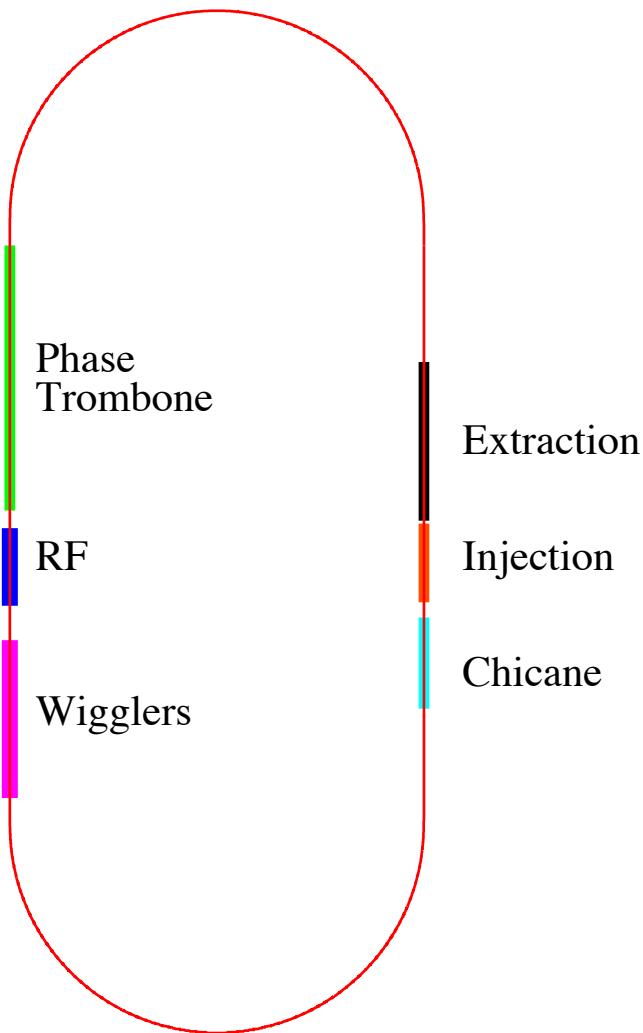


ILC Damping Ring Lattice

D. Rubin and J. Shanks
Cornell
April 24, 2012

Layout



Circumference - 3238 m
 $5.6 \mu\text{-rad} < \gamma\varepsilon_x < 6.4 \mu\text{-rad}$
54 Wigglers

length 2.1 m

B_{peak} 2.2 T

Poles 14

Period 30cm

$24\text{ms} > \tau_x > 12\text{ms}$

Phase trombone $\rightarrow \pm 0.5 \lambda_\beta$

Chicane $\rightarrow \pm 3\text{mm pathlength}$

$\leq 12 - 650\text{MHz RF cavities}$

$\Rightarrow \sigma_l = 6\text{mm}$

Lattice

- Arc

Each cell contains :

1 - 3m dipole, $\theta = \pi/75$

3 – quadrupoles

4 - sextupoles

3 - corrector magnets

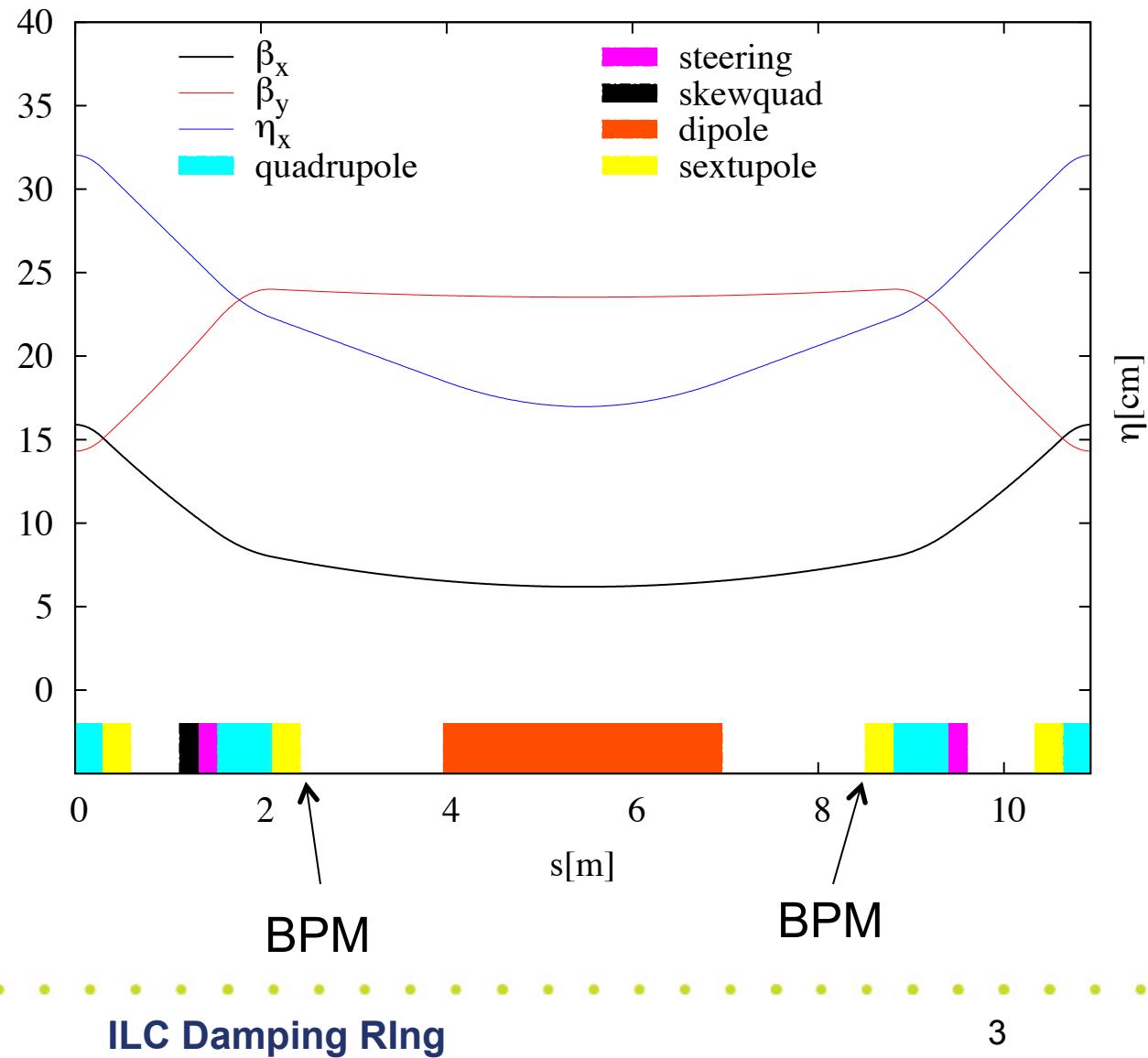
1-horizontal steering

1-vertical steering

1- skew quad

2 beam position monitors

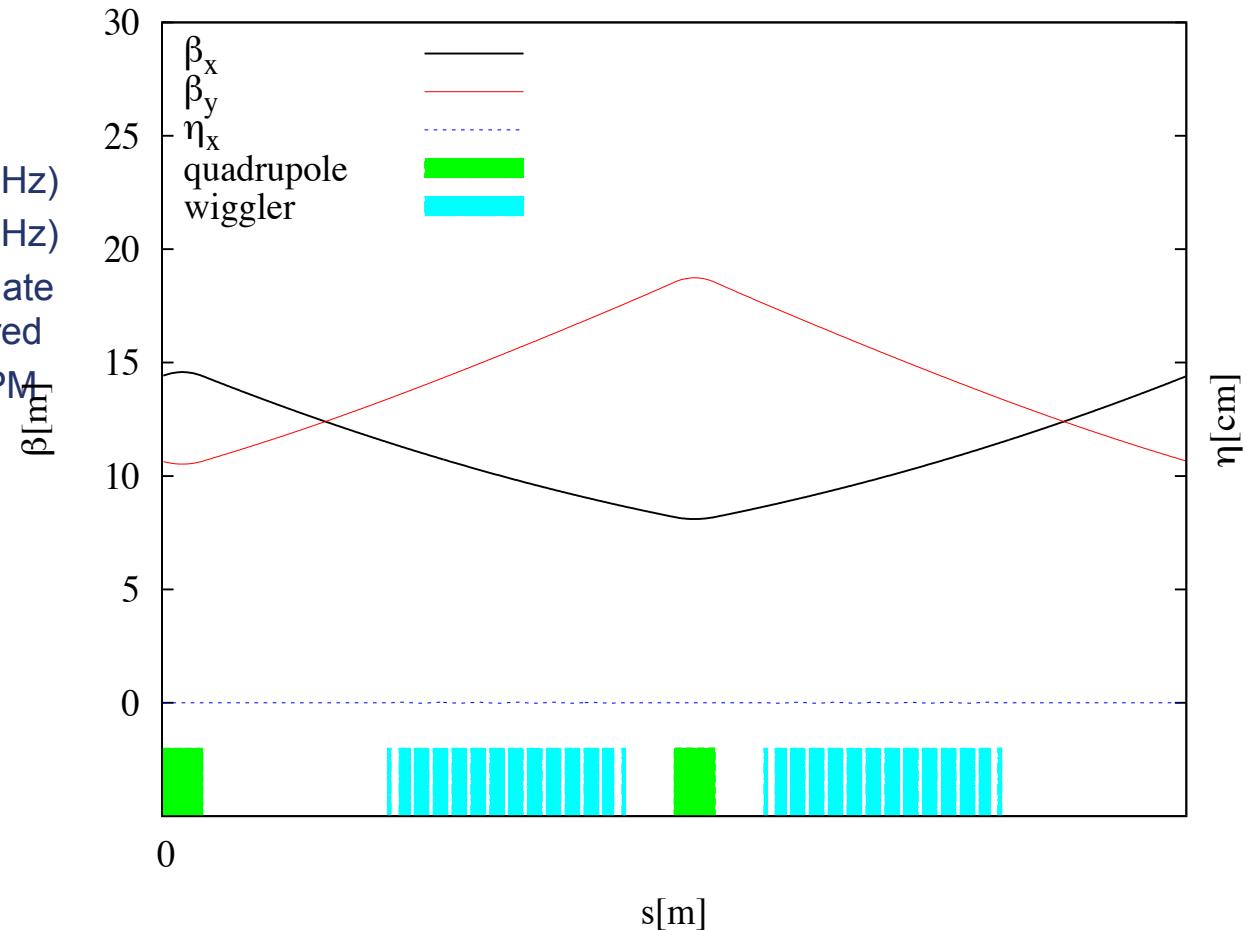
75-cells/arc



Damping Wigglers

- Wiggler straight

- 2 wigglers/cell
- 30 cells
- 2.1 m wiggler
- $1.5T < B_{peak} < 2.2T$
- 54 @ 2.16T $\Rightarrow \tau_x = 13\text{ms}$ (10Hz)
- 54 @ 1.51T $\Rightarrow \tau_x = 25\text{ms}$ (5Hz)
- 3 empty cells will accommodate 6 additional wigglers if required
- H&V dipole corrector and BPM adjacent to each quad



RF straight

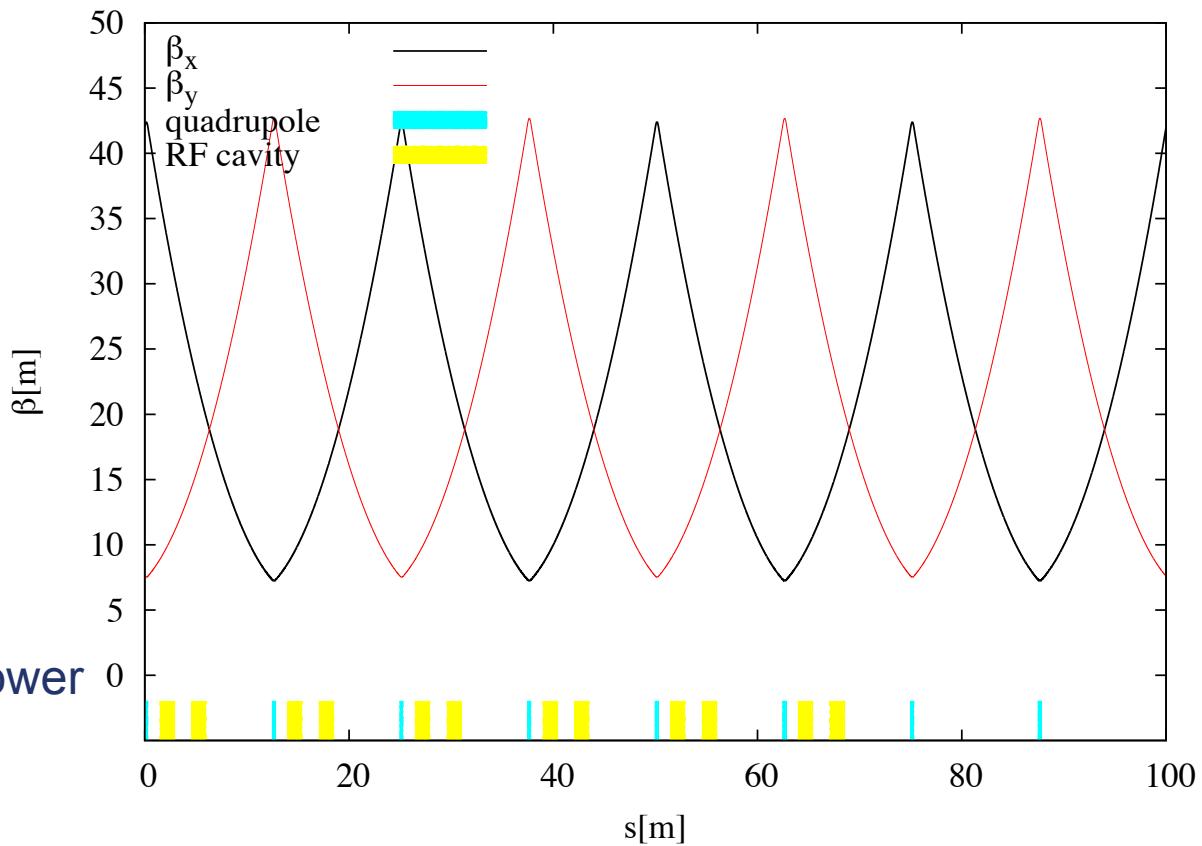
• RF

- 2 cavities/cell
- 22.4 MV => 6mm bunch length @ $\tau_x = 13\text{ms}$
=> for 12 cavities
1.9MV/cavity
272kW/coupler

Lattice can accommodate 16 cavities if required

Cavities offset so that waveguides of upper and lower rings are interleaved

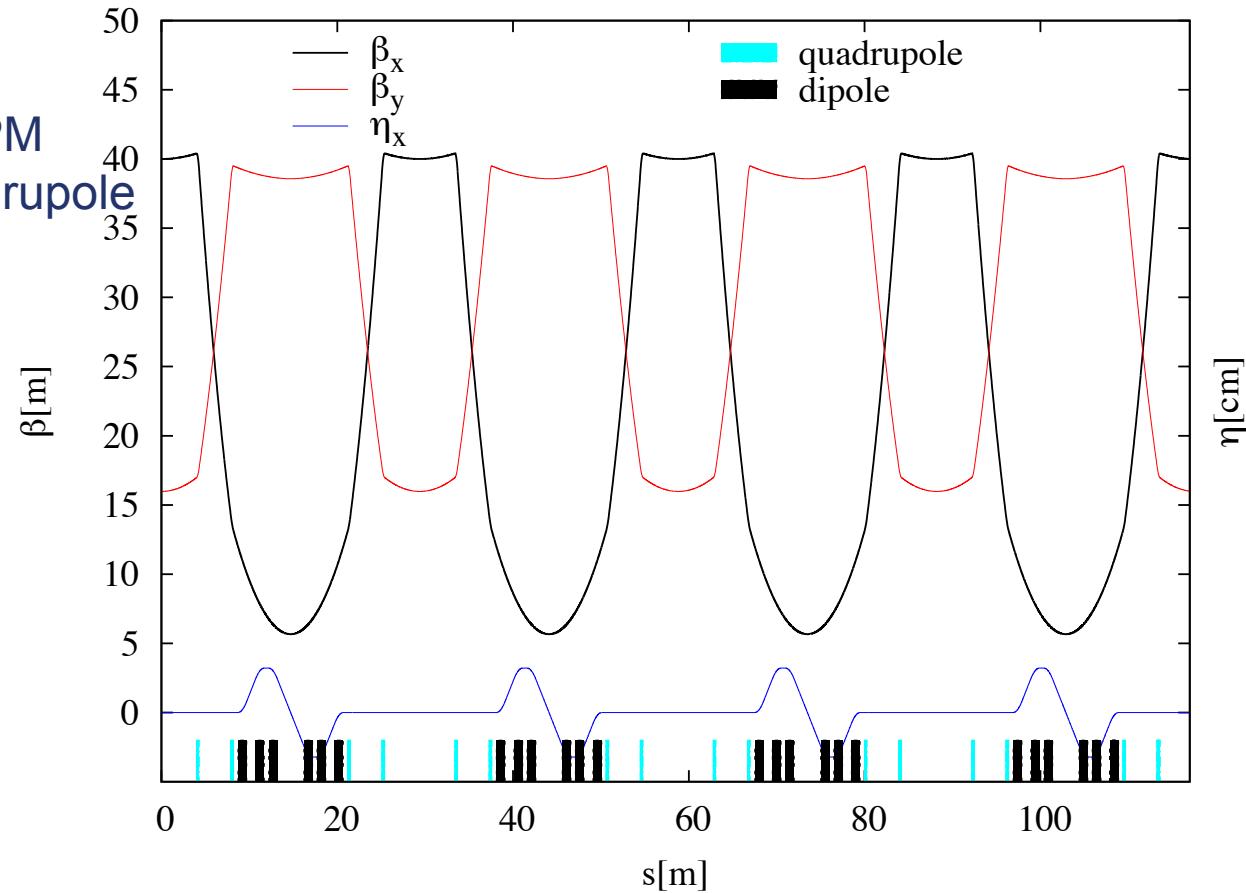
H&V corrector and BPM adjacent to each quadrupole



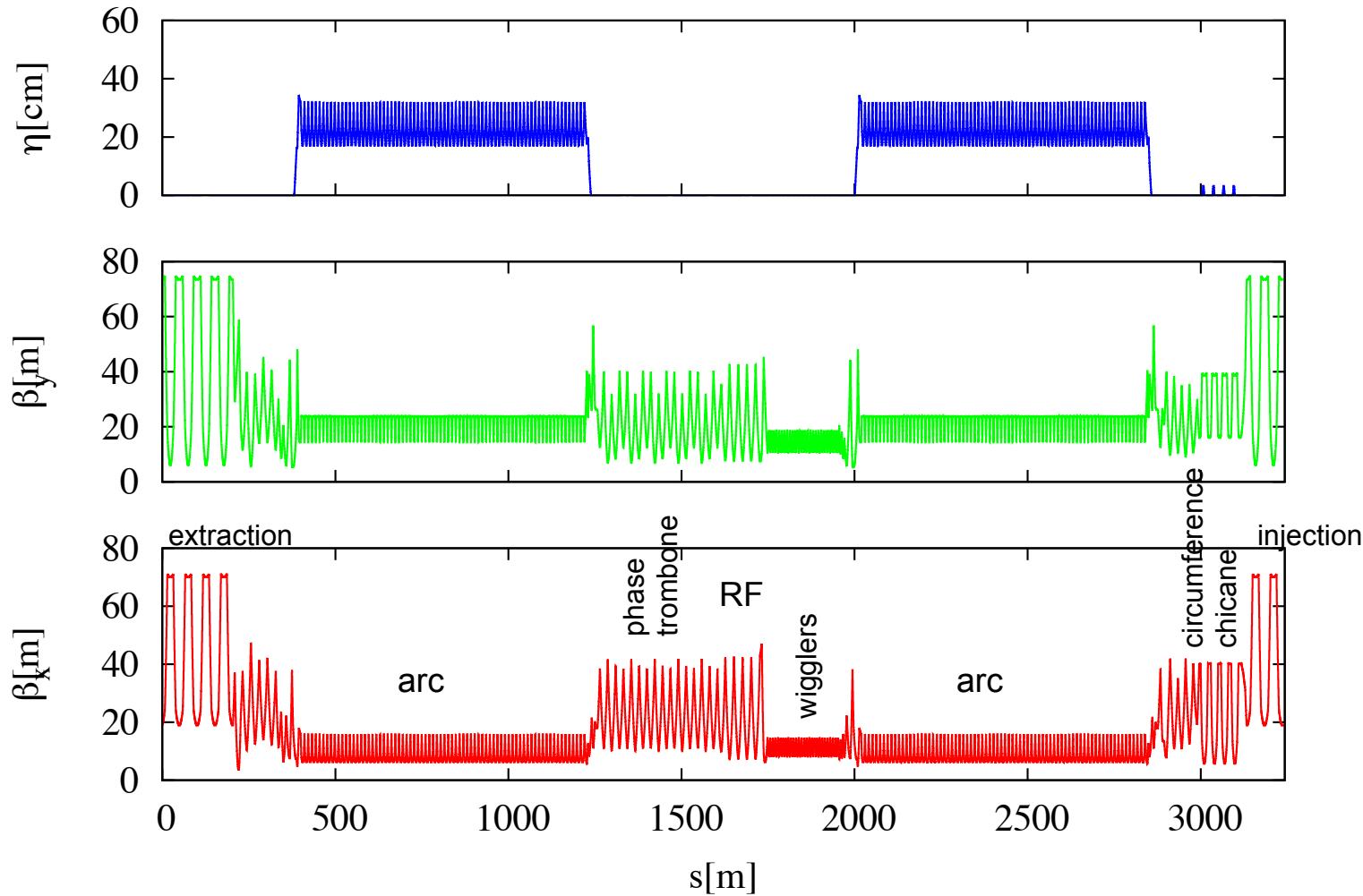
Circumference chicane

- Chicane

- $\Delta C = \pm 4\text{mm}$
- $\Delta \varepsilon_y < 3\%$
- H&V corrector and BPM adjacent to each quadrupole



Ring lattice



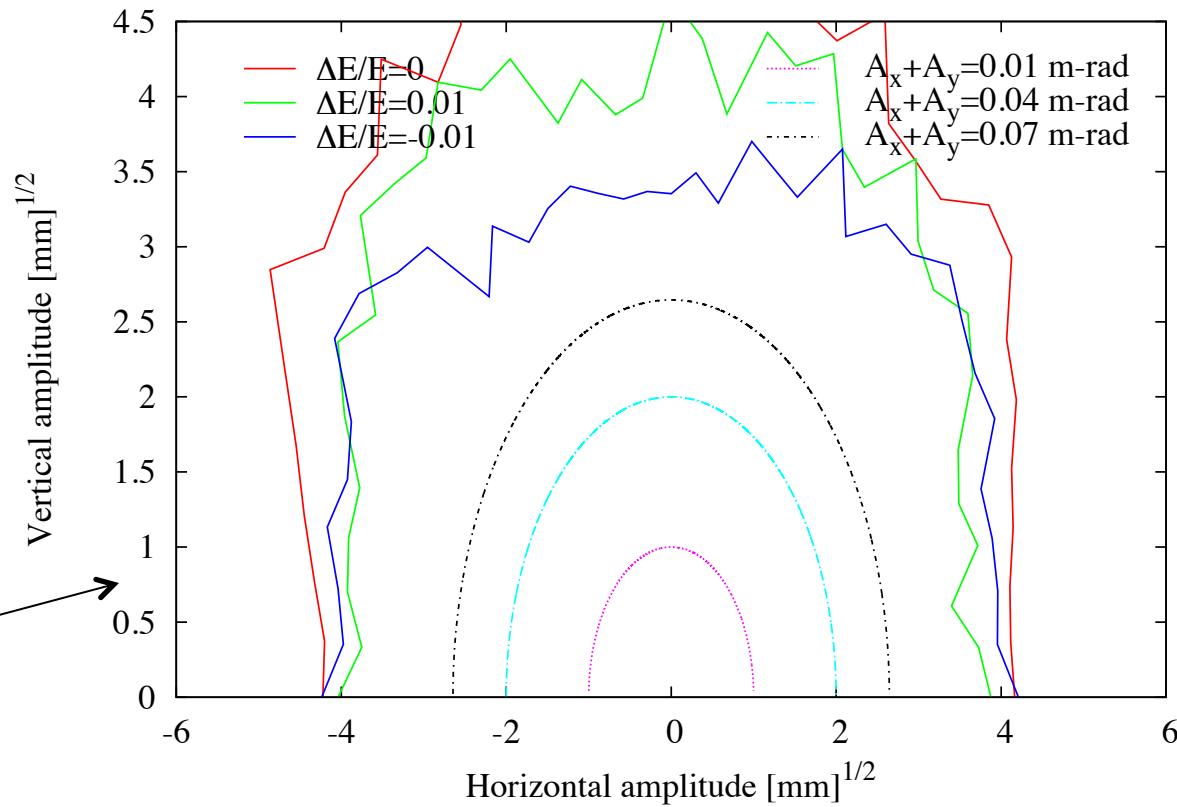
Ring lattice

Parameter	10 Hz(Low)	5 Hz (Low)	5 Hz (High)	10 Hz (electrons)
Circumference	3.238 km	3.238 km	3.238 km	3.238 km
RF frequency	650 MHz	650MHz	650 MHz	650 MHz
τ_x/τ_y [ms]	12.86	23.95	23.95	17.5
T_z [ms]	6.4	12.0	12.0	8.7
σ_s [mm]	6.02	6.02	6.02	6.01
σ_δ	0.137%	0.11%	0.11%	0.12%
a_p	3.3×10^{-4}	3.3×10^{-4}	3.3×10^{-4}	3.3×10^{-4}
$\gamma \epsilon_x$ [μm]	6.4	5.7	5.7	5.6
RF [MV] Total/Per cav(12)	22.4/1.9	14.2 /1.2	14.2/1.2	17.9/1.5
RF – synchronous phase[deg]	21.9	18.5	18.5	20.3
ξ_x/ξ_y	-50.9/-44.1	-51.3/-43.3	-51.3/-43.3	-51.3/-43.3
Wiggler- N _{cells} @B[T]	27@2.16	27@1.51	27@1.51	27@1.81
Energy loss/turn [MeV]	8.4	4.5	4.5	6.19
sextupoles	3.34/-4.34	3.34/-4.23	3.34/-4.23	3.34/-4.23
Number of bunches	1312	1312	2450	1312
Particles/bunch [$\times 10^{10}$]	2	2	1.74	2
Power/RF coupler [kW]*	272 (389mA)	146 (389mA)	237 (632mA)	200 (389mA)

*Power/coupler is computed as (Current) X (Energy loss/turn)/(Number of cavities)

Dynamic Aperture

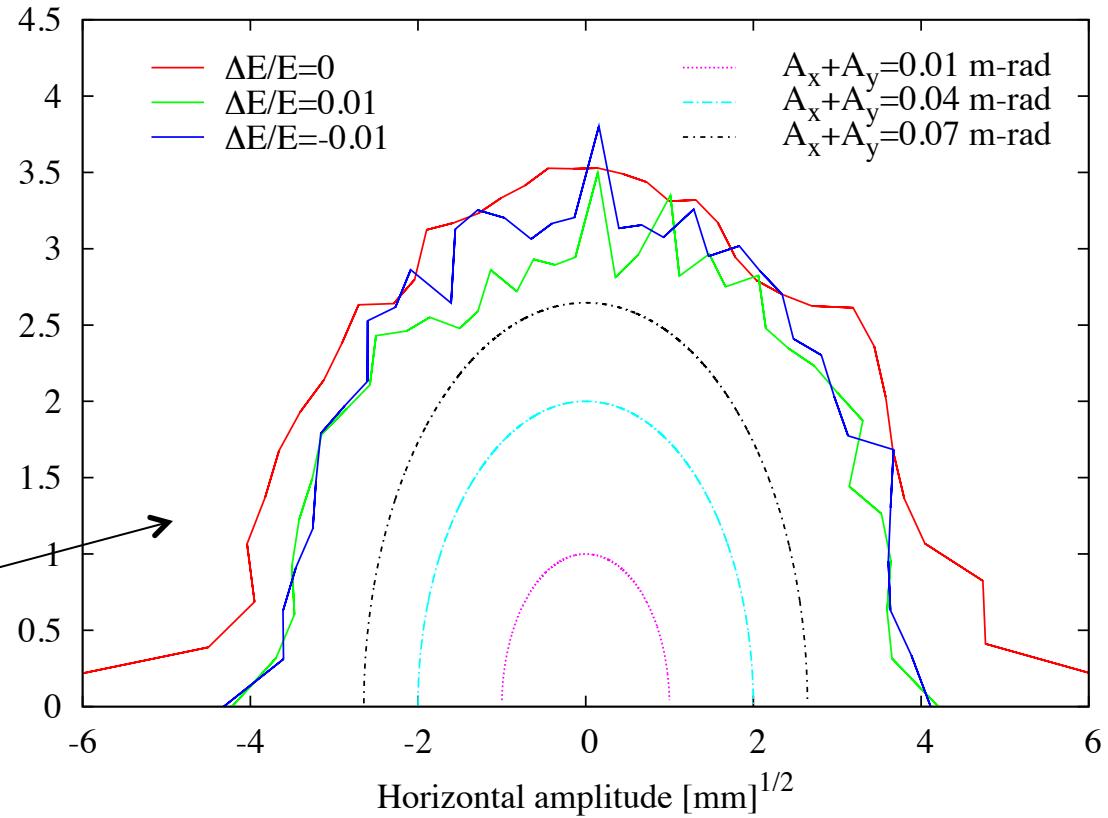
- Dynamic aperture
 - 2 family sextupole distribution
 - Chromaticity ~ 1 (h and v)
 - Track for 1000 turns
 - Phase space amplitude of injected bunch
 $A_x + A_y < 0.07$ m-rad
(normalized)
 - No misalignment
 - No multipoles
 - No wiggler nonlinearities



Dynamic Aperture

- Dynamic aperture

- 2 family sextupole distribution
- Chromaticity ~ 1 (h and v)
- Track for 1000 turns
- Phase space amplitude of injected bunch
 $A_x + A_y < 0.07 \text{ m-rad}$ (normalized)
- No misalignment
- No multipoles
- Includes wiggler nonlinearities and end effects
 - Field table computed by finite element code (*Jim Crittenden*)
 - Fitted to Fourier expansion that satisfies Maxwell equations (*JC*)
 - Symplectic tracking

 A_x Vertical amplitude [mm] $^{1/2}$ 

Guide field multipole errors

Dipole multipoles, r=3cm

Multipole	Systematic		Random	
	$a_n (\times 10^{-4})$	$b_n (\times 10^{-4})$	$a_n (\times 10^{-4})$	$b_n (\times 10^{-4})$
3	1.60	0.0	0.8	0.0
4	-0.16	0.0	0.08	0.0
5	0.76	0	0.38	0.0

Quadrupole multipoles, r=5cm

Multipole	Systematic		Random	
	$a_n (\times 10^{-4})$	$b_n (\times 10^{-4})$	$a_n (\times 10^{-4})$	$b_n (\times 10^{-4})$
3	-0.124	-0.115	0.761	0.725
4	0.023	0.141	1.32	1.27
5	-0.043	0.0062	0.15	0.162
6	3.40	-0.493	1.65	3.63
7	0.003	-0.0102	0.067	0.066
8	0.006	0.0038	0.089	0.066
9	0.006	-0.0028	0.046	0.049
10	-0.617	-0.577	2.46	2.33
11	-0.002	-0.0038	0.042	0.035
12	0.036	-0.0653	0.348	0.366
13	0.006	0.012	0.092	0.086
14	0.01	-0.0074	0.476	0.446

$$(B_y + iB_x) = B(r) \sum_{n=1} (b_n + ia_n) \left(\frac{x}{r} + i \frac{y}{r} \right)^{n-1}$$

Sextupole multipoles, r=3.2cm

Multipole	Systematic		Random	
	$a_n (\times 10^{-4})$	$b_n (\times 10^{-4})$	$a_n (\times 10^{-4})$	$b_n (\times 10^{-4})$
4	2	0	1	0
5	1	0	0.3	0
6	7	0	1	0
7	1	0	0.3	0
8	1	0	0.3	0
9	1	0	0.3	0
10	1	0	0.3	0
11	1	0	0.3	0
12	32	0	1	0
13	1	0	0.3	0
14	1	0	0.3	0

SPEAR3 and PEPII
Measured multipoles – Y. Cai

Misalignments and BPM resolution

Parameter	RMS
BPM – Differential resolution	1 μm
BPM – Absolute resolution	50 μm
BPM – Tilt	5 mrad
BPM button – Gain variation	0.5%
Quads + Sexts – Offset (H+V)	25 μm
Quads – Tilt	50 μrad
Dipole – Roll	50 μrad
Wiggler – Offset (V only)	100 μm
Wiggler - Roll	100 μrad

Emittance tuning procedure

- Measure and correct orbit using all steerings
- Measure betatron phase advance (by resonant excitation) – and correct using quadrupoles
- Measure coupling (by resonant excitation) and correct with skew quads
- Measure orbit, coupling, and vertical dispersion and simultaneously correct with vertical steerings and skew quads

All measurements include finite resolution of BPMs

Emittance Tuned lattice

- Misaligned as per misalignment table
- Multipoles as per multipole table
- Emittance tuning assuming BPM accuracy as tabulated and
 - 1 skew quad in each arc cell
 - 2 skew quads in each dispersion suppressor line
 - 1 H and V steering in each arc cell
 - 1 H&V steering adjacent to each quad in straights
 - BPM at every quadrupole

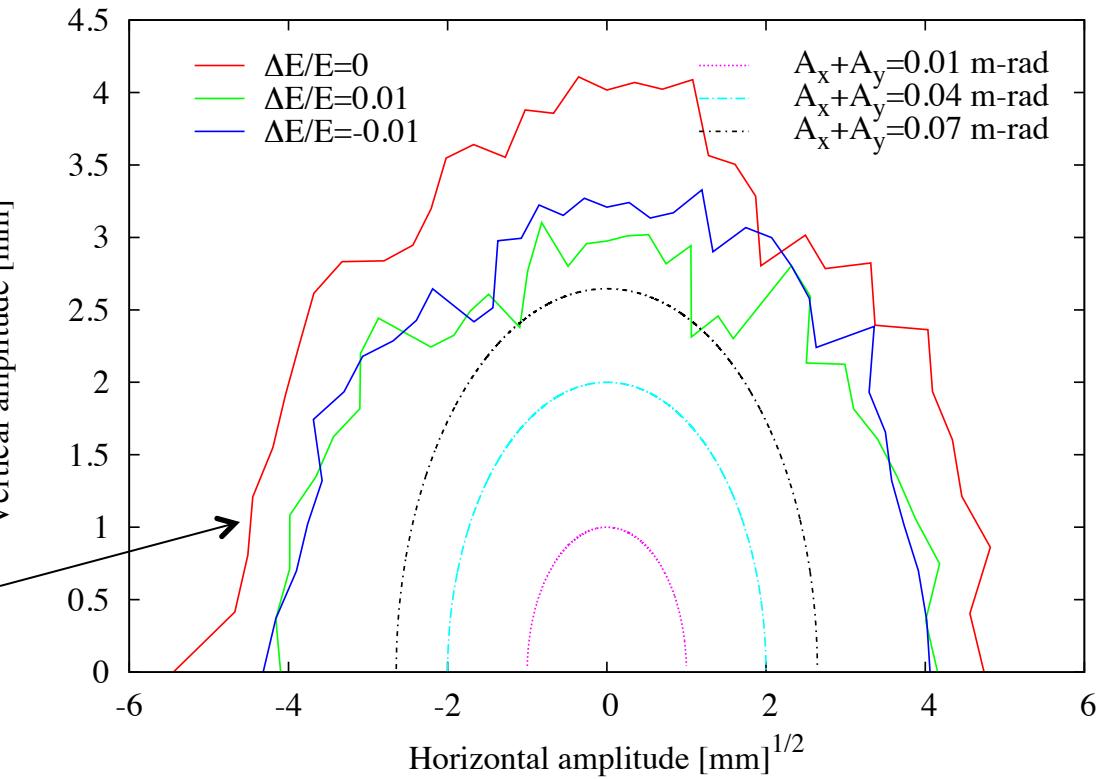
Max Vertical emittance, dispersion and coupling after emittance tuning
for 95% of 50 seeds

Parameter	DTC04-5Hz			DTC04-10Hz		
	No Multipoles	Static Multipoles	Static+Random Multipoles	No Multipoles	Static Multipoles	Static+Random Multipoles
ϵ_y	0.18 pm	0.22 pm	0.18 pm	0.29 pm	0.28 pm	0.30 pm
η_y	0.53 mm	0.60 mm	0.58 mm	0.52 mm	0.52 mm	0.52 mm
C_{12}	3.77×10^{-4}	3.82×10^{-4}	3.98×10^{-4}	3.98×10^{-4}	3.55×10^{-4}	3.70×10^{-4}

Dynamic Aperture

- Dynamic aperture

- 2 family sextupole distribution
- Chromaticity ~ 1 (h and v)
- Track for 1000 turns
- Phase space amplitude of injected bunch
 $+A_y < 0.07 \text{ m-rad}$ (normalized)
- Misalignments as per table
- Multipoles as per table
- (No wiggler nonlinearities)
- Emittance tuning

 A_x $A_y = [mm]^{1/2}$ 

Reduced dynamic aperture is predominantly due to random multipoles

Increase all misalignments (including BPM errors) by 2x, 3x, and 4x
(Ignore multipoles)

Parameter	DTC04-5Hz			DTC04-10Hz		
	2x	3x	4x*	2x	3x	4x
ε_y	0.59 pm	3.56 pm	1059 pm	0.92 pm	11.14 pm	166 pm
η_y	1.17 mm	3.30 mm	87.1 mm	1.19 mm	4.82 mm	100.1 mm
C_{12}	8.80×10^{-4}	15.96×10^{-4}	4.26×10^{-2}	8.75×10^{-4}	34.1×10^{-4}	76.4×10^{-4}

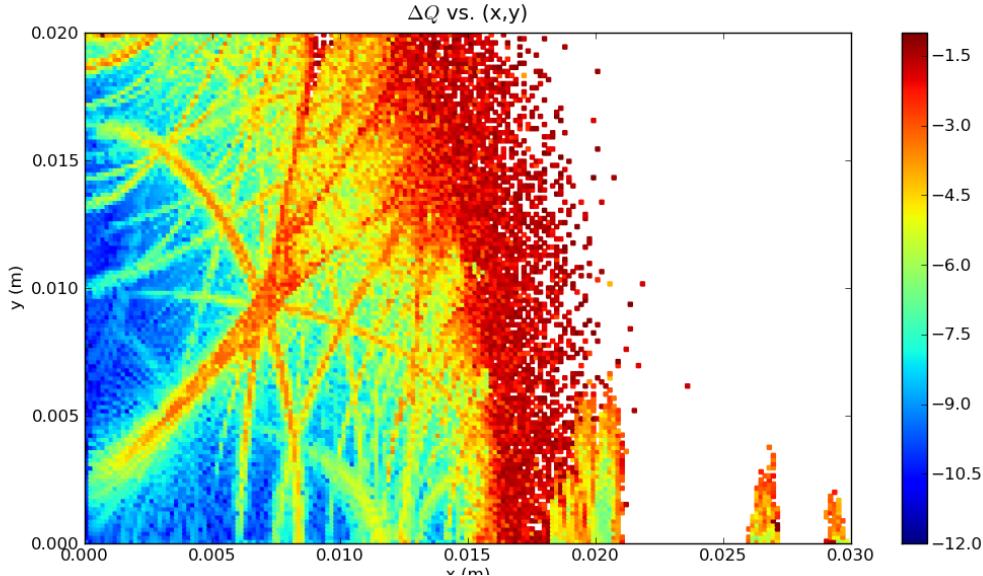
We find that we can double misalignments in page 12 table and achieve 2pm-rad vertical emittance with tuning

Parameter	RMS
BPM – Differential resolution	2 μm
BPM – Absolute resolution	100 μm
BPM – Tilt	10 mrad
BPM button – Gain variation	1%
Quads + Sexts – Offset (H+V)	50 μm
Quads – Tilt	100 μrad
Dipole – Roll	100 μrad
Wiggler – Offset (V only)	200 μm
Wiggler - Roll	200 μrad

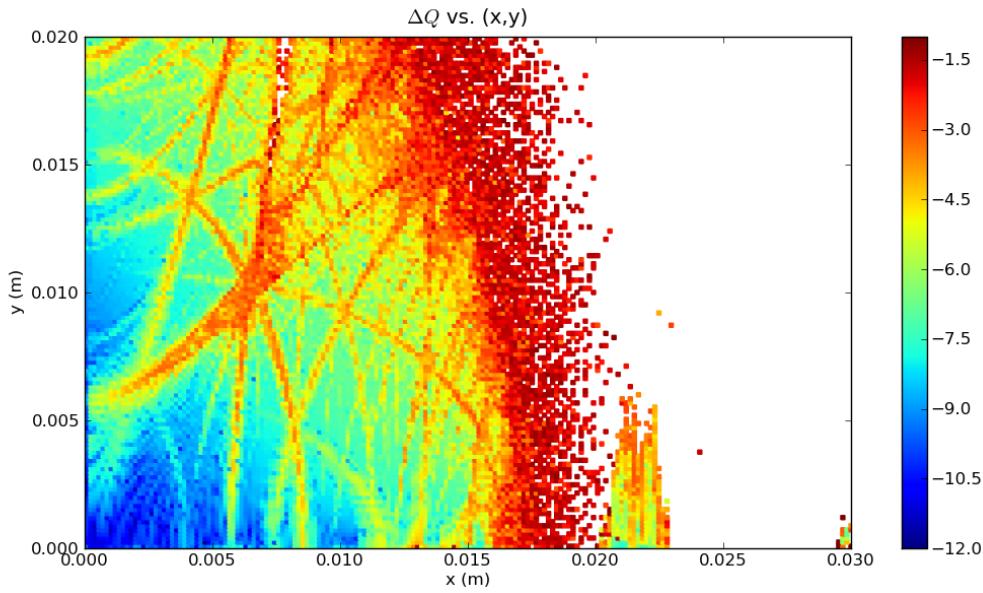
Frequency maps

- With and without multipoles
 - (static + random) vs. no multipoles
 - Scan amplitudes (0:30mm)x(0:20mm)
 - Track 2048 turns; FFT first and last 1024 turns
 - Plot:
 - ΔQ vs. (x,y)
 - ΔQ vs. (Q_x, Q_y) [tunes from first 1024 turns]
- Maps for a single seed (with misalignments and corrections) per scenario

DTC04-5Hz Frequency maps

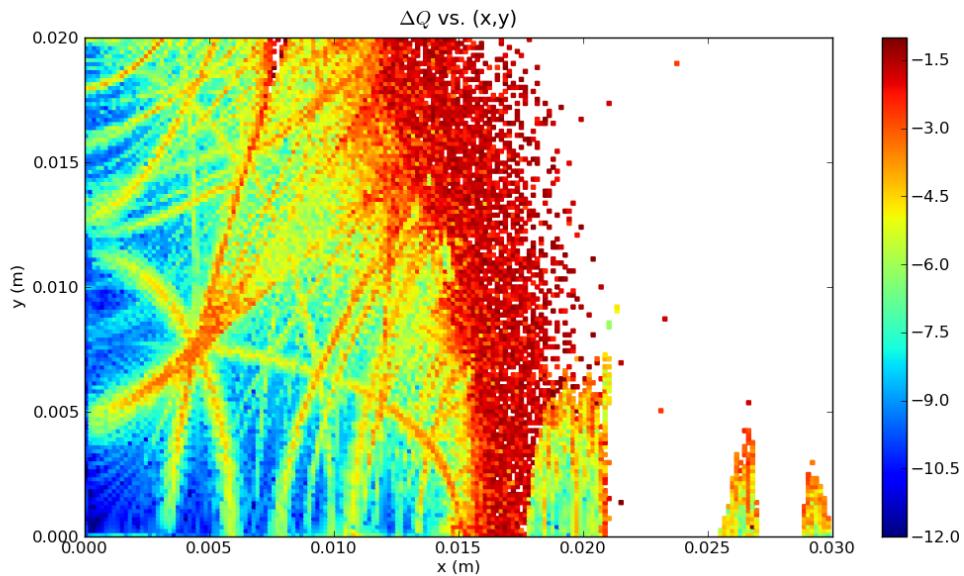


- No Multipoles
- Random misalignments
- Corrections

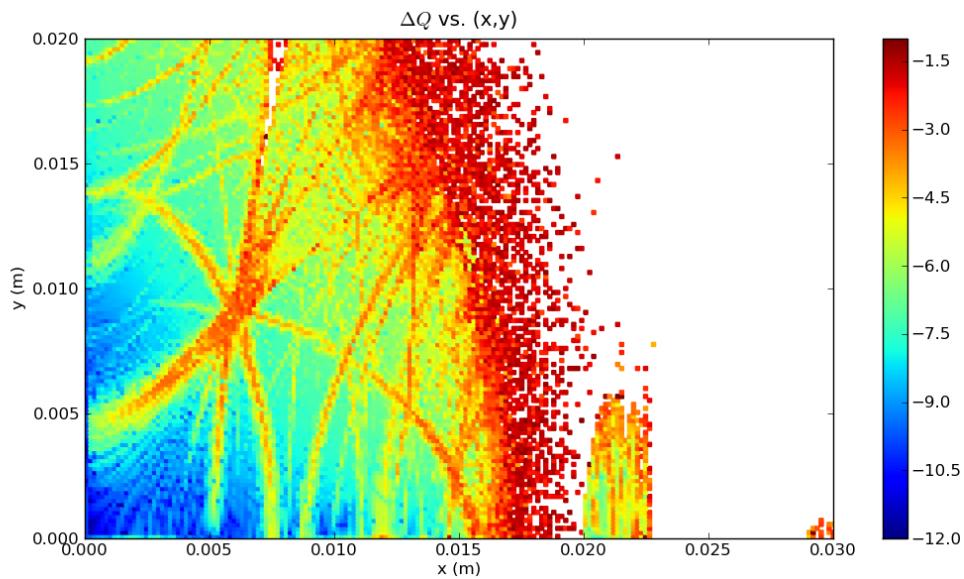


- Static + Random Multipoles
- Random misalignments
- Corrections

DTC04-10Hz Frequency maps



- No Multipoles
- Random misalignments
- Corrections

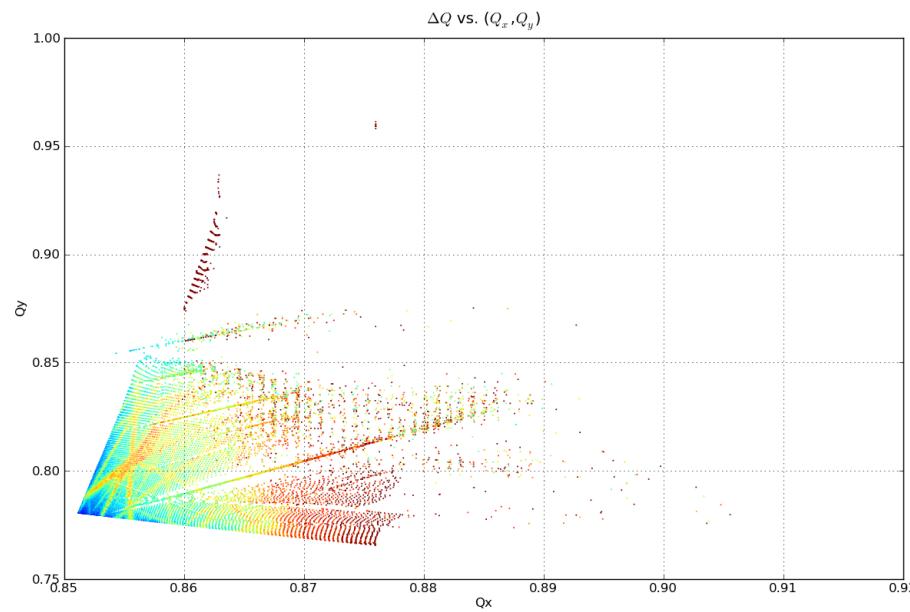
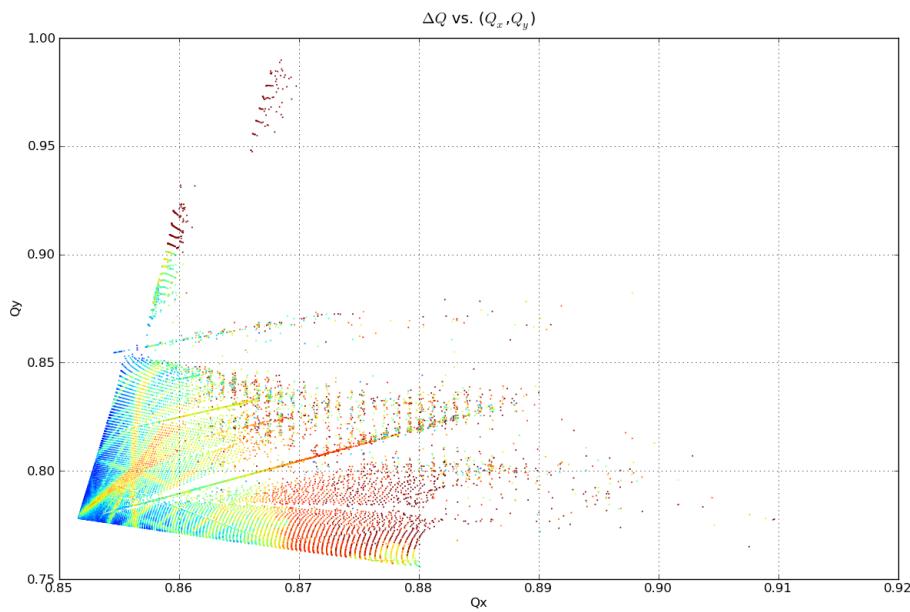


- Static + Random Multipoles
- Random misalignments
- Corrections

ΔQ vs. (Q_x , Q_y)

- No Multipoles
- Random misalignments
- Corrections

- Static + Random Multipoles
- Random misalignments
- Corrections



Status

- All collider operating configurations can be accommodated (5Hz, 10Hz, electrons, positrons)
- Tunable
 - Range of phase trombone $> 1 \lambda$
 - Range of chicane $\pm 4\text{mm}$
- Established BPM resolution and alignment tolerances required to achieve $< 2 \text{ pm-rad}$ with emittance tuning
- Demonstrated existence of a particular deployment of corrector magnets sufficient to achieve $< 2\text{pm-rad}$
- Demonstrated adequate dynamic aperture with wiggler nonlinearities and magnet multipole errors (but not simultaneously)

Ongoing effort

- Explore range of tolerable multipole errors
- Identify the multipole responsible for reducing dynamic aperture
- Explore tune plane to identify operating point with more DA
- Compute DA with wiggler nonlinearities and multipole errors and misalignments simultaneously
- Investigate emittance tuning with fewer BPMs and/or fewer correctors
- Investigate alternate sextupole distributions for more DA
- Explore implications of reduced energy spread of injected bunch (0.75%)

Acknowledgement

DTC04 straights are based on their counterparts in the 6.4km DCO4 lattice created by Andy Wolski and Maxim Krostev