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Localized Beampipe Heating due to e^- Capture and Nuclear Excitation in Heavy Ion Colliders

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Abstract

At heavy ion colliders, two major sources of beam loss are expected to be e^+e^- production, where the e^- is bound to one of the nuclei, and photonuclear excitation and decay via neutron emission. Both processes alter the ions charged to mass ratio by well defined amounts, creating beams of particles with altered magnetic rigidity. These beams will deposit their energy in a localized region of the accelerator, causing localized heating, The size of the target region depends on the collider optics. For medium and heavy ions, at design luminosity at the Large Hadron Collider, local heating may be more than an order of magnitude higher than expected. This could cause magnet quenches if the local cooling is inadequate. The altered-rigidity beams will also produce localized radiation damage. The beams could also be extracted and used for fixed target experiments.

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I. INTRODUCTION

Ion colliders are expected to lose beam particles via ion-ion collisions. Besides purely hadronic interactions, photonuclear interactions are of considerable interest [1] [2] and many electromagnetic processes have cross sections larger than the hadronic cross section. Two electromagnetic processes are expected to be major sources of beam particle loss: production of e^+e^- pairs by the colliding electromagnetic fields, where the electron is produced bound to one of the nuclei, and the excitation of one nucleus by the electromagnetic field of the other. In the latter case, the nucleus will be excited to a Giant Dipole Resonance (GDR) or higher state. Usually, the GDR decays by emitting one or more neutrons.

Both of these interactions alter the mass to charge ratio (rigidity) of the affected ion. For the heavy ions like gold or lead, the rigidity increases about 1% for electron capture, and decreases about 0.5% for neutron loss. For lighter ions, the change is larger. Because these changes are larger than the acceptance of the magnetic optics, these ions are lost from the beam, and eventually strike the beam pipe. The hadronic showers from these collisions will deposit their energy in the cryogenic magnets around the beampipe. Averaged over the entire ring, the energy deposition is small. However, because of the well defined rigidities, the target area is a small fraction of the ring, and localized heating and radiation damage may be a problem. The altered rigidity beams could also be extracted from the collider and used as a test beam.

Here, we consider these reactions for the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory [3] and the Large Hadron Collider (LHC) now under construction at CERN [4]. Table I lists energies and luminosities for the systems considered here. For the LHC, different sources quote somewhat different luminosities. This paper will use the peak (initial) luminosities given in the RHIC conceptual design report and the ALICE proposal for the LHC. The LHC luminosities are for 125 nsec bunch spacing and collisions in 1 experimental hall [4]. If the bunch spacing is decreased to 25 nsec, the luminosity increases by a factor of 5.

II. E^+E^- PRODUCTION AND E^- CAPTURE

The electromagnetic fields of the colliding nuclei may interact and produce e^+e^- pairs. The electron can be produced bound to one of the nuclei, reducing the net charge by 1; usually the electron is captured by the K-shell.

The cross section for pair production and electron capture can be calculated using a number of techniques. Although some coupled channel calculations have found very high cross sections, new all-orders analytic calculations support the results of perturbative calculations [5], despite the large coupling constant, $Z\alpha \sim 0.6$. For beams of identical nuclei, the cross section for capture to a K-shell by a charge Z nucleus is [6] [2]

$$\sigma(A + A \rightarrow Ae^- + A + e^+) = \frac{33\pi Z^8\alpha^6 r_e^2}{10} \frac{1}{e^{2\pi\alpha Z} - 1} \Big[\ln \big(\frac{\delta(\gamma^2 - 1)}{2} \big) - \frac{5}{3} \Big] \tag{1}$$

where $\alpha = e^2/\hbar c$ is the fine structure constant, r_e the classical electron radius, γ the Lorentz boost of a single beam, and $\delta \sim 0.681$. This is the cross section to excite a specific nucleus; the cross section to excite either nucleus is twice as large.

The effect of inclusion of higher shells is to boost this cross section by 20% [6]. With this correction, the cross sections are given in Table I; the cross sections drop dramatically as Z decreases; the energy dependence is moderate.

A recent extrapolation from lower energy data [7] found higher cross sections, 94 barns for gold at RHIC and 204 barns for lead at the LHC, twice the perturbative result. If this result is correct, then heating will be twice that predicted.

The particle loss rates, the products of these cross sections and the luminosity, are given in Table II. The very strong Z dependence of the cross section is compensated by the rapid luminosity increase as Z decreases, and the particle losses are largest for medium ions. Table II also gives the single beam energy losses, which scales with the atomic number A. Because the escaping positron has a very small momentum, the tiny nuclear momentum change will not affect the rigidity.

III. NUCLEAR EXCITATION

Many types of electromagnetic excitation are possible for nuclei. Single or multiple photon absorption is possible, and the excited states can decay via single or multiple neutron emission or by nuclear breakup. The most common is a Giant Dipole Resonance (GDR), where the protons and neutrons oscillate collectively against each other. GDRs usually decay by single neutron emission. Because of its large cross section, we focus on GDR excitation and single neutron decay. Higher resonances typically have more complex decays, often involving multiple neutrons.

The cross section for photonuclear excitation of a given nucleus is

$$\sigma(A + A \rightarrow A_{GDR} + A) = \int_0^\infty \frac{dn_\gamma}{dk}\sigma_{GDR}(k)dk \tag{2}$$

where k is the photon energy, dn_γ/dk is the Weizsäcker-Williams photon spectrum, subject to the condition that the nuclei don't interact hadronically [2] [8], and $\sigma_{GDR}(k)$ is the GDR excitation cross section. For heavy nuclei, the cross section peaks $k = 31.2A^{-1/3}$ MeV + $20.6A^{-1/6}$ MeV [9]. For symmetric systems, the cross section can be parameterized [10]

$$\sigma(A + A \rightarrow A_{GDR} + A) = 3.42\mu b\frac{(A-Z)Z^3}{A^{2/3}}\ln{(2\gamma^2 - 1)}. \tag{3}$$

Because this formula does not include other photoexcitation processes this cross section is lower than some quoted elsewhere. For example, Ref. [4] gives a formula for GDR electromagnetic dissociation with a coefficient about 20% higher than Eq. (3). The cross sections from Eq. (3), listed in Table I, are less well determined than for electron capture, because of competition with higher order processes, which can lead to multiple neutron emission. For lower energy gold interactions, the cross section for 2-neutron emission is about 20% of single neutron emission cross section [11]. Of course, this ratio could rise at higher energies. For lighter nuclei, the higher order processes should be much less important. Since Eq. (3) fits existing low energy data fairly well, we use it here.

For heavy ions, these cross sections are comparable to those for electron capture. Table II shows single beam loss rates for GDR excitation. For heavy ions, losses are comparable with electron capture. Because GDR excitation is much less Z-dependent than electron capture, it is the dominant process for lighter ions. Losses range up to 1.6 million particles/second and 36 watts for calcium at the LHC.

Unlike electron capture, with neutron emission, the nuclear recoil is significant. The $\gamma + A \rightarrow (A-1) + n$ reaction is a two-body problem; neglecting the small change in binding energy, in the rest frame the nuclear recoil momentum is $p_{exc.} = \sqrt{2m_n k}$, where m_n is the nucleon mass. In the lab frame, the nuclear momentum change is a maximum of $\Delta/p = p_{exc.}/Am_n$, depending on the emission direction.

IV. TARGET REGION

Because the rigidity change is small, the affected nuclei will strike the beampipe a considerable distance down the beampipe, with the exact location depending on the beam optics. Here, we consider a simple model, with the nuclei in circular orbits in a constant magnetic field. The radius of curvature is $R = p_A/ZecB$, where p_A is nuclear momentum and B the magnetic field. For an intact nucleus, R must match the accelerator radius R_0.

Electron capture decreases Z by 1, so the radius of curvature increases to $R = Z/(Z-1)R_0$, a change of $\Delta R = R_0/Z$. The trajectory will gradually be displaced outward from the beampipe centerline, with the displacement from the center growing as the square of the distance travelled. If the nucleus travels an angle θ around the accelerator, the displacement is $x = 2\Delta R\theta^2/\pi^2$. It will strike a beampipe with radius d after moving an angle $\sqrt{\pi d/2\Delta R}$, a distance

$$D_c = \theta R_0 = \pi\sqrt{\frac{R_0 Z d}{2}} \tag{4}$$

downstream from the interaction region. In the RHIC magnets, $d = 3.45$ cm [3] while for LHC the horizontal magnet opening is $d = 4.4$ cm [12]. Values of D_c are listed in Table IV.

Neutron loss decreases the rigidity by a factor $(A-1)/A$, reducing the radius of curvature to $R = (A-1)/AR_0$. With $\Delta R = R_0/A$, the nucleus will hit the beampipe a distance

$$D_d = \pi\sqrt{\frac{R_0 A d}{2}} \tag{5}$$

downstream. Table IV gives values of D_d. Since $A \sim 2Z$, $D_d \sim \sqrt{2}D_c$.

D_c and D_d are the distances to the middle of the target regions; the length of the target region depends on the spreading of the altered beam. Several factors contribute to the spreading: the momentum spread of the incident beam, nuclear recoil (for GDR excitation), and the size of the hadronic shower when the particle hits the beampipe. Focusing from the beam optics will also have a big effect; this factor is neglected here. We simply assume that the optics remove the effect of perpendicular momentum variations, leaving the longitudinal momentum variations unaffected. We will add the rms momentum spreading for each of these factors in quadrature, neglecting corrections due to the non-Gaussian nature of the distributions.

RHIC is designed for a maximum momentum spread, $\Delta p/p = 1.5 \times 10^{-3}$ [3] [13]. At the LHC $\Delta p/p = 10^{-4}$ [14]. These $\Delta p/p$ are maximum variation; $\sigma p/p \approx (1/\sqrt{3})\ \Delta p/p$. These numbers are typical; with time, intra-beam scattering and beam-beam interactions increase the momentum spread.

The momentum spread also affects the radius of curvature, with $\sigma R/R_0 = \sigma p/p$. Neglecting magnetic focusing, an intact beam particle with individual momentum variation δ will hit the beampipe a distance

$$D_\delta = \pi\sqrt{\frac{Rd}{2(|\delta|/p)}} \tag{6}$$

downstream from the interaction region. Without magnetic focusing, particles with $\delta/p = \sigma p/p$ would strike the beampipe 118 meters and 12 km downstream at RHIC and LHC respectively.

For GDR excitation, the recoil from the neutron emission affects the ion momentum. $p_{exc.}$ is the maximum momentum change; this can be approximated as a Gaussian with $\sigma p/p \approx 0.6 p_{exc}/p_A$. This $\sigma p/p$ is added in quadrature to the beam spread. It is usually the dominant factor.

The interactions and momentum changes are combined by adding the σR, with

$$D_\pm = \pi R \sqrt{\frac{d}{2\sigma R_\pm}} \tag{7}$$

where $\sigma R_\pm$ are found by adding and subtracting the σR due to momentum spread from the σR from the rigidity change. Energy is deposited over a length $L = D_+ - D_-$. Assuming that the individual particle momenta follow a Gaussian distribution, 68% of the particles hit within this target area. These L, given in Table IV, are small compared to $D_\pm$. The small $L : D$ ratio is an indication that magnetic focusing will not drastically change the picture presented here.

When the nucleus hits the beampipe, the size and shape of the hadronic shower depend on the target geometry and magnetic field. This will affect how much of the energy is deposited in the cryogenically cooled magnet. The magnet assembly can be approximated as copper [15], which has a hadronic interaction length $\Lambda = 15$ cm. At 100 GeV/nucleon (3.5 TeV/nucleon), 99% (95%) of the energy is deposited within 10Λ [14], or 1.5 meters. Most of this energy is deposited within a few Λ of the point of maximum shower development; we treat the energy deposition as a Gaussian, with $2\sigma = 6\Lambda$=0.9 meters. This 2σ is added in quadrature with L to give the total target length. So, 68% of the total energy should be deposited within this region.

Of course, some of the energy will escape down the beampipe or into the surrounding environment. Here, we assume that half of the energy reaches the cold volume, with the other half escaping. With these assumptions, the average power dissipations are given in Table V. Even though the electron capture and GDR beams have similar power, the energy deposition is more localized for electron capture because of the GDR nuclear recoil. Lead and niobium are the most problematic, depositing 2.1 W/m and 3.0 W/m respectively.

These loads must be compared with the local cooling capacity. The RHIC Conceptual Design Report does not specify a value for beam induced heating loads. However, at 4^oK, 2.5 Watts of cooling is planned for a 9.7 meter long dipole [3]. The power dissipations are far smaller than this.

At the LHC, the expected heat loads are much higher. The main sources, synchrotron radiation and image currents are expected to deposit 0.6 W/m and 0.8 W/m on the beampipe respectively. A screen will be installed inside the magnets to divert this heat from the 1.9^{o}K magnets [16]; less than 0.1 W/m is expected to leak through the screen. The accelerator design also allows for 0.1 W/m from inelastic nuclear scattering which cannot be shielded [12], for a total of 0.2 W/m. Because of the low luminosity, synchrotron radiation and image currents are negligible for ion collisions, so the entire 0.2 W/m could be 'allocated' to beam losses. This 0.2 W/m is less than 10% of the 2.1 and 3.0 W/m expected from electron capture for lead and niobium beams.

The local temperature rise from this energy will depend on the local cooling capacity and thermal resistance. At 7 TeV, a loss of 8×10^6 protons/meter/second will induce a quench [15]; this is about 8 watts/meter, uncomfortably close to the heat loads calculated above.

Since the altered-rigidity beams will remain in the horizontal plane of the accelerator, and strike the outside (for electron capture) and inside (for GDR excitation) of the beampipe, the heating will be uneven, and local hot spots are likely. These hot spots could induce a quench even if the average power is below the quench limit.

V. DISCUSSION

At RHIC, the local heating due to altered-rigidity beams is within the available cooling capacity. At the LHC, these altered rigidity beams have higher powers, up to 36 watts. At the same time, the target regions are shorter than at RHIC, and the cooling capacities are somewhat lower, because the LHC uses supercooled magnets. With niobium beams, the expected heating is 3.0 W/m, 15 times the expected beam heat load of 0.2 W/m. For lead, the 'standard' ion choice, the heating is 2.1 W/m, 10 times the expected load.

These loads are close to the expected quench limit of 8 W/m. When the detailed distribution of energy deposition is considered, electron capture from either lead or niobium beams might deposit enough energy to cause a magnet quench. With GDR, the heat loads are lower, but may be problematic for niobium and calcium beams.

These estimates are based on back-of-the-envelope calculations; the uncertainties are correspondingly large. The most important missing factors are the charged particle optics and the magnet arrangement. The former could change the pattern of the energy deposition, by decreasing or increasing the length of the target area, while the latter determines how the energy affects the magnet. Detailed simulations are needed to study both factors. At the LHC, a calculation using the magnetic dispersion finds target regions with $L = 1$ m for lead, 30% smaller than was found here [18].

However, for lead and niobium, it is not unlikely that supplementary cooling will be required. Alternately, it might be possible to install new collimators to channel the energy deposition. Current LHC plans call for a single collimator, located in one of the interaction regions [19].

In higher-luminosity scenarios, the heating can be up to five times higher. In these scenarios, localized energy deposition could be the luminosity limiting factor.

The beams will also deposit significant radiation in these regions. Although radiation damage is beyond the scope of this article, current studies neglect this source [17].

Finally, it might be possible to extract these altered-rigidity beams and use them for fixed target experiments. Electron capture beams are the most appropriate for extraction, because of the smaller emittance. The particle rates are comparable to those at existing fixed target heavy ion accelerators. At the LHC, the beam energies would exceed existing fixed target sources.

VI. CONCLUSIONS

Both pair production with capture and nuclear excitation with neutron emission produce beams of ions with altered magnetic rigidity. These beams will follow defined trajectories and strike the collider beampipe downstream of the interaction regions, producing localized energy deposition.

At RHIC, this energy deposition is small, and should not cause problems. However, with lead, niobium or calcium beams at the LHC, simple calculations indicate that the energy deposition will be far larger than the planned cooling. Further studies are needed to confirm these simple models. If the local heating exceeds the available cooling, the magnets could quench; electron capture could limit the luminosity achievable with heavy or medium ions. In addition, these beams could cause localized radiation damage. These problems become even worse for high luminosity running, with 25 nsec spacing between heavy ion bunches.

On the positive side, with appropriate optics, these beams could be extracted and used for fixed target experiments.

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Machine	Ion	Beam Energy	Design Luminosity	σ (e^- capture)	$\sigma(GDR)$
RHIC	gold	100 GeV/n	$2 \times 10^{26} cm^{-2}s^{-1}$	45 b	58 b
RHIC	iodine	104 GeV/n	$2.7 \times 10^{27} cm^{-2}s^{-1}$	6.5 b	15 b
RHIC	silicon	125 GeV/n	$4.4 \times 10^{28} cm^{-2}s^{-1}$	1.8 mb	150 mb
LHC	lead	2.76 TeV/n	$1 \times 10^{27} cm^{-2}s^{-1}$	102 b	113 b
LHC	niobium	3.1 TeV/n	$6.5 \times 10^{28} cm^{-2}s^{-1}$	3.1 b	10 b
LHC	calcium	3.5 TeV/n	$2 \times 10^{30} cm^{-2}s^{-1}$	36 mb	800 mb
LHC	oxygen	3.5 TeV/n	$3 \times 10^{31} cm^{-2}s^{-1}$	81 μb	37 mb

TABLE I. Luminosity and beam kinetic energy for heavy ion beams at RHIC and LHC. The RHIC luminosities are from Ref. [3]. Different references quote somewhat different ion luminosities for the LHC; these are the peak luminosities for a single experiment and 125 nsec bunch spacing from Table 8.3 of Ref. [4]. Also given are cross sections for electron capture and for electromagnetic GDR excitation followed by single neutron emission.

Beam	Capture Loss (pps)	Capture Power Loss	GDR loss (pps)	GDR Power loss
RHIC - Au	8,900	28 mW	12,000	37 mW
RHIC - I	18,000	37 mW	40,000	85 mW
RHIC - Si	82	46μW	6,500	3.6 mW
LHC- Pb	102,000	10. W	113,000	11 W
LHC- Nb	196,000	9.1 W	650,000	30 W
LHC- Ca	73,000	1.6 W	1,600,000	36 W
LHC- O	2,400	22 mW	1,100,000	10 W

TABLE II. Single Beam loss rates, in particles per second (pps), and single beam power losses, for electron capture and GDR excitation.

Accelerator	Mean Accelerator Radius	Beam Pipe Radius	$\Delta p/p$
RHIC	610 m	3.45 cm	1.5×10^{-3}
LHC	4245 m	4.4 cm	1×10^{-4}

TABLE III. Some characteristics of RHIC and LHC. The accelerators are not perfectly circular; the radius is calculated from the overall circumference. The beampipe radius is the horizontal aperture inside the magnets. The momentum spread is somewhat ion-dependent. The spread will increase gradually as the beams circulate and collide.

Beam	Capture-Distance	Capture L	GDR Distance	GDR L
RHIC - Au	91 m	6.2 m	143 m	28 m
RHIC - I	74 m	3.4 m	115 m	18 m
RHIC - Si	38 m	0.5 m	54 m	7 m
LHC- Pb	275 m	1.3 m	438 m	44 m
LHC- Nb	194 m	0.5 m	293 m	32 m
LHC- Ca	136 m	0.16 m	192 m	23 m
LHC- O	86 m	0.04 m	121 m	16 m

TABLE IV. Beam impact point (distance from the interaction region) for electron capture and GDR excited nuclei, based on a simple geometric model. The L columns show the variation in impact distance due to the beam momentum spread and, for GDR excitation, including nuclear recoil; the recoil usually dominates over the accelerator energy spread. The hadronic shower development is not included.

Beam	Capture Power Dissipation	GDR Power Dissipation	Cooling Capacity
RHIC - Au	1.5 mW/m	0.4 mW/m	-
RHIC - I	3.6 mW/m	1.6 mW/m	-
RHIC - Si	15 μW/m	0.2 mW/m	-
LHC - Pb	2.1 W/m	0.1 W/m	0.2 W/m
LHC - Nb	3.0 W/m	0.3 W/m	0.2 W/m
LHC - Ca	0.6 W/m	0.5 W/m	0.2 W/m
LHC - O	82 mW/m	0.2 W/m	0.2 W/m

TABLE V. Power dissipation per unit length for electron capture and GDR excitation. Both dissipations assume 68% of the power is deposited within a $\pm 1\sigma$ target region, where the σ includes the momentum spread, GDR recoil, and hadronic shower. Half of this energy is assumed to end up in the magnet, with the other half escaping. Also shown, for comparison, is the planned cooling capacity at the LHC. If the LHC uses a 25 nsec bunch spacing to increase the luminosity, the dissipation will grow by a factor of 5.