A Very Low Emittance Damping Ring for ILC

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May 26, 2006

Acknowledgment

- The design was initialized under the instruction of Shekhar Mishra (FNAL) and George Gollin (UIUC).
- The work has been benefited a lot from inspiring discussions with Louis Emery, Vadim Sajaev and Andy Wolski (Daresbury, UK).
- Special thanks to Kwang-Je Kim, Michael Borland and Jean Slaughter (FNAL) for their strong encouragement and support.

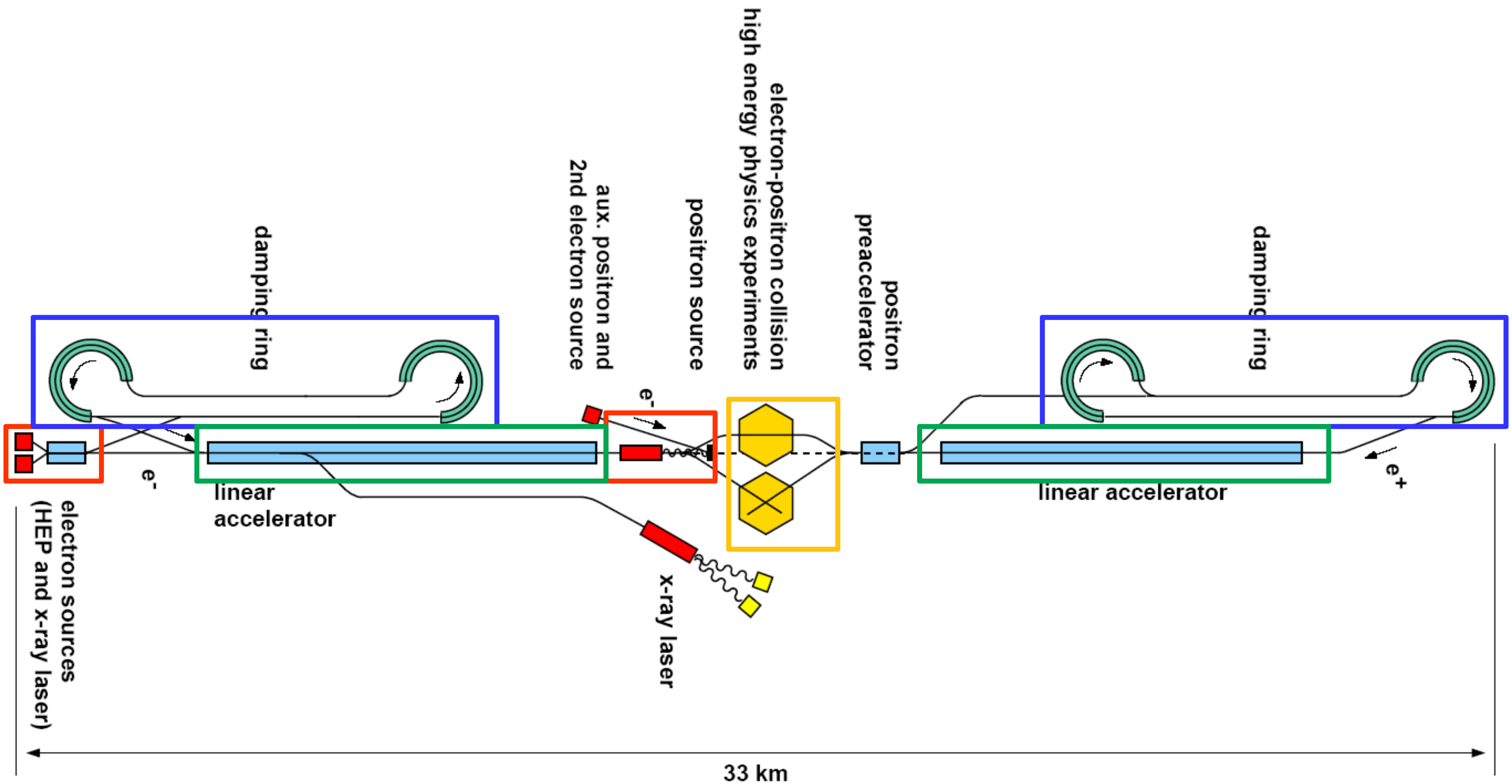
History of International Linear Collider

- Linear Collider has been studied for more than a decade
- Two major technologies were pursued in the past for building Linear Collider
  - Normal conducting accelerating structure
  - Superconducting accelerating structure
- Decision had to be made to maximizes the benefit from limited research resources

Superconducting technology was chosen by ITRP at August 2004

- GDE (Global Design Effort) committee requires:
  - Baseline design configuration recommendation to be finished by 2005.
  - A Reference Design Report has to be finished by 2006.
  - A Technical Design Report has to be finished by 2009.

TESLA – TDR



damping ring
aux. positron and
2nd electron source
positron source
high energy physics experiments
electron-positron collision
positron
preaccelerator
damping ring
e-
e-
e+
linear
accelerator
linear accelerator
electron sources
(HEP and x-ray laser)
x-ray laser
33 km

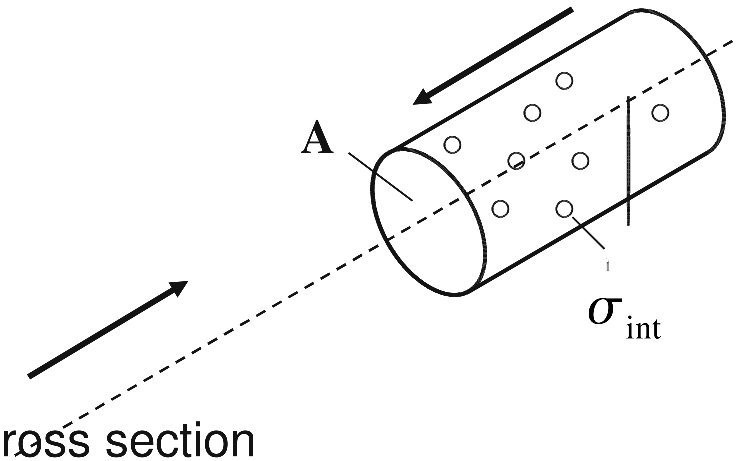
Why damping ring is needed?

- Rate of particle collision - Luminosity
  - The interaction rate is

$$R = f\frac{N^2}{A}\sigma_{int}$$

  - Luminosity is the interaction rate per unit cross section

$$L = f\frac{N^2}{A}$$



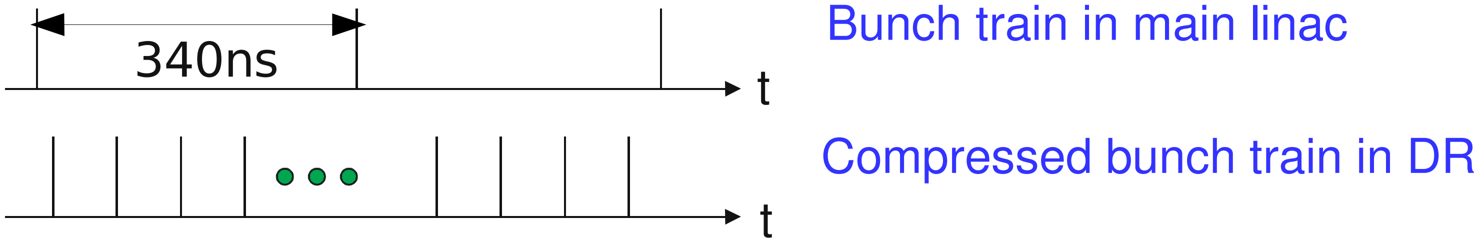
- Damping Ring – reduce beam size at interaction point

Challenges faced by ILC Damping Ring

- Injection/Extraction – technology and related optic design

  TESLA Damping Ring – 5GeV, 17 km – What???

  - Superconducting main linac: working in pulsed mode, each pulse train contains 2800 bunches and last for 1ms (300 km!!!)
  - Bunches has to be compressed inside damping ring



  Kicker rise and fall time is the key parameter determining the circumference of damping ring.

- Very large dynamic aperture required for positron beam injection
  - Injected positron beam size is 3.03mm @ β=1m
- Various collective effects
- And more

Injection/Extraction Technology – Fast Strip-line Kicker

- Recent testing of fast pulser at KEK has demonstrated with 3ns rise/fall time
  - Allows a shorter DR design

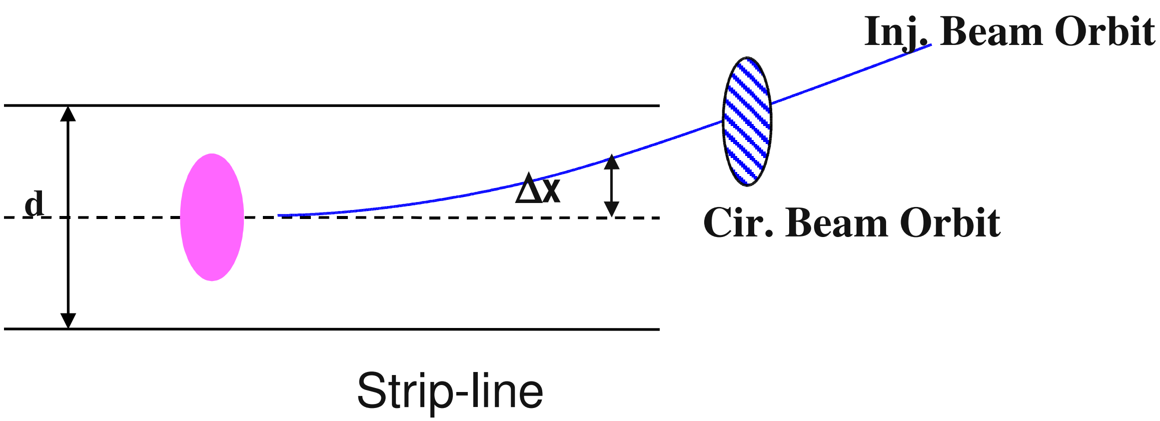
- Kicking angle of fast strip-line kicker:

$$\Delta\theta = 2g\frac{eV}{E}\frac{L}{d}$$

  - "g" geometry factor <=1;
  - Technical specifications for fast strip-line kicker: L=300mm (length); d=30mm (gap); pulser V=10kV;
  - kick angle from each strip-line kicker is **0.04mrad**
  - APS is 1.5 mrad

Optical Requirements at Fast Strip-line Kicker

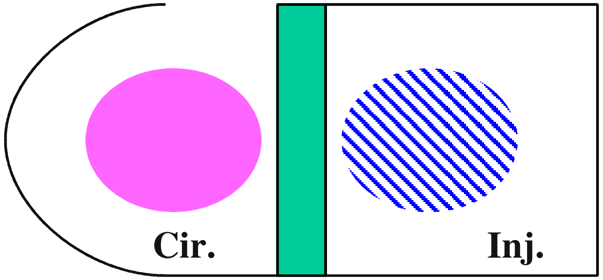
- Injection happens within a very short time (~1ms)
  - No damping for previous injected bunch during injection progress
- Large injected positron beam size ⇒ limited beta function at strip-line kicker
  - Injected beam orbit offset + injected beam size < d/2
- Assuming $\Delta x \leq$ 2mm, β_x < 16m



Injection Section

- Injected beam orbit:

$$\sqrt{\beta_{x,k}\beta_{x,s}}\,\theta\sin\left(\Delta\phi\right)\geq 2\sqrt{\beta_{x,s}\frac{A_{x,\max}}{\gamma}}+\Delta d_s$$



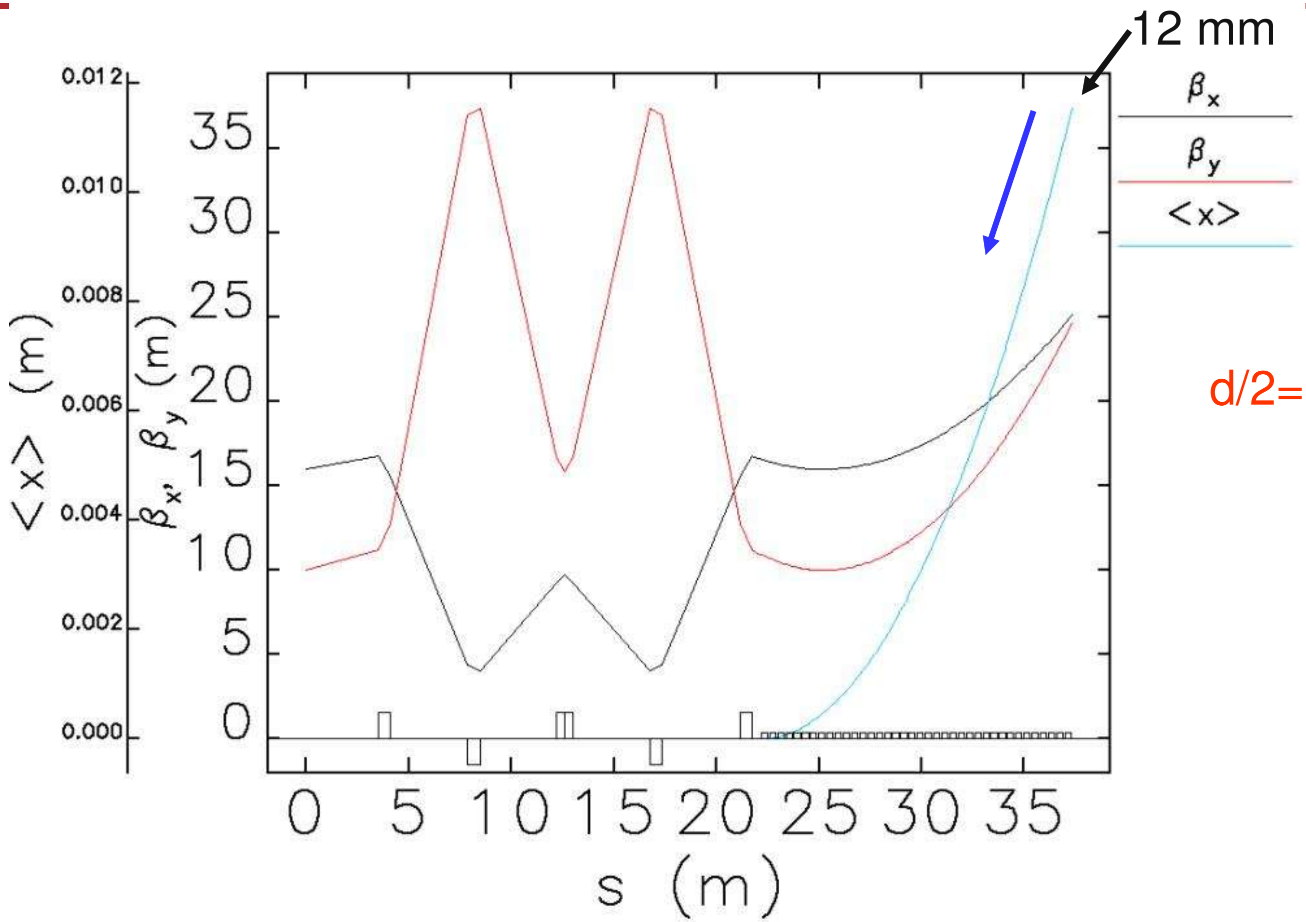
Septum

- Neglect septum thickness, and assume sin $\Delta\Phi$ =1
  - Minimum required kicking angle depends only on injected beam size and beta function at kicker.

$$\theta_{min}=2\sqrt{\frac{A_{x,max}}{\gamma}\frac{1}{\beta_{x,0}}}$$

  - The minimum number of strip-line kickers is about 38.

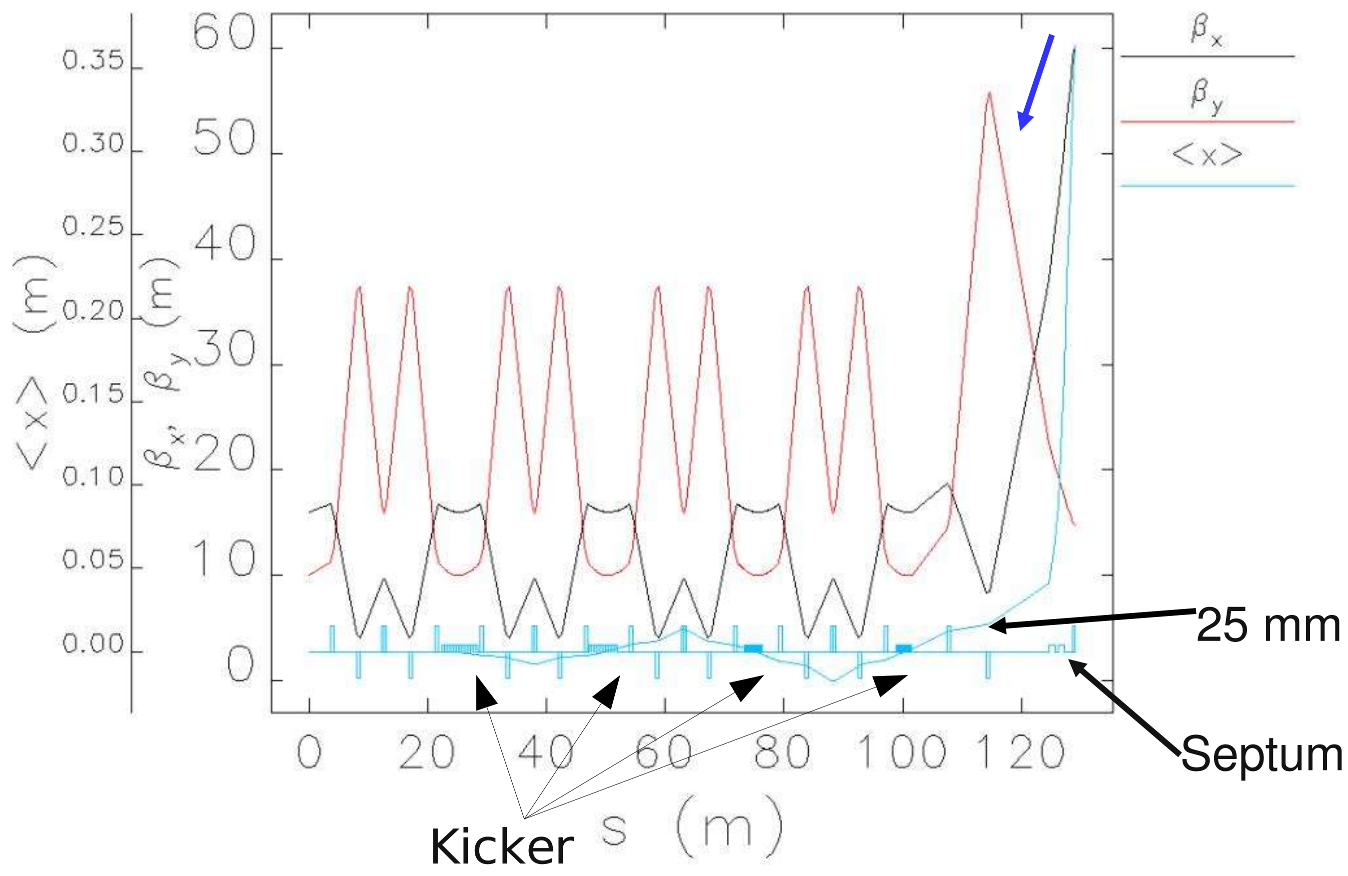
Lumped Kicker Injection Scheme



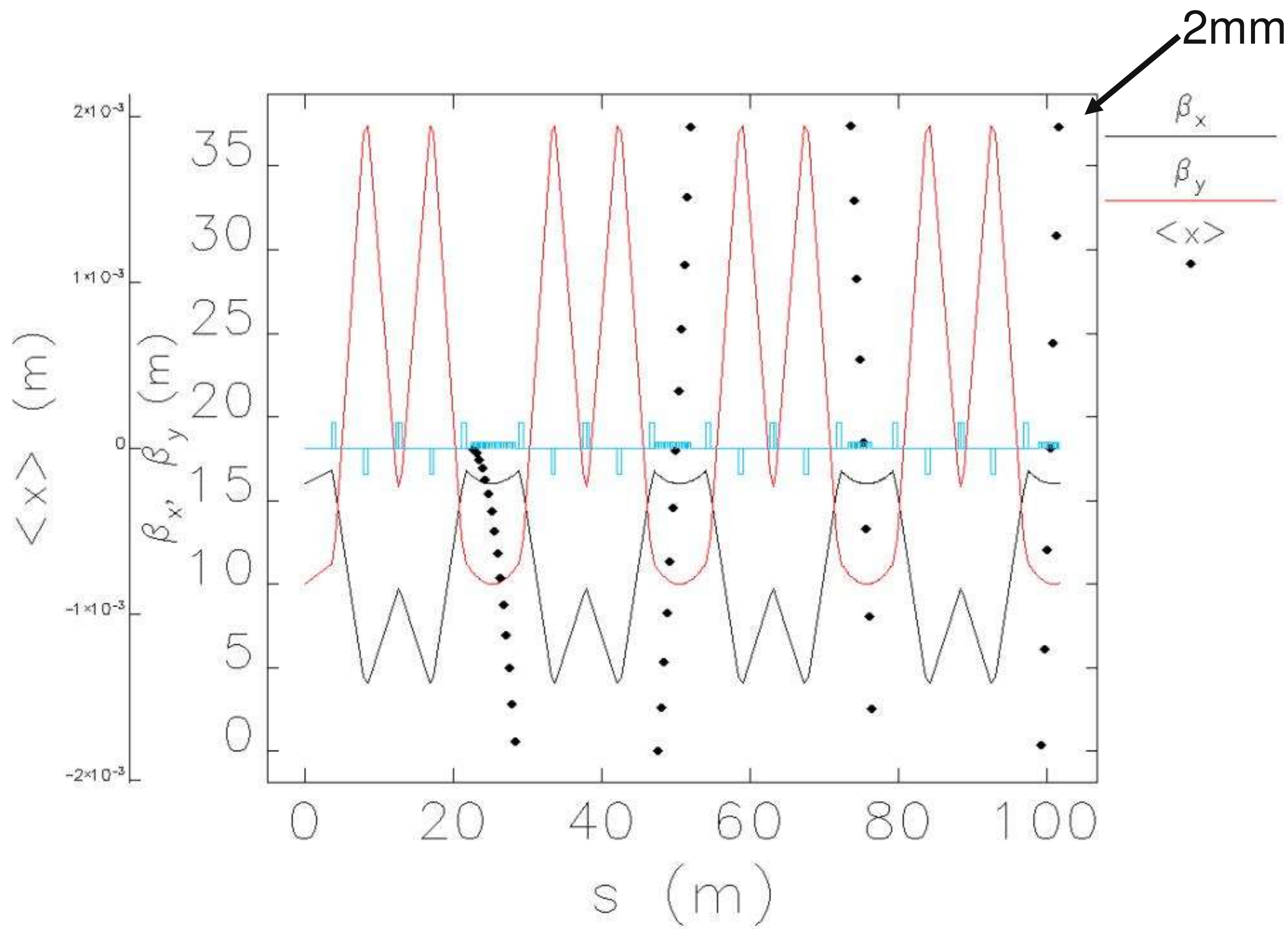
d/2=15mm

Too much injected beam trajectory excursion inside strip-line kicker!!!

Solution – Distributed Kicker Injection Scheme



Distributed Kicker Injection Scheme



Note: Number of kicker in each cluster is different

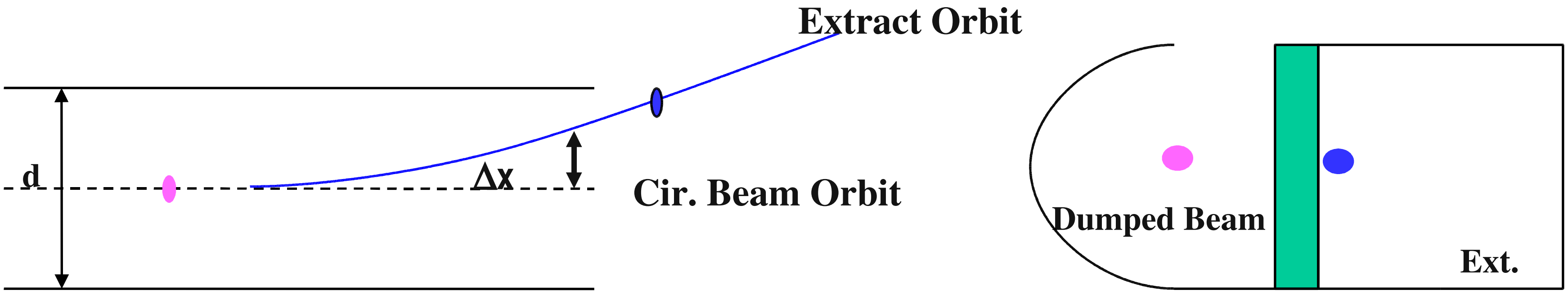
Extraction section (1)

- Similar to injection except the extracted beam size is much smaller

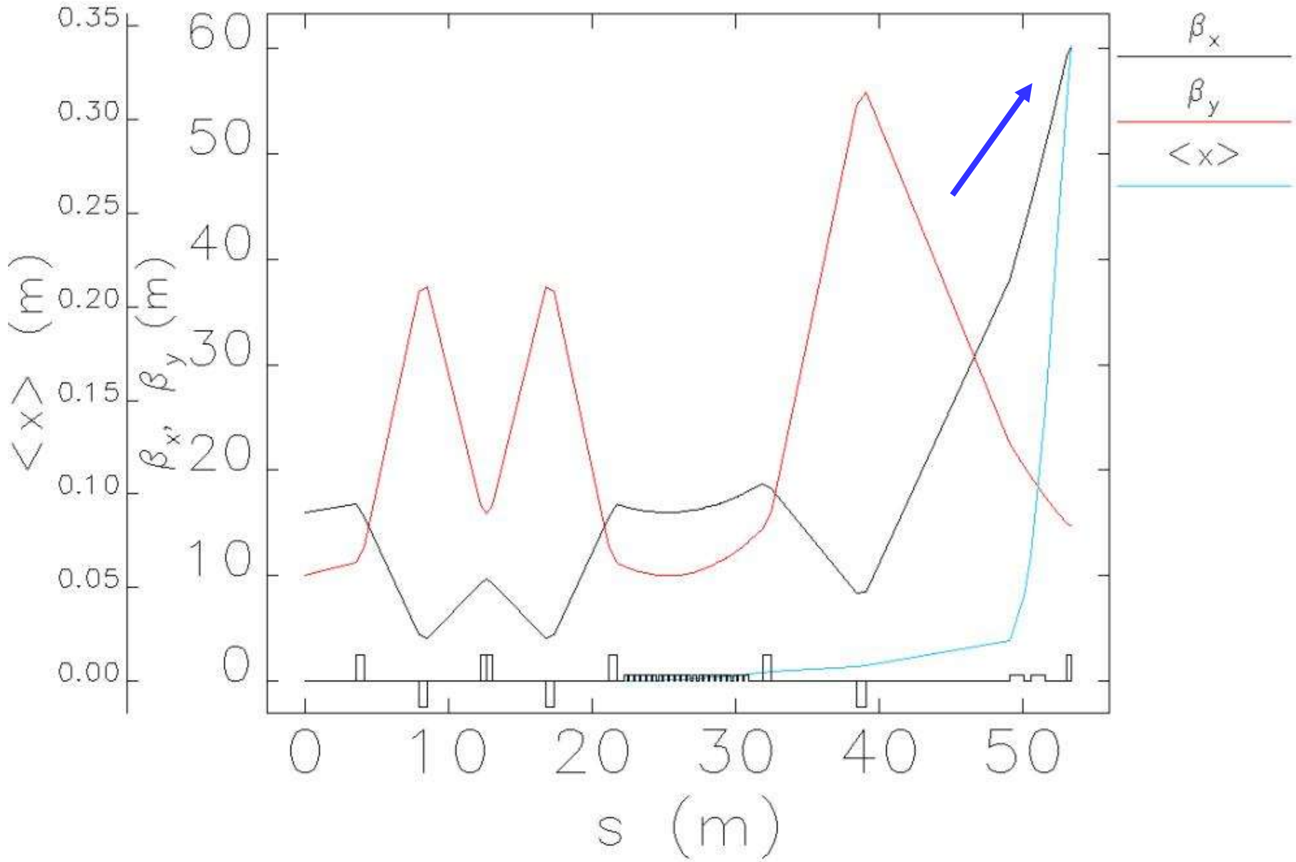
$$A_{inj} = 0.09\, m - rad$$
$$A_{ext} = 5 \times 10^{-6}\, m - rad$$

- Required kicker angle (total strip-line number) is about half of Injection
  - Injection/Extraction happens at the same time

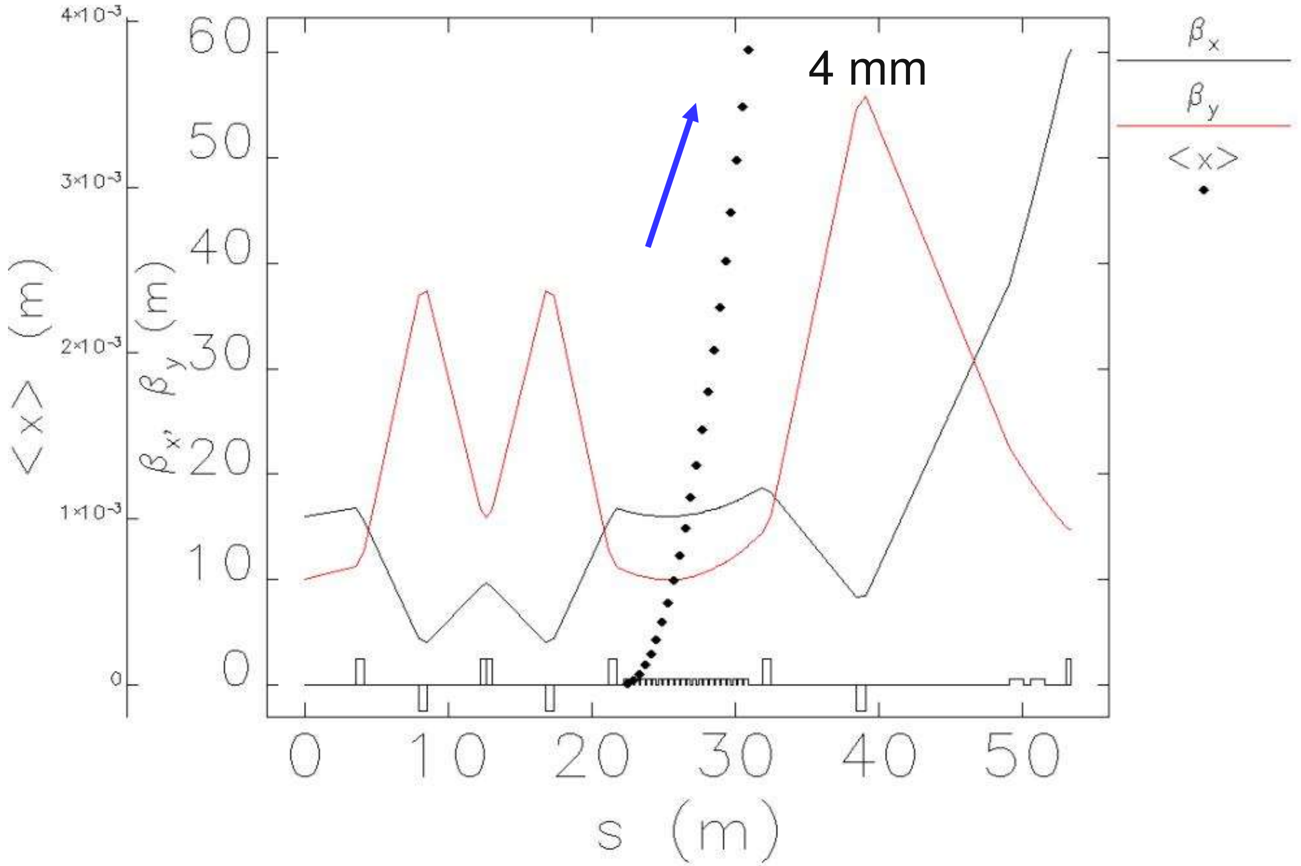
- The amplitude of extracted beam trajectory (Δx) in kicker can be large



Lattice of Entire Extraction Line



Lumped Kicker Extraction Scheme



ILCDR – baseline specifications

ILC Damping Rings Baseline Configuration Lattice Specifications

23 January 2006 – 650 MHz RF frequency

General Parameters

Circumference	6642.4784 m
Energy	5 GeV
RF frequency	**650 MHz**
Harmonic number	14402
Transverse damping time, e^+ DR (e^- DR)	<25 ms (<50 ms)
Normalized natural emittance	5 μm
Equilibrium bunch length	6 mm
Equilibrium energy spread	<0.13%
Momentum compaction	$\sim 4\times10^{-4}$
Damping wiggler peak field	1.67 T
Damping wiggler period	0.4 m
Energy acceptance	$\|\delta\|<0.5\%$
Dynamic aperture	$A_x+A_y<0.09$ m-rad (up to $\|\delta\|=0.5\%$)

Most concern for lattice design

- Emittance and damping time:

$$\tau_y = \frac{3C}{r_e c \gamma^3 I_2} = \frac{3C}{r_e c \gamma^3 (I_{2a} + I_{2w})}$$

→ I_2 mainly comes from wiggler section

$$\gamma \varepsilon_x = \frac{C_q \gamma^3 I_5}{J_x I_2}$$

→ I_5 mainly comes from arc cell

Specified from main linac

- Momentum compaction:

$$I_1 = \int_{dipoles} \frac{\eta}{\rho} ds \qquad \alpha = \frac{I_1}{C}$$

$$\bar{\eta} \approx 4 \times 10^{-4} \times 6500/2\pi \approx 0.4m$$

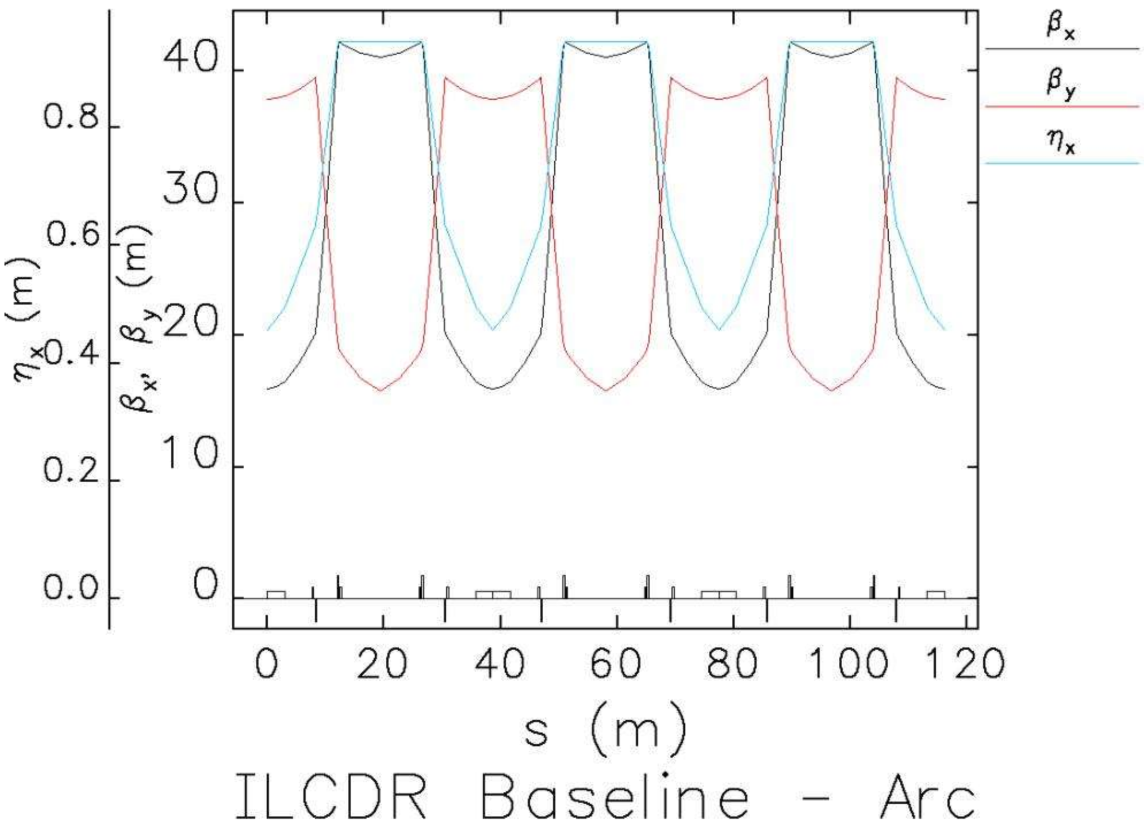
- Bunch length:

$$\sigma_L = \left[\frac{2\pi h \alpha c^2}{\omega_{RF}^2 \cos\phi_s} \frac{E}{eV_{RF}} \right]^{1/2} \sigma_E$$

Note: After all parameter be set up, bunch length can only be varied using RF voltage.

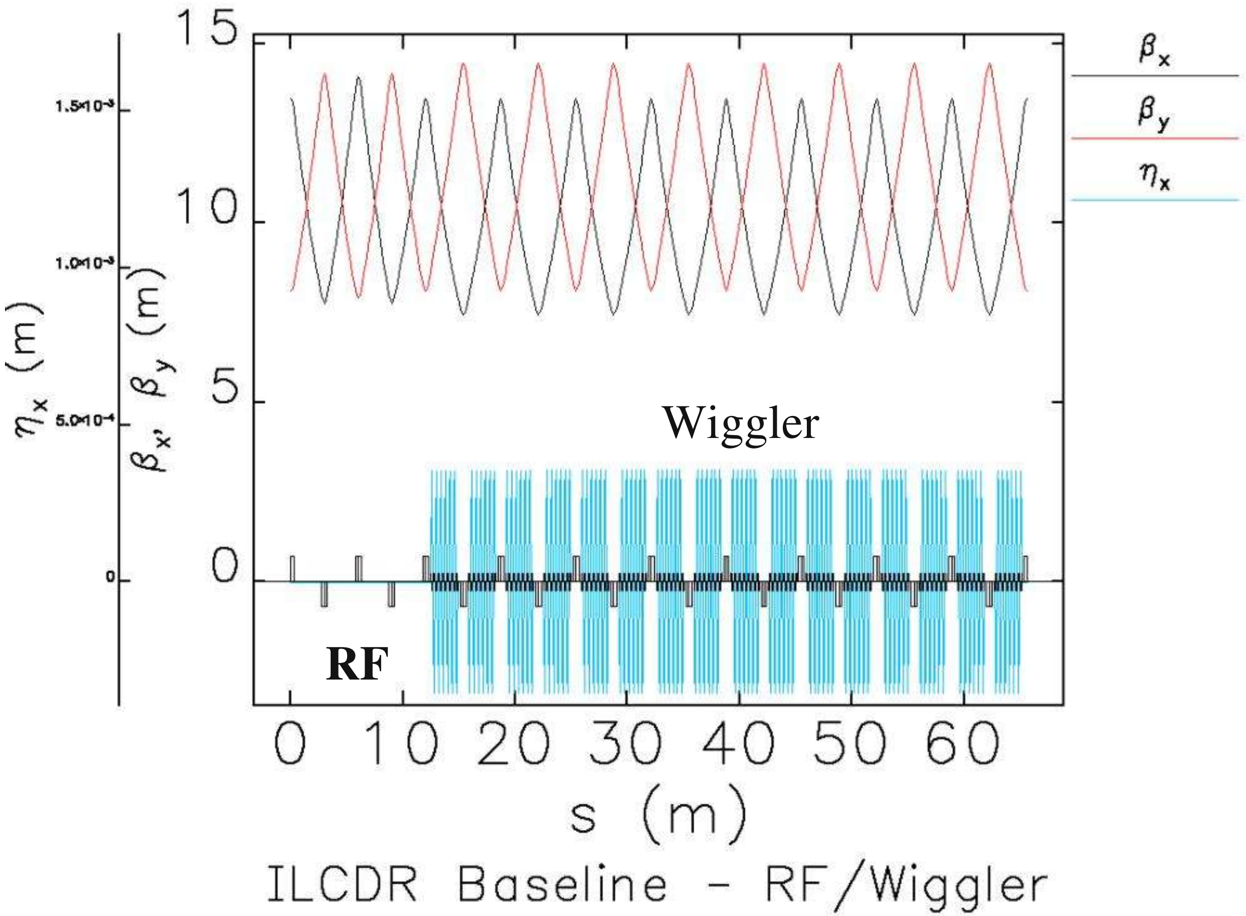
Arc Section

- Arc section is designed for required momentum compaction
- 90^0 TME cell has been chosen for better dynamic aperture



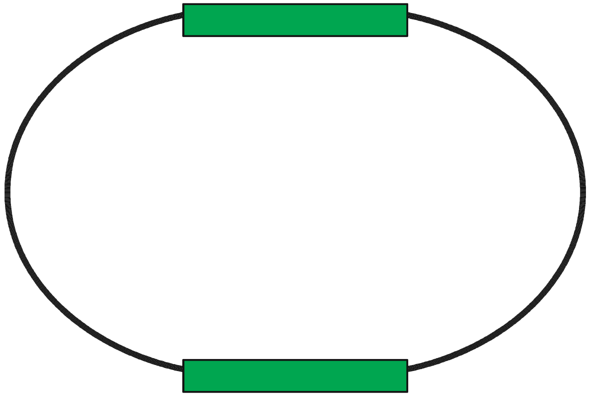
RF/Wiggler Section

- Determines emittance, damping time, and energy spread

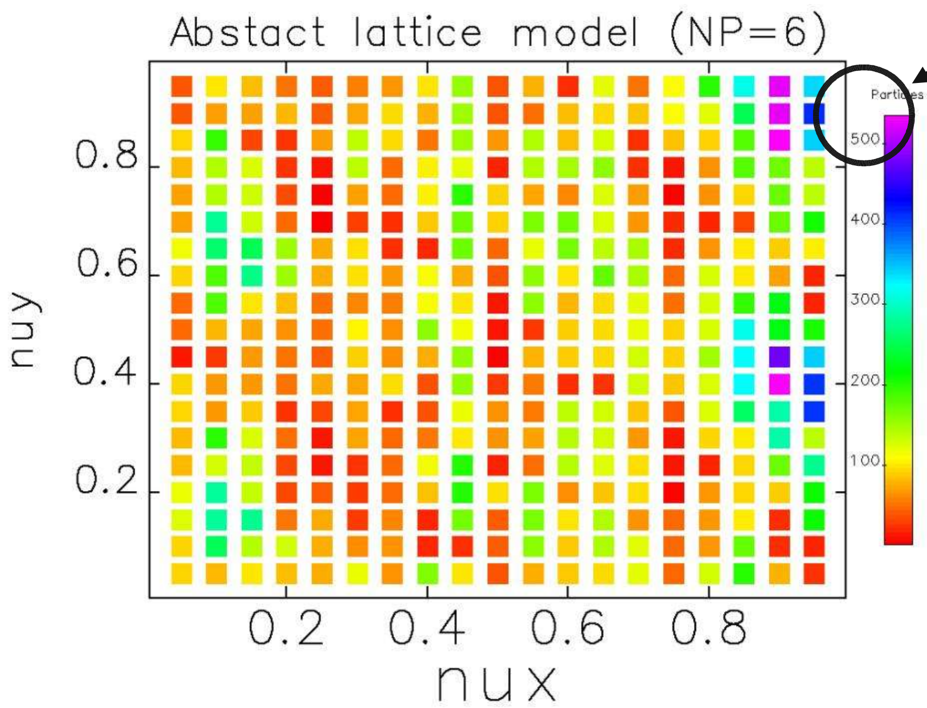


Dynamic Aperture Optimization – Abstract Lattice Model (1)

- Dynamic aperture optimization is a big challenge for low emittance accelerator
- Long wiggler sections make the issue much harder to solve
- We need to vary phase advance between arcs to optimize design
  - Represent straights with matrix giving chosen phase advance
  - Call this “abstract lattice model”
  - Allows optimization without detailed design
- Number of arc (super periods) in arc can also be varied
- “Elegant”+Weed cluster

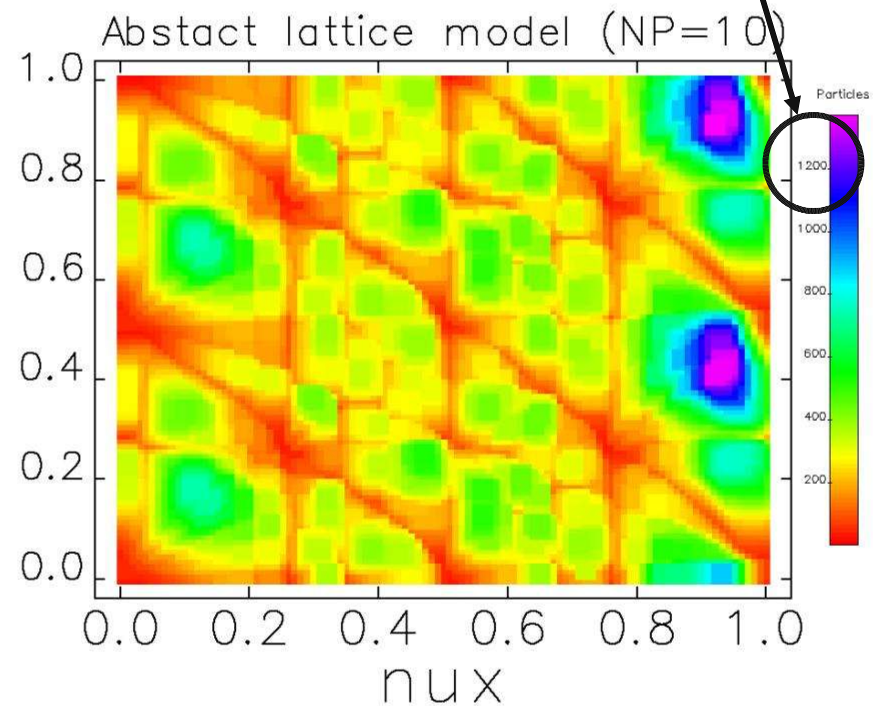


Dynamic Aperture Optimization – Abstract Lattice Model (2)



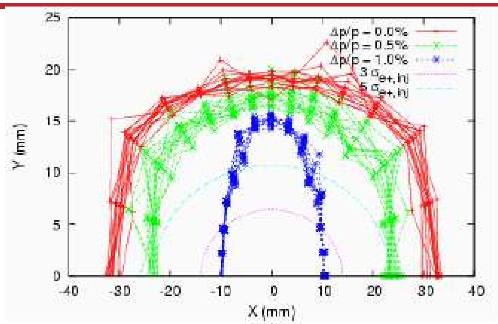
500

1200

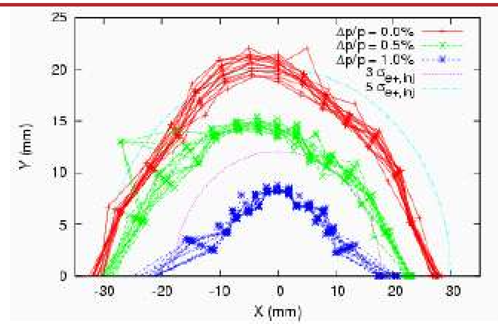


10000 runs!

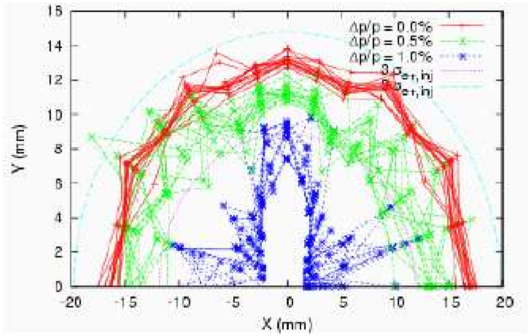
Dynamic Aperture Optimization – Application of ALM



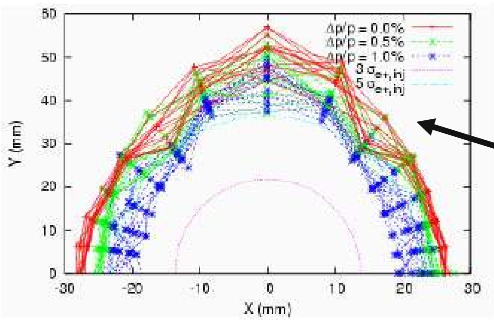
(a) PPA



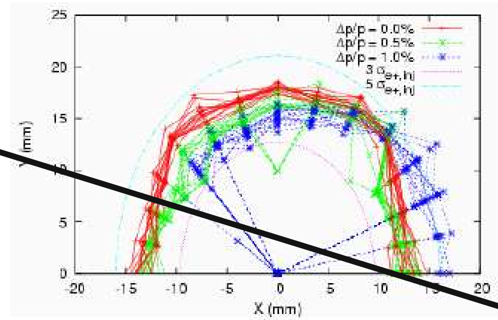
(b) OTW



(g) TESLA



(c) OCS

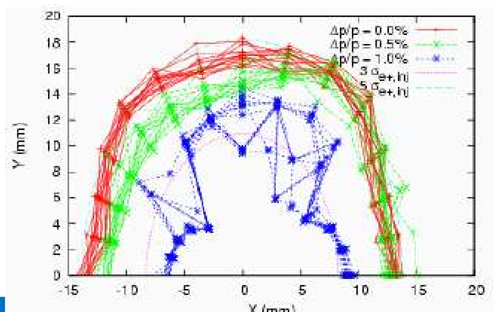


(d) BRU

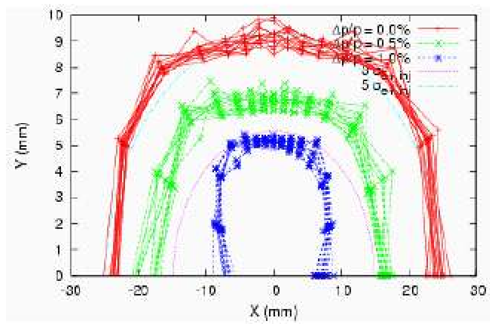
Seven reference lattices for baseline configuration study

OCS (our design):
- Has more super periods
- Optimized phase advance between arcs

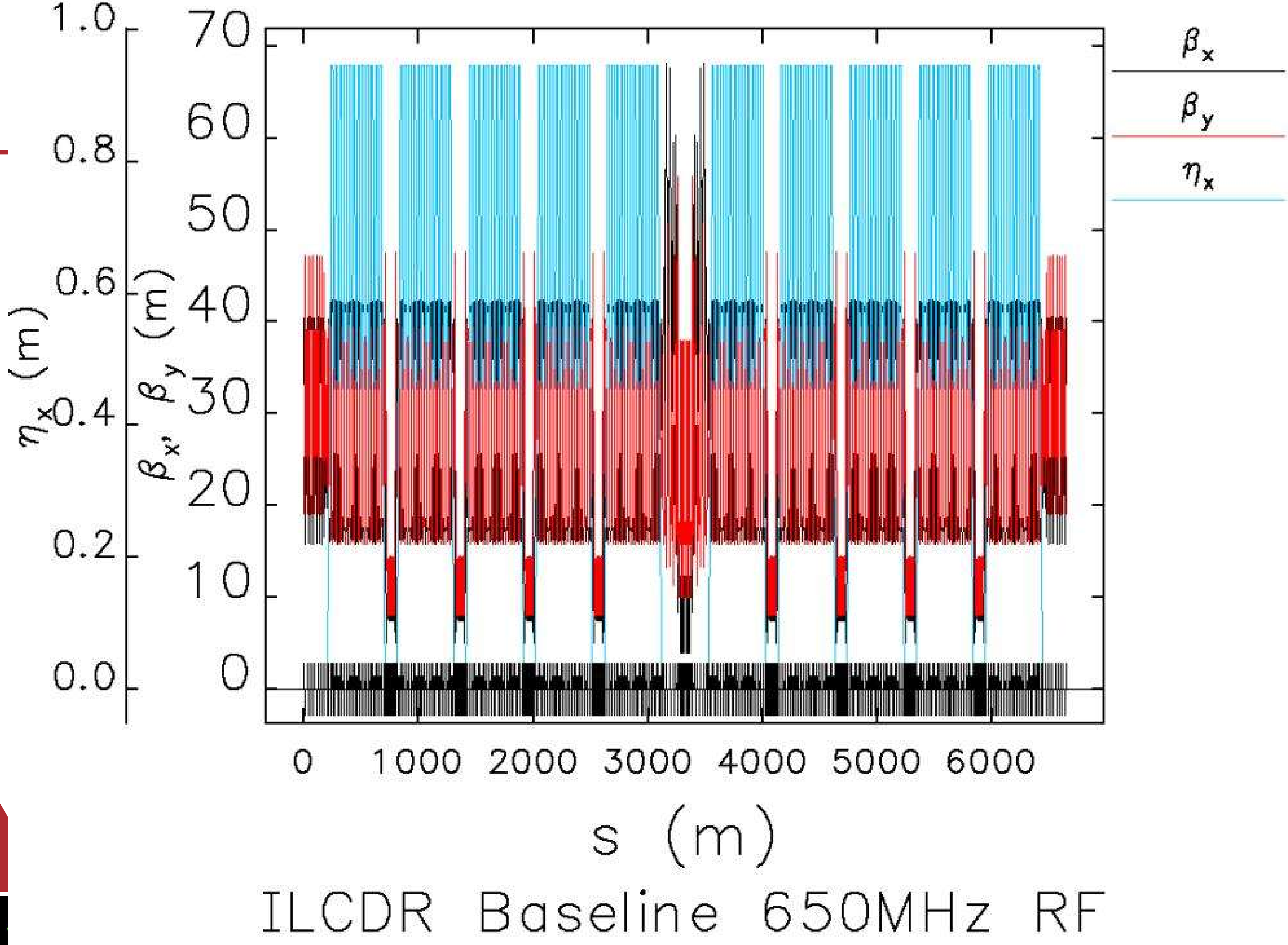
The successful application of abstract lattice model!!!



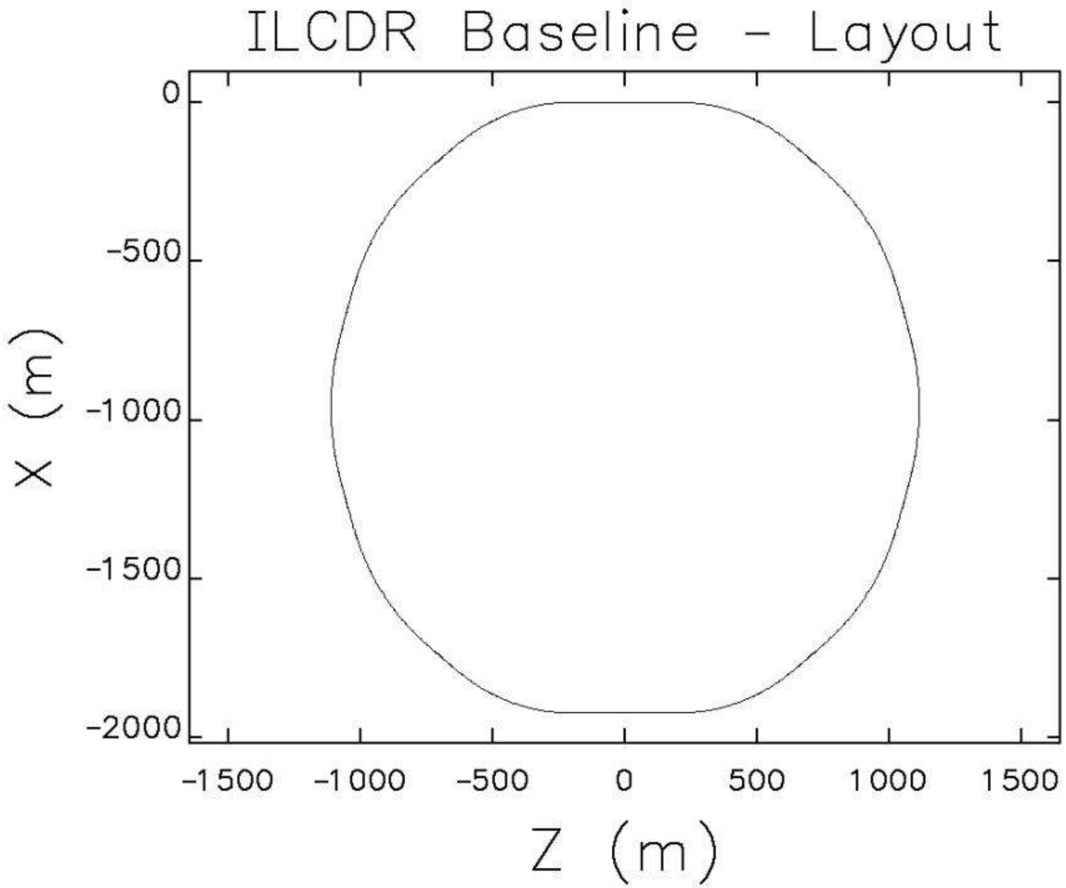
(e) MCH



(f) DAS


1.0
0.8
0.6
0.4
0.2
0.0
η_x (m)
70
60
50
40
30
20
10
0
β_x, β_y (m)
β_x
β_y
η_x
0
1000
2000
3000
4000
5000
6000
s (m)
ILCDR Baseline 650MHz RF

Layout



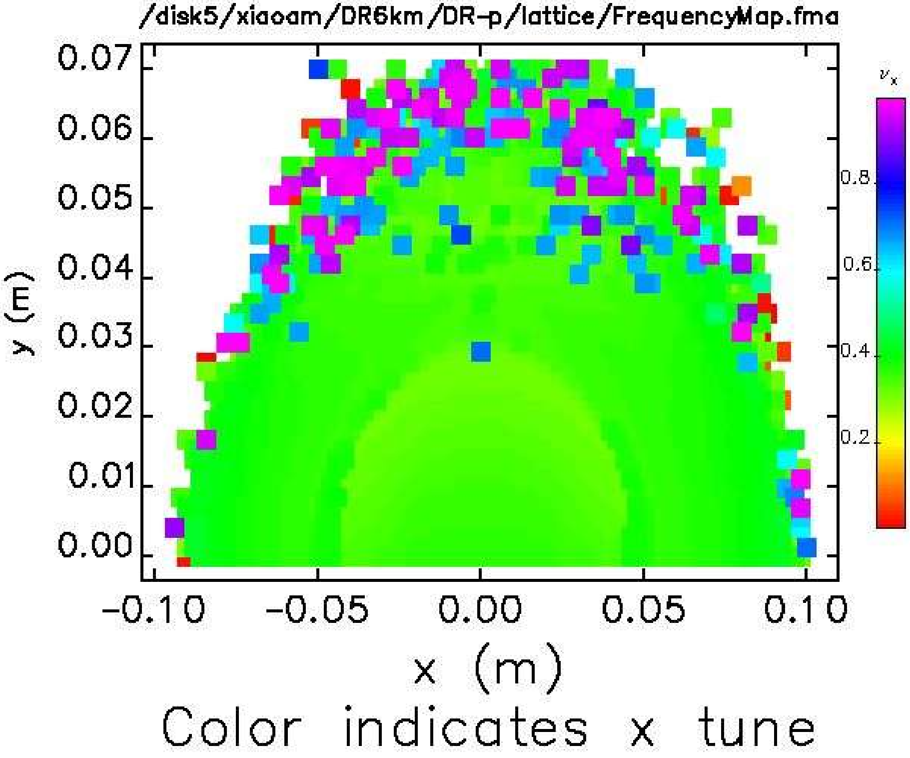
ILCDR Baseline - Layout
0
-500
-1000
-1500
-2000
X (m)
-1500
-1000
-500
0
500
1000
1500
Z (m)

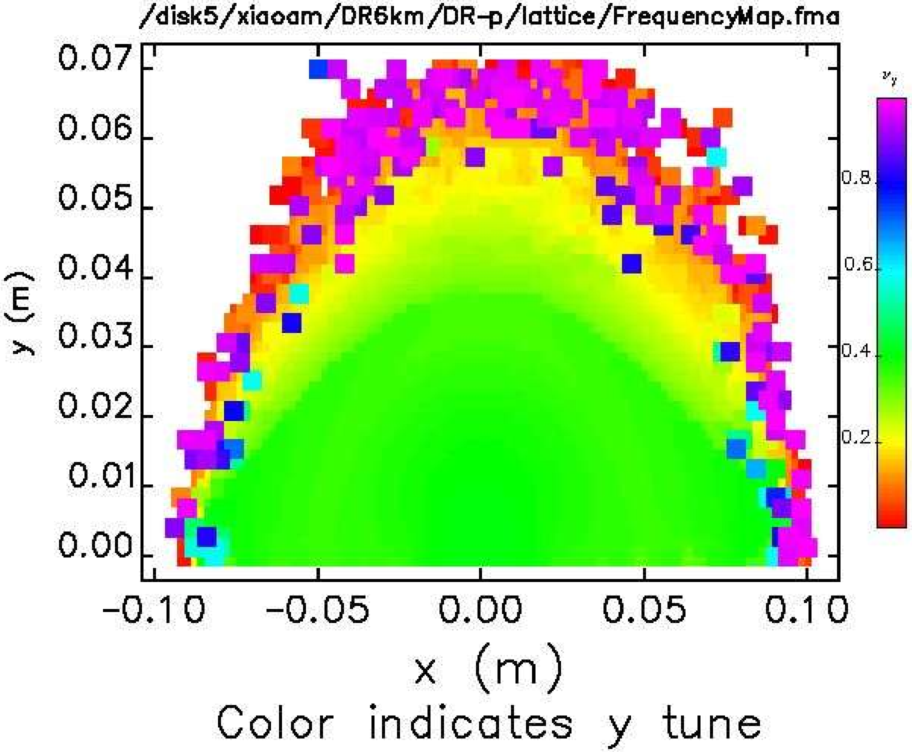
General lattice parameters

	TESLA-TDR	ILCDR
Energy E	5 GeV	5 GeV
Circumference C	17 km	6695 m
Horizontal Emittance ε_x	0.8 nm-rad	0.51 nm-rad
Damping Time τ_x	28 ms	25.7 ms
Tunes, ν_x,ν_y,ν_s	72.28/44.18	52.28,/47.4
Natural Chromaticity, ξ_x,ξ_y	-125,-68	-58.5,-56.9
Momentum Compaction Factor α_p	1.2E-4	4E-4
Bunch Length σ_z	6 mm	6 mm
Energy Spread $\delta p/p$	1.3E-3	1.28E-3
V_{RF}	50MV	46.6 MV
Energy Loss per Turn U_0	21 MeV	8.7 MeV
RF Acceptance δmax		2.7%

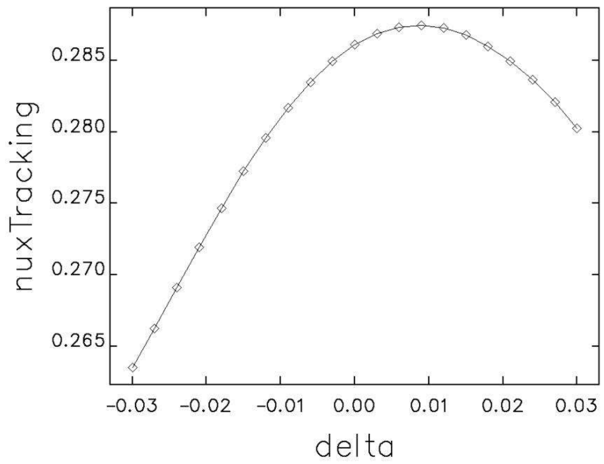
Frequency Map Analysis – Ideal lattice

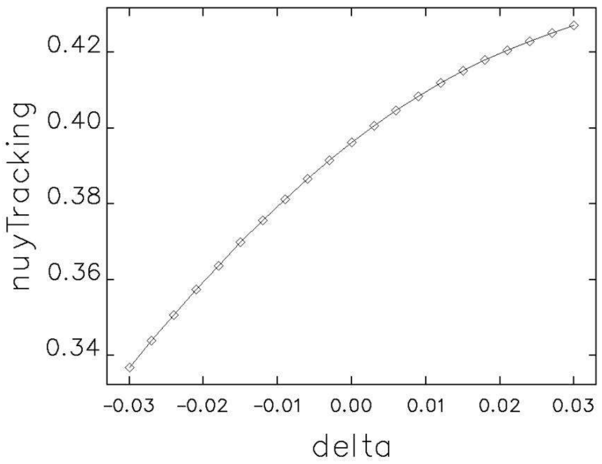
Linear wiggler model without machine errors

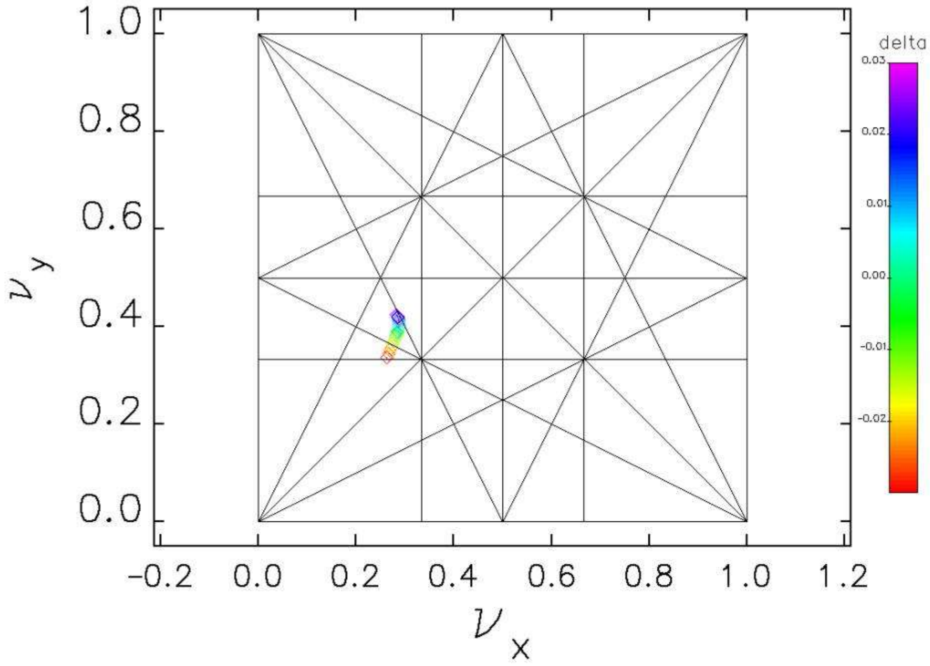




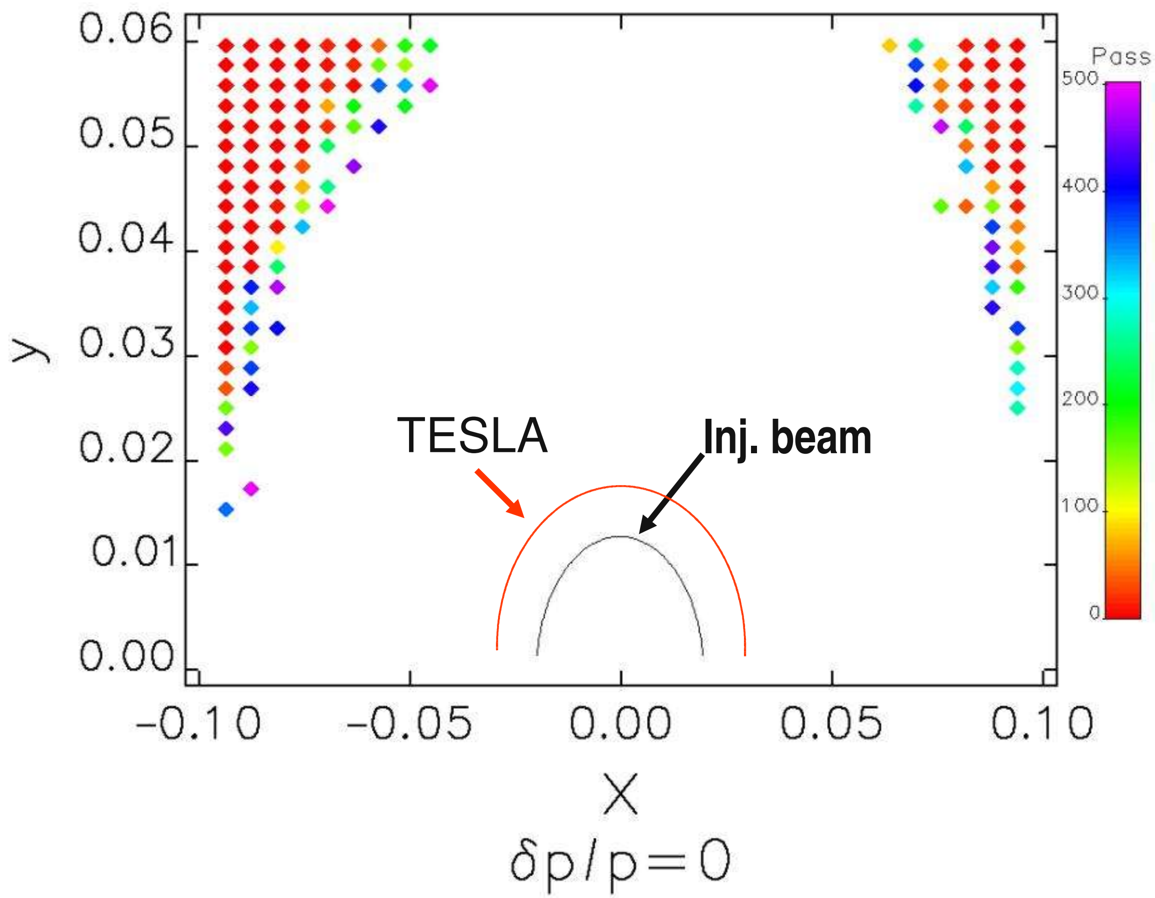
Tune Shift with Energy



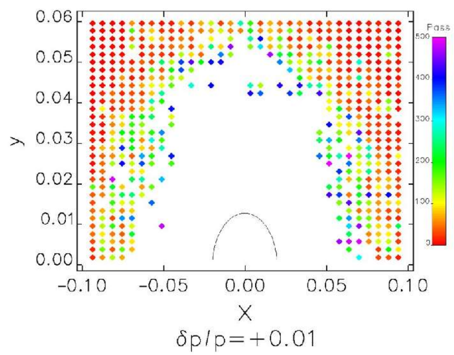




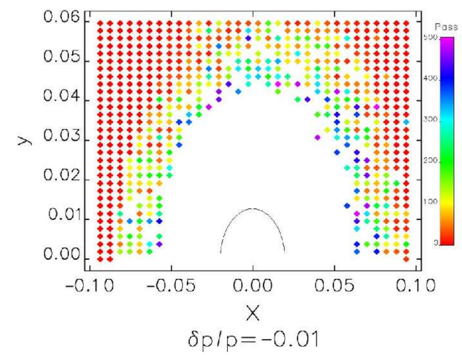
Dynamic Aperture for on-momentum particles



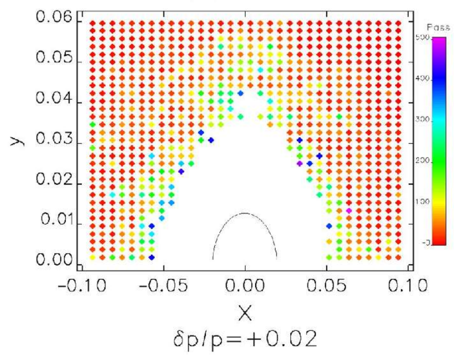
Off-momentum Dynamic Aperture



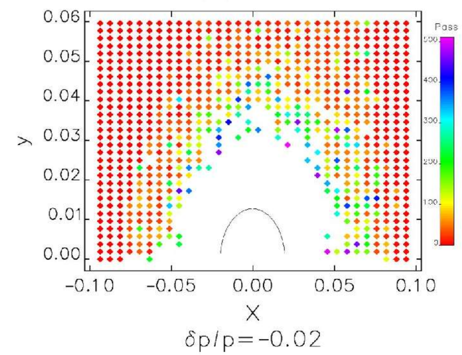
δp/p=-0.01



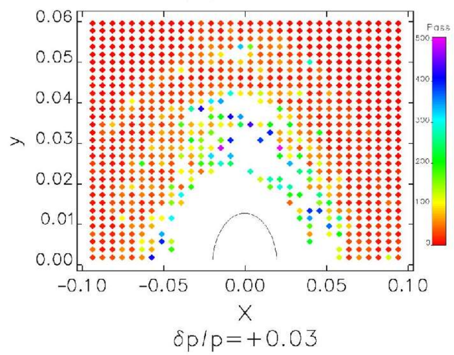
δp/p=0.01



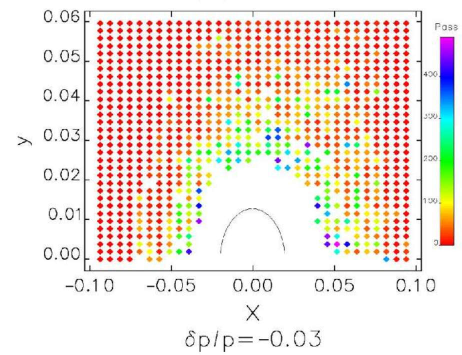
δp/p=-0.02



δp/p=0.02



δp/p=-0.03

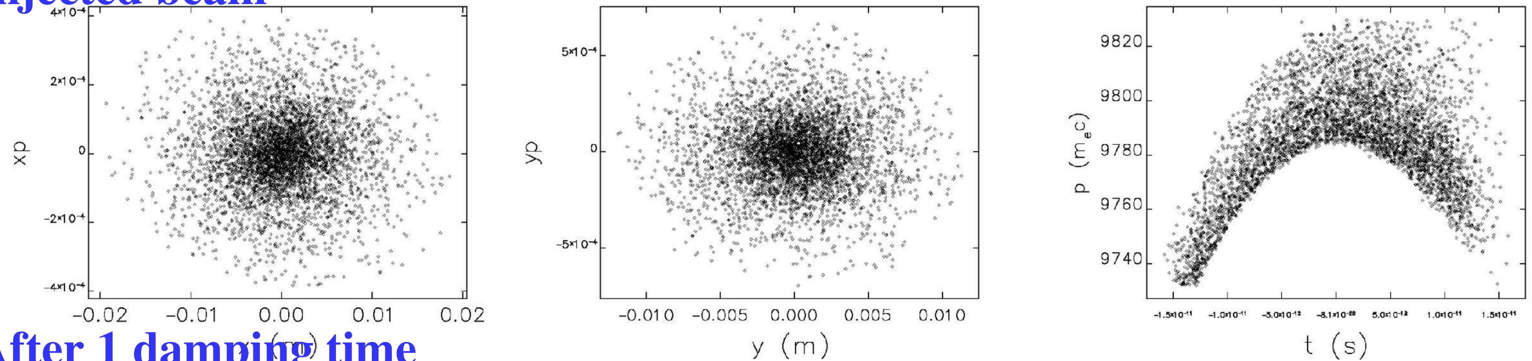


δp/p=0.03

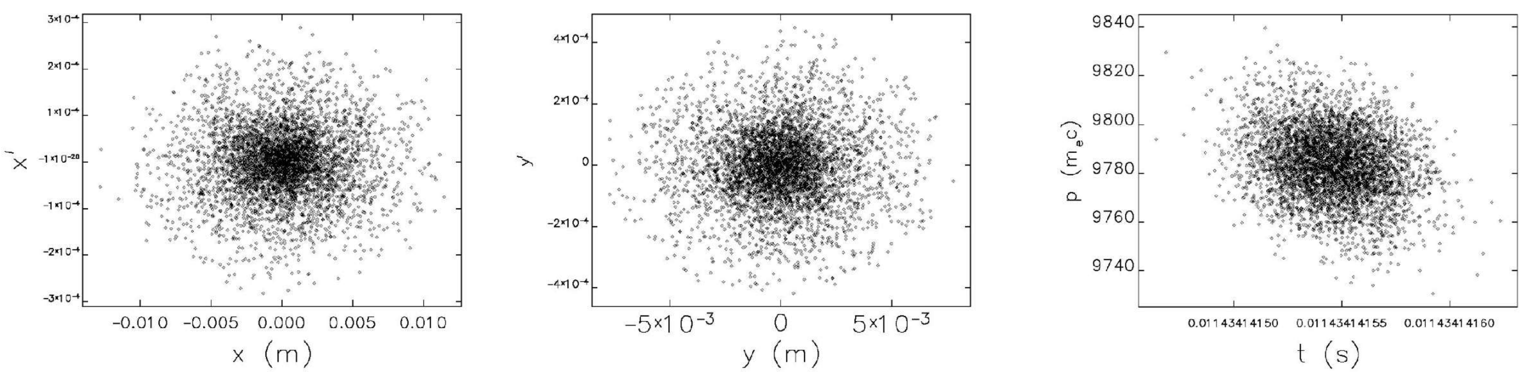
Tracking result of sample particles

- Total injected beam power is ~226 kW. Need enough dynamic aperture to reduce radiation load due to beam loss.
- We tracked with 4604 sample particles from W. Gai (ANL-HEP), all survived after 1 damping time (1380 turns) with/without damping.

Injected beam



After 1 damping time



Future study

- Low emittance tuning – add orbit and optics tuning scheme
- Vary momentum compaction – reducing RF voltage
- Reduce number of wiggler locations – big challenge to acceptance
- Injection/extraction efficiency simulation

Thank you!