FCC-ee - Lepton Collider

Optics Challenges

Bernhard Holzer *... court J. Wenninger*

For the TLEP Lattice and Optics Design Team:

B. Haerer, R. Martin, H. Garcia, R. Tomas, Y. Cai and many colleagues

There is only one real challenge ...
the parameter list

	Z	W	H	tt
Beam energy [GeV]	45.5	80	120	175
Beam current [mA]	1450	152	30	6.6
Bunches / beam	16700	4490	1360	98
Bunch population [10^{11}]	1.8	0.7	0.46	1.4
Transverse emittance e				
- Horizontal [nm]	29.2	3.3	0.94	2
- Vertical [pm]	60	7	1.9	2
Momentum comp. [10^{-5}]	18	2	0.5	0.5
Betatron function at IP b*				
- Horizontal [m]	0.5	0.5	0.5	1
- Vertical [mm]	1	1	1	1
Beam size at IP s* [mm]				
- Horizontal	121	26	22	45
- Vertical	0.25	0.13	0.044	0.045
Bunch length [mm]				
- Synchrotron radiation	1.64	1.01	0.81	1.16
- Total	2.56	1.49	1.17	1.49
Energy loss / turn [GeV]	0.03	0.33	1.67	7.55
Total RF voltage [GV]	2.5	4	5.5	11

design & optimise a lattice for 4 different energies

Interaction Region layout for a large number of bunches
Δs = 6m (LHC = 7.5m)

small hor. emittance increasing with reduced energy
$\varepsilon_y / \varepsilon_x = 10^{-3}$

extremely small vert. beta
β_y=1mm
→ *high chromaticity*
→ *challenging dynamic aperture*

high synchrotron radiation losses include sophisticated absorber design in the lattice

Challenge 1: TLEP ... Lattice Design
Definition of the cell to get the right hor. emittance

Text-Book like approach: Start with a FODO

high fill factor, robustness & flexibility, easy to handle & modify
easy to optimise analytically

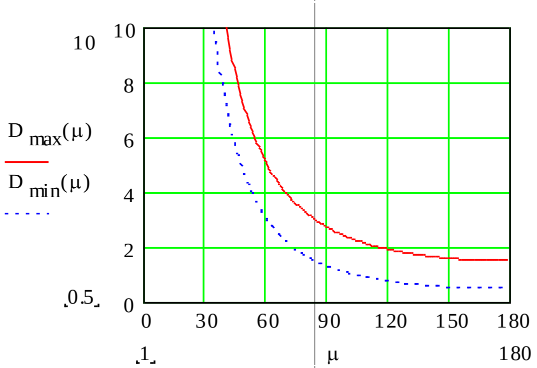
Design of single cell: L_{cell} = 50m

equilibrium emittance

$$\varepsilon = \left(\frac{\delta p}{p}\right)^2 \left(\gamma D^2 + 2\alpha D D' + \beta D'^2\right)$$

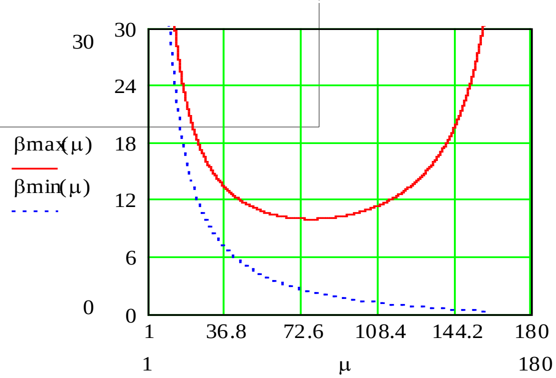
scaling of dispersion in a FoDo

$$\hat{D} = \frac{L_{cell}^2}{\rho} * \frac{(1 + \frac{1}{2}\sin\frac{\psi_{cell}}{2})}{\sin^2\frac{\psi_{cell}}{2}}$$



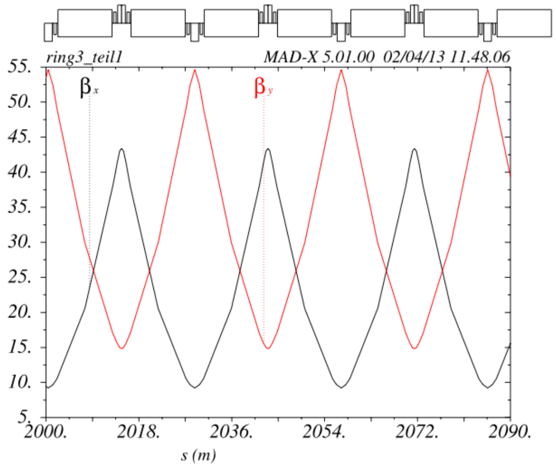
scaling of beta-function in a FoDo

$$\hat{\beta} = \frac{(1 + \sin\frac{\psi_{cell}}{2}) L_{cell}}{\sin\psi_{cell}}$$



→ *cell length to define the emittance*
→ *phase advance for fine tuning*
→ *re-arranging & re-scaling for the different energies*

Challenge 1: TLEP ... Lattice Design
Definition of the cell



Arc: the single FoDo cell

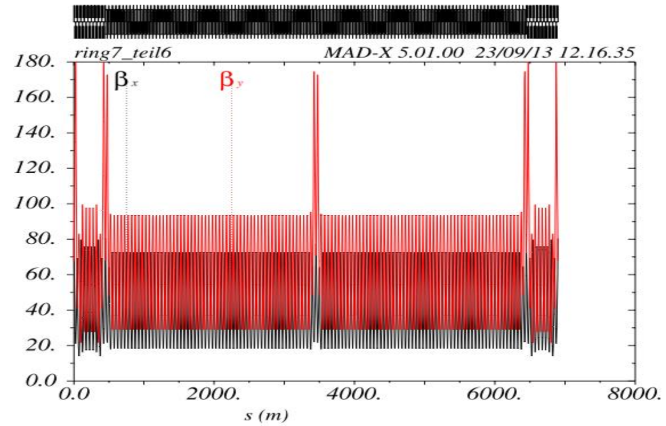
phase advance: 90^0 / 60^0

to be discussed ...

90^0 horizontally: small dispersion & emittance

60^0 vertically: small beam size (β_y)

and better orbit correction tolerance (LEP experience)



Main Parameters:

momentum compaction

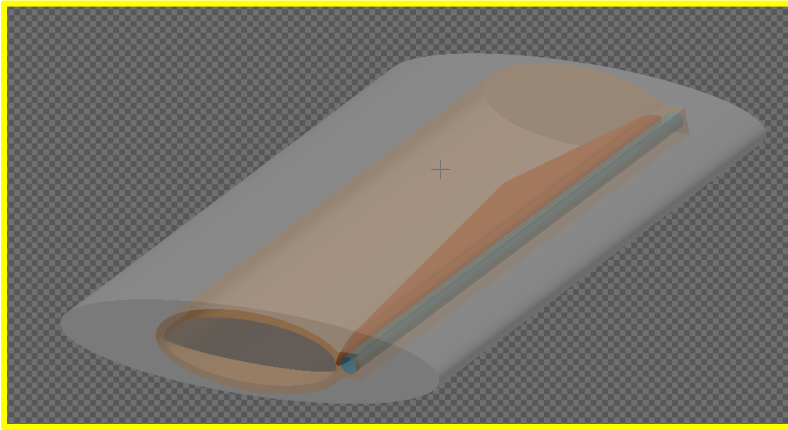
$$\alpha_{cp} \approx \frac{\langle D \rangle}{R} = \frac{12*10^{-2}m}{L_0/(2\pi)} \approx 7.7*10^{-6}$$

MADX: $\alpha_{cp} \approx 6.6*10^{-6}$ (80km)

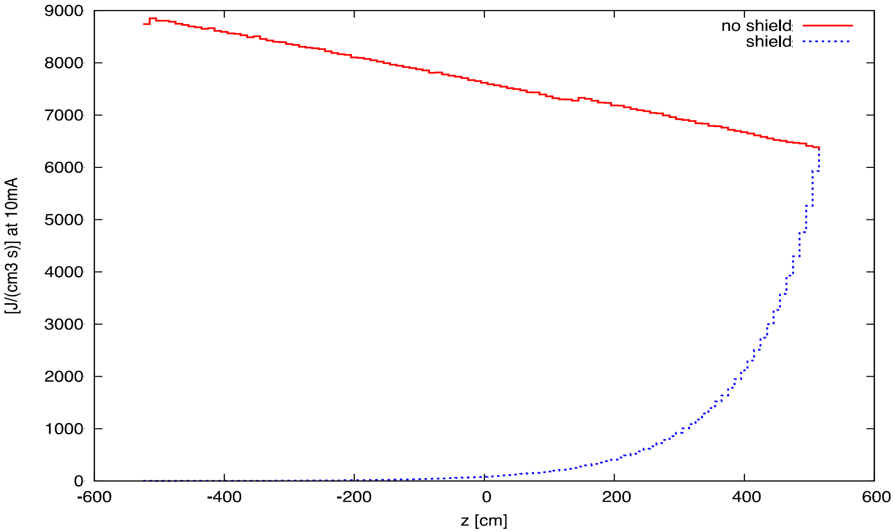
Question 1: can we follow with a flexible lattice design the parameters for the 4 energies ? Dispersion suppressor ? Geometry ?

Challenge 2: Lattice Design … Layout of the Magnets

Achieve highest possible fill factor
to limit synchrotron radiation losses
Include Absorber Design in the lattice layout
Distribute RF straights to limit saw tooth effect
(dispersion suppressor layout)



power density along the dipole magnet

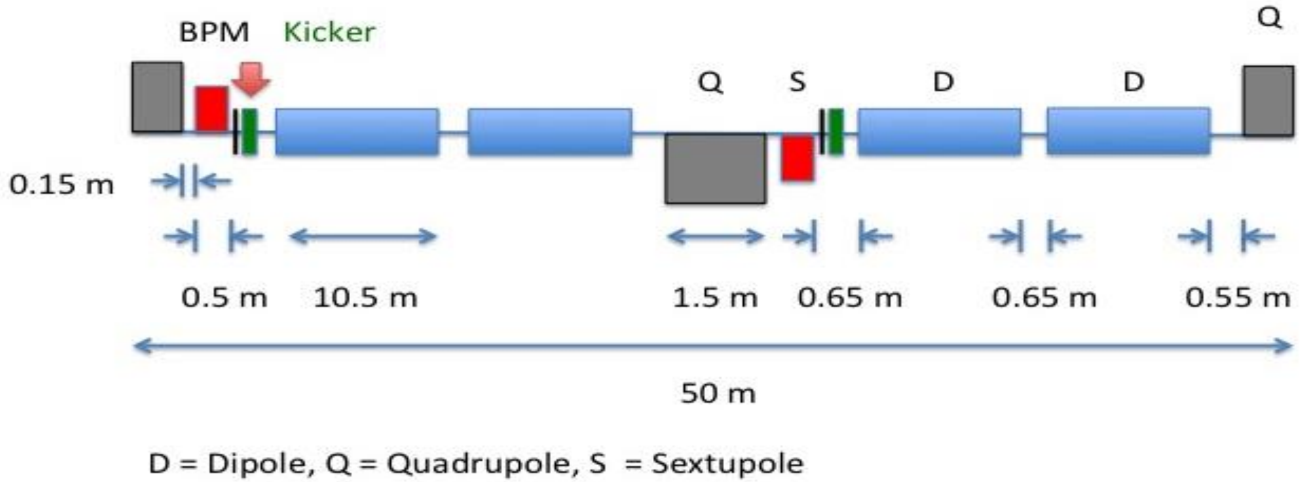


Dipole length defined by synchrotron radiation load
$L_{dipole} < 11m$

court. Luisella Lari et al

Challenge 2: Lattice Design ... Layout of the Magnets

include boundary conditions into the cell design ... dipole length / absorbers



$N_{dipoles} = 6048$

$L_{dipoles} = 10.5\,\text{m}$

$\theta = \dfrac{2\pi}{6048} = 1.04\,\text{mrad per dipole}$

$E = 175\,GeV, \quad B\rho = 583.33$

$\rho = \dfrac{L_B}{\theta} \approx 10\,km$

$$\Delta U_0(keV) \approx \frac{89 * E^4(GeV)}{\rho}$$

$$\Delta U_0 \approx 8.3\,GeV \quad \ldots 7.6\,GeV\ (100\,km)$$

court. Bastian Haerer

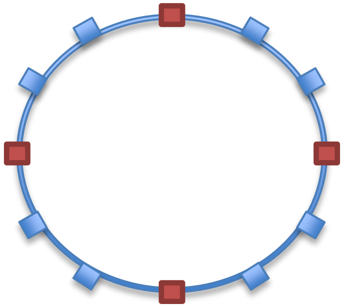
TLEP ... Lattice Design

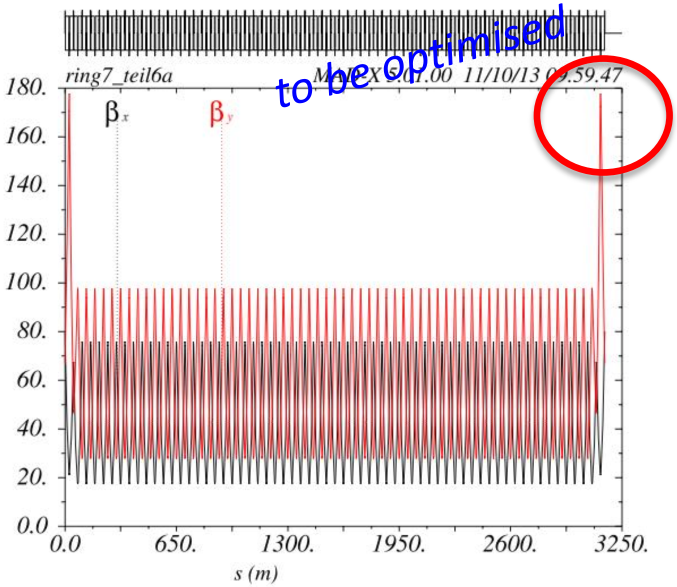
12 Arcs : *built out of 2*56 standard FoDo cells* & *2 half bend cells* at beginning and end

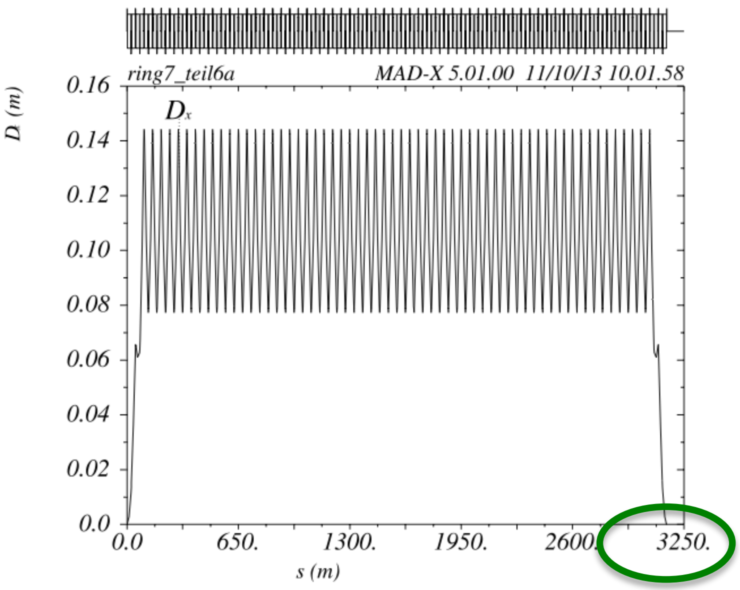
length of arc: ≈ 3.0km

each arc is embedded in dispersion free regions ...

arcs are connected by straight. sections ... 12 long (mini β and RF)







Question 2: Is a FODO the best solution ?

... for fill factor yes, for momentum acceptance ???

Challenge 3: Beam Emittance Ratio ... can we make it ?

required: ***$\varepsilon_y / \varepsilon_x = 1*10^{-3}$***

horizontal ... defined by energy, cell length and focusing properties

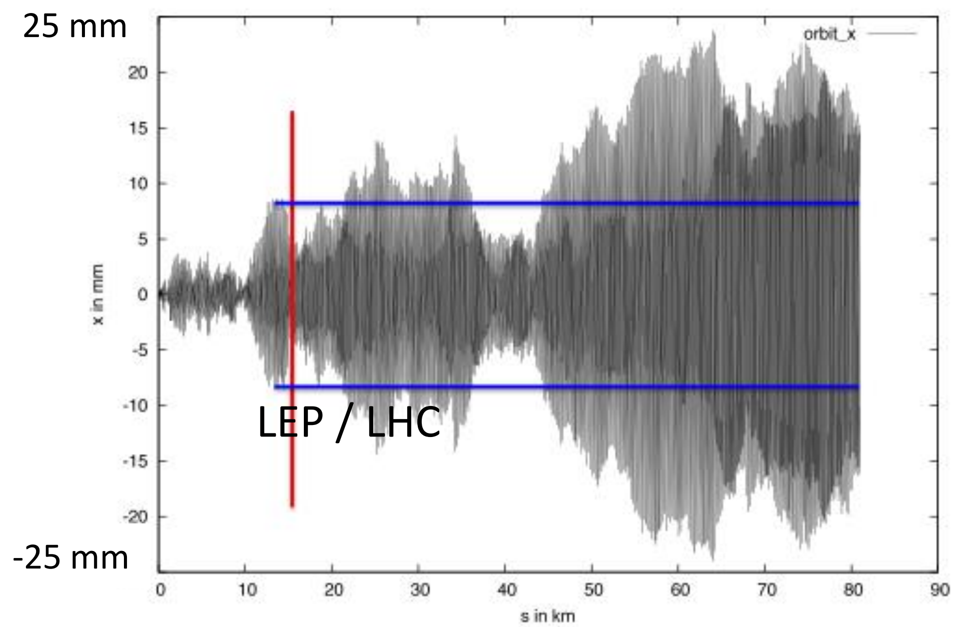
vertical ... defined by orbit tolerances (magnet misalignment & coupling)

... without mini-beta-insertion !!

$$\Delta x = \Delta y = 150\ \mu m$$

assumed magnet alignment tolerance (D. Missiaen)

$$x_{rms} = \frac{\sqrt{N_d}}{\sqrt{2}\sin(\pi Q_x)\cos(\phi/2)}$$

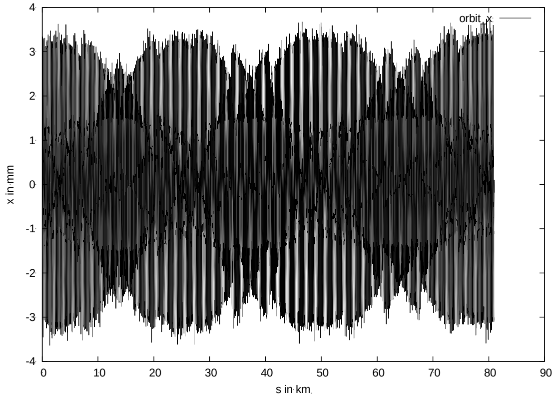


orbit tolerances add up to very large distortions and are amplified by the extreme mini-beta concept

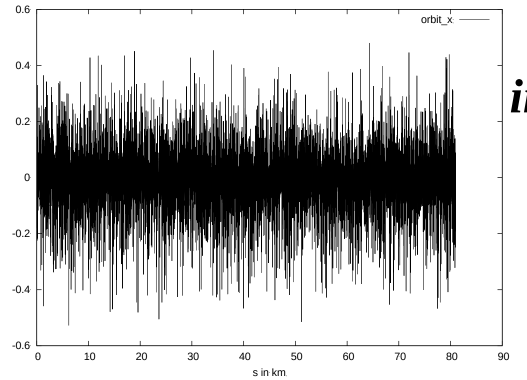
court. Bastian Haerer

Challenge 3: Beam Emittance Ratio ... can we make it ?

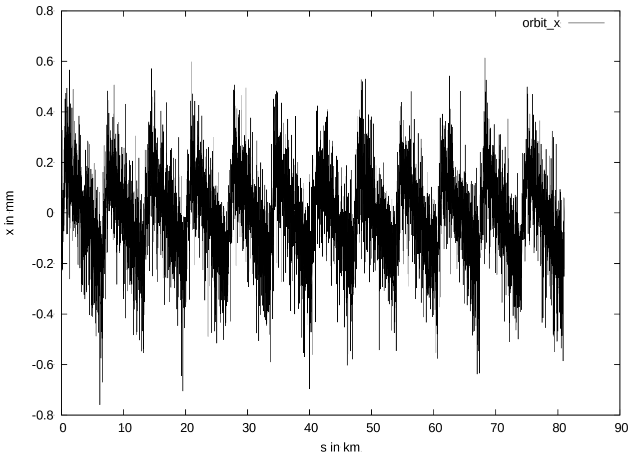
horizontal orbit after 3 iterations



after final correction
& switching on sextupoles



including radiation & rf structures



Horizontal emittance : $\varepsilon_x = 1.23\ \mathrm{nm}$ (2 nm)

Vertical emittance: $\varepsilon_y = 1.05\ \mathrm{pm}$ (2 pm)

***Question 3** ... can we maintain this values including ...*
coupling ? / beam beam effects ?
... how do we deal with the extreme sensitivity in the mini-beta-sections ... special quadrup[ole alingment features (piezo) ?

Challenge 4: ... Lattice Modifications for smaller energies

... the most interesting challenge !!

	Z	W	H	tt
Beam energy [GeV]	45.5	80	120	175
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Transverse emittance e - Horizontal [nm] - Vertical [pm]	 29.2 60	 3.3 7	 0.94 1.9	 2 2
Momentum comp. [10^{-5}]	18	2	0.5	0.5

emittance is a factor 15 higher at low energy compared to 175 GeV

... positiv for luminosity ←→ counter productive for beam dynamics

$$\varepsilon_0 = C_q \gamma^2 \frac{I_5}{j_x I_2},$$

$$I_2 = \oint \frac{1}{\rho^2} ds$$

$$I_5 = \oint \frac{\mathcal{H}_x}{|\rho|^3} ds, \qquad \mathcal{H}_x = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta_{px} + \beta_x \eta_{px}^2$$

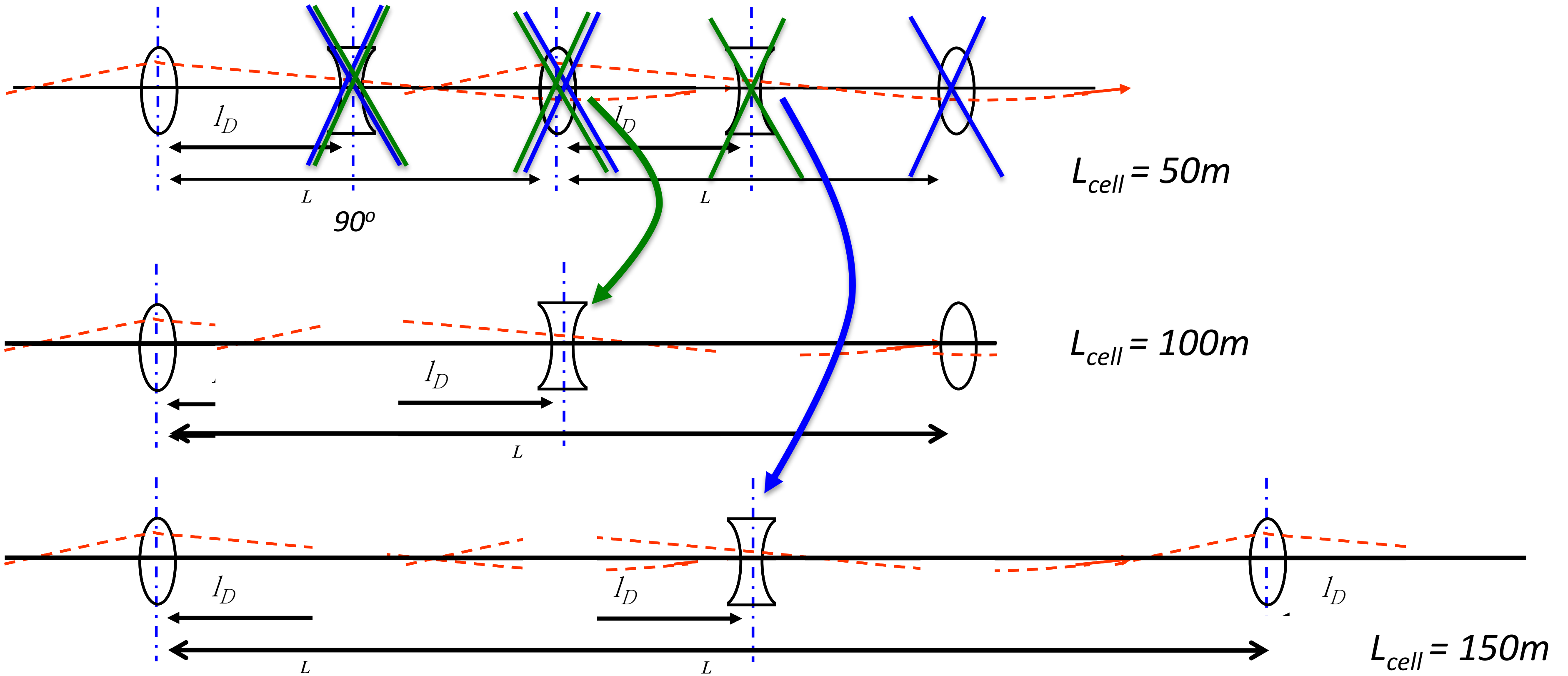
***Question 4a:* how can we counteract the natural emittance shrinking for lower energies ?**

Challenge 4: ... Lattice Modifications for smaller energies

$$\varepsilon = \left(\frac{\delta p}{p}\right)^2 \left(\gamma D^2 + 2\alpha D D' + \beta D'^2\right)$$

$$\hat{D} = \frac{l^2}{\rho} * \frac{\left(1 + \frac{1}{2}\sin\frac{\psi_{cell}}{2}\right)}{\sin^2\frac{\psi_{cell}}{2}}$$

coarse tuning via cell length,
fine tuning via phase advance
& wigglers ??

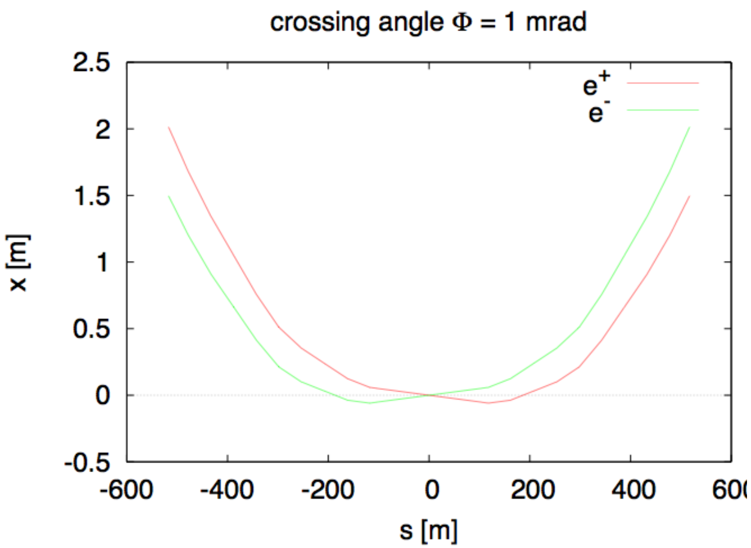


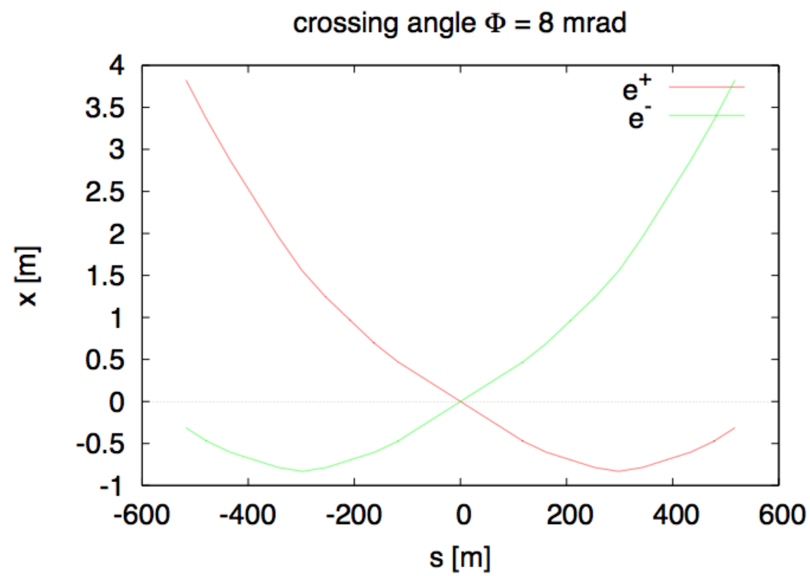
Question 4b: do we need wigglers for emittance tuning ? (... yes)

Challenge 5: Interaction Region Lattice

large bunch number requires two rings & crossing angle

→ ***influence on mini beta optics / beam separation scheme***



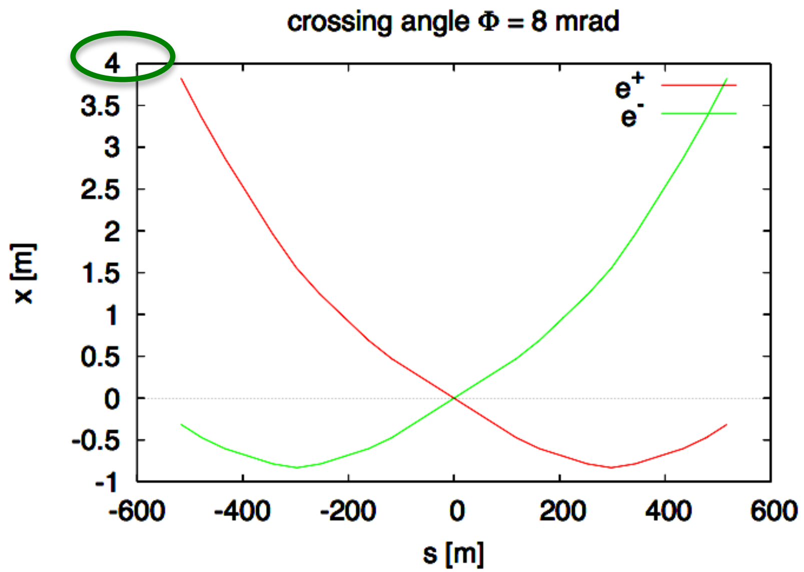


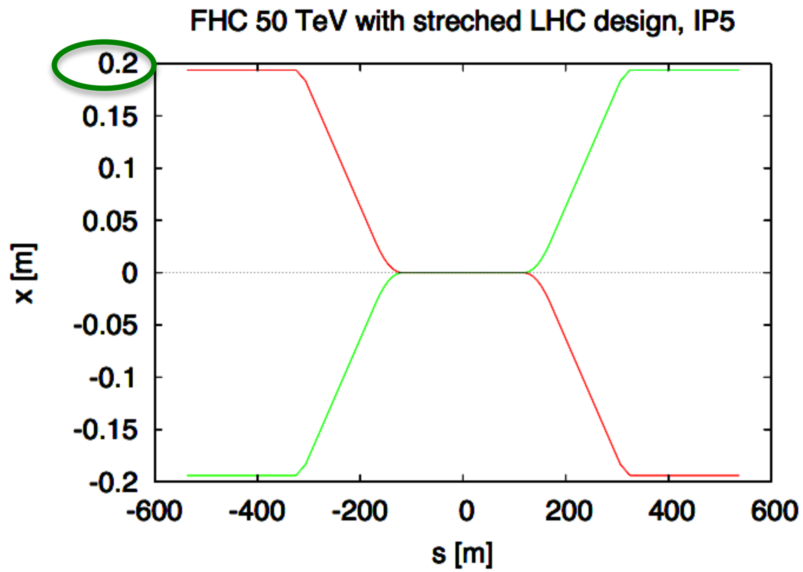
*** A scheme with 2Φ =70 mrad was presented by A. Bogomyagkov et al.*

Question 5a: ***How do we get sufficient separation (beam-beam-effect) ?***
How do we bend back the beams into their closed orbit ?
How do we avoid to large synchrotron radiation background ?
Do we need a 10% bend at the end of the arc ?

court. R. Tomas, R. Martin

Challenge 5: Interaction Region Lattice





Beam orbits for the e+/e- case
requires two well separate rings

... for the p/p- case
calls for a twin-aperture design ? !

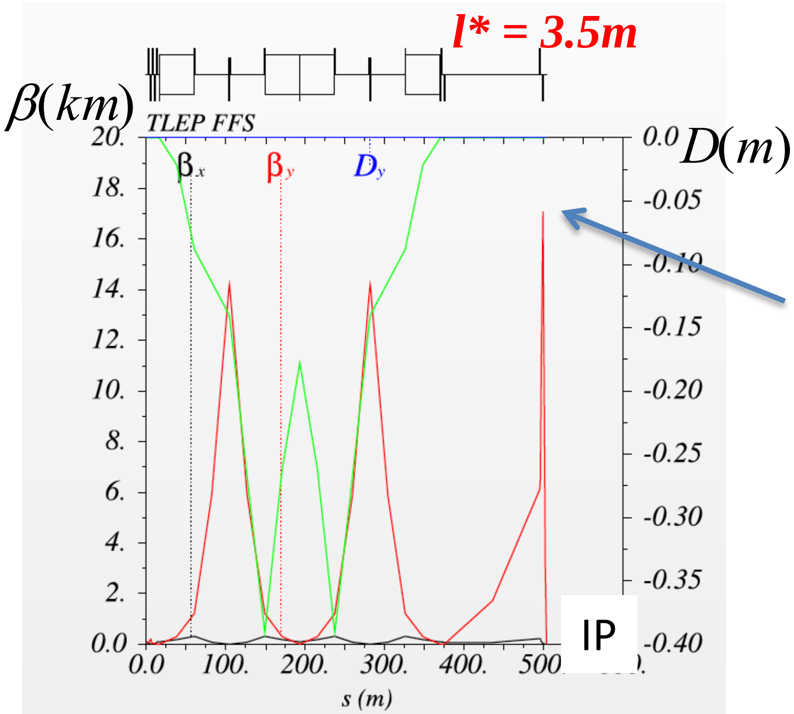
Question 5b: ***How do we get proton and electron geometry together ?***
... in the interaction regions ?
... for the complete ring ?

Challenge 6: Mini-Beta-Optics

extreme (!!) mini beta requirements call for a Linear Collider like Interaction Region

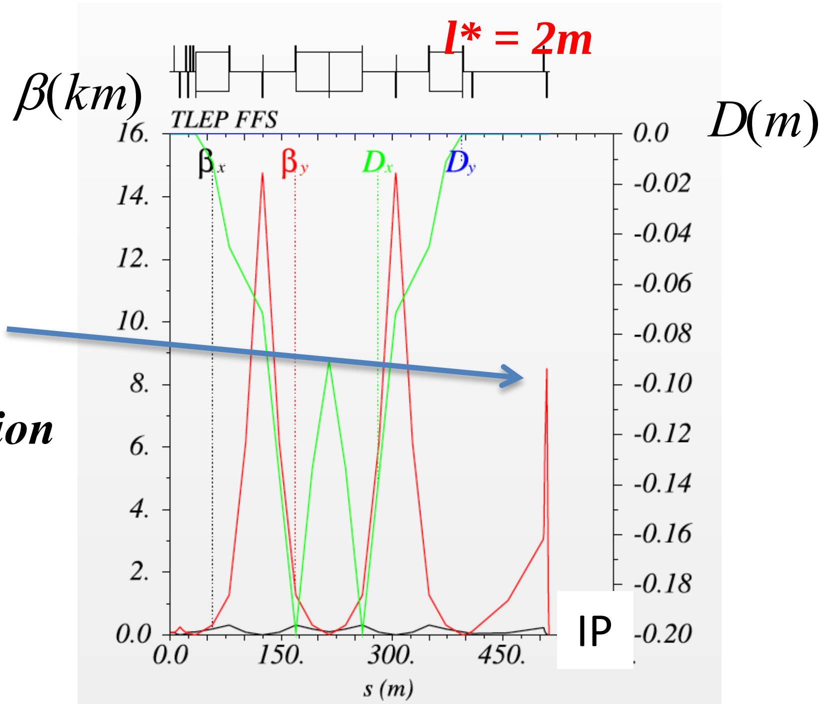
standard straight section / dispersion suppressor / mini beta combined with quasi local chromaticity control

court. Hector Garcia
Yuhai Cai



Liouville

Q' correction



L^* [m]	Magnet	L [m]	k [m^{-2}]	G [T/m]	Ap. rad. ($15\sigma_x$) [mm]	B ($15\sigma_x$) [T]
3.5	QD0	2.02	-0.195	113.6	3.4	0.4
3.5	QF1	1.15	0.195	113.6	9.8	1.11
2.0	QD0	2.66	-0.195	113.6	2.6	0.3
2.0	QF1	1.16	0.195	113.6	9.8	1.11

Challenge 6: Mini-Beta-Optics / Non-linear beam dynamics

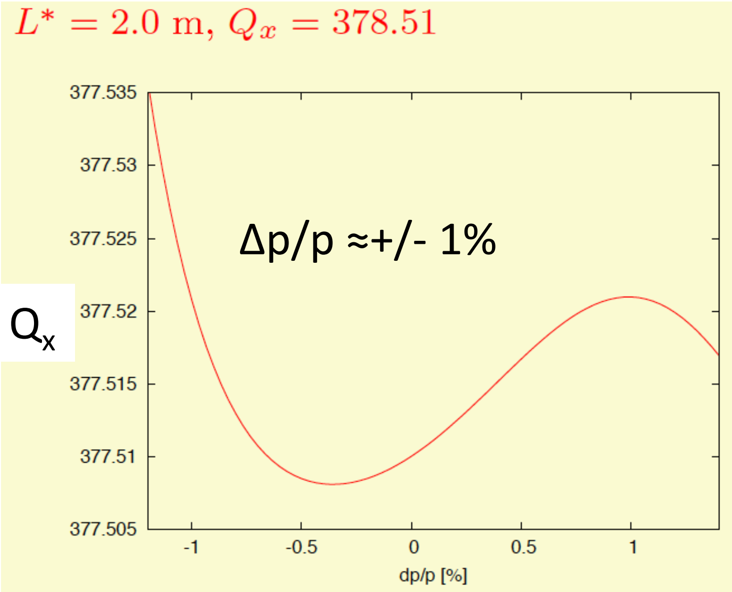
challenging (!!) mini beta requirements

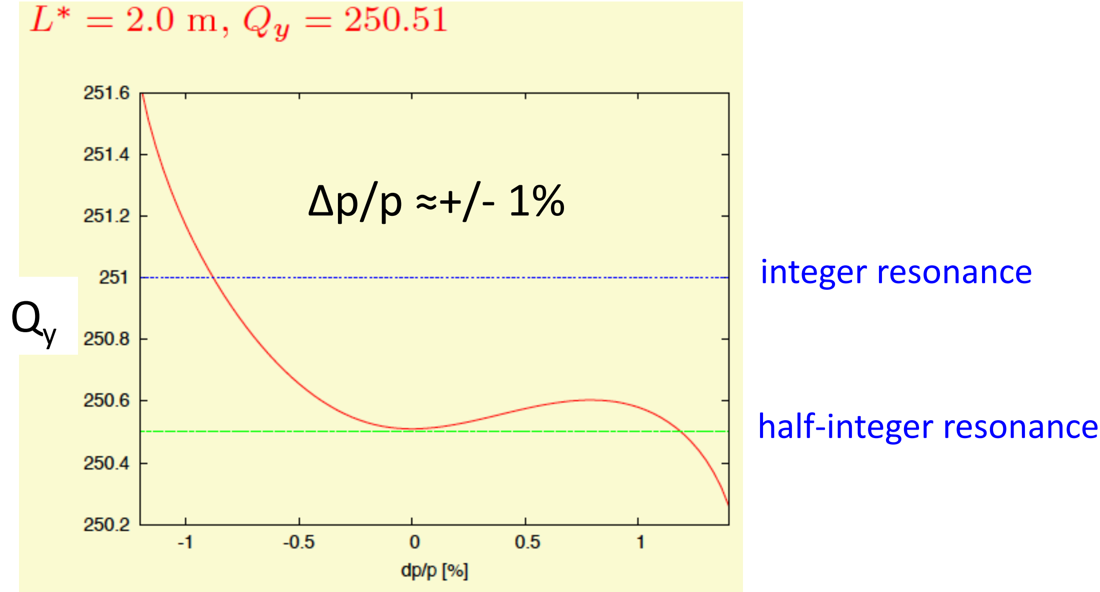
β_y^* = 1mm drives chromaticity to extreme values

without mini-beta: Q'x = -399 Q'y = -332

with mini-beta: Q'x = -483 Q'y = -3066

up to now: state of the art mini-betas ≈ double the Q' budget of the ring





Non-linear tune shift with momentum drives the off-momentum particles on strong resonances

Question 6: ***How do compensate the higher order chromaticity ?***

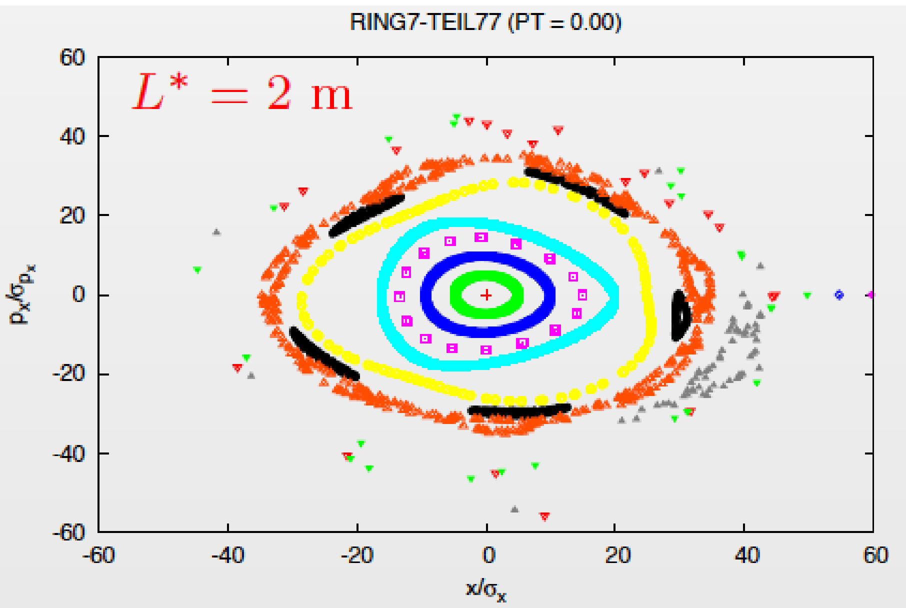
How do we get the required momentum acceptance $\Delta p/p$ > +/- 2%

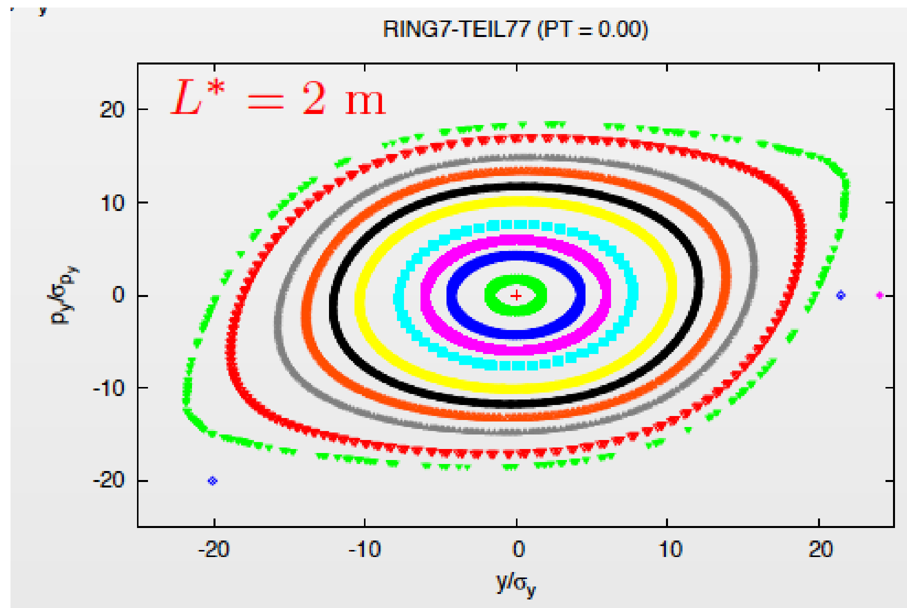
court. Hector Garcia

Challenge 7: Non-linear beam dynamics and dynamic aperture

very first dynamic aperture calculations for the case
 l*=2m (guess why ...)

... and ideal momentum $\Delta p/p = 0$





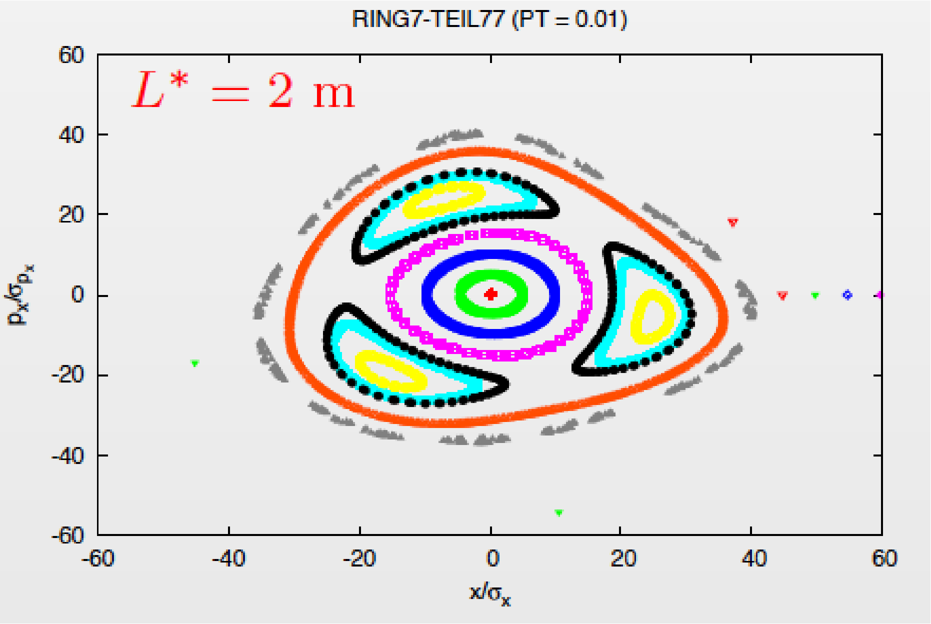
On Energy everything looks ok.

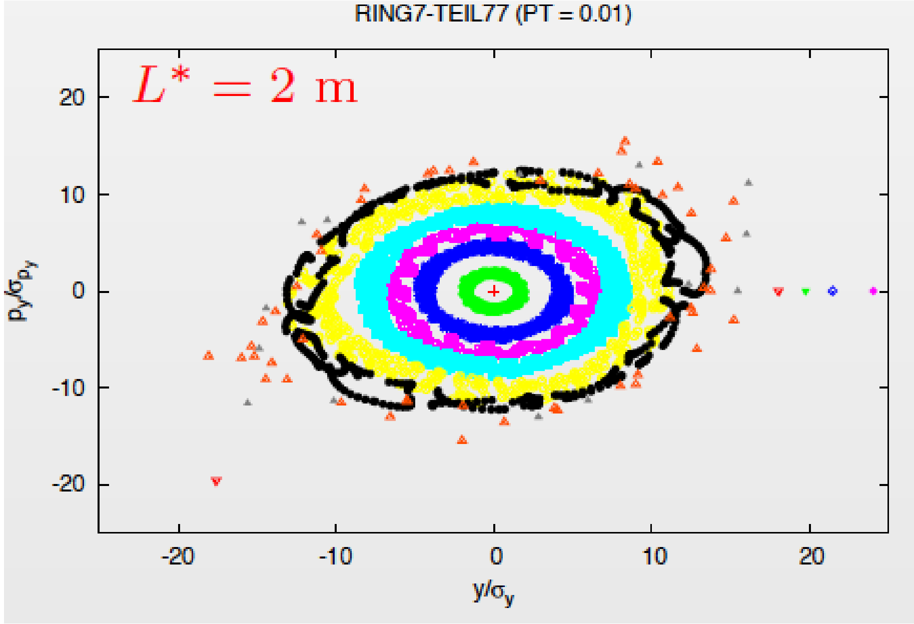
court. Hector Garcia

Challenge 7: Non-linear beam dynamics and dynamic aperture

very first dynamic aperture calculations for the case
l*=2m (guess why ...)

and off momentum Δp/p = +/- 1%



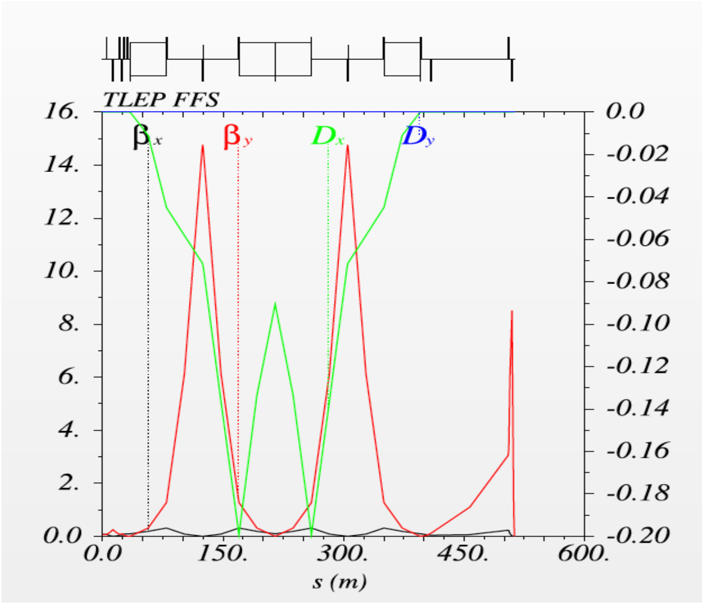


Question 7: ***How do we improve the dynamic aperture for Δp/p > +/- 2%***
How does the best chromaticity compensation look like ?
Should we go for a true local compensation (i.e. D'(IP) ≠ 0) ?

court. Hector Garcia

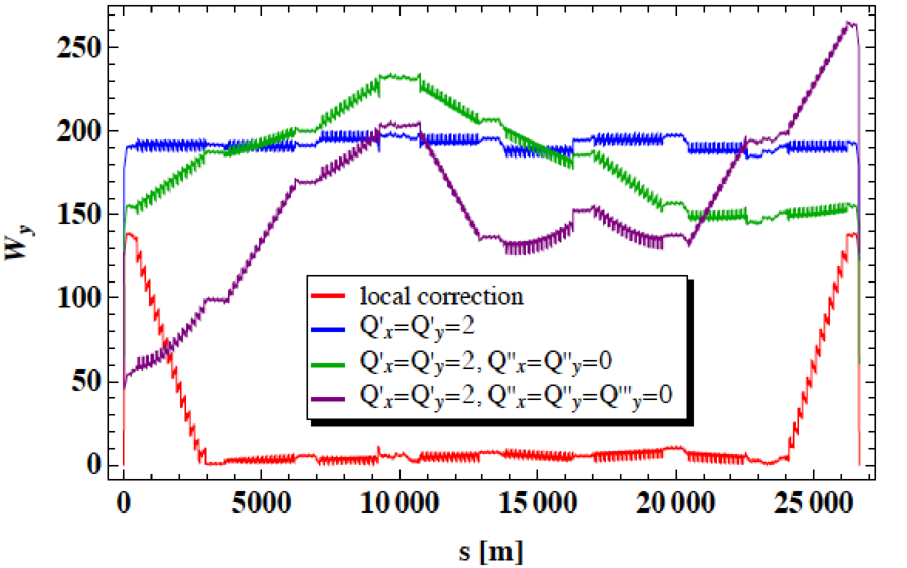
Challenge 7b: get the best momentum acceptance

Question 7b: ***What about combining a local or a quasi-local Q' correction system ...***
with a state of the art (2+3) sextupole family concept in the arc ?
to get an achromatic structure between arc-IR-arc !!
and distribute the correction load between IR and arc ???



present quasi-local Q' compensation design

&



LHeC design with arc-IR-arc Q' compensation
court. Miriam Fitterer

Resume:

I.) We need a lattice design with highest flexibility to create a set of beam optics valuable for 4 different energies

II.) We have to establish beam optics to get the required emittances and $\varepsilon_y / \varepsilon_x$ emittance ratios

III.) We have to deign a beam separation scheme with tolerable synchrotron light conditions

IV.) ... in combination with the layout of the pp collider

V.) We have to build mini-beta insertions with $\beta^* = 1mm$

VI.) And still control / compensate the up to now unknown chromaticity budget

VII.) We have to obtain a momentum acceptance of $\Delta p/ p = +/- 2\%$

FCC-ee - Lepton Collider

... feel motivated to join the Friday afternoon break out session