Transverse Tracking of the AHF Rings

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Overview

- **Required acceptance set by Laslett Tune Shift -0.2 at injection**
  - tracking includes only single-particle effects, but required beam size is determined by collective effects
- **Beam tracking done with with the program TEAPOT**
  - No space-charge, but magnet field errors, position and rotation errors
  - Correctors included: steering magnets, chromaticity sextupoles.
  - In every run the closed orbit is corrected using the existing BPMs and steering magnets, then the tunes are set to nominal values by resetting all quadrupoles (no local quadrupole trims)
- **Three rings studied: Booster and two versions of the main ring**
  - All rings studied at injection energy
  - 4 GeV Booster is nine-sided standard (B9L)
  - 50 GeV Conventional main ring has periodicity four (R19)
  - Transition-less ring has periodicity three (I25)
- **Error multipoles used in tracking**
  - Dipole errors from MI dipoles (scaled to the larger aperture for the booster)
  - Quadrupole errors from MI quadrupoles or from new requirements

Tracking with TEAPOT

- Developed by R. Talman (Cornell) and L. Schachinger (Berkeley)

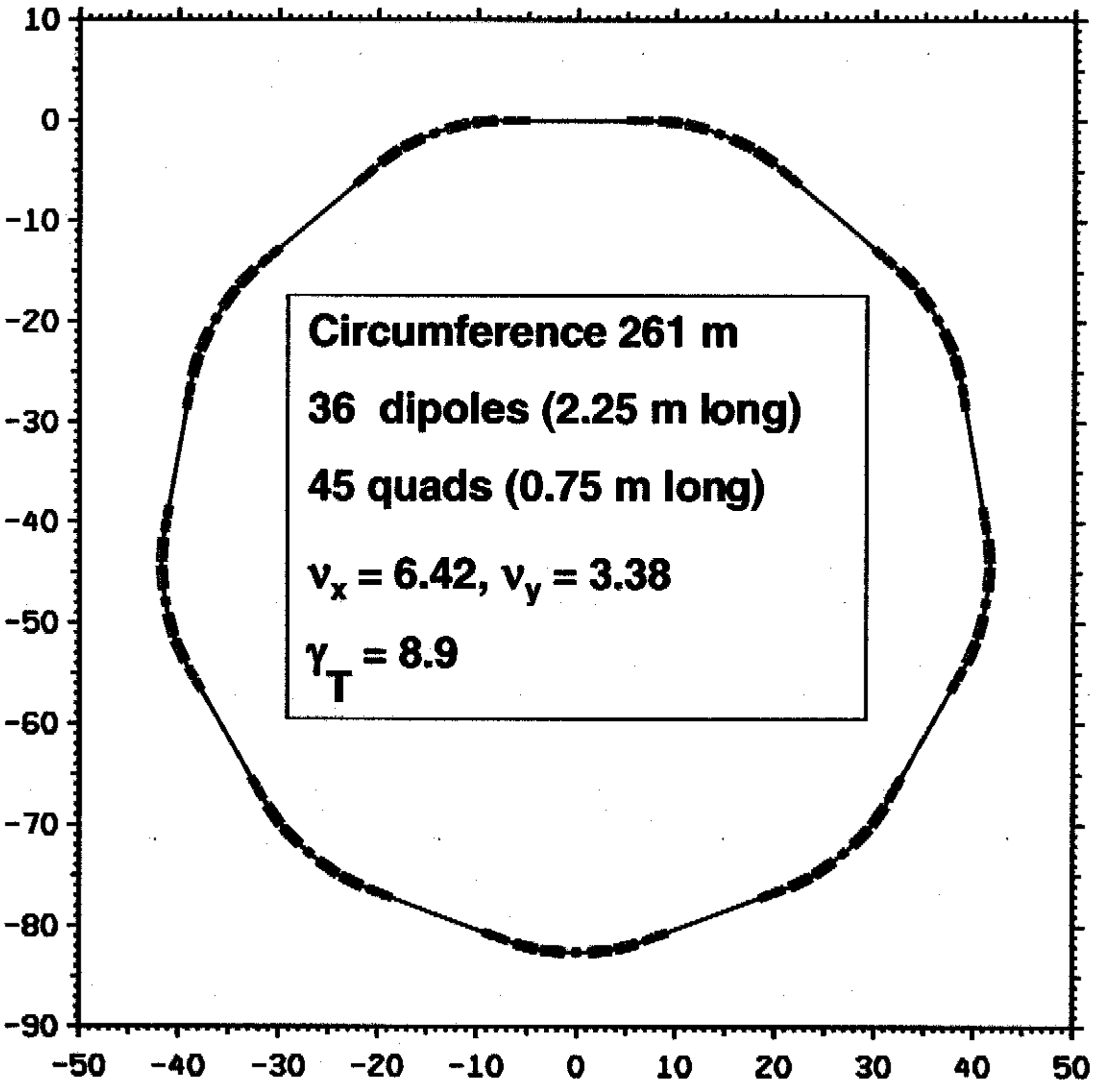
- Classic UNIX FORTRAN version as used at SSC
  - But many improvements since then, including some local ones

- Exact physics
  - Hamiltonian-based (canonical variables)
  - Symplectic integration (no spurious emittance growth)
  - Closed-orbit and alignment errors treated exactly (no truncation)
  - 6-D tracking, including synchrotron oscillations

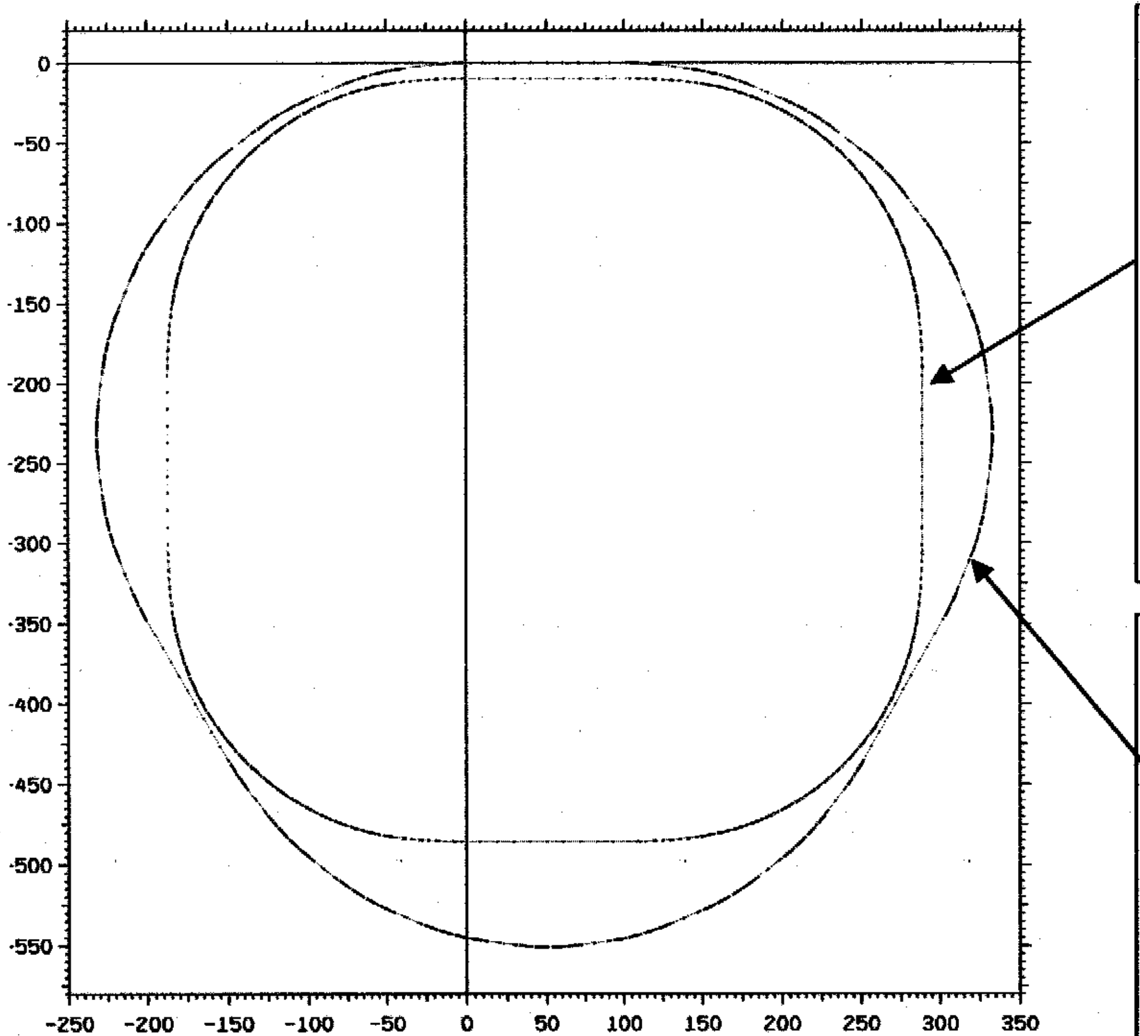
- Powerful, MAD-like front end
  - Uses the same input language as design codes
  - Simplifies setting up correctors, BPMs

- Problems
  - No space-charge forces in standard version
  - Slow (needed fastest UNIX workstations in the past, now also PCs with LINUX)

4 GeV Booster Layout (see talk by P. Schwandt)



Two 50 GeV Main Ring Designs under Study
Conventional 4-sided and Transitionless 3-sided



Conventional 4-sided ring:

Circumference 1613.42 m

80 dipoles (6.78 m long)

32 dipoles (3.39 m long)

152 quads (1.295 m long)

$\nu_x = 19.42$, $\nu_y = 19.38$

$\gamma_T = 14.99$

Transitionless 3-sided ring:

Circumference 1757.4 m

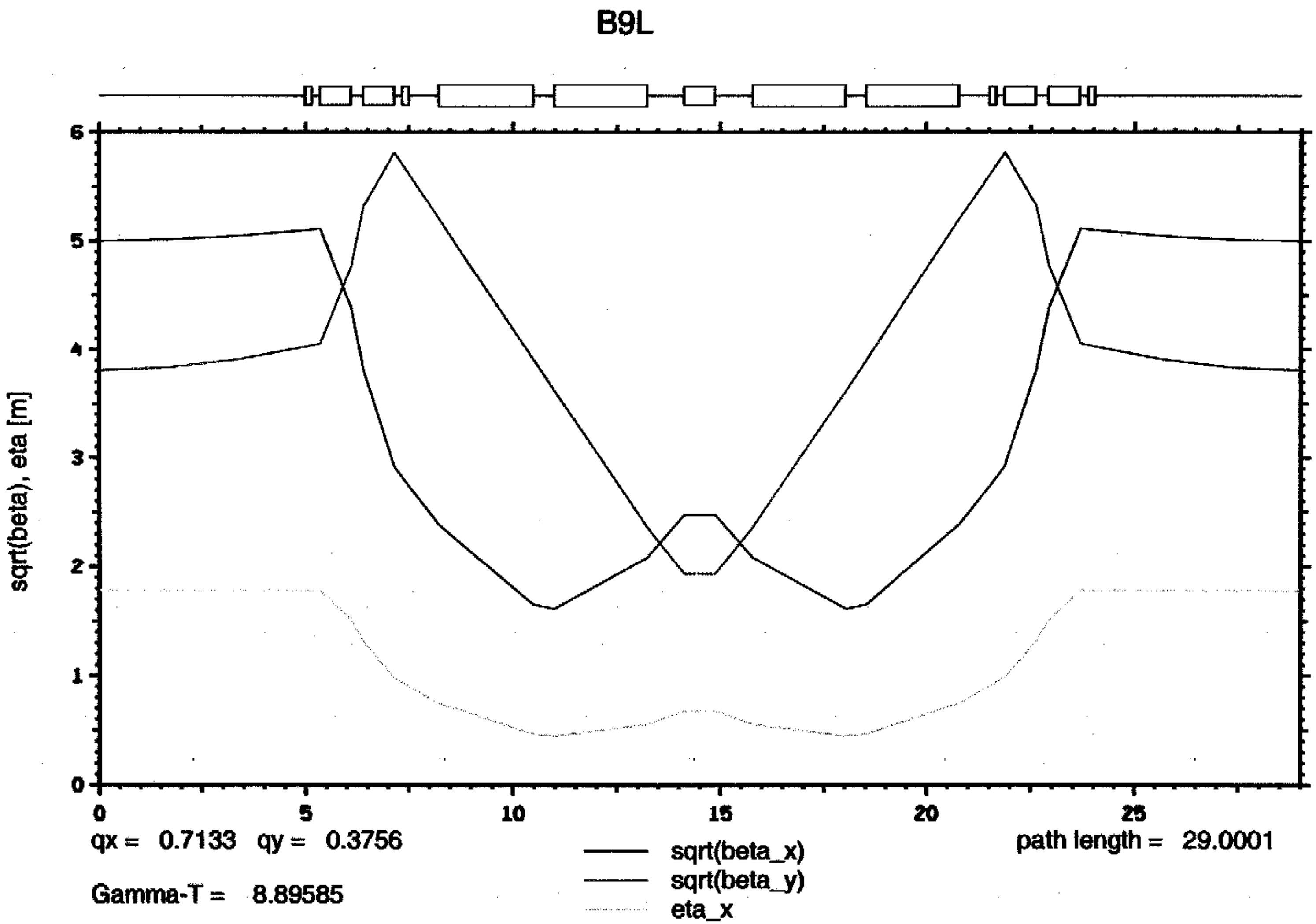
96 dipoles (6.78 m long)

172 quads (1.55 m long)

$\nu_x = 25.42$, $\nu_y = 22.38$

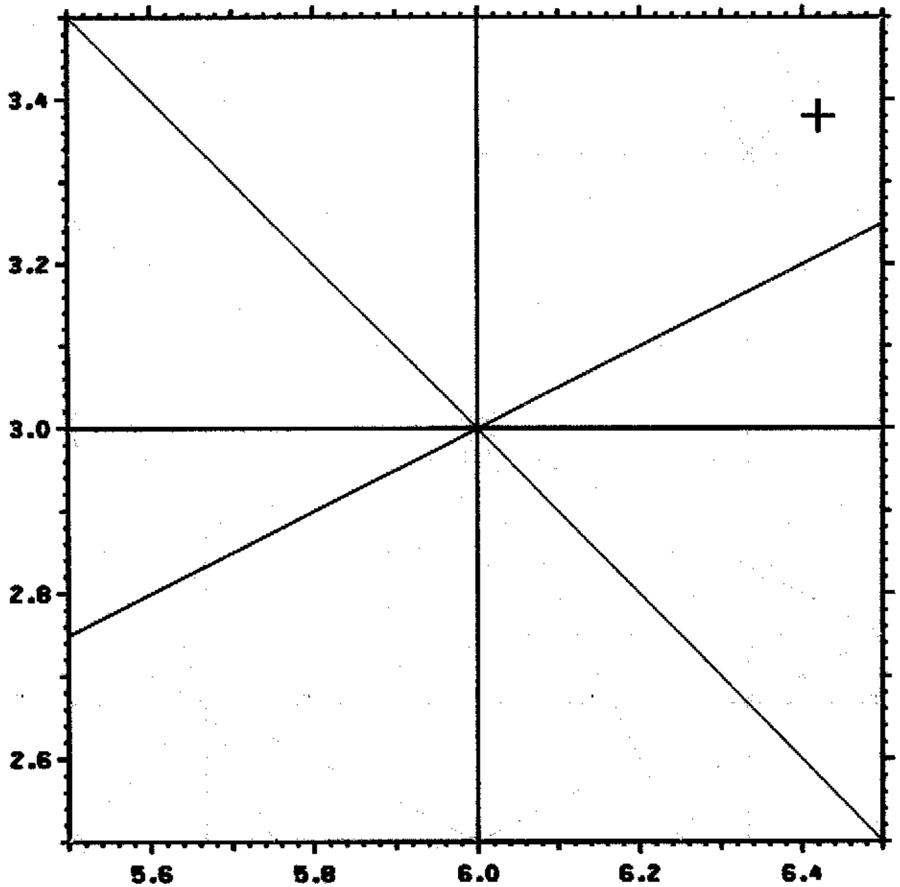
$\gamma_T = i26.02$

4 GeV Booster Lattice Functions for one Cell (1/9 of Ring)



Los Alamos

4 GeV Booster Tune Diagram

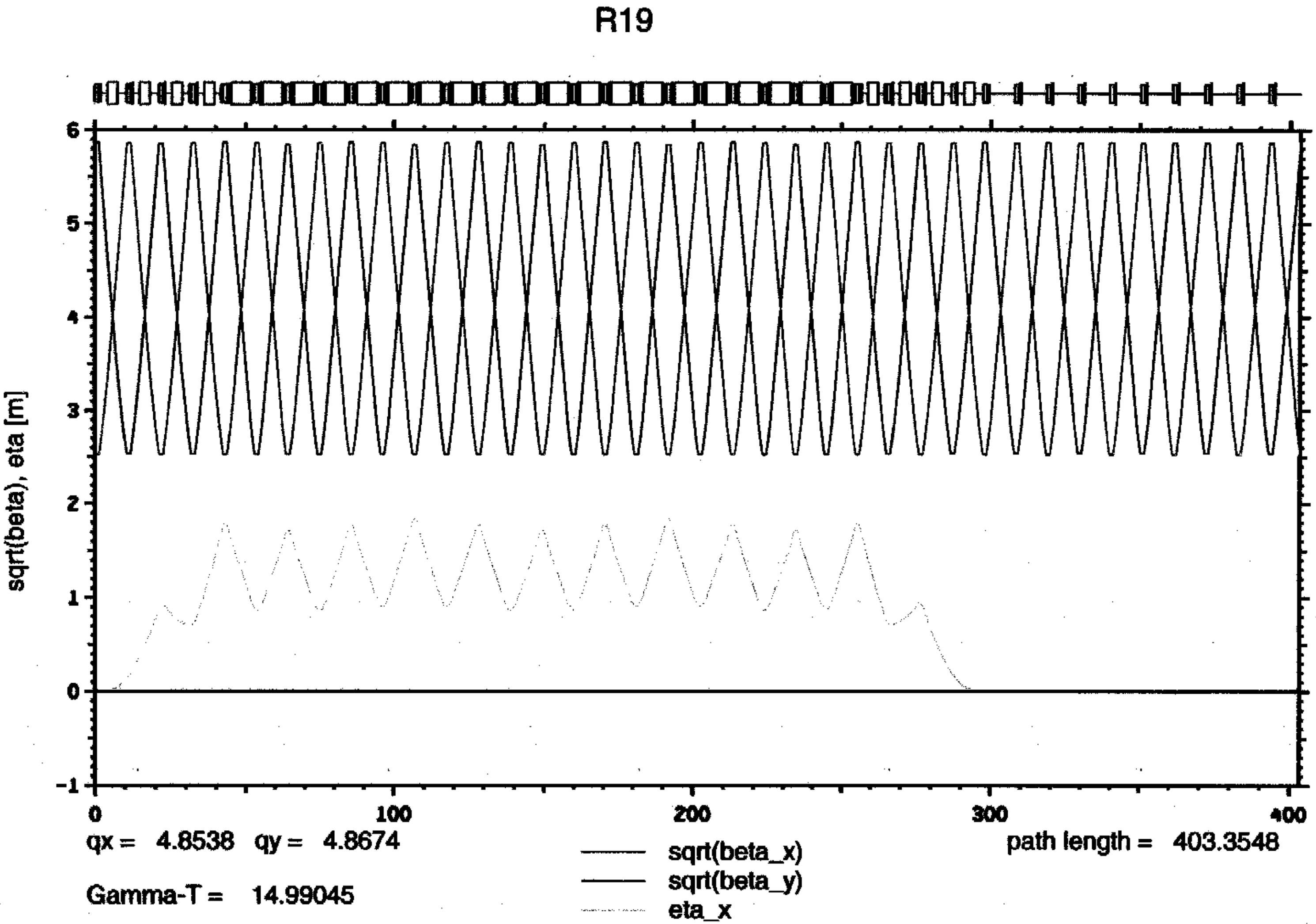


Structural resonances are in color

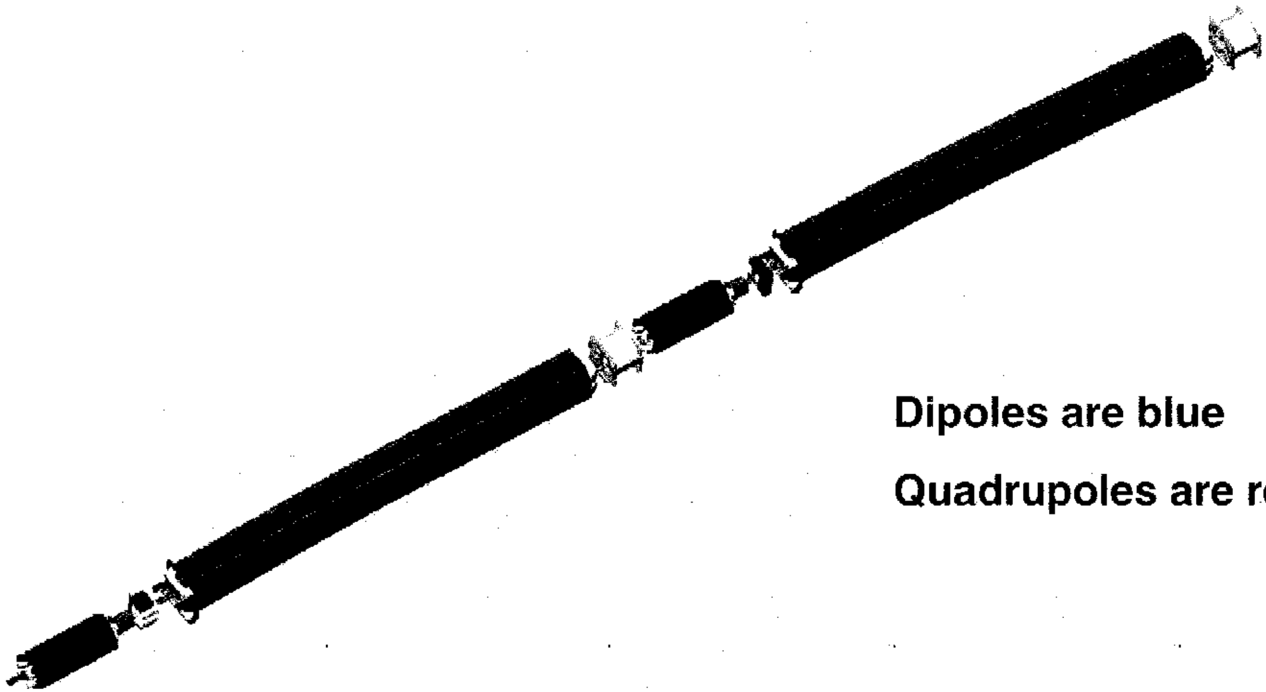
The only structural resonance near the operating point is

$2\nu_y - \nu_x = 0$

Conventional 4-sided Ring Lattice Functions for 1/4 of the Ring



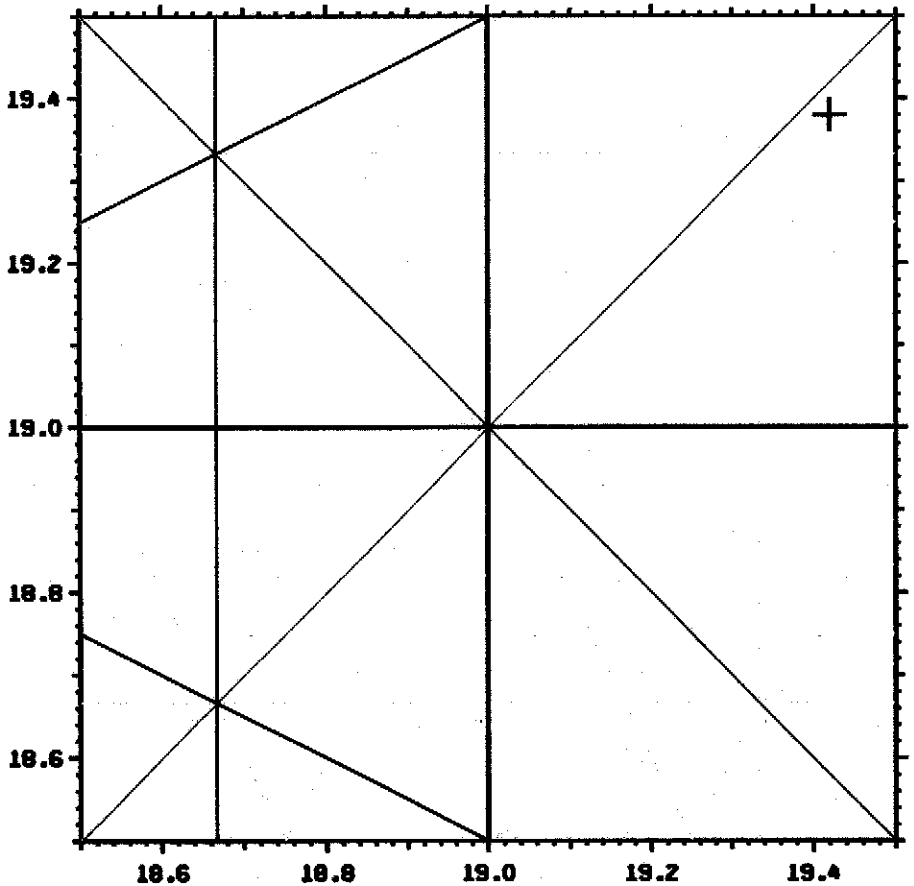
Conventional 4-sided Ring Arc Cell



Dipoles are blue

Quadrupoles are red

Conventional 4-sided Lattice Tune Diagram

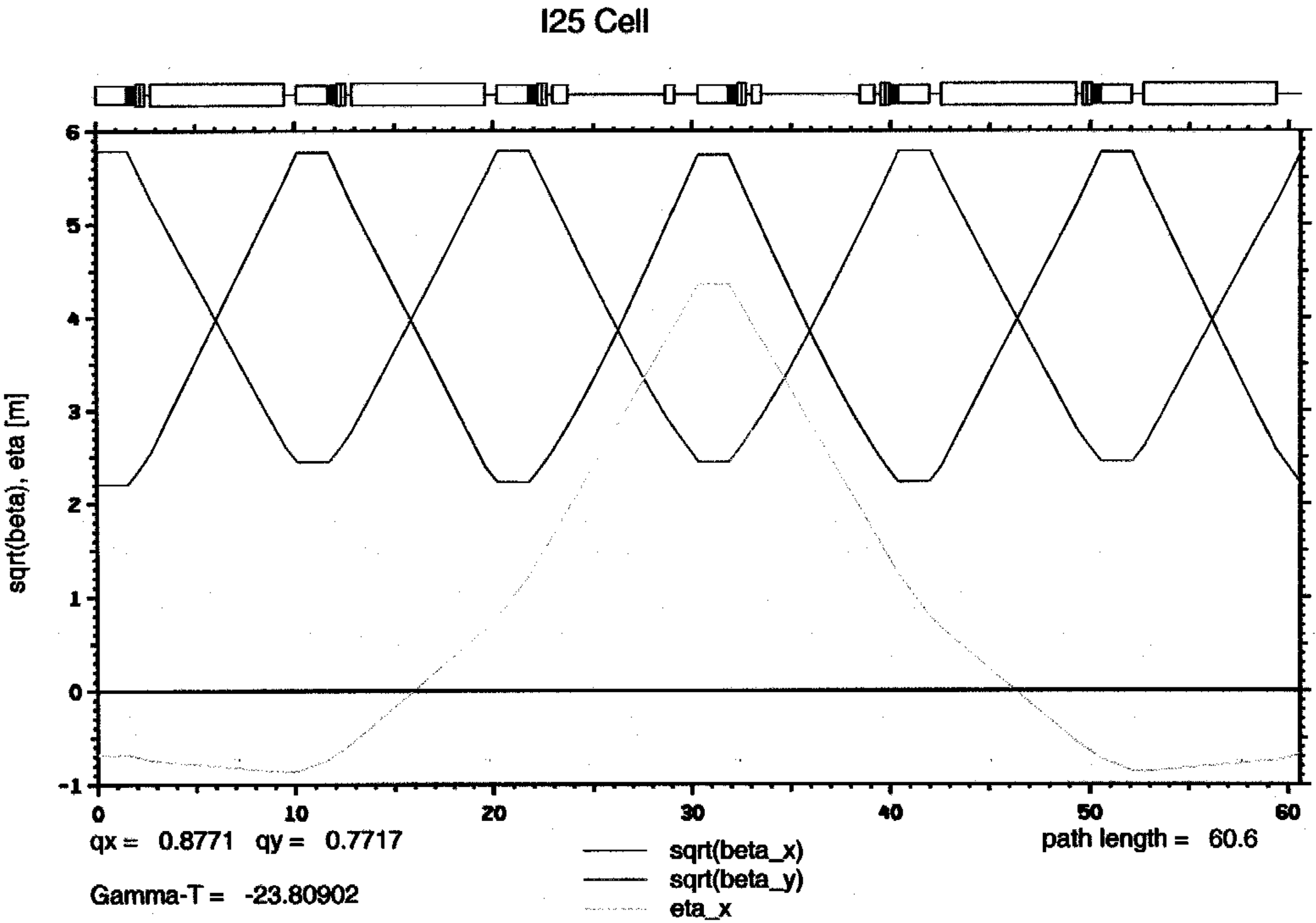


Structural resonances are in color

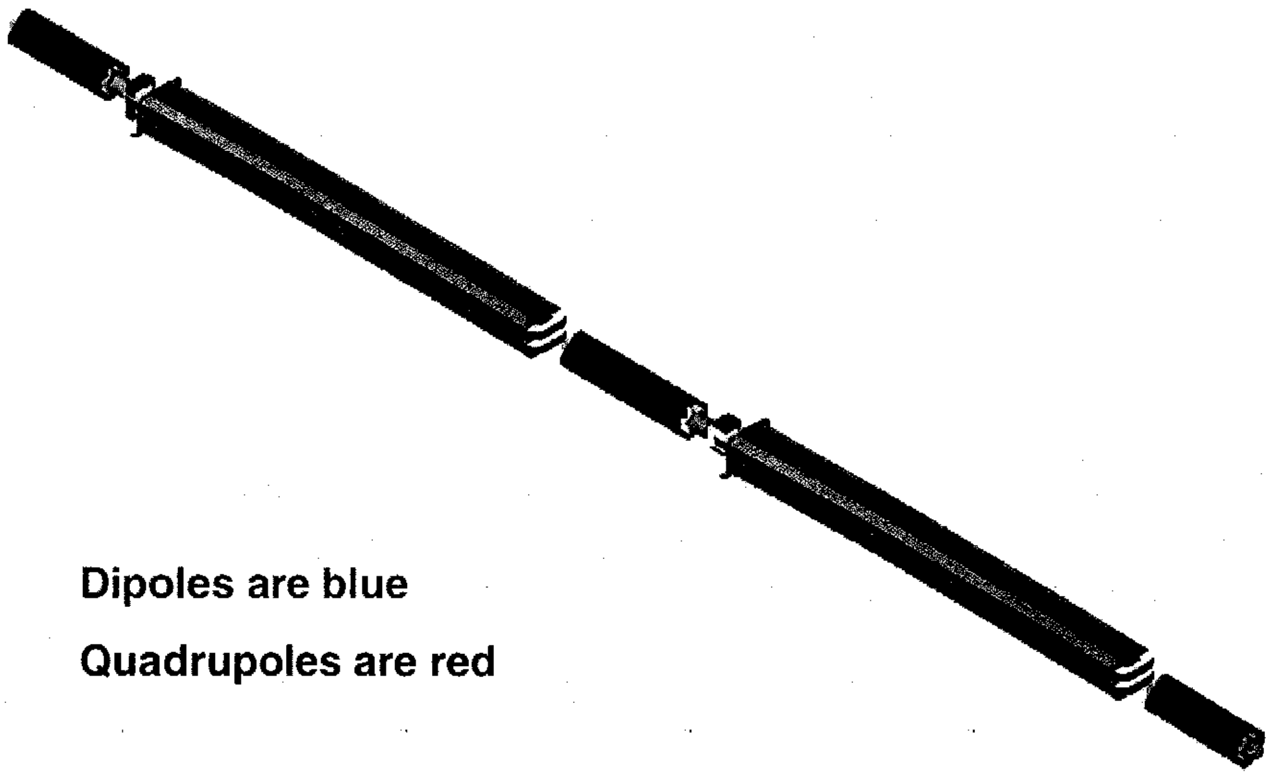
The only structural resonance near the operating point is

$2\nu_y - 2\nu_x = 0$

Transition-Less 3-sided Lattice Functions (Arc Cell)



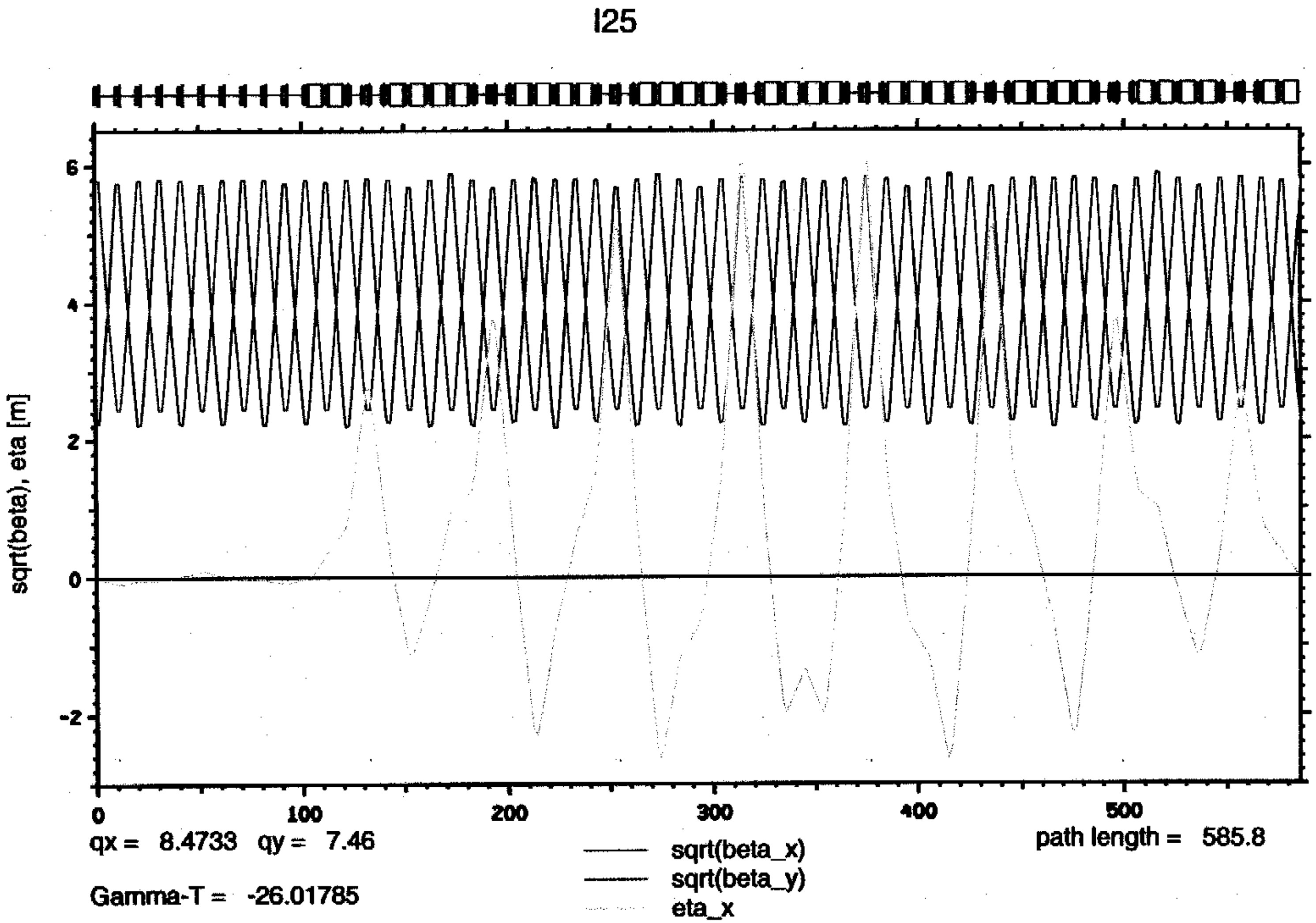
Transition-Less 3-sided Ring Arc Cell



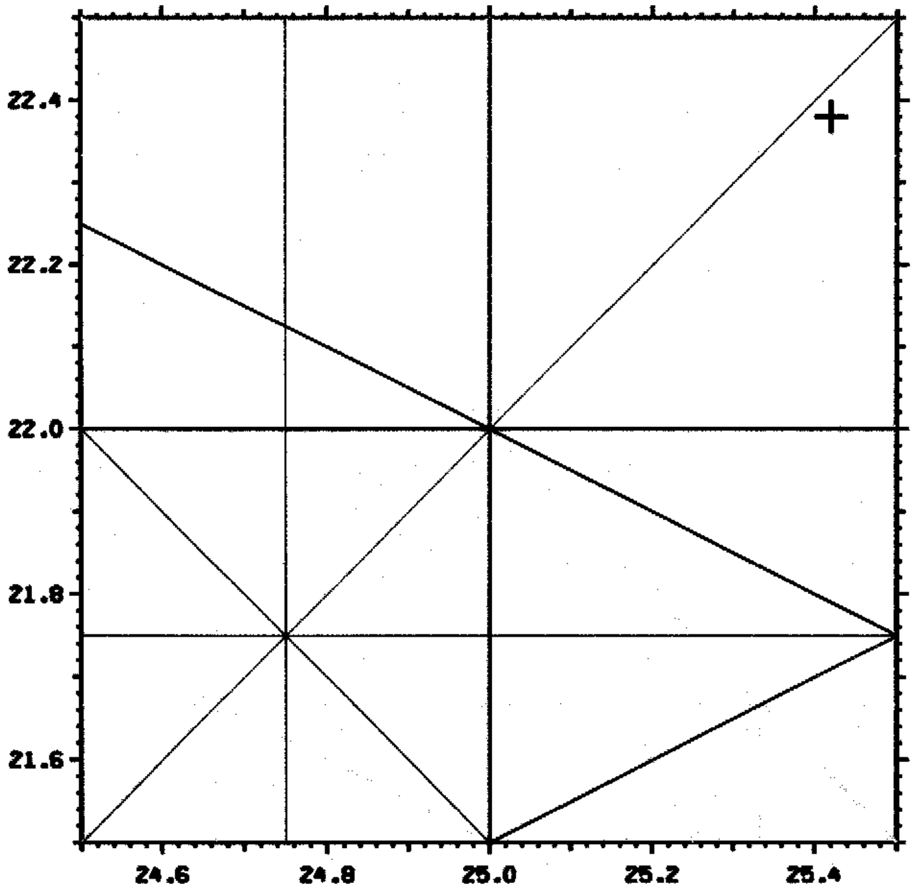
Dipoles are blue

Quadrupoles are red

Transition-Less 3-sided Lattice Functions (1/3 of the Ring)



Transition-less 3-sided Lattice Tune Diagram



Structural resonances are in color

The only structural resonance near the operating point is

$2\nu_x - 2\nu_y = 6$

MI Dipole Error Multipoles at injection
1 part in 10^4 at 1 inch (used for all three rings)

Harmonic Number	Normal Systematic	Skew Systematic	Normal Random	Skew Random
1	0.737	-	10.251	-
2	0.06	-	0.8	-
3	-0.6	0	0.18	0.12
4	0.04	0.03	0.06	0.03
5	0.33	0	0.05	0.05
6	-0.01	-0.03	0.05	0.04
7	-0.03	0	0.05	0.05

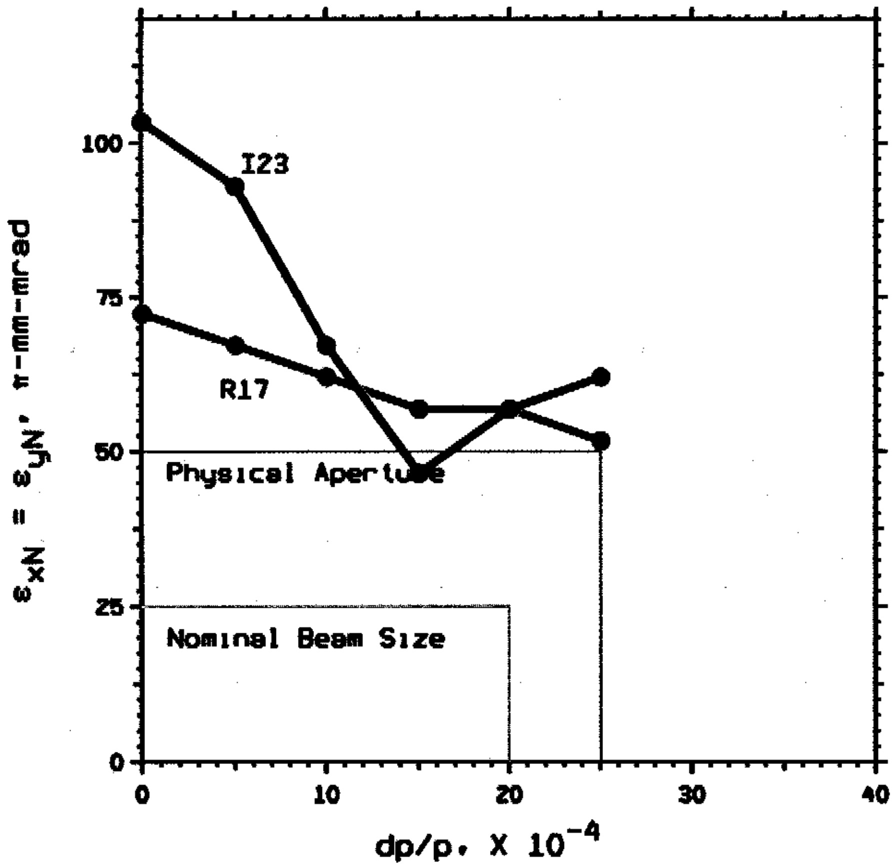
Original MI Quadrupole Error Multipoles at injection - 1 part in 10^4 at 1 inch (used for 50 GeV ring and scaled for 4 GeV)

Harmonic Number	Normal Systematic	Skew Systematic	Normal Random	Skew Random
2	-	-	24	-
3	-0.51	1.08	2.73	1.85
4	1	-2.05	1.02	2.38
5	0.03	-0.75	1.12	0.47
6	-1.49	0.43	0.63	0.70
7	0.21	-	0.64	0.44
8	1.14	-	0.64	-
9	-0.19	-0.07	0.12	0.16
10	-0.77	-0.12	0.06	0.07

New AHF Quadrupole Error Multipole at injection - 1 part in 10^4 at 1 inch (used for 50 GeV ring and scaled for 4 GeV)

Harmonic Number	Normal Systematic	Skew Systematic	Normal Random	Skew Random
2	0	-	12	-
3	0.2	0.3	1	1
4	-0.5	0.1	1	0.3
5	-0.1	-0.1	0.15	0.1
6	0.4	-0.1	0.1	0.1
9	-	-	-	-
10	-	-	-	-

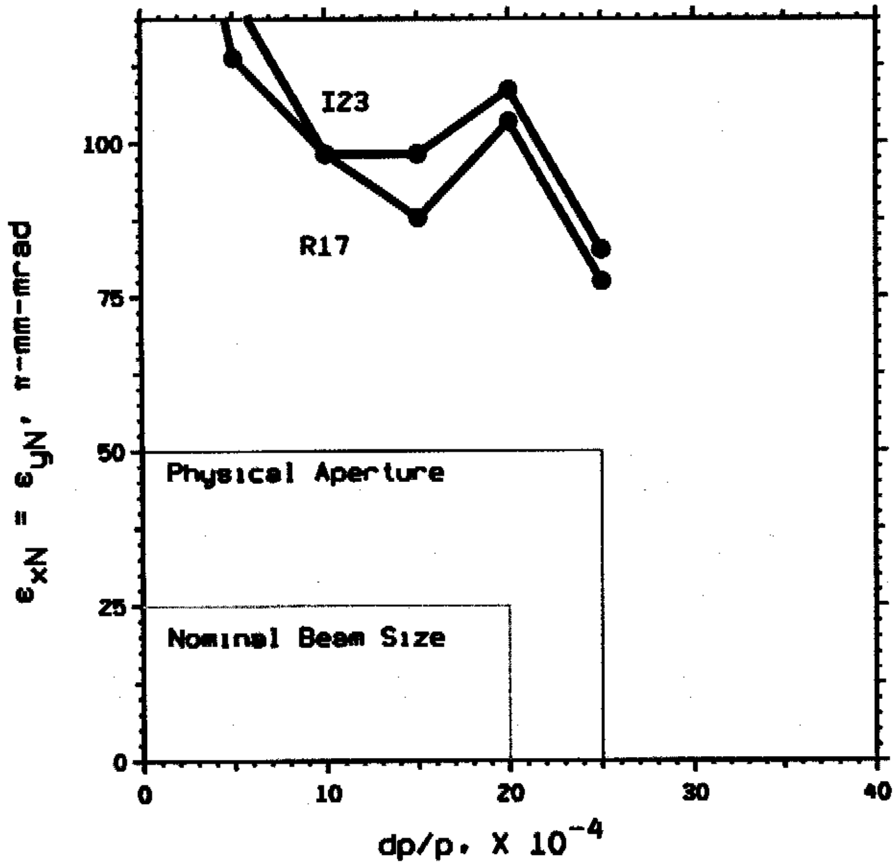
Both Main Ring Dynamic Apertures at 4 GeV (MI Quad errors) Conventional 4-sided in blue - Transitionless 3-sided in red



Using FNAL MI quadrupoles the dynamic aperture is barely sufficient

Chromaticity corrected to -6 for both rings

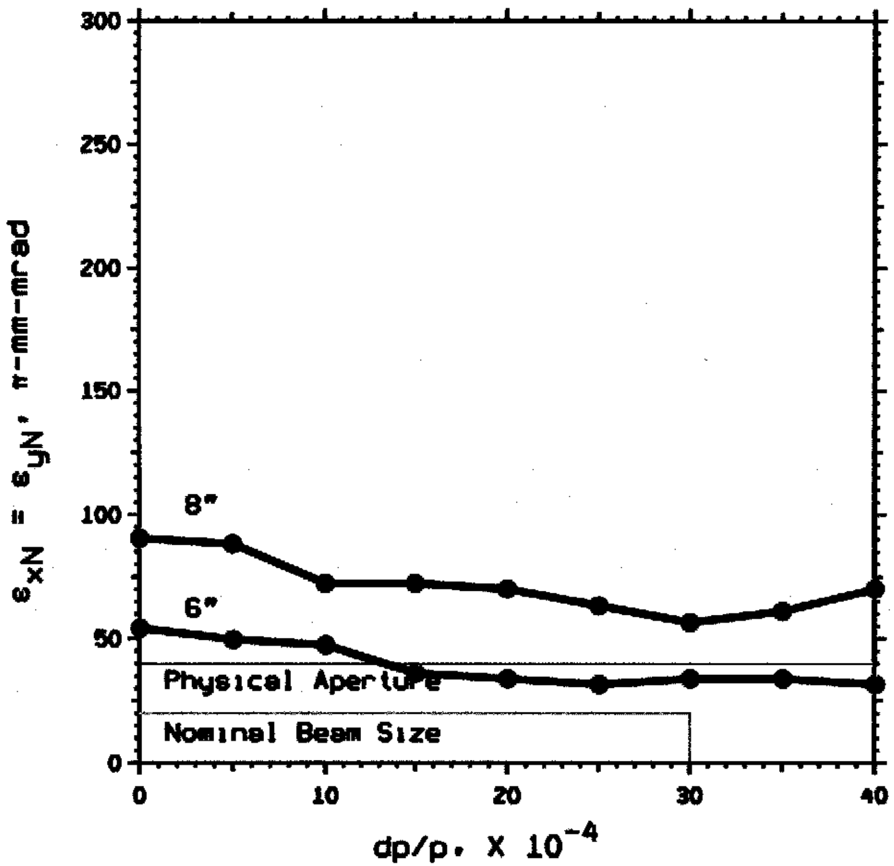
Both Main Ring Dynamic Apertures at 4 GeV with New Errors Conventional 4-sided in blue - Transitionless 3-sided in red



The dynamic aperture is comfortably larger than the physical aperture

Chromaticity corrected to -6 for both rings

4 GeV Booster Dynamic Aperture at 140 MeV with MI Errors
6 in Quads shown in blue - 8 in Quads shown in red



Quadrupoles error multipoles scaled from FNAL MI quadrupoles

Shown are the results for two different quadrupole diameters

Insufficient dynamical aperture in the 6" case

Scaling Multipole Errors

- **When comparing magnets of different apertures the errors are assumed to be the same at a radius proportional to the magnet size**

- **The error multipole at different radii are related as**

- $$b_m(R) = (R/r)^{(m-1)}\, b_m(r)$$

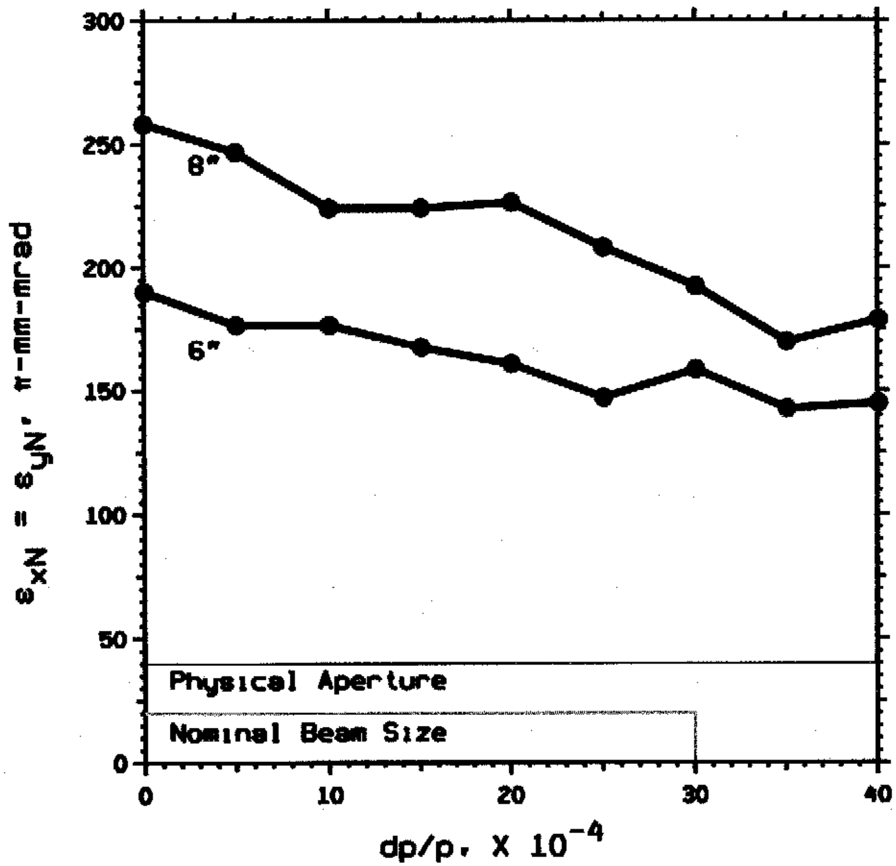
  - **Here $b_m(R)$ and $b_m(r)$ are the errors as a fraction of the main field at R and r and m is the harmonic number.**

- **For quadrupoles the relation is**

- $$b_m(R) = (R/r)^{(m-2)}\, b_m(r)$$

  - **Because the scaling is with respect to the quadrupole field at the same radius.**

4 GeV Booster Dynamic Aperture at 140 MeV with New Errors 6 in Quads shown in blue - 8 in Quads shown in red

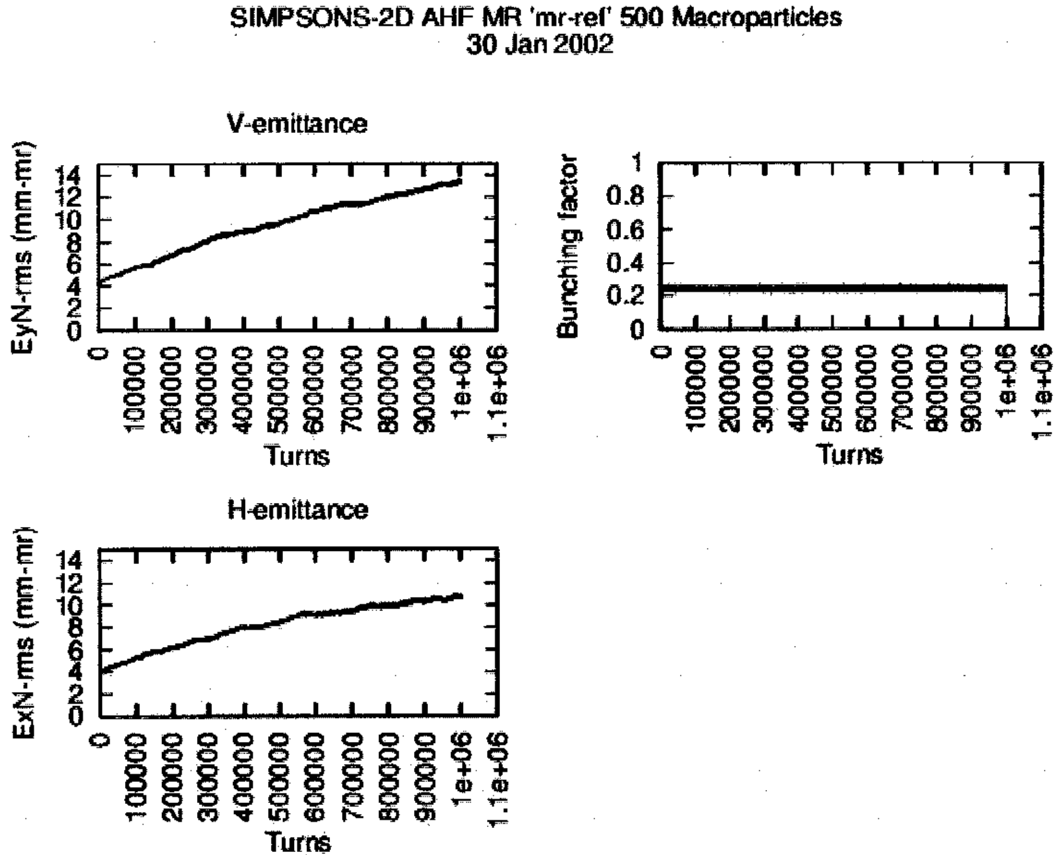


- Quadrupoles error multipoles scaled from AHF main ring quadrupole error requirements
- Shown are the results for two different quadrupoles diameters
- Dynamic apertures seems dominated by dipoles (not much different for larger quadrupoles)
- The dynamic apertures is much larger than the physical aperture

Space-Charge Studies

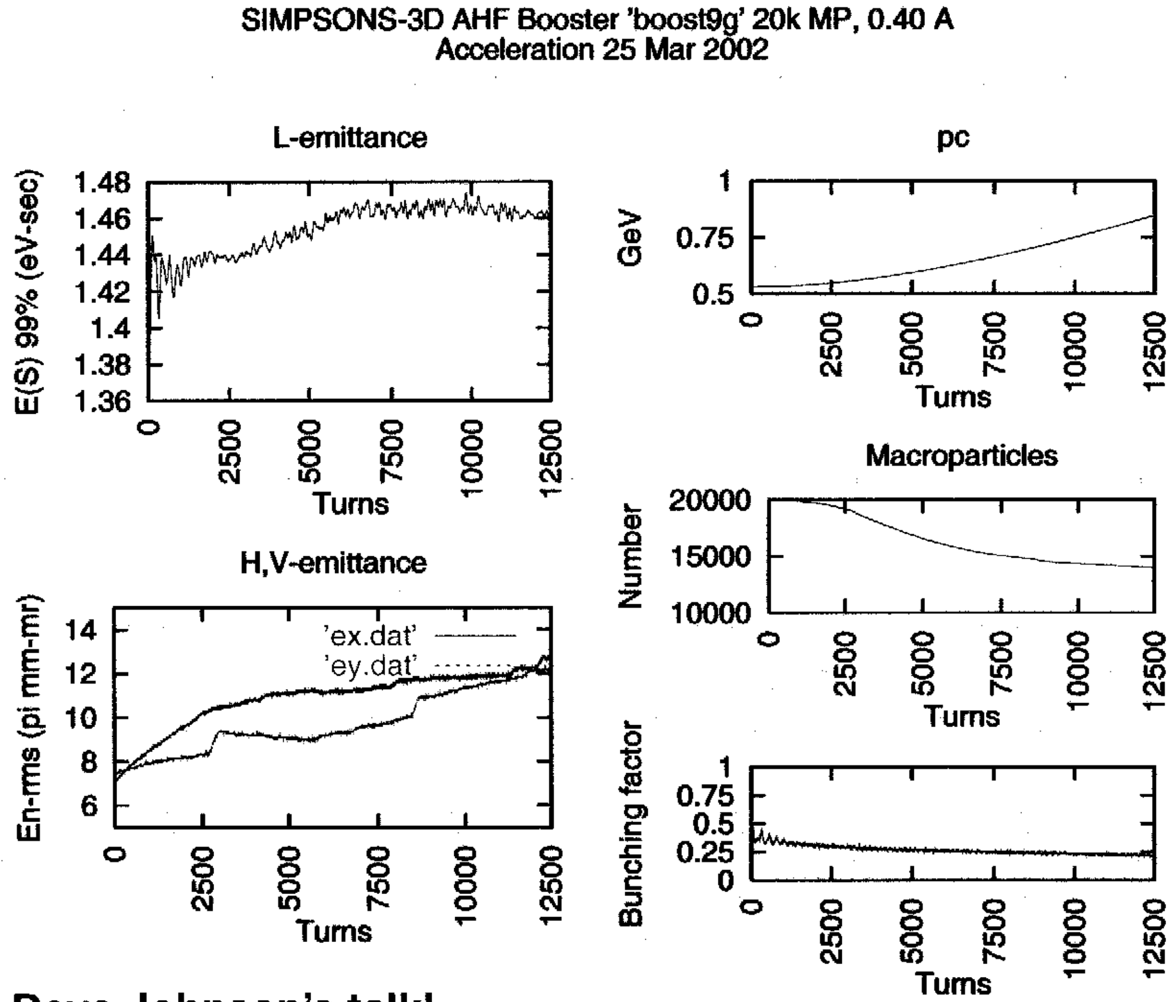
- The studies presented do not include the effect of space-charge
- Space-charge effects are important
  - At injection and parabola in the booster
  - During accumulation in the main ring (1000000 turns at tune shift of ~0.2)
- Preliminary studies use the code Simpson (from S. Machida)
  - Simpson is based on TEAPOT
  - Simpson includes the effect from magnet errors, correctors and space-charge
  - Both 2D and 3D versions exist
  - 3D version not extensively tested
  - 3D version can do acceleration
- One Million turn runs now possible (see next slide)
  - Only 2D model used
  - 3D version only used for booster for now, but results are encouraging

Million-Turn Simulation of Conventional 50 GeV Main Ring at injection - no particle loss was observed



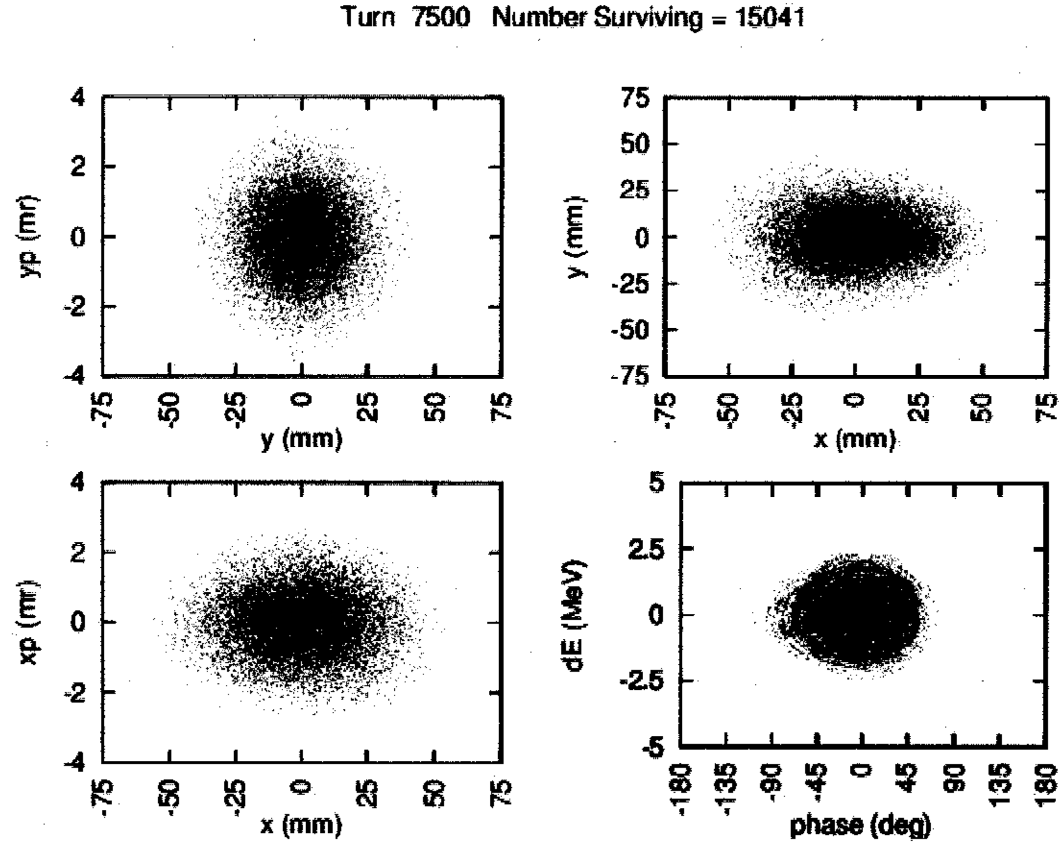
The emittance growth observed is possibly spurious, but not one particle was lost!

3D Simulation of 4 GeV Booster at injection including beginning of parabola - emittance growth



See Dave Johnson's talk!

3D Simulation of 4 GeV Booster at injection including beginning of parabola - phase-space



See Dave Johnson's talk!

Conclusions

- **The two main ring designs have comparable transverse acceptances**
  - **Final choice between them depends on longitudinal phase-space and cost considerations**
- **FMI Dipoles give a sufficient dynamic aperture**
- **Need smaller error multipoles than in FNAL Main Injector quads**
- **Booster needs better field than scaled from MI**
  - **Same conclusion as for the main ring**
- **New requirements on quadrupole errors give sufficient dynamic aperture**
  - **Same conclusions for booster (when errors are scaled appropriately)**
  - **Magnets can be built to meet the requirements** (see M Schulze talk)