MKI PERFORMANCE DURING 2016 AND PLANS FOR EYETS

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Abstract

Substantial upgrades were carried out to the MKI beam screen during LS1: MKI heating has not limited LHC operation since LS1, and is not expected to do so during Run 2. Similarly, during LS1, the vacuum systems on the interconnects between MKI magnets were upgraded: as a result there haven't been any issues with SIS vacuum thresholds on the interconnects between adjacent MKIs. However, during 2016, dynamic pressure increase on the MKI8D-Q5 interconnect limited the number of bunches that could be injected for Beam 2. The MKI2D kicker magnet caused several issues during 2016, including limiting the length of the field pulse from August onwards and a high impedance contact from October. As a result of further deterioration of the high impedance contact the MKI2D was exchanged during TS3. During November the Surveillance Voltage Monitoring system interlocked the MKI2 installation on several occasions. This paper reviews the MKI performance during 2016, the plans for the EYETS and the expected performance during 2017.

INTRODUCTION

The Large Hadron Collider (LHC) is equipped with two injection kicker (MKI) systems for deflecting the incoming particle beams onto the accelerator's equilibrium orbits. Counter-rotating beams circulate in two horizontally separated beam pipes. Each beam pipe is filled by 12 consecutive injections, at 450 GeV. The injected beam is first deflected in the horizontal plane by a series of septum magnets followed by a vertical deflection by four MKI systems [1]. The total deflection by the four MKI magnets is 0.85 mrad, requiring an integrated field strength of 1.3 T·m. Reflections and flat top ripple of the field pulse must be less than ±0.5%, a demanding requirement, to limit the beam emittance blow-up due to injection oscillations.

A low impedance (5 Ω) and carefully matched high bandwidth system meets the stringent pulse response requirements. An MKI kicker system consists of a multi-cell PFN and a multi-cell travelling wave kicker magnet [2], connected by a matched transmission line and terminated by a matched termination resistor (TMR). Each travelling wave magnet has 33 cells. A cell consists of a U-core ferrite sandwiched between HV conducting plates: two ceramic capacitors are sandwiched between a HV plate and a plate connected to ground (Fig. 1). The magnets are operated in vacuum of ~10^{-11} mbar. The complete magnet is baked out at 300°C before HV conditioning and tests.

BEAM INDUCED HEATING

With high LHC bunch intensity and short bunch lengths, integrated over many hours of a good physics fill, the impedance of the magnet ferrite yoke can lead to significant beam induced heating. To limit longitudinal beam coupling impedance, while allowing a fast magnetic field rise-time, an alumina tube with screen conductors lodged in its inner wall is placed within the aperture of the magnet [2]. The conductors, which provide a path for the image current of the beam, are connected to the standard LHC vacuum chamber at one end and are capacitively coupled to it at the other end. Prior to Long Shutdown 1 (LS1) the MKIs generally had only 15 of a possible 24 screen conductors installed, positioned closest to the return busbar: the other 9 were omitted due to issues with surface flashover during magnet pulsing [3]. For one MKI magnet which limited LHC operation, the screen conductors were found not to be straight, but had a 90 degree twist over their length: based on impedance measurements the beam induced power deposition in this MKI was ~160 W/m average, compared to ~70 W/m average for a magnet with 15 straight conductors [4]: these power depositions assume that, as a worst case, all the power deposition is in the ferrite yoke. During LS1 the number of screen conductors was increased to the full complement of 24 [4, 5].

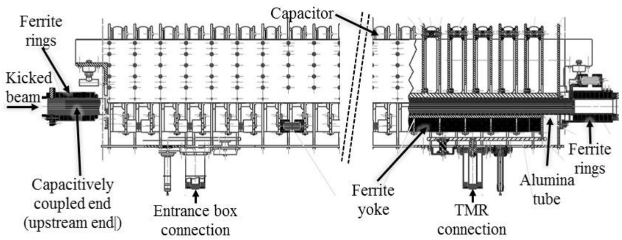

Figure 1: MKI kicker magnet.

There are toroidal ferrite rings mounted around each end of the alumina tube, outside of the aperture of the kicker magnet. The purpose of the rings mounted on the end where the screen conductors are connected to the beam pipe was to damp low-frequency resonances [6]. Each set of nine toroids has two types of Ferroxcube NiZn ferrite, namely: 4M2 and 4B3, with a Curie point of 200˚C and 250˚C, respectively. During Run 1 of the LHC one set of toroids, at the capacitively coupled end, of the beam screen, occasionally reached 193˚C measured; all others remained below 100˚C measured [6].

During Run 2 it was noted that the measured temperatures at the upstream (capacitively coupled) end of the MKI magnets were consistently higher than those measured at the downstream ends [7]. Thus studies were launched to understand this behaviour. CST Particle Studio [8] allows the placement of frequency dependent volume loss monitors, compatible with ferrite materials, in the simulation - volume losses are considered as the majority of losses in the system [9]. The predicted longitudinal distribution of volume losses of the post-LS1 kicker magnets is non-uniform - the ferrite rings at the capacitively coupled end of the structure experience more than 25% of the total power deposition, for a structure that has relatively little volume. The power deposition in the yoke is predominantly in the upstream end of the magnet, with losses being relatively low in the downstream half of the magnet: the first cell, at the upstream end, experiences ~9% of the total power deposition.

Thermal simulations have been carried out using ANSYS in order to confirm that the calculated power losses for Run 2 correspond to the measured temperatures during LHC operation. To compare the results with the measurements it must be taken into account that the PT100 temperature sensors are located on a side plate of each magnet. There is good agreement between measurements and simulations of the side-plate temperature: this validates both the power loss calculations and the thermal model [9]. From the measurements and simulations:

- Maximum measured side-plate temperature during Run 2 is 57˚C, at the upstream end of MKI8D (fill #5069, 1.25×10^{11} ppb, 2076 bunches, 25.5 hrs stable beam);
- From, steady-state thermal simulation 57˚C corresponds to a temperature, in the first cell at the upstream end, of ~80˚C and a total power deposition of almost 100 W in the magnet

Scaling total power deposition linearly with the number of bunches, to 2808 bunches, and assuming 1.25×10^{11} ppb, the total expected power is almost 150 W. The corresponding predicted temperature, in the first cell at the upstream end, is 107˚C and a "measured" side-plate temperature, at the upstream end, is 77˚C. The 107˚C is below the Curie temperature (125˚C), hence no issues with MKI heating are expected during Run 2. Therefore no changes are planned during the EYETS. Nevertheless, if necessary the bake-out jackets could be removed, during a Technical Stop (TS): this would reduce the highest temperature rise in the ferrite yoke, above ambient, by approximately 7%.

ELECTRON CLOUD

Significant pressure rise, due to electron-cloud, occurs in and nearby the MKIs: the predominant gas desorbed from surfaces is H_2. Conditioning of surfaces reduces electron-cloud, and thus pressure rise, but further conditioning is often required when beam parameters (e.g. bunch spacing, bunch length and bunch intensity) are pushed.

Voltage is induced on the screen conductors during field rise (up to 30 kV) and fall (to -17 kV). Rise in vacuum pressure, at the capacitively coupled end, can result in breakdown/flashover – hence there is an (SIS) interlock to prevent injection when this pressure is above threshold. In general these SIS thresholds, for the interconnects, are 5×10^{-8} mbar.

During LS1, the vacuum systems on the interconnects between MKI magnets were upgraded:

- ✓ Interconnects NEG coated;
- ✓ Prior to LS1, ion pumps provided a nominal pumping rate of 30 l/s of hydrogen.
  - ✓ During LS1, a NEG cartridge was integrated to give a nominal pumping speed of 400 l/s for H_2.

The alumina tube of each of the MKIs upgraded during LS1 has a high secondary electron yield (~10) when installed and required conditioning with beam, together with metallic surfaces facing the beam (e.g. screen conductors). However, during Run 2, there haven't been any issues with the SIS vacuum thresholds, on the interconnects between adjacent MKIs, limiting injection of beam.

By mid-2016 electron cloud resulted in a factor of ~20 rise in pressure, in comparison to the background pressure, in most MKI8 interconnects: the pressure rise in the MKI tanks was a factor of ~10. However, in the MKI8D-Q5interconnect, electron cloud resulted in a factor of ~1000 rise in pressure. Figure 2 shows the pressure in the MKI8D-Q5 interconnect, and beam B2 intensity during June 2016: the SIS threshold on this interconnect was set to 6×10^{-8} mbar.

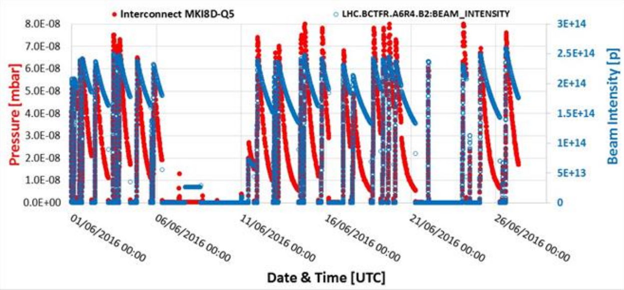

Figure 2: pressure in the MKI8D-Q5 interconnect, and beam B2 intensity during June 2016: the SIS threshold on this interconnect was set to 6×10^{-8} mbar.

Figure 3 shows pressure normalized to the number of protons for interconnect MKI8C-MKI8D, tank MKI8D, and interconnect MKI8D-Q5: in addition, beam B2 intensity is shown. Figure 4 shows a zoom of Fig. 3 for 24 June through to 27 June.

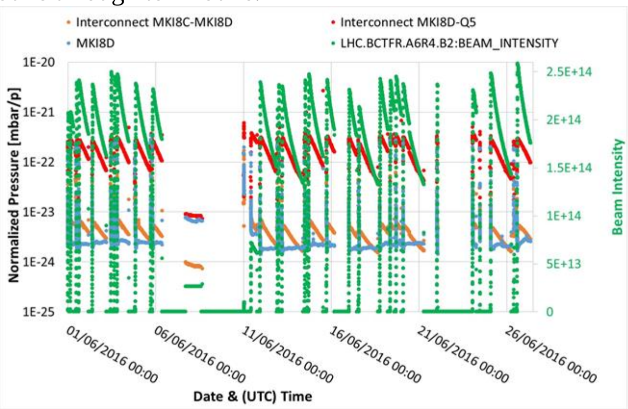

Figure 3: pressure normalized to the number of protons for interconnect MKI8C-MKI8D, tank MKI8D, and interconnect MKI8D-Q5. In addition, beam B2 intensity is shown.

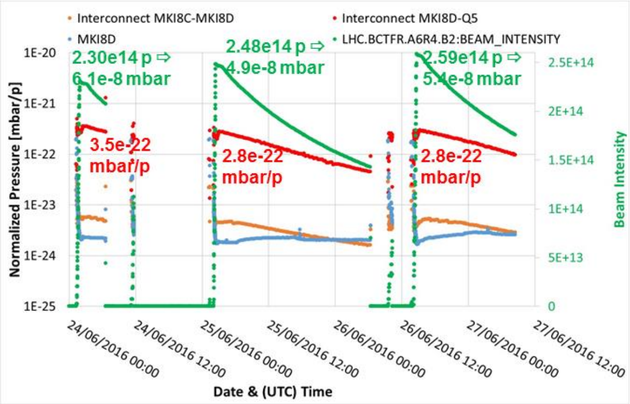

Figure 4: (zoom of end of Figure 3) pressure normalized to the number of protons for: interconnect MKI8C-MKI8D, tank MKI8D, and interconnect MKI8D-Q5. In addition, beam B2 intensity is shown.

The first fill shown in Fig. 4 is fill #5038: 25 ns bunch spacing, 72 bpi, 30 injections, 1.11×10^{11} ppb and 2040 bunches. Three injections where missing from B2 due to the MKI8D-Q5 threshold exceeding 6×10^{-8} mbar – the normalized pressure in the MKI8D-Q5 interconnect was 3.5×10^{-22} mbar/p.

The second long fill shown in Fig. 4 is fill #5043: 25 ns bunch spacing, 96 bpi (2 x 48 batches, each batch separated by 250 ns), 23 injections, 1.18×10^{11} ppb and 2076 bunches. The normalized pressure in the MKI8D-Q5 interconnect was 2.8×10^{-22} mbar/p.

The third long fill shown in Fig. 4 is fill #5045: 25 ns bunch spacing, 96 bpi (2 x 48 batches, each batch separated by 250 ns), 23 injections, 1.23×10^{11} ppb and 2076 bunches. The normalized pressure in the MKI8D-Q5 interconnect was 2.8×10^{-22} mbar/p.

The 20% lower normalized pressure for fills #5043 and #5045, in comparison with fill #5038, is attributable to the 250 ns gap, in the train, between the two injected 48 bunch batches.

During the EYETS two new NEG cartridges of 400 l/s each (nominal speed for H2) will be integrated in new modules of vacuum sector I5R8 (see Fig. 5). The upgrade will locally increase the pumping speed and hence is expected to maintain the dynamic pressure increase in the MKI8D-Q5 interconnect (VGPB.176.5R8.R) well below the SIS interlock threshold (5×10^{-8} mbar) up to the nominal number of 25 ns bunches.

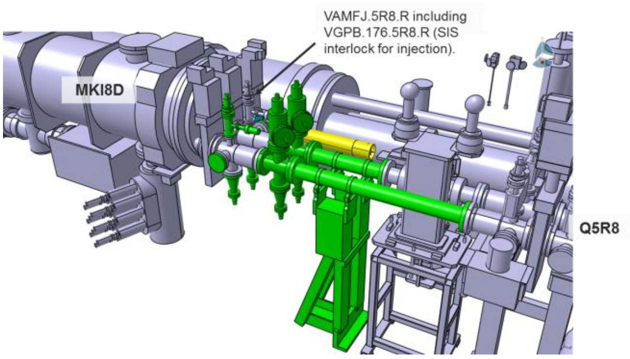

Figure 5: new layout of vacuum sector I5R8, with two new NEG cartridges of 400 l/s each.

During Technical Stop 3, 2016, it was necessary to replace magnet MKI2D (see below). Hence, although electron cloud around MKI2D has not limited injection during Run 2, the alumina tube in the new MKI2D will not have seen high intensity proton beam and will require conditioning after the EYETS. To assist the conditioning two new NEG cartridges of 400 l/s each (nominal speed for H_2) will be integrated in new modules of vacuum sector I5L2 (Fig. 6).

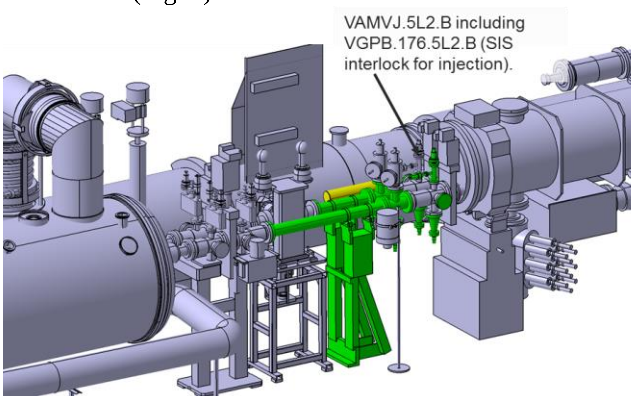

Figure 6: new layout of vacuum sector I5L2, with two new NEG cartridges of 400 l/s each.

Nevertheless, despite the upgrade to the I5L2 vacuum sector, the rise in pressure in the MKI2D-Q5 interconnect is expected to initially limit injection of LHC beam 1. Figure 7 show the normalized pressure in the MKI2D interconnects, following the installation of MKIs with new alumina tubes during LS1.

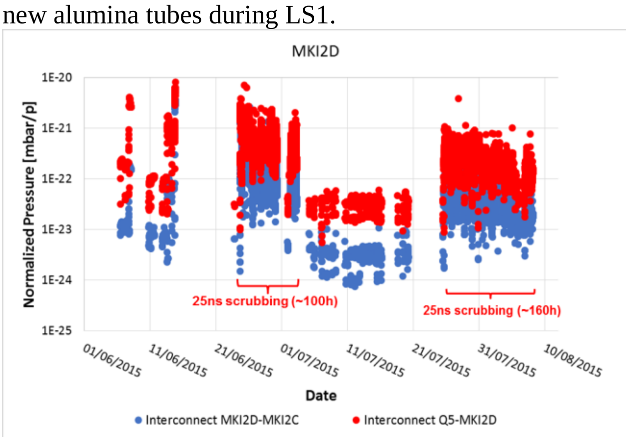

Figure 7: normalized pressure in the MKI2D interconnects, following the installation of MKIs with new alumina tubes during LS1.

Assuming an SIS interlock threshold of 6×10^{-8} mbar, to remain below this threshold with 1.25×10^{11} ppb and 2808 bunches, requires a normalized pressure of not more than 1.7×10^{-22} mbar/p. The I5L2 vacuum sector upgrade will assist to more rapidly increase the number of bunches: nevertheless, from Fig. 7, it is expected that 200-300 hours with high-intensity, 25 ns spaced, beam may be required before the nominal beam B1 can be injected. As per fills #5043 and #5045, the normalized pressure could be reduced by including an appropriate gap between batches of an injected train.

For the longer term a coating of Cr_2O_3, applied to the inside of the alumina tube by magnetron sputtering, is promising. Measurements in the lab show that the naked alumina has an SEY of approximately 10. A 25 nm or 50 nm Cr_2O_3 coating applied by magnetron sputtering, reduces the maximum value to approximately 2.3: bombarding the surface with electrons further reduces the SEY to less than 1.4 (Fig. 8).

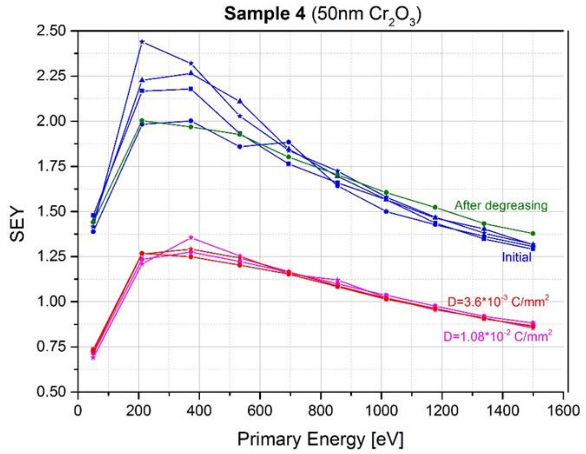

Figure 8: Measured SEY of 50 nm Cr_2O_3 coating, applied by magnetron sputtering on high-purity alumina (blue & green curves): bombarding the surface with electrons further reduces the SEY to less than 1.4 (red & cyan curves). [Measurements courtesy of E. Garcia-Tabares Valdivieso and H. Neupert].

Two sets of aluminium liners have been sputtered with the 50 nm Cr_2O_3 coating: these liners will be installed in the SPS, during the current EYETS, for tests with beam. The other set of liners will be installed in a multipacting setup.

MKI2D FLASHOVERS

Table 1: Electrical breakdowns of MKI2D during Run 2

Date	PFN Voltage	Pulse Length	Comments
30-Oct-15	50.8 kV	Top of rising edge, very close to magnet centre	Spark during SS
24-Jul-16	48.53 kV	~3.6 μs into flat-top, very close to magnet input	Spark during injection
02-Aug-16	50.7 kV	~2.5 μs into flat-top, very close to magnet input	Spark during SS

Table 1 summarizes the electrical breakdowns in magnet MKI2D (MKIMA-08 T-11 MC-09) during Run 2. Until mid-July 2016 there had been only a single electrical breakdown, and this occurred during a SoftStart (SS) at a PFN voltage ~1.3 kV above the normal operating voltage. On 24th July 2016 there was an electrical breakdown of the MKI2D magnet, during injection, close to the input of the magnet. On 2nd August 2016 there was another electrical breakdown of the MKI2D magnet, during a SS, again close to the input of the magnet: subsequently there was vacuum activity on every pulse (Fig. 9). Investigations showed that, for a given voltage, the breakdowns and thus vacuum activity were correlated with longer pulse lengths. Hence from August 2016 to TS3 2016 the MKIs were operated with ~3 μs field pulse flattop.

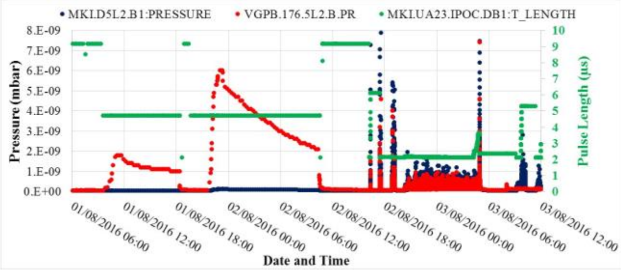

Figure 9: MKI2D tank pressure (blue), pressure on Q5 side of MKI2D (red) and pulse length (green).

The MKI2D magnet was exchanged during TS3, 2016, and thus no further activity is planned during the EYETS.

MKI2D HIGH IMPEDANCE CONTACT

During early October 2016 a high impedance contact issue developed in the MKI2D magnet, at the input end. This issue was characterized by this magnet not initially carrying current (Fig. 10): the dashed curves in Fig. 10 shown currents for MKI2C and solid curves for MKI2D – these two curves should be more or less identical..

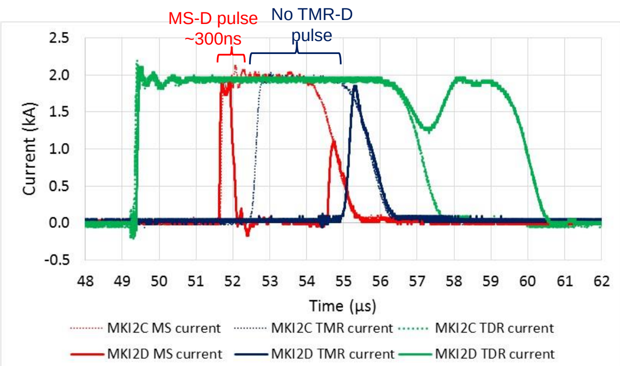

Figure 10: First pulse of a SS (at 20 kV): dashed curves are magnet MKI2C, solid curves are for MKI2D.

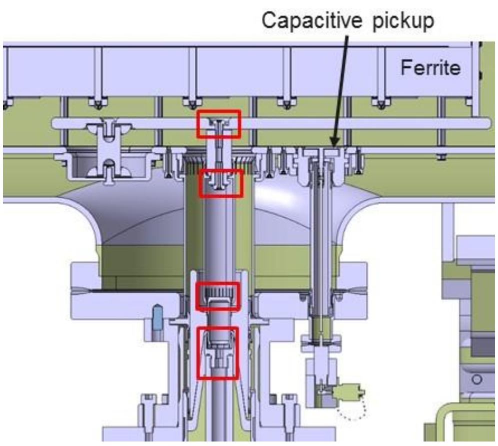

Figure 11: MKI input – red boxes show possible position of high impedance contact.

An analysis of the waveforms, combined with simulating faults using PSpice, show that the fault is likely due to a high impedance on or close to the feedthrough at the entrance of the magnet (Fig. 11). The MKI2D magnet was exchanged during TS3 2016 as the high impedance contact showed evidence of further deterioration. The removed MKI2D was carefully examined mid-January 2017: it was not possible to inspect, in the clean room, before this date due to the high priority of EYETS MKE and MKP preparation work. The inspection confirmed that the problem was a high impedance contact at the magnet input. Since MKI2D has already been exchanged, no further work is planned in the tunnel, for EYETS, concerning this magnet.

MKI2 SVM FAULTS

Surveillance Voltage Monitoring (SVM) of +5V and ±15V, for the MKI, was introduced during TS#1 and TS#2, 2016: the decision to do this was based on LBDS experience. The SVM system worked correctly until November 2016: subsequently non-existent faults started to be indicated by the SVM system, interlocking the MKI2 system – hence it was necessary to mask SVM signals. The source of the SVM faults is an incorrect value of resistors mounted on the PCB during hardware production and not detected during lab tests before installation. The concerned hardware will be returned for correction during EYETS and then reinstalled.

MKIs: ERRATIC TURN-ON

One Main Switch (MS) thyratron erratic (spontaneous turn-on), during resonant charging of the PFN in preparation for injection, occurred on 2nd September 2016 (on MKI2D system!): at the time there where 876 circulating bunches, of which approximately 210 were miskicked.

Since November 2014 there has been a total, for the two MKI systems, of ~1.2 million pulses. During 2015:

- 20% of the pulses were for injection;
- 80% of the pulses were during SoftStarts;
- Almost 60% of the pulses were at or above the nominal injection voltage.

Since November 2014 there has been a total of three erratics (all on MS's): one at each of P2 and P8 during SS's, both at voltages >2 kV above nominal. The erratic on 2nd September 2016 was the only one that occurred below nominal voltage.

Based on the above, the estimated probability of a Main Switch erratic during resonant charging is ~4×10^{-6} per pulse per system. The probability of an erratic occurring is known to be dependent upon the magnitude of the reservoir voltage of the thyratron. Hence, during the EYETS, the setting and output voltage of the reservoir power supplies will be checked.

SUMMARY

MKI2:

- Several issues occurred with MKI2D during 2016 including electrical breakdowns, a high impedance contact; and a Main Switch erratic;
- As a result of a deteriorating situation with the high impedance contact, magnet MKI2D was exchanged during TS3 2016;
- An upgrade of the MKI2D-Q5 vacuum sector is planned for EYETS to increase the pumping speed. This upgrade will reduce the conditioning time of the new MKI2D alumina tube with beam.

MKI8:

- No magnet exchange planned during EYETS;
- An upgrade of the MKI8D-Q5 vacuum sector is planned for EYETS to increase pumping speed. As a result the MKI8D-Q5 SIS interlock is no longer expected to limit injection with the nominal number of 25 ns bunches.

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