MINI- β insertion and Luminosity for the RHIC Lattice

S.Y. Lee

BNL--41668

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Accelerator Development Department

Brookhaven National Laboratory

Abstract:

Requirement and implication of the mini- β insertion in RHIC lattice is studied. For the heavy ion operation, we find that (1) When the gradient is maintained at 67T/m, the free space for the experimental setup becomes $\pm 4\text{m}$ at $\beta^* = 1.5\text{m}$ with maximum crossing angle of 3mrad at 100GeV/amu. (2) To maintain a minimum of $\pm 5\text{m}$ free space for experimental setup, a higher gradient is needed. At 84.5T/m gradient, $\beta^* = 1\text{m}$ can be achieved. In this case, the beam size limitation is located at BC2, where 10cm coil i.d. is designed. When the machine is operating at the proton-heavy ion interaction mode, these common quadrupoles should be removed physically in order to let both beams crossing the center line at 3.5mrad. These mini- β insertion can increase the luminosity by a factor of 2 3.

For the proton operational mode, we find that $\beta^* = 1\text{m}$, which corresponds to $\beta = 1200\text{m}$ is also operable without the mini- β quadrupoles. When the mini- β quads are used, $\beta^* = 0.25\text{m}$ can be achieved.

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I. Introduction.

The luminosity of the many colliders are limited by the beam-beam tune shift. When the linear beam-beam tune shift is large, the nonlinear driving term in the beam-beam space charge force determines the life time of the storage beam. It is important to note however that the beam-beam tune shift is independent of the β^* value at the IP. Thus most of the colliders are designed to operate at the smallest β^* value achievable. To obtain small β^* while limiting the maximum $\hat{\beta}$ value at the high β quads region, a MINI- β insertion is considered.

The normal operation range for the RHIC collider design is constrained by the available dynamical aperture at Q2 and Q3 in the insertion, where the β -function is high. In the normal insertion, there are 9 quadrupoles in each side of the interaction point(IP) excited anti-symmetrically with respect to IP. When the β^* , the β value at the IP, is 3m, the maximum $\hat{\beta}$ values at Q2 and Q3 are 400m, while $\beta^*=2\text{m}$, $\hat{\beta}$ becomes 625m. Table 1 compares the beam size with the magnet coil i.d. at various operational conditions.

Table 1. Beam size vs. Coil i.d.⁺ in Au on Au operation

	<u>MINI-β insertions</u>		
β^* (m)	3	2	1
$\hat{\beta}$ (m)	400	625	500
ϵ_N ($\mu\text{-m}$)	33	33	33
$6\sigma/\text{coil i.d.}$ (at $B\rho=840\text{ Tm}$)	0.42	0.52	0.48
$6\sigma/\text{coil i.d.}$ (at $B\rho=420\text{ Tm}$)	0.59	(0.73)	0.68

⁺Coil i.d. of Q2 and Q3 are both 131mm

Based on the the tracking calculations of Dell and Parzen¹, we expect that $\beta^* = 2\text{m}$ can be achieved at the the top energy. Therefore, the luminosity is increased by 50% in this process. Since $\hat{\beta}$ is approximately inverse proportional to β^* , $\hat{\beta}$ becomes too large for heavy ion operation when β^* value is less than 2m . The only way to avoid the dynamical

aperture problem in Q2 and Q3 is to resort to a MINI- β insertion. Note however that the free space available in RHIC standard insertion is $\pm 10\text{m}$. The mini- β insertion would require the experimental set up to be limited to an even smaller space or the COMMON mini- β quadrupoles should be incorporated in the detector design.

This study is intended to investigate the possible mini- β insertions. Our aim is to leave as much of space as possible for the experimental set-up while keep the ratio of ($6\sigma/\text{coil i.d.}$) to be less than 0.6 0.7 in order to maintain useful dynamical aperture. This rule of long term stability is established by many tracking studies of Tevatron, SSC, and RHIC. In section 2, we shall discuss the MINI- β insertion layout and find the requirement of these quadrupoles. Section 3 discuss the operable condition for the proton collision. Section 4 discusses the implication of mini- β insertions.

2. The Layout of MINI- β insertion.

To maintain the antisymmetry of the RHIC insertion, two pairs common quadrupoles, QX1 and QX2, should be placed in the interaction region between two common beam crossing dipoles, BC1, on both sides of the IP. To maximize the available free space for experimental set-up, the distance between QX2 and BC1 is set to 0.5m, which is needed for coil end of magnets. The beam line in the interaction region is arranged as following:

BC1I DX2 QX2I DX1 QX1I DX0 IP DX0 QX1O DX1 QX2O BC1O

2.1 $B'=67\text{ T/m}$ as the basic assumption.

Assuming the 8 cm coil i.d. quadrupoles for QX2 and QX1, which is operating at 67 T/m norminally, we ask what is the length of the magnets to obtain $\beta^* = 1.5\text{m}$ while keeping $\hat{\beta}=400\text{m}$. The result of the matching is shown in the first column of Table 2. We observe that the available free space becomes 4m for the experimental setup. Note that the mini- β insertion configuration can only support the crossing angles up to 3 mrad at 100GeV/amu or 2 mrad at 50GeV/amu. The constraint is limited by

the crossing angle of the collision species rather than the β^* at the IP. Thus to obtain maximum Luminosity, crossing angle should be kept as small as possible.

Table 2. Mini- β insertion constraint for RHIC

β (m)	1.5	1.5	1.0
DX0(m)	4.0468084	5.0	5.0
LQX1(m)	1.8967767	1.5	1.5
DX1(m)	1.8999972	1.5	1.5
LQX2(m)	1.6564177	1.5	1.5
$\beta_{\max}$ (m)	400.	400.	500.
GF(1/m)	0.099520	0.099520	0.099520
GD(1/m)	0.099650	0.099650	0.099650
K1I(1/m)	0.149993	0.135168	0.150904
K2I(1/m)	0.130986	0.135652	0.147122
G1I(1/m)	0.133826	0.137238	0.137711
G2I(1/m)	0.157707	0.157785	0.156988
G3I(1/m)	0.055416	0.051932	0.050933
G4I(1/m)	0.084231	0.085321	0.076361
G5I(1/m)	0.101945	0.103415	0.093903
G6I(1/m)	0.120539	0.125538	0.121913
G7I(1/m)	0.137715	0.138627	0.140795
G8I(1/m)	0.111765	0.111907	0.112740
G9I(1/m)	0.085117	0.085220	0.086562
K10(1/m)	0.152250	0.133922	0.150941
K20(1/m)	0.130878	0.134911	0.146960
G10(1/m)	0.133977	0.137239	0.137679
G20(1/m)	0.157225	0.157845	0.156421
G30(1/m)	0.055035	0.052178	0.050841
G40(1/m)	0.081062	0.081848	0.075912
G50(1/m)	0.094511	0.094168	0.085706
G60(1/m)	0.124678	0.126434	0.129953
G70(1/m)	0.140527	0.139806	0.140081
G80(1/m)	0.114963	0.114443	0.114472
G90(1/m)	0.093322	0.092587	0.091758

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2.2 Assumption with the available free space to be 5m.

When the maximum gradient is held with 67 T/m, we found that the available free space becomes 4 m. In order to increase the available free space to 5m, we shall decrease the length of quadrupoles to 1.5m each. The result of the beam matching is given in the column 2 of table 2 for $\beta^* = 1.5m$ and $\beta = 400m$. Since the dynamical aperture in this case is not limited by the quadrupoles Q2 and Q3, one can decrease further β^* to 1m, shown in the COLUMN 3 of Table 2. Note that the gradient requirement of QX1 becomes 84.5 T/m at $B_p = 840$ Tm. At $\beta^* = 1m$, the β -value at BC2 is about 350m. Thus the ratio of beam size to the magnet coil i.d. would be about 51% at BC2. We conclude that $\beta^* = 1m$ has almost reached the capability of the insertion. To decrease even further the β^* value, it is necessary to decrease further the available experimental free space.

Because of the higher gradient requirement in the present case, smaller coil i.d. of 6.3cm may be needed for QX1 and QX2. This consideration also prevent the crossing angle larger than 2mrad.

3. Luminosity in the proton operation mode.

For the proton operation at top energy with $B_p = 840$ Tm, the emittance is considerably smaller than that of heavy ions. Thus $\beta^* = 1m$, or 0.5m may indeed be achievable without mini- β insertion. Table 3 shows the beam size in this operation mode. To obtain an even smaller betavalue at the crossing point, the mini- β insertion discussed in section 2 can be used to lower the β^* value by a factor of 2-3. Thus the luminosity for the proton will be $10^{32}/cm^2sec$ in the mini- β configuration without any intensity upgrade to the RHIC conceptual design. To reach an even higher luminosity, more number of bunches and/or more number of particles per bunch are needed. It is however worth pointing out that the number of interaction per bunch crossing has already reach 1 at the luminosity of $10^{32}/cm^2sec$ with the proposed 57 bunches in each ring. The proper design of detectors may be an important issue for higher luminosity.

Table 3. Beam size vs. Coil l.d.⁺ in proton operation

					MINI- β
β^* (m)	3	2	1	0.5	0.25
$\hat{\beta}$ (m)	400	625	1290	2460	2409
ϵ_N (μ -m)	20	20	20	20	20
6σ /coil l.d. (at $B\rho=840$ Tm)	0.21	0.26	0.38	0.54	0.54
6σ /coil l.d. (at $B\rho=420$ Tm)	0.29	0.37	0.54	----	----
Chromaticity ^{&} (per insertion)	-5.5	-8.5	-17.	-32.	-32.
Luminosity [#] (10^{32} /cm ² sec)	.095	.143	.285	.57	1.14

⁺Coil l.d. of Q2 and Q3 are both 131mm

[&]The total contribution of six arcs is -24 unit of chromaticity.

[#]Based on 10^{11} particles per bunch and 57 bunches per ring.
When the intensity is increased by a factor of two, the luminosity is increased by a factor of 4. When 114 bunches are circulating in a ring the luminosity is increased by another factor of 2. In this case the luminosity can be as high as 10^{33} /cm²/sec.

4. Implication and Hardware requirement.

The mini- β insertion in the present study requires two pairs of common quadrupoles in each of mini- β section. Because of the extra quadrupoles, the phase advance of the insertion is increased by about 0.06. To prevent the low order resonances in the collider, the tune of the machine is maintained by readjusting the rest of the accelerator. Thus it is necessary to setup the accelerator before the mini- β run. Because of the high gradient requirement for these common quadrupoles, smaller coil l.d. magnet is conceived. This limits the crossing angle configuration to be less than 2mrad at at 100 GeV/amu for heavy ion beams. For proton beam, the requirement is relaxed slightly because of smaller beam size.

We have discussed only the basic mini- β lattice. Since the $\hat{\beta}$ remains small, we expect that the dynamical aperture is changed

appreciably for the mini- β insertion. The half integer stop band should be minimized by the sextupole families. Tracking calculation should be used to establish the available dynamical aperture. In order to optimize the configuration, these common quadrupoles should be incorporated into the detector design, where the high luminosity is required.

In conclusion, we have find some possible mini- β insertion to the present IR design. For 10 hours of heavy ion operation, it is possible to obtain β^* value of 1m without much beam size constraint to the rest of the machine. Two pairs of common quadrupoles are needed. The available free space for the experimental instrument becomes ± 5 m. Because of the smaller aperture of these common quadrupoles, smaller crossing angle is required in the mini- β insertion. For the proton operation, $\beta^* = 0.5$ m is operable without mini- β insertion at the top energy. When mini- β insertion is used, a factor of 2-3 increase in the luminosity may be achieved. The corresponding luminosity becomes $10^{32}/\text{cm}^2\text{sec}$ or higher. Detector design may be an important issue as well.

At the unequal species operational mode, these common quadrupoles should be removed for beam clearance.

Reference:

1. F.G. Dell and G. Parzen, private communications.