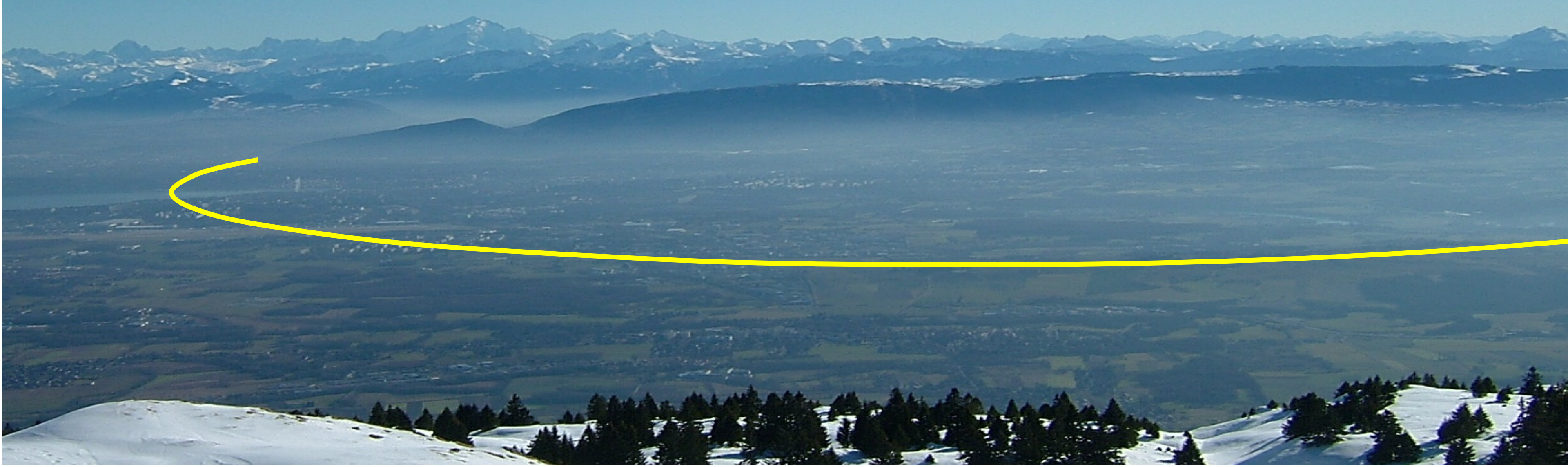
The FCC-ee booster synchrotron

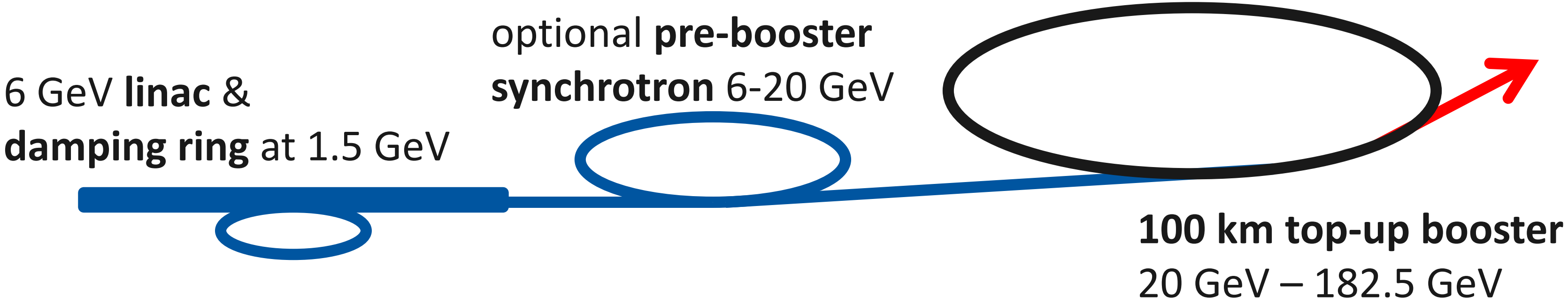
A summary and outlook



Bastian Haerer (CERN)
for the FCC-ee lattice design team

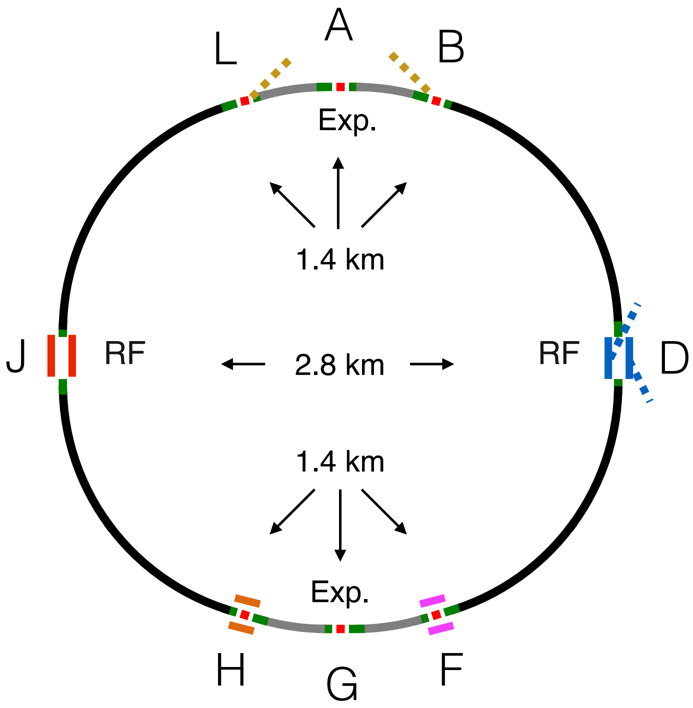
19th FCCee Injector Meeting
09 August 2018

Parameter overview



Accelerator	FCCee-Z		FCCee-W		FCCee-H		FCCee-tt	
Energy [GeV]	45.6		80		120		182.5	
Type of filling	Full	Top-up	Full	Top-up	Full	Top-up	Full	Top-up
BR # of bunches	16640		2000		393		39	
BR cycle time [s]	51.74		14.4		7.53		5.49	
#of BR cycles	10	1	10	1	10	1	20	1
Filling time (both species) [sec]	1034.8	103.5	288	28.8	150.6	15.06	219.9	11.0
Injected bunch population [10^{10}]	1.7	0.085	1.5	0.045	1.5	0.045	2.2	0.066

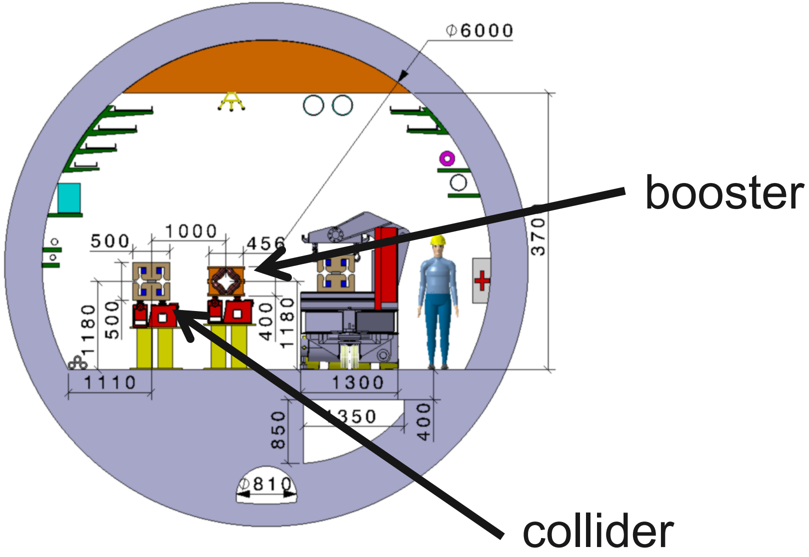
FCC Layout

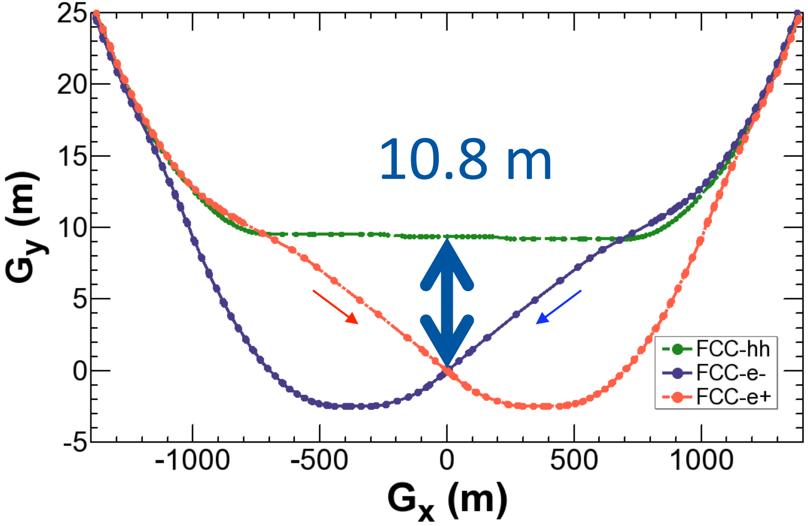


Circumference: C = 97.75 km
Bending radius: ρ = 10.5 km

2 experimental straight sections (A & G)
2 RF sections in points D and J

Tunnel and IR cavern

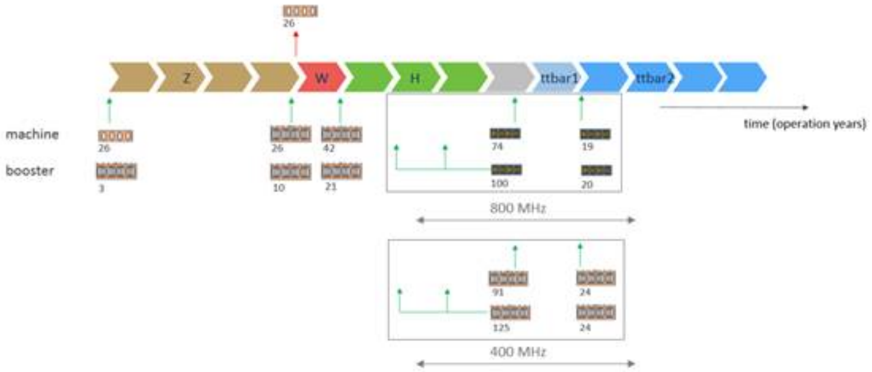




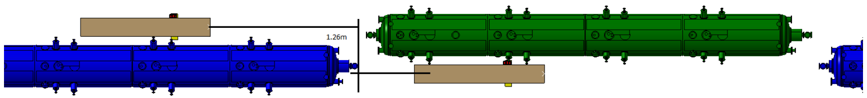
The layout of the booster follows the footprint of FCC-hh
→ inside the experiments

RF system

available for every operation mode



booster



collider

1.26 m distance

Table 1.2: Detailed RF configuration of each machine and booster ring.

	Z		*W*		*H*		**$ttbar_1$**		**$ttbar_2$**	
	per beam	booster	per beam	booster	per beam	booster	2 beams	booster	2 beams	booster
Total RF voltage [MV]	100	140	750	750	2000	2000	9500	9500	10930	10930
frequency [MHz]	**400**									
RF voltage [MV]	100	140	750	750	2000	2000	4000	2000	4000	2000
E_{acc} [MV/m]	5.1	8	9.6	9.6	9.8	9.8	10		10	
# cell / cav	1	4	4		4		4		4	
V_{cavity} [MV]	1.92	12	14.4	14.4	14.7	14.7	15		15	
# cavities	52	12	52	52	136	136	272	136	272	116
# CM	13	3	13	13	34	34	68	34	68	34
T operation [K]	4.5		4.5		4.5		4.5		4.5	
dyn losses/cav [W]	14	11	210	26	202	29	210	30	210	30
stat losses/cav [W]	8		8		8		8		8	
Q_{ext}	4.4 10^4		6.6 10^5		1.9 10^6					
P_{cav} [kW]	962		962		368		155		135	
frequency [MHz]	**800**									
RF voltage [MV]							5500	7500	6930	8930
E_{acc} [MV/m]							19.8	20	19.8	19.8
# cell / cav							5		5	
V_{cavity} [MV]							18.6	18.75	18.6	18.6
# cavities							296	400	372	480
# CM							74	100	93	120
T operation [K]							2		2	
Q dyn/cav [W]							66	10	66	10
Q stat [W]							8		8	
Q_{ext}							4 10^6		4 10^6	
P_{cav} [kW]							196		170	

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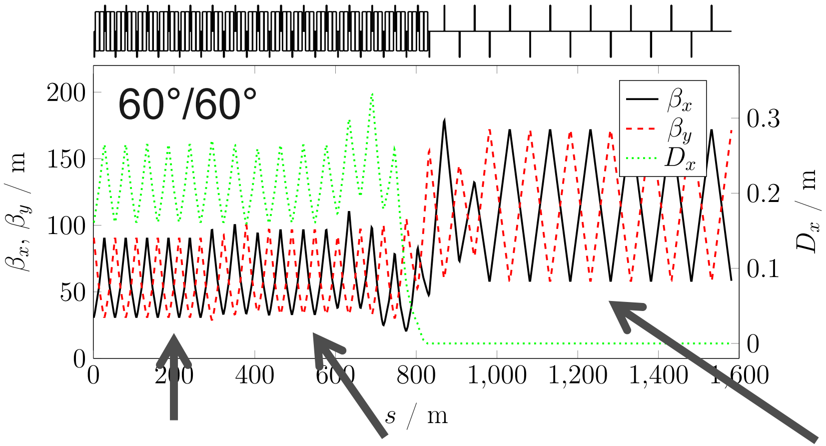
Lattice and optics (version 3)



Long arcs
$L_{cell} \approx 54$ m
R = 13.15 km

FCC-hh
disp. suppressor
$L_{cell} = 56.6$ m
R = 15.06 km

Straight section
with RF
$L_{cell} = 100$ m

- 90°/90° optics for *H* an *tt*
- 60°/60° optics for *W* and *Z*
- Non-interleaved sextupole scheme, 1 family per plane

- No tapering!

Equilibrium emittances

beam energy (in GeV)	emittance booster (in nm rad)	emittance collider (in nm rad)	
182.5	1.30	1.48	90°/90° optics
120.0	0.55	0.63	
80.0	0.73	0.84	60°/60° optics
45.5	0.24	0.24	

Low synchrotron radiation at 20 GeV beam energy:

→ ε_x = 15 pm rad (90°/90° optics)

τ_x = 10.05 s

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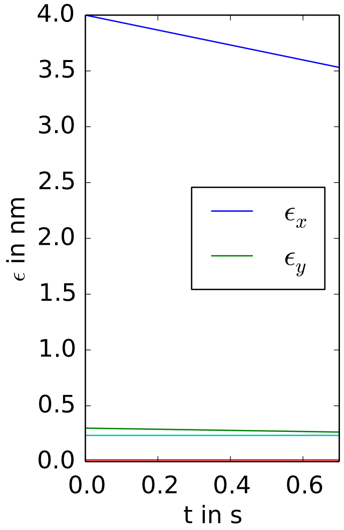
Emittance with IBS



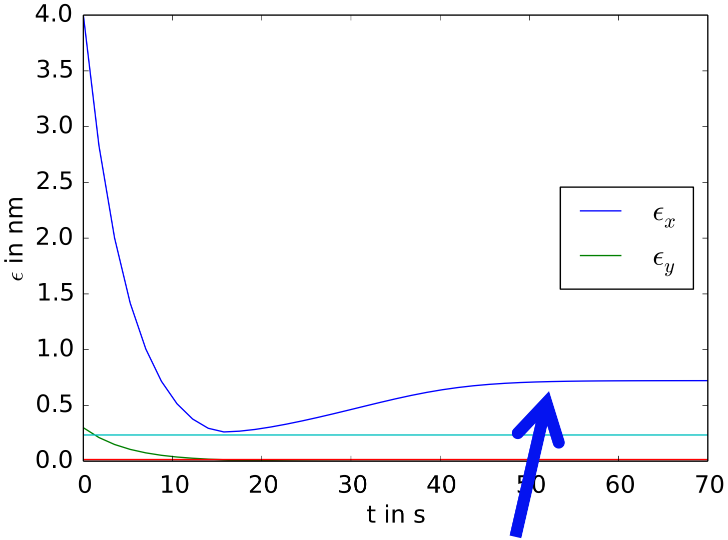
Emittances after 0.7 s

90°/90°

Hor. equilibrium emittance $\boldsymbol{\varepsilon}_x$:

@ 45.5 GeV

@ 20 GeV



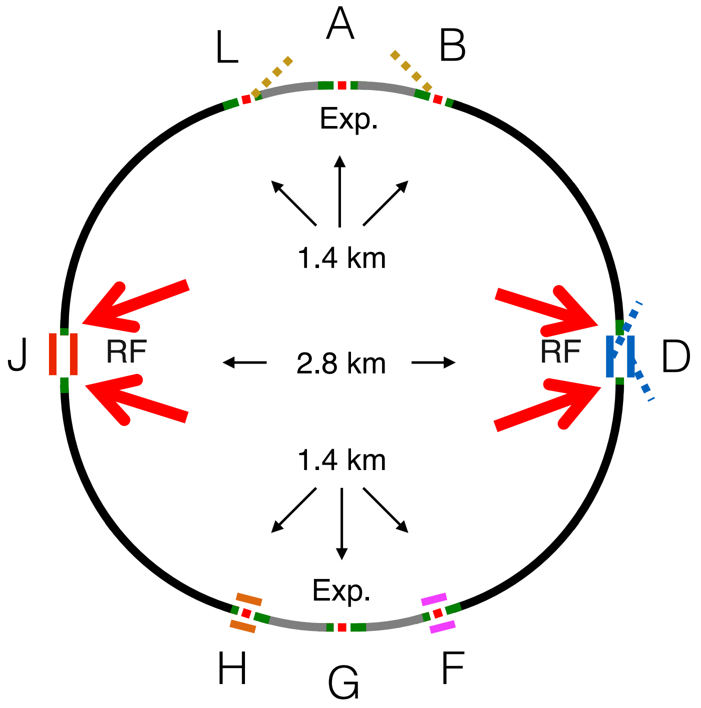
Emittance blow-up due to IBS

$\boldsymbol{\varepsilon}_x$ = 722 pm rad

≈ 48 × $\boldsymbol{\varepsilon}_x$ without IBS

Wiggler parameters and locations

Wiggler parameters		
B_{pole}	(T)	1.8
$B_{wiggler}$	(T)	1.45
L_{pole}	(cm)	9.5
g	(cm)	5
# poles		79
L	(m)	9.065
# wigglers		16
τ_x	(s)	0.1
ε_x (60°/60°)	(pm rad)	235
ε_x (90°/90°)	(pm rad)	196



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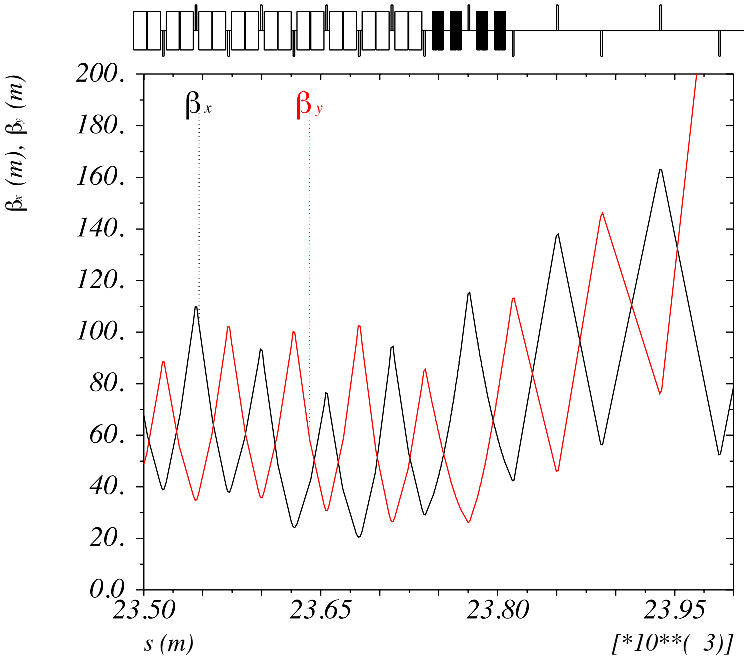
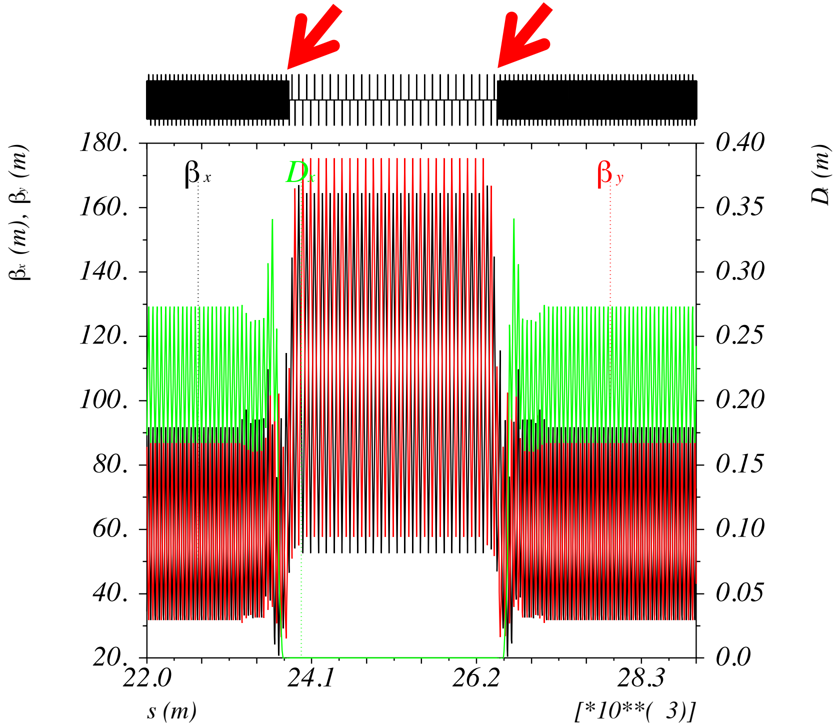
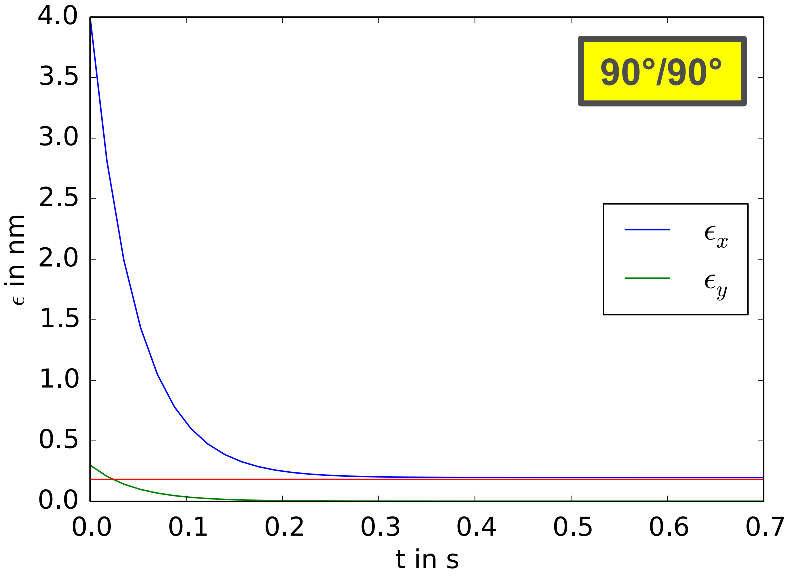
Optics at wiggler location





Emittance evolution with wigglers



New damping time: τ_x = 104 ms

New eq. emittance: ε_x = 196 pm rad

Emittances after 7 damping times:

ε_x = 197 pm rad

≈ 1.003 × ε_x without IBS

ε_y = 1.96 pm rad

≈ 1.000 × ε_y without IBS*

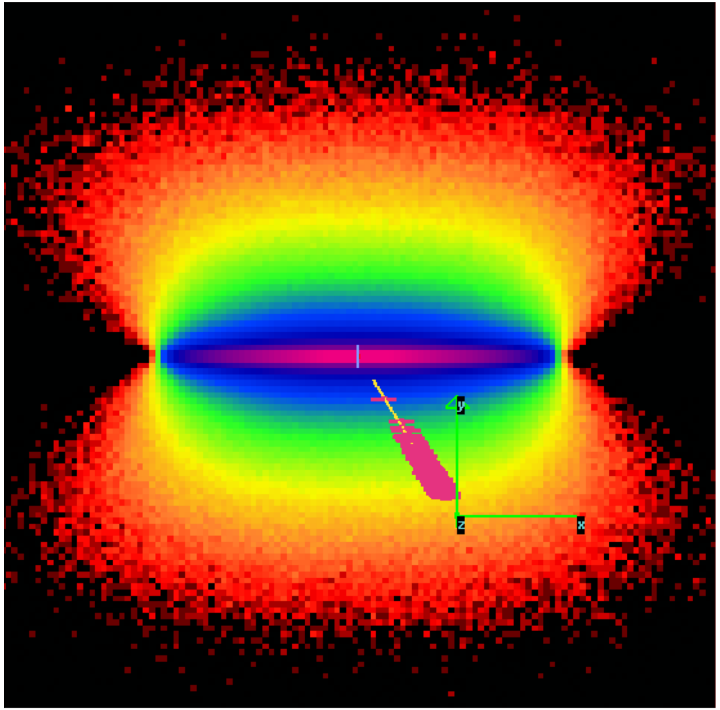
* assuming 1 % coupling

Additional synchrotron radiation

E (GeV)	U_0 (MeV)		U_0 (MeV) with wiggler	
20.0	1.3	→	126.2	✓
45.5	34.7	→	681.3	✗
182.5	9.057.1	→	19981.2	✗

- Wigglers need to be ramped down during the acceleration process
- RF voltage was increased to V_{rf} = 140 MV
- Synchrotron radiation power per wiggler: $P_w \approx 2.1$ MW (Z, full filling)

Implication on the vacuum system



is being investigated by Marton Ady and Roberto Kersevan:

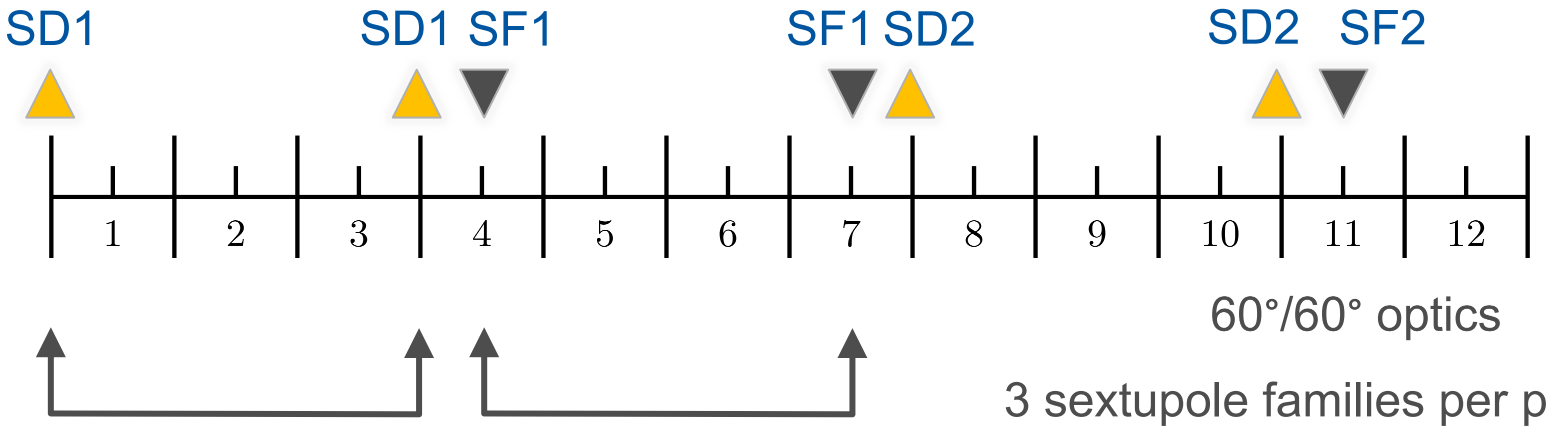
- Can wigglers be installed in the RF sections?
- What kind of absorbers are needed?

Are there special requirements on the beam pipe coming from eddy currents?

Marton Ady

Work in progress…

Non-interleaved sextupole scheme



60°/60° optics

3 sextupole families per plane
(→ only used as one)

$\mu_x = \mu_y = 180°$ (→ -I transformation)

Dynamic aperture studies

Tracking with PTC by Tobias

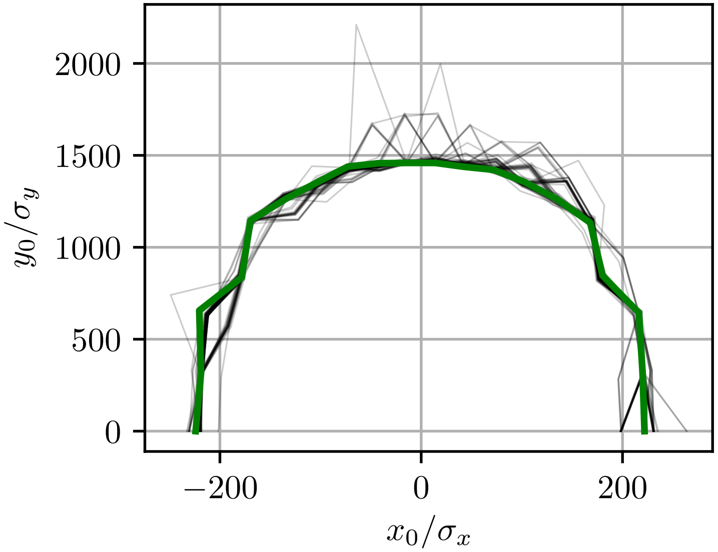
So far: version 2 with 50 m long cells in RF section
& dummy RF system

The studies include

radiation damping and quantum excitation

and were performed for 20 GeV beam energy

DA of 60°/60° optics with 100 µm misalignents



- with ε_x = 45 pm rad and β_x = β_y = 100 m
  → x_{max} = 16.0 mm
  → y_{max} = 9.7 mm

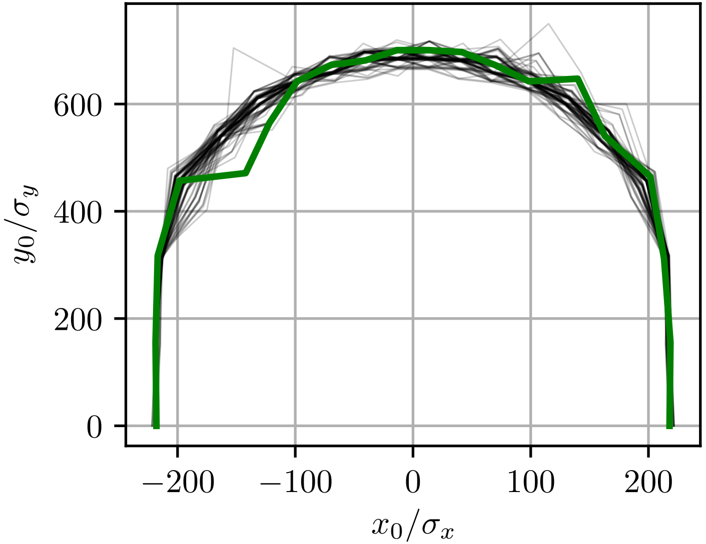
On-axis on-energy injection foreseen.

Without wigglers

Ideal lattice for 1 % coupling

Lattice with transverse quadrupole misalignments (100 seeds)

DA of 90°/90° optics with 100 µm misalignments



- with $\boldsymbol{\varepsilon}_x$ = 15 pm rad and $\beta_x = \beta_y$ = 100 m
  → x_{max} = 8.7 mm
  → y_{max} = 2.6 mm

On-axis on-energy injection foreseen.

Without wigglers

Ideal lattice for 1 % coupling

Lattice with transverse quadrupole misalignments (100 seeds)

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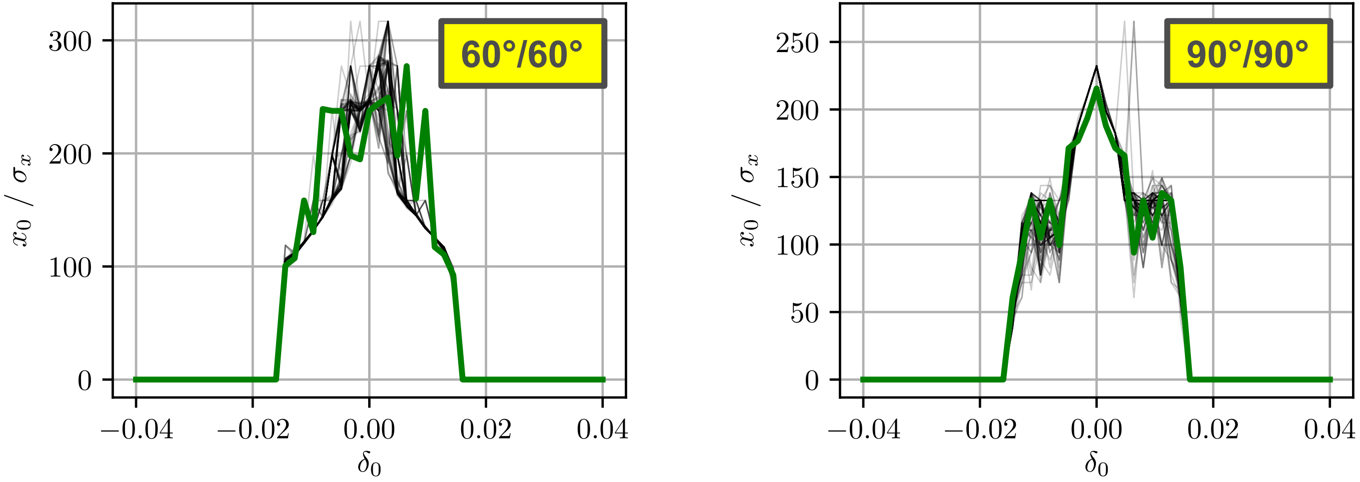
Momentum aperture



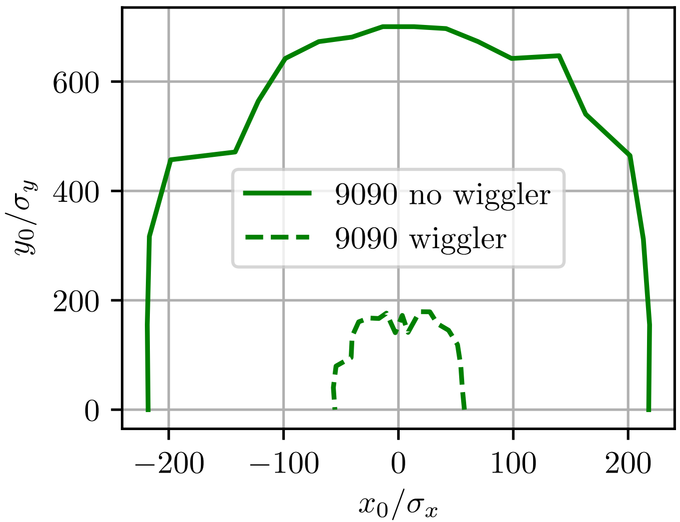
Without wigglers

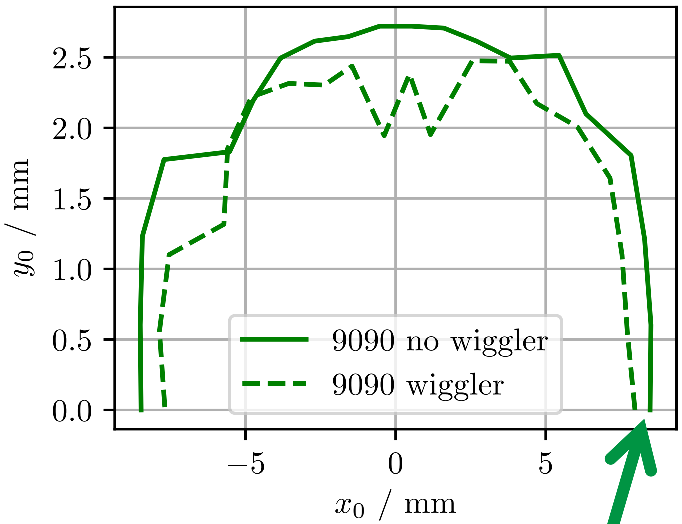
Energy spread of injected beam: σ_E/E ≈ 0.001 (pre-booster)

≈ 0.01 (linac)

DA with wigglers

for $\beta_x = \beta_y = 100$ m





196 pm rad (with wiggler)

Emittance ε_x = 15 pm rad (no wiggler)

0.4 mm
≃ sawtooth amplitude

DA studies outlook

Repeat tracking for V3 with

- 150 µm misalignment (Mark Jones said this would make a difference for the alignment)
- With wigglers next to RF section
- With realistic RF section

→ Unfortunately we are having troubles with the closed orbit search in PTC at the moment (discussion with Piotr)

Work in progress…

Further work ongoing

- Investigation of TMCI due to resistive wall
  → waiting for feedback from Eleonora
- Effect of gradient errors
  → Tessa's investigation using Sandra's scripts
- Synchrotron radiation created by the wigglers
  → Marton & Roberto

Summary

Lattice design finished

→ follows FCC-hh geometry, 100 m cell length in ESS sections

→ optics and RF installations for every operation mode

→ wiggler magnets decrease damping time and intra-beam scattering at injection energy

→ Non-interleaved sextupole scheme provides largest DA

→ Misalignment do not decrease DA

→ Final DA studies including wigglers and misalignments are ongoing

Thank you for your attention!

Acknowledgements:

Thanks to T. Tydecks for the tracking calculations!

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