LBNL/SLAC Ring and Lattice Issues

Yunhai Cai

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In collaboration with John Byrd, Alex Chao, Yuri Nosochkov, Uli Wienands, and Frank Zimmermann

Luminosity

- Bunch luminosity

$$L_b = f_{rev} \frac{N_b^2}{4\pi\sigma_x\sigma_y} R_h$$

where R_h is a geometrical reduction from the hourglass effect and is written as

$$R_h = \sqrt{\frac{2}{\pi}} a e^{a^2} K_0(a^2), a = \frac{\beta_y^*}{\sqrt{2}\sigma_z}$$

- Total luminosity

$$L = n_b L_b$$

Beam-Beam Limit

- Given the beam-beam parameter

$$\xi_y = \frac{r_e N_b \beta_y^*}{2\pi\gamma\sigma_y(\sigma_x + \sigma_y)}$$

The luminosity can be re-written as

$$L = \frac{cI\gamma\xi_y}{2r_e^2 I_A \beta_y^*} R_h$$

where I_A=17045 A. Smaller β_y* is absolutely necessary. For example, in our design we have I=7.2 mA, E_0=120 GeV, ξ_y=0.07, R_h=0.76, β_y*=1mm, gives 1×10^{34} $cm^{-2}s^{-1}$ in luminosity. So what is the beam-beam limit for Higgs factory?

LEP2 Experience

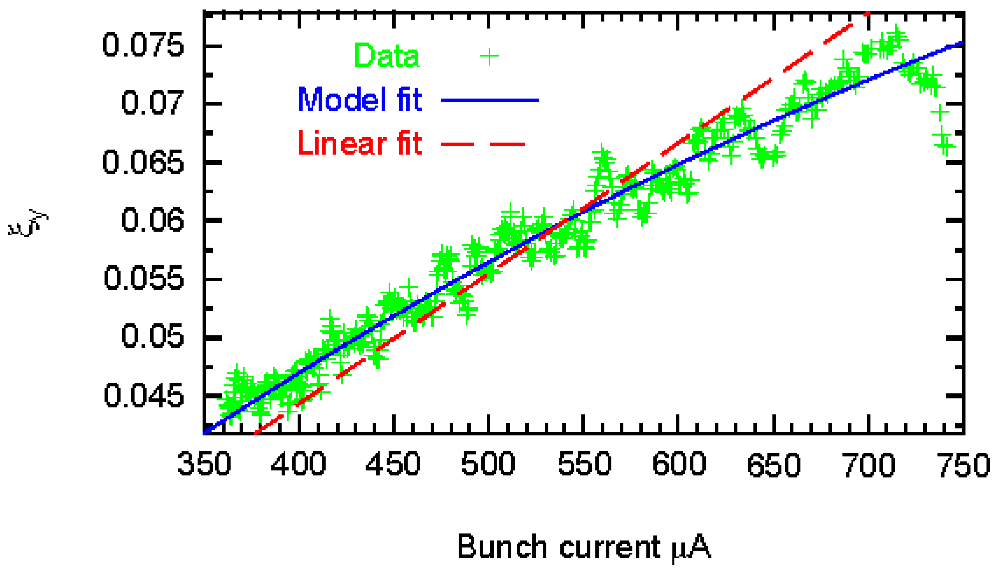


Figure 1: Measured ξ_y at 94.5 GeV versus bunch current. The data is fitted with ("Model fit") and without ("Linear fit") beam-beam limitation.

R. Assmann and K. Cornelis, Proceeding of EPAC 2000, Vienna, Austria

Power Limitation

- Synchrotron radiation

$$U_0 = \frac{4\pi}{3} \frac{r_e mc^2}{\rho} \gamma^4$$

- Beam power given by RF

$$P_b = U_0 I / e$$

- Limits the total beam current I

For example, E_0=120 GeV, ρ=2.6 km, U_0=6.97 GeV, I=7.2 mA, lead to P_b=50 MW in our design.

Scaling of Luminosity

- If there is a beam-beam limit as suggested by the simulation and beam power is also limited, the luminosity can be re-written as

$$L = \frac{3c}{8\pi r_e^3} \frac{\xi_y \rho}{\gamma^3 \beta_y^*} \frac{P_b}{P_A} R_h$$

where $P_A = mc^2 I_A / e = 8.7$ GW. This scaling was first given by B. Richter, Nucl. Instr. Meth. 136 (1976) 47-60.

Beamstrahlung Effects

- Beam lifetime due to large single photon emission (for 30 minutes, V.I. Telnov, 2012)

$$\frac{N_b}{\sigma_x \sigma_z} < 0.1\eta \frac{\alpha}{3\gamma r_e^2}$$

- Large RF-buckets and large momentum aperture η
- Large σ_z and σ_x. Favors longer and larger horizontal beam size.
- Limits bunch population N_b

Are there any reasonable solutions?

Analysis of Design Constraints

- To achieve the beam-beam parameter and assuming $\beta_y=\kappa_\beta\beta_x$ and $\varepsilon_y=\kappa_\varepsilon\varepsilon_x$ we have

$$\frac{N_b}{\varepsilon_x} = \frac{2\pi\gamma\xi_y}{r_e}\sqrt{\frac{\kappa_e}{\kappa_\beta}}$$

- To have adequate beam lifetime (due to beamstrahlung)

$$\frac{N_b}{\sqrt{\varepsilon_x}} < 0.1\eta\frac{\alpha\sigma_z}{3\gamma r_e^2}\sqrt{\frac{\beta_y^*}{\kappa_\beta}}$$

- Clearly, smaller coupling κ_e is better and larger momentum acceptance η is better but they have their own limits.

Solution of the Constraints

- Given a momentum acceptance η, we solve

$$\varepsilon_x < (\frac{0.1\eta\alpha\sigma_z}{6\pi\gamma^2\xi_y r_e})^2 \frac{\beta_y^*}{\kappa_e}$$

Note that it does not depends on $\kappa_{\beta.}$ We can use κ_β to adjust the bunch population N_b or the number of bunches n_b. Clearly, there are many possible solutions. But is there any self-consistent one?

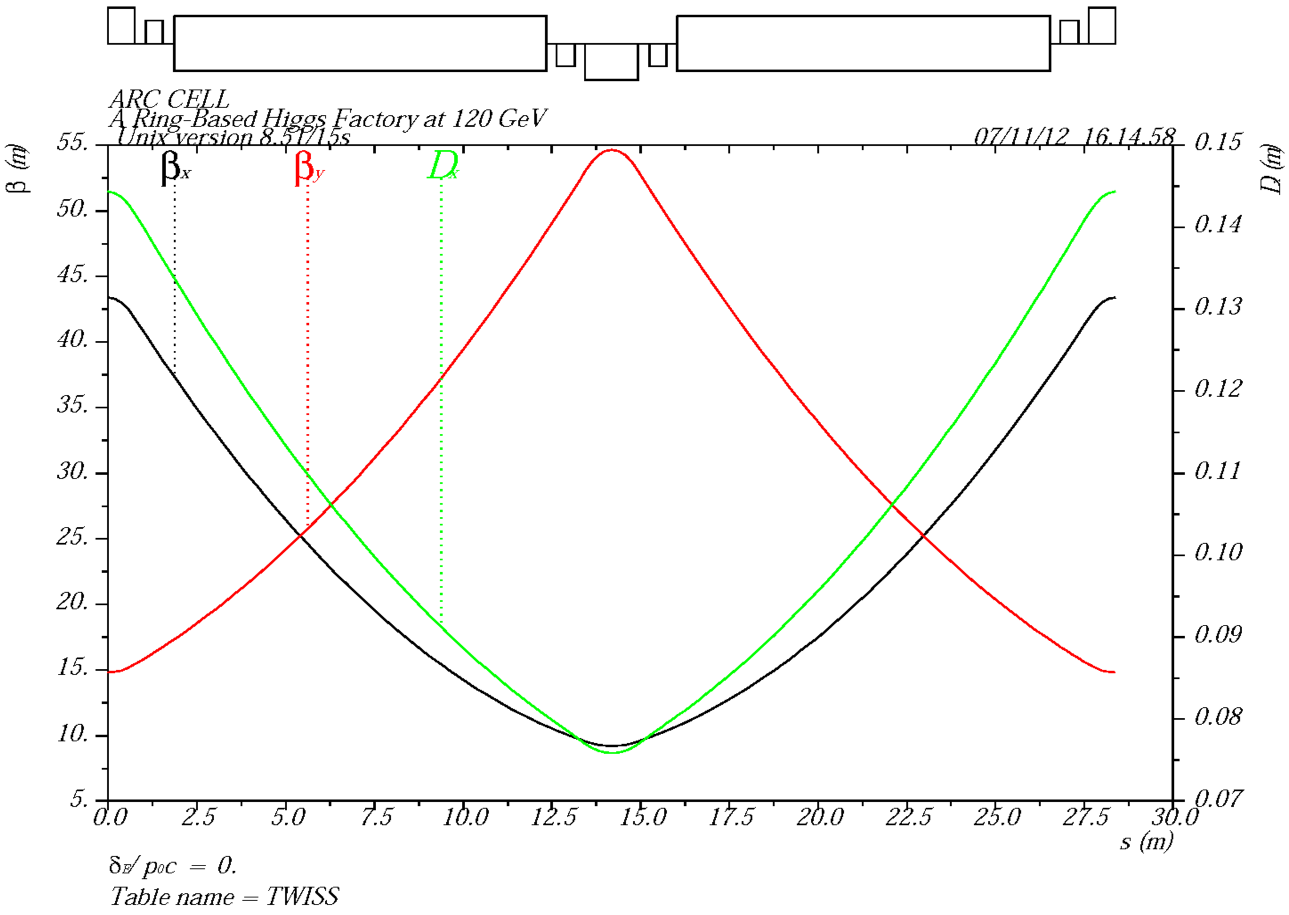
- The requirement of accommodating beamstrahlung is translated to design a low emttance lattice.

- Normally, the emittance scales as γ^2. This relation requires a scaling of γ^{-4}, indicating a difficulty to design a machine with much higher energy than 120 GeV.

LBNL/SLAC Design Parameters

	LEP2	LBNL/SLAC Design
Beam Energy [GeV]	104.5	120
Circumference [km]	26.7	26.7
Beam current [mA]	4	7.2
Number of bunches	4	50
Bunch population [10^{10}]	57.5	8.0
Horizontal emittance [nm]	48	4.3
Vertical emittance [nm]	0.25	0.0215
Momentum compaction factor	18.5×10^{-5}	2.4×10^{-5}
β_x^* [mm]	1500	50
β_y^* [mm]	50	1
Hourglass factor	0.98	0.76
SR power [MW]	11	50
Bunch length [mm]	16.1	1.5
Beam-beam parameter	0.07	0.07
Luminosity [10^{34} cm^{-2}s^{-1}]	**0.0125**	**1.01**

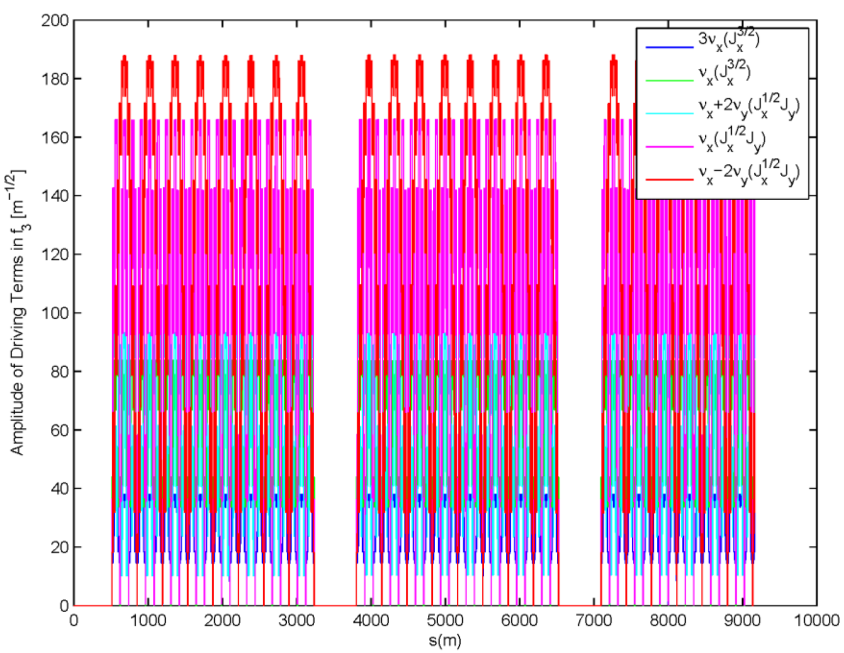
90^0/60^0 Arc Cell



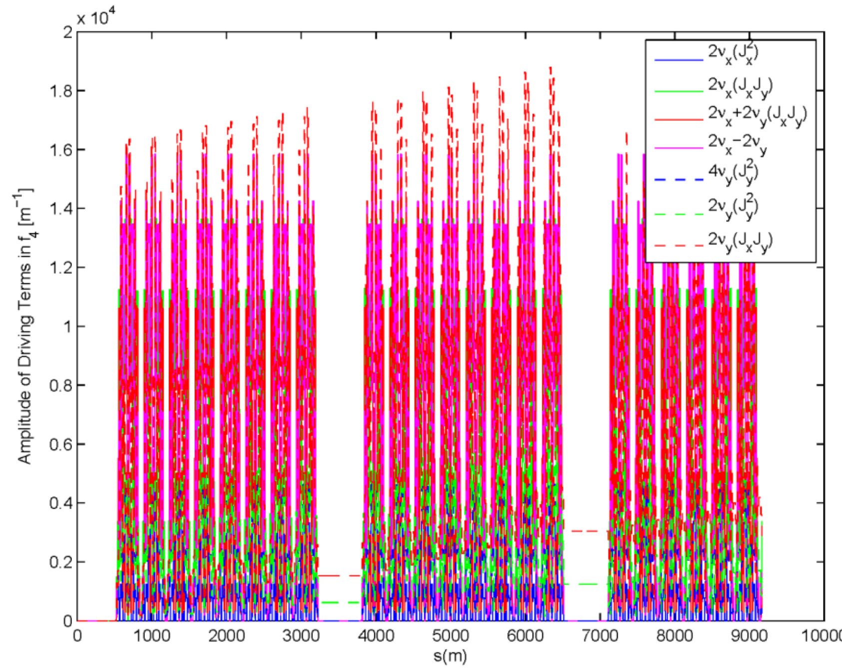
12 cells make an achromat (unit transformation).

Quasi (4^{th} Order) Achromat

3^{rd} order driving terms



4^{th} order driving terms

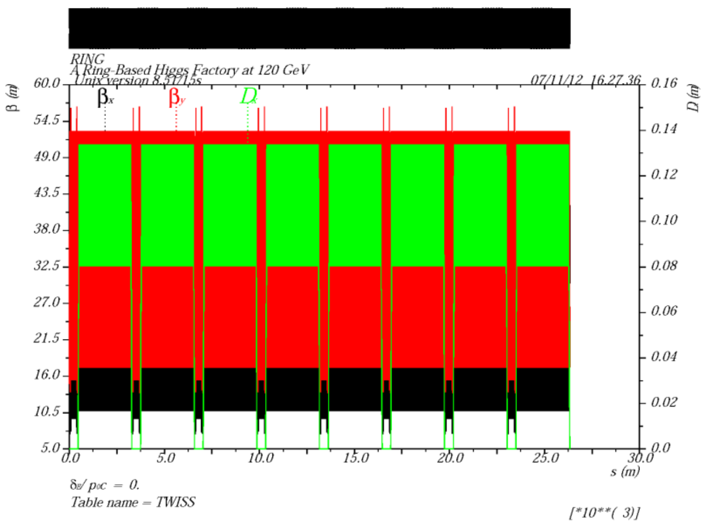


The cancellation occurs in every 12 cells in arcs.

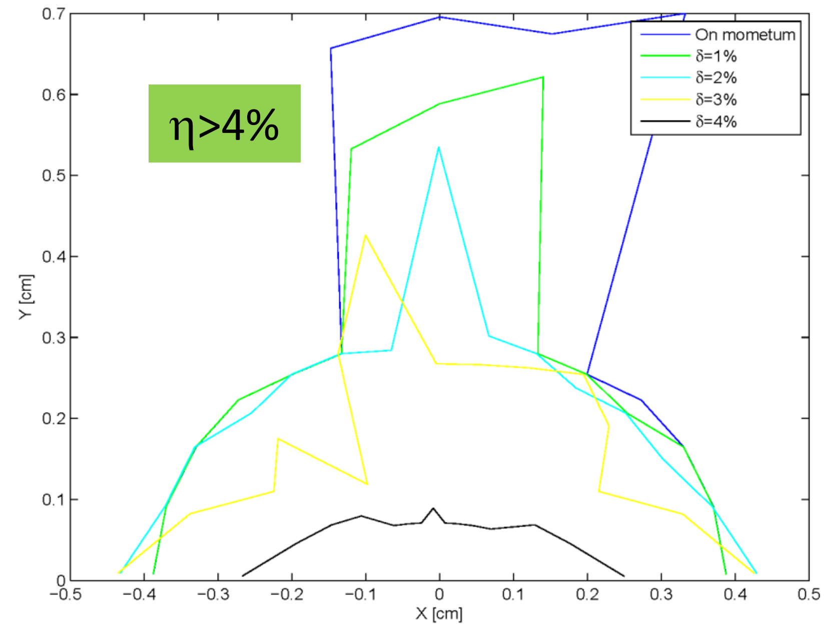
Only non-vanishing resonance is $4\nu_x$.

Arc Design

$90^0/60^0$ FODO Lattice



Dynamic/Momentum Aperture



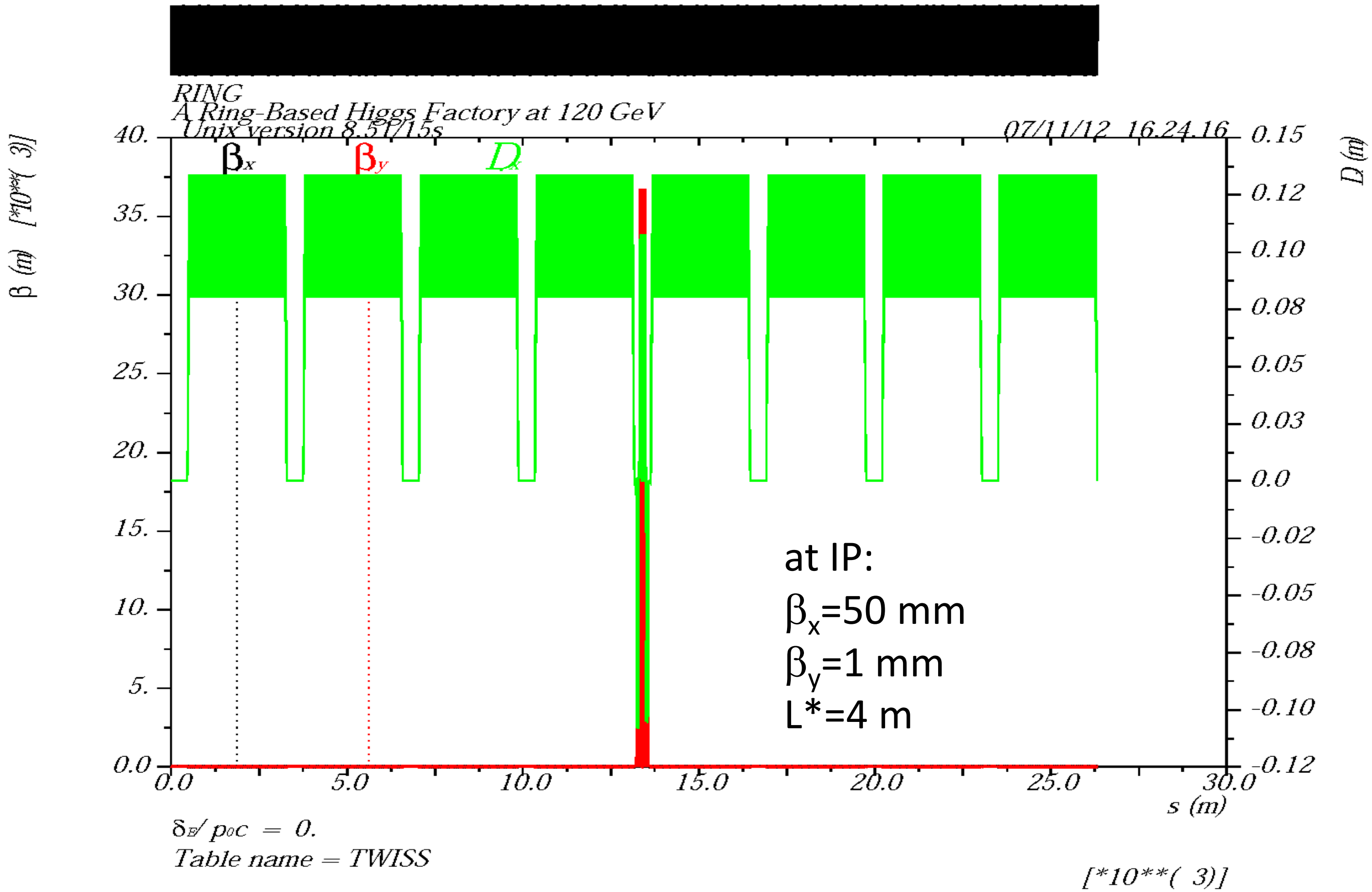
Emittance:

$$\varepsilon_x = F_c \frac{C_q \gamma^2}{J_x} \theta^3$$

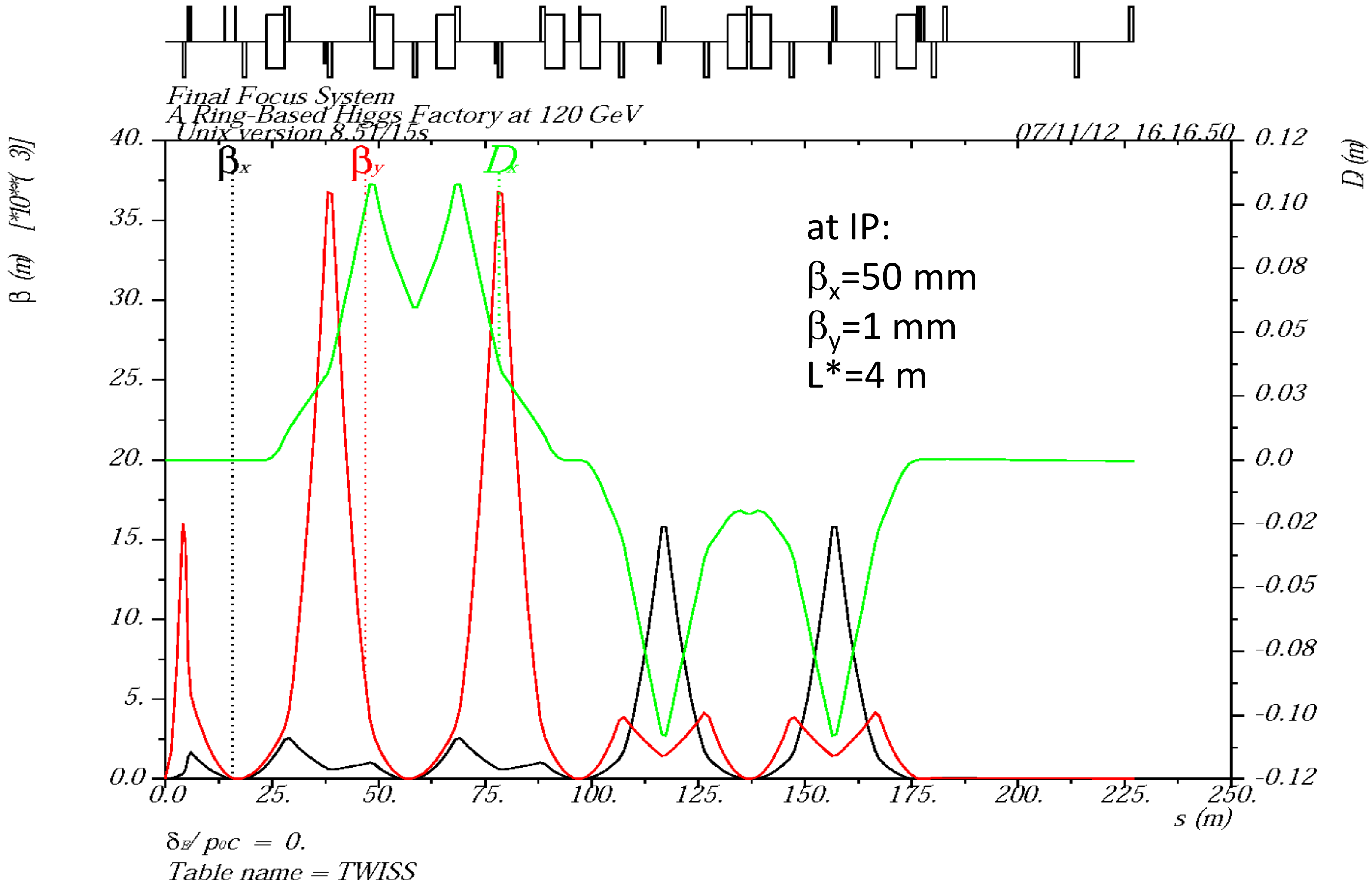
where θ is the bending angle in a cell.

Natural emittance: ε_x=4.3 nm and cell length is 28.375 m

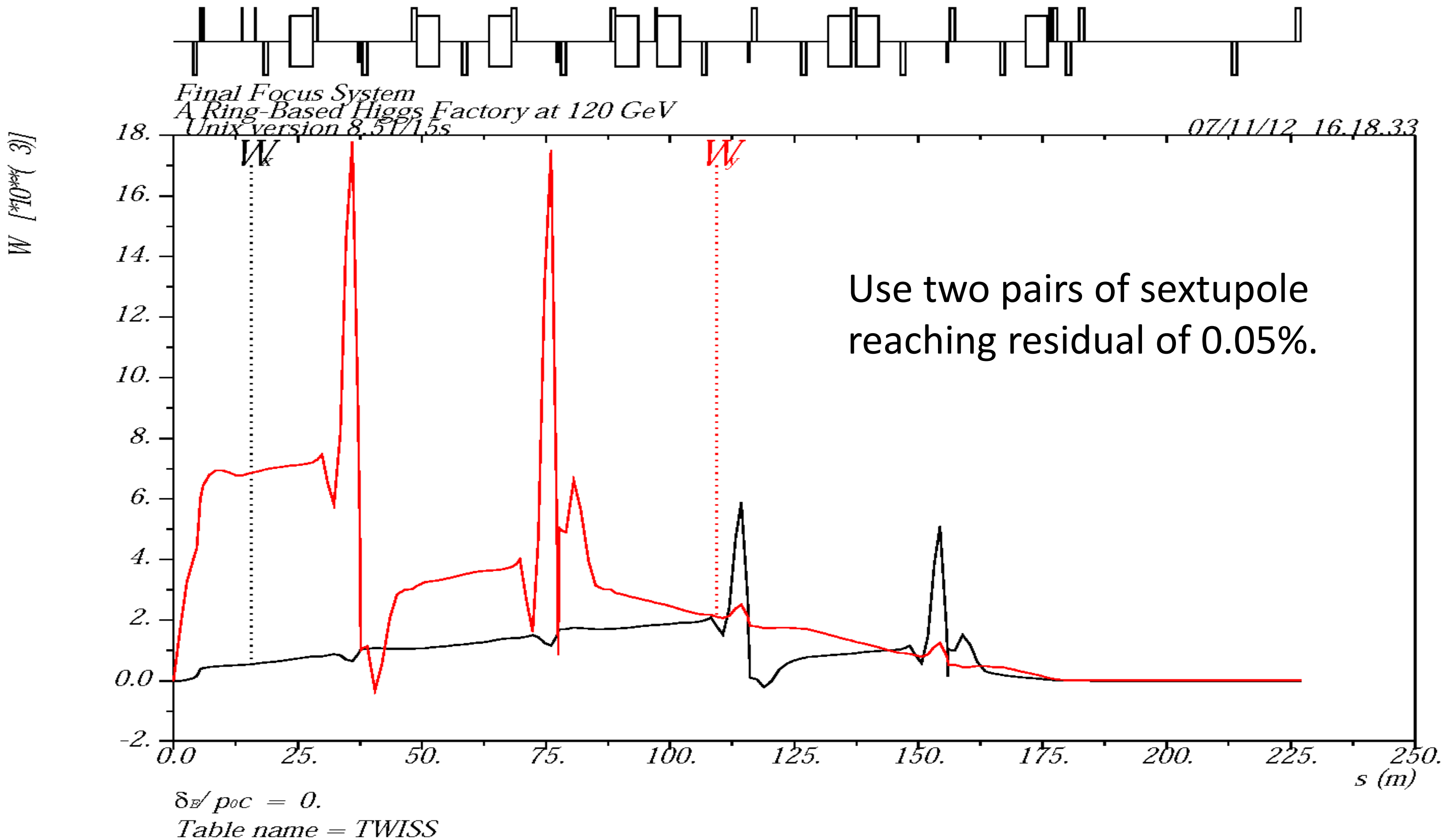
Lattice of Collider Ring



Final Focus System

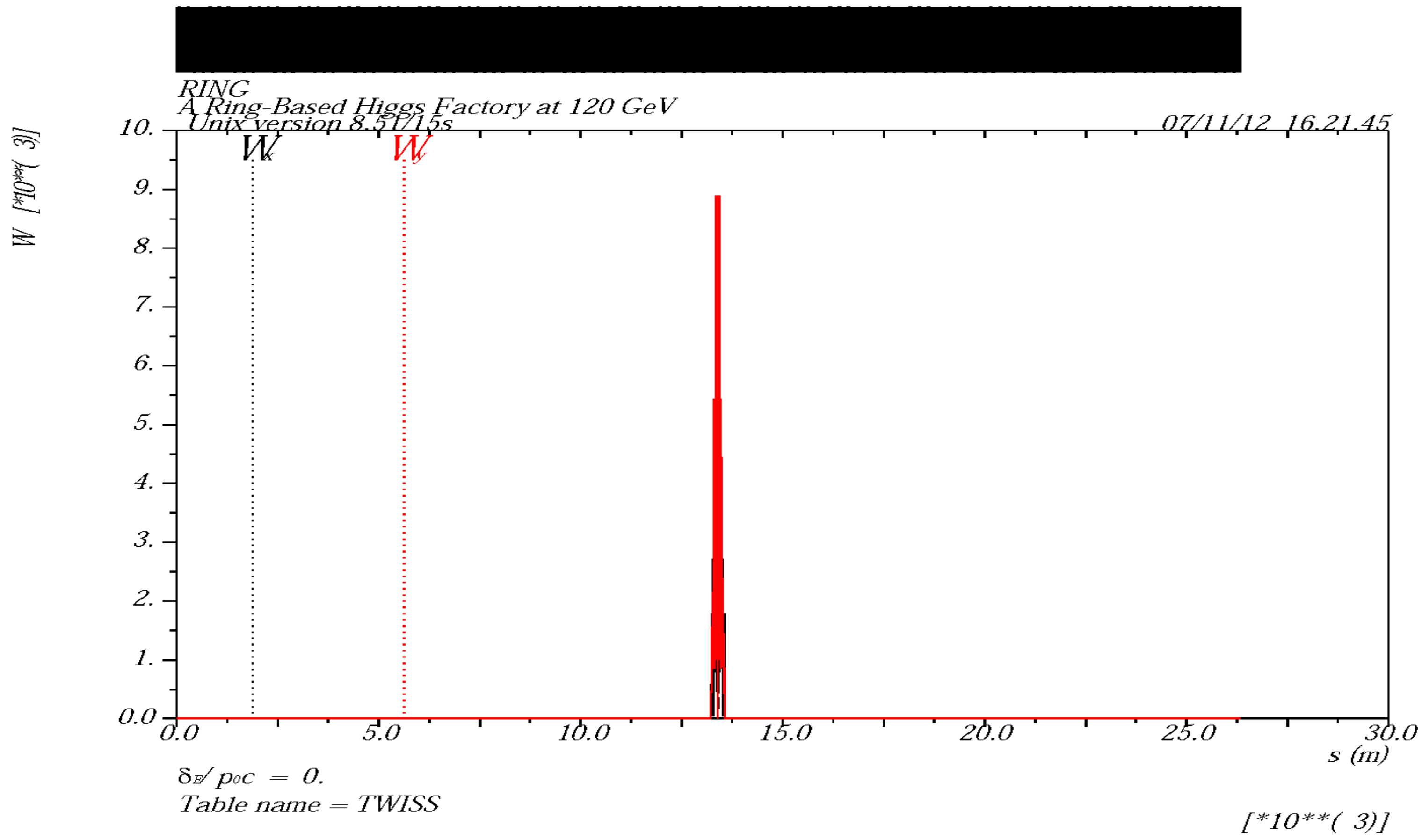


Local Chromatic Correction



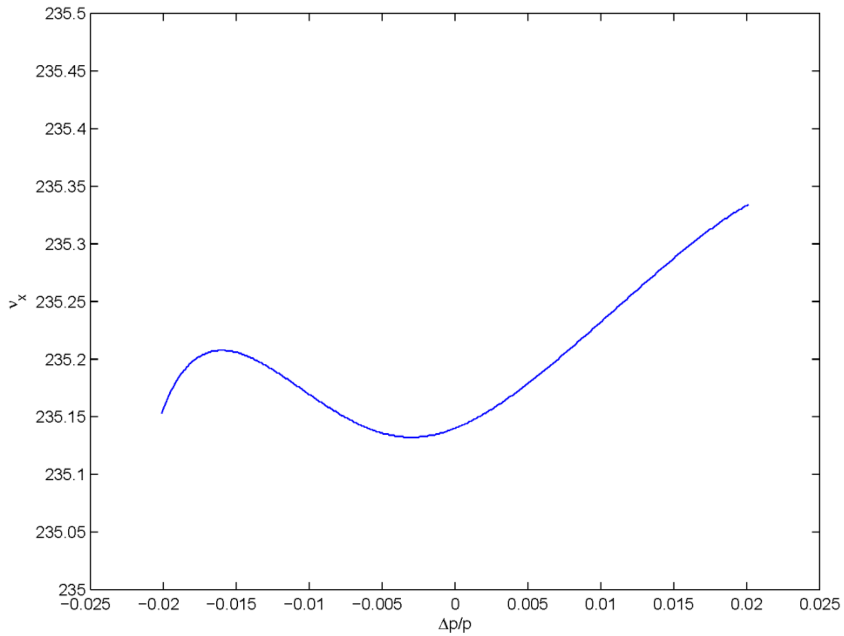
Use two pairs of sextupole reaching residual of 0.05%.

Chromatic Beating in Collider Ring

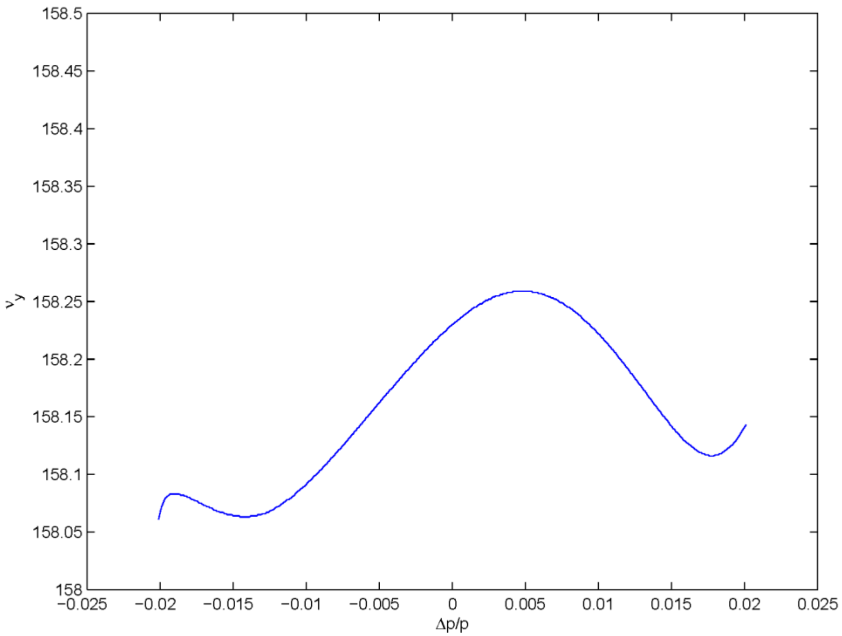


Betatron Tune vs. Momentum

Horizontal



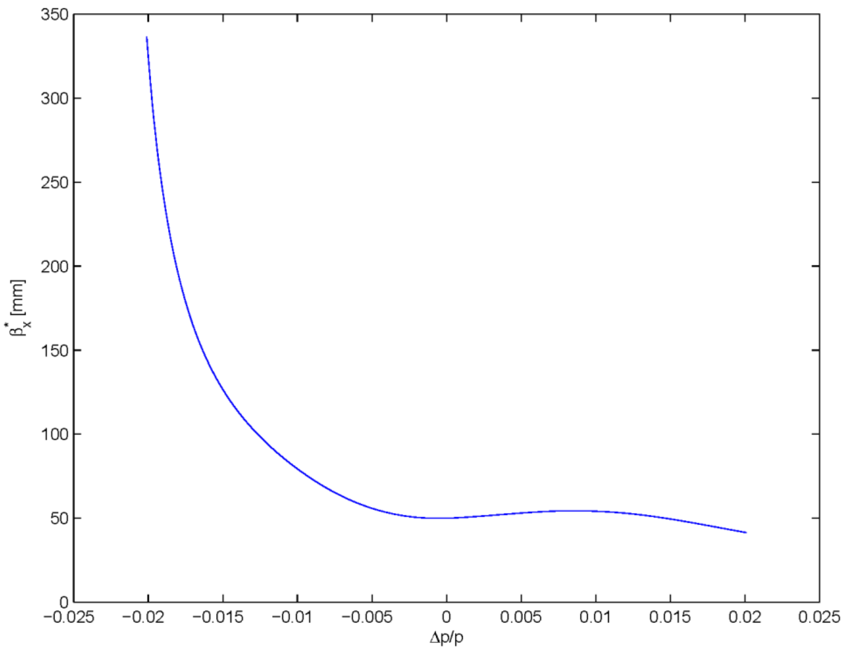
Vertical



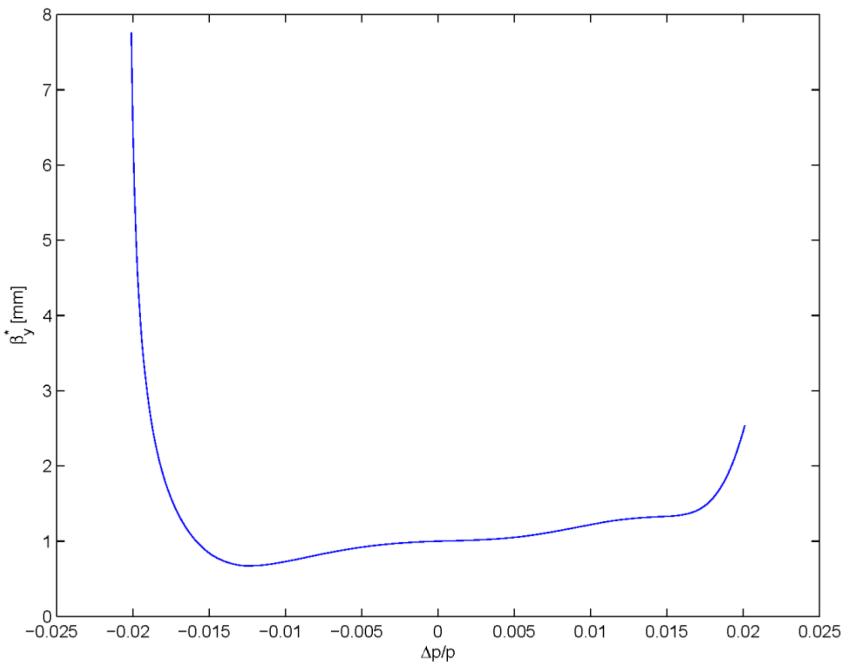
Four families of sextupole used in the optimization, achieving ±2% momentum bandwidth.

Beta Functions at IP vs. Momentum

Horizontal

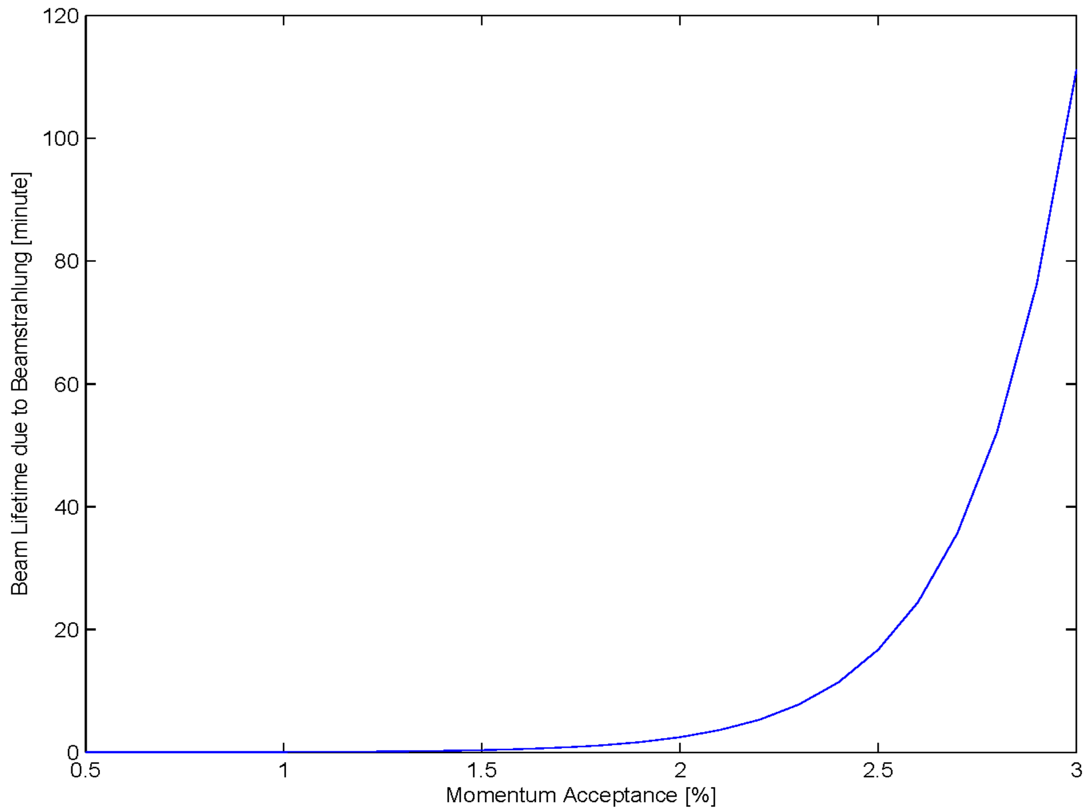


Vertical



Good region of ±0.4% in Δp/p is necessary for the core in beam distribution.

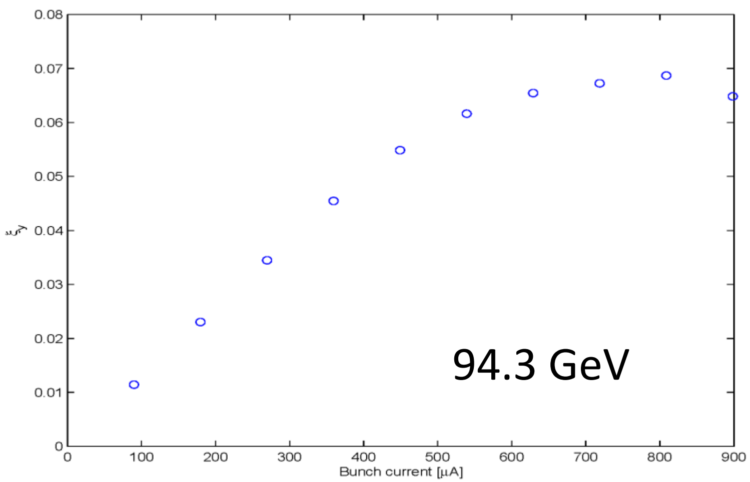
Beam Lifetime due to Beamstrahlung



Estimate for LBNL/SLAC ring based on Telnov's paper.

Benchmark of Beam-Beam Code

3D PIC Simulation (BBI)



Parameters provided by
Frank Zimmermann
Helmut Burkhardt

http://hbu.web.cern.ch/hbu/BeamDyn/LEP.html

ε_y=0.19 nm, without beam-beam perturbation

Measurement

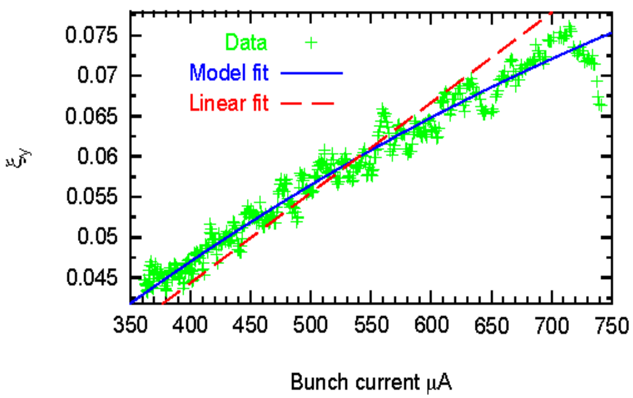


Figure 1: Measured ξ_y at 94.5 GeV versus bunch current. The data is fitted with ("Model fit") and without ("Linear fit") beam-beam limitation.

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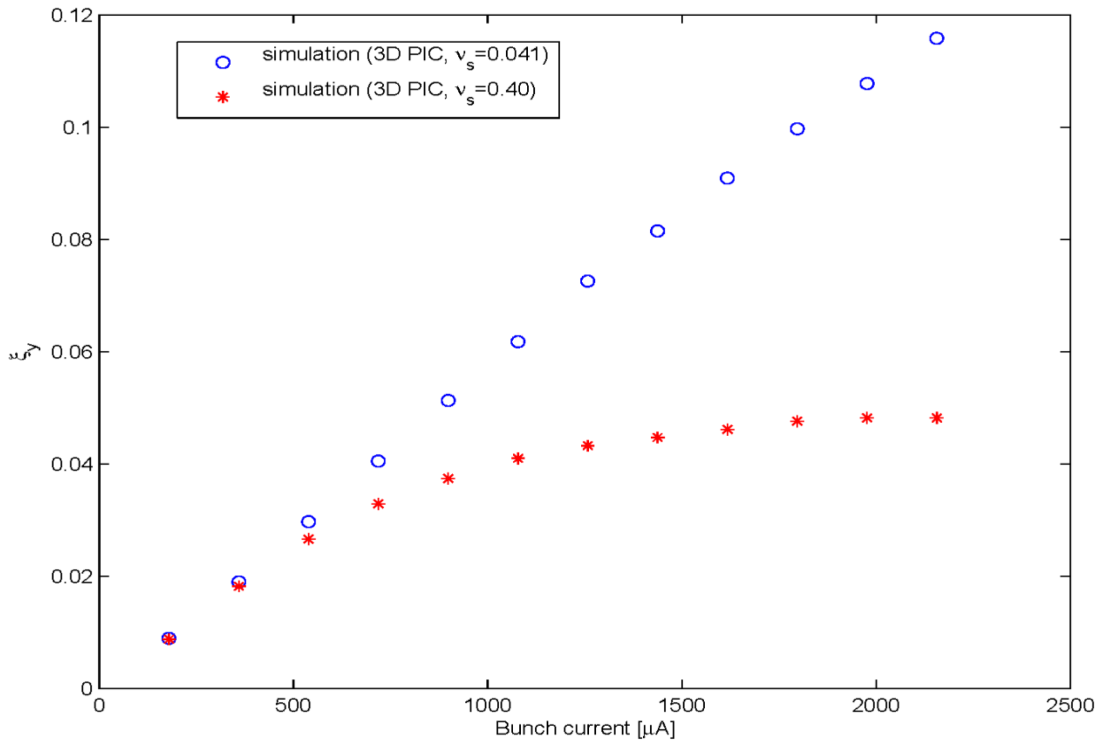
Beam-Beam Simulation
(LEP3, Frank Zimmermann's parameters)



Beam-beam limit can be as low as 0.05 if synchrotron tune is too high, even with very strong radiation damping.

Longitudinal Dynamics

- Synchrotron tune:

$$\nu_s = \sqrt{\frac{h\alpha_p}{2\pi}\frac{eV_{RF}}{E_0}\cos\phi_s}$$

to lower ν_s one wants lower RF frequency and momentum compaction factor. This also makes RF bucket height

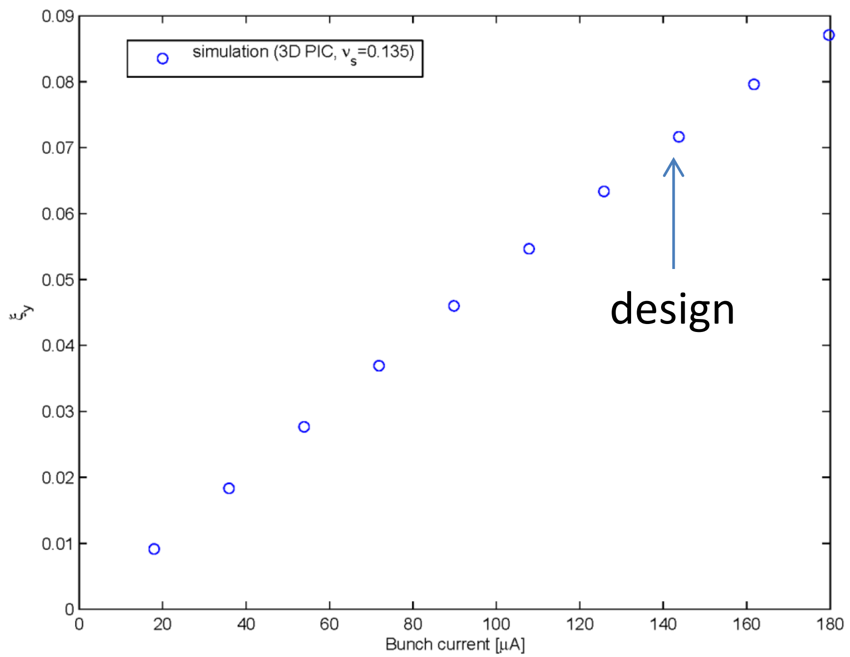
$$\delta_{RF,\max} = \sqrt{\frac{F(q)U_0}{\pi h\alpha_p E_0}}$$

larger and allows a larger momentum acceptance.

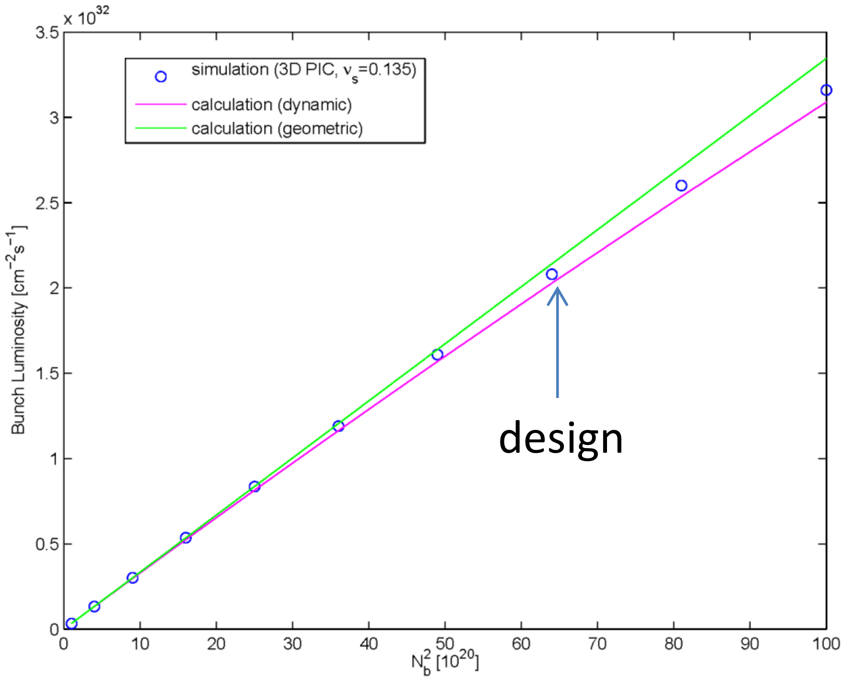
Beam-Beam Simulation

LBNL/SLAC Design (f_{RF}=700 MHz and α_p=2.4x10^{-5})

Beam-beam parameter



Bunch luminosity



There is no surprise. It simply confirms calculations.

Lattice Issues

- Ultra-low beta (1mm) IR design with large momentum bandwidth (3%)
- Low emittance lattice and ultra-low beta IR with adequate dynamic aperture (10 σ)
- Large synchrotron radiation, saw-tooth (1-2%) in arcs of two beams in single ring
- Machine tolerances, especially alignment tolerance and orbit stability

Risks & Mitigations & RD Items

- Ultra-low beta* with large energy bandwidth in ring

  β_y*=1 mm and η > 3% (lower emittance)
- RF parameters: frequency, voltage, gradient?

  What's length is necessary for RF system

  (f_{RF}=700 MHz and V_{RF}=12 GV) ?

  is HOM a problem?
- What is the shortest bunch we can make?

  Coherent synchrotron radiation, heating
- What is energy reach of ring? How large is can be?

  How about 80 km?

Summary

- Impact on design due to beamstrahlung is analyzed. We found a formula of minimum natural emittance that is necessary for beam lifetime.
- A systematic design procedure is outlined. There are many possible solutions. The final choice should be to made with other considerations, including the interaction region design.
- We have achieved 2% momentum bandwidth in a lattice with an ultra-low beta interaction region