BNL-102121-2014-TECH

RHIC/AP/10;BNL-102121-2013-IR

Beam Dynamics and Commissioning

S. Peggs

September 1993

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

DISCLAIMER

Beam Dynamics and Commissioning

S. Peggs, Sept 14, '93

Overview and recent RHIC design developments

Introduction: machine parameters, operating scenarios, and lifetime issues.

Correction systems: single layer and four layer correctors in the arcs and in the Interaction Regions.

Active beam dynamics issues

Magnetic field quality control: expected harmonics, contractual harmonics, and as-built harmonics.

Longitudinal manipulations: emittance preservation during passage through transition and re-bucketing.

Instabilities and impedances: impedance budget and feedback systems.

Flexibility: Species, IR optics in the collider, matching in the transfer lines.

Commissioning - the sextant test

Physics goals: beam and optics measurements. Cf LEP octant test.

Controls goals: hardware and software.

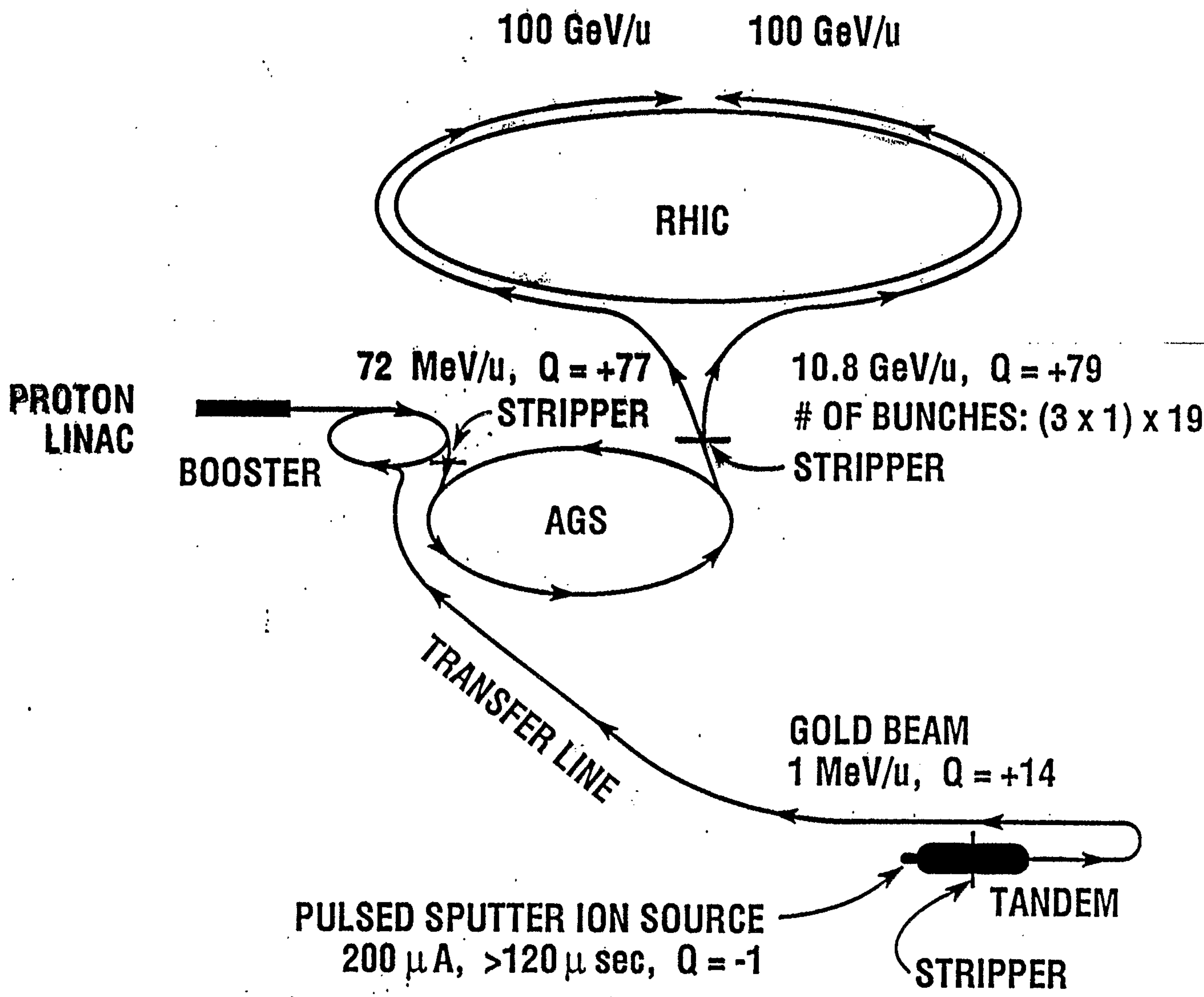
Databases: information integration.

Conclusions

Beam dynamics design is complete, bar routine maintenance and investigation of performance limitations.

Strong new emphasis: commission the sextant as fully as possible

RHIC ACCELERATION SCENARIO Au



Relativistic **H**eavy **I**on **C**ollider

BASIC PARAMETERS

ION SPECIES	p(1/1) -> Au (79/197)
ENERGY RANGE	30 Gev/u -> 100 Gev/u (Au) 250 Gev (p)
BUNCH INTENSITIES	10^9 (Au) -> 10^{11} (p)
# OF BUNCHES	57 -> 114
BUNCH SPACING	220ns -> 110ns
PEAK LUMINOSITY	2×10^{26} (Au), $\sim10^{31}$ (p)
UP TO 6 IR'S	
STORE LENGTH	~ 10 hrs

LAYOUT TWO COUNTER-ROTATING SUPERCONDUCTING RINGS
+ EXISTING ACCELERATOR COMPLEX AS INJECTOR

RHIC SPECIFIC ISSUES

WIDE OPERATING RANGE -> field quality -> aperture -> corrections systems
DIFFERENT SPECIES COLLISIONS -> IR design
INTRABEAM SCATTERING -> large energy spread beams -> field quality -> aperture -> corrections systems; RF voltage
BEAM LOSS SENSITIVITY -> beam loss detection -> collimators -> abort dump

OPERATING SCENARIO

3 bunches per AGS cycle - 19 cycles per ring - >
~25s fill time per ring

26 MHz acceleration RF system - 83 A/s ->
55s to top energy

recapture into storage RF system 200 MHz -
20 cm rms interaction length

increase focussing and bring beams into collision - 120s

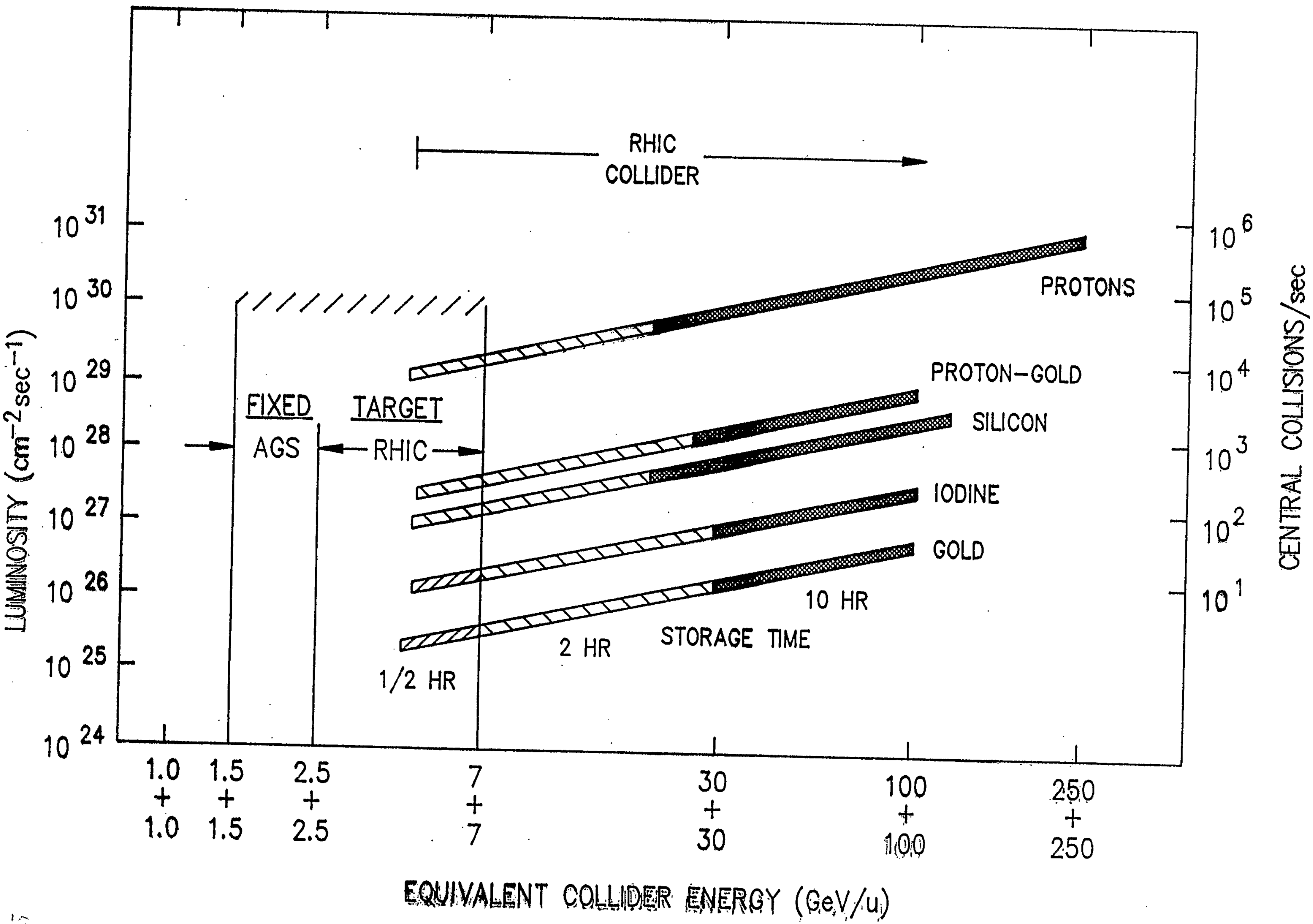
Total turn on time ~ 5 mins

Long range operating scenarios based on 40 weeks/year

2 high luminosity IR's

2 low luminosity IR's

2 initially unused IR's



RHIC
COLLIDER
PROTONS
PROTON–GOLD
SILICON
IODINE
GOLD
FIXED TARGET
AGS
RHIC
10 HR
STORAGE TIME
2 HR
1/2 HR
10^31
10^30
10^29
10^28
10^27
10^26
10^25
10^24
LUMINOSITY (cm^-2 sec^-1)
10^6
10^5
10^4
10^3
10^2
10^1
CENTRAL COLLISIONS/sec
1.0 + 1.0
1.5 + 1.5
2.5 + 2.5
7 + 7
30 + 30
100 + 100
250 + 250
EQUIVALENT COLLIDER ENERGY (GeV/u)

LIFETIME ISSUES

1) **Intrabeam Scattering - multiple coulomb within bunch**

growth rate α $(Z^4/A^2)\sqrt{L}$

precise lifetime depends on detailed beam parameters

2) **Boring Physics - particle loss mechanisms**

electron pair production + capture
$Au + Au \rightarrow Au + (Au + e^+) + e^-$ ~150 barn

coulomb nuclear excitation
N* production, nuclear dipole resonance ~90 barn

2 high L IR's at 2×10^{26} $\tau = 110$ hrs

6 high L IR's at 10^{27} $\tau = 7$ hrs !!!!

3) **Dynamic Aperture - focussing quads removed from IR**

aperture defined by large beta values in the triplet

Maximum Integrated Luminosity -> short stores
rapid detector turn-on

Detector Backgrounds -> beam collimation

Lattice RHIC92 version 0.3

Several minor modifications have been made in the last 12 months, reflected in the RHIC92.0.3 optics database, and in the Design Manual:

split integer working point:	Q_h, Q_v	= 28.19, 29.18
phase advance between low beta IP's:	$\Delta Q_h, \Delta Q_v$	= 5.238, 4.247

first order matched transition jump
relocated octupole/decapole correctors
refined triplet quadrupole correction strategy

8 cm correctors are either 1 layer (dipole) or 4 layer

dipole layers:	normal or skew	closed orbit, H and V
quad layer:	normal or skew	transition jump, linear decoupling
octupole layer:	normal	quadratic chromaticity
decapole layer	normal	not connected - contingency

13 cm correctors in IR quad triplets are 4 layer, and fit in with a detailed correction strategy

field quality measurements are made on every IR quad, prior to individual (quadrupole) and group (triplet) dead-reckoned correction.

$\beta_{max} \approx 1400$ meters in low beta quads (because of D0 and DX dipoles between the interaction point and Q1).

after 10 hours of gold storage, $\epsilon_N = 40\ \pi$ mm mrad, and the 5σ beam size is 71% of the 6.5 cm coil radius.

all IR's have identical IR optics layout, but different correction layer connections according to nature of each IP.

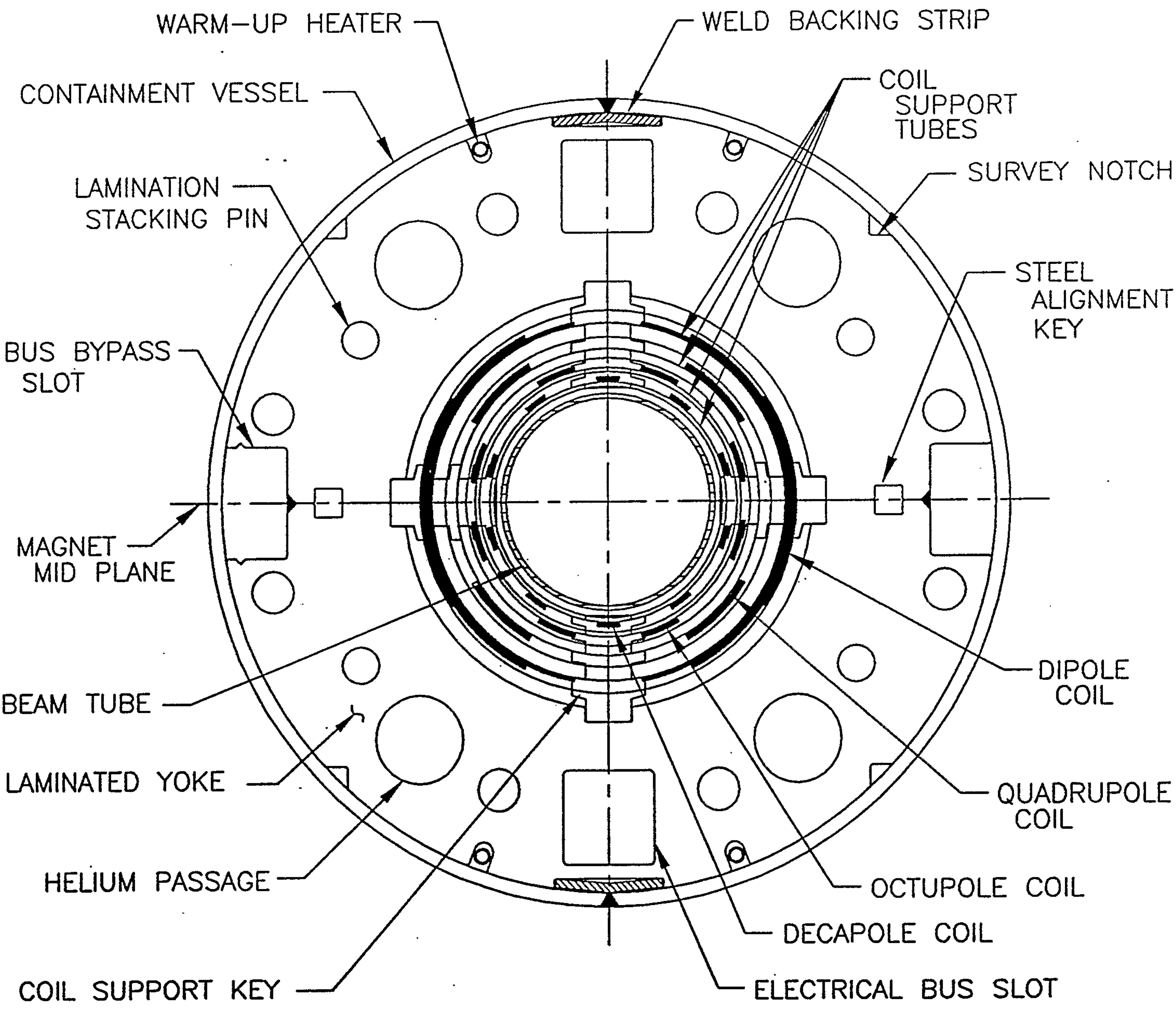
triplets lie side-by-side in Yellow and Blue rings, with a common cryostat for Q1 magnets.

Table 11-4. Trim/Correction Magnet Systems Per Ring with Power Supplies on Day-One

Magnet System	Beam Optical Purpose	Units/Ring, Location, Strength
Dipole	Correct closed orbit, beam separation @ crossing point during acceleration and storage	222 b_o/a_o units, 0.3 T·m each @ each QF/QD, Q4-Q9, and focussing Q2, Q3 individually powered
		12 a_o units/insertion, 0.3 T·m each @ defocussing Q2, Q3 individually powered
Quadrupole	γ_T-jump	8 b_1 units/sextant, 1.5 T each @ QF in insertion and arc 2 families*/sextant
	Correct β_x, β_y, X_p @ crossing points and arcs	Trim power supplies @ Q1 - Q3, Q7, QFA, QDA Trim magnets, 21 T each @ Q4, Q5, Q6
Skew Quadrupole	Correct linear coupling and tune splitting	8 a_1 units/insertion, 1.5 T each 2 families/insertion 2 a_1 units/insertion, 0.8 T each @ Q2, individually powered
	Correct vertical dispersion @ crossing points	Future option
Octupole	Correct quadratic chromaticity	15 b_3 units/sextant, 3.6 kT/m^2 each 2 F + 2 D families/sextant
	Triplet correction	4 b_3 units/insertion, 240 T/m^2 @ Q2, Q3 in low beta insertions individually powered
Decapole	Correct tune spread due to $\langle b_4 \rangle \neq 0$ in dipoles iron saturation	Future option
	Triplet correction	4 b_4 units/insertion, 565 kT/m^3 each @ Q2, Q3 in low beta insertions individually powered
Dodecapole	Correct tune spread due to $\langle b_5 \rangle \neq 0$ in high-beta quads iron saturation	4 b_5 units/insertion, 4.9 MT/m^4 each @ Q2, Q3 in low beta insertions individually powered

*A family of corrector magnets is powered by one supply.

RHIC ARC CORRECTOR



sk/s00487ml

9

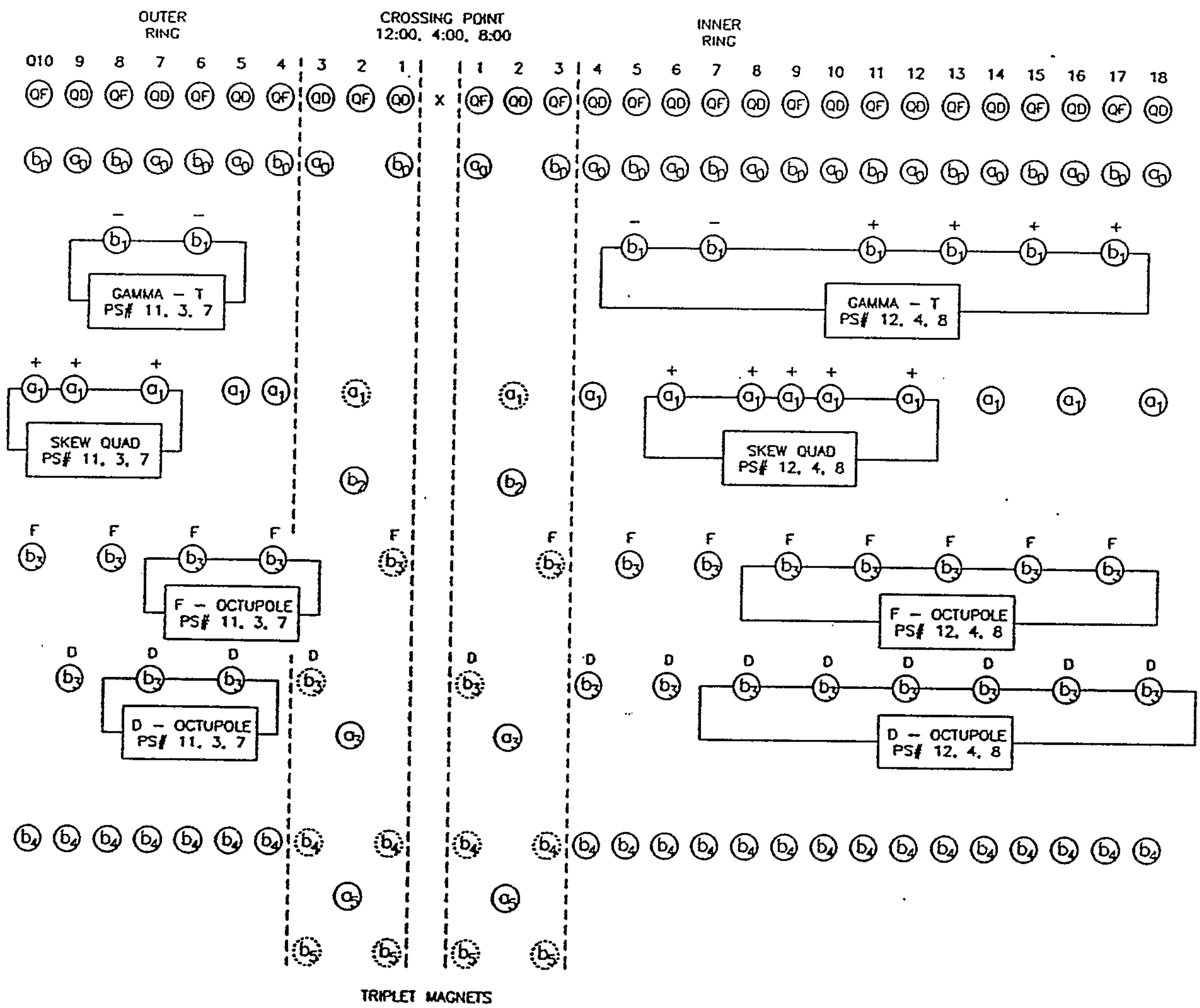


Fig. 2-12. Corrector power supplies at 12, 4 and 8 o'clock.

The RHIC γ_T-jump will maintain a physically small beam size during the jump and will not exceed the beam size at injection.

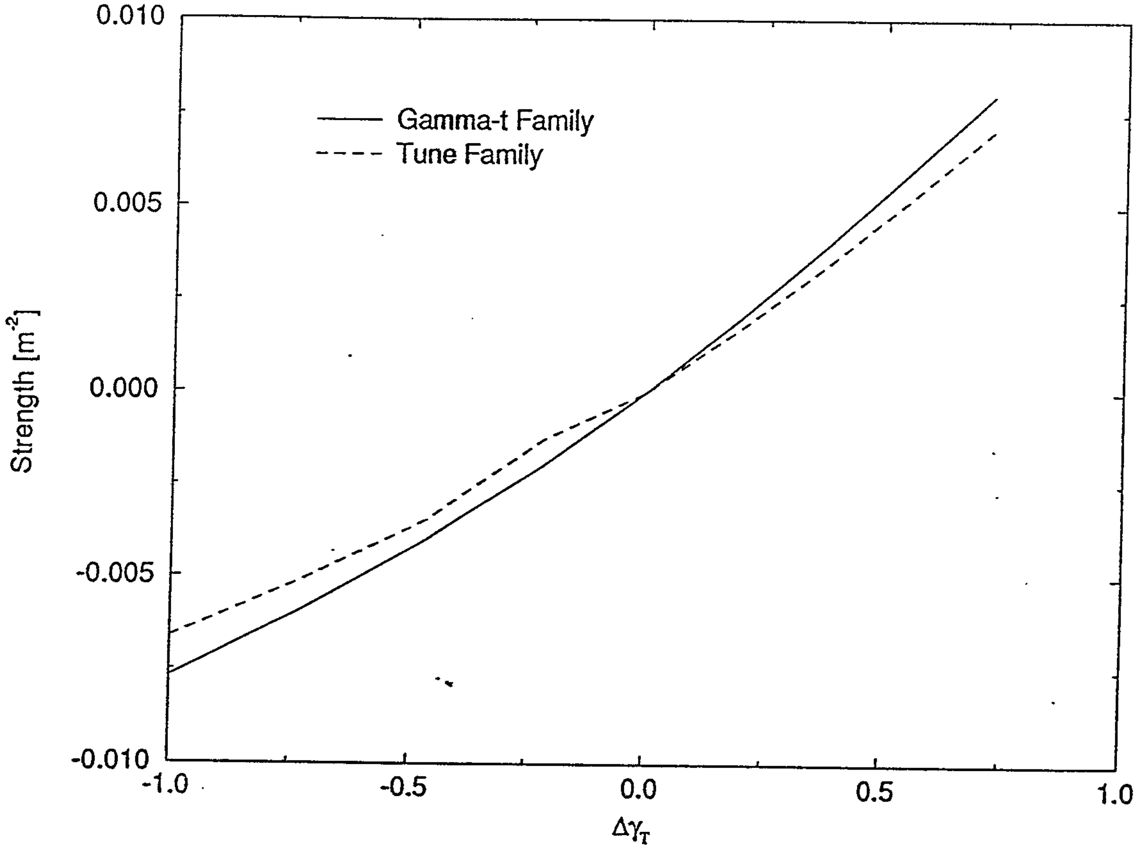


Fig. 11-13. b_1**-corrector strength versus the change in** γ_T **.**

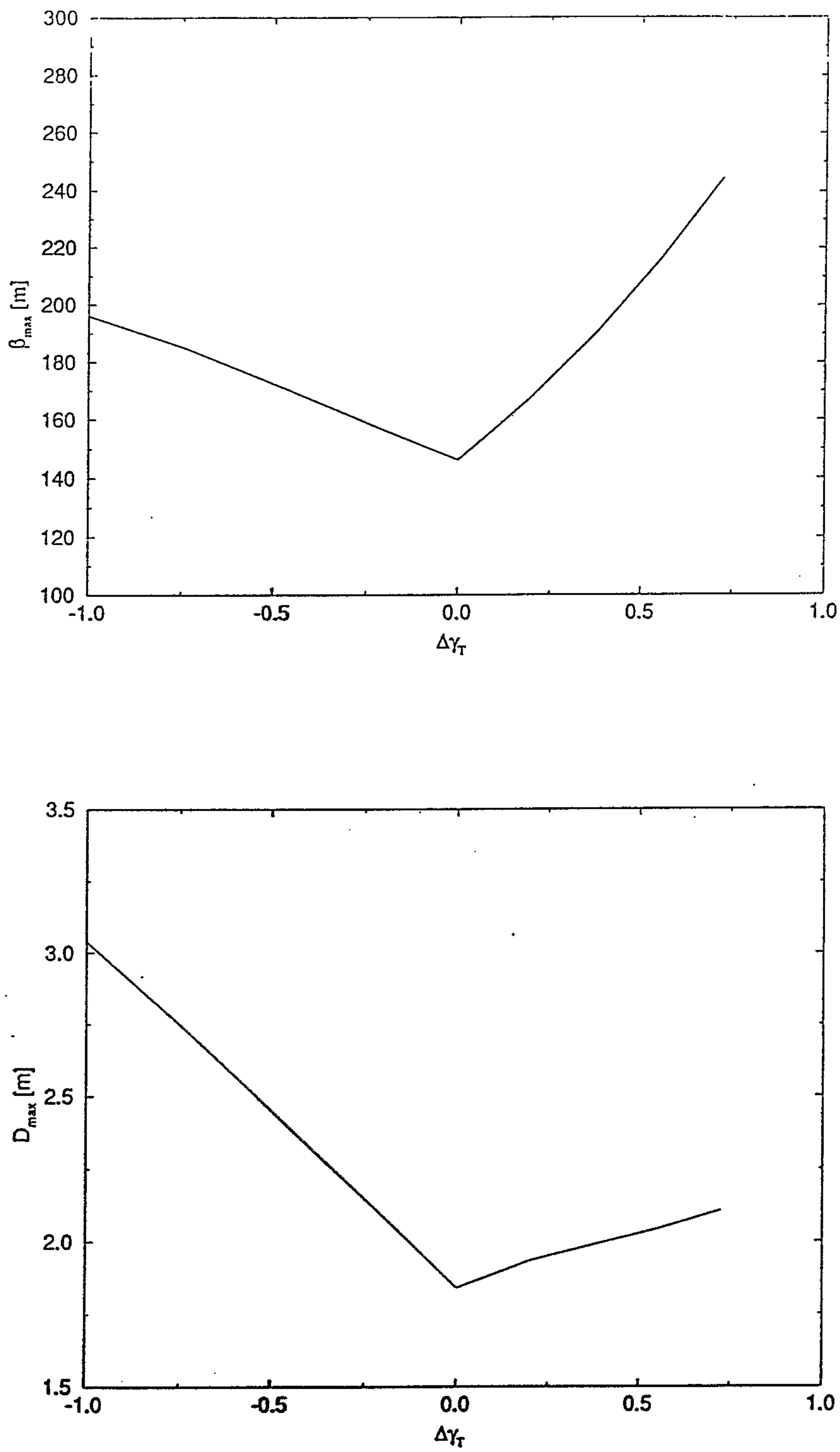


Fig. 11-14. The maximum beta function and the maximum dispersion during the γ_T-jump.

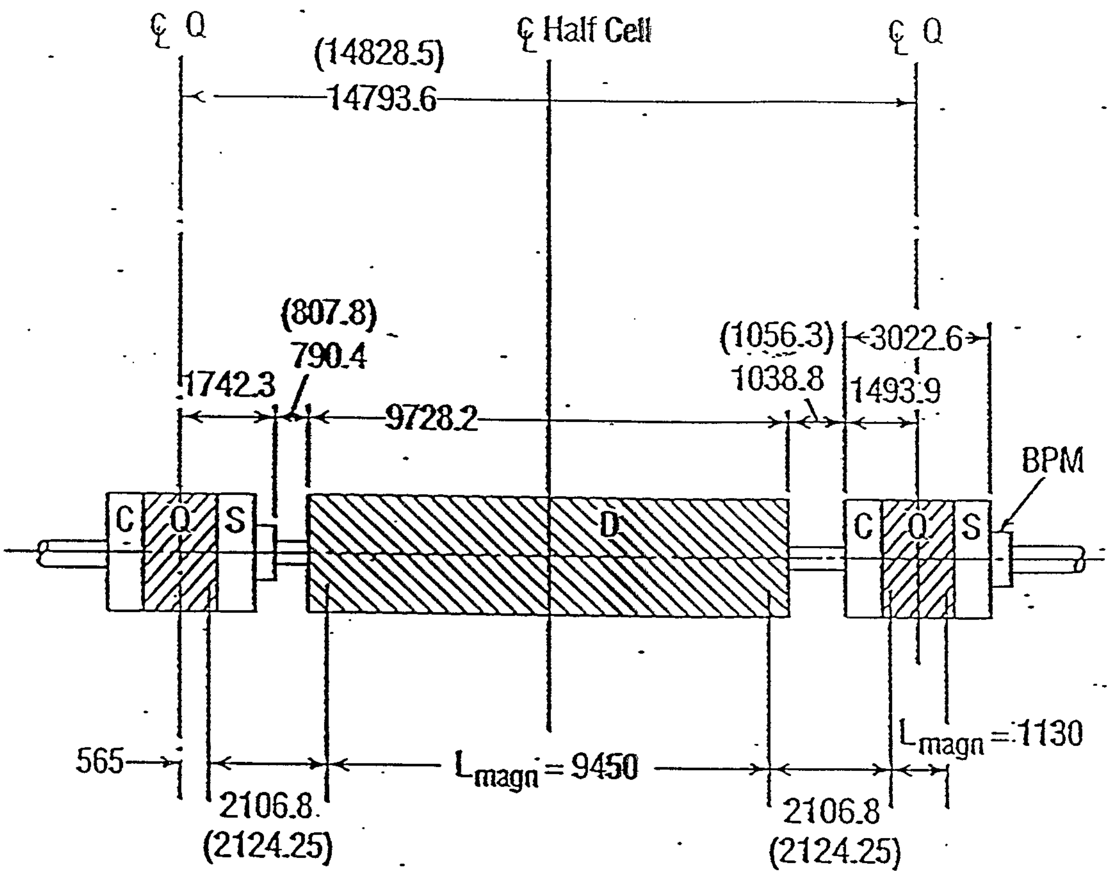


Fig. 11-2. Layout of inner(outer) arc half cell.

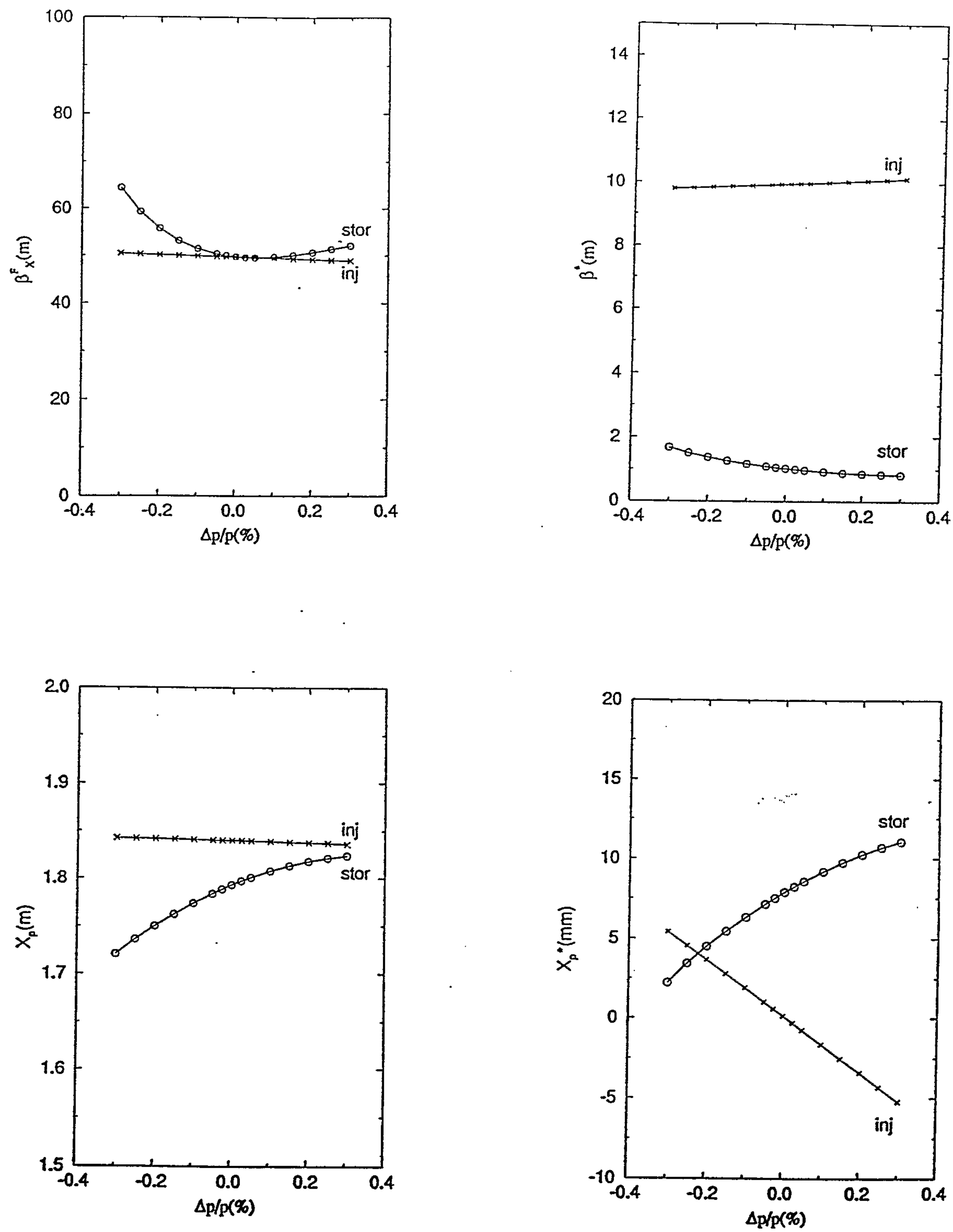


Fig. 11-11. Variation of betatron and dispersion functions versus momentum at the center of inner arcs (left) and at the crossing point (right) at injection ($6 \times \beta^*=10$ m) and storage ($2 \times \beta^*=1$ m & $4 \times \beta^*=10$ m). The chromaticity is corrected with 2 families of sextupoles.

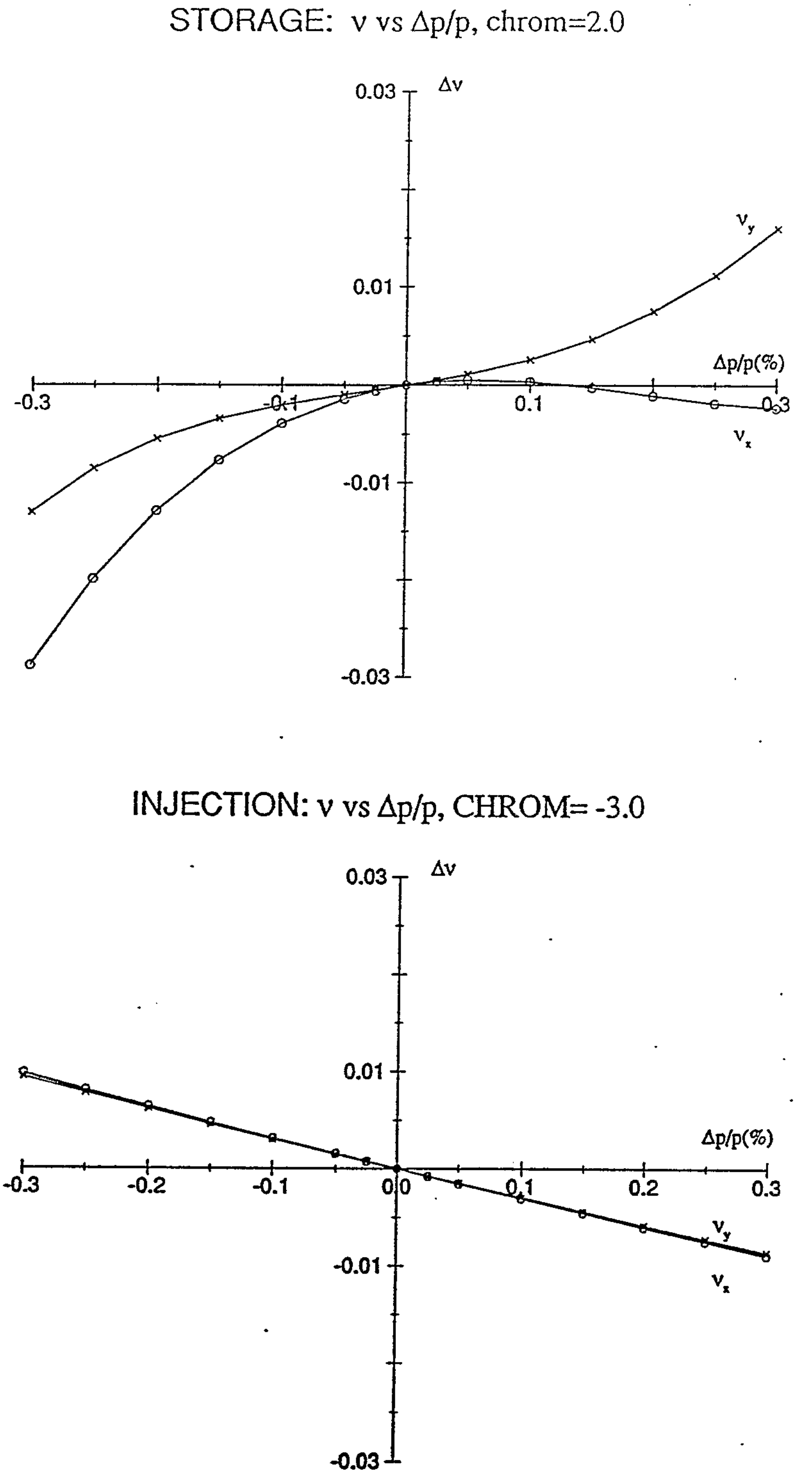


Fig. 11-12. Variation of betatron tunes with momentum at injection ($6 \times \beta^* = 10$ m) and storage ($2 \times \beta^* = 1$ m & $4 \times \beta^* = 10$ m). The chromaticity is corrected with 2 families of sextupoles.

Triplet correction strategy

Nominal operating tunes, 29.18 and 28.19, lie between 5th and 6th order resonances - tune spread must be << 0.033..

Design dispersion is small - chromatic tune spread is dominated by chromaticity (2 x 2.5 x 0.0009 = 0.0045)

First, the integrated harmonics of individual quads are measured, and then trimmed to zero using "tuning shims"

Second, body and end measurements from 3 quads and 1 D0 dipole are used to set triplet corrector settings to minimize tune spread

Local correction is necessary because β varies rapidly in the triplet

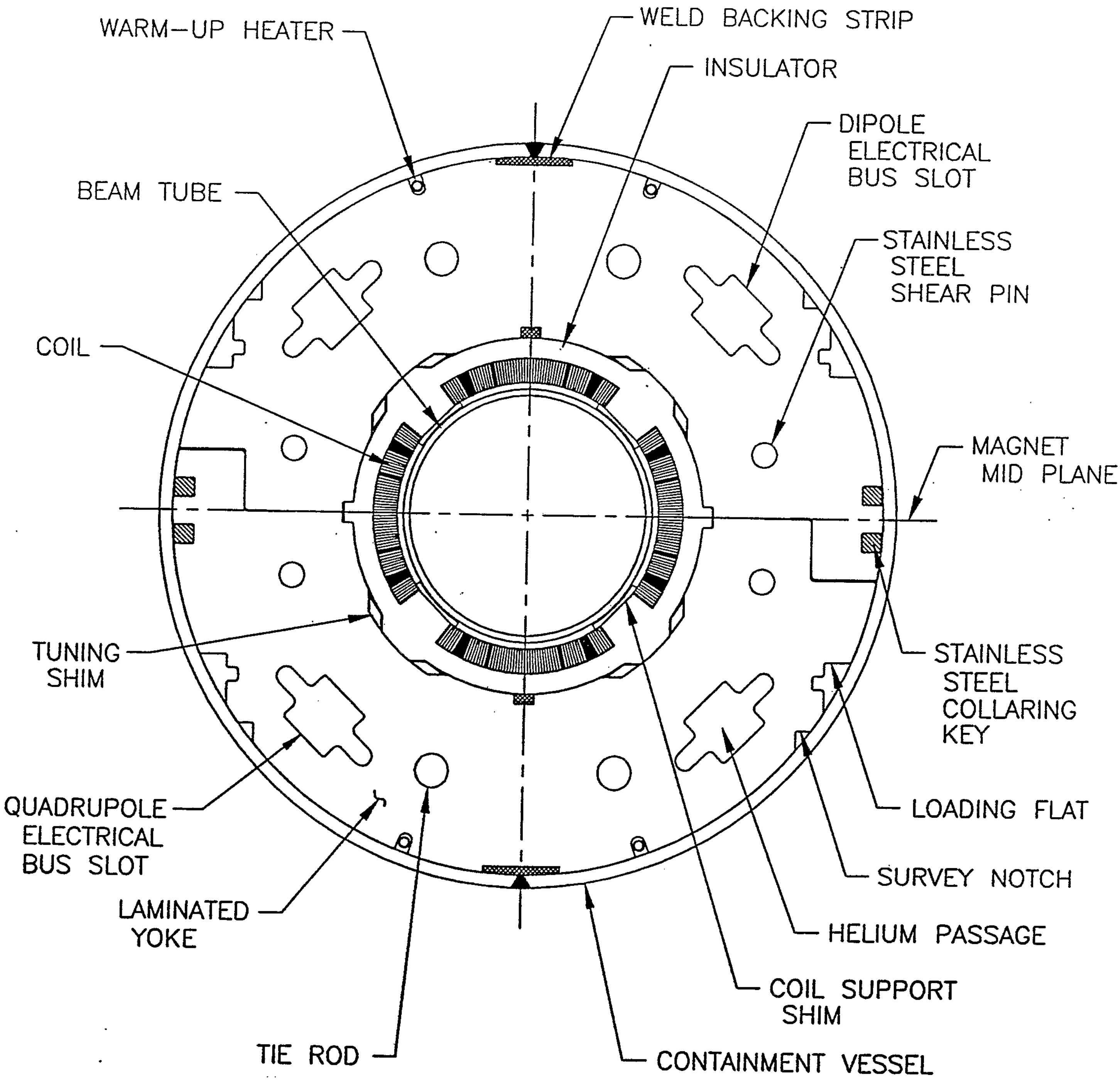
In the table below, "S" implies shimming, and "C1", et cetera, implies excitation of a corrector winding

ORDER, n	NORMAL, b_n	SKEW, a_n
0	C1 or C3	C3 or C1
1	-	C2
2	S, (C2)	S
3	S, C1, C3	S, (C2)
4	S, C1, C3	S
5	S, C1, C3	S, (C2)
6+	-	-

Tune spread before correction is unacceptable: tune spread after correction is less than that due to linear chromaticity

Performance predicted by simple perturbation theory is consistent with results from complex long time tracking

RHIC INSERTION QUADRUPOLE



sk/s00488ml

Magnetic field quality control

Arc dipoles and quadrupoles are being built in industry, with first assembly in February '94. First production run of 30 will be used in the sextant test.

IR quads, correctors, DX and D0 dipoles, et cetera, are being built at BNL. Assembly of CQS packages is performed at BNL.

BNL has extensive experience in the construction and measurement of multiple prototypes of all magnets critical to beam dynamics performance. Expected harmonics based on these measurements are passed to RHIC Accelerator Physics for evaluation, and updated as design iterations occur.

Rule of thumb: systematic errors are more important than randoms, due to consistent superconducting cable dimensions. Hence, expected harmonics also include expected variation of systematics, for example due to plant tooling particulars.

Field harmonic specifications and mechanical tolerances are written into the industrial contracts. Experience shows that tight control of coil tolerances leads to good field harmonics.

Accelerator Physics will concentrate in future on rapid evaluation of as-built harmonics, as the data come in, via the Magnet Division. This will rely on perturbation analysis (fast) and tracking (not so fast).

More magnet details on Wednesday morning, including harmonic data presented by Peter Wanderer.

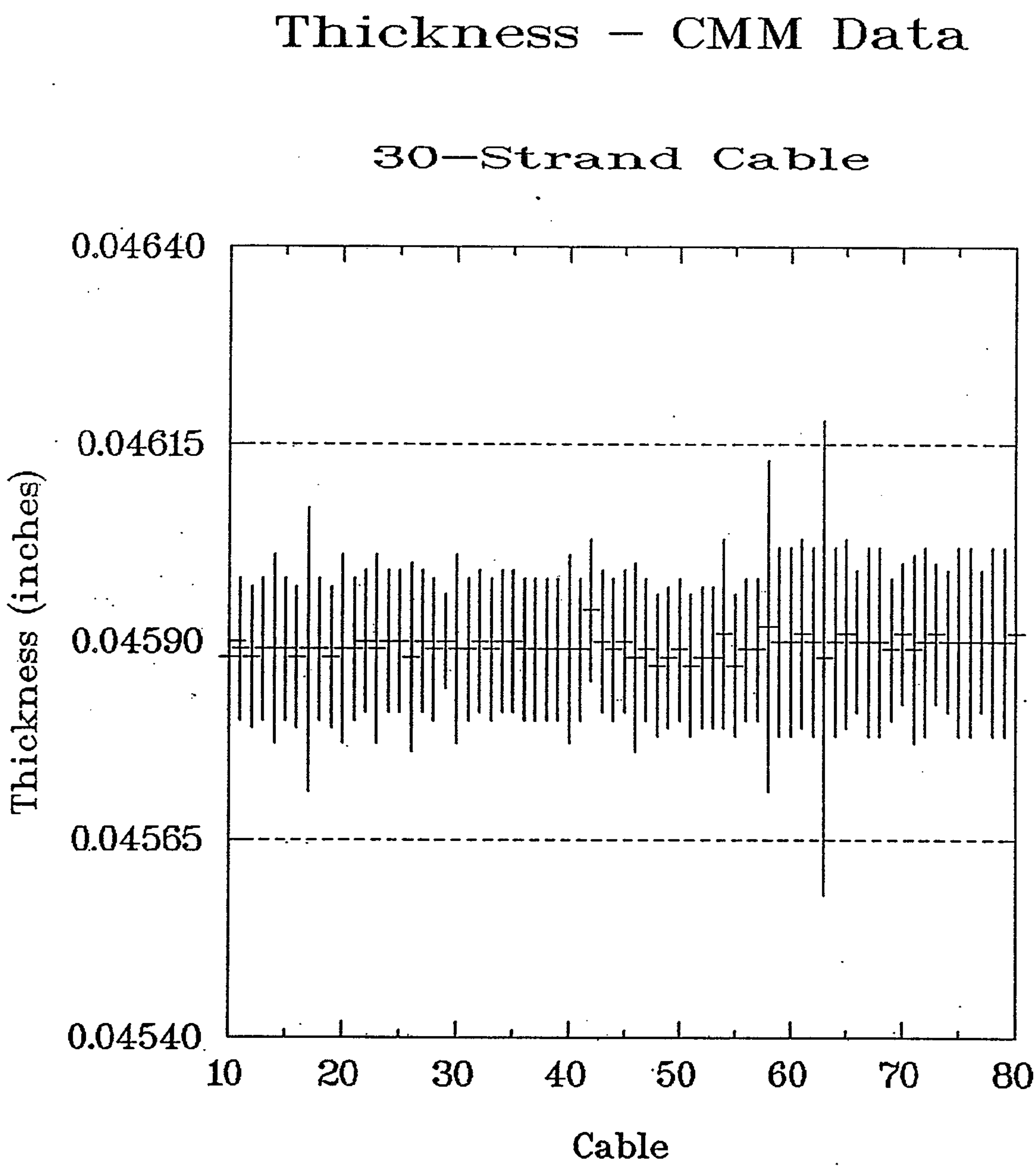
Table 11-3. Summary of Dipole and Quadrupole Parameters

	Coil i.d. (mm)	Eff. Length (m)	Field @ 100 GeV/u† (T;T/m)		Location	Number
DIPOLES	80	9.45**	3.45		ARC, D8	288
	80	2.95	3.45		D6, D9	48
	80	8.71	3.45		D5O	12
	80	6.92	3.45		D5I	12
Subtotal, 80 mm						360
	100	3.60	3.52		D0	24
	200	3.70	4.27		DX	12
QUADRUPOLES			$\beta^*=10$ m	$\beta^*=1$ m		
	80	1.11	68.2	69.5	QF	138
	80	1.11	70.5	71.8	QD	138
	80	1.11	65.4	73.5	QFA (Q9I, Q8O)	24
	80	1.11	66.4	74.6	QDA (Q9O, Q8I)	24
	80	1.11	75.5	75.5	Q5, Q6¶	48
	80	0.93	76.3	72.0	Q7	24
	80	1.81	75.5	75.5	Q4¶	24
Subtotal, 80 mm						420
	130	1.44	46.7	48.5	Q1	24
	130	3.40	46.3	47.1	Q2	24
	130	2.10	46.0	47.3	Q3	24
Subtotal, 130 mm						72
TOTAL, dipole and quadrupole magnets						888

**physical length 9.728 m (383.0 in.)

† Quench field in
- 80 mm Dipole 4.6 T
- 100 mm Dipole 4.42 T
- 200 mm Dipole 5.14 T
- 80 mm Quad 107 T/m
- 130 mm Quad 75.3 T/m

¶ Trim quadrupoles at Q4, Q5, Q6 provide gradient changes from $\beta^* = 10$ to 1 m.



Bar = mean +– 3 Std.

Data from vendor, using BNL-supplied software

Longitudinal manipulations: emittance preservation

Sequence of manipulations, and their effect on the emittance budget:

Inject box car fashion into 26 MHz "acceleration" system buckets. The AGS injector is required to provide a nominal emittance of 0.2 eV-sec for Au ions, in order to achieve the emittance budget. Some Au bunches will grow by about 20% due to IBS during the 60 second worst case time that they are stored at injection energy.

Accelerate to top energy in about 55 seconds, at 83 A/s.

Cross transition (except for protons) early in the acceleration. RHIC will be the first superconducting collider to cross transition. Transition is a bottle neck for Au, according to standard simulations, with a nominal minimum emittance of about 0.3 eV-sec after passage

Re-bucket from acceleration system to "storage" system (196 MHz). Turn off(on) acceleration(storage) system Allow beam to filament about unstable fixed points of the storage buckets. Snap the RF phase.so that bunch ends up at stable fixed points. Efficient rebucketing requires an emittance of less than 0.4 eV-sec

Store for 10 hours. Intra Beam Scattering and RF noise cause significant leakage of Au ions from storage buckets. Periodically scrape the coasting beam, if experimental background gets too high.

Nominal RF parameters are undergoing modest final optimizations.

Tolerance to noise is being investigated. Noise levels achieved at the SPS appear to be acceptable, even near the separatrix.

More detailed transition crossing simulations are being made.

The significance of IBS coupling strength is being investigated.

For more information, see "The Conceptual Design of the RHIC RF System", May '93, as reviewed by the Machine Advisory Committee.

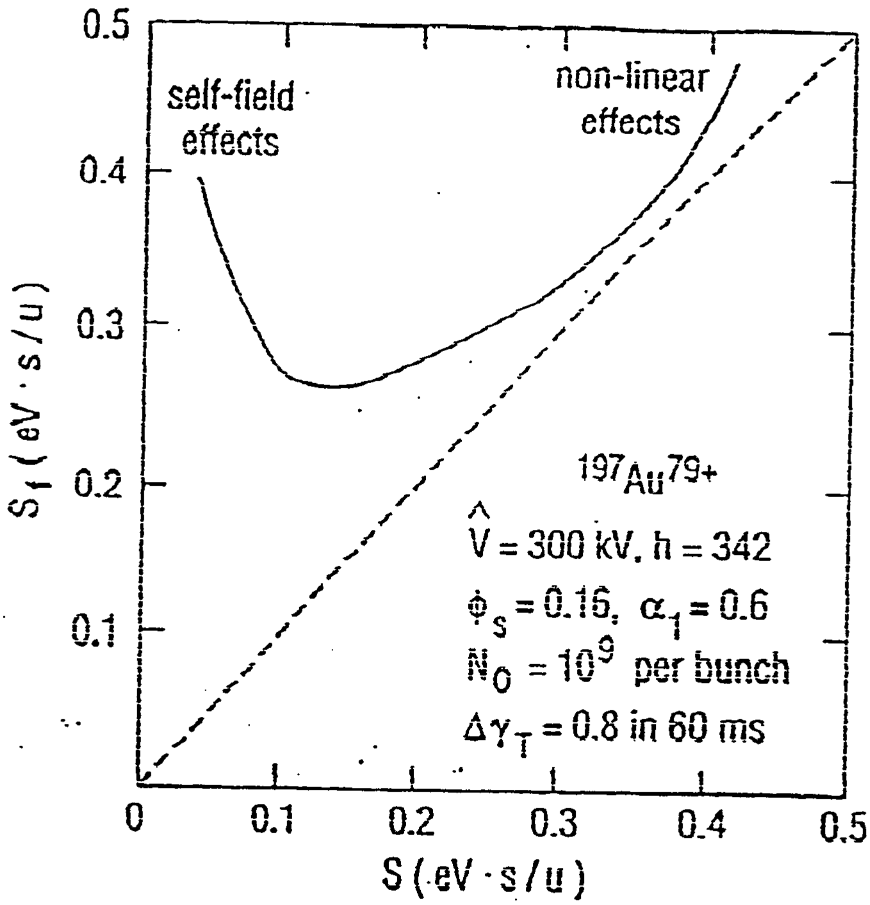


Figure 4.1: Initial and Final longitudinal emittances with a 60 ms transition jump

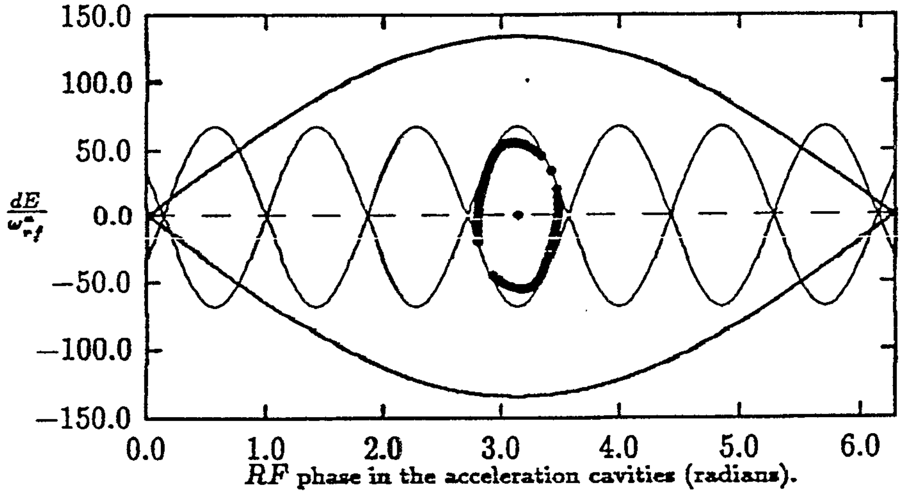


Figure 5.3: Dashed line is the bucket in 26 MHz bucket, solid line is the storage bucket, dots are representative particles, $\varepsilon = 0.3$ eV s/u, $V^{a}_{rf,a} = 550$ kV.

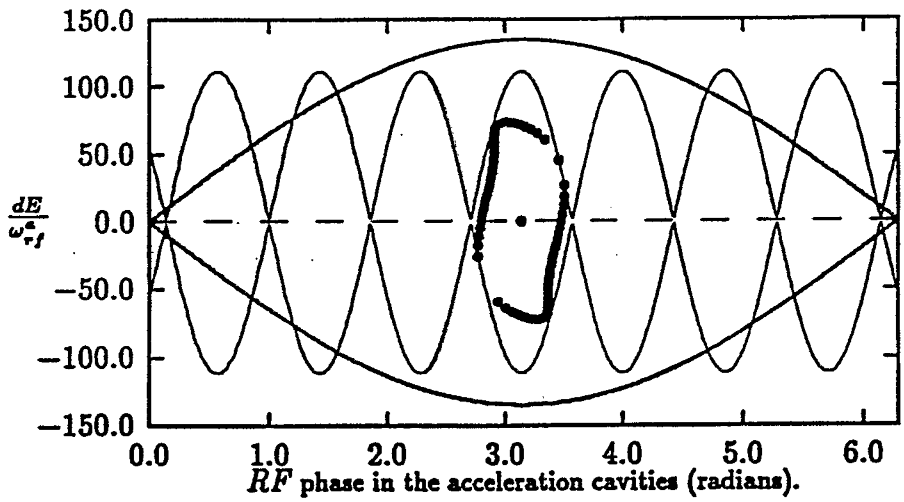


Figure 5.4: Dashed line is the bucket in 26 MHz bucket, solid line is the storage bucket, dots are representative particles, $\varepsilon = 0.4$ eV s/u, $V^{a}_{rf,a} = 300$ kV, $V^{s}_{rf,s} = 1500$ kV.

Instabilities and impedances

Instabilities

Microwave instability: proton beams have the highest intensity, and are the most vulnerable, with a threshold Z/n of about 10 Ohms at 250 GeV.

Longitudinal couple bunch instability: calculation of thresholds and growth rates show that gold and proton beams appear to be Landau damped and stable in storage.

The longitudinal damper also used to damp injection oscillations will be able to handle longitudinal coupled bunch modes growth rates as high as 10 s^{-1}.

Transverse mode effects are under study, but are not expected to be important.

Impedances

Unshielded bellows would account for about half of the broad band impedance, according to calculations of the impedance budget. Consequently they will be shielded, bringing the Z/n down from about $-2\ i\Omega$ to about $-1\ i\Omega$.

Bench measurements of bellows impedances are in "reasonable" (20%) agreement with calculation.

Narrow band longitudinal coupled bunch modes in the RF cavities are reduced by higher order mode damping to less than 2 s^{-1} - before Landau damping, and assuming worst case overlap.

"Impedance working group" includes participants from Accelerator Physics, RF, and Instrumentation sections.

Flexibility

Species

The most awkward pair of species, Gold on protons, has a rigidity ratio of about 2.5, leading to variable trajectories in shared DX splitting dipole.

RHIC92.0.3 incorporates a "hinged" DX magnet, 20 cm coil ID, currently under design. Even with identical species, the beam passes off-center, exploring field nonlinearities.

RHIC optics

Linear optics in six IR's and six arcs are tuned (almost) independently of one another, to give $\beta^* = 1$ to 10 meters, and ΔQ of approximately 1 unit, along and perpendicular to the diagonal.

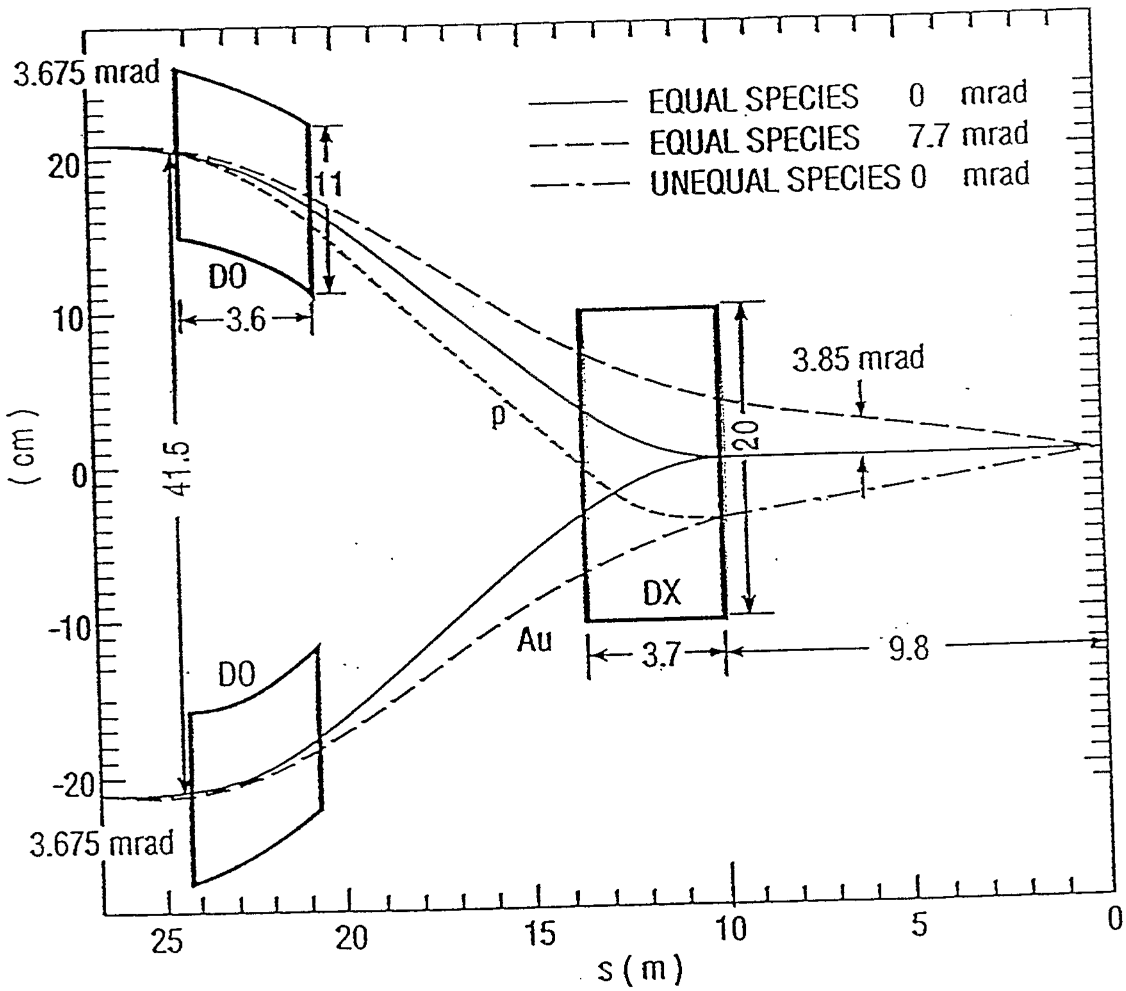
Smooth interpolation between "stepping stones" in a ramp (eg low beta squeeze) must be assured within achievable bounds of parameter space, using function generators responding to the Real Time Data Link, RTDL.

In one proposal the 720 Hz RTDL would carry 20 or 30 key parameters, such as K_F, K_D, S_F, S_D, skew quad family strengths ..., to achieve knob-like performance.

Transfer line optics

Transfer line takes beam from the AGS, with as yet unconfirmed distribution characteristics, to either the Blue or Yellow ring. Beam/optics matching in or out of all 3 rings must be flexible and diagnosable over a wide range.

Simulations - simple or sophisticated - may be trivially interchanged with reality if the processes have clean data interfaces, and are "sequenced". Low overhead is essential - simulations must teach, not divert.



TEPIKIAN 4 3/92 IR

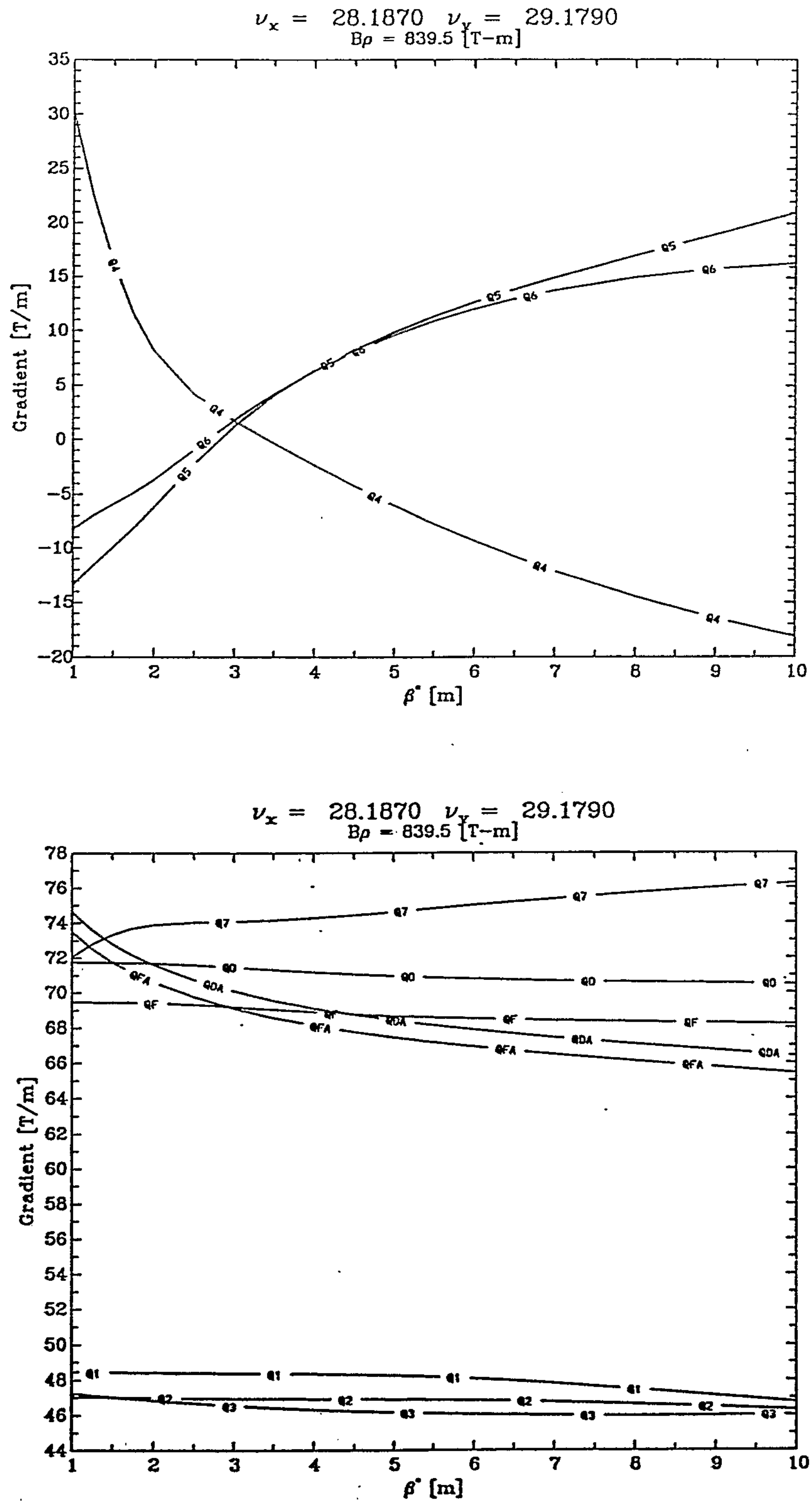
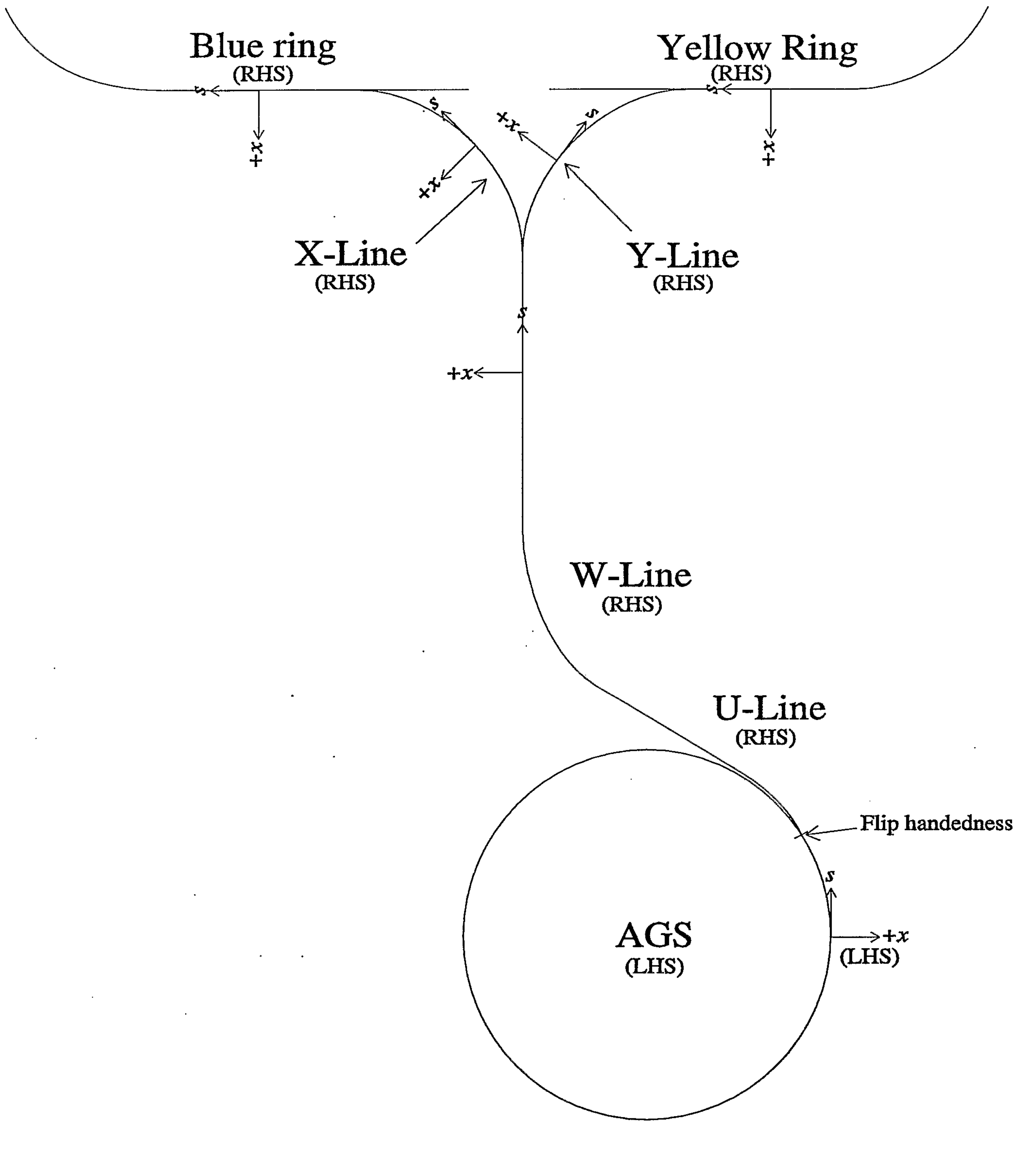
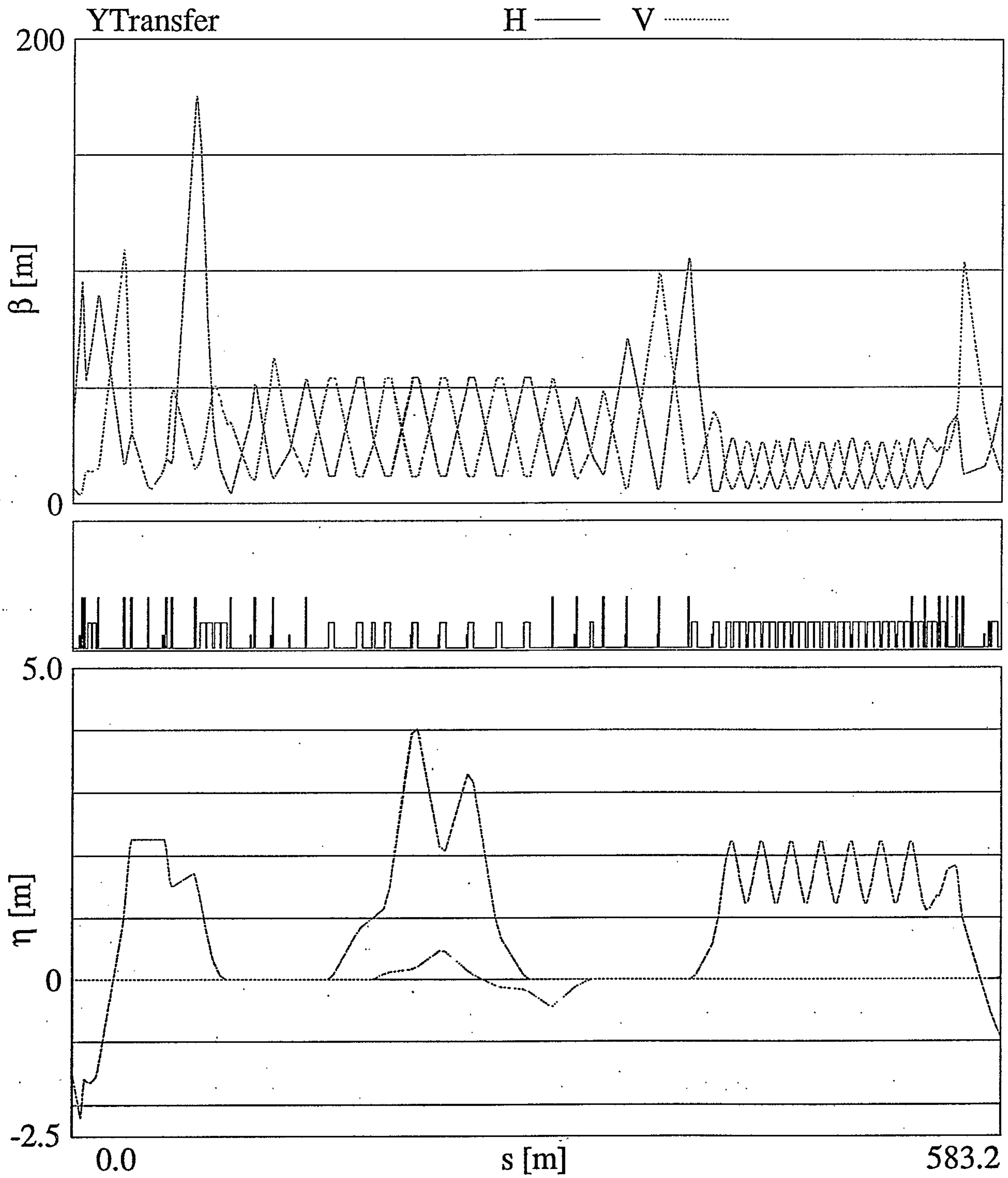


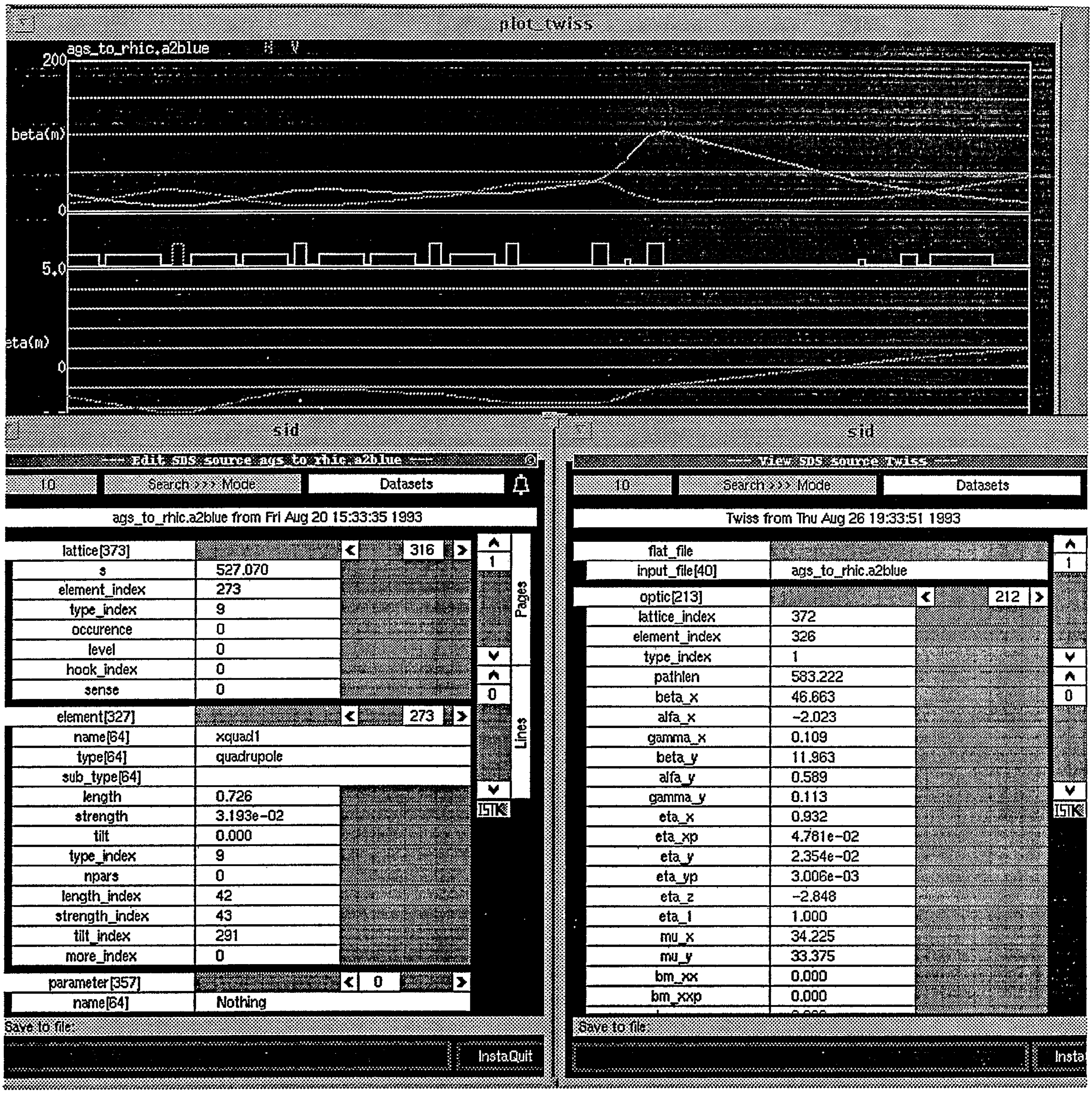
Fig. 11-9. Strength of Insertion Quadrupoles versus β^* at the nominal operating H/V tune of 28.19/29.18.

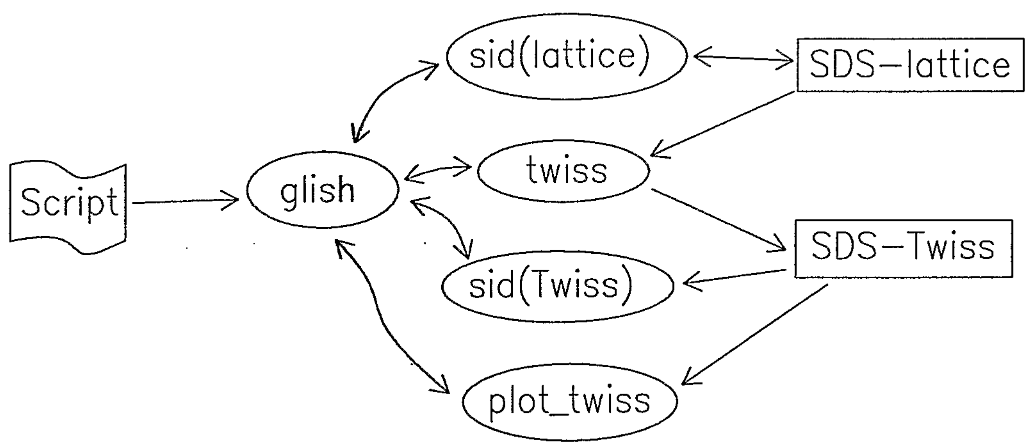


Blue ring
(RHS)
Yellow Ring
(RHS)
X-Line
(RHS)
Y-Line
(RHS)
W-Line
(RHS)
U-Line
(RHS)
Flip handedness
AGS
(LHS)
(LHS)



YTransfer
H
V
200
β [m]
0
5.0
η [m]
0
-2.5
0.0
s [m]
583.2


plot_twiss
ags_to_rhic.a2blue
200
beta(m)
0
5.0
eta(m)
0
sid
Edit SDS source ags_to_rhic.a2blue
IO
Search >>> Mode
Datasets
ags_to_rhic.a2blue from Fri Aug 20 15:33:35 1993
lattice[373] 316
s 527.070
element_index 273
type_index 9
occurence 0
level 0
hook_index 0
sense 0
element[327] 273
name[64] xquad1
type[64] quadrupole
sub_type[64]
length 0.726
strength 3.193e-02
tilt 0.000
type_index 9
npars 0
length_index 42
strength_index 43
tilt_index 291
more_index 0
parameter[357] 0
name[64] Nothing
Pages
Lines
Save to file:
InstaQuit
sid
View SDS source Twiss
IO
Search >>> Mode
Datasets
Twiss from Thu Aug 26 19:33:51 1993
flat_file
input_file[40] ags_to_rhic.a2blue
optic[213] 212
lattice_index 372
element_index 326
type_index 1
pathlen 583.222
beta_x 46.663
alfa_x -2.023
gamma_x 0.109
beta_y 11.963
alfa_y 0.589
gamma_y 0.113
eta_x 0.932
eta_xp 4.781e-02
eta_y 2.354e-02
eta_yp 3.006e-03
eta_z -2.848
eta_l 1.000
mu_x 34.225
mu_y 33.375
bm_xx 0.000
bm_xxp 0.000
Save to file:


sid(lattice)
SDS–lattice
Script
glish
twiss
SDS–Twiss
sid(Twiss)
plot_twiss

Sextant test physics goals

<u>The LEP octant test</u> experience is instructive:

Discovered the dipole bus had to be set 1% or 2% away from its expected value. This proved, much later, to be an injector (SPS) miscalibration.

Beam then ran to the beam stop with little or no steering.

Extensive experiments showed that the phase advance per cell was off by 1 or 2 degrees, due to a systematic quadrupole transfer function error.

Conclude: there will be much to learn from accelerator physics experiments on the sextant, if the experiments are properly planned, with adequate control system and instrumentation support.

<u>Beam distribution experiment</u>

Measurements on AGS fixed target beams have only qualitatively confirmed that the dimensions of the 6-D "hyperfootball" are as expected. Adjustment of front end transfer line optics depends on accurate beam measurements.

Beam profiles are digitized in 2-D by CCD cameras looking at 'destructive' profile monitors. Data from a pair of profile monitors can be deconvolved for non-pathological locations, without scanning intervening optics.

Independent control of the momentum spread, for example by a high dispersion slit, should confirm that the momentum size is relatively small.

<u>Beam optics experiment</u>

Optical transfer functions - matrices - can be measured by observing the response of the beam centroid on downstream Beam Position Monitors, as upstream dipole correctors are perturbed. This is essentially the LEP cell phase advance experiment.

A necessary pre-requisite is a "beam threading" application program that can steer beam down to the beam stop, and that can confirm the absence of unusual losses on Beam Loss Monitors.

Sextant test controls goals

Despite the success of the octant test, the LEP control system became notorious for its slow response during storage ring commissioning.

This was partly due to labyrinthine networks - a feature that RHIC will not have - and partly to lack of system integration. The implicit controls paradigm emphasized testing single accelerator devices, albeit remotely.

The most basic aspect of the sextant test - hardware commissioning - fits this paradigm. Getting beam to the end of the sextant requires a significant amount of high level integration, and the accelerator physics experiments outlined above require even more.

RHIC will benefit most from a fully functional control system on day one - when storage is commissioned in '98. Therefore the control system needs to be exercised as fully as possible in '95.

For example, an energy ramp in the sextant does not make sense to the single pass beam, and is an excessive way to test that the power supplies can put out 5,000 Amps without a magnet quench, but it is still a crucial exercise.

Databases: information integration

BNL has selected Sybase as its standard relational DataBase Management System (rDBMS). Various sections of the RHIC project are building and filling Sybase databases to fit their own needs.

RHIC collider and transfer line design optics are maintained in "ideal optics" databases by the Accelerator Physics section, who are also developing "engineering optics" and other databases.

Controls and Accelerator Physics sections are collaborating on the development of a "configuration" database, for controls routing.

Also in use or in construction are a survey database, an installation database, a wiring database, and an engineering drawing database. More database types will come with the passage of time.

If the design, construction, and maintenance of these databases is properly coordinated, the "relations" between different data sets will enable the powerful integration of information.

Success requires a balance between the autonomous ownership of databases by RHIC sections, and cooperative design of the key features of the tables within each database.

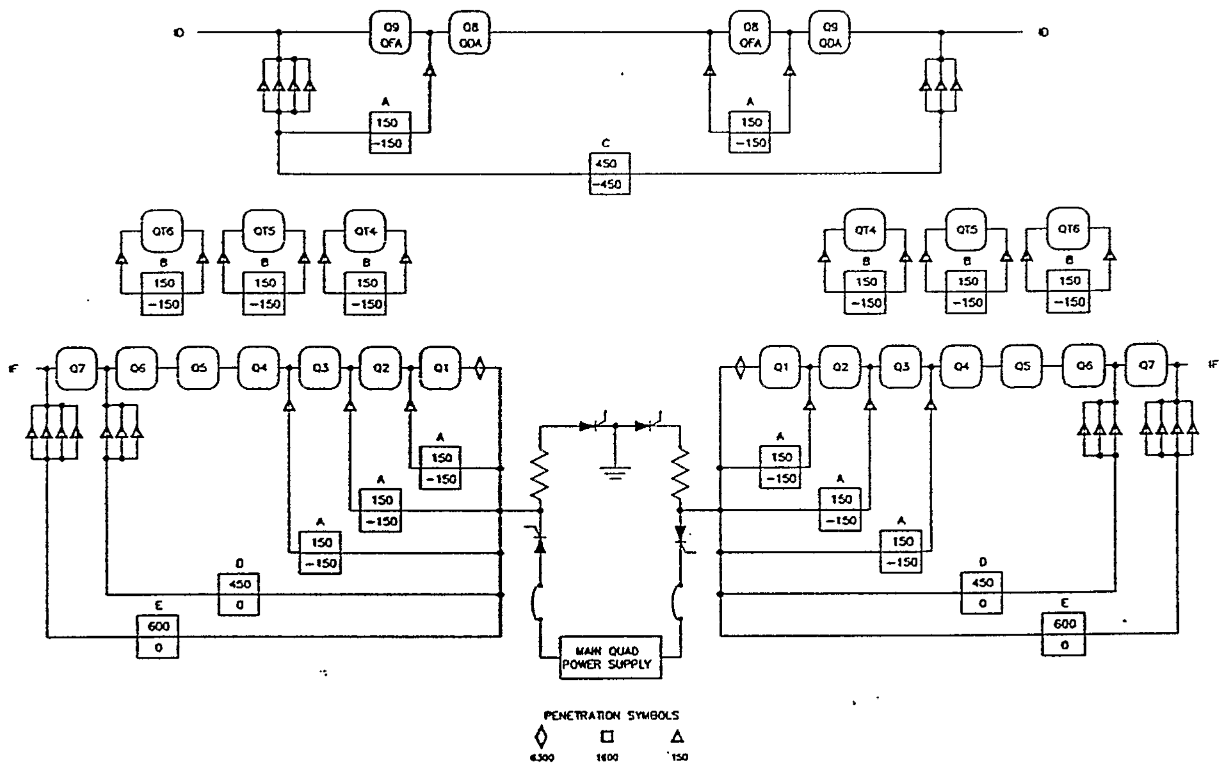


Fig. 2-10. Insertion quads at 4 o'clock.

CONCLUSIONS

1 Performance of the RHIC92.0.3 lattice has undergone 2 successful technical Machine Advisory Committee reviews in the last year.

2 Recent minor modifications include split integer nominal tunes, a linear transition jump, hinged DX magnets, reorganized corrector layout, and a revised IR quad field quality correction strategy.

3 Now that the basic design is complete and stable, we are honing our understanding of RHIC ultimate performance limitations. The limitations under study include the preservation of longitudinal emittance, Intra Beam Scattering, magnetic field quality, transition crossing, IR correction strategies, and the refill time.

4 Coherent instabilities are not expected to be a problem Their study continues and the impedance budget remains controlled. The broadband impedance is halved by shielding the bellows.

5 We eagerly await the industrially built arc dipoles and quadrupoles, scheduled for early next year, and continue to improve our evaluation techniques.

6 Commissioning work focuses on the sextant test of '95, when beam will be passed from the AGS, through the transfer line and across one arcs worth of cells.

7 Experiments on beam quality and optical transfer functions are physics goals for the sextant test that naturally stress a high level of system integration.

8 The even higher level controls functionalities required for '98 storage commissioning will be exercised in the sextant test, wherever possible.