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THE RCS DESIGN STATUS FOR THE ELECTRON ION COLLIDER *

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Abstract

The design of the Electron-Ion Collider Rapid Cycling Synchrotron (RCS) to be constructed at Brookhaven National Laboratory is advancing to meet the injection requirements for the Electron Storage Ring (ESR). Over the past year activities are focused on developing the approach to inject two 28 nC bunches every second, up from the original design of one 10 nC bunch every second. The solution requires several key changes concerning the injection and extraction kickers, charge accumulation via bunch merging and a carefully calibrated RF acceleration profile to match the longitudinal emittance required by the ESR.

INTRODUCTION

A Rapid Cycling Synchrotron (RCS) will be used to accelerate, accumulate and inject up two 28 nC polarized electron bunches into the EIC electron storage ring (ESR) per second [1]. In the peak current regimes, the RCS will take two trains of four 7 nC bunches for a total of 8 bunches injected from the LINAC. These will be injected at 400 MeV at a rate of two 7 nC bunches per LINAC cycle. Each LINAC cycle should take 100 Hz requiring at least 40 msecs to fill the RCS. We have budgeted 54 msecs for the whole injection process as shown in Fig. 1 [2]. These bunches will be injected into two trains of four adjacent 591 MHz buckets. Since a rise time of 1.69 ns is necessary to inject into neighboring buckets a special system of RF-crab like cavity kickers will be used to generate the necessary kick profile [3]. The two bunch trains will then be accelerated to 1 GeV and held there for 0.15 seconds while the eight bunches are merged into two 28 nC bunches. These will then be accelerated at a ramp rate of 0.176 GeV/ms to their final energy of 5, or 10 GeV and extracted on a 20 msec flattop. In the case of 18 GeV only two slightly lower charge bunches will be injected and merged per train. These yield two 11.7 nC merged bunches at 1 GeV which will be accelerated and extracted at 18 GeV. The dipole power supply profile is illustrated in Fig. 2 and the main parameters of the RCS are summarized in Table 1.

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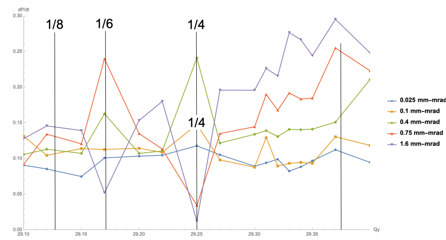

Figure 1: RCS injection pulse structure.

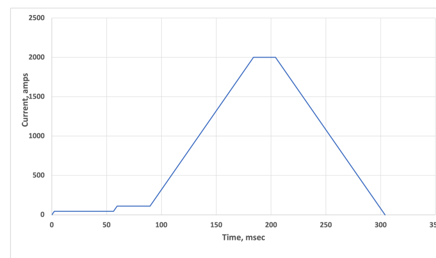

Figure 2: Power supply profile of RCS Ramp.

RCS SPIN RESONANCE-FREE DESIGN

A spin resonance-free design has been proposed in [4]. In a typical circular lattice where the field is dominated by the guide dipole field, the rate of spin precession per turn, or spin tune (ν_s), is determined by the energy and conveniently expressed as $a\gamma$, where $a = \frac{g-2}{2}$ is the anomalous magnetic moment coefficient for an electron (0.001159), and γ is the relativistic factor. For the case of a depolarizing intrinsic spin resonance this occurs whenever the spin tune $a\gamma = nP \pm Q_y$. Here n is an arbitrary integer, P is the periodicity of the lattice, and Q_y is the vertical betatron tune.

Thus the first two important intrinsic spin resonances that an accelerating electron will encounter occur at $a\gamma = Q_y$ and at $a\gamma = P - Q_y$ (for $P > Q_y$) . If we now ensure that both Q_y and $P - Q_y$ are greater than the maximum $a\gamma$ value, (or Q_y is greater and $P - Q_y$ is less than the lowest $a\gamma$ value), then all the important intrinsic spin depolarizing resonances will be avoided.

We chose $P = 96$, constraining the integer part of the vertical betatron tune to be $41 < [Q_y] < 55$, since we accelerate to energies less than $a\gamma = 41$. Here $[Q_y]$ indicates the nearest integer of the vertical betatron tune. We chose $[Q_y] = 50$. As a result, the two first intrinsic resonances will occur near $a\gamma = 50$, and $a\gamma = 96 - 50 = 46$.

A side benefit is that in addition to the intrinsic resonances, the imperfection resonances are also minimized due to the

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Table 1: Basic Parameters of the RCS Injector

Parameter	**5 GeV**	**10 GeV**	**18 GeV**
Injection energy [MeV]		400	
Momentum compaction α_c		0.000372	
Max relative pol. loss		5%	
Circumference [m]		3841.35	
Ramping repetition rate [Hz]		1	
Acceleration time [ms], [turns]		100, 8000	
Total number of “spin effective” superperiods		96	
Integer horizontal tune		57	
Integer vertical tune		60	
Round beam pipe inner diameter [mm]		32.9	
Number of bunches injected	8	8	2
Charge per bunch at injection [nC]	7	7	5.5
Number of bunches at extraction		2	
Radio frequency [MHz]		591	
Total Cavity peak Voltage [MV]		60	
Bunching Cavity 1 [MHz]		295.5	
Bunching Cavity 2 [MHz]		147.8	
Bunch length injection [ps]		40	
Bunch length extraction [ps]	23.3	23.3	30
Hor. and Ver. emittance normalized (inj.) [mm-mrad]		26, 26	
Emittances at RCS extraction $\varepsilon_x/\varepsilon_y$ [nm]	20/2	20/1.2	24/2
RMS energy deviation at injection dp/p [10^{-3}]		2.5	
RMS energy deviation at extraction dp/p [10^{-3}]	0.68	0.58	1.09

design of this lattice. This is because the strongest imperfection resonances, like the intrinsic resonances for a pure ring, will be at $nP \pm [Q_y]$.

RCS Geometry

The RCS geometry has to fit inside the RHIC tunnel which resembles a hexagon with rounded corners rather than a circle, and therefore has a natural periodicity of 6 which spoils the 96 periodicity we want to accomplish. However the spin precession, advances by $a\gamma$, only in the dipoles, so one can maintain the periodicity of 96 from the point of view of $a\gamma$ precession. This can be accomplished by designing the straight sections such that each has a betatron phase advance equal to 2π. In this way the straight sections will not contribute to the integral that defines the strength of the spin resonance (see Fig. 3). Thus we can maintain the 96 super-periodicity from the point of view of the spin precession.

The lattice incorporates the existing RHIC straight sections that do not contribute to the intrinsic spin resonance strength, thus preserving the 96 periodicity from a spin precession point of view. The proposed layout for the RCS places it at a radius outside of the existing RHIC beam line but within the tunnel.

RCS Spin Transparent Detector Bypass

Experiments are located at interaction regions IP6 and IP8. At these locations the RCS beamline needs to bypass the detector achieving greater than 5 m displacement from the center of the IP based on the current sPHENIX and eSTAR detector design. This displacement is achieved by moving the last three and first three dipoles from the arcs around IP6 and IP8 towards the center of the IP and to two other symmetric locations in the straight section. In this configuration the RCS beam trajectory misses the detector center by 3.86 m and avoids the other potential obstructions in the tunnel. In the remaining IP2, IP4, IP10 and IP12 a geometry is adopted which yields an 153 m long straight section at the center of the IP. This geometry is accomplished also by moving three dipoles from the arcs on either end. The long straight is necessary to accommodate the RF system modules located at IP10, but we maintain this geometry

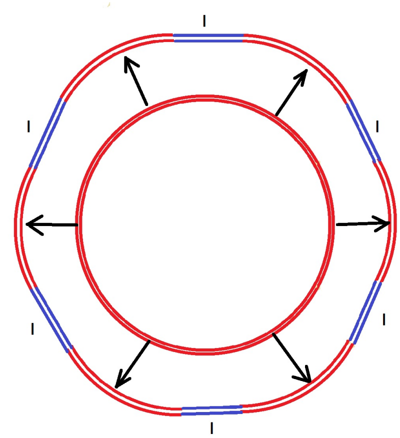

Figure 3: Projecting the pure ring lattice with 96 superperiodicity onto the RHIC six fold periodic ring.

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through the remaining IP's. Accommodating both these bypasses while controlling the intrinsic spin resonances for the whole lattice has the negative consequence of raising our maximum β function from 50 to 160 m.

DYNAMIC APERTURE IN THE RCS

Tracking results have shown that the RCS lattice is capable of reaching an off-momentum dynamic aperture of dp/p = 1.0% as shown in Fig. 4. This was achieved by controlling the betatron tunes, chromaticity and the sextupole settings. In Fig. 5 we can see the losses as a function of horizontal betatron tune. This shows the optimal tune has a fractional component of 0.88. Additionally, part of the mechanism for loss was due to tune-modulation effect which create a parametric resonance due to momentum oscillation caused by synchrotron oscillations. This was improved by lowering the linear chromaticity to close to zero. Further improvement was achieved by optimizing on the sextupole settings in the RCS. In order to keep our injected bunches below three sigma of the off-momentum aperture given by dp/p = 1.0% we limit our RMS dp/p to be below 2.5×10^{-3}.

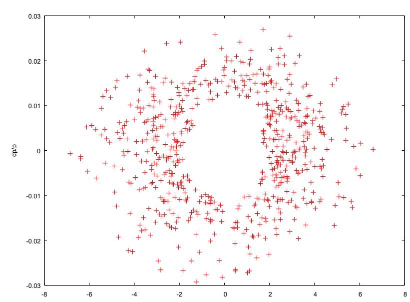

Figure 4: RCS lattice Phase space plot of dp/p and cm showing lost particles over 200 turns.

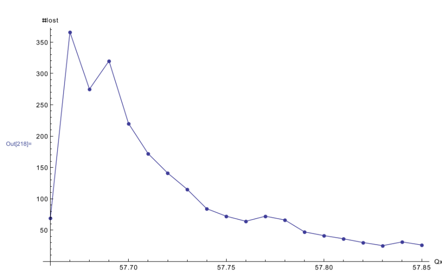

Figure 5: Particle losses through the 18 GeV RCS acceleration cycle as a function of horizontal tune. The initial bunch parameters were RMS dp/p = 4.3e-3, and bunch length of 71 ps RMS.

RCS RAMP AND MERGE

After the injection of eight 7 nC bunches into two four bunch trains, they will then be accelerated to 1 GeV and merged into two 28 nC with two steps of pairwise merging using 295.5 MHz and 147.8 MHz RF systems, respectively as shown in Fig. 6. The bunches will begin with dp/p = 2.5×10^{-3} and a bunch length of 40 ps giving a longitudinal emittance $\sigma_t \sigma_E = 4 \times 10^{-5}$ eV-s, at 7 nC this should be above the longitudinal microwave instability threshold of Z/n = 0.138 Ω [5]. During acceleration we will increase the voltage and slew the phase to keep the dp/p fixed at 2.5×10^{-3} while shrinking the bunch length to 16 ps and the synchrotron tune will increase from 0.059 to 0.14. With these bunch parameters our microwave threshold at 1 GeV would be 0.2 Ω.

Simulations show that through two successive merges from four to two to one will cause longitudinal emittance growth of approximately 42% above the 4× the initial 4e-5 eV-s that a lossless merge would give. Thus our final merged longitudinal emittance will be 23×10^{-5} eV-s with a bunch length of 91 ps and dp/p remaining fixed at 2.5×10^{-3}. The microwave stability threshold for the merged bunches will be 0.196 Ω.

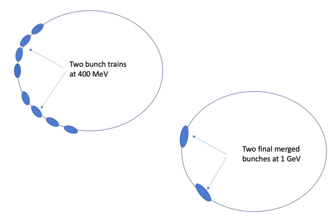

Figure 6: 8 bunches injected into two trains of four bunches in the RCS at 400 MeV. (left plot). Bunches merge at 1 GeV into two bunches.

CONCLUSION AND FUTURE PLANS

The layout around the two detectors is currently being modified to include a magnet free beam pipe in the collision hall. Additionally trajectory at IP12 is also being modified to avoid interference with other items in the tunnel. This has resulted in a slightly modified RCS geometry and optics. The new lattice is presently being optimized to recover both the spin and dynamic aperture properties.

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