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Electron Ion Collider Machine Protection System: Requirements for an Electron Storage Ring abort system

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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 hazards and risks 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 consider the machine protection against direct hit by the electron beam in the electron Storage Ring (ESR). We derive the requirements to the reaction time of the ESR MPS and define the main parameters of the ESR emergency abort system, which includes an abort kicker, an extraction line and a dump.

2. Electron Storage Ring

Beam energy [GeV]	5	10	18
Bunch charge [nC]	27.5	27.5	10
Number of stored bunches	1160	1160	290
Geometric emittance $\varepsilon_x/\varepsilon_y$ [nm]	20/2	20/1.2	24/2

Table 1: ESR parameters

The ESR stores the electron beam at three energies 5, 10 and 18 GeV. The beam parameters relevant to the MPS considerations are given for each energy in Table 1.

For this exercise we assume a copper vacuum chamber. We also assume that the ESR is equipped with stainless steel vacuum valves.

3. Possible failures causing direct hit of ESR 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 store, 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).

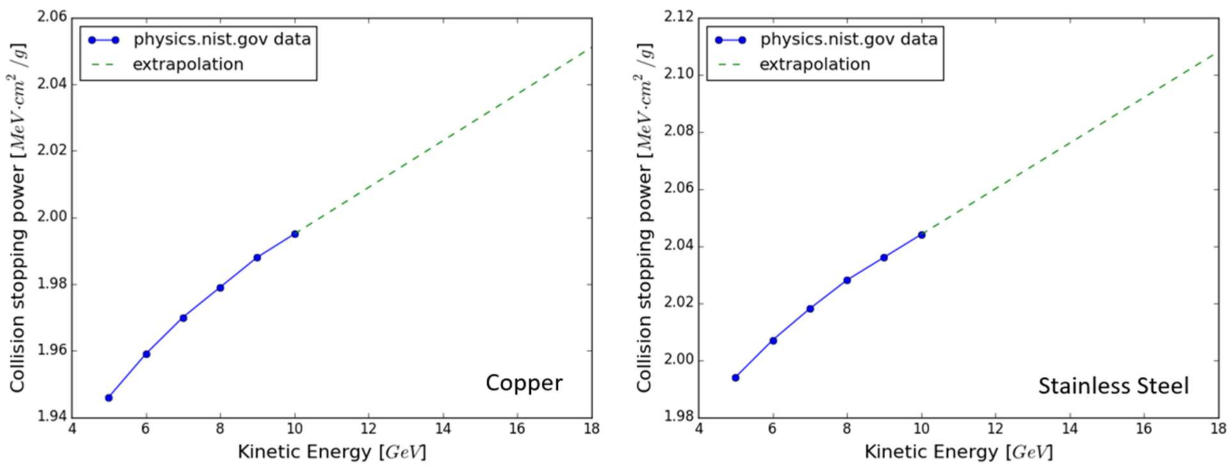

Figure 1: Copper and stainless steel collision stopping power for electrons.

The NIST calculations [2] (with extrapolation to 18 GeV) for the collision stopping power, which is a good approximation for calculating the "energy loss to heat" conversion, are shown for both stainless steel and copper in Fig. 1.

Assuming $w = 2$ mm for the width of the vacuum valve (or chamber) we can calculate the "heat" energy loss per electron on a single hit for various electron energies.

For the most dangerous case of 10 GeV electrons, the energy converted to heat for copper and stainless steel is respectively $H_{Cu} = 3.57$ MeV/electron and $H_{StSt} = 3.27$ MeV/electron.

We farther make a generous assumption of $\beta_x = 10$ m and $\beta_y = 25$ m for horizontal and vertical beta-functions at the hit location. The thermal energy deposit on the hit surface for 1160 bunches with a charge of 27.5 nC/bunch is $E_b = 104$ J for stainless steel and is $E_b = 116$ J for copper. Then, the instantaneous temperature increase of the hotspot hit by e-beam is:

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

Here, $\sqrt{2}\sigma_{x,y}$ are the semi axes of the transverse uniform distribution having the same density as the peak density of the Gaussian distribution with rms sizes $\sigma_{x,y}$, *SHC* is the specific heat capacity of the material (385 J/kg/K for copper and 502 J/kg/K for stainless steel) and ρ is the material density (8960 kg/m^3 for copper and 8000 kg/m^3 for stainless steel).

Substituting the relevant numbers in (1) we get the instantaneous temperature increase of the hot spot of $\Delta T_{StSt} = 2.7 \cdot 10^4$ K and $\Delta T_{Cu} = 3.5 \cdot 10^4$ K for stainless steel and copper respectively. Of course, such an enormous temperature jump will immediately melt the material at the point of impact.

The direct hit of in-vacuum components at normal incident angle must be avoided at any cost. The failures causing such a hit are relatively slow (most probably in tens of milliseconds range) and can be detected before the beam impact happens.

To protect the ESR from the "normal incident angle hit" the MPS must be monitoring the readings of "out" position limiters on all the ESR vacuum valves and the return current (read by dedicated DCCTs) of each bending magnet.

3.2. Direct hit at grazing incident angle

Let's consider the electron beam hitting the vacuum chamber at a grazing angle (θ).

The distance (d) that the electrons with kinetic energy (K) travels through the material is determined by the total stopping power (E_{st}) at this energy: $d = \frac{K}{E_{st}\rho}$. If $d \leq \frac{w}{\theta}$, then from the collision stopping power (E_{col}) we can calculate an electron's "thermal" energy loss (H) in the vacuum chamber wall for various beam energies:

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

For the whole range of the beam energies $d \approx 14$ mm, which is much shorter than $\frac{w}{\theta}$ even for angles of tens of milliradians.

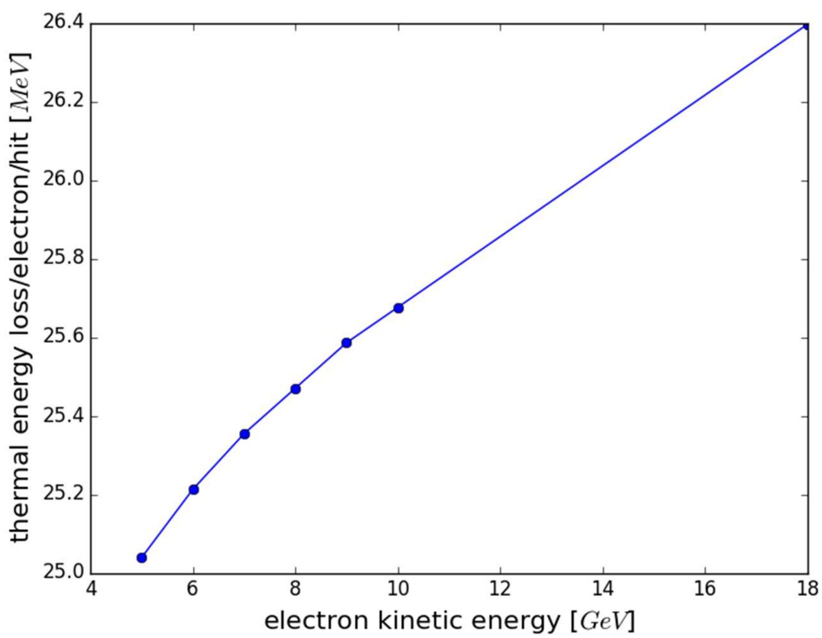

Figure 2: Electrons energy loss in vacuum chamber wall on a single hit at a grazing angle.

Figure 2 shows the thermal deposit for various electron energies calculated according to Eq. (2).

Assuming the hotspot on the vacuum chamber to be an ellipse with semi-axis of $\sqrt{2}\sigma_x$ and $\sqrt{2}\sigma_y/\theta$, we get from Eq. (1) for 10 GeV beam the hot spot temperature increase depending on angle of incident (see Fig. 3).

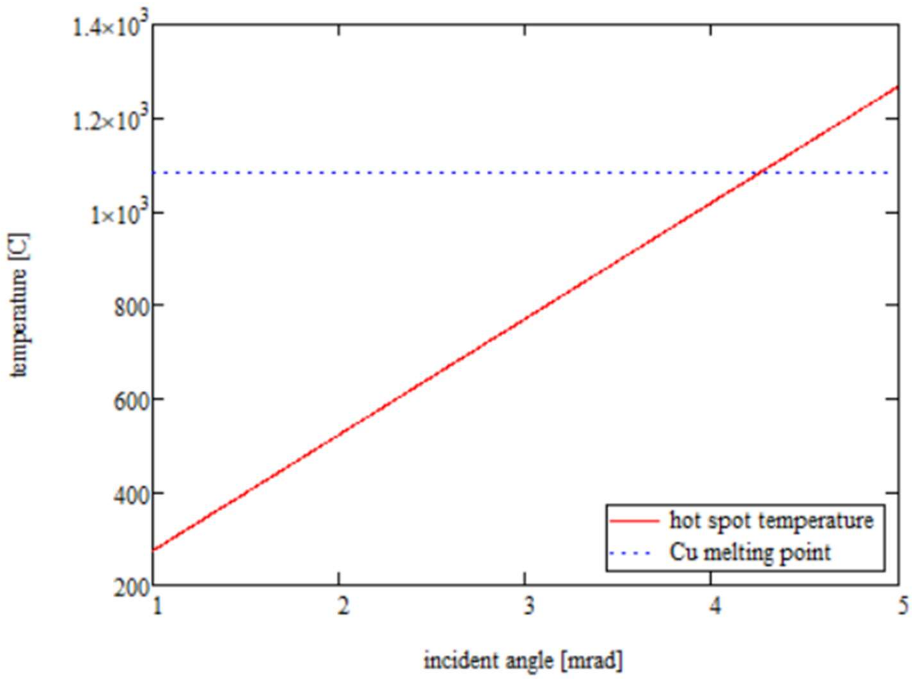

Figure 3: Temperature increase of the hot spot depending on the incident angle.

Apparently, one has to avoid the vacuum chamber hit by the full e-beam even at a grazing angle. The failure conditions resulting in such a hit can be detected by monitoring the ESR BPMs as well as a dedicated system of fast beam loss monitors. The reasonable requirement to the MPS reaction time is to fire the emergency abort kicker after detecting the failure in a timeframe of a single turn in the ESR, which is about 12 μs. Although the required reaction time is short, it was demonstrated in an operational MPS [3] that an overall reaction time (from the moment of the failure to the beam abort) of better than 5 μs is achievable.

4. Requirements to emergency abort system

The emergency abort kicker must extract the full e-beam from the ESR within one turn (~12 μs) upon detection of the failure conditions.

The dump must be able to absorb in a single shot the full energy stored in the electron beam. Let us assume that the dump is made of stainless steel. The thermal energy loss of the fully stopped electron beam can be calculated from Eq. (2). For the most dangerous case of 10 GeV operations the thermal energy load from the full e-beam is 909 J. For the full range of ESR energies the electrons will be completely stopped by about 17 mm of the stainless steel. The hot spot temperature rise after a single instance of the beam deposit can be calculated from Eq. (1). Figure 4 shows dependence of the hot spot temperature increase on the size of the hot spot (here we assume a round beam on the dump).

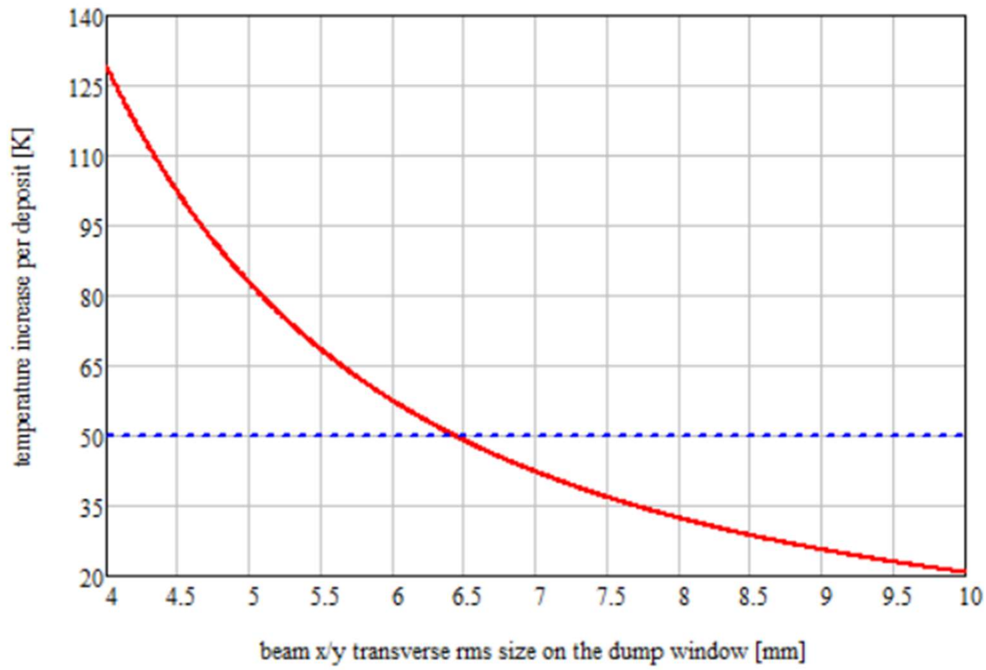

Figure 4: Temperature increase of the hot spot depending on the rms beam size.

Requesting that the temperature increase per deposit is less than 50 K we get $\sigma_{x,y} \geq 6.5$ mm.

Inclining the dump surface vertically so that it makes $\theta_y = 15°$ with respect to the direction of the beam motion, we get a requirement of $\beta_x = \beta_y \geq 2300$ m for beat-functions at the dump location.

Assuming that the injection is happening with the 2 Hz rate with 28 nC per injection, the minimal time between emergency aborts of the full beam is 580 s. That gives the maximum power load for the emergency dump of 1.6 W.

The extraction line must be equipped with warm quadrupoles. Assuming 3-inch inner diameter for the quadrupoles and limiting the pole-tip field to 1 T we get $K_1 = 0.44$ m^{-2} for the quadrupole strength. A toy-example of the extraction line including three 0.5 m long quadrupoles is shown in Fig. 5.

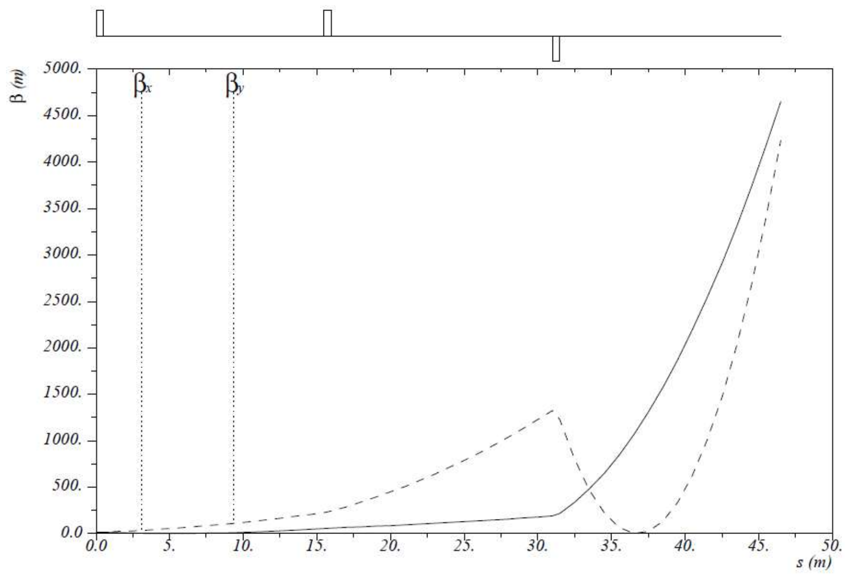

Figure 5: A toy example of the emergency extraction line.

5. Summary

The ESR MPS must be able to extract the stored electron beam in less than 12 μs upon detection of fault conditions. Both the BPMs and the BLMs must be employed as fast MPS diagnostic subsystems.

The emergency abort system must be equipped with a one turn kicker.

The abort dump can feature as an impact surface a 2 cm thick stainless steel plate vertically inclined by 15 degrees with respect to the beam direction. The dump cooling system must provide 1.6 W cooling capacity.

The beam beta functions at the dump must be larger than 2300 m. The extraction line must be equipped with several warm quadrupoles providing the required beam expansion.

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., Status of the BNL LEReC machine protection system, Proceedings of IBIC2018 (2018).