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Equipment protection system for CBETA

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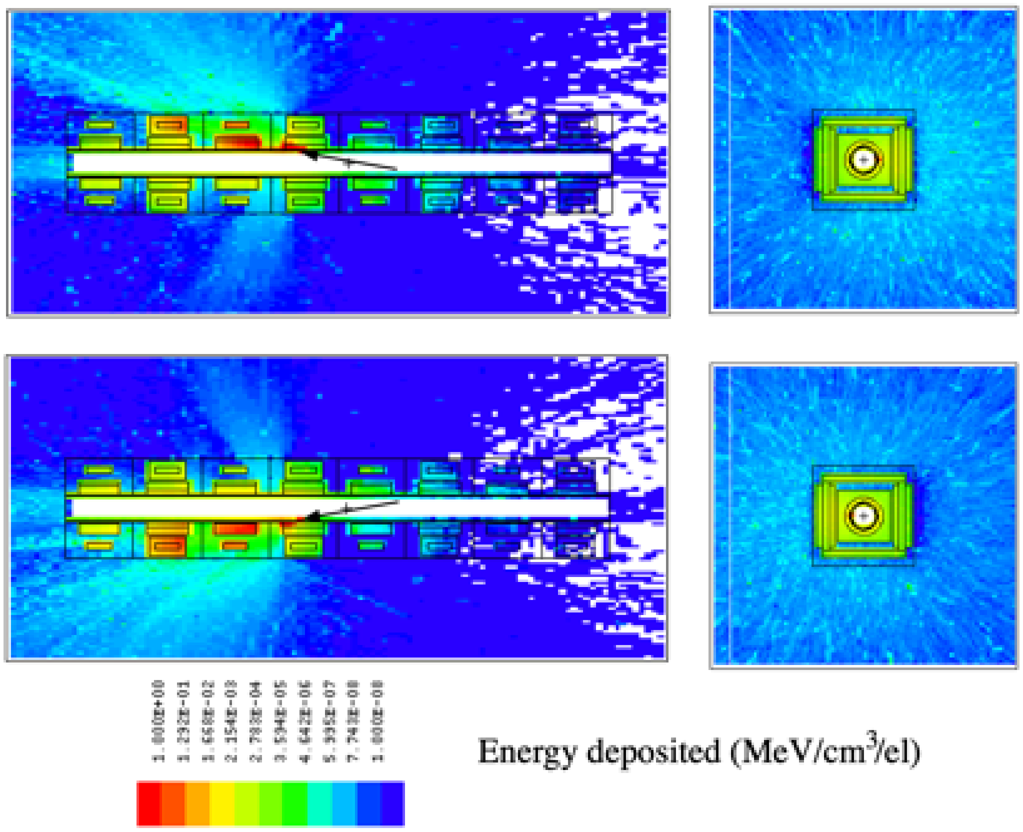

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1. Introduction

The ultimate goal of CBETA is to be the first high-current multi turn Energy Recovery Linac operating at 40 mA. The power of highest energy beam at this configuration is going to be 6 MW. Hence equipment protection against radiation is an important issue. Through our stages of commissioning we will slowly increase the beam current, starting from 100 pA all the way to 1 mA during the current commissioning phase. The electron beams hitting any in-vacuum component either on purpose (eg. view screens, beam stops or during commissioning) or due to some component failure will generate a radiation shower which has the potential to damage various parts of the accelerator.

In this document, we describe the various scenarios which generate unwanted radiation in our machine and list the damage thresholds of critical components. Then we discuss our diagnostic systems which can detect component failure and the resulting radiation generated. We further list the possible beam modes of the machine which we have designed taking into account the damage thresholds and the sensitivity of the diagnostics. Finally, we document our design of the Equipment Protection System (EPS) and outline protocols of calibration and operation.

1.1 Radiation Sources

There are various sources of radiation in CBETA most of which scale up with beam current.

1.1.1 Total Beam Loss

This happens when the beam hits any in-vacuum component such as beam pipes, cavities and HOM absorbers either as a result of an instability or on purpose during commissioning. Catastrophic beam loss can lead to local heating of beam pipes which can lead to vacuum failure. This is the primary concern for most high-current accelerators using electromagnets and requires the EPS to have fast shutdown capability with response at micro-second time scales. However radiation damage to the permanent magnet blocks is the biggest concern for CBETA and quantifying the radiation dose in response to the loss of a certain beam current is important in deciding safe currents for commissioning.

During the Fractional Arc Test, the beam was repeatedly parked in various locations in the 42 MeV splitter line which irradiated the permanent magnets. A set of thin film dosimeters were placed on the last four magnets of the arc as shown in Fig. 1.1.

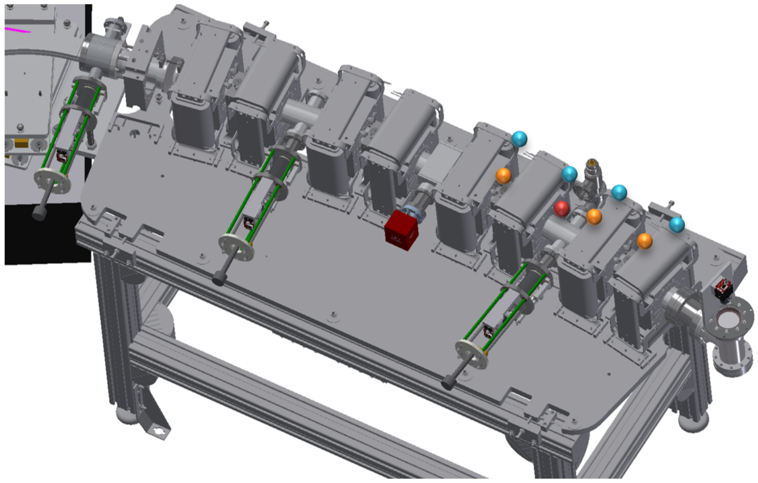


Figure 1.1: The PM girder used in the Fractional Arc Test showing the placement of thin film dosimeters denoted by the small circles.

X (mm)	Z (mm)	Face Angle (degrees)	Dose (cGy)
9157	34133	40	577.405
9193	34124	35	382.246
8996	34242	35	3805.015
9033	34246	125	240.258
8899	34317	35	2021.120
8882	34350	125	623.760
8726	34427	30	1104.855
8715	34462	120	228.640

Table 1.I: Approximate positions, orientation and doses recorded by the dosimeters. The coordinates are with respect to the global coordinate system of L0E and all dosimeters were placed at y=0 which is the plane of the design orbit. The face angle is the angle between the plane of the dosimeter and the YZ plane.

The dosimeters measured integrated dose throughout the period of FAT and the observations span a wide range of dose as shown in Tab. 1.I. The dosimeters placed on the sides of the magnets as shown by the blue circles consistently reported smaller doses than the ones nearer to the beam pipe. The maximum dose is about 4000 cGy. The dosimeter material is different from the permanent magnets, however to first order this a good estimate of the worst dose in the nearby permanent magnet block. This integrated dose is about 4% of the damage threshold of the permanent magnets as explained in the next section. This observation led us to decide on lowering the repetition rate of the low current mode by about a factor of 20 with respect to the FAT.

The results from the FAT suggests that the radiation generated with low current beams over the course of commissioning is a significant source of radiation to the permanent magnet optics. Understanding the effect of radiation on the multipole fields requires numerical modelling of the radiation distribution over the individual magnetic blocks and the procedure used is depicted in Tab. 1.II.

Charge (#e or C) → Dose (Gy)	Dose (Gy) → Magnetisation loss (%)	Magnetisation loss (%) → Field change at beam (T)
Particle loss and shower simulations •GEANT4 (John Dobbins) •MCNP6 (Val Kostroun)	•Experimental demagnetisation studies with e radiation A.B. Temnykh, NIM A **587**(2008) 13-19 •B-H curves measured by manufacturer (AllStar Magnetics/United Magnetics)	Sheet current model magnet design code PM2D (Stephen Brooks), same as used to design magnets
Typical values: 1uC loss = 100pA*2.7hours	Typical values: CBETA note 036 suggested 1kGy as a fairly cautious limit	Typical values: 1.5G was the field error limit during magnet production

Table 1.II: Methodology of radiation modelling used for the FFA.

We have modelled beam loss in the straight FFA sections using both GEANT4 and MCNP6 packages as shown in Fig. 1.2. The GEANT4 simulation incorporates a QF magnet modelled as an annulus around the pipe. Showers were simulated at 42 MeV and 150 MeV with glancing and 15° incidence angles with 10^5 electrons. The MCNP6 model includes more detailed geometry including BD magnets and whole girder while the showers were simulated using 150 MeV electrons at 10° incidence angle (cases: hit left or right side of pipe) with 10^7 electrons.

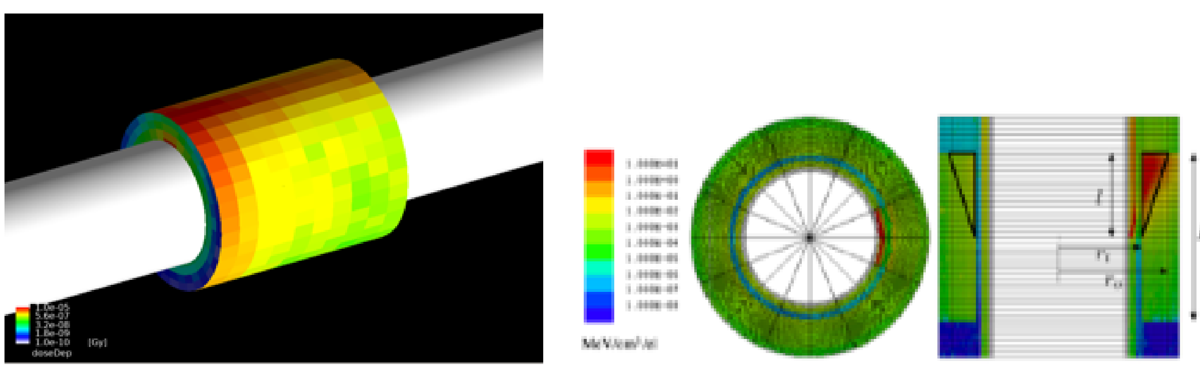


Figure 1.2: Comparison of dose distributions between GEANT4 (left) and MCNP6 (right).

We can use this data along with simulations of demagnetization to evaluate safety limits on beam loss at different currents and energies. As an initial estimate, we use the comparatively strict dose limit of 1 kGy as suggested in CBETA note 36 to calculate the maximum time it takes for a 100 pA beam hitting a pipe to permanently damage a magnet. The results are shown in Tab. 1.III. The dose calculations over the whole magnet on average agree well over the two simulations which indicate that fairly well-known physics is at play. We can probably attribute the discrepancy between the maximum dose values to the different binning volumes (Max dose bin ~0.5cm^3 for GEANT4 but only ~0.1cm^3 for MCNP6) used in the two simulations.

GEANT4	42MeV, 1deg	150MeV, 1deg	150MeV, 15deg
Max dose bin (Gy/uC)	225.1 12.3hr	410.0 6.77hr	2265 1.22hr
Average dose in PM (Gy/uC)	3.147 882hr (5wk)	7.463 372hr (2wk)	21.96 126hr (5d)

MCNP6			150MeV, 10deg
Max dose bin (Gy/uC)			19550 0.142hr (8.5min)
Average dose in PM (Gy/uC)			16.52 168hr (1wk)

Table 1.III: Comparison between dose calculations using GEANT4 and MCNP6.

The GEANT4 data in Tab. III leads us to conclude that an "allowed" mistake in beam-threading mode at 42 MeV over the commissioning period would be 100 pA loss for 1 minute (6 nC), which leads to a dose of ~1.35 Gy (< 0.2 % of the 1kGy limit) if all is lost the same place. The amount of time to demagnetize one region of the permanent magnets with a 100pA beam at 150 MeV is of the order of 1 hour while damaging the whole magnet takes about ~ 100 hours. At 1uA this would be 0.36 sec for a small region and 36 sec for the magnet average. At 1mA, 360us for a small region and 36ms for the whole magnet. The response time of the fast detection system will be within 10 us, when running with high current which gives us a worst case budget of 36 trips per magnet in 1 mA mode.

1.1.2 Scattering

View screens, beam stops and the high power dump all generate radiation when the beam is incident on them. View screens are placed in all permanent magnet arcs and quantifying a current limit which is safe for nearby magnets is an important step. Radiation produced by parking the beam at gate valves, or other smaller beam stops, including the one in the diagnostic line should also be taken into account. We are currently in the process of running simulations using GEANT4 which we will verify by placing our CsI dosimeters in important locations. Estimating safe current limits by experimentally finding radiation dosage to magnets and other components will be part of the EPS calibration process.

High Power Beam Dump

The high power beam dump shown in Fig. 1.3 is the strongest source of radiation in CBETA and has been designed with adequate shielding to reduce its effect on the nearby beam line.

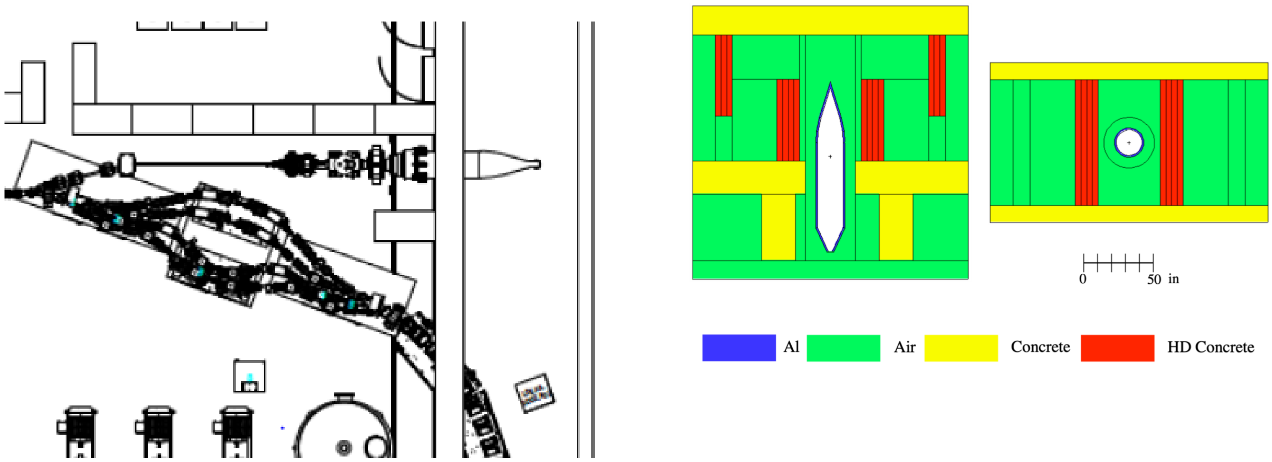


Figure 1.3: The position of the high power beam dump, showing the nearby splitter line and the PM arc nearest to it is shown on the left. The image on the right shows the proposed location of the concrete shielding blocks.

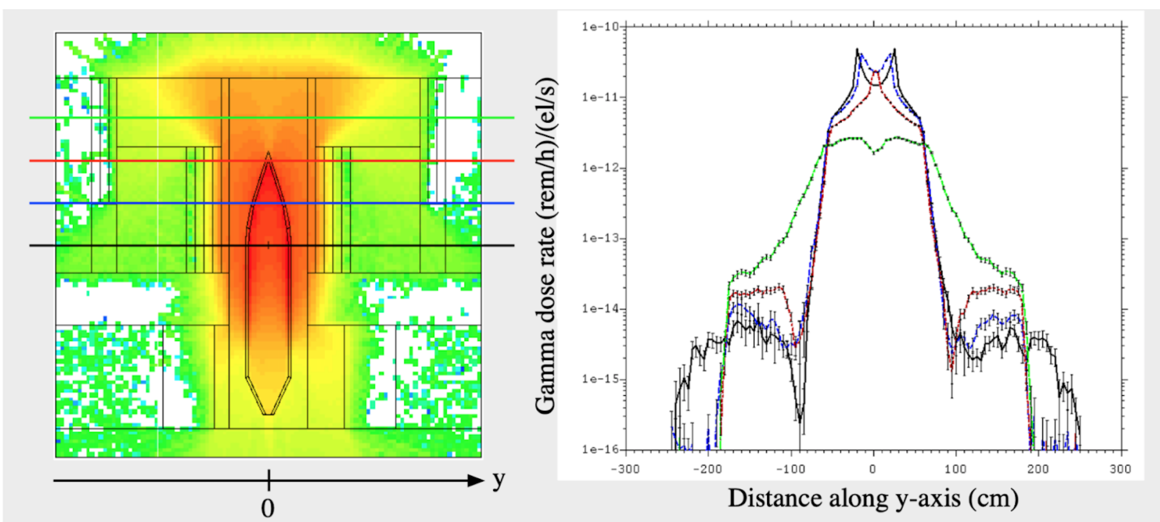


Figure 1.4: Dose rate from gamma as a function of position near the beam dump is shown on the left. The dose rate as a function of y-position along different contours is shown on the right.

Fig. 1.4 shows the radiation dose rate per electron per second generated by a 6 MeV incident on the beam dump. The average dose rate at 250 cm from the center of the dump is ~ 5.0×10^{-15} (rem/h)/(el/s). For a 1 mA electron beam, or 6.24×10^{15} el/s, this corresponds to a dose rate of 31.2 rem/h which is fairly high. The nearest permanent magnets are farther away from this point, however the effect of the dump should be further analyzed and measured during high-current operation.

View Screens

A beam incident on a view screen generates both optical and ionizing radiation, of which the latter is capable of damaging the permanent magnets. A simple simulation was done using the model shown in Fig. 1.5. to estimate the dose rate from this loss mechanism.

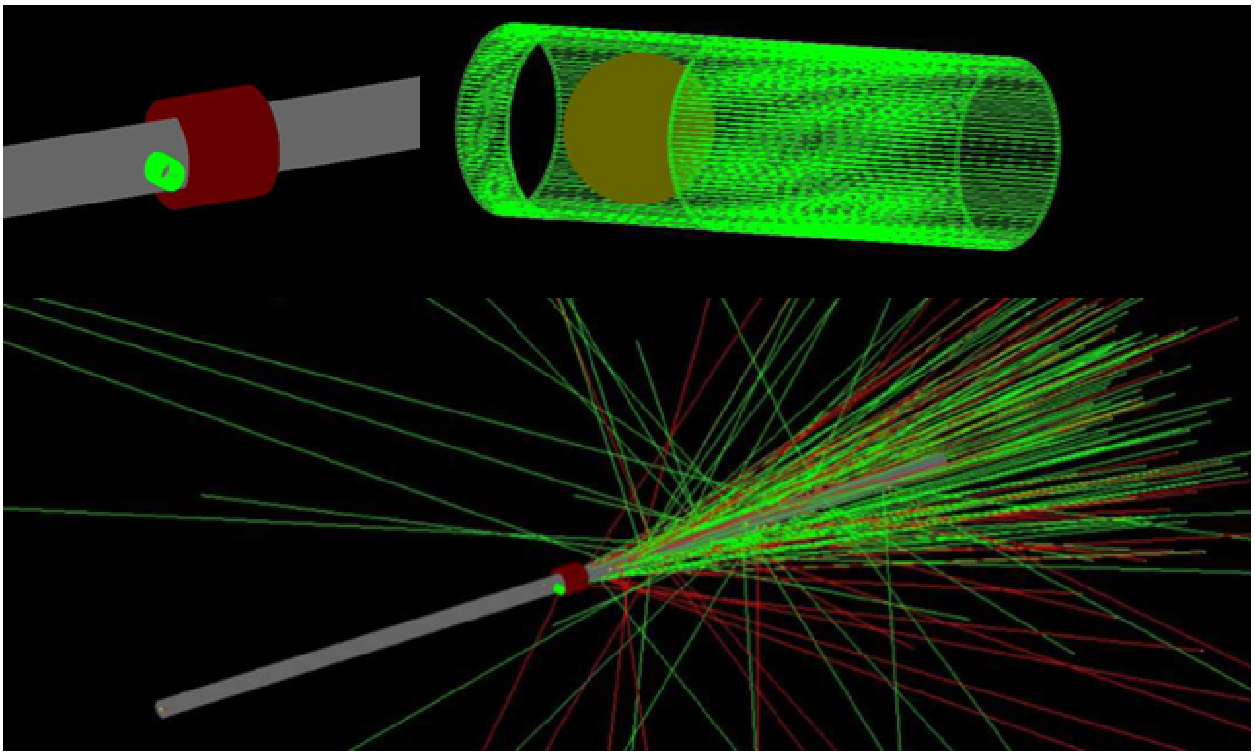


Figure 1.5: GEANT4 simulation to estimate the absorbed dose in a permanent magnet from a beam hitting a viewscreen. Top left shows the aluminium beam pipe in grey, Neodymium magnet in red and view screen holder in green. The top right image shows the view screen and its stainless steel holder. The bottom image shows an example shower with 50 particles.

Using a cylindrical beam at 42 MeV consisting of 800,000 electrons, the simulation predicts an average dose rate on the neodymium magnet of 0.0743 ± 0.0006 Gy/μC. Comparing with Tab. III, the dose due to an electron beam scattering from a view screen is more than an order of magnitude weaker than total beam loss at the same energy. Hence it is tolerable to use view screens at the current deemed safe in the presence of total beam loss in the FFA girders.

1.1.3 Beam Halo

Halo, though difficult to define in a precise scientific sense, is fairly simple to define in an operational sense. Halo is beam that is unintentionally lost in the pipe as the beam traverses the accelerator, but is not a large enough percentage to be measurable using traditional beam diagnostics. This lost beam causes radiation, which can be bad for personnel and machine protection, and also can complicate energy recovery if a significant enough amount is lost. The sources and propagation of beam halo in CBETA are yet to be studied. Experimentally, it will be quantified as steady state beam loss into the vacuum chamber which irradiates the magnets. We will use CsI dosimeters to measure steady state loss and calibrate it as a function of beam current. We are also considering beam diagnostics to measure halo directly.

1.1.4 Miscellaneous

Field emission from cavities and guns constitute dark current. Both are quite unlikely at the fields with which we will be operating. Radiation measurements near the gun and the cryomodules during the FAT show nominal values further supporting this assumption.

Bremsstrahlung generated by the scattering of the electron beam with particles inside the beam pipe is also another source. This effect can be amplified by ion trapping which scales quadratically with the beam current. We will use radiation measurements as functions of beam current to quantify this effect.

1.2 Damage Thresholds

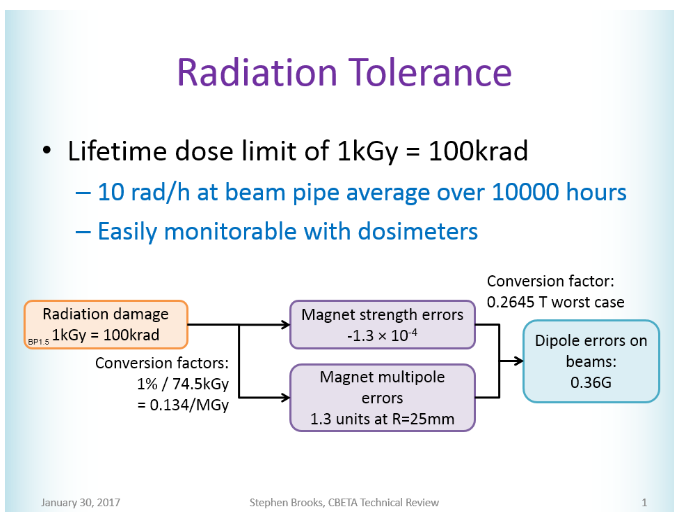
1.2.1 Permanent Magnets

Safe Levels

Both simple calculations and more detailed studies support a lifetime radiation dose limit for a magnet of 1kGy = 100krad. This preserves the magnetic field to a high degree of accuracy. In terms of energy per mass this is 1000J/kg = 1J/gram.
For a good machine lifetime of 10000 hours, this gives a safe continuous radiation level of 10rad/hr.

Units

1Gy = 1J/kg absorbed energy. 1Gy = 100rad in American units.



Calculation Details (simple method)

Temnykh's data agrees with the model that the dose for a 1% demagnetisation has the following formula: (eqn. (12) in NIM A 587 (2008) 13–19)

$$\text{Dose}_{1\%} = 10^{m0} * 10^{T\_demag/Tbar}$$

Here,

- $\text{Dose}_{1\%}$ in this formula is measured in Mrad (10^4 Gy).
- m_0=-2.68 is a fit constant to Temnykh's data.
- T_{demag} is the "demagnetising temperature" of the material sample, basically the Curie temperature, which depends on how the material B-H curve changes and when the demagnetising part of the curve hits the "working point", which is determined by the local H field, which is determined by the material shape. So, both the material grade and geometry affect T_{demag}. Note that T_{demag} is in °C and assumes some "room" temperature (around 30°C for Temnykh's study, correct for CBETA too).
- Tbar=41.4K is another fit constant that shows the change in Curie temperature that causes a 10x decrease in radiation damage levels. This is produces an exponential dependence: a small change in T_{demag} can make a large change in $\text{Dose}_{1\%}$.

For the CBETA material grade N35EH, the T_{demag} stated by the vendor is 200°C. This value needs to be corrected for the H field in the Halbach magnet as opposed to the vendor's test piece geometry. The vendor's test piece had H=-0.67T, while the bad corners of the Halbach have H=-1.3T. The change in H field demagnetisation point as a function of temperature is 1.19 Tesla per 100 Kelvin based on B-H curves measured at different temperatures. This can be used to extrapolate T_{demag} to the worst case in the Halbach magnet, which is 147°C (=200°C-(1.3-0.67)/0.0119).

Plugging this into Temnykh's formula gives $\text{Dose}_{1\%}$ equal to 74kGy (7.4Mrad).

Considering the effects of these doses on the magnetic field, a 1kGy (100krad) level, which produces a 0.013% field loss (1.3 magnetic "units"), is the level at which field loss is basically negligible. Perhaps detectable at the precision level, but can't endanger the running of the machine at all.

The reason for giving a fairly pessimistic dose limit here is that the radiation monitors can't cover every point in space, so keeping the places are monitored below that level means any hotspots missed are reasonable (i.e. certainly not above the 74kGy=$\text{Dose}_{1\%}$ level) too.

Demagnetisation Simulation Results

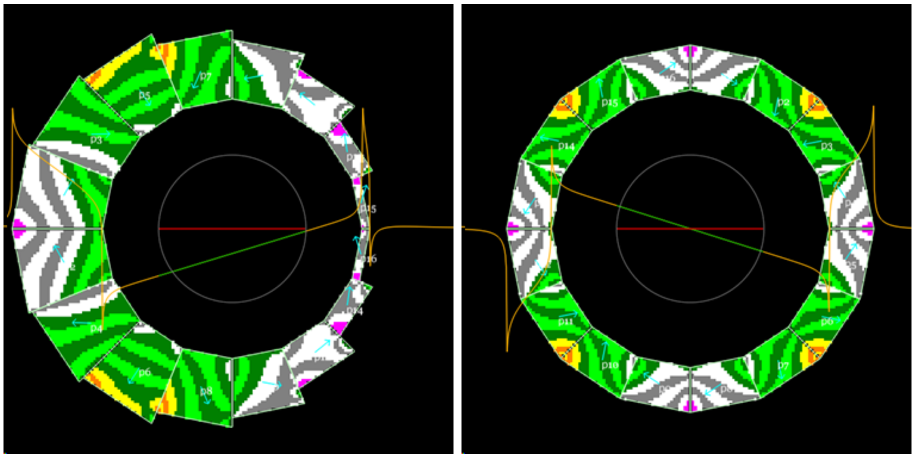


Figure 1.6: Field H within the material for the BD (left) and QF (right) magnets.

In addition to the dose calculations, 2D magnet simulations were done including demagnetisation of each part of the magnet individually for a uniform dose. Figure 1.6 shows the H field within the material for the BD (left) and QF (right) magnets. More negative values of H increase the demagnetisation rate with radiation, the same as in the previous section. The colour scale is: white 0 to -0.5T; green -0.5 to -1T; yellow/orange -1T to -1.5T (0.1T stripes) and only the component of the **H** vector opposing the blocks' magnetisation **M** is plotted.

A uniform radiation dose of 1MGy was applied in the simulation and the magnetic results on the good field region are summarised in Tab. 1.IV. This allows a radiation limit to be extrapolated for each magnet, where the field just crosses the field quality acceptance threshold. The limits take the magnet right to the edge of acceptability, assuming a (very unrealistic) uniform dose distribution and with no safety factor for uncertainties in material behaviour etc. However, order of magnitude is as expected. In other words, reducing the ~30kGy limits in the table down to the 1kGy limit is where the safety factors are applied.

Magnet Type	Quad strength loss @ 1MGy	Max field error on midplane (G) @ 1MGy	Max multipole (unit) @ 1MGy	Dose limit (only valid for uniform!)
BD	1.026%	53.5	17.00	28.0kGy
QF	1.063%	28.6	6.86	47.1kGy
BDT1	1.010%	40.3	9.35	37.2kGy
BDT2	0.988%	52.4	11.89	28.6kGy
QD	1.118%	27.9	10.74	44.7kGy

Production limit:	0.05%	1.5	10 (sqrt sum of squares)	

Table 1.IV: Effect of a total dose on various magnets.

1.2.2 In-vacuum Components

Beam pipes

Beam loss into pipes is widely considered in accelerators. While the beam halo can generate significant amounts of radiation, the energy deposited on to the pipe will be uniform. However, when an intense beam hits the pipe the local heating might be large enough to melt the pipe and significantly degrade the vacuum. This has been studied by the bERLinPro collaboration with a 100 mA beam at 50 MeV which is comparable to the CBETA regime.

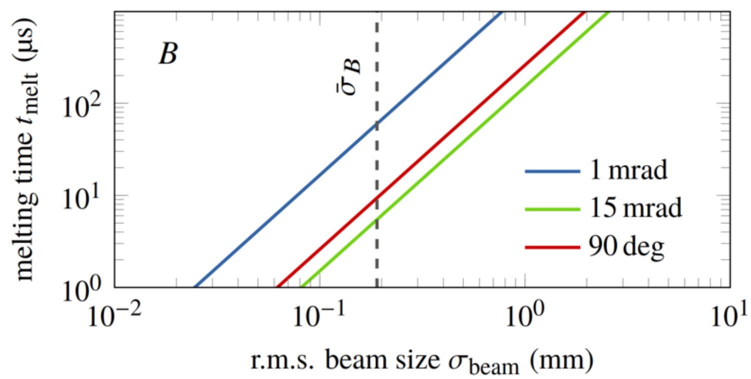


Figure 1.7: Melting time of an aluminium chamber as a function of beam size for different angles of incidence.

The melting time of a 0.2 mm beam with current 100 mA and energy 50 MeV is about 5 micro-seconds as shown in Fig. 1.7. This is comparable to the maximum design beam current of 40 mA in CBETA requires the fast shutdown system to operate in those time scales.

SRF Cavities

The surface resistance of superconducting RF cavities is sensitive to localized damage. Steady beam loss generated by beam halo can affect the intrinsic quality factor of the cavities in the long term while total beam loss can cause localized heating and leading to a quench where the whole cavity transitions from a superconducting to a normal conducting state. The amount of Helium gas pumping power available to the individual cryomodules limit the amount of Q0 degradation we can tolerate. Currently, we are using about 25 % of the available capacity during nominal operation of the cryomodules. Routine (perhaps once a month) Q0 measurement should be included in the operations schedule to track this effect.

HOM Absorbers

Higher Order Mode absorbers made of various ceramic materials such as ferrite and graphite loaded silicon carbide are used to absorb parasitic higher order eigenmodes in the SRF cavities. These materials have been used in high current accelerators for some time and significant damage has not been reported in literature.

2. EPS Diagnostics

The Equipment Protection System will use different diagnostics to make sure that important parameters of the machine are within acceptable ranges. The primary focus of EPS development is to be able to shutdown the beam before the magnets get fatal doses of radiation, or we cause permanent damage to any of the vacuum components.

2.1 CsI Dosimeters

These are slow beam loss monitors based on Cesium Iodide scintillating crystals as shown in Fig. 2.1 which are pre-calibrated and will serve as movable standard dosimeters which we can place in various sections of the machine to characterize steady state radiation losses from various sources.

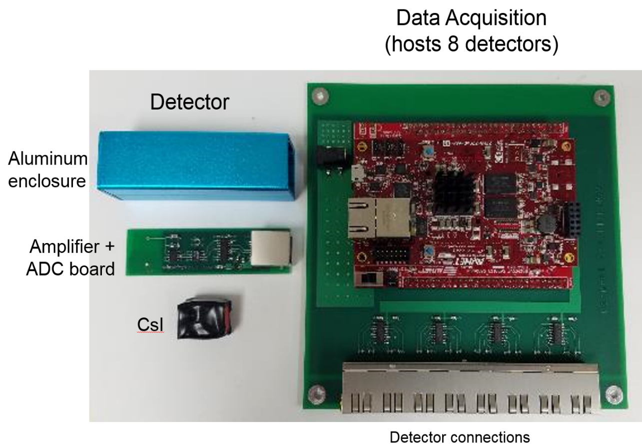


Figure 2.1: CsI based slow radiation monitor, showing various hardware components.

The dosimeters are capable of measuring dose rates over a wide range from 10 mR/hr to 1 kR/hr with an update rate of 7.5 Hz. These are insensitive to magnetic field and we will have a 100 of them to be placed anywhere in CBETA forming an important part of EPS system.

2.2 Fast Fibre Monitors

Scintillating fibres coupled to Photomultiplier tubes (PMTs) will form the fast radiation detection system for CBETA. These have response time scales better than a microsecond and will be attached to the permanent magnets as shown in Fig. 2.2.

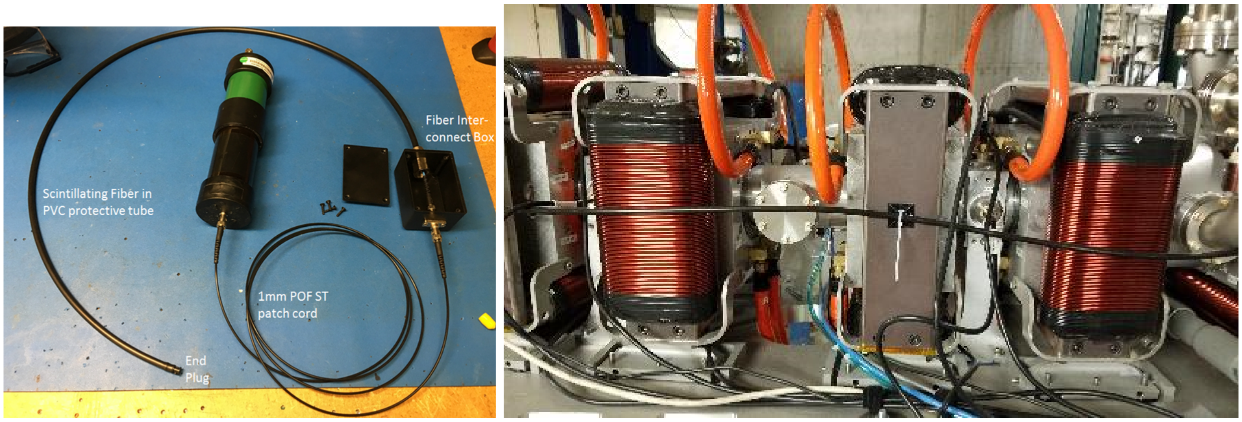


Figure 2.2: Fast fibre monitors showing the scintillating fibre, the PMT and how they were attached to the sides of the permanent magnets during the FAT.

These monitors were tested during the FAT using a 300 nS train of bunches at 50 MHz and the raw signal is shown in Fig. 2.3. This clearly demonstrates their effectiveness in detecting bunch trains in sub-microsecond time scales.

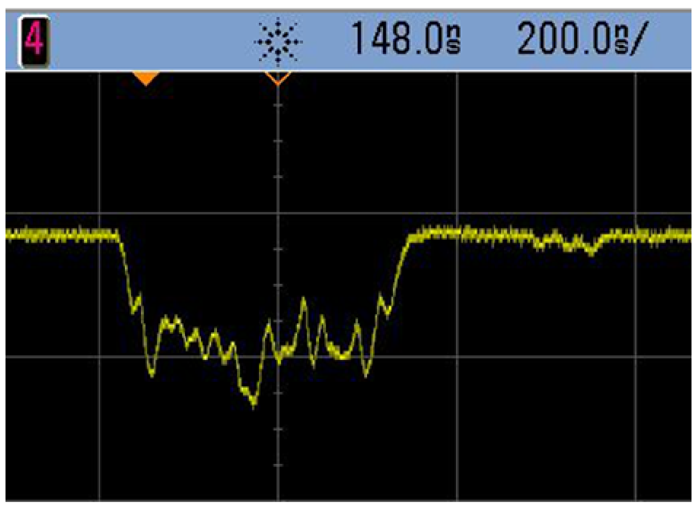


Figure 2.3: Raw PMT signals from the fast fibre monitors clearly showing the 300 ns bunch train.

The response of this diagnostic is heavily dependent on beam loss scenario and simple thresholds to trigger the fast laser shutdown system might trigger on harmless beam loss or be completely insensitive to certain loss modes. It will be fast enough to stop the machine before catastrophic vacuum failure takes place, but will not be reliable for magnet protection. Chapter 5 of this document outlines some of the calibration procedures we are going to use to set the EPS thresholds.

2.3 Beam Position Monitors

Beam position monitors can serve as an early warning system of detecting an instability before total beam loss happens. Both, the total signal intensity and beam position will be monitored and trigger the fast laser shutdown when any of the values monitored stray outside their limits. This will be especially useful in high current operation.

2.4 Vacuum Pressures

Vacuum failure can cause significant damage to the machine so all pressures are monitored including the beamline, gun, cavities, input couplers and many others. These are slow signals operating in millisecond time scales. When vacuum gauges go beyond their threshold, they trip their respective subsystems which in turn trigger the fast shutdown system. If a complete beam loss occurs, then it will ideally trigger the fast shutdown system before the vacuum system is triggered.

2.5 Low Level RF

The SRF Linacs control the energy of the beam and hence failure in field regulation can lead to beam loss. Each Low Level Radio Frequency (LLRF) control board generates a field regulation status (RF_FIELD_OK) signal which trips when the measured field goes beyond a certain margin from the set point. The RF system can fail due to numerous reasons.

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. This can also be triggered by beam loss into the cavity wall.
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.

The LLRF system responds in microsecond time scales and will be used to trigger the fast shutdown system.

3. Machine Modes

CBETA has multiple loss mechanisms, as described in section 1 with total beam loss into the pipe being the strongest source of radiation to the components. Permanent magnets are the most sensitive elements which can suffer permanent demagnetization in response to beam loss. In this section, we enumerate various types of modes that the machine may be in and the consequent steps taken as part of the EPS system primarily to protect the FFA magnets. The beam mode is determined automatically, according to limits on EPICS variables, described in section 4.3. If all of the requirements of a mode are set, then machine protection limits will be enforced automatically. In general, the modes are designed such that when the beam has a chance of scraping towards the permanent magnets, the current limit is

125 pA. As described in section 1.1.1, a 150 MeV beam at this current would take 1-2 hours to bring any permanent magnet material to the dose limit, if 100% of the beam was lost at one point. We use the beam pulse generator to limit the average beam current by controlling the number of pulses the laser makes over a certain time period consequently limiting the radiation dose on the magnets.

The modes are grouped into various classes, which do not specify the bunch pattern, and only have a restriction on beam current. The interlocks required for some of the mode classes are listed below.

- **FFA tuning** requires automatic beam off after substantial losses. Primary mechanism is ~7Hz readout from CsI monitors (warn at 10rad/hr, beam off at 1krad/hr).
- **High Current** mode requires the interlocks above (without 1min exception) and further interlocks to ensure all the following values are in nominal ranges vs. design: magnet currents, beam positions, beam arrival times, RF phase and power. A specific design (e.g. 4-pass ERL) with approved nominal operating ranges must be loaded.
- Other modes should retain the CsI monitor and fibre BLM radiation interlocks from the FFA tuning mode to prevent damage from radiation spraying across onto the FFA.

The modes in **bold** represent classes and the others are detailed examples within one of the broad categories, highlighted here because they are expected to be particularly useful.

A chart of the beam modes is provided below.
Definitions of column names

- ID : Mode index.
- Name : The name of the mode.
- Description : Description of its use.
- Max I : The maximum current obtainable.
- Max Q : The single bunch charge.
- Period : The time period used by the BPG to count pulses.
- N Bunches : Maximum number of bunches allowed in the Period.
- BPM Error : Expected standard deviation of a single BPM “measurement” at 5 Hz. A single 5 pC bunch has ~1.75 mm standard deviation

ID	Name	Description	Max I	Max Q	Period	N bunches	BPM Error
0	Undefined	Error state	0	0	10 min	0	NA
	Injector Tuning	Useful for emittance measurements, injector setup, phasing.	1 µA	Any	Any	Any	NA
1	Gun-ICM Only	Beam ends at MA3DPA01, used for phasing the injector cryomodule. (e.g. 50 bunches at 2 kHz)	1 µA	5 pC	10 min	1.2×10^8	0.01 mm

2	Diagnostic Line (Slits IN)	6 MeV beam through diagnostic line, beam lost on shielded slits. (e.g. 50 bunches at 2 kHz)	1 µA	5 pC	10 min	1.2×10^8	0.01 mm
3	Diagnostic Line (Slits OUT)	6 MeV beam through diagnostic line, beam lost at the end of line. (e.g. 20 bunches at 500 Hz)	100 nA	5 pC	10 min	1.2×10^7	0.04 mm
	MLC Single Cavity	Useful for single MLC cavity phasing and other tests.	0.3 µA	Any	Any	Any	NA
4	MLC (Single Cavity)	MLC single cavity phasing and calibration. (e.g. 20 bunches at 500 Hz)	100 nA	5 pC	10 min	1.2×10^7	0.04 mm
	Full MLC, no FFA	Useful for MLC phasing, splitter and dump line commissioning. (e.g. 20 bunches at 500 Hz)	100 nA	Any	Any	Any	0.04 mm
5	MLC	Many cavity operation. (e.g. 11 bunches at 120 Hz)	10 nA	5 pC	10 min	1.2×10^6	0.1 mm
6	Dump Line	Beam enters dump line at 6 MeV (e.g. 20 bunches at 500 Hz)	100 nA	5 pC	10 min	1.2×10^7	0.04 mm
7	S1 Splitter	Beam in S1 line, but not in the FFA. (e.g. 11 bunches at 120 Hz)	10 nA	5 pC	10 min	1.2×10^6	0.1 mm
	FFA Tuning	Threading beam through the FFA arcs.	125 pA	Any	Any	Any	0.5 mm
8	FFA Arc: Bunch Train	Beam into the FFA line. (e.g. 11 bunches at 2 Hz)	125 pA	5 pC	10 min	1.5×10^4	0.5 mm
	High Current	CW at 42 MHz, excluding gap for pilot bunches, through all of CBETA.	1 mA	Any	Any	Any	NA

Table 3.I: Beam modes used in CBETA.

4. EPS Implementation

Equipment protection for CBETA is designed around the diagnostics described in section 2 taking into account the requirements of various beam modes in section 3. It is implemented in two ways. The Fast Shutdown system automatically turns off the beam in response to any major failure in the machine including but not limited to beam loss. This system is responsible for the safety of all machine components when we are running in high current mode. On the other hand, we also have EPICS restrictions which protect the machine from operator error especially during beam commissioning. This poses a set of limits which minimizes unintended damage to permanent magnets when a low current beam scatters off various surfaces in the accelerator including beam pipes, stops and view screens.

4.1 Fast Shutdown

The fast shutdown system uses two Equipment Protection Shutters in the path of the laser beam to the cathode. The fast shutter provides a fast response time but cannot sustain the continuous full laser power, therefore the slow shutter which can sustain the continuous full laser power closes soon after the fast shutter closes. The design goals of the system used to trigger these shutters are:

1. <u>Fast Response Times</u>: The time scale between fault detection and system shutdown should be within a few micro-seconds with an exception where the sources themselves are slow.
2. <u>Redundant System</u>: One failure mode must be able to trigger multiple signal chains. For example, a beam swerving into a pipe should first be detected by a BPM, then a BLM and finally the vacuum gauge.
3. <u>Forensic Data Dumps</u>: 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!

The Fast Laser Shutdown receives inputs from a number of systems. The inputs are:

1. Beam Loss Monitors
2. EPS (from EPS PLC)
3. RF Interlocks
    a. Buncher
    b. Injector Cryomodule Cavities
    c. Main Linac Cryomodule Cavities
4. Gun HV (HV on signal from Gun HVPS)
5. Raster Magnet
6. Dump Quadrant Detector (current detectors)
    a. Top, Bottom, and Top-Bottom
    b. Left, Right, and Left-Right

The different inputs are described in the following subsections.

4.1.1 Fibre Loss Monitors

The fibre beam loss monitors will be connected to the Fast Shutdown system. The data acquisition system is currently under development.

4.1.2 Equipment Protection PLC

Many important subsystems generate trips in milli-second time scales, these are fed to a dedicated Programmable Logic Controller (PLC), which in turn signals the fast laser shutter system. Appendix I contains a list of signals used by this PLC.

4.1.3 RF Interlocks

The RF interlocks operate in micro-second timescales.

Injector

The RF interlocks involve the interaction of several independent pieces of hardware.

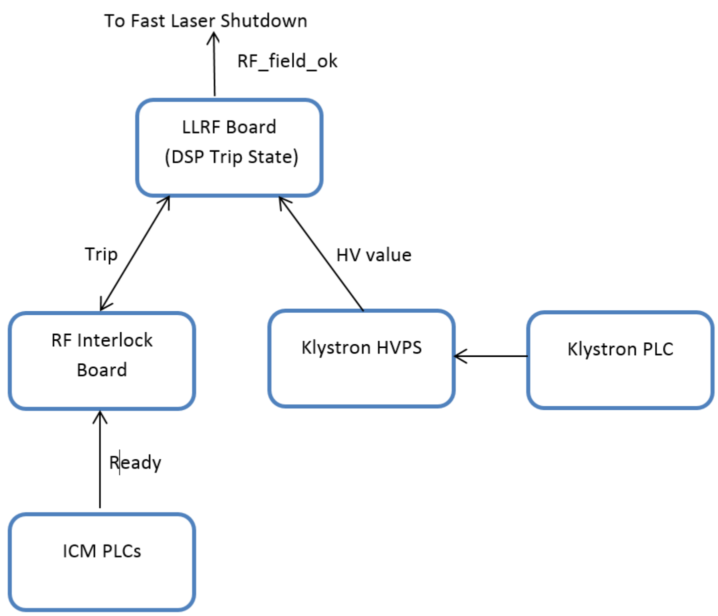


Figure 4.1: Signal flow for RF fast interlock system in the injector.

Main Linac

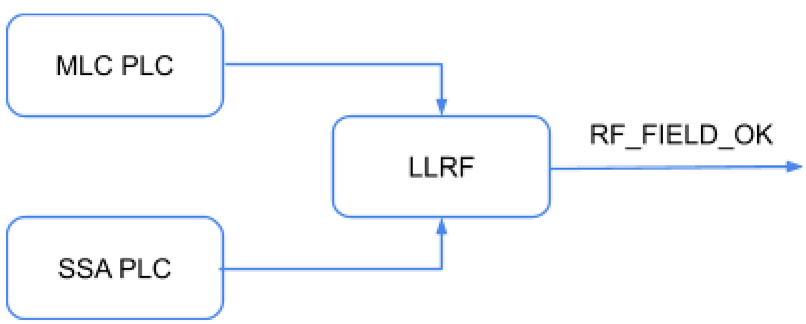


Figure 4.2: Signal flow for RF fast shutdown system in the main linac.

4.1.4 BPM Interlocks

Options under consideration for BPM beam interlocks include the following:

<u>Basic interlocks</u>

1. Interlock when the beam position is greater than a high threshold value
2. Interlock when the beam position is less than a low threshold value

3. Interlock when the analog to digital converter (ADC) overflow bit is set, indicating that the position value is invalid

More elaborate interlocks

4. Interlock when beam is expected, but not detected. This is important for a case where beam is mis-steered and never makes it to downstream BPMs, and would be considered as a beam present or beam not present signal. Not that this interlock will also be generated if the BPM timing is not correctly configured to the bunch. When a BPM trigger occurs, the sum signal would be compared against a beam present threshold value and generate an interlock if the sum is less than the threshold. This would require that triggers only be generated when beam is actually produced. Methods of disabling BPMs downstream of an inserted view screen must be developed to prevent interlocking when the beam is purposely not expected to be detected at certain BPMs. When beam is initiated, this interlock will need to be disabled for some time period as beam is established and detected at all BPMs.
5. After establishing a steady state beam condition, set a threshold level on the BPM sum signal such that if the sum signal drops below the threshold value, then interlock. This is similar to the beam not present detection above, but is intended to be used as a loss detector, such that the threshold value is only slightly lower than the expected sum signal.
6. After establishing a good operating orbit, configure BPM tolerance thresholds to be plus and minus the presently measured position value, and interlock if the beam position moves outside this tolerance window. This would be useful for continuous steady state operating modes. It would also be useful when gradually increasing beam current.

4.2 Slow Radiation Monitors

The Cesium Iodide based slow radiation monitors complement the fast shutdown system by precisely monitoring the dose rates at different locations of the machine providing us a means to understand the radiation distribution in different loss scenarios including steady state losses. Based on typical results obtained from radiation simulations, we have proposed a distribution of the 120 CsI dosimeters throughout the machine. Most of these are placed as near the beam pipe as possible on the midplane of the machine. The first girder of the FA will be heavily monitored, with two dosimeters on either side at the upstream position of each of the 8 magnets, while most of the straight girders will have 2 dosimeters. The dose measurements will be used to warn the operator and shut down the beam when instantaneous or integrated dose levels exceed thresholds. In addition to protecting the magnets, these measurements will be used to verify radiation simulations and measure the effect of halo. Appendix II contains a detailed plan for the placement of these detectors.

4.3 Beam Current Limiting

Apart from the fast shutdown which uses the slow and fast laser shutters to fully inhibit the laser beam, we have a separate system called the Beam Pulse Generator (BPG) which is also used as a part of the

EPS. The BPG used to control the bunch patterns in CBETA, incorporates a timer and counts the number of pulses a laser makes in a certain given time period. If the number of pulses exceed a threshold set through EPICS, then all subsequent pulses in that period are vetoed. This provides a mechanism to limit the average beam current.

The machine modes described in section 3 are automatically determined using a python script based on the following EPICS settings. When in a mode, the BPG time period and maximum number of pulses are set to the values given by Tab. 3.I to prevent the current from going above desired levels.

0 : Undefined

- This state occurs when none of the other states are valid. It should not happen in normal operation

1 : Gun-ICM Only

- | MA3DPA01 _cmd | < 0.1 amps

2 : Diagnostic Line (Slits IN)

- MA3DPA01 _cmd > 0.1 amps
- At least one slit in: (IB2SLH01 _in_led = 1) || (IB2SLV01 _in_led = 1) || (IB2SLH02 _in_led = 1) || (IB2SLV02 _in_led = 1)

3 : Diagnostic Line (Slits OUT)

- MA3DPA01 _cmd > 0.1 amps
- All slits out: (IB2SLH01 _in_led = 0) && (IB2SLV01 _in_led = 0) && (IB2SLH02 _in_led = 0) && (IB2SLV02 _in_led = 0)

4 : MLC (Single Cavity)

- Only one of RD1CAV01_mode, RD1CAV02_mode, RD1CAV03_mode,RD1CAV04_mode, RD1CAV05_mode or RD1CAV06_mode equals ‘CAV_LOOP’
- MA3DPA01 _cmd < 0.1 amps
- MS1DIP01 _cmd <= 0.5

5 : MLC

- More than one of RD1CAV01_mode, RD1CAV02_mode, RD1CAV03_mode,RD1CAV04_mode, RD1CAV05_mode or RD1CAV06_mode equals ‘CAV_LOOP’
- MA3DPA01 _cmd < 0.1 amps
- MS1DIP01 _cmd <= 0.5

6 : Dump Line

- Not implement yet

7 : S1 Splitter

- MA3DPA01 _cmd < 0.1 amps
- MS1DIP01 _cmd > 0.5
- MS1DIP08 _cmd < 0.5

8 : FFA Arc

- MA3DPA01 _cmd < 0.1 amps
- MS1DIP01 _cmd > 0.5
- MS1DIP08 _cmd > 0.5

High current

- Requires the fast shutdown system to be enabled
- Requires a High Current EPICS switch to be enabled, which is only able to be commanded by "advanced" operators. Initially, nobody will be on this list so it's impossible to do.

5. EPS Operation

5.1 Calibration Procedures

5.1.1 CsI Dosimeters

The CsI dosimeters consisting of scintillators attached to photodiodes are slow monitors which can be calibrated against a standard source and a calibrated Gamma probe as shown in Fig. 5.1.

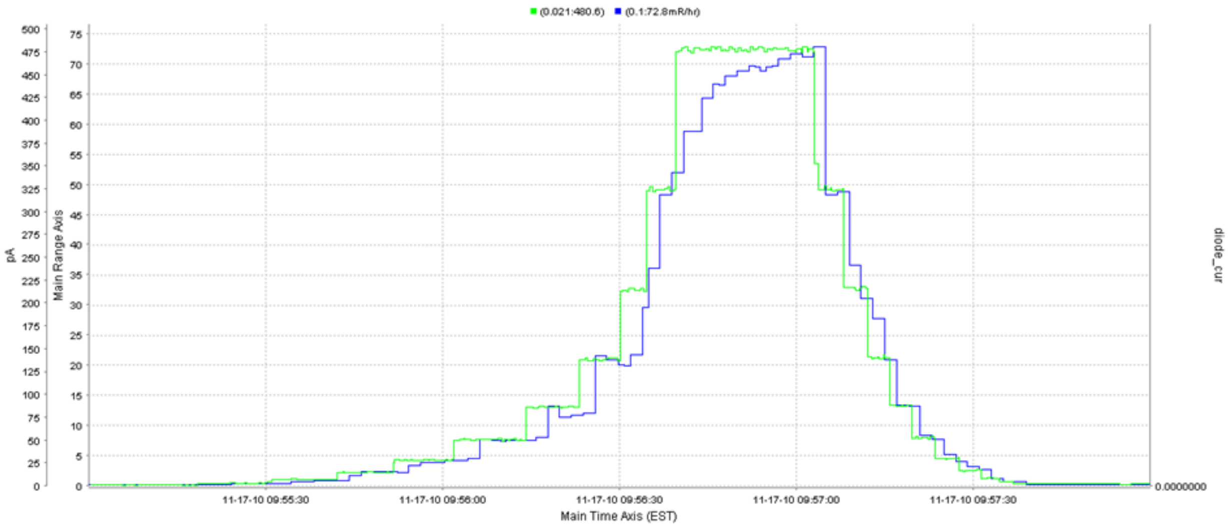


Figure 5.1: Current from photodiode(green) in pA and reading from Gamma probe (blue) in mR/hr.

Each of the 120 CsI dosimeters will be calibrated in the same way before use.

5.1.2 Fast Fibre Monitors

5.2 Operations and Testing

6. Conclusion

Permanent magnets are the most sensitive components in the CBETA project with a planned dose limit of 1 kGy on each magnet. The primary purpose of the EPS is to limit the total losses on every permanent magnet to this value over the entire lifetime of CBETA. The high power beam dump and total beam loss in the pipe are the strongest sources of radiation, out of the various loss mechanisms we have studied. With adequate shielding the dose from the beam dump can be limited to less than 31.2 rem/h at a beam current of 1 mA, which corresponds to several thousand hours of continuous high current operation before the nearby magnets get a noticeable change in their multipole strength. On the other hand, total beam loss can happen in the vicinity of the magnets and can lead to a significant absorbed dose. The Fast shutdown system being designed for CBETA can switch off the beam within 10 µs which gives us a worst case budget of 36 trips per permanent magnet. This also illustrates the need to continuously monitor radiation from halo and limit the current during the commissioning process.

CBETA incorporates various mechanisms for EPS working at different time scales. Fast fibre monitors and CsI dosimeters monitor radiation in µs and 100 ms timescales respectively, the first being an input to the fast shutdown system. Complementing the fibre monitors are the BPMs and the LLRF which can detect changes in beam position and cavity field respectively, and consequently can be used to detect instabilities or predict impending beam loss. Finally other subsystems, including the gun, vacuum, magnets, beam dump, etc are also used to stop the beam before substantial damage takes place.

The beam mode used in operation determines the dose rates generated from various loss mechanisms, and hence presents different requirements for the EPS system. Each beam mode listed in this document comes with its own set of restrictions on beam current. The beam current will be limited to 125 pA during the process of commissioning, when the beam will be intentionally dumped near the permanent magnets. Whereas in high current mode, the fast shutdown system will need to be active to safely run the machine.

The implementation of the EPS system is divided into fast shutdown, slow radiation monitoring and beam current limiting. The fast shutdown system, still under development will use the fast and slow laser shutters to inhibit the laser beam within 10 µs of a triggering event. The slow monitoring system using the CsI dosimeters responds at 100 ms timescales and will be used to quantify steady state radiation from various sources including scattering from beam stops or beam halo. The data will then be used to warn the operator or switch off the laser beyond certain thresholds. Finally, the BPG will be used to limit the average beam current in the machine depending on which is the active beam mode.

Appendix

I. EPS PLC Inputs

Most of the signal names here are outdated. This list will be modified in the coming months.

1) Gun Tank SF6
    a) Pressure High/Low
    b) Temperature High/Low
2) Vacuum
    a) Ion Pump Pressure High
        i) VA1IPA01 (V = vacuum, A1 = beamline section, IP = Ion Pump, A = Size)
        ii) VA1IPC01
        iii) VA1IPB01
        iv) VA3IPI01
        v) VA4IPB01
        vi) VA5IPF01
        vii) VA5IPF02
        viii) VC1IPB01
    b) Ion Pump Off
        i) VA1IPC01
        ii) VA4IPB01
        iii) VC1IPB01
    c) Pirani Gauge Trip
        i) VA1IPC01
        ii) VA3PGA01
        iii) VA4PGA01
        iv) VA5PGA01
    d) Ion Gauge Pressure High
        i) VA3IGC01
        ii) VA4IGC01
        iii) VC2IGC01
3) Gate Valves
    a) Gate Valve Closed
        i) VA1GVA01
        ii) VA2GVA01
        iii) VA2GVA02
        iv) VA3GVA01
        v) VA5GVA01
4) Dump

a) Max Temperature (out of 80 TCs)
b) Dump Water Valve Closed
c) Dump Water Flow High/Low
d) Dump Water In Temperature High
e) Dump Water Out Temperature High
f) Dump Water Conductivity High
g) 45 F Water Flow High/Low
h) H2 Gas Concentration High
i) H2Gas Detector Trip
j) Dump Water Leak Detector

5) Magnets
   a) Temperature High
      i) MA1SLA01 (M = magnet, A1 = beamline section, SL = solenoid, A = type)
      ii) MA1SLA02
      iii) MA3QUA01
      iv) MA3QUA02
      v) MA3QUA03
      vi) MA4QUA01
      vii) MA5QUC01
      viii) MA5RST01
      ix) MA5QUD01
      x) Corrector Power Supply Heat Sink
   b) Water Flow
      i) Corrector 65 F Water
   c) Valve Closed
      i) Magnet 85 F Source
      ii) Magnet 85 F Return
      iii) Gun 65 F Source
      iv) Gun 65 F Return
   d) Current High/Low
      i) MA5QUC01
      ii) MA5QUD01
      iii) MA5RST01
      iv) MA5RST02
   e) Voltage High/Low
      i) MA5QUC01
      ii) MA5QUD01
      iii) MA5RST01
      iv) MA5RST02

6) RF
   a) Injector Linac
   b) Main Linac

The cryogenic system, vacuum system and the SSAs are controlled by separate PLCs which communicate with one another and the LLRF system as shown in Fig 8.

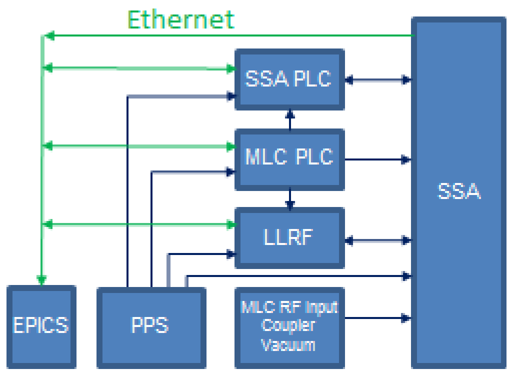


Figure A.I.1: Simplified communication diagram for the Main Linac subsystems.

The trip signals from all the LLRF boards is combined into a single trigger which goes into the EPS PLC.

7) GUN High Voltage
   a) High Voltage On
   b) High Voltage Low
   c) Input Surge Suppressors Not Ready (Phase 1/2/3)
   d) Ground Surge Suppressor Not Ready
   e) Power Conditioner Alarm
   f) SF6 Blower Thermal Overload
   g) SF6 Blower Off
8) Radiator Monitors

   The personnel protection radiation monitors are configured to trip off the accelerator before reaching the personnel protection trip level.

II. Placement of CsI dosimeters

Always put as near to the pipe as possible on the magnet and on the machine midplane (unless otherwise stated). Don't use "left" and "right", they change depending on where we are looking from.

Girder Config:		2A		2B		4		8		8R		16	
Magnet #	Type	US I	US O	US I	US O	US I	US O	US I	US O	DS I	DS O	US I	US O
1	QF	1	1			1	1	1	1			1	1
2	BD/BDT/QD			1	1			1	1	1	1	1	1
3	QF											1	1

4	BD/BDT/QD							1	1			1	1
5	QF									1	1	1	1
6	BD/BDT/QD					1	1					1	1
7	QF							1	1	1	1	1	1
8	BD/BDT/QD									1	1	1	1

Table A.II.1: Glossary of girder configuration for placement of dosimeters. Abbreviations used in this table are: US: Upstream, DS: Downstream, I: Inside, O: Outside. The FFA magnet types follow the convention used in the lattice descriptions of CBETA.

Girders	FA GD1	FA GD2	FA GD3	FA GD4	TA GD1	TA GD2	TA GD3	TA GD4	TA GD5	TA GD6	ZA GD1	ZA GD2	ZA GD2	ZM GD
Configuration	16	8	4	2A	8	4	4	2A	2B	2A	8	4	2A	2B
Girders	ZB GD1	ZB GD2	ZB GD3	TB GD1	TB GD2	TB GD3	TB GD4	TB GD5	TB GD6	FB GD1	FB GD2	FB GD3	FB GD4	
Configuration	2A	2B	2A	8	4	2A	4	2A	2B	8	4	2A	2B 8R	

Table A.II.2: Configuration for all FFA girders. Each configuration is detailed in Tab. A.I.1.

Statistics: Two per girder: 54, Extras at beginning of FA: 22, Extras at beginning of TA, ZA, TB, FB: 32, Extras for TA GD3 and TB GD4 magnet change: 4, Extras for TA GD3 and TB GD4 magnet change: 8