Conceptual Design of a Pre-Booster Ring for FCC e^+e^- Injector

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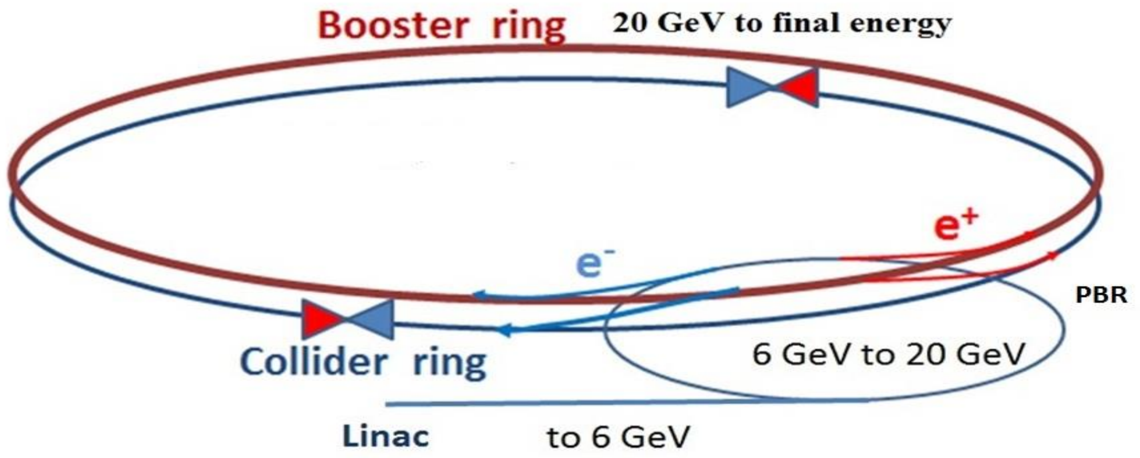
Outline

- Why an alternative Design?
- FCC e^+e^- injector parameters with alternative PBR
- Parameter scaling
- Some calculations for general design parameters
- Phase advance-chromaticity-emittance relations
- Lattice design
- DA calculations
- Preliminary IBS simulations
- SPS as PBR

Alternative Pre-Booster Ring Synchrotron Design



- Linac
- Pre-booster
- Booster same tunnel with main ring,
- Collider ring.

- Baseline parameters are considering ~6 GeV Linac and SPS as Pre-Booster Ring (PBR) but issues with:
  - machine availability, synchrotron radiation, new RF system…
- This is why a “green field” alternative design is interesting

FCCee Injector Parameters with alternative PBR

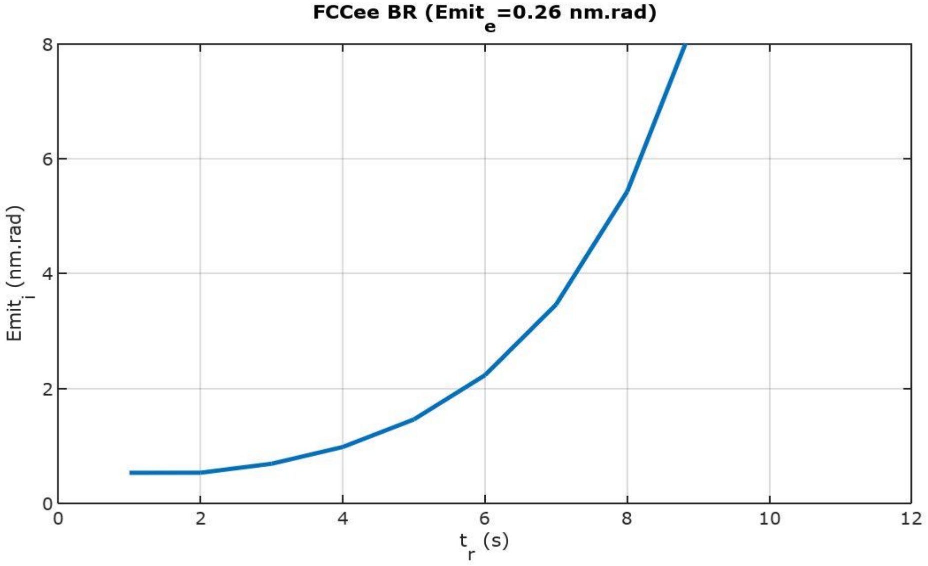
Accelerator	FCCee-Z		FCCee-W		FCCee-H		FCCee-tt	
Type of filling	Full	Top-up	Full	Top-up	Full	Top-up	Full	Top-up
Energy [GeV]	45,6		80		120		175	
Linac bunches	2		1					
Linac repetition rate [Hz]	200		100					
linac RF freq [MHz]	2800							
Linac bunch population [10^10]	2,66	0,26	1,25	0,25	1,10	0,43	2,55	0,125
PBR bunch spacing [MHz]	400							
PBR bunches/injection	2		1					
PBR bunch population [10^10]	2,66	0,26	1,25	0,25	1,10	0,43	2,55	0,125
Number of linac injections	122	3538	364		59		62	
PBR number of bunches	305	3538	364		59		64	
BR bunch spacing [MHz]	400							
BR number of bunches	4880	70760	7280		826		64	
BR bunch population [10^{11}]	0,26	0,02	0,12	0,02	0,11	0,04	0,25	0,2
Total number of bunches	70760		7280		826		64	
Filling time (both species) [sec]	1088	735	710,4	177,6	340,1	42,52	142,4	
Required FCCe^+e^- bunch population [10^{11}]	0,42	0,02	0,40	0,02	0,71	0,03	2,04	0,01

Emittance in pre-booster ring

The emittance at extraction of the PBR has to satisfy the requirement for the injected emittance in the main booster ring, which in turn is established by the demands of the collider. The lowest injection emittance target of the collider ring is 0.26 nm.rad.

The emittance $\varepsilon(t)$ at a certain instant t can be given by

$$\varepsilon(t) = \varepsilon_{inj}\, e^{-\frac{2t}{\tau}} + \varepsilon_{equ}(1 - e^{-\frac{2t}{\tau}})$$



The emittance at the entrance of the booster ring should be about 0.7 nm.rad, corresponding to an accelerating time of 3 seconds.

Parameter space

Scaling of important parameters impacting machine layout;

- Energy loss per turn → $U_0 = \frac{2\pi . C_\gamma . E^4}{FF . C}$

- Damping times → $\alpha_s = \frac{E^3 . c . C_\gamma}{FF^2 . C^2}$

- Energy spread → $(\sigma_s)^2 = \frac{C_q . \gamma^2 . 2\pi}{FF . C}$

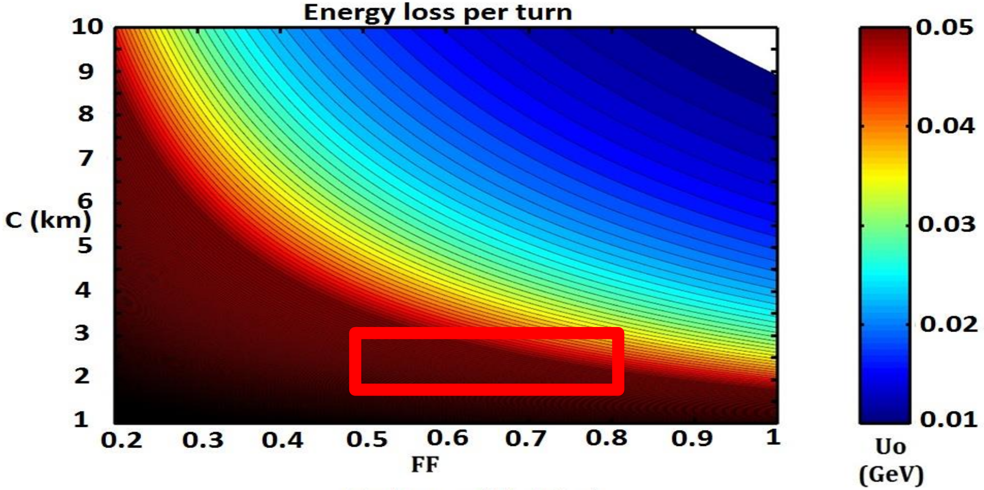
- Emittance → $\varepsilon_s = \frac{F_{lattice} . C_q . \gamma^2 . (2\pi)^3 . l^3}{FF^3 . C^3}$

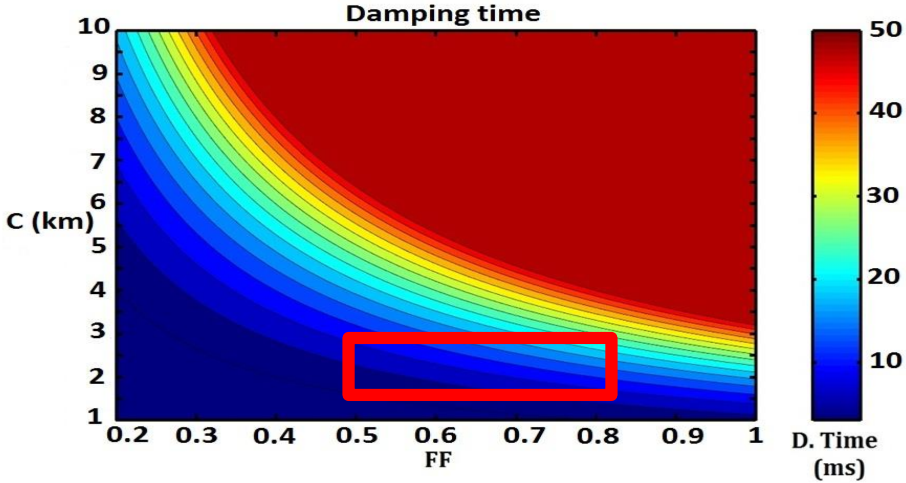
Filling Factor

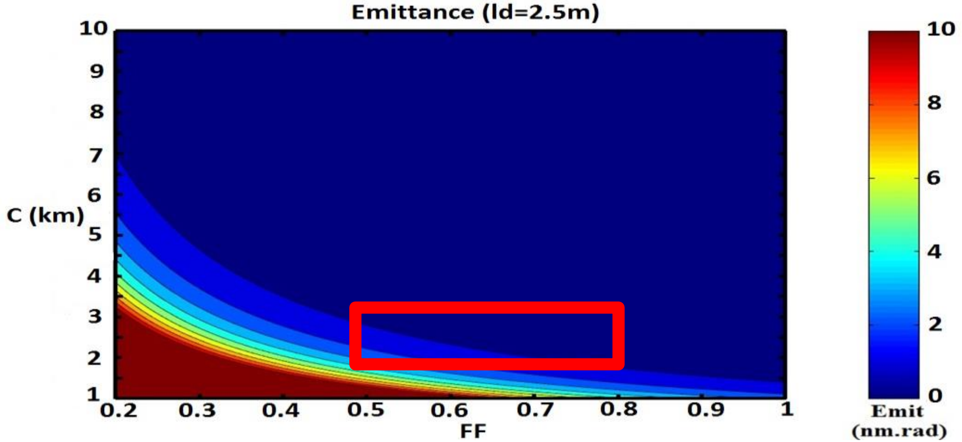
↓

$$FF = \frac{N . l}{C}$$

Parameter Scaling







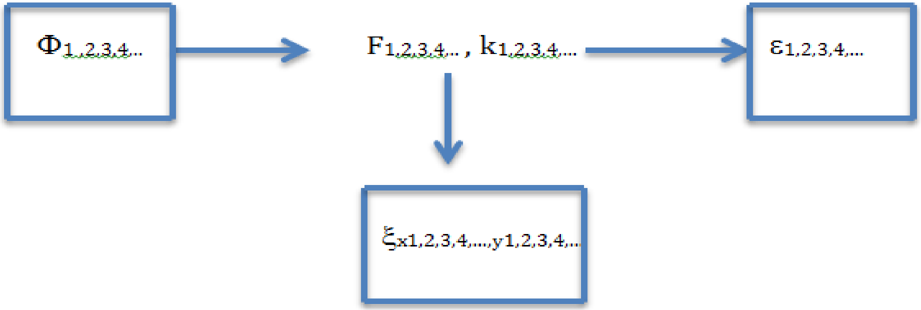
- Scaling of energy loss/turn, damping time and emittance with filling factor and circumference

- For 20 GeV, the area below 50MeV/turn, around 1 nm.rad emittance and a few ms damping time, the lowest circumference of around 2.5 km is for high filling factors (FF) of around 0.7

Phase Advance, Emittance and Chromaticity

$$\epsilon_{fodo} = F_{fodo}\, C_q \gamma^2 \theta^3$$ → Emittance

$$F_{fodo} = \frac{1 - \frac{3}{4} sin^2(\emptyset/_2)}{sin^3\left(\emptyset/_2\right)\cos(\emptyset/_2)} J_x^{-1}$$



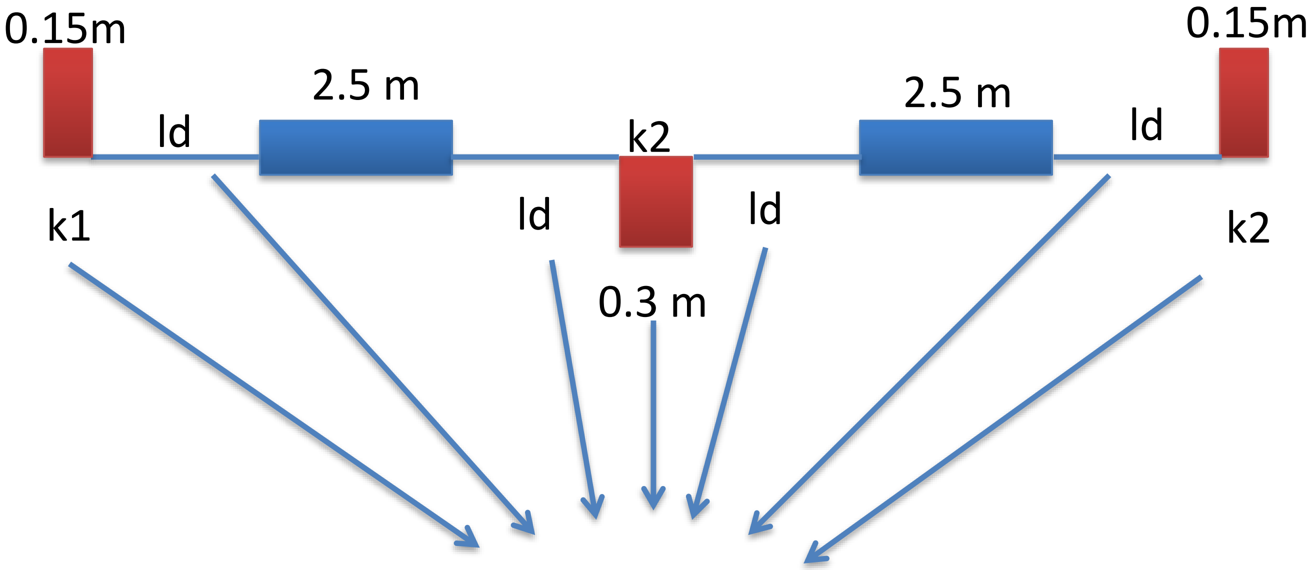
$$\xi_{x0} = -\frac{1}{4\pi}\oint \beta_z k dz$$

$$\xi_{y0} = \frac{1}{4\pi}\oint \beta_y k dz$$

→ Chromaticity

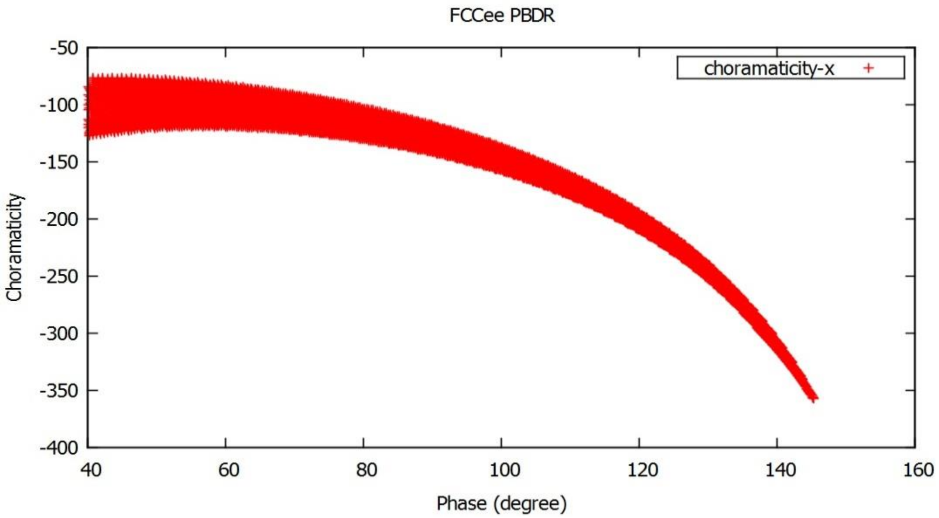
$$\emptyset = arccos(^1/_2\, trace\,(M))$$ → Phase

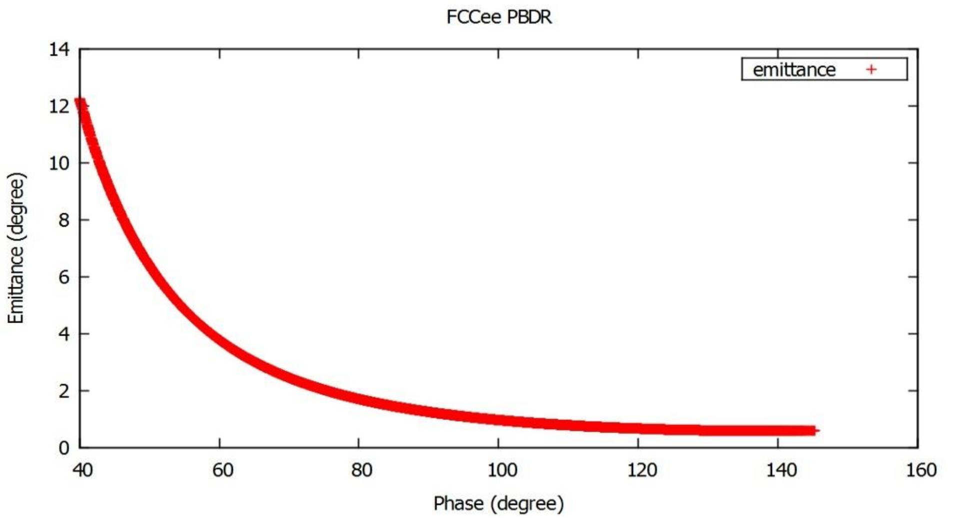
Determining the main cell



All k1, k2, ld values are scanned and 'emittance & chromaticity' are calculated to be able to obtain most optimum machine

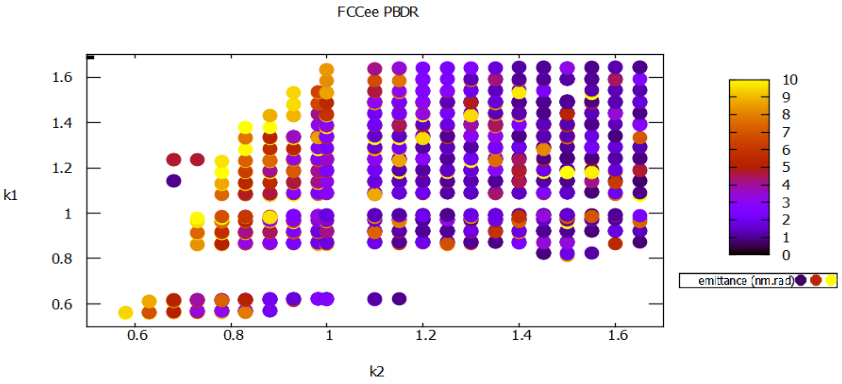
Analytic Approach

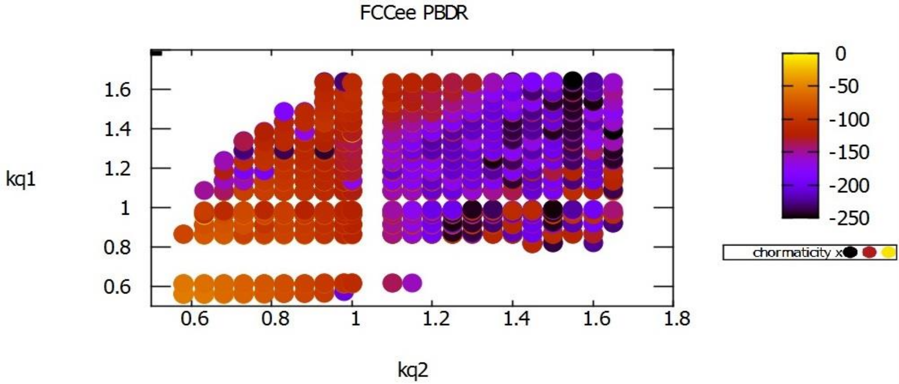


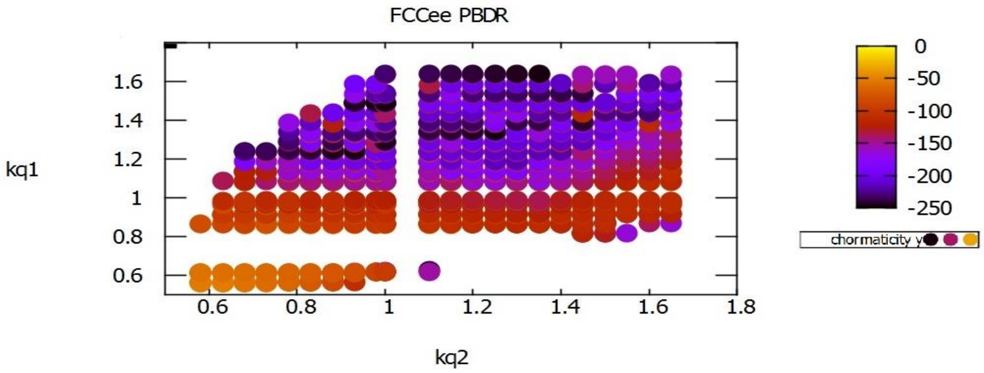


- Analytical calculation to parameterise chromaticity and emittances with cell phase advance,
- As expected, choosing phase advance around 90 degree helps to have minimum emittance and chromaticity.

MADX simulations for emittance and chromaticity

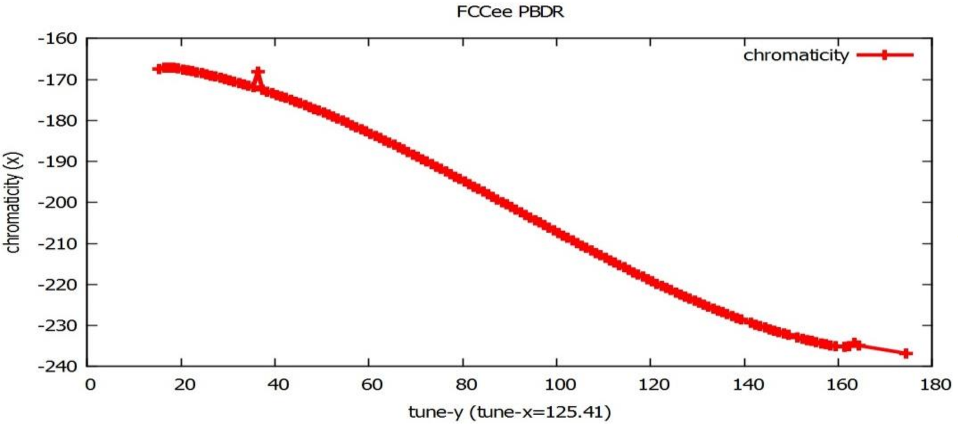


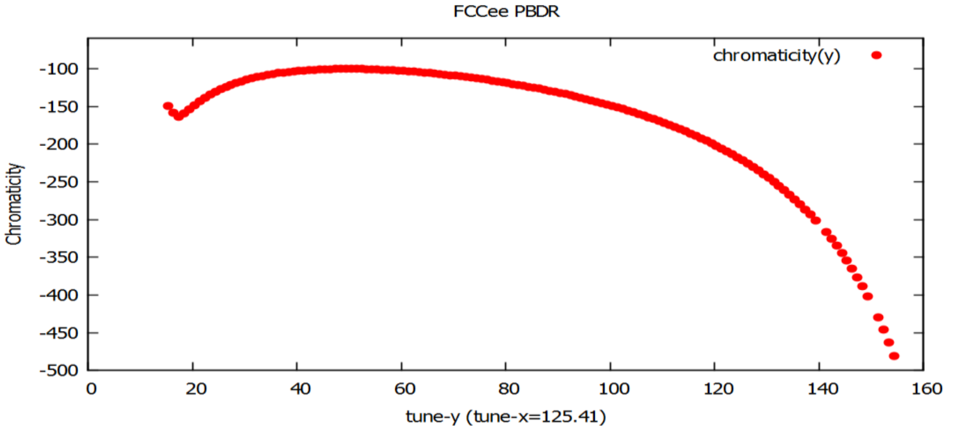




- Parametrisation of emittance, chromaticities with quadrupole strength (drift length also changes).

Tune optimization





- Dependence of chromaticity with tune (y), while tune-x kept constant (same emittance)

The vertival tune has to become as small as possible for reducing chromaticity as well.

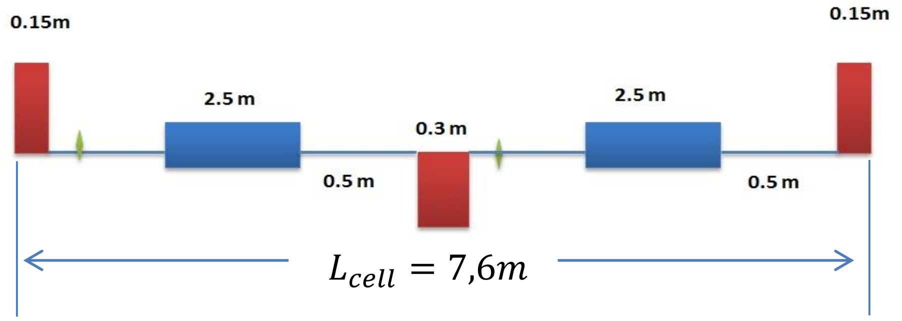
All these results are checked; and below parameters are determined

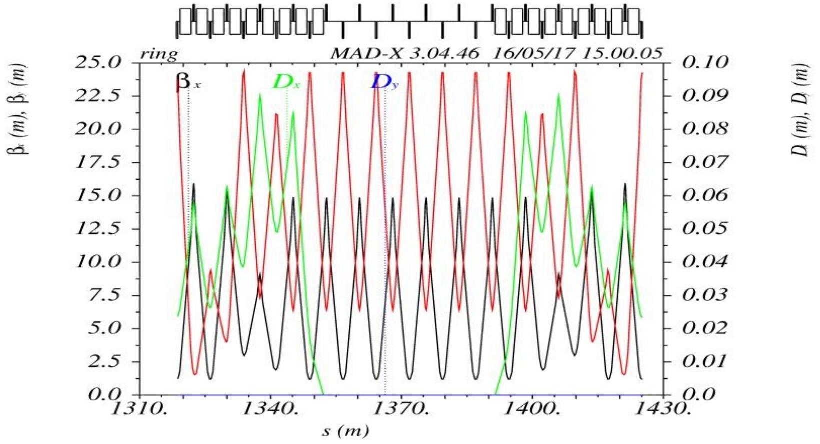
k_1= -0.94

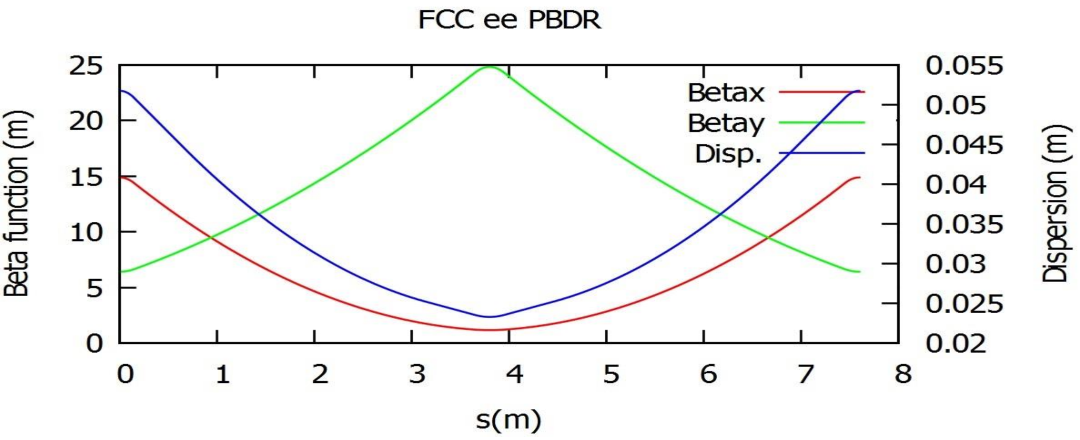
K_2= 1.59

l_{drift}= 0.5 m (length between quadrupole and dipole magnet)

Main cell of the pre-booster and parameters

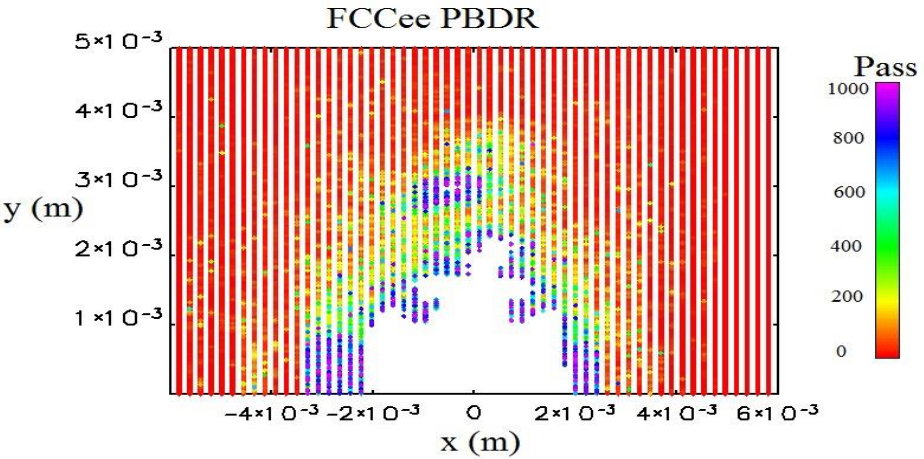


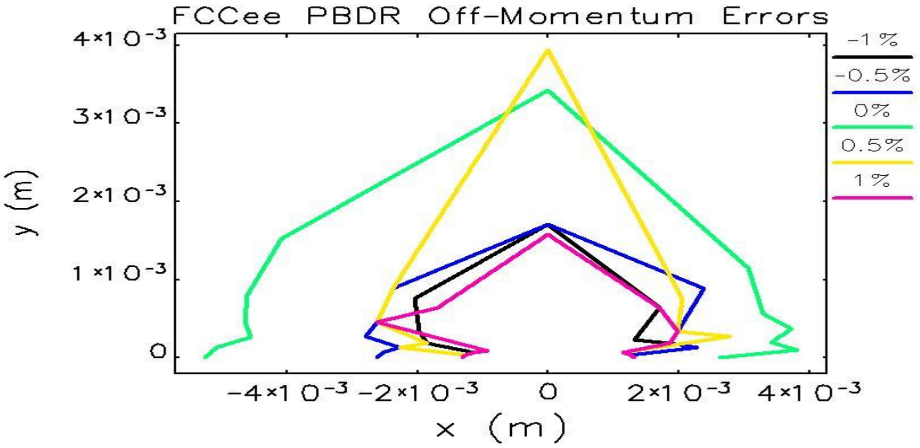


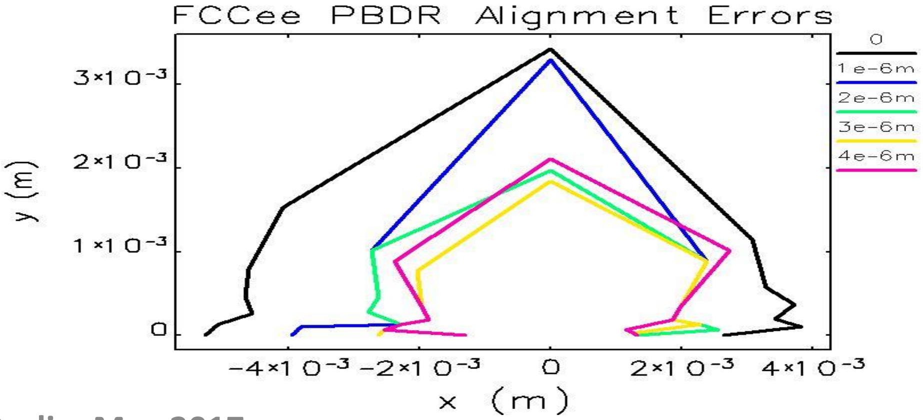


Parameters	Values
Energy [GeV]	20
Circumference [m]	2751.2
Emittance [pm.rad]	659
Energy loss / turn [MeV]	50.85
Natural chromaticity	-190/-111
Dx max [m]	0.08
Betax max [m]	16.0
Betay max [m]	25.3
Damping times [ms]	7.2/7.2/3.6

Dynamic aperture with momentum and alignment errors



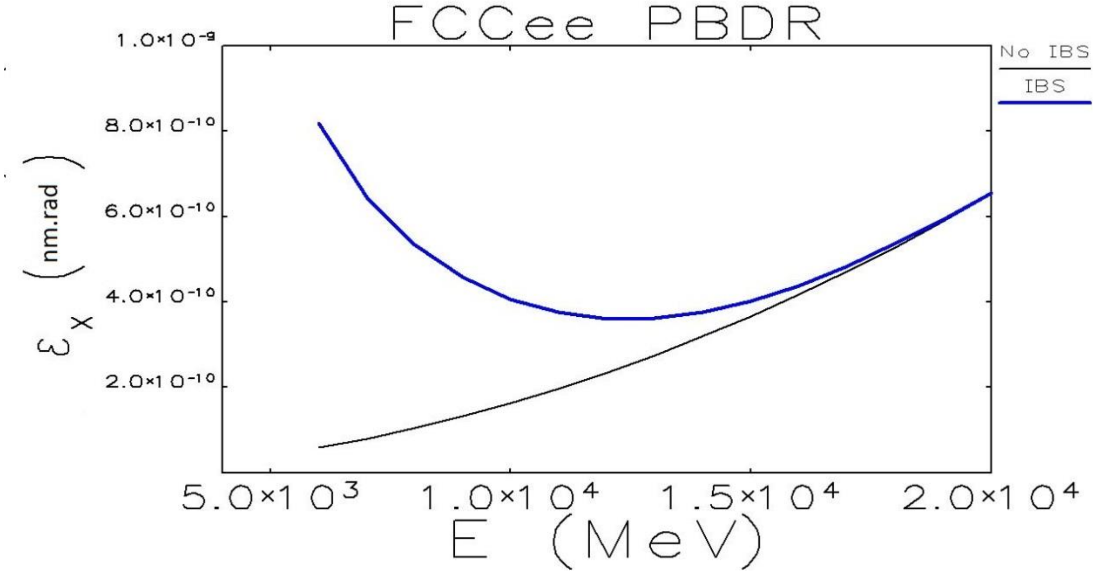




- For the injected emittance of around 0.7 nm.rad, the beam size is equal to 0.19 mm, so the DA obtained is around 16 σ without any error. And with the given off-momentum error up to 1% and alignment errors after a few μm, it reduces to around 8 σ at minimum.
- This can be indeed improved by a better working point choice, which is presently being optimised.

IBS vs Energy

The Intrabeam scattering (IBS) effect causes emittance growth in all three dimensions. It basically depends on the optics and beam properties and in particular with the beam energy. The scaling of the horizontal emittance including the IBS effect is presented below. At high energy, the effect of IBS is indeed negligible.



$\varepsilon = 0.7\ nm.rad$

bunch populations: $2.8\text{x}10^{10}$

coupling: 0.01

turns: 5000

SPS as pre-booster

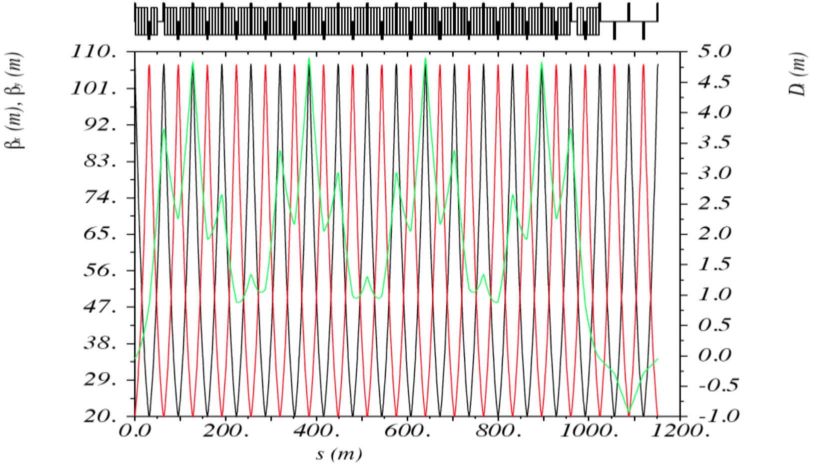
SPS Parameters	
SPS Bending radius [m]	741,63
SPS injection energy [GeV]	6
SPS extraction energy [GeV]	20
Dipole length	6,26*4
Bending field @ injection [Gauss]	269,811
Bending field @ extraction [Gauss]	899,3703
Emittance @ injection	2.44×10^{-9}
Emittance @ extraction	$2,71 \times 10^{-8}$
Energy Loss / turn @ injection [MeV]	0,155
Energy Loss / turn @ extraction [MeV]	19,085
Transverse Damping time @ injection [s]	1,788
Longitudinal Damping time @ injection [s]	0,894

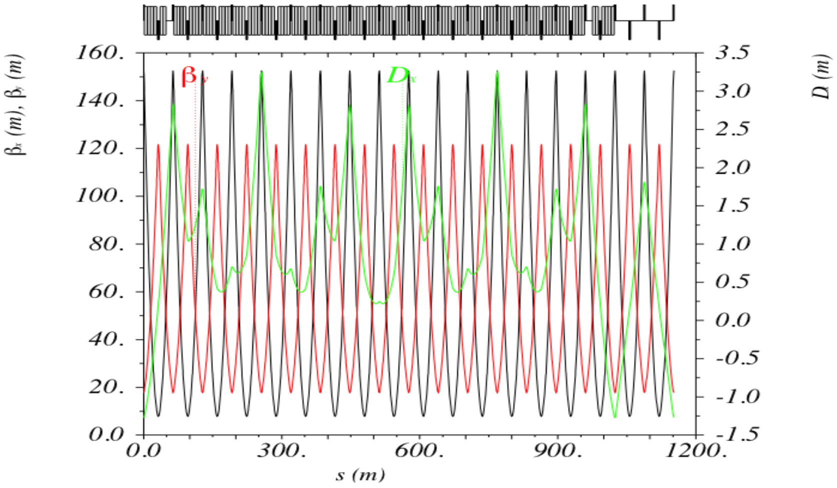
This table shows the parameters with the existing SPS cell but with energy of pre-booster for FCC e^+e^-.

- FODO with 6 long straight sections
- 6 identical periods each superperiod is composed of 18 cells
- Each superperiod is 63,9954 m
- The circumference is 18*6*63,9954= 6911,5 m (11*200 π!)
- 744 dipoles with 6,26 m length

SPS low emittance optics

- SPS is an all **FODO** cell lattice (6 sextants), with missing dipole
- Usually tuned to π/2 phase advance for fixed target beams with integer tune of 26 (**Q26**) and since 2012 to 3π/8 (**Q20**) for LHC beams and considering even **Q22**
- Move horizontal phase advance to 3π/4 (**Q40**)
- **Geometrical emittance** with nominal optics @ **6 GeV** of about **3 nm**
  - Mainly due to dispersion decrease
- Natural chromaticities of -71,-39 (from -20,-27)
- **Damping times** of **1.8 s**
- Can be reduced with Damping wigglers (also the emittance)





Y. Papaphilippou et al., IPAC 2013

Future studies

- **Further detail design for alternative PBR,**
- **Further studies on SPS as PBR,**
- **DA optimization,**
- **Further studies on collective effects**

Thank you

for this opportunity!