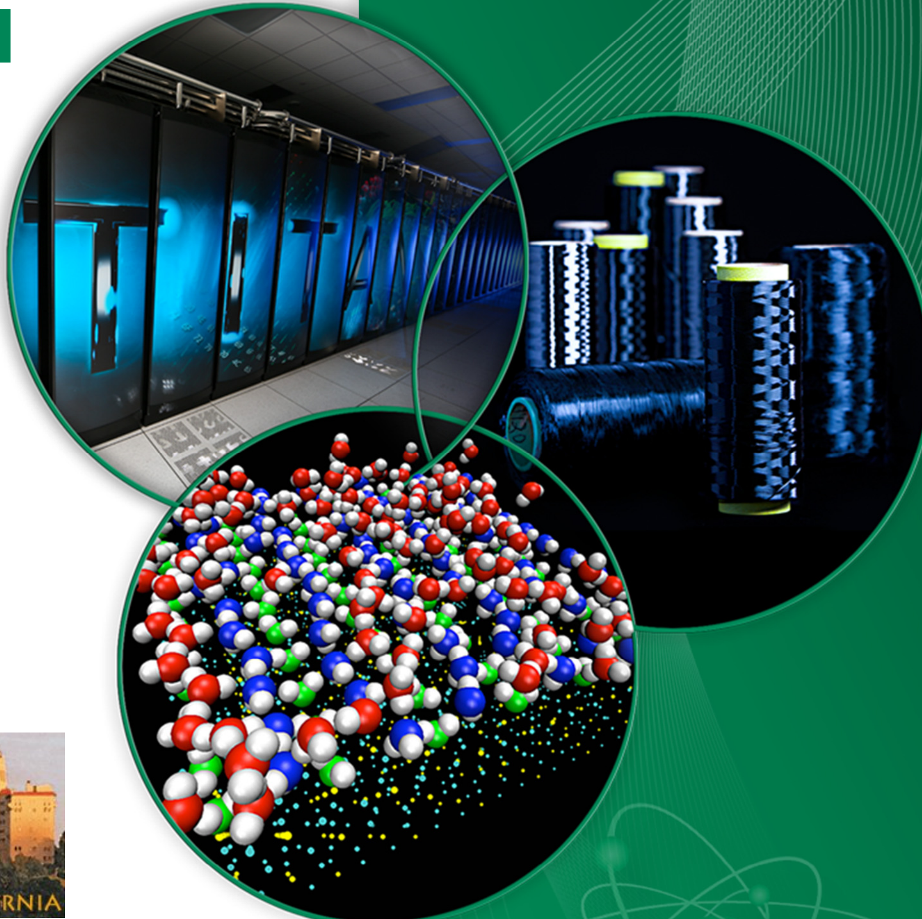
Experience with the SNS Loss Monitoring and Machine Protection



A. Zhukov

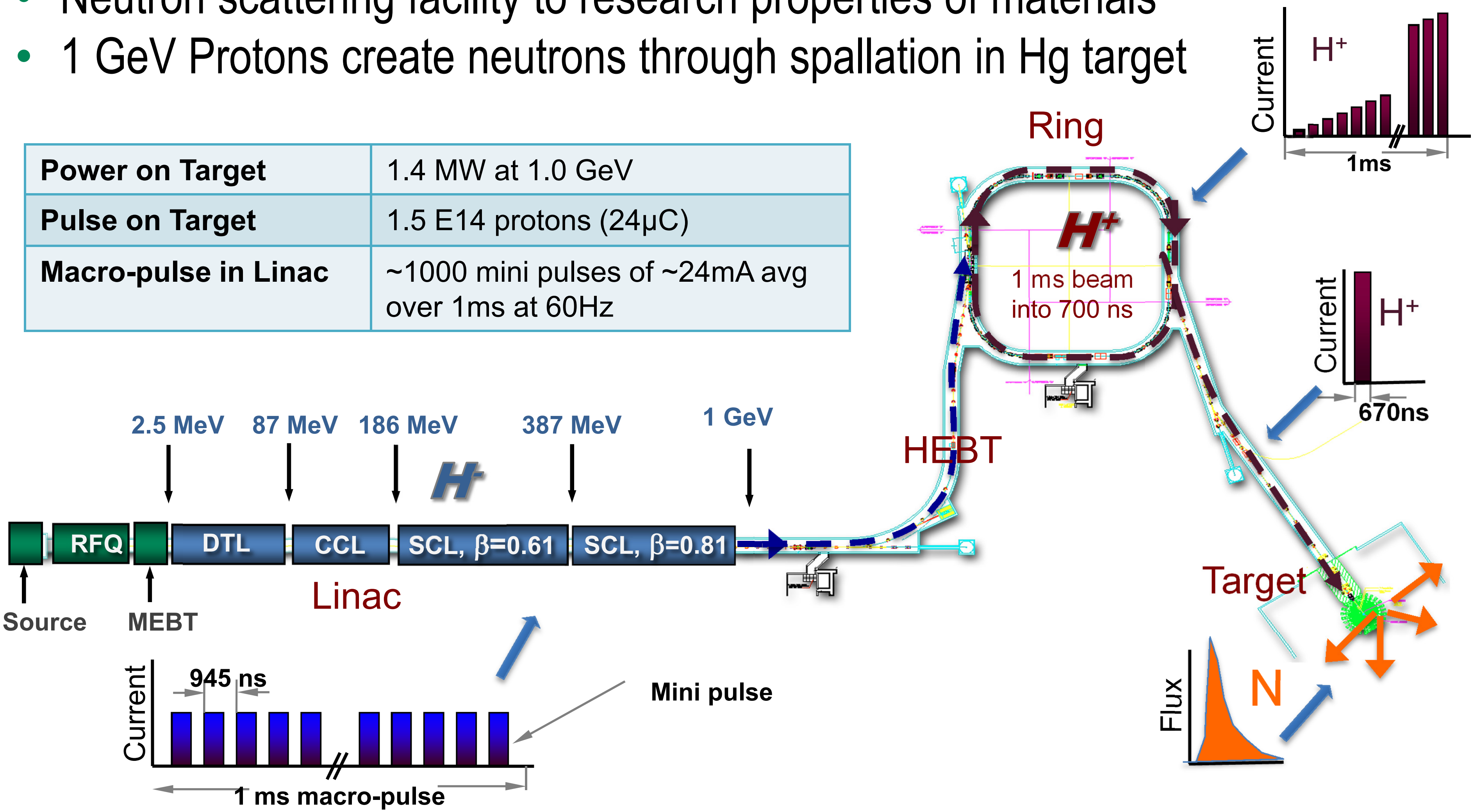
Spallation Neutron Source
Oak Ridge National Laboratory

* ORNL/SNS is managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725

Spallation Neutron Source

- Neutron scattering facility to research properties of materials
- 1 GeV Protons create neutrons through spallation in Hg target

Power on Target	1.4 MW at 1.0 GeV
Pulse on Target	1.5 E14 protons (24μC)
Macro-pulse in Linac	~1000 mini pulses of ~24mA avg over 1ms at 60Hz



BLM system requirements

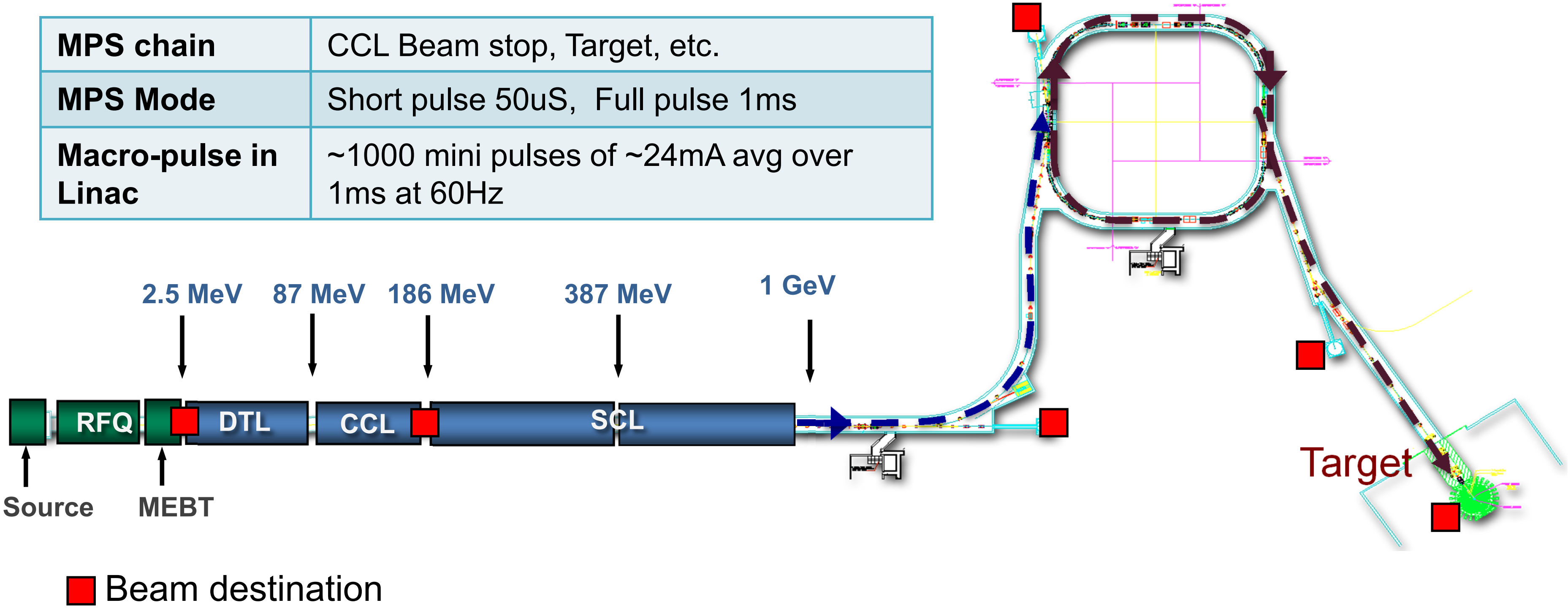
- Sensitive enough to reliably measure and limit average loss at **1W/m**
- Reaction time of BLM system **~5uS** to instantaneous loss
- Analog waveform output to see loss along macro-pulse
- Hardware implementation of MPS for reliability
- No dependence on timing system
- No electronics in tunnel

Machine Protection System

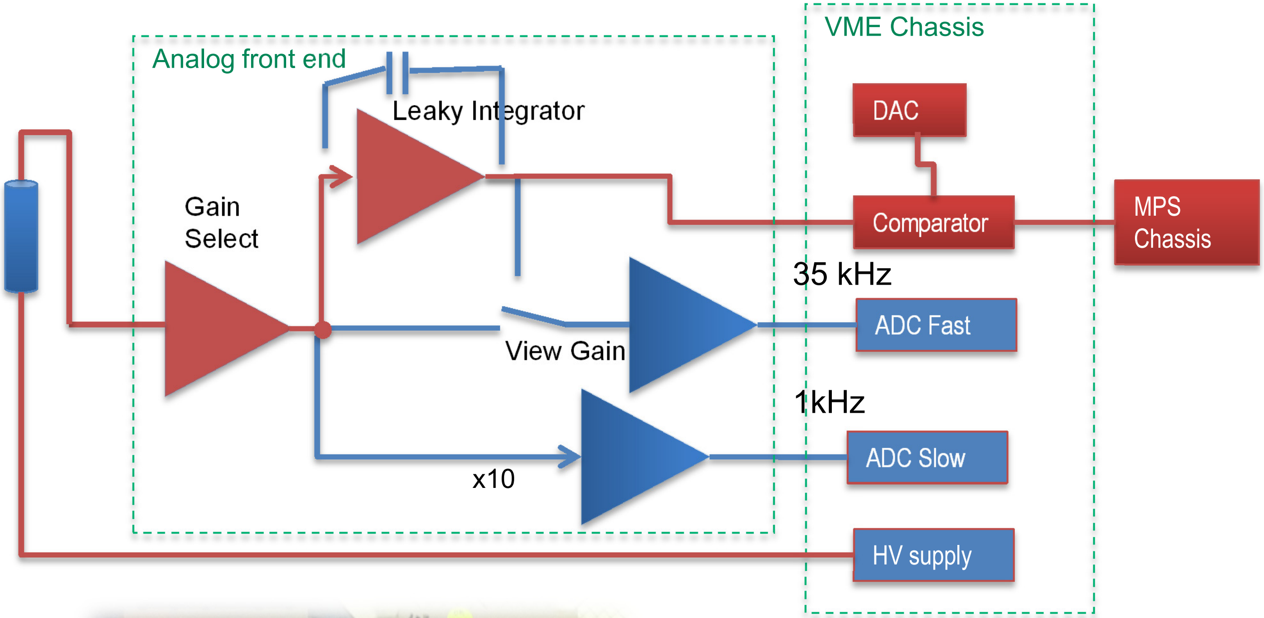
Two types of loss interlock

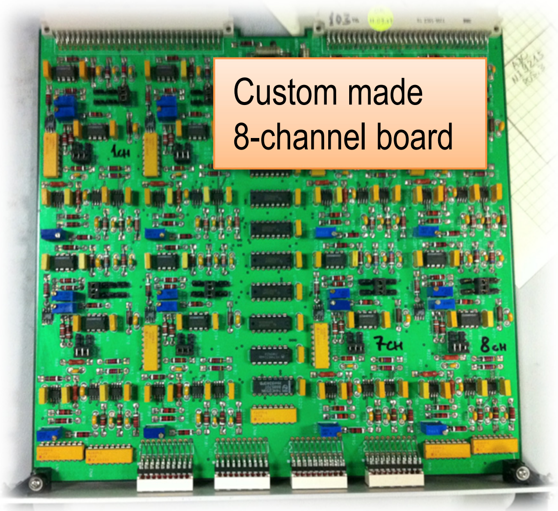
- Hardware (fast) implemented in analog electronics to abort **current** beam pulse and maybe activate interlock to require operator intervention to re-enable the beam
- Software interlock (slow) implemented programmatically to trip the beam if total loss over **1 second** is higher than threshold

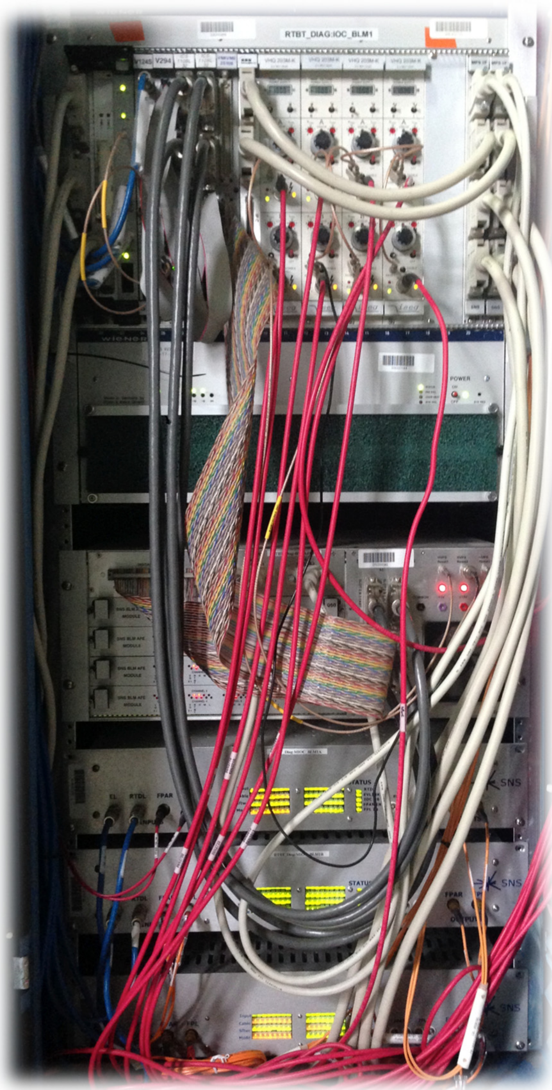
MPS chain	CCL Beam stop, Target, etc.
MPS Mode	Short pulse 50uS, Full pulse 1ms
Macro-pulse in Linac	~1000 mini pulses of ~24mA avg over 1ms at 60Hz



Detector Interface







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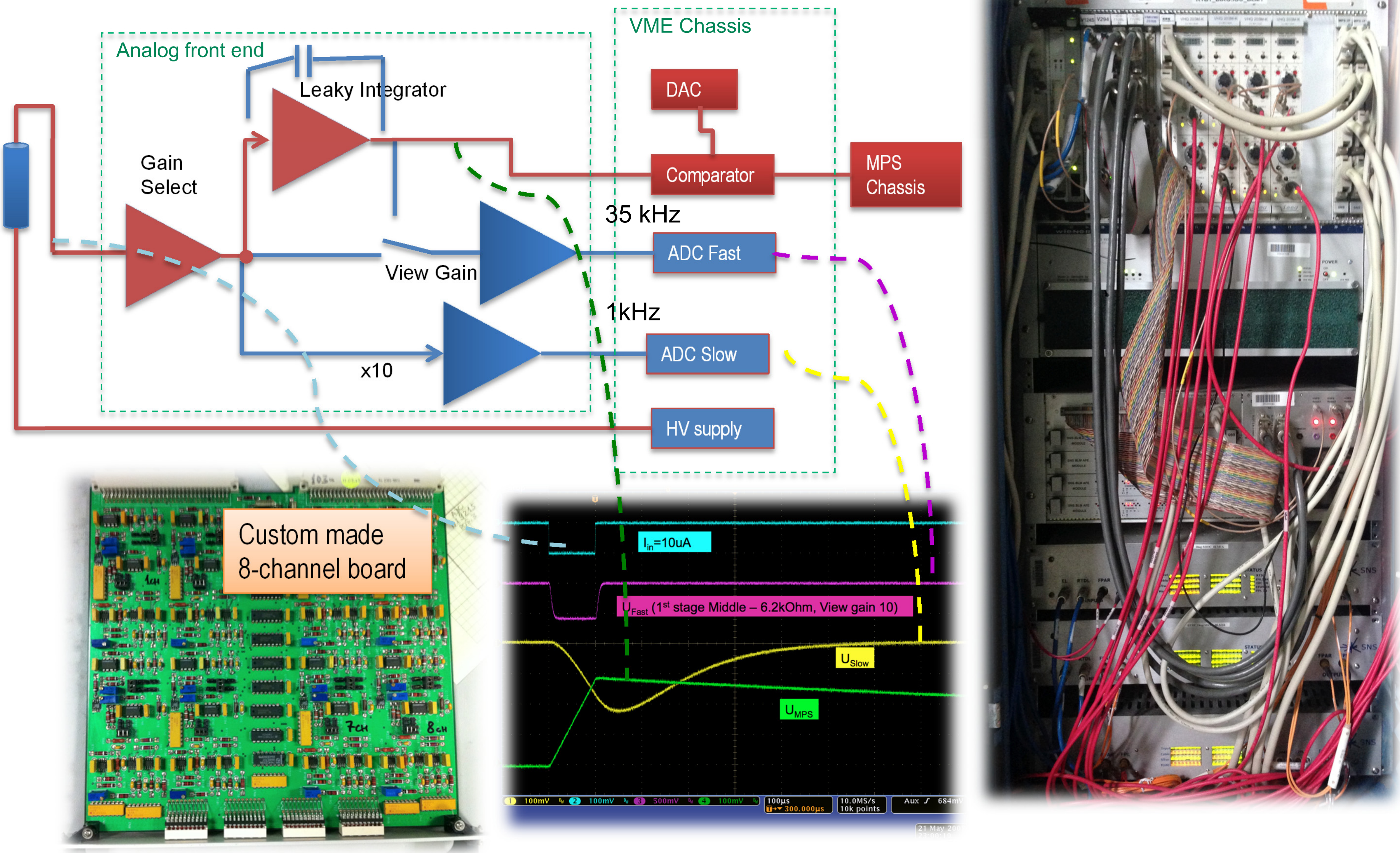
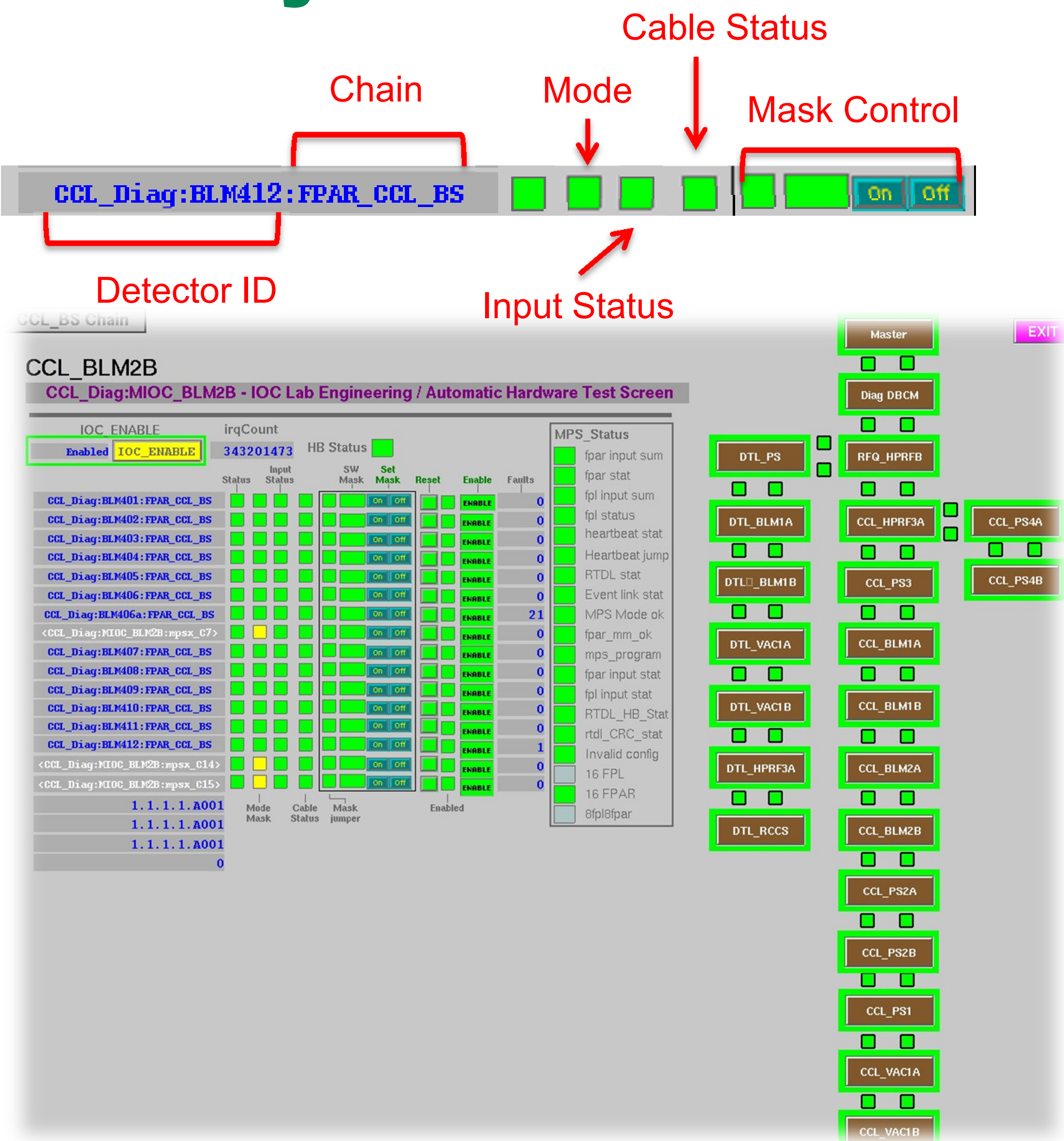
Detector Interface



MPS System Interface



MPS chassis

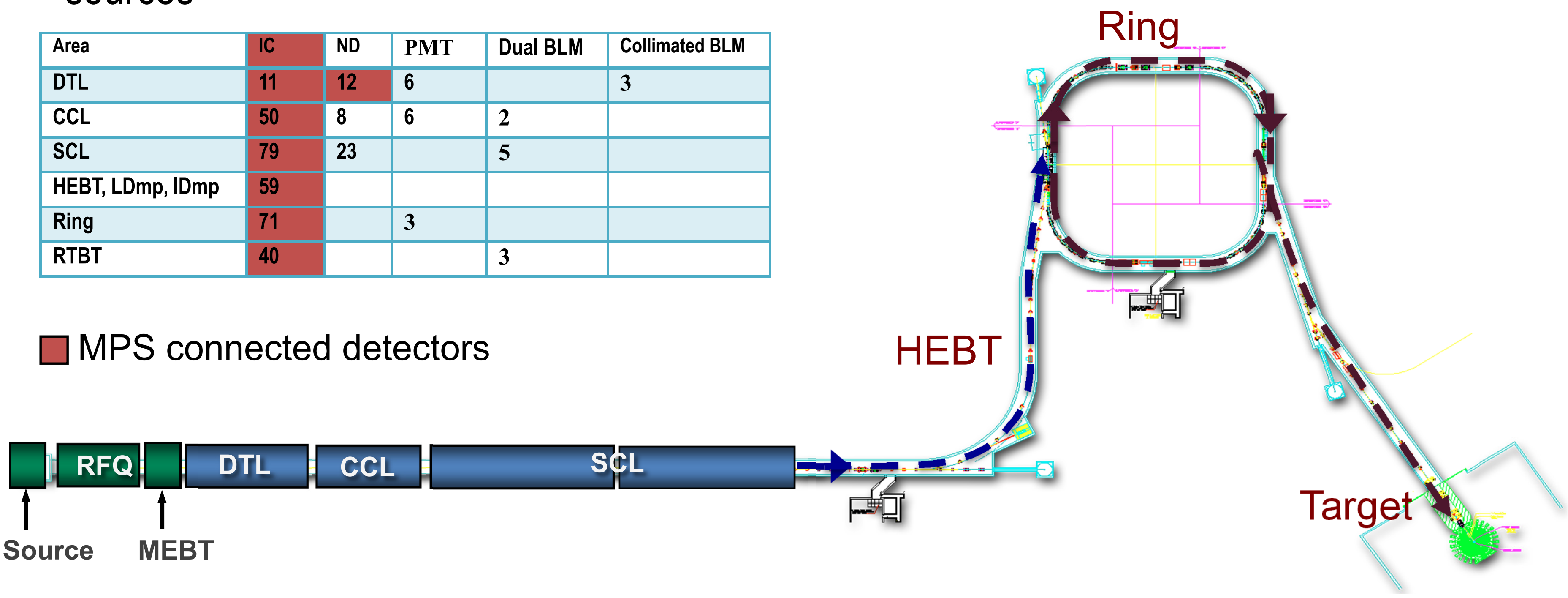
- 16 Inputs
- Controlled by PMC card with FPGA
- PMC card is controlled by software running in BLM VxWorks based IOC
- MPS chassis are interconnected with fiber links that propagate trip up to the master node that shuts down beam at the front end
- Both hardware and software interlocks use the same MPS input channel
- MPS channel can be masked

BLM Types and Distribution

- Beam interlocking devices (Ion Chambers, Neutron Detectors)
- Research devices Fast BLMs (PMTs), Dual BLMs and Collimated BLMs
- All BLMs are similar for electronics interfacing as they represent current sources

Area	IC	ND	PMT	Dual BLM	Collimated BLM
DTL	11	12	6		3
CCL	50	8	6	2	
SCL	79	23		5	
HEBT, LDmp, IDmp	59				
Ring	71		3		
RTBT	40			3	

■ MPS connected detectors



NA-PAC'13 WEYA2 A.Zhukov *Experience with the SNS Loss Monitoring and Machine Protection*

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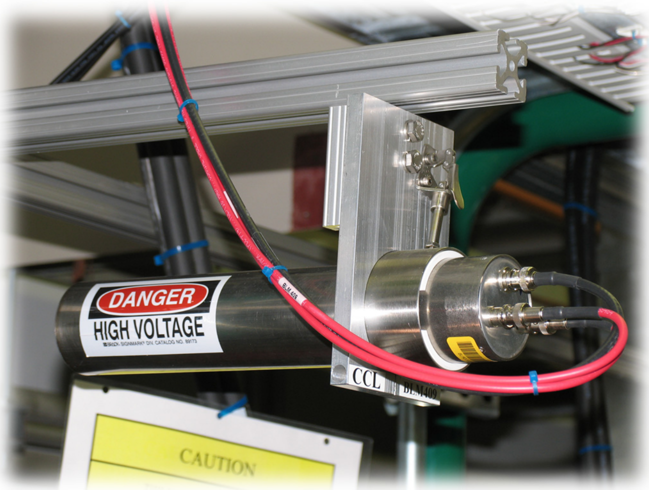
Detectors: Ionization Chamber (BLM)



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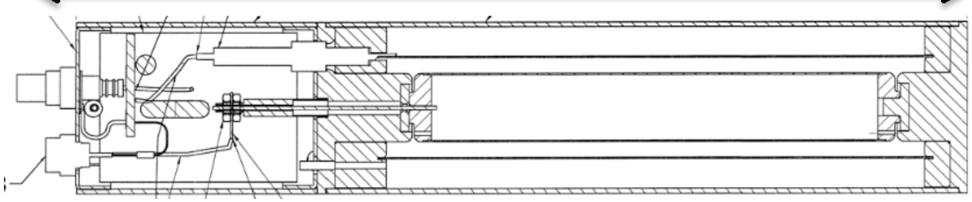
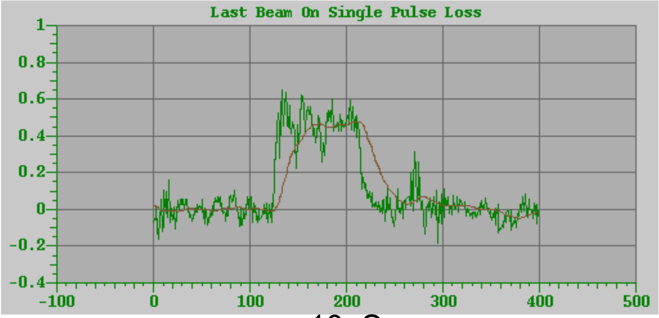


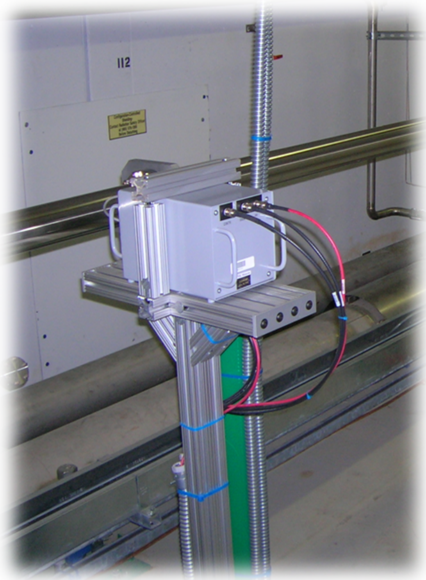
Detector Type	Ionization chamber
Detector medium	Ar, 113cc
Typical HV bias, V	-1000
Response time	~2us
Primary sensitivity	gamma
Particle energy range	>500 keV
Typical sensitivity	70nC/Rad
Installed	310
Connectors	Sig (BNC), HV in (SHV), HV out (for daisy chain)

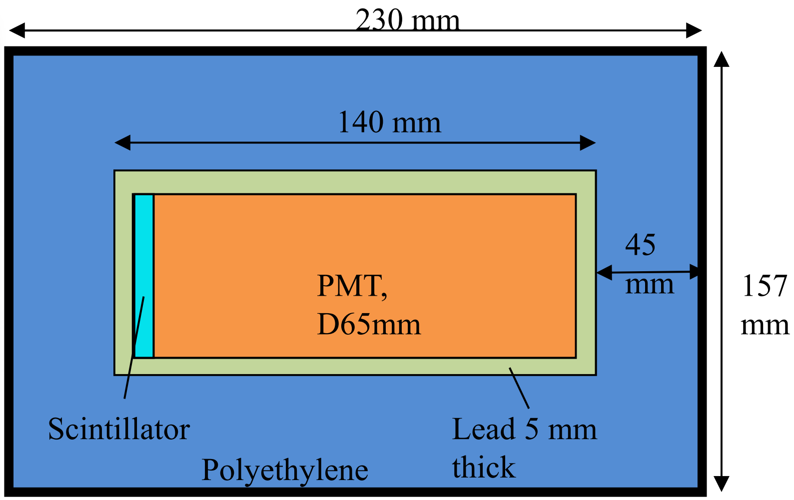


x10uS

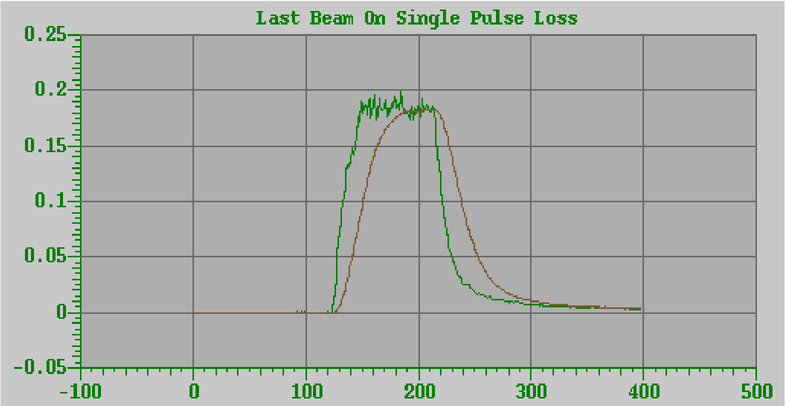
- main MPS detector
- used all over machine
- Rad hard
- HV independent sensitivity
- not sensitive enough at low energy

Detectors: Neutron Detector (ND)





Detector Type	ND
	Neutron sensitive plastic scintillator + PMT
Detector medium	Polyethylene moderator, Li (n, alpha)
Typical HV bias, V	-700
Response time	~50us
Primary sensitivity	neutron
Particle energy range	0.03eV – 3MeV
Typical sensitivity	80 pC/n/cm^2
Installed	43
Connectors	Sig (BNC), HV in (SHV), Test(BNC)



x10uS

- used in linac
- in DTL connected to MPS
- dynamic range provided by HV
- amplification performed in detector itself
- scintillator degradation under radiation

Detector calibration

- All ion chambers were calibrated with gamma source for absolute conversion factor
  - Hard to estimate radiation fields caused by particular loss scenario
  - Doesn't work very well in terms of recalculating from BLM reading into number of particles lost
- Use of Faraday Cups in DTL for ND calibration
  - Gives good agreement with corresponding simulation of neutron flux
  - Doesn't emulate a real distributed loss
- Controlled spill by laser wire profile device
  - Short pulse laser strips H^- into H^0 it is lost downstream
  - This method suggests that fractional loss in SCL is ~1-3 10^{-5}
- Residual activation calibration
  - Doesn't work very well since loss pattern doesn't always repeat activation pattern

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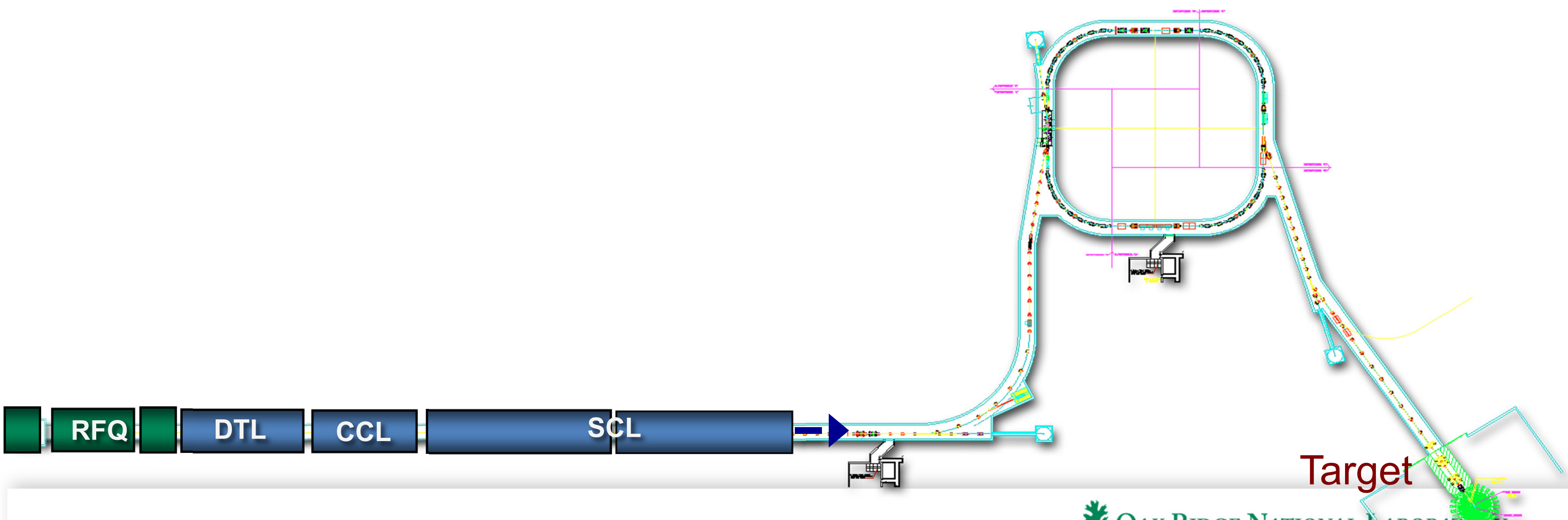
Detector Location

- Fixed BLMs
- Moveable BLMs, located on a movable stand usually not included in MPS
- Distance to beam line 0-3 ft
- Some balance between placing detectors too close - too localized loss and moving too far - too weak signal
- Big relocations since installation for increased sensitivity
  - SCL warm area were lowered down
  - CCL lowered down



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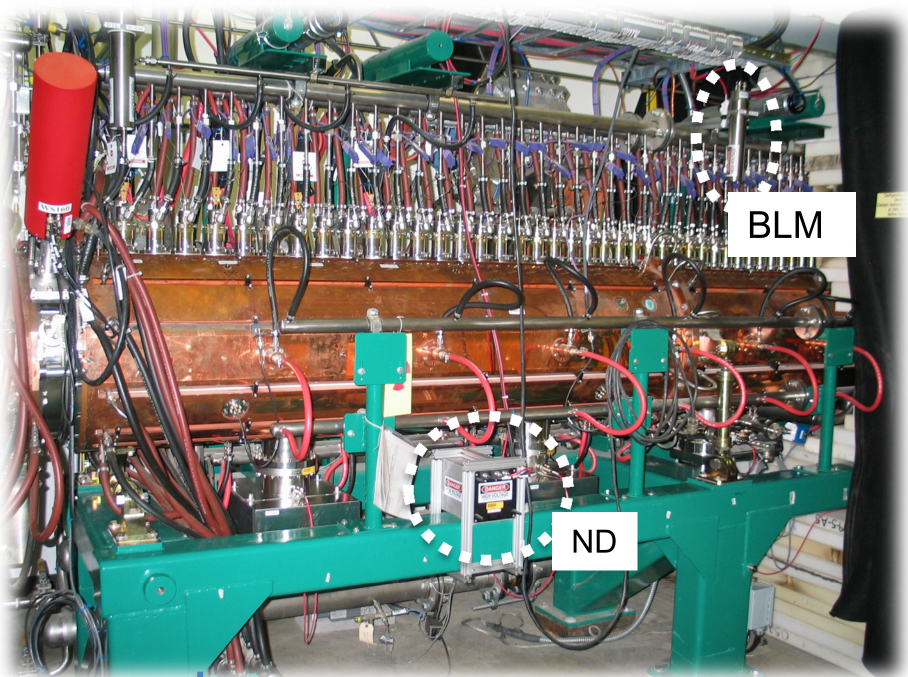

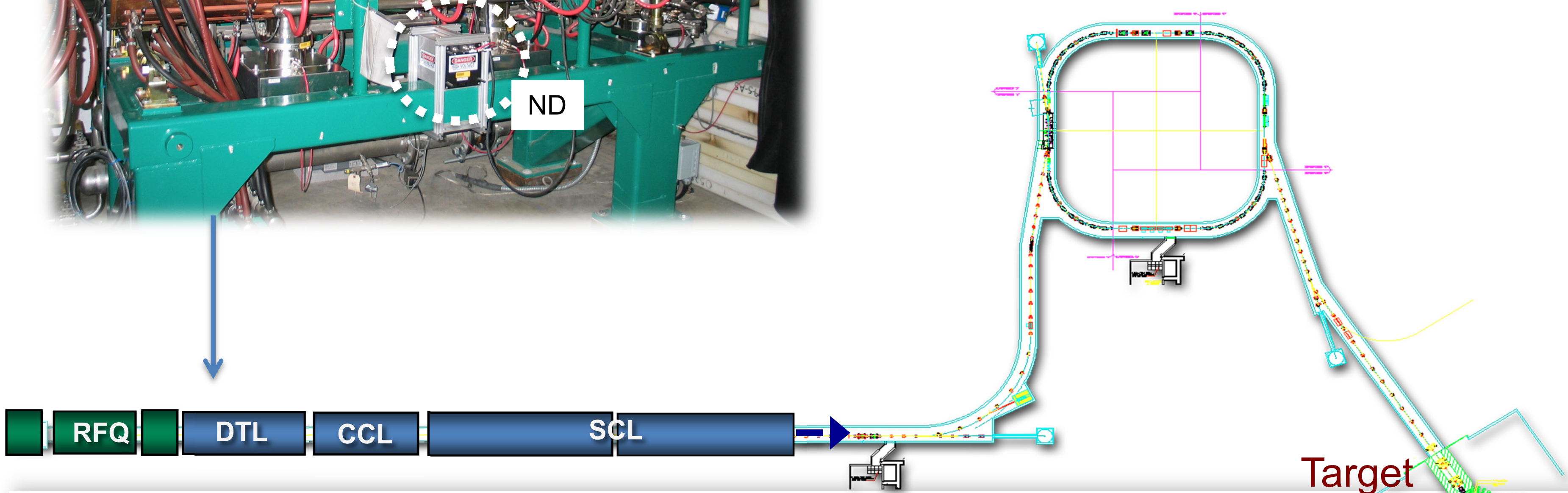

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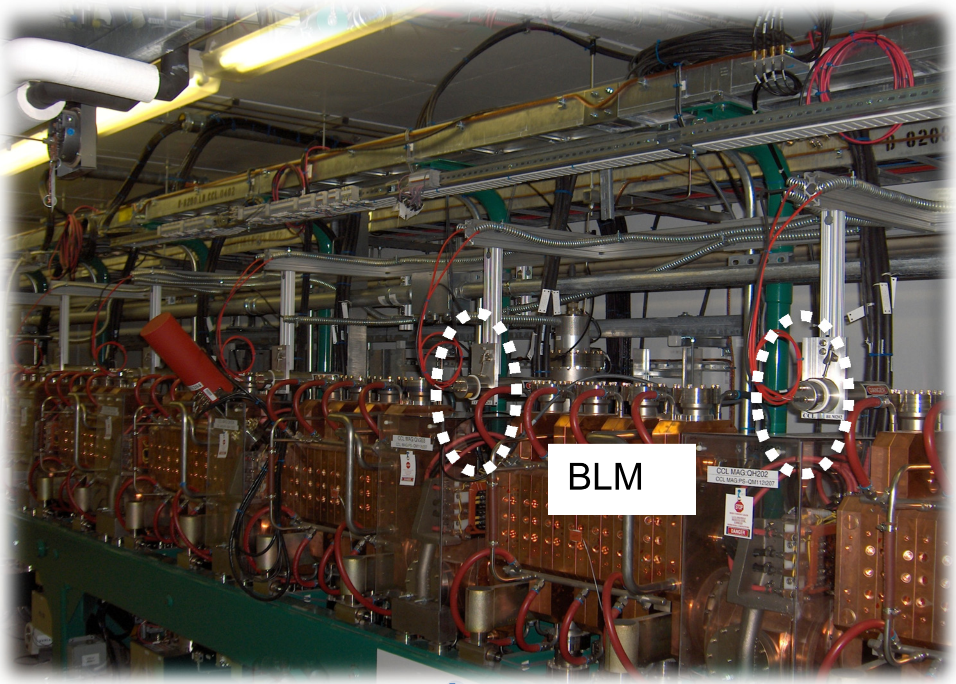

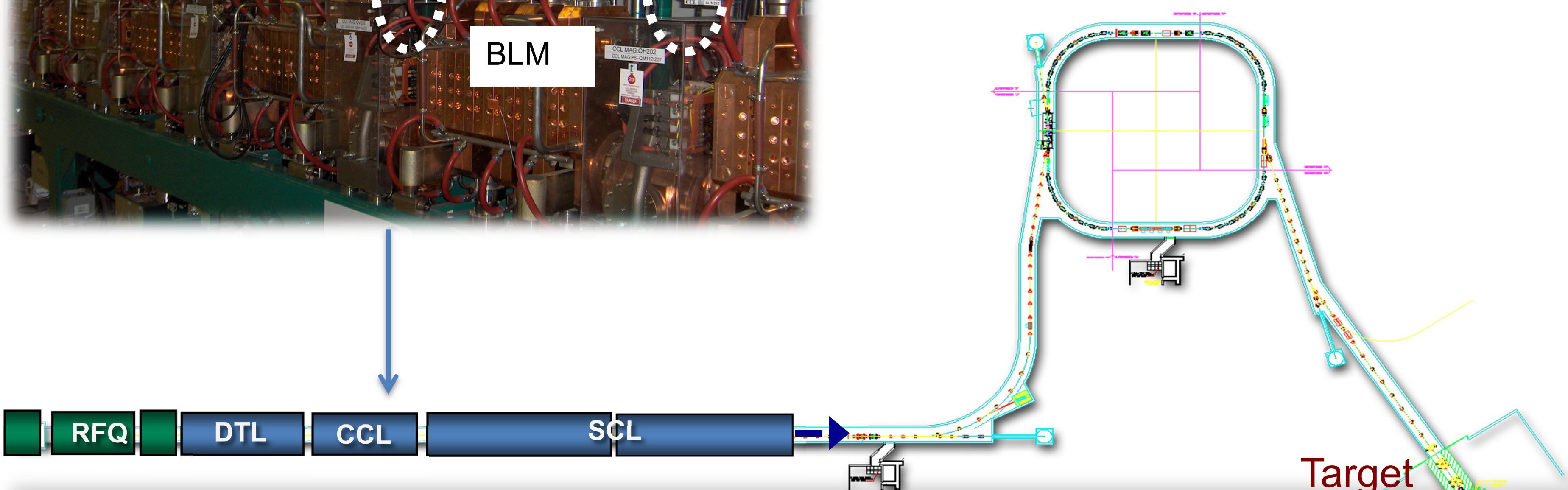

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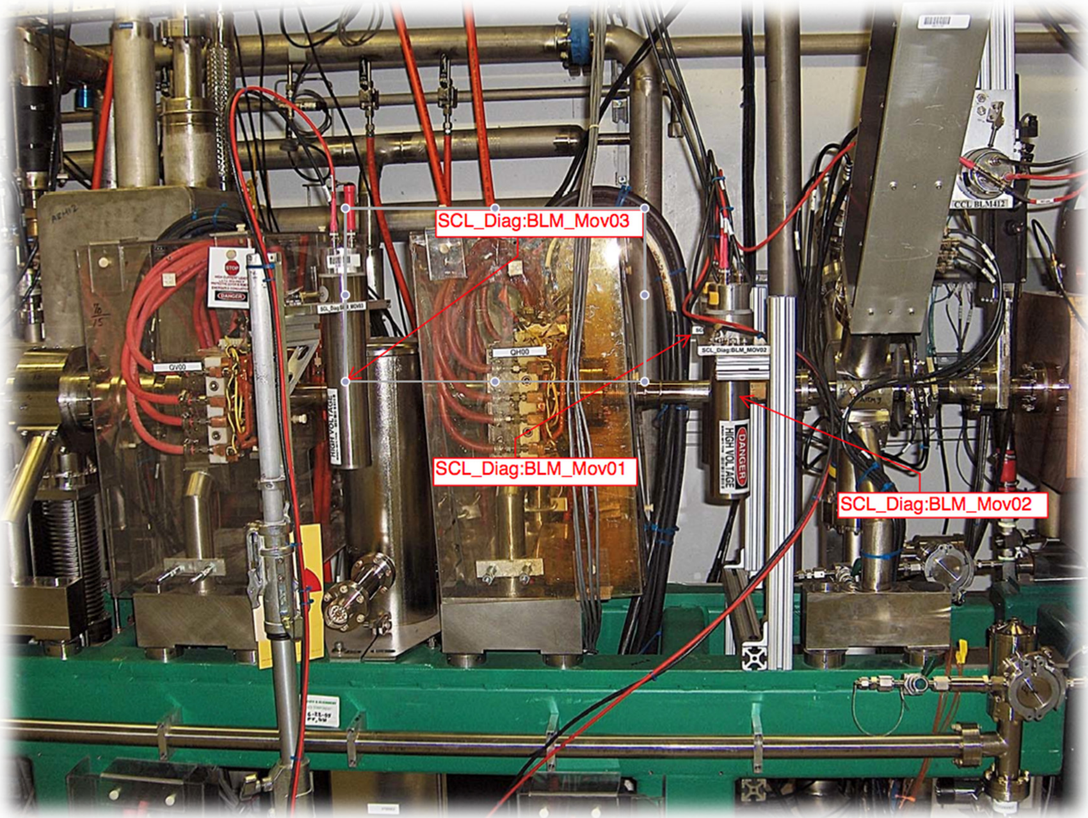

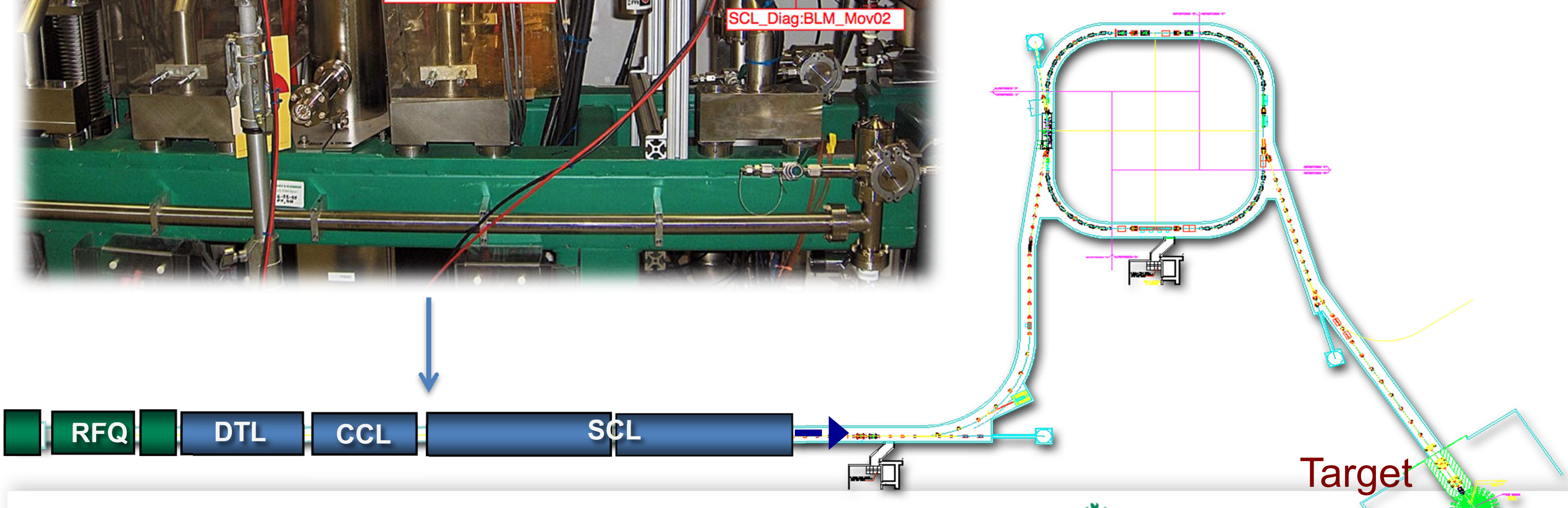

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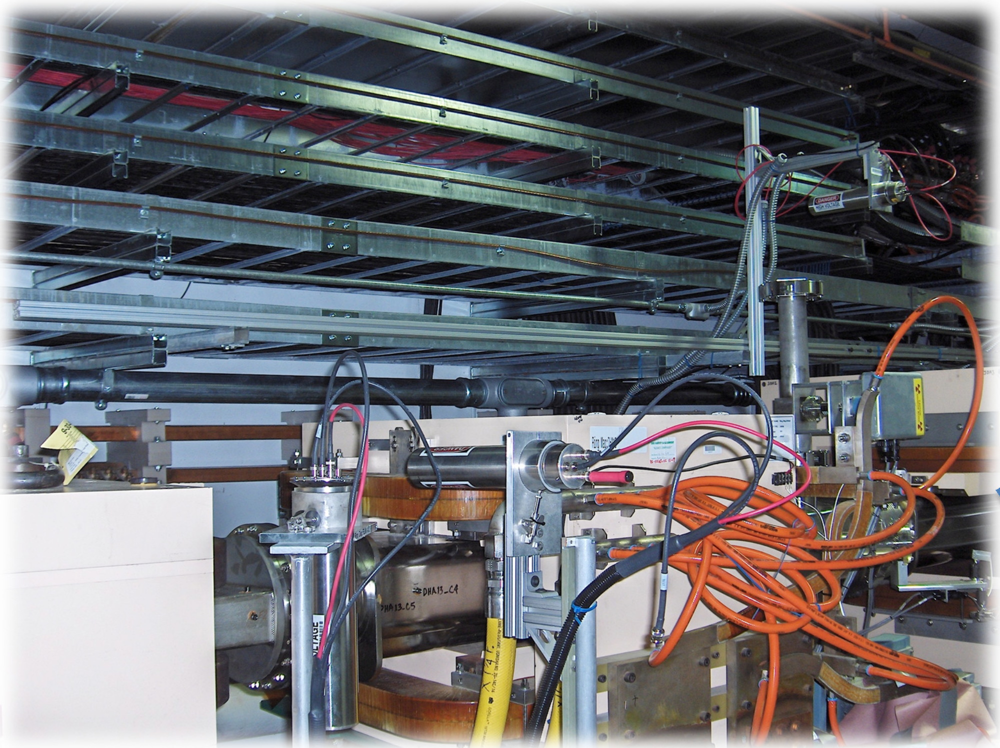

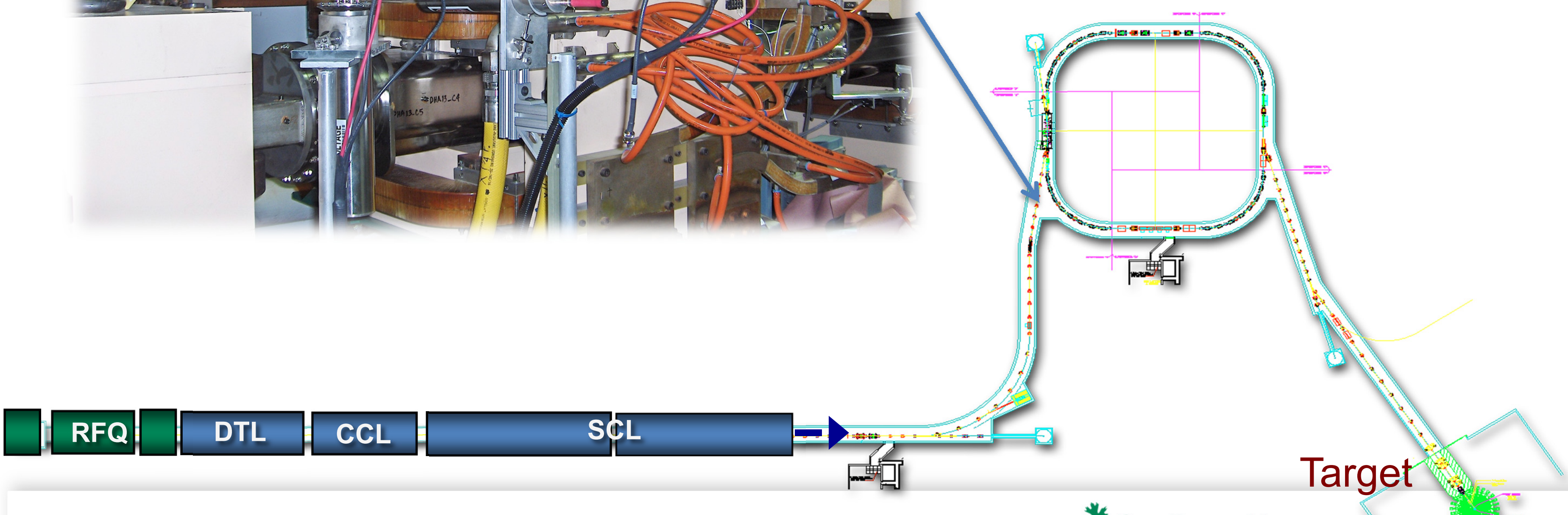

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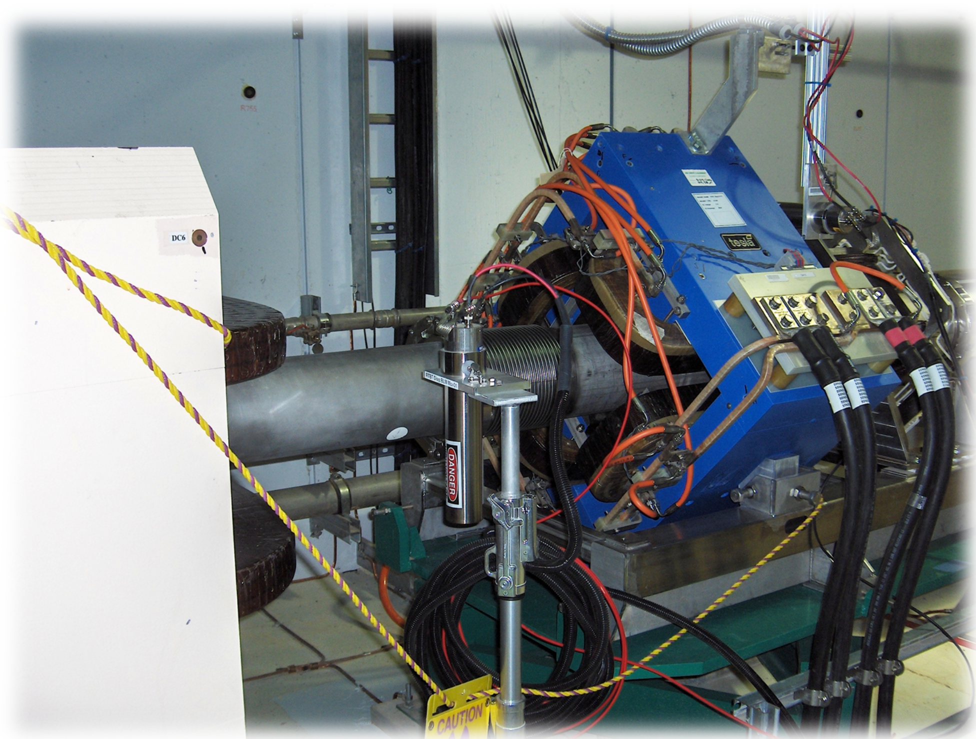
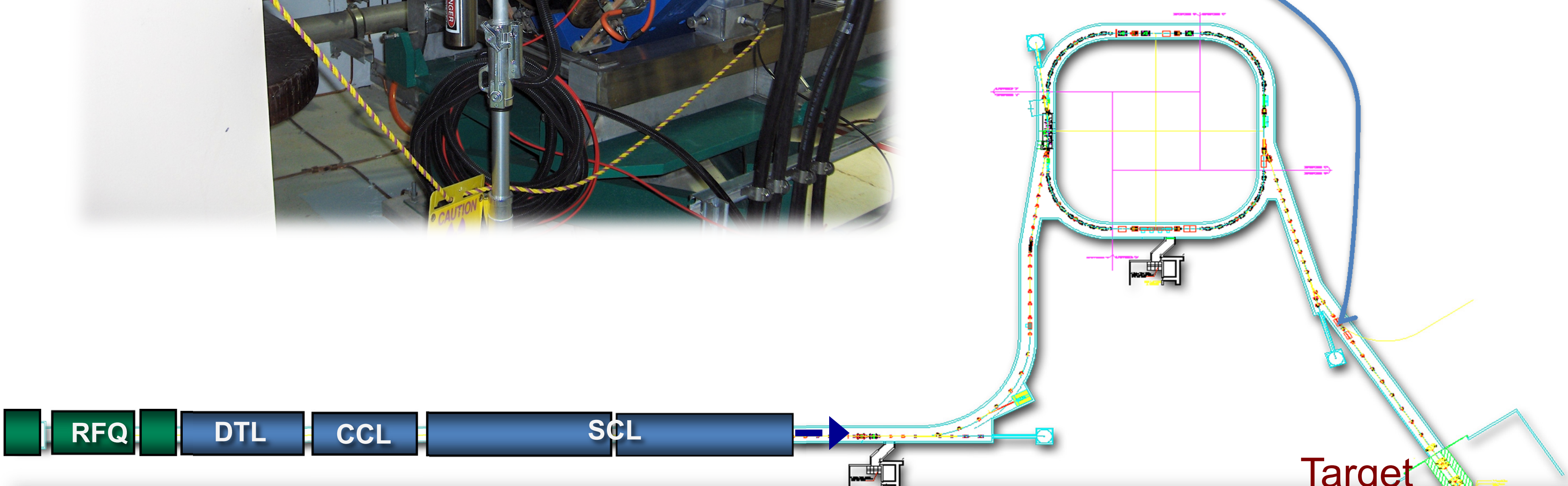
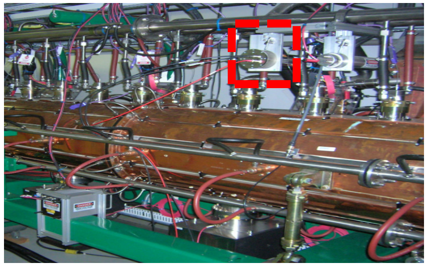
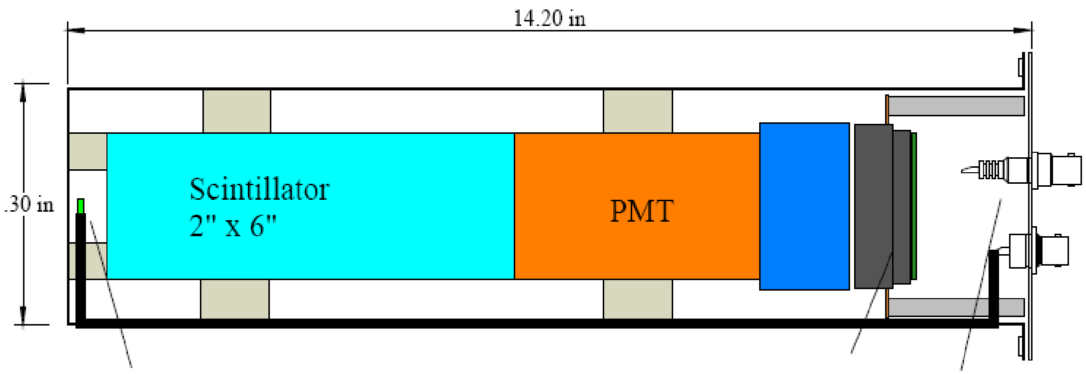
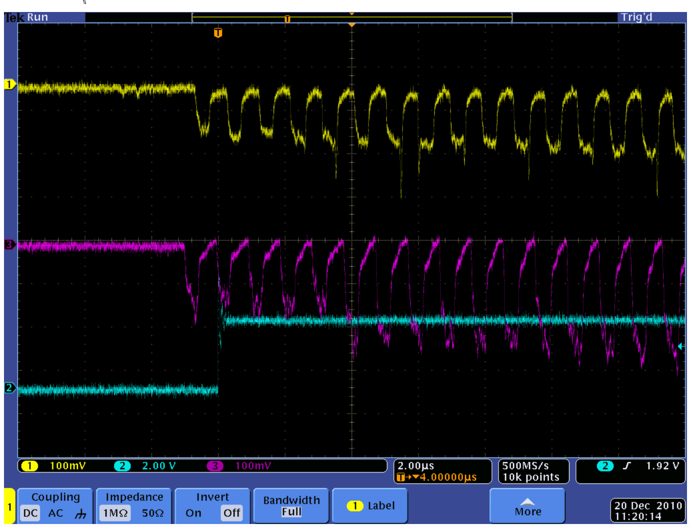




Detectors: Fast BLM (PMT)







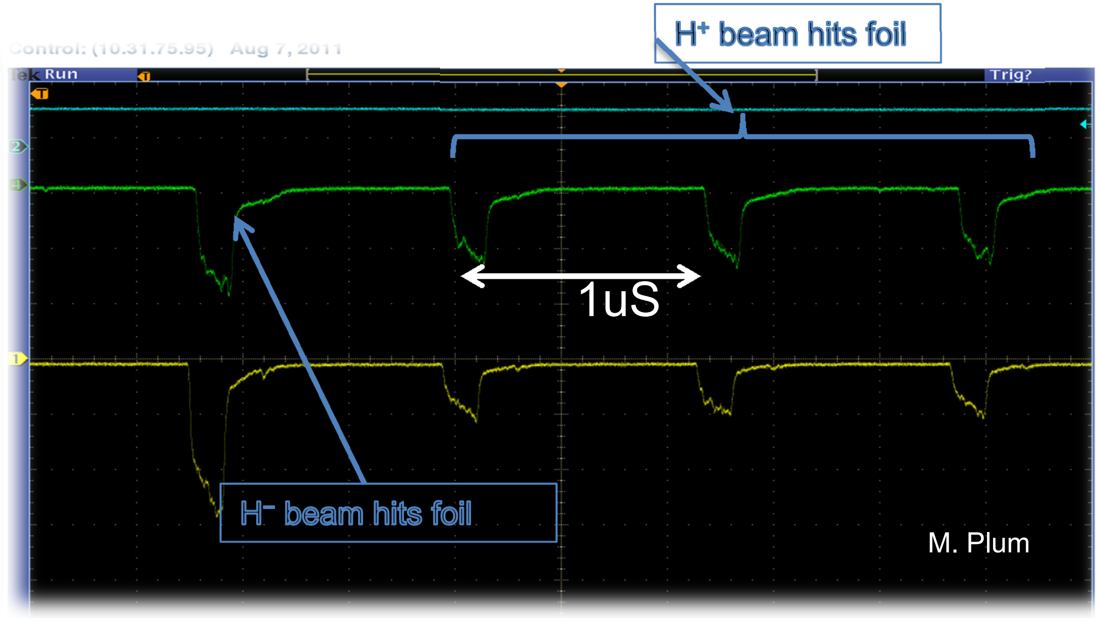
Detector Type	PMT
	Plastics scintillator +PMT
Detector medium	EJ-208 scint
Typical HV bias, V	-700
Response time	~10ns
Primary sensitivity	gamma
Particle energy range	>60keV
Typical sensitivity	2mA/R/hr
Installed	12
Connectors	Sig (BNC), HV in (SHV), Test(BNC)

- experimental device
- no connection to MPS
- dynamic range provided by HV
- PMT/scintillator based
- fast enough to see separate mini-pulses
- “incompatible” with standard electronics

Applications of Fast PMTs

PMTs can be used in any experiment where experimental setup generates loss and fine time resolution is needed

- Fine loss structure
  - Looking into mini pulse edges and estimating chopper quality
  - Separating losses of H- beam hitting the foil from H+ beam

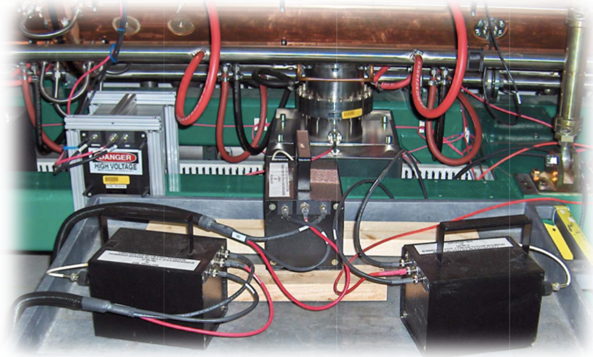


- Interceptive scanning
  - Wire scans
  - Slit-Slit emittance scans with beam interception (generating loss) by downstream Faraday Cup
  - Laser emittance scans (laser used as a slit): intercepting particles that passed the “slit” with a downstream wire and measuring loss signal from this

Dual BLM and Collimated BLM

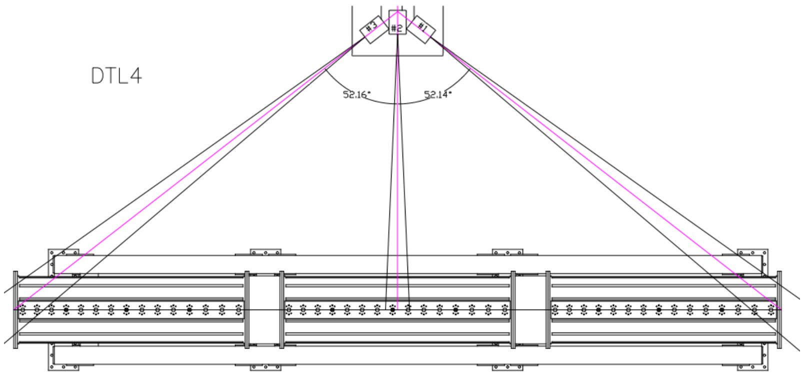
Dual BLM

- Contains two scintillator based detectors
- One has increased sensitivity for neutrons
- By subtracting signals with appropriate coefficients we can get a measurement of neutrons only flux
- Can be used as a true loss detector that neglects x-ray radiations



Collimated BLM

- Scintillator based detector
- Angle selectivity 7-10 times for gammas
- Intended to be used on a rotating stage to scan along DTL tank to find true loss location
- First tests in tunnel didn't give any useful results although source calibration demonstrated angular selectivity. Reasons unclear so far.



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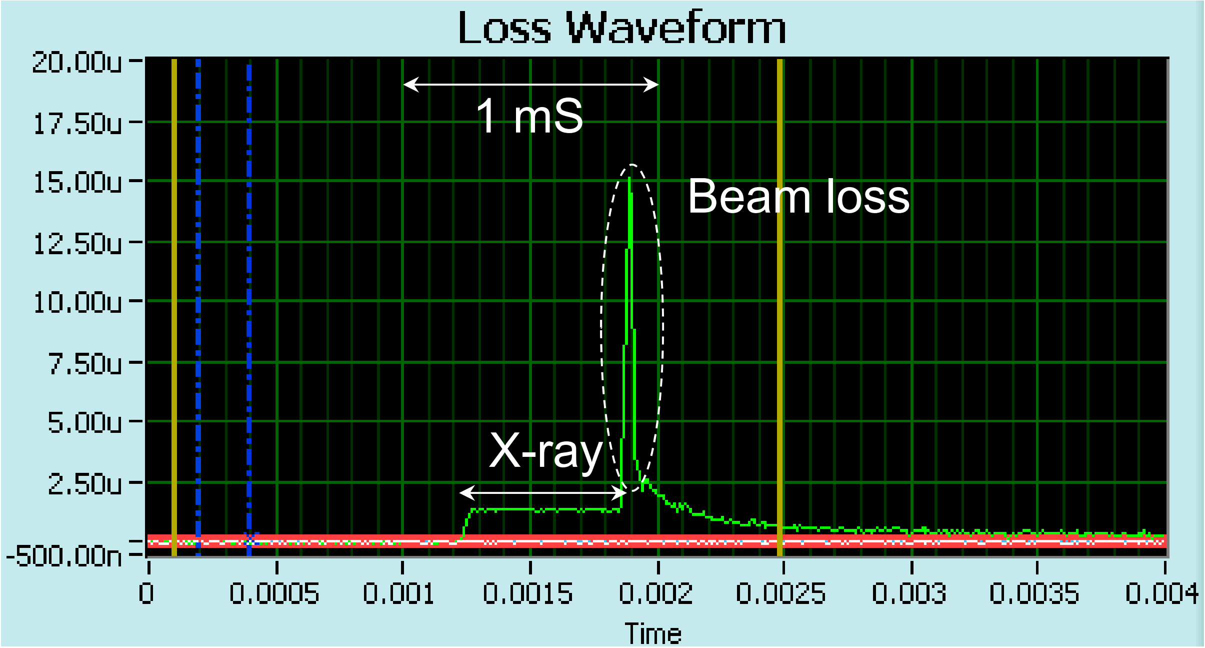
RF X-rays

X-rays from RF cavities are also detected by loss monitors.
This poses a problem of adequate measuring **beam related losses**.



Raw loss signal from short beam pulse measured by PMT

Possible solutions

- Come up with new detector type that will not see x-rays: Dual BLM
- Shield loss monitors
- Implement subtraction algorithm in software

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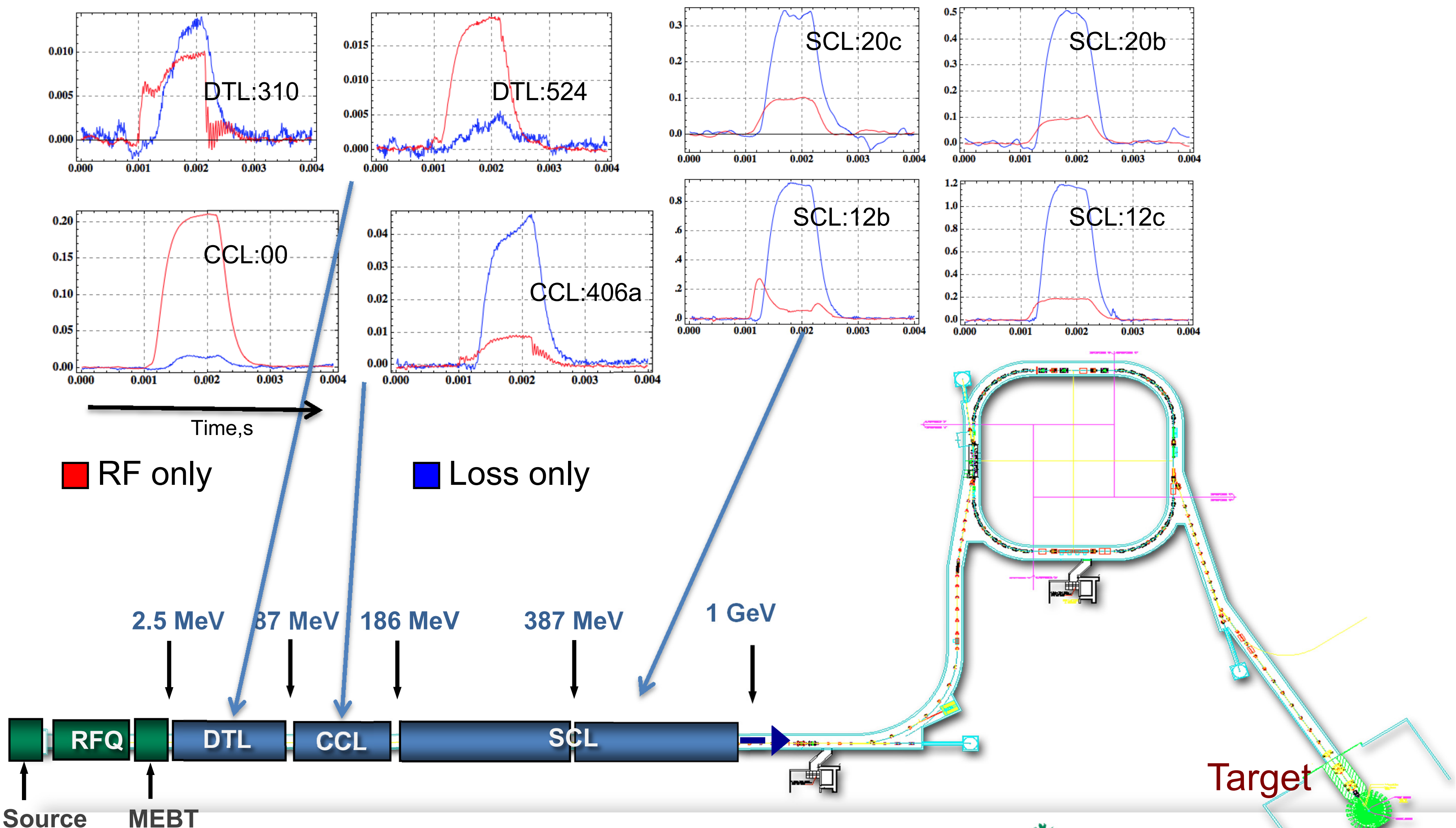
Waveform subtraction

- RF runs at 60Hz, beam runs at 59.9Hz, Every 10 seconds there is an empty RF pulse with no beam
- The reference waveform is stored in software and subtracted from all real pulses
- Software MPS accounts for that and reports real loss only
- **Hardware MPS is compromised**



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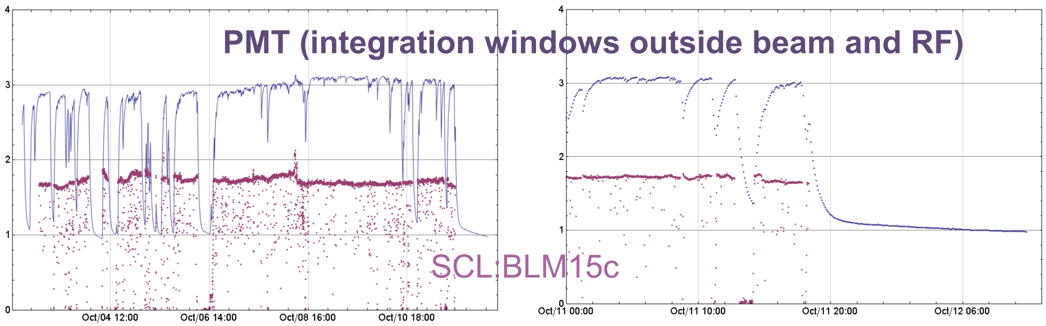
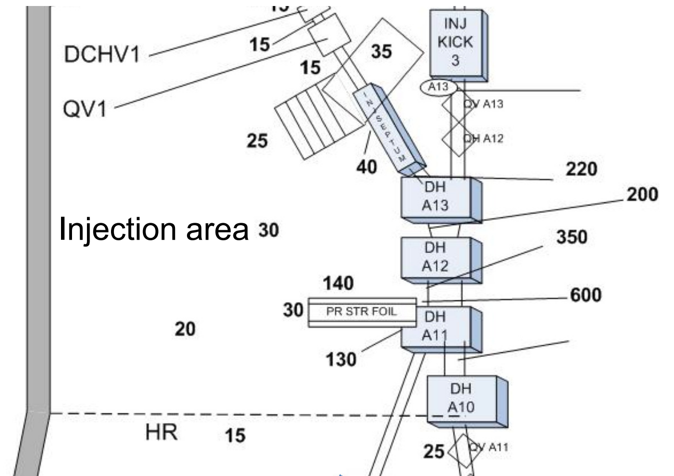
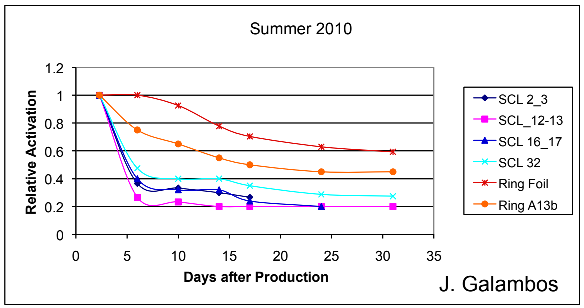
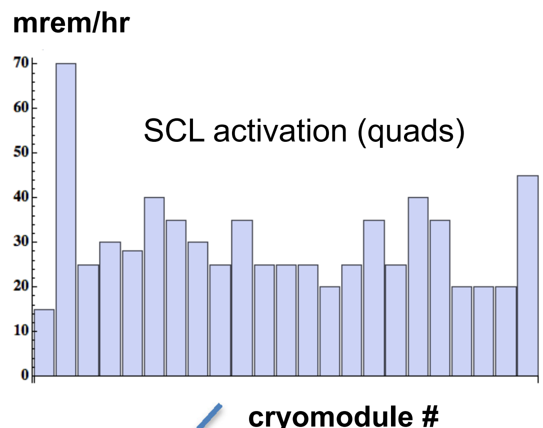
Residual activation

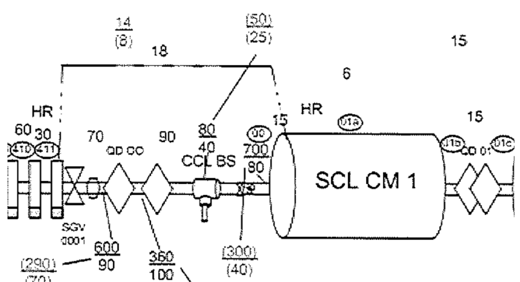
Can we use loss monitors directly
to measure residual activation instead of predicting it?

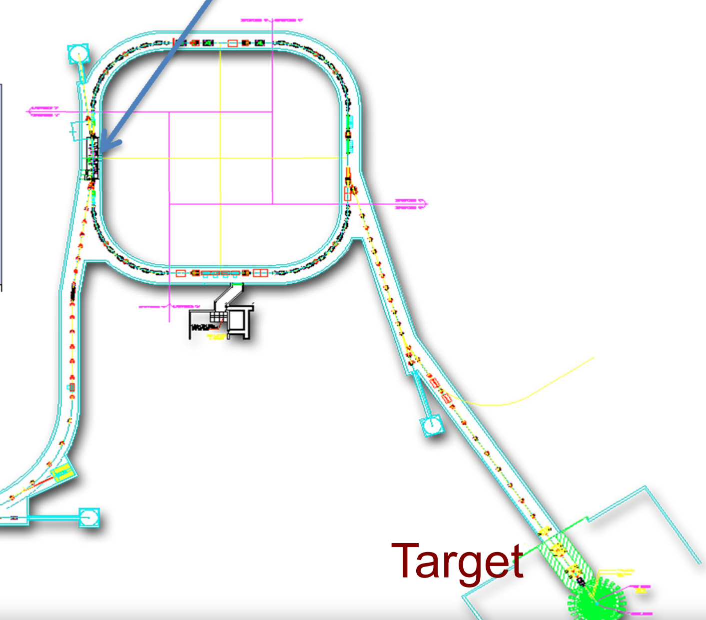


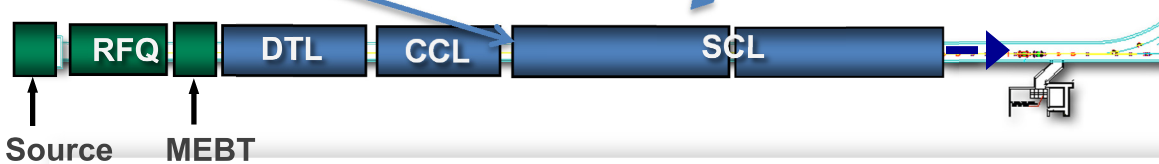




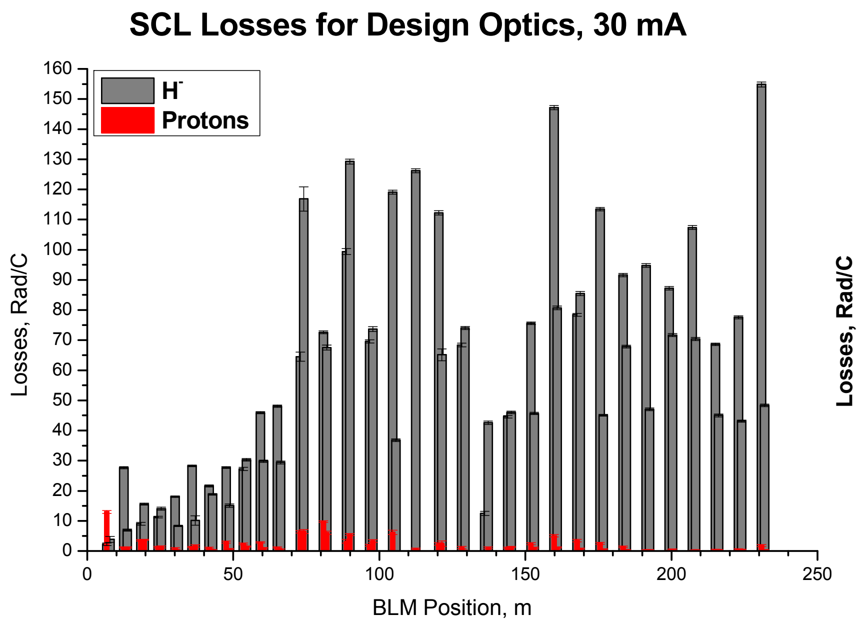


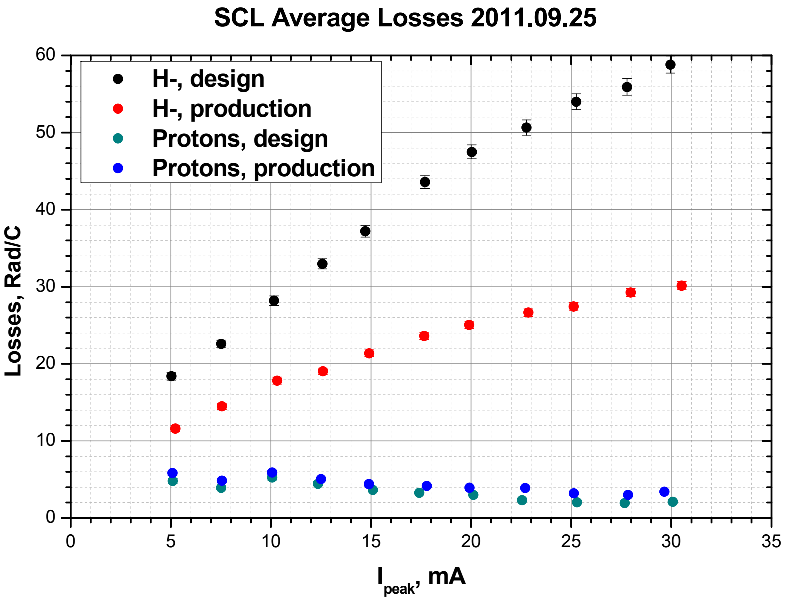




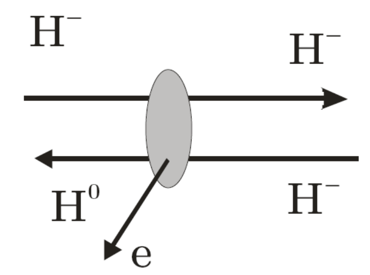


SCL Losses and Intra Beam Stripping



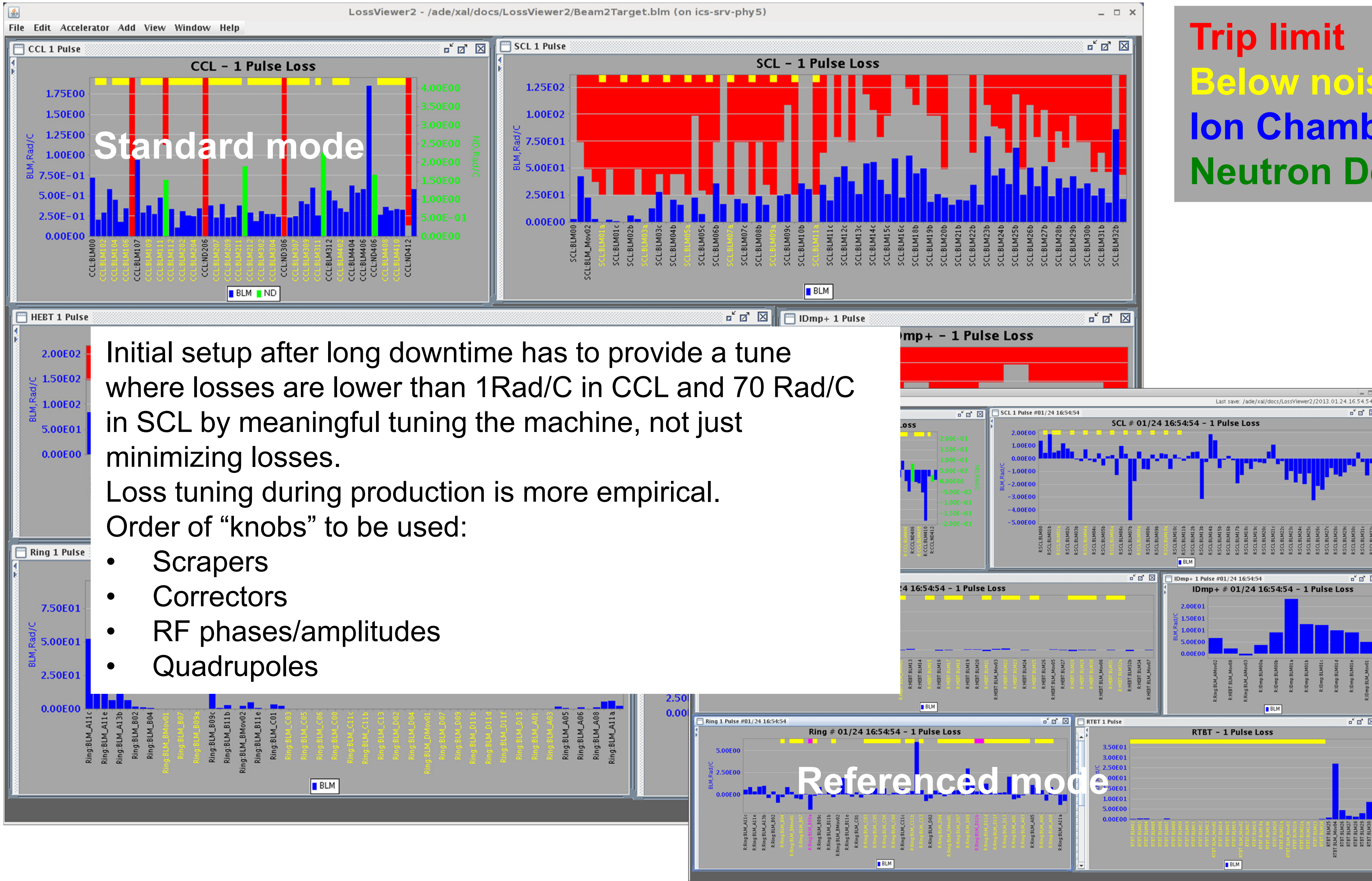


- According to the design the SCL should be loss and activation free
  - Beam pipe aperture is about 10 times beam rms
  - Vacuum is one order of magnitude better than in DTL, CCL
- Found unexpected beam loss and activation during the SNS power ramp up in 2008
- Loss and activation were reduced by reducing the SCL quads' gradients – counterintuitive



A. Shishlo

Operation and tune up



Trip limit
Below noise
Ion Chambers
Neutron Det

Initial setup after long downtime has to provide a tune where losses are lower than 1Rad/C in CCL and 70 Rad/C in SCL by meaningful tuning the machine, not just minimizing losses.
Loss tuning during production is more empirical.
Order of "knobs" to be used:

- Scrapers
- Correctors
- RF phases/amplitudes
- Quadrupoles

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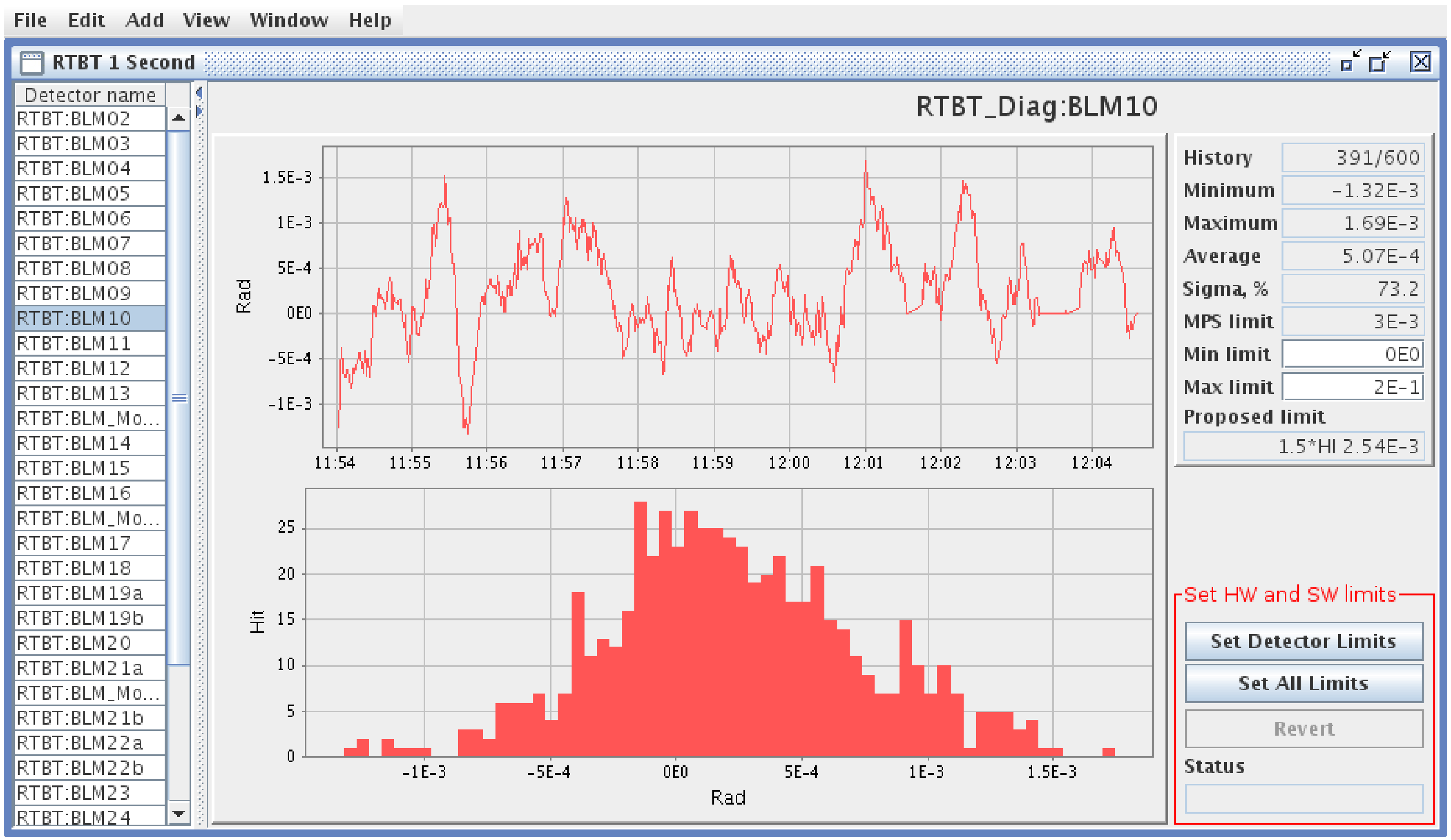
Errant beam control in RTBT

- BLMs are used as one of the mechanisms to protect target from beam deviation.
- Loss limits are set as tight as possible to preserve beam in tuned state.



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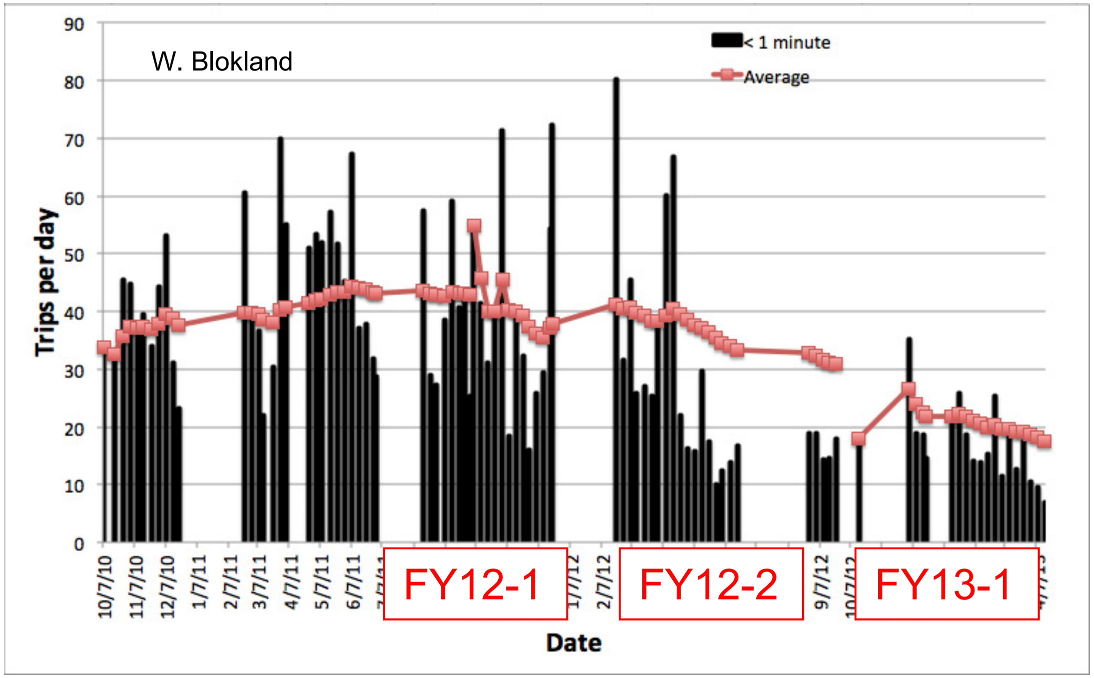
Number of errant beam loss trips

RF Adjustments: gradient changes, resonant frequency changes, and preventative maintenance on vacuum systems

- → fault frequency reduced by more than a factor of two.
- → SCL downtime was reduced by a factor of six



Errant beam loss from 30 to 15 events a day

Summary of current BLM system

GOOD vs. BAD

GOOD

- Protects the accelerator
  - Software and hardware timing independent interlocking
  - Covers all energies 2.5MeV-1GeV
  - No beam-pipe damage or burning holes
- Reliable operation since 2006
  - 3 ADC failures (when one channel exhibited excessive noise) – no beam downtime
  - Four VME PS failures (~ 2hr downtime)
  - Software issues (~ 5hr downtime)
- Fast PMT is a useful device for beam studies

BAD

- Electronics obsolescence
  - 32 channel VME based ADC discontinued
  - AFE board uses discontinued DIP components
- Multi-channel system
  - no repairs possible without stopping machine
  - No debug outputs. Virtually impossible to probe signals without compromising MPS (beam needs to be shut down for any trouble-shooting)
- MPS related issues
  - Software based WF subtraction
  - True hardware implementation gives no flexibility

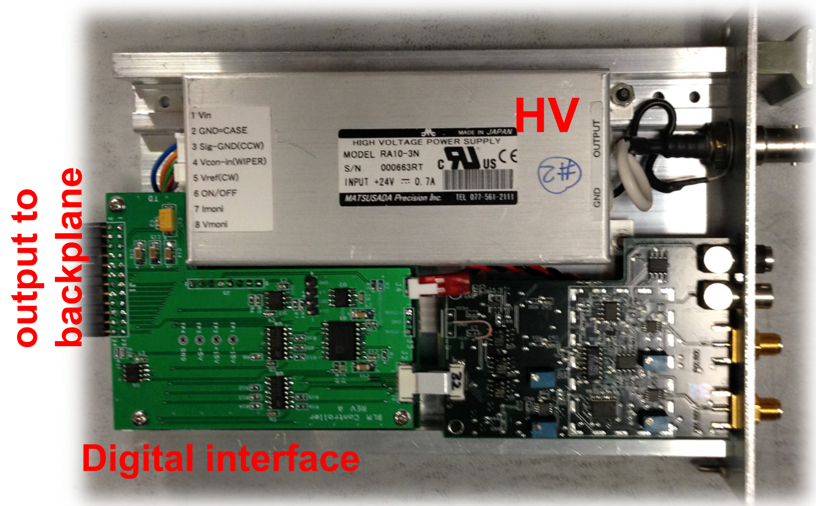
New BLM system core concepts

- Detectors and cabling should stay the same if possible
- Useage of subtracting dual input electronics:
  - Connecting either dual BLM
  - or noise reference
- Everything related to MPS should be removed from software running in CPU
- Waveform subtraction if needed should be made on the fly (point by point while sampling analog signal)
- Sampling rate increased to 1MS/s
- Flexible MPS calculation: instead of one pulse loss and 1 second loss integration windows will become arbitrary
  - Instantaneous loss
  - One pulse integral
  - Using timing
- Custom **single** channel front end with ability to replace within minutes
  - Capability for different types for different detectors or cases
  - All custom made electronics either analog or very primitive digital interface

Single channel module with analog front end

Module capabilities

- Analog subtraction using fader IC
- PGA gain
- HV power supply
- Every module has its own MPS integrator
- DAC for threshold settings, HV control, subtraction control, test signal control
- Analog front end can have several options
  - Maximum configuration for Dual BLM (already designed and being under test)
  - Only MPS integrator and fixed gain amplifier for ion chamber with shared HV supply



Module outputs

- Analog signal for digitization
- MPS status
- HV status voltage and current read backs
- All outputs go to passive backplane
- Amplifies signal can be probed at front panel

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FPGA will be used as main MPS processor

- Design based on National Instruments cRIO FPGA platform
  - No custom FPGA hardware design
  - Everything programmed in LabVIEW (no need for vxWorks C programmer or FPGA programmer)
  - Real time software serves for publishing signals and setup, MPS runs completely independent in FPGA
- Data acquisition system processes 8 (16) channels
- MPS functionality programmed in FPGA in addition to analog integrator in AFE
- MPS reaction time becomes ~ 1 uS (limited by sampling rate)
- Virtually any digital filtering algorithm can be used for generating interlocks
- Combinations of signals from several detectors can be used for sophisticated on the fly condition evaluation – still 1 uS reaction time
  - Sum of losses form from different detectors
  - Comparison of loss pattern to pre-programmed one

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Summary

- BLM system works and provides adequate protection
- Ionization chamber is the main detector used for MPS with dynamic range at least 10^5 and capable to measure down to 10^{-6} of fractional loss
- RF x-rays present a major problem for loss measuring in linac
- Critical parts of the system use obsolete components and need to be replaced
- Replacement for these parts and FPGA based design are under development