ILC Damping Ring Lattice Error Tolerances

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DTC04 Summary – KILC

Status

- All collider operating configurations can be accommodated (5Hz, 10Hz, electrons, positrons)
- Tunable
  - Range of phase trombone > 1 λ
  - Range of chicane ± 4mm
- Established BPM resolution and alignment tolerances required to achieve <2 pm-rad with emittance tuning
- Demonstrated existence of a particular deployment of corrector magnets sufficient to achieve < 2pm-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%)

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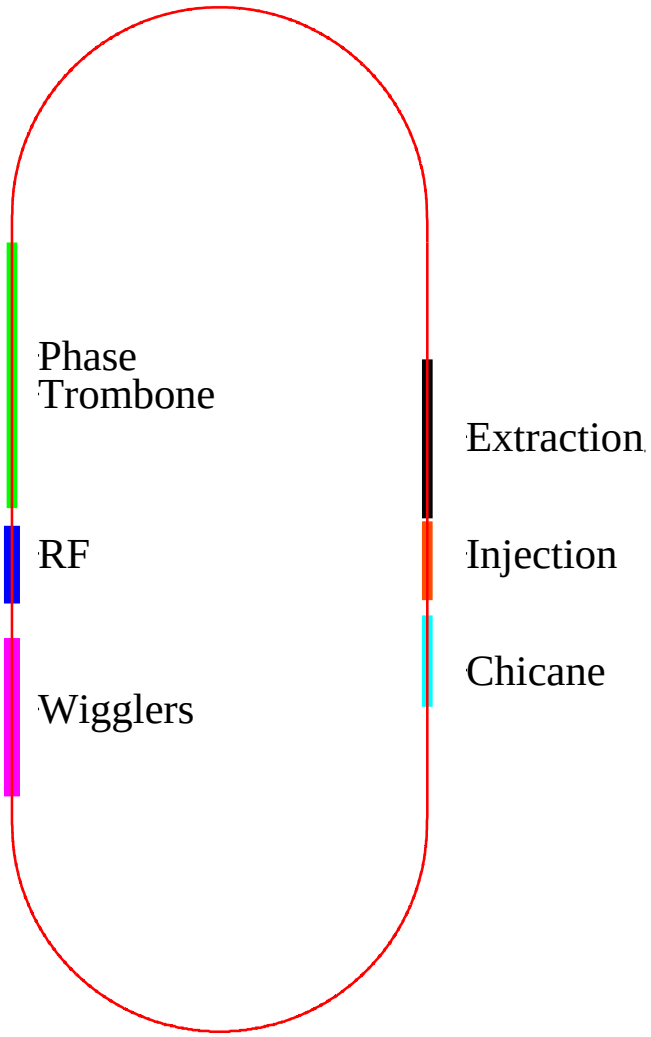
Layout - Reminder



Circumference - 3238 m

5.6 μm-rad < $\gamma\varepsilon_x$ < 6.4μm-rad

54 Wigglers

- length 2.1 m
- B_{peak} 2.2 T
- Poles 14
- Period 30cm
- 24ms > τ_x > 12ms

Phase trombone ➔ ± 0.5 λ_β

Chicane ➔ ± 3mm pathlength

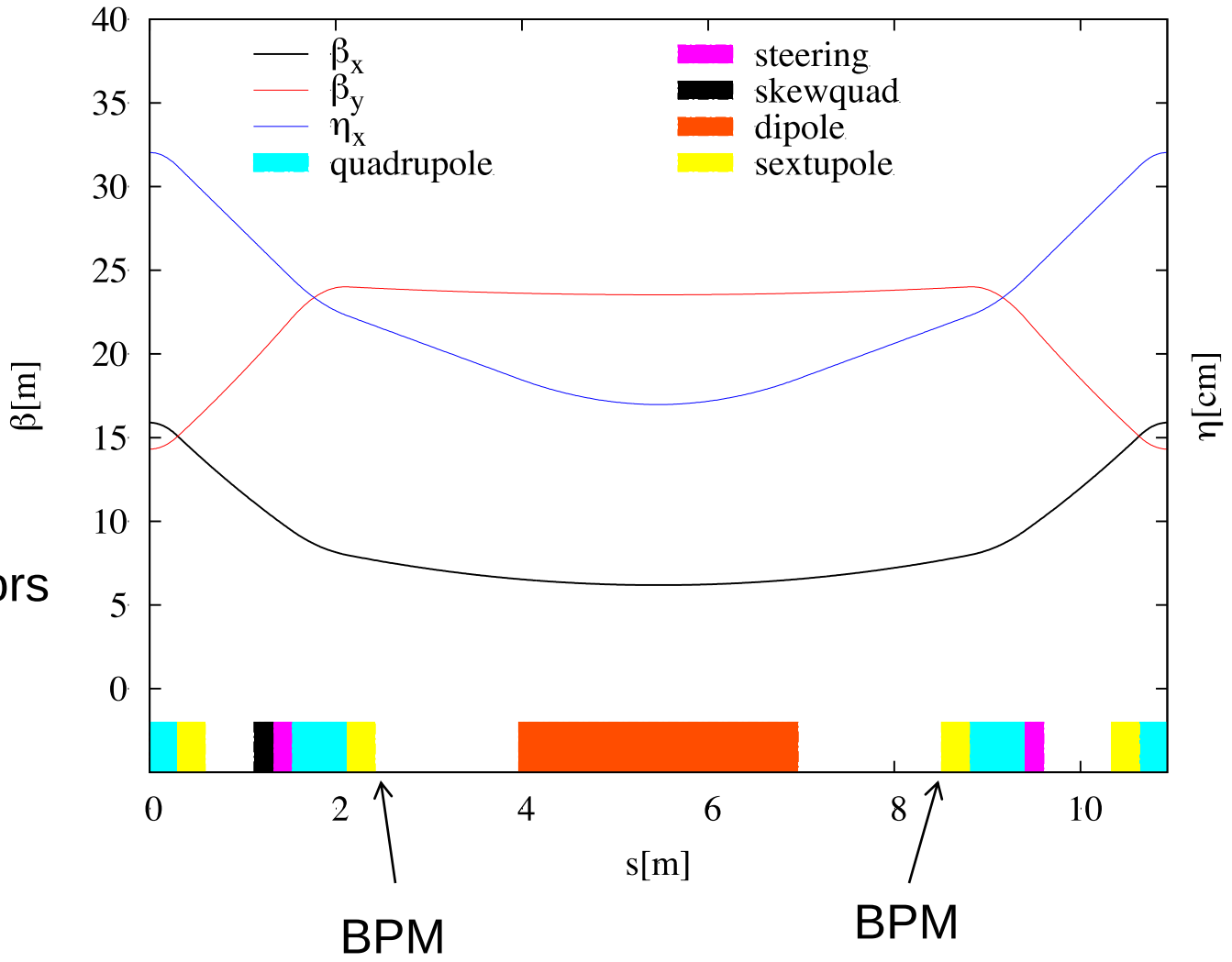
Up to 12 - 650MHz RF cavities

=> σ_l = 6mm

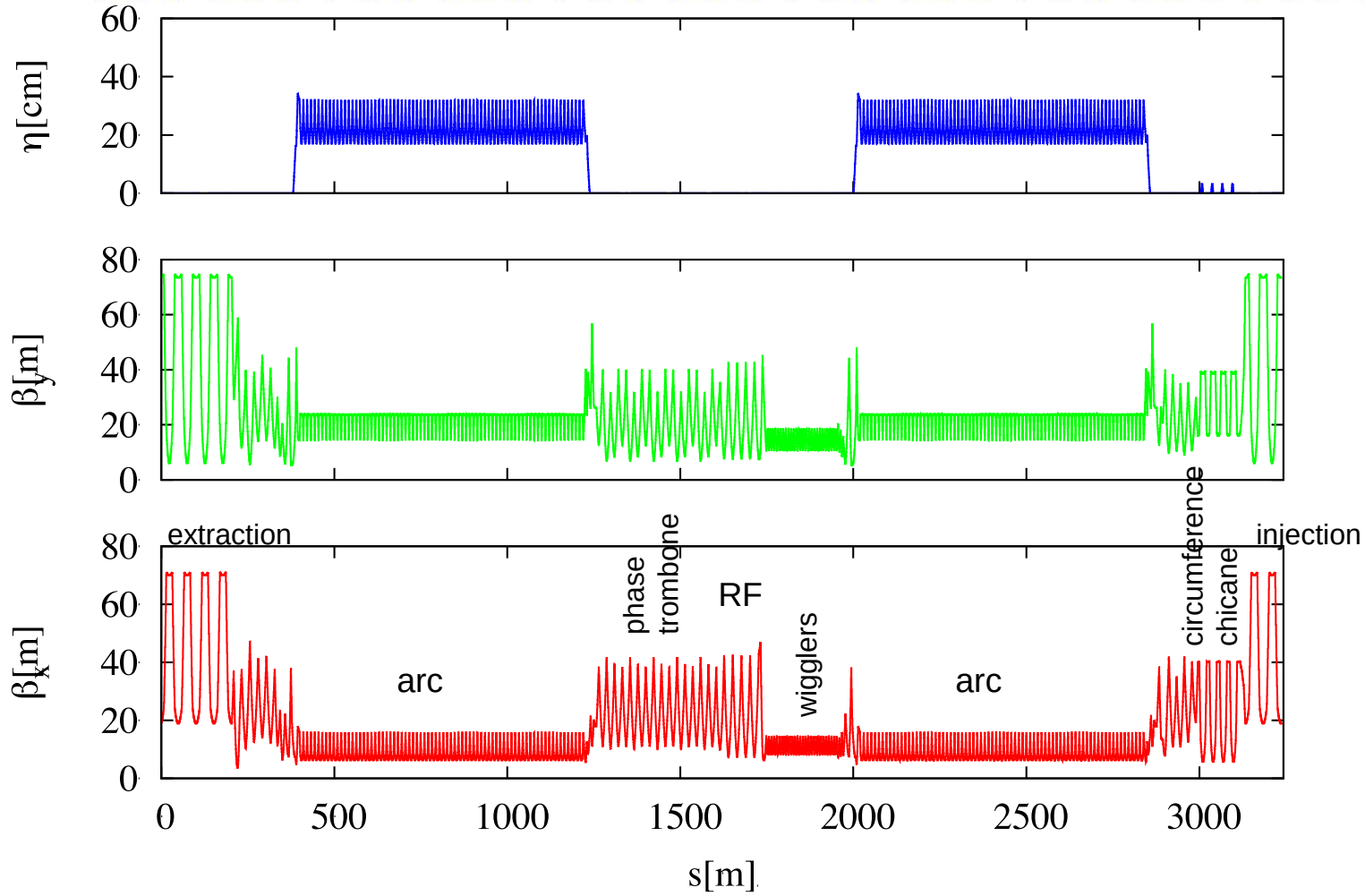
Lattice – Arc Cell - Reminder

Each cell contains :
1 - 3m dipole, θ = π/75
3 – quadrupoles
4 - sextupoles
3 - corrector magnets
    1-horizontal steering
    1-vertical steering
    1- skew quad
2 beam position monitors

75-cells/arc



Lattice – Optics Functions - Reminder



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

Parameter Table

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%
α_p	3.3×10^{-4}	3.3×10^{-4}	3.3×10^{-4}	3.3×10^{-4}
$\gamma\varepsilon_x$ [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
Wigglers- 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 [x 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)

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Characterization – Dynamic Aperture

- Focus on **5Hz low-power lattice**
  - Previous studies have shown minimal difference for the 10Hz lattice
- 2-family sextupole distribution
  - Chromaticity ~ 1 (horizontal and vertical)
- Track for 1000 turns; if particle lost, record amplitude
- Overlay phase space amplitude of injected bunch:
  - **A_x+A_y < 0.07 m-rad (normalized)**

Guide field multipole errors

Dipole multipoles, r=3cm

	Systematic		Random	
Multipole	$a_n(\times 10^{-4})$	$b_n(\times 10^{-4})$	$a_n(\times 10^{-4})$	$b_n(\times 10^{-4})$
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

	Systematic		Random	
Multipole	$a_n(\times 10^{-4})$	$b_n(\times 10^{-4})$	$a_n(\times 10^{-4})$	$b_n(\times 10^{-4})$
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

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

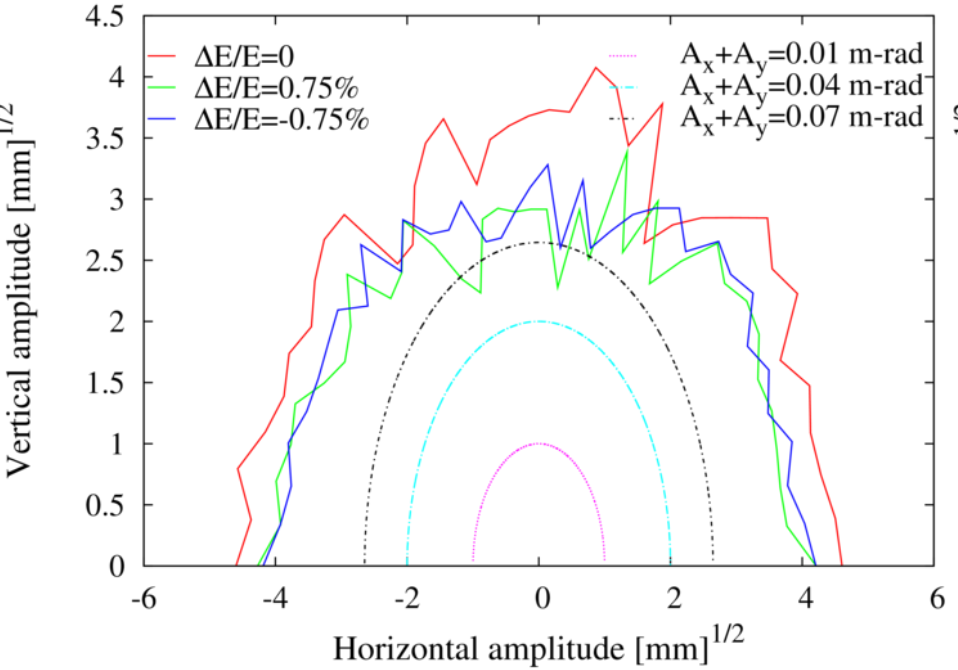
Sextupole multipoles, r=3.2cm

	Systematic		Random	
Multipole	$a_n(\times 10^{-4})$	$b_n(\times 10^{-4})$	$a_n(\times 10^{-4})$	$b_n(\times 10^{-4})$
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

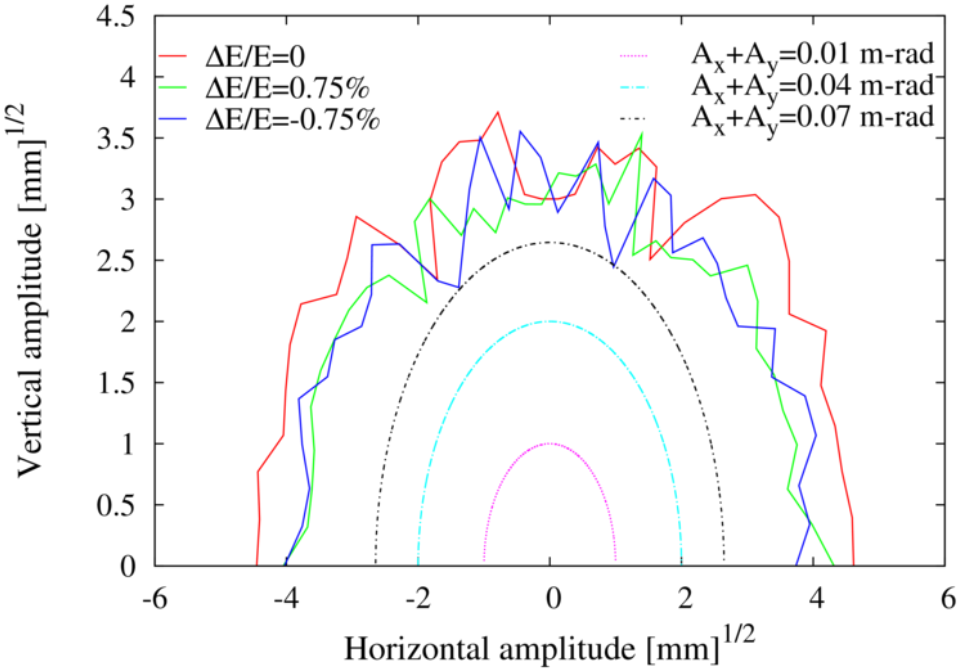
SPEAR3 and PEPII
Measured multipoles – Y. Cai

Use 2x these values in simulations

Ideal Lattice – Bend-Drift-Bend Wigglers



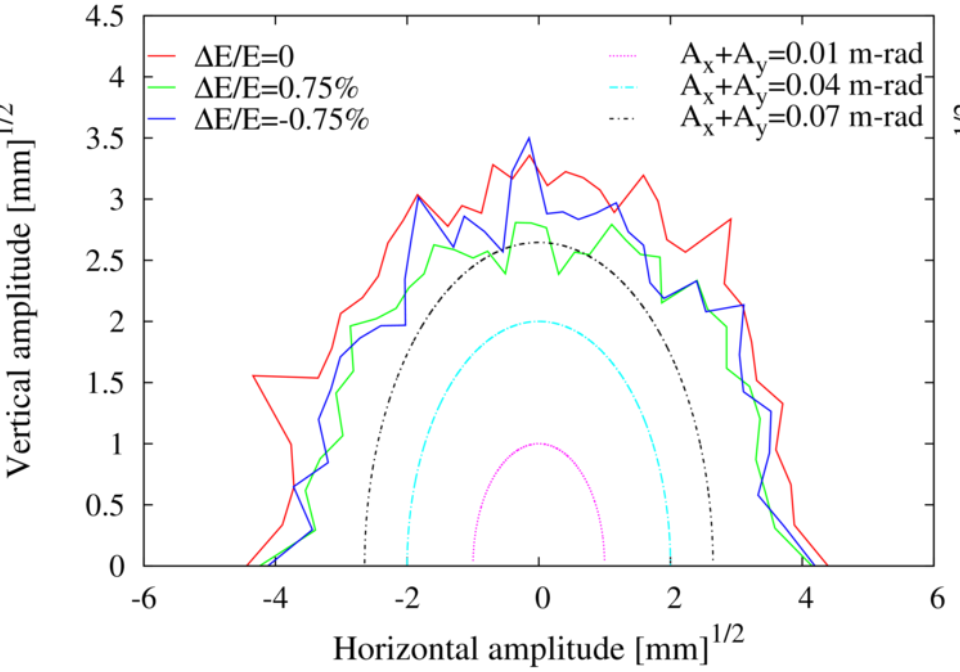
No multipoles



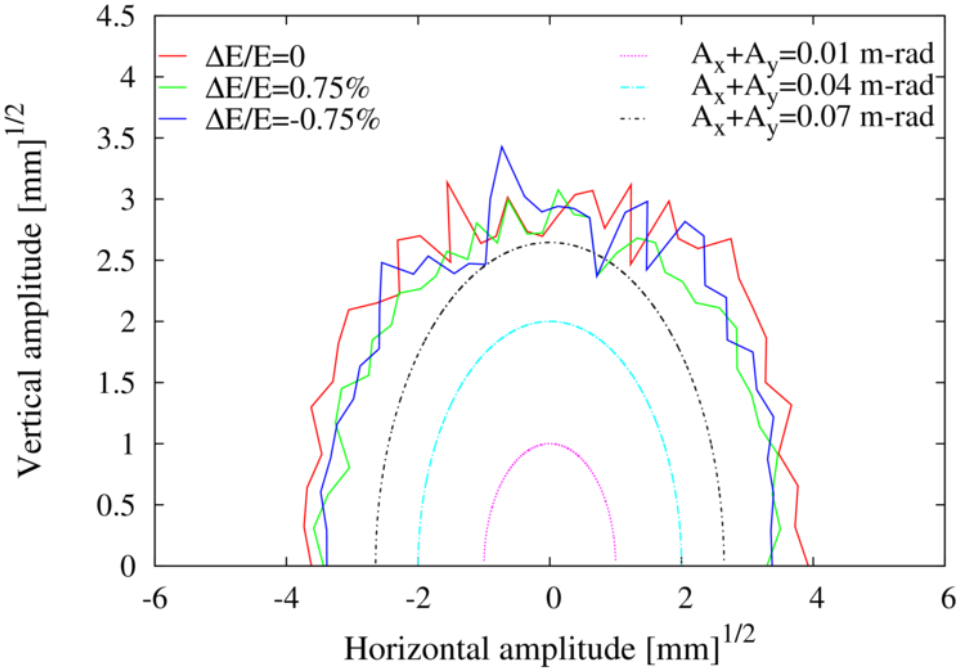
Systematic + random multipoles

- Using MAD-style wiggler model
- DA improves slightly when including multipoles

Ideal Lattice – Wigglers with Taylor Map



No multipoles



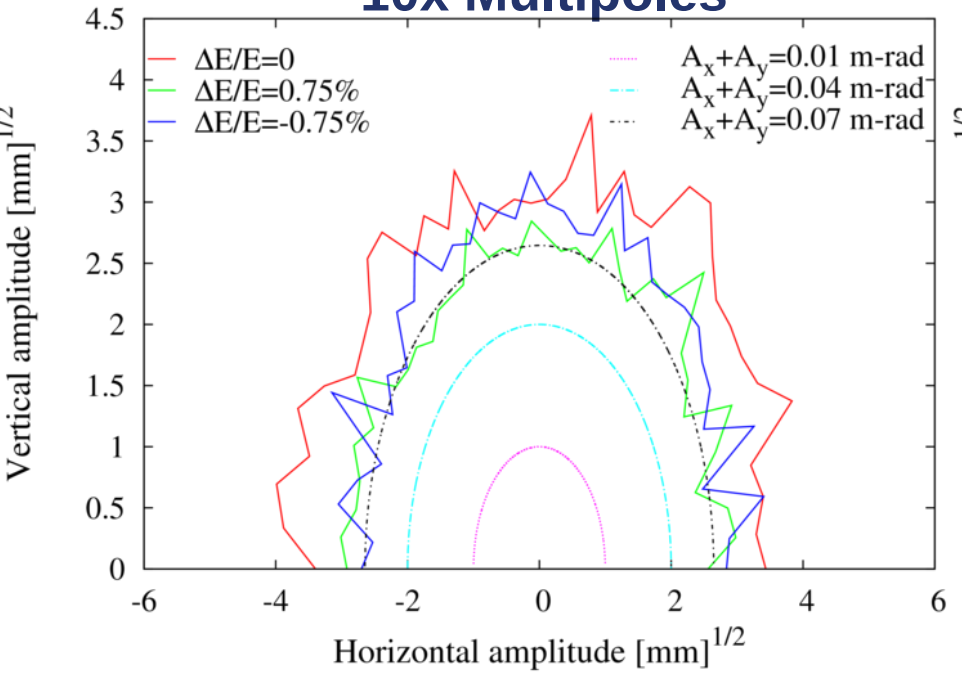
Systematic + random multipoles

- DA much reduced by including full wiggler map, but is still sufficient for ideal lattice

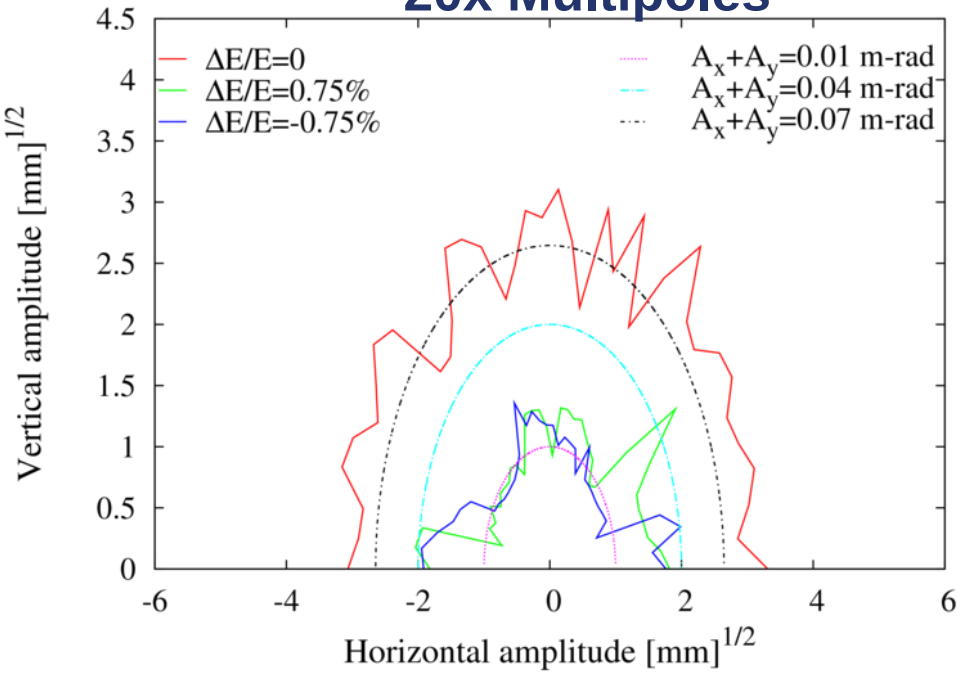
From this point on, only consider Taylor map wigglers for DA

Increased Multipoles

10x Multipoles



20x Multipoles



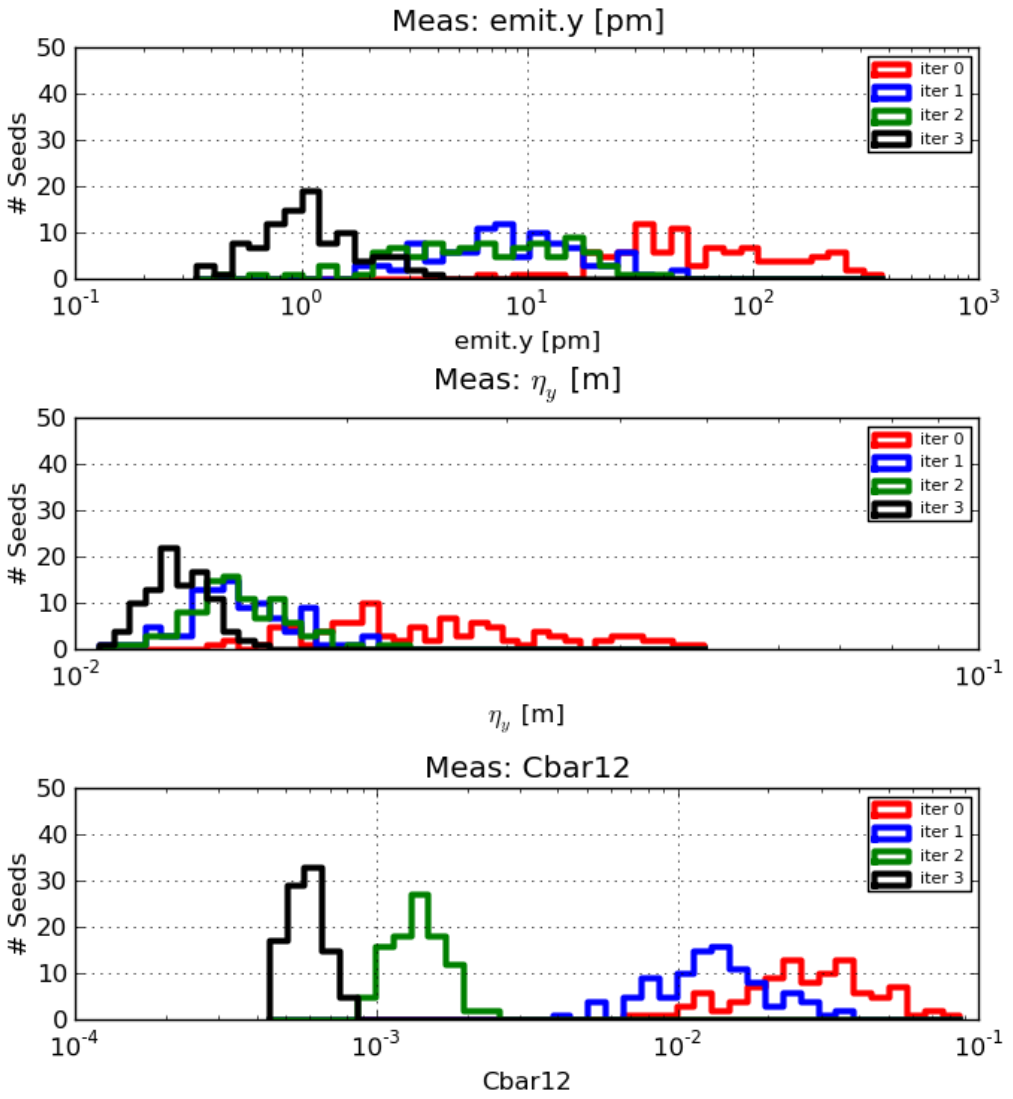
- Using Taylor map for wigglers
- Increase multipoles from Y. Cai's table until dynamic aperture is impaired
- For ideal lattice, ~10x multipoles (systematic + random) may be acceptable
  - However, tolerance must be a balance between multipoles, misalignments, and number of BPMs; can't just consider multipoles by themselves

Error Tolerance – ring_ma

- Built on Bmad library
- Capable of introducing errors to any parameter for any element described by Bmad
  - Examples: offset (x,y,z), roll, pitch, k1, k2, arbitrary multipoles, corrector calibrations, …
- Thorough characterization of BPM errors
  - Offset with respect to nearest quad; BPM tilt; relative button-to-button gain error; shot-to-shot repeatability
  - All simulated measurements used for corrections have BPM errors
- Multi-stage corrections
  - Simulate new measurements after each level of correction

Example: Emittance Tuning at CESRTA

- Model emittance correction procedure at CESRTA
- Typical 95%CL correction levels:
  - η_y = 15mm
  - Cbar12 = 1x10^{-3}
- Consistent with measurements
- Confidence in ring_ma for describing correction levels for coupling, dispersion



Misalignments and BPM Resolution

Parameter	RMS	Affected by multiplier?
BPM – Differential resolution	1 μm	No
BPM – Absolute resolution	50 μm	No
BPM – Tilt	5 mrad	No
BPM button – Gain variation	0.5%	No
Quads + Sexts – Offset (H+V)	25 μm	Yes
Quads – Tilt	50 μrad	Yes
Dipole – Roll	50 μrad	Yes
Wiggler – Offset (V only)	100 μm	Yes
Wiggler - Roll	100 μrad	Yes
Multipoles (sys+rand)	2x PEP-II tables	Yes (random only)

Nominal misalignments and BPM tolerances for ring_ma studies

Emittance Tuning Procedure

1) Measure and correct orbit using all steerings
2) Measure betatron phase advance and coupling (by resonant excitation)
   - Correct using quadrupoles and skew quadrupoles
3) Measure orbit, coupling, and vertical dispersion
   - Simultaneously correct with vertical steerings and skew quadrupoles

DTC04 – Error Tolerance

- Misaligned as per misalignment table
- Optics correction 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

Vertical emittance, dispersion and coupling (actual, not observed) after emittance tuning for 95%CL of 100 seeds

	1x Errors		2x Errors	
Parameter	No Multipoles	Systematic+Random Multipoles	No Multipoles	Systematic+Random Multipoles
ε_y	0.20 pm	0.20 pm	0.33 pm	0.41 pm
η_y	0.54 mm	0.53 pm	0.98 mm	1.07 mm
C_{12}	3.86×10^{-4}	3.83×10^{-4}	7.76×10^{-4}	8.71×10^{-4}

Error Tolerance – MAD Wigglers

- Multipoles do not have a significant effect on optics correction
  - Will have a bigger effect on dynamic aperture, after misalignments and corrections
- Optics corrections are more or less unaffected by wiggler model
  - Opt to use MAD-type wigglers to increase simulation throughput

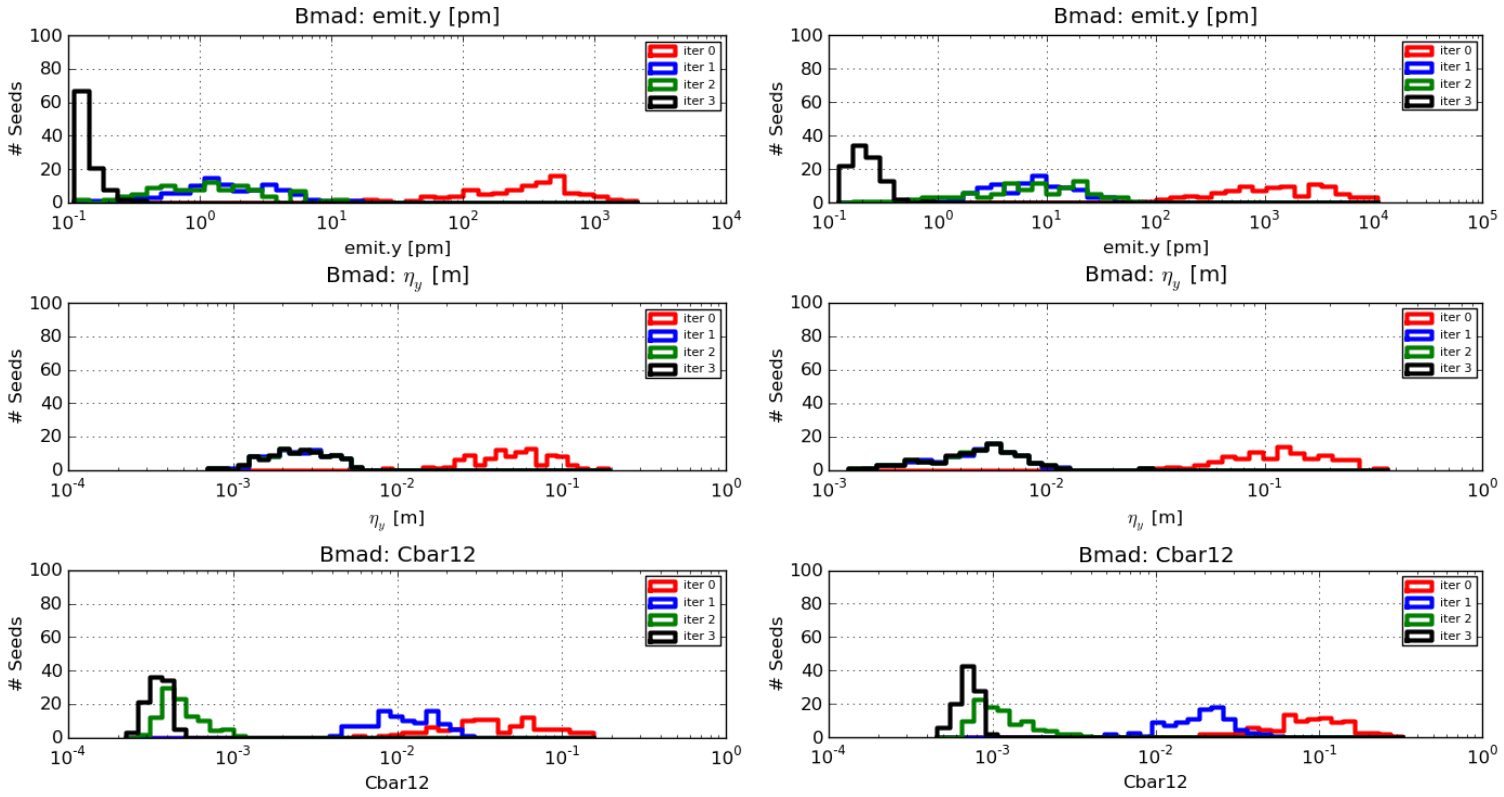
Plots:

MAD wigglers

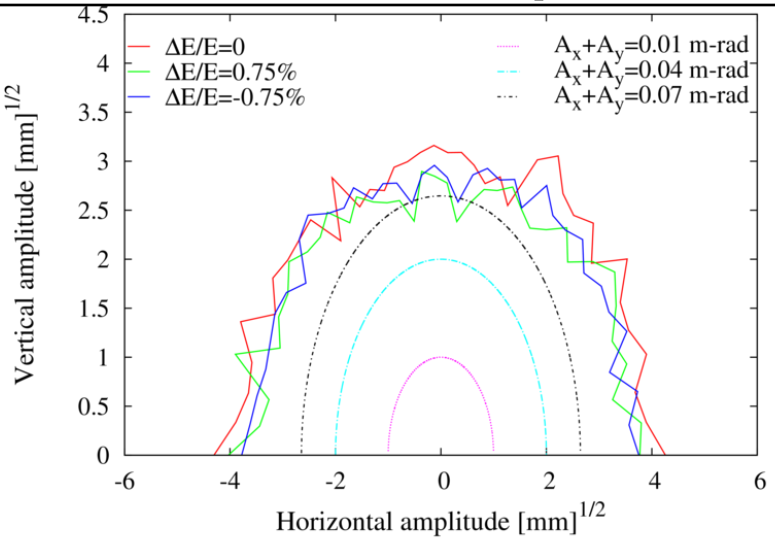
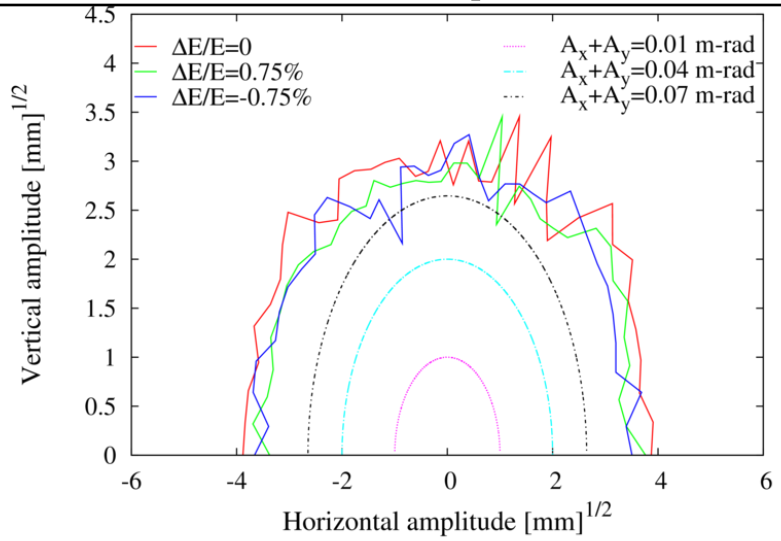
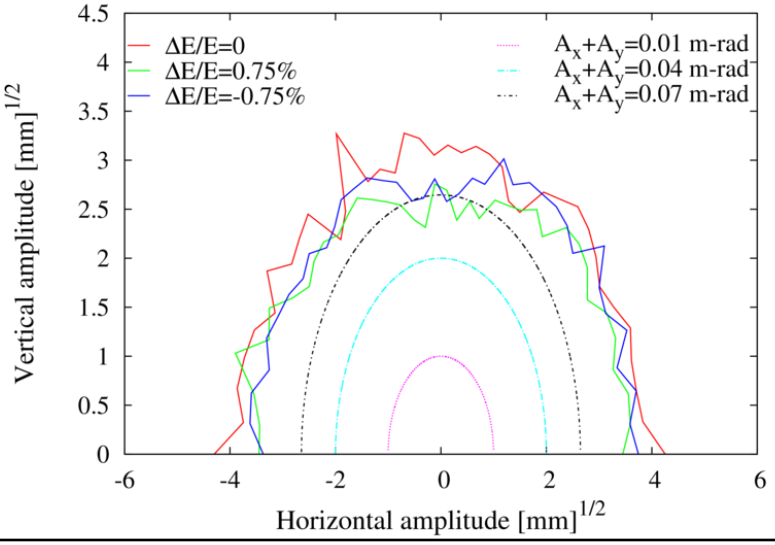
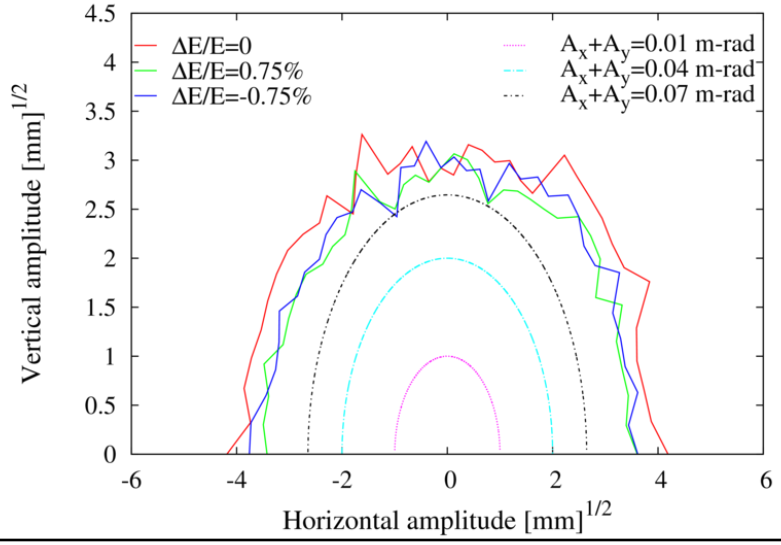
No multipoles

Left: 1x errors

Right: 2x errors

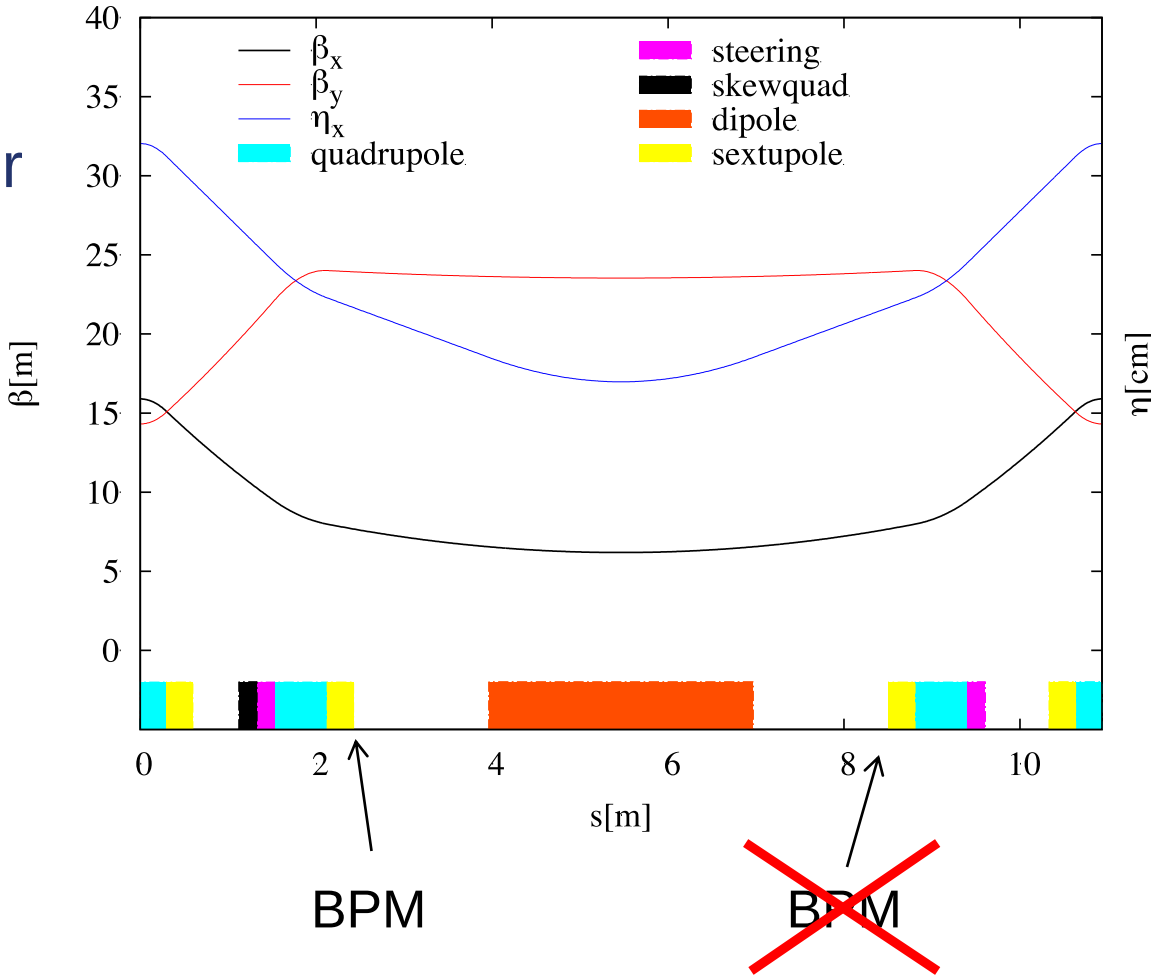


Error Tolerance – Taylor Map Wigglers

	Without Multipoles	With Multipoles
1x Errors		
2x Errors		

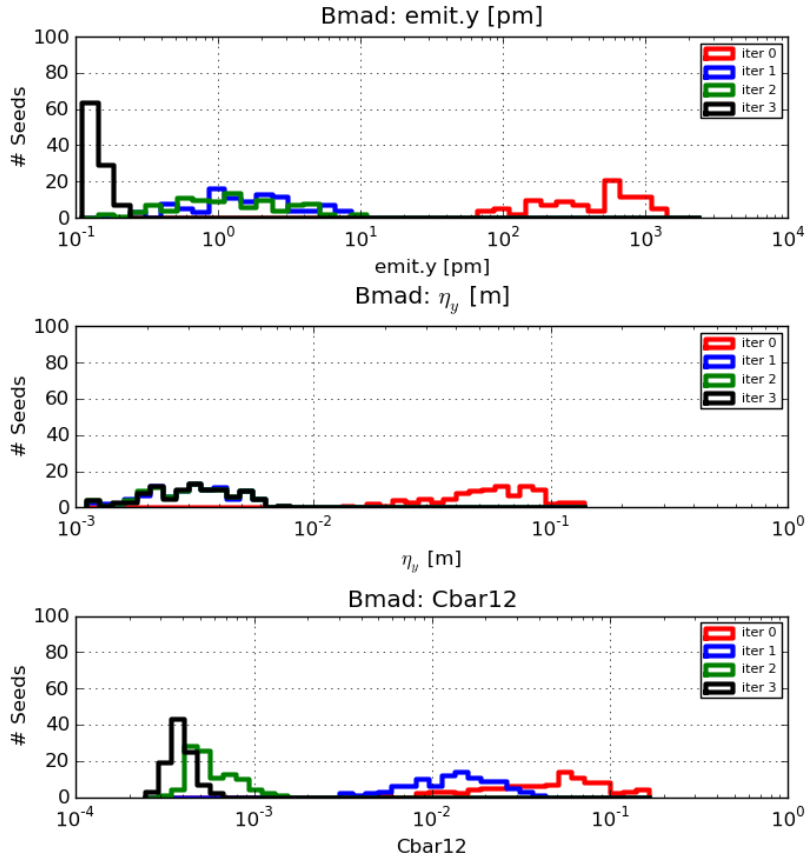
Reduced Number of BPMs

- Reduce the total number of BPMs in the arcs by 50% (from 2/cell to 1/cell)

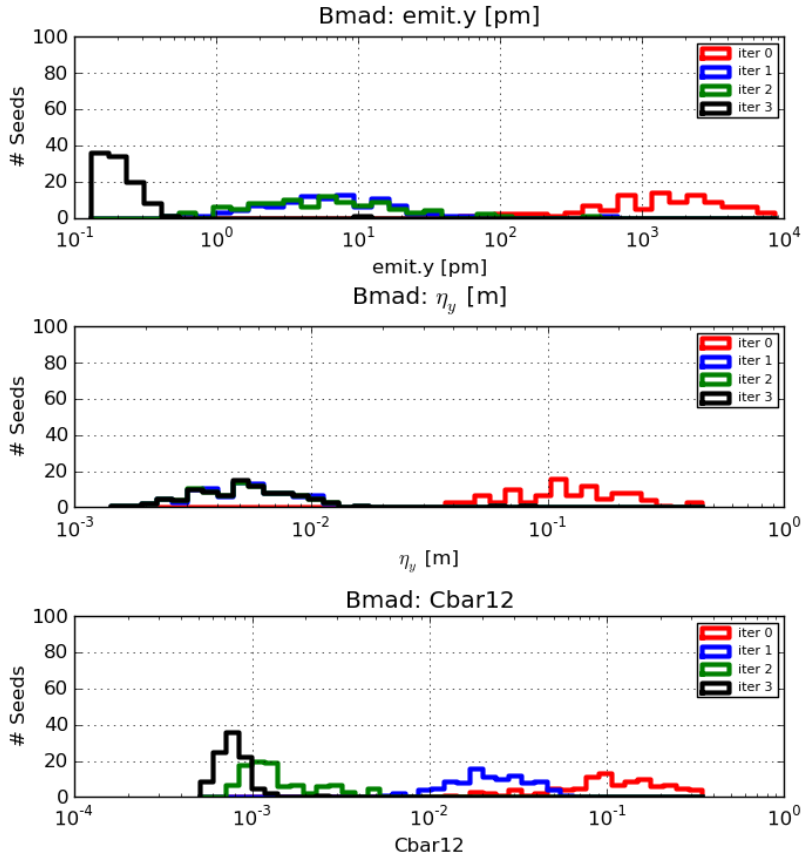


Error Tolerance – Reduce BPMs in Arcs

- With reduced number of BPMs in arcs, still achieve emittance target
- Significant cost savings (511 BPMs → 361 BPMs = 30% reduction in BPMs)

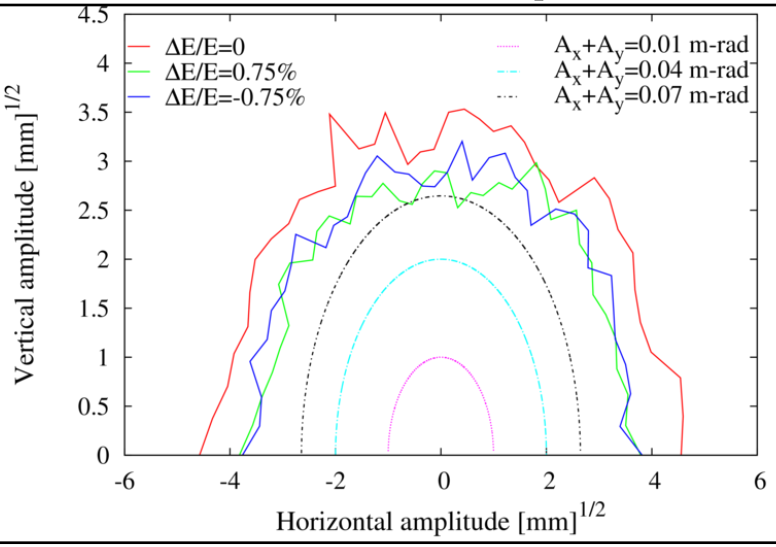
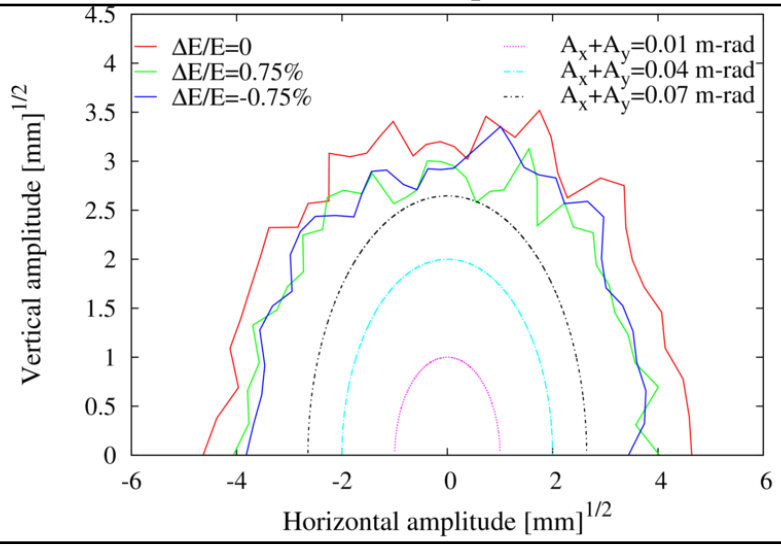
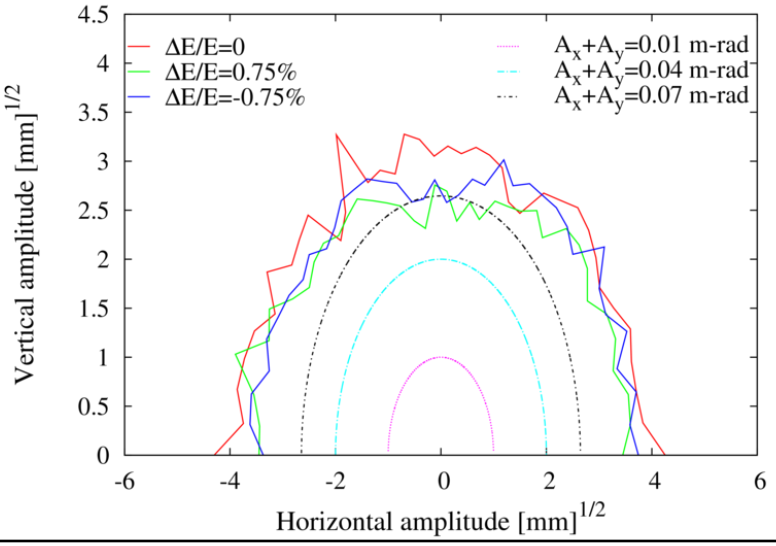
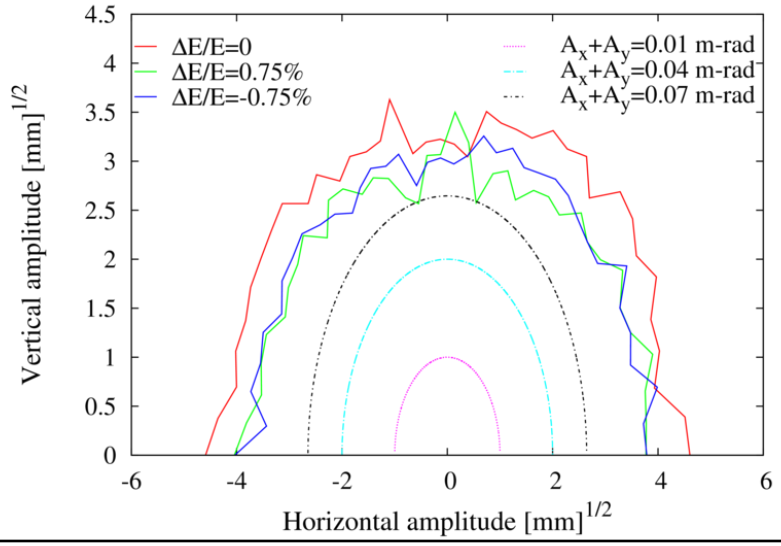


MAD-type wigglers, 1x errors

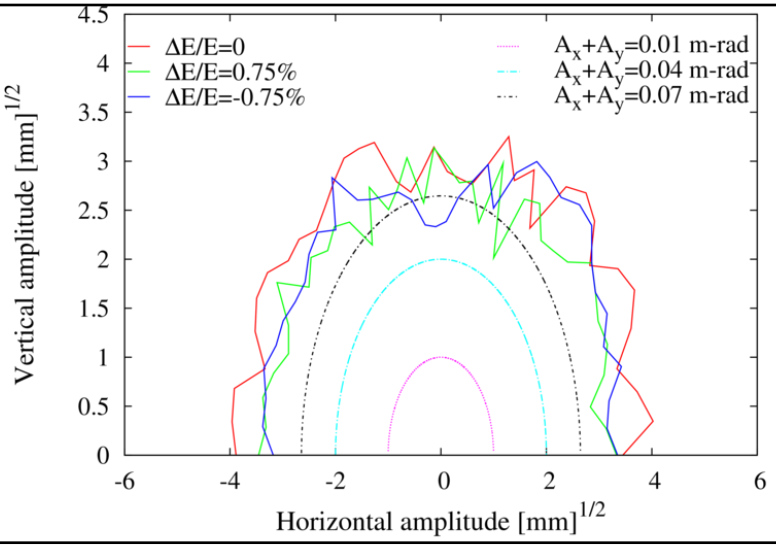
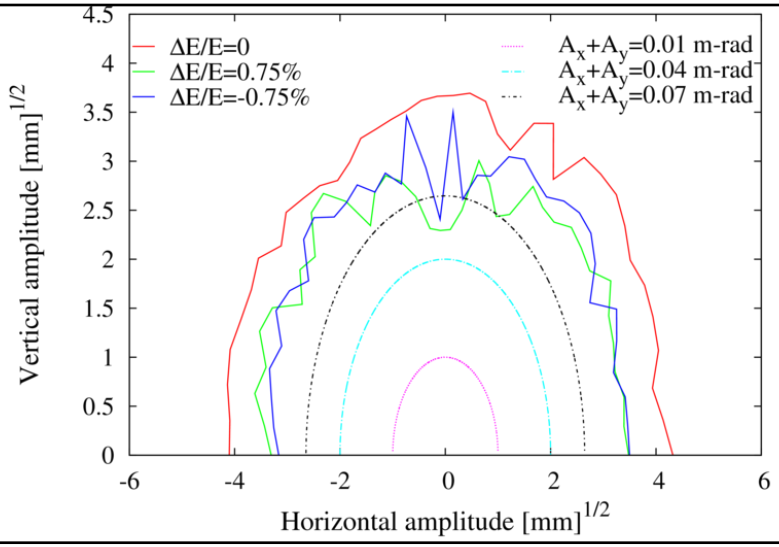
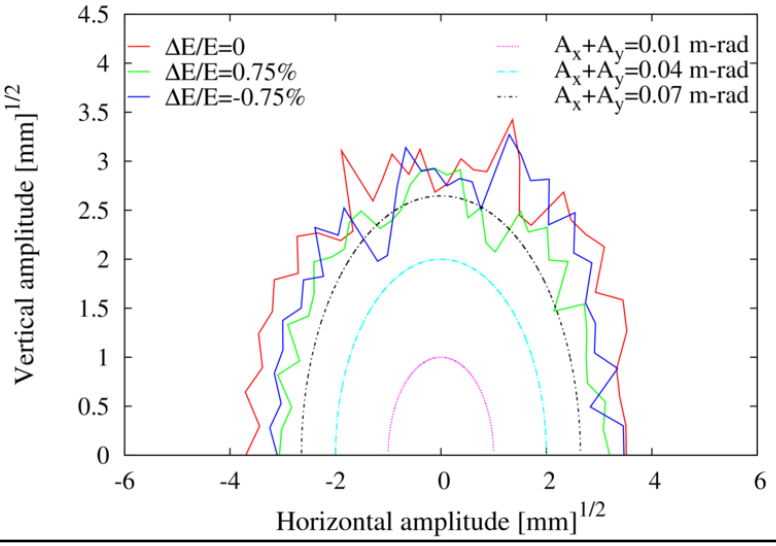
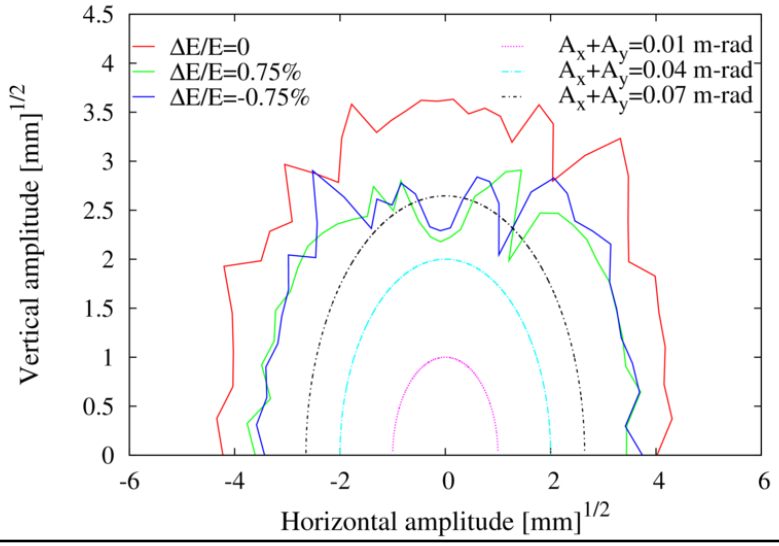


MAD-type wigglers 2x errors

50% Arc BPMs, 100% Straight BPMs

	Without Multipoles	With Multipoles
1x Errors		
2x Errors		

Increase to 5x Multipoles

	Nominal BPM Scheme	50% Arc BPMs
1x Errors		
2x Errors		

Misalignment and BPM Resolution Tolerance

Updated to reflect maximum tolerance for ε_y < 2pm-rad **and** sufficient dynamic aperture

Parameter	RMS
# of BPMs	361 (50% in arcs, 100% in straights)
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)	50 μm
Quads – Tilt	100 μrad
Dipole – Roll	100 μrad
Wiggler – Offset (V only)	200 μm
Wiggler - Roll	200 μrad
Multipoles	2x PEP-II (systematic) 4x PEP-II (random)

DTC04 Summary

Status

- Updated constraints on magnet multipole and misalignment tolerances, consistent with ε_y = 2pm-rad and DA > 0.07m-rad:
  - Systematic multipoles: 2x PEP-II multipoles
  - Random multipoles: 4x PEP-II multipoles
  - Misalignments and BPM errors as per previous slide
- Reduced BPM count by 30% (511 → 361)
  - 50% BPMs in arcs; maintain all BPMs in straights
- Sufficient dynamic aperture confirmed with reduced BPM count, full wiggler map, misalignments and corrections, and multipoles

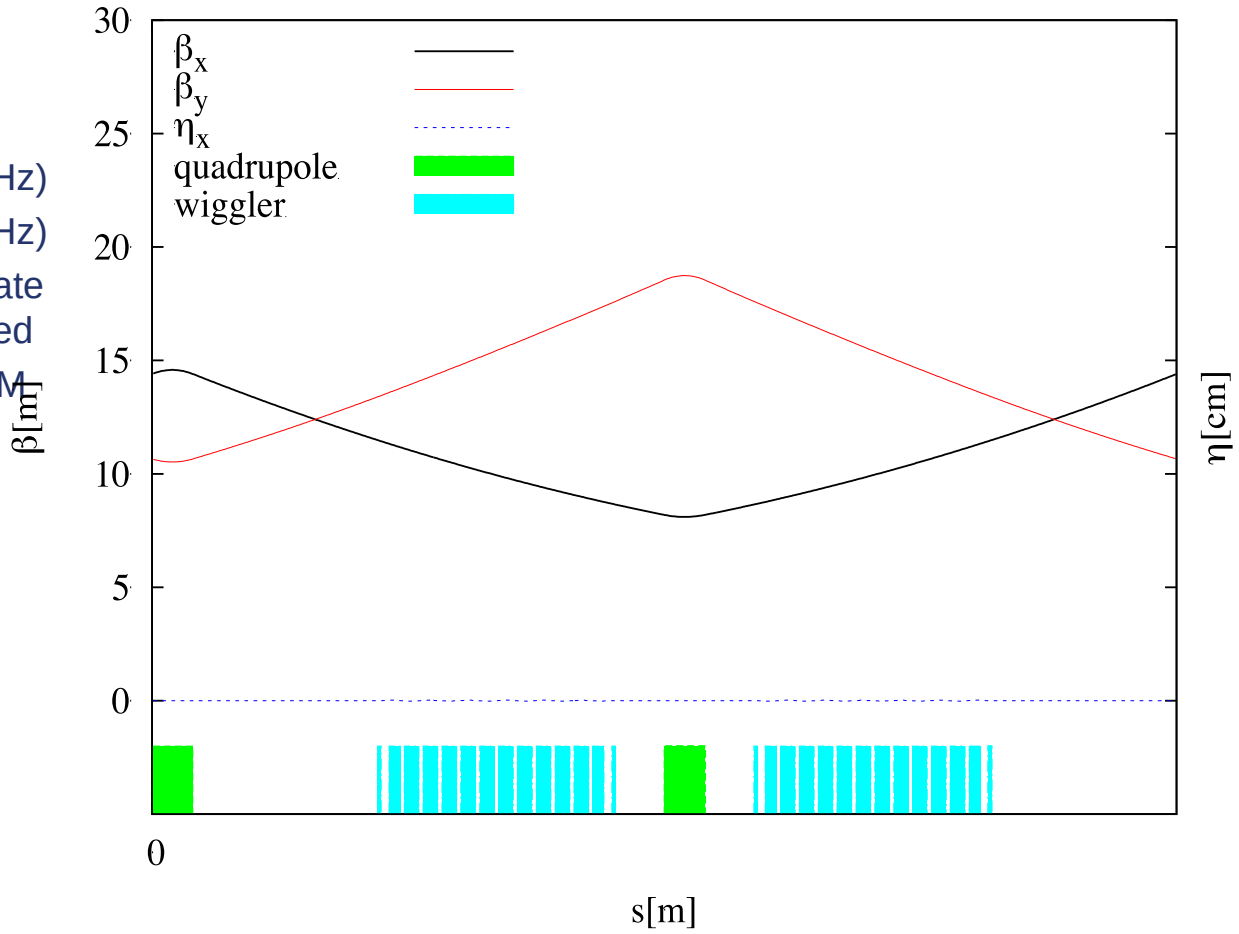
Ongoing effort

- Investigate increasing misalignment tolerances beyond 2x nominal values
  - Include dipole strength, quad k1, sextupole k2 errors
- Emittance tuning with fewer correctors; reduced number of BPMs in straights
- Explore tune plane for better dynamic aperture
- Alternate sextupole distributions for more DA

Backup Slides

Damping Wigglers

- Wiggler straight
  - 2 wigglers/cell
  - 30 cells
  - 2.1 m wiggler
  - 1.5T< B_{peak}< 2.2T
  - 54 @ 2.16T => τ_x =13ms (10Hz)
  - 54 @ 1.51T => τ_x = 25ms (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 @ τ_x =13ms

    => for 12 cavities

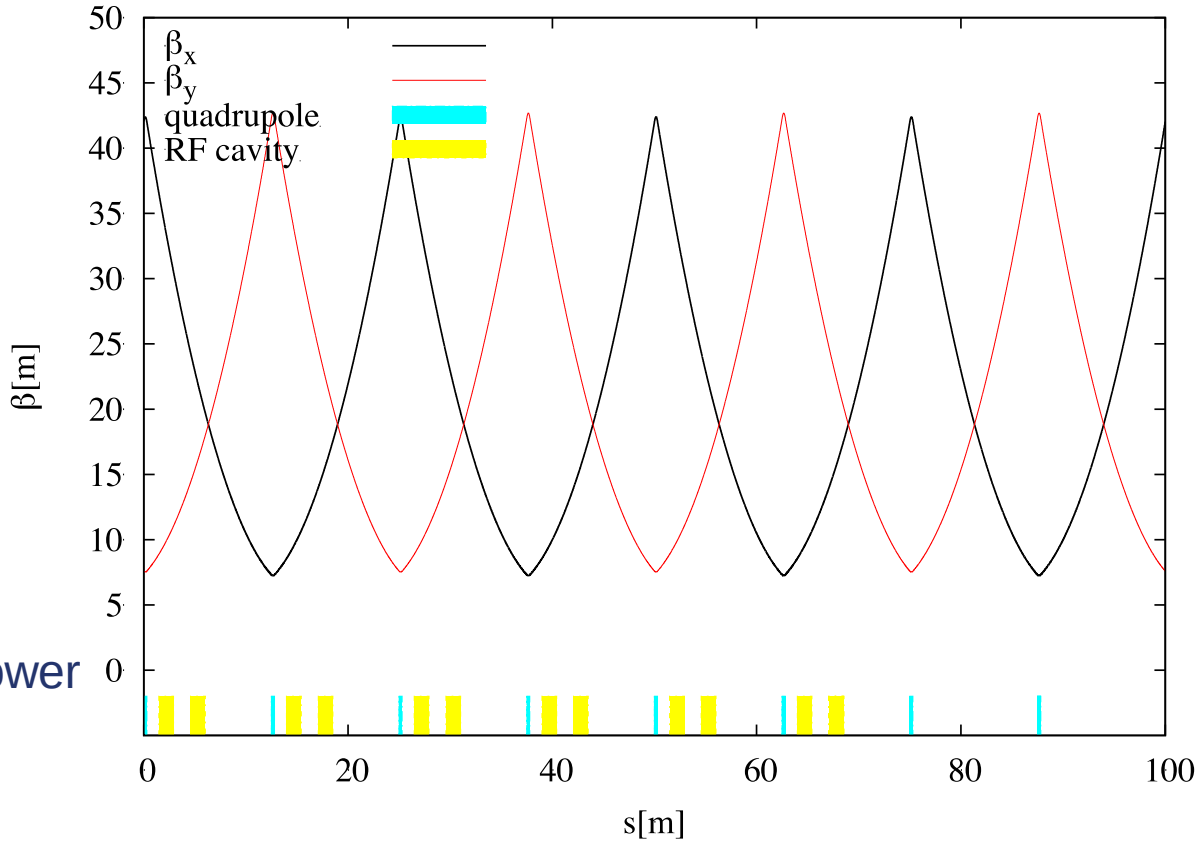
    1.9MV/cavity

    272kW/coupler

Lattice can accommodate 16 cavities if required

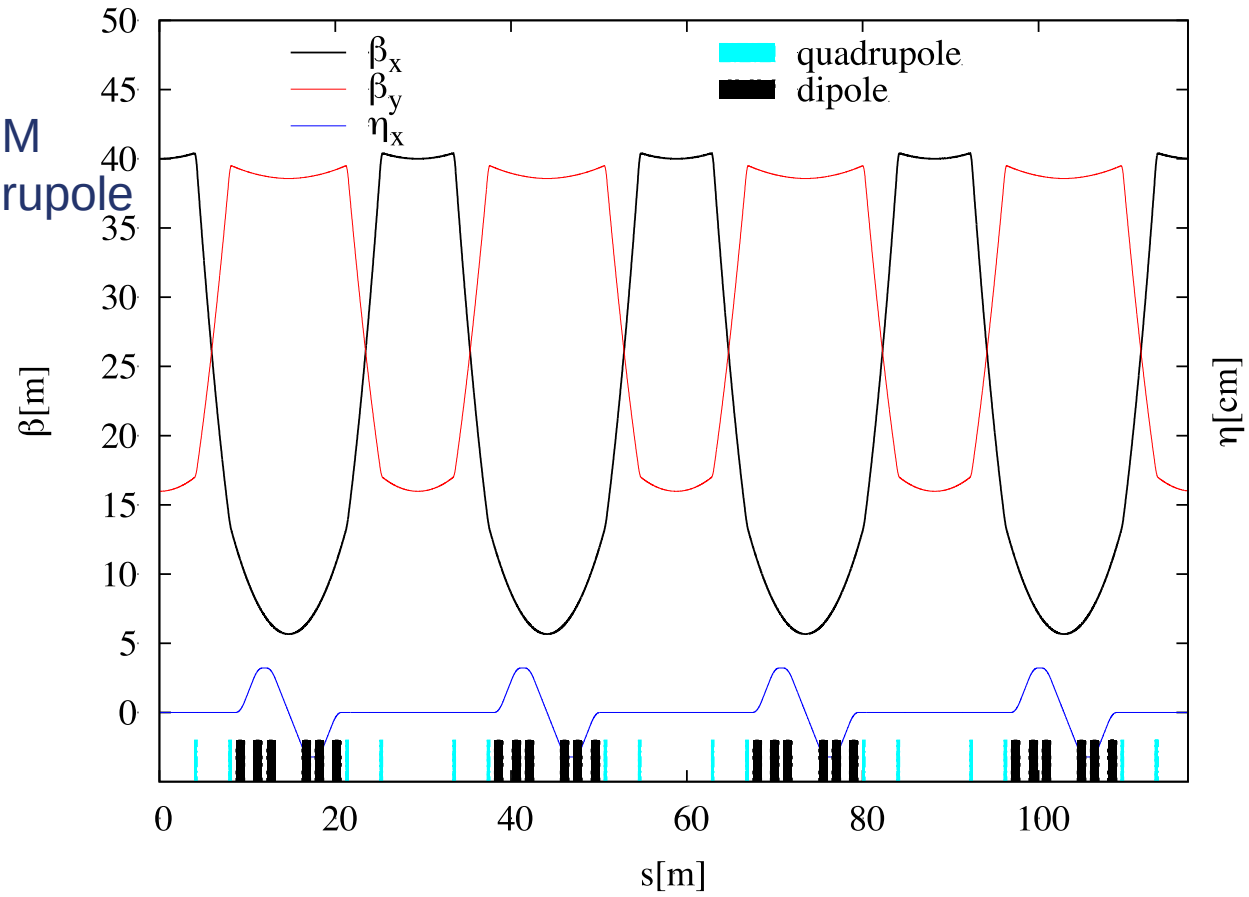
Cavities offset so that waveguides of upper and lower rings are interleaved

H&V corrector and BPM adjacent to each quadrupole



Circumference chicane

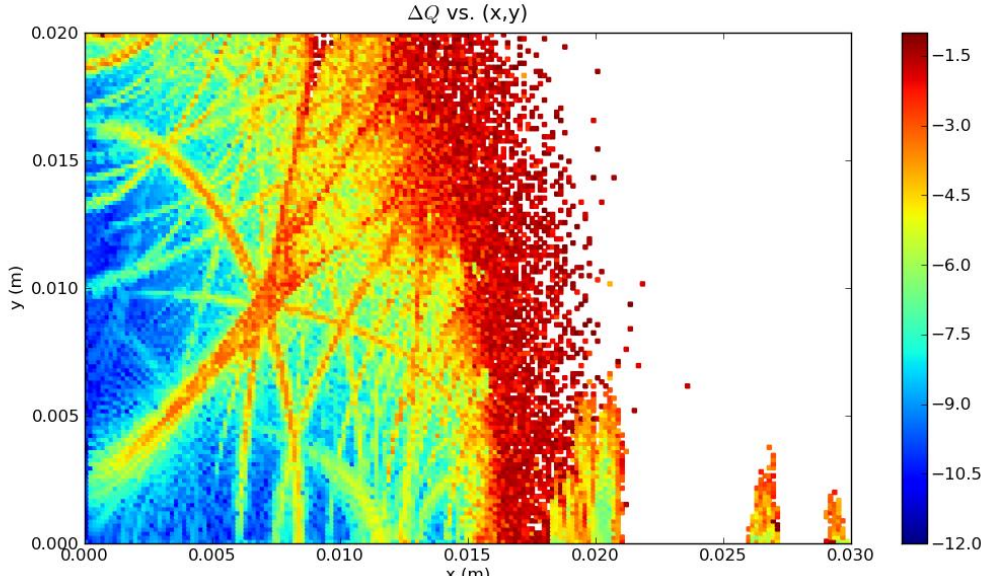
- Chicane
  - $\Delta C = \pm 4mm$
  - $\Delta\varepsilon_y < 3\%$
  - H&V corrector and BPM adjacent to each quadrupole



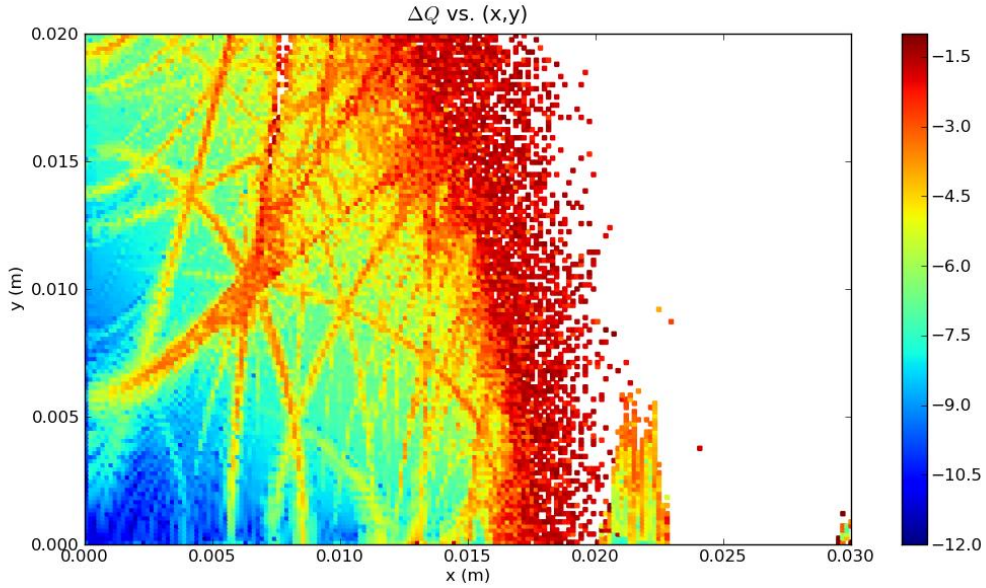
Frequency maps

- 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. (Qx, Qy) [tunes from first 1024 turns]
- Maps for a single seed (with misalignments and corrections) per scenario

DTC04-5Hz Frequency maps

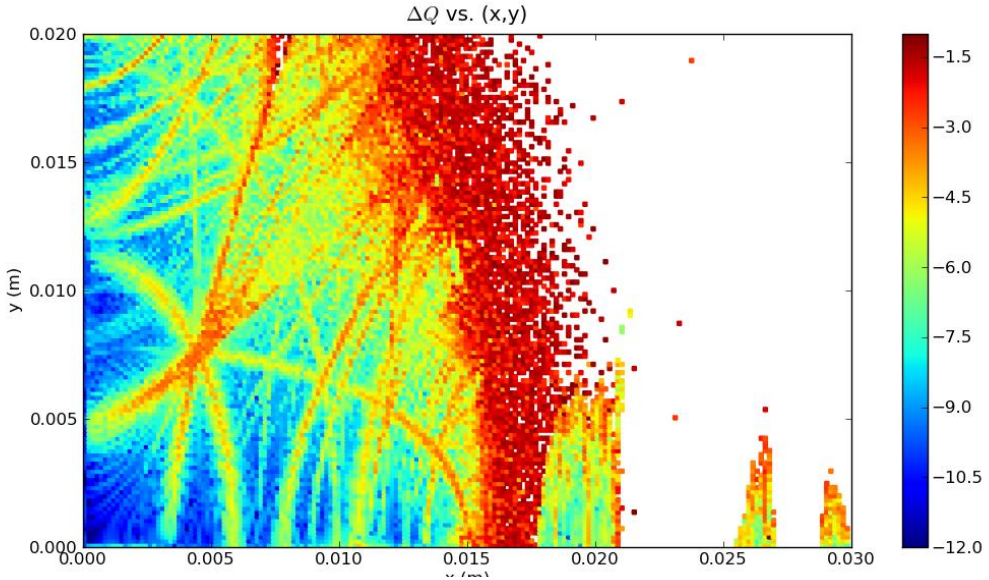


- No Multipoles
- Random misalignments
- Corrections

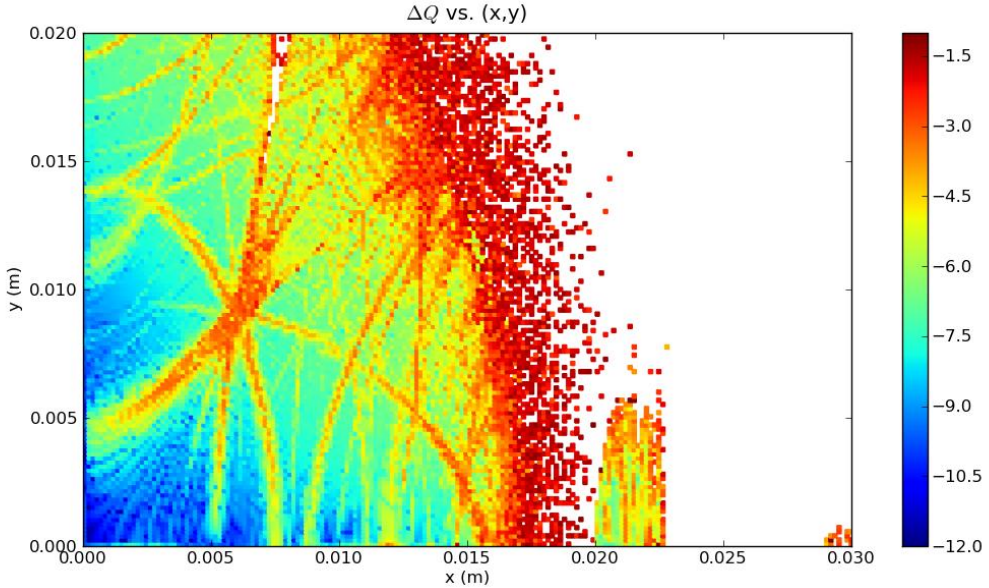


- Static + Random Multipoles
- Random misalignments
- Corrections

DTC04-10Hz Frequency maps



- No Multipoles
- Random misalignments
- Corrections

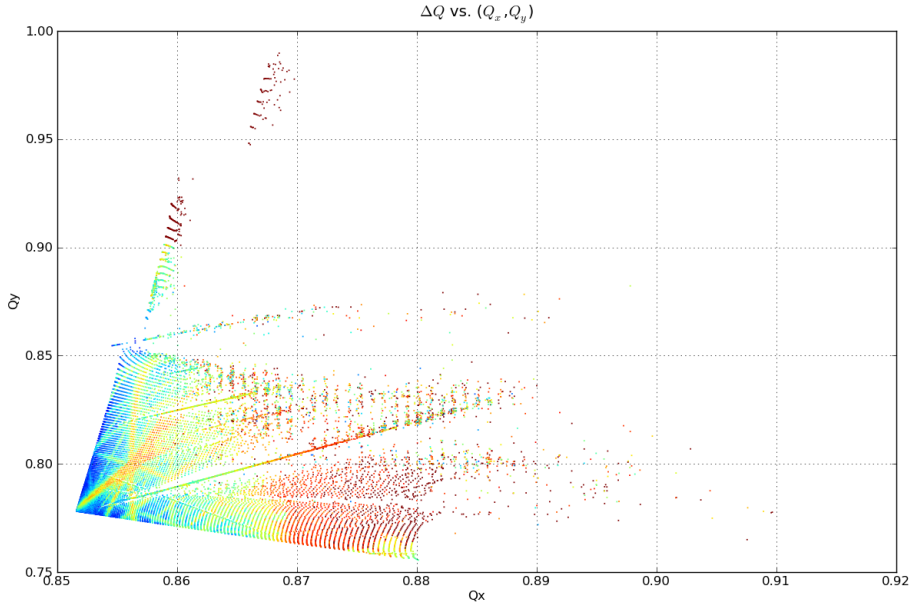


- Static + Random Multipoles
- Random misalignments
- Corrections

DTC04-5Hz Frequency Maps

ΔQ vs. (Q_x, Q_y)

- No Multipoles
- Random misalignments
- Corrections



- Static + Random Multipoles
- Random misalignments
- Corrections