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Electron Ion Collider Machine Protection System: On the necessity of the MPS abort system for Rapid Cycling Synchrotron

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Electron Ion Collider Machine Protection System: on the necessity of the MPS abort system for Rapid Cycling Synchrotron

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1. Introduction

The Electron Ion Collider (EIC) accelerator complex includes multiple high-energy high-power accelerators [1]. Operation of such a complex is associated with numerous dangers of possible damage to the equipment.

The EIC machine protection system (MPS) scope is to protect the components of each accelerator from damage by the beam.

The EIC MPS design, commissioning and operation is closely interconnected with the protection of various accelerator subsystems, such as RF-system, cryogenics, vacuum system etc. Yet, the primary goal of the MPS is to protect the EIC accelerators from the possible damage caused by electron and proton beams.

There are two types of possible beam-caused damage: the direct beam deposit (DBD) on the in-vacuum components, and the excessive power load from synchrotron radiation of the e-beam.

The DBD includes, direct hit by the beam, excessive halo scraping, and possible radiation damage of sensitive equipment due to the DBD.

In this note we will consider whether a dedicated MPS abort system is required for the EIC Rapid Cycling Synchrotron (RCS).

The necessity for such a system is determined by an effect of the direct hit of the in-vacuum components by the e-beam. Below we will consider the possible failures causing the direct hit and the consequences of these failures.

2. Rapid Cycling Synchrotron

The RCS receives 400 MeV electron bunches with 2 Hz repetition rate and accelerates them to up to 18 GeV in 100 msec. The RCS parameters relevant for the MPS considerations are given in Table 1.

The design of the RCS, as well as of the other EIC accelerators, is a preliminary one. Therefore, all the considerations that follow will have to be revisited as the design features of the EIC are getting clarified.

Top energy [GeV]	5	10	18
Bunch charge [nC]	14	14	6
Number of bunches per injection cycle	2	2	2
Injection emittance (norm.) ε_x, ε_y [um]	20, 20	20, 20	55, 55
Extraction emittance (norm. after blow-up @ last 100 turns) ε_x, ε_y [um]			775, 115
Minimum β_x, β_y [m]	2.5, 2.5		
Repetition rate [Hz]	2		

Table 1: RCS parameters

3. Possible failures causing direct hit of RCS in-vacuum components

3.1. Direct hit at normal incident angle

Let's consider the most severe failure scenario - an e-bunch directly hitting the in-vacuum surface at normal incident angle. Such a scenario corresponds to either a vacuum valve being closed during the beam injection or ramp-up, or a bending magnet failure directing the beam to the crotch of the Y-shaped vacuum chamber (there must be a few of them if we use synchrotron radiation for the beam size measurements).

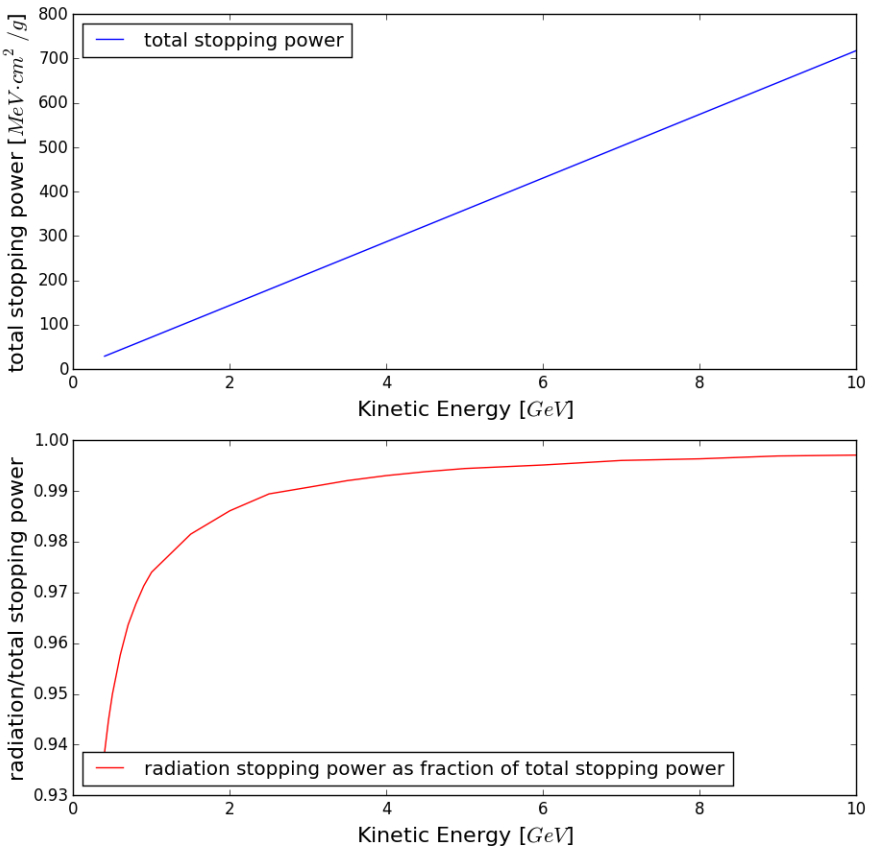


Figure 1: Stainless steel total and radiation stopping power for electrons.

Assuming, that the valves and vacuum chamber are made of stainless steel we calculate the stopping power and electron energy loss at various e-beam energies [2]. The NIST calculations based on provided stainless still composition and extrapolated to 18 GeV are shown in Fig. 1 and 2.

As one can see from Fig. 1 the total stopping power is rather high in the whole range of RCS energies, but most of this power will be lost in a form of radiation. The collision stopping power, which is a good approximation for calculating the "energy loss to heat" conversion, is shown in Fig. 2.

Assuming $w = 2$ mm for the width of the vacuum valve (or chamber) we can calculate both the "heat" energy loss per electron on a single hit and the total energy loss per hit relative to the beam energy.

As one can see from Fig. 3 the relative energy loss of the electrons is about 11-12% for the whole range of RSC energies. Assuming that the maximum RCS dispersion is about 0.8 m and taking 20 mm for the vacuum pipe radius, we can roughly estimate the RCS momentum acceptance to be about 2.5%. Therefore, the electron bunch will be lost on a single turn after colliding with the valve.

The highest "thermal" energy loss of $H = 3.4$ MeV/electron is happening at 18 GeV. Since the intentional emittance blow-up at 18 GeV is designed to happen only during the last 100 turns, the 18 GeV collision represents the most extreme case of a single hit event.

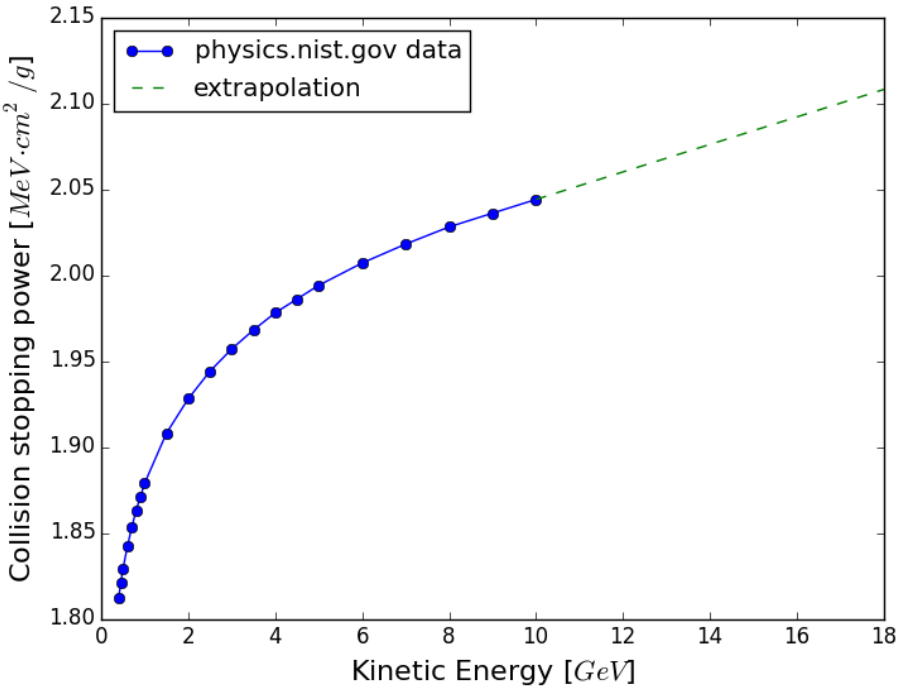


Figure 2: Stainless steel collision stopping power for electrons.

The minimum rms transverse size of the e-bunch at this energy is $\sigma_x = \sqrt{\frac{\varepsilon_x}{\gamma}\beta_x} \approx 62$ um. The thermal energy deposit on the hit surface for 2 bunches with total charge of 12 nC will be $E_b = 0.041$ J. Then the instantaneous temperature increase of the hotspot hit by a single e-bunch is:

$$\Delta T = \frac{E_b}{SHC \cdot \rho \cdot \pi\left(\sqrt{2}\sigma_x\right)^2 w} \quad (1)$$

Here, $\sqrt{2}\sigma_x$ is the radius of the transverse uniform distribution having the same density as the peak density of the Gaussian distribution with rms radius σ_x, the stainless steel specific heat capacity (*SHC*) is 502.4 J/(kg·K) and its density ρ=7999.5 kg/m^3.

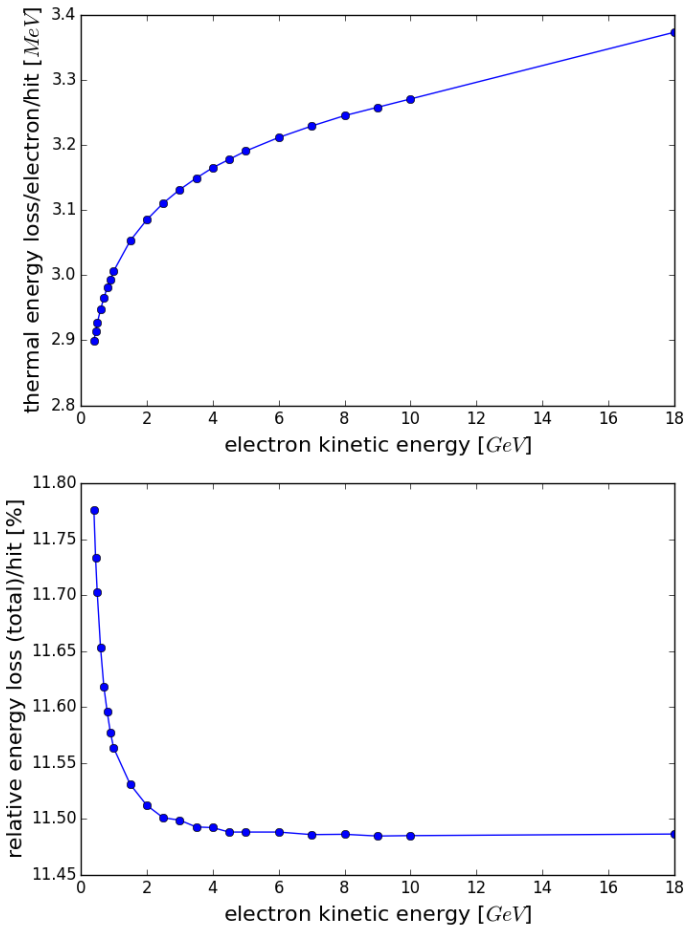


Figure 3: Electrons energy loss on a single hit.

Hence, the temperature increase of a hot-spot of an in-vacuum surface hit at normal incident angle by a single 18 GeV beam is $\Delta T_{18} = 207$ K.

In a similar fashion, the minimum size of the 5 GeV beam is 72 um. Then, from (1), for charge of 28 nC the temperature increase of a hotspot becomes $\Delta T_5 = 347$ K.

For 10 GeV beam, similar calculations give $\Delta T_{10} = 700$ K.

The stainless steel 304 melting temperature is 1450 C. Therefore, the single hit will not drill through the in-vacuum component.

On the other hand, an instantaneous temperature increase of 700 K of a spot with $1.6 \cdot 10^{-8}$ m^2 area will definitely cause stainless steel to reach its ultimate yield strength (590 Mpa). So, under the most severe failure scenario, mechanical damage to the in-vacuum components is possible even for a single hit.

Mitigation of such a failure requires aborting the RCS beam between the moment the failure is detected by the MPS and the moment the beam hits the in-vacuum surface. Of course, the continuous injection also must be interrupted upon detection of the failure.

Monitoring the valves in/out status (valve status is "in" as soon as its "out-position" sensor isn't touched), bending magnets current (with the DCCT measurements on the return current loop) and the BPMs can provide a fast response. The time before either of the considered failures causes the beam to hit the in-vacuum component is on the order of milliseconds (possibly, tens of milliseconds). This will define the requirement to the reaction time of the MPS and the rise time of the abort kicker.

3.2. Direct hit at grazing incident angle

Let's consider the tightly focused beam ($\beta_x = 2.5$ m) hitting the vacuum chamber at a grazing angle.

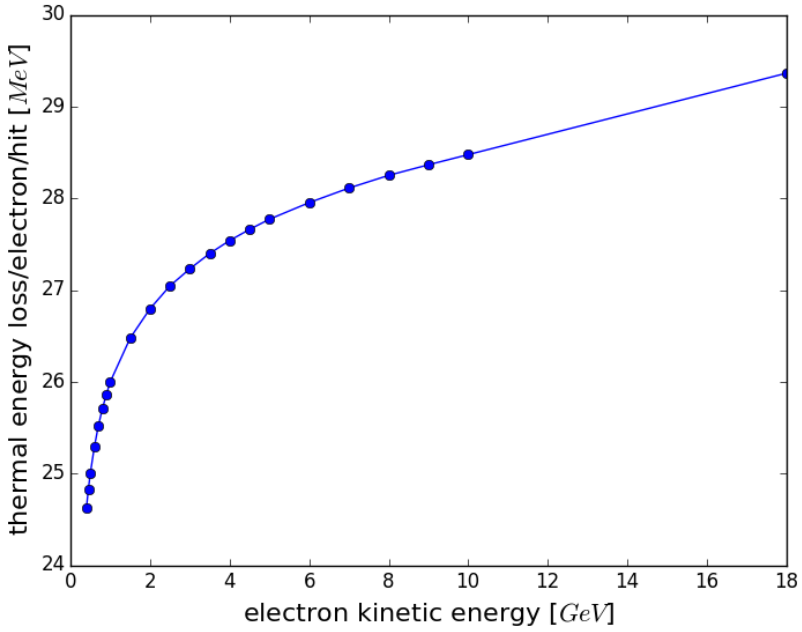


Figure 4: Electrons energy loss in vacuum chamber wall on a single hit at a grazing angle.

Since the vacuum chamber radius is *R*=20 mm and the maximum strength of *L*=0.6 m long quadrupole is $K_1 = 0.42$ m^{-2}, the maximum beam trajectory angle at quadrupole exit is about $\theta_q = K_1 LR = 5$ mrad.

Assuming one corrector per quadrupole scheme and assuming the strength of corrector $\theta_c = 5$ mrad, we get for the maximum grazing angle $\theta = \theta_q + \theta_c = 10$ mrad.

Then, the smallest thickness of material that e-bunch intercepts is $\frac{w}{\theta} = 200$ mm. The distance (*d*) that the electrons with kinetic energy (*K*) travel through the material is determined by the total stopping power (E_{st}) at this energy: $d = \frac{K}{E_{st}\rho}$. Then, from the collision stopping power (E_{col}) we can calculate an electron "thermal" energy loss in vacuum chamber material for various beam energies:

$$H = E_{col}\rho d = \frac{E_{col}K}{E_{st}} \quad (2)$$

For the whole range of the RCS beam energies $d \approx 17$ mm, which is order of magnitude smaller than $\frac{w}{\theta}$. Since the beam hitting vacuum chamber at grazing angle will be completely stopped, equation (2) is valid for estimating thermal energy loss. Figure 4 shows *H* calculated for various beam energies.

Assuming the hotspot on the vacuum chamber to be an ellipse with semi-axis of $\sqrt{2}\sigma_x$ and $\sqrt{2}\sigma_x/\theta$, we get from (1) $\Delta T_{10} = 62$ K. Of course, now the area of the hotspot is $\approx 1.6 \cdot 10^{-6}$ m^2.

The ANSIS studies performed for LEReC [3], showed that the hotspot with area of $\approx 4 \cdot 10^{-7}$ m^2 reaches the ultimate yield strength at 170 K temperature increase. Therefore, we expect no mechanical damage of the vacuum chamber due to a single electron bunch hitting it at 10 mrad angle.

Apparently, the EIC injection cycle must be interrupted upon detection of the considered failure.

The failure conditions can be detected by monitoring the BPMs. For example, in the RCS the largest beam Twiss $\beta \approx 160$ m. Hence, the largest rms beam size at the injection energy (400 MeV) is about 3.3 mm. It would suffice to keep the beam trajectory within $\mp 3\sigma_x \approx 10$ mm to guarantee that the direct hit is not happening.

Another important conclusion that we can draw is that the mitigation of the failure resulting in a normal incident angle hit (Section 3.1) does not require a dedicated abort dump. It is enough to have a dedicated MPS abort kicker spreading the e-beam along the vacuum chamber.

4. Summary

A possible failure resulting in the e-beam hitting the in-vacuum RCS component at a normal incident angle does require the dedicated MPS abort system.

The rise time of the abort kicker as well as the reaction time of the MPS will be determined by the fastest of the two processes: either the insertion of the vacuum valve or the drop in the bending magnet field. Most probably the time requirements will be on the order of a few (maybe a few tens of) milliseconds.

No dedicated beam dump is required for such a failure. The abort kicker must spread the beam along the RCS vacuum chamber.

Possible failures resulting in the beam hitting the RCS vacuum chamber at a grazing angle do not require any other mitigation than interrupting the continuous EIC injection cycle.

The following sub-systems must be monitored for the RCS MPS: BPMs, vacuum valves, bending magnets currents.

References

[1] Electron Ion Collider Pre-Conceptual Design Report, Report No. BNL-211943-2019-FORE, BNL (2019).

[2] NIST Stopping power and range tables for electrons, https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html

[3] S. Seletskiy et al., LEReC Machine Protection System, (2018).