Status and Design of The Radiation Monitor

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Abstract

A short document to summarise the progress so far on the design and implementation of the radiation monitor for MICE. The layout of the document is a little unorthodox, but it is designed to show coherently the progress made so far and to be easily adapted to use it as the basis for a paper/note in the future.

1 Workforce

Those involved so far: Sergey Balashov[1], Alan Bross[2], Norbert Collomb[1], Tim Hayler[1], Pierrick Hanlet[3], Chris Hunt[4], Ken Long[4], Jaroslaw Pasternak[4], Pat Sangsingkeow[5], Graham Stokes[1], Shane Toal[6] and Melissa Uchida[4].

2 Purpose and Requirements

A radiation monitor is required as a safety measure, to ensure that the beam shutters stay closed until the radiation monitor sensors indicate that safe conditions have been achieved.

- It should sit on the radiation shield.
- It will monitor x-rays, gamma-rays and electrons of a few MeV. The maximum energy that an electron/photon can get is 8 MeV (all 8 RF cavities (1 MeV per RF cavity) when no middle absorber is there), therefore, it is likely that the spectrum will peak at very low energies. This is relevant for step VI for Step IV the radiation monitor will act as an extra safety measure against the beam.
- The readout and power supply will be passed through the vacuum feed-through.
- Readout will be monitored in the control room.

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[3]Illinois Institute of Technology
[4]Imperial College
[5]ORTEC
[6]Ametek

3 Radiation Shield

Some technical drawings of the radiation sheild to which the monitor will attach are shown in Figures 1– 3.

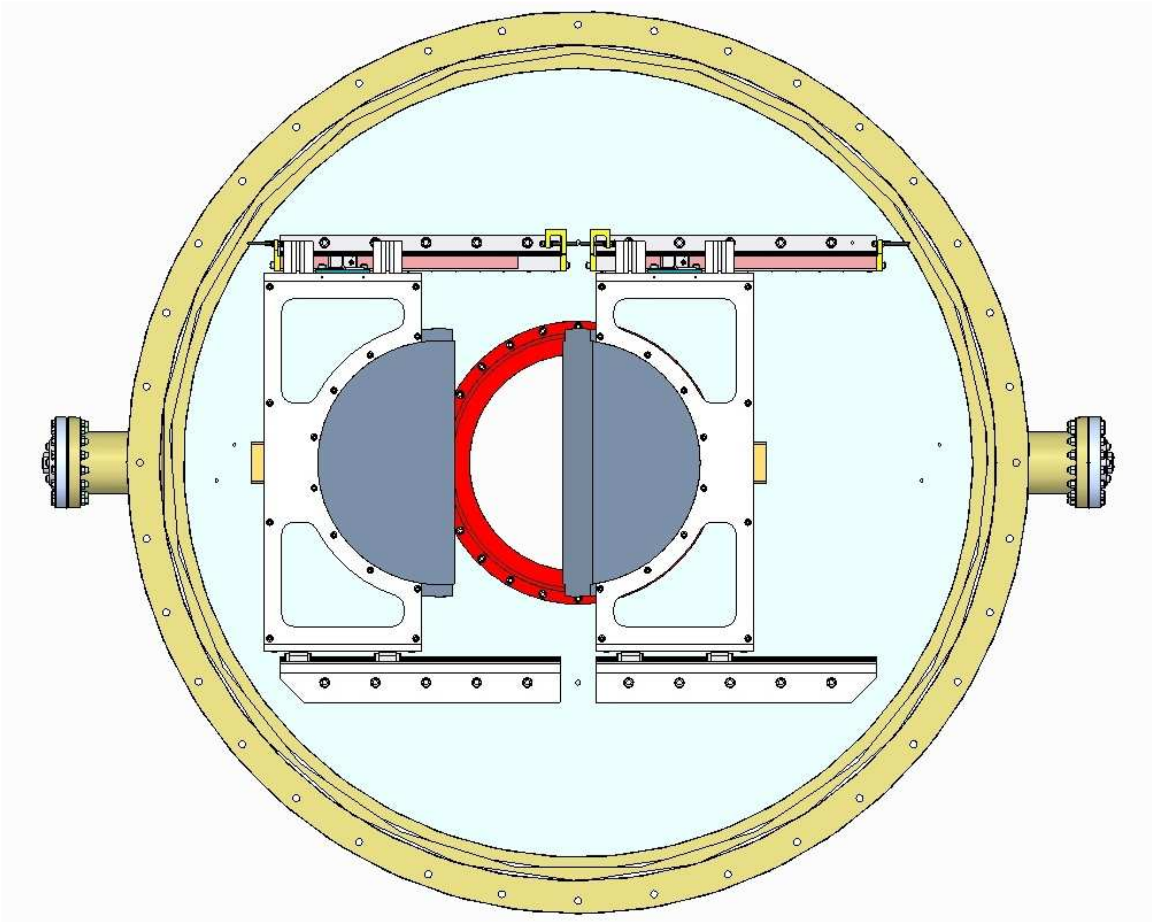

Figure 1: Drawing showing the sheild assembly.

4 Design

The technology required already exists and so the system can be designed using parts bought directly from manufacturers. Several such manufacturers have been considered including Hammamatsu and ORTEC. ORTEC is the front-runner so far.

The design process has been ongoing for a couple of years and has involved experts from specific companies and engineers and physicists from MICE and the larger STFC community.

4.1 Detectors

Silicon detectors can be used for detecting, counting and determining the energy of charged particles. The energy resolution of the detector is significantly affected by its capacitance, which is in turn dependent on the active area. ORTEC offer implanted and diffused silicon surface barrier type detectors. Implanted silicon

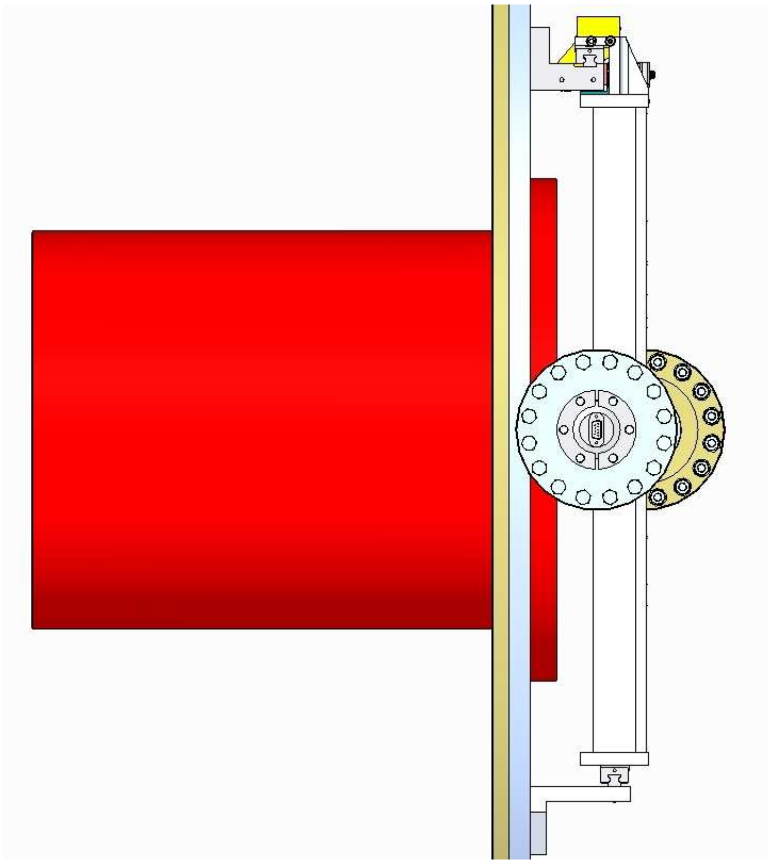

Figure 2: Drawing showing the end view of the sheild.

detectors perform better within the range of parameters where they are appropriate, but there is a broader range of device parameters available from the silicon surface barrier type detectors (SSBDs).

The majority of SSBDs are partially depleted (active counting depth within the silicon) but the 'B' type is fully depleted meaning that apart from thin surface layers the full thickness of the silicon is actively detecting. Partially depleted detectors are closed at the back as the intention is that all particles incident on the front of the detector will be absorbed by the depletion layer and certainly will not be expected to pass through the detector completely. In the case of fully depleted detectors it is expected that at least some of the particles will be energetic enough to pass through. In these cases a second detector is sometimes placed behind the first. The majority of these detectors can be mounted and supported rigidly by the coaxial connector[1].

It is likely that the spectrum will peak at very low energies, since the maximum electron/photon energy is 8 MeV (as we have already mentioned). Therefore, the radiation monitor was designed to have a thin sensor, sensitive to the high rate of low energy photons/electrons and a thicker one sensitive to higher energy, lower flux.

We were initially considering using two pairs of the 'B' type, fully depleted detectors which are open on both sides. These detectors can be used in a vacuum, have an operating temperature of $^{+}25 -^{-} 30°C$ and a guaranteed maximum resolution for alpha and beta test counts in tens of KeV (the first three digits of the model numbers below indicate the total system resolution FWHM for ^{241}Am, 5.486 MeV alphas, using standard ORTEC electronics and 0.5 μs shaping time constants)[2].

1. 2 x B-015-050-150
2. 2 x B-026-450-2000

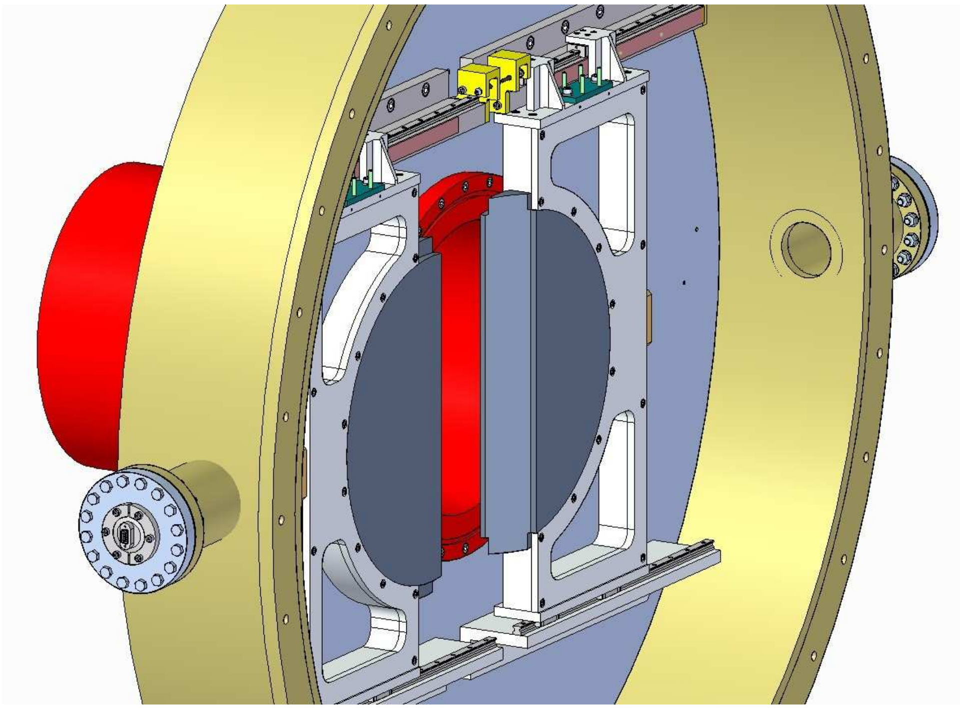

Figure 3: Drawing showing the sheild in close up.

The thicker 2000 micron detectors (2.) will have better conversion capability and be sensitive to high energy x-rays and the thinner smaller sensors will be sensitive to the lower energy end of the spectrum. The active areas of the detectors are 50-450 mm^2 respectively. The max resolution for alpha and betas is 18 and 13 KeV respectively for detector 1. and 26 and 21 KeV respectively for detector 2.

B type detectors use T mounts (a microdot (small coaxial connector) mounted on the side of the detector can)[3].

It has since been suggested that it is not necessary to use the thicker, a fully depleted detector and type A detectors have been suggested as an alternative. Work in this area is ongoing.

4.1.1 Cost and Availability

In order to decide between the possible detectors that are fit for purpose it is useful and necessary to consider cost and availability. This is summarised in Table 1.

Thin Detector	Availability (days)	Cost (£)
B-015-050-150	21	863
Thick Detector		
A-026-450-2000	120	9257
B-026-450-2000	120	9765
A-022-300-2000	21	6512
B-023-300-2000	80	7224

Table 1: Cost and availability of the different detectors.

5 Electronics Chain

The electronics chain typically has a cable from detector to local pre-amplifier that sits fairly close to the detector (9-12 V, the selection of the preamp is matched to the capacitance of the detector). There are a number of pre-amplifiers which can be mounted in a vacuum. Cables run from the pre-amplifier to MICE control room for readout (NIM). We could probably consider housing the electronics in the tracker racks.

Things to determine (work ongoing):

- Choice of pre-amplifier?
- How to handle pulse-shaping?
- Cabling?
- Signal amplification?
- Read out system?
- Interlocking design, how does safety system tie into existing interlock systems?

Items 1 and 2 are discussed in more detail in the next section.

5.1 Pre-Amplifiers

Pre-amplifiers are used to extract and boost the signal from the detector without degrading its signal to noise ratio (SNR), to minimise noise they are usually placed as close as possible to the detector. Pulse shaping is normally implemented in a separate module (usually the amplifier) which is placed further away from the detector using a coaxial cable, at a distance where the signal is not depleted by the length of the cable. There are three main types of pre-amplifier:

- current sensitive,
- parasitic capacitance and
- charge sensitive.

The first two are high noise and are mainly used for detectors that produce large signals such as photomultiplier tubes and scintillator detectors. Silicon charge particle detectors such as we will use for the radiation monitor require the pre-amp be charge sensitive 4 and are often used with a field effect transistor (FET) input stage to reduce noise. Two general types of charge sensitive pre-amplifiers are in common use: the resistive-feedback pre-amplifier and the pulsed-reset pre-amplifier.

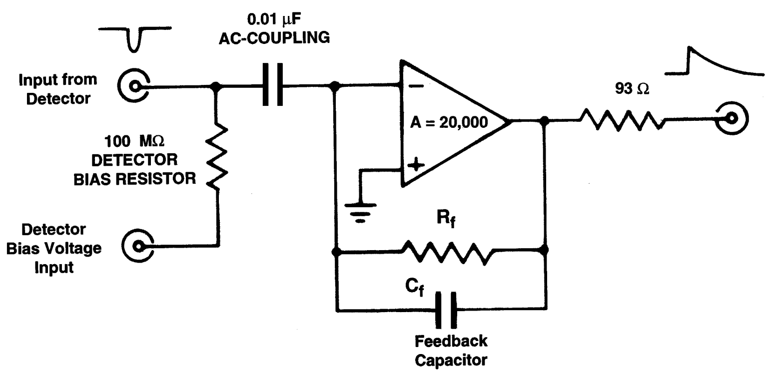

Figure 4: Simplified Schematic of the ORTEC AC-Coupled Charge-Sensitive pre-amplifier. (For a dc-coupled pre-amplifier, the detector bias resistor is removed, and the 0.01 μF capacitor is replaced by a wire. [4])

ORTEC provide a range of such systems and can tailor them to our system and budget, so this is probably the way to go. From now on much of the material in this section is garnered from ORTEC documentation and it is the recommendation that the final decision be made in following conversation with them. [4].

The signal from our detector (whichever of those short-listed we choose) will be a current pulse lasting from 10^9 to 10^5 s, depending on the type of detector and its size. The charge and time of an event is of interest to us and the pre-amp can deliver both since it is not sensitive to changes in detector capacitance (in the ideal case, the rise time of the output pulse is equal to the detector current pulse width). To operate optimally: input capacitance must be much greater than other sources of capacitance (eg. cable and pre-amp).

The output Voltage V_o and gain G are given by:

$$V_o = Ee(10^6)/C_f \tag{1}$$

$$G = V_o/E = e(10^6)/C_f\epsilon \tag{2}$$

Where E is the energy in MeV of the incident radiation, e is the charge of the electron (1.6 X 10^{19} coulomb), 10^6 converts MeV to eV, C_f is the feedback capacitor (0.1 to 5 pF) and ϵ is the amount of energy required to produce an electron-hole pair in the detector and in our case $\epsilon = 3.62$ (at 300 K) and 3.71 (at 77 K). Therefore, the sensitivity of a silicon detector and pre-amplifier at room temperature with $C_f = 1x10^{-12}\,F$, is 44 mV/meV.

Noise in the system is determine by: FET, total capacitance at input C_f, resistance connected and input leakage currents from detector and FET.

The rise time of the voltage pulse V_o at the output of the charge-sensitive pre-amplifier, in the ideal case, is equal to the charge collection time of the detector. When detectors with very fast collection times or large capacitances are used, the pre-amplifier itself may limit the rise time of V_o. If a time reference mark is being determined from V_o, it is desirable that the rise time tr of V_o be as short as possible. Time resolution of silicon detectors is usually limited by:

$$Timingresolution(FWHM) = \frac{outputnoise}{(dV_o/dt)} \tag{3}$$

5.2 Amplifiers

Since the detectors and per-amplifiers will likely be bought from ORTEC it is sensible for the amplifier to also be ORTEC and it was therefore their documentation which is used for this short overview and where further information can be obtained [5].

Amplifiers can be broken down into two main types: Fast Timing amplifiers for applications that require excellent timing resolution and Linear, Pulse-Shaping Amplifiers for pulse-height (energy) spectroscopy. Figure 5 shows typical amplifier usage in the various categories of pulse processing, options a to c are the most common for silicon detectors.

In our case both timing information and energy resolution are important, but to some extent these are in conflict since optimum energy resolution requires long pulse widths but short pulse widths facilitate high counting rates. Various techniques are available for pulse shaping in the linear amplifier in order to find the correct balance between timing and energy requirements.

A brief overview of the types of amplifier and pulse shaping available and their possible applications is given in Table 2.

It is necessary that further study into beam dynamics be considered prior to final selection of the amplifier and processing chain and that discussion with electronics experts take place.

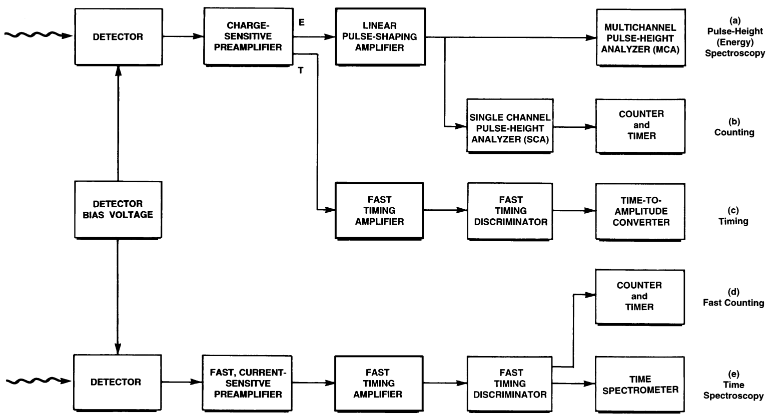

Figure 5: Typical Amplifier Applications in Pulse Processing. [5]

Fast Timing Amp	~~Timing~~	Used for Germanium Detectors
	Wideband	Offer no control over rise or decay time of signal. Typically used with si detectors where the fastest rise times are required for good time resolution. Wideband amplifiers rely on the preceding electronics to limit the pulse length.
Linear, Pulse Shaping Amp	~~Decay Line~~	Used for Scintillation Detectors.
	~~LN-RC~~	The simplest concept for pulse shaping is the use of a CR high-pass filter followed by an RC low-pass filter. This rudimentary filter is rarely used.
	Pole Zero	The benefit of pole-zero cancellation is improved peak shapes and resolution on the LN-RC method, in the energy spectrum at high counting rates.
	Semi Gaussian	Improves the signal-to-noise ratio of the Pole Zero pulse-shaping amplifier by 17% to 19% at the noise corner time constant.
	Quasi Triangular	By summing contributions from the various filter stages in a semi-Gaussian amplifier, a unipolar output pulse with a much more linear rise can be generated.
	~~Gated Integrator~~	Used for Germanium Detectors

Table 2: Brief table of amplifier types.

5.3 Signals Out and Readout Options

The choice and detector and pre-amp—amplifier chain will determine exactly what signals we expect to see at each stage in the chain, what the final pulse shaping will be and what sort of voltage and time resolution we have. How we then read these signals will be determined then.

6 Positioning

It is difficult to determine the best positioning of the radiation monitor until the simulation of the expected radiation distribution is completed. Nevertheless, here are some of the factors to consider.

- Located at the end of the spectrometer on the radiation shield.
- Detectors positioned on downstream shield.
- Perpendicular to the beam.
- Detector should not infringe on the beam/stay clear of the aperture.
- Detectors should be positioned so as to have give a clear picture of the radiation "cross-section". Do we expect a broad symmetric distribution?
- Coaxial cable point outwards and be tied to support.
- Should we shield cable?
- Ideally amplifier should be away from radiation and magnetic field, i.e. outside the vessel. Special consideration should be given here to the signal/noise ratio, that can be affected by long cable lengths.

6.1 Magnetic Fields and their Effect on Positioning

The MICE experiment will now implement a partial return yoke (PRY) for both steps IV and VI [6]. The PRY will be 8 m long (in step IV) and made up of 8 panels of AISI 1010 steel that are either 10 or 12 cm thick. The effect of the PRY is to reduce the stray magnetic field from 30-60 mT at a radius of 1.5 m from beam to 1 mT for the 10 cm shield and 0.6 mT for the 12 cm shield. In step IV the 5 G (0.5 mT) line will then be at 3.5 m longitudinally, 4.5 m vertically and in the horizontal direction assuming a 12 cm thick shield) is located directly behind the shield; therefore all of the main floor of the MICE Hall will have a field below 5 G 6. There are horizontal gaps in the PRY through which cables can be fed. These gaps have no significant effect on the stray field (a 20 cm gap giving rise to only a 1 mT rise in field).

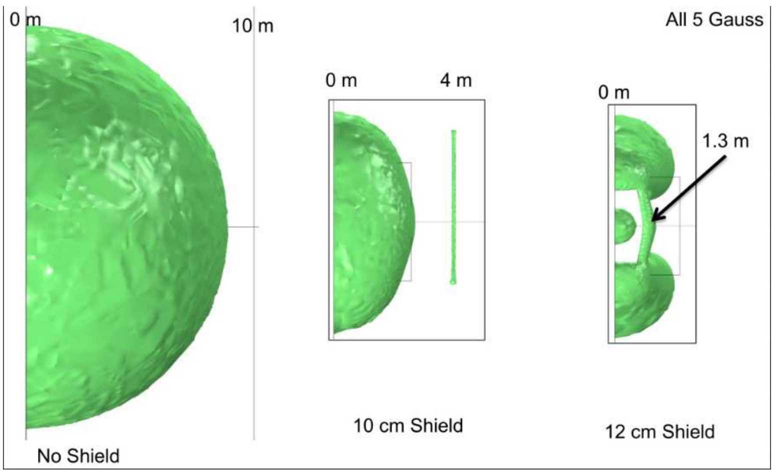

Figure 6: 5 G iso-surface plot of MICE for the 200 MeV flip mode, shielded and unshielded, in frontal view. [6]

As the PRY has a radius of 1.5 m and the field outside this point is less than 5 G the pre-amplifier would only need to operate in a 5 G field if it can be mounted just outside the PRY with a cable length of 1.5 m from the detector without this affecting the SNR. The amplifier would then not be a problem as it could be placed at any reasonable location in the MICE hall.

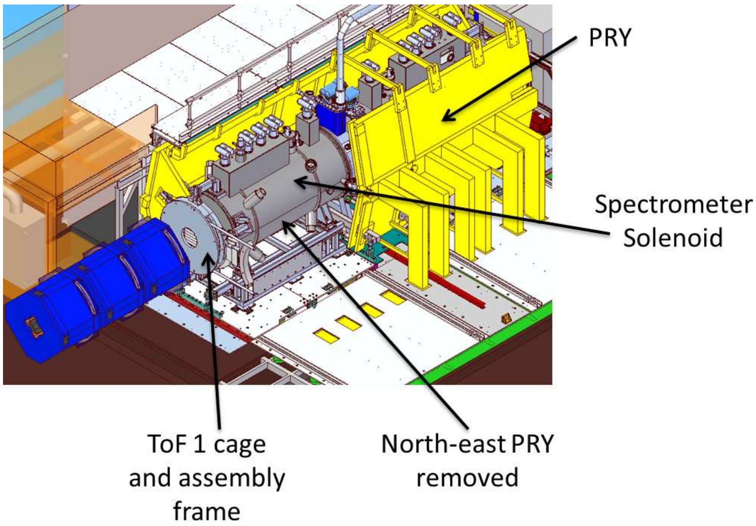

Figure 7: PRY around TOF1 and spectrometer solenoid. [6]

7 Outstanding Questions

- Design Position
  1. Attach to shutter?
  2. Exact position?
  3. Proximity to beam centre?
  4. Off Centre?
  5. How to determine directionality?
- Understand the beam
  1. Is it symmetric in all cases?
  2. Determine width and cross section.
- Detector Type, do we need thick detectors as well as thin ones?
- Cable length (signal/noise ratio calculation)
- Time resolution
- Energy resolution
- There is a possibility of using multiple detectors simply counting hits, to detect radiation, is this a viable solution? Limited by pre-amplifier and cabling?
- The radiation monitor is unlikely to be a reliable trigger for misbehaviour in the cavities as the detectors will be withdrawn with the shutters. We should also consider what triggers the closure of the windows?

8 Conclusions

Whilst much of the design work is well advanced there are still some outstanding questions and more work to be done. In particular much of the simulation work has yet to be been done and the physics implications of the detectors position and electronics chain are yet to be fully investigated. This is where extra effort will be focused in the coming months.

References

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