Damping Rings and Ring Colliders
Damping Ring Lattices

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Outline

- A3.1 - DR Basics: Introduction to Damping Rings
- A3.2 - DR Basics: General Linear Beam Dynamics
- A3.3 - LER Design: Radiation Damping and Equilibrium Emittance
- A3.4 - LER Design: Damping Ring Lattices
  - ILC Damping Ring Design Optimization
  - The ILC DR Lattice, Parameters and Design Choices
  - CLIC Damping Ring Design Optimization
  - The CLIC DR Lattice, Parameters and Design Choices
- A3.5 – DR Technical systems
- A3.6 – Beam Dynamics
- A3.7 – R&D Challenges and Test Facilities
- A3.8 – Circular Colliders

These slides have been presented at the 2010 LC school by Mark Palmer with a few additions and updates by myself

The ILC Damping Rings Lattice

- The TDR baseline foresees to operate the ILC with half the number of bunches with respect to the Reference Design Report (RDR) value
- This allows to reduce the damping ring circumference by a factor 2 maintaining the same current

	New Baseline	RDR
Number of bunches	1312	2625
Circumference (km)	3.2	6.4
Particles/bunch	$2\ 10^{10}$	$2\ 10^{10}$
Bunch spacing (ns)	6.2	6.2
Current (A)	0.39	0.39

Lattice Requirements

- The layout is a racetrack
- structure of straight sections, similar to that of the DCO4 lattice used as a baseline for the 6.4 km ring.
- Except for the number of bunches, the parameters of the injected and extracted beams are the same as the RDR
- The target momentum compaction value is in the range from $2 \cdot 10^{-4}$ to $3 \cdot 10^{-4}$.
- Moreover the lattice has to satisfy the requirements for 3 different configurations:
  - 5 Hz “baseline" operation with 1312 bunches
  - a 10 Hz operating mode to allow low energy operation of the main linac
  - a luminosity upgrade configuration that envisions a return to 2625 bunches per main linac pulse

Nominal parameters of beams

injected into damping rings

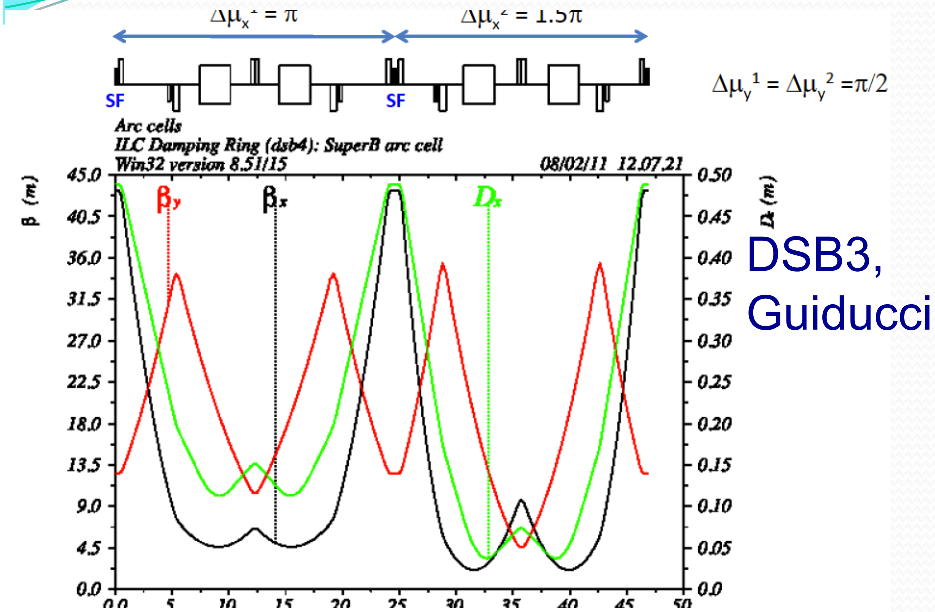
	Baseline	Luminosity update	10 Hz mode
Train rep. rate	5 Hz	5 Hz	10 Hz
Number of bunches/train	1312	2625	1312
Number of particles/bunch	2×10^{10}		
e^+ max. transverse amplitude A_x+A_y	0.07 m.rad		
e^+ max. energy error δ_{max}	±0.75%		
e^+ max bunch length	±35 mm		
e- normalized injected emittance	45 μm		
e^- rms relative injected energy spread	0.1%		

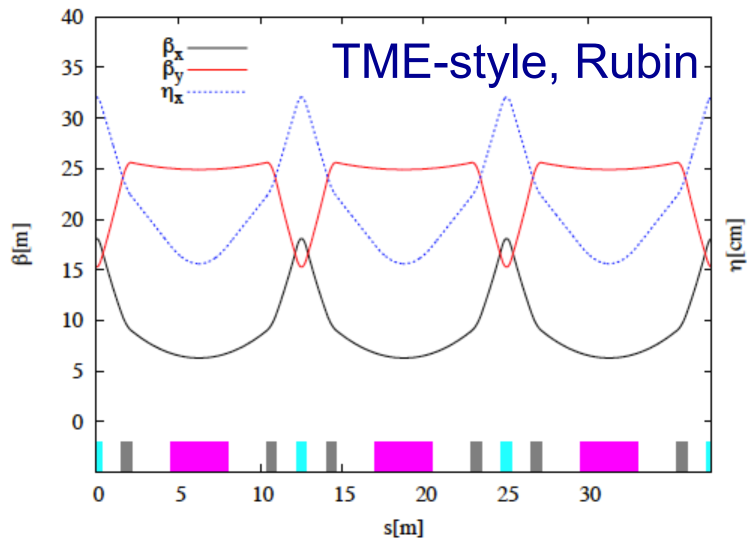
extracted from damping rings

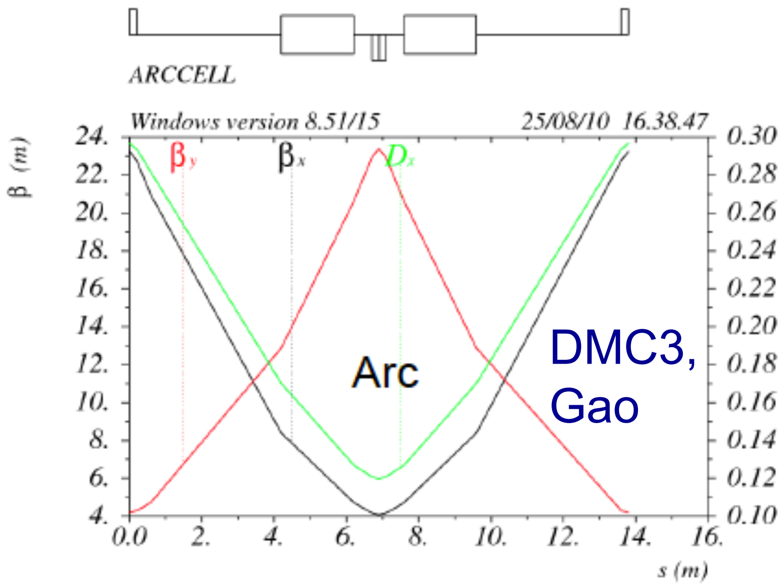
	Baseline	Luminosity update	10 Hz mode
Train rep. rate	5 Hz	5 Hz	10 Hz
Number of bunches/train	1312	2625	1312
Number of particles/bunch	2×10^{10}		
Energy	5 GeV		
Horizontal emittance	$<8.0\ 10^{-10}$ m.rad		
Vertical emittance	$2.0\ 10^{-12}$ m.rad		
rms relative energy spread	<0.15%		
rms bunch length	6 mm		
e^+ Vertical damping time	24 ms	24 ms	13 ms
e^- Vertical damping time	24 ms	24 ms	18 ms
Horizontal/vertical jitter	$<0.1\sigma_x/\sigma_y$		

Same as RDR except for the number of bunches

Lattice Comparison





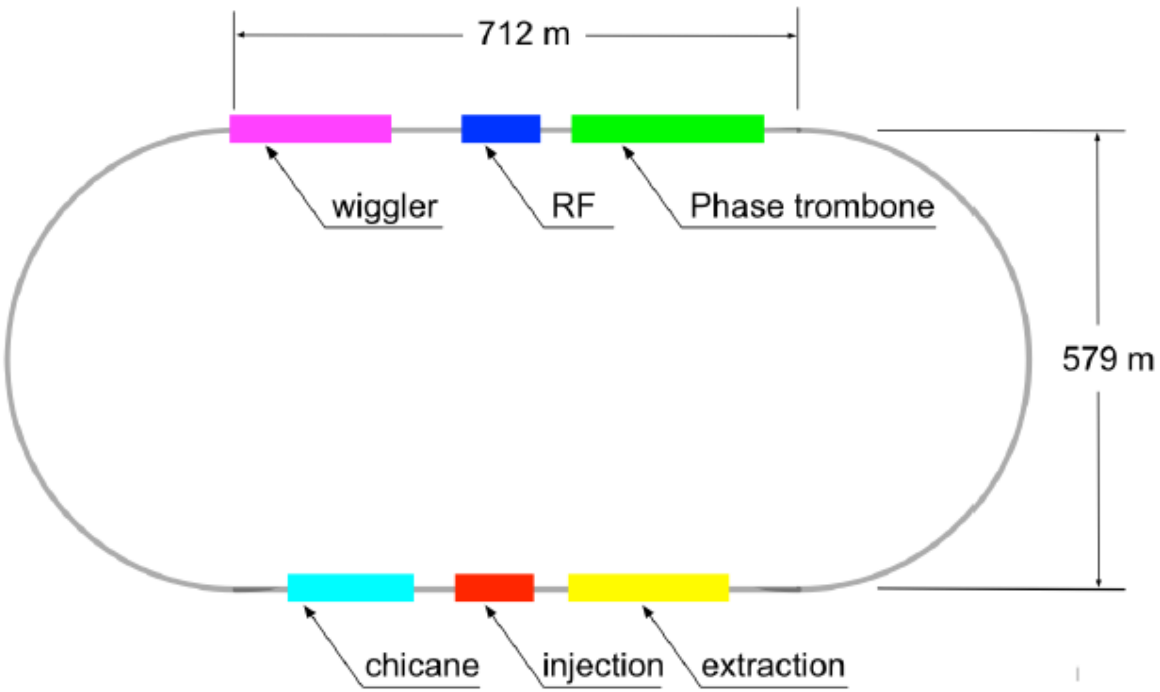


Three different lattices were compared:

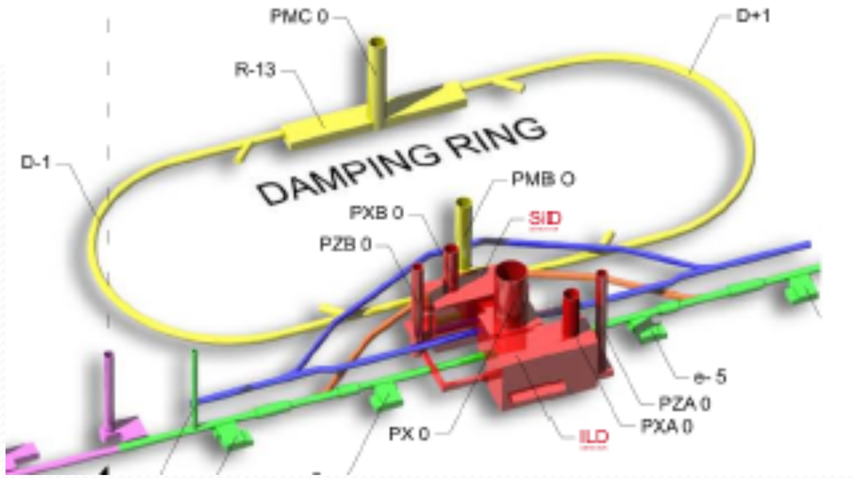
1. DSB lattice, with an arc cell similar to that proposed for the SuperB collider
2. DMC lattice, based on FODO cells,
3. DTC lattice based on a TME-style cell

On the basis of design completeness the DTC lattice was designated as the baseline.

DTC04 Lattice



- Circumference 3238 m
- 54 wigglers
- Space for 12 RF cavities
- 6 phase trombone to vary the tune
- Circumference tuning chicane

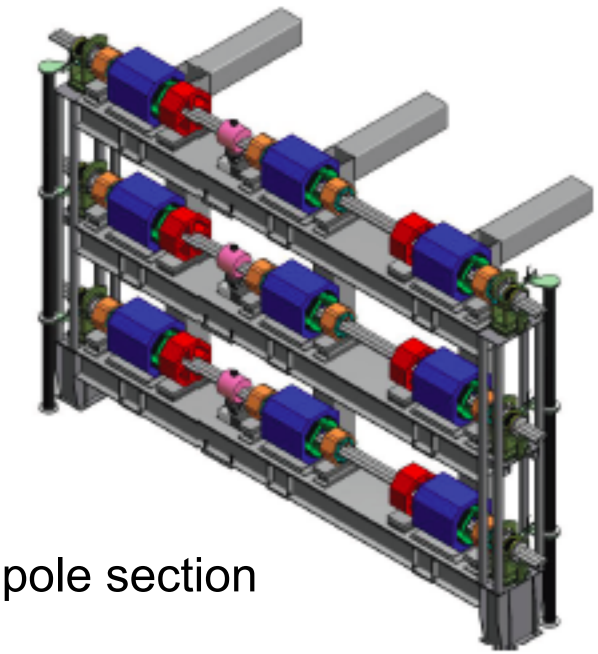


DTC04 Parameters

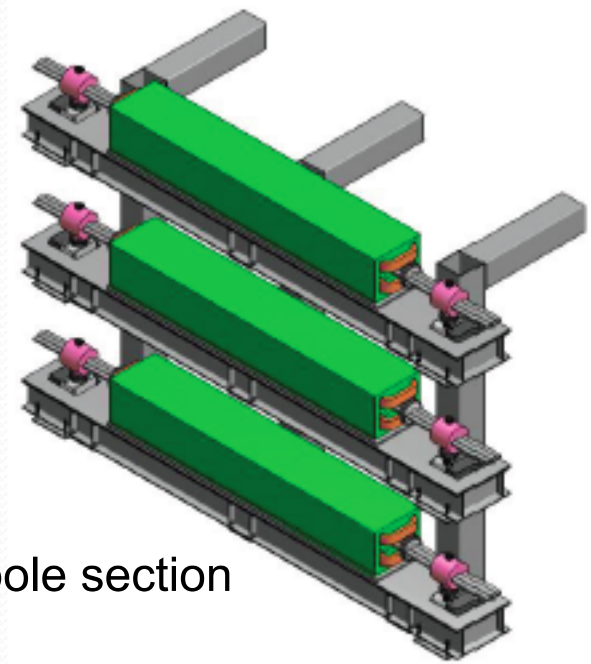
Parameter	5 Hz Baseline	10 Hz	Luminosity upgrade
Energy [GeV]	5	5	5
τ_X[ms]	23.9	12.9	23.9
τ_Z[ms]	11.9	6.4	11.9
σ_z[mm]	6	6	6
σ_δ[%]	0.11	0.14	0.11
α_p(x10^4)	3.3	3.3	3.3
$\gamma\varepsilon_x$[μm]	5.5	6.3	5.4
RF [MHz]	650	650	650
RF[MV]	14	22	14
ξ_x/ξ_y	-51/-43	-51/-44	-52/-43
$B_{wiggler}$[T]	1.5	2.1	1.5
ΔE/turn[MeV]	4.5	8.0	4.5
Sext[m^{-3}]	3.3/-4.2	3.3/-4.3	3.3/-4.2
I [A]	0.39	0.39	0.78
Beam power[MW]	1.7	3.1	3.5
No. of RF cavities	10	12	12

Damping-ring arc magnet layout

positron ring at the bottom and electron ring directly above.



Quadrupole section



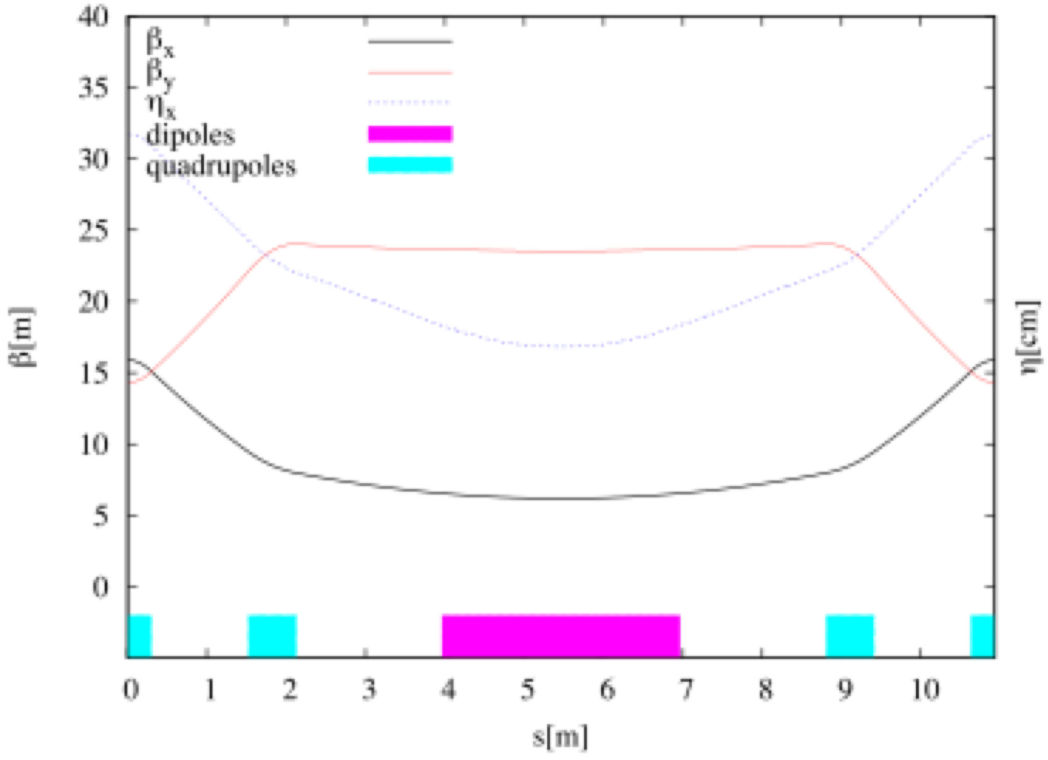
Dipole section

In the event that the electron-cloud mitigations are insufficient to achieve the required performance for the high luminosity configuration (2625 bunches), allowance had been made for the installation of a second positron ring in the same tunnel.

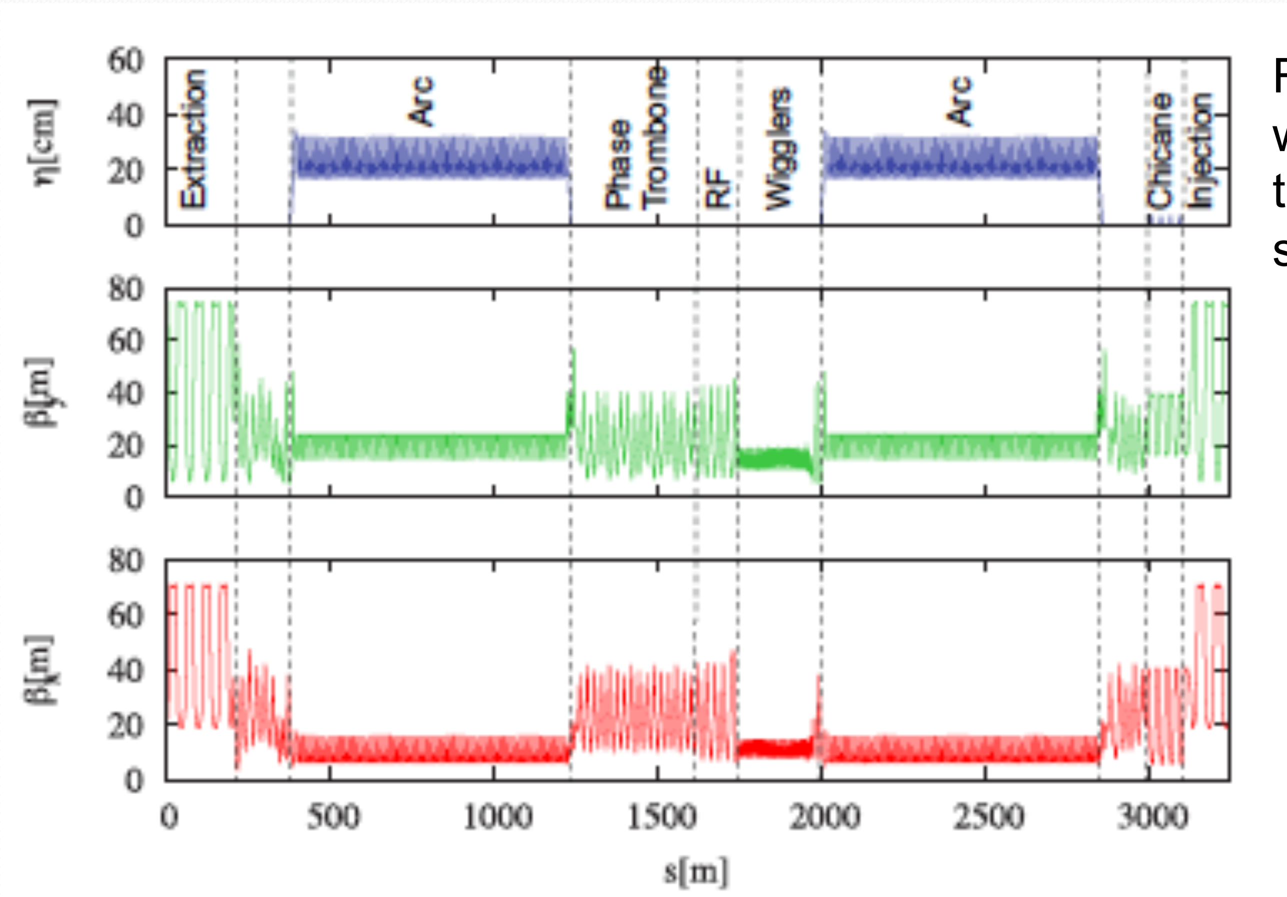
Arc Cell

Cell length = 10.93m
Bend length = 3.0m
75 cells/arc

There is some flexibility to vary emittance and momentum compaction by adjusting the arc cell focusing, but typically this comes at the expense of dynamic aperture

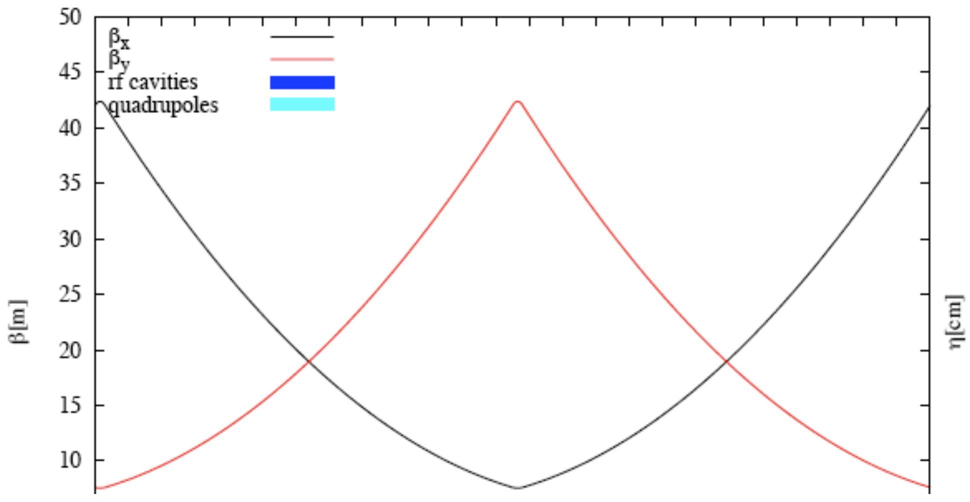


DTC04 ring optical functions



RF is upstream of wigglers in both rings to avoid damage from synchrotron radiation

RF and wigglers

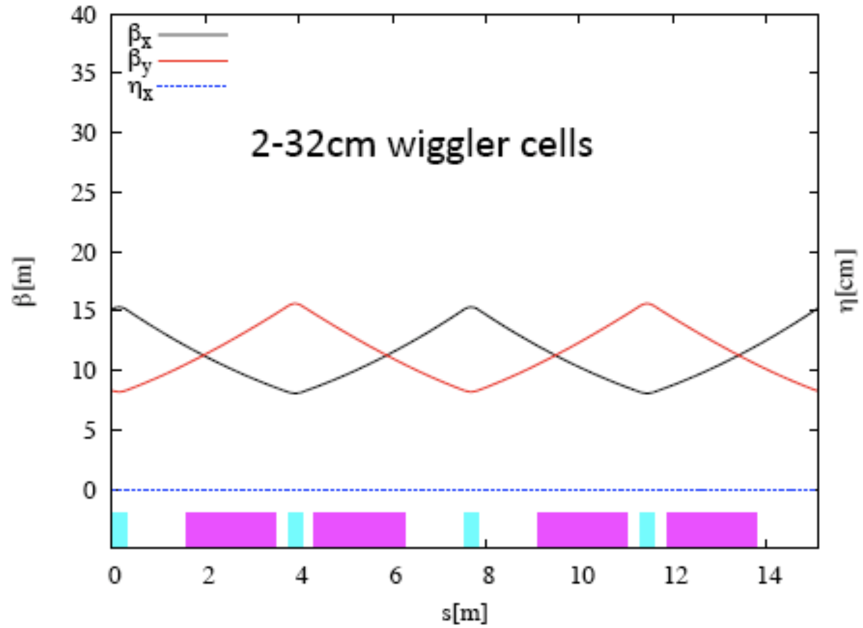


Parameter	Unit	CESR-c	ILC RDR	ILC TDR
Peak Field	T	2.10	1.67	2.16
No. Poles		8	14	14
Length	m	1.3	2.5	1.875
Period	m	0.40	0.40	0.30
Pole Width	cm	23.8	23.8	23.8
Pole Gap	cm	7.6	7.6	7.6
$\Delta B/B\|_{x=10\,\mathrm{mm}}$	%	0.0077	0.0077	0.06
Coil Current	A	141	112	141
Beam Energy	GeV	1.5–2.5	5	5

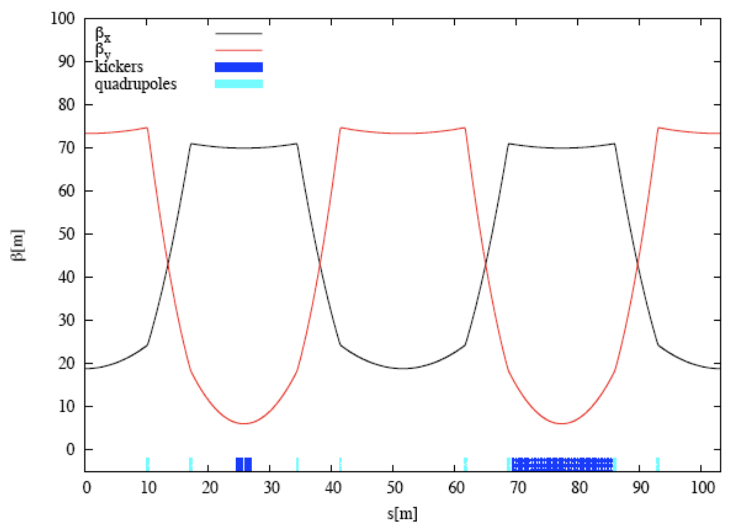
For the other two configurations, requiring nearly twice the beam power, 12 cavities are needed to keep the coupler power reasonably low.
There is space for 16 cavities in the lattice

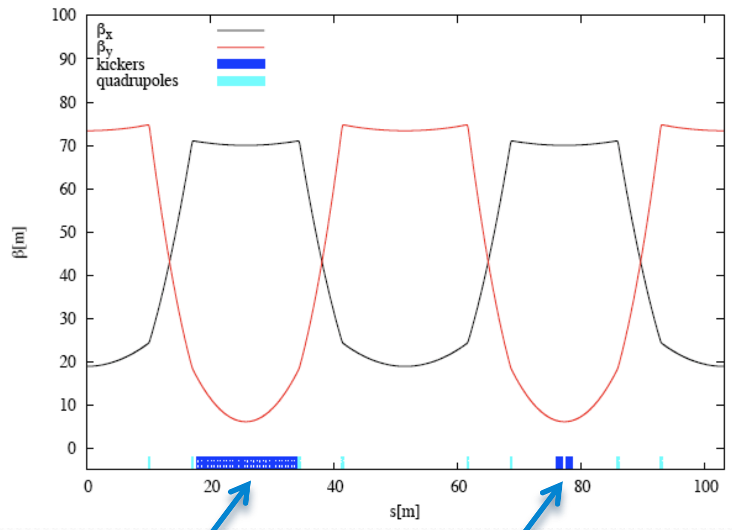
The superferric wigglers are based on the CESR-c design with relatively few but rather long periods to simplify fabrication and to minimize cubic nonlinearity

Peak field	2.16 T
Length	1.9 m
Period	30 cm
Number of poles	14



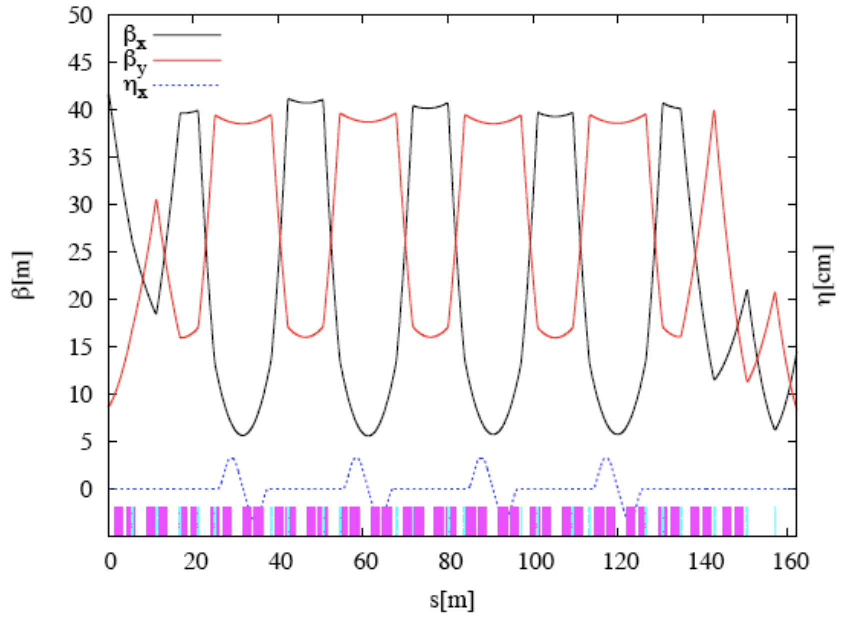
Injection/Extraction





Kickers

Septum



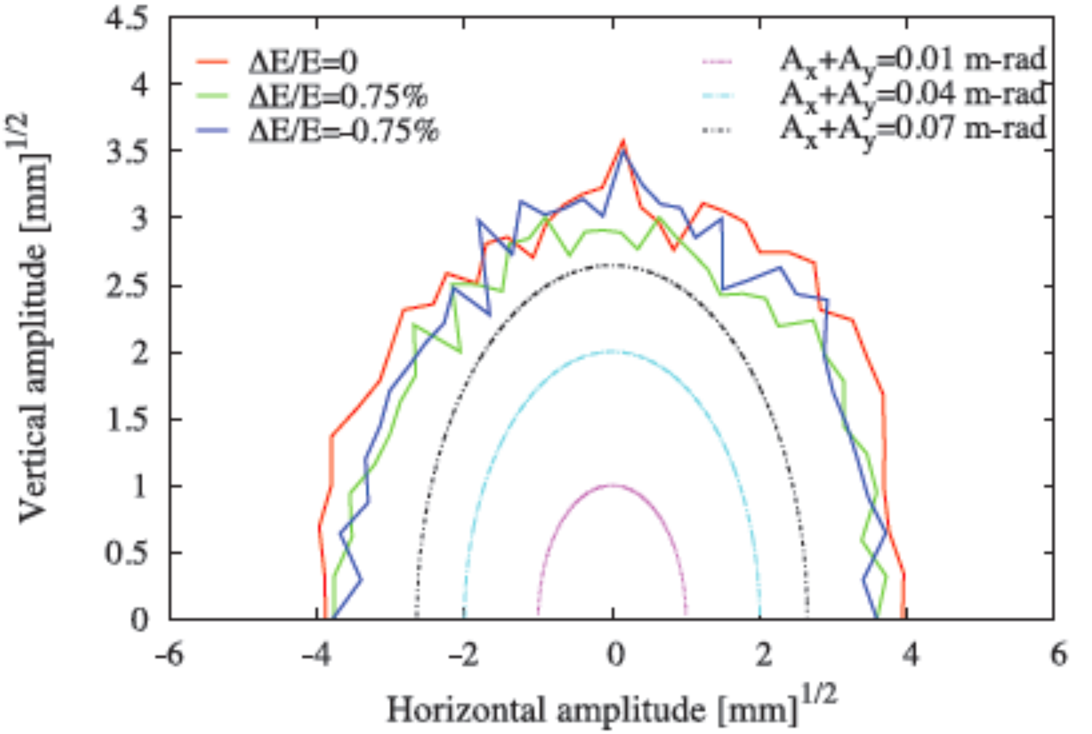
and Circumference Changing Chicane

Dynamic Aperture

Non-linear particle dynamics can limit the phase space volume of stable particles. The principal source of the non-linear behavior arises from the sextupoles used to correct the ring chromaticity. Typically a great deal of effort is spent in trying to achieve the "best" sextupole distribution for a given ring. Of course there are other sources of non-linearities (eg, magnet field errrors). Given the extreme performance parameters that we are pursuing, it is preferable to include all such errors in the analysis.

In calculating the dynamic aperture, particles with a range of initial coordinates and energies are tracked through the ring, typically for several hundred to several thousand turns. The particles which are not lost define the stable phase space volume.

Dynamic Aperture



The wiggler field is computed with a finite-element code (Vector Fields), and fit to an analytic form as a Fourier expansion that automatically satises Maxwell's equations. A symplectic tracking algorithm ensures that the phase space is not distorted by numerical noise

Dynamic Aperture: the largest stable aperture after tracking 1000 turns
Tracking includes misalignments, multipole errors, and wiggler nonlinearities
None of the injected particles are lost in these simulations.

The CLIC Damping Ring

At this point we take a short tour of the present state of design of the CLIC DR. I will acknowledge in advance Y. Papaphilippou and the CLIC DR team for the information presented here

Design Parameters	CLIC	ILC
Energy [GeV]	2.86	5.0
Circumference [m]	420.56	6476
Energy loss/turn [MeV]	4.2	10.3
RF voltage [MV]	4.9	24
Momentum Compaction Factor	$8x10^{-5}$	$1.3\text{-}2.8\times10^{-4}$
Damping time trans/long [ms]	1.88/0.96	21/11
# dipoles / wigglers	100/52	192/88
Dipole/ wiggler field [T]	1.4/2.5	1.6

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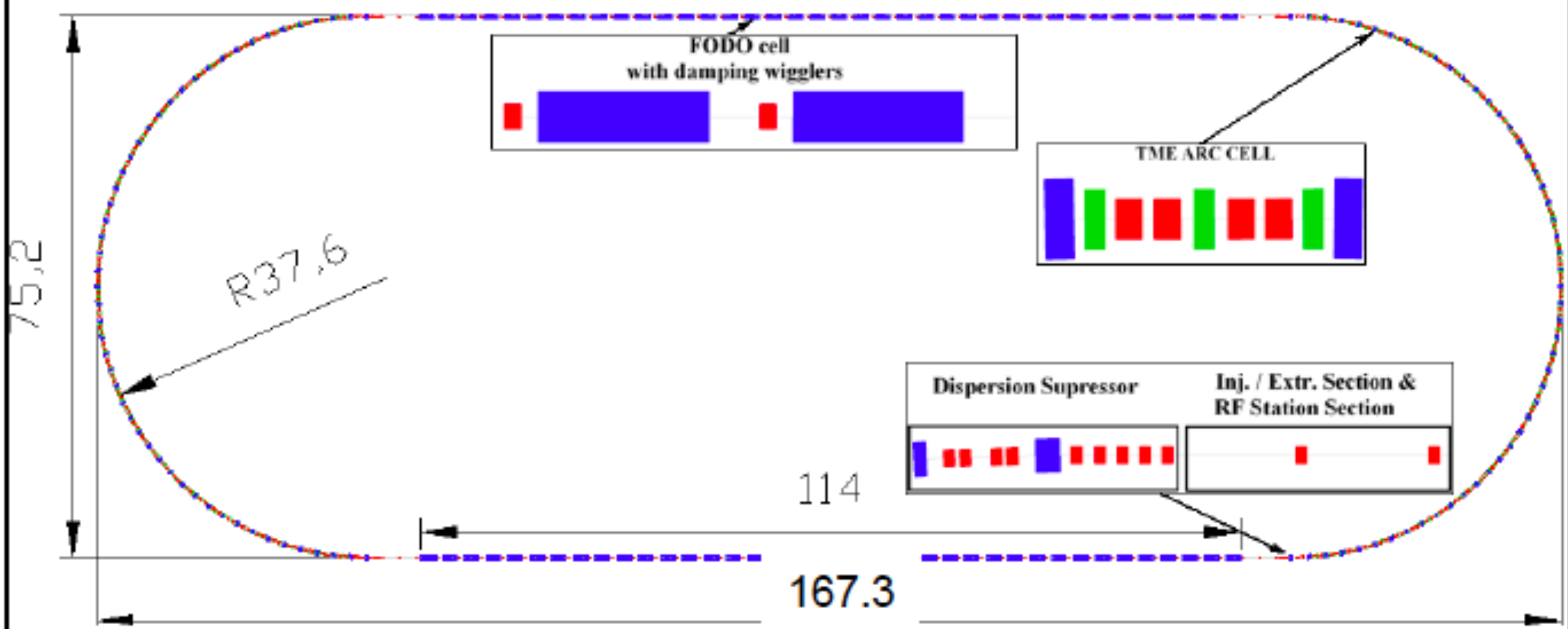
Design Parameters	CLIC	ILC
Energy [GeV]	2.86	5
Circumference [m]	427.5	3238
Energy loss/turn [MeV]	4	4.5
RF voltage [MV]	5.1	14
Momentum Compaction Factor	1.3×10^{-4}	3.3×10^{-4}
Damping time trans/long [ms]	2.0 / 1.0	24 / 12
#dipoles / wigglers	100 / 52	150 / 54
Dipole/ wiggler field [T]	1.0 / 2.5	0.23 / 2.16

Updated 2012

CLIC Damping Ring Layout

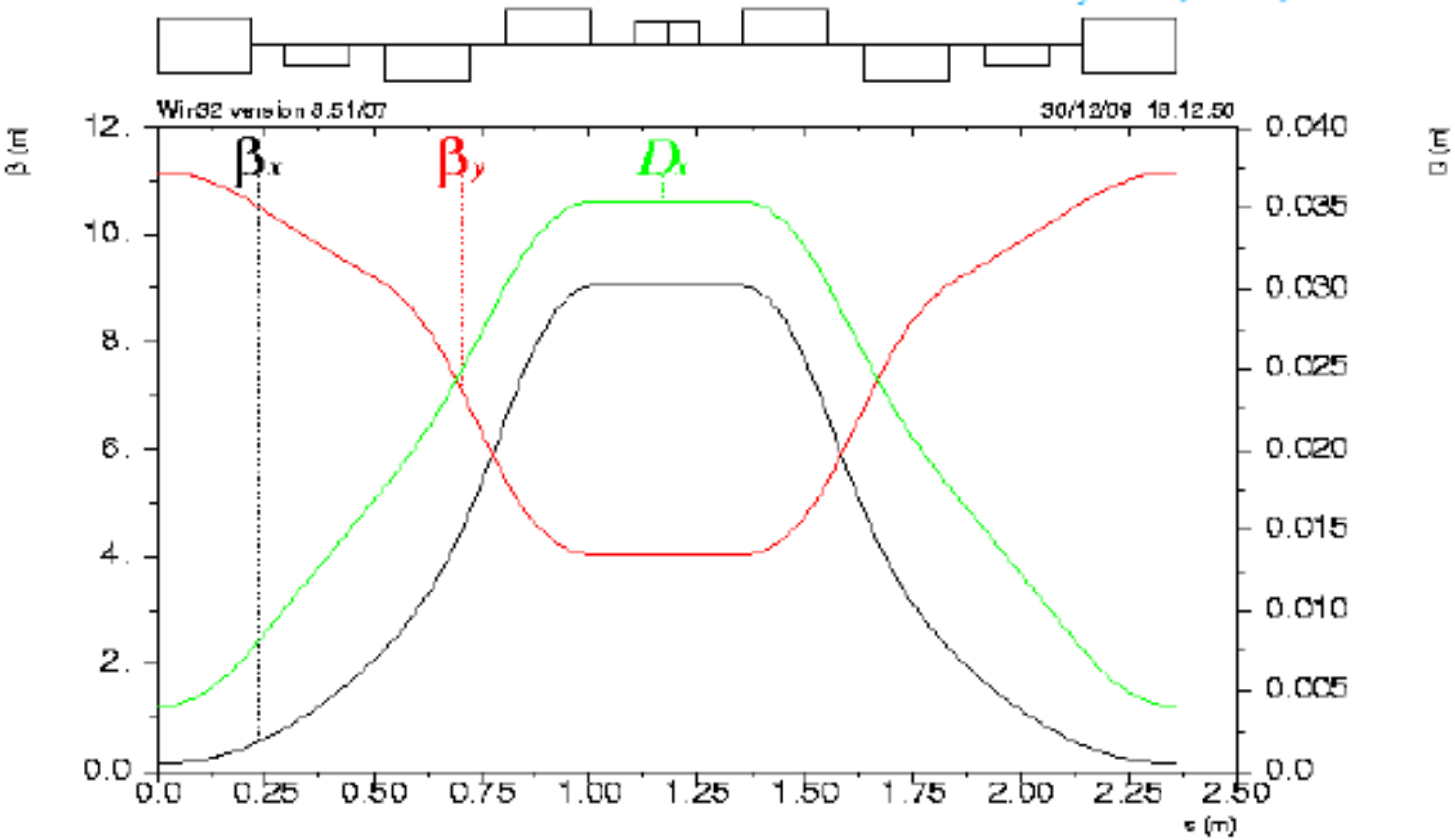
S. Sinyatkin, et al., LER 2010



- Racetrack shape with
  - 96 TME arc cells (4 half cells for dispersion suppression)
  - 26 Damping wiggler FODO cells in the long straight sections (LSS)
  - Space reserved upstream the LSS for injection/extraction elements and RF cavities

Arc Cell

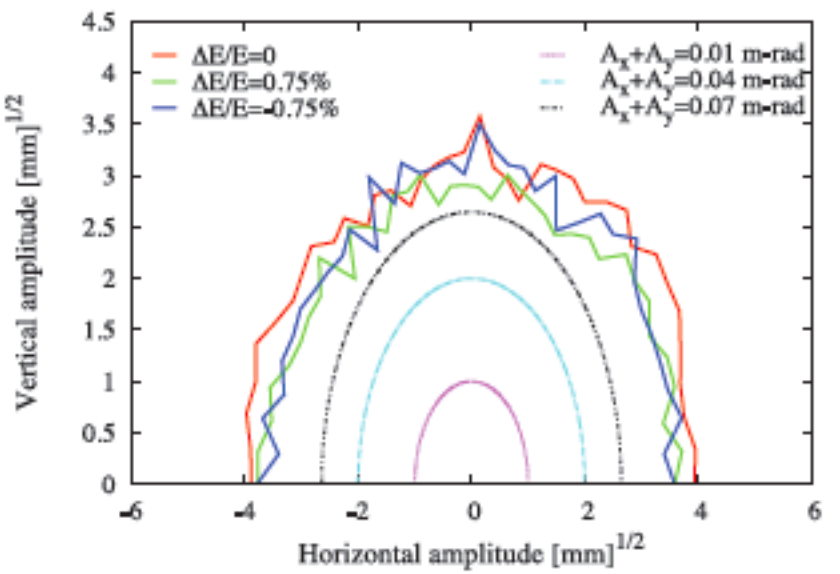
S. Sinyatkin, et al., LER 2010



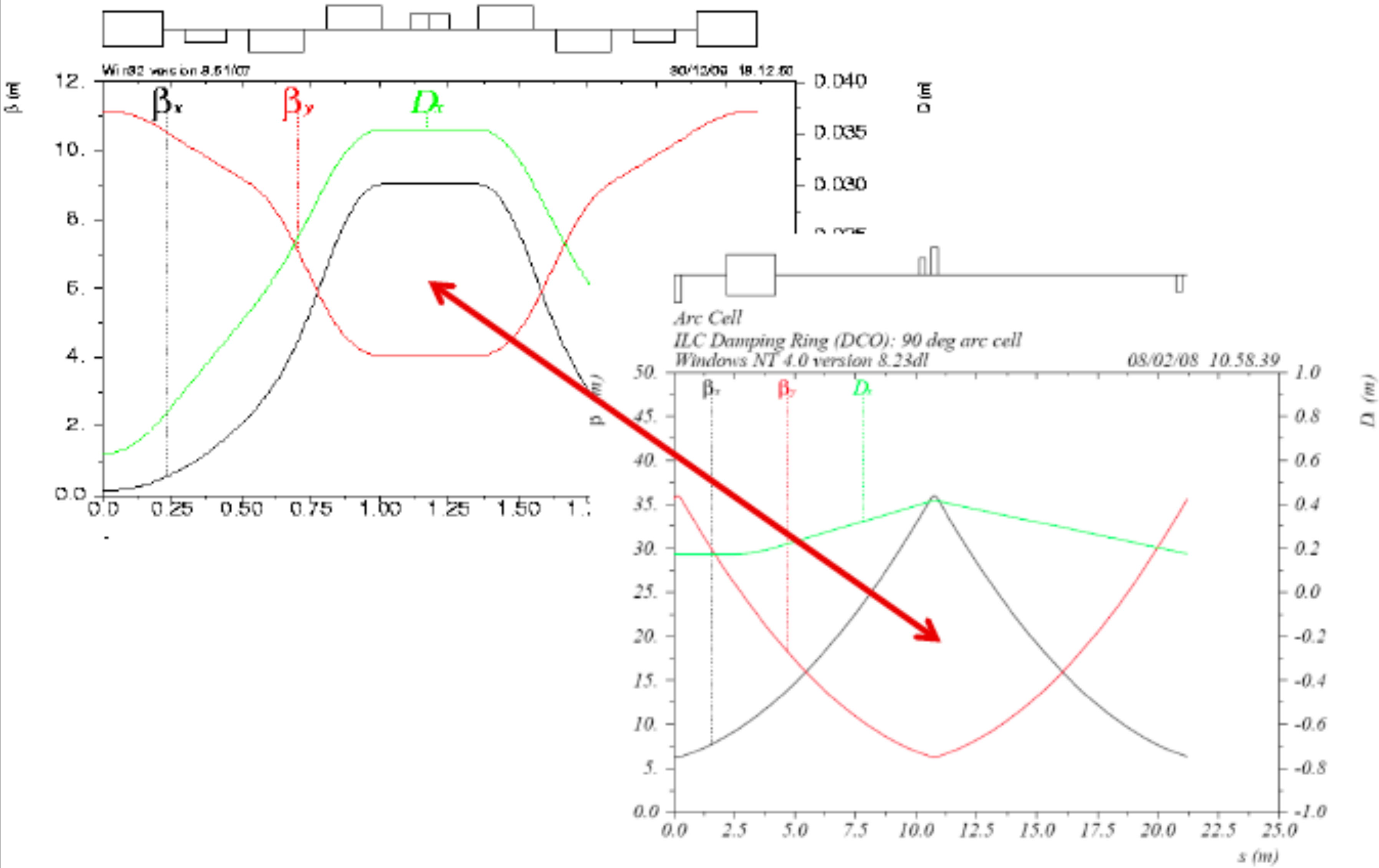
Special Features:

- 2.36m-long TME cells with bends including small gradient
- Detailed control of optics functions throughout the cell enable mitigation of IBS effects

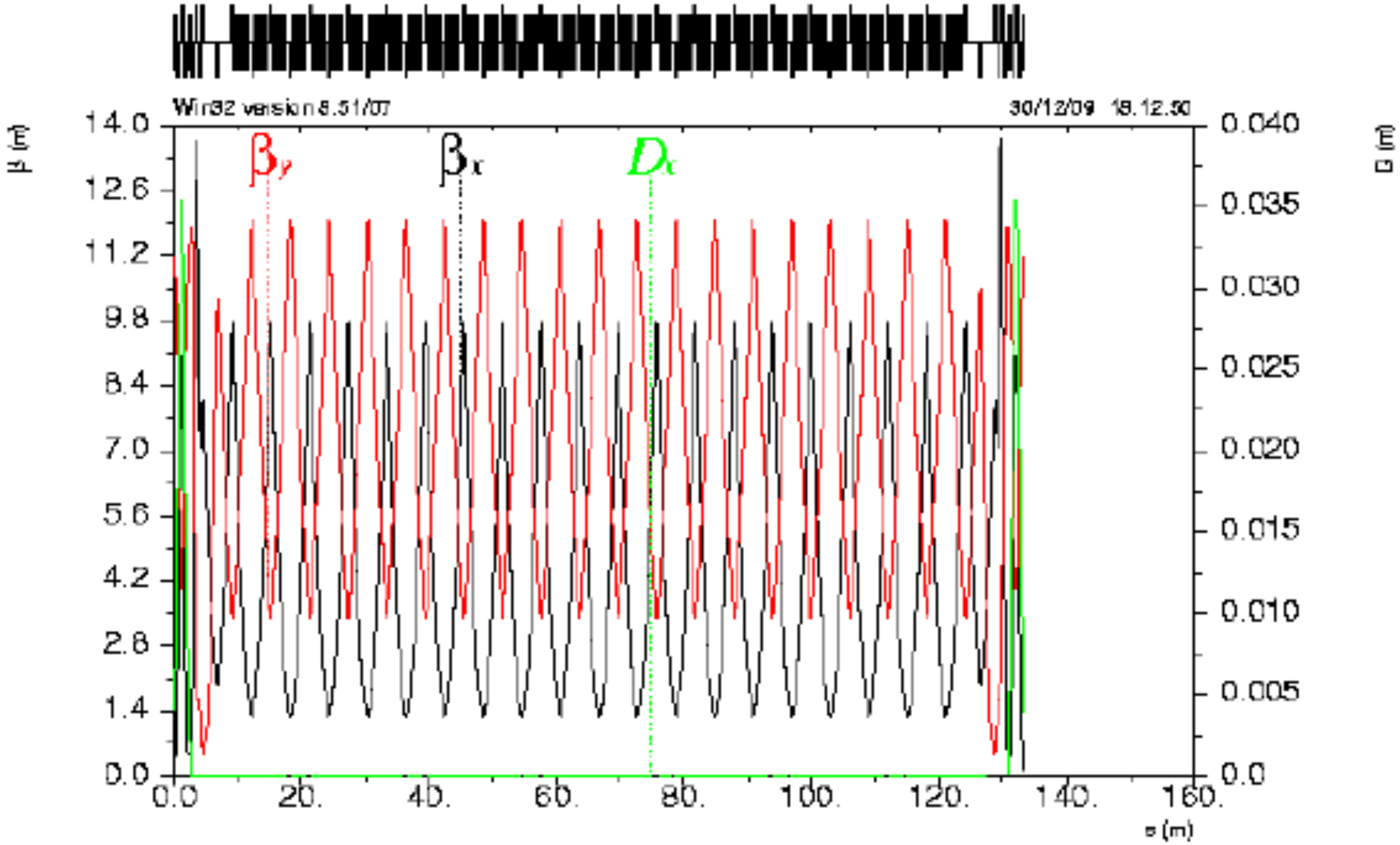
Dynamic aperture



Compare with DCO4



Long Straight Section

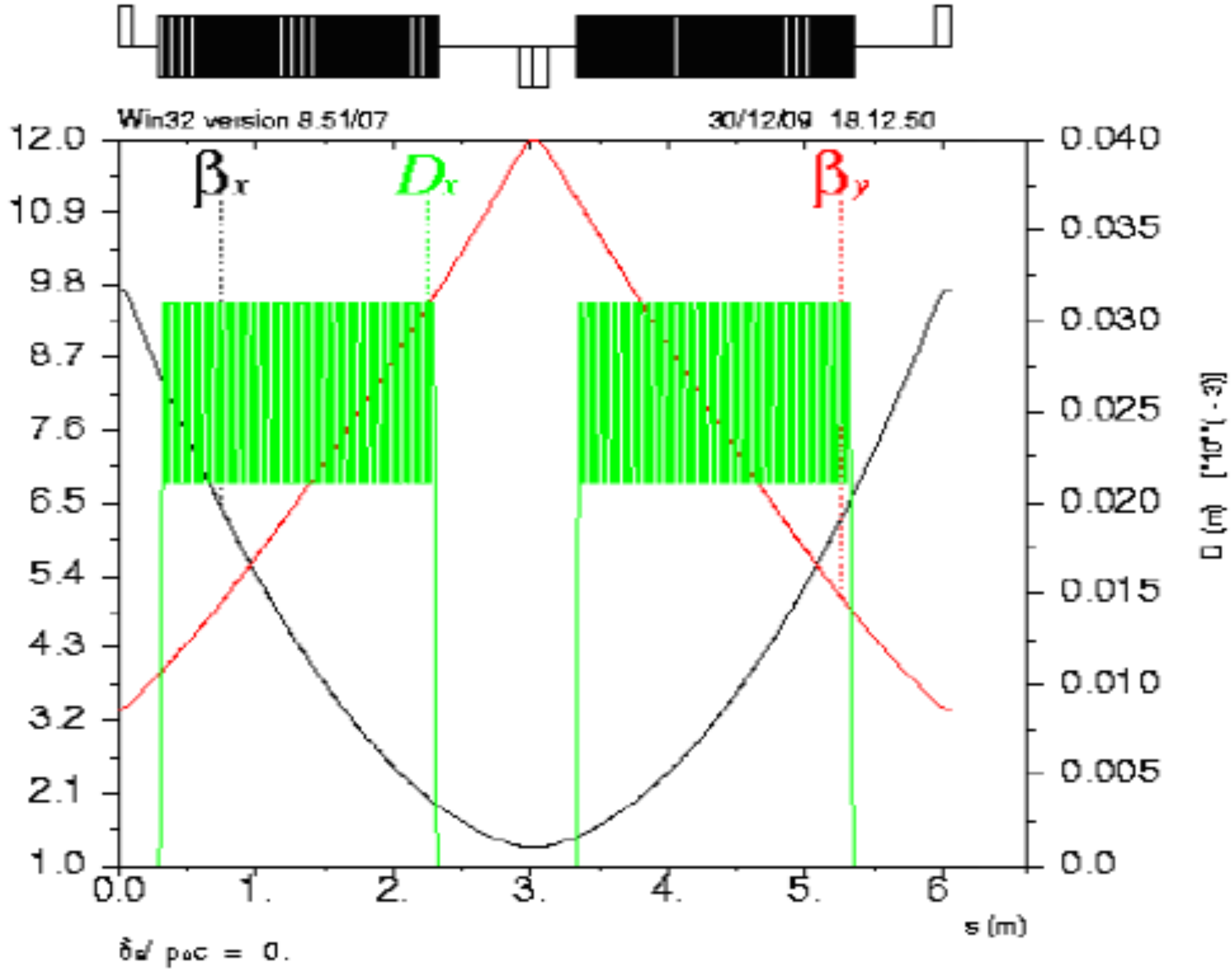


The straight sections are dominated by the 6m FODO cells for the wigglers

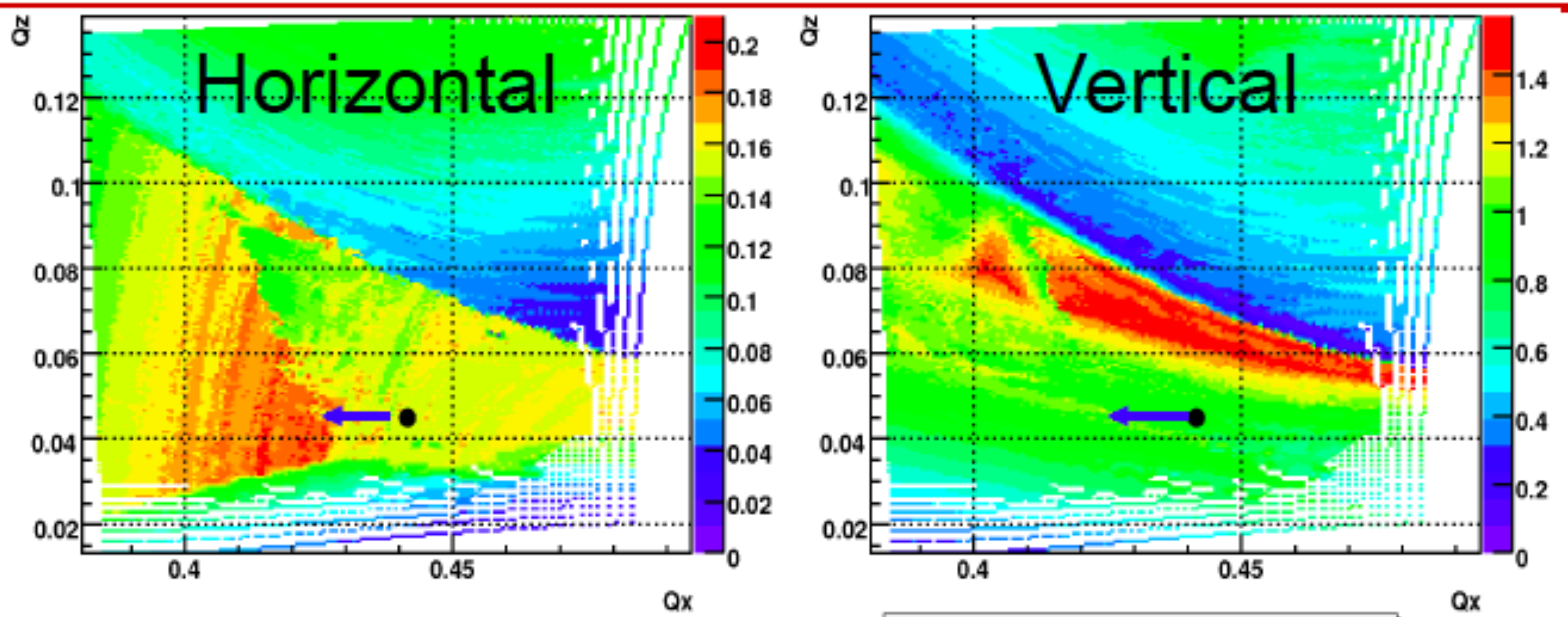
Wiggler Cell

Horizontal phase advance has been optimized for low emittance (we will come back to this later)

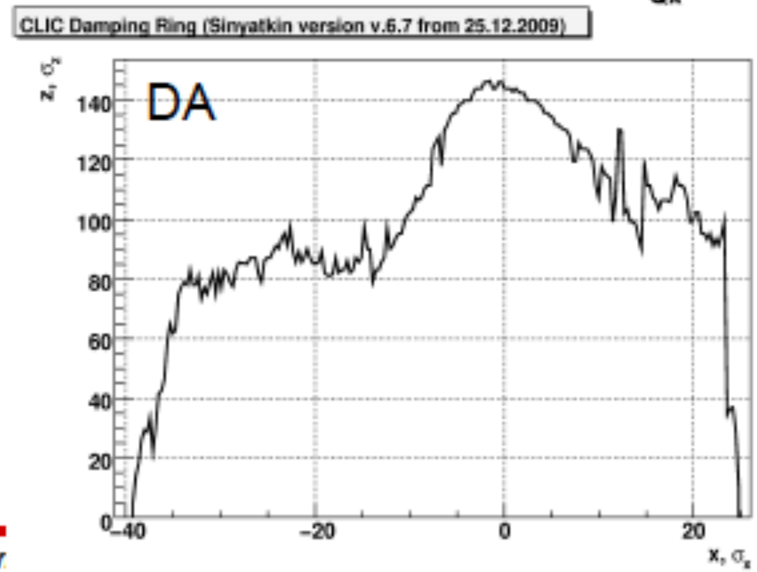
Short drift sections are required due to the need for photon stops



Another look at Dynamic Aperture



- Tune scan simulation to determine optimum working point
- Dynamic aperture appears very good, but
  - Wigglers, misalignments and field errors not yet included



CLIC DR Parameter Summary

At its present stage of development, work has been carried out to ensure that the basic ring components can be built and fit into a physical layout

A significant difference from the ILC design is the use of a combined function (dipole-quad) in the arcs

This has allowed a design with good dynamic aperture and much reduced sensitivity to IBS effects to emerge

But, as with the ILC, much work remains…

Parameters	Value
Energy [GeV]	2.86
Circumference [m]	420.56
Coupling	0.0013
Energy loss/turn [MeV]	4.2
RF voltage [MV]	4.9
Natural chromaticity x / y	-168/-60
Momentum compaction factor	8e-5
Damping time x / s [ms]	1.9/ 0.96
Dynamic aperture x / y [σ_{inj}]	30 / 120
Number of dipoles/wigglers	100/52
Cell /dipole length [m]	2.36 / 0.43
Dipole/Wiggler field [T]	1.4/2.5
Bend gradient [1/m^2]	-1.10
Max. Quad. gradient [T/m]	73.4
Max. Sext. strength [kT/m^2]	6.6
Phase advance x / z	0.452/0.056
Bunch population, [10^9]	4.1
IBS growth factor	1.4
Hor./ Ver Norm. Emittance [nm.rad]	400 / 4.5
Bunch length [mm]	1.6
Longitudinal emittance [keVm]	5.5

Summary

During today's lecture, we have reviewed the basics of storage ring physics with particular attention on the effect know as radiation damping which is central to the operation of storage and damping rings. We have also had an overview of the key design elements presently incorporated into the ILC damping ring lattice and the CLIC damping ring lattice. The homework problems will provide an opportunity to become more familiar with some of these issues.

Tomorrow we will look in greater detail at specific systems and specific physics effects which play significant roles in the successful operation of a damping ring.