Low emittance lattice for 6km ILC damping ring

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LC-UK damping rings research goals

Lattice design (Maxim Korostelev)

- Make necessary modifications and improvements to the present 6.4 km baseline lattice.
- Develop designs for the injection/extraction lines.

Vacuum system technical design and costing (Oleg Malyshev/Norbert Collomb/John Lucas/Steve Postlethwaite)

- Develop technical design for vacuum system and magnet supports.
- Produce costing based on technical design.

Impedance model and instabilities (Maxim Korostelev)

- Develop impedance model based on technical design of vacuum system.
- Evaluate impact of impedance on beam dynamics.

Low-emittance tuning (Kosmas Panagiotidis)

- Evaluate techniques for low-emittance tuning based on experience at ATF, CesrTA, and other machines.
- Specify requirements for diagnostics and correction systems.

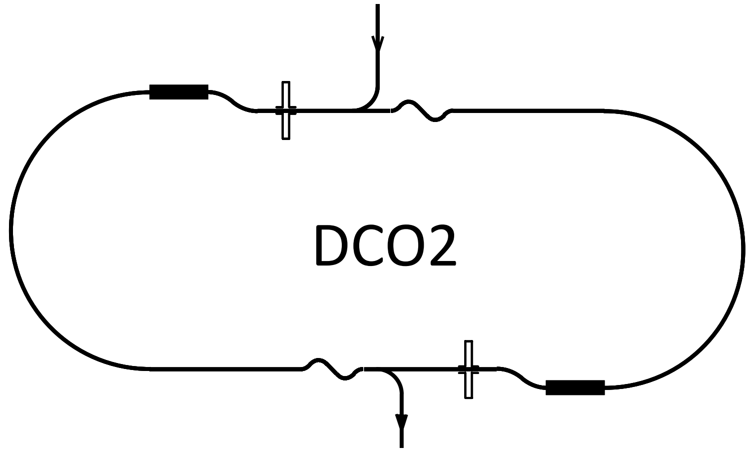
Coordination of LC-UK damping ring activity listed above (Andy Wolski)

Evolution of the lattice design

Jan 2008: DCO2

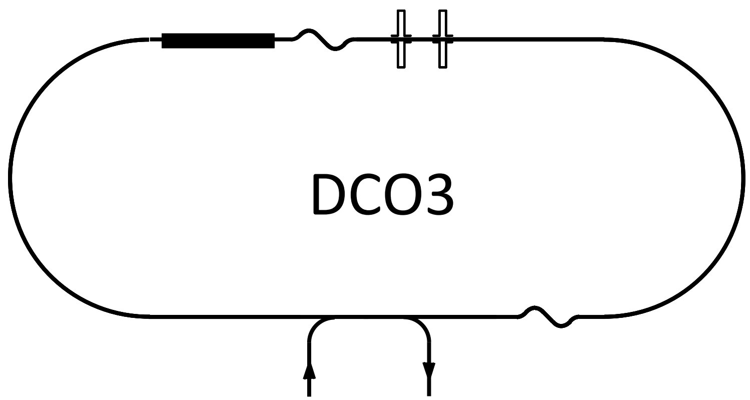
A new lattice design (DCO2) for the ILC damping ring has been developed since the beginning of 2008 as a lower cost alternative to the previous OCS6 design.

- 6.4 km circumference racetrack layout
- FODO - style arc cells
- Injection/extraction in opposite straights
- The left straight section is similar to the write straight section



Mar 2009: DCO3

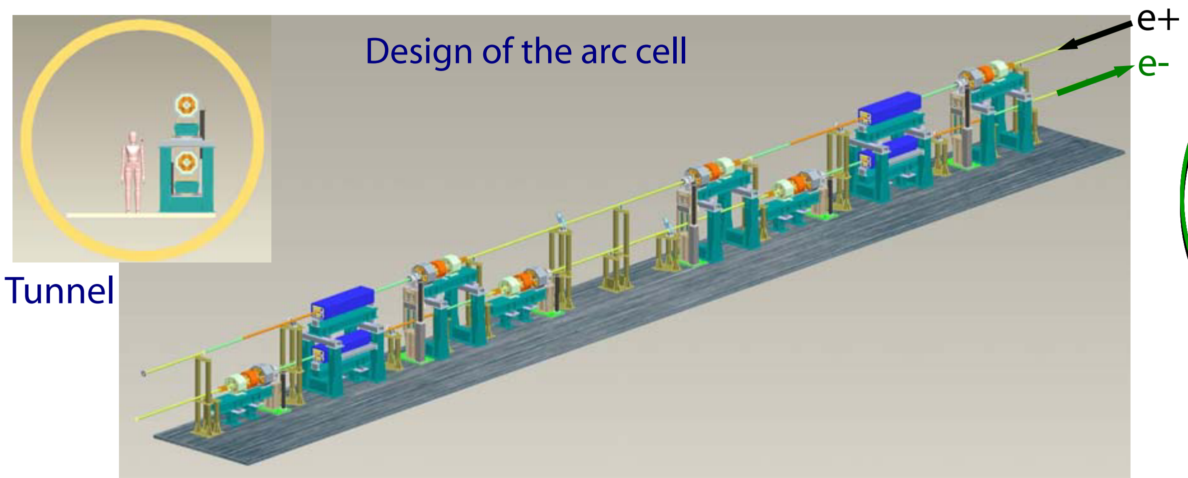
Redesign of the long straight sections was done to arrange the injection and extraction in one straight and to locate all wigglers and RF cavities into other straight.

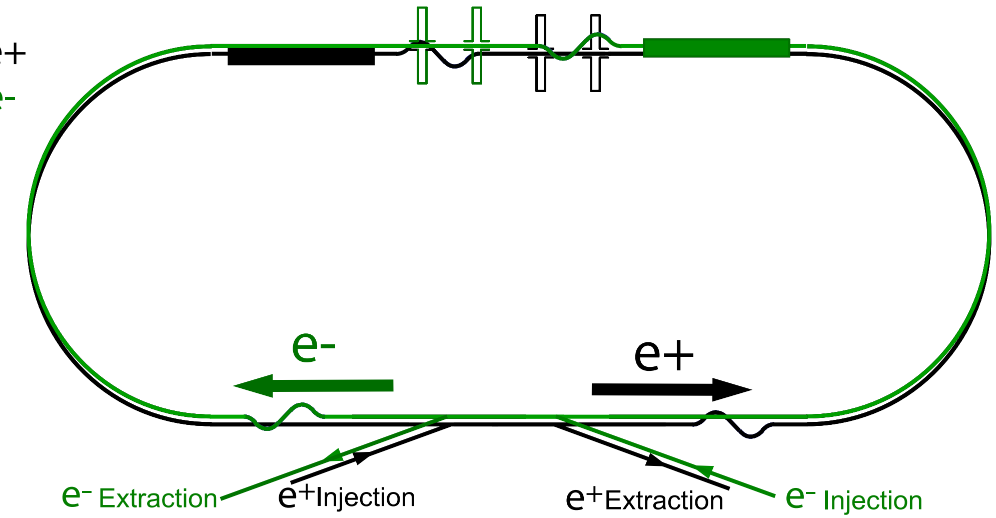


Evolution of the lattice design

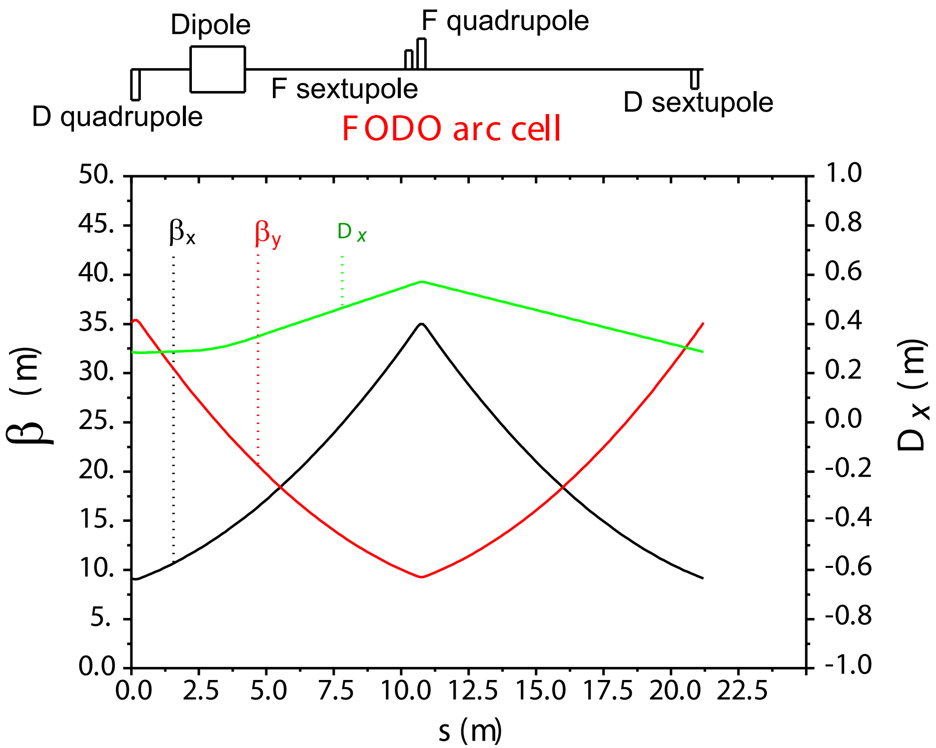
Aug 2009: DCO4 - the latest design

- The lattices for the electron and positron damping rings are identical
- The lattice meets the engineering requirements for arrangement of the positron ring directly above the electron ring in the same tunnel, using common girders for the arc dipole magnets in the two rings, but with the beams circulating in opposite directions.
- Single tunnel for the injection and extraction beam lines can be used.
- RF cavities of the e+ and e- DR rings do not overlap each other

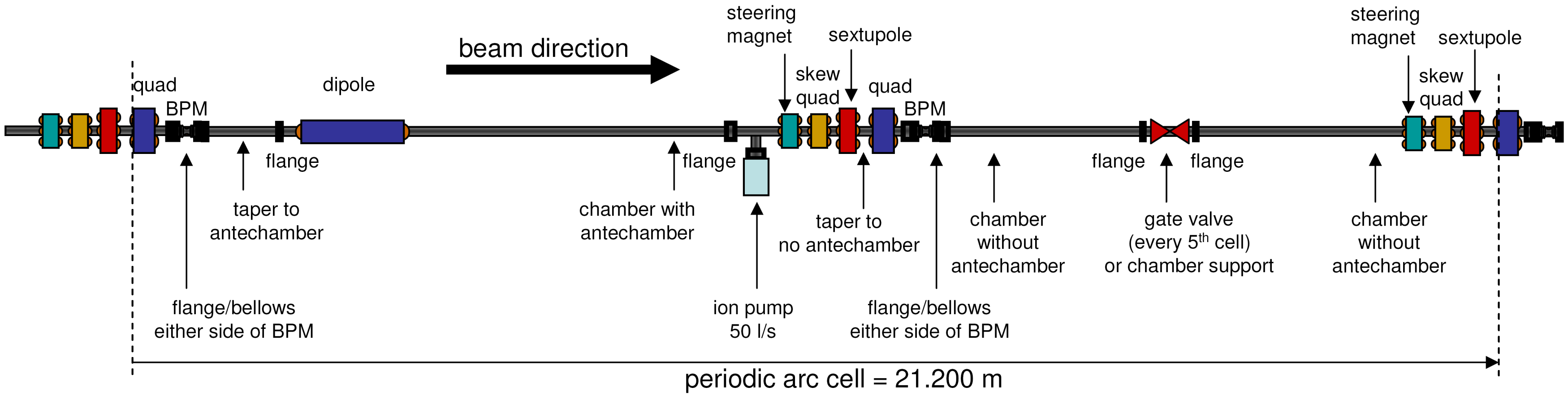




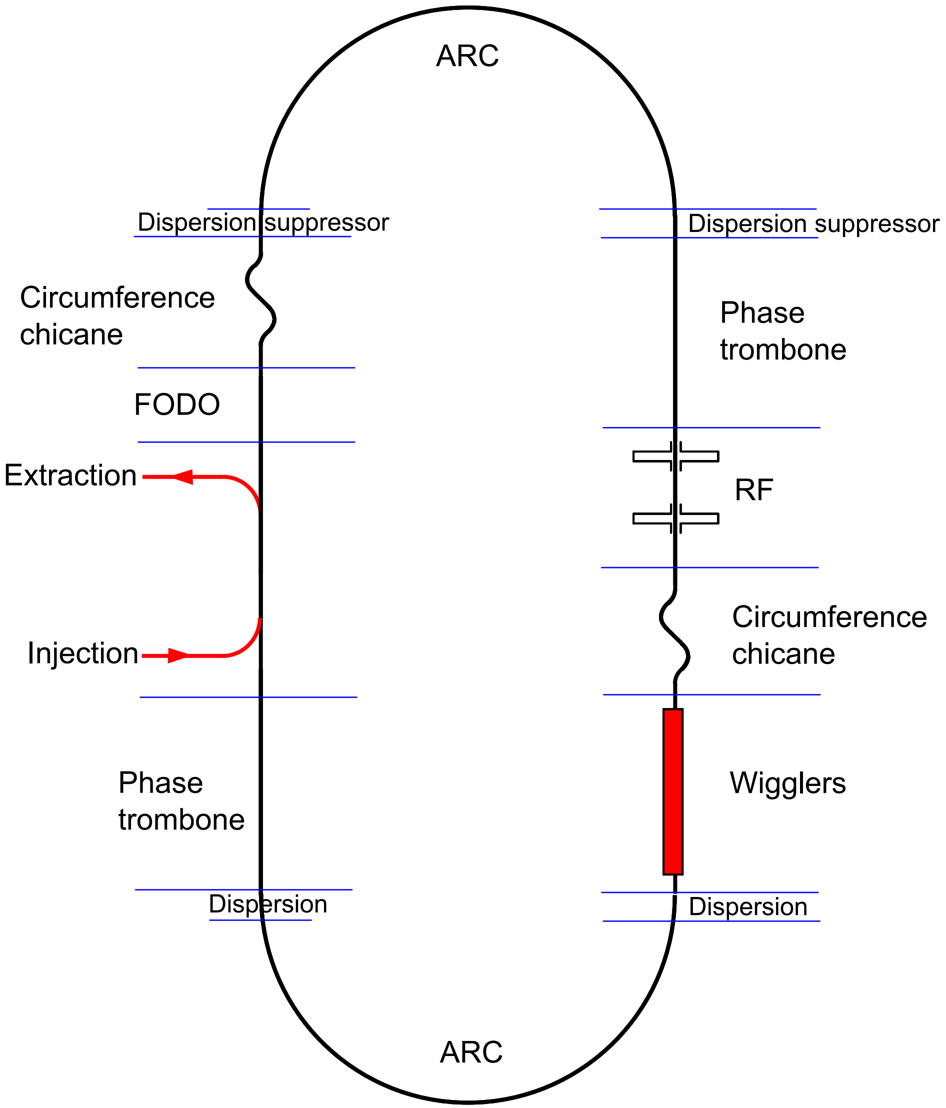
DCO4 lattice design: FODO arc cell

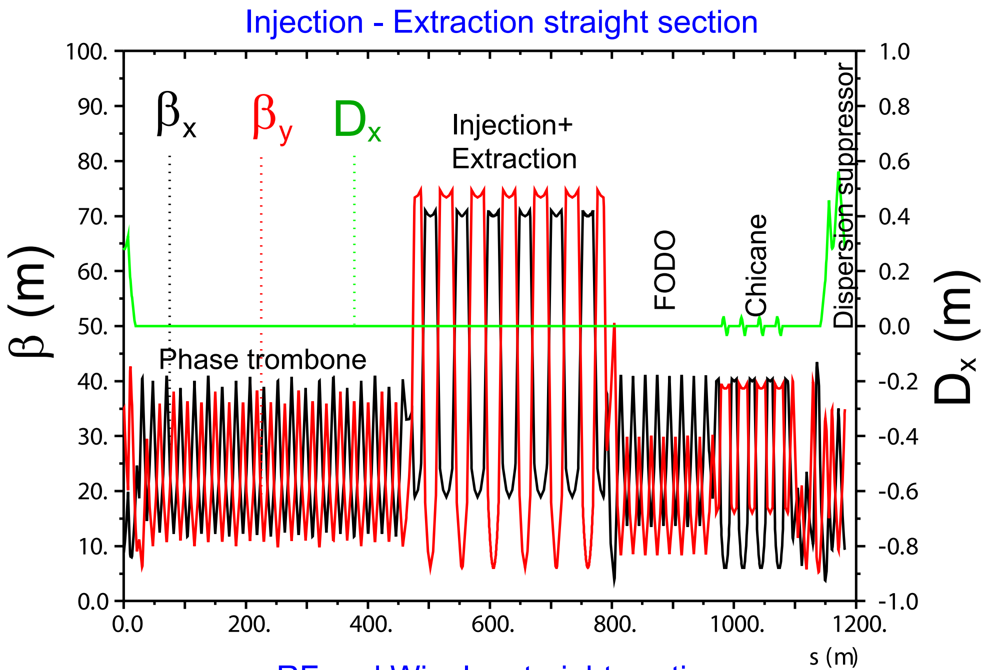


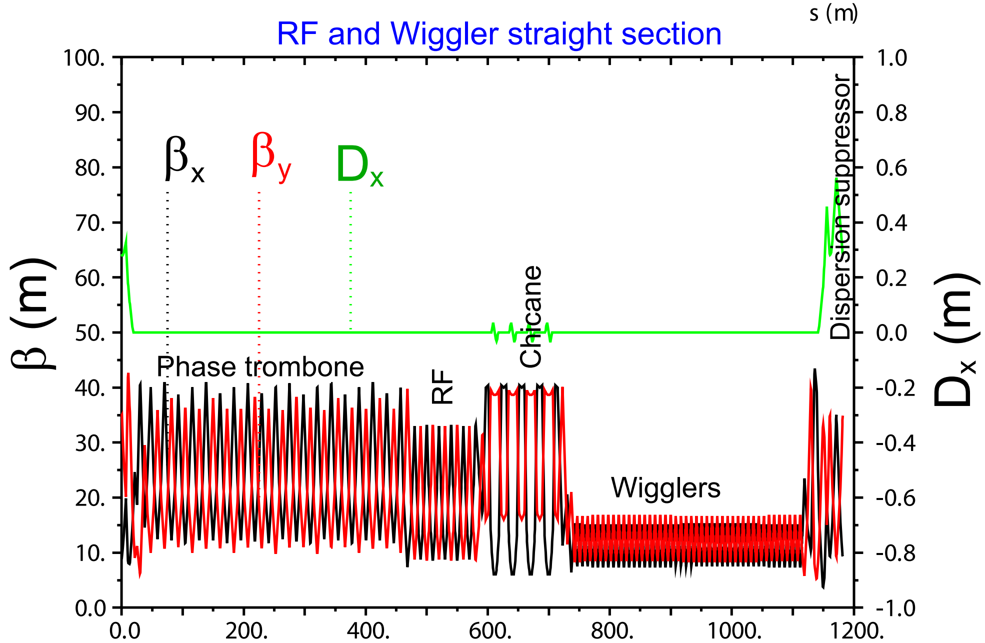
Arc FODO cell length	21.2 m
Arc dipole length	2.0 m
Number of FODO cells	200
Total number of sextupoles	392
Arc dipole field	0.262 T



DCO4 lattice design: straight sections



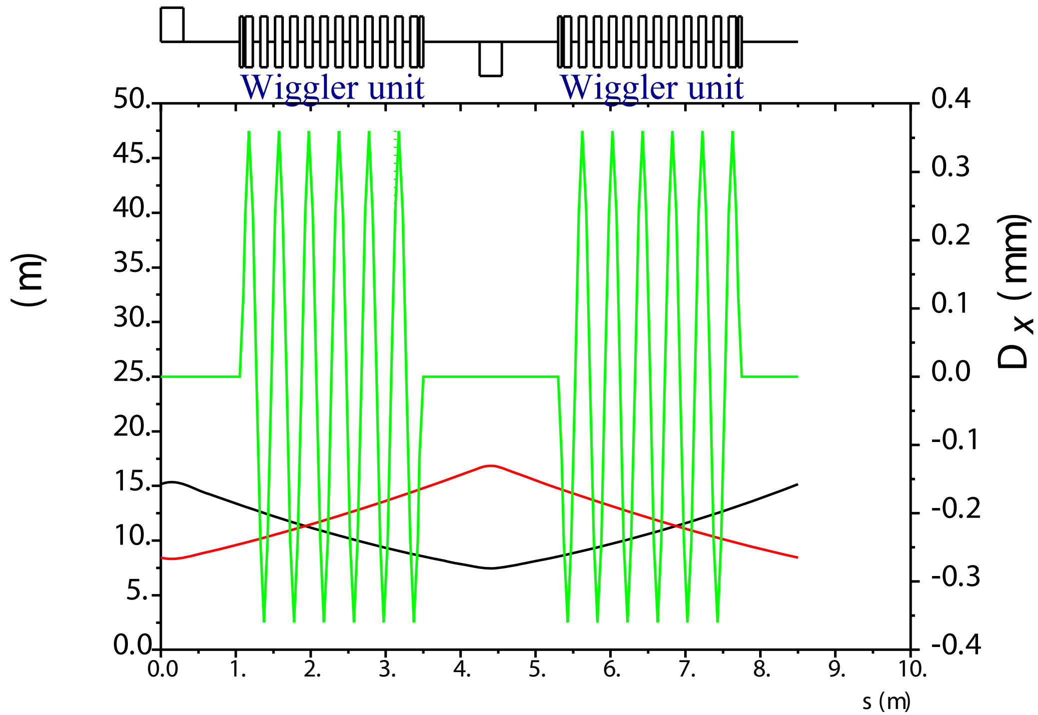


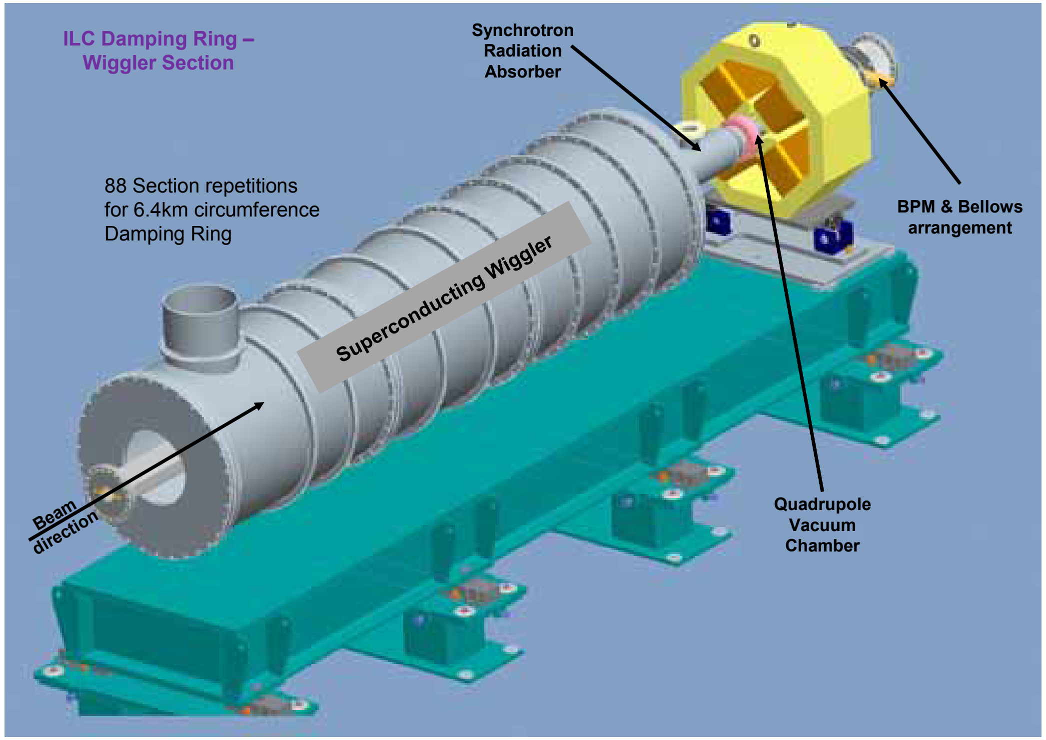


DCO4 lattice design: FODO wiggler section

88 superconducting wiggler magnets in the ring

Wiggler type	Superconducting
Wiggler peak field	1.6 T
Wiggler period	0.4 m
Wiggler unit length	2.45 m
Wiggler total length	215.6 m





DCO4 lattice parameters and beam characteristics

Beam energy	5 GeV
Circumference	6476.4 m
RF frequency	650 MHz
Harmonic number	14042
Transverse damping time	21.1 ms
Type and # of arc cells	FODO with one dipole 200
Total length of wigglers	215.6 m
Wiggler peak field	1.6 T
Relative damping factor	10.08
Energy loss per turn	10.23 MeV/turn

Phase advance per arc cell	72°	90°	100°
Momentum compaction	2.9×10^{-4}	1.6×10^{-4}	1.3×10^{-4}
Normalized horiz. emittance	6.4 μm	4.4 μm	3.9 μm
RMS bunch length	6.0 mm	6.0 mm	6.0 mm
RMS energy spread	1.27×10^{-3}	1.27×10^{-3}	1.27×10^{-3}
RF voltage	32.6 MV	20.4 MV	17.1 MV
RF acceptance	2.38 %	1.96 %	1.72 %
Synchrotron tune	0.063	0.036	0.028
Horizontal betatron tune	61.12	71.12	76.12
Vertical betatron tune	60.41	71.41	75.41
Natural horiz. chromaticity	-71.0	-89.2	-99.8
Natural vert. chromaticity	-72.6	-91.0	-100.7

692 - quads, BPMs; 392 - sextupoles, skew quads; 20 RF cavities

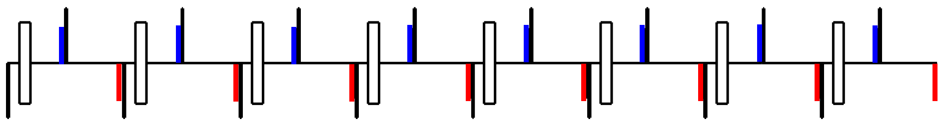
- Ability to adjust phase advance in the arcs allows possibility to balance rf voltage requirements versus instability thresholds.
- Low momentum compaction allows the machine to operate with reduced rf voltage and shorter bunch length.
- The reduced rf voltage helps reduce the costs of the damping rings.

Arrangement of sextupoles in the arcs

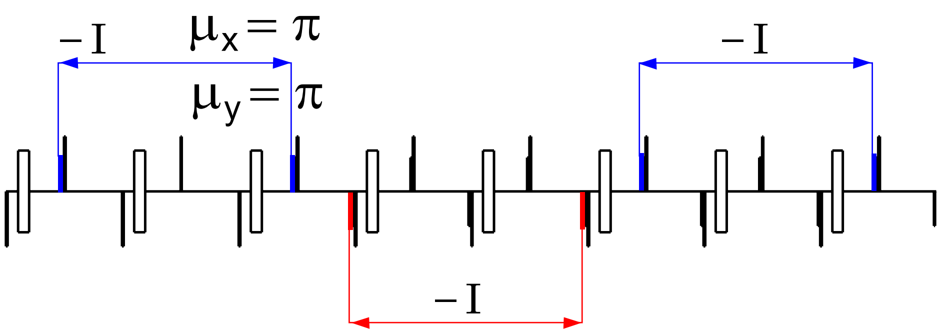
- Two interleaved sextupole families are arranged in the arcs when phase advance per FODO arc cell is 72 or 100 degree.

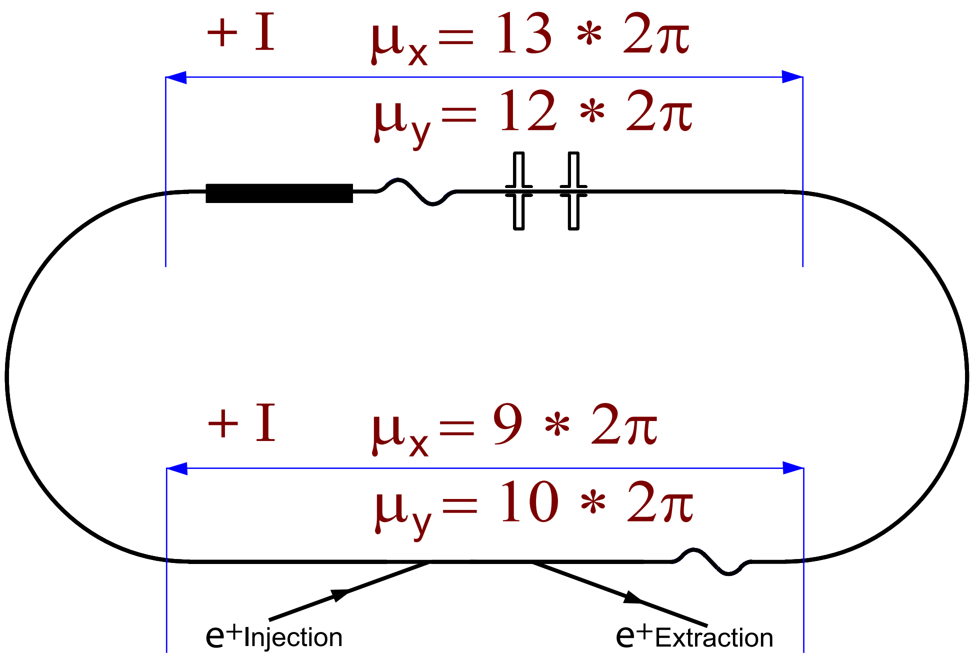
- For the particular case when phase advance in the arc cell is close to 90 degree a non-interleaved -I arrangement of the sextupole pairs is applied.

Interleaved arrangement of sextupole at phase advance of 72 and 100 degree



Non-interleaved arrangement of sextupole at phase advance of 90 degree

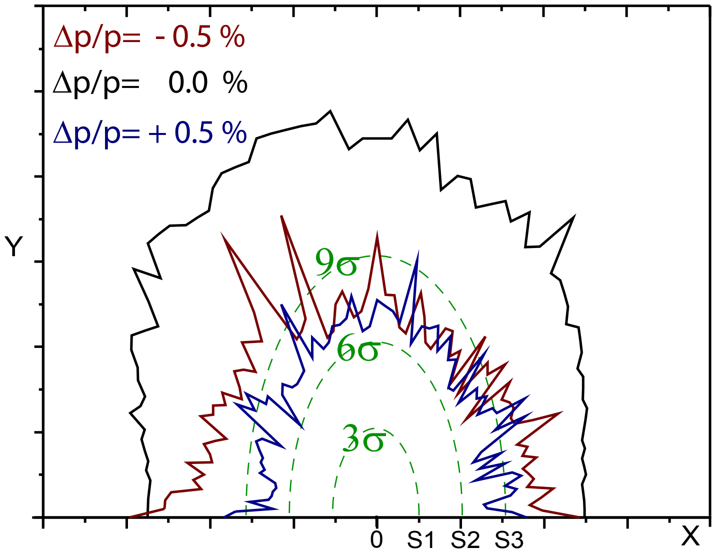




Dynamic aperture of the DCO4 lattice at the arc cell phase advance close to:

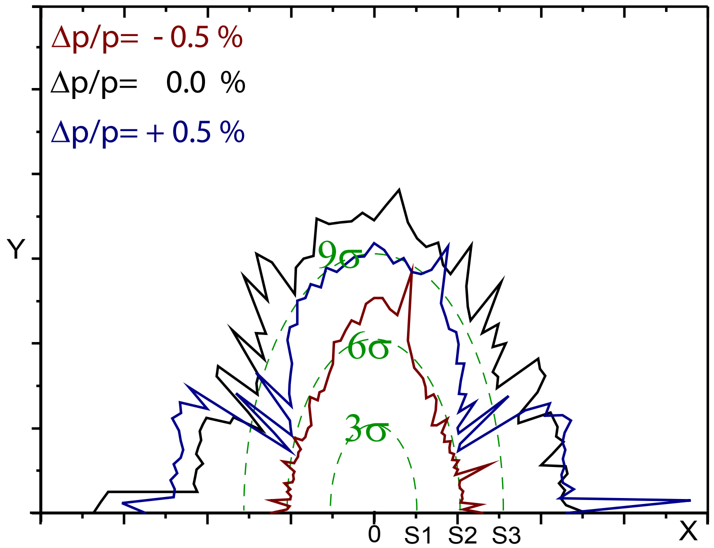
72°	90°	100°

DCO4 ($\nu x/\nu y$ = 61.12 / 60.41)



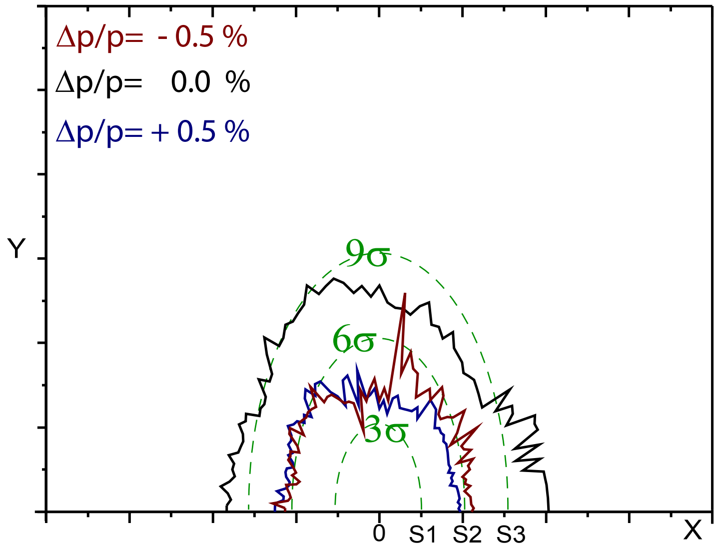
Interleaved arrangement

DCO4 ($\nu x/\nu y$ = 71.12 / 71.41)



Non-interleaved arrangement

DCO4 ($\nu x/\nu y$ = 76.12 / 75.41)



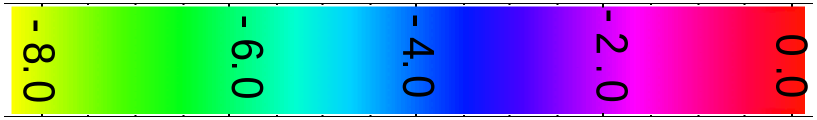
Interleaved arrangement

Dashed ellipses show maximum particle coordinates for injected beam size:

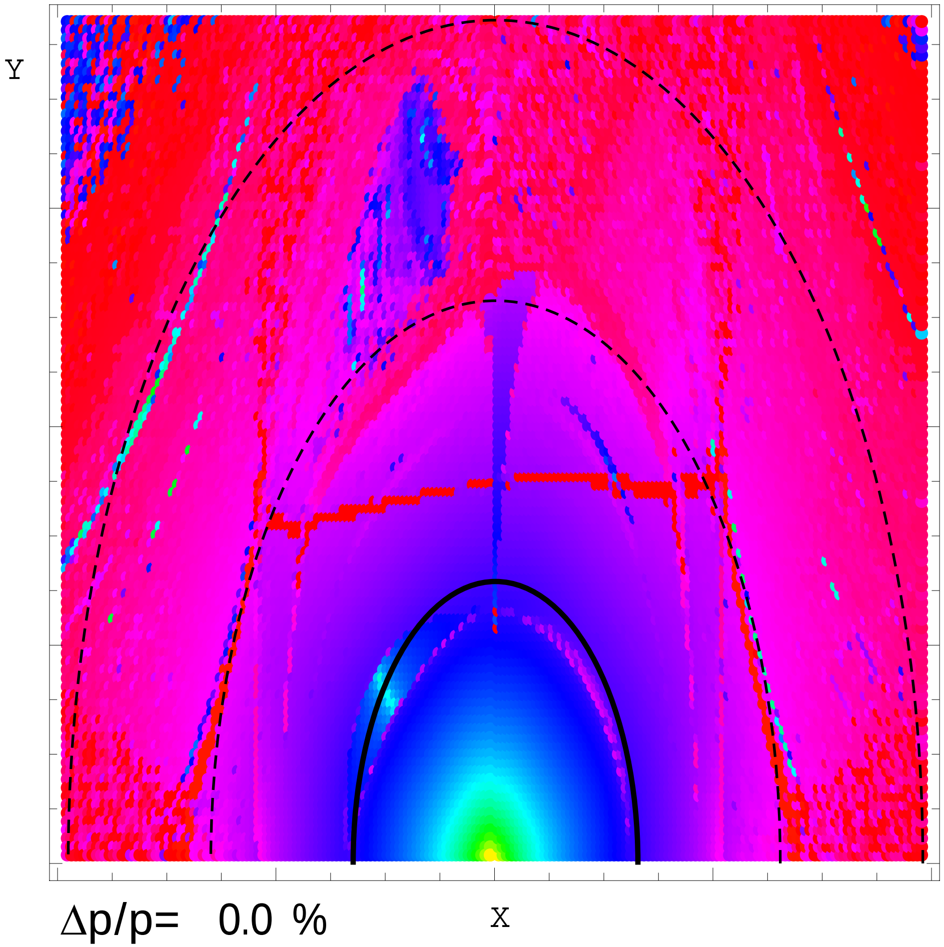
S1 is one maximum injected beam size truncated at 3σ : 25 mm horizontally and 7.4 mm vertically

S1 - one injected beam size
S2 - double injected beam size
S3 - triple injected beam size

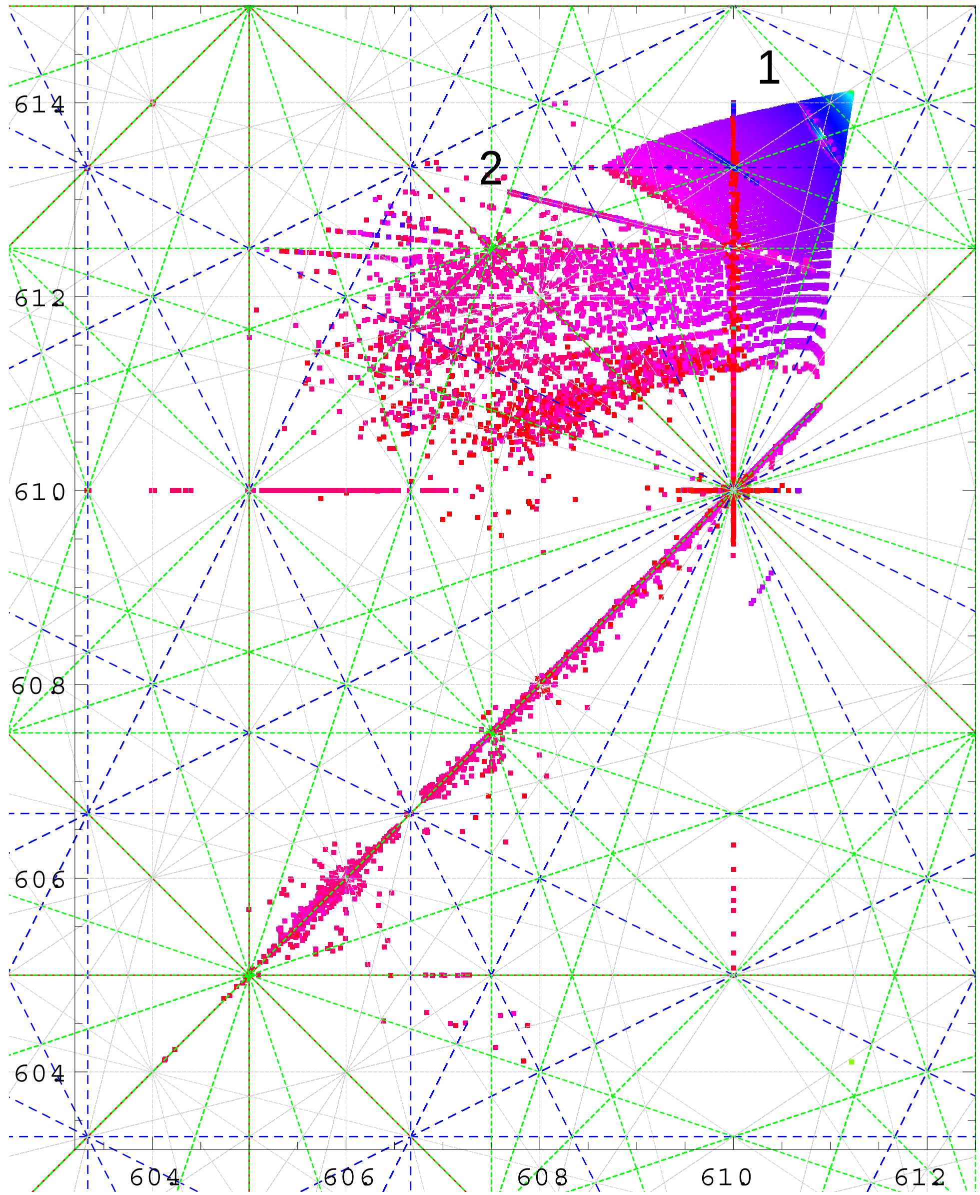
Frequency map analysis of the lattice



$$\Delta\nu = \log_{10}\sqrt{(\nu_x^{1024}-\nu_x^{512})^2+\left(\nu_y^{1024}-\nu_y^{512}\right)^2}$$



Δp/p= 0.0 %



1) $3\nu x + 2\nu y = 306$

2) $\nu x + 4\nu y = 306$

IBS contribution to beam emittance: Piwinski solution

Equilibrium beam emittance by the solution

$$\frac{d\epsilon_x}{dt} = -\frac{2}{\tau_x}(\epsilon_x - \epsilon_{x0}) + \frac{2\epsilon_x}{T_x(\epsilon_x, \epsilon_y, \sigma_p)}$$

$$\frac{d\epsilon_y}{dt} = -\frac{2}{\tau_y}(\epsilon_y - \epsilon_{y0}) + \frac{2\epsilon_y}{T_y(\epsilon_x, \epsilon_y, \sigma_p)}$$

$$\frac{d\sigma_p}{dt} = -\frac{1}{\tau_p}(\sigma_p - \sigma_{p0}) + \frac{\sigma_p}{T_p(\epsilon_x, \epsilon_y, \sigma_p)}$$

$$\frac{d\epsilon_x}{dt} = \frac{d\epsilon_y}{dt} = \frac{d\sigma_p}{dt} = 0$$

Modified Piwinski formulation have been used

$$\frac{1}{\sigma_h^2} = \frac{1}{\sigma_p^2} + \frac{D_x^2}{\beta_x\,\epsilon_x} + \frac{D_y^2}{\beta_y\,\epsilon_y} \longrightarrow \frac{1}{\sigma_H^2} = \frac{1}{\sigma_p^2} + \frac{\mathcal{H}_x}{\epsilon_x} + \frac{\mathcal{H}_y}{\epsilon_y}$$

IBS growth time

$$\frac{1}{T_p} = A\left\langle \frac{\sigma_h^2}{\sigma_p^2} f(\tilde{a}, \tilde{b}, \tilde{q}) \right\rangle$$

$$\frac{1}{T_x} = A\left\langle f\left(\frac{1}{\tilde{a}}, \frac{\tilde{b}}{\tilde{a}}, \frac{\tilde{q}}{\tilde{a}}\right) + \frac{D_x^2\sigma_h^2}{\beta_x\epsilon_x} f(\tilde{a}, \tilde{b}, \tilde{q}) \right\rangle$$

$$\frac{1}{T_y} = A\left\langle f\left(\frac{1}{\tilde{b}}, \frac{\tilde{a}}{\tilde{b}}, \frac{\tilde{q}}{\tilde{b}}\right) + \frac{D_y^2\sigma_h^2}{\beta_y\epsilon_y} f(\tilde{a}, \tilde{b}, \tilde{q}) \right\rangle$$

$$f(\tilde{a}, \tilde{b}, \tilde{q}) = 8\pi \int_0^1 du\, \frac{(1-3u^2)}{PQ} \left\{ 2\ln\left[\frac{\tilde{q}}{2}\left(\frac{1}{P} + \frac{1}{Q}\right)\right] - 0.577\cdots \right\}$$

$$P^2 = \tilde{a}^2 + (1-\tilde{a}^2)u^2$$

$$Q^2 = \tilde{b}^2 + (1-\tilde{b}^2)u^2$$

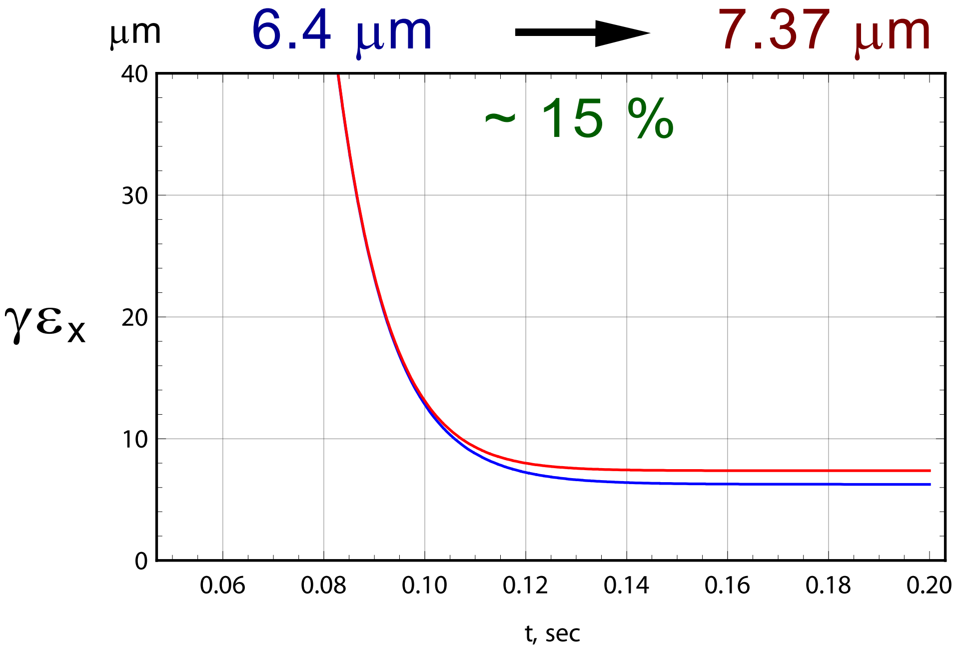
$$\tilde{b} = \frac{\sigma_h}{\gamma}\sqrt{\frac{\beta_y}{\epsilon_y}}$$

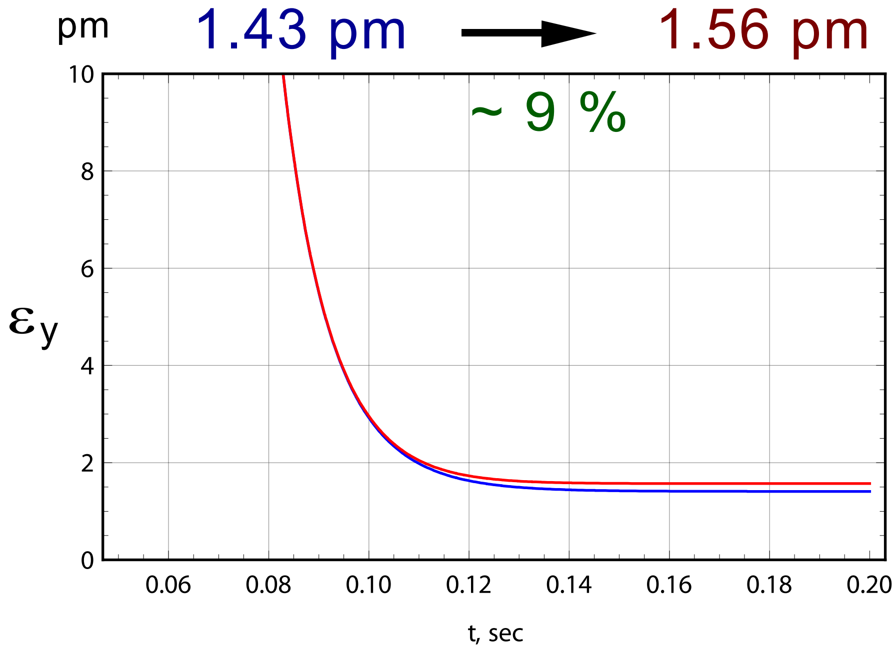
$$\tilde{a} = \frac{\sigma_h}{\gamma}\sqrt{\frac{\beta_x}{\epsilon_x}} \qquad \tilde{q} = \sigma_h \beta \sqrt{\frac{2d}{r_0}}$$

IBS contribution to beam emittance at the phase advance of 72 degree

Standard deviation of random errors assigned to the sextupoles (no corrections were applied)

$$\langle \Delta Y_{\text{sext}} \rangle = \langle \Delta X_{\text{sext}} \rangle = 20\ \mu m$$





Betatron coupling: k = 0.14 %

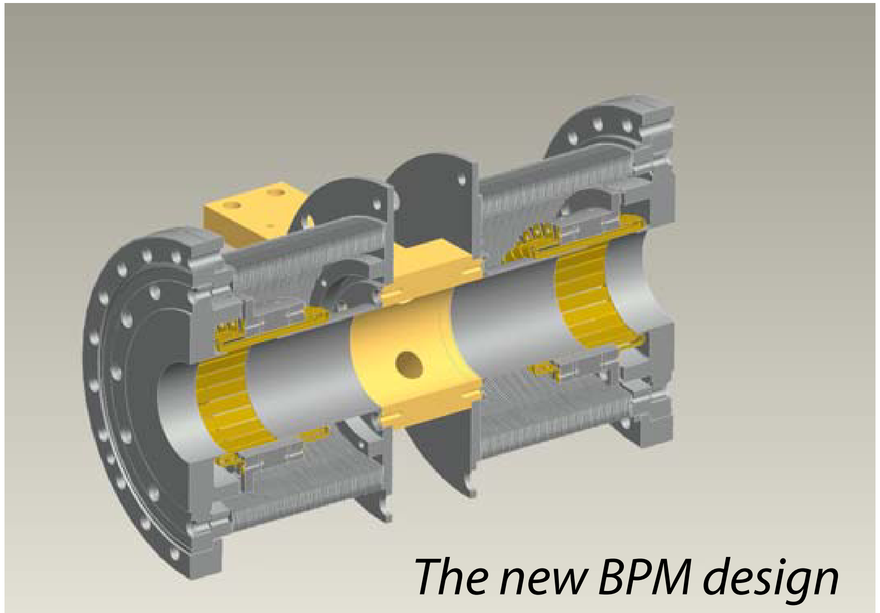
Bunch population: $2\text{x}10^{10}$

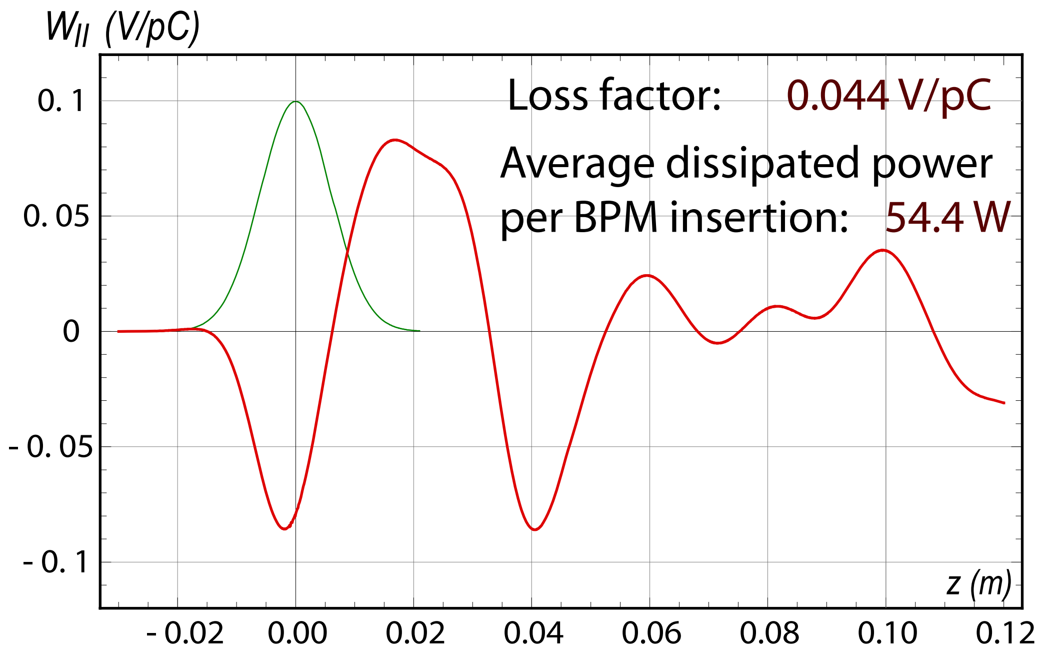
$$\epsilon_{y0,d} = \frac{J_e}{J_y}\langle \mathcal{H}_y \rangle \sigma_\delta^2 = 0.56\ \text{pm}$$

$$\epsilon_{y0} = \epsilon_{y0,\,min} + \epsilon_{y0,d} + \kappa \epsilon_{x0} = 1.43\ \text{pm}$$

Change of the bunch length and RMS energy spread is negligible (less than 1 %)

Longitudinal wake potential of the BPM


The new BPM design

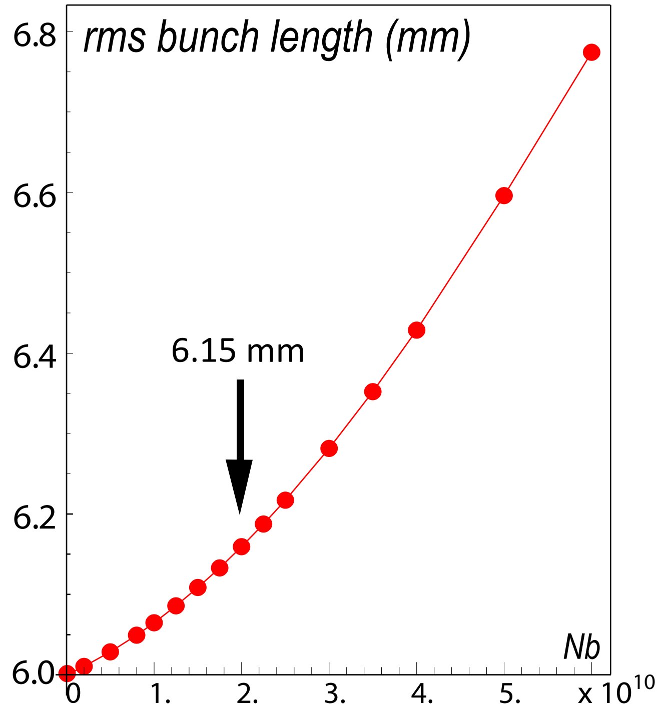


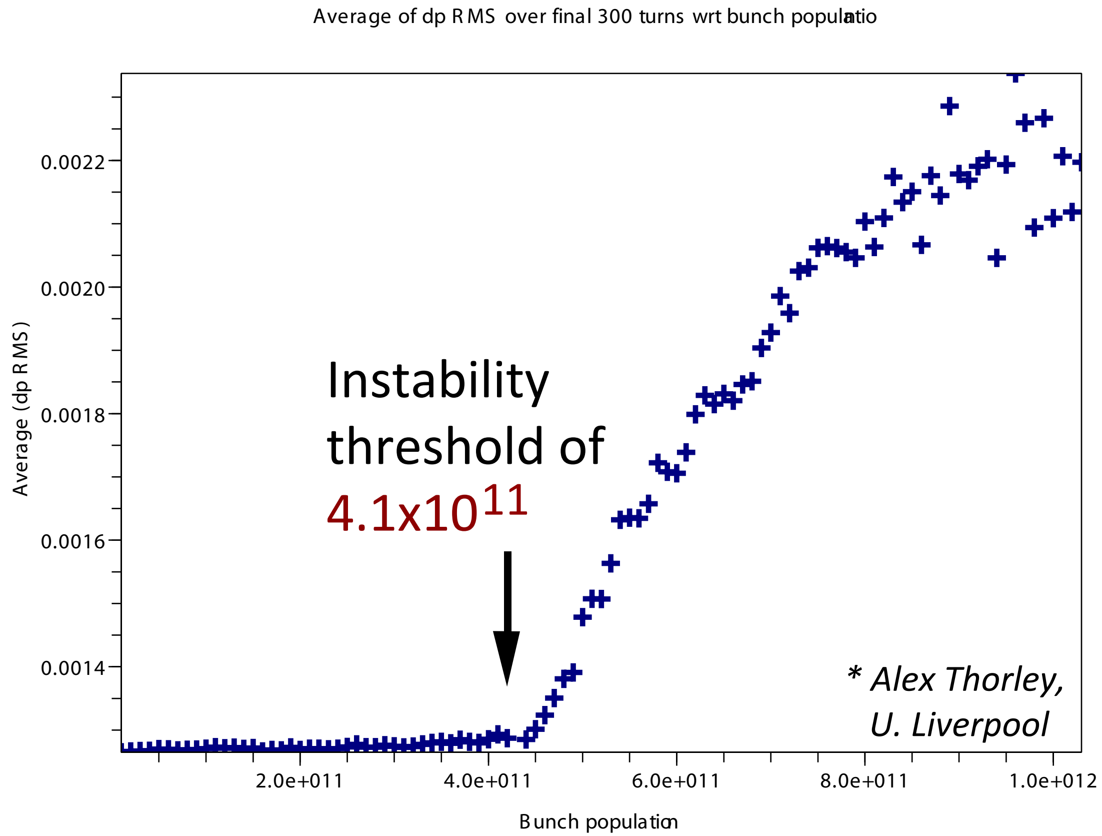
- A new bellows design with improved rf shielding, based on a design from INFN-LNF, has been implemented in the BPM model.
- The longitudinal wakefield excited in the BPM by a Gaussian relativistic electron bunch with rms length of 6 mm have been computed by using 3D code, CST Particle Studio.
- Applying an inverse Fourier transform to the impedance with the limits plus/minus 25 GHz, the wake functions have been computed.

Bunch lengthening and instability threshold

The Haissinski equation has been solved using a numerical iterative technique to estimate bunch lengthening due to the total number of BPMs (692) in the ring.

The instability threshold of 4.1×10^{11} particles per bunch has been determined using a parallel tracking code.*





* *Alex Thorley, U. Liverpool*

Conclusions

- The lattice design is now complete, and provides:

  - intense, 5 GeV beam with low emittance at extraction,
  - sufficient dynamic aperture for the large positron beam at injection,
  - identical lattice for the positron and electron DRs,
  - stable baseline for the TDR.

- The lattice also meets the engineering requirements for arrangement of the positron ring directly above the electron ring in the same tunnel.