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Field and Alignment Quality Issues of BNL-Built LHC Dipoles

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J. Wei and S. Tepikian

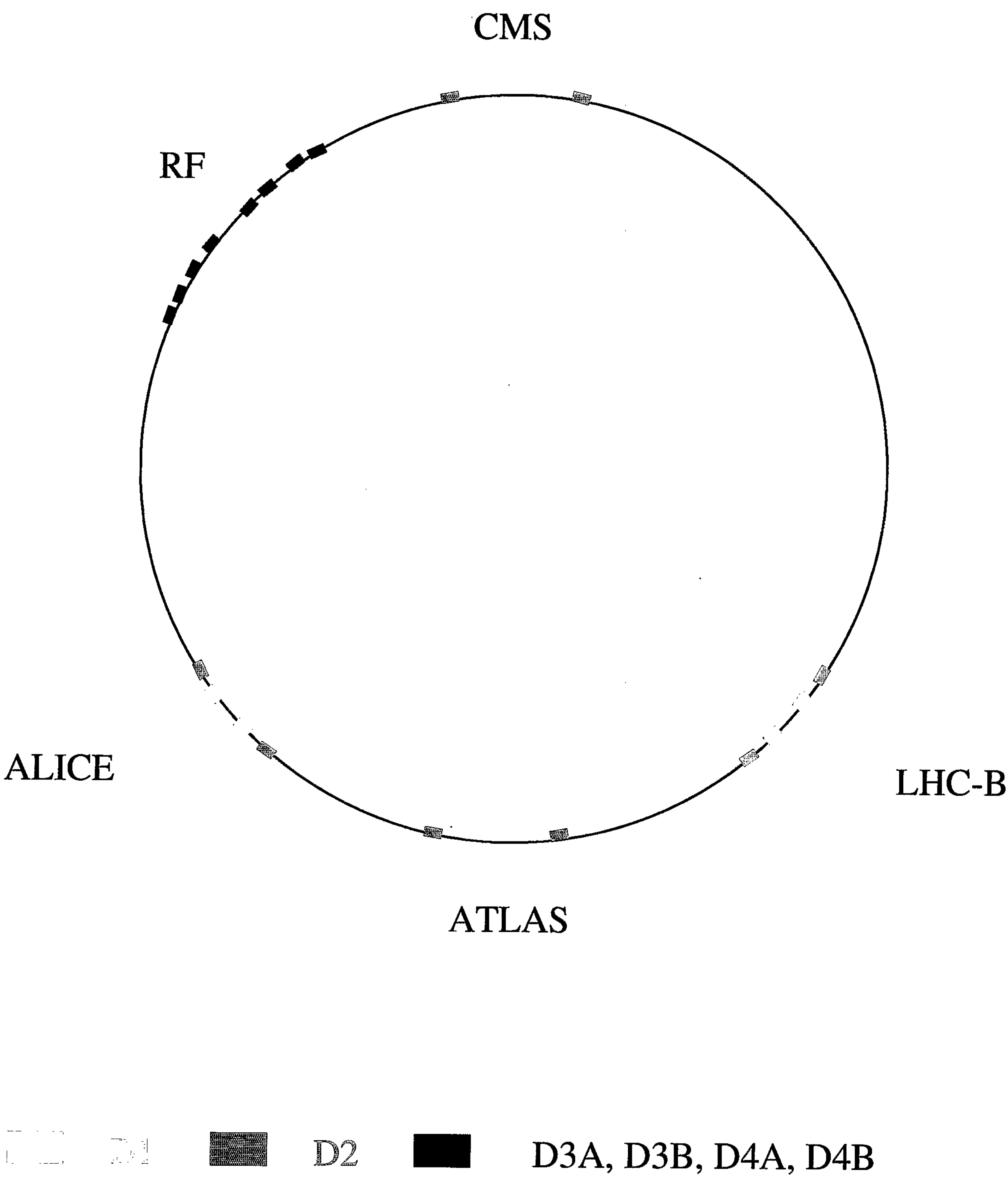
* Introduction

* RF Region Dipoles
  - Injection
  - Collision

* Insertion Region Dipoles
  - Proton operation
  - Heavy ion operation

* Discussion

Locations of BNL-built Dipoles:



LHC IR & RF Section Parameters (Proton Run)

Quantity	Injection	Collision
Energy [GeV]	450	7000
Betatron tunes (H/V)	63.28/59.31	63.31/59.32
Synchrotron tune	0.006	0.00212
Chromaticity (H/V)	2/2	2/2
rms emittance, ϵ_N [m·r]	3.75×10^{-6}	3.75×10^{-6}
rms momentum dev., σ_p	4.7×10^{-4}	1.1×10^{-4}

Quantity	Injection			Collision		
	IP1/5	IP2/8	RF	IP1/5	IP2/8	RF
β^* [m]	18/18	12/15		0.5/0.5	> 10	
Max. β [m]	224	185	209	4705	281	209
Max. $\sigma_{x,y}$ [mm]	1.3	1.2	1.3	1.5	0.37	0.32

Expected BNL-built D1 & D3 errors at collision: ($R_0 = 17$ mm)

n	Normal			Skew		
	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
Body	[unit]					
2	0.07	0.54	0.19	0.43	2.4	1.1
3	-1.5	1.6	0.84	-0.12	0.27	0.10
4	0.00	0.08	0.03	0.01	0.34	0.13
5	0.11	0.17	0.09	-0.01	0.04	0.01
7	0.11	0.02	0.01	-0.00	0.01	0.00
9	0.00	0.01	0.00	-0.00	0.00	0.00
LE	[unit·m]		(Length=0.73 m)			
2	-0.3	1.5	0.7	-1.0	2.9	1.2
3	10.3	1.4	0.5	-4.6	0.5	0.2
5	-0.1	0.2	0.1	0.5	0.1	0.0
RE	[unit·m]		(Length=0.73 m)			
2	0.2	1.2	0.5	0.6	3.1	1.3
3	2.8	1.2	0.5	0.1	0.5	0.2

Expected BNL-built D1 & D3 errors at injection: ($R_0 = 17$ mm)

n	Normal			Skew		
	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
Body	[unit]					
2	0.08	0.51	0.19	0.14	2.8	1.1
3	-6.3	2.5	0.92	-0.03	0.24	0.09
4	-0.02	0.07	0.03	0.04	0.37	0.13
5	0.14	0.18	0.09	-0.01	0.04	0.01
7	-0.04	0.02	0.01	0.0	0.01	0.0
9	0.01	0.01	0.0	0.0	0.0	0.0
LE	[unit·m]		(Length=0.73 m)			
2	-0.2	1.5	0.7	-1.6	2.9	1.1
3	8.7	1.3	0.5	-4.6	0.5	0.2
5	-0.1	0.2	0.1	0.5	0.1	0.0
RE	[unit·m]		(Length=0.73 m)			
2	0.2	1.3	0.5	-0.2	3.	1.1
3	1.8	1.1	0.5	0.1	0.5	0.2

Expected BNL-built D2 & D4B errors at collision: ($R_0 = 17$ mm)

n	Normal			Skew		
	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
Body	[unit]					
2	0.06	0.54	0.19	0.41	2.4	1.1
3	-0.48	1.6	0.84	-0.03	0.27	0.10
4	-0.04	0.08	0.03	0.01	0.34	0.13
5	0.05	0.17	0.09	-0.01	0.04	0.01
7	-0.01	0.02	0.01	-0.0	0.01	0.0
9	0.00	0.01	0.0	-0.0	0.0	0.0
LE	[unit·m]		(Length=0.73 m)			
2	-0.3	1.5	0.7	-1.0	2.9	1.2
3	10.3	1.4	0.5	-4.6	0.5	0.2
5	-0.1	0.2	0.1	0.5	0.1	0.0
RE	[unit·m]		(Length=0.73 m)			
2	0.2	1.2	0.5	0.6	3.1	1.3
3	2.8	1.2	0.5	0.1	0.5	0.2

Expected BNL-built D2 & D4B errors at injection: ($R_0 = 17$ mm)

n	Normal			Skew		
	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
Body	[unit]					
2	0.06	0.51	0.19	0.12	2.8	1.1
3	-5.7	2.5	0.92	-0.03	0.24	0.09
4	-0.02	0.07	0.03	0.04	0.37	0.13
5	0.14	0.18	0.09	-0.01	0.04	0.01
7	-0.04	0.02	0.01	0.0	0.01	0.0
9	0.01	0.01	0.00	0.0	0.0	0.0
LE	[unit·m]		(Length=0.73 m)			
2	-0.2	1.5	0.7	-1.6	2.9	1.1
3	8.7	1.3	0.5	-4.6	0.5	0.2
5	-0.1	0.2	0.1	0.5	0.1	0.0
RE	[unit·m]		(Length=0.73 m)			
2	0.2	1.3	0.5	-0.2	3.	1.1
3	1.8	1.1	0.5	0.1	0.5	0.2

Expected BNL-built D4A errors at collision: ($R_0 = 17$ mm)

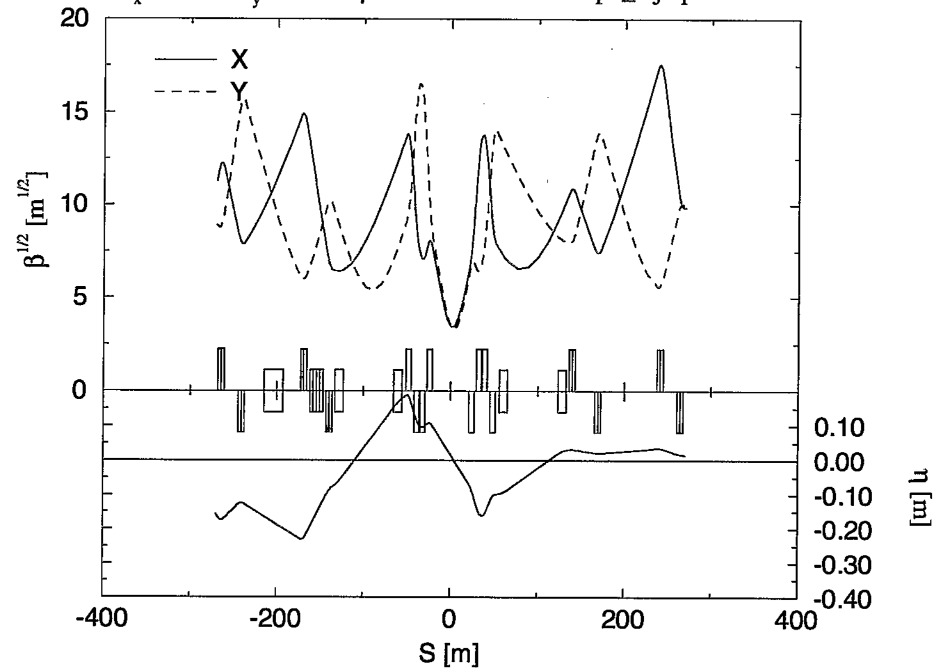
n	Normal			Skew		
	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
Body	[unit]					
2	0.07	0.54	0.19	0.41	2.4	1.1
3	-0.38	1.6	0.84	-0.03	0.27	0.10
4	-0.01	0.08	0.03	0.01	0.34	0.13
5	0.04	0.17	0.09	-0.01	0.04	0.01
7	-0.01	0.02	0.01	-0.0	0.01	0.0
9	0.0	0.01	0.0	-0.0	0.0	0.0
LE	[unit·m]		(Length=0.73 m)			
2	-0.3	1.5	0.7	-1.0	2.9	1.2
3	10.3	1.4	0.5	-4.6	0.5	0.2
5	-0.1	0.2	0.1	0.5	0.1	0.0
RE	[unit·m]		(Length=0.73 m)			
2	0.2	1.2	0.5	0.6	3.1	1.3
3	2.8	1.2	0.5	0.1	0.5	0.2

Expected BNL-built D4A errors at injection: ($R_0 = 17$ mm)

n	Normal			Skew		
	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
Body	[unit]					
2	0.06	0.51	0.19	0.12	2.8	1.1
3	-5.7	2.5	0.92	-0.03	0.24	0.09
4	-0.02	0.07	0.03	0.04	0.37	0.13
5	0.14	0.18	0.09	-0.01	0.04	0.01
7	-0.04	0.02	0.01	0.0	0.01	0.0
9	0.01	0.01	0.0	0.0	0.0	0.0
LE	[unit·m]		(Length=0.73 m)			
2	-0.2	1.5	0.7	-1.6	2.9	1.1
3	8.7	1.3	0.5	-4.6	0.5	0.2
5	-0.1	0.2	0.1	0.5	0.1	0.0
RE	[unit·m]		(Length=0.73 m)			
2	0.2	1.3	0.5	-0.2	3.	1.1
3	1.8	1.1	0.5	0.1	0.5	0.2

lhc version 5.0 injection optics

$\nu_x = 63.28$ $\nu_y = 59.31$ $\beta^* = 11.7423$ FILE = ip2_inj.optics



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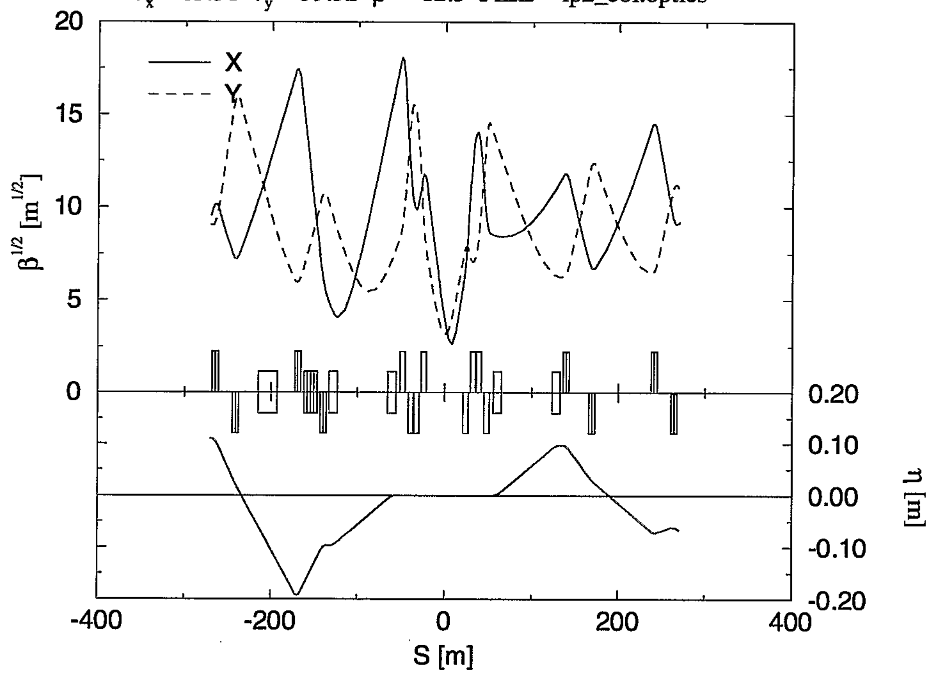
lhc version 5.0 collision optics

$\nu_x = 63.31$ $\nu_y = 59.32$ $\beta^* = 12.5$ FILE = ip2_col.optics



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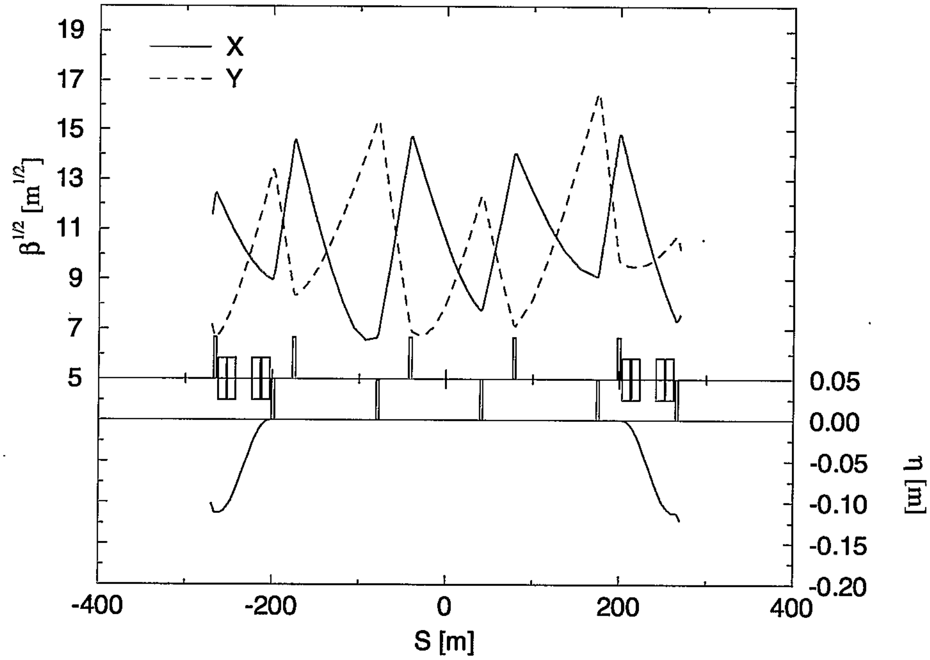
lhc version 5.0 injection optics

$\nu_x = 63.28$ $\nu_y = 59.31$ $\beta^* = 87.5$ FILE = ip4_inj.optics



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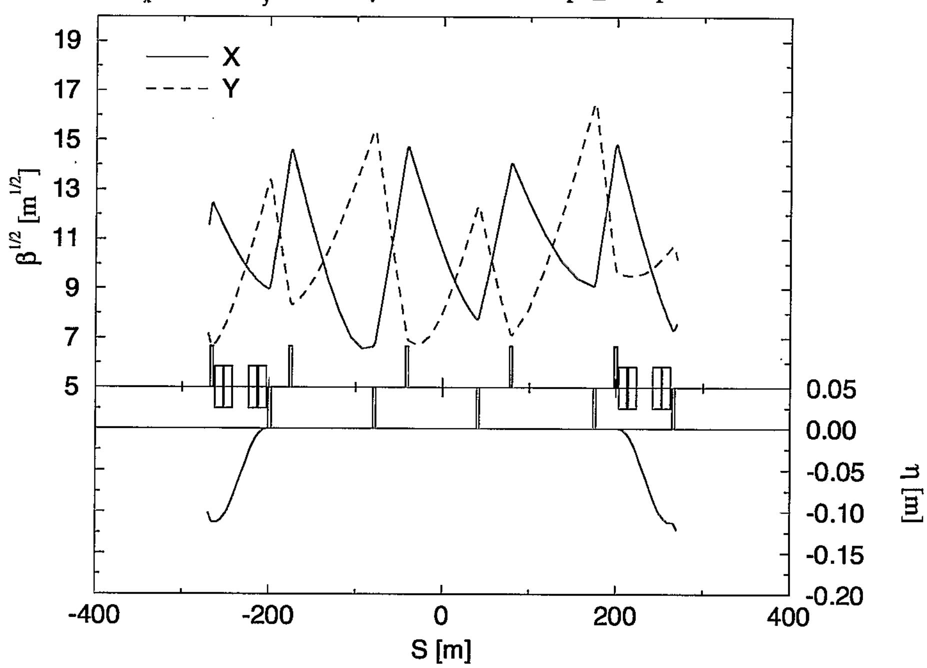
lhc version 5.0 collision optics

$\nu_x = 63.31$ $\nu_y = 59.32$ $\beta^* = 87.5$ FILE = ip4_col.optics



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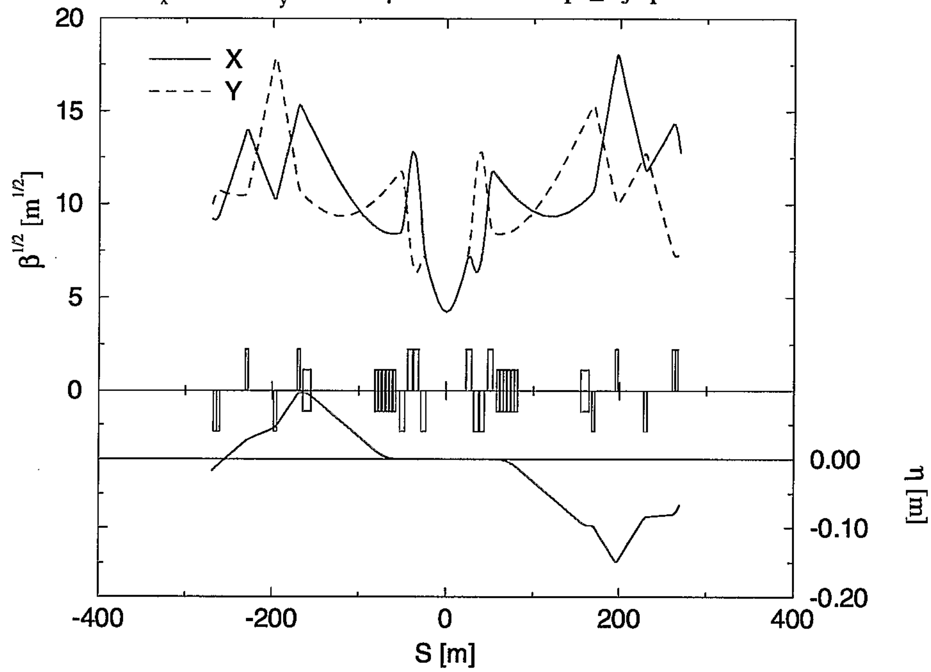
lhc version 5.0 injection optics

$\nu_x = 63.28$ $\nu_y = 59.31$ $\beta^* = 18$ FILE = ip5_inj.optics



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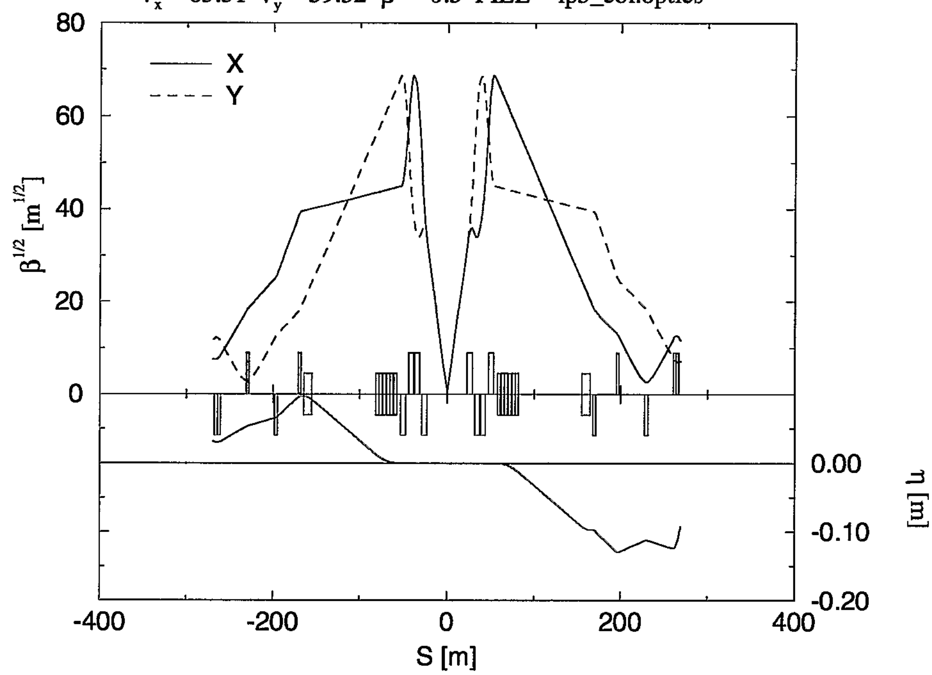
lhc version 5.0 collision optics

$\nu_x = 63.31$ $\nu_y = 59.32$ $\beta^* = 0.5$ FILE = ip5_col.optics



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* RF Region Dipoles

Field Quality (RF Region: D3A, D3B, D4A, D4B):

- Determined by injection optics
  beam size reduced by 4 times at collision

- relatively large persistent b_3

  LHC: 300 A; optimized for RHIC injection at 600 A;

  but the dispersion is small in the RF Region

Quantity	Arc dipoles	RF dipoles
Persistent b_3 [u]	-9	-9
Dispersion [m]	1.5	0.1
Chromaticity	500	0.03

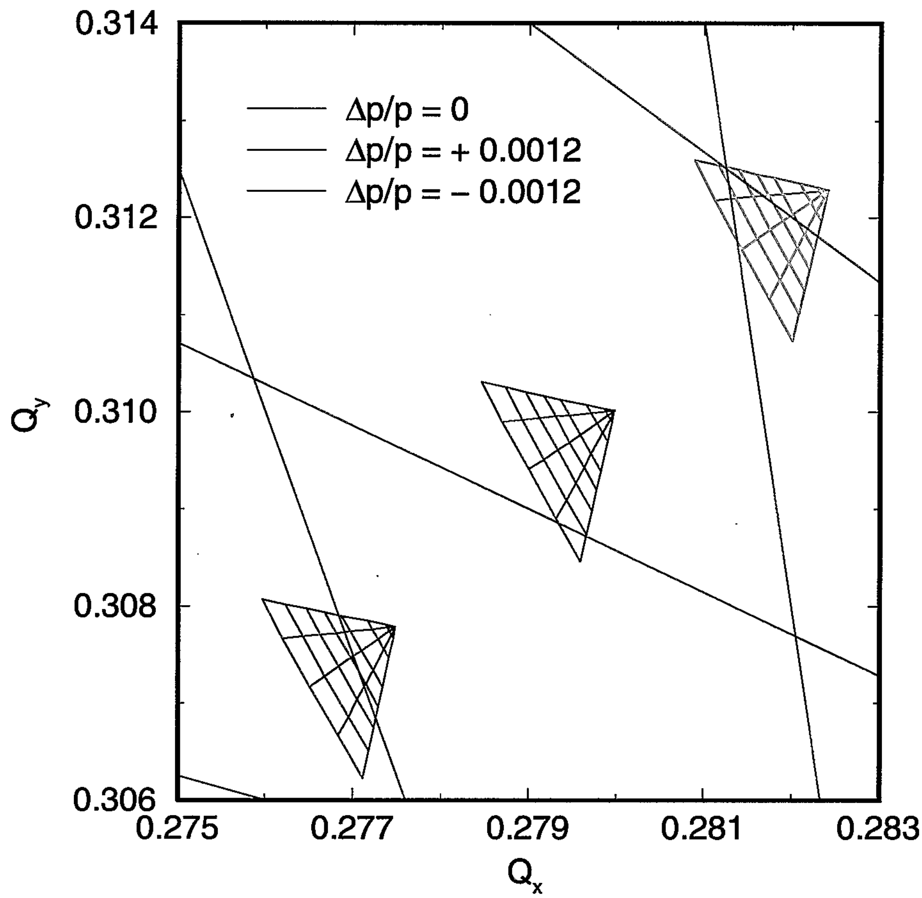
- Saturation b_3 at collision no noticeable impact
  (b_3 of about -4 units at top energy)

- Tracking study indicates no noticeable impact

- $\Rightarrow$ RHIC field quality is adequate

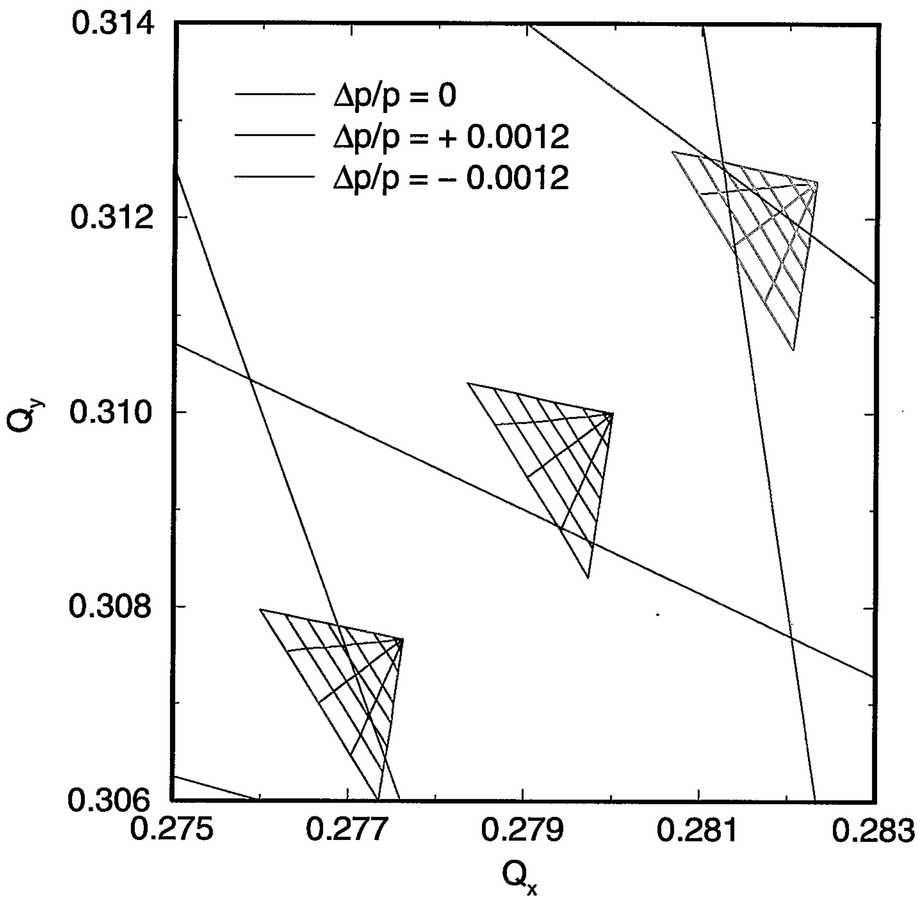
Impact of BNL dipoles at injection

(Tune spread for up to $11\sigma_{x,y}$ particles; $\Phi = 0$)



Ideal LHC operating point at injection

(Tune spread for up to $11\sigma_{x,y}$ particles; $\Phi = 0$)



Alignment Quality (RF Region dipoles):

Expected BNL-built Dipole misalignments:

Integral field, magnet-to-magnet variation, rms	5×10^{-4}
Single coldmass, mean dipole angle, α	$\pm$ 5 mrad
Single coldmass, variation (twist) of dipole angle ($\Delta\alpha$) from mean, rms	3 mrad
Mean angle between apertures, rms	0.5 mrad

- Beam orbit offset within each BNL dipole: $\pm$3.4 mm;
- Actual geometry of beam orbit vs. aperture separation to be studied;
- Expected field parallelism similar to arc dipole's;
- Requirements on closed-orbit corrector strength similar to arc dipole's.

* Insertion Region Dipoles

Field Quality (IR dipoles D1, D2):

- Adequate for nominal proton operation
  high β^* at IP2 & IP8 at collision
  transverse beam size 4 times smaller than IP1 & IP5

- D1 impact significant in ion operation
  $\beta^* = 0.5$ m at IP2 collision during ion operation
  heavy-ion lattice available around August 98 for detailed study
  similar sensitivity for D1 dipole and MQX triplet quads

- Effective compensation is needed, similar to MQX

- Alignment for D2 is similar to RF Region dipoles

Reference FNAL-MQX errors at collision: ($R_0 = 17$ mm)

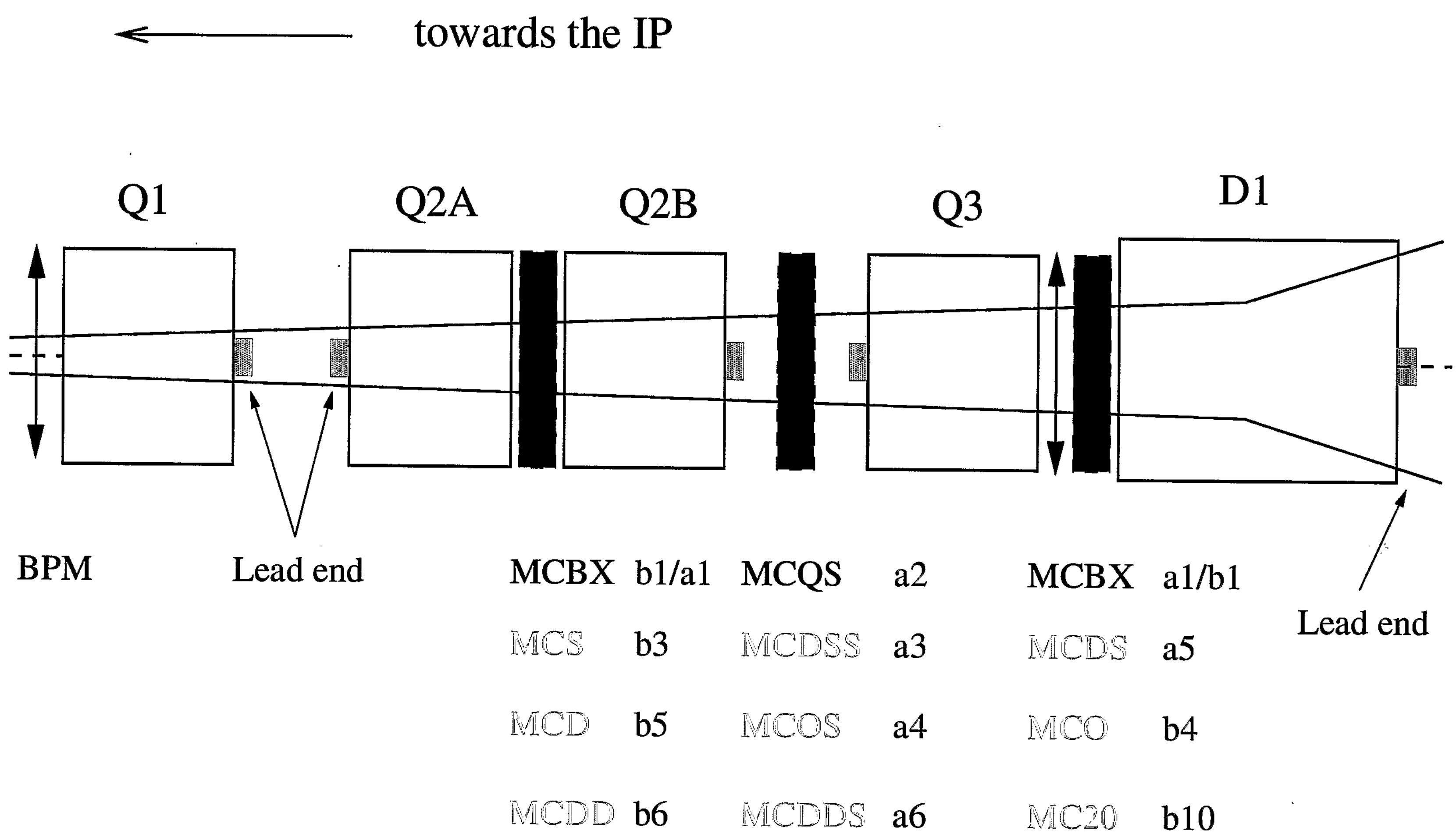
n	Normal			Skew		
	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
Body	[unit]					
3	0.0	0.34	0.85	0.0	0.34	0.85
4	0.0	0.26	0.87	0.0	0.26	0.87
5	0.0	0.20	0.34	0.0	0.20	0.34
6	0.0	0.17	0.25	0.0	0.17	0.25
7	0.0	0.14	0.11	0.0	0.14	0.11
8	0.0	0.10	0.07	0.0	0.10	0.07
9	0.0	0.08	0.07	0.0	0.08	0.07
10	0.0	0.06	0.03	0.0	0.06	0.03
LE	[unit·m]		(Length=0.41 m)			
2	0.0	0.0	0.0	16.0	0.0	0.0
6	2.3	0.0	0.0	0.07	0.0	0.0
10	-0.09	0.0	0.0	-0.03	0.0	0.0
RE	[unit·m]		(Length=0.33 m)			
6	0.39	0.0	0.0	0.0	0.0	0.0
10	-0.07	0.0	0.0	0.0	0.0	0.0

- Magnet Orientation Optimization
  - orient D1 lead end away from IP
- Body-End Compensation
  - already implemented for the systematic b_3

D1:

$$b_3(\text{Body}) = -0.095\, B_3(\text{LE}) - 0.116\, B_3(\text{RE}) = -1.3[\text{u}]$$

- IR Correctors
  - use the same IR correctors proposed for MQX quads;
  - layout and strength seems practically achievable;
  - a_3 compensation especially important;
  - to be studied in detail after August 98;
  - based on bench measurement (assuming 10% rms error)
  - comparing with MQX correction, similar performance expected


towards the IP
Q1
Q2A
Q2B
Q3
D1
BPM
Lead end
MCBX b1/a1
MCS b3
MCD b5
MCDD b6
MCQS a2
MCDSS a3
MCOS a4
MCDDS a6
MCBX a1/b1
MCDS a5
MCO b4
MC20 b10
Lead end

Effects of MQX and D1, D2 errors
(10^3-turn 6D DA; 4D $6\sigma_{xy}$ maximum tune spread)

Case	DA (σ_{xy})	Min. DA	$\Delta\nu_{max}$ (10^{-3})
Full error (incl. a_2)	9.6±2.8	$6\sigma_{xy}$	coupled
Full error, $\Phi = 0$	12.7±1.8	$9\sigma_{xy}$	coupled
Full error excl. a_2	10.7±1.7	$8\sigma_{xy}$	1.9±1.1
Systematic only	11.2±1.0	$10\sigma_{xy}$	2.6
Random only	13.6±1.7[a]	$9\sigma_{xy}$	1.1±0.5
LE and RE only	16.4±1.0[a]	$13\sigma_{xy}$	0.7
$n = 3, 4$ only	21.7±5.8[a,b]	$12\sigma_{xy}$	1.1±0.6
IR dipoles only	physical ap.[a]		0.2±0.01

a) Here, MQX physical aperture of 60 mm corresponds to $15.8 \pm 1.3\sigma_{xy}$.

b) The working point is near 3rd-order integer.

Comparison of IR correction efficiency

Case	DA (σ_{xy})	Min. DA	$\Delta\nu_{max}$ (10^{-3})	layers
0	10.7±1.7	$8\sigma_{xy}$	1.9±1.1	1
1	10.7±1.3	$9\sigma_{xy}$	2.1±1.0	2
2	12.5±1.9	$9\sigma_{xy}$	1.9±1.5	2
3	13.3±1.6	$10\sigma_{xy}$	1.0±0.7	3
4	13.6±1.5	$11\sigma_{xy}$	0.5±0.3	4
5	14.1±1.5	$11\sigma_{xy}$	0.5±0.4	4

case 0: b_1, a_1, a_2
case 1: case 0 plus b_3, a_3, b_4
case 2: case 0 plus b_6, b_6, a_6
case 3: case 0 plus b_3, b_4, b_6, a_3, a_4, a_6
case 4: case 0 plus b_3, b_4, b_5, b_6, b_6, a_3, a_4, a_5, a_6
case 5: case 0 plus b_3, b_4, b_5, b_6, b_{10}, a_3, a_4, a_5, a_6

- Nonlinear corrections are activated in IP1 and 5 only.
- Assume 10% rms measurement error.

* Discussion

- Field quality of BNL dipoles is adequate for nominal proton operation
- Compensation is needed for D1 magnets in ion operation
- Alignment (2−1) is expected to be consistent with arc dipole's
- Further studies are planned:
  heavy-ion operation lattice of version 6.0;
  S. Tepikian's CERN visit in August 1998
  (heavy-ion & ring 2 lattice of version 6);
  tracking studies to follow;
  IR corrector optimization to follow.