Diagnostics for High Power Accelerator Machine Protection Systems

Steve Lidia

Facility for Rare Isotope Beams

Michigan State University

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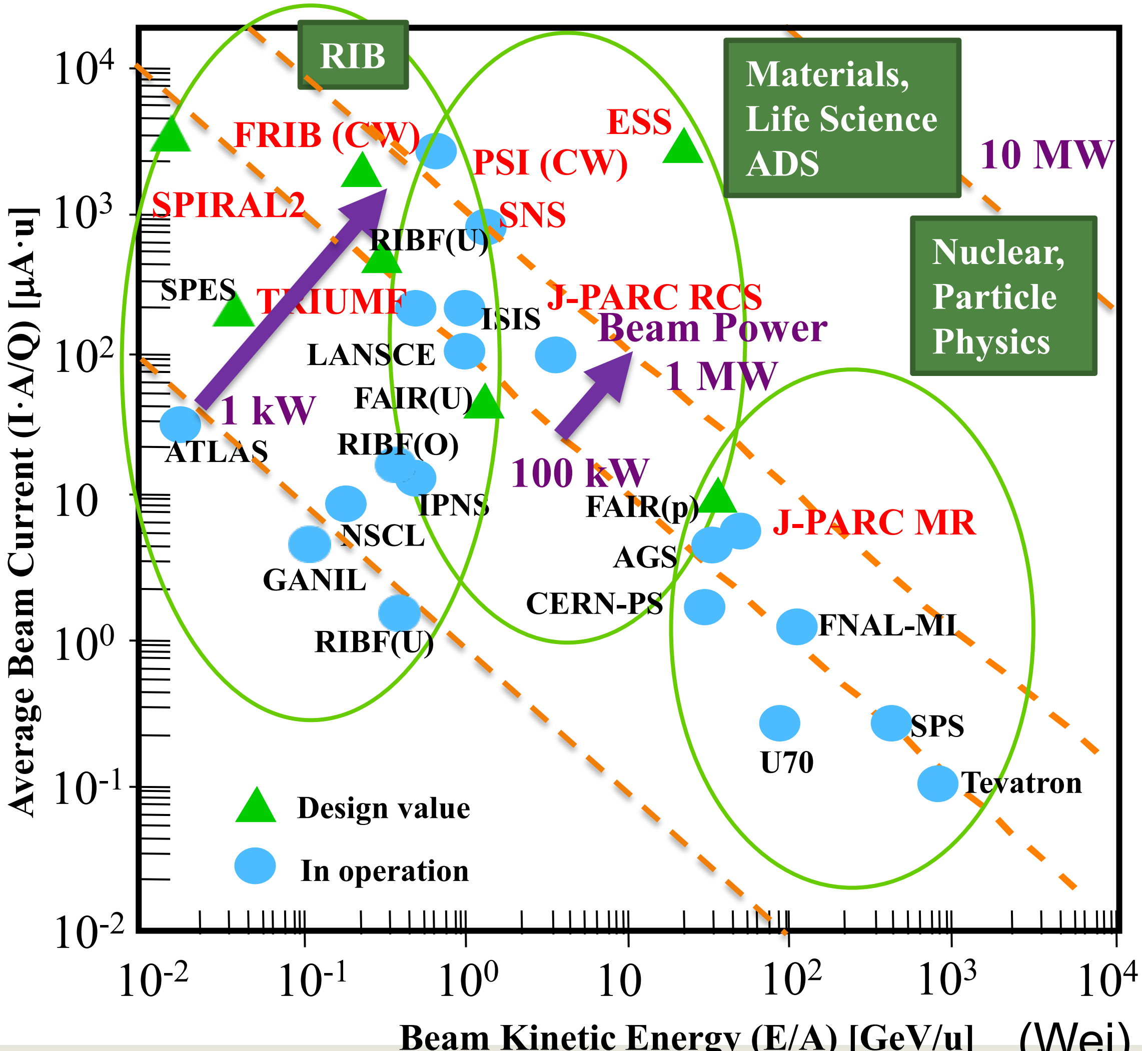
Pushing the boundaries of beam power

- During the past decade, proton accelerators raised beam power to ~ 1 MW
  - SNS (USA): 1 MW pulsed; SRF linac/accumulator
  - J-PARC (Japan): 0.3 MW pulsed; warm linac/RCS
  - PSI (Switzerland): 1.4 MW CW; cyclotron
  - 5 MW in design (ESS)
- Heavy Ion linacs are approaching 0.5 MW
  - FRIB 400 kW
  - From proton to ^{238}U
- Stored energy in proton colliders is unprecedented
  - 1-3 MJ (SPS,RHIC,HERA,TEVATRON)
  - 140 MJ (LHC) – design 360 MJ



(Wei)

Key technologies driving the push

- RF and large scale cryogenics
- Ion sources, RFQs, LEBT
- High power collimators, charge strippers
- Rapid-cycling booster synchrotrons
- High power targets and radiation-tolerant magnets
- Loss detection and MPS

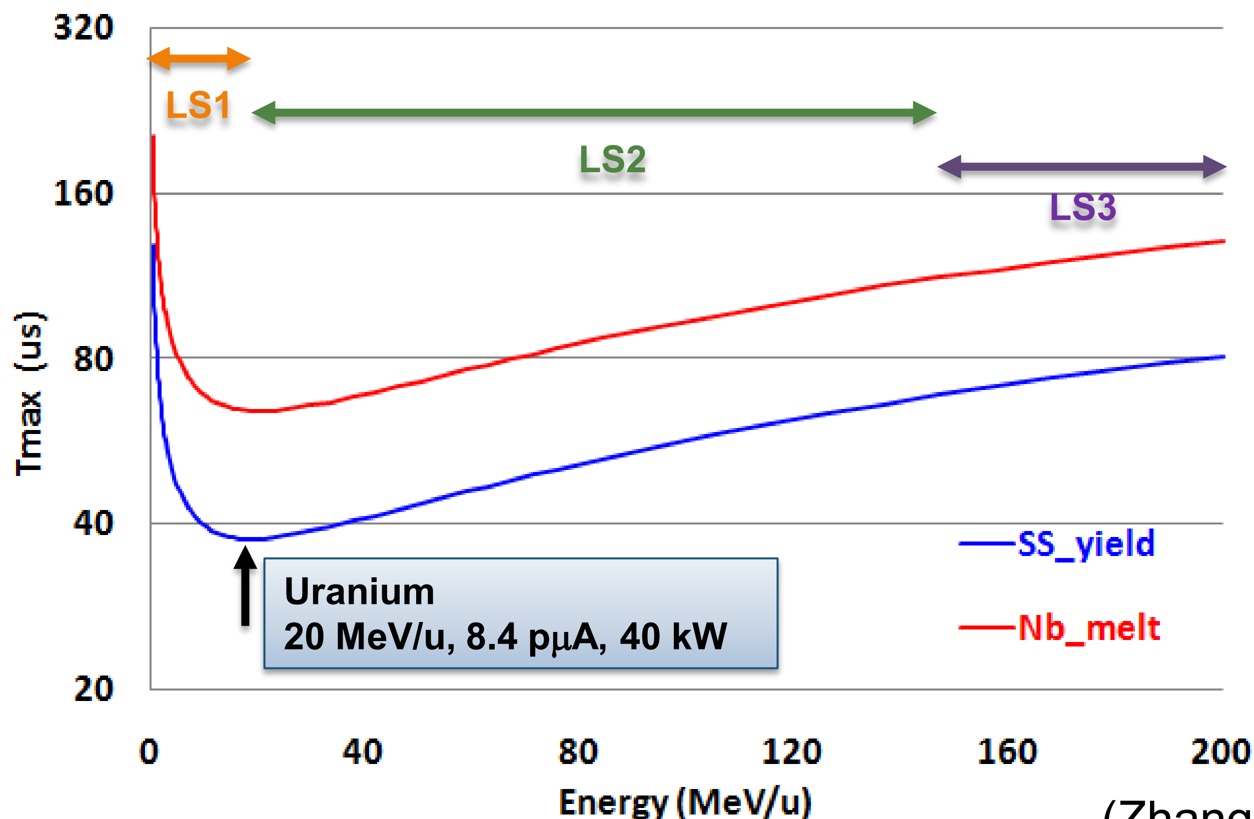
Machine Protection Systems

- Exist
  - to prevent or minimize prompt and long-term damage to accelerator and experimental instrumentation,
  - to minimize the number of false-trips that limit production,
  - and to provide evidence of failures or fault events when interlocks occur
- Must respond to many types of events
  - Hardware failures
  - Control system failures
  - Operational and administrative failures
  - Beam instabilities and other unforeseen events
- Time scales are encompass Fast Protection and Run Permit Systems
  - FPS protects against prompt damage at several to 100s μs
  - RPS operates at milliseconds to many seconds; verifies machine state and external conditions
- MPS must be flexible to cope with wide ranging operating modes

Time scale for component failure from errant beams

Stopping ranges of beam particles in materials vary with species, energy, and target material.

- High energy proton or hadron beams create cascades that deposit energy deeply (m's).
- Low energy heavy ion beams deposit energy mainly on surfaces (μm's to mm's)
- Component failure results from fast deposition, thermal transport, and material stress.



(Zhang)

Errant beam detection times

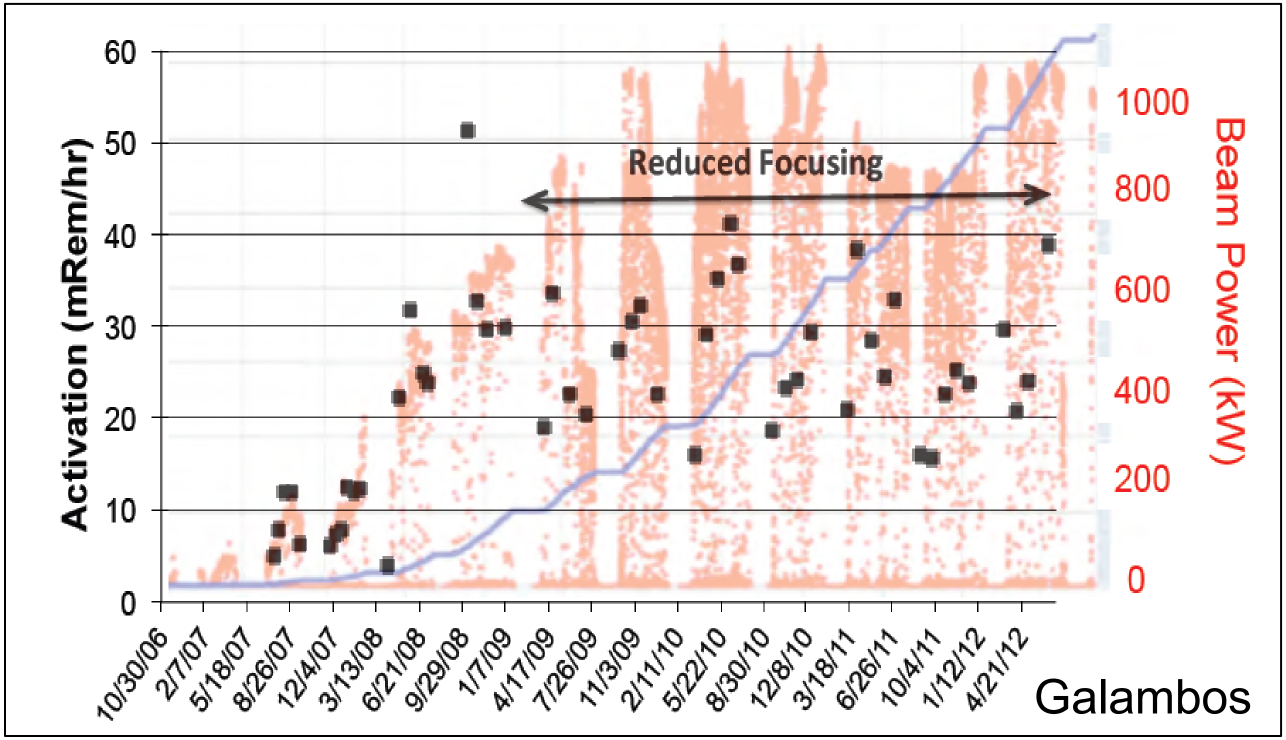
	Ion	Energy [MeV/u]	Beam Power [MW]	Detection time limit [μs]
PSI	H^+	590	1.3	few 100
SNS	H^-/H^+	1000	1-2	5-10*
ESS	H^-/H^+	2000	5	1-2
SPIRAL-2	D/HI	20	0.2	10
FRIB	HI	200	0.4	10
JPARC-MR	H+	$3\ 10^4$	0.75	10
LHC	H^+	$7\ 10^6$	$4\ 10^6$	40

*25 μs response time (design)

Slow beam losses

Leads to radioactivation, cryogenic thermal loading, and SRF cavity degradation

Previous experience indicates 1 W/m losses generates 100 mRem/hr activation.
LANSCE : 100 mRem/hr @ 780 kW
SNS : 30-40 mRem/hr @ 1 MW



Galambos

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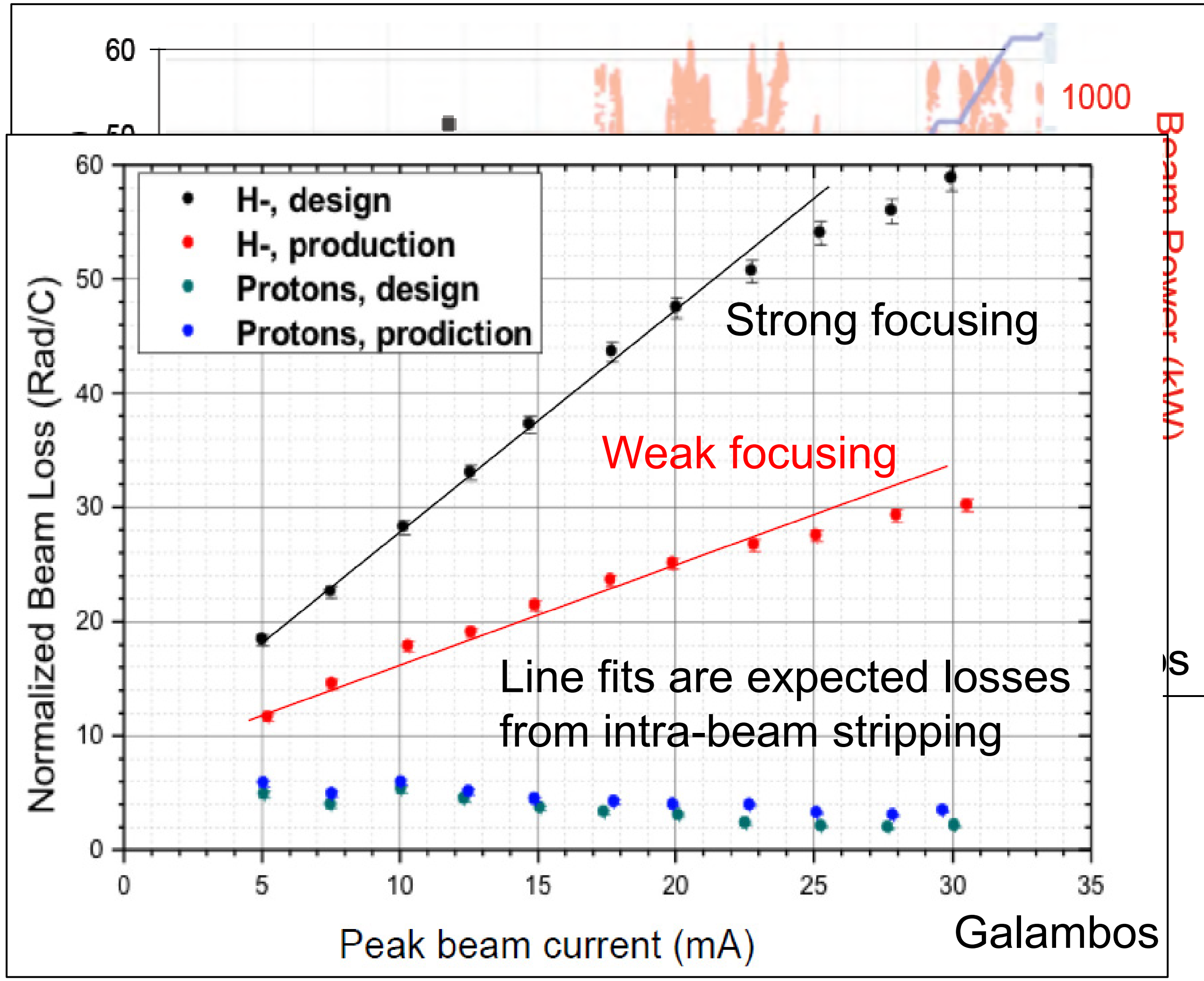
Slow losses have multiple sources.
E.g. intra-beam stripping losses of H^- beam in SNS



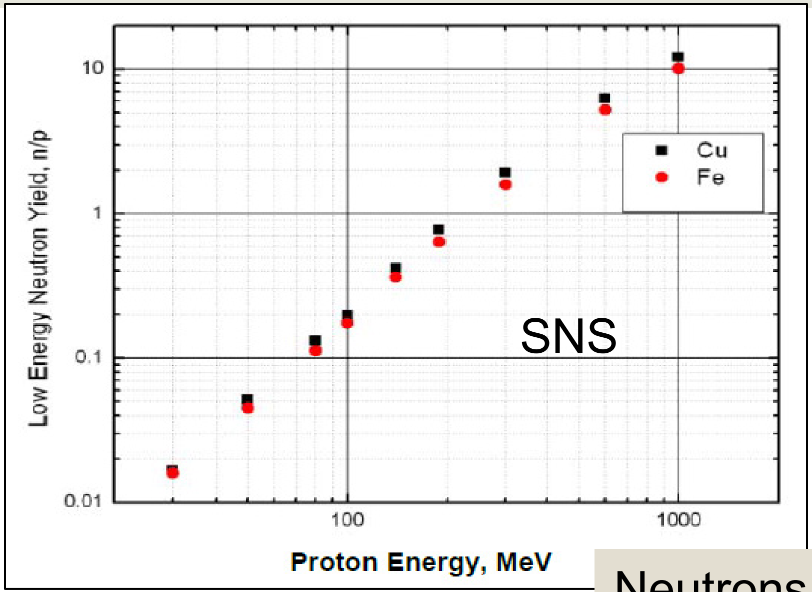
Challenges and Opportunities

- Dynamic range of intensities and time scales (beam current, pulse formats, fast/slow losses)
- Contend with high radiation field and EMI backgrounds
- Need for fast and robust reporting and control networks, with low error rates
- Simulation and modeling of radiation fields from slow and fast losses; loss patterns from specific fault events

MPS inputs

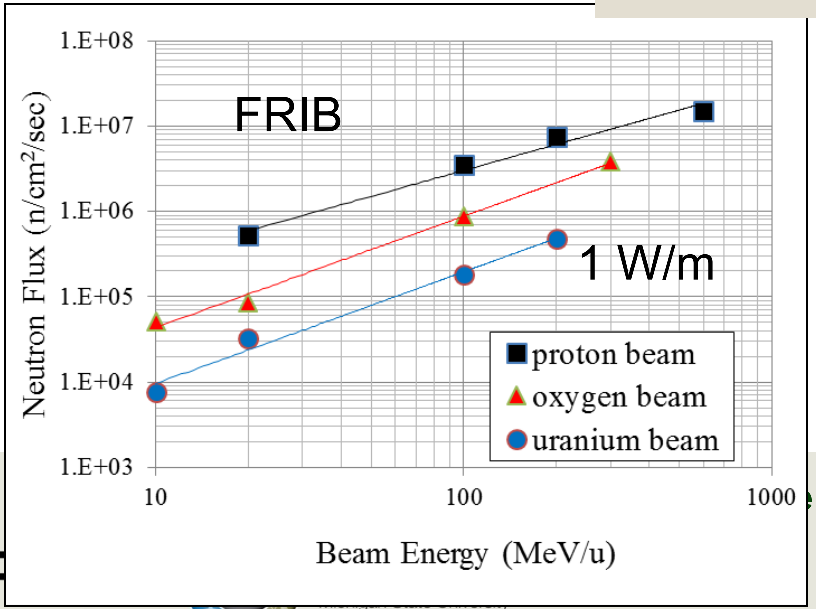
- Beam loss monitors
  - Prompt radiation fields from accelerator components – rf cavities, distribution lines, rf sources
  - Secondary particle fields produced by beam collisions
    - » Gammas, neutrons, hadronic showers
- Direct beam measurements
  - Peak and average beam current or intensity
  - Beam orbit
  - Beam halo
  - Micro pulse duration
  - Spot size
- Vacuum monitoring
  - Fast leak detection
  - Slow drift in background pressure
- Cryogenic and SRF monitors
  - Thermal loads
  - Quench detection
  - LLRF
- Magnet power supplies
  - DCCTs
- Machine status
  - Beam interlocks
  - Power limiting devices

Gamma and neutron production

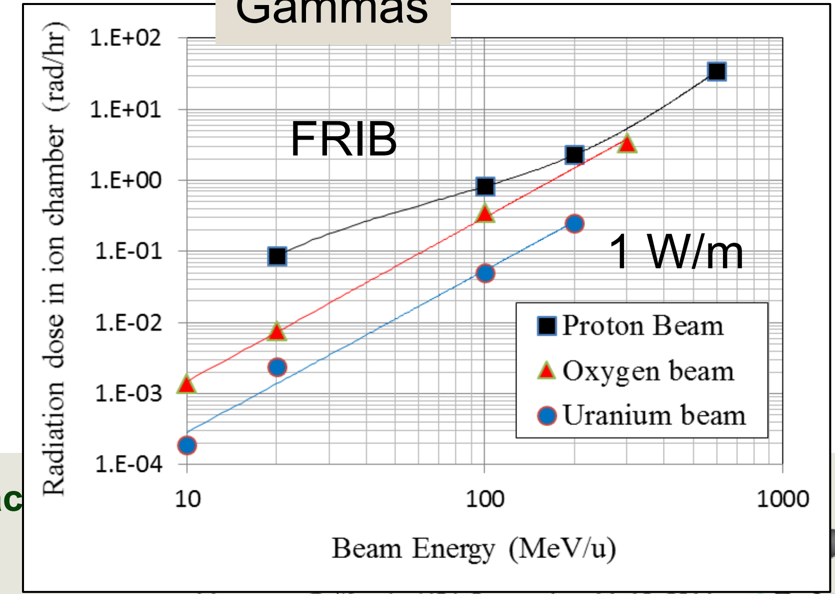


- Secondary radiation produced by primary beam particle collisions with vacuum chamber or residual gases.
- For low and medium energy beams, the background is primarily gammas and neutrons.
- Production yields are have strong energy dependence

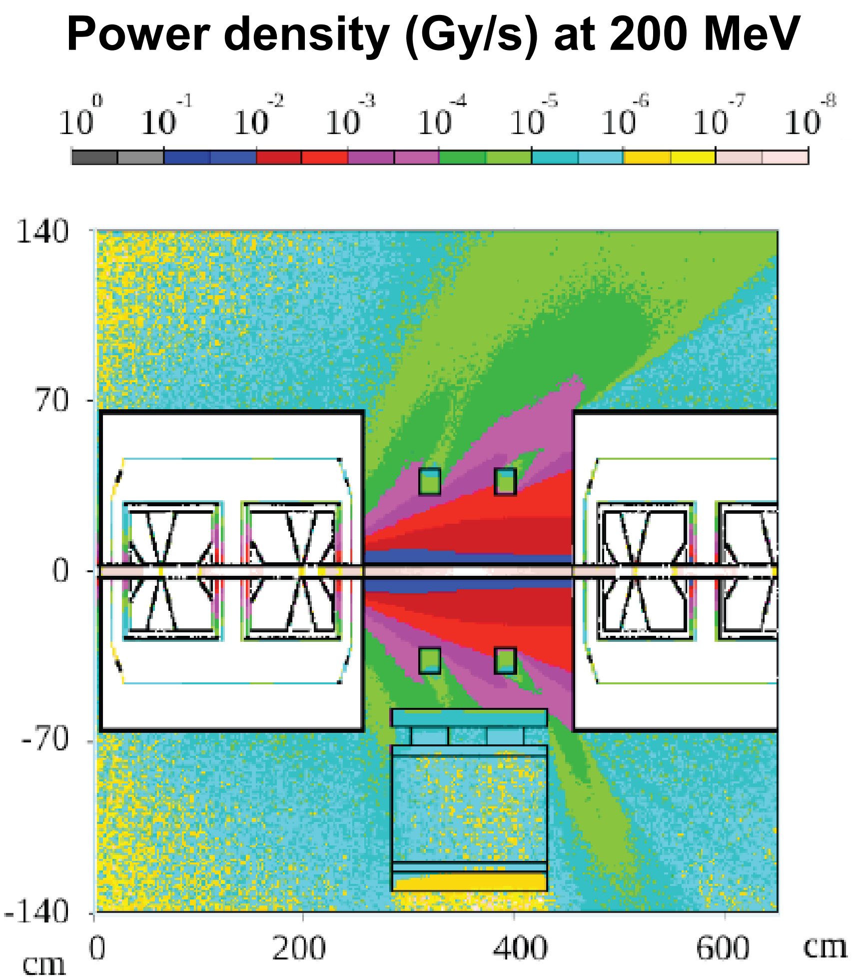
Neutrons

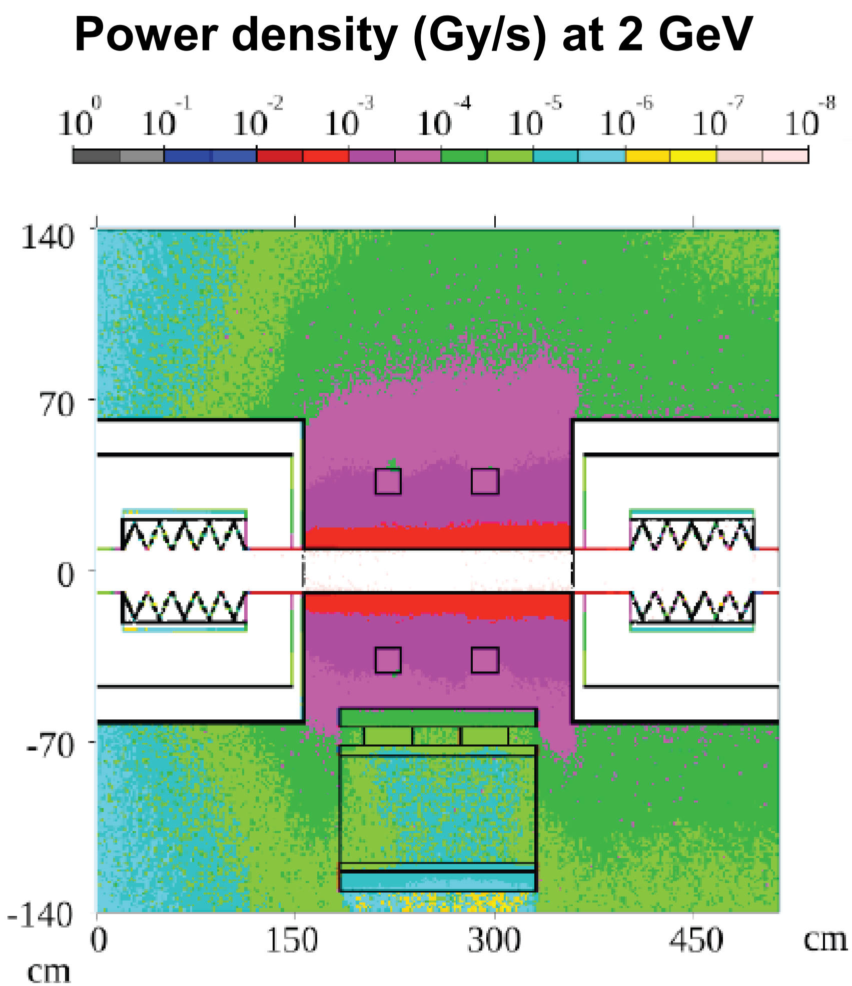


Gammas



Energy dependent radiation fields for 1 W/m loss (ESS)



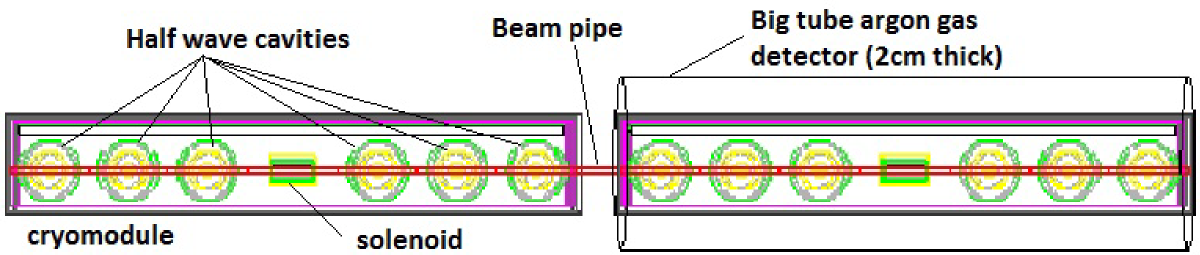


(Tchelidze)

Radiation transport models are essential to understand the background

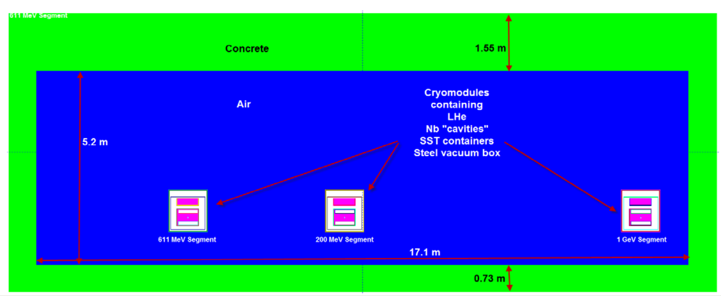
- Simulations with two codes are implemented and compared
  - Detailed two-cryomodule geometry model implemented in GEANT4. γ dose is calculated as an average around cryomodule
  - Simplified homogenous tunnel model implemented in PHITS. γ dose is calculated in an "ion chamber" 1 foot below each segment
- Results from these two models are comparable

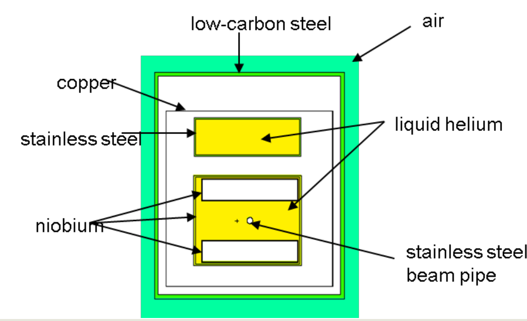
Geant4 model (side view)



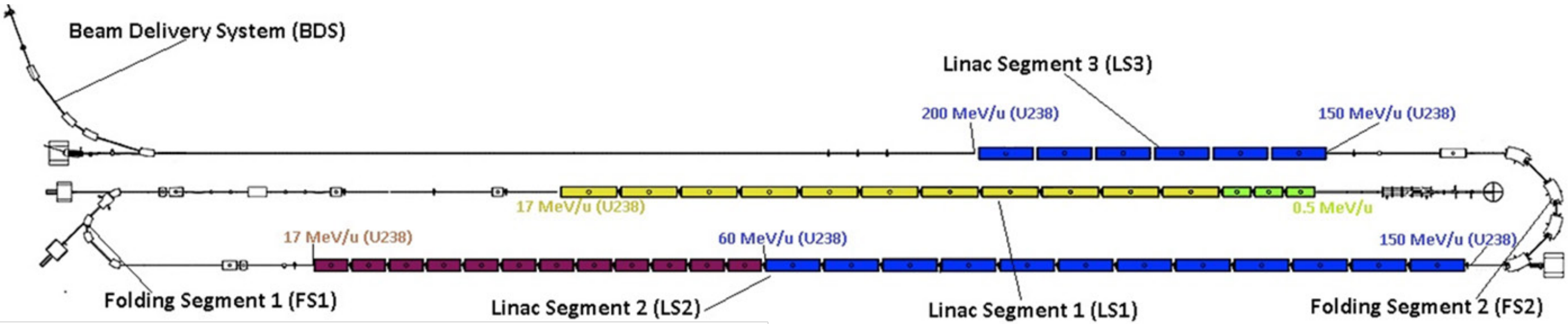
PHITS model (cross section)

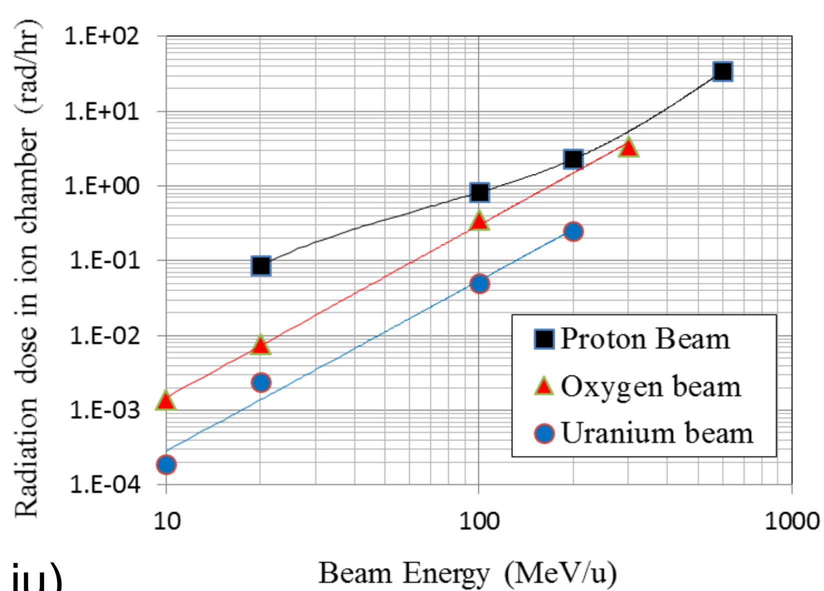
(Liu)





Crosstalk effects confuse spatial location and mask events





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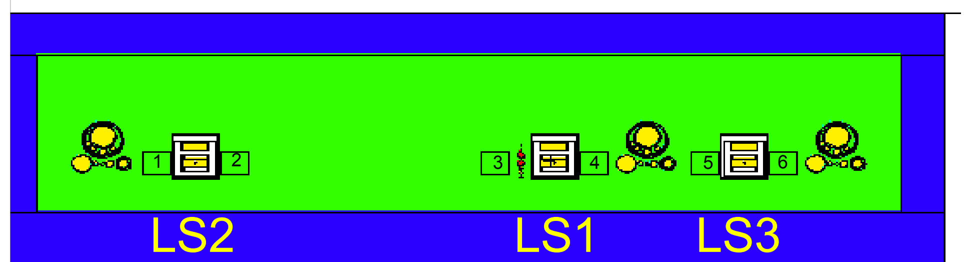

Neutron induced by 1 W/m ^{18}O loss	Flux at box 4 by LS1 loss	Flux at box 4 by LS2 loss	Flux at box 4 by LS3 loss
n/cm²/sec	1.03×10^5	5.81×10^5	3.2×10^6

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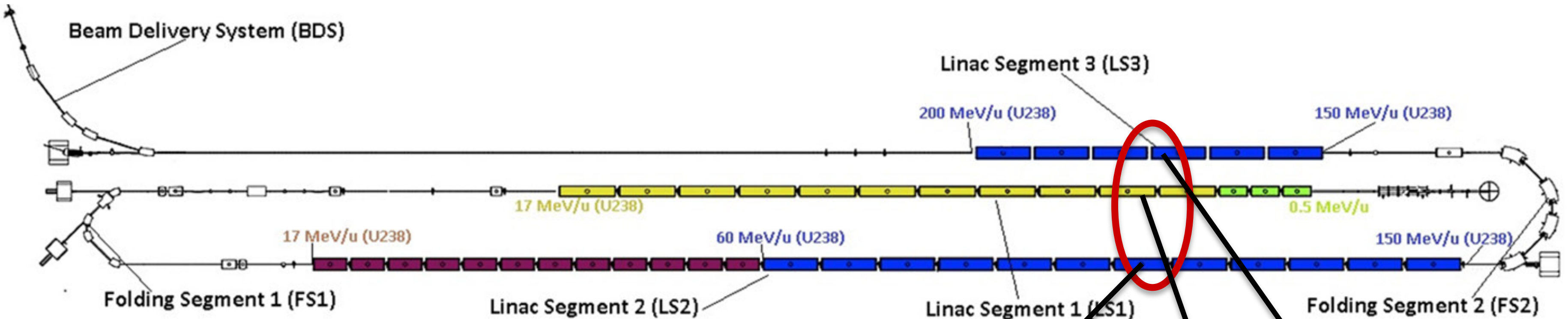

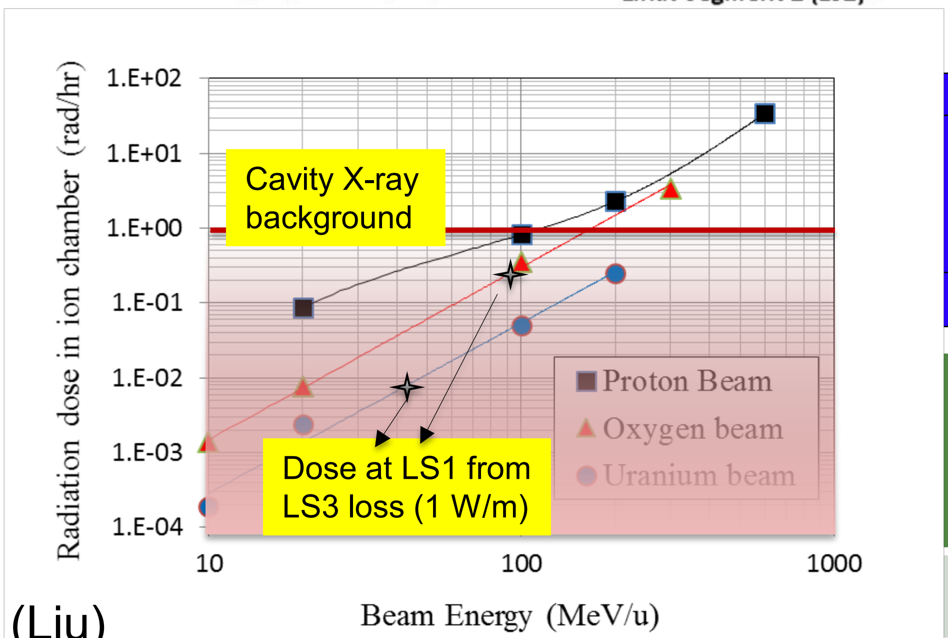

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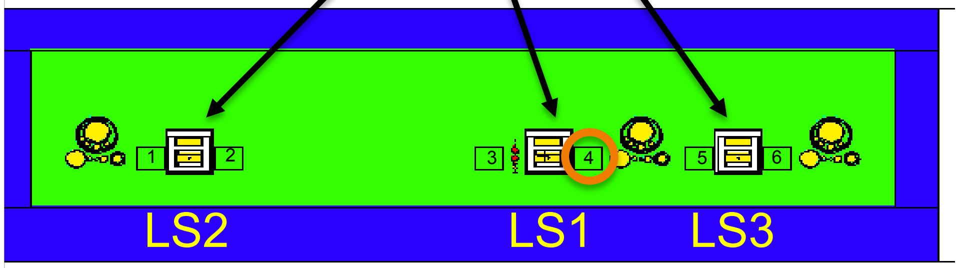

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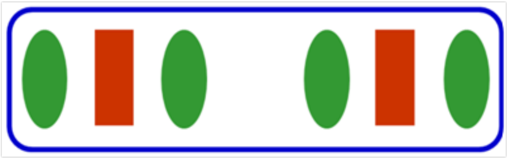
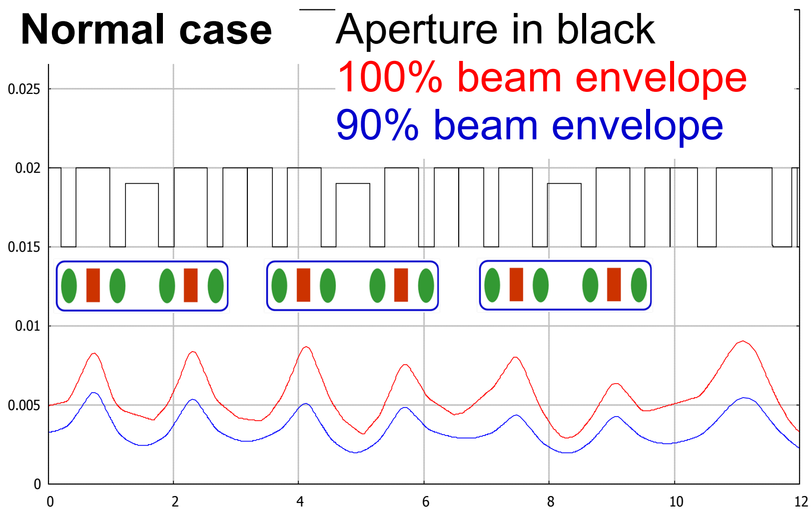
Loss patterns from beam dynamics simulations

- To assess risk from chronic and infrequent, fast loss events beam spill patterns can be generated and analyzed
- Spill pattern maps can assist in optimum placement of beam loss monitors and passive protection devices
- Realistic lattice errors and beam distributions can place bounds on loss from halo and core interception
  - Still very model dependent
- Spill patterns from component errors or faults can assist post-mortem analyzes
- Machine learning frameworks are being developed to optimize loss monitor networks and to reconstruct events

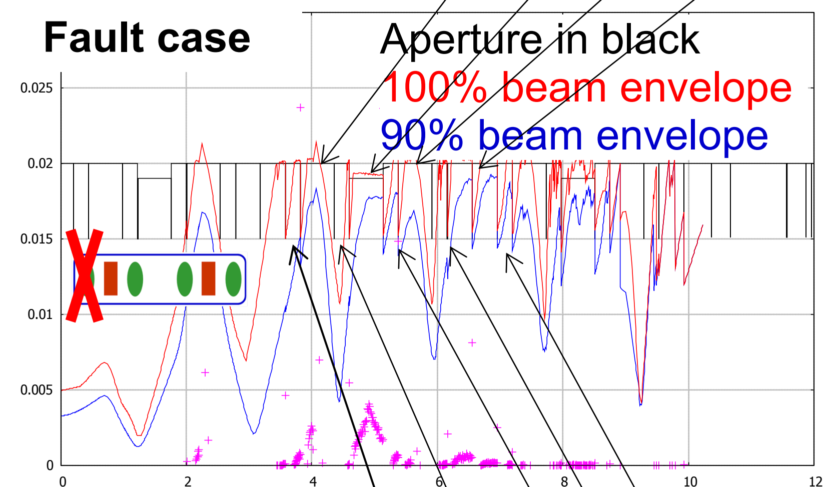
Example: Beam Loss Distributions with Single Cavity Failure (FRIB)

- Superconducting linac starts with 3 β=0.041 cryomodules
  - Each module has 4 cavities and 2 solenoids
- First cavity in the linac 1 failure
- All beam lost in the first 3 CMs
  - Beam loss on a cavity ~40 W
  - Beam loss on a pipe area ~500 W





beam loss on pipe (W): 77 485 5.5 109

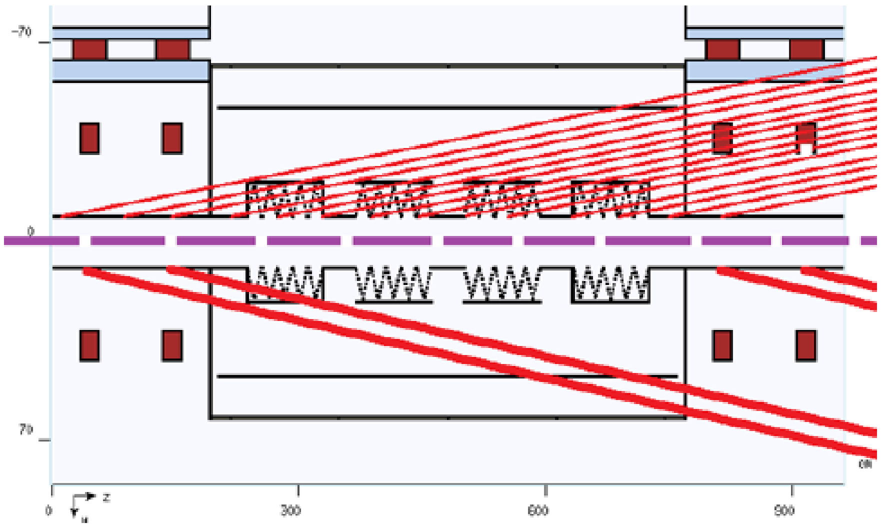


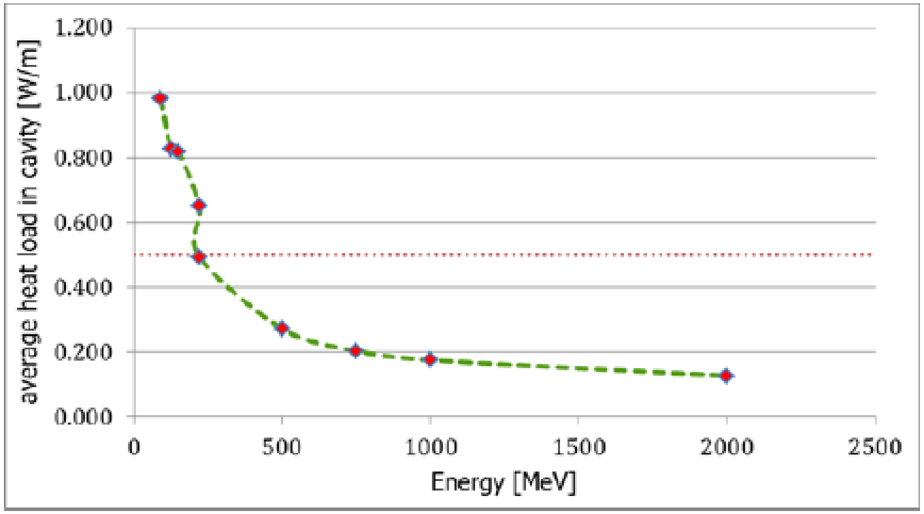
beam loss on cavity (W): 39 1.1 34 5 3

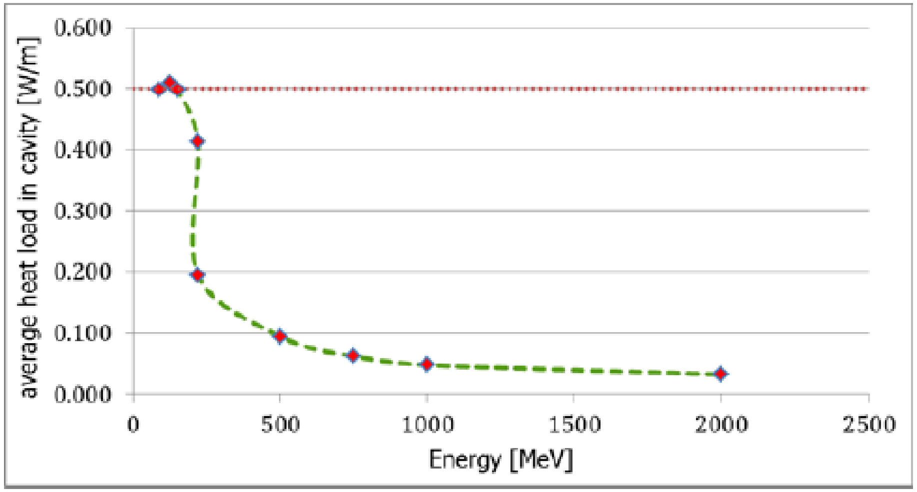
(Zhao)

Distributed and localized losses inform thermal loading in SRF cavities

1 W/m



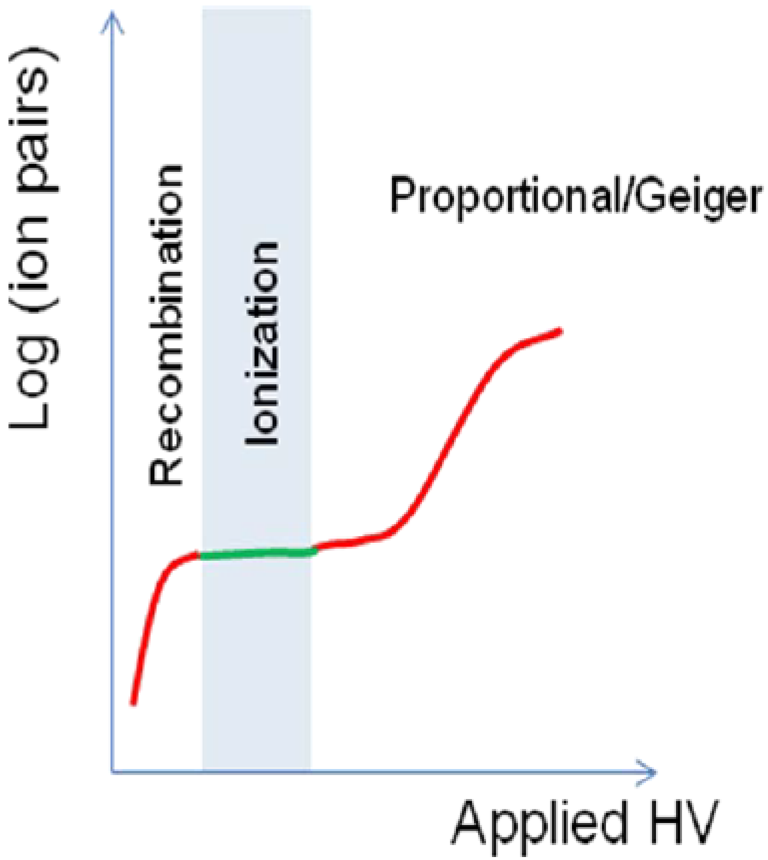




(source M. Jarosz)

Ionization Chambers

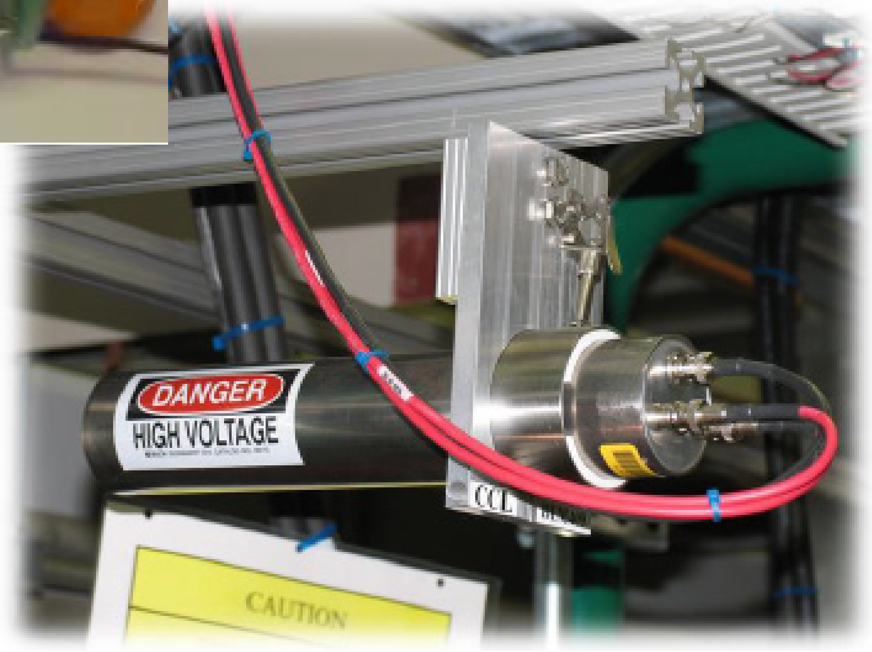
- Ionization chambers are the main type of loss monitors used in hadron machines.
- Gas-filled chambers containing an electrode pair with biasing high voltage.
- Operated in 'ionization' mode, the detector is insensitive to HV fluctuations.
- Small chambers are installed along specific components and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



(Zhukov)

SNS-type ionization chamber

R.L. Witkover
D. Gassner



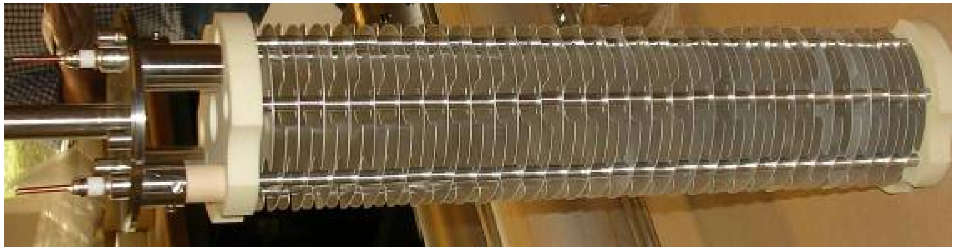
133 cm^3 Ar gas
Typical bias 1 kV
Sensitivity 70 nC/rad
Response time ~1-2 μs

LHC-type ionization chamber

- Ionization chambers to detect beam losses:
  - Reaction time ~ ½ turn (40 μs)
  - Very large dynamic range (> 10^6)
- There are ~3600 chambers distributed over the ring

1.5 L volume - 50-cm long, 9-cm diameter
100 mbar overpressure N_2
0.5-mm separated Al plates
1500 V bias (end-to-end)

Sensitivity ~ 54 μC/Gy
Response time ~300 ns e^-, 80 μs ions

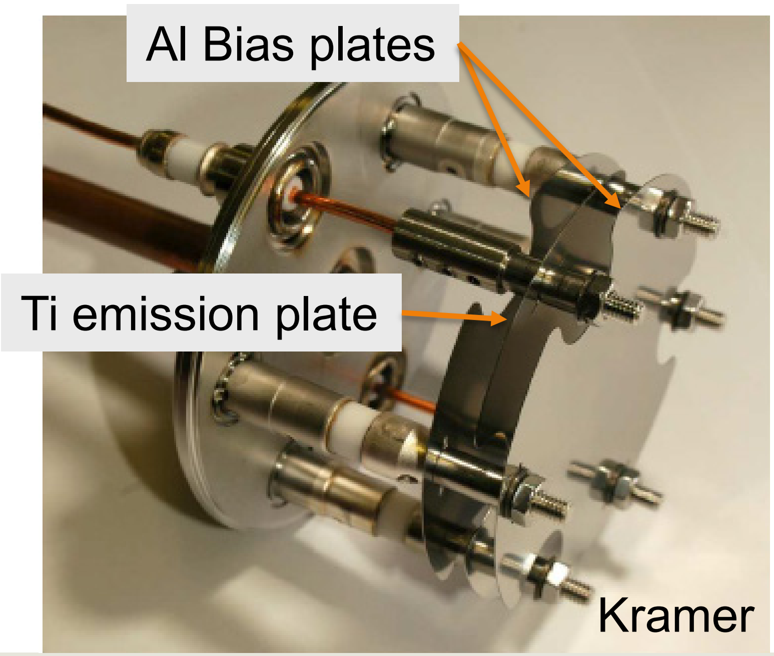


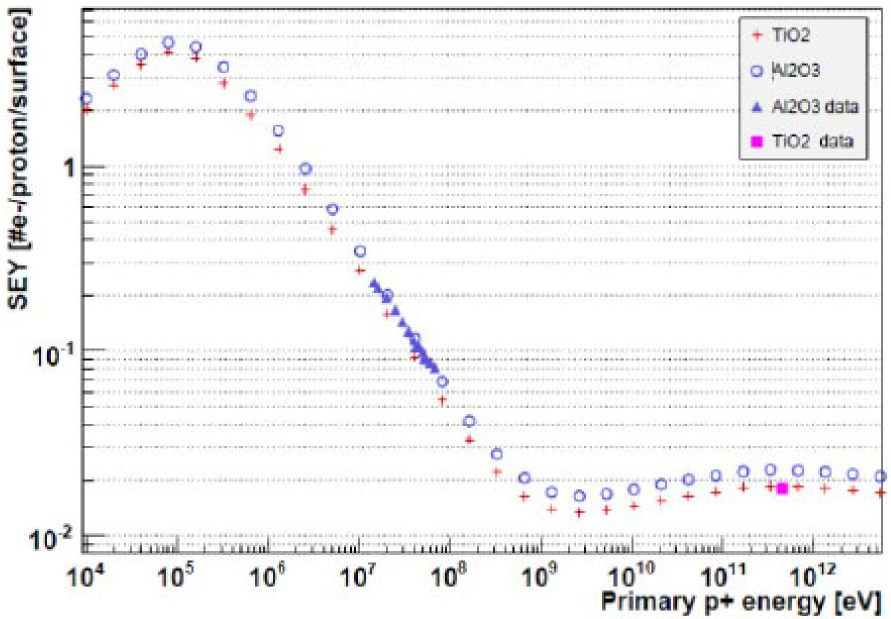
Secondary emission monitors (SEM)

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





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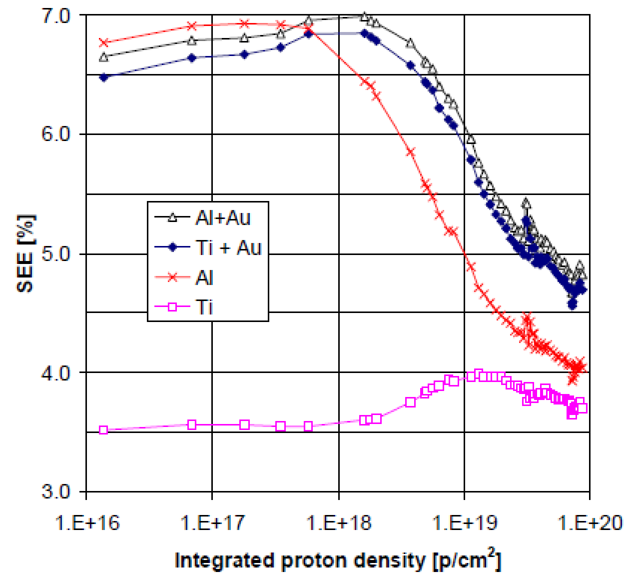
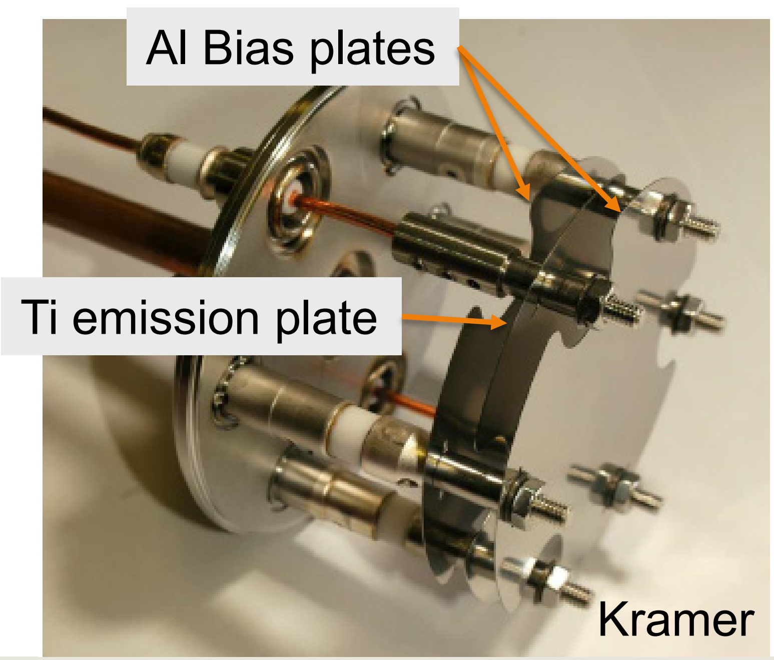
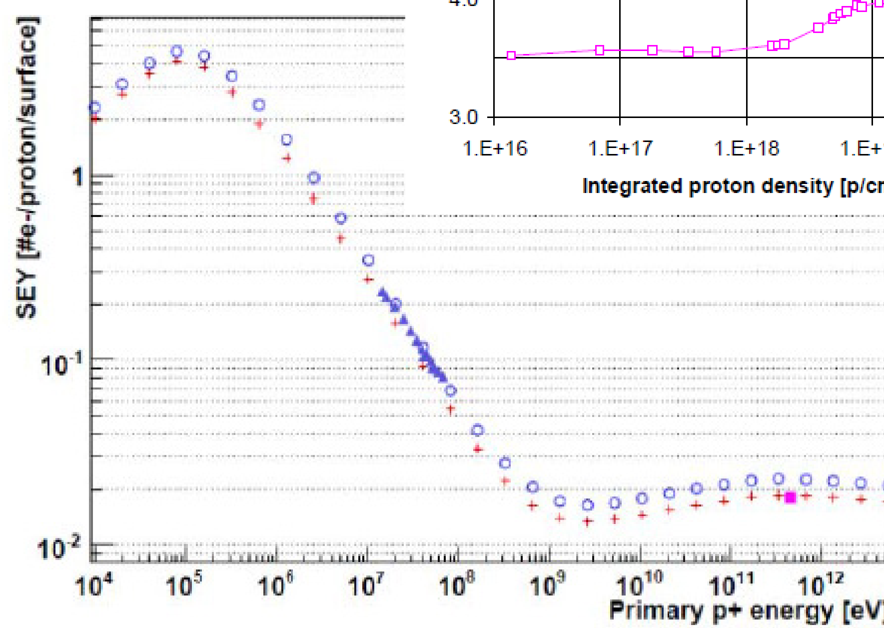


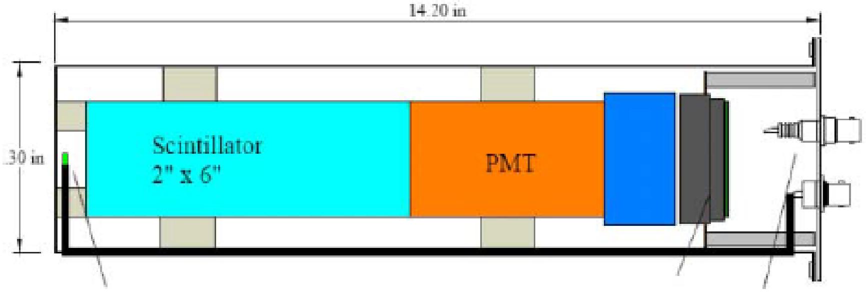




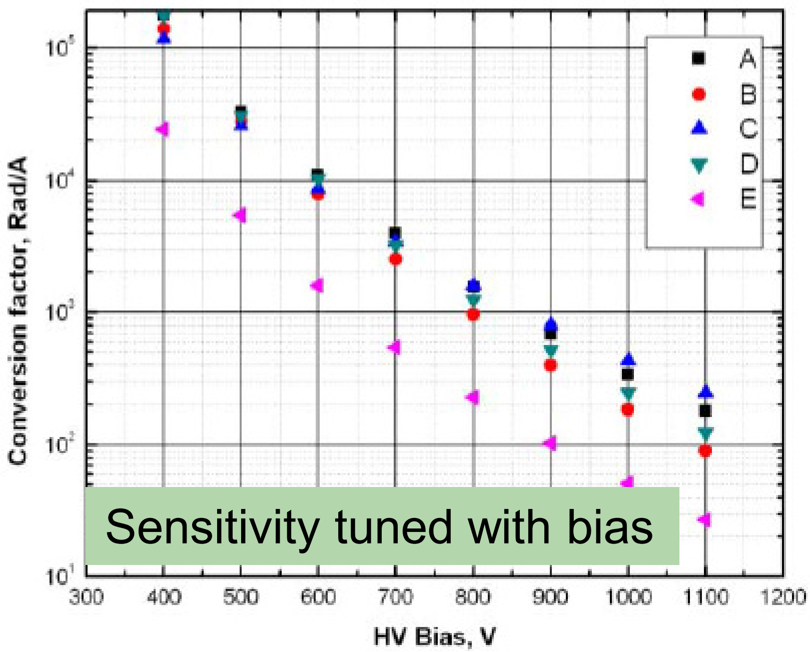
FRIB Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

International Beam Instrumentation Conference
Monterey, California, USA September 14–18, 2014

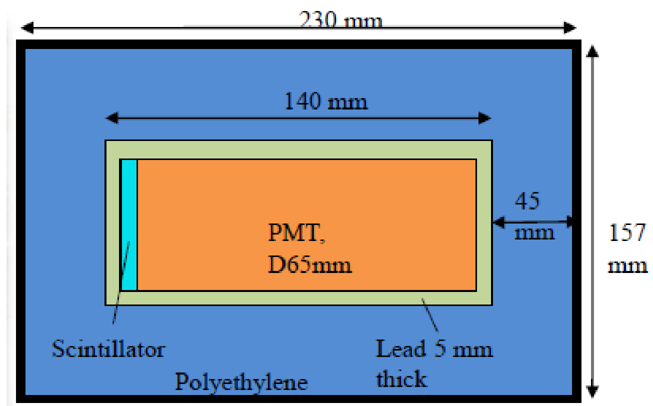
Scintillation based detectors



SNS Fast Detector



- Typically employ photomultiplier tubes for high gain (10^5-10^8) with applied HV
- Many types of scinitillators fluoresce under gamma bombardment
- Li- or B- doped plastic scintillators respond to neutrons
- Additional moderation increases sensitivity at the expense of time response.



SNS Neutron chamber (SBLM)

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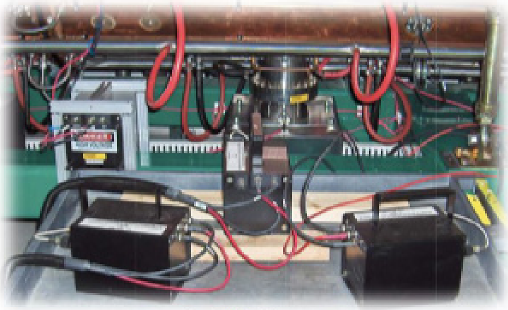
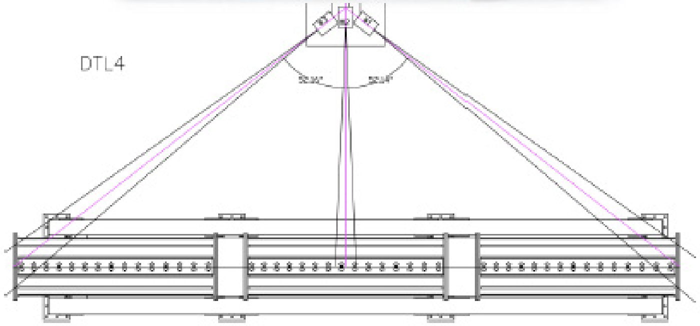
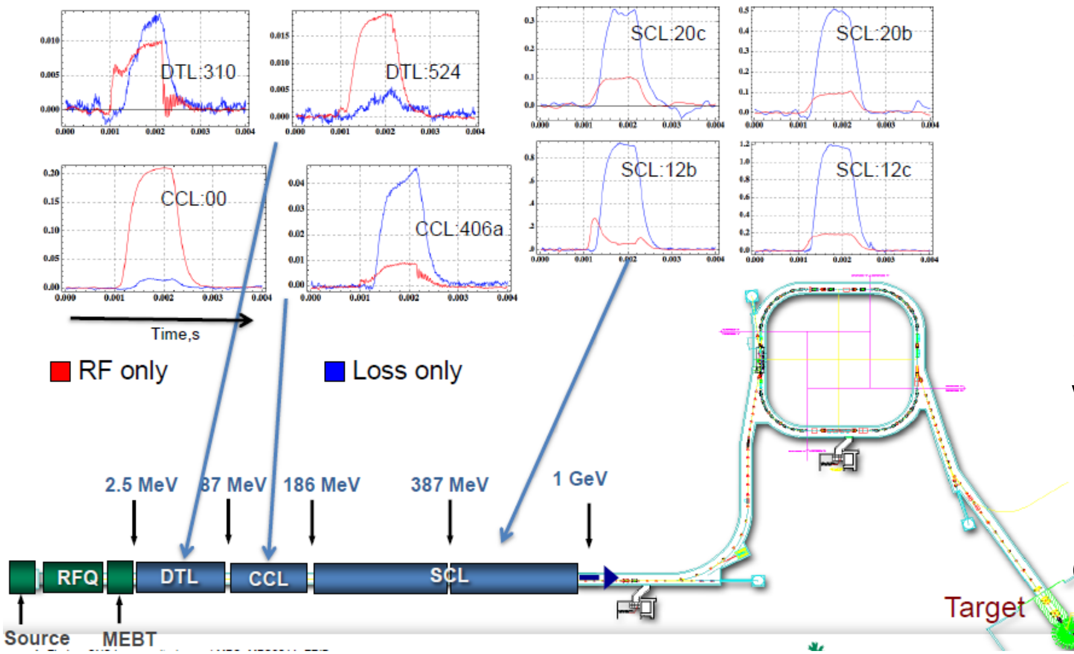
Differential Radiation Loss Monitoring

- Background subtraction techniques improve loss resolution along waveform
- Implemented in software, too slow for fast MPS
- FPGA implementation could service fast MPS





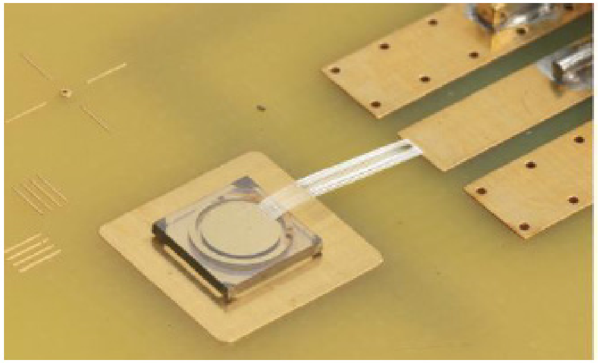


Collimated BLM – lead shielded with window, angle selectivity of gammas

Dual BLM – two scintillator based detectors, one with enhanced neutron sensitivity

New schemes seek to detect losses in cryogenic environments

- Detection of losses within cryomodules can help to minimize damage to cavity surfaces and to prevent quenching of magnets with high stored energy
- Recent work at LHC and Fermilab
  - CVD diamond, silicon
    - » Cryogenic monitoring near magnet windings (1.9 K)
    - » Slow losses with sensitivities 0.1-10 mGy/s, response time < 1ms
    - » Fast beam halo loss detection
    - » Response times 2.5 ns (Si), 3.6 ns (diamond) to Minimum Ionizing Particles
    - » Signal degradation over 20 year integrated dose is 25x (Si) and 14x (diamond)
  - LHe ionization chamber
    - » Limited response to slow losses (> ~200μs)
    - » Radiation tolerant – self-healing material
    - » 200 V/mm bias yields ~0.1 fC/cm/MIP
    - » Fermilab electronics design generate <1ns time response



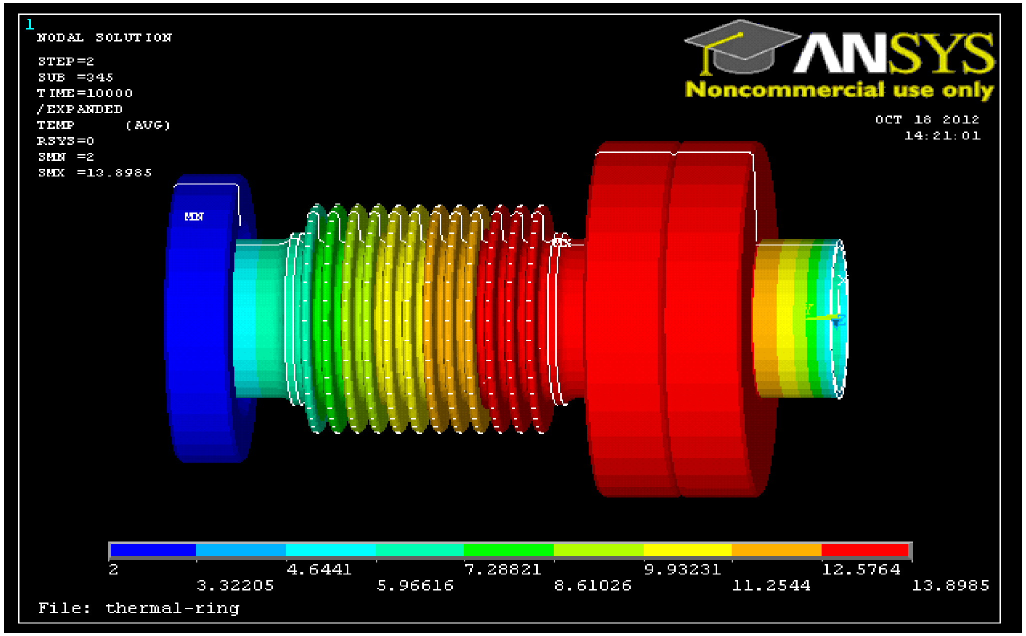
Installation on CM2 (FNAL)

(Warner)

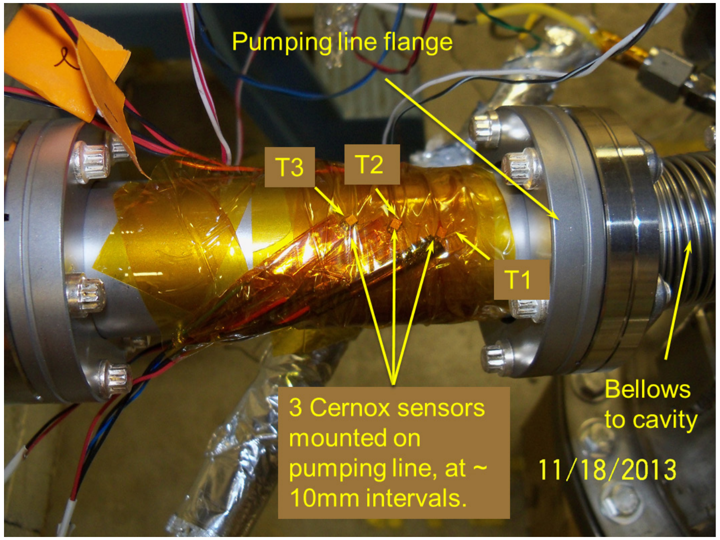
Slow leam Loss – vacuum chamber heating

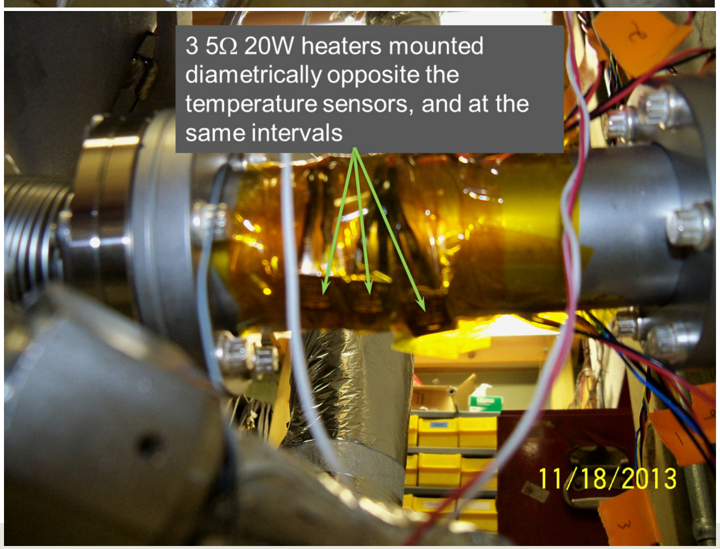
Rising time for 0.1K temperature difference from beam loss		
Beam loss in cryomodule	0.1 W/m	1 W/m
0.1K rising time	1 min	7 sec
Maximum temperature rising	1.83 K	8.9 K
Total rising time	30 min	20 min

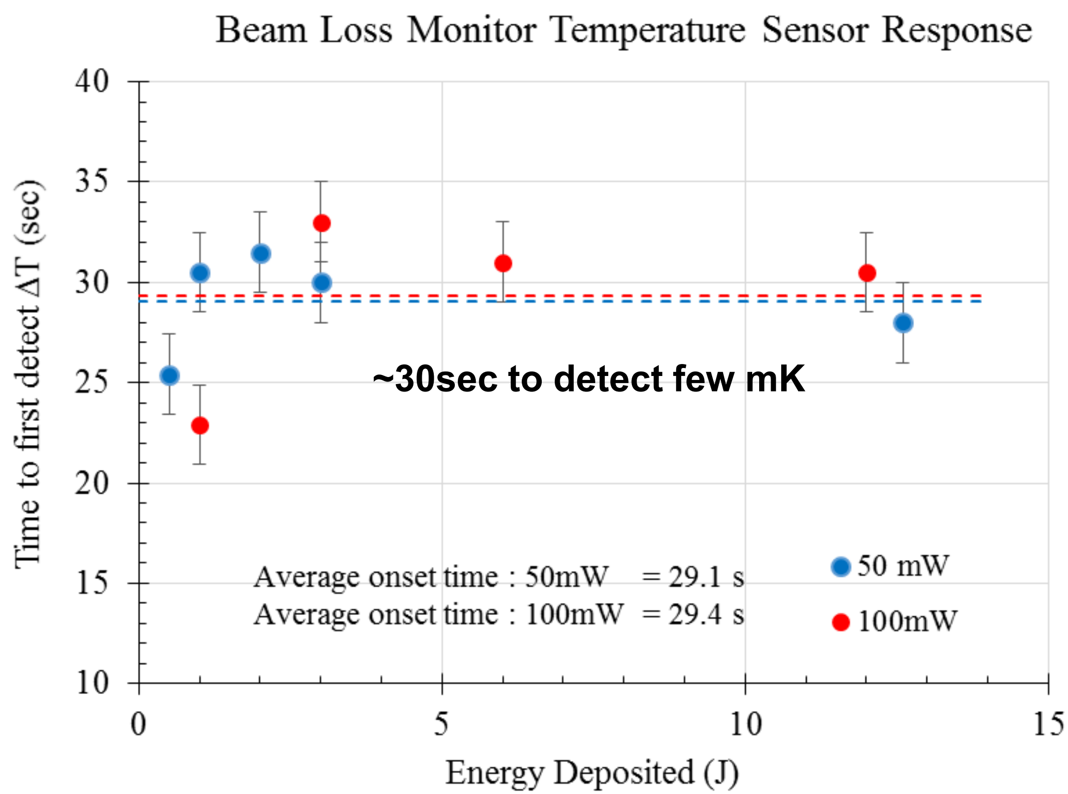
Systems employing thermometry or calorimetry to monitor temperature of cryogenic components and vacuum chambers are being developed.



Fast thermometry at aperture limits in SCL







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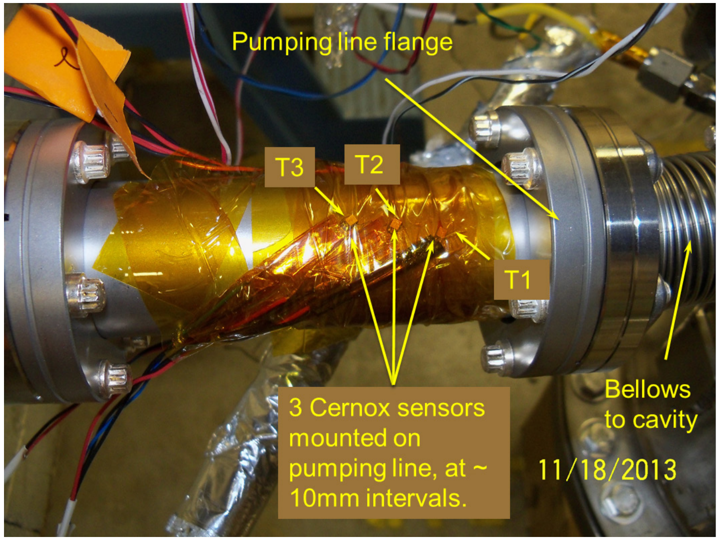

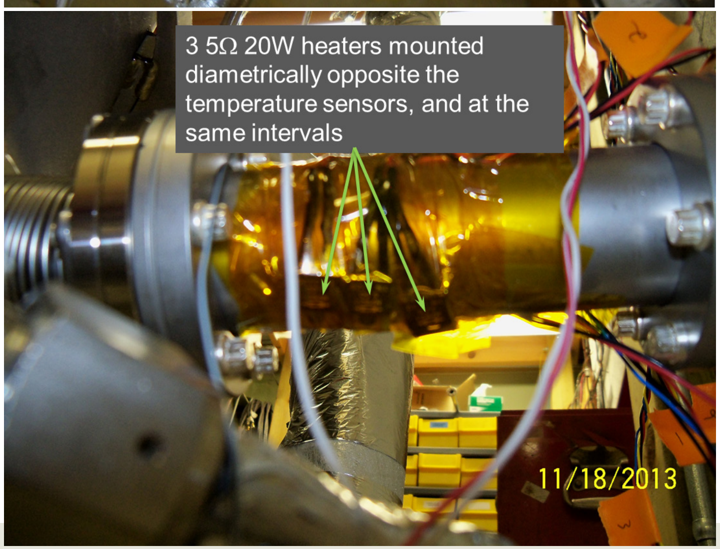

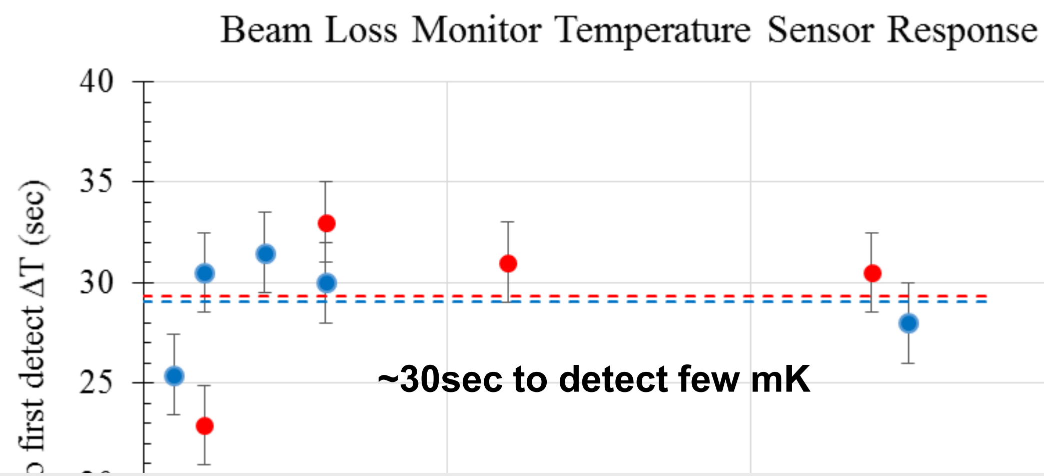

Faster detection requires

- **~mK resolution/stability**
- **More sophisticated DAQ (eg. Fermilab FTS – 1-10kHz timing, mK resolution)**

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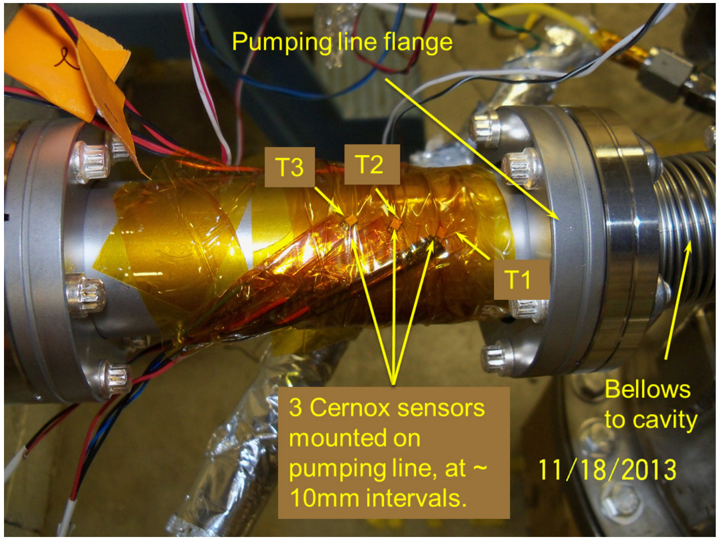
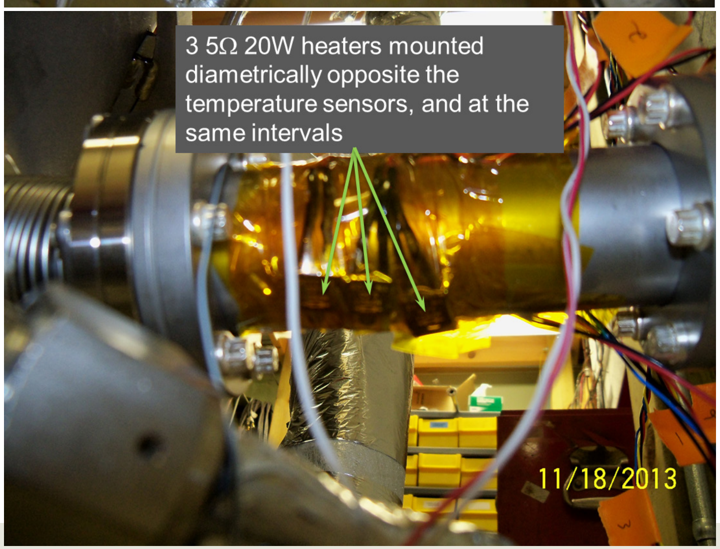
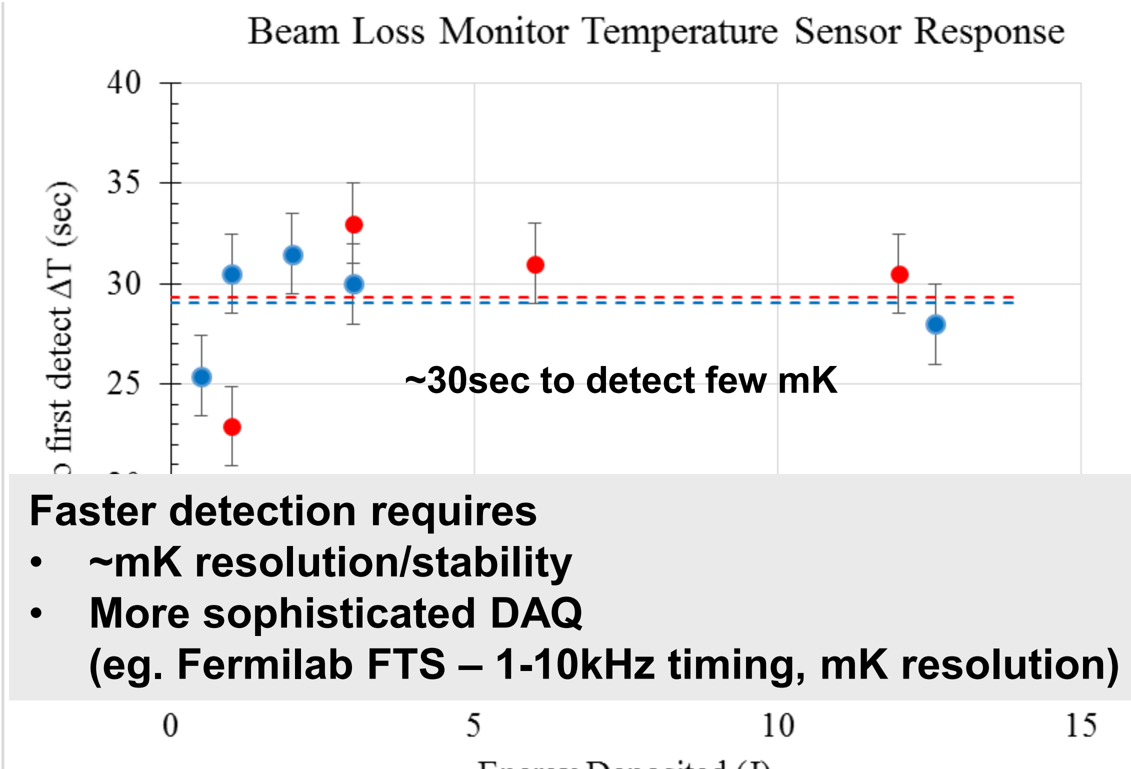






Faster detection requires

- **~mK resolution/stability**
- **More sophisticated DAQ (eg. Fermilab FTS – 1-10kHz timing, mK resolution)**

WEPMN105 Proceedings of PAC07, Albuquerque, New Mexico, USA

FAST THERMOMETRY FOR SUPERCONDUCTING RF CAVITY TESTING*

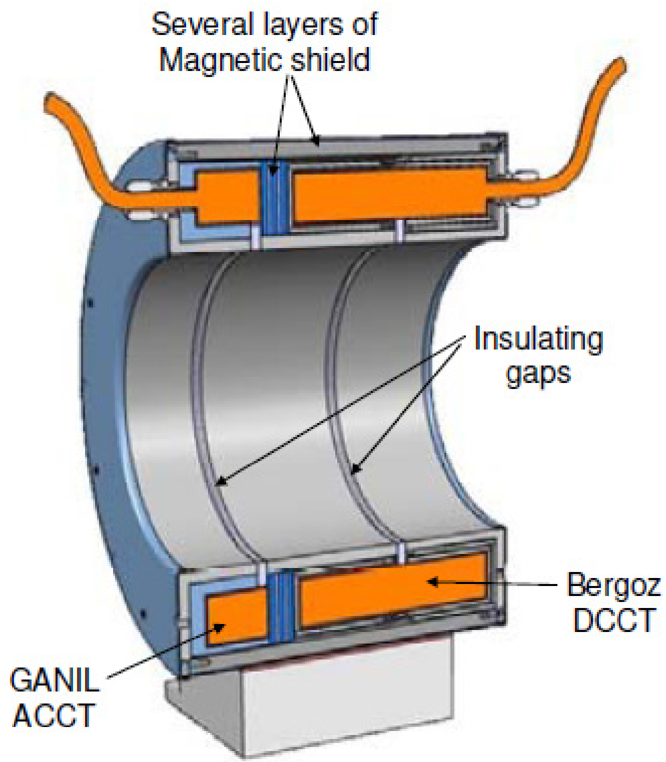
Darryl Orris#, Leo Bellantoni, Ruben H. Carcagno, Helen Edwards, Elvin Robert Harms, Timergali N. Khabiboulline, Sergey Kotelnikov, Andrzej Makulski, Roger Nehring, Yuriy Pischalnikov
Fermilab, Batavia, Illinois, USA

Direct beam diagnostics for fast detection

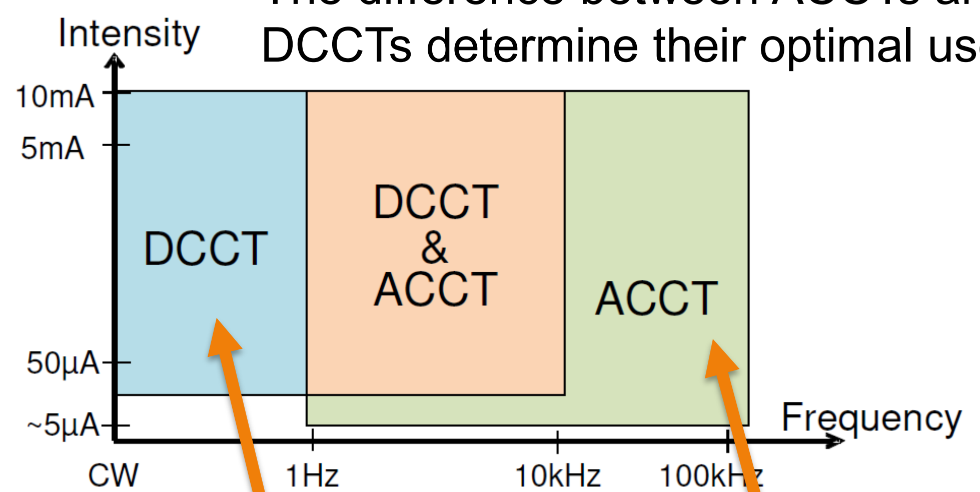
- Fast detection and beam interdiction requires accurate and robust measurements at time scales down to 1-10 μs
  - Detection and interdiction time is inversely proportional to intensity
- Beam current measurements
  - Robust monitoring at 1-10% of nominal level on
- Beam position monitors
  - Orbit shifts, intensity calibration
- Capacitive pickups and current sensing intercepting devices
  - Halo loss rings

Beam current monitors (ACCTs, DCCTs)

Most current sensing of intense beams is conducted with AC or DC current transformers, with appropriate analog front end, analog-to-digital conversion, and digital signal processing.



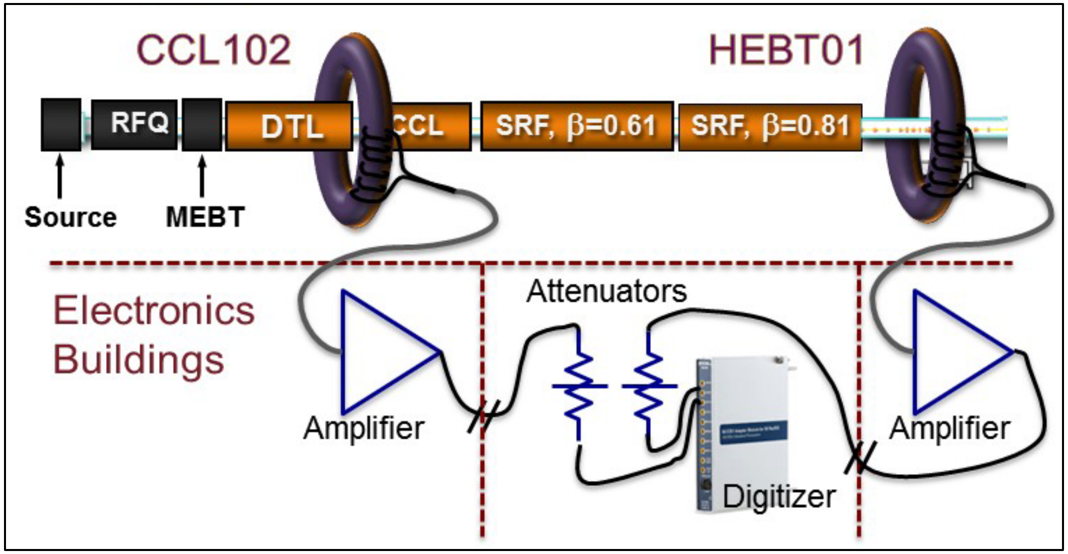
The difference between ACCTs and DCCTs determine their optimal use.



Low frequency response to DC
Require offset correction
Limited high frequency response

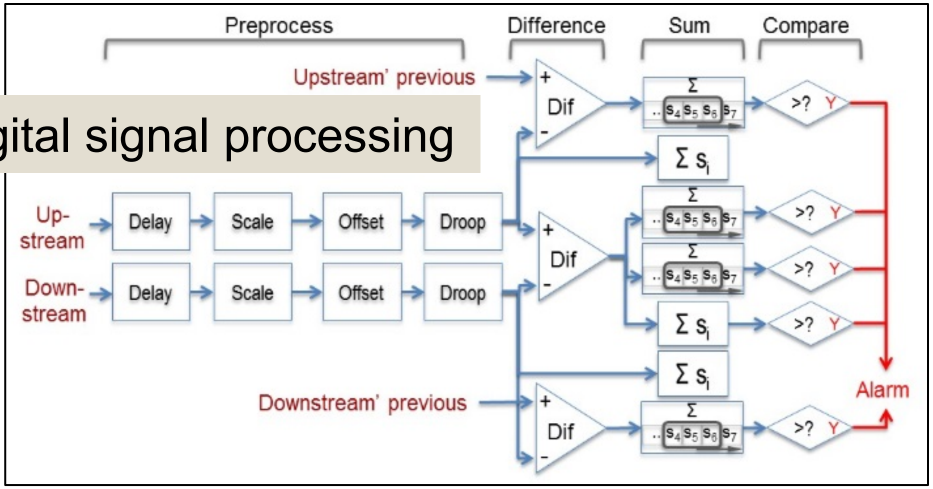
Good high frequency response
Require frequent re-baselining

SNS Differential Beam Current Monitoring

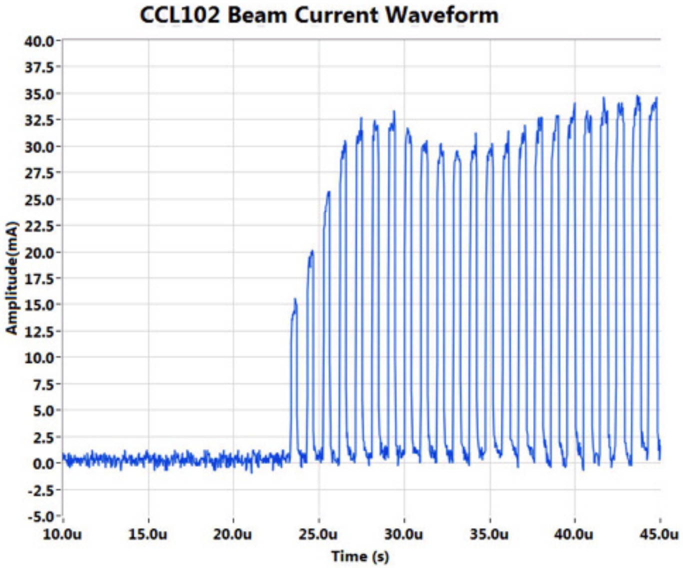


Demonstration of fast MPS network to detect errant beams

- Wideband CTs:
  - 1 GHz with 1 ms droop time constant
  - Nearest one before and after SCL
  - Long cable lengths (500-1200ft)



Digital signal processing



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Abort test demonstrates improved response time

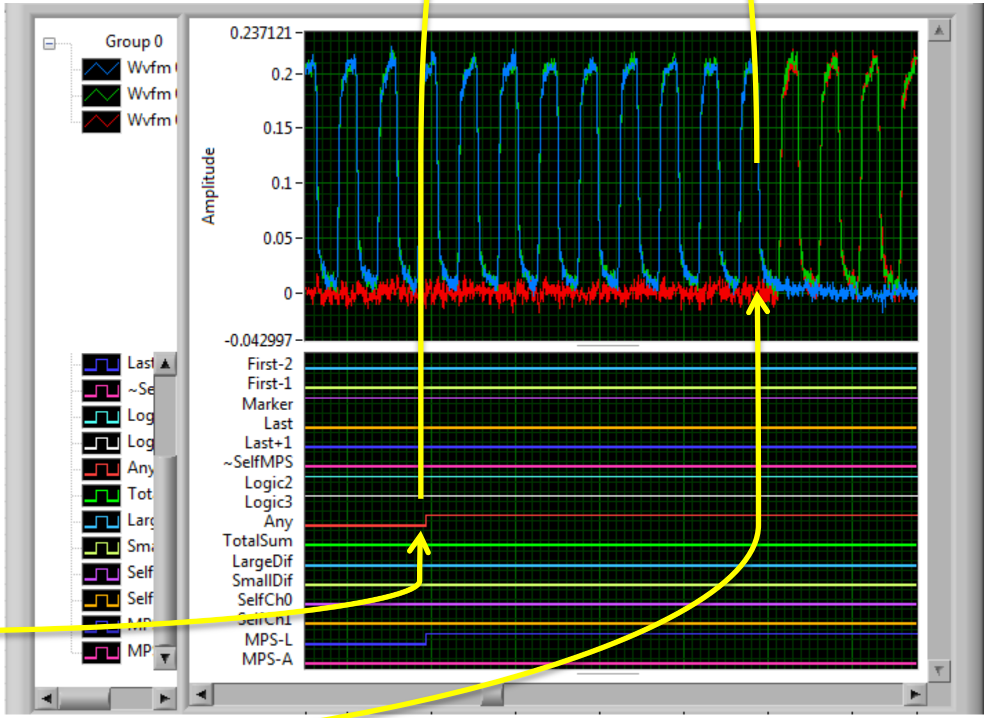
- Temporary change to the Machine Protect System
- DBCM will automatically abort in middle of the beam pulse
- Using slow and long cables

→ ~8.5μs abort time

→ 2-3x improvement

→~6μs best possible once optimized for cable length, pickup locations, and abort mechanism

Reaction Time



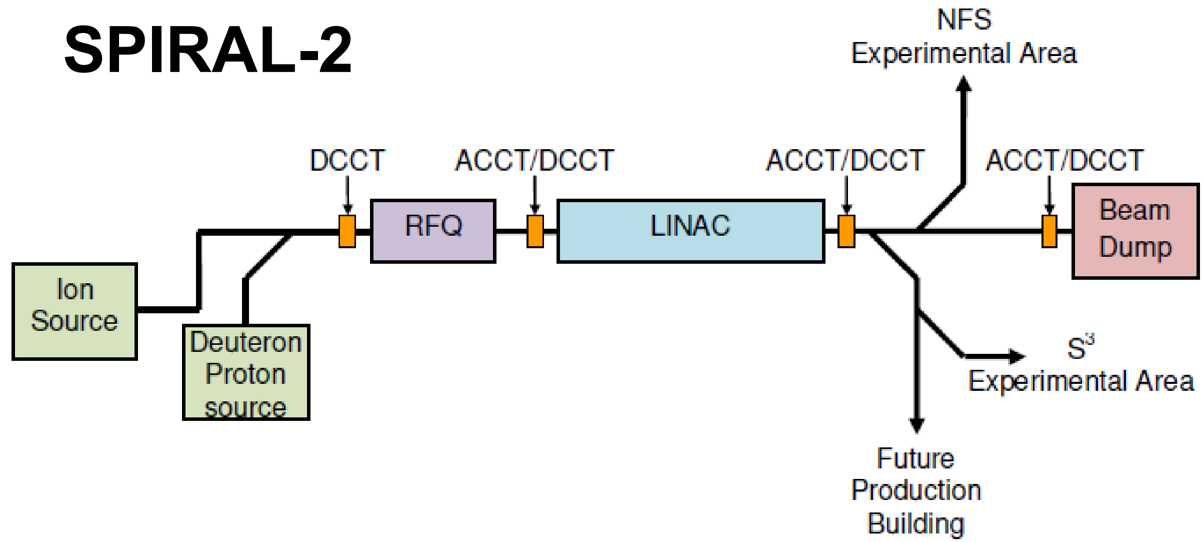
DBCM pulls abort

Beam gone

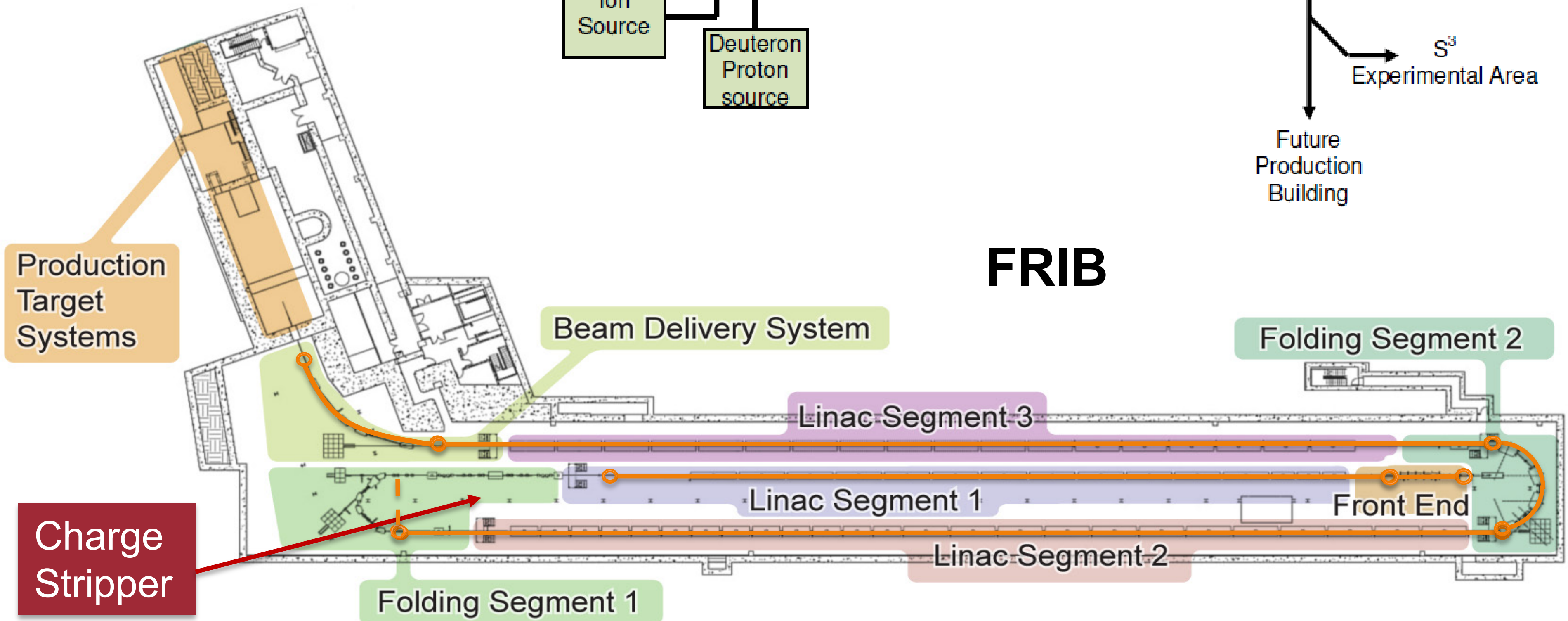
Current and previous beam pulse

Low Energy Differential Beam Current Monitoring at Heavy Ion Facilities

SPIRAL-2

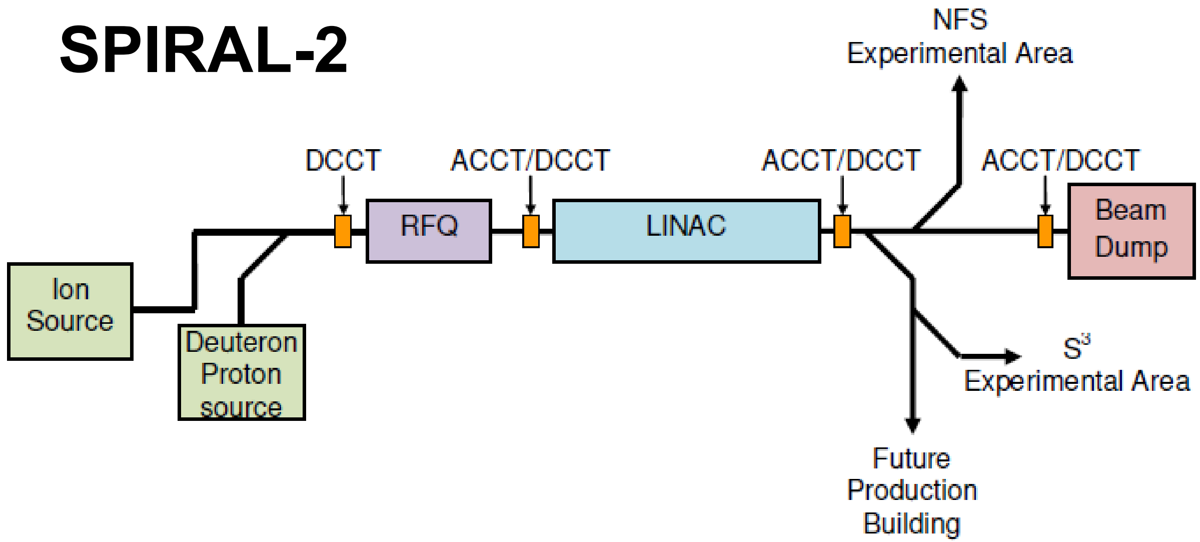


FRIB

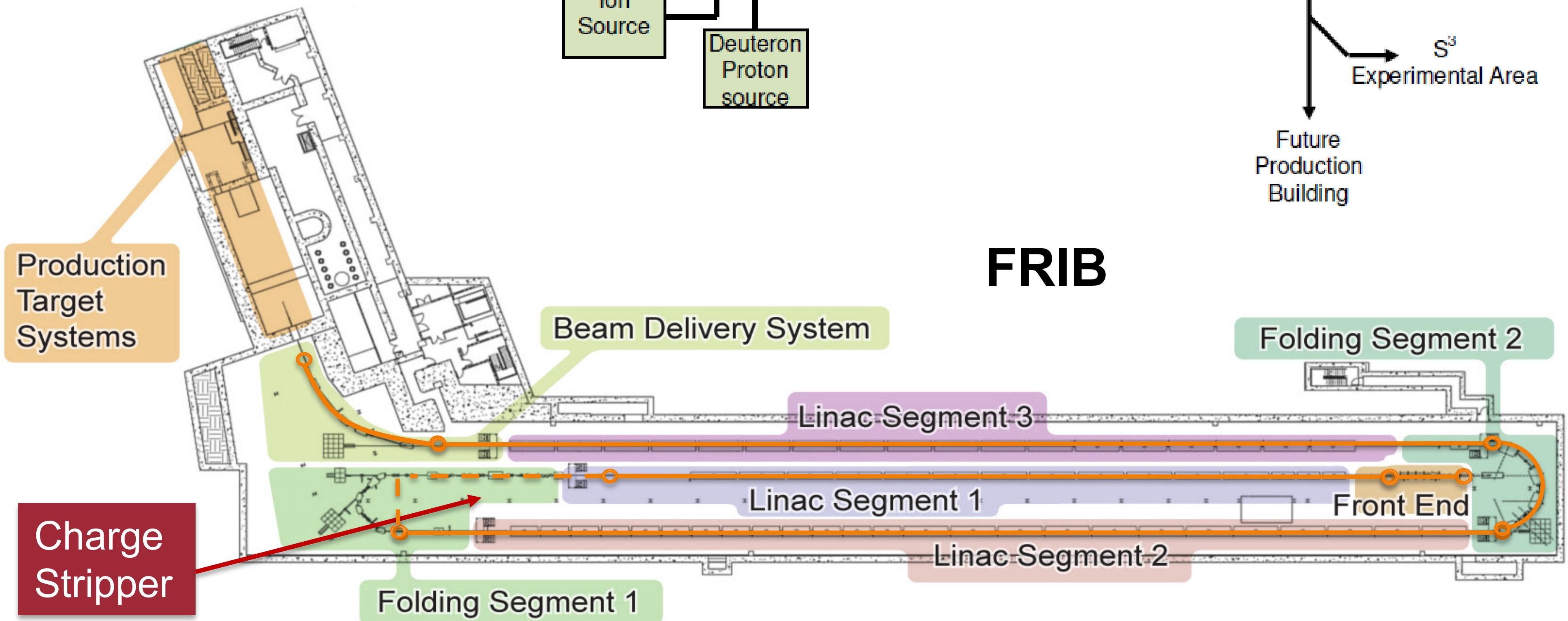


Low Energy Differential Beam Current Monitoring at Heavy Ion Facilities

SPIRAL-2

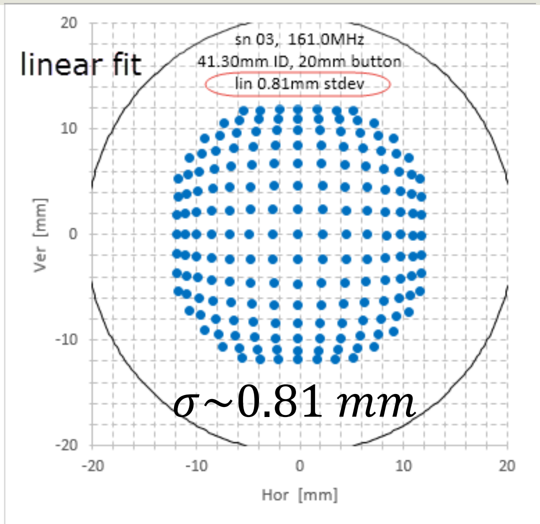


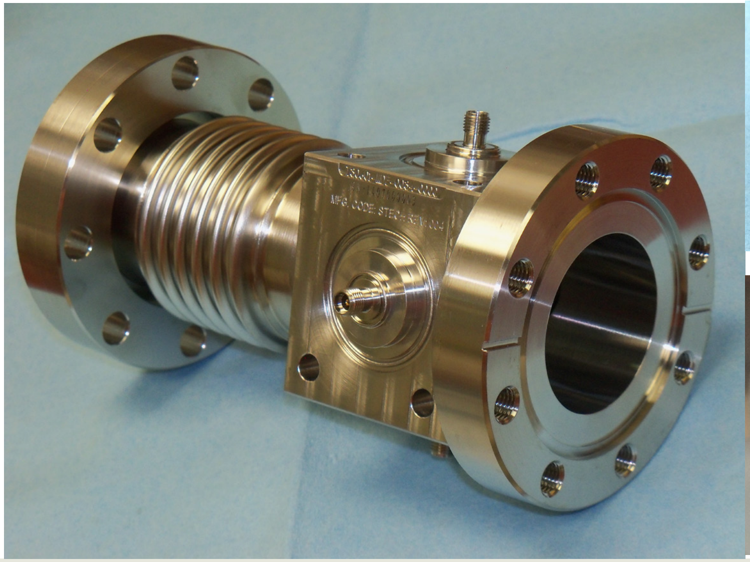
FRIB

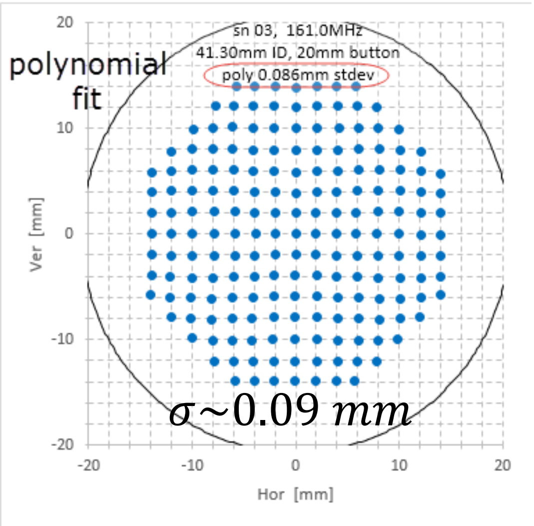


Beam position monitors have a natural place in MPS

- Denser network than BCMs
- Can monitor fast beam intensity changes, orbit deviations
- Suffer from position sensitivity and nonlinearity, low-β effects, differential gain drifts
- Narrow band RF receivers sensitive to bunch duration

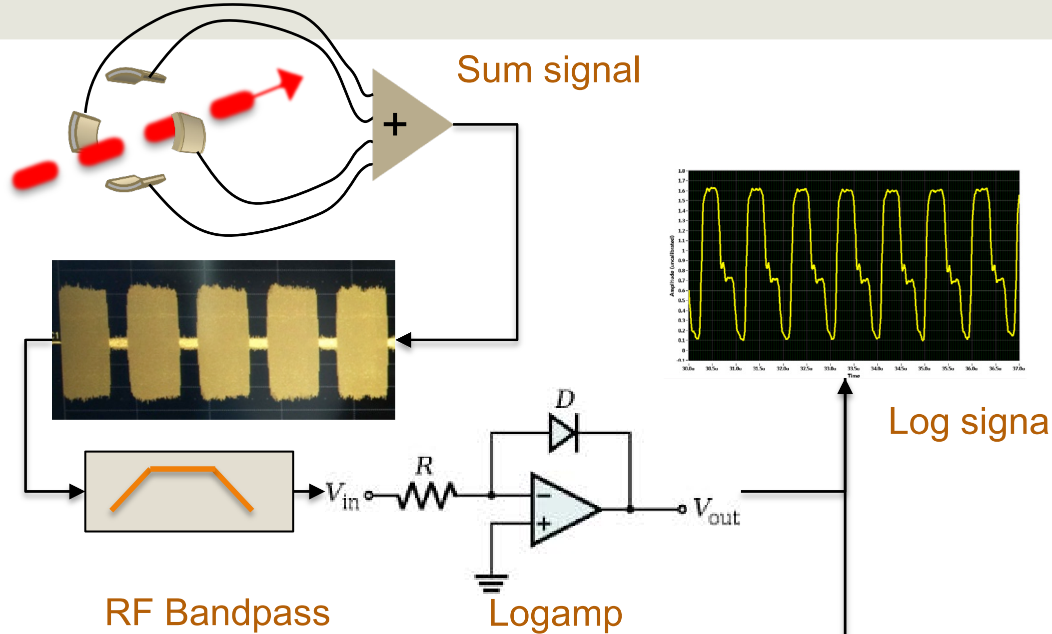


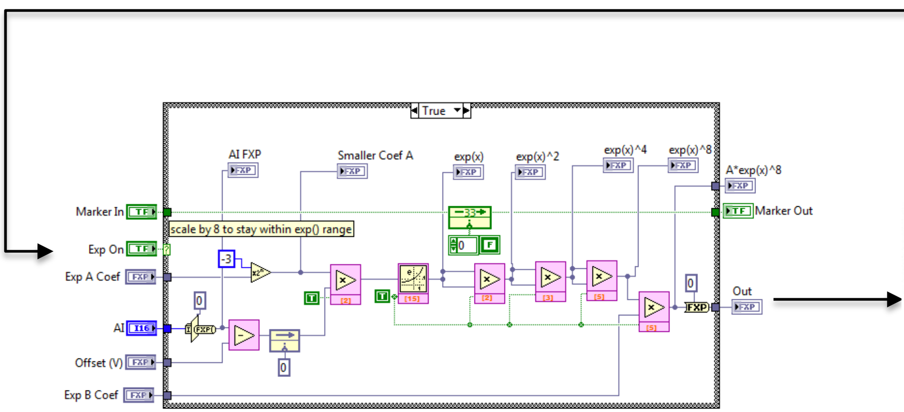




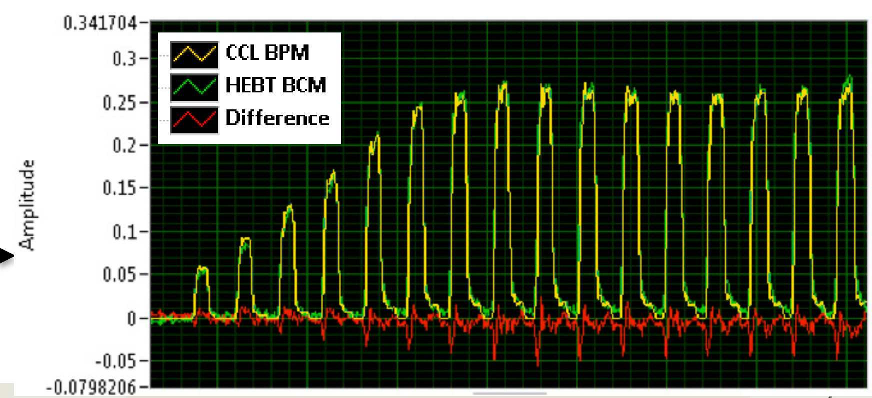
Current measurements using BPMs (SNS)

- 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





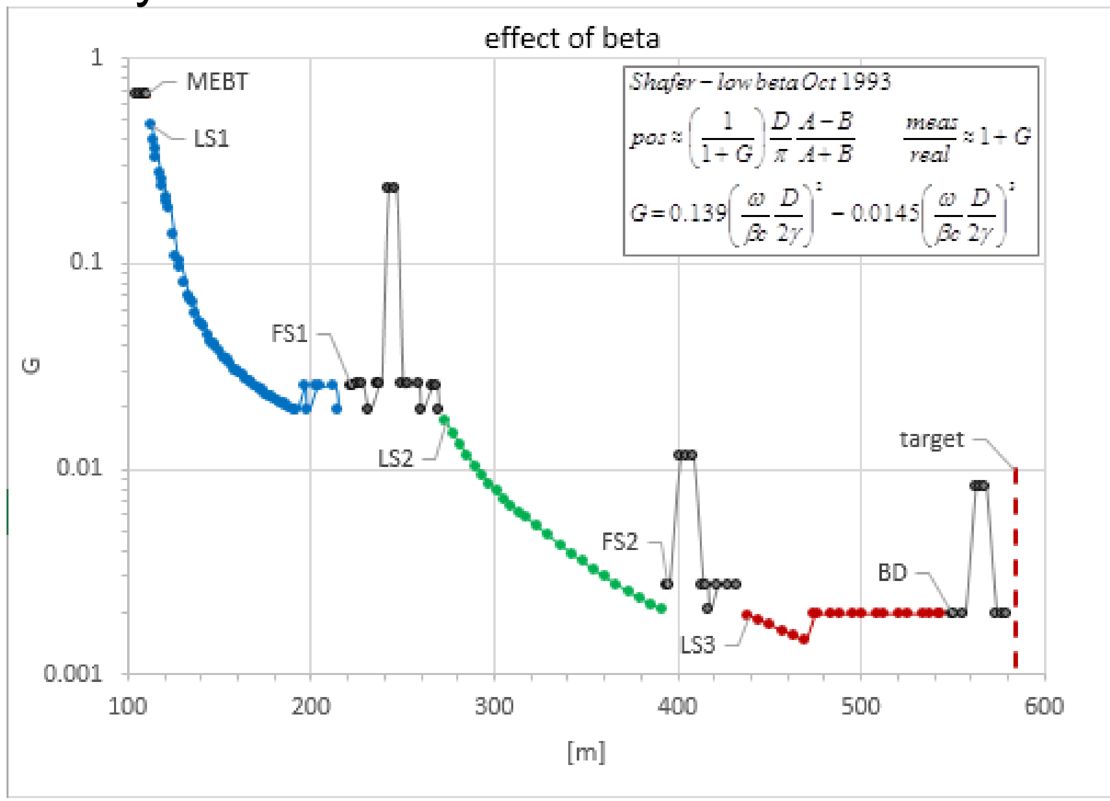
FPGA code to correct log signal



Final signals. Calibration done using downstream BCM

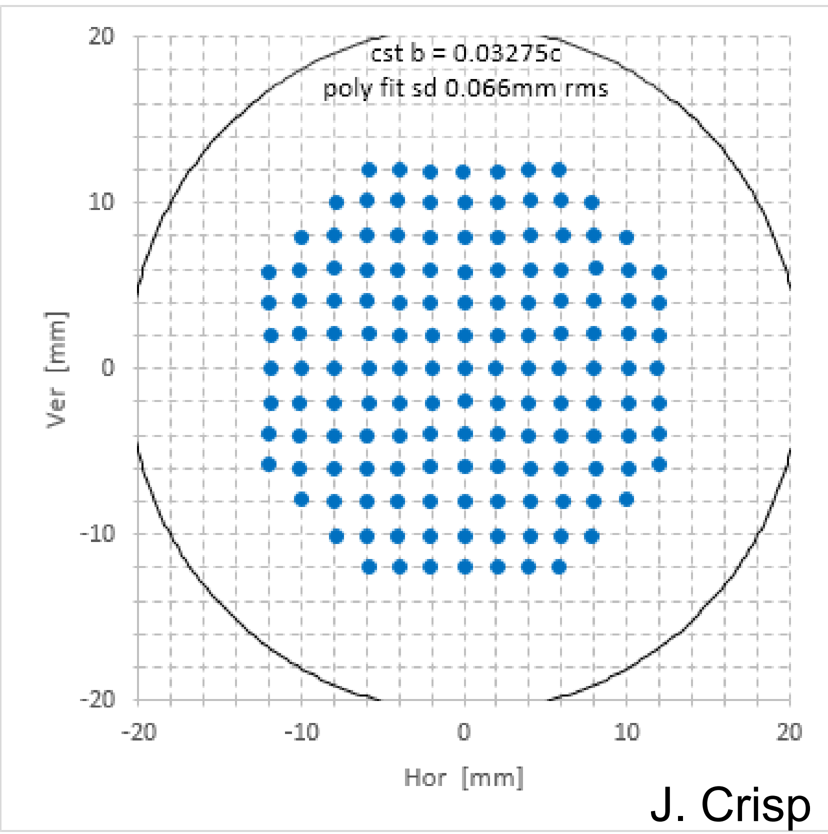
Low-β effect in FRIB

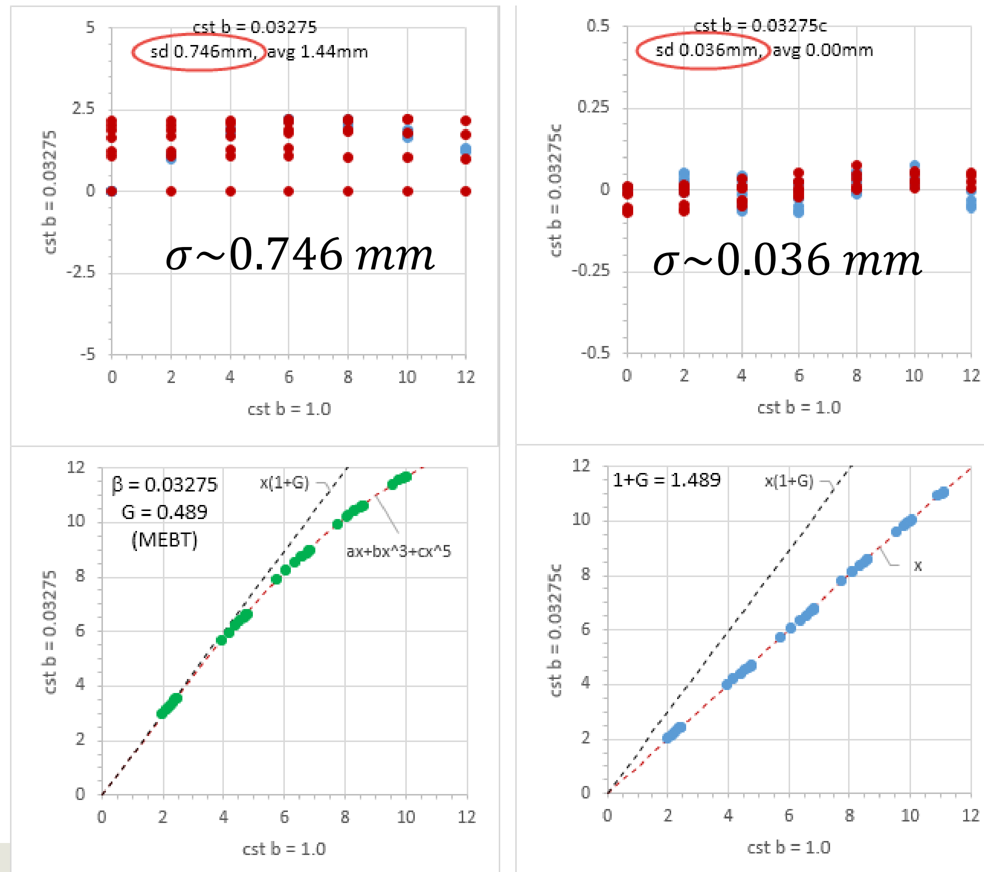
- at low beta, electric field spreads out longitudinally
  - reduces high frequency content
  - effect is larger with beam off center
  - exaggerates bpm position sensitivity
  - can't be measured with wire
- Shafer – Low-beta (1993)
  - 50% gain error in MEBT
  - <2% after FS1



Low β correction

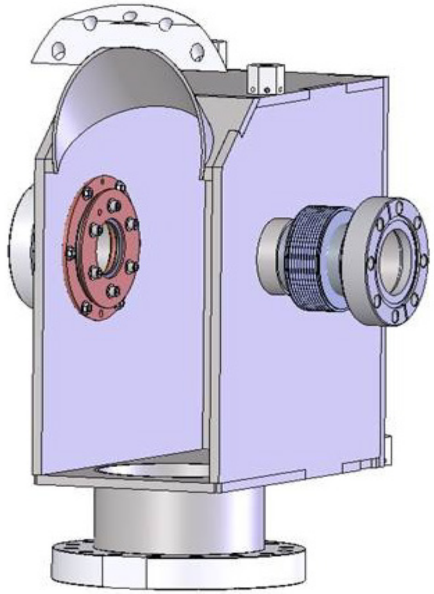
- With correction, the rms error over the working aperture improves 20x





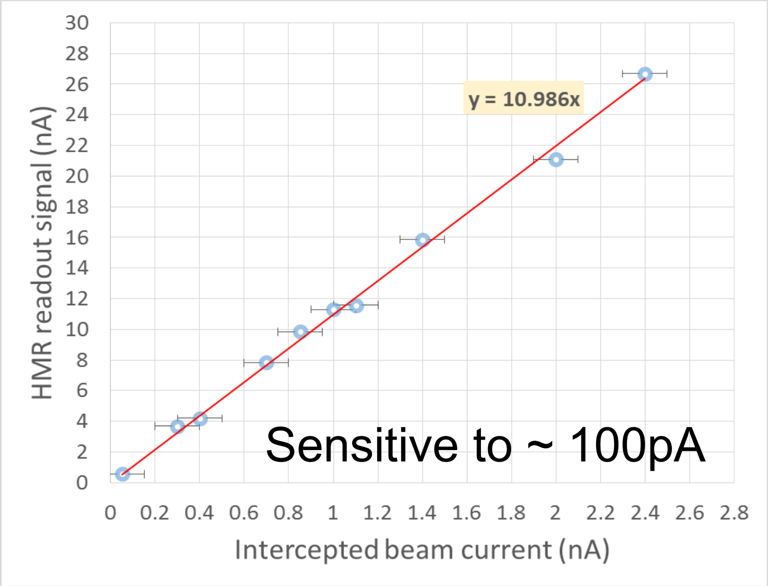
Halo Monitor Ring (HMR) detects loss by minimal interception

- 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



(Liu)

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



Advantages of HMR at Low Energy Regime

- HMR signal does not suffer from radiation cross-talk and background
- Intercepted beam current signal >> ionization chamber signal

Loss Mode	Loss Source Location	^{238}U Energy / Charge [(MeV/u) / Q]	Loss Level [W/m]	Ion Chamber Signal [pA]	HMR Intercepted Beam [nA]
Slow loss	LS1	10 / 33+	1	0.003 *	72 **
	LS2	60 / 78+	1	0.3 *	29 **
	LS3	200 / 78+	1	4.2 ***	9 **
Fast loss	3rd ⇦=0.29 cavity	20 / 78+	~1300 (in ~15m)	~7.0	29×10^3

* Assume the transfer function of ion chamber is 16.9 pA/R/hr (SNS).
** Assume HMR intercepts 1 W/m × 5 m beam power.
*** LS3 signal is calculated from loss in a superconducting structure.

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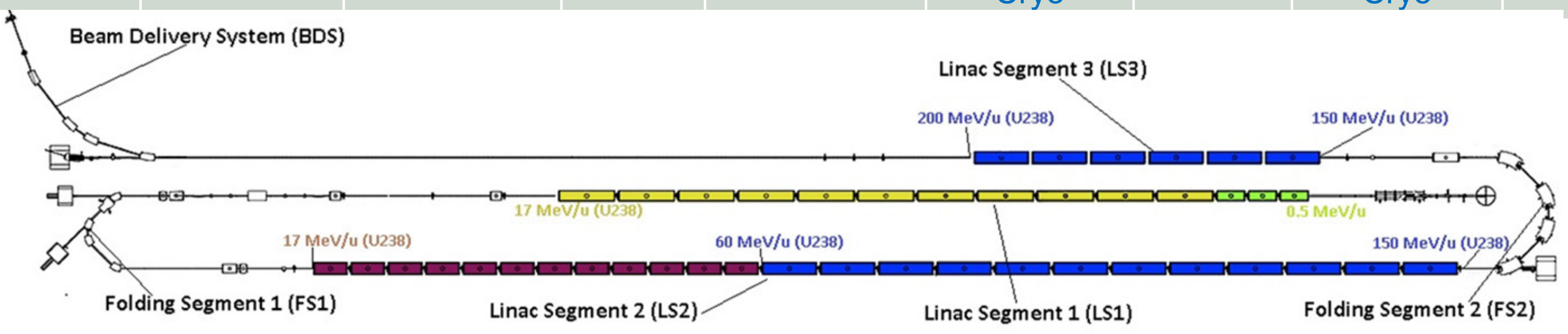
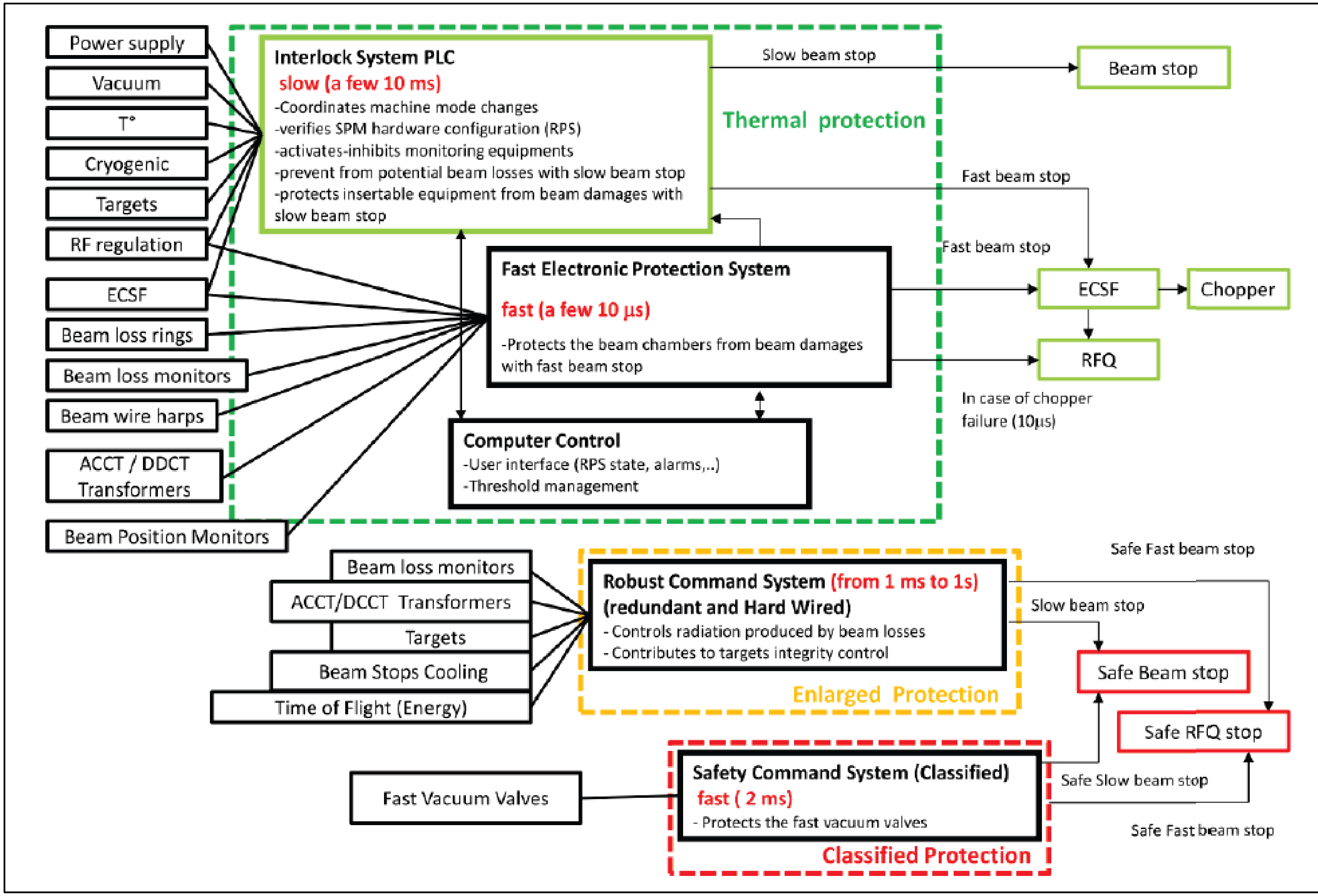
Proposed Beam Loss Detection Methods (FRIB)

		LS1	FS1	LS2 low energy	LS2 high energy	FS2	LS3	BDS
Fast Loss	Primary	DBCM	DBCM	DBCM	DBCM	DBCM	DBCM	DBCM
< 35 μs	Secondary	HMR	HMR	HMR	BLM	BLM	BLM	BLM
	Tertiary				HMR	HMR	HMR	
Slow loss	Primary	HMR/Temp	HMR	HMR/Temp	BLM	BLM	BLM	BLM
> 100 ms	Secondary	HMR/Temp		HMR/Temp	HMR/Temp	HMR	HMR/Temp	
	Tertiary	Cryo		Cryo	HMR/Temp		HMR/Temp	
					Cryo		Cryo	



Layering of SPIRAL-2 detection method and time scales schemes

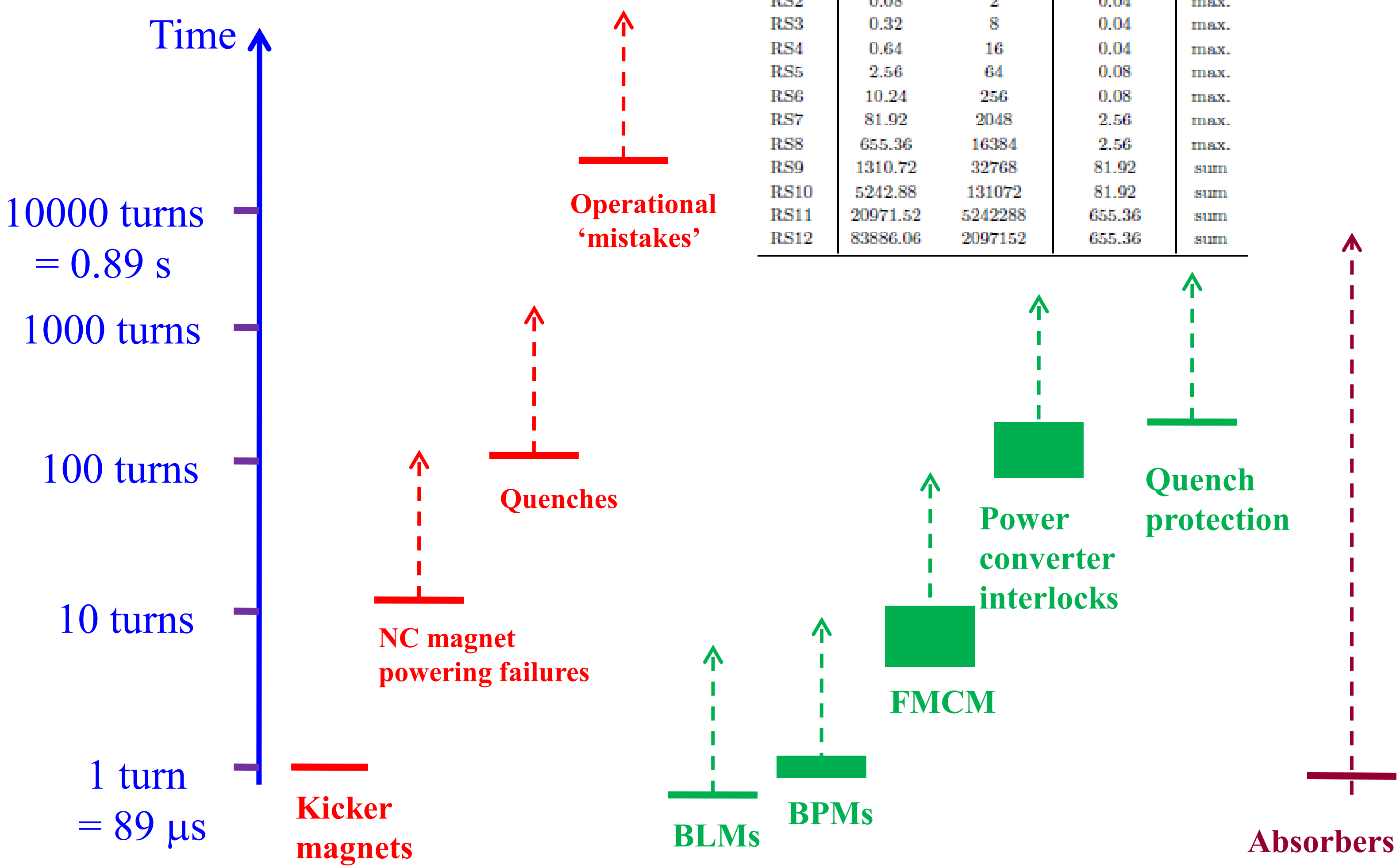


Redundant, Multi-layered Machine Protection Responds to Fast Events and Slow Losses

Mode	Response time	Main purpose and approach	Detection technique	Loss mitigation technique
Fast protection system	**~ 35 µs**	• Prevent damage from acute beam loss by quickly activating the beam inhibit device; • Lower sensitivity	• Low-Level RF controller; • Dipole current monitor • Differential BCM; • Ion chamber; • Halo monitor ring; • Fast neutron detector; • Differential BPM	• LEBT bend electrostatic deflector
Run permit system [1]	**~ 100 ms**	• Continuously queries the machine state and provides permission to operate with beam	• Vacuum; • Cryomodule status; • Non-dipole magnet PS; • Interceptive diagnostics; • Differential BCM; • Quench signal; • Differential BPM; • Ion chamber; • Slow neutron detector	• LEBT bend electrostatic deflector; • ECR source HV
Run permit system [2]	**> 1 s**	• Prevent slow degradation of SRF system under small beam loss; • Require high sensitivity detection	• Thermo-sensor near solenoids for beam loss monitoring; • Cryogenic heater power	• LEBT bend e- deflector; • ECR source HV

MPS Timescales at LHC, 40 μs to 84 s

Signal Name	Time Window Δt_i [ms]	40μs Steps	Refreshing Rate [ms]	Data Type
RS1	0.04	1	0.04	max.
RS2	0.08	2	0.04	max.
RS3	0.32	8	0.04	max.
RS4	0.64	16	0.04	max.
RS5	2.56	64	0.08	max.
RS6	10.24	256	0.08	max.
RS7	81.92	2048	2.56	max.
RS8	655.36	16384	2.56	max.
RS9	1310.72	32768	81.92	sum
RS10	5242.88	131072	81.92	sum
RS11	20971.52	524288	655.36	sum
RS12	83886.06	2097152	655.36	sum



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Summary

- Elements of modern MPS design for high power hadron machines have been presented.
- Modes of beam loss, and detection techniques were discussed.
- Differential beam current monitoring is beginning to eclipse beam loss monitoring as the primary detection scheme.
- Integrating and layering schemes with multiple time-scales and redundant detection mechanisms is necessary for reliable and robust operation.
- Incorporation of beam loss detection with other cryomodule instrumentation will tax heat load budgets but must be pursued.
- Simulation, modeling, network building can optimize monitor placement and assist event post-mortem analysis.

Acknowledgment

- Participants of the 2014 Machine Protection Systems for High Power Superconducting Hadron Accelerators Workshop

MPS2014
East Lansing, MI
5-6 March 2014
Machine Protection Systems
for High Power Superconducting
Hadron Accelerators Workshop

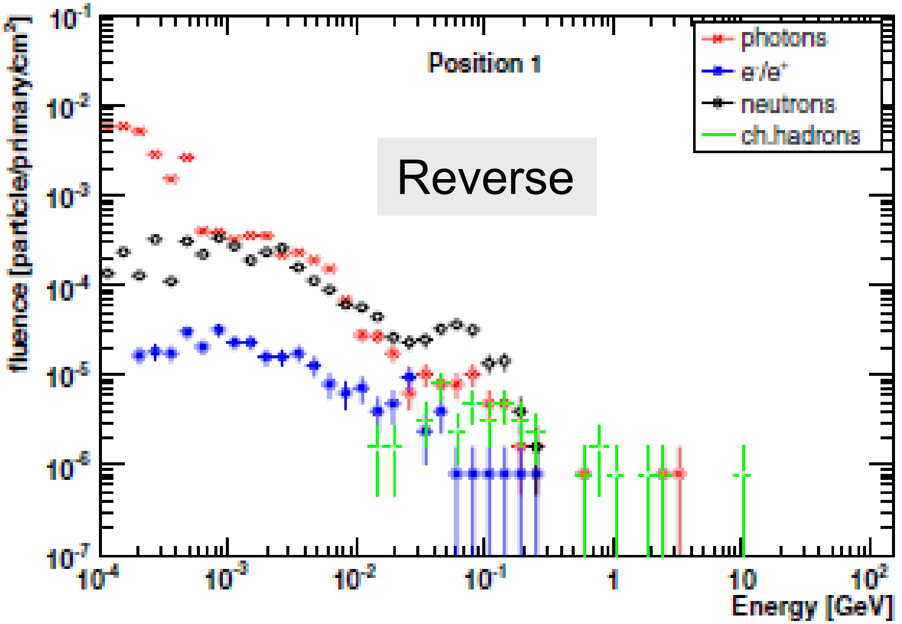
- Materials and discussions: A. Zhukov, W. Blokland, R. Doelling, C. Jamet, M, Ross, B. Dehning, D., McCormick, Z. Liu, Y. Zhang, Q. Zhao, A. Jansson, J. Crisp

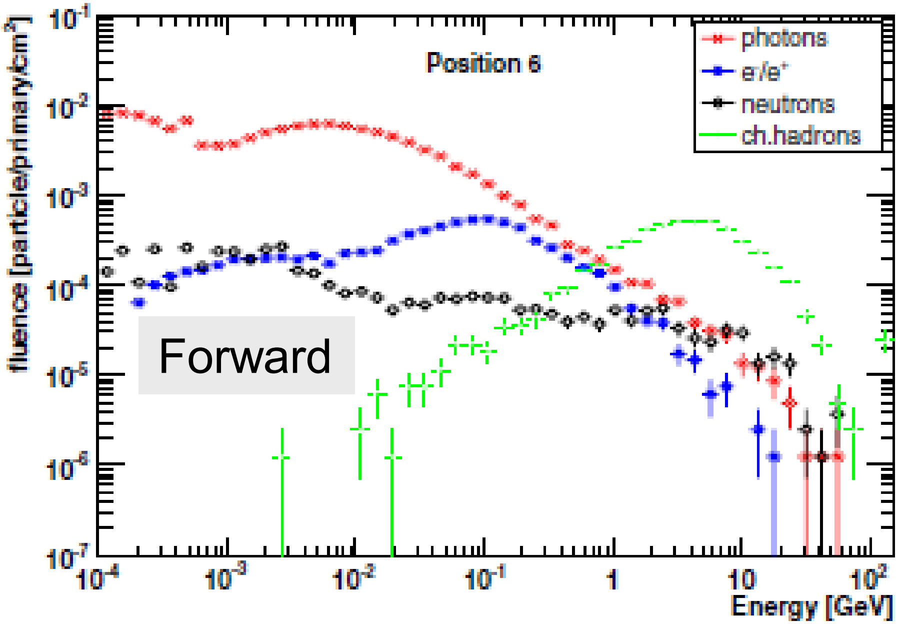
Thank You

Mixed radiation fields

Measured spectra at CERF

Particle composition in %	π^+	protons	K^+
	60.7	34.8	4.5
Momentum	120 GeV/c		
Intensity used	up to 9.5×10^7 hadrons (4000 PIC) per 16.8 s		
Gaussian beam shape approximation (4000 PIC)	$\sigma_{horizontal}$	1.3 cm	
	$\sigma_{vertical}$	1.0 cm	

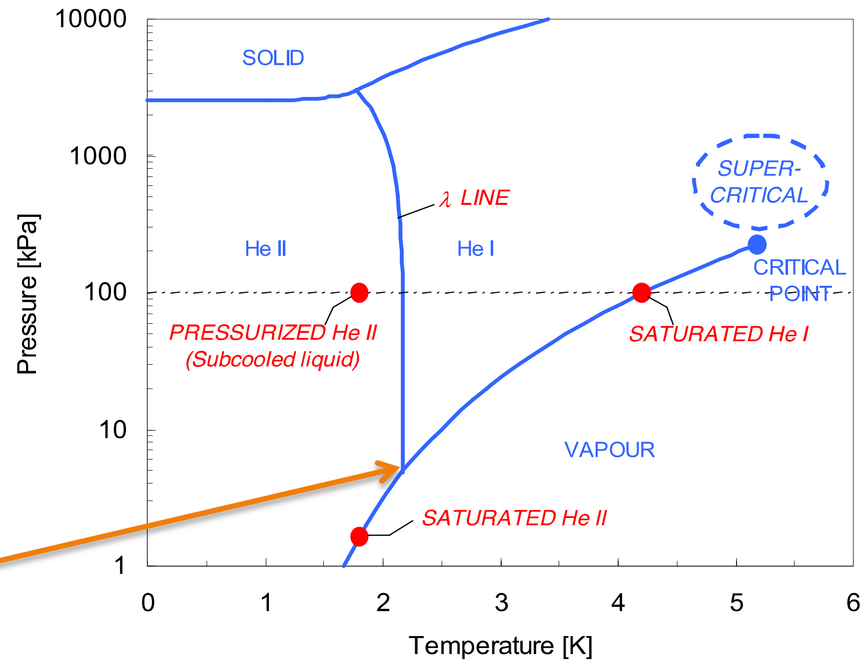




Stockner

Cryomodule – Operating Temperature

- 2 K generally refers to liquid helium temperature from 1.8 K to 2.1 K
- Temperature difference is relatively small, but the difference of pressure is significant: from 1.6 kPa to 4.1 kPa, so are costs of cryoplant and operation
- Operational temperature of the FRIB cavity is under evaluation **B03**-Casagrande

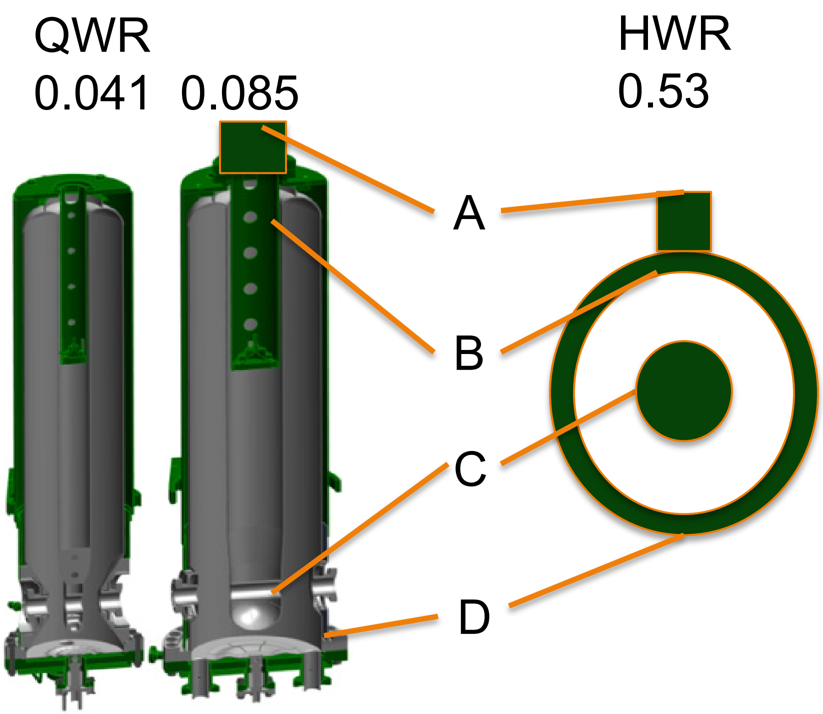


Lambda point:
5.05 kPa, 2.177 K

Phase diagram of helium

LHe Pressure and Temperature Correlation Studied

- Pressure builds up with the depth of helium bath, so as the saturation temperature Ts
- The maximum surface temperature Tmax should below saturation and Lambda point



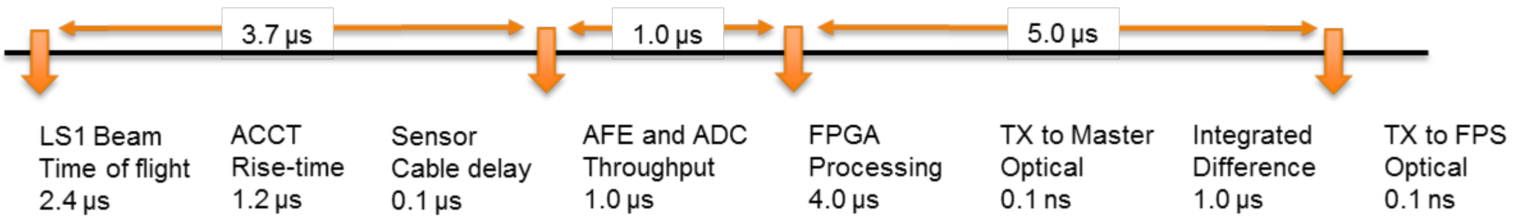
QWR				
Pos.	P (Pa)	Ts (K)	Tmax	h (cm)
A	4141	2.100	2.100	0
B	4427	2.123	2.102	20
C	5572	2.218	2.111	100
D	5858	2.240	2.113	120

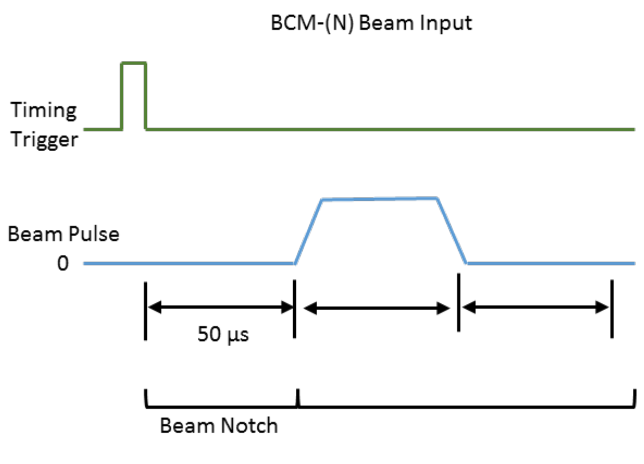
HWR				
Pos.	P (Pa)	Ts (K)	Tmax	h (cm)
A	4141	2.100	2.100	0
B	4427	2.123	2.102	20
C	4785	2.154	2.107	45
D	5142	2.184	2.110	70

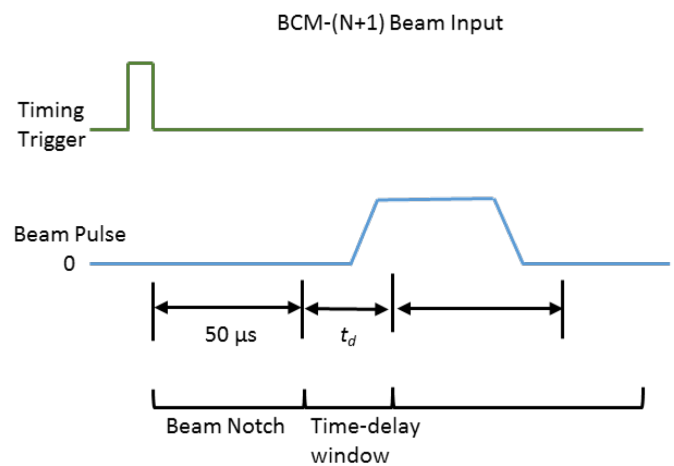
- In the current design of helium vessel, heat flux in the cavity is minimized
- Tmax is estimated with a constant flux 0.5 W/cm^2, gradient ~ 0.1 mK/cm

Design Example of DBCM (Bergoz BCM)

- Example: LS1 differential currents
  - Current difference measurements are performed in <10 μs with a current resolution better than 4 μA (~1% of full beam current)

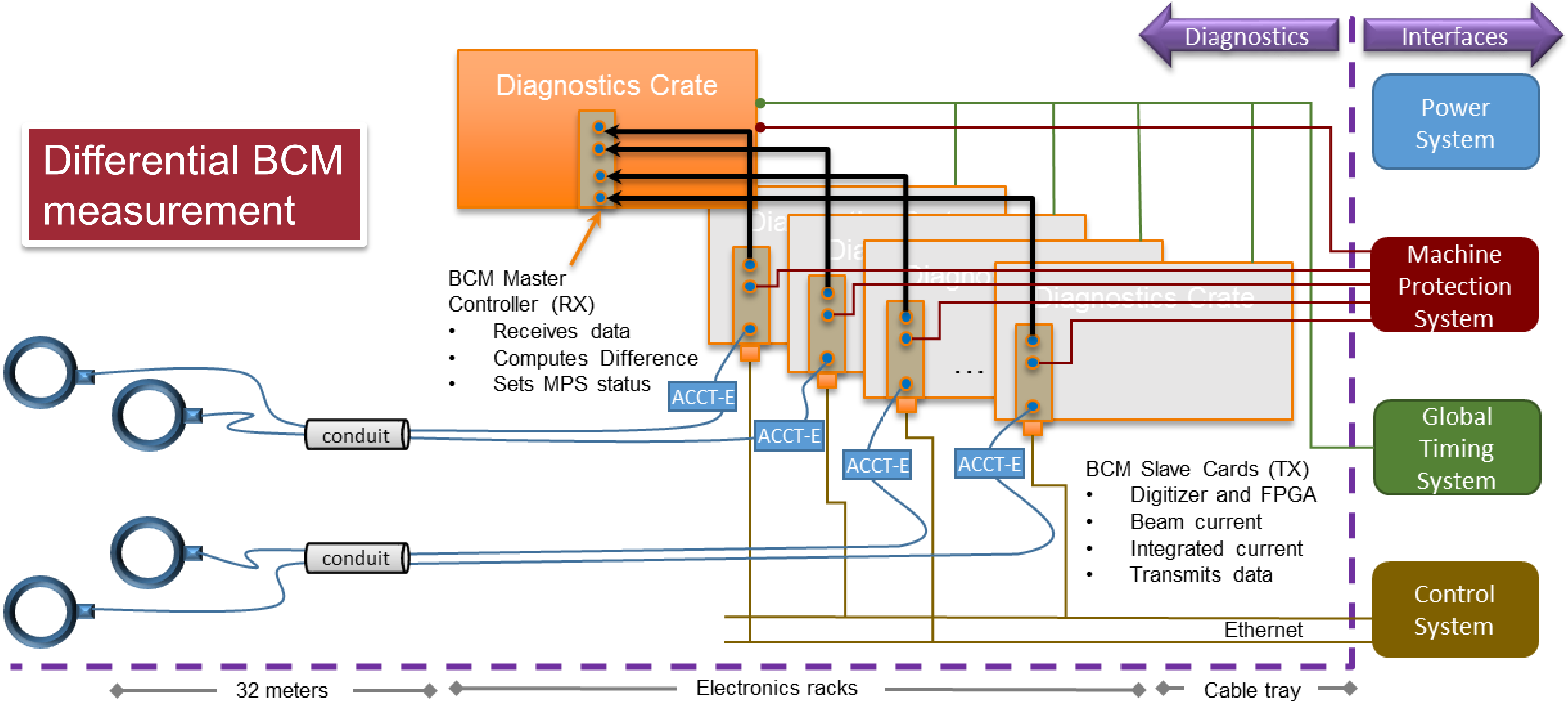






Beamline Segment	Time of flight (μs)
LEBT	1.3
RFQ	0.7
MEBT	0.7
LS1	**2.4**
FS1	1.4
LS2	1.2
FS2	0.3
LS3 and BDS	0.9

System Architecture and Interfaces



Individual nodes to digitize and filter the transformer signals, to perform digital processing to recover the beam current, and to compute integrated current values

Dedicated data links to master controller to compute differential current information

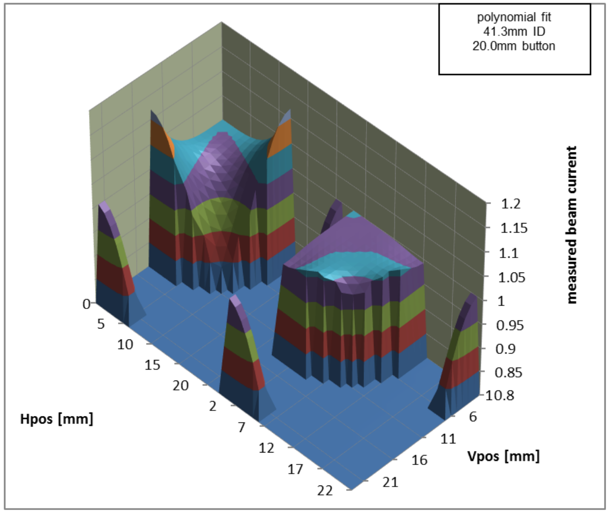
Differential Current Monitoring by BPM Pair

- Experiment was set up at ReA3 with Fermilab BPM receivers
  - Measures second harmonic 161 MHz
  - 81 dB gain pre-amp; 1.32 dB cable loss
  - Effective BW ~37kHz (τ~4.3μs)
- For 37 kHz, the calculated intensity RMS resolution (std) is 126 nA.
- From experiment, the RMS intensity resolution (std) for single BPM is measured as 67-106 nA for 204800 samples, assuming beam is at the center. The differential intensity resolution is ~140 nA.
- FRIB BPM intensity resolution is comparable with ReA3 BPM, and it features fast evaluation (~15μs).
- **BPM resolution is very sensitive to beam position and beam velocity. Calibration is necessary.**

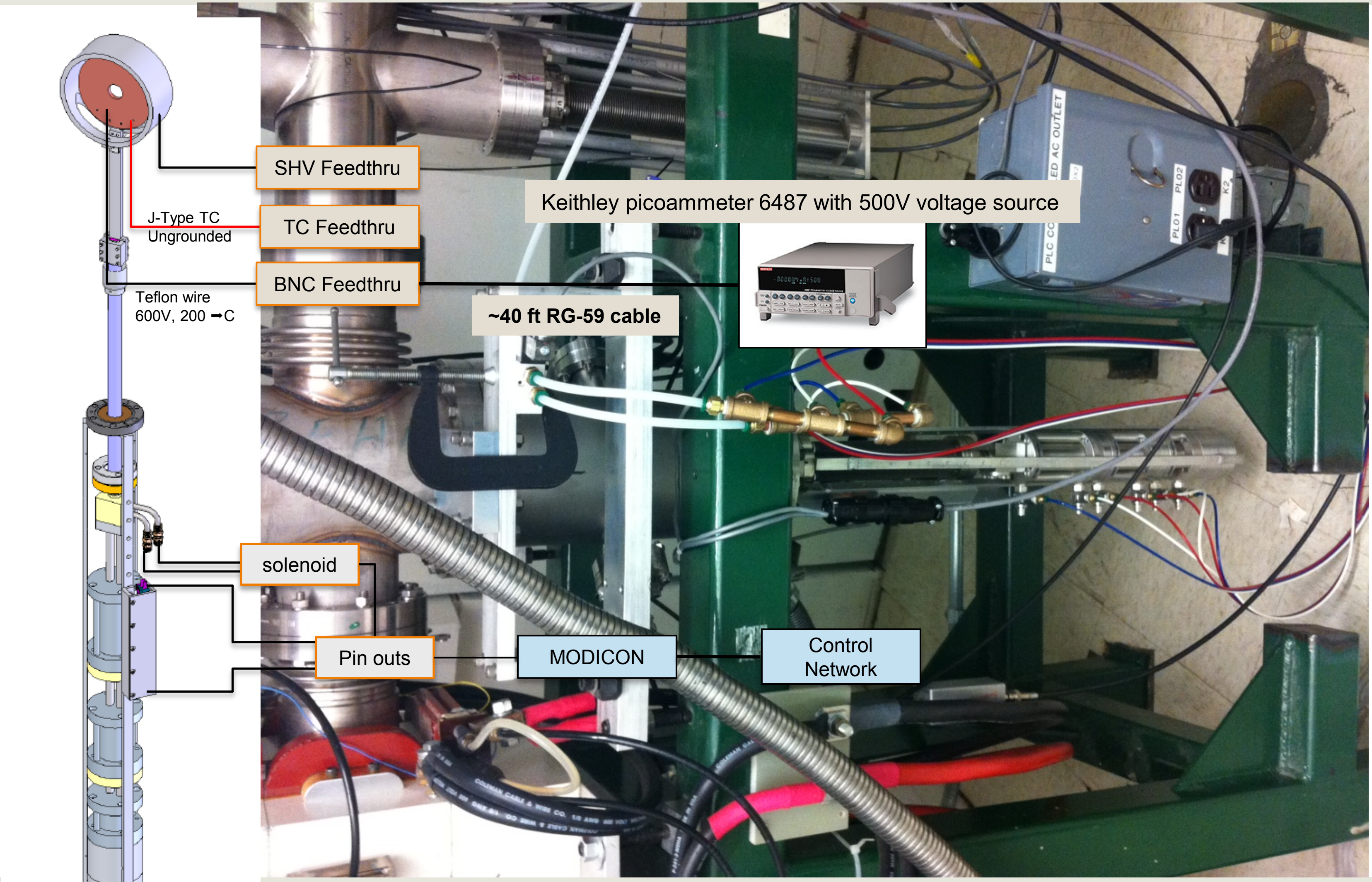
FRIB BPM intensity resolution

		rms bunch lgth			
	beta	MeV/u	rms deg	mm	nA-rms
rfq out	0.03275	0.5	2.7	0.9	323
ls1 in	0.03275	0.5	1.8	0.6	322
ls1 out	0.18647	16.63	0.9	1.7	763
ls2 out	0.50624	148.63	0.6	3.1	2023
ls3 out	0.56985	202.06	4.7	27.7	2306
target	0.56985	202.06	7.5	44.2	2355

Linear and Polynomial fit for BPM intensity



Prototype HMR Test Set-up at NSCL



(Liu)