Status of the ASTA Facility Machine Protection System at Fermilab

Arden Warner June 6th, 2012

The reason and the goals of the MPS

Machine Damage Potential:
The accelerator is being designed with the capability to operate with up to 3000 bunches per macro-pulse, 5Hz repetition rate and 1.5 GeV beam energy. It will be able to sustain an average beam power of ~72 KW at the bunch charge of 3.2 nC. Operation at full intensity will deposit enough energy in niobium material to approach the melting point of 2500 °C.

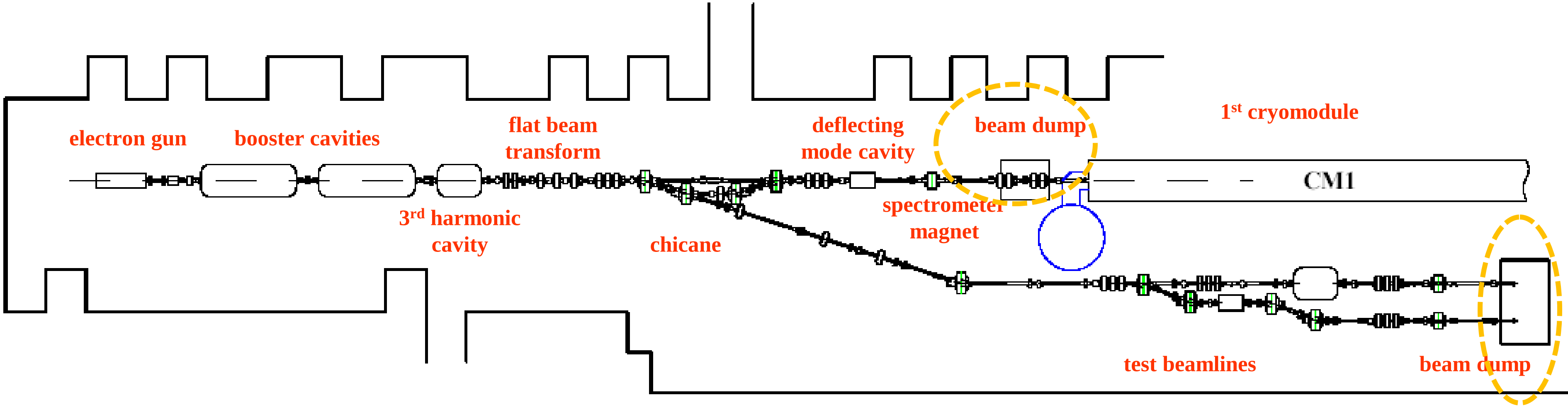
- 3 cryo-modules, 45 KW , 900 MeV

System Goals:

- Protect the accelerator from beam induced damage.
- Manage beam intensity
- Safely switch off or reduce beam intensity in case of failures
- Determine the operational modes of the machine
- Manage and display alarms
- Comprehensive overview of machine status i.e. subsystem status (ok/not-ok)

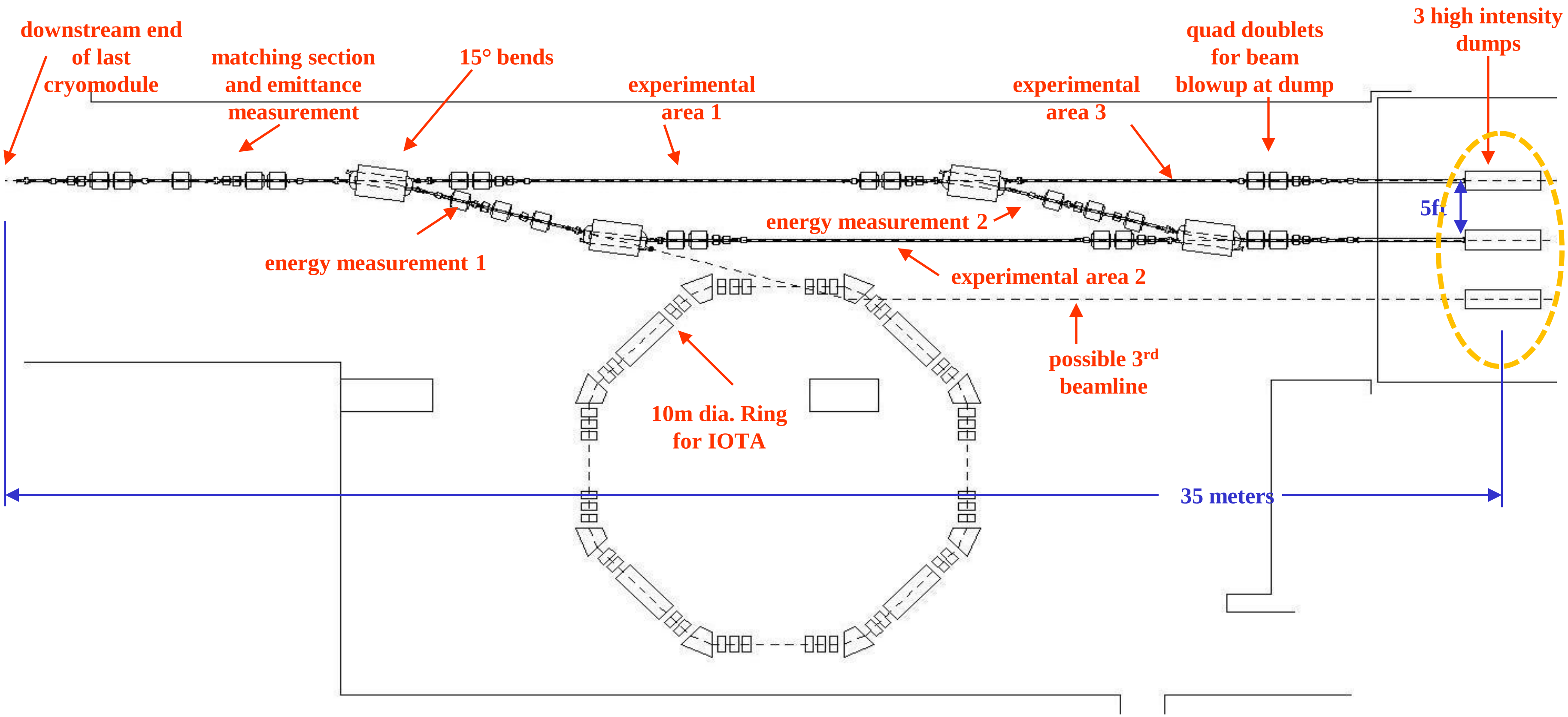
- MPS is Not part of Personnel Protection

Injection Beamline and Low Energy Test Beamline Layout



Dumps designed to handle max 100 KW

Potential Downstream Beam Experimental Areas



Dumps designed to handle max 100 KW

Machine Lay-out/Operational modes

LE dump mode 1

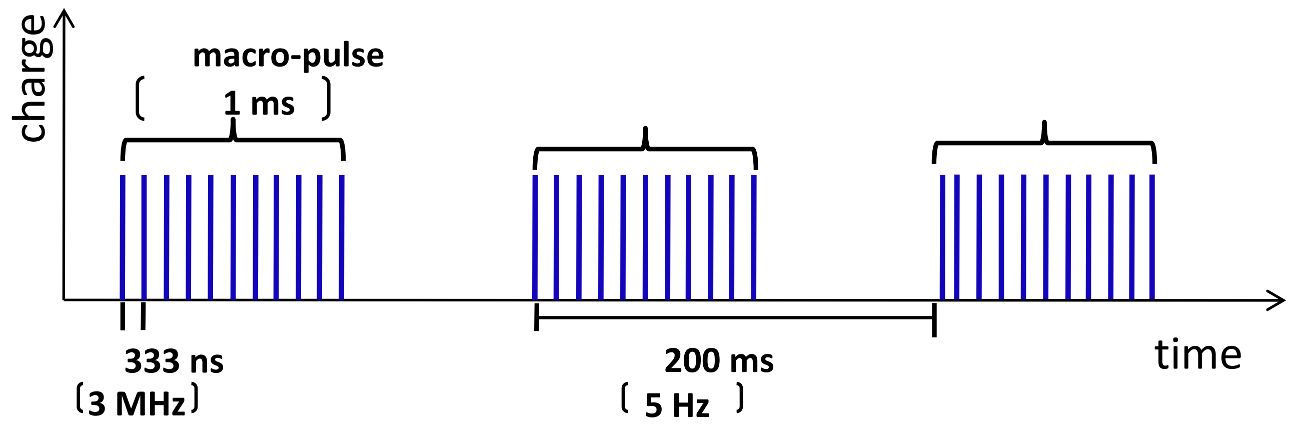
LE dump mode 2

LE dump mode 3

Operational modes define the path beam have to take to reach dumps

An operational mode represents a valid beam path through the machine. All modes are defined by a unique list of critical components with their valid states.

Important time scales for MPS



Fast Signals (nano-second sensor response, microsecond system reaction times) :

- Required for switching the beam off or reducing intensity within a bunch train.
  - Fast Beam Loss Monitors (ns response, single bunch resolution)
  - Toroids (~ 100 MHz bw, 1% accuracy, 500 mV/ns sensitivity, < 1μs ~ 500 ns at 120 metres)
  - RF related signals, …)

Slower signals

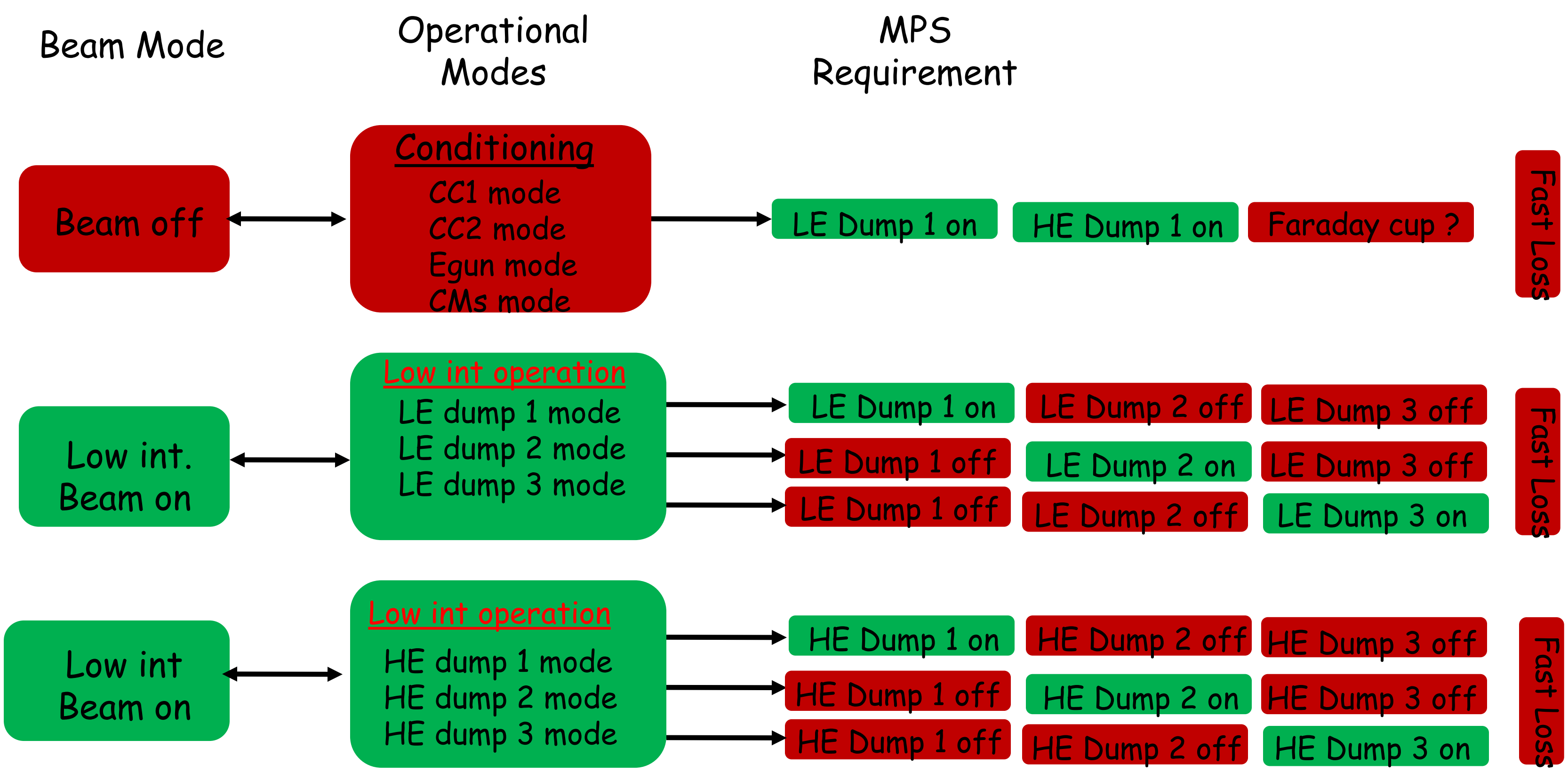
- < 200 ms reaction time determined by max rep rate of 5Hz.
  - Magnet power supplies
  - OTR/YAG screens (movable devices)
  - Vacuum valves
  - Laser Shutter

Operational Modes For Low Intensity Operation

Operational modes define the path beam have to take to reach dumps

Low Intensity Mode (a few bunches with total charge ~ 30 bunches (1e12 electrons/sec))
which allows the minimal beam intensity needed for OTR diagnostics. This is below the threshold potential for beam induced damage. In this mode there is no fast reaction to beam loss within a bunch train.

- Start up conditions
- Meets threshold for instrumentation

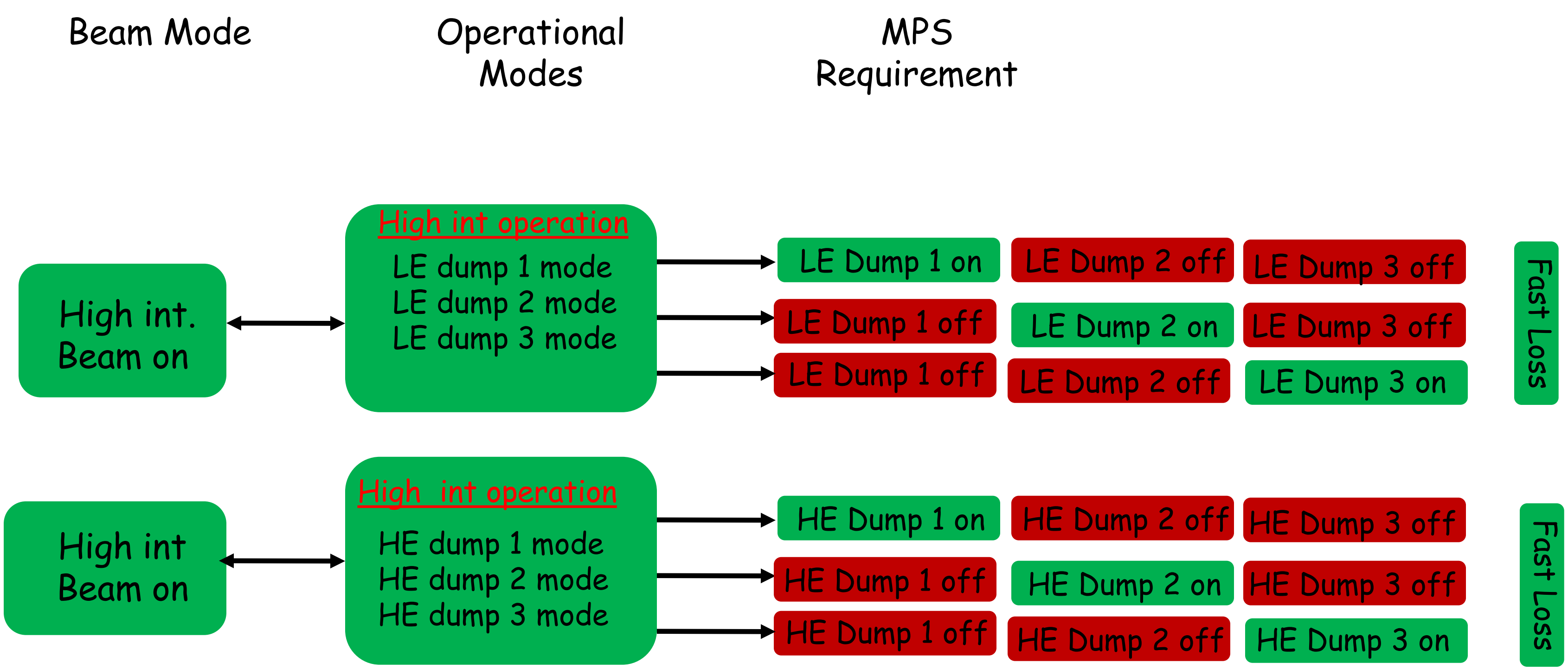


Operational Modes For High Intensity Operation

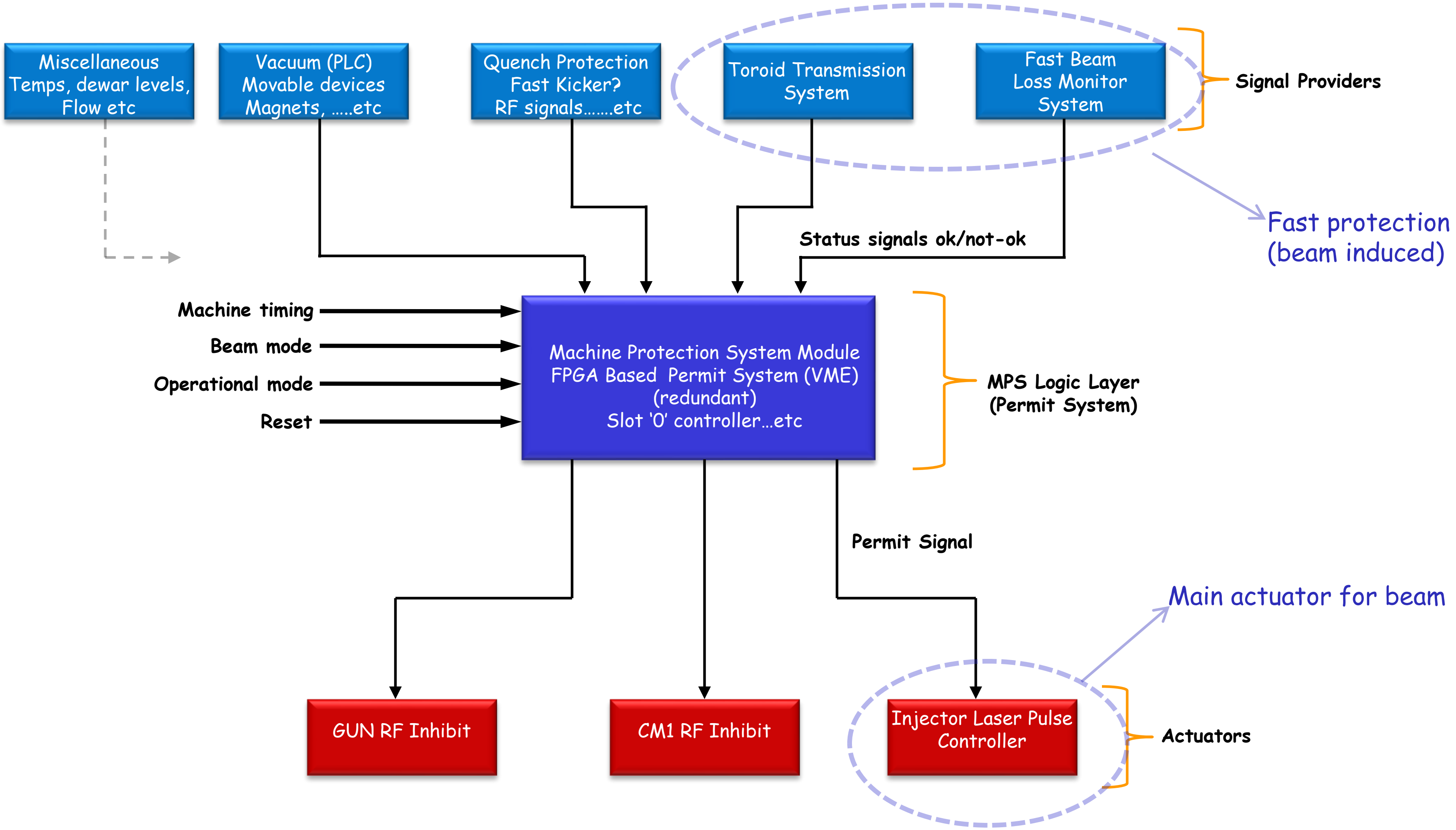
Operational modes define the path beam have to take to reach dumps

High Intensity Mode (full Beam Current(3000 bunches max))
which does not impose a limit on the number of bunches, but enables fast intra-train protection by the MPS.

- Meets threshold requirements for beam losses and transmission losses
- Valves and dipoles are set to correctly guide beam to a dump

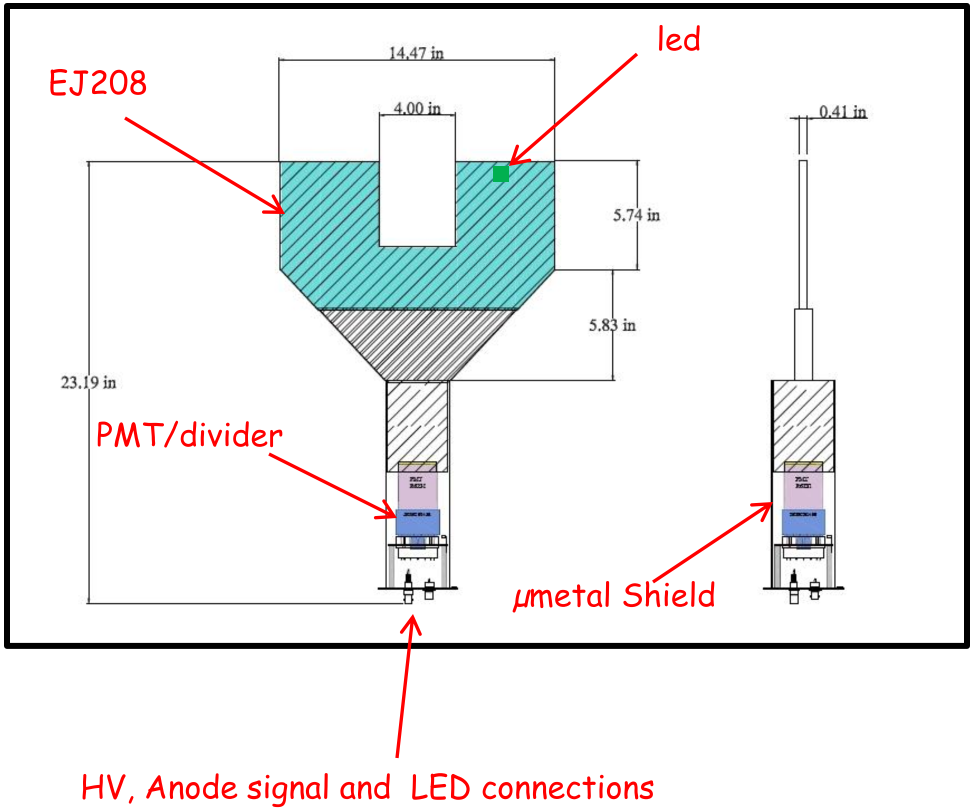


Simplified Over-view of MPS



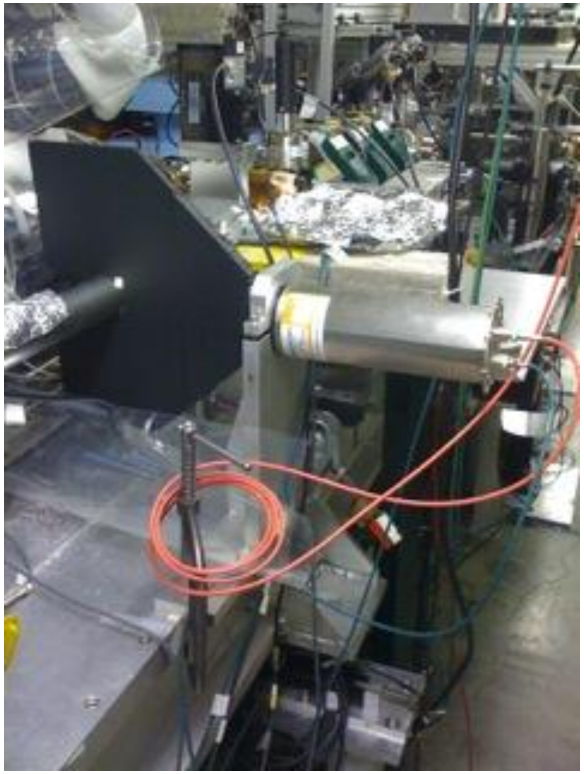
Fast Beam Loss Monitors

The fast protection system is being designed to interrupt the beam within a macro-pulse and will rely heavily on the ability to detect and react to losses within a few nanoseconds; for this reason monitors made of plastic scintillator with PMTs have been built.



EJ208 Scintillator properties	Value
Rise time	1.0 ns
Scintillator Brightness	76 p.e./ MeV
Wavelength of max emission	435 nm
Detector sensitivity	7.0 pC/Mev
Decay time	3.3 ns
Density	1.023 g/cc
Light attenuation length 1/e	210 cm
Number of electrons	$3.37/cm^3$
PMT Specifications	
Rise time	3-5 ns
Gain (min)	2.7×10^5
Supply voltage (max)	2000 volts
Sensitivity	0.1 – 200 A/lm

Fast Beam Loss Monitors



Specifications for NMLTA Loss Monitor System

Purpose and functionality:

- Provide both machine protection (alarm signal) and diagnostic functions for the machine; allowing to tune-up and monitor beam operations while machine protection is integrating the same signal (linear, logarithmic and integrating amplifiers)
- Instantaneous read-back of beam loss
- Fast response << 1 μs

- Macro-pulse repetition rate 1-5 Hz
- Sampling frequency of ADC output (3MHz)
- FPGA controlled
- VME interface and fully integrated into ACNET
- Built-in-self-test (voltage monitor) and onboard signal injection
- Local data buffer for beam loss transient play-back

- Minimum ADC buffer length per macro-pulse 1 ms (rf gate length)
- Max reaction time from analog beam loss signal to digital alarm ~ 1-2 μs (3-6 bunches)
- ADC resolution 12 bits (16 bits)
- Full ADC resolution for single\multi-bunch thresholds
- Signal discrimination between two successive ADC samples
- Resolution for integration over RF gate
- Pulse beam monitoring + continuous monitoring
- channels per board (8?) to handle a total ~40 fast loss monitors at NML

Cryogenic Beam Loss Monitors (Ionization chamber)

Monitors and recycling integrator electronics fabricated and calibrated by Bridgeport Instruments, LLC.

Highlights

- operation in air and high vacuum
- Operates from 5K to 350K
- Stainless steel vessel, 120cm^3, filled with He-gas
- He-gas filling at 1.0- 1.5 bar pressure
- Sensitivity: 1.9 pA/(Rad/hr)
- Readout via current-to-frequency converter (1.9 Hz/(Rad/hr) and FPGA-TDC
- Pulses can be sent through long cables

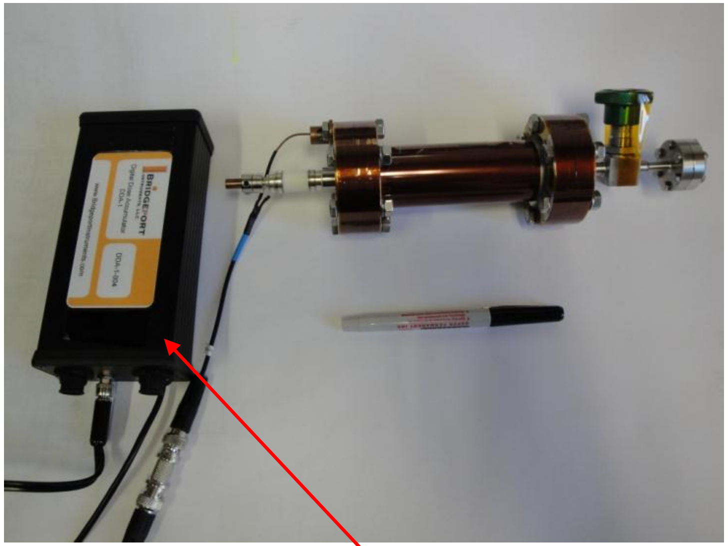
Features

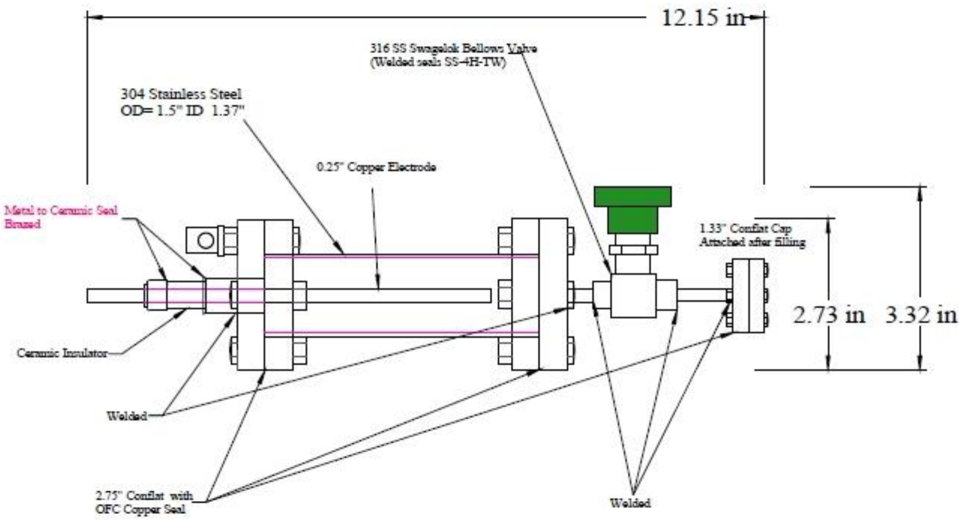
- Custom-built prototype detector for operation as a beam loss monitor at cryogenic temperatures
- Helium filled ionization chamber with signal current proportional to dose rate
- All material radiation hard and suitable for operation at 5K
- Current is measured with a recycling integrator I-F converter for low current and a wide dynamic range. A Fermilab designed FPGA based TDC measures time intervals between pulses output from the recycling integrator ensures a fast response along with current measurement resolution better than 10-bits.

Cryogenic Beam Loss Monitors Specifications

Parameter	*Symbol*	*Min*	*Typ.*	*Max*	*Comment*
Mechanical					
He-volume	V		120 cm^3		
Fill pressure	p		1.0 bar		absolute
Diameter			2.73 inch		without shroud
Length			11.2 inch		without shroud
Detector Operation					
HV			-95 V	-120 V	on chamber body
Sensitivity			1.9 pA / (Rad/hr)		calculated
			6.84 nC/Rad		calculated
Electronic I/O					
Ballast resistor	RB		1.0 MΩ		safety resistor
Supply voltage	Vdd	4.5 V	5.0 V	5.5 V	
Supply current	Idd		105 mA		
Charge per pulse	Qp		**2.286 pC**		
Frequency out	f		**0.831Hz / (Rad/hr)**		after offset of 100 Hz nominal
Offset current	Ioff		100 pA		
Offset current drift	dIoff/dT			10 pA/K	
Environmental					
Operating temperature	T	5K		350K	chamber only
Magnetic field				TBD	

Cryogenic Ionization chamber 5k - 350K





Bias voltage and electronics

- The electronics is self-contained and requires no computer to operate.
- Helium was chosen because of its properties (boiling point 5K) and the fact that it will be in a helium environment during operation anyway.

Fill port

Source test and calibration

R2D-He120-001	Dose Rate Response

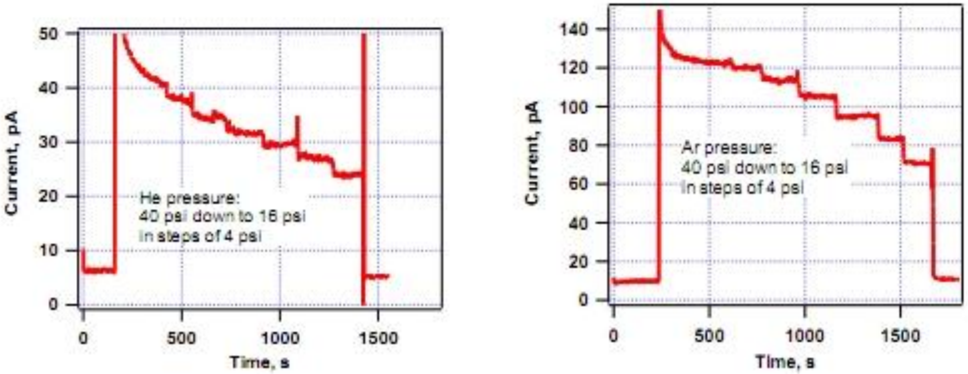


Figure 2: Response of the dose rate monitor to a chamber loaded with an Am-241 source. The source produces about 3010 cps and was mounted on the central electrode. The chamber was pressurized to 40 psi and the pressure was reduced in 4 psi steps. The big signal steps are due to plugging and unplugging the device. About 15 pA of current are due to cabling on the device.

Cryogenic Loss Monitor operation

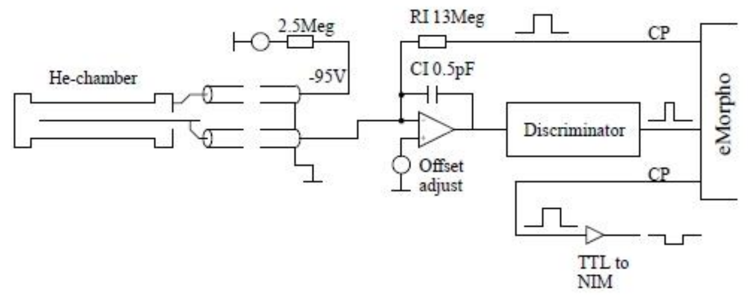
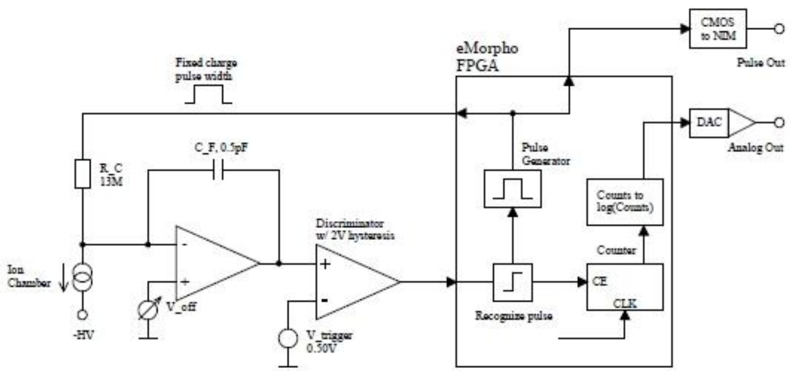


Figure 1: Schematic view of the dose rate monitor.



Drawing 1: Simplified schematics of the digital dose accumulator using a recycling inegrator and the eMorpho platform. Future versions may use a lower-cost platform.

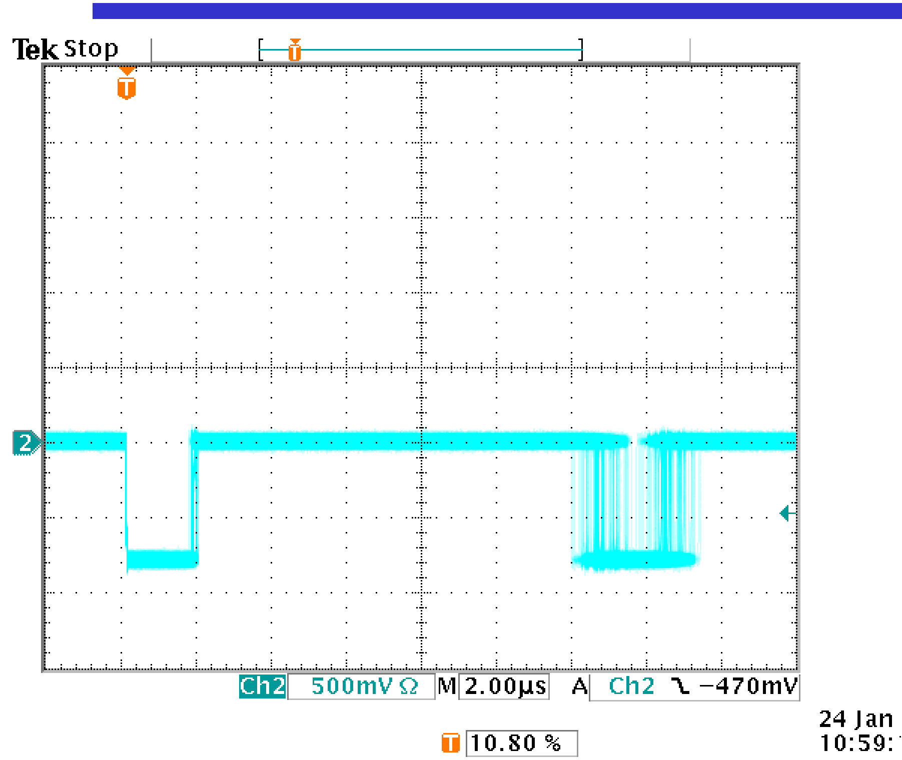
The chamber housing is held at negative potential and negative charge is collected on the center electrode. The HV is -95 V and is kept well below the minimum breakdown voltage of 156V in Helium.

The electronics uses a recycling integrator as a current to frequency converter with a wide dynamic range. The charge per pulse is 1.63pC or 238μR at 1 atm (room temp) of He.

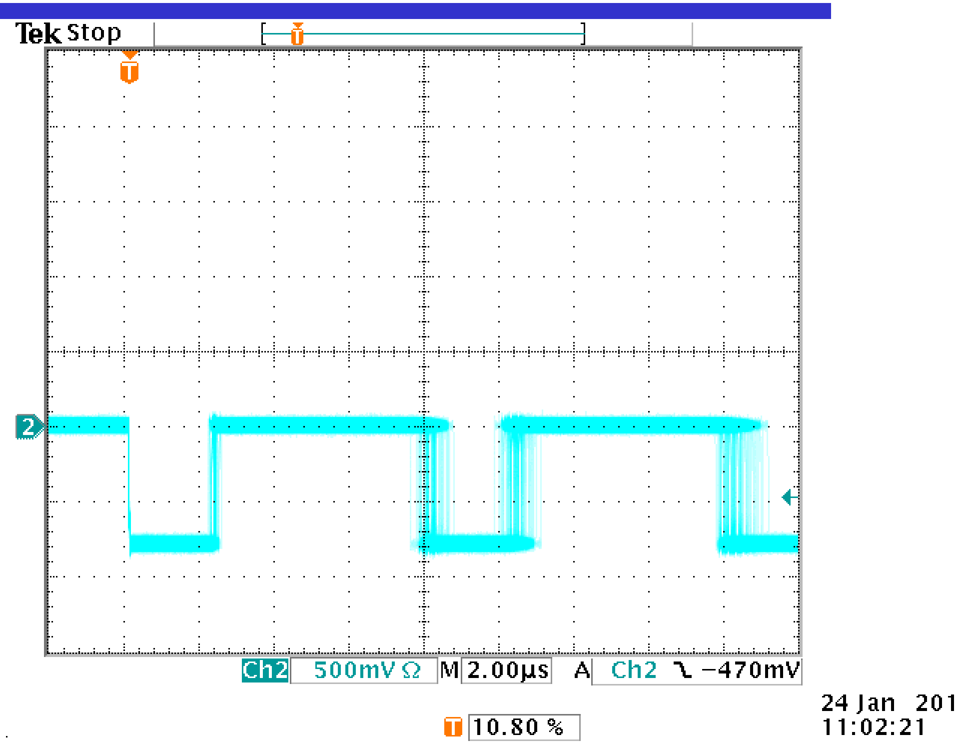
The recycling integrator consist of a charge integrating amplifier with a 0.50 pF capacitance followed by a discriminator which senses when the capacitor is fully charged.

The FPGA generates a fixed-width (1.2μs) discharge pulse with an amplitude of 3.3V. It connects to the amplifier input via a 13 MΩ resistor, creating a 254 nA discharge current

Bench top measurements



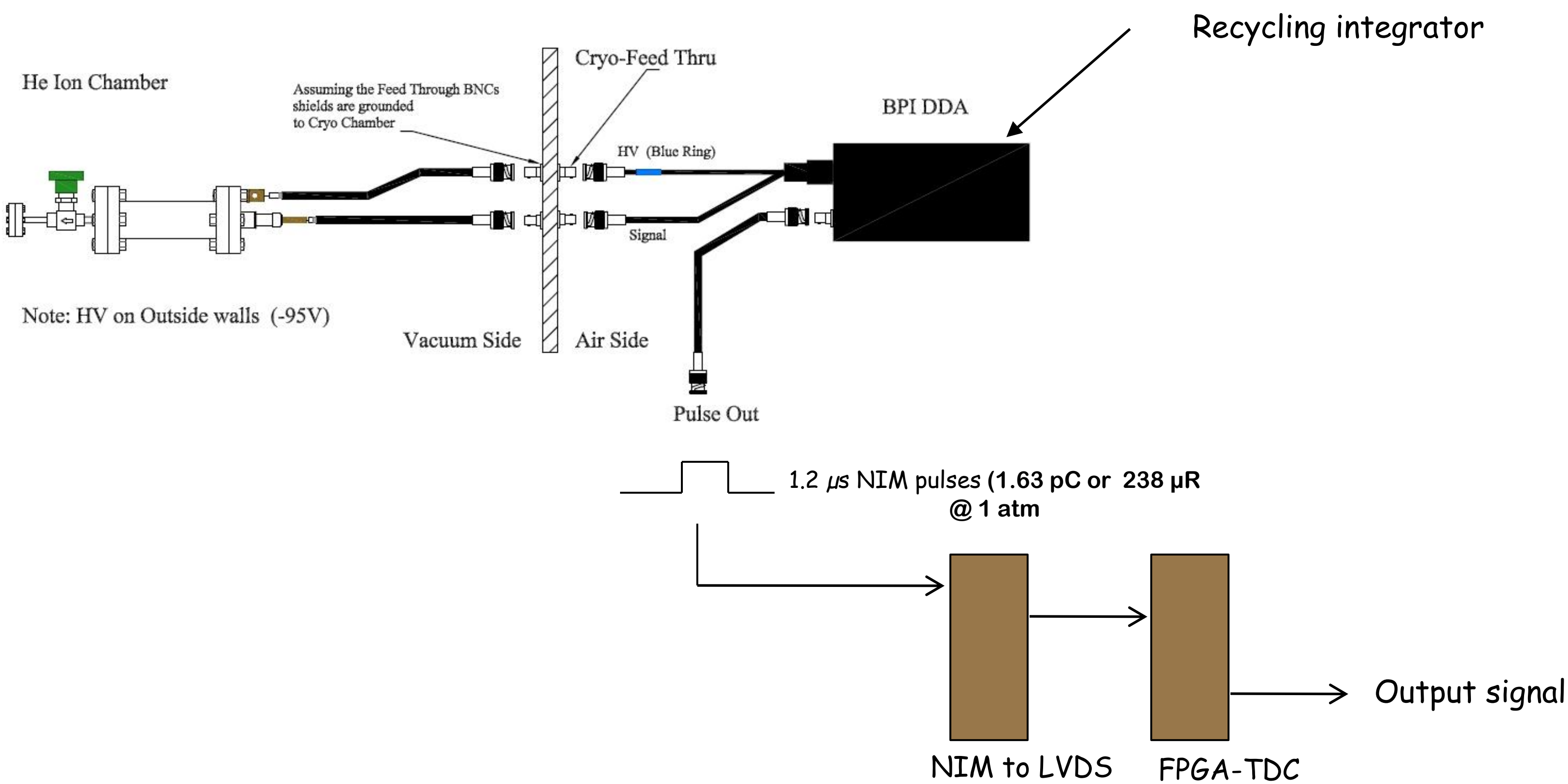
Pulses with 150nA input current



Pulses with 300nA input current

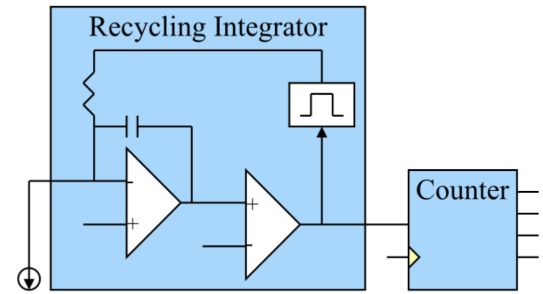
The maximum periodic pulse rate at the output is close to 700 KHz. The corresponding maximum chamber current is 1.60 μA or 842 KR/hr. Pulses can be sent loss-free over great distances and the technique allows to measure radiation levels with dynamic range of 100,000: 1

Cryogenic Loss Monitor Connection and signal path



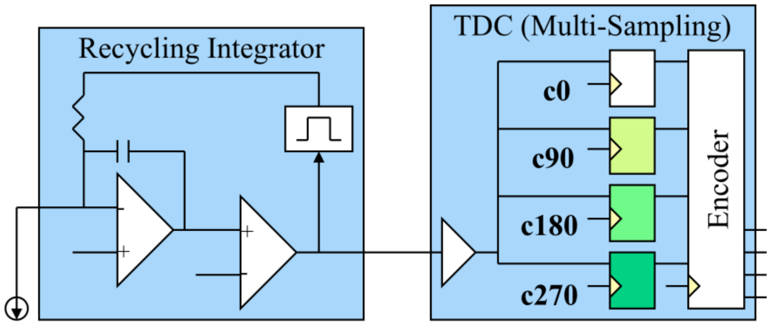
TDC Implemented with FPGA

In typical digitization/readout schemes as shown in Fig., a counter is utilized to accumulate the number of pulses generated by the recycling integrator to digitize the total charge. In order to calculate current with reasonable resolution, a long period must be waited for each sample. For example, to achieve 7-bit resolution, the sampling period corresponds to 128 pulses when input current is at upper limit. This scheme provides a total dosage of the radiation over long period but is not fast enough for accelerator beam protection.



Typical digitization scheme with a counter.

In our new scheme, the same recycling integrator output is sent to an FPGA in which a time-to-digital converter (TDC) is implemented. The TDC is based on a multi-sampling scheme in which the input transition is sampled with four different phases of the system clock. With system clock rates of 250 MHz and four-phase sampling, a 1-ns time measurement resolution can be achieved.

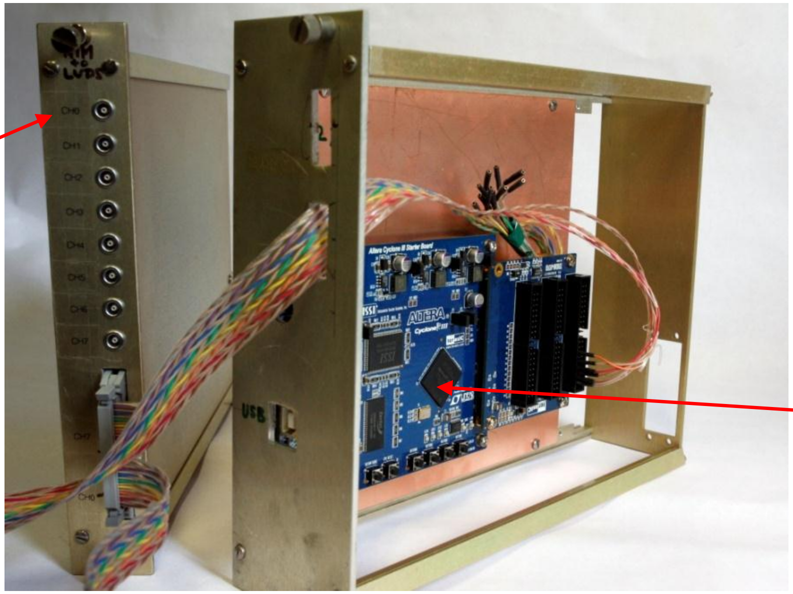


digitization scheme using an FPGA based TDC.

TDC Implemented with FPGA

- There are two popular schemes for FPGA TDC:
  - Multiple sampling based scheme: LSB: 0.6 to 1 ns.
  - Delay line based scheme: LSB: 40 to 100 ps.
- We are currently working on a variation of the delay line based TDC called Wave Union TDC.

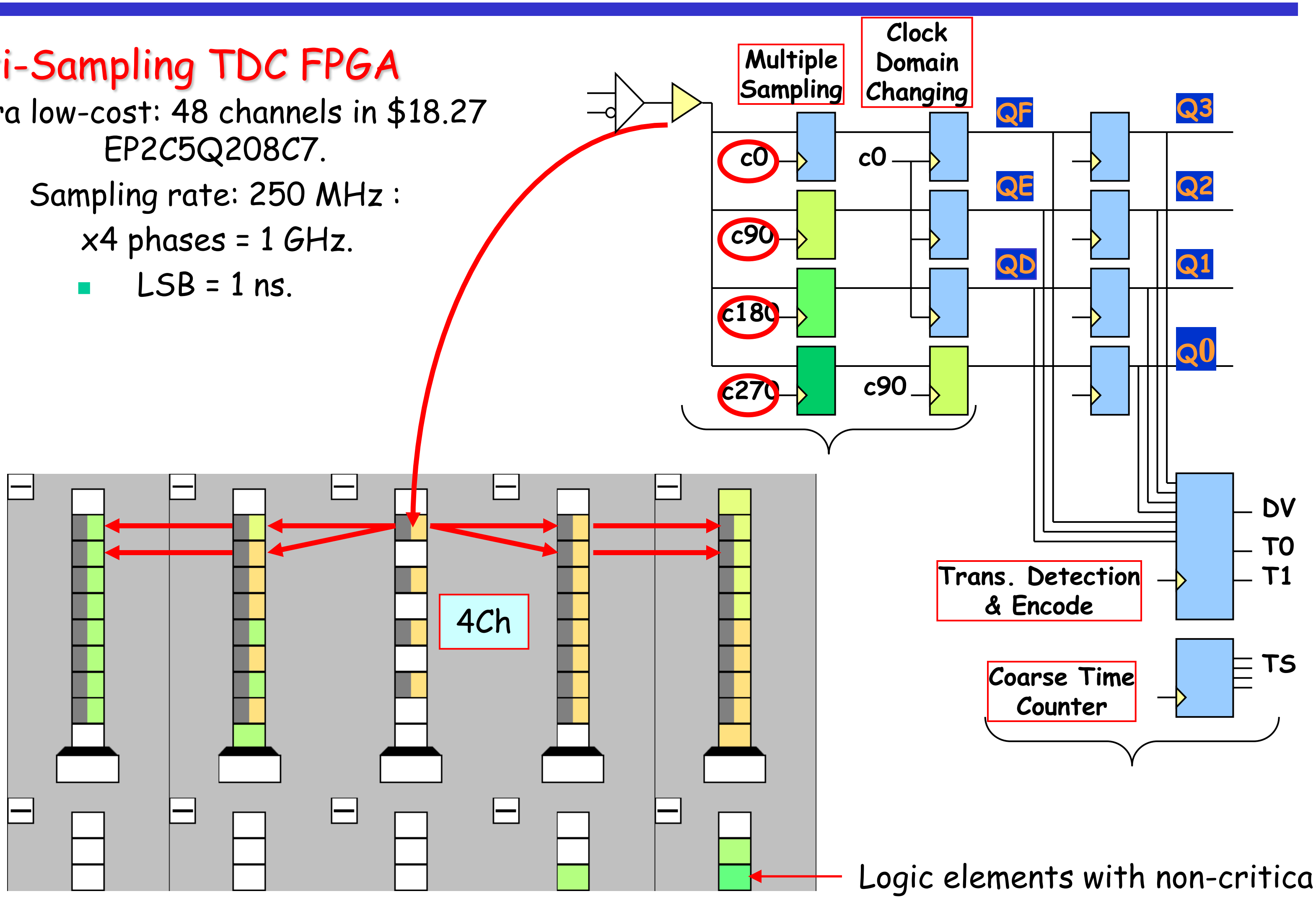
pulse input to 8 Channel LVDS



Cyclone III FPGA

Multi-Sampling TDC FPGA

- Ultra low-cost: 48 channels in $18.27 EP2C5Q208C7.
  - Sampling rate: 250 MHz : x4 phases = 1 GHz.
    - LSB = 1 ns.



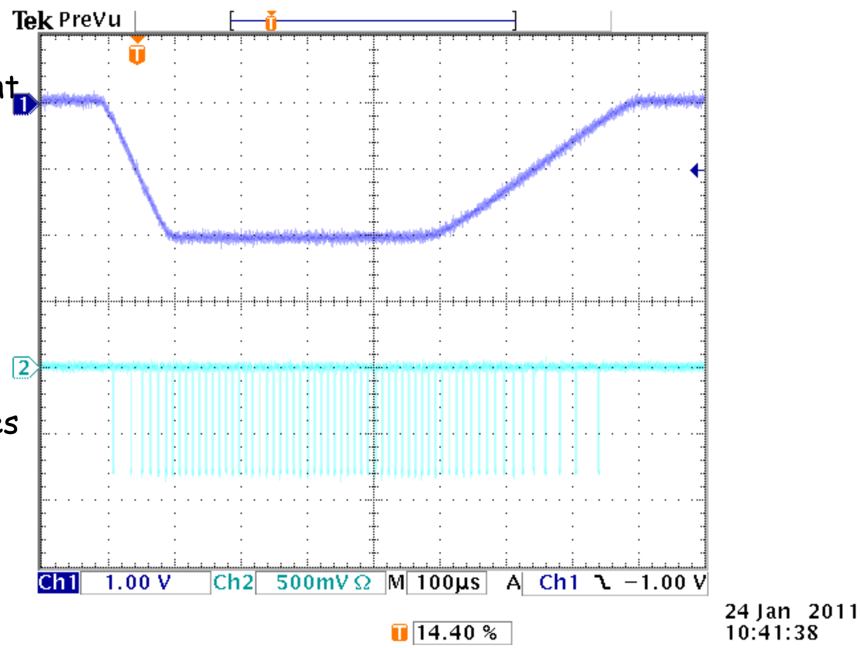
This picture represent a placement in Cyclone FPGA

Logic elements with non-critical timing are freely placed by the fitter of the compiler.

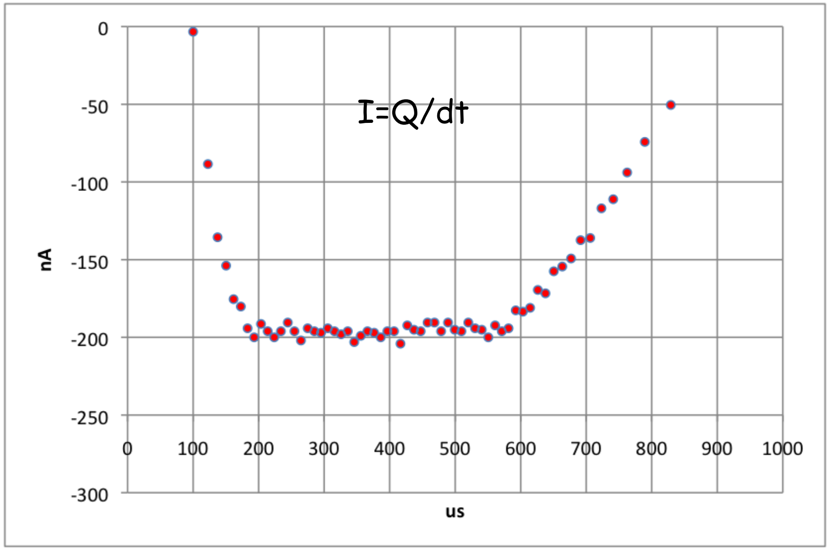
Bench-top measurements with FPGA-TDC

Input Current
100 nA/div

Output Pulses



Input current and out-put pulses



FPGA-TDC data generated by measuring time between pulses

A Scheme using FPGA-based time-to-digital converter (TDC) to measure time intervals between pulses output from the recycling integrator is employed to ensure a fast beam loss response along with a current measurement resolution better than 10-bit.

Dark current measurements at Photo-injector and HTS

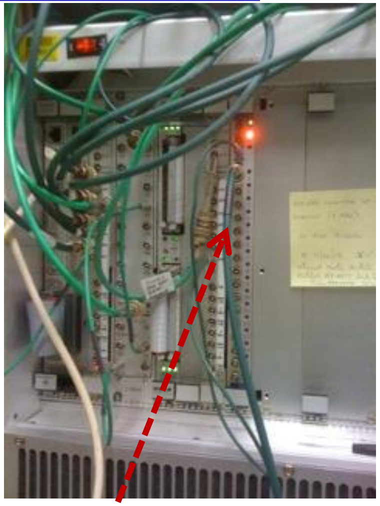
Counter/timer show 630 counts = 150 mR

Initial cold measurements were done at the horizontal test stand (HTS) shown here. A VME based counter timer board was used to count pulse in ACNET: Counter/timer showed counts corresponding to 150mR

Test are now being done using the FPGA-TDC method which is faster with better resolution

Test cavity

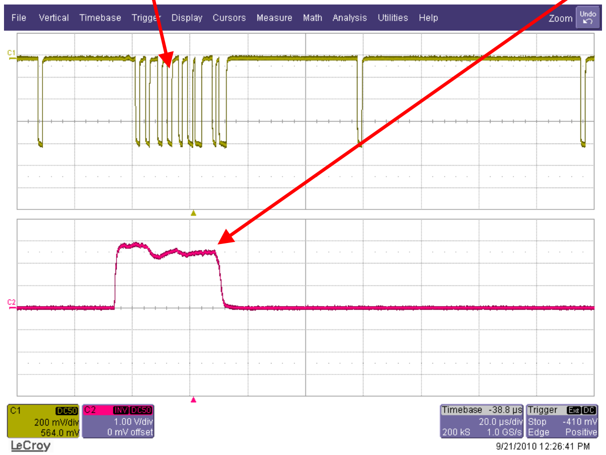
HTS installation

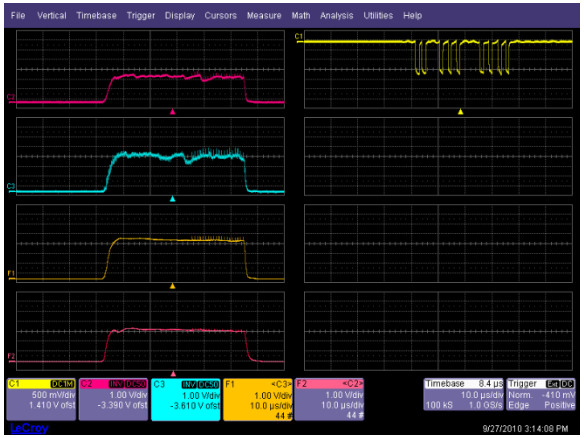


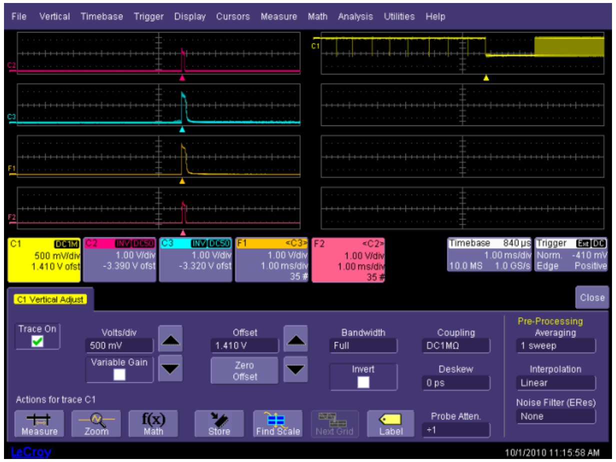
VME based counter/Timer board

Loss due to Dark current background at A0-photo-injector. Measured to be ~ 400 nA downstream of bend magnet

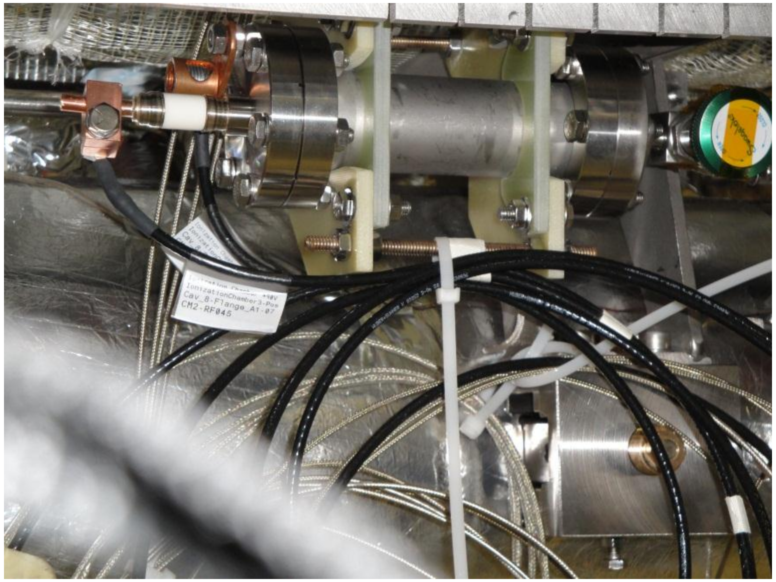
40 μs rf gate (dark current only no photo-electrons injected)

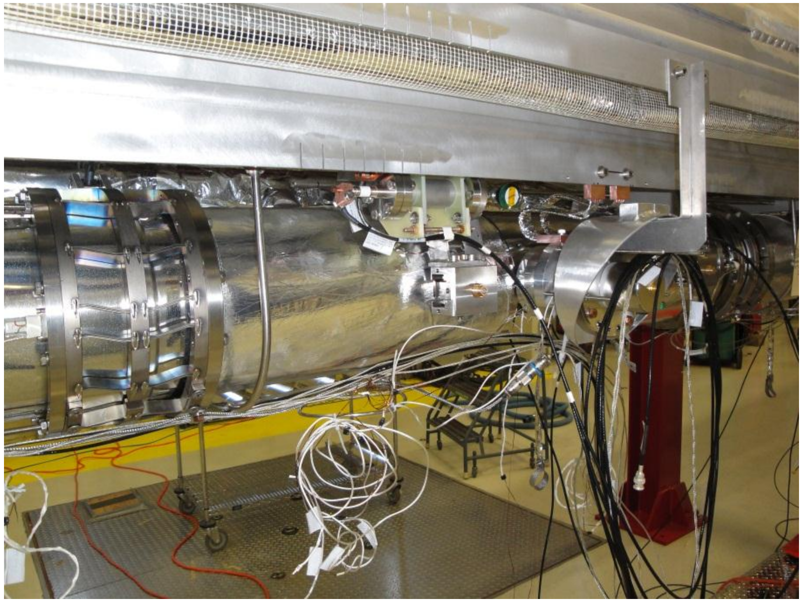




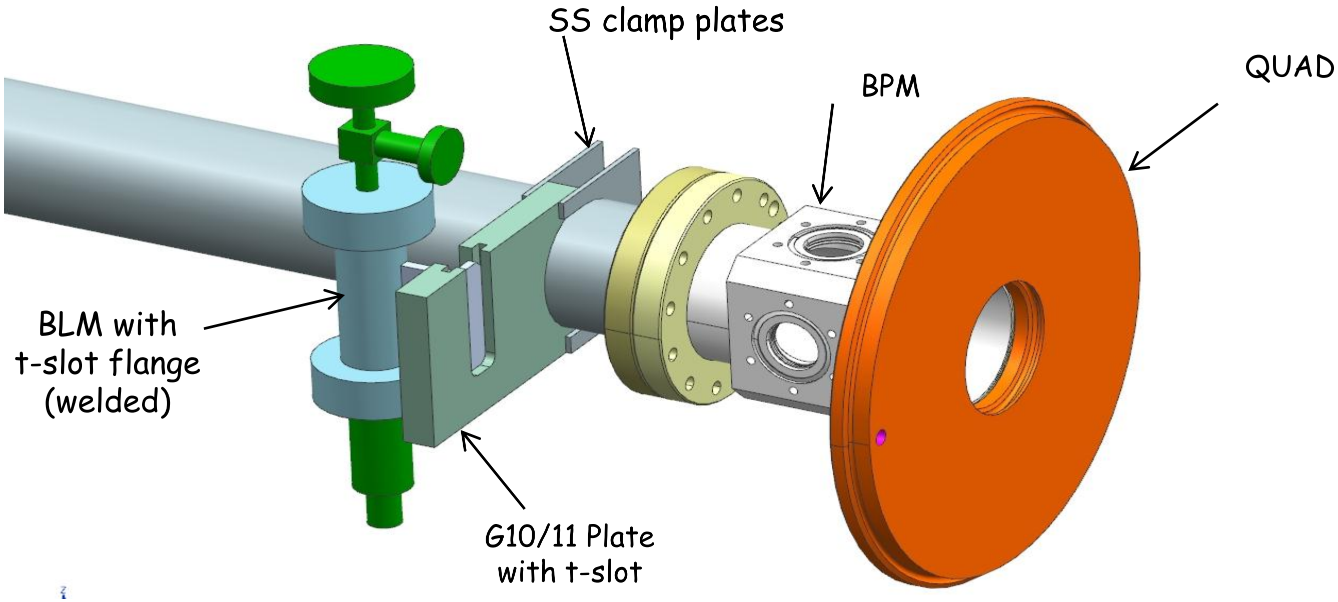


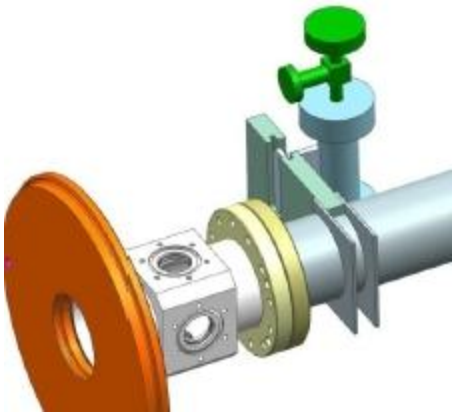
Cryogenic Loss Monitor installation in CM2





Proposed installation option





Design improvements and modifications

Final test are underway with FNAL designed FPGA-TDC at HTS

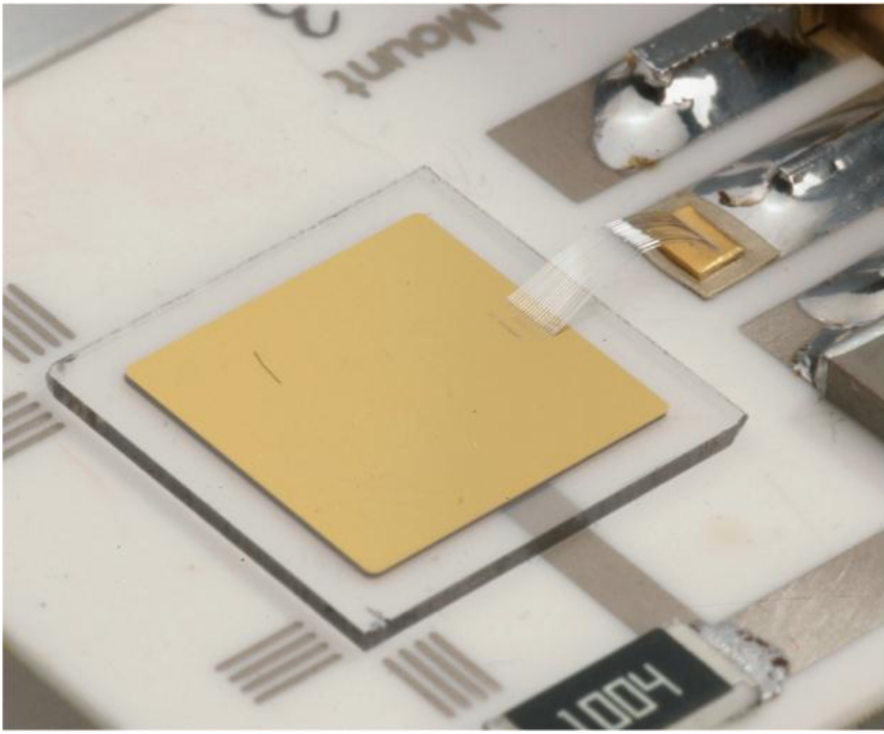
- We have increased the pressure from 1bar to 1.5bars to establish the best operating point for the device. The calibration "S" of the monitors is almost completely determined by the volume "V" of the enclosed gas and by the type of gas:

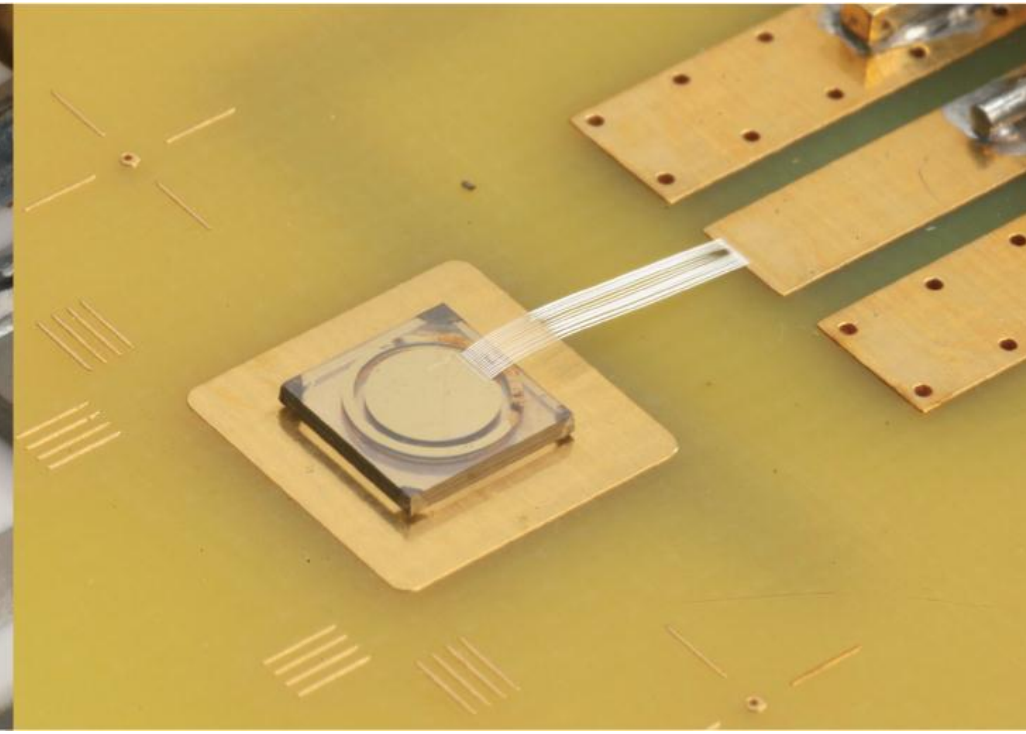
$S \approx V \rho \, . \, e/E_{ion}$ ("ρ" is gas density and E_{ion} is mean energy deposition to create electron-ion pairs)

- We had Bridgeport Instruments modify they FPGA code in the recycling integrator electronics box so that the leading edge of the discriminator can be seen at the NIM port output. This improves would improve the resolution of the TDC measurement between pulses.

- A mechanical scheme to easily mount the loss monitor in a cryomodule near the quads and BPMs is being done as shown in the following example.

Diamond Detectors in CM2

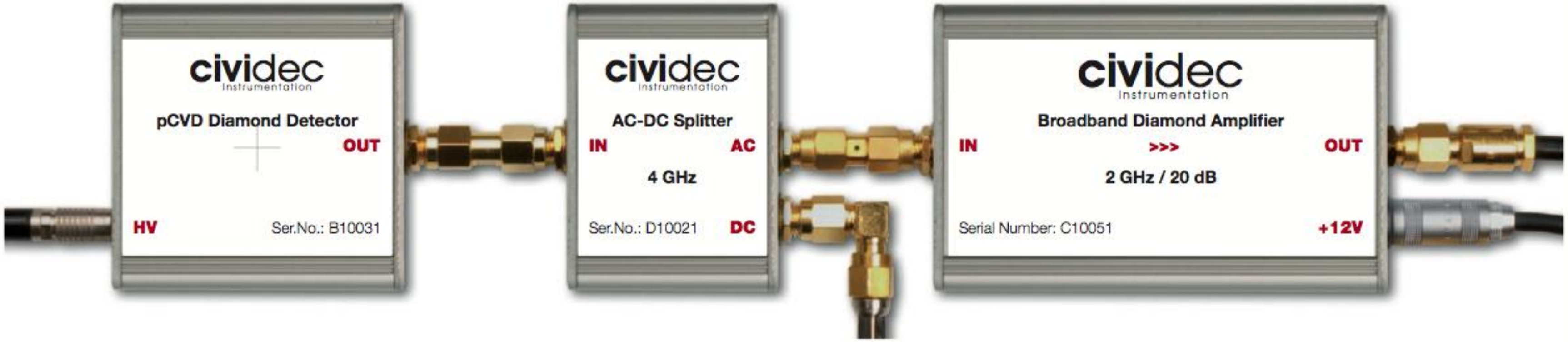




pCVD **sCVD**

Devices and data provided by Prof. Dr. Erich Griesmayer
CIVIDEC Instrumentation GmbH

Diamond Beam Monitor

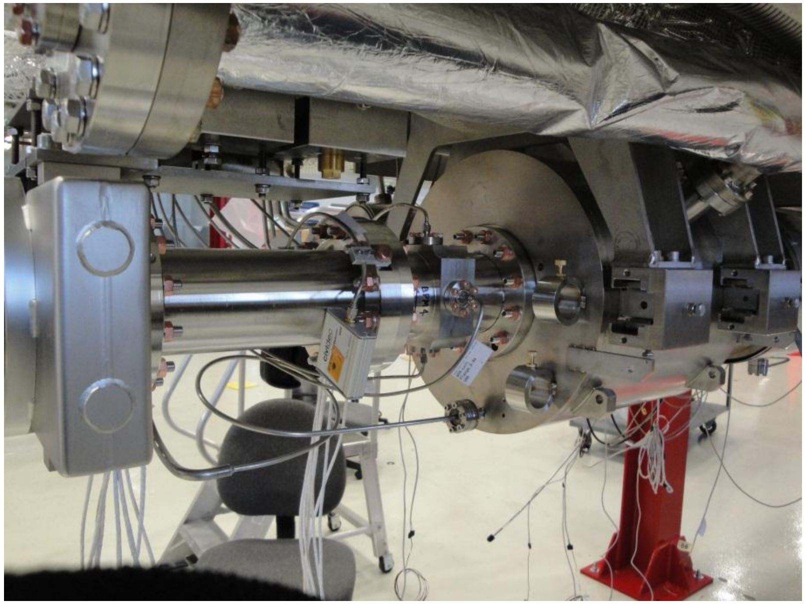


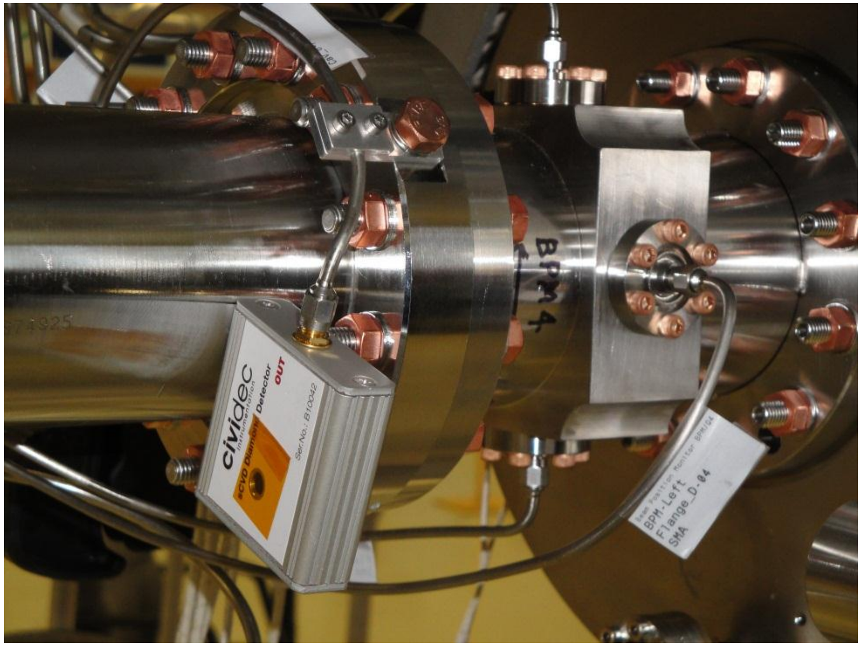
Detector AC/DC Splitter 2 GHz Amplifier

CVD Parameter

Property	Diamond	Silicon	Advantage
Band gap [eV]	5.5	1.12	Low leakage
Breakdown field [V/cm]	10^7	$3 \cdot 10^5$	
Intrinsic resistivity @ R.T. [Ω cm]	$> 10^{11}$	$2.3 \cdot 10^5$	
Intrinsic carrier density [cm^{-3}]	$< 10^3$	$1.5 \cdot 10^{1}0$	
Electron mobility [cm^2/Vs]	1900	1350	
Hole mobility [cm^2/Vs]	2300	480	
Saturation velocity [cm/s]	e^-: $0.9 \cdot 10^7$ holes: $1.4 \cdot 10^7$	$0.82 \cdot 10^7$	
Density [g/cm^3]	3.52	2.33	
Atomic number - Z	6	14	
Dielectric constant - ε	5.7	11.9	Low capacitance
Displacement energy [eV/atom]	43	13-20	Radiation hard
Thermal conductivity [W/m.K]	≈ 2000	150	Heat spreader
Energy to create e-h pair [eV]	13	3.61	
Radiation length [cm]	12.2	9.36	
Interaction length [cm]	24.5	45.5	
Spec. Ionization Loss [MeV/cm]	6.07	3.21	
Aver. Signal Created / 100 μm [e_0]	3602	8892	Low signal, Low Noise
Aver. Signal Created / 0.1 X0 [e_0]	4401	8323	

Diamond Beam Monitor installation in CM2





Laser Pulse Control

Main Purpose - Main actuator for beam inhibits: Controls the number and spacing of bunches in a macro-pulse by varying the width of the Gate to Pockels cell.

Inputs –

- MPS Alarm state
- Beam Mode (user request) i.e. Low intensity/ High intensity
- 3 MHz machine timing
- 1 MHz machine timing
- First Toroid (beam intensity)
- Laser diode (light intensity)
- Macro-pulse Trigger (5 Hz)

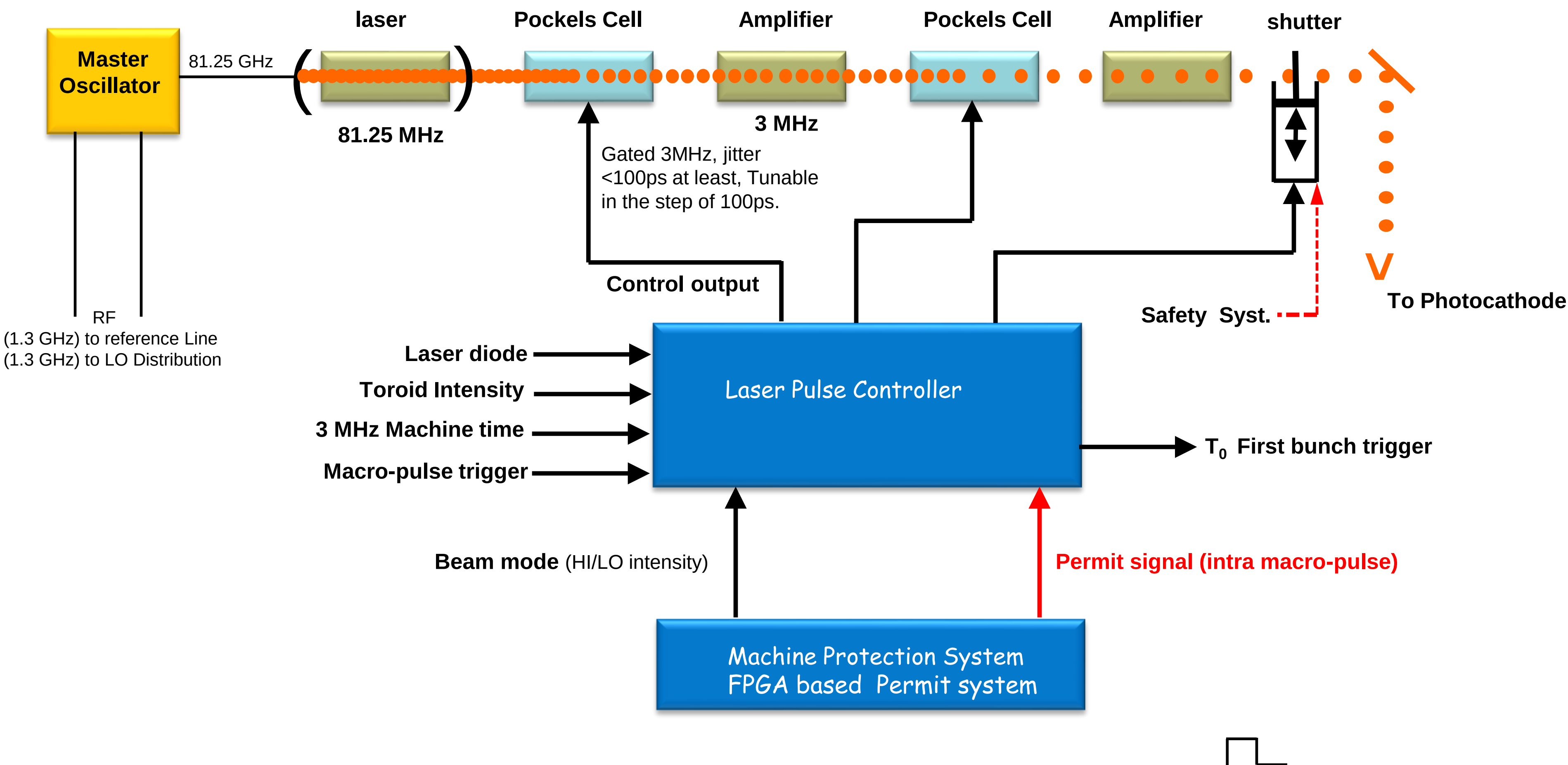
Outputs –

- Laser Gate
- Line to close Mechanical shutter
- T_0 first bunch trigger

Design Feature: VME based card with FPGA that

- Stops beam or reduce to low intensity (depends on nature of alarms)
- Enforce the limits on number of bunches defined by beam mode
- Close shutter (depends on alarm state).

MPS Laser pulse control

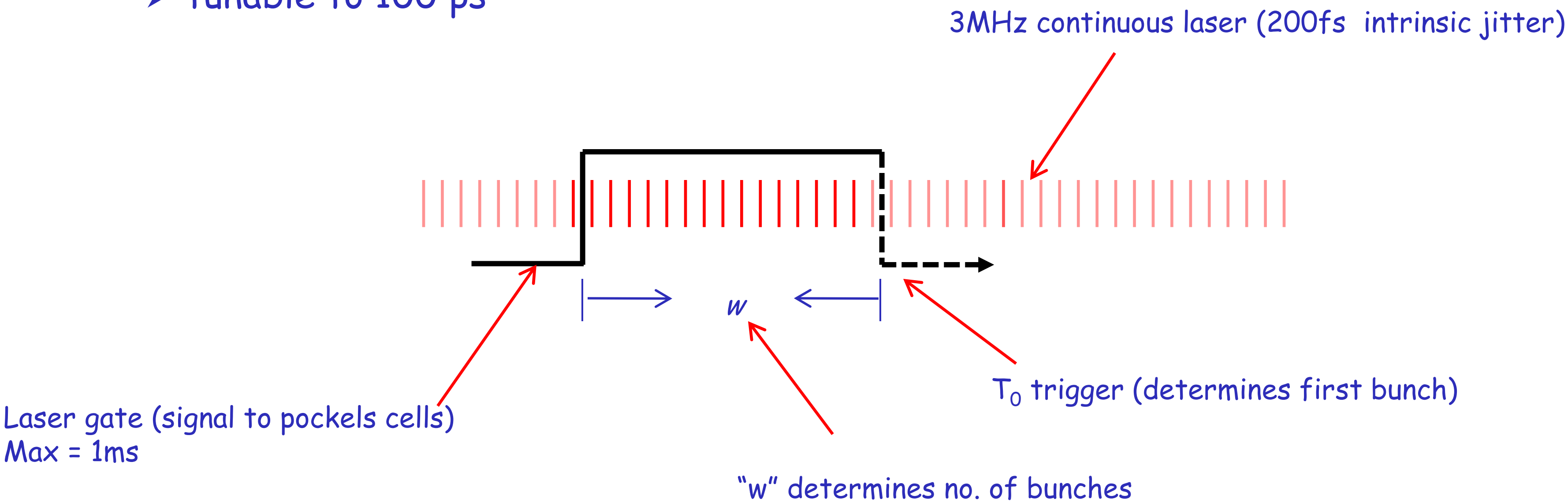


See thesis - Lars Frohlich

- Block the Pockels cell based pulse kickers as long as the MPS input is in an alarm state.
- Enforce the limit on the number of bunches as given by the currently selected beam mode.
- Close the laser shutter on request of the MPS. This may happen when there is no valid operational mode or when some combination of loss monitors exceed thresholds which trigger a dump condition.

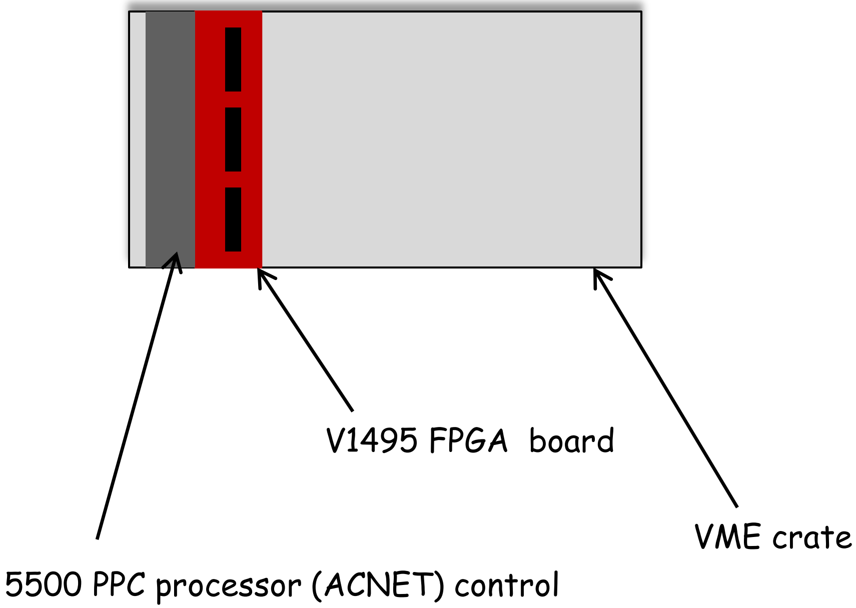
Laser Gate and Pulse Control

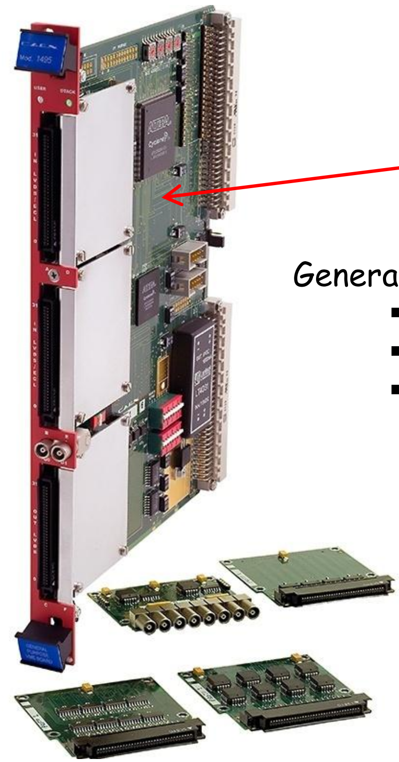
Gate signal Specifications:
- < 100 ps jitter
- tunable to 100 ps



Q.E of gun/laser system determined from measured inputs :
- Diode (light)
- Charge measured (toroid)
- number of bunches

Laser Gate and Pulse Control FPGA Board





General purpose FPGA Board
- 64 inputs expandable to 162
- 32 outputs
- 405 MHz max for registered logic

The FPGA "User" can be programmed "on the fly" via VME, without any external hardware tools, without disconnecting the board from the set up, and without resetting it or turning the crate off. A flash memory on the board stores the programming file, which can be loaded to the FPGA "User" at any moment. Four (independent, digital, programmable, asynchronous, chainable) timers, are available for Gate/Trigger applications.

Summary and Plans

- Lots to consider operationally for this system but the first order task is to make a fail safe system that protects the machine.

- Integration with others is going to be very important

- Want to make the system as modular, expandable and user-friendly

- Requires some redundancy in places

Considering other instrumentation :

- Secondary emission monitors (SEMs) or Aluminum cathode PMTs near dumps
- Fast Kicker
- Cryogenic Loss monitors sensitive to dark current as close to the beam pipe as possible (5K)
- Diamond loss monitors also close to the beam pipe (1.8K)

- The overall length of the NML accelerator is 133.5 meters. Based on expected FPGA processing times of ~1ns and cable delay times of ~ 0.4 μs it would be reasonable to expect total response times of about 1-2 μs from the protection system. This implies that for high intensity operation at the design bunch frequency of 3MHz, approximately 3-6 bunches can be present in the machine even when the MPS reacts (~ 45 - 90 watts). Depending on no. of cryo-modules.