

DE LA RECHERCHE À L'INDUSTRIE



## Status and plan for the FCC-ee booster design

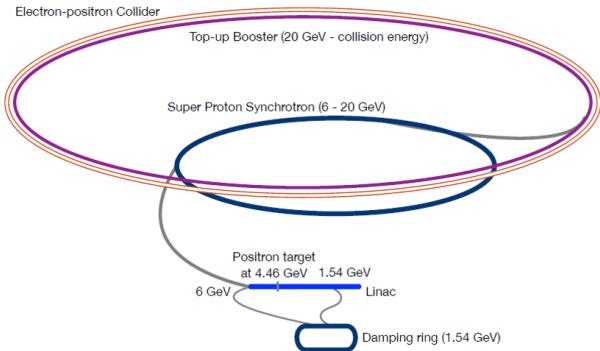
Antoine CHANCE <sup>1</sup> Barbara DALENA <sup>1</sup>  
Bastian HAERER <sup>2</sup>

<sup>1</sup>CEA IRFU DACM

<sup>2</sup>KIT

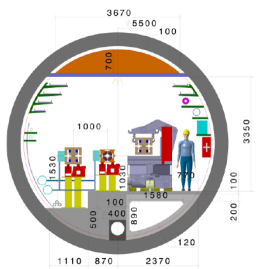
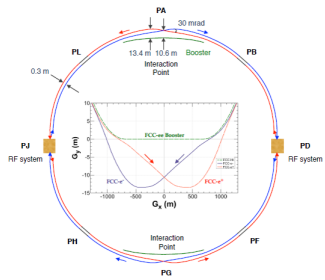
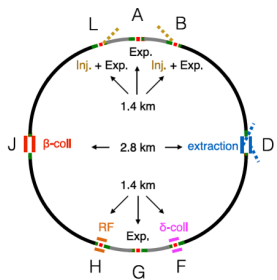
FCC November week 2020  
FCCIS kick-off meeting  
9-12 November 2020





- ▶ Injection energy into the booster: 20 GeV (alternative: 16 GeV).
- ▶ Top-up injection mode into the collider.
- ▶ Ramping similar to SPS:  $80 \text{ GeVs}^{-1}$ .
- ▶ Total filling time  $< 20 \text{ min}$ .
- ▶ Charge variation bunch to bunch  $< \%$ .

	FCC-ee Z		FCC-ee W		FCC-ee H		FCC-ee tt	
Energy (GeV)	45.6		80		120		182.5	
Type of filling	Full	Top-up	Full	Top-up	Full	Top-up	Full	Top-up
LINAC # bunches, 2.8 GHz RF	2		2		1		1	
LINAC repetition rate (Hz)	200		100		100		100	
LINAC/PBR bunch popul. ( $10^{10}$ )	2.13	1.06	1.88	0.56	1.88	0.56	1.38	0.83
# of LINAC injections	1040		1000		393		50	
PBR bunch spacing (ns)	2.5		22.5		57.5		450	
# PBR cycles	8		1		1		1	
PBR # of bunches	2080		2000		393		50	
PBR cycle time (s)	6.3		11.1		4.33		0.9	
PBR duty factor	0.84		0.56		0.35		0.08	
BR # of bunches	16640		2000		393		50	
BR cycle time (s)	51.74		13.3		7.53		5.6	
# BR cycles	10	1	10	1	10	1	20	1
# injections/collider bucket	10	1	10	1	10	1	20	1
Total number of bunches	16640		2000		393		50	
Filling time (both species) (s)	1034.8	103.5	288	28.8	150.6	15.6	224	11.2
Injected bunch population ( $10^{10}$ )	2.13	1.06	1.44	1.44	1.13	1.13	2.00	2.00

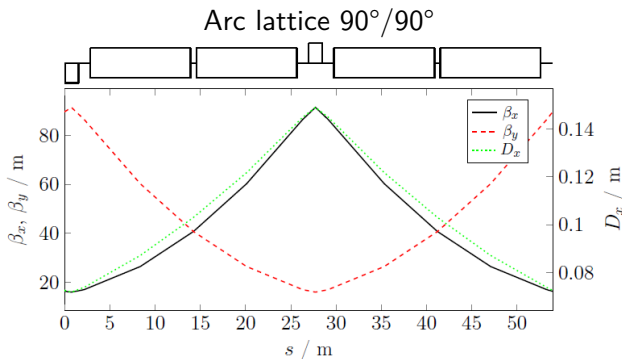


- ▶ High-energy booster follows the footprint of FCC-hh.
- ▶ Transverse offset of 1 m respectively to FCC-ee collider.
- ▶ Booster bypasses FCC-ee detectors on the inside of the cavern.
- ▶ Injection into and extraction from the booster probably located in PB and PL.

- ▶ The arcs are 16.6 km long and made of FODO cells (best filling ratio).
  - ▶ The arc FODO cells in the booster are **a bit shorter than in the collider**: 54 m against 56 m.
  - ▶ **Smaller equilibrium emittance**: 1.3 nm against 1.48 nm at 182.5 GeV.
  - ▶ A FODO cell is made of 4 dipoles, 2 quadrupoles and 2 sextupoles.
  - ▶ Filling ratio: 81.5% including spaces for correctors, flanges and interconnections

Magnet type	Parameter	Unit	Value
Dipole	Field at injection (20 GeV)	T	0.006
	Field at peak energy (182.5 GeV)	T	0.058
	Magnet length	m	11.1
Quadrupole	Max gradient at injection (20 GeV)	T/m	2.6
	Max gradient at peak energy (182.5 GeV)	T/m	23.7
	Magnet length	m	1.5
Sextupole	Max strength at injection (20 GeV)	$T\ m^{-2}$	161
	Max strength at peak energy (182.5 GeV)	$T\ m^{-2}$	1467
	Magnet length	m	0.5

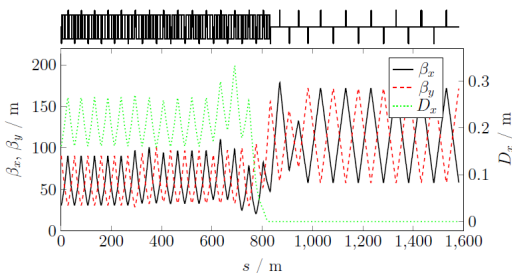
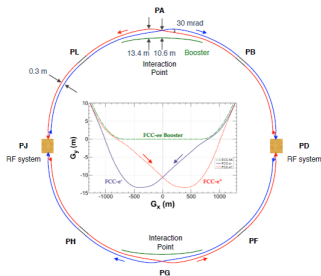
- ▶ **3 optics** with different phase advances per plane were investigated:
  - ▶  $90^\circ/60^\circ$  (like in LEP).
  - ▶  $90^\circ/90^\circ$  (similar to collider in H and ttbar operation).
  - ▶  $60^\circ/60^\circ$  (similar to collider in Z and W operation).
    - ☺ Larger momentum compaction and thus bunch length: **good for microwave instability and IBS.**
    - ☹ **Larger equilibrium emittance.**
  - ▶ Two last optics were retained to get similar (slightly smaller) emittance than in the collider.
- ▶ **No tapering** (more complicated operation since energy is changing during acceleration).

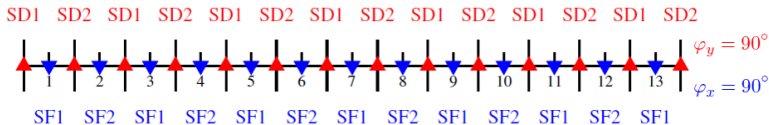


beam energy (in GeV)	emittance booster (in nm rad)	emittance collider (in nm rad)
45.6	0.24	0.24
80.0	0.73	0.84
120.0	0.55	0.63
182.5	1.30	1.48

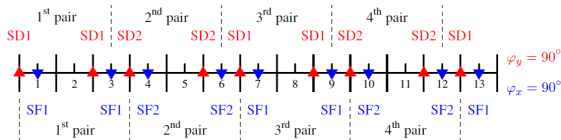
	90°/60°	90°/90°	60°/60°
$Q_x$	457.225	459.225	306.225
$Q_y$	304.290	457.290	304.290
$\xi_x$	-507.658	-584.643	-338.778
$\xi_y$	-420.928	-582.910	-336.455
$\alpha_c / 10^{-6}$	6.5	6.7	13.7
$\epsilon_x$ (20 GeV)/nm rad	0.015	0.015	0.045
$\epsilon_x$ (45.6 GeV)/nm rad	0.075	0.078	0.235
$\epsilon_x$ (175 GeV)/nm rad	1.124	1.172	3.540

- ▶ Short straight sections (1.4 km): FODO cells of 50 m. **Injection section to be designed.**
- ▶ Long straight sections (2.8 km): FODO cells of 100 m to host RF cavities.
- ▶ Dispersion suppressors of 0.566 km made of FODO cells.
  - ▶ The **curvature radius** is **larger** to follow FCC-hh geometry:  $R = 15.06 \text{ km}$  instead of  $13.15 \text{ km}$ .
  - ▶ 10 FODO cells long of 56.6 m.
  - ▶ The quadrupoles of the last 5 cells are used to match optical functions.

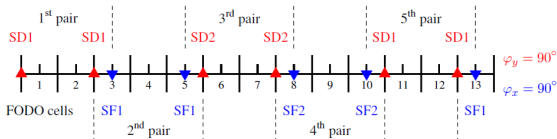




- ▶ 3 schemes were investigated:
  - ▶ **Interleaved sextupole scheme.** Uses all available sextupoles but interlaces families: no perfect cancellation of geometric aberrations but lower sextupole strength.
  - ▶ « **Partially** » **non-interleaved sextupole scheme.** The interlaced sextupole is in the defocusing plane with lower betatron function: smaller effect.
  - ▶ **Non-Interleaved sextupole scheme.** Best cancellation of geometric aberrations. Needs for less sextupoles
- ▶ **Non-interleaved sextupoles give the largest dynamic aperture.** If another scheme is selected, a smaller deviation from  $90^\circ$  or  $60^\circ$  may avoid inner resonances in the long arcs of 16 km.

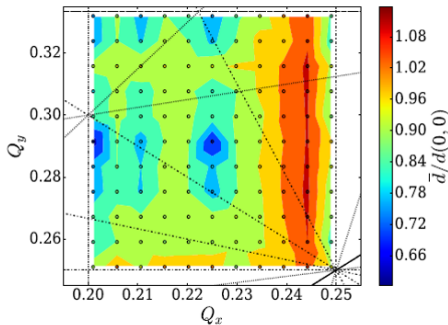


- ▶ 3 schemes were investigated:
  - ▶ **Interleaved sextupole scheme.** Uses all available sextupoles but interlaces families: no perfect cancellation of geometric aberrations but lower sextupole strength.
  - ▶ « **Partially** » **non-interleaved sextupole scheme.** The interleaved sextupole is in the defocusing plane with lower betatron function: smaller effect.
  - ▶ **Non-Interleaved sextupole scheme.** Best cancellation of geometric aberrations. Needs for less sextupoles
- ▶ **Non-interleaved sextupoles give the largest dynamic aperture.** If another scheme is selected, a smaller deviation from  $90^\circ$  or  $60^\circ$  may avoid inner resonances in the long arcs of 16 km.



- ▶ 3 schemes were investigated:
  - ▶ **Interleaved sextupole scheme.** Uses all available sextupoles but interlaces families: no perfect cancellation of geometric aberrations but lower sextupole strength.
  - ▶ « **Partially** » **non-interleaved sextupole scheme.** The interlaced sextupole is in the defocusing plane with lower betatron function: smaller effect.
  - ▶ **Non-Interleaved sextupole scheme.** Best cancellation of geometric aberrations. Needs for less sextupoles
- ▶ **Non-interleaved sextupoles give the largest dynamic aperture.** If another scheme is selected, a smaller deviation from  $90^\circ$  or  $60^\circ$  may avoid inner resonances in the long arcs of 16 km.

- ▶ Frequency map analysis and dynamic aperture performed with MADX-PTC with 2000 turns and radiation on.
- ▶ First version used phase advances of  $90^\circ/60^\circ$  (like LEP).
- ▶ Diffusion factor explored for different working points with interleaved sextupoles at 182.5 GeV.
  - ▶ **Best fractional part: 0.225/0.29.**
  - ▶ Can be optimised again according to collective effects.



- ▶ Frequency map analysis and dynamic aperture performed with MADX-PTC with 2000 turns and radiation on.
- ▶ First version used phase advances of  $90^\circ/60^\circ$  (like LEP).
- ▶ Diffusion factor explored for different working points with interleaved sextupoles at 182.5 GeV.

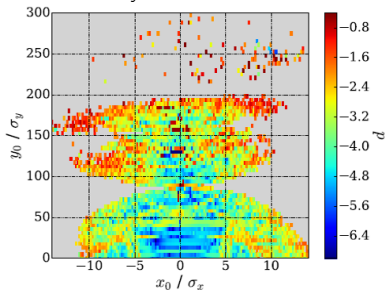
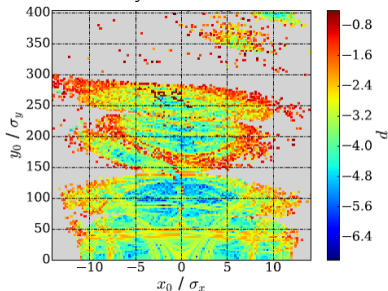
- ▶ **Best fractional part: 0.225/0.29.**

- ▶ Can be optimised again according to collective effects.

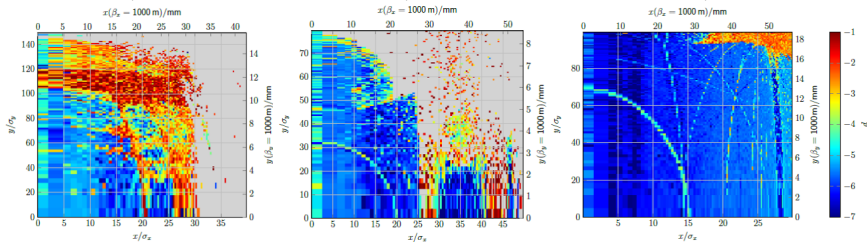
$$Q_x/Q_y = 487.28/327.34$$

 $\Rightarrow$ 

$$Q_x/Q_y = 487.225/327.29$$



Diffusion level with dynamic aperture (at 182.5 GeV).  
 $90^\circ/60^\circ$                        $90^\circ/90^\circ$                        $60^\circ/60^\circ$



- ▶ Non interleaved sextupole scheme.
- ▶ **Clear improvement** from interleaved to non-interleaved scheme.
- ▶ Optic  $90^\circ/60^\circ$  has a larger diffusion level and shows heavy resonance interaction for large apertures: more sensitive to imperfections.
- ▶  $90^\circ/90^\circ$  and  $60^\circ/60^\circ$  optics retained.

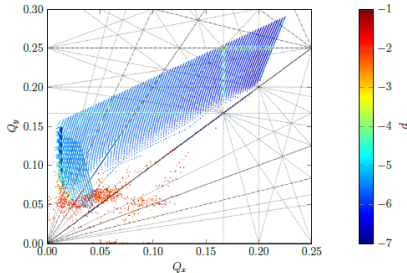
- ▶ Comparison for the 60°/60° optics between:
  - ▶ The diffusion level as a function of the motion frequency for the particles within the dynamic aperture.
  - ▶ The tune shift with amplitude is (coefficients given by MADX-PTC):

$$\Delta Q_x(J_x, J_y) = a_{1,0}J_x + a_{0,1}J_y + \frac{1}{2} \left[ a_{2,0} \cdot J_x^2 + 2a_{1,1} \cdot J_x \cdot J_y + a_{0,2} \cdot J_y^2 \right]$$

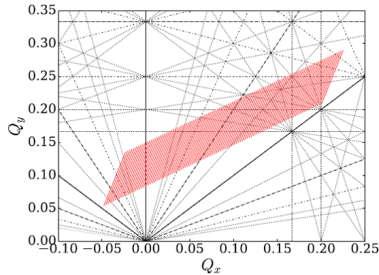
$J_x = \frac{\gamma_x x_0^2}{2}$  and  $J_y = \frac{\gamma_y y_0^2}{2}$  are the actions of the initial particle.

- ▶ **Good agreement** between both tune footprints.

Diffusion vs working point

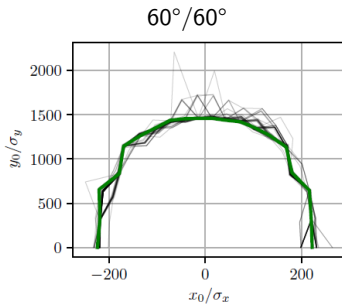
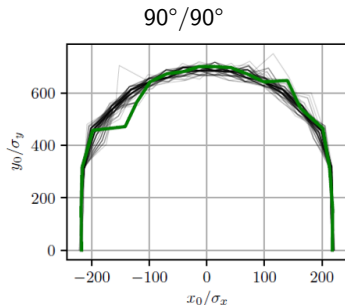


Tune shift with amplitude



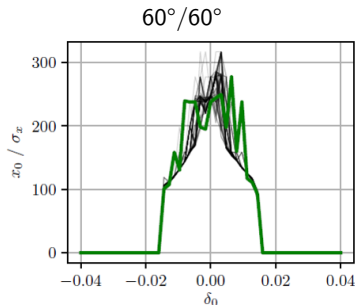
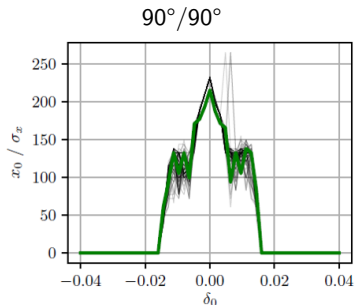
- ▶ **Same correction procedure** of the linear errors (orbit correction, beta and dispersion beating, coupling, ...) as in the collider.
- ▶ Dynamic and momentum aperture calculations performed with MADX-PTC for 2000 turns and 100 seeds with radiation on.
- ▶ Non-interleaved sextupole scheme.
- ▶ Quadrupole misalignment: 100  $\mu\text{m}$ .

Dynamic aperture at 20 GeV



- ▶ **Same correction procedure** of the linear errors (orbit correction, beta and dispersion beating, coupling, ...) as in the collider.
- ▶ Dynamic and momentum aperture calculations performed with MADX-PTC for 2000 turns and 100 seeds with radiation on.
- ▶ Non-interleaved sextupole scheme.
- ▶ Quadrupole misalignment: 100  $\mu\text{m}$ .

Momentum aperture

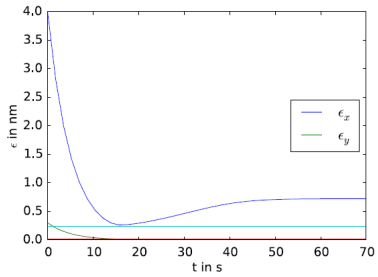


- ▶ With no wiggler: damping time of 10 s at injection (20 GeV).
- ▶ Target damping time: 0.1 s.
- ▶ Advantages to add wigglers:
  - ▶ To increase the integrate  $\mathcal{I}_2$ : **to reduce the damping time.**
  - ▶ Larger equilibrium momentum spread and thus **larger bunch length.**
  - ▶ **Good** to mitigate **IBS.**
  - ▶ **Good** to mitigate **microwave instability** (Boussard's criteria).

No wiggler

Beam energy (GeV)	Eq. emittance (nm rad)	Eq. emittance (nm rad)	Transv. damping time (s)
	60°/60° optics	90°/90° optics	
20.0	0.045	0.015	10.054
45.6	0.235	0.078	0.854
80.0	0.729	0.242	0.157
120.0	4.229	0.545	0.047
175.0	3.540	1.172	0.015

No wiggler

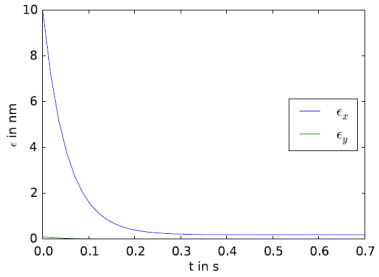


- ▶ With no wiggler: damping time of 10 s at injection (20 GeV).
- ▶ Target damping time: 0.1 s.
- ▶ Advantages to add wigglers:
  - ▶ To increase the integrate  $\mathcal{I}_2$ : **to reduce the damping time.**
  - ▶ Larger equilibrium momentum spread and thus **larger bunch length.**
  - ▶ **Good** to mitigate **IBS.**
  - ▶ **Good** to mitigate **microwave instability** (Boussard's criteria).

No wiggler

Beam energy (GeV)	Eq. emittance (nm rad)	Eq. emittance (nm rad)	Transv. damping time (s)
	60°/60° optics	90°/90° optics	
20.0	0.045	0.015	10.054
45.6	0.235	0.078	0.854
80.0	0.729	0.242	0.157
120.0	4.229	0.545	0.047
175.0	3.540	1.172	0.015

With wiggler



- ▶ With no wiggler: damping time of 10 s at injection (20 GeV).
- ▶ Target damping time: 0.1 s.
- ▶ Advantages to add wigglers:
  - ▶ To increase the integrate  $\mathcal{I}_2$ : **to reduce the damping time.**
  - ▶ Larger equilibrium momentum spread and thus **larger bunch length.**
  - ▶ **Good** to mitigate **IBS.**
  - ▶ **Good** to mitigate **microwave instability** (Boussard's criteria).

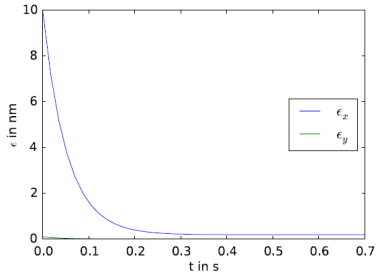
No wiggler

Beam energy (GeV)	Eq. emittance (nm rad) 60°/60° optics	Eq. emittance (nm rad) 90°/90° optics	Transv. damping time (s)
20.0	0.045	0.015	10.054
45.6	0.235	0.078	0.854
80.0	0.729	0.242	0.157
120.0	4.229	0.545	0.047
175.0	3.540	1.172	0.015

→ see Migliorati's talk.

$$N_{b,th}^{MI} \propto \frac{\alpha_c E_0 \sigma_{\delta,0}^2 \sigma_{z,0}}{|Z_{||}|/n} \quad n = f/f_0$$

With wiggler



- ▶ Lost energy per turn:

$$U_0 = \frac{C_\gamma}{2\pi} E^4 \mathcal{I}_2 \quad \mathcal{I}_2 = \oint \frac{ds}{\rho} \quad C_\gamma = 8.846 \times 10^{-5} \text{ m GeV}^{-3}$$

- ▶ Ratio between damping times (with and without wiggler):

$$\frac{\tau_{x,0}}{\tau_{x,w}} = \frac{U_{0,w}}{U_{0,0}} = 1 + \frac{\mathcal{I}_{2,w}}{\mathcal{I}_{2,0}}$$

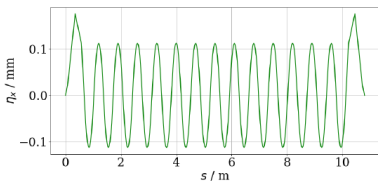
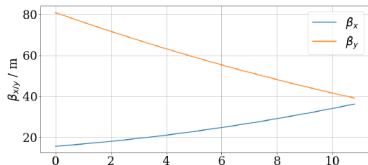
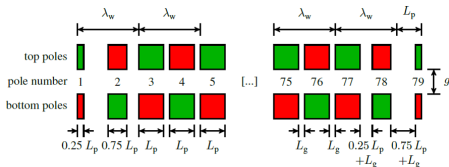
- ▶ For  $n_w$  wigglers with  $n_p$  poles of length  $L_p$  and on-axis peak field  $B_w$ :

$$\mathcal{I}_2^w \approx n_w (n_p - 2) L_p \left( \frac{eB}{p} \right)^2$$

- ▶ New equilibrium emittance:

$$\frac{\epsilon_{x,w}}{\epsilon_{x,0}} = \frac{1 + \mathcal{I}_{5,w}/\mathcal{I}_{5,0}}{1 + \mathcal{I}_{2,w}/\mathcal{I}_{2,0}} \quad \mathcal{I}_5 = \oint \frac{\mathcal{H} ds}{|\rho|^3} \quad \mathcal{H} = \beta_x D_x'^2 + 2\alpha_x D_x D_x' + \gamma_x D_x^2$$

- ▶ Goal:  $\tau_x = 0.1\text{ s}$  at 20 GeV.



- ▶ Equilibrium emittance at 45.6 GeV:  $300\text{ pm} > 235\text{ pm}$  (emittance in the collider).
- ▶ **Still room for optimisation** with shorter pole length and larger number of poles for instance.

Pole length	0.095 m
Pole separation	0.020 m
Gap	0.050 m
Number of poles	79
Wiggler length	9.065 m
Magnetic field	1.45 T

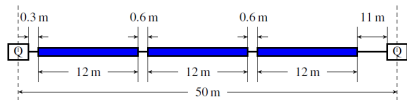
Energy loss per turn	126 MeV
Hor. damping time	104 ms
Hor. emittance (60°optics)	300 pm rad

	Z	W	H	ttbar <sub>1</sub>	ttbar <sub>2</sub>
Total RF voltage (MV)	140	750	2000	9500	10930
<b>frequency (MHz)</b>	<b>400</b>				
RF voltage (MV)	140	750	2000	2000	2000
$E_{acc}$ (MV/m)	8.0	9.6	9.8	10.0	10.0
# CM	3	13	34	34	34
# cavities	12	52	136	136	136
# cells/cav.	4	4	4	4	4
<b>frequency (MHz)</b>	<b>800</b>				
RF voltage (MV)				7500	8930
$E_{acc}$ (MV/m)				20	19.8
# CM				100	120
# cavities				400	480
# cells/cav.				5	5

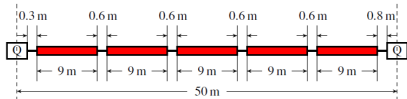
frequency (MHz)	400	800
length of cryo module (m)	12	9
no. of cavities per module	4	4
no. of cells per cavity	4	5
cell length (m)	0.375	0.1875

- ▶ Two long RF sections in D and J instead of distributed RF stations to reduce costs.
- ▶ At Z operation: total voltage of 140 MV against 100 MV because of wigglers.
- ▶ The number of RF cavities per FODO cell is 6 at 400 MHz and 10 at 800 MHz.
- ▶ Diameter of the cryomodules (CMs): > 1 m.
  - ▶ The CMs cannot be installed in parallel with the CMs of the collider
  - ⇒ The CMs are staggered.

## RF cavities of 400 MHz

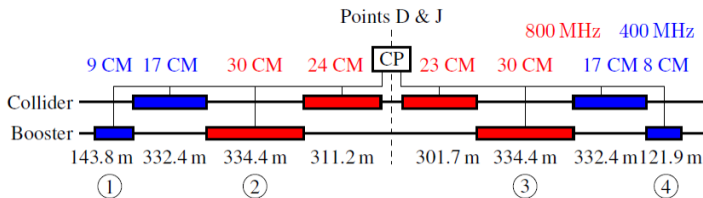


## RF cavities of 800 MHz



frequency (MHz)	400	800
length of cryo module (m)	12	9
no. of cavities per module	4	4
no. of cells per cavity	4	5
cell length (m)	0.375	0.1875

- ▶ Two long RF sections in D and J instead of distributed RF stations to reduce costs.
- ▶ At Z operation: total voltage of 140 MV against 100 MV because of wigglers.
- ▶ The number of RF cavities per FODO cell is 6 at 400 MHz and 10 at 800 MHz.
- ▶ Diameter of the cryomodules (CMs): > 1 m.
  - ▶ The CMs cannot be installed in parallel with the CMs of the collider
  - ⇒ **The CMs are staggered.**

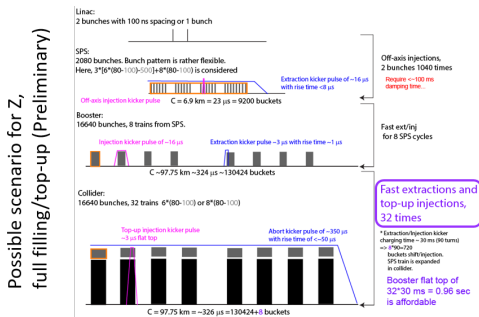


- ① **45.6 GeV**: 12 400 MHz cavities in 3 CMs (2 in section 1 and 1 in section 4 around J). Total RF voltage: 140 MV.
- ② **80.0 GeV**: 52 400 MHz cavities in 13 CMs (7 in section 1 and 6 in section 4 around J). Total RF voltage: 750 MV.
- ③ **120.0 GeV**: 136 400 MHz cavities in 34 CMs (9 in section 1 and 8 in section 4 around D and J). Total RF voltage: 2 GV.
- ④ **182.5 GeV**: 480 800 MHz cavities in 120 CMs (30 in sections 2 and 3 around D and J). Total RF voltage: 2 GV + 8.9 GV.

- ▶ **Two optics** for the high-energy booster like the collider:
  - ▶  $60^\circ/60^\circ$  for the Z and W operation.
  - ▶  $90^\circ/90^\circ$  for the H and  $t\bar{t}$  operation.
- ▶ 3 sextupole schemes were compared (interleaved, partially interleaved and non-interleaved). The **interleaved sextupole scheme** gives the best performances on the dynamic and momentum aperture.
- ▶ **Working point** was optimised by minimising the diffusion level for the  $90^\circ/60^\circ$  optics with the interleaved scheme.
  - ▶ Chosen fractional part of the tune: 0.225/0.29.
  - ▶ **Dynamic aperture quite large** and momentum aperture greater than 1%.
- ▶ **Wigglers are mandatory** to speed up the damping at injection, to reduce IBS effects and to mitigate microwave instability.
- ▶ A **staging RF scenario** has been made for the booster.

- ▶ **To consolidate the booster layout and correction schemes** accordingly to the changes on FCC-hh and FCC-ee layouts.
- ▶ The working point was optimised for the optics  $90^\circ/60^\circ$  with interleaved sextupole scheme.
- ⇒ **The working point can be optimised** again for  $60^\circ/60^\circ$  and  $90^\circ/90^\circ$  (for instance to mitigate collective effects).
- ▶ The **protection of the RF cavities from the radiation** from the wigglers should be investigated.
- ▶ There is still room **to optimise the wigglers**: the equilibrium emittance at 45.6 GeV is still a bit too large.
- ▶ **Eddy currents** are to be evaluated. To check if wigglers can be switched off in a few seconds.
- ▶ The optics  $90^\circ/90^\circ$  is more critical for collective effects at injection because of smaller momentum spread and smaller bunch length. **To check that collective effects are acceptable** at 20 GeV and 16 GeV.

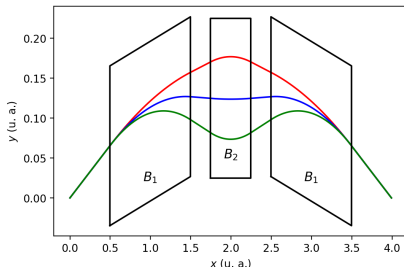
- ▶ **Injection** into the booster could be done **like in a proton machine**: with septum and kicker line.
- ▶ **No show-stopper**: but detailed study of the injection still to be done.
- ▶ Optics of the injection and extraction sections have to be done.
- ▶ **Impact of very low field at injection** should be investigated (especially for an injection at 16 GeV with the SPS).

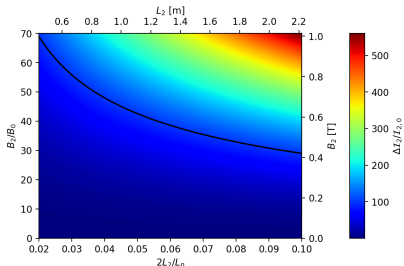
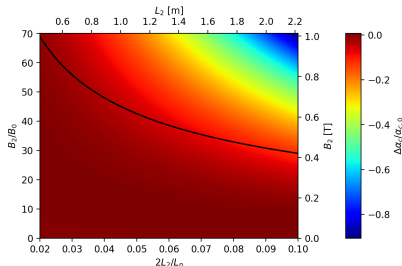


Courtesy: M. Aiba

The number of injections from booster to collider per booster cycle, " $N_{\text{split}}$ ", can be  $\gg 1$

- ▶ Proposed for the electron-ion collider: 2 dipole families with 2 different curvatures.
- ▶ A family with long dipoles but small field (high  $\rho$ ) and another with short dipoles but high field (low  $\rho$ ).
- ▶ The value of  $\mathcal{I}_2$  **can be modified** by playing on the ratio between both fields.
- ▶ **No impact on the layout**: the final position and angle stay unchanged.



Integrate  $\mathcal{I}_2$ Momentum compaction  $60^\circ/60^\circ$ 

- ▶ Factor 100 on  $\mathcal{I}_2$  with a bend of 0.5 m and 1 T at 45.6 GeV.
- ▶ **Advantages:**
  - ☺ No additional hardware like wigglers.
  - ☺ Larger magnetic field at injection.
- ▶ **Drawbacks:**
  - ☹ Different orbits with energy: path length to be corrected and smaller beam-stay clear.
  - ☹ Reduction of the filling ratio. More synchrotron radiation (by a factor  $0.65\text{ m}/2 \times 11.1\text{ m} = 3\%$ ).

- ▶ The preliminary calculations should be validated with MAD-X.
- ▶ The impact on the emittance should be evaluated and compared with the solution with wigglers.
- ▶ The impact on the path length and how to cure it (for instance by using dipole correctors) should be evaluated.

- ▶ Some worries about the interaction between the electron beam and the radiated photons in the wigglers.
- ▶ Very preliminary calculations give:

$$\lambda_w = 0.23 \text{ m} \quad B_w = 1.45 \text{ T} \quad a_w = \frac{eB_w \lambda_w}{2\pi m_e c} \approx 31$$

$$\gamma = 9e4 \quad \lambda = \frac{\lambda_w}{2\gamma^2} \left( 1 + \frac{a_w^2}{2} \right) = 7 \text{ nm} \quad \rho = 3.7 \times 10^{-3}$$

$$L_G \approx \frac{\lambda_w}{4\sqrt{3}\pi\rho} = 2.88 \text{ m} \quad N_w = 39 \times 16$$

- ▶ We verify the conditions for the 1D model:

$$\sigma_E < \rho \quad N_w \lambda_w \gg L_G \quad \epsilon < \frac{\lambda}{4\pi} \quad L_G < L_R \quad N_w \lambda < \sigma_z$$

- ▶  $L_S \approx 20L_G \approx 58 \text{ m}$  smaller than total undulator length.
- ▶ **We should check that SASE mode is not excited in the booster.**

# FCCIS Kickoff meeting

09–13/11/2020

ONLINE EVENT

Register here ↓

<https://cern.ch/FCCISKickOff>

Combined with the 4<sup>th</sup> FCC Physics  
and Experiments Workshop

Dedicated agenda and registration → <https://cds.cern.ch/Event/9329734>



FCCIS – The Future Circular Collider Innovation Study  
This INFRAEQ3 Research and Innovation Action project  
receives funding from the European Union's Horizon  
Europe Programme under grant agreement no. 821754

**Thank you for your  
attention !**

**Special thank to  
Bastian Haerer for  
providing most of  
the material!**