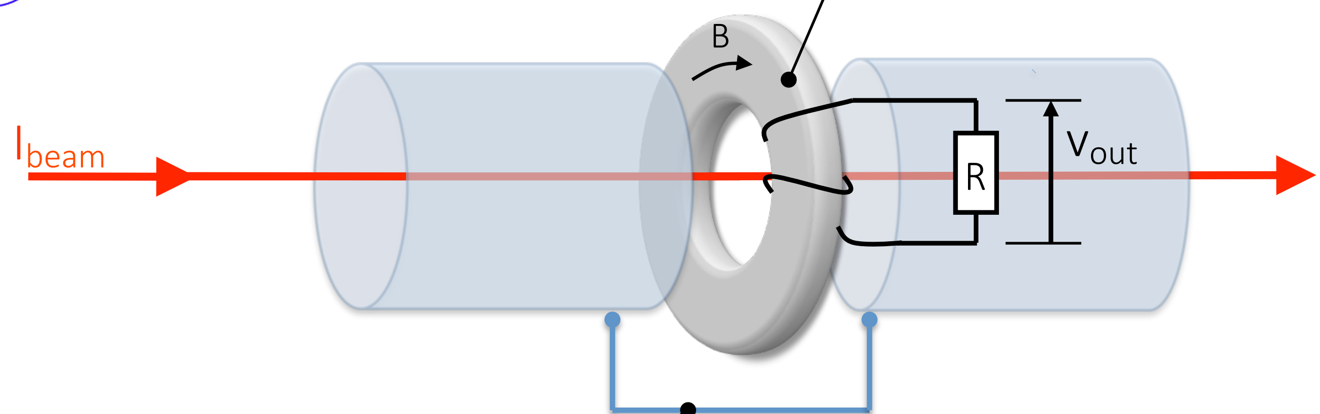
Current transformer

Measure the beam current through the magnetic field of the beam.



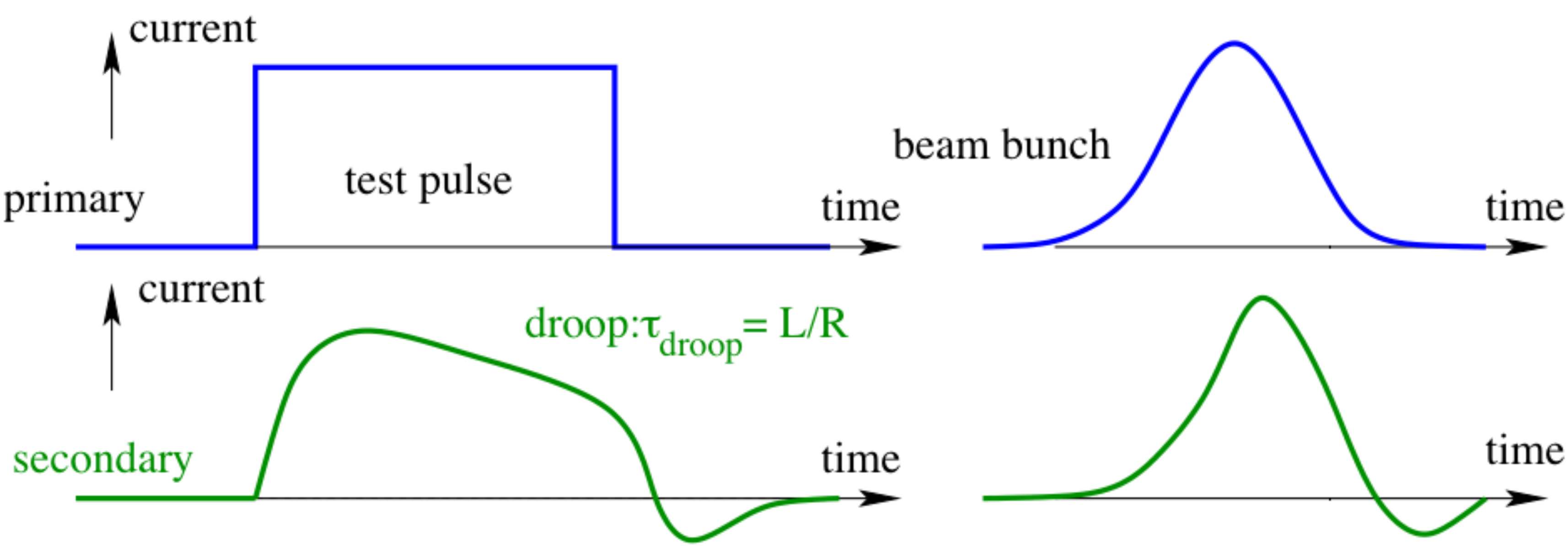
[1]

High permeability core to guide the magnetic field through N-turn secondary winding



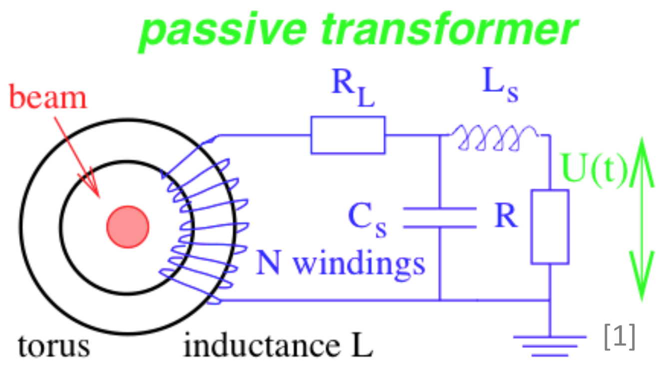
Path for the return current outside the core

Bandpass effects on pulse shape



Current Transformer

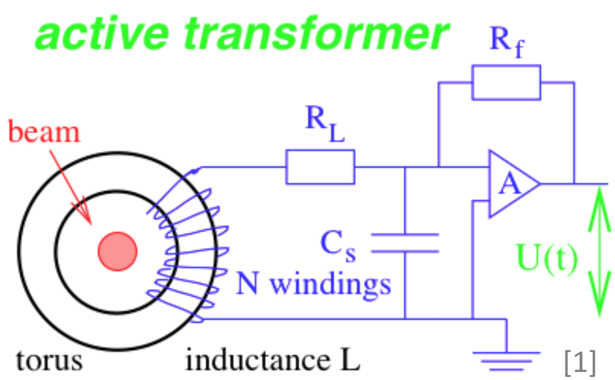
Add (long) cable to current transformer: add cable resistance, capacitance and inductance:



$$\tau_{rise} = \sqrt{L_s C_s}$$

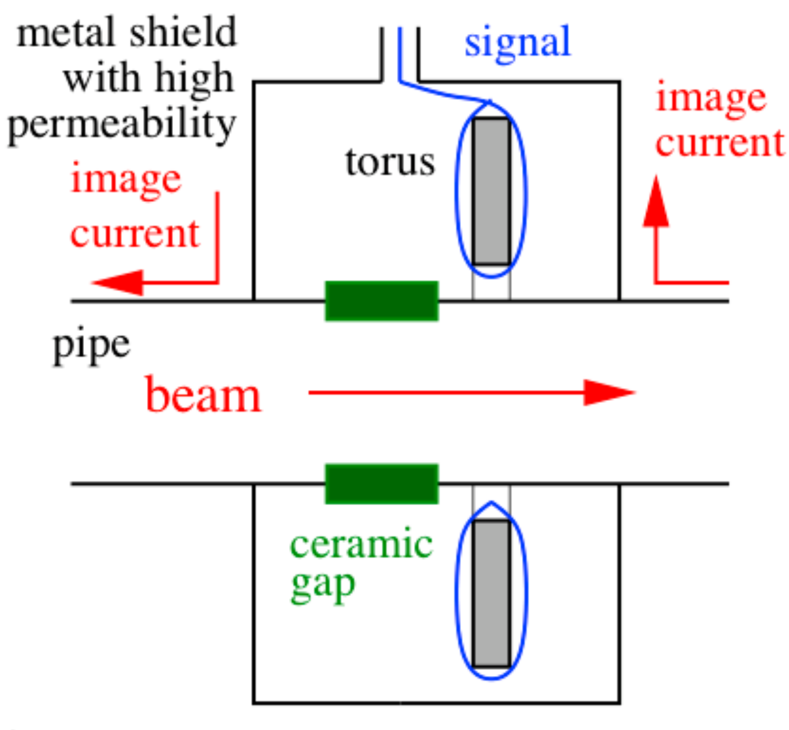
$$\tau_{droop} = L/(R + R_L)$$

Active Transformer: use a trans-impedance circuit to lower the load impedance.



$$\tau_{droop} = L/(R_f / A + R_L) = L/R_L$$

Design of Current Transformer



Passive transformer

Torus radii	$r_i = 70$ mm, $r_o = 90$ mm
Torus thickness	$l = 16$ mm
Torus material	Vitrovac 6025: $(CoFe)_{70\%}(MoSiB)_{30\%}$
Torus permeability	$\mu_r \simeq 10^5$ for $f < 100$ kHz, $\mu_r \propto 1/f$ above
Number of windings	10
Sensitivity	4 V/A at $R = 50\ \Omega$, 10^4 V/A with amplifier
Resolution for $S/N = 1$	40 μA_{rms} for full bandwidth
$\tau_{droop} = L/R$	0.2 ms
$\tau_{rise} = \sqrt{L_S C_S}$	1 ns
Bandwidth	2 kHz to 300 MHz

Active transformer

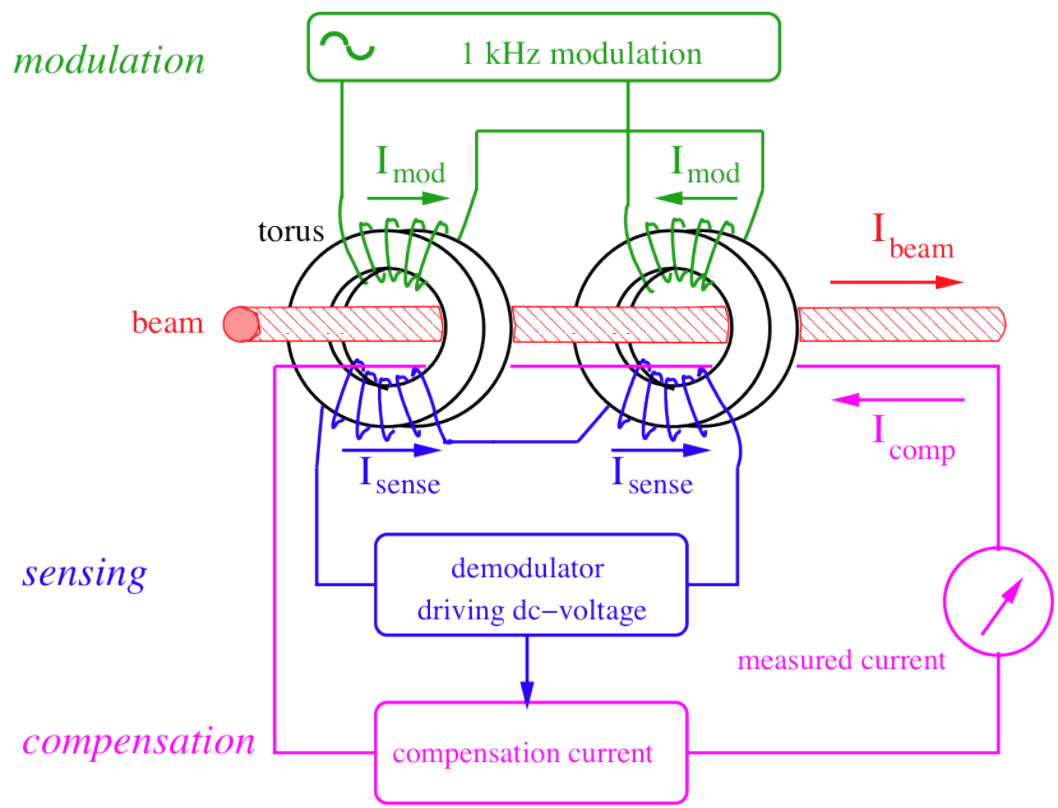
Torus radii	$r_i = 30$ mm, $r_o = 45$ mm
Torus thickness	$l = 25$ mm
Torus material	Vitrovac 6025: $(CoFe)_{70\%}(MoSiB)_{30\%}$
Torus permeability	$\mu_r \simeq 10^5$
Number of windings	2×10 with opposite orientation
Maximal sensitivity	10^6 V/A
Ranges of the beam current	10 μA to 100 mA
Resolution for $S/N = 1$	0.2 μA_{rms} for full bandwidth
Droop	< 0.5 % for 5 ms pulse length
Maximum pulse length	8 ms

Forck, Blokland, Bergoz

DC Current Transformer

- How to measure the DC current? The current transformer discussed sees only changes in the flux.
- The DC Current Transformer (DCCT): look at the magnetic saturation of the torus.

- Modulation of the primary windings forces the torus into saturation twice per cycle.
- Secondary windings sense modulation signal and cancel each other.
- But with the I_{beam}, the saturation is shifted and I_{sense} is not zero
- Adjust compensation current until I_{sense} is zero once again.



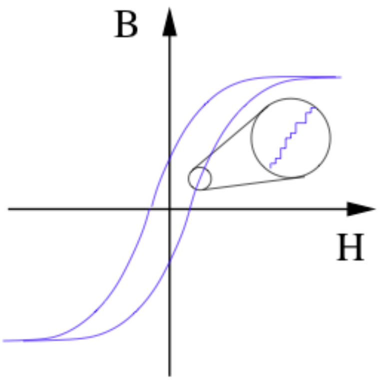
Current Monitor Limitations

Limitation to transformers:

- The permeability of a core can be saturated: specs of max B field or max current time product I*t,

- Thermal noise: $V_n \approx \sqrt{4 k_b T f_{high} R}$

- Weiss domains lead to Barkhausen noise if terminating with high impedance (limit for DC-type)
- External magnetic fields and interference
- Torus material has dependency of μ_r on temperature or on mechanical stress (micro-phonic pickup)
- Secondary electrons and similar background

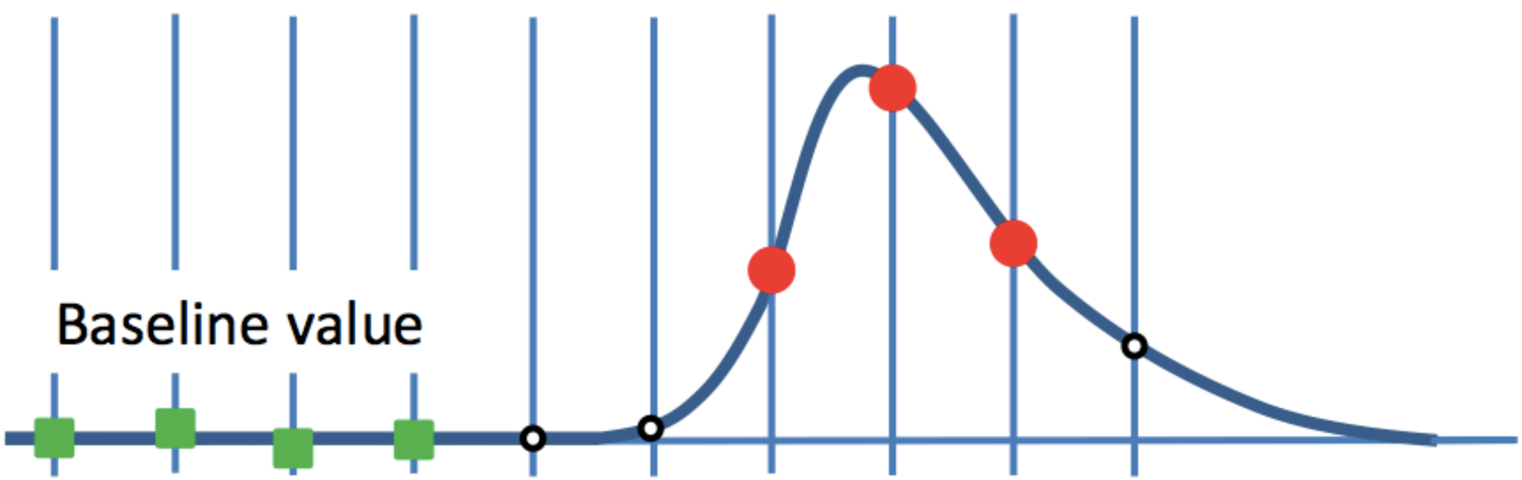


~ 1 μA for DCCT
~ 30 μA for FCT with 500 MHz bandwidth
~ 0.3 μA for ACT with 1 MHz bandwidth.

Overgeneralization for MPS use: rely on current monitor to detect current variations that are at least 1% of the maximum operational beam current

Typical Sampled Acquisition

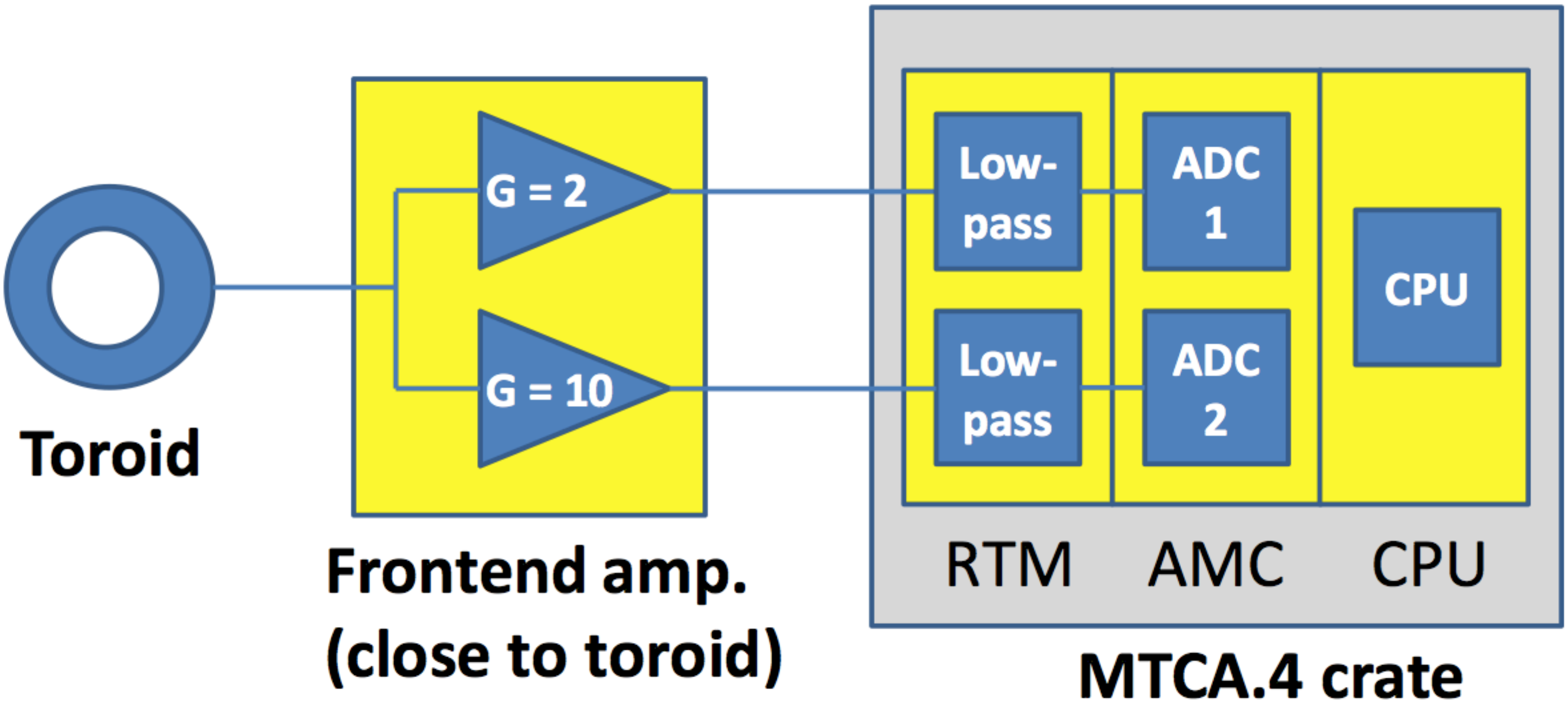
- Low pass filtering
- Oversample baseband signal
- Baseline determination on each pulse



For pulse beams, consider self triggering in MPS applications: reduces dependence on external systems like timing.

BCM Electronics

- Also: Self test/calibration pulse through separate window is important for MPS applications
- Many signal processing functions now implemented in field programmable gate array (FPGA) directly after digitizer.



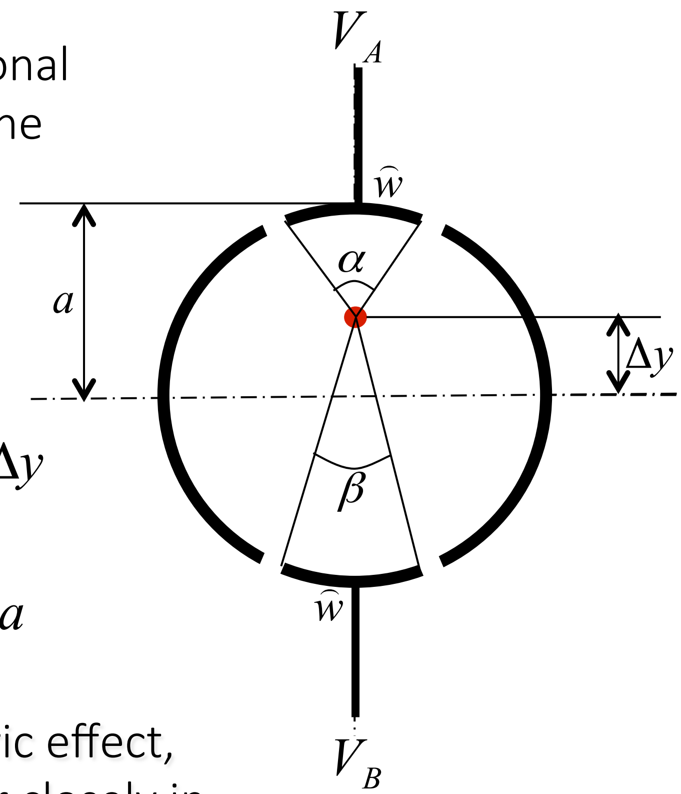
Tom Shea, Beam Instrumentation for Machine Protection, JAS Newport Beach, 2014

Electromagnetic Beam Position Monitors

Simplified model: image charge in an electrode is proportional to the beam current and to the angle included between the beam and the electrode extremes:

$$V_A = G\,I\,\alpha$$
$$V_B = G\,I\,\beta$$

$$But \quad \widehat{w} = \alpha(a - \Delta y) = \beta(a + \Delta y)$$



$$\Rightarrow \quad V_A = G\,I\,\frac{\widehat{w}}{a - \Delta y} \qquad V_B = G\,I\,\frac{\widehat{w}}{a + \Delta y}$$

$$\Rightarrow \quad V_A - V_B = \frac{2\,G\,\widehat{w}}{a^2 - \Delta y^2}\,I\,\Delta y \qquad V_A + V_B = \frac{2\,G\,\widehat{w}}{a^2 - \Delta y^2}\,I\,a$$

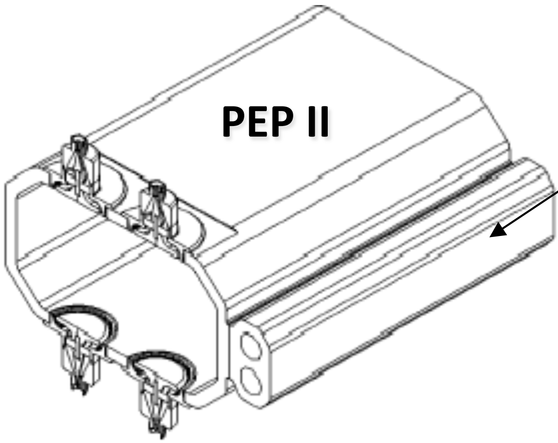
$$\Rightarrow \quad \frac{V_A - V_B}{V_A + V_B} = \frac{\Delta y}{a}$$

$\Rightarrow$ In addition to this geometric effect, the field lines tend to cluster closely in the region of the nearest electrode (the E field must be perpendicular to the walls). For this geometry, this gives an additional factor two.

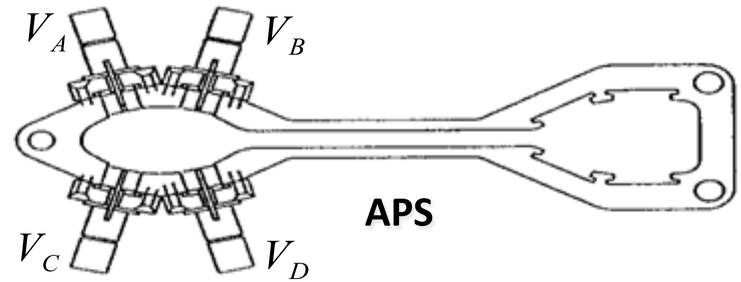
$$\Delta y \cong \frac{a}{2}\,\frac{V_A - V_B}{V_A + V_B}$$

Pro Tip: Analytical approximations for concept development, FEM for detailed design

"Button" Type BPMs

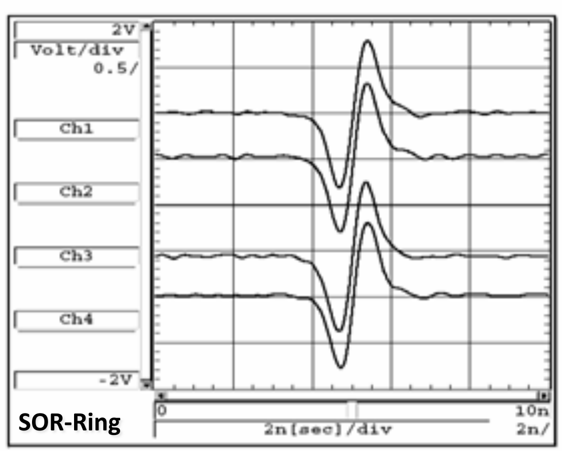


Typical geometry used in the presence of synchrotron radiation.



$$\Delta x = K\frac{(V_A+V_C)-(V_B+V_D)}{V_A+V_B+V_C+V_D}, \qquad \Delta y = K\frac{(V_A+V_B)-(V_C+V_D)}{V_A+V_B+V_C+V_D}$$

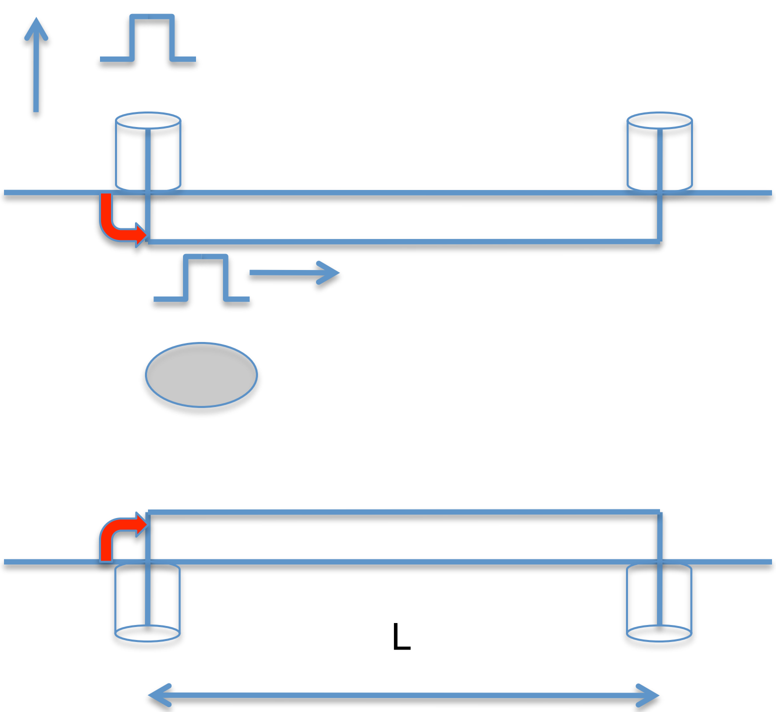
Capacitive (derivative response), low coupling impedance, best for continuous bunches.



Additional types: cavity and other resonant structures (for low charge); diagonal cut (linear), magnetic loop, …

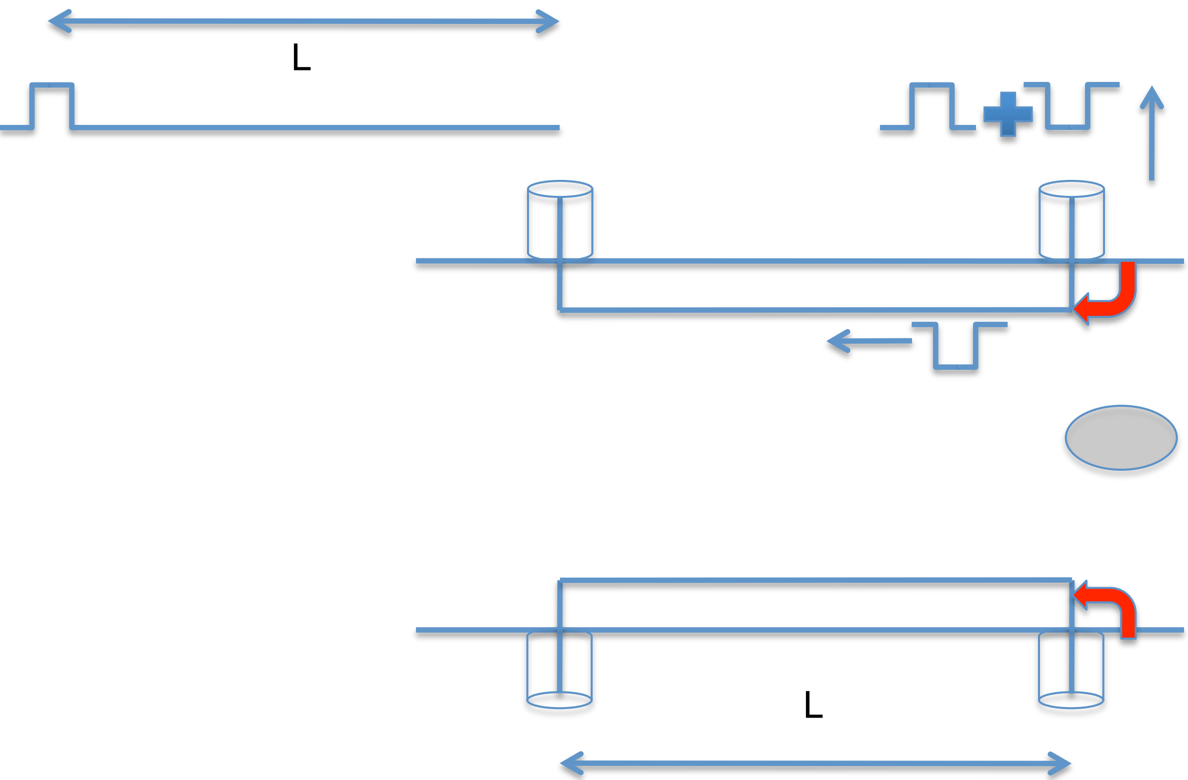
Stripline Signal

- Beam passes upstream port of PU
  - Induced voltage at gap
  - If stripline impedance is matched to upstream output port, half of pulse exits port, the other half travels downstream. For vacuum, pulses moves at c.



Stripline Signal

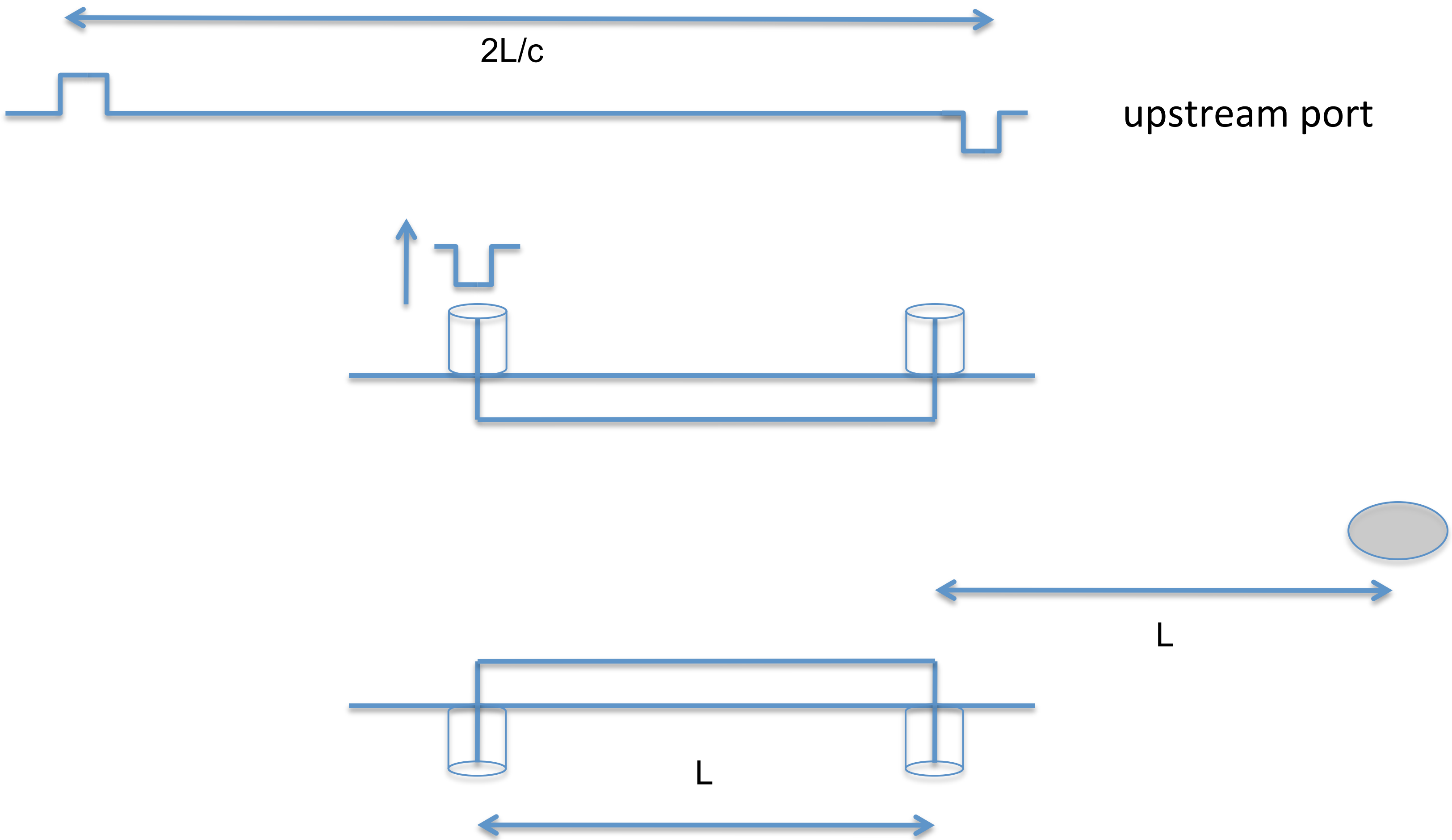
- Beam passes downstream port of PU
  - Induced voltage at gap (opposite polarity to upstream port)
  - If stripline impedance is matched to downstream output port, half of pulse cancels pulse from upstream port, the other half travels upstream and is observed at upstream port at a time 2L/c.



J. Byrd

Stripline Signal

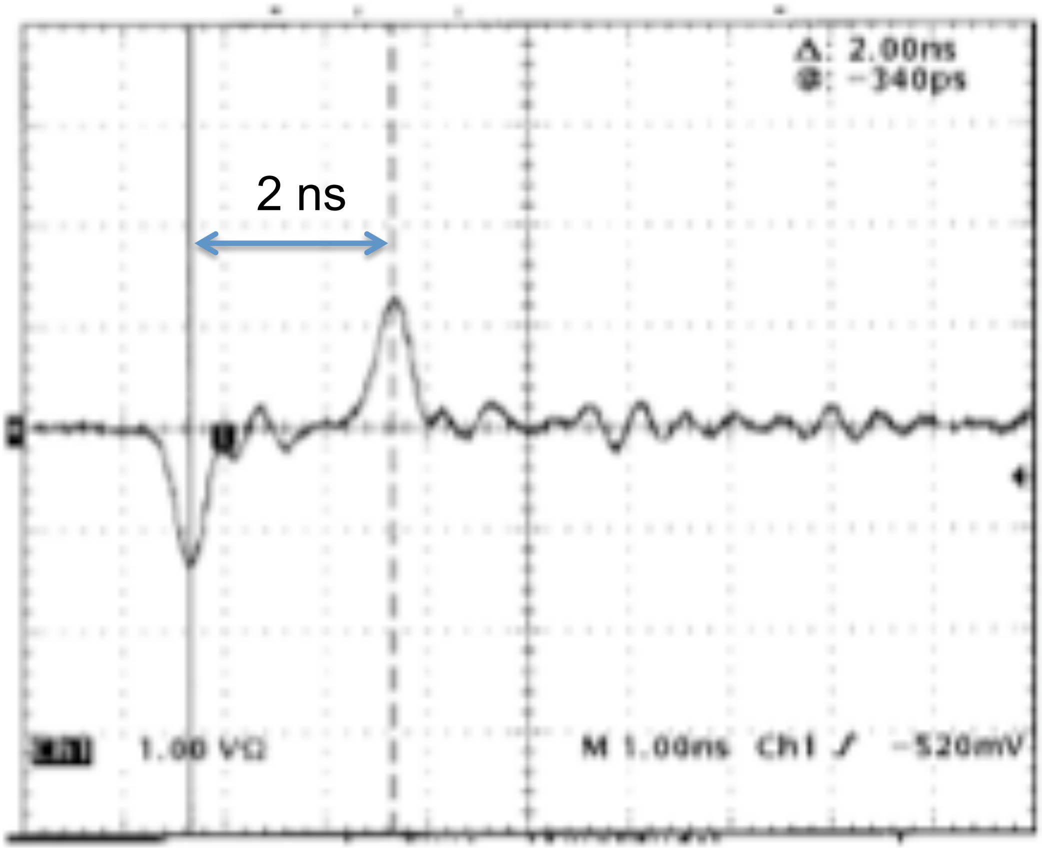
- The downstream pulse exits through the upstream port at a time 2L/c. No signal from downstream port (ideal case)



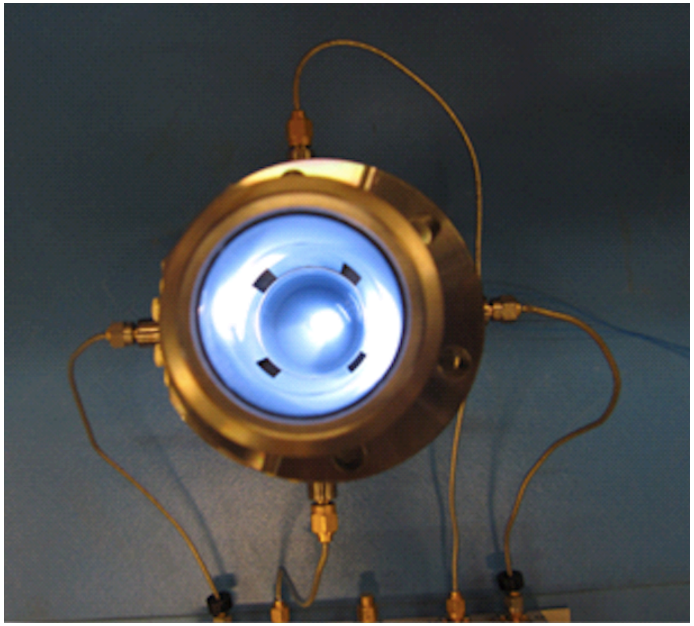
J. Byrd

Stripline Signal

Advanced Light Source stripline signal. Signal at the upstream port. Stripline length is 1 ns (30 cm)



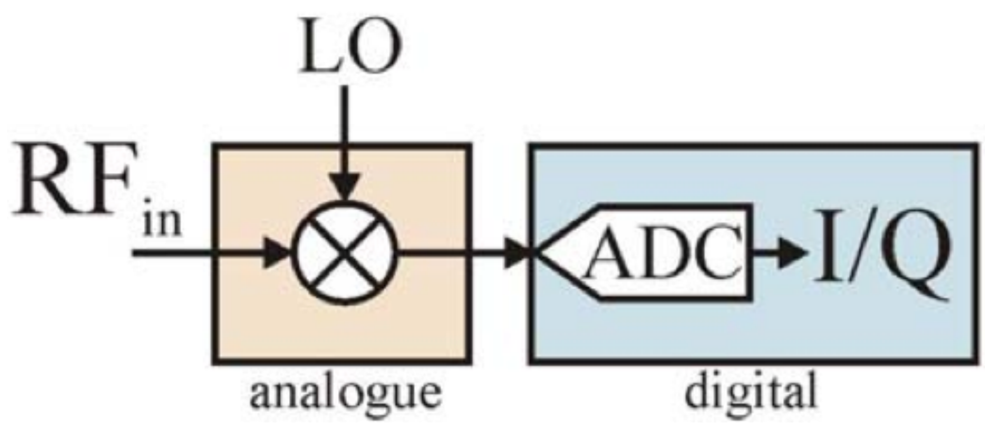
J-Lab stipline



J. Byrd, J. Musson

BPM Electronics

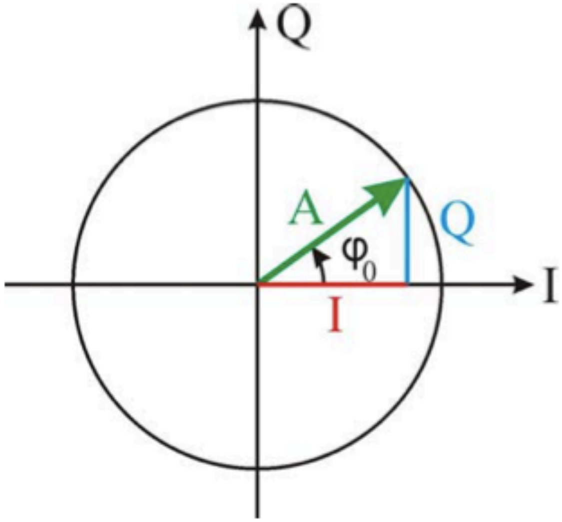
Example receiver for RF signals



Typical input impedance of 50 ohms matches signal cable and individual stripline impedance

Phasor

representation of any sinusoidal RF signal: phasor
(assumption: we measure the vertical component with ADC)



$$y(t) = A \cdot \sin(\omega t + \varphi_0)$$

$$y(t) = \underbrace{A\cos\varphi_0}_{=:I}\sin\omega t + \underbrace{A\sin\varphi_0}_{=:Q}\cos\omega t$$

I: in-phase component

Q: quadrature-phase component

$$y(t) = I \cdot \sin\omega t + Q \cdot \cos\omega t$$

$$I = A \cdot \cos\varphi_0 \qquad A = \sqrt{I^2 + Q^2}$$

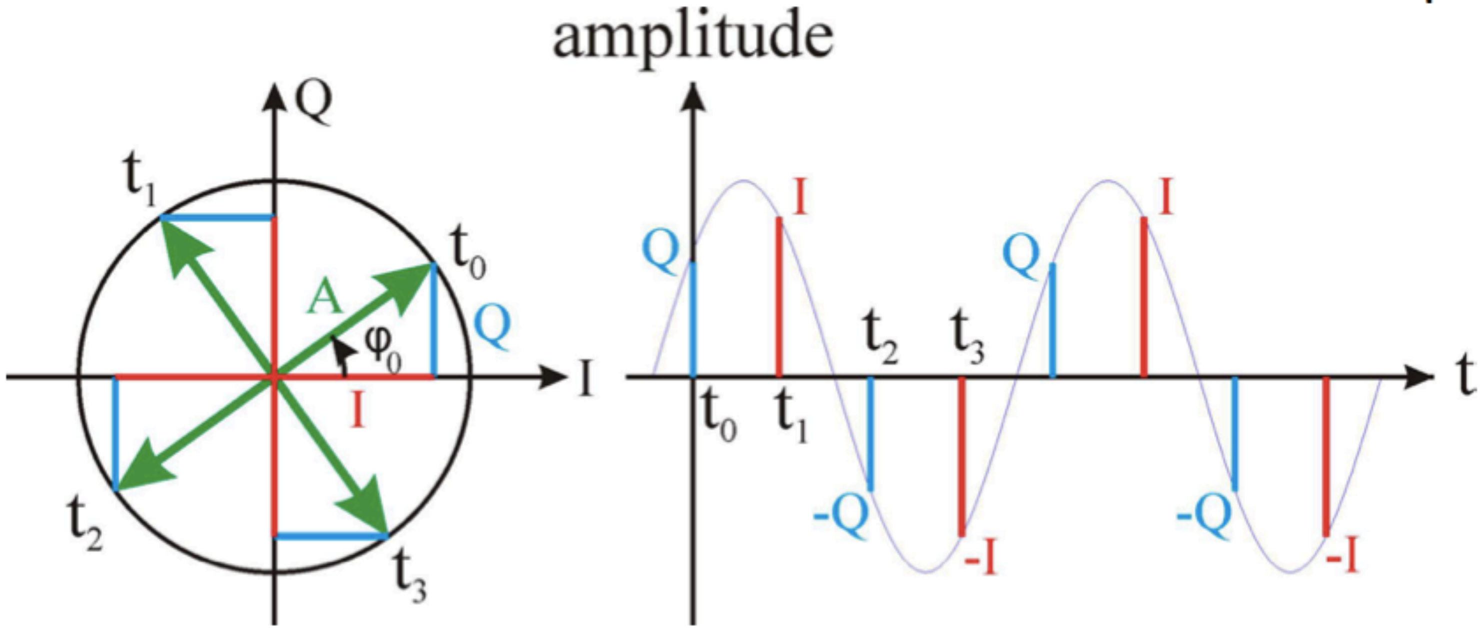
$$Q = A \cdot \sin\varphi_0 \qquad \varphi_0 = \operatorname{atan}\left(\frac{Q}{I}\right)$$

(sometimes I/Q are defined vice versa!)

definition:
positive frequencies
↔ counterclockwise rotating phasor

I-Q Sampling

sampling of RF/IF freq.: $f_s = 4 \cdot f$ (i.e. 90° phase advance between two samples)



$$y(t) = I \cdot \sin \omega t + Q \cdot \cos \omega t$$
$$I = A \cdot \cos \varphi_0$$
$$Q = A \cdot \sin \varphi_0$$

$\omega t_0 = 0 :$ $y(t_0) = Q$

$\omega t_1 = \pi/2 :$ $y(t_1) = I$

$\omega t_2 = \pi :$ $y(t_2) = -Q$

$\omega t_3 = 3\pi/2 :$ $y(t_3) = -I$

Position Monitor Wrapup

- Can measure multiple beam parameters:
  - Position
  - Phase (w.r.t. reference and other monitors)
  - Amplitude (proportional to current, but usually dependent on beam's frequency content)
- Overgeneralizations for machine protection:
  - Position precision: ~ 1% of full aperture
  - Phase/time precision: ~ 1 degree at beam bunching frequency
  - Amplitude: better to use a BCM, but BPM could see debunching even if it did not yet lead to beam current loss.
  - Latency: ~ μs through filtering/ADC/FPGA to MPS

Profile Monitors

Multiwire

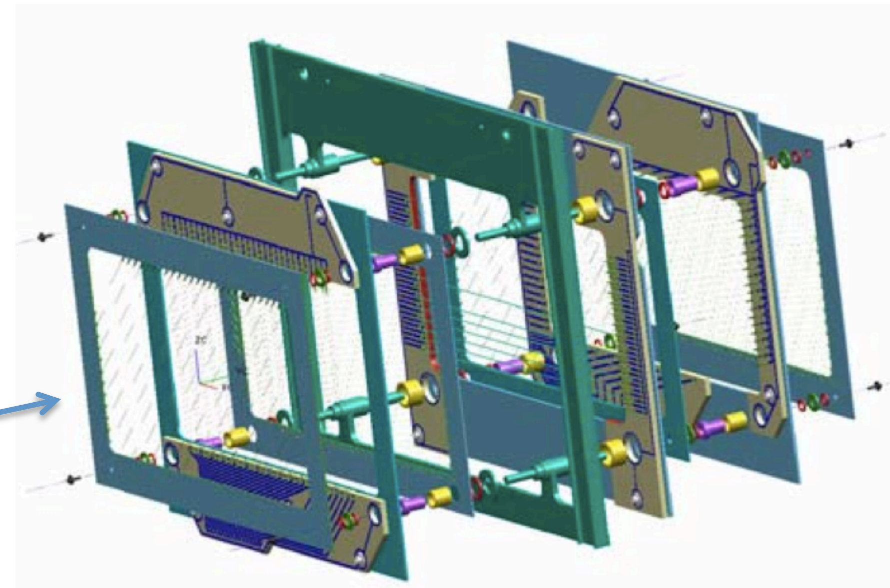
Luminescence

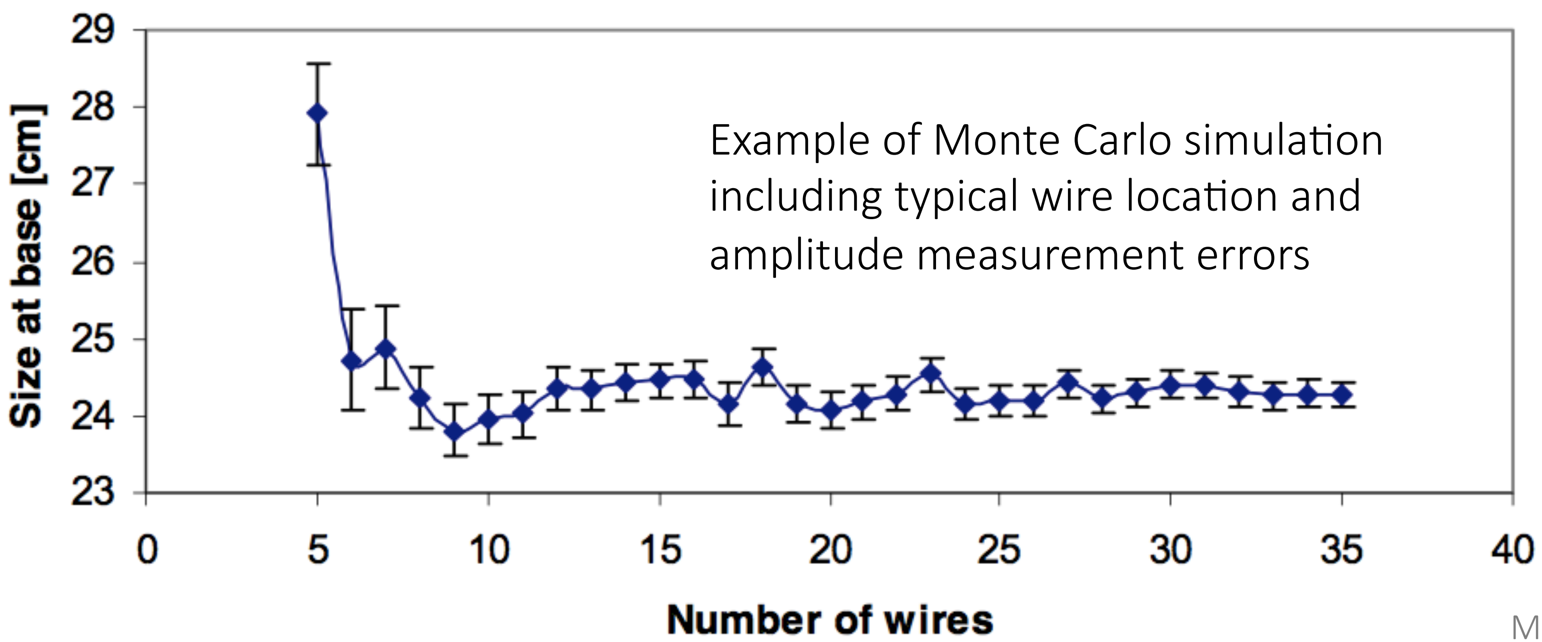
Ionization

And several others not covered

Profile: Multiwire

- Minimum of about 10 wires per plane – typically > 30
- > 1 mm spacing for large beams on targets
- Additional wire planes to provide bias field

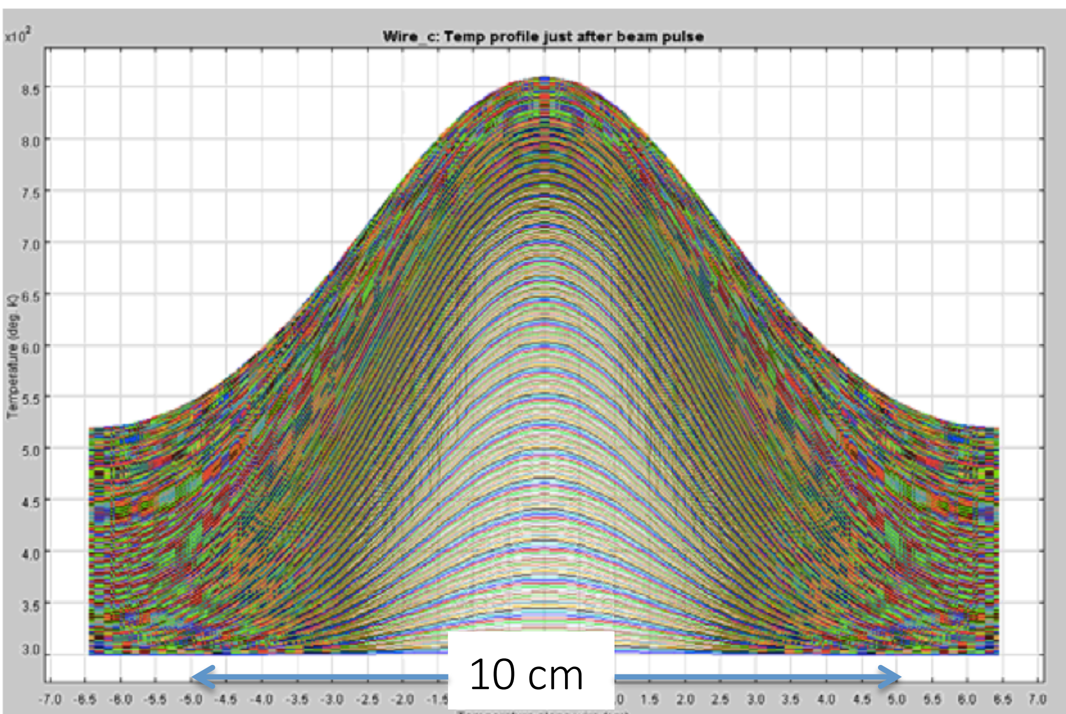


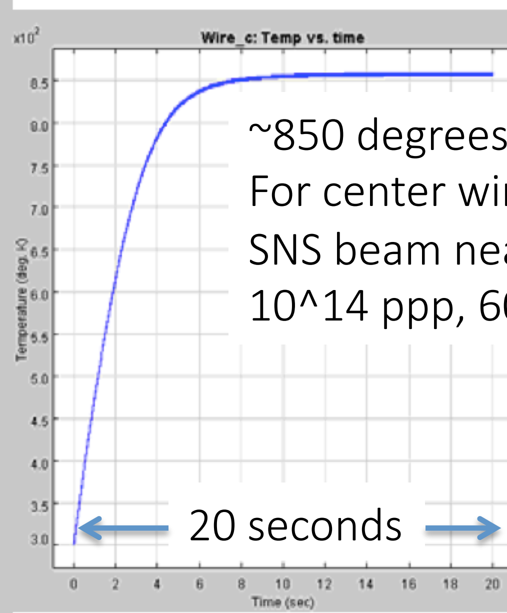


Multiwire Temperature

But aren't wires invasive?

- Typical wire: 100 micron diameter Tungsten, OK in beam where target/window is OK.
- Use only near fixed targets and dumps, where radiation levels are already high
- Assure that wire temperatures are always well below thermionic emission (<< 2000 K) temperatures (and melting point), even when detecting errant beam conditions.
- Special case: Robust mesh of Tungsten wires can emit usable near-IR/visible light when heated by the beam





Multiwire Signal – Low Energy Secondary Emission

- Simultaneous beam-wire interaction: induced current detection is preferred over shower detection.
- Sternglass predicted yield for low energy secondary emission electrons.

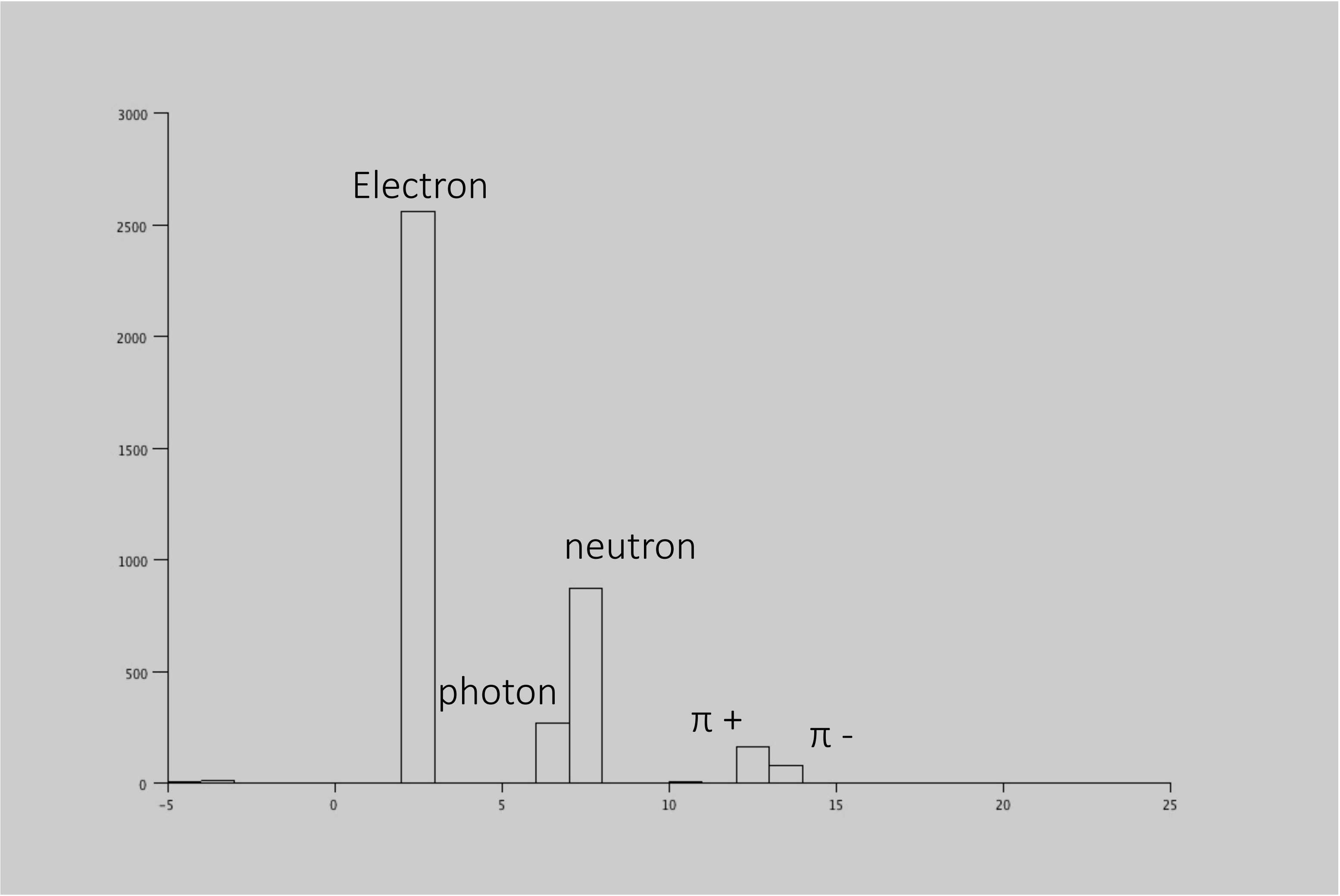
$$Y = \frac{P\, d_s}{E^*} \frac{dE}{dx} = (0.002 \text{ cm/MeV}) \frac{dE}{dx}$$

  P=probability of electron escaping surface layer (~50%)
  d= thickness of surface layer (~1 nm)
  E=ionization energy (~25 eV)

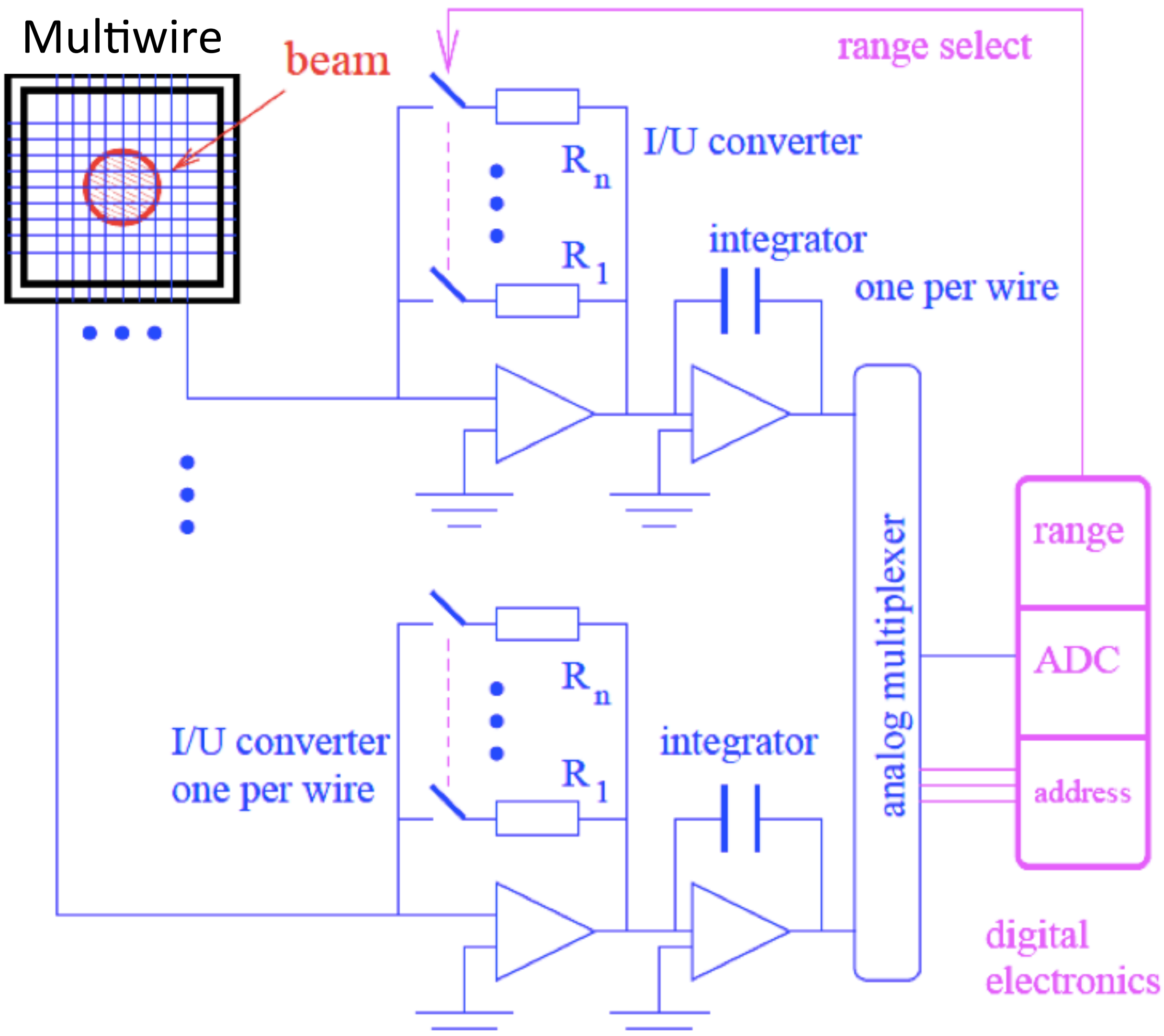
- "Secondary electron emission is like a 1-nm-thin ion chamber fastened to the surface of the wire (or foil), with a ionization energy of 25 eV (much like a gas) and a collection efficiency of ~50%" (M. Plum)
- To assure that the secondary electrons depart, apply a moderate bias voltage (< 100 V)

Plum

Multiwire Signal – Also Energetic Charged Particle Emission



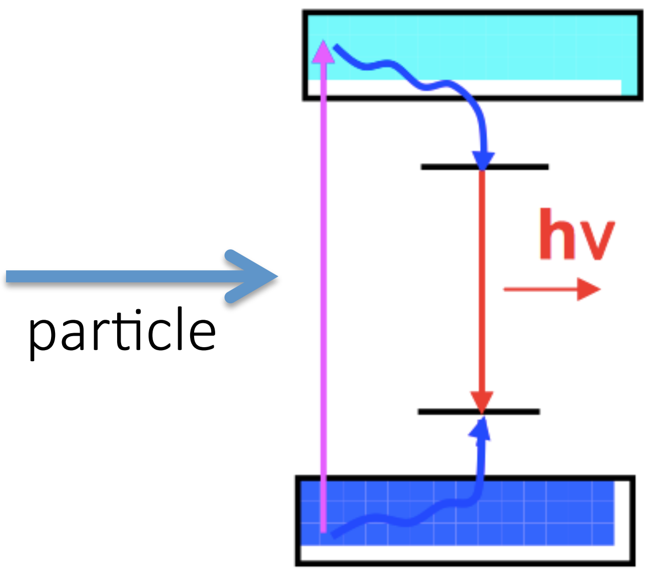
Multiwire Electronics



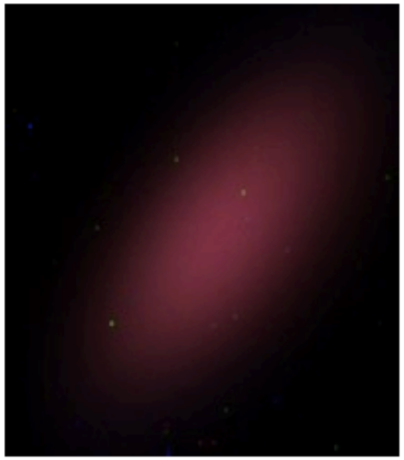
Option for lower latency detection of errant beam: independent digitizers and digital threshold comparison

Profile Monitor: Luminescence

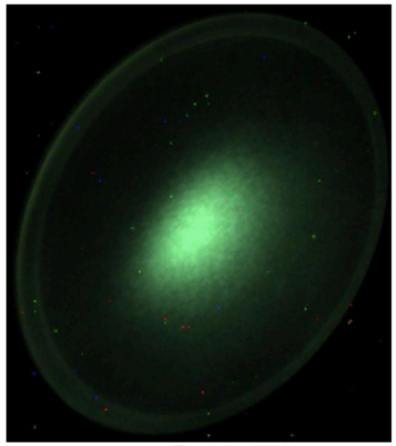
- Charged particle beam passing through thin layer of material deposits energy (calculate as usual).
- With a typical efficiency of order 1%, the deposited energy produces an excited state that eventually emits a useful photon as decay channel.
- Competing decay channels are modified with temperature, radiation dose, etc



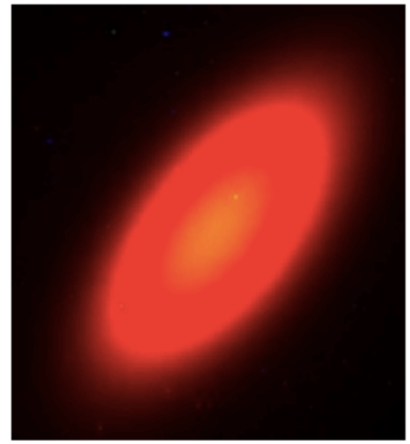
Profile Monitor: Luminescent Materials



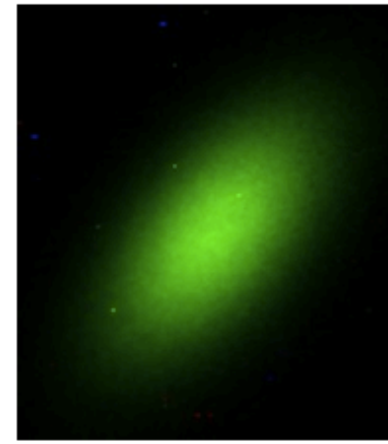
Al_2O_3



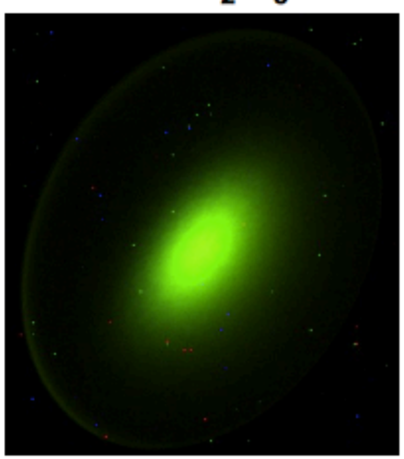
CsI:Tl



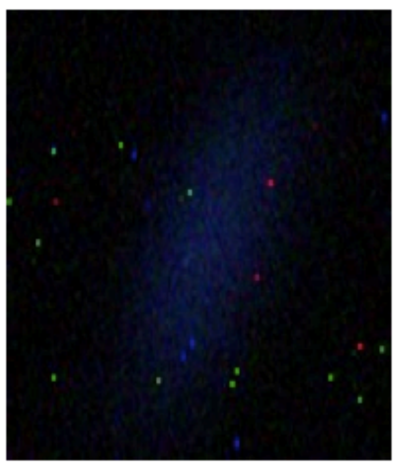
Al_2O_3:Cr



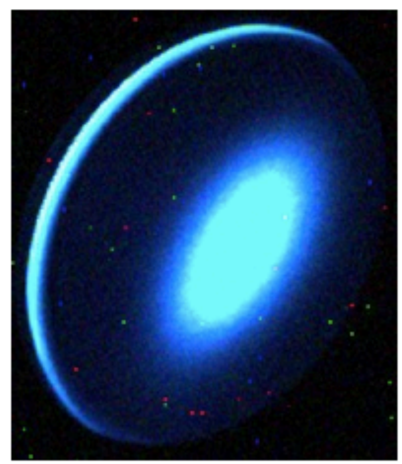
P43



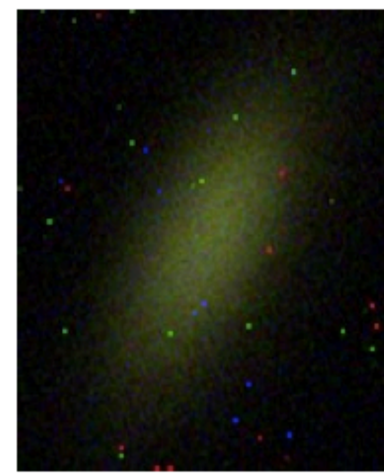
YAG:Ce



Herasil



Quartz:Ce

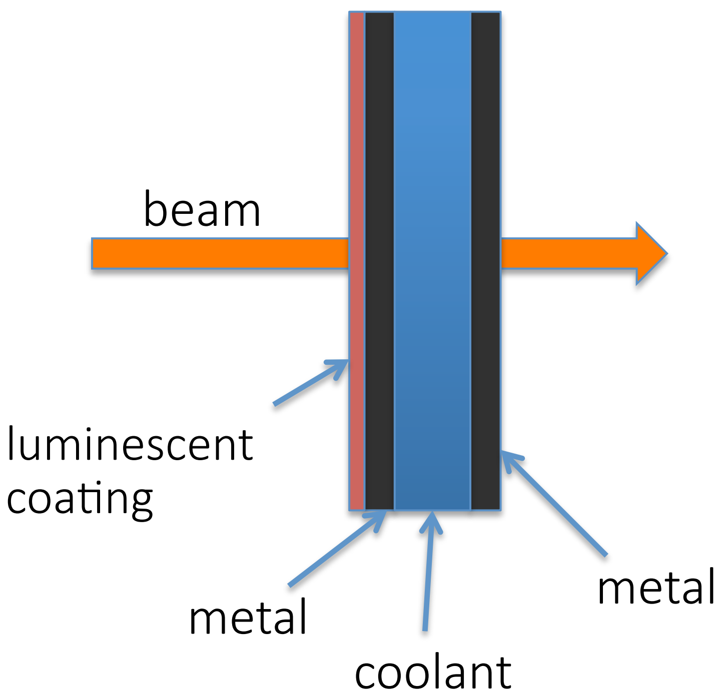


ZrO_2:Mg

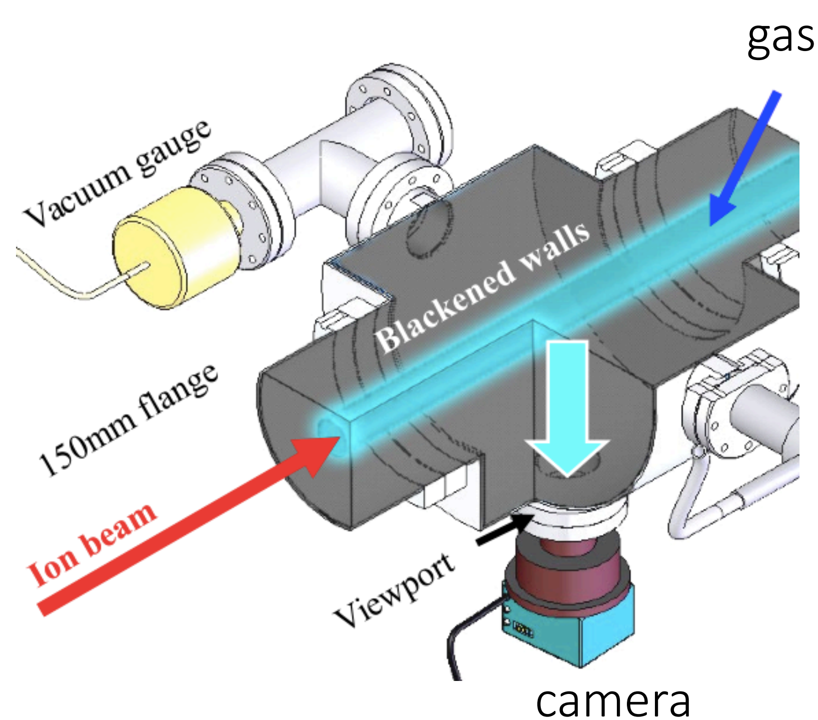
Profile Monitor: Luminescent Coatings and Gases

Inserting luminescent materials into the beam is invasive, but there are options for protection applications

Apply thin coating to cooled surfaces of targets and windows

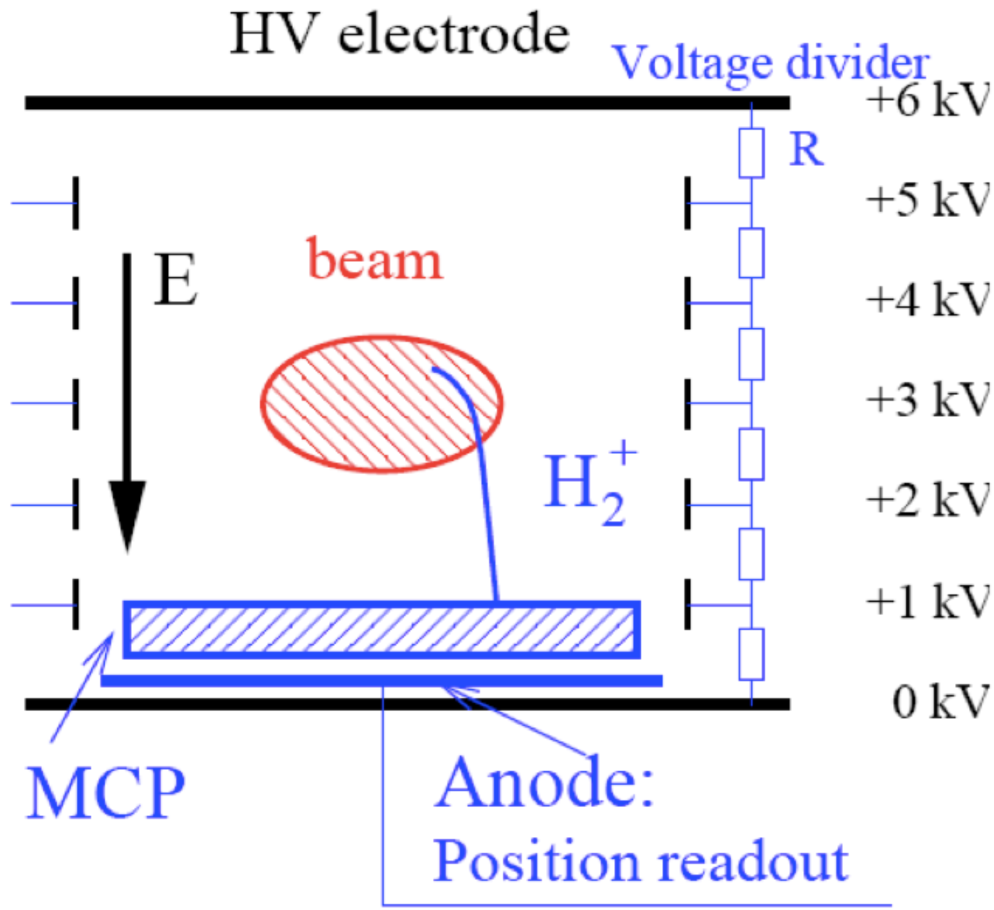


Use residual gas (N, H, or near targets, He)



Ionization Profile Monitor (IPM) Collecting Ions

- Beam ionizes residual gas (predict yield using the usual tools)
- Ions collected in transverse electric field
- Detector options
  - Micro-channel plate and metal strips. Electronics then looks like that of the multiwire grid
  - Luminescent screen and camera (usually intensified). Frame rate typically < 1 kHz.

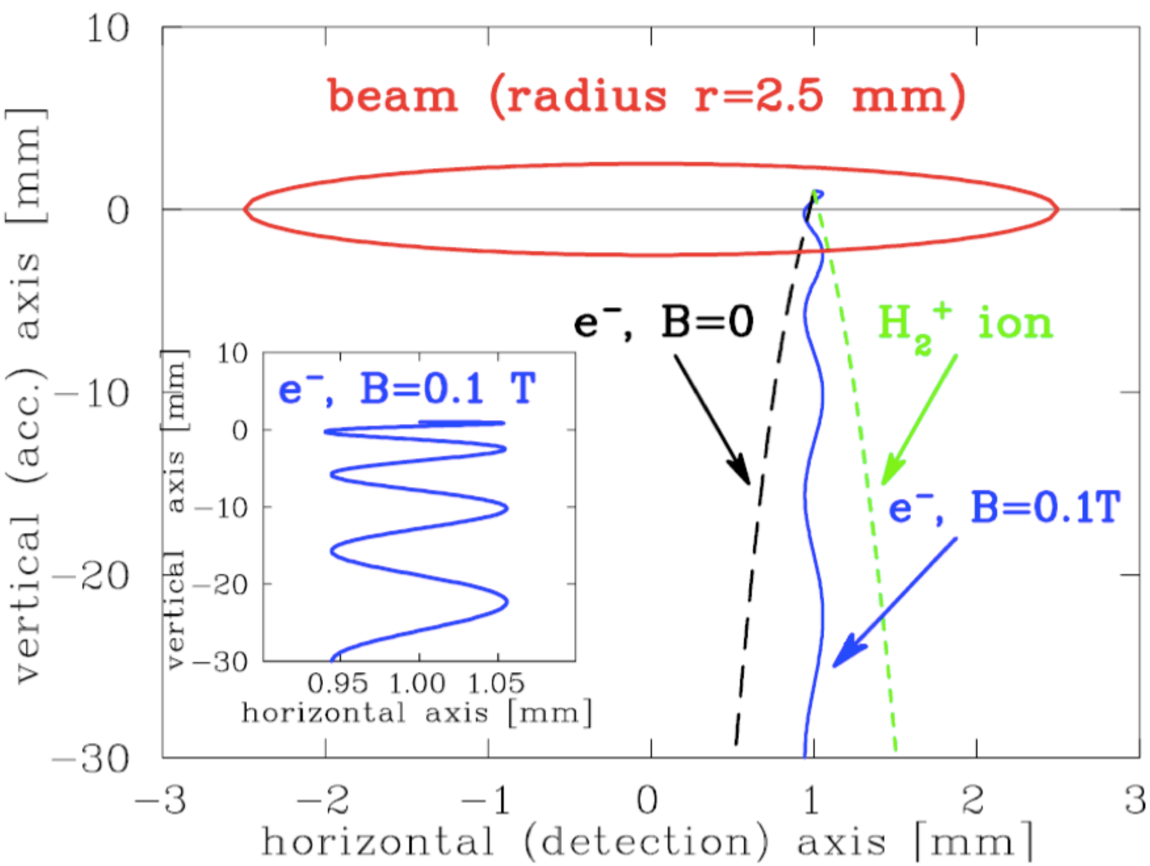


Ionization Profile Monitor Collecting Electrons

- Electronics collected in electric and magnetic fields
- Confined to small Larmor radius:

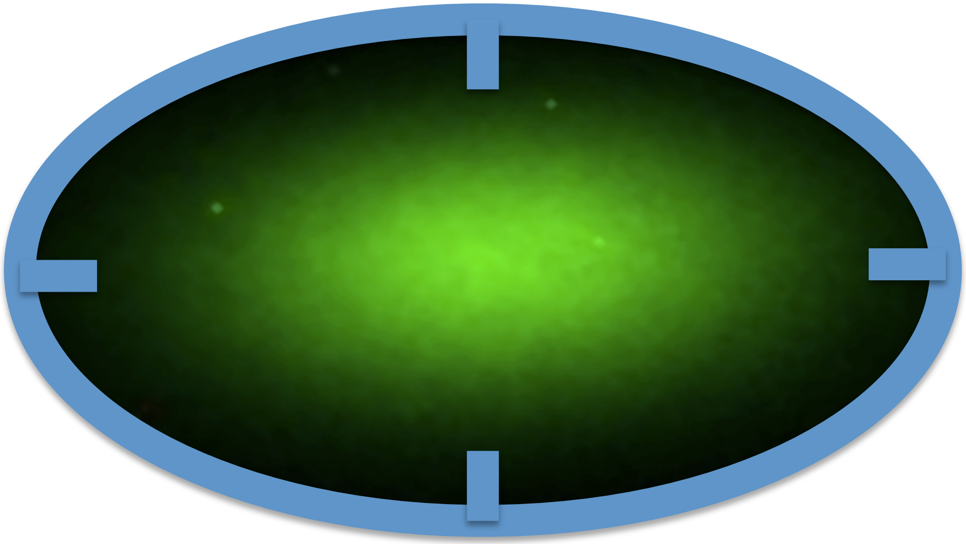
$$r_c = \sqrt{2m_e E_{kin,\perp}} \,/\, eB$$

- Same beam-gas interaction and electronics as for ion collecting IPM



Aperture Monitors

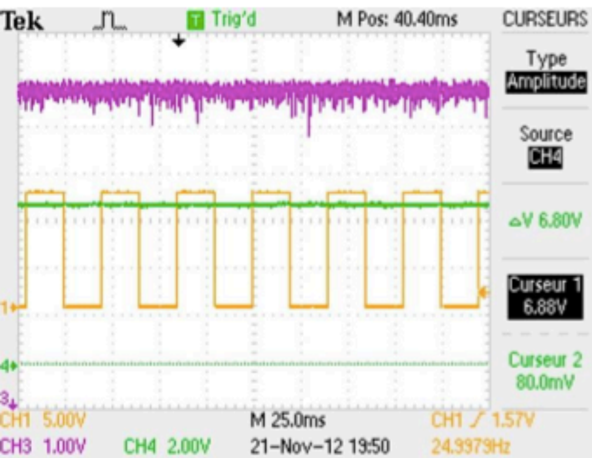
- Intercept a fraction of the beam near the aperture
- Options
  - Thermocouples
  - Deposition or secondary emission current
  - Shower to external detector



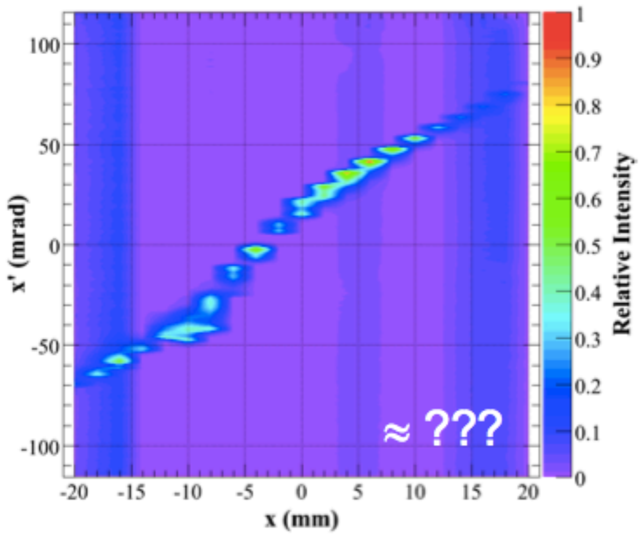
A Tour of Some Applications

Invasive Device
IFMIF Emittance Slit

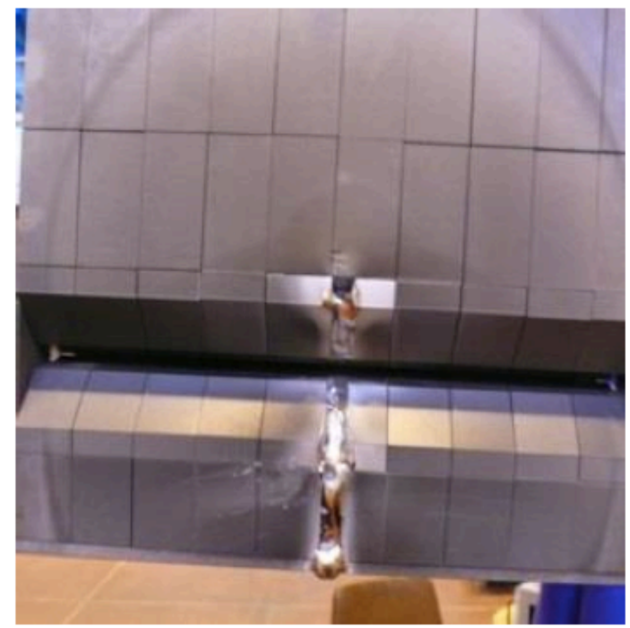
Pb… is the focused beam !!!



Continuous beam



Emitt. measurement

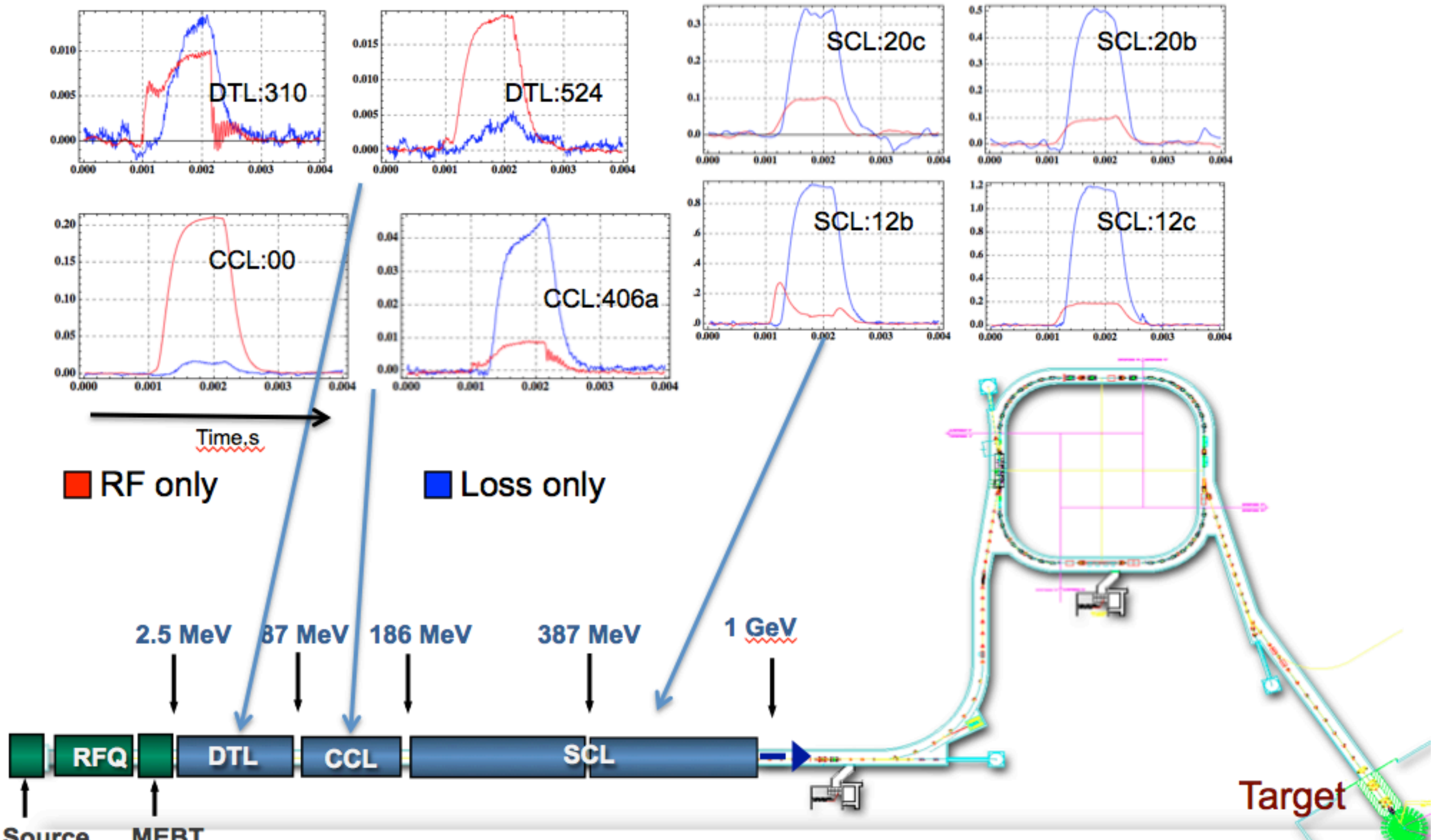


Recall: Tungsten melting point = 3500°C

An unprecedented D^+ beam of 140 mA at 100 kV
has been extracted and transported
(with I_{tot} = 175 mA and V_{puller} = - 42 kV)

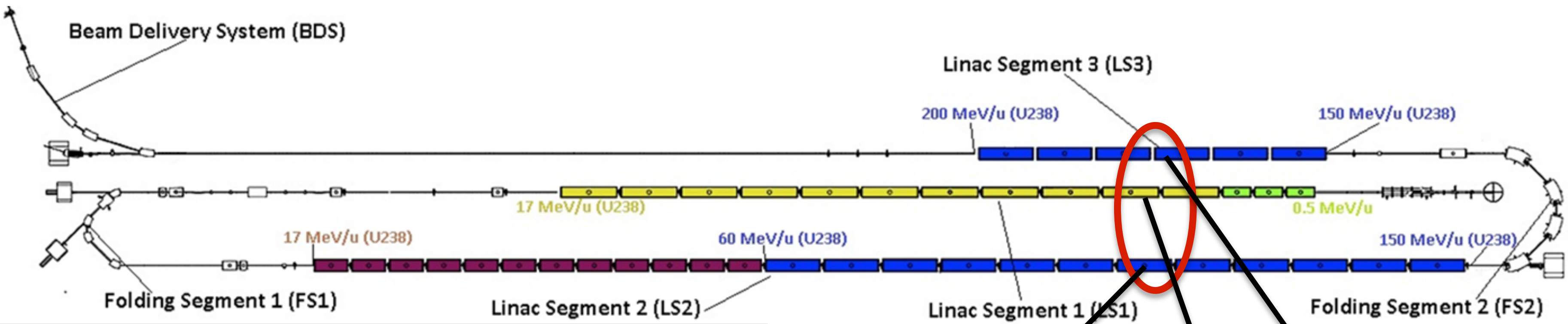
R. Gobin

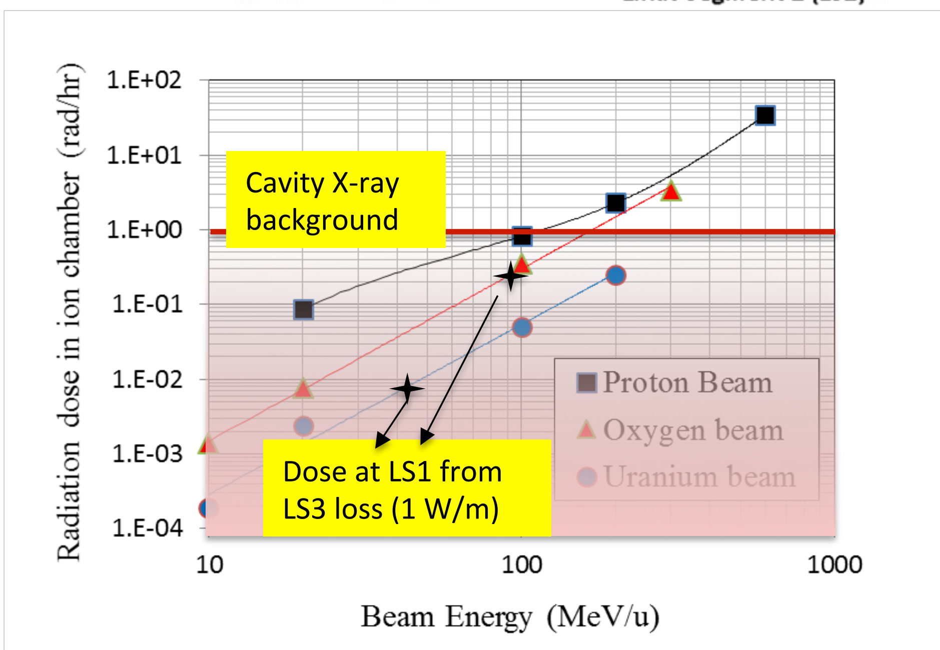
Ion Chambers in the SNS Linac Background from Cavities

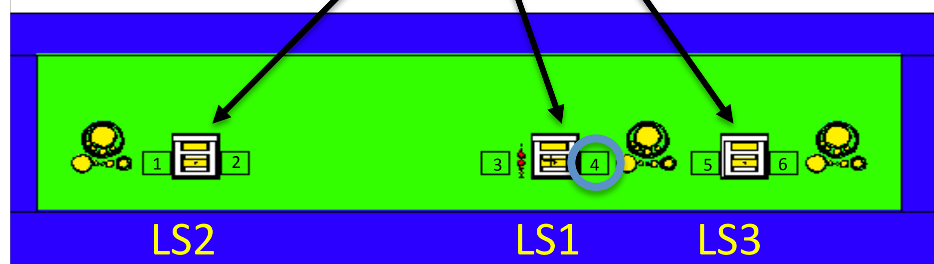


Zhukov

At FRIB: Crosstalk confuses spatial location and masks events





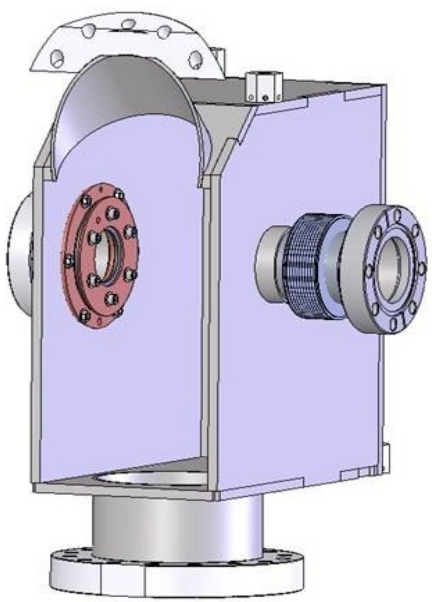


Neutron induced by 1 W/m ^{18}O loss	Flux at box 4 by LS1 loss	Flux at box 4 by LS2 loss	Flux at box 4 by LS3 loss
n/cm²/sec	1.03×10^5	5.81×10^5	3.2×10^6

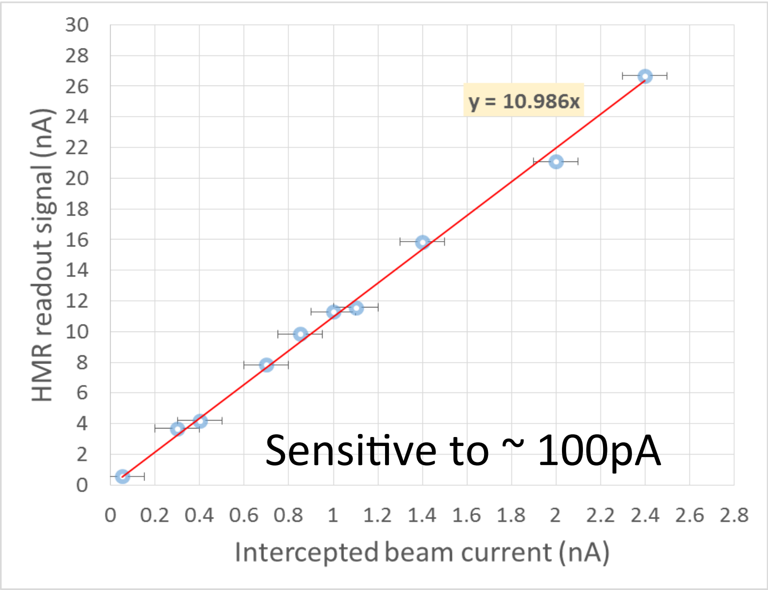
(Liu)

Another Option: Halo Monitor Ring (HMR) for FRIB

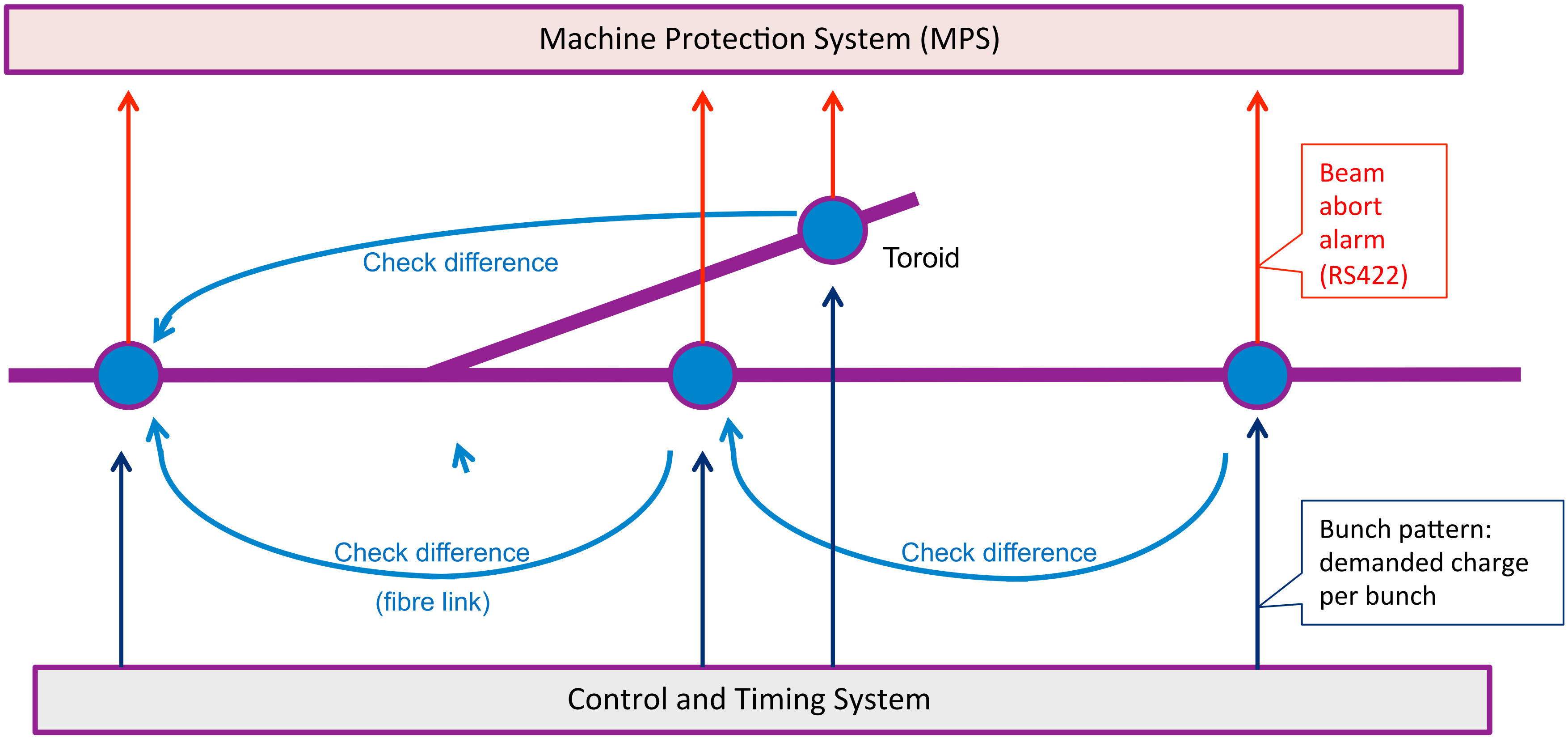
- The halo ring monitor is a niobium ring designed to intercept ions in the halo of the beam that are likely to be lost farther downstream
- It has high sensitivity (~0.1nA) for integrated small signal and fast response time (~10 µs) for large signal
- Optimize aperture based on fault mode studies. Monitor signal for large beam excursions. Install in warm sections between cryomodules



HMR measurement at NSCL with $^{18}O^{3+}$ at 11 MeV/u



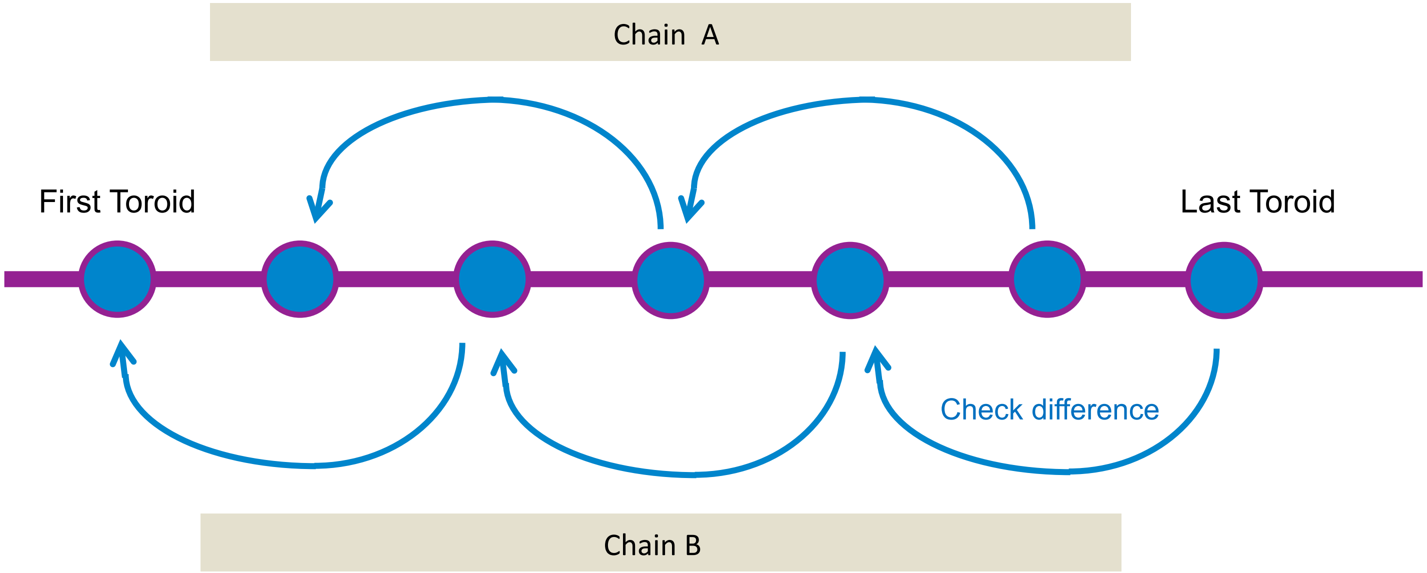
Toroid System: TPS principle for XFEL



- “Toroid Protection System“ (TPS) is one application of the Toroid system:
- Compare charge (bunch by bunch) of neighbored Toroids: abort beam if difference is too large
- Compare beam intensity with requirements from control system: abort beam if charge too high (too much produced, or beam to wrong destination) or too low (beam loss at previous section)

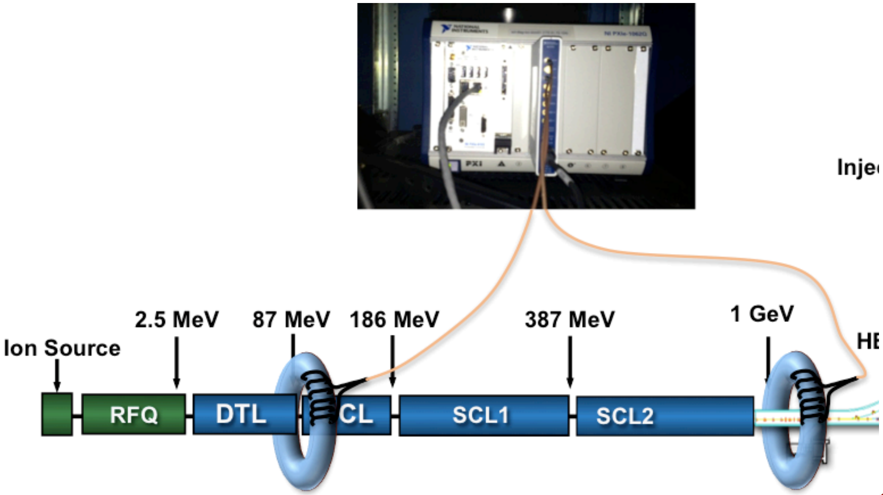
Werner

Toroid system: Redundancy, Availability



- Redundancy for the TPS functionality is added by interleaved fibre chains.
- If one Toroid fails (except the very first or very last device), the accelerator can still be operated with full TPS protection. This results in high availability.

SNS DBCM: difference in locations

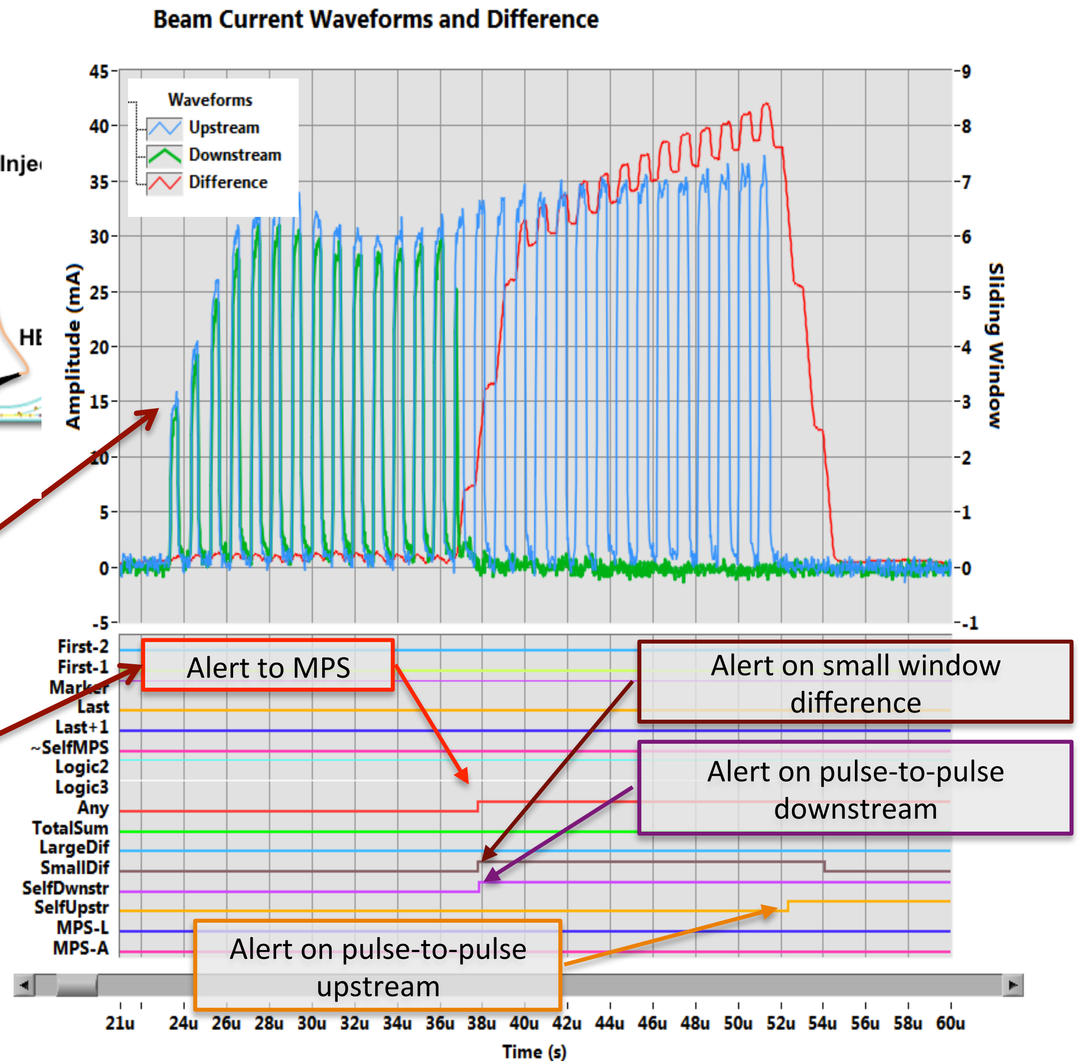


Waveforms:

1. Upstream (Blue)
2. Downstream (Green)
3. Difference after short sliding window (Red)

Alert was given in <1.5 μs (could be faster with lower thresholds and still avoid false alerts)

Analyzed to be due to a Warm Linac RF drop



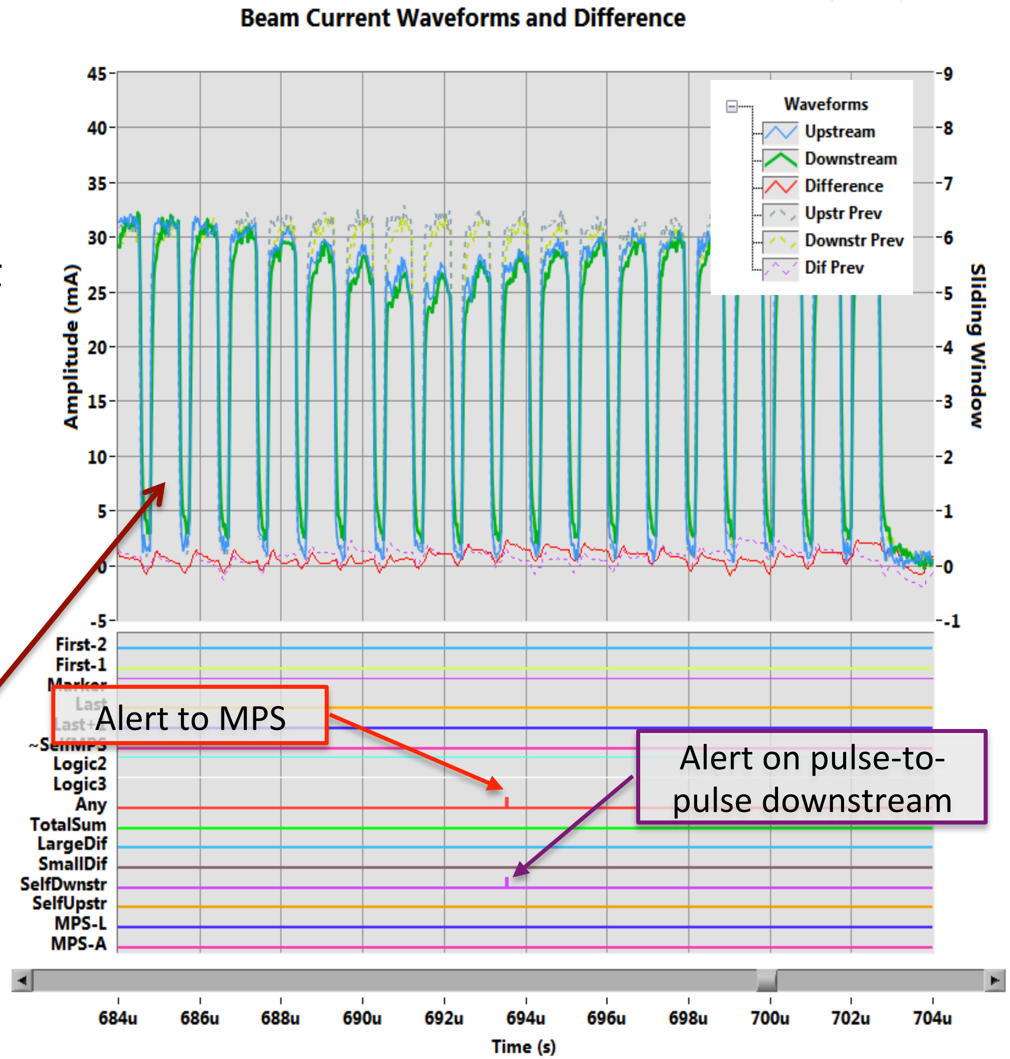
DBCM waveforms

SNS DBCM: difference in time

- Example of slow drop in current from pulse-to-pulse
- Analyzed to be due to RF Fill problem [2,3]
- Pre-mortem Analysis!

Waveforms for errant AND previous beam pulse:

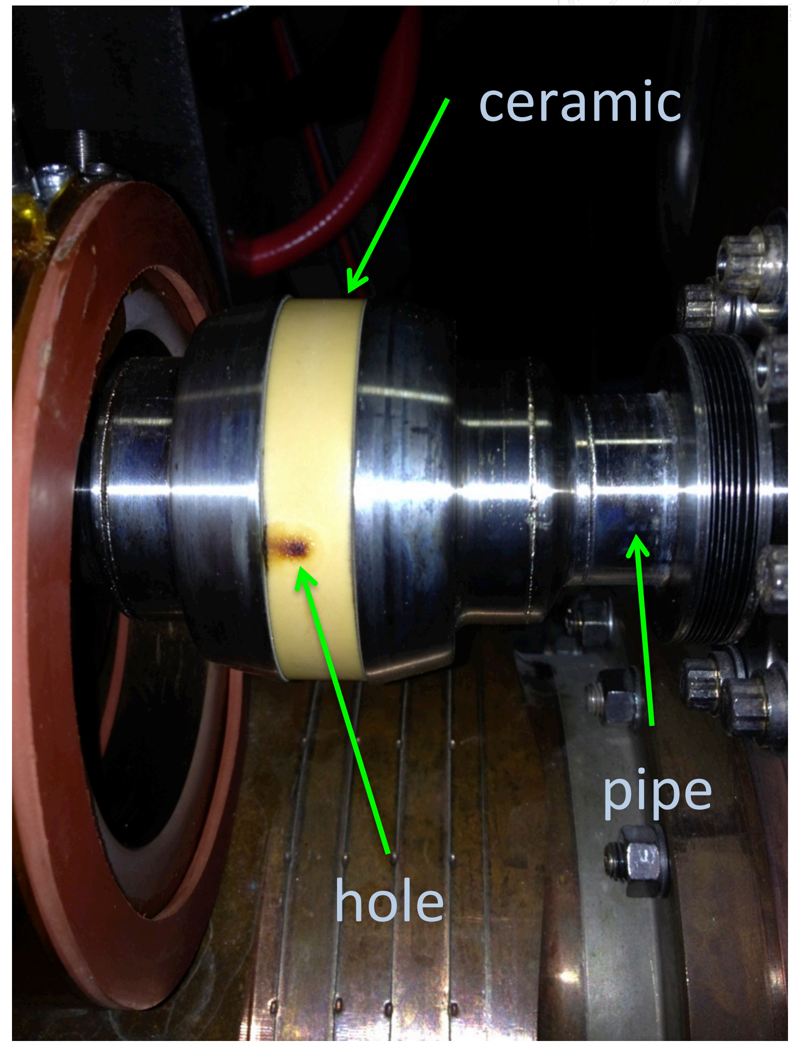
1. Upstream
2. Downstream
3. Difference



DBCM waveforms

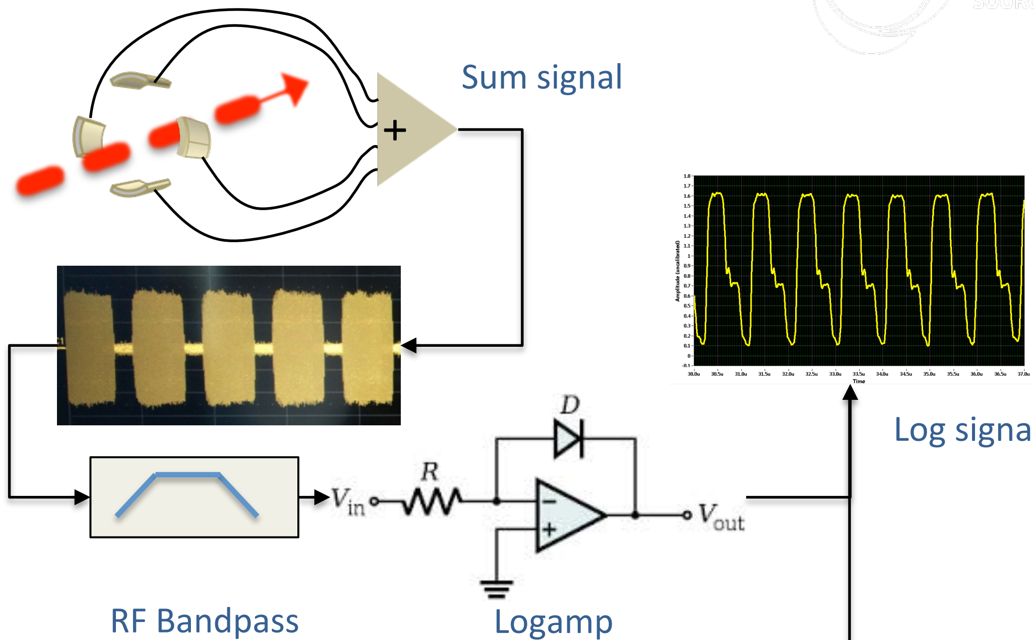
First current monitor is lost

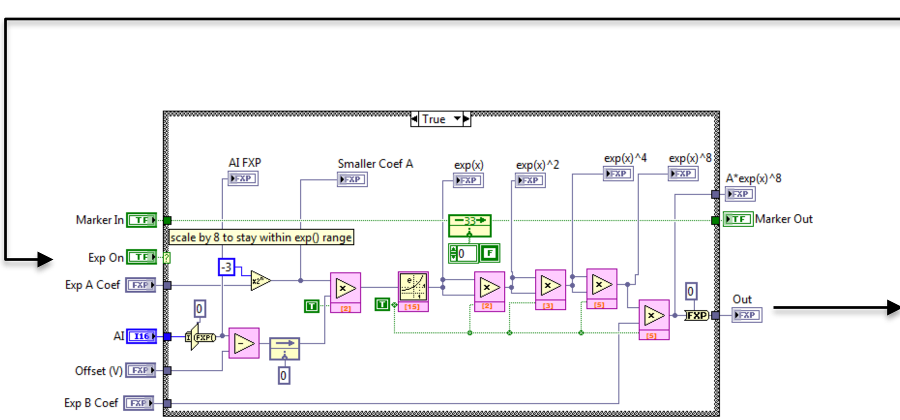
- Current transformer needs to see magnetic fields to measure current → ceramic break in beam pipe
- Hole burnt into ceramic causing vacuum leak! (RF electrons?) → BCM replaced with spool piece. Replacement is long term (aka years).
- No nearby current monitors that are suitable
- End of DBCM?



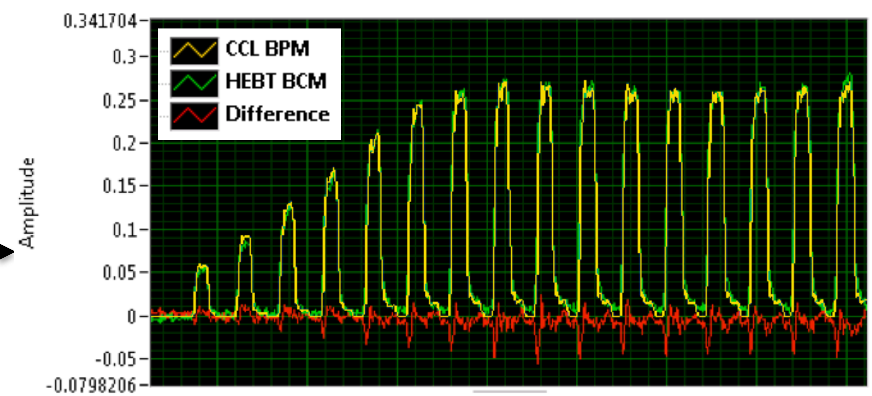
Current measurements using BPMs

- Beam Position Monitor:
  - ✓Use sum from all four plates
  - ✓Use demo log-amp board with band-pass filter in front
  - ✓Add correction in FPGA with exponential function
  - ✓Use existing BCM as reference for calibration
  - → We got our DBCM back and extra locations!





FPGA code to correct log signal

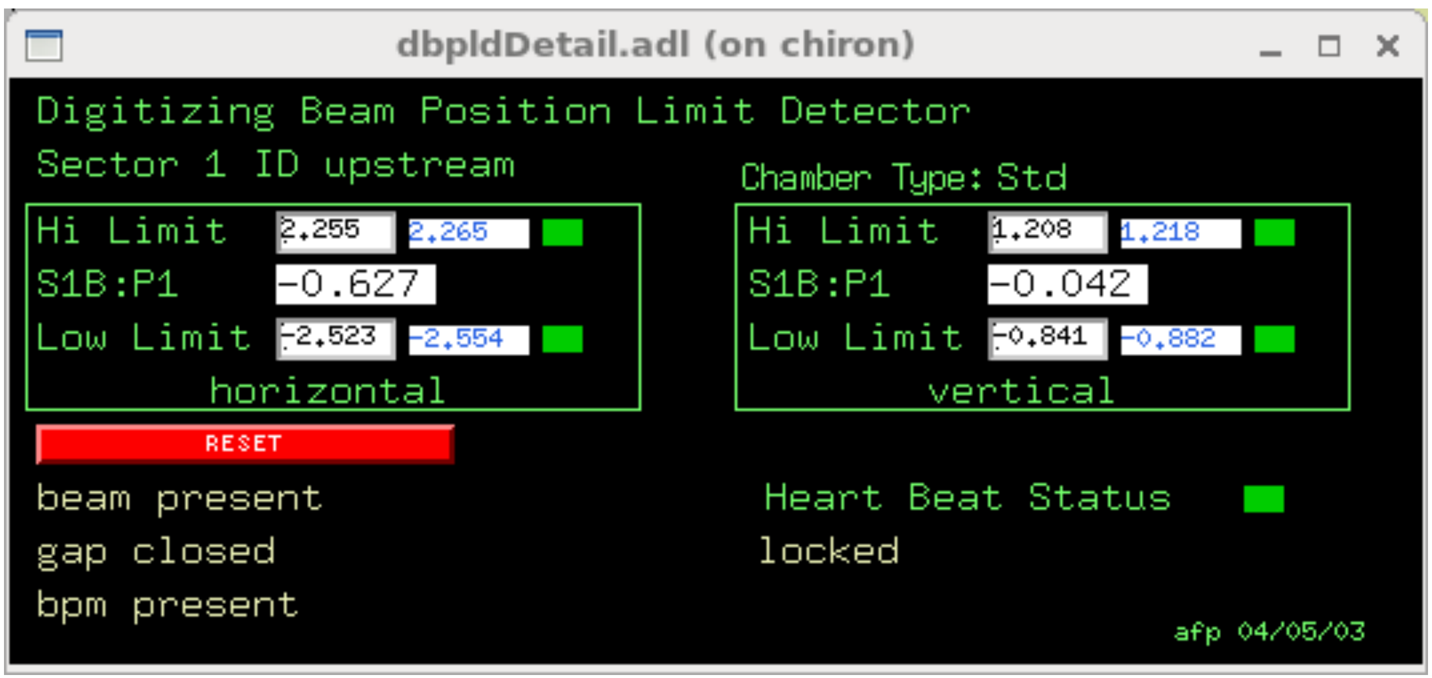


Final signals. Calibration done using downstream BCM

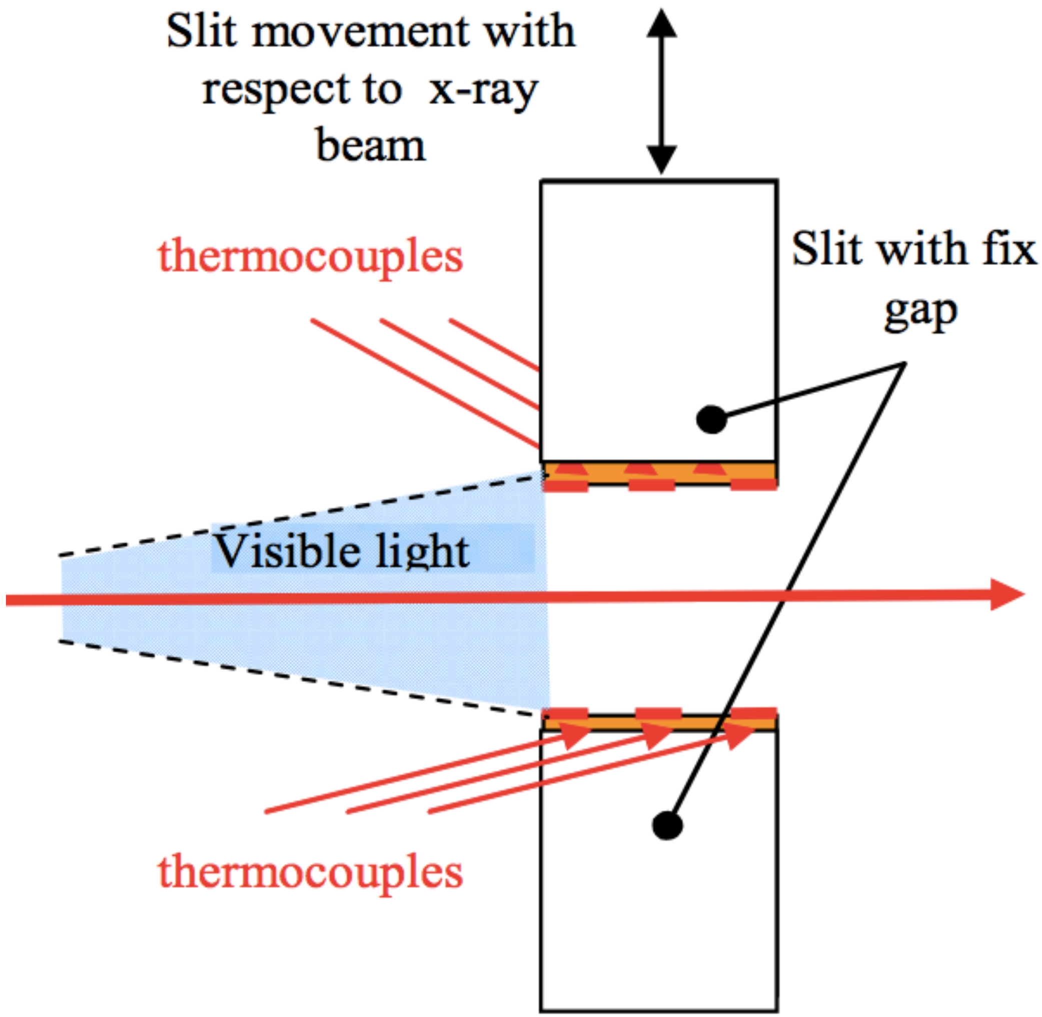
3rd Generation Light Source (APS and Diamond): Position Limit Detection

- For standard chambers, order of limit intervals: millimeters. (at Diamond: 172 BPMs have a ±1 mm interlock limit at 10 kSa/s)
- Heartbeat

APS screen

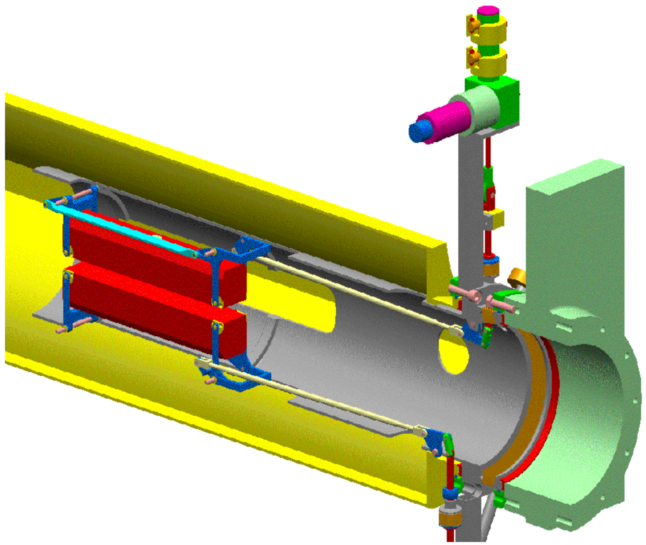


3rd Generation Light Source (Soleil): Instability Monitor, Orbit Monitor



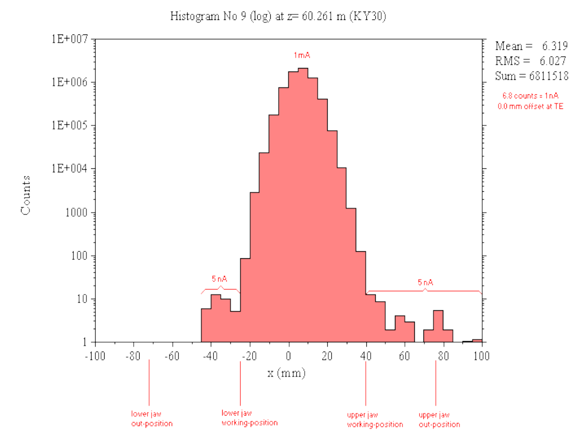
- Position
  - Initially, +/-1 mm limit, vertical only on 32 of 120 button BPMs
  - Then both horizontal and vertical
- Beam size
  - Instabilities can enlarge beam
  - Detect increased thermal load driven by synchrotron radiation
  - Thermocouples read out by PLC

Slit KHNY30 Test at PSI for MEGAPIE



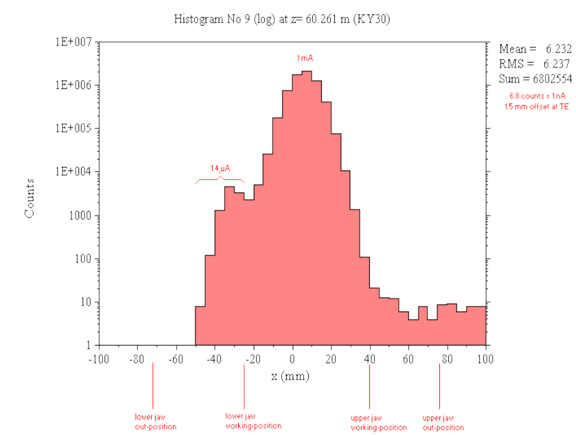
- Path for improperly scattered protons blocked, current of jaws monitored
- Interlocked, but massive copper bars provide even short-term passive safety
- Confirmed sensitivity at the 0.1 % level

well centered beam



beam shifted 1.5 mm

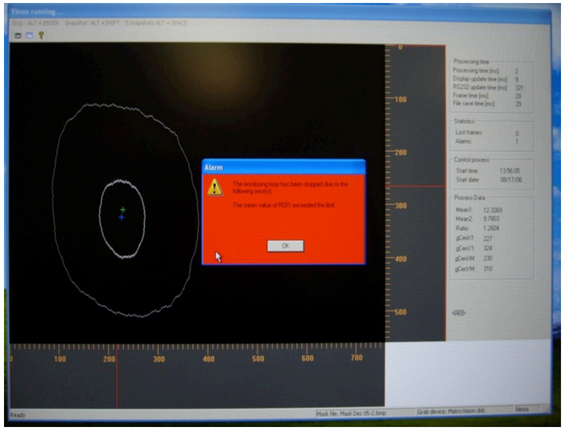
appr. 0.1 % protons by-pass Target E

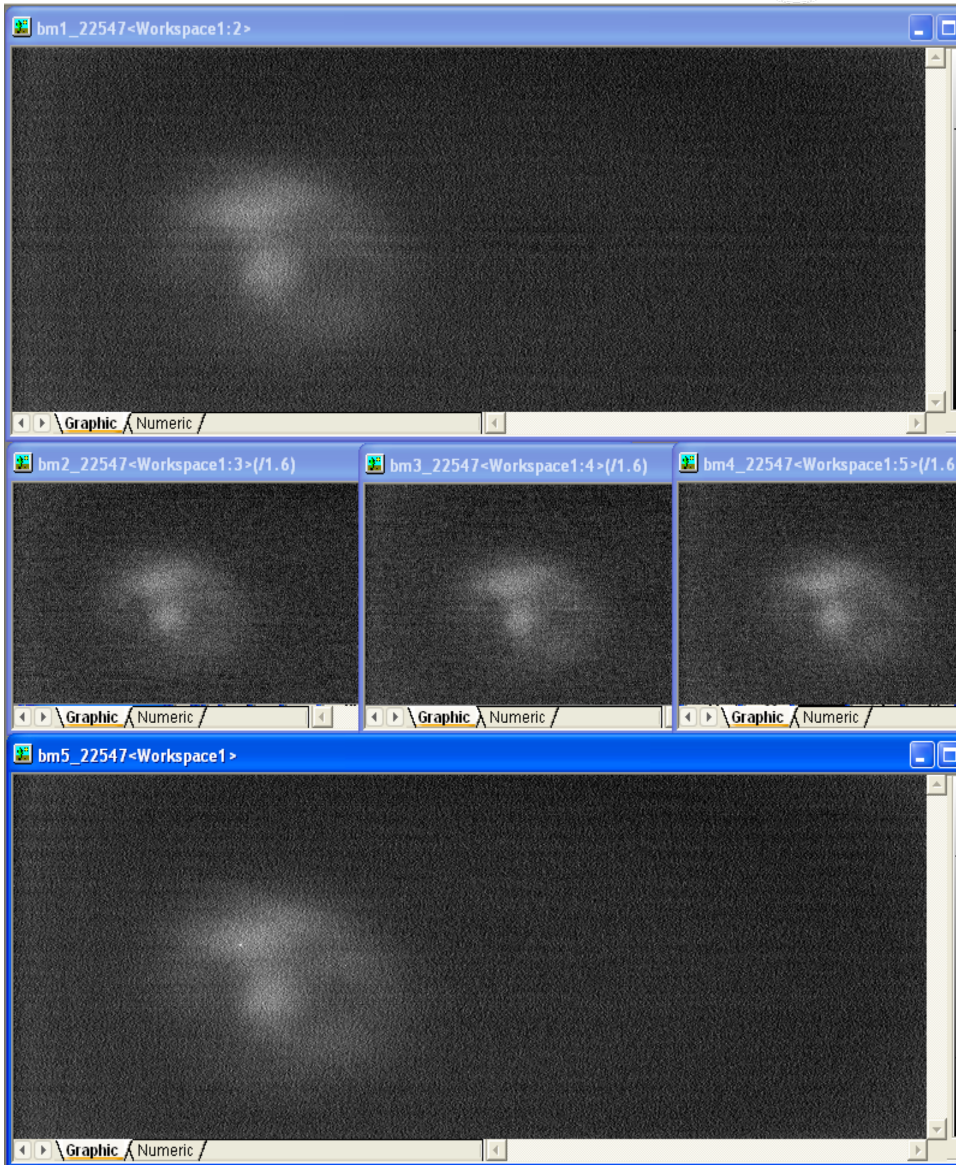


K. Thompsen

Also at PSI, VIMOS trigger test @ 900 µA

- Glowing tungsten mesh heated by beam
- At reduced beam current, very low emission in NIR and visible

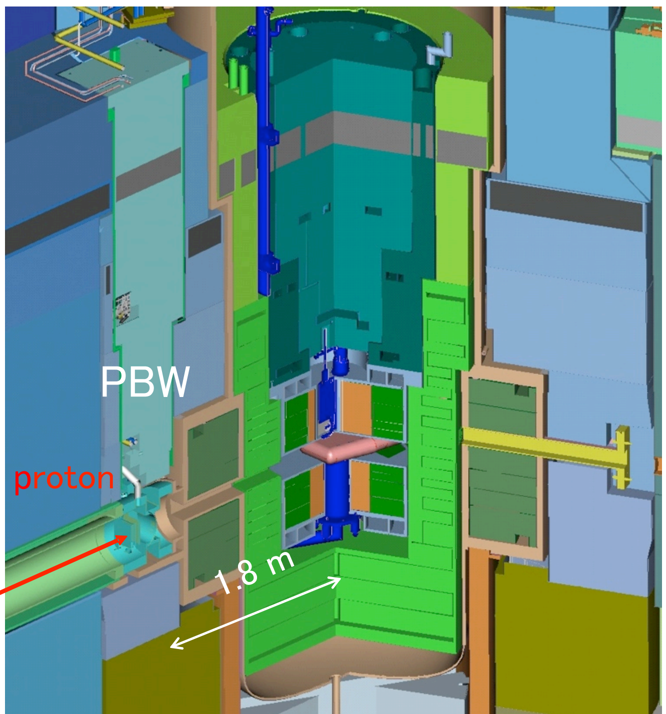




K. Thompsen

J-PARC: Beam monitor around target

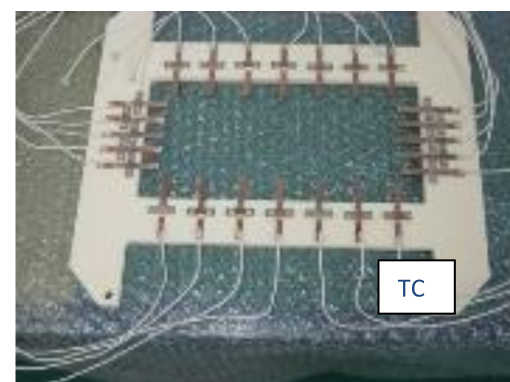
- Beam monitors placed at
  - Proton Beam Window (PBW)
  - Beam entrance at target station

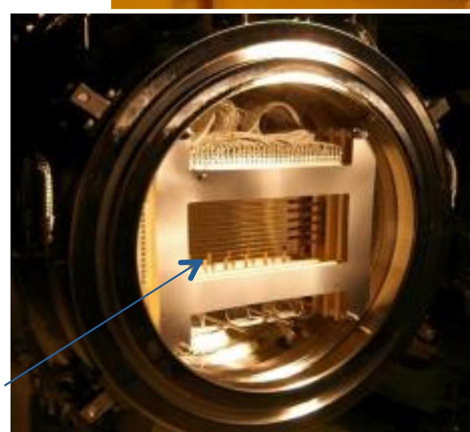


Entrance of beam

Thermo couple(TC)

Beam halo monitor
･SEC(Secondary electron)
･ TC (Thermo couple)



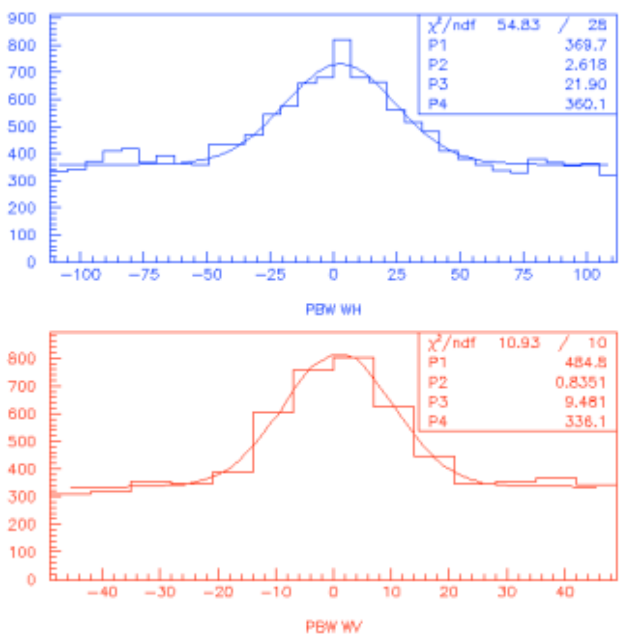


Multi Wire Profile Monitor (MWPM)

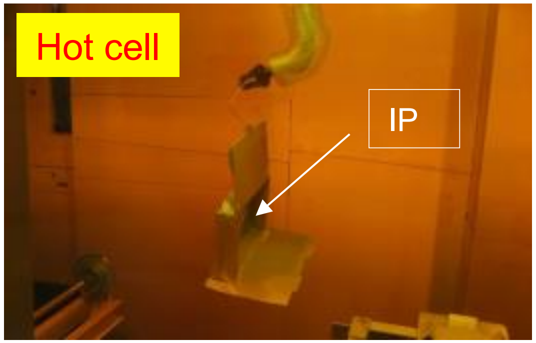
Beam protection system at J-PARC

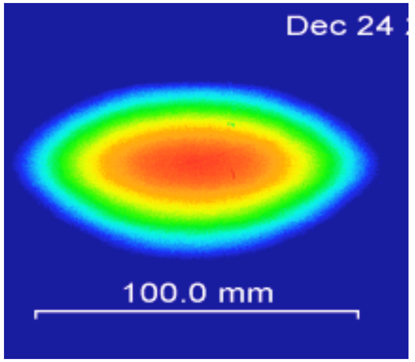
- Beam monitors for target
  - MPS stopped automatically when anomaly found at profile
  - Periodically 2D profile observed at the target

Watched continuously:
peak and position



Offline: 2D profile at the mercury target observed by Imaging Plate(IP)

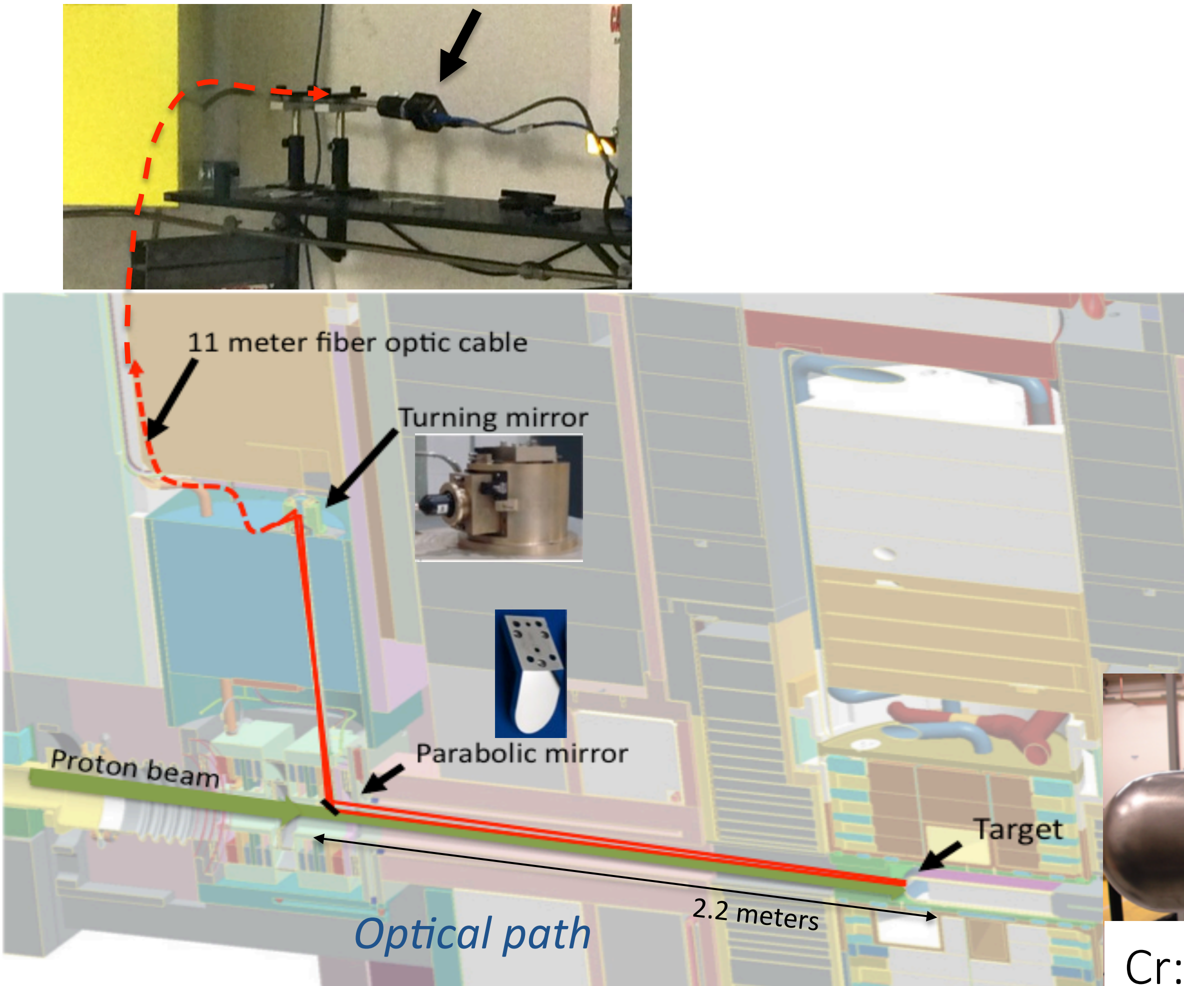


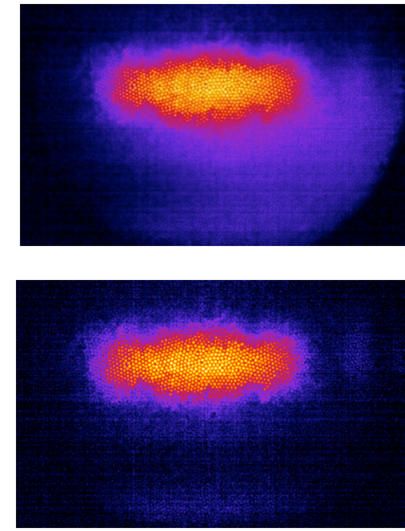


Meigo

Target Imaging System (TIS) at SNS

GigE Camera, single pulse acquisition





With and without
He gas scintillation

Cr:Al2O3 thermal
sprayed coating

Bonus material

Let's protect the 5 MW ESS target station
(high level conceptual summary and status report)

Instrumentation and Machine Protection Strategy for the ESS Target Station

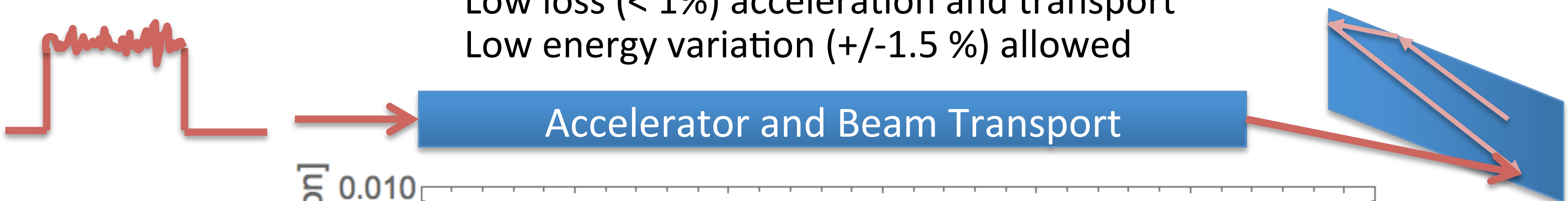
Thomas Shea, Linda Coney,
Rikard Linander, Andreas Jansson,
Eric Pitcher, Annika Nordt, Cyrille Thomas,
Heine Thomsen

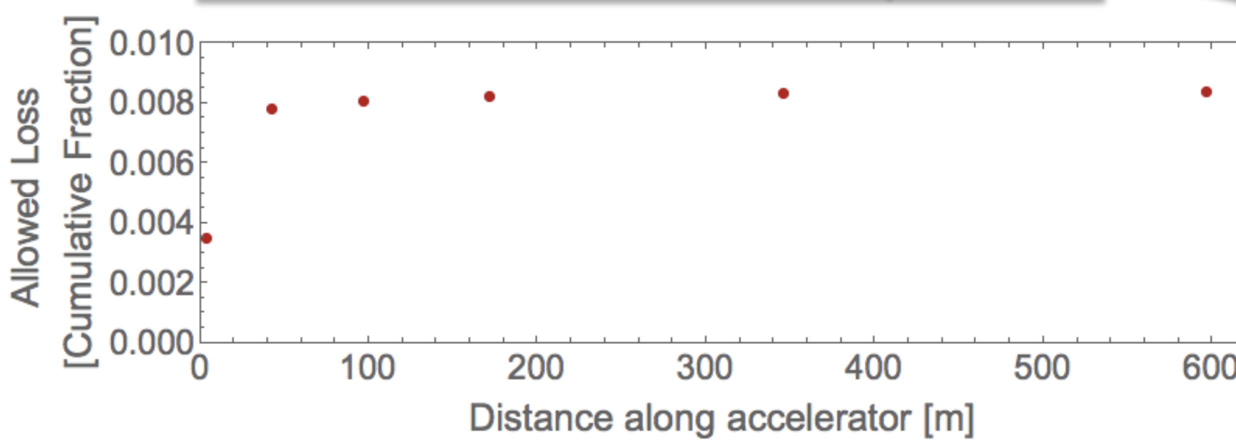
ESS Proton Beam Acceleration and Transport

1. Ion Source and RFQ produces proton pulses

2. Raster System scans proton beam across target

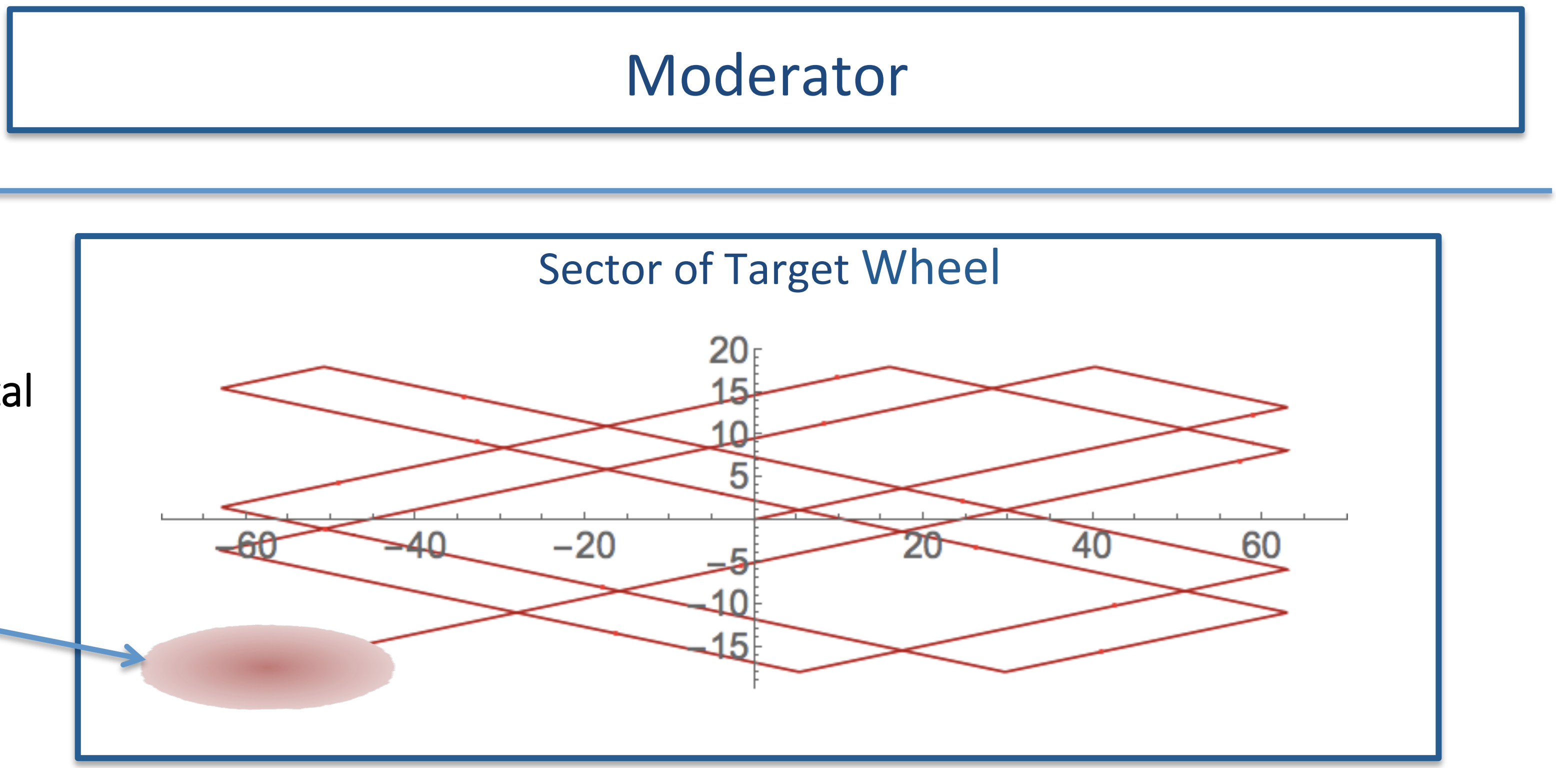
Low loss (< 1%) acceleration and transport
Low energy variation (+/-1.5 %) allowed





Raster Pattern

Conceptual view of target and upper moderator
(Downstream view)



Raster scanning frequencies:

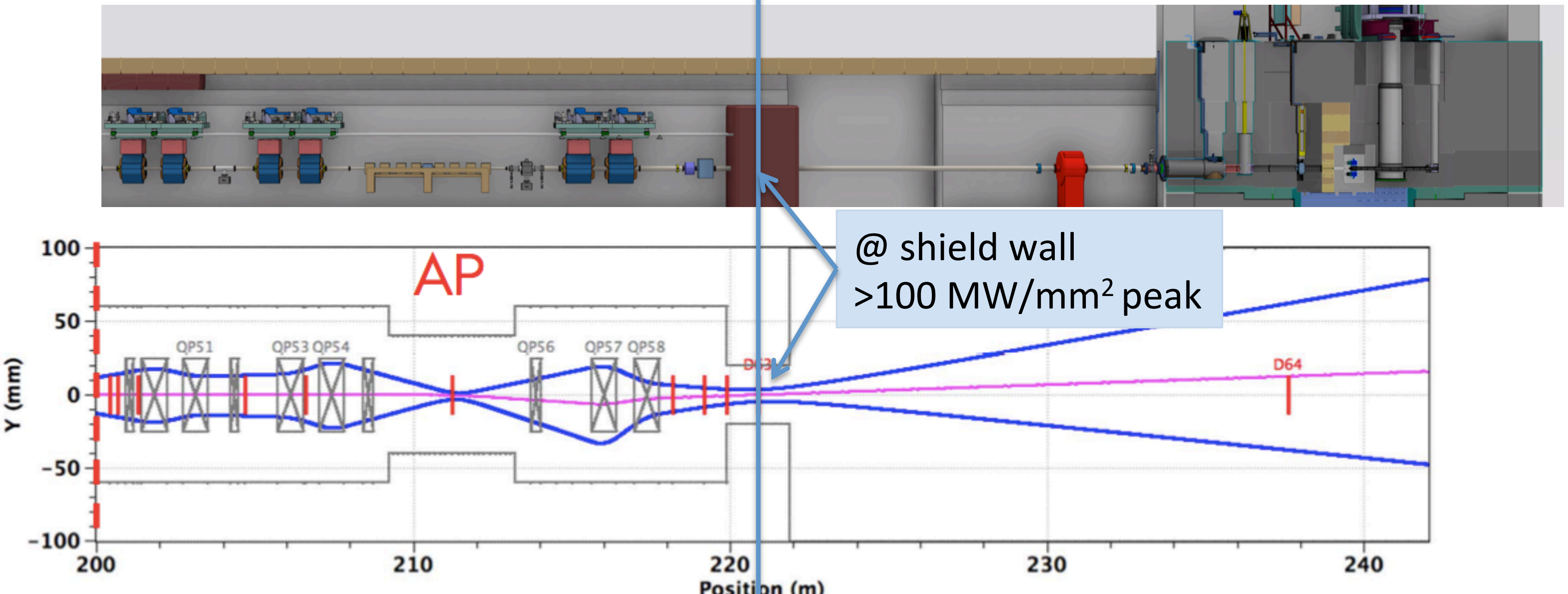
40 kHz Horizontal

29 kHz Vertical

Gaussian beamlet

Two Regions, Two Rulebooks

Accelerator region | Target region



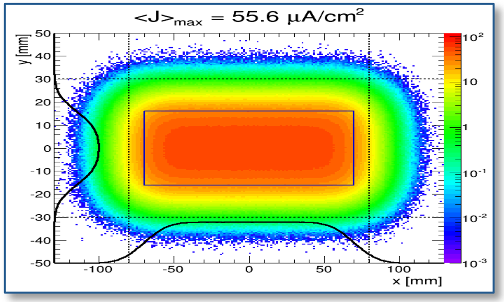
- Small beam in large aperture
- 1 W/m onto components
- Hands-on maintenance

- Large beam to target/moderator
- 5 MW onto components
- Remote maintenance

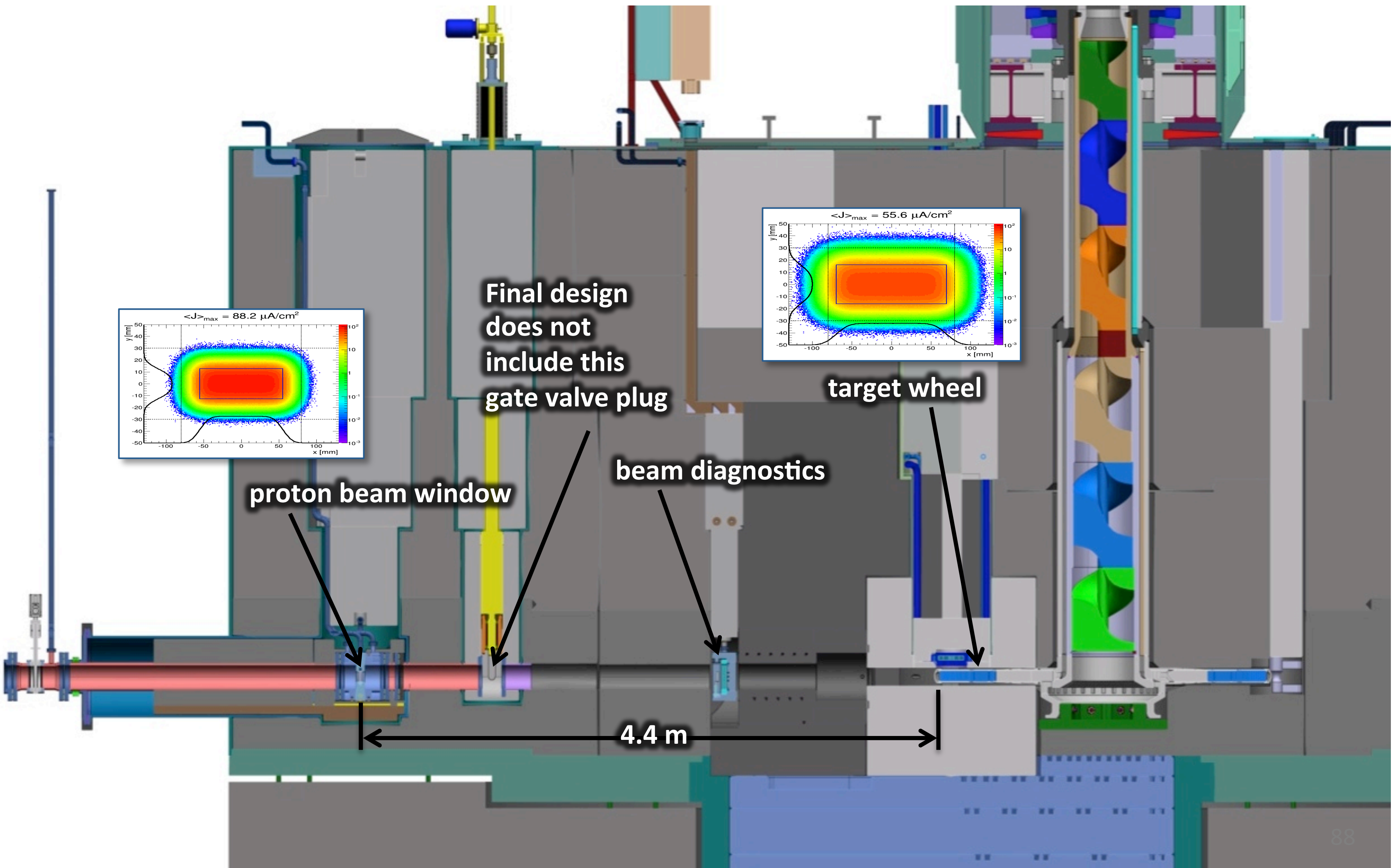
Beam on Target Parameters

Beam footprint enclosing 97.5% beam fraction	180 mm (horizontal) 60 mm (vertical)
Nominal time-averaged peak current density	56 µA/cm^2
Max displacement of footprint from nominal position	±5 mm (horizontal), ±3 mm (vertical)
Nominal RMS size of Gaussian beamlet	16 mm (horizontal) 5.3 mm (vertical)
Raster frequencies	40 kHz (horizontal) 29 kHz (vertical)

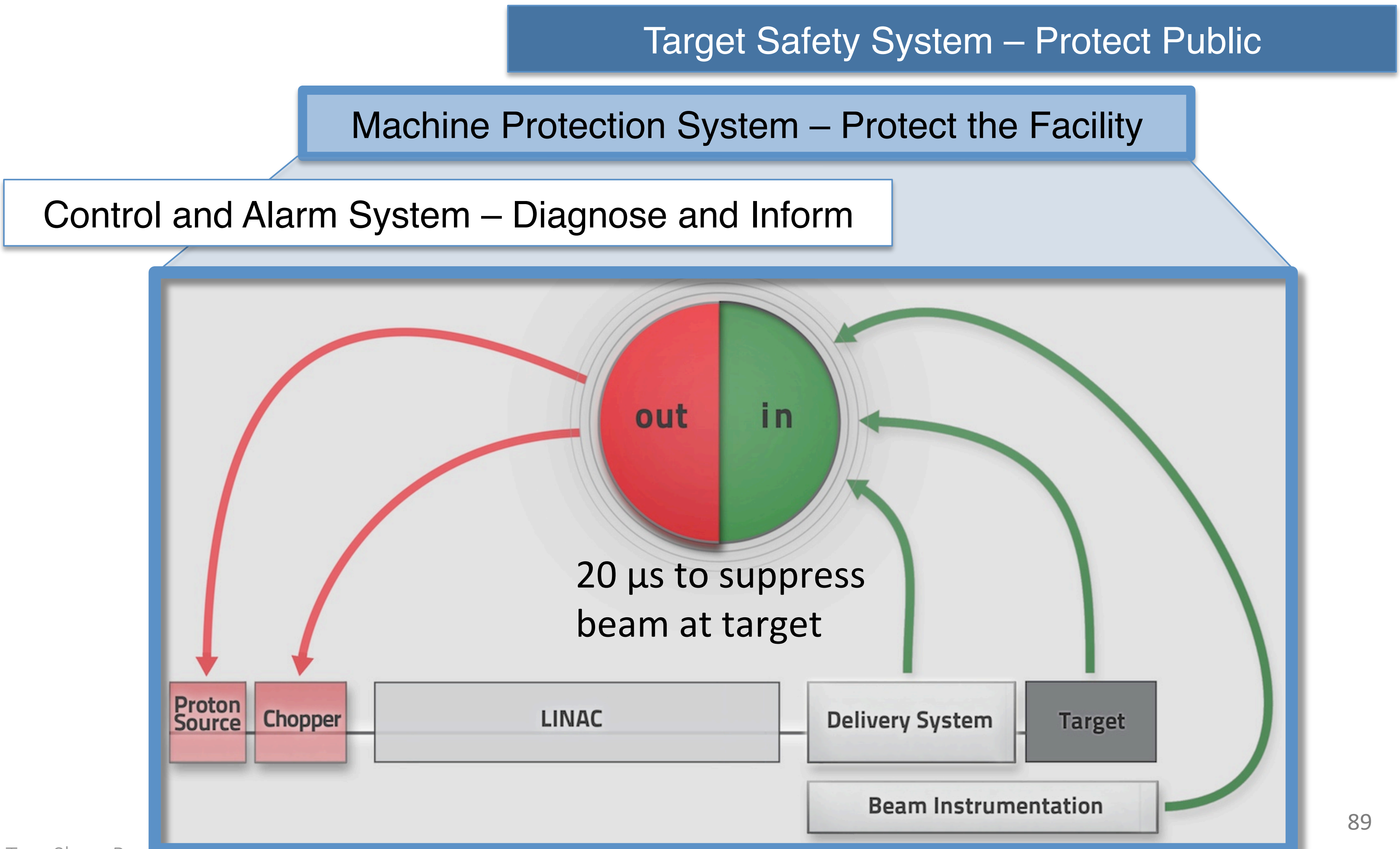
- Higher nominal current density (89 µA/cm^2) on proton beam window due to geometry.
- Nuclear scattering from window is not included in above parameters



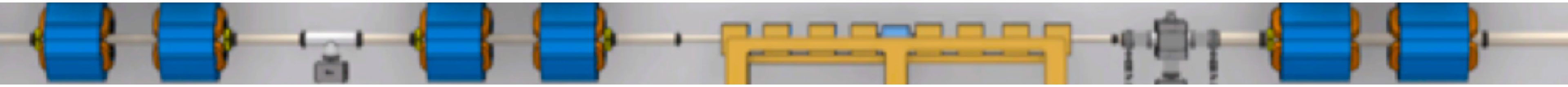
Monolith and beam image

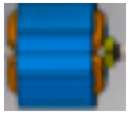
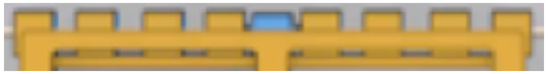


Graded Active Protection

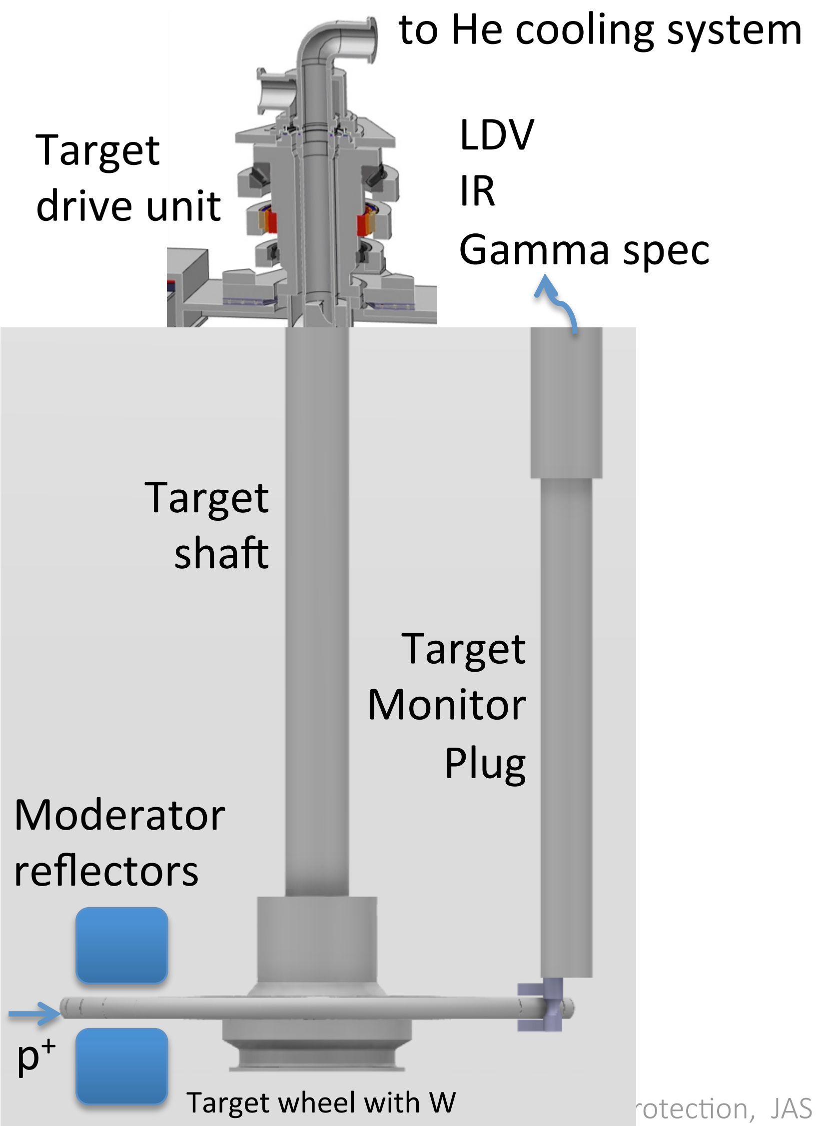


Beam Delivery System Instrumentation



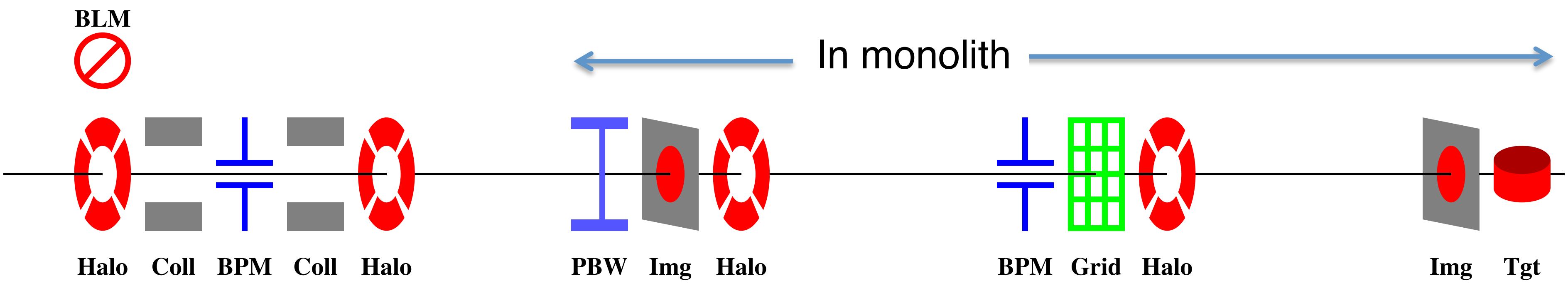
- Monitoring DC magnet systems: 
  - Voltage and Current at power supplies for dipoles, quadrupoles, and correctors
  - Option for field measurement
- Monitoring raster system: 
  - Waveform template comparison: voltage, current, B-dot
  - Relative to timing system and to beam current signal

Target System Instrumentation Candidates for Machine Protection



- Helium cooling system instrumentation
  - Flow and Temperature monitors
  - Radioisotope sampling
- Instrumentation on the target drive unit
  - Rotary encoders, magneto resistive sensors
  - Vibration and balance monitors
  - Motor and bearing condition monitors
- Short-lived wheel instrumentation for calibration
  - Thermocouples
  - Strain gauges and accelerometers
- Target monitoring
  - Laser Doppler Vibrometer (LDV)
  - Infrared temperature measurement
  - Visible imaging

Proton Beam Instrumentation



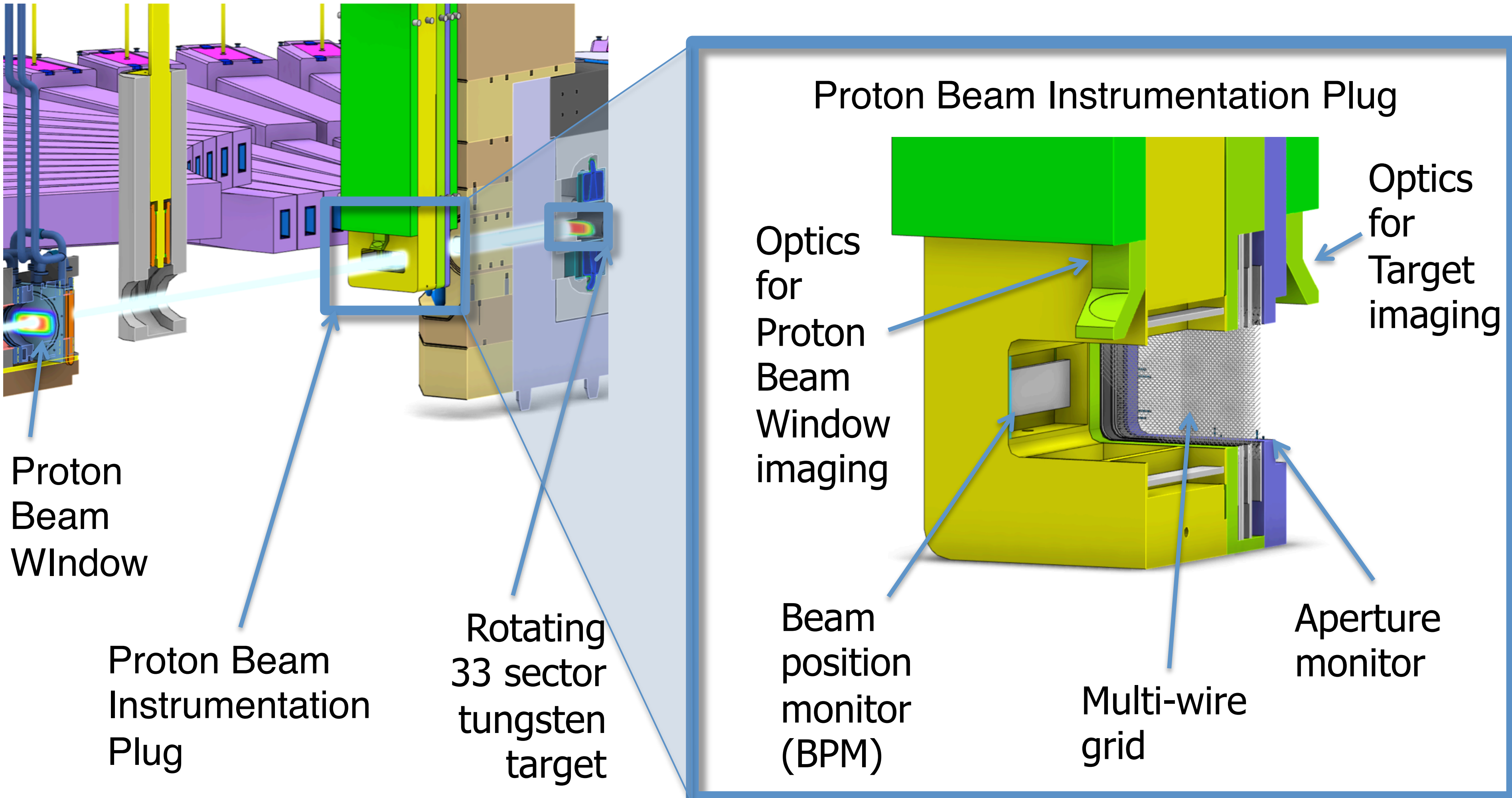
In accelerator tunnel

- Loss monitors
- Position monitors
- Aperture Monitor
- Current monitors

In-monolith

- Aperture Monitor
- Position Monitor
- Grid
- Imaging Systems

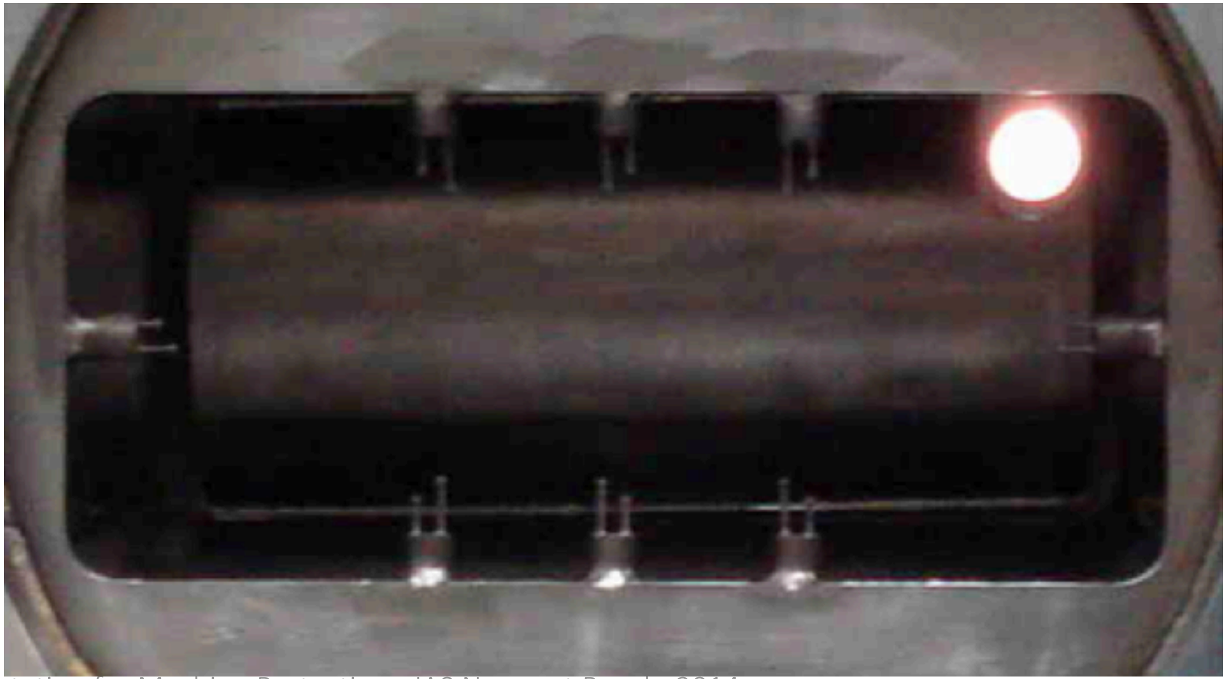
Proton Beam Instrumentation Plug in monolith



Upstream: position, current, aperture, and loss monitors

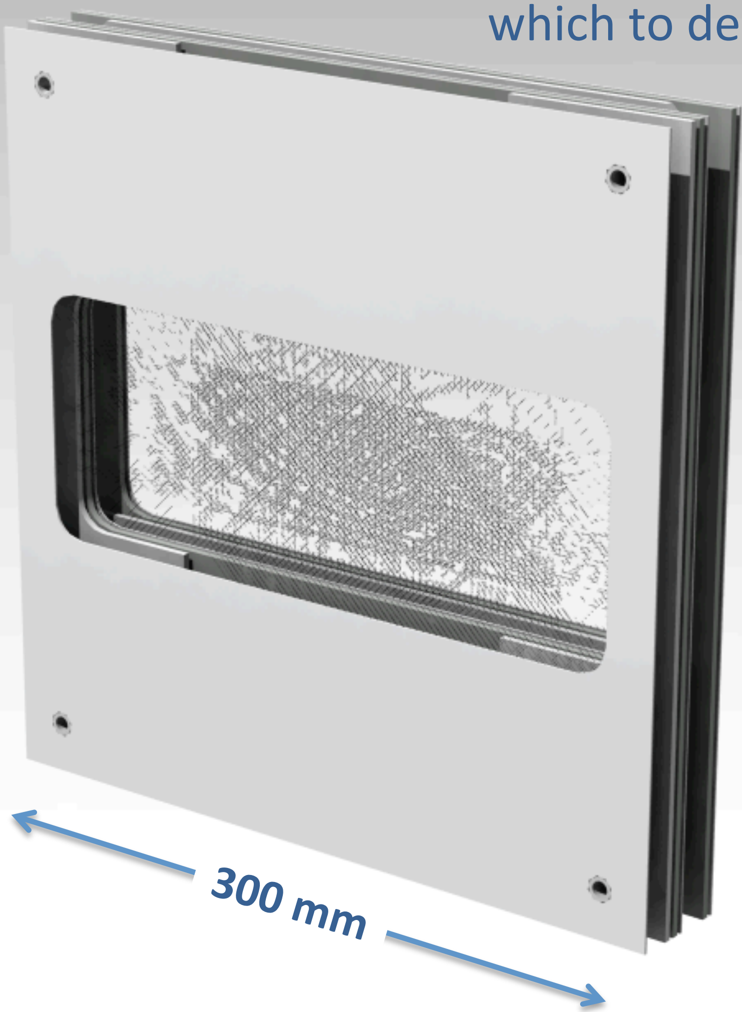
Aperture Monitors in Monolith

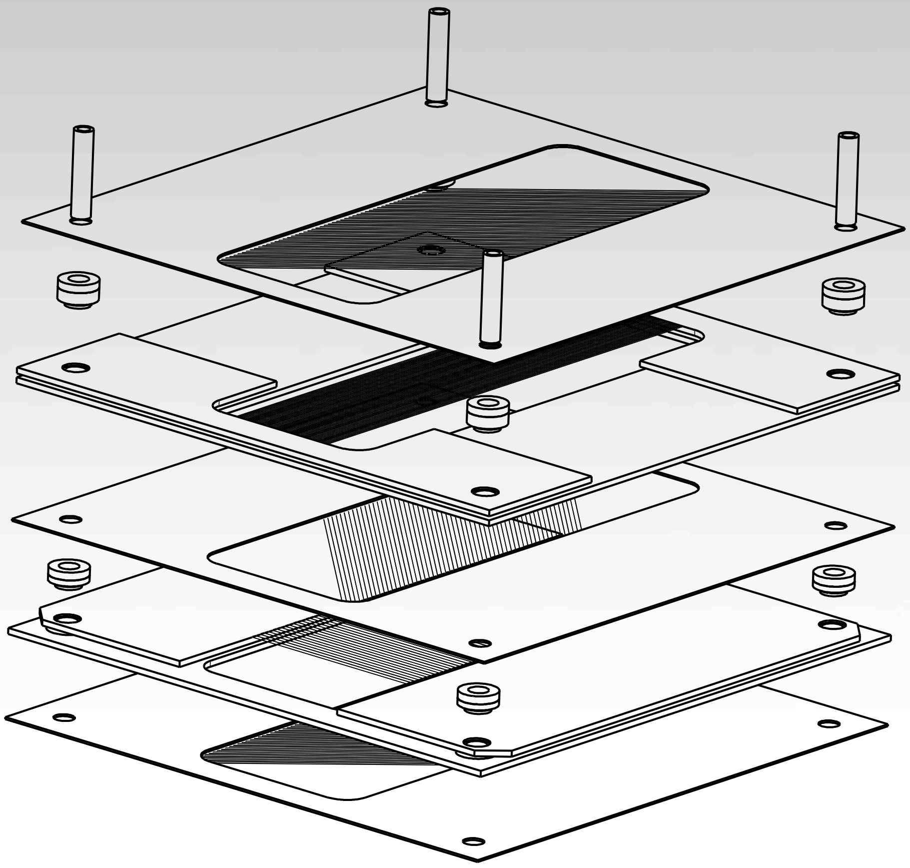
- Baseline: Low mass K type thermocouples (interpulse or slower) in both PBIP and PBW, similar to ISIS, SNS, etc.
  Additional option: Current measurement from intercepting foils (intrapulse), similar to J-PARC (target station) and PSI (collimators)
- Early example from SNS shown in proton beam window assembly.



Grid

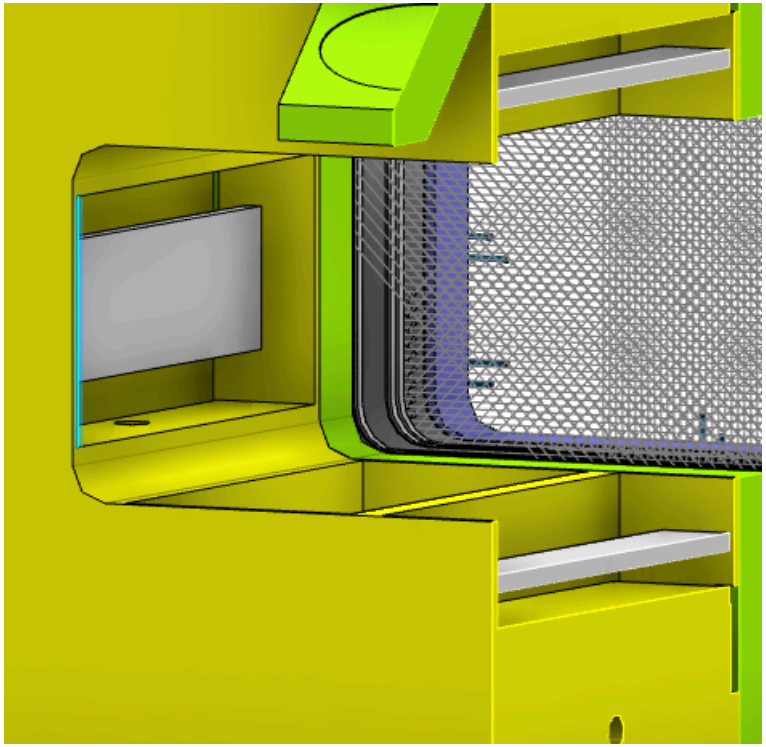
2 similar designs. Decide after preliminary design phase which to deploy: in vacuum (SEM+) or in He (ionization)





Position Monitor for Rastered Beamlet

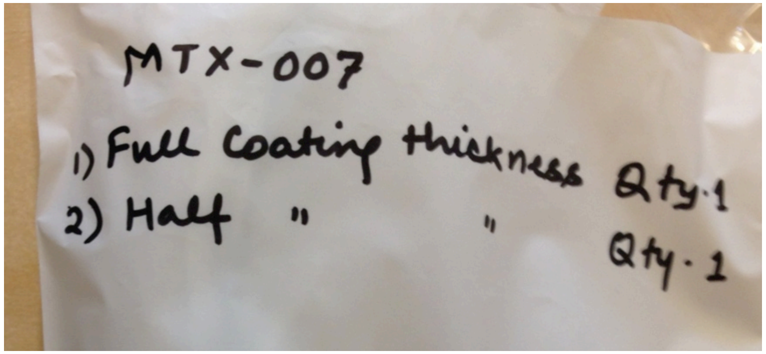
- Raster speed >10 mm/μs
- Extreme radiation - only metal and shadowed alumina (or similar) within 1 m of beam flight path
- Heat deposition -> Shorted striplines provide thermal path to cooled body
- Longer microbunches
- Large aperture – up to 260 by 100 mm
- Cheap and replaceable up to twice/year (if in proton beam window assembly)
- Reliable enough to provide machine protect input
- FPGA-based processing: realtime estimation of temperature map by tracking position and applying filter.



Imaging: Luminescent Coating

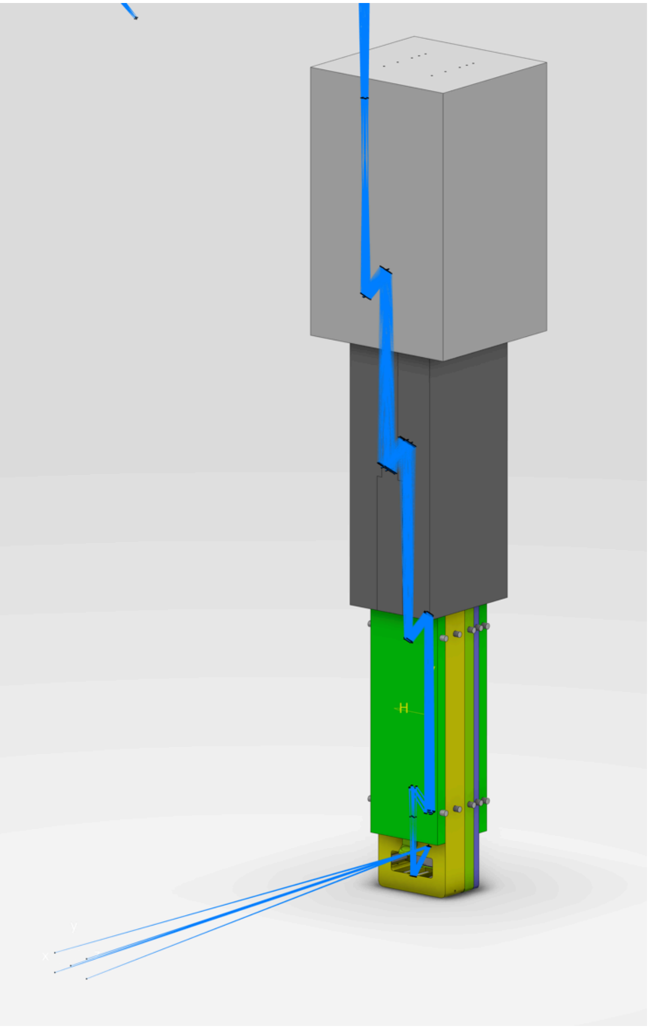
- Baseline photon source: luminescent coating on target wheel and on proton beam window
- Development: thinner coating for PBW, alternative materials
- Alternatives:
  - He gas luminescence
  - OTR??

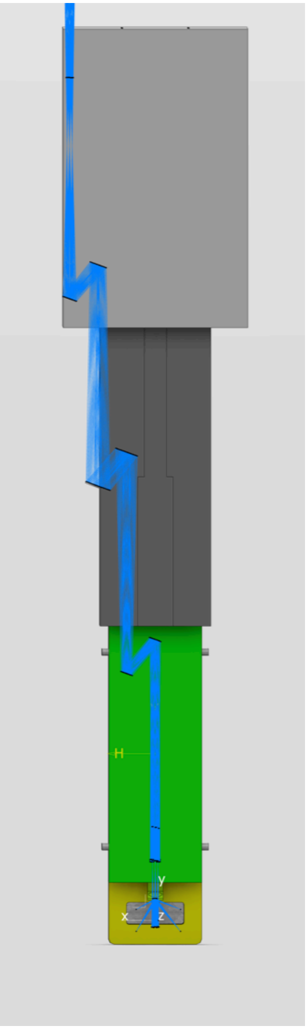
Sample Cr:Al2O3 coatings

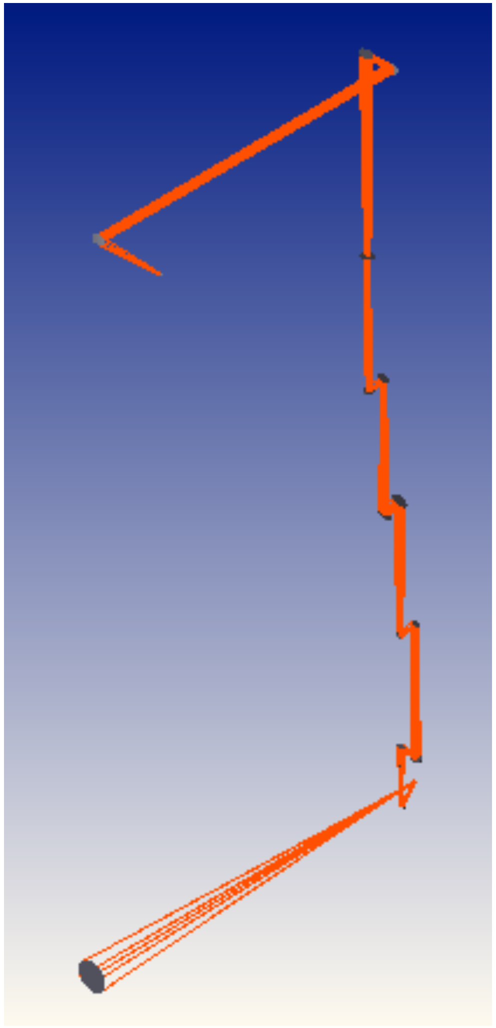


Imaging: Optics

Schematic view of the PBIB with optical system scratch design





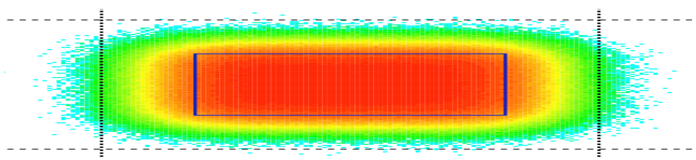


Some Examples of Faults

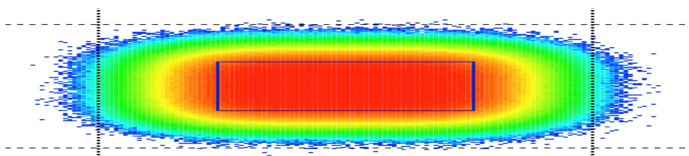
- **Raster amplitude error**
- Multiple faults of beam delivery components
  - **Goldilocks tune: no rastering; quads mis-adjusted to move focal point toward target station components; maintain minimal loss in beamline**
  - No rastering, DC steering to put virtually all beam into monolith beam aperture just upstream of the upper moderator.
- RF errors or cavity trips, off-energy beam
- Synchronization problem between beam and target position

Raster Amplitude Error

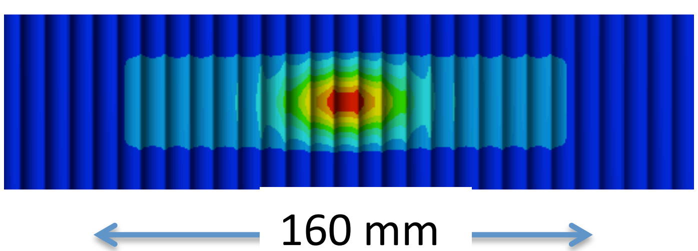
Beam Instrumentation used:
Position monitor (intra-pulse), Grid (intra-pulse) and Imaging (inter-pulse)



Nominal density map on proton beam window: 89 µA/cm^2



Increased density with raster amplitude reduction, using all operating flexibility (20%) and measurement accuracy (20%): 127 µA/cm^2.
Detection: Beam Delivery instrumentation, and Inter-pulse and intra-pulse instrumentation.

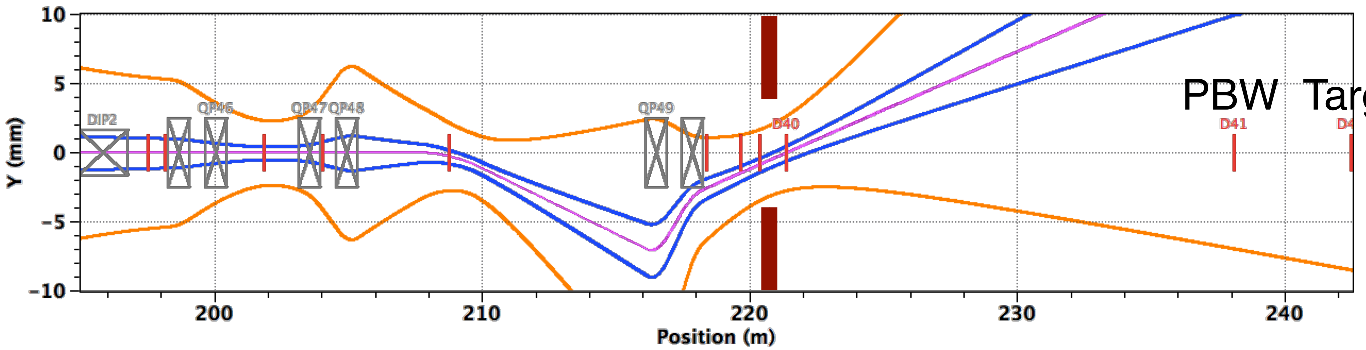


Temperature map after one unrastered full pulse
Peak temperature: 490˚C.
Detection: Beam Delivery instrumentation, and intra-pulse instrumentation.

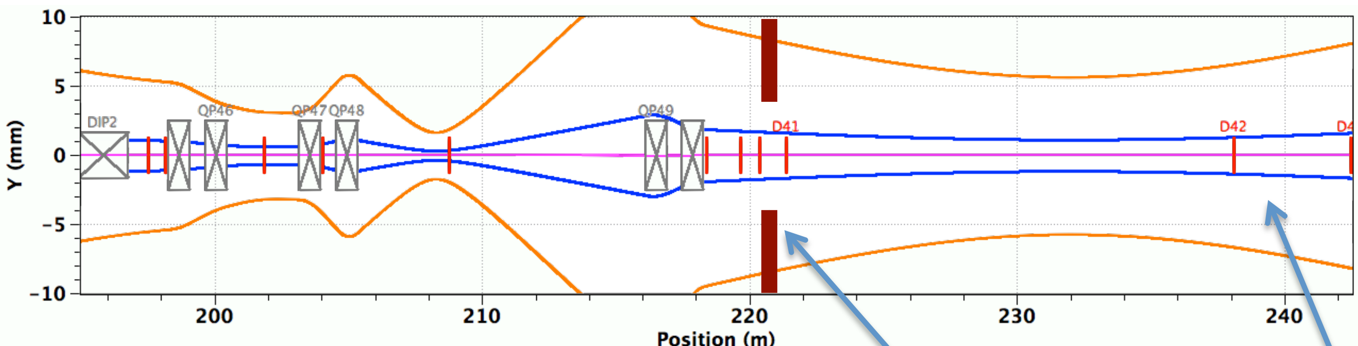
Multiple Faults
Goldilocks Beam Line Tune

Beamlet centroid   Beamlet 1 sigma   Beamlet 5 sigma (~3 W)

Nominal Tune:



Goldilocks Tune:



Detection: Intra-pulse Instrumentation in addition to beam delivery instrumentation

Adjustable collimator with aperture monitor

In monolith:

- Position Monitor
- Grid

Outlook

- Diverse and redundant Instrumentation proposed for machine protection
- Continue risk assessment
- Complete simulations of faults and insidious scenarios by “black hat” team.
- Plan fault studies for system verification