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Performance Limitations In High-Energy Ion Colliders

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PERFORMANCE LIMITATIONS IN HIGH-ENERGY ION COLLIDERS*

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Abstract

High-energy ion colliders (hadron colliders operating with ions other than protons) are premier research tools for nuclear physics. The collision energy and high luminosity are important design and operations considerations. The experiments also expect flexibility with frequent changes in the collision energy, detector fields, and ion species, including asymmetric collisions. For the creation, acceleration, and storage of bright intense ion beams limits are set by space charge, charge exchange, and intrabeam scattering effects. The latter leads to luminosity lifetimes of only a few hours for intense heavy ions beams. Currently, the Relativistic Heavy Ion Collider (RHIC) at BNL is the only operating high-energy ion collider. Later this decade the Large Hadron Collider (LHC), under construction at CERN, will also run with heavy ions.

1 INTRODUCTION

High-energy ion colliders are premier research tools for nuclear physics. The collisions of high-energy ions creates matter of a temperature and density that existed only microseconds after the Big Bang. In RHIC this new form of matter was found to behave like a perfect liquid, and is often referred to as the strongly interacting quark gluon plasma or sQGP [1].

To study the phase transition from nuclear matter to the quark gluon plasma a sufficiently high center-of-mass energy, and large integrated luminosities are required. In addition, a large degree of flexibility in the machine operation is needed, with frequent changes in the collision energy, detector fields, and colliding species. This includes, as an important control experiment in the physics program, the collision of light with heavy nuclei.

Currently RHIC is the only existing heavy ion collider, and a machine dedicated to nuclear physics research. In a second scientific program at RHIC, based on the collision of polarized proton beam, the spin structure of the proton is studied, in particular the degree of polarization of the gluons and antiquarks [2, 3]. The LHC, under construction at CERN [4], will begin operation in a few years. Besides its high energy program, based on proton-proton collisions, it will also have a significant heavy ion program. The main parameters of both machines are shown in Tab. 1. Fig. 1 shows the nucleon-pair luminosity (Eq. (2)) that RHIC has

Table 1: Main operating parameters for the heaviest ions in RHIC and LHC [4, 22].

parameter	unit	RHIC achieved	LHC design
circumference C	km	3.8	26.6
heaviest ion	...	$^{197}Au^{79+}$	$^{208}Pb^{82+}$
maximum energy	GeV/n	100	2759
bunch intensity	10^9	1.1	0.07
bunch number	...	45	592
peak luminosity	$10^{26}cm^{-2}s^{-1}$	15	10
luminosity lifetime	h	2.5	< 6

delivered to one of its experiments, illustrating the demand for luminosity and different species. Tab. 2 lists all RHIC running modes and the total delivered luminosities to date. In the following performance limiting effects in the preparation and acceleration of ion beams are reviewed, as well as luminosity limitations of colliding beams.

2 ION BEAM PREPARATION

Tab. 3 shows the accelerator chain for the heaviest ion species in RHIC and the LHC. As the energy is increased the charge state is changed multiple times to minimize space charge, intrabeam scattering (IBS) and charge exchange effects.

For RHIC, only species for which negative ion sources exist can be used currently. These negative ions are accelerated in the electrostatic Tandem accelerator, electrons are stripped and the now positive ions are accelerated further [6]. The stripping foils inside and just after the Tandem have only a limited lifetime, and foil changes occasionally delay operation. Gold ions are injected into.the Booster over 30-40 turns. The beam intensity and brightness is limited by the painting process and space charge effects. Injection with higher charge state ions lead to large beam losses and significant pressure rises [7]. It was later concluded that charge exchange processes caused the beam loss and

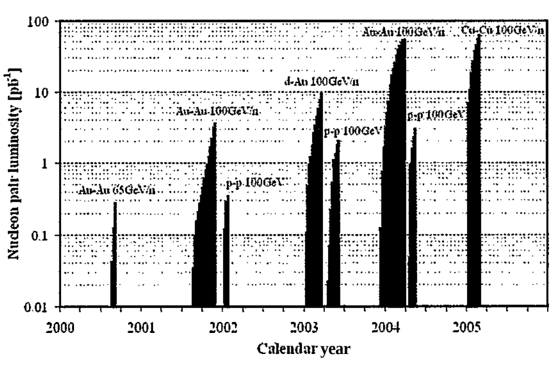

Figure 1: Nucleon-pair luminosity delivered to PHENIX, one of the RHIC high-luminosity experiments.

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Table 2: RHIC operating modes and total integrated luminosity delivered to 5 experiments [5].

run	species	total particle energy [GeV/n]	total delivered luminosity
Run-1	Au^{79+}-Au^{79+}	27.9	$< 0.001 \mu b^{-1}$
2000	Au^{79+}-Au^{79+}	65.2	$20 \mu b^{-1}$
Run-2	Au^{79+}-Au^{79+}	100.0	$258 \mu b^{-1}$
2001/02	Au^{79+}-Au^{79+}	9.8	$0.4 \mu b^{-1}$
	pol. p^+-p^+	100.0	$1.4 pb^{-1}$
Run-3	d^+-Au^{79+}	100.0	$73 nb^{-1}$
2002/03	pol. p^+-p^+	100.0	$5.5 pb^{-1}$
Run-4	Au^{79+}-Au^{79+}	100.0	$3740 \mu b^{-1}$
2003/04	Au^{79+}-Au^{79+}	31.2	$67 \mu b^{-1}$
	pol. p^+-p^+	100.0	$7.1 pb^{-1}$
Run-5	Cu^{29+}-Cu^{29+}	100.0	$42.1 nb^{-1}$
2004/05	Cu^{29+}-Cu^{29+}	31.2	$1.5 nb^{-1}$
	Cu^{29+}-Cu^{29+}	11.2	$0.02 nb^{-1}$
	pol. p^+-p^+	100.0	(under way)

resulted in ion-impact desorption. The same process limits the GSI SIS18 [8]. Before injection into the AGS the beam passes another stripping foil, resulting in a more than two-fold increase in the longitudinal emittance.

It is planned to replace the 35-year old Tandem with an EBIS followed by a RFQ and short Linac [9]. EBIS would allow the preparation of any species, including uranium and polarized ^{3}He. For injection into the Booster 3-4 turns would be sufficient, and beam can be injected at a higher energy. The overall system reliability is expected to be improved at reduced operating costs.

At CERN an ECR ion source is used, followed by an RFQ and Linac. The ions are then accumulated and accelerated in LEIR [10]. To achieve the desired emittances, LEIR is equipped with electron cooling. In this machine charge-exchange processes leading to ion-impact desorption are also expected to be relevant [11]. After acceleration through the PS, ion beams are injected into the SPS where IBS at injection is a concern.

Table 3: Preparation of the heaviest ions for RHIC and LHC. For each each accelerator the kinetic energy is given at extraction, the charge state is in the following transfer line [6, 12].

RHIC (Au)			LHC (Pb)		
	ion charge	energy [eV/n]		ion charge	energy [eV/n]
PSC*	1-	150	ECR	27+	2.5 k
Tandem	32+	0.9 M	LINAC3	54+	4.2 M
Booster	77+	101 M	LEIR	54+	72.2 M
AGS	79+	8.8 G	PS	82+	5.9 G
RHIC	79+	99 G	SPS	82+	177 G
			LHC	82+	2.76 T

* Pulsed sputter source [13].

3 ACCELERATION IN THE COLLIDER

The ion beams are most vulnerable at injection for a number of reasons. First the beam size is at its maximum as well as the magnetic field errors of the superconducting magnets due to persistent currents. Space charge effects can lead to substantial tune spread, and IBS to visible beam growth. The injection of intense ion beams can be limited by dynamic pressure rises, caused by electron clouds. Like for proton acceleration, the snap-back effect at the beginning of the ramp can lead to beam loss due to fast changing sextupole fields. This of particular concern in the LHC, where the effect is almost 2 orders of magnitude larger than in RHIC.

Transition crossing RHIC is the only superconducting machine in which particles cross the transition energy (all ions except protons). To mitigate problems a γ_t-jump is implemented ($\Delta\gamma_t$ of 1 in 30 ms). Near transition the bunches are shortened which can lead to instabilities. These instabilities were generally single bunch, and 2 distinct growth times were observed (15 ms and 100 ms) [14]. Recently it was seen that electron clouds can lower the instability threshold [15]. In Fig. 2 a longitudinal tomographic reconstruction of a bunch is shown that became unstable during transition crossing [16]. Part of the longitudinal distribution is missing showing that the transverse instability is fast compared to the synchrotron period.

The instabilities could be suppressed with chromaticity settings and octupoles [16]. It was found that it is advantageous to let the chromaticity crosses zero shortly before transition. The instabilities limit the bunch intensity in RHIC, in particular for light ions. Particles do not cross the transition energy in the LHC.

Asymmetric species For the physics program of ion colliders, the collision of different ions is important. RHIC has collided deuterons with gold in 2002/03 (see Tab. 2). During stores both beams must have the same revolution frequency to maintain good beam lifetimes and high luminosity. RHIC operation has shown that with shortly spaced intense bunches the same revolution frequency must also be maintained at injection and acceleration. Early operation with injection of beams of the same rigidity and a 120 Hz difference in the revolution frequency lead to unacceptable

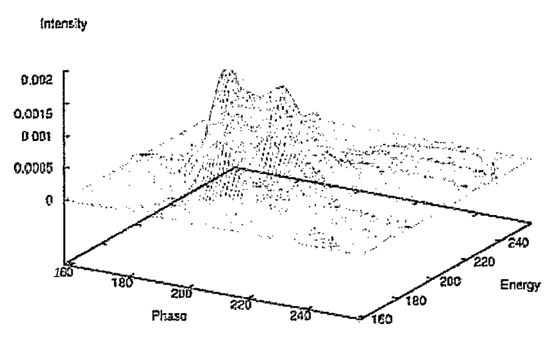

Figure 2: Tomographic reconstruction of the longitudinal phase space distribution for a deuteron bunch that experienced a fast transverse instability at transition. Part of the longitudinal distribution is lost (courtesy C. Montag).

Table 4: Required radius offset between the two rings for the storage of deuterons with gold (RHIC) or lead (LHC), assuming the same rigidity and revolution frequency in both rings.

parameter	unit	RHIC (Au)		LHC (Pb)	
		inj.	store	inj.	store
γ Au/Pb	...	11	107	180	2800
γ d	...	13	132	222	3454
average radius R	m	610		4242	
radius offset ΔR	mm	959	9.1	22.5	0.1

$$\mathcal{L} = (\beta\gamma)\frac{f_0}{4\pi}N_b\frac{N_1N_2}{\beta^*\epsilon_N} \quad (1)$$

where $(\beta\gamma)$ is the relativistic factor, f_0 the revolution fiequency, N_b is the bunch number, N_1, N_2 the number of ions per bunch in the two beam respectively, β^* the lattice function at the collision point (the same for the horizontal and vertical plane, and both beams), and ϵ_N the normalized rms emittance (also the same for all transverse planes). To

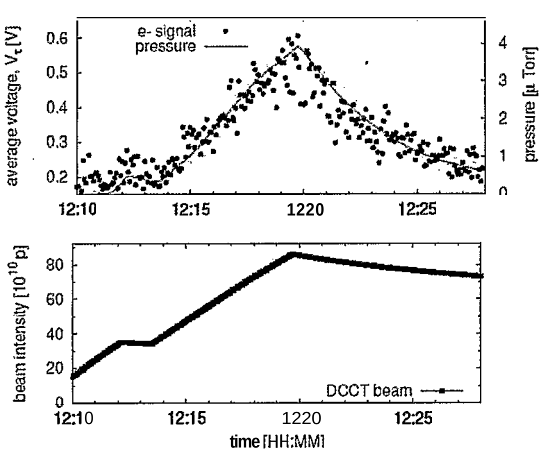

Figure 3: RHIC pressure rise observation. The bottom part shows the intensity of a proton beam being filled into one of the rings. The top part shows the signal of an electron detector, and the pressure reading close to the detector [18]. Dynamic pressure rises were observe with all species.

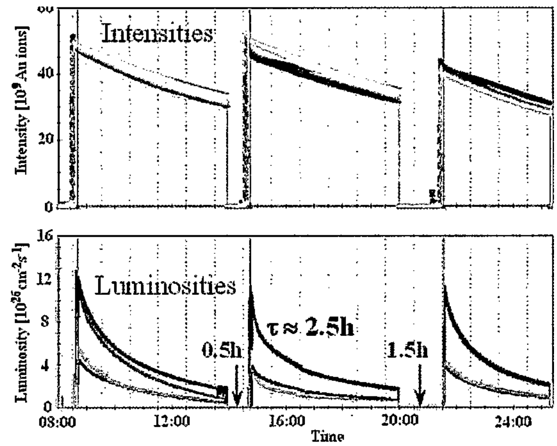

Figure 4: Typical RHIC stores and refill times with gold ions. The beam lifetime is limited by IBS leading to particle loss from the rf buckets. The luminosity lifetime is further reduced by transverse beam size growth from IBS. The luminosities are for the four RHIC experiments with $\beta^* = 1$ m and $\beta^* = 3$ m.

compare the luminosities for different species the nucleon-pair luminosity

$$\mathcal{L}_{np} = A_1A_2\mathcal{L} \quad (2)$$

can be used where A_1 and A_2 are the number of nucleons for the ions in the two beams respectively (see Fig. 1). For the nucleon-pair luminosity the beams are thought of being made of nucleons, not ions.

Bunch intensity For the same species the luminosity $\mathcal{L}$ is quadratic in the bunch intensity $N = N_{1,2}$, and it is best to maximize this quantity first. N is either limited by the injectors (Sec. 2), or, in RHIC, by instabilities near transition (Sec. 3). The achievable beam brightness N/ϵ_N is also limited by charge dependent effects in the injectors.

Bunch number In RHIC the bunch number is limited by electron cloud induced pressure rises [19]. So far, the most limiting effect is seen at store, when electron clouds are formed in some of the experiments after the bunches are transferred from the accelerating to the storage rf system. In this process the bunch length is shortened from 10 ns to 5 ns. The induced pressure rise can produce unacceptable experimental background [17, 20]. Electron clouds were also seen to lower the stability threshold at transition, and can even prevent the injection of a large number of bunches of the highest intensities. The electron impact desorption could be observed with all species, and in the warm and cold machine regions. Over the last few years the electron cloud effects were mitigated by baking, the installation of NEG coated beam pipes, and the use of optimized bunch patterns [21]. After completion of all the vacuum upgrades, RHIC is expected to operate with 111 bunches of 108 ns spacing, thereby doubling the current ion luminosity. Due to the low bunch intensity, no electron cloud effects are expected in the LHC.

Intrabeam scattering In Fig. 4 the intensities and luminosities of typical RHIC Au-Au stores are shown [22].

The beam lifetime is dominated by IBS leading to particles leaving the rf buckets. These particles are continuously cleaned out of the abort gap to avoid a quench when the beam is dumped. The luminosity lifetime is further reduced by transverse emittance growth, also predominantly caused by IBS [24]. To achieve a high average luminosity, stores are only a few hours long, and fast refills are required. Ultimately, colling is needed to overcome the effect of IBS. In the LHC, IBS is greatly reduced, and the emittance growth from IBS is balanced by synchrotron radiation cooling [29].

Two efforts are under way to cool colliding ion beams in RHIC. Tests for stochastic cooling were performed with Cu beams [25]. Stochastic cooling is most effective for particle in regions of low density near the edge of the beam. Heavy ions offer several advantages over protons for stochastic cooling. Fewer particles with larger charges improve the signal to noise ratio, and coherent signals are manageable. Longitudinal stochastic cooling aims to prevent debunching and would therefore improve the beam lifetime. With a fully developed stochastic cooling system, up to a factor 2 in luminosity improvements may be achieved for the heaviest ions.

An even larger luminosity gain may be achieved with electron cooling. An R&D effort is under way for bunched beam electron cooling at collision energy based on an energy recovery linac (ERL) [26]. Fig. 5 shows a possible layout of an electron cooler. An electron beam with an energy of 54 MeV, and current of 100-200 mA is required, a large margin above existing ERLs. With successful electron cooling a factor 10 increase in the average luminosity is anticipated, and the ion beams would be consumed in a few hours through the nuclear interactions in the collisions.

Beam-beam interactions With gold beams in RHIC, a beam-beam parameter of $\xi = 0.002$/IP is reached, and collisions are provided at up to 4 experiments. This requires a careful choice of the working point, and frequency locking on the ramps, challenging near transition. With lighter ions, higher bunch charges can be provided by the injectors, and the beam-beam interaction becomes more pronounced. Coherent oscillations modes were observed with protons [27], but until recently no adverse strong-strong effects were seen in operation.

In Fig. 6 an instability is shown trigged by a strong-

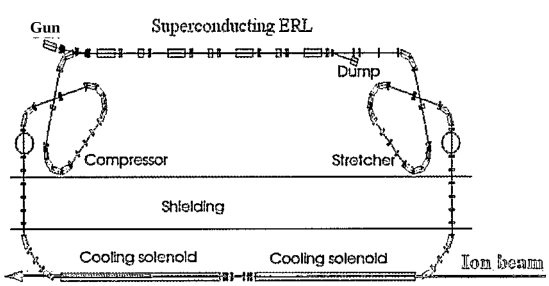

Figure 5: Possible layout for electron cooling at RHIC, based on a superconducting ERL [26].

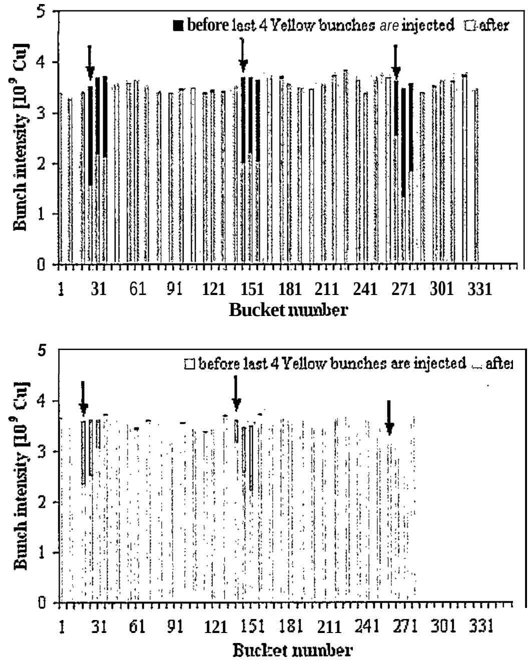

Figure 6: Beam-beam triggered instability in operation with Cu beams. After injection of the last group of 4 Yellow bunches, 9 bunches in each of the rings loose a substantial fraction of their intensity. The bunches marked with an arrow are coupled by the beam-beam interaction.

strong beam-beam interaction. The upper part shows the intensities of the bunches in one ring after injection. The the second beam was filled, and after a certain number of bunches were injected, 9 bunches in each ring suffered an intensity loss. In RHIC 3 bunches of one ring and 3 bunches of the other ring can be coupled by the beam-beam interaction. The unstable bunches in both ring were beam-beam coupled. One such group is marked with arrows. This instability could be suppressed by a change in the chromaticity, and a separation of the vertical tunes in both rings. Beam-beam effects are expected to play only a minor role in the LHC.

Quenches from collision products The interaction of high-energy ion beams can produce secondary beams with a charge-to mass ratio different from the primary beam. Two such processes are electromagnetic dissociation (EMD) and bound-free pair production (BFPP) [29]. In the former process the ion looses a nucleon, in the latter it captures an electron. For the LHC, this process is

$$^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} ^{208}\mathrm{Pb}^{82+} + ^{208}\mathrm{Pb}^{81+} + e^{+} \quad (3)$$

with a calculated cross section of σ = 281 barn. The secondary Pb^{81+} beam will hit the beam screen after about 400 m from the IP (see Fig. 7), and the deposited energy can lead, if large enough, to a quench. Collimation of this secondary beam is difficult, and counter measures are under investigation.

In RHIC Au^{78+} beams are within the momentum aper-

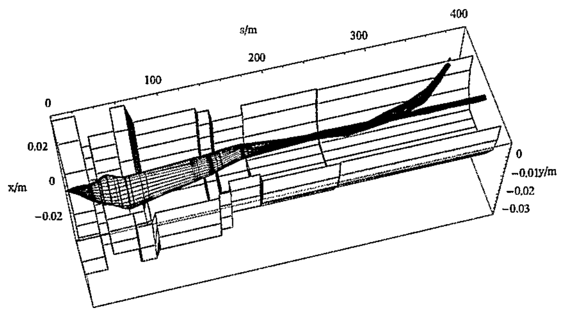

Figure 7: LHC beam screen and 5-σ beam envelope for Pb^{82+} and Pb^{81+} beams coming out of the interaction point. The Pb^{81+} is created due to bound-free electron pair production, and hits the beam screen after about 400 m [4].

ture, and are therefore not all lost in a single location. The loss of a secondary Cu^{28+} beam could be observed about 141 m from the interaction point of a high-luminosity experiment with especially installed PIN diodes [28]. The deposited energy did not create any operational problem.

Collimation The collimation of protons relies on scattering on a primary collimator followed by interception on secondary collimators. For heavy ions, a large fraction of the incident ions breaks up in the primary collimator and will be lost in the vicinity. The high ionization loss also leads to an much higher energy deposition in the collimators. Fragments with a charge to mass ratio close to the primary beam one can travel long distances, and are like particles with large momentum errors.

In the LHC only small beam losses can be tolerated to avoid quenches of the superconducting magnets. The performance of the collimation system, designed for protons, is under study [30]. Intensity limitations from collimation are expected to be comparable to those of BFPP. In RHIC, collimation is primarily needed for background reduction, not machine for protection. Secondary collimators were effective in reducing the background in heavy ion operation [31].

5 SUMMARY

Collision energy, luminosity, and flexibility are the main requirement of high-energy ion colliders. Flexibility can include the collision at varying energies, with different field configurations of the experimental magnets, and different species, including light on heavy ions. In the preparation of ion beams space charge, IBS, and charge exchange effects need to be considered to produce intense bunches. For RHIC, IBS is the most severe luminosity limit for heavy ion operation, for the LHC it is expected to be the quench limit due to a secondary beam out of the collisions.

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