Equipment Protection System for CBETA

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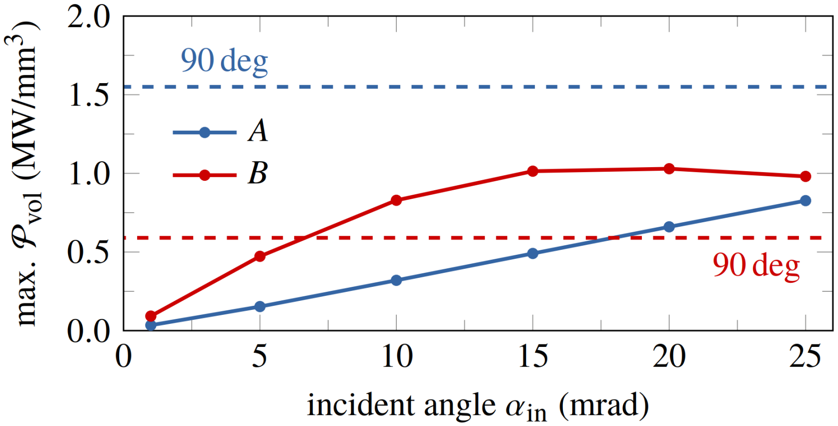
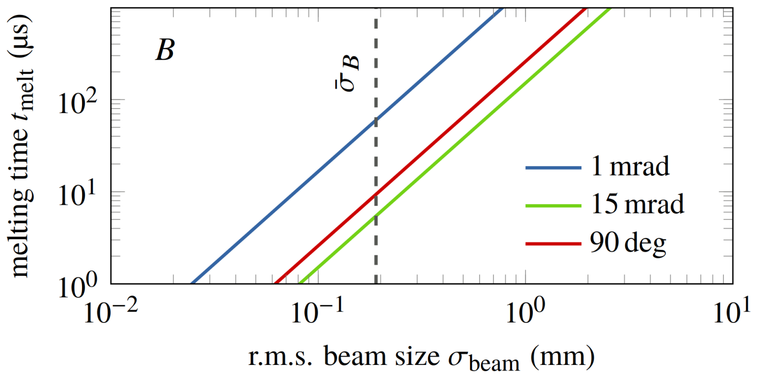
Introduction

Electron beams striking **any beam line components (even inside the cryomodule!)** can lead to damage to the material and a corresponding shower.

Radiation calculations were done for bERLinPro[1] with a 100 mA, 50 MeV beam.





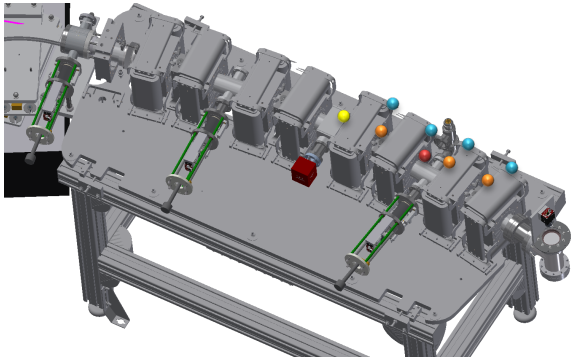
[1] S. Wesch et al., Machine Protection Considerations for bERLinPro, IPAC’ 2014, THPRI091

Observations

- Maximum deposited power density is a function of angle of incidence, perpendicular incidence is not the worst case. This is due to the Bragg Peak and is dependent on beam energy.
- For a beam size of 0.2 mm, melting time for beam pipe is about 5 us.
- **Damage to FFA magnets is the biggest worry!**

Radiation Sources

- Total Beam Loss
  - This happens when the **whole beam hits the pipe** either due to an instability or on purpose during commissioning.
  - Some Film dosimeters were placed on the last 4 FFA magnets for the FAT.



Observations:

- More dose registered on faces than sides. This may be due to the difference in solid angle covered.
- Maximum dose of ~ 4000 cGy ~ 4% of the no damage threshold proposed by Stephen Brooks.
- Very simple triangulation yields a source position near the pumping position rather than the stop.

*"During the FAT, the minimum current that we ran was 9 nA = 6 pC * 100 Hz * (300 ns * (50 MHz)). We were using a bunchtrain of 300 ns duration so that the RF-based BPMs would work.* ***Suggestion:*** *What would you say to keeping that same bunch train duration of 300 ns, but having the bunch trains be injected at 5 Hz? That would make: 6 pC * 5 Hz * (300 ns * (42 MHz)) = 400 pA?" – Adam*

- What happens when we loose beam into a cavity? It probably quenches. Q0 measurement?
- Fibre Loss Monitors will provide a signal for fast shutdown.

Radiation Sources: Work Needed

- **Beam Halo**

  Theoretical work is needed and direct diagnostics need to be implemented. Suggestions?

  Slow beam loss monitors will detect steady beam loss. We have to decide on acceptable thresholds.

- Scattering

  Beam screens, beam stops (including diagnostic line) and the high power beam dump.

  Joseph will look into the radiation absorbed by the individual magnet blocks scattered off from the view screen and the beam stops.

- Dark Current
  - Field emission from cavities is unlikely at the nominal fields for CBETA as evidenced by the lack of substantial readings during the FAT.
  - Dark current from the gun?

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Goals

We already used a Fast Shutdown System in ERL injector operations. It uses two equipment protection shutters (fast and slow) in the laser path to the cathode. The EPS system is the framework to activate these shutters.

Design Goals:

1. Fast Response Times

   Except for slow signal sources, the response times should be within a **few microseconds.**

2. Redundant System

   One failure mode must be able to **trigger multiple signal chains.**
   Example: Beam swerving into a pipe should be detected by BPMs, BLMs, and worst of all vacuum gauges.

3. Forensic Data Dumps

   Operate data buffers to **log important data**, RF, BPM, BLM, Gun voltage etc and save it to disk for analysis.
   This will require the subsystems to not only be able to generate an EPS trigger but also detect it!

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Gun and Laser

The photo-injection system has multiple failure points:

1. Laser Timing and Position (Medium)
   - Oscillator Synchronization Failure

     Lead to improperly timed bunches which will get the wrong energy gain and eventually hit the wall.
   - Laser Position Unstable

     This will in turn lead to bunches with the wrong transverse position and phase space distribution which can also eventually hit the pipe.

2. High Voltage Power Supply (Has been done)
   - Supply failure or large voltage ripple

     Wrong beam energy may not be bunched properly and will have different emittance. In case of failure, space charge can accumulate in front of the cathode.
   - Large Current

     Large current is indicative of breakdown, can also trigger gun vacuum.

3. SF6 System

   SF6 keeps the power supply running without breakdown. Any problems here can lead to gun high voltage failure.

4. Gun Vacuum

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SRF Linacs: LLRF

RF control systems are slightly different for the Buncher, Injector and Main Linac, but mostly trip on the same things.

1. High RF Powers
   High forward or reflected power can damage the system.
2. High Cavity Field
   High cavity fields beyond a threshold can potentially lead to quench.
3. Quench
   During a quench the intrinsic quality factor of the cavity drops drastically, dissipating a lot of heat into the Helium system. It can be detected by the accompanying field drop and reduction in reflected power from the cavity.
4. High Detuning
   Large microphonics events can shift the phase of the cavity field drastically.
5. Klystron/SSA Problems
   In the case of the ICM, the Klystron HV and for the MLC the reflected power going into the SSA are monitored by the LLRF.
6. Coupler Vacuum
   The LLRF also monitors an analog coupler vacuum pressure signal.

Sometimes the cavity field can deviate from the set point beyond a certain margin, but not necessarily cause a trip. The LLRF generates a RF_Field_OK signal which can trigger the EPS system in this case.

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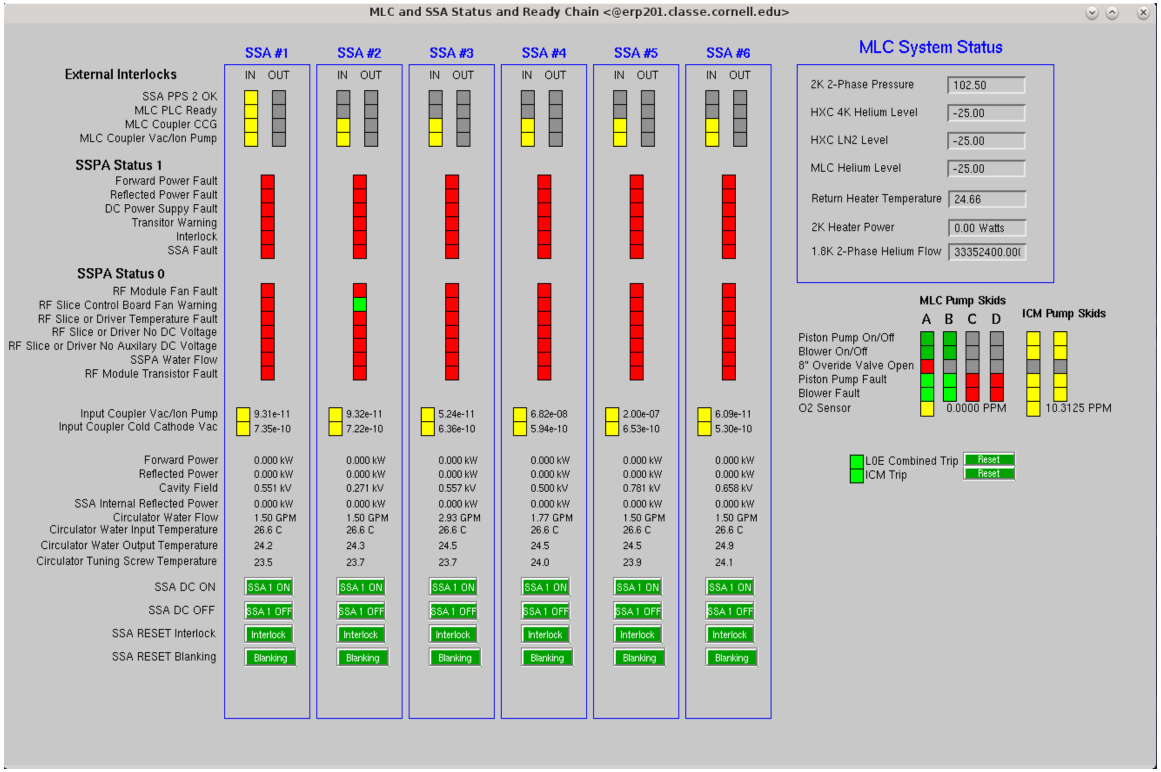
Solid State Amplifiers



MLC and SSA Status and Ready Chain <@erp201.classe.cornell.edu>

External Interlocks
SSA PPS 2 OK
MLC PLC Ready
MLC Coupler CCG
MLC Coupler Vac/Ion Pump

SSPA Status 1
Forward Power Fault
Reflected Power Fault
DC Power Suppy Fault
Transitor Warning
Interlock
SSA Fault

SSPA Status 0
RF Module Fan Fault
RF Slice Control Board Fan Warning
RF Slice or Driver Temperature Fault
RF Slice or Driver No DC Voltage
RF Slice or Driver No Auxilary DC Voltage
SSPA Water Flow
RF Module Transistor Fault

	SSA #1	SSA #2	SSA #3	SSA #4	SSA #5	SSA #6
Input Coupler Vac/Ion Pump	9.31e-11	9.32e-11	5.24e-11	6.82e-08	2.00e-07	6.09e-11
Input Coupler Cold Cathode Vac	7.35e-10	7.22e-10	6.36e-10	5.94e-10	6.53e-10	5.30e-10
Forward Power	0.000 kW	0.000 kW	0.000 kW	0.000 kW	0.000 kW	0.000 kW
Reflected Power	0.000 kW	0.000 kW	0.000 kW	0.000 kW	0.000 kW	0.000 kW
Cavity Field	0.551 kV	0.271 kV	0.557 kV	0.500 kV	0.781 kV	0.658 kV
SSA Internal Reflected Power	0.000 kW	0.000 kW	0.000 kW	0.000 kW	0.000 kW	0.000 kW
Circulator Water Flow	1.50 GPM	1.50 GPM	2.93 GPM	1.77 GPM	1.50 GPM	1.50 GPM
Circulator Water Input Temperature	26.6 C	26.6 C	26.6 C	26.6 C	26.6 C	26.6 C
Circulator Water Output Temperature	24.2	24.3	24.5	24.5	24.5	24.9
Circulator Tuning Screw Temperature	23.5	23.7	23.7	24.0	23.9	24.1
SSA DC ON	SSA 1 ON	SSA 1 ON	SSA 1 ON	SSA 1 ON	SSA 1 ON	SSA 1 ON
SSA DC OFF	SSA 1 OFF	SSA 1 OFF	SSA 1 OFF	SSA 1 OFF	SSA 1 OFF	SSA 1 OFF
SSA RESET Interlock	Interlock	Interlock	Interlock	Interlock	Interlock	Interlock
SSA RESET Blanking	Blanking	Blanking	Blanking	Blanking	Blanking	Blanking

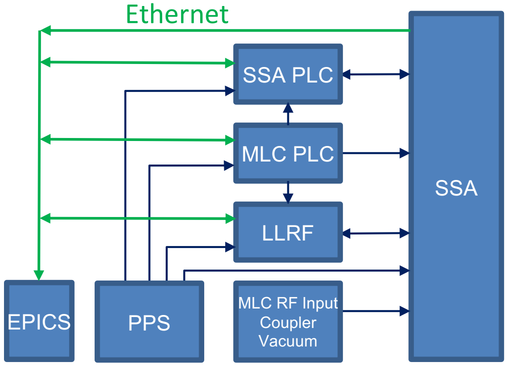
MLC System Status

2K 2-Phase Pressure	102.50
HXC 4K Helium Level	-25.00
HXC LN2 Level	-25.00
MLC Helium Level	-25.00
Return Heater Temperature	24.66
2K Heater Power	0.00 Watts
1.8K 2-Phase Helium Flow	33352400.00(

MLC Pump Skids A B C D — 0.0000 PPM
ICM Pump Skids — 10.3125 PPM

Piston Pump On/Off
Blower On/Off
8" Overide Valve Open
Piston Pump Fault
Blower Fault
O2 Sensor

L0E Combined Trip Reset
ICM Trip Reset



Plenty of internal faults to monitor. Feeds into a Programmable Logic Controller (PLC) with millisecond response times.

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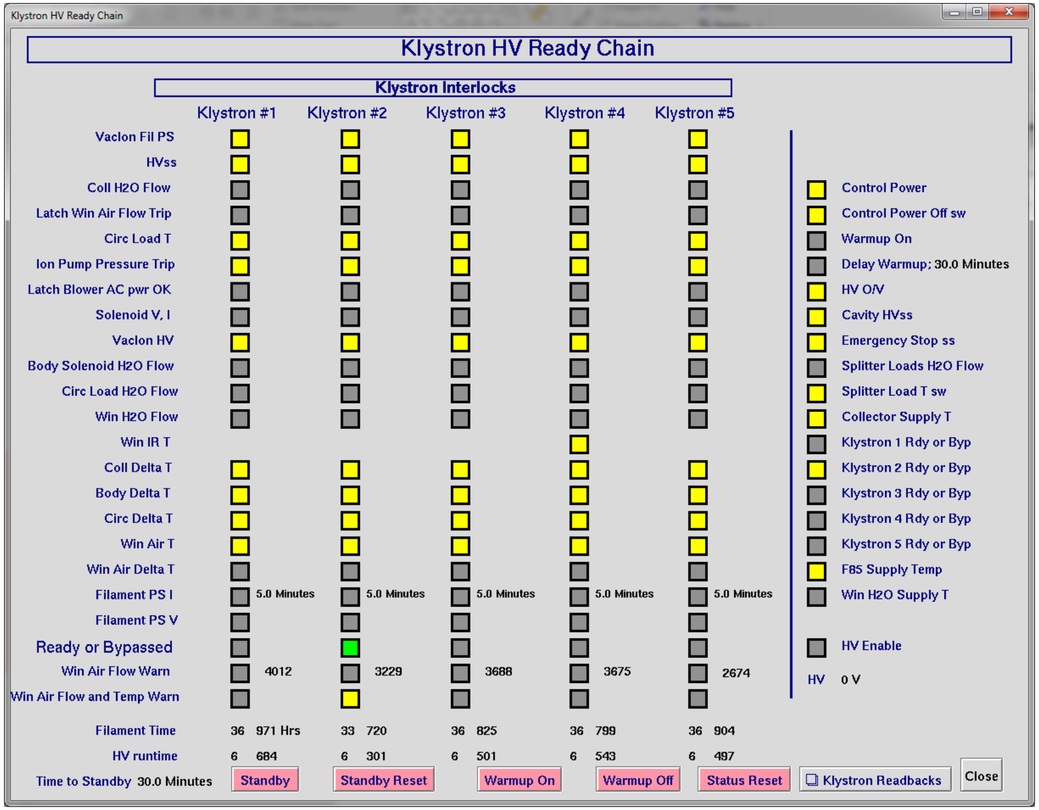
Klystrons

Complicated but well understood system with ample monitoring by PLCs.



Klystron HV Ready Chain

Klystron Interlocks

	Klystron #1		Klystron #2		Klystron #3		Klystron #4		Klystron #5	
Vaclon Fil PS	🟨		🟨		🟨		🟨		🟨	
HVss	🟨		🟨		🟨		🟨		🟨	
Coll H2O Flow	⬛		⬛		⬛		⬛		⬛	
Latch Win Air Flow Trip	⬛		⬛		⬛		⬛		⬛	
Circ Load T	🟨		🟨		🟨		🟨		🟨	
Ion Pump Pressure Trip	🟨		🟨		🟨		🟨		🟨	
Latch Blower AC pwr OK	⬛		⬛		⬛		⬛		⬛	
Solenoid V, I	⬛		⬛		⬛		⬛		⬛	
Vaclon HV	🟨		🟨		🟨		🟨		🟨	
Body Solenoid H2O Flow	⬛		⬛		⬛		⬛		⬛	
Circ Load H2O Flow	⬛		⬛		⬛		⬛		⬛	
Win H2O Flow	⬛		⬛		⬛		⬛		⬛	
Win IR T							🟨			
Coll Delta T	🟨		🟨		🟨		🟨		🟨	
Body Delta T	🟨		🟨		🟨		🟨		🟨	
Circ Delta T	🟨		🟨		🟨		🟨		🟨	
Win Air T	🟨		🟨		🟨		🟨		🟨	
Win Air Delta T	⬛		⬛		⬛		⬛		⬛	
Filament PS I	⬛	5.0 Minutes	⬛	5.0 Minutes	⬛	5.0 Minutes	⬛	5.0 Minutes	⬛	5.0 Minutes
Filament PS V	⬛		⬛		⬛		⬛		⬛	
Ready or Bypassed	⬛		🟩		⬛		⬛		⬛	
Win Air Flow Warn	⬛	4012	⬛	3229	⬛	3688	⬛	3675	⬛	2674
Win Air Flow and Temp Warn	⬛		🟨		⬛		⬛		⬛	
Filament Time	36	971 Hrs	33	720	36	825	36	799	36	904
HV runtime	6	684	6	301	6	501	6	543	6	497

🟨	Control Power
🟨	Control Power Off sw
⬛	Warmup On
⬛	Delay Warmup; 30.0 Minutes
🟨	HV O/V
🟨	Cavity HVss
🟨	Emergency Stop ss
⬛	Splitter Loads H2O Flow
🟨	Splitter Load T sw
🟨	Collector Supply T
⬛	Klystron 1 Rdy or Byp
🟨	Klystron 2 Rdy or Byp
⬛	Klystron 3 Rdy or Byp
⬛	Klystron 4 Rdy or Byp
⬛	Klystron 5 Rdy or Byp
🟨	F85 Supply Temp
⬛	Win H2O Supply T
⬛	HV Enable
HV	0 V

Time to Standby 30.0 Minutes

If these faults perturb the cavity fields, then that will trigger the EPS system first.

Klystron RF powers, VSWR, Arc detectors are monitored using the RF interlock boards which operate in sub microsecond time scales.

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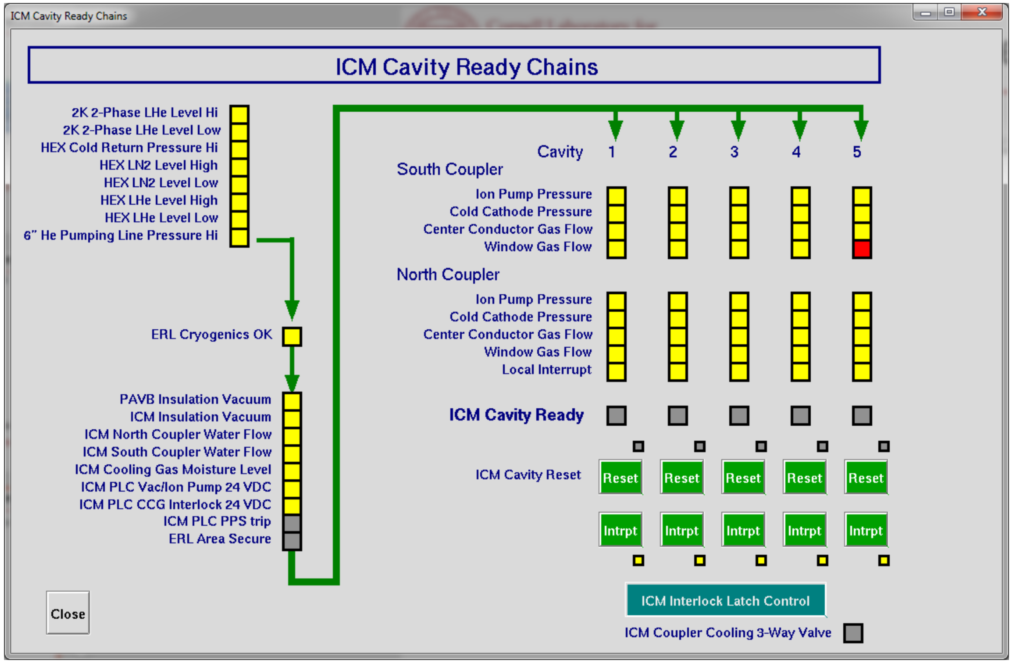
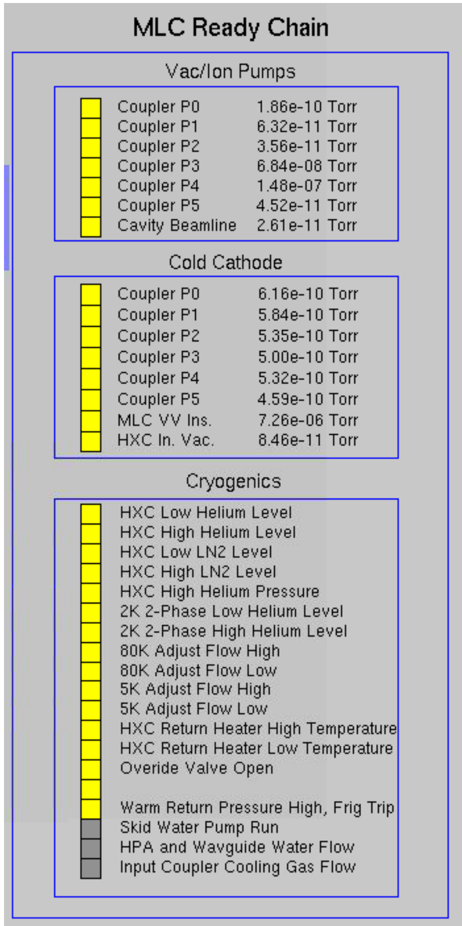
Cryomodule

The ICM and MLC are different but well understood systems monitored by separate PLCs.





Vac/Ion Pumps

Coupler P0	1.86e-10 Torr
Coupler P1	6.32e-11 Torr
Coupler P2	3.56e-11 Torr
Coupler P3	6.84e-08 Torr
Coupler P4	1.48e-07 Torr
Coupler P5	4.52e-11 Torr
Cavity Beamline	2.61e-11 Torr

Cold Cathode

Coupler P0	6.16e-10 Torr
Coupler P1	5.84e-10 Torr
Coupler P2	5.35e-10 Torr
Coupler P3	5.00e-10 Torr
Coupler P4	5.32e-10 Torr
Coupler P5	4.59e-10 Torr
MLC VV Ins.	7.26e-06 Torr
HXC In. Vac.	8.46e-11 Torr

Liquid Nitrogen, Helium levels, pressures and various vacuum gauges are monitored.

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Magnets

Magnets need to be a part of the EPS system to shut off the beam before the field changes drastically. (May be a trip. Can this be armed?)

1. Current High/Low
   Magnet currents should be within limits and should not have a lot of noise.

2. Magnet and Power Supply Temperatures
   Magnet and power supplies should be within acceptable temperature limits.

3. Water Flow and Temperature
   Problems in water flow should shut the machine off.

4. Water Conductivity
   Is this a good thing to measure?

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Beam Position Monitors

Beam position monitors can be used to detect spontaneous orbit excursions before the beam hits the pipe. BBU detection? (Non trivial due to hardware limitations)

1. Position Monitoring

   Once the machine is tuned, the beam position should be within some acceptable window, otherwise trigger the EPS system.

2. Intensity Monitoring

   The beam intensity as measured by the BPM should not change much during high-current operation. A change would indicate beam loss somewhere upstream.

Once the operator completes tuning CBETA, the BPM system can be 'armed' to trip the EPS.

The BPM system should log position information and waveform history for a few milliseconds before and after the EPS system is triggered. Use ring buffers?

The V301 system has been used for machine protection in LEReC, and a post mortem system has also been demonstrated. However, switching between different energies is associated with a dead time of 100s of us and this limits where we can use this.
Dedicate 1 BPM per splitter and merger line for this?

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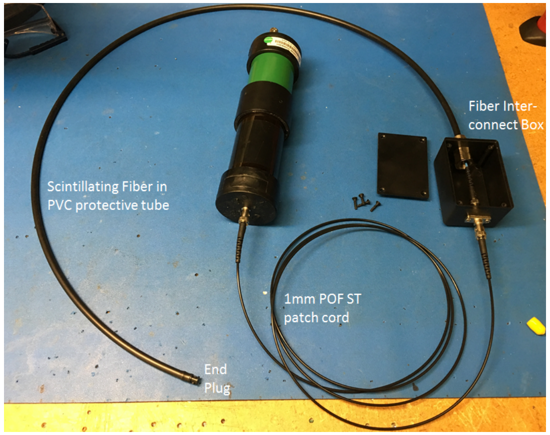
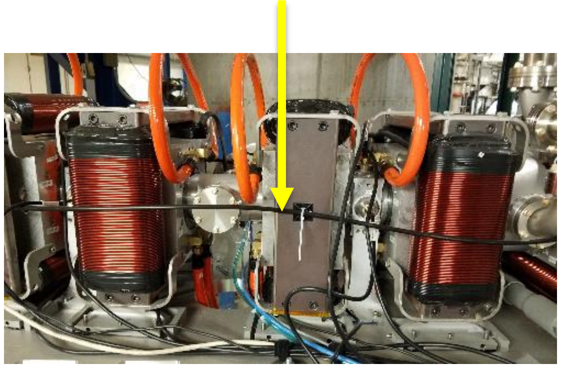
Beam Loss Monitors

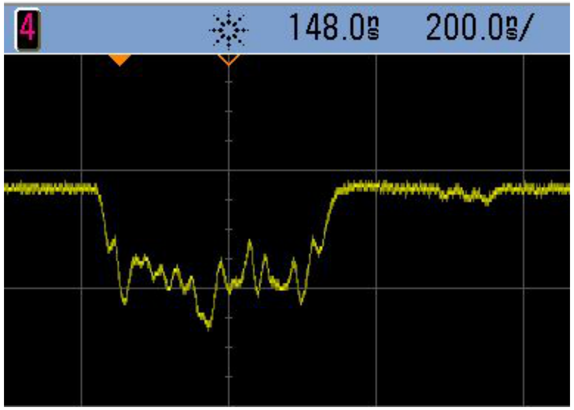
Scintillating fibers connected to a PMT can be an effective fast beam loss monitor.



1 mm fiber (2 m long) running along side of magnets

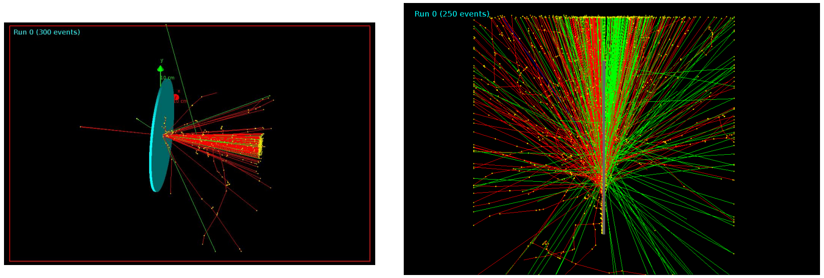


FAT PMT output for 300 nS train of 10 pC bunches @ 50 MHz



Log these signals?

We did rough simulations for 42 MeV beam incident on a aluminium disk of thickness 3 mm



Energy deposition of 1.25 MeV and 7.75 MeV per electron respectively.

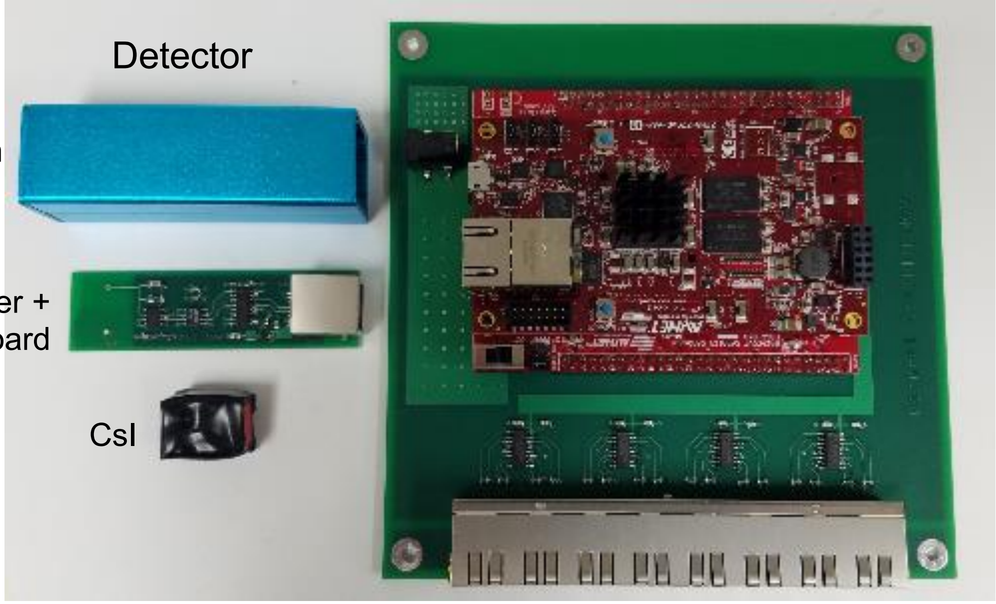
ANSYS model of a 3 mm Al disk with a heat flux of 35 W over a spot diameter of 0.1 mm, limits the max temperature to 150°C.

If a lost electron deposits ~ 7 MeV,
5 uA -> 35 Watts
Calibrate at a safe current ~ nA?

Beam Loss Monitors: Slow?

Beam Loss Monitors (Not part of fast shutdown)

CsI based slow loss monitor



Tested in FAT.

- wide range (10 mR/hr ~ 1K R/hr)
- B field OK
- easily relocated (100 total)
- 7.5 Hz update rate

Production Status:

Printed circuit boards in assembly

Chassis for data acquisition board needed

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Vacuum and Gate Valves

A beam hitting any of the pipes (cavities) or gate valves may cause vacuum events.

This may act as a last resort to detect beam induced chamber wall damage.

MLC – lots of questions

Beam Dynamics: can beam hit inside cryo-module? Where and how?

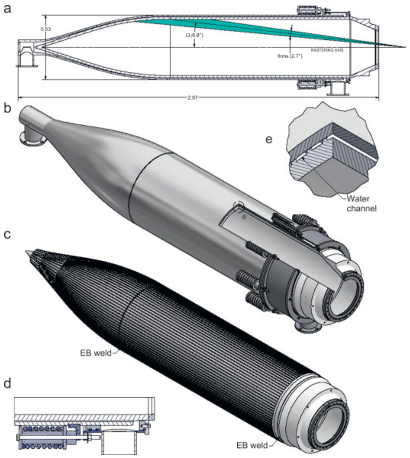
What is the impact of the beam hitting inside the cryo-module?

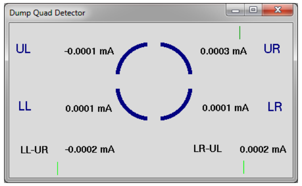
What amount of current is dangerous?

What does the resulting radiation look like?

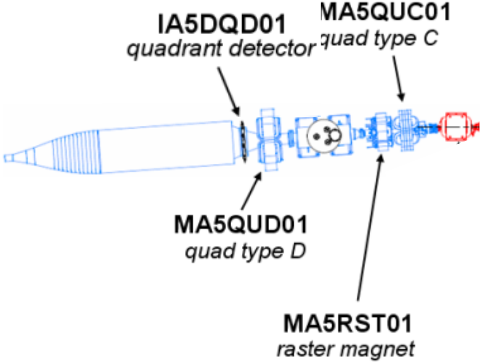
Beam Dump

The dump has been in use with the EPS in the past, we will just need to resurrect the system.




Dump Quad Detector

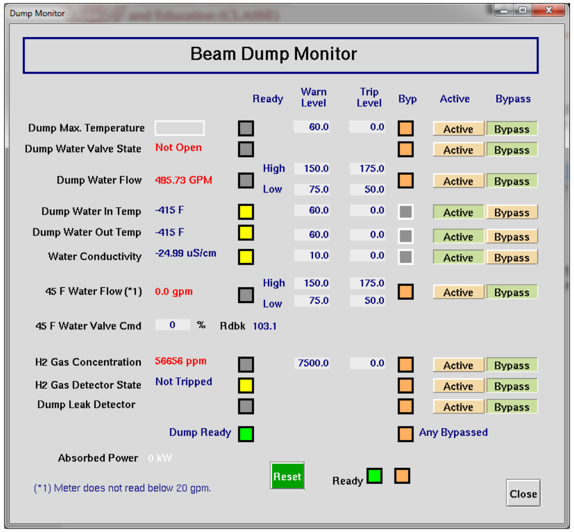
UL	-0.0001 mA	0.0003 mA	UR
LL	0.0001 mA	0.0001 mA	LR
LL-UR	-0.0002 mA	LR-UL	0.0002 mA


IA5DQD01
quadrant detector

MA5QUC01
quad type C

MA5QUD01
quad type D

MA5RST01
raster magnet


Dump Monitor

Beam Dump Monitor

		Ready		Warn Level	Trip Level	Byp	Active	Bypass
Dump Max. Temperature		■		60.0	0.0	🟧	Active	Bypass
Dump Water Valve State	Not Open	■				🟧	Active	Bypass
Dump Water Flow	495.73 GPM	■	High	150.0	175.0	🟧	Active	Bypass
			Low	75.0	50.0			
Dump Water In Temp	-415 F	🟨		60.0	0.0	■	Active	Bypass
Dump Water Out Temp	-415 F	🟨		60.0	0.0	■	Active	Bypass
Water Conductivity	-24.99 uS/cm	🟨		10.0	0.0	■	Active	Bypass
45 F Water Flow (*1)	0.0 gpm	■	High	150.0	175.0	🟧	Active	Bypass
			Low	75.0	50.0			
H2 Gas Concentration	56656 ppm	■		7500.0	0.0	🟧	Active	Bypass
H2 Gas Detector State	Not Tripped	🟨				🟧	Active	Bypass
Dump Leak Detector		■				🟧	Active	Bypass

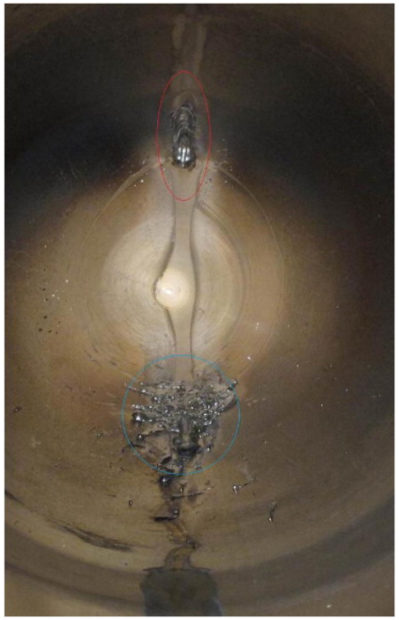
45 F Water Valve Cmd 0 % Rdbk 103.1

Dump Ready 🟩 🟧 Any Bypassed

Absorbed Power 0 kW

Reset Ready 🟩 🟧

(*1) Meter does not read below 20 gpm.



1. Thermal and Water Flow
2. Hydrogen Detection
3. Quadrant Current Detection
4. Raster Magnet Status?

Things can go wrong!

Human Error

Ideally the operators will be well trained and know what not to do but can we protect CBETA from unintended operator error?

Examples:

- Limit the laser repetition rate if any gate valve or screen is in. Has been done earlier.
- Have some system to limit changing magnet or cavity set points when beam current exceeds a certain threshold.

More ideas?

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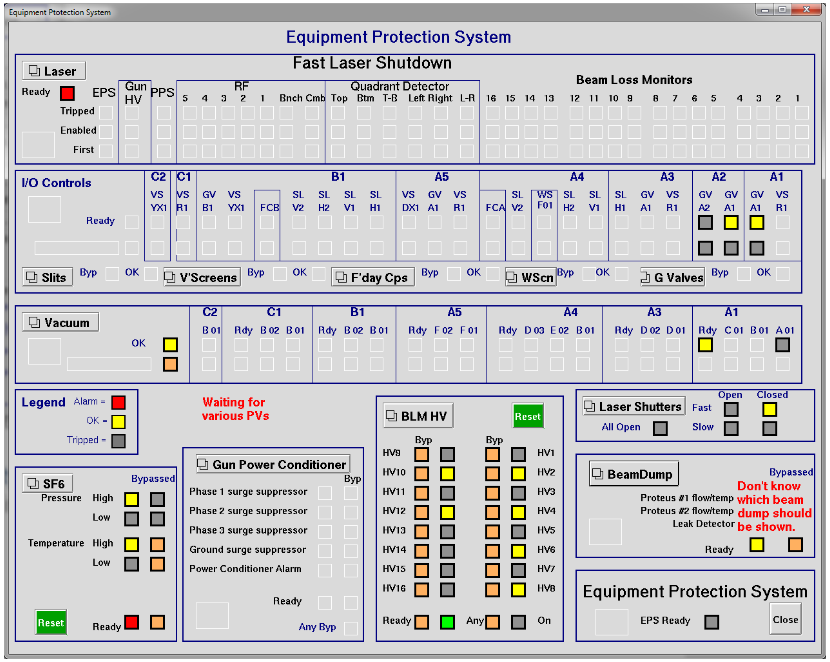
Conclusion

We have done this before!



Waiting for various PVs

Don't know which beam dump should be shown.

We will need to monitor a few hundred signals and log nearly a hundred of them.

The EPS system will have its own cabling.

We have to estimate the danger thresholds of all these signals.

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