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

4^{th} FCC Week

Özgür ETİŞKEN (CERN & Ankara University)

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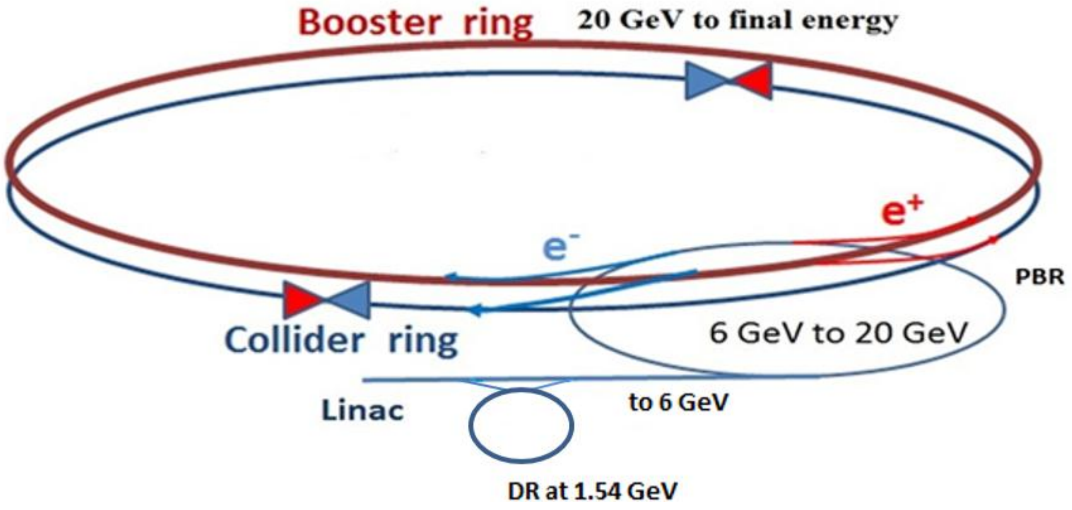
FCC e^+e^- Injector Layout

Two different options are under consideration as pre-accelerator before the bunches are transferred to the high-energy booster: <u>using the existing SPS and a completely new ring.</u>



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- Pre-booster ring
- Booster same tunnel with collider ring,
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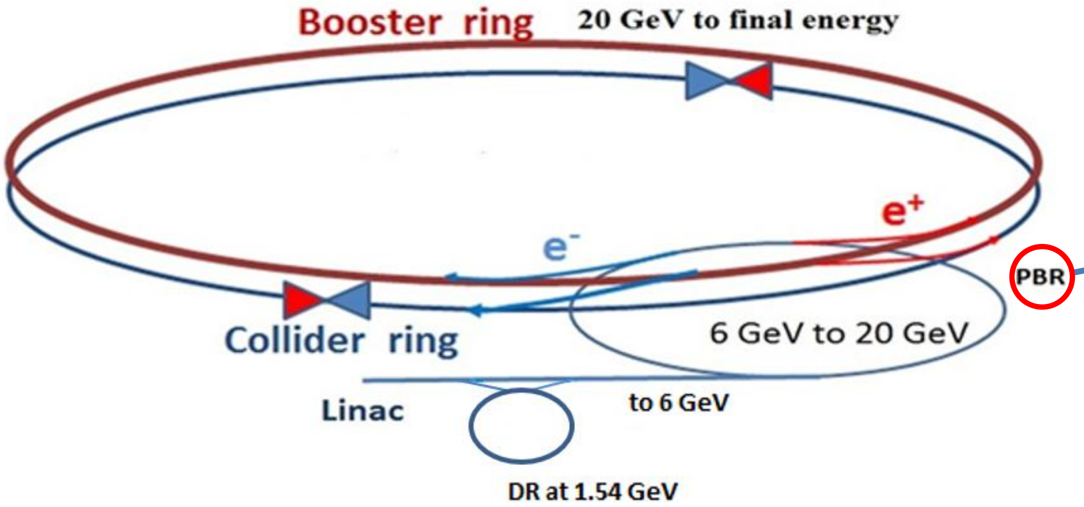

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SPS

- Baseline parameters are considering 6 GeV Linac and SPS as Pre-Booster Ring (PBR) but issues with:
  - machine availability, synchrotron radiation, new RF system…

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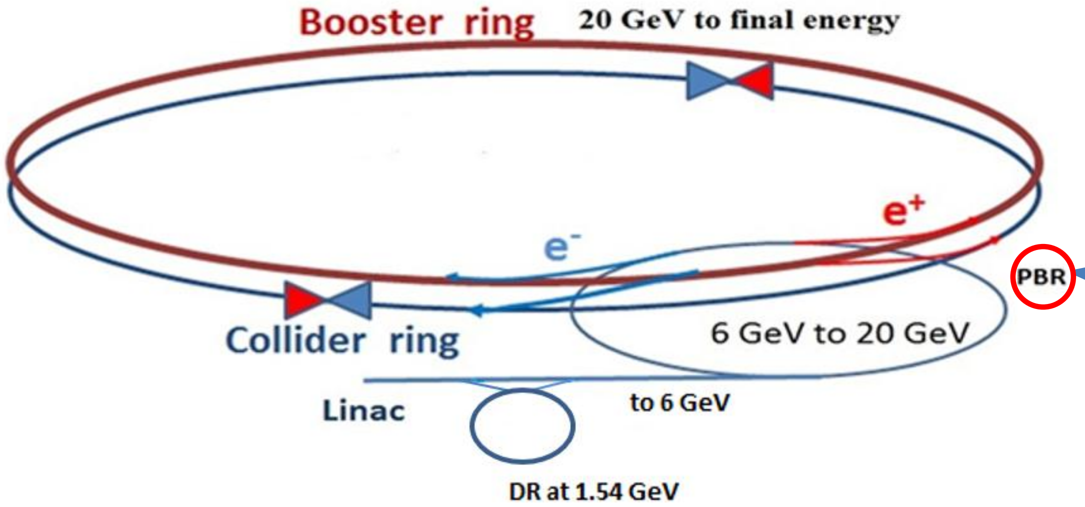

- Linac with a damping ring
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SPS

or

Alternative 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

Outline

- **Pre-booster ring (PBR) in FCC e^+e^- injector layout,**
- **Alternative pre-booster design for FCC e^+e^-,**
  - Main constraints,
  - Comparison with last year design for general parameters,
  - Optic design,
  - Phase space scanning,
  - Working point and tune shift with amplitude,
  - Dynamic aperture,
  - Wiggler consideration for alternative design.
- **SPS as pre-booster of FCC e^+e^-,**
  - Phase advance selection,
  - Working point selection,
  - Dynamic aperture,
  - Wiggler (normal) magnets in SPS,
- **Energy acceptance for SPS and Alternative PBR,**
- **RF Voltage and RF Power estimations for SPS and Alternative PBR.**

Main constraints (Alternative)

1

Energy loss per turn

$E_{loss/turn} = 50\ MeV$

Energy loss per turn should not exceed 50 MeV because of high RF voltage requirement.

2

Damping time

$\tau \sim 0.1\ s$

It should be 0.1 s. It is necessary for injection and to have the beam which has the same properties with fast damping before energy ramping.

3

Emittance

Energy (GeV)	ε (nm.rad) (main ring)	ε (nm.rad) (booster ring at extraction)	ε (nm.rad) (alternative pre-booster ring at 20 GeV)	ε (nm.rad) (SPS at 20 GeV)
45.6	0.27	~0.27	~ 5	~ 5
80	0.28	~0.28	~ 5	~ 5
120	0.63	~0.63	~ 5	~ 5
182.5	1.46	~1.46	~ 5	~ 5

4

Energy acceptance

$\frac{\delta E}{E} = \sim \mp \%\ 1.5$ @6 GeV

5

Dynamic aperture

Should be at least ~7-8 mm with off-momentum tolerances

Main constraints (Alternative)

1

Energy loss per turn

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Energy loss per turn should not exceed 50 MeV because of high RF voltage requirement.

Emittance, damping time and energy acceptance are the main differences from **last year (Berlin).**

- Horizontal emittance is decided as 5 nm.rad considering emittance chain through the injector complex and DA of main booster.
- Damping time is decided as 0.1 s for injection efficiency and energy ramping (with the recommendation of Y. Papaphilippou and M.Aiba).

2

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It should be 0.1 s. It is necessary for injection and to have the beam which has the same properties with fast damping before energy ramping.

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Should be at least ~7-8 mm with off-momentum tolerances

Comparison of general parameters with last year (Alternative)

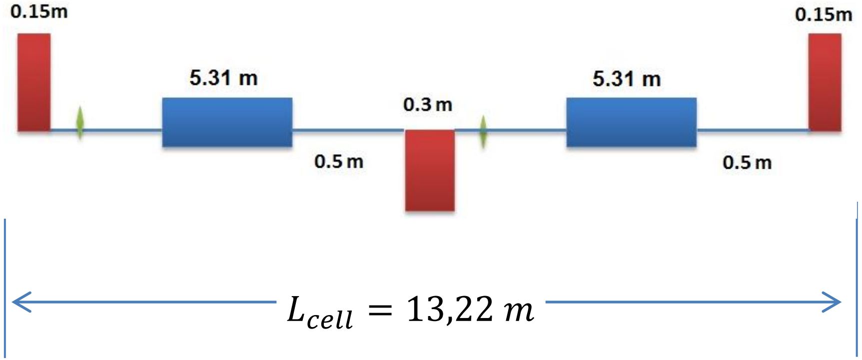
At this point, a comparison is stated here between old and new design parameters after quick calculation for main parameters.

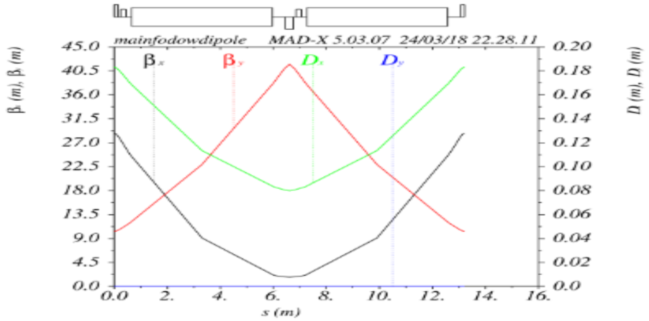
	FCC Week 2018	FCC Week 2017
Horizontal emittance	5 nm.rad	1 nm.rad
Dipole magnet quantity	332	700
Dipole magnet length	~ 5.31 m	~ 2.5 m
Bending angle	$\sim 1.07^0$	$\sim 0.5^0$
Max. magnetic field	~ 0.23 T	~ 0.23 T
Min. magnetic field	~ 0.07 T	~ 0.07 T
Cell quantity	166	350
Circumference	~2.3 km	~2.7 km

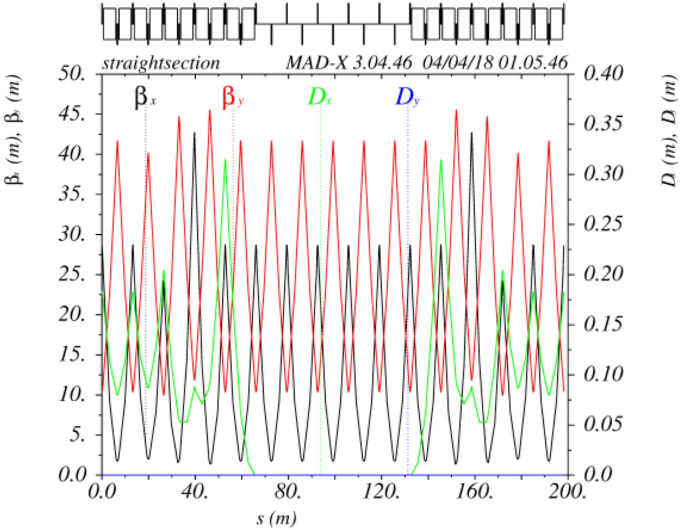
The emittance increase allows us to provide shorter ring by using longer dipole magnets with less cell.

Additionally, it is expected that the emittance increase would relax the quadrupole strengths, chromaticty and finally dynamic aperture.

Optic design and parameters (Alternative)

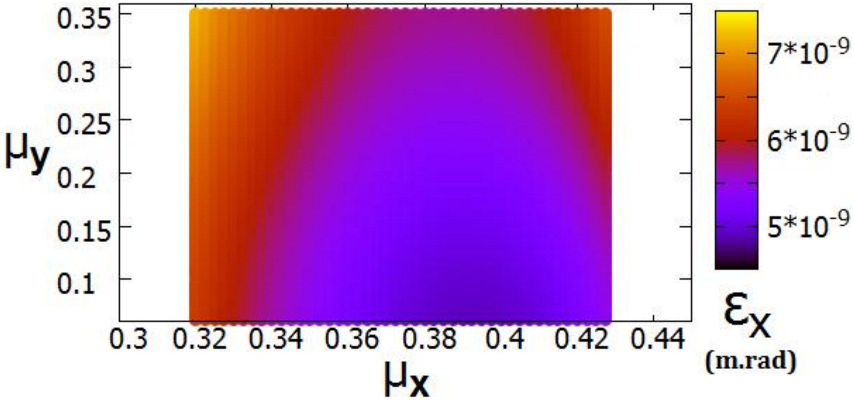






Parameters	Values	
Energy [GeV]	20	6
Circumference [m]	2326.72	
Emittance [nm.rad]	5.04	0.45
Energy loss / turn [MeV]	50.4	0.40
Natural horizontal chromaticity	-108	
Natural vertical chromaticity	-54	
Dx max [m]	0.31	
Betax max [m]	48.8	
Betay max [m]	45.5	
Horizontal Damping times [ms]	6.15	230
Vertical Damping times [ms]	6.15	230
Longitudinal Damping times [ms]	3.07	113
Horizontal Tune	66.61	
Vertical Tune	18.17	

Phase advance scanning (Alternative)
(Emittance, chromaticities and tune shift with amplitude)



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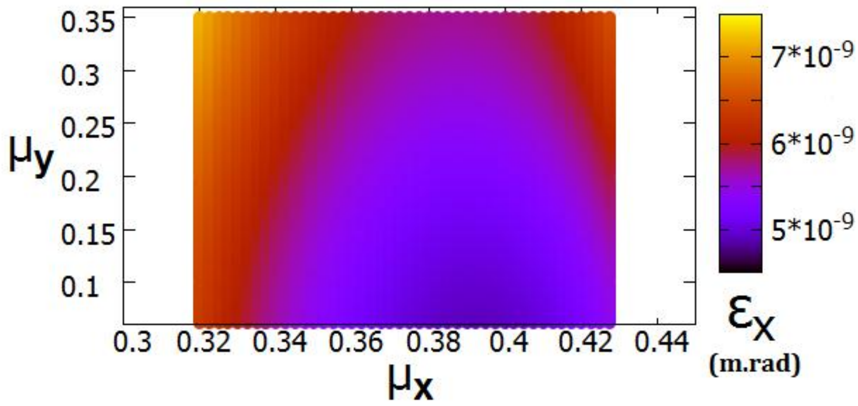

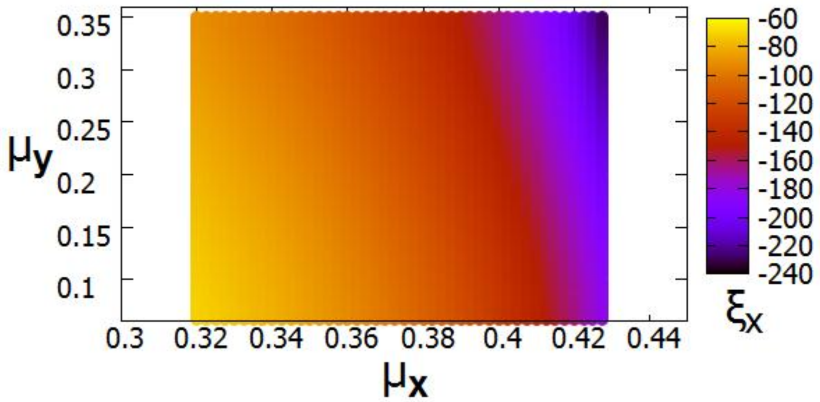

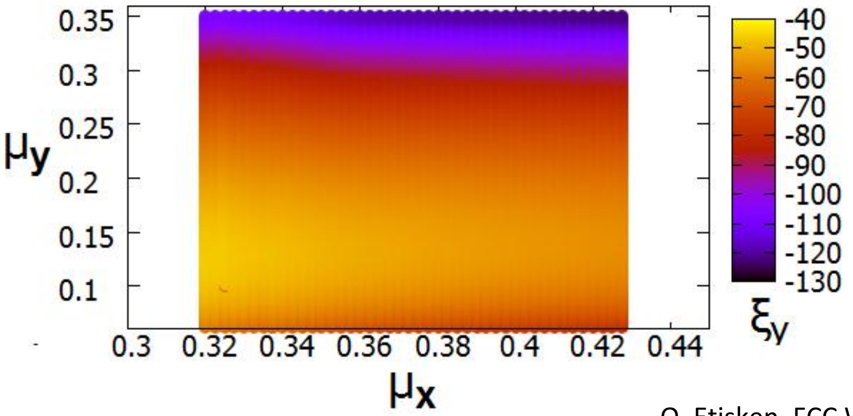

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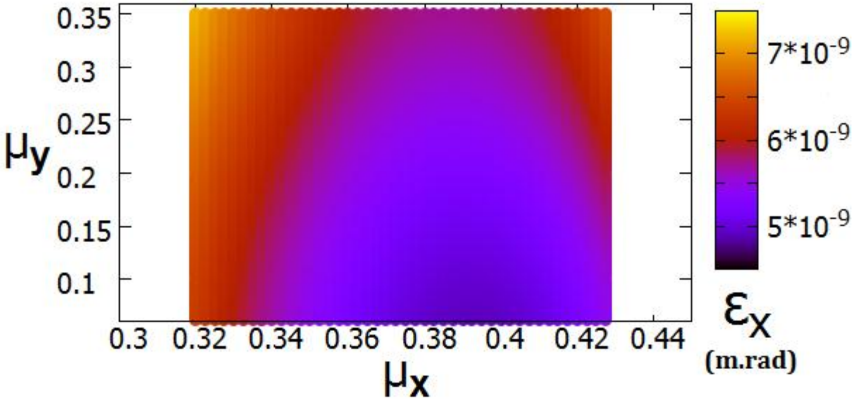

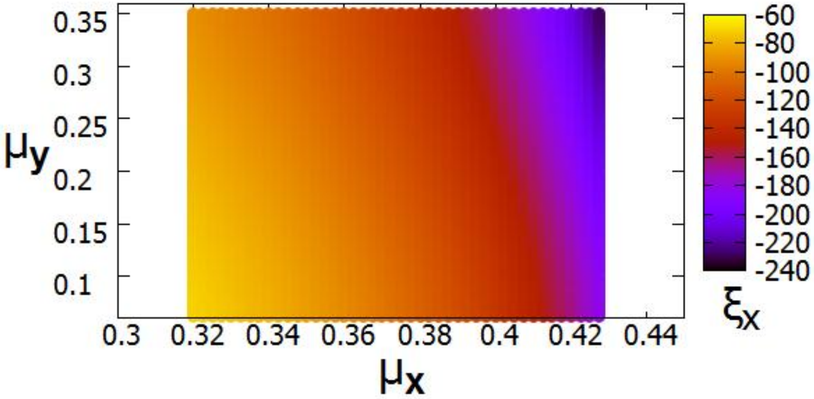

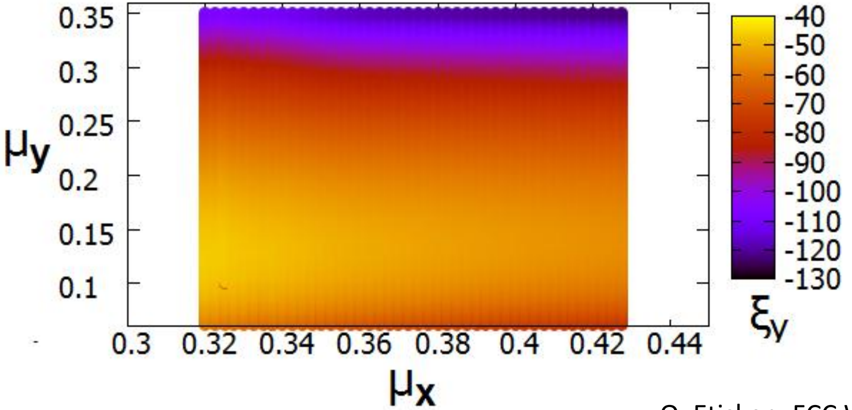

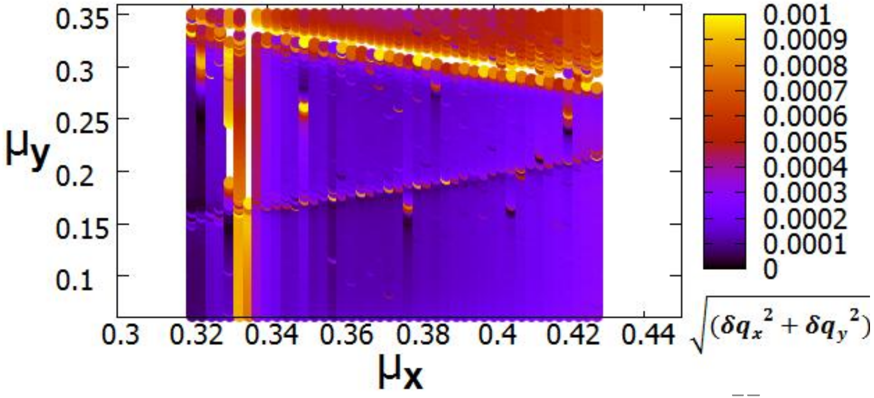

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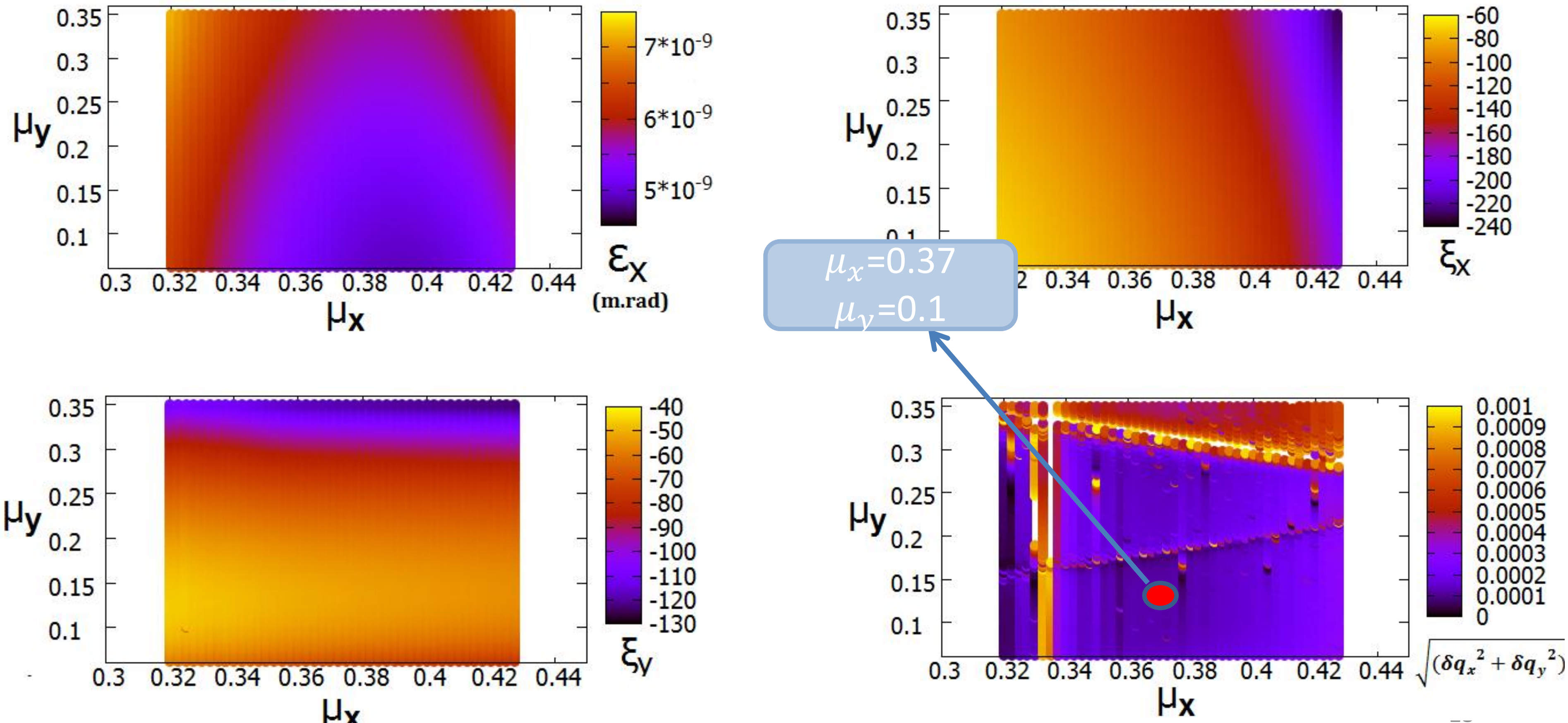
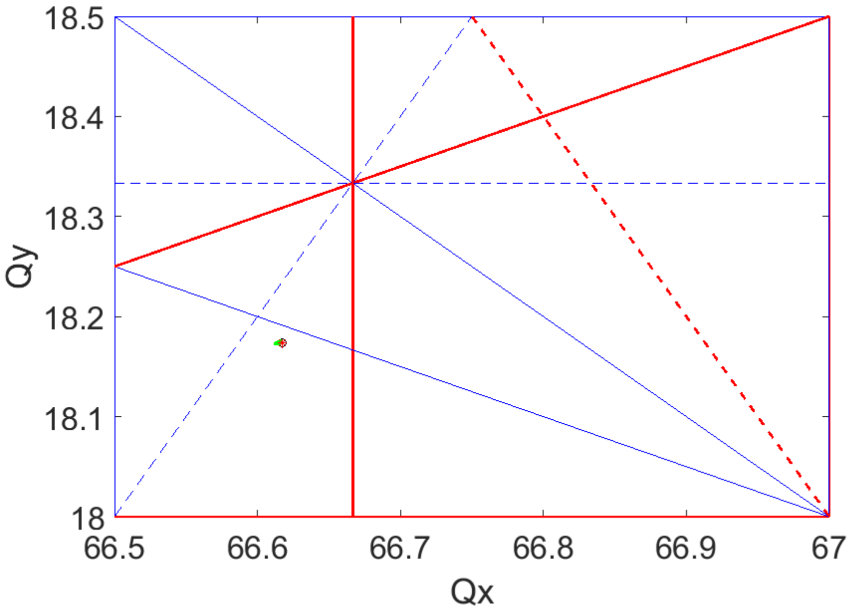
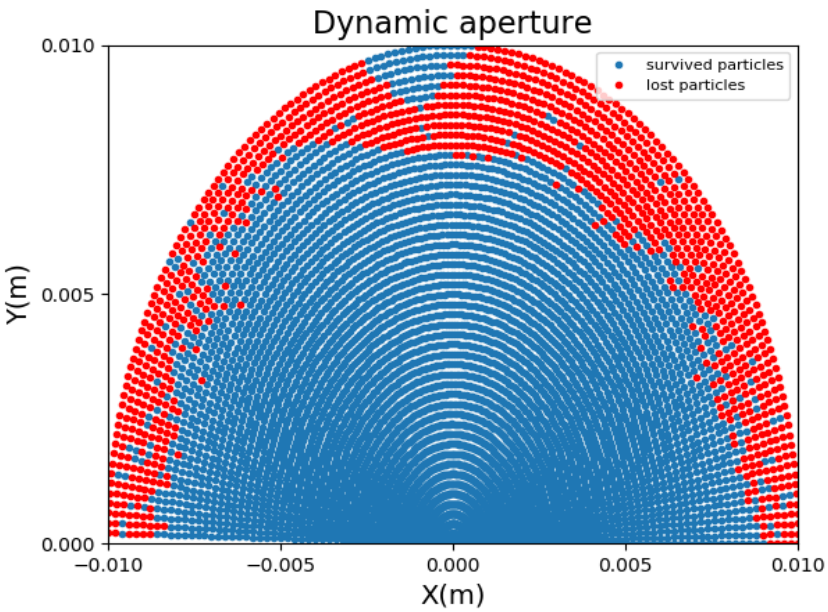


Tune Shift and Dynamic Aperture (Alternative)



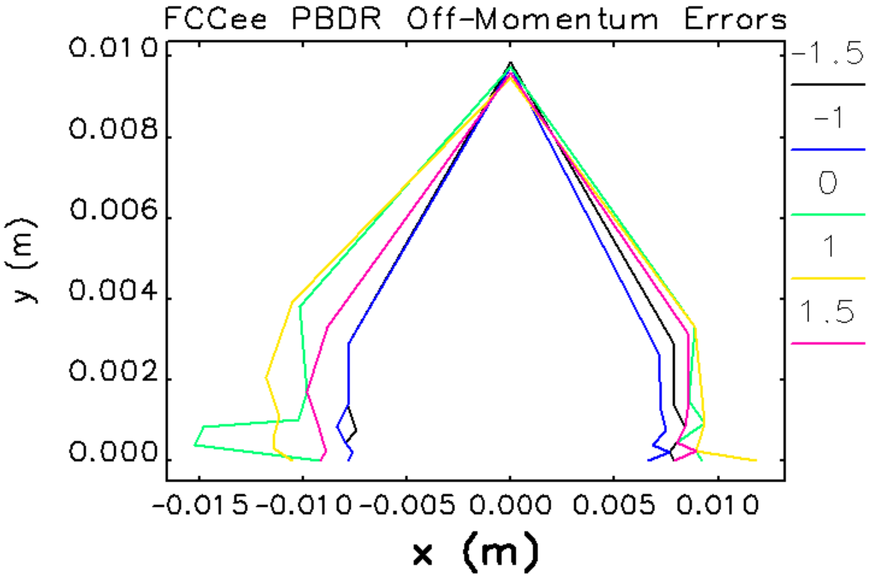


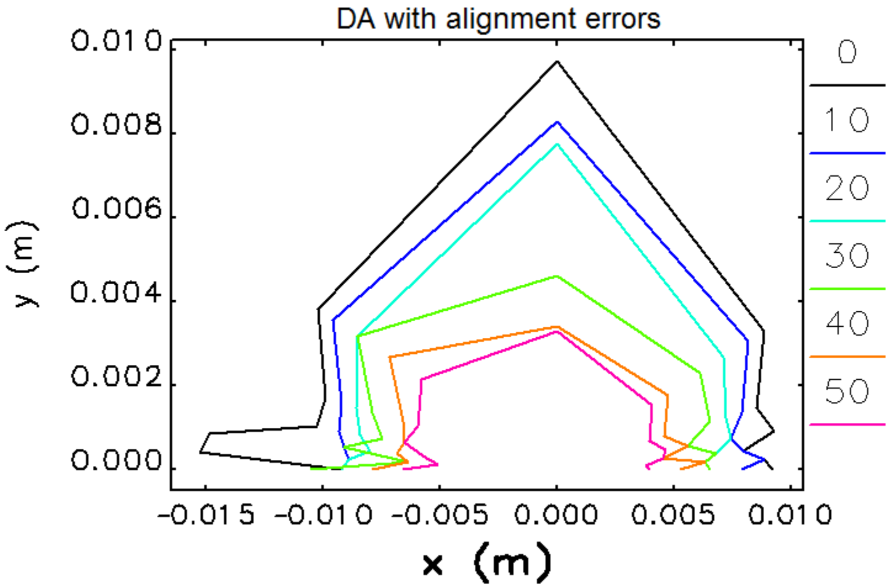
An optimal choice of phase advances is chosen to be $(\mu_x, \mu_y) = (0.37/2\pi, 0.1/2\pi)$, corresponding to a tune working point of $(Q_x, Q_y) = (66.61, 18.17)$.

Dynamic aperture simulations were undertaken, the horizontal versus vertical DA for different momentum deviations using MADX-PTC.

Dynamic Aperture Tolerances (Alternative)

Considering that the injected horizontal emittance is around 1 nm.rad provided from the linac at the moment, the DA is around 40 beam size for up to $\pm 1.5\%$ momentum deviation in horizontal plane.





Wiggler magnet consideration (Alternative)

Parameters	Values	
Energy [GeV]	20	6
Circumference [m]	2326.72	
Emittance [nm.rad]	0.45	5.04
Energy loss / turn [MeV]	0.40	50.4
Natural horizontal chromaticity	-108	
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Options are considered to decrease the damping time at flat-bottom energy to 0.1s.

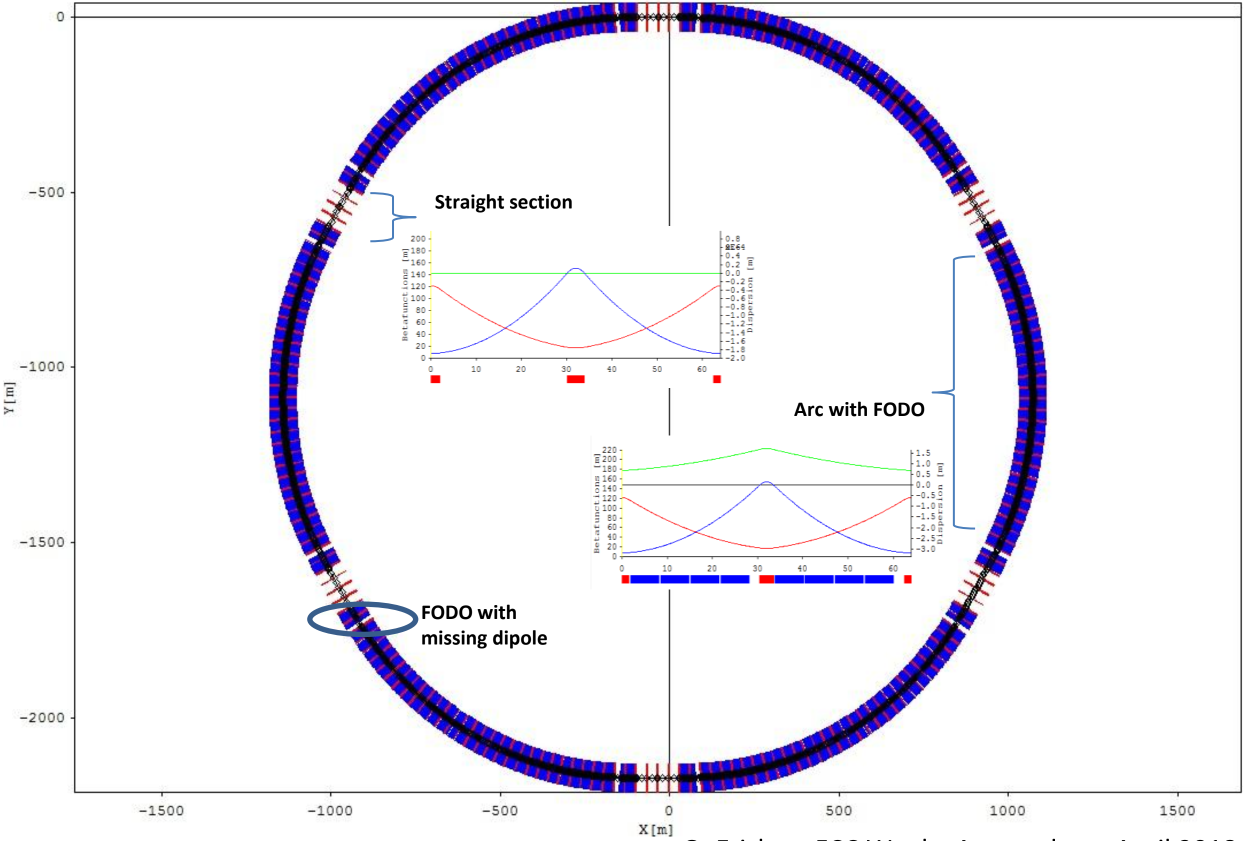
- Change the circumference (increase around 1 km),
- Adding wiggler magnet.

$B_w\ (T)$	$L_w(m)$	$\tau\ (s)$
1	~20	0.1
2	~5	0.1
3	~2.5	0.1
4	~1.4	0.1
5	~0.9	0.1

$$\tau_x = \frac{(FF.C)^2}{\pi.c.E^3.c_\gamma} \cdot \frac{1}{(1+F_w)} \quad ; F_w = \frac{L_w.{B_w}^2}{4.\pi.B^2}$$

P.S Wiggler effect on emittance is not major.

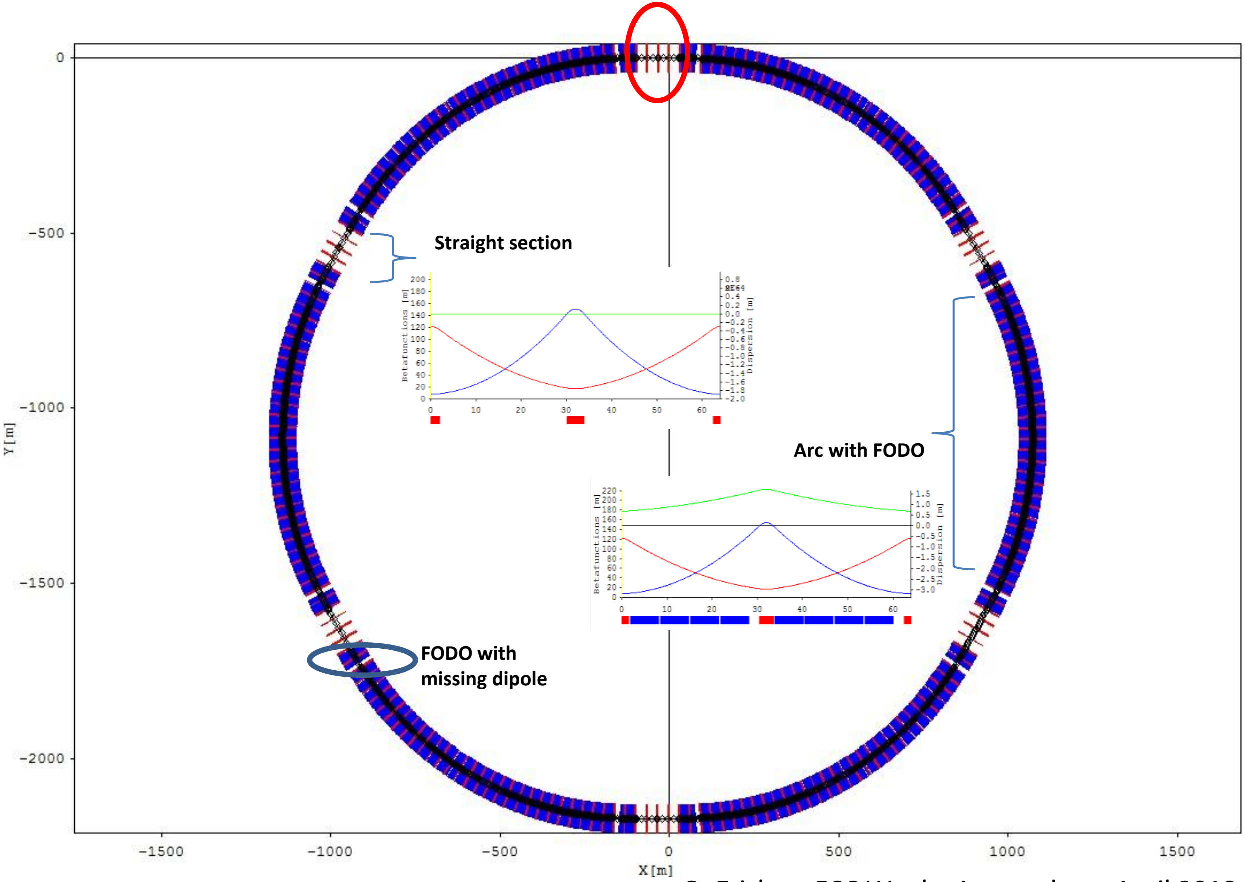
SPS as Pre-booster of FCC e^+e^-



- The ring consist of 6 arcs and 6 straight sections,
- 6 identical periods; each super period is composed of 18 FODO cells,
- Each super-period is around 1.15 km,
- The circumference is around 6.9 km,
- 744 dipoles with 6.26 m length,

Constraint: minimum modification can be done!

SPS as Pre-booster of FCC e^+e^-



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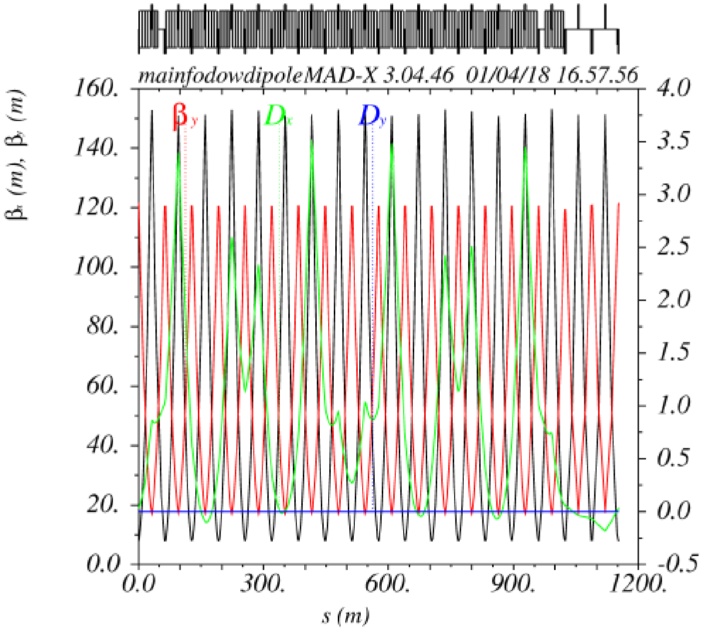
- 744 dipoles with 6.26 m length,

- FODO with wiggler magnets are planned to be added to one of the straight section.

Constraint: minimum modification can be done!

SPS as Pre-booster of FCC e^+e^-

Using the SPS as pre-booster for the FCC-e^+e^- injector chain imposes various constraints, as minimum modifications can be applied to the existing machine, following to the lepton collider requirements. The SPS is constructed by FODO cells and the dispersion suppression is achieved by keeping the total arc phase advance a multiple of 2π.



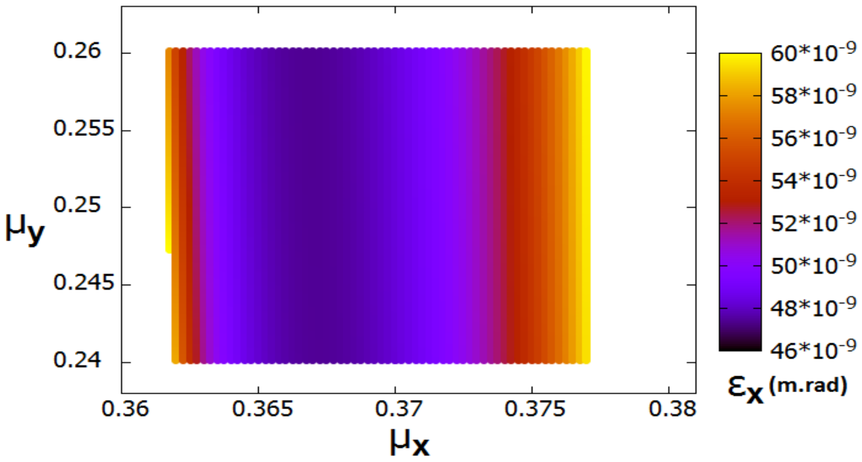
- SPS, usually tuned to π/2 phase advance for fixed target beams with integer tune of 26 (Q26) and since 2012 to 3π/8 (Q20) for LHC beams and considering even Q22

- Move horizontal phase advance to 3π/4 (Q40);

- Geometrical emittance with nominal optics @ 6 GeV of about 3 nm
- Natural chromaticities of -71,-39 (from -20,-27)
- Damping times of 1.8 s

Y. Papaphilippou et al., IPAC 2013

Phase advance scanning (SPS)



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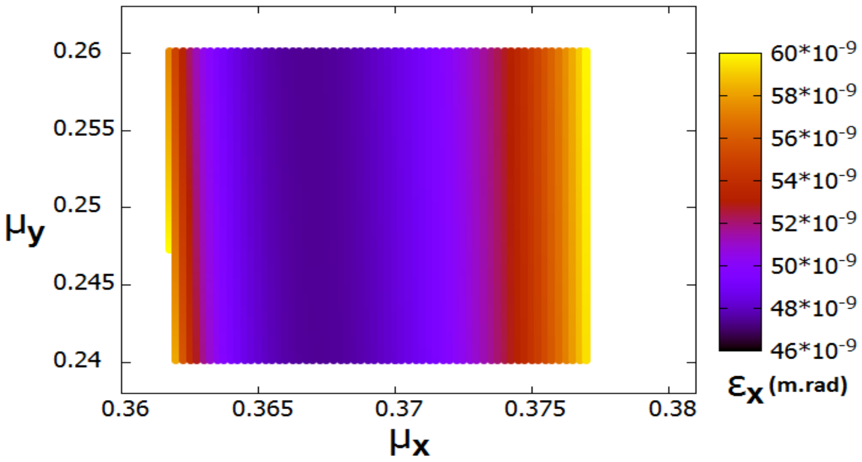

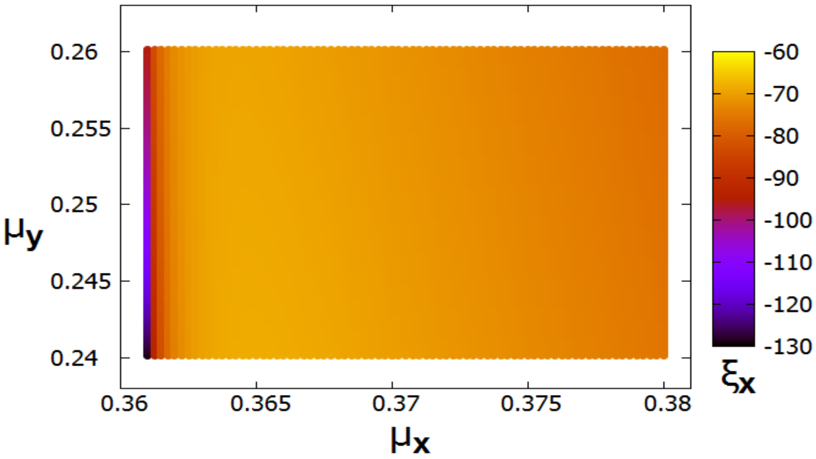

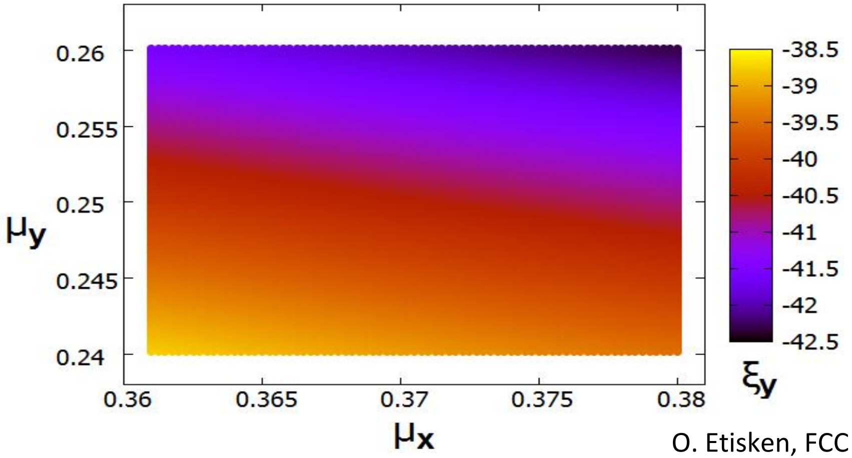

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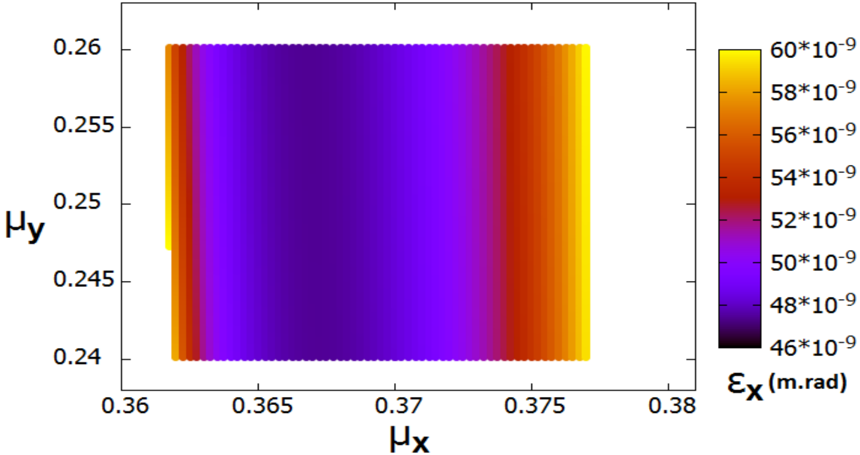

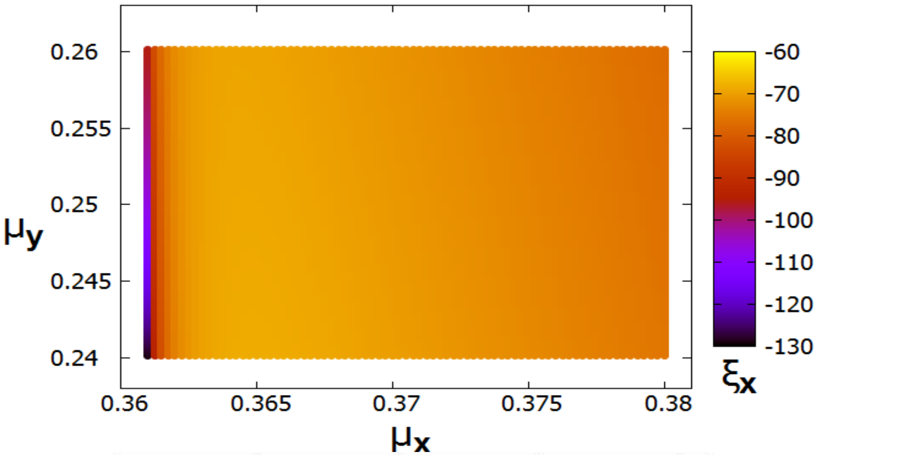

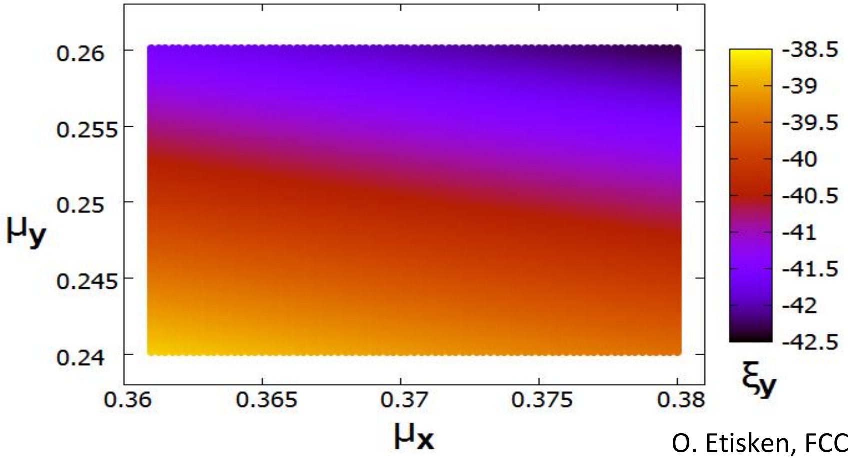

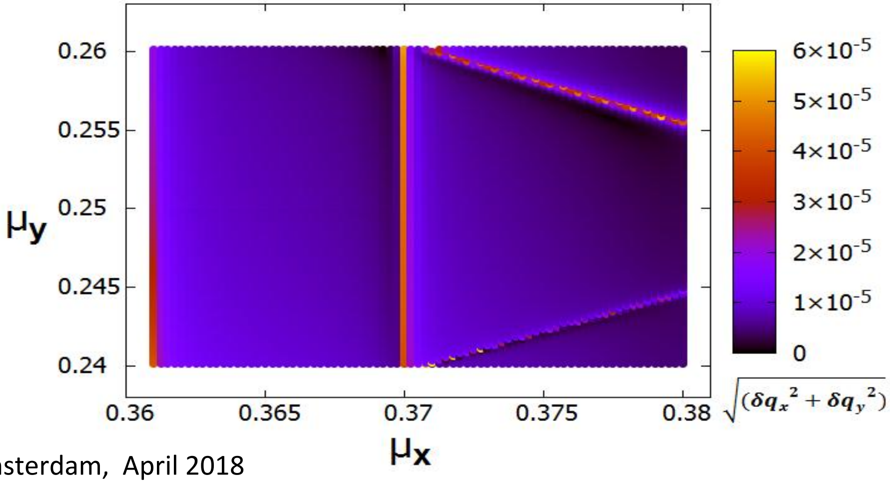

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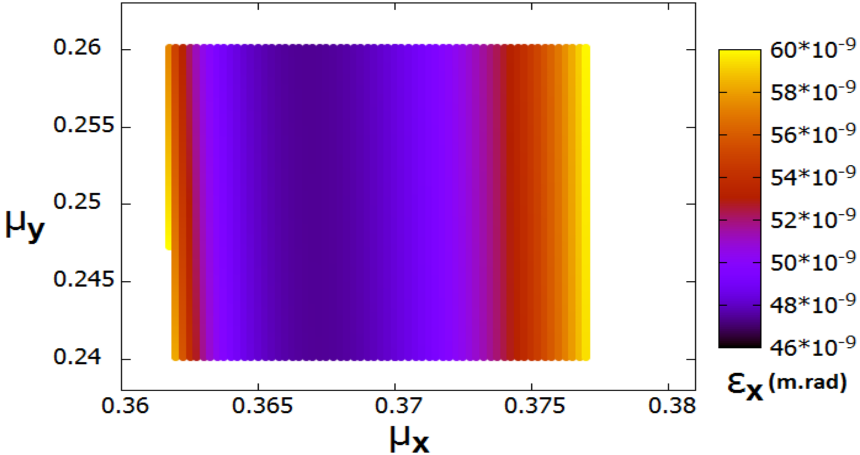
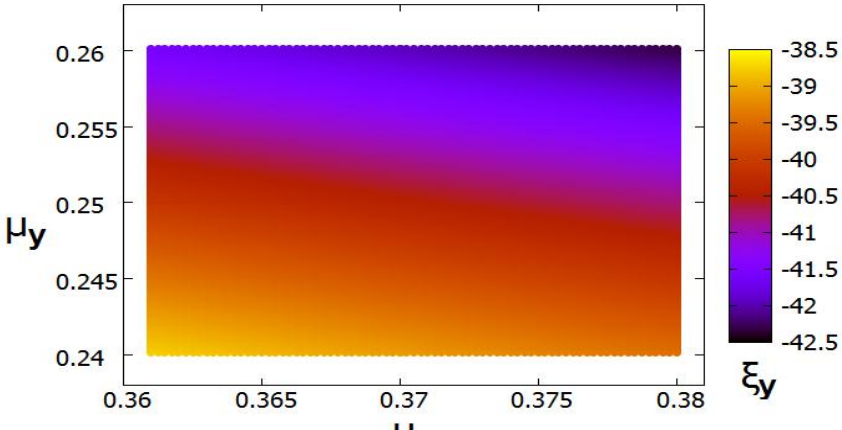
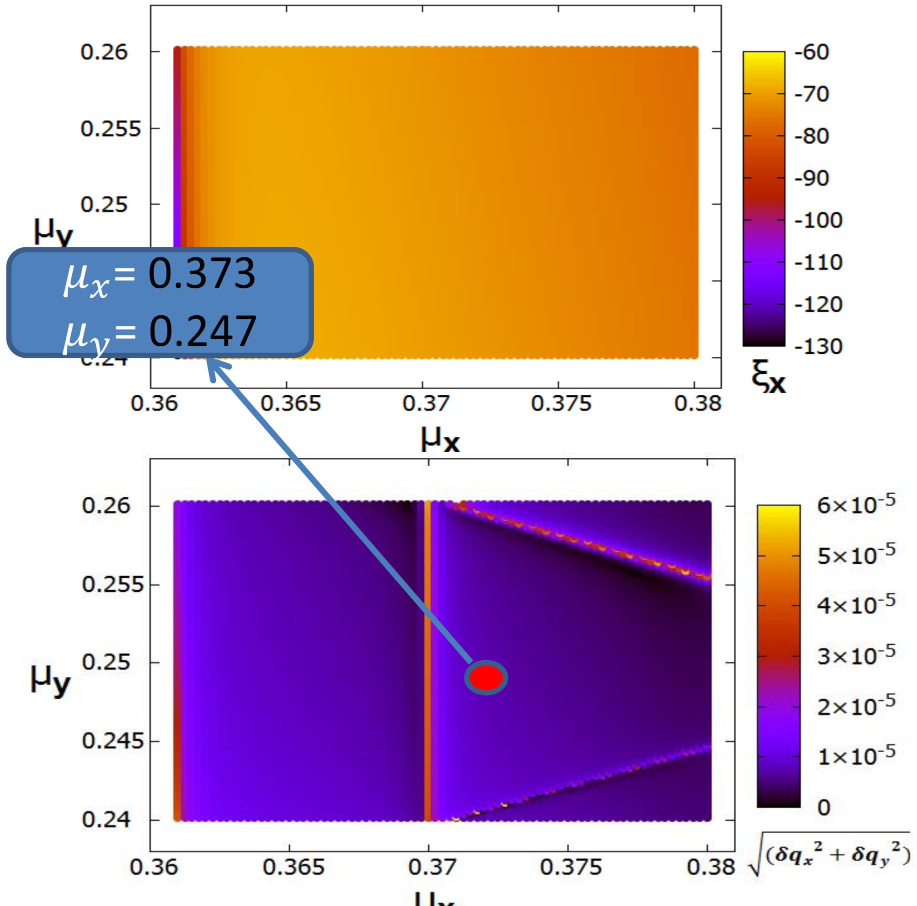
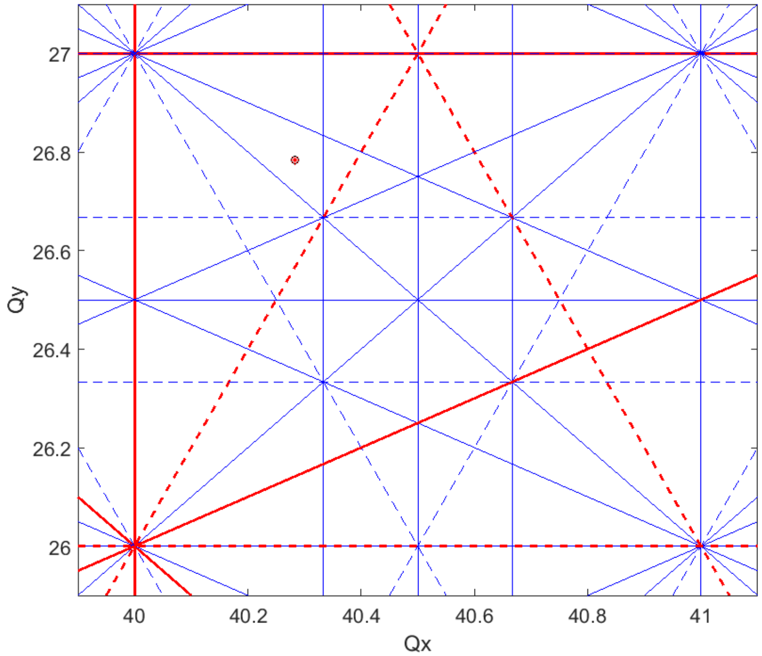
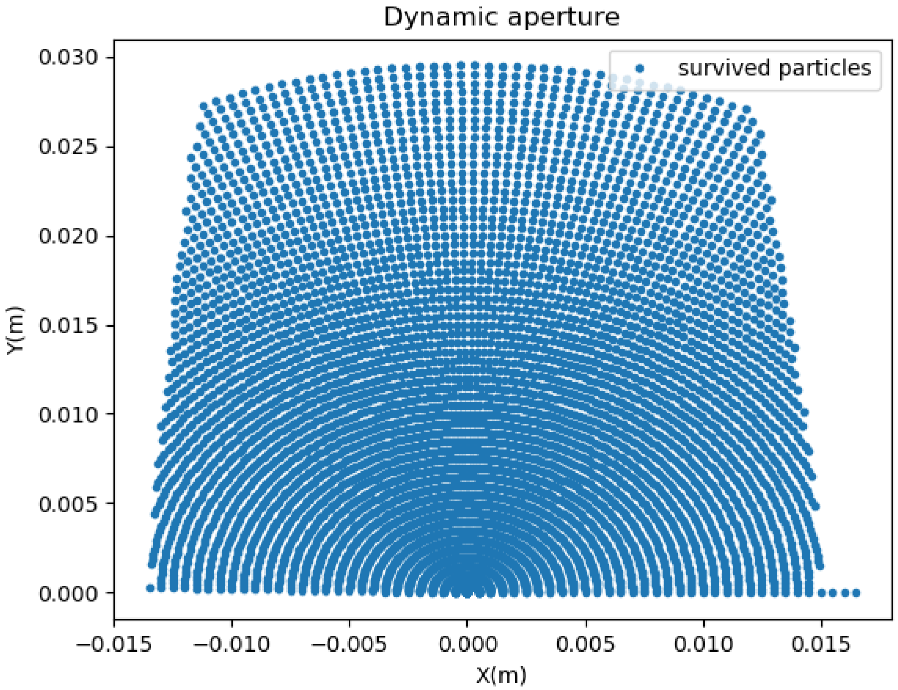






Working point and Dynamic Aperture (SPS)





An optimal choice of phase advances for achieving a small emittance at extraction, while providing minimum emitance in straight section low, was chosen to be $(\mu_x, \mu_y) = (0.372/2\pi, 0.247/2\pi)$, corresponding to a tune working point of $(Q_x, Q_y) = (40.28, 26.78)$ (left). And corresponding DA is shown (right).

Wiggler magnet considerations (SPS)

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 (m.rad)	4.5×10^{-9}
Emittance @ extraction	51×10^{-9}
Energy Loss / turn @ injection [MeV]	0.154
Energy Loss / turn @ extraction [MeV]	19.094
Transverse Damping time @ injection [s]	1.79
Longitudinal Damping time @ injection [s]	0.894
Natural chromaticity h/v	-72/-40

Should be decreased to 5 nm.rad at least!

Should be 0.1 s or less

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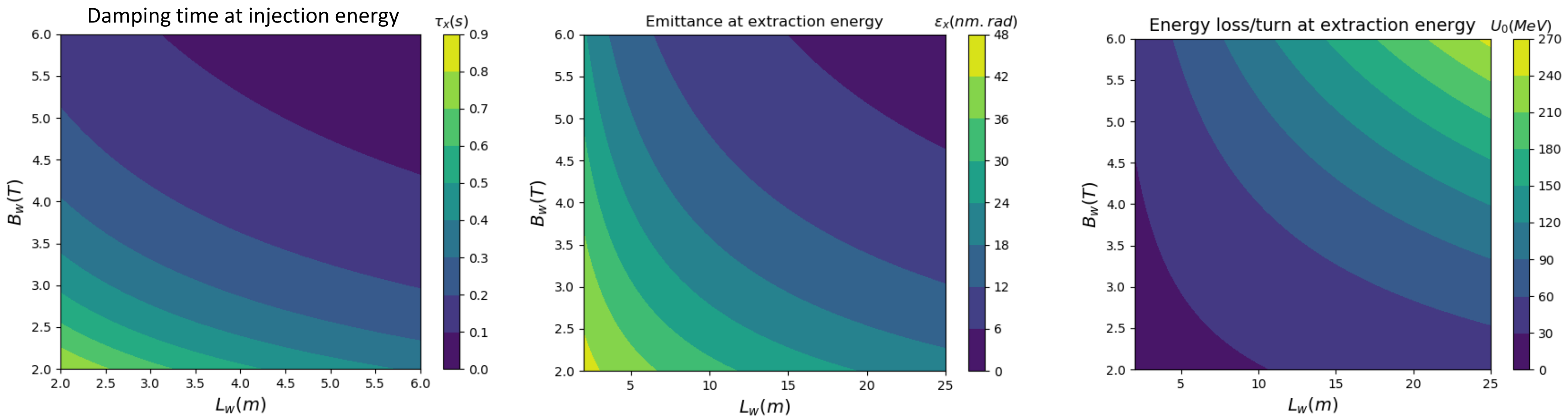
Adding wiggler magnets

In order to achieve the required emittance and shorten the damping times by roughly an order of magnitude, the employment of damping wiggler magnets are proposed to be installed in the straight sections of the SPS.

Beam Parameters with Wiggler Magnet (SPS)



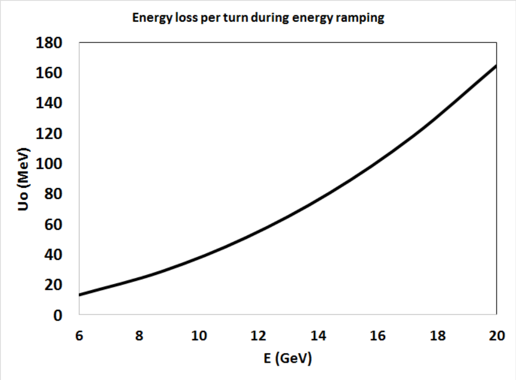
Horizontal emittance, damping time and energy loss per turn are stated in the table with wiggler with the total length of 23 m and 5 T magnetic field.

	6 GeV		20 GeV	
	Wout W	With W	Wout W	With W
$\varepsilon_h\ (nm.rad)$	4.5	0.05	~50	~5
$\tau\ (s)$	1.7	0.02	0.005	0.002
$U_0(MeV)$	0.15	13.2	19	164

RF Voltage and Energy Acceptance

The energy acceptance calculation is needed to confirm that the PBR can accept the incoming beam from the linac. The energy acceptance can be determined by the following:

$$\frac{\Delta \boldsymbol{E}}{\boldsymbol{E}} = \pm\sqrt{\frac{q.V}{\pi.h.\alpha_c.E_0}.\left(2cos(\emptyset_s) + (2.\emptyset_s - \pi)sin(\emptyset_s)\right)}$$



For alternative design:

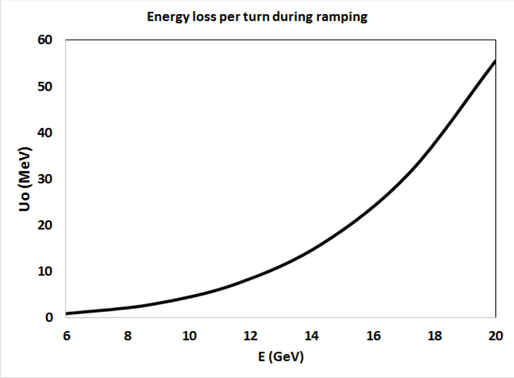
V_{rf} (MV)= 4.1
α_c= 4x10^{-4}
h= 3102
$\emptyset_s$ (degree)=12
$U_0(MeV)$= 0.86 at 6 GeV

$$\frac{\delta E}{E} = \mp\%\ 1.5\ at\ 6\ GeV$$

For SPS as pre-booster:

V_{rf} (MV)= 38
α_c=9.8x10^{-4}
h= 9214
$\emptyset_s$ (degree)=~20
$U_0(MeV)$=13.2 at 6 GeV

$$\frac{\delta E}{E} = \mp\%1.5\ at\ 6\ GeV$$



RF Power and Summary of the parameters

RF voltage and RF power estimations are summarized in this table for both options and both modes;

	SPS				Alternative			
	Full		Top-up		Full		Top-up	
	6 GeV	20 GeV	6 GeV	20 GeV	6 GeV	20 GeV	6 GeV	20 GeV
Energy loss per turn(MeV)	13.2	164.5	13.2	164.5	0.86	55.5	1.04	57.5
RF voltage (MV)	38	192	38	192	4.1	64	4.1	64
RF phase(^{0})	20	60	20	60	12	60	12	60
Energy acceptance ($\pm$%)	1.5	0.5	1.5	0.5	1.5	0.84	1.5	0.84
Bunch population	2.3×10^{10}		1.06×10^{10}		1.77×10^{10}		1.06×10^{10}	
Number of bunches	2080		2080		1040		1040	
Current(mA)	307		153		380		227	
Cycle length (s)	5.9				3.7			
Ramping time (s)	0.25				0.25			
RF power (MW)	5.8	29.4	4.59	18.06	1.55	24.3	0.9	14.5
Average RF power (MW)	~13.9		~6.9		~3.2		~1.91	

Summary & Next Step

Summary updates since FCC Week 2017 in Berlin:

Alternative ring:

- Emittance values are re-evaluated and a new design has been made for 5 nm.rad extraction emittance,
- Wiggler magnets are decided to use in alternative ring to reduce the damping time at injection energy and related calculations are done,

SPS:

- Horizontal phase advance is moved to $3\pi/4$ to have lower emittance values and provide dispersion suppressor in SPS,
- Required calculations are done to reduce 'the emittance at extraction' and 'damping time at injection energy' by adding wiggler magnets to the straight sections of SPS,

RF Voltages and Energy acceptance:

- RF voltage & power estimations and energy acceptance calculations are done for both options.

Next steps:

- Further detailed studies are in progress; the study of collective effects should be considered, after studies are finished with the wiggler magnets and working point selection.

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Thank you!