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Magnet Quality and Collider Performance Prediction

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I. Overview

- Field quality of the arc dipoles determines the machine performance at injection.
- Field quality of the insertion region magnets determines the performance at $\beta^* = 1$ m storage.
- Intra-beam scattering is strong for high charge-state ions. Beam-beam effects are small.

Table 1: Comparison of storage and injection parameters for Au^{79+} beams in RHIC.

Quantity	Injection ($\beta^* = 10$ m)	Storage ($\beta^* = 1$ m)
ϵ_N (95%)	10 πmm·mr	40 πmm·mr
$\sigma_{\Delta p/p}$	0.43×10^{-3}	0.89×10^{-3}
β_{arc}	50 m	50 m
$\beta_{triplet}$	145 m	1400 m
$\sigma_{x,arc}$	2.5 mm	1.8 mm
$\sigma_{x,triplet}$	4.5 mm	9.3 mm

Goals:

- Storage and collision of beams of broad range ion species from proton to Au^{79+} at energies from 250 GeV to 100 GeV/u.

- An average luminosity (Au^{79+}) of 2×10^{26} cm^{-2}s^{-1} over 10 hours; Upgradable.

II. Arc Dipoles

- All arc dipoles have been built, warm measured, accepted by the "Magnet Acceptance Committee", and installed in the tunnel.
- 0 dipoles have been rejected.
- All dipoles are sorted on their *Integral Transfer Function* to minimize the corrector strength.
- For all the arc dipoles, warm (100%) and cold ($\sim$20%) measurement data are available in database for automated computer tracking, statistical analysis, and machine control.

Performance Comparison:

The high quality of RHIC dipoles is demonstrated by comparing their field profiles with those from other super-conducting machines. The following plots extend out to the appropriate 2/3 coil ID.

- RHIC, HERA, and the Tevatron have almost identical coil IDs (80.0, 75.0, and 76.2 mm).
- Plot lines show systematic harmonics, while error bars show random harmonics ($\pm 1\sigma$).
- INJECTION: HERA is hampered by persistent currents (low field), while the Tevatron is dominated by an intentional b_8. RHIC benefits from "high" field (systematics) and small filaments (randoms).

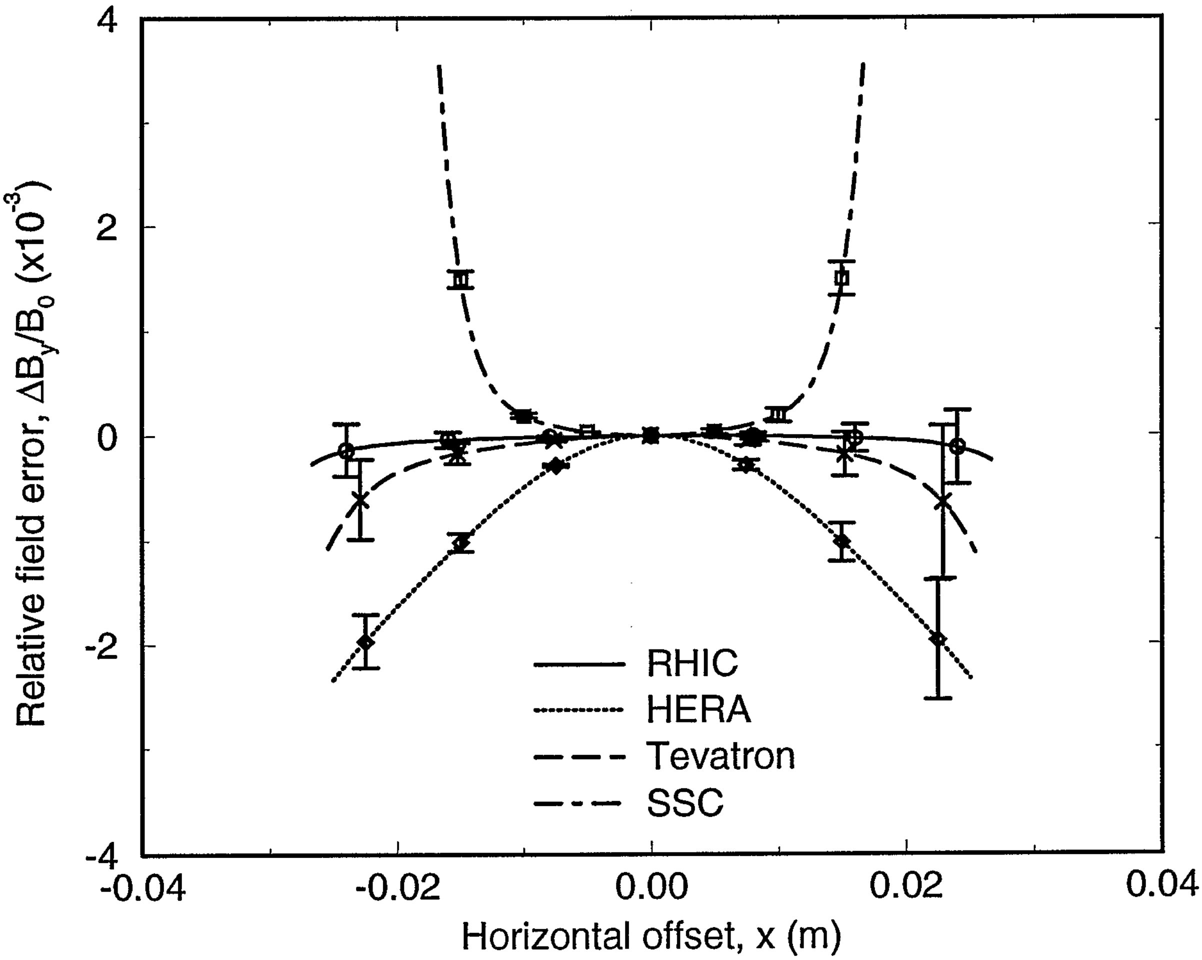

Figure 1: A comparison of systematic and random field error at injection for RHIC, HERA, Tevatron, and SSC. The plotted range is 2/3 of the coil ID. Multipoles up to order 12 have been taken into account.

III. CQS Assemblies

- CQS evaluation consists of two steps — first on individual cold masses (Corrector, Quad and Sextupole components), then on the complete assembly.
- All CQS individual components have been built and measured; A total of 335 out of 426 CQ assemblies (8 cm) have been built; All CQ assemblies for the sextant test have been built, measured, and accepted.
- Careful *alignments* and *measurements* are essential during assembly.
- Extremely accurate "harmonic antenna" and "colloidal cell" measurements of the field center of a *warm* cold mass (quad., sextupole, corrector), relative to externally available surveying fiducials, makes tight alignment possible on installation.

CQS Alignment Performance:

Individual magnets are examined for 2σ deviations from distribution norms, and for violations of absolute limits, on various quantities, including:

- Quadrupole field angle — which is used to align the CQS on the design trajectory. (Also watch sextupole and corrector angles).
- Corrector and BPM offsets — which indicate the CQS straightness.
- "Antenna (Colloidal) – Mechanical" difference of the quadrupole center — which gives an internal consistency check on quad misalignment.

Trends in the distribution parameters are also tracked, as with all other magnets.

Table 2: Statistics of dipole and CQS magnetic integral field angle, horizontal (H), and vertical (V) center offsets.

Quantity	H/V	Units	Mean	S.D.
Dipole field angle[a]		[mr]	−0.8	0.7
Quad. field angle[a]		[mr]	−1.7	0.3
Sext. field angle		[mr]	−0.3	0.7
Corr. field angle[b]		[mr]	−4.5	3.9
Quad. center offset	H	[μm]	14	61
	V	[μm]	110	64
Sext. center offset	H	[μm]	15	88
	V	[μm]	28	34
Corr. center offset[b]	H	[μm]	70	80
	V	[μm]	50	100

a) To be corrected during CQS ring installation.

b) Dipole layer of the corrector only.

Table 3: Measurement statistics of CQS cold mass center position and straightness.

Quantity	H/V	Units	Mean	S.D.
Quad. center difference	H	[μm]	35	157
(Antenna–Mechanical)	V	[μm]	18	72
Quad. center difference	H	[μm]	62	276
(Colloid–Mechanical)	V	[μm]	−39	148
Corrector offset	H	[μm]	−150	605
	V	[μm]	4	412
BPM offset	H	[μm]	145	335
	V	[μm]	100	277

IV. Insertion Region Magnets

- All the magnets necessary for the sextant test have been built, measured, and accepted.
- A sophisticated compensation scheme is used for the IR triplets.

Figure of merit:

$$\frac{\Delta J_{x,y}}{J_{x,y}} \sim \frac{(2J)^{\frac{n-1}{2}}}{4\pi\rho} \frac{10^{-4}}{R_0^n} \int b_n \beta_{x,y}^{\frac{n+1}{2}} ds \longrightarrow 0$$

IR triplet Compensation Methods:

- Minimized undesired multipole harmonics at storage; use magnet body to compensate the ends on systematic b_5 and a_5, taking into account the expected beam size variation in the magnet.

- Choose lead-end orientation to minimize the effects of the stronger end.

- Shim individually using 8 tuning shims after warm/cold measurements — reduce error to $\sim 10\%$ of the original.

- Sort golden quads and correctors for two low-β^* IRs.

- "Harmonic antenna" plus welding stripes to reduce twists and offsets during assembly, and field angle shimming to reduce rolls between corrector layers.

- Use IR correctors for orbit smoothing, decoupling, and higher order compensation.

Multiple measurements indicate dependence of certain multipole values on quench and thermal cycle. Simulation shows within tolerance.

V. Tracking and Simulation

- Numerical results are based on actual magnet measurements.
- Linear aperture (short time scale) *simulations* investigate the complete list of correction procedures (e.g., closed orbit, nonlinear correction of the IR triplets, local linear decoupling, ...).
- Dynamic aperture studies are mainly performed as "spot checks".
- Actual distribution values of non-harmonic parameters are also used, whenever possible. For example, an RMS quadrupole misalignment error of $\sigma = 0.25$ [mm] is assumed.

Dynamic Aperture at Injection:

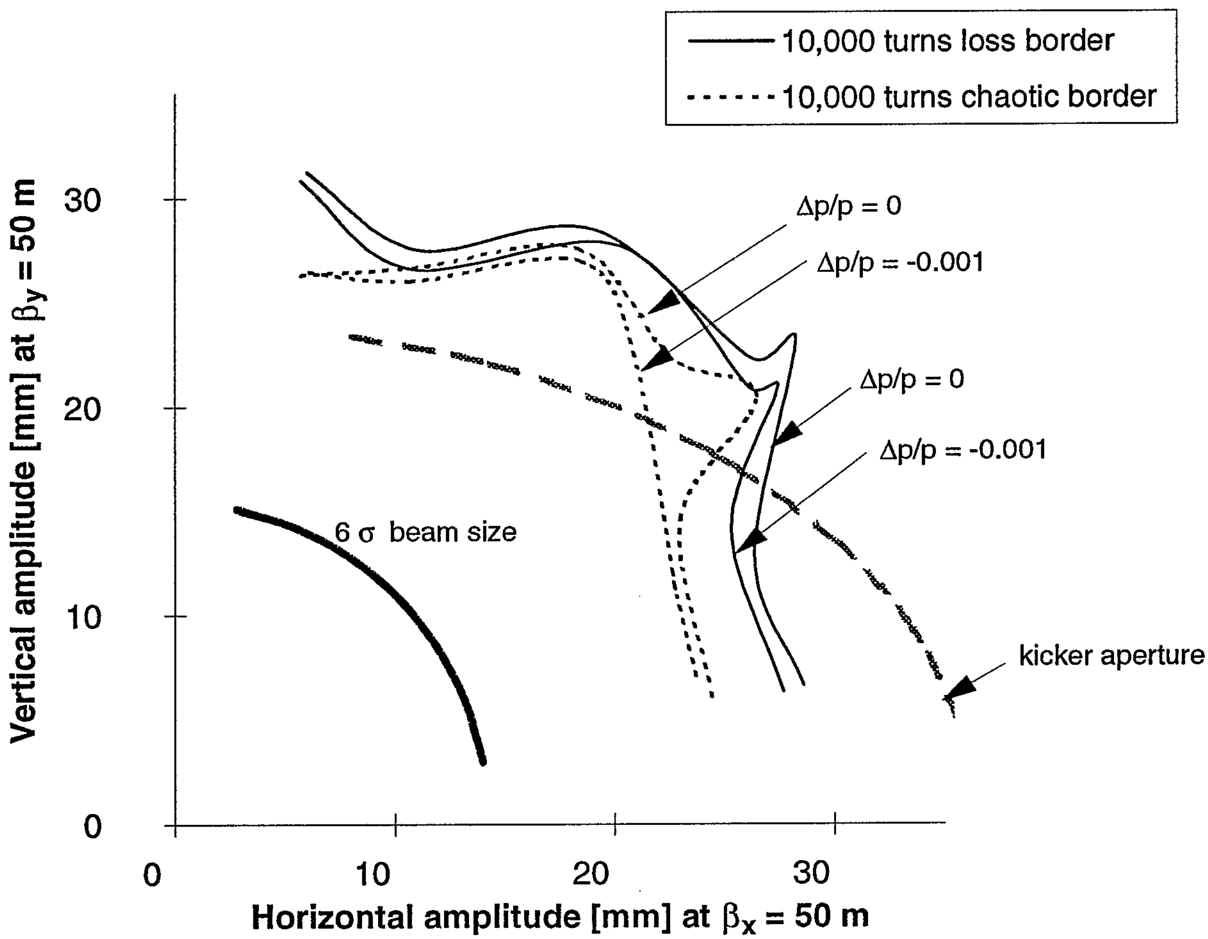

Figure 2: RHIC dynamic aperture at injection for Au^{79+} particles.

Dynamic Aperture at Storage:

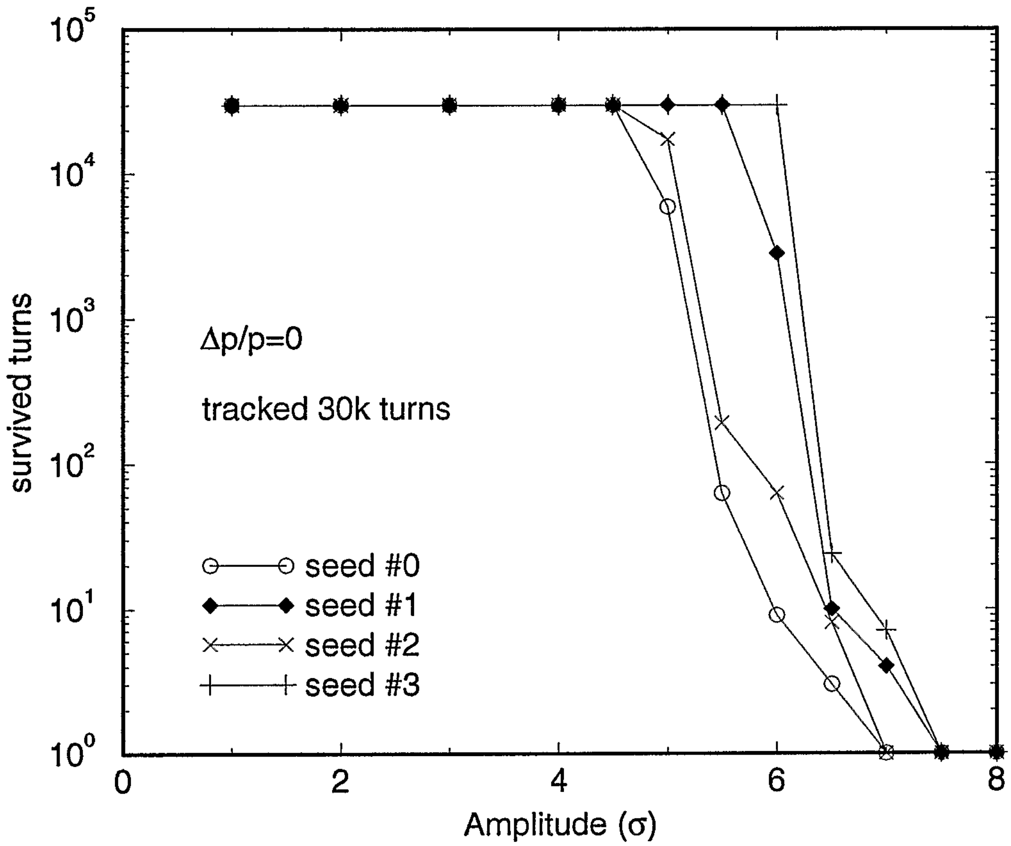

Figure 3: RHIC dynamic aperture at the end of storage with $\beta^* = 1$ m for on-momentum ($\Delta p/p = 0$) Au^{79+} particles.

Luminosity Performance:

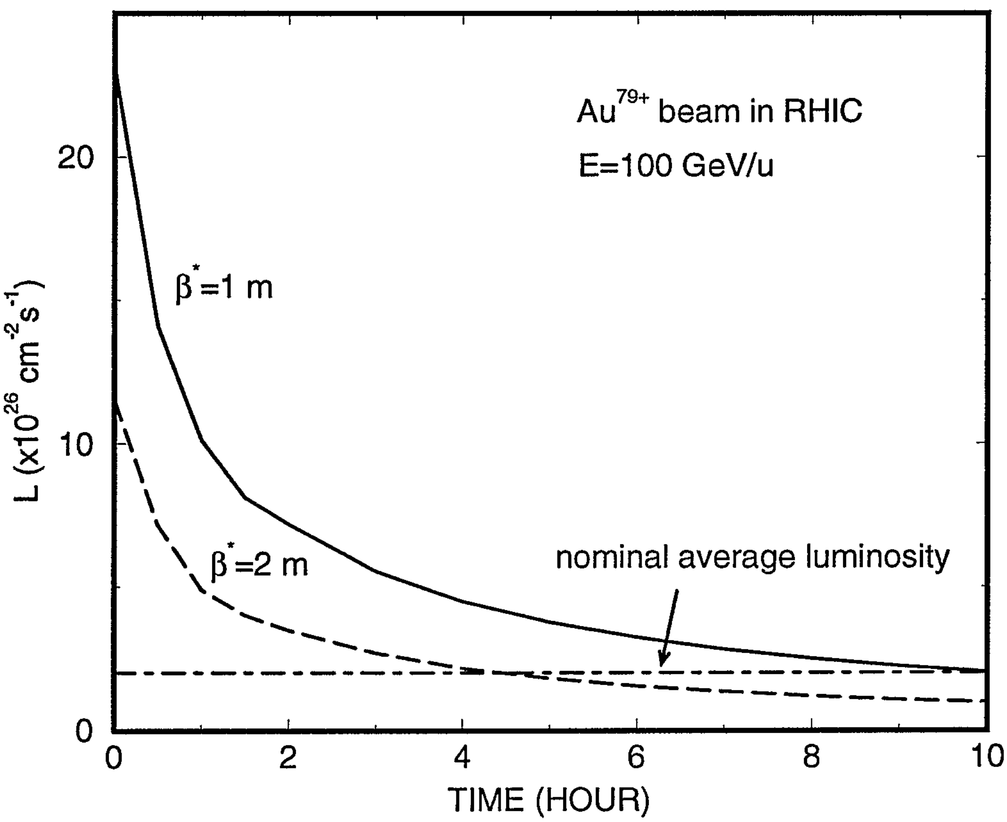

Figure 4: Luminosity performance during the gold storage.

VI. Summary

- All arc dipoles have been completed with excellent field quality and quench performance.

- All sextant magnets have been built and accepted. The field quality meets $\beta^* = 1$ m operational requirements.

- CQS and IR triplets have been carefully aligned during assembly to minimize twists, rolls, and offsets.

- The design goals can be met with a continuing effort to maintain the construction and alignment quality of the magnets.