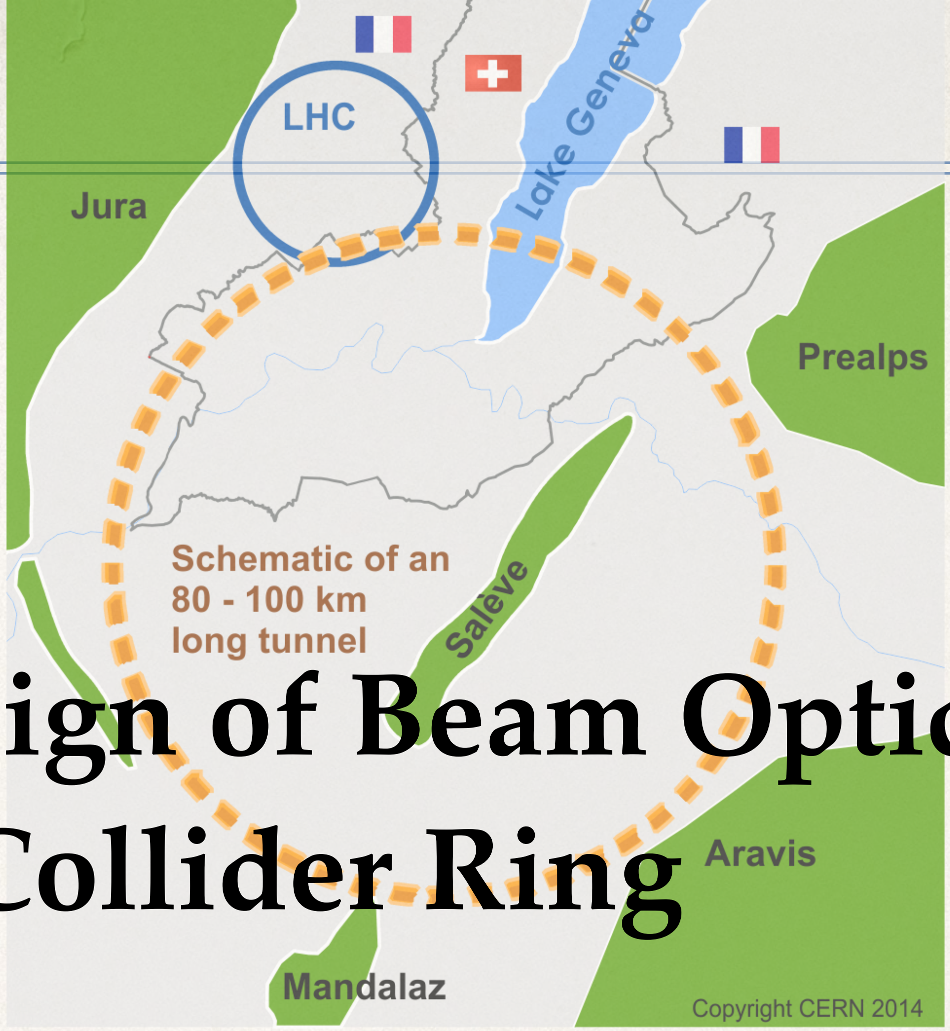

Progress in the Design of Beam Optics for FCC-ee Collider Ring

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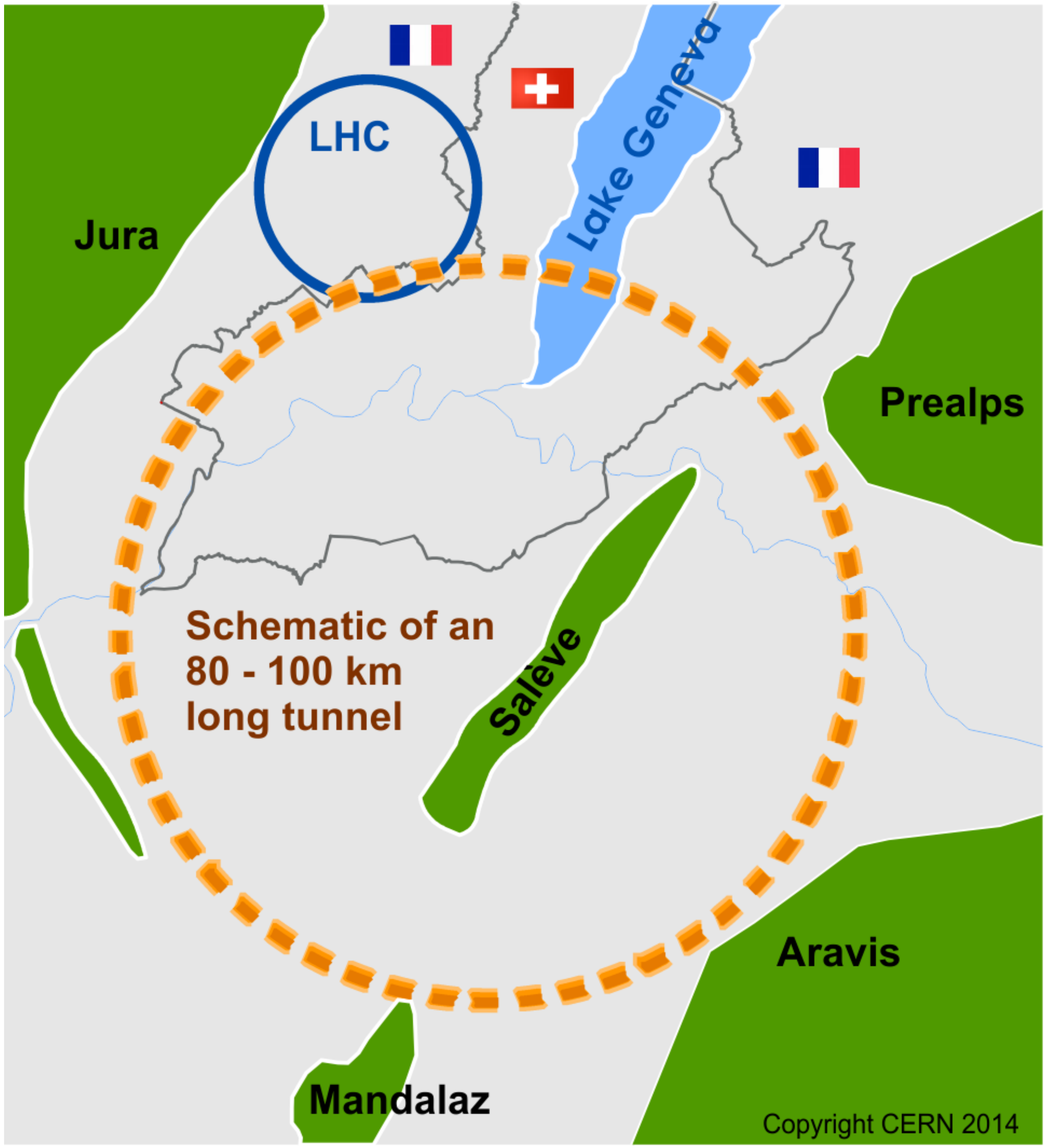
Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2018)

International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km infrastructure** in Geneva area
- ***e⁺e⁻* collider (*FCC-ee*) as potential intermediate step / as a possible first step**
- *p-e* (*FCC-he*) option, HE-LHC …



FCC-ee Beam Optics

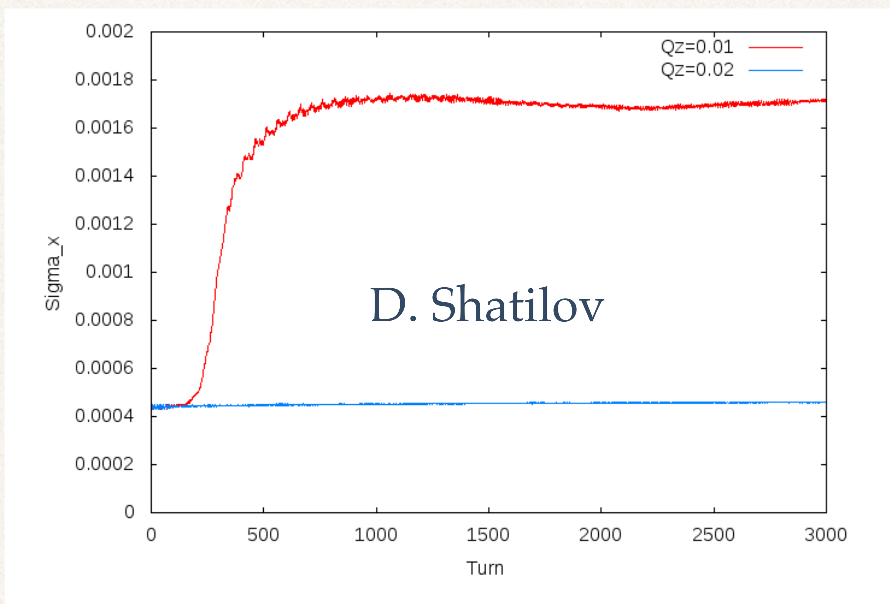
- A baseline optics* for FCC-ee was once established in Oct. 2016 characterized by:
  - 100 km circumference, 2 IP/ring
  - common lattice for all energies
  - 90°/90° FODO cell in the arc with non-interleaved sextupole pairs
  - 30 mrad crossing angle at the IP, with the crab-waist scheme
  - local chromaticity correction for *y*-plane, incorporated with crab sextupoles
  - 100 MW total SR power for all energies
  - limit the SR toward the IP below 100 keV at 175 GeV, up to 450 m upstream
  - Tapering of magnets along the ring to compensate the effects of SR on orbit/optics
  - Sufficient dynamic aperture for beamstrahlung and top-up injection

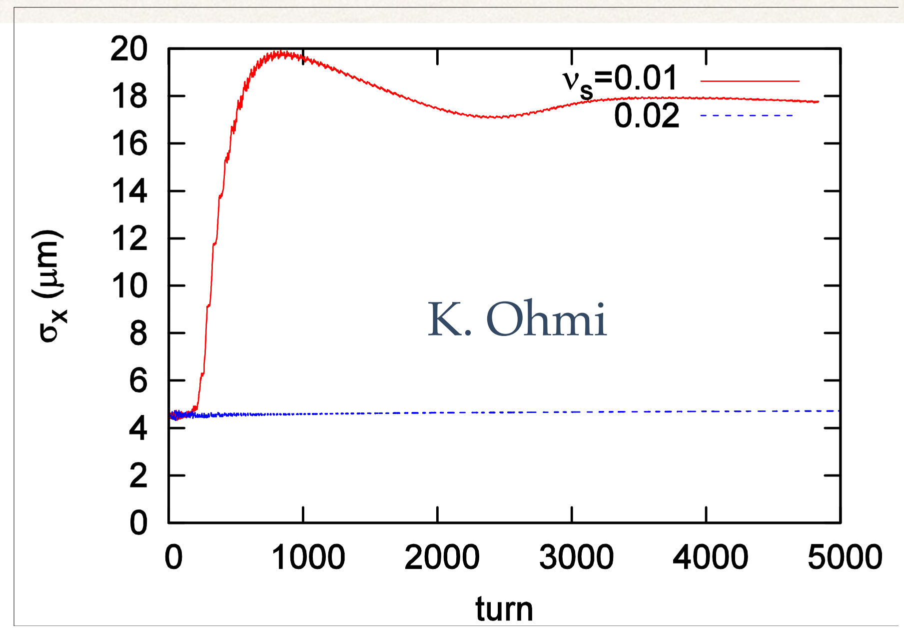
- Motivations for change in 2017:
  - Mitigation of the coherent beam-beam instability at Z
    - *Smaller* β_x^*
    - *60°/60° cell in the arc, only at Z*
  - Adopt the “Twin Aperture Quadrupole” scheme for arc quadrupoles
  - Fit the footprint to a new FCC-hh layout

*Phys.Rev.Accel.Beams 19 (2016) no.11, 111005

Mitigation of Coherent Beam-Beam Instability at *Z*

- A new coherent instability in x-z plane was first found by K. Ohmi by FCC Week 2016 with a strong-strong beam-beam simulation.
- D. Shatilov confirmed their phenomenon by a completely independent simulation with a tunr-by-turn alternating quasi-strong-strong simulation. The result of these two agrees with each other very well.





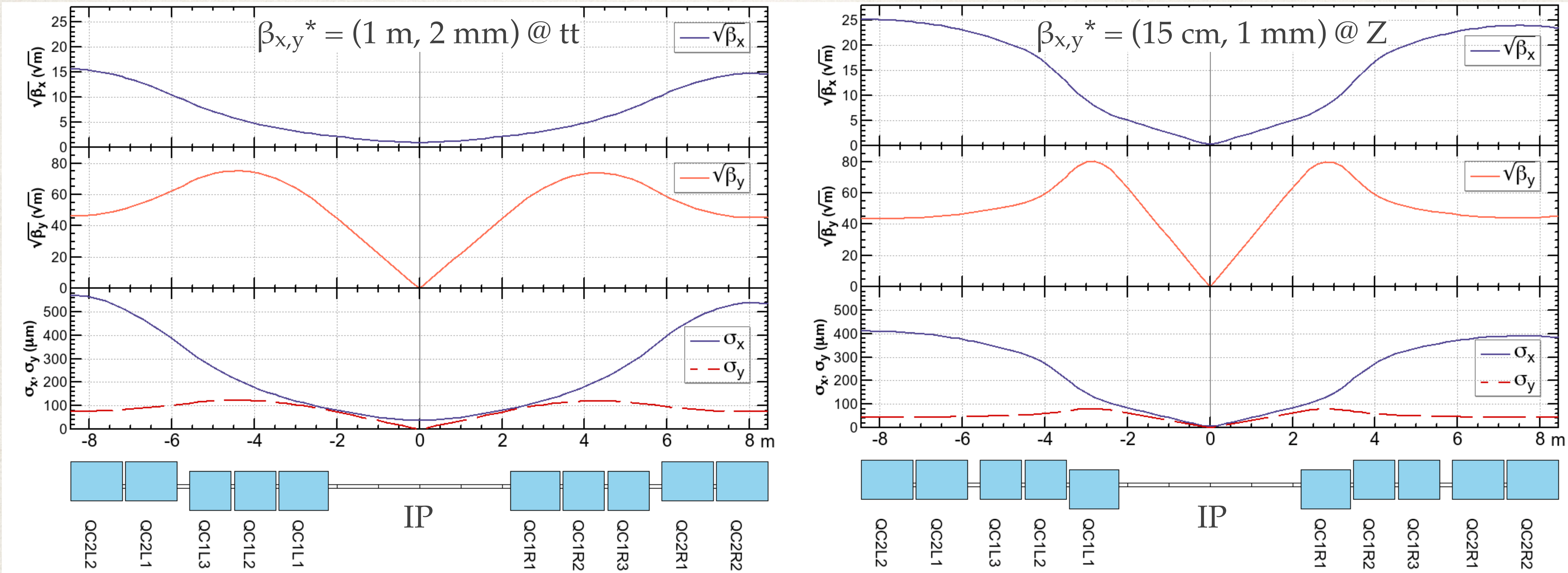
- A semi-analytic scaling the threshold bunch intensity has been derived by K. Ohmi, *et al.**:

$$N_{\rm th} \propto \frac{\alpha_p \sigma_\delta \sigma_z}{\beta_x^*}$$

- Thus a smaller $\beta_x{}^*$ and a larger momentum compaction α_p are favorable. The latter can be achieved by changing the phase advances at *Z*.
- We have reduced $\beta_x{}^*$ to about 1/3, and increased α_p by a factor of 2.

*K. Ohmi, N. Kuroo, in these preceedings, THPAB021

Reduce βx*, from 50 cm to 15 cm



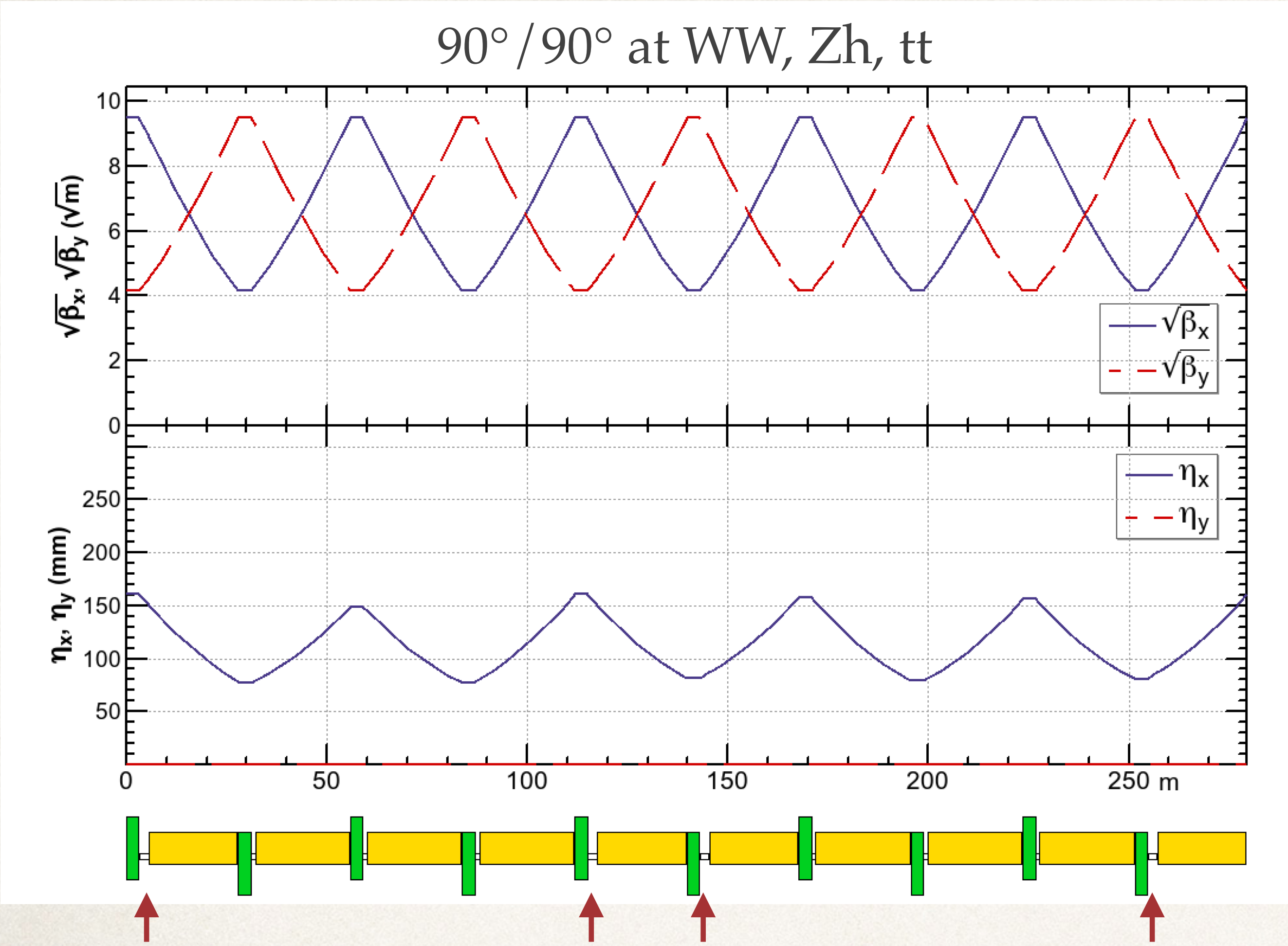
- Divide QC1 into three independent pieces, reverse the polarity at Z.

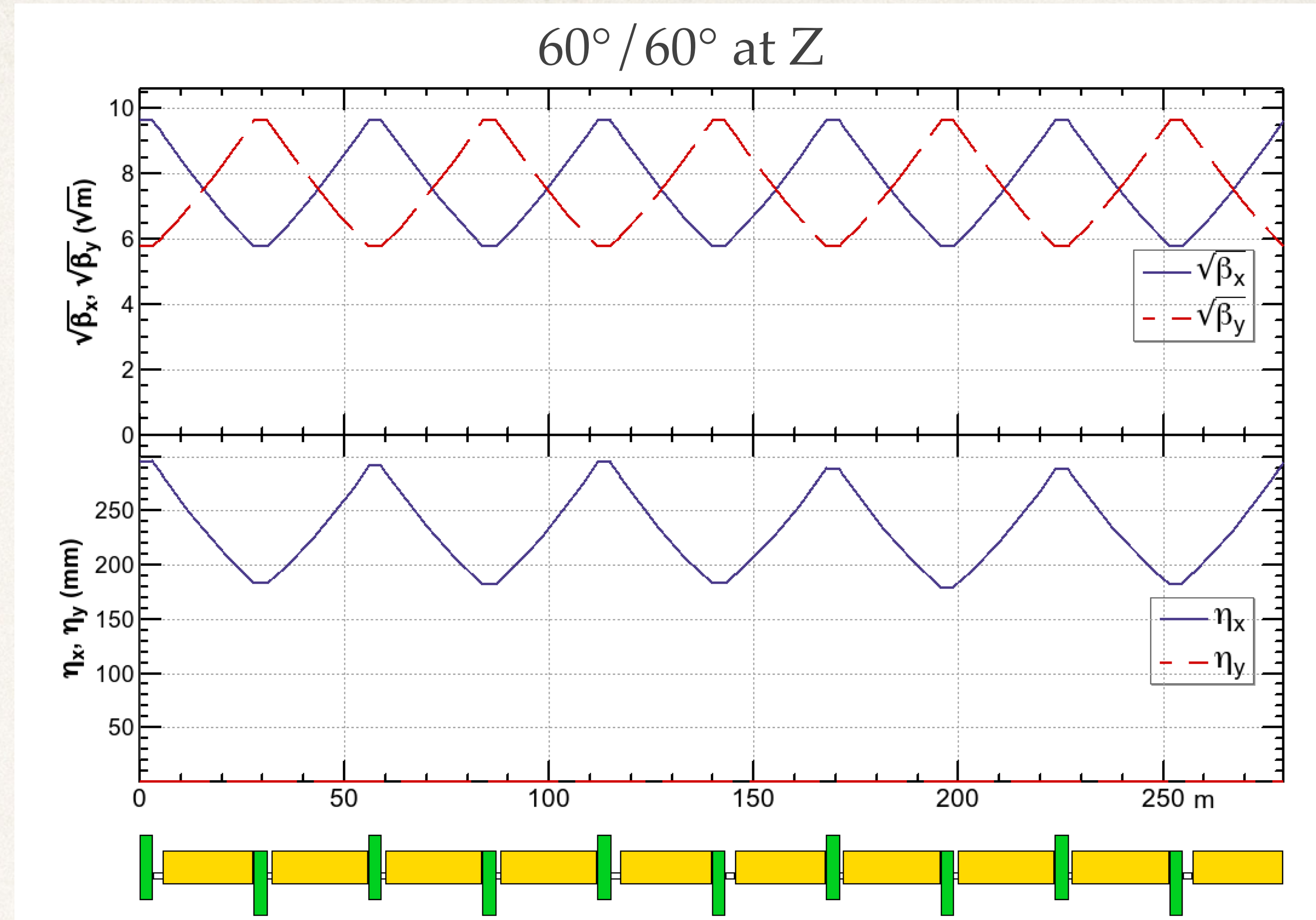
	L (m)	B′ @ tt (T/m)	B′ @ Z (T/m)
QC1L1	1.2	-94.4	-96.3
QC1L2	1	-92.6	+50.3
QC1L3	1	-96.7	+9.8
QC2L1	1.25	+45.8	+6.7
QC2L2	1.25	+74.0	+3.2

	L (m)	B′ @ tt (T/m)	B′ @ Z (T/m)
QC1R1	1.2	-99.9	-97.2
QC1R2	1	-99.9	+51.2
QC1R3	1	-99.9	+12.0
QC2R1	1.25	+78.6	+7.3
QC2R2	1.25	+76.2	+7.2

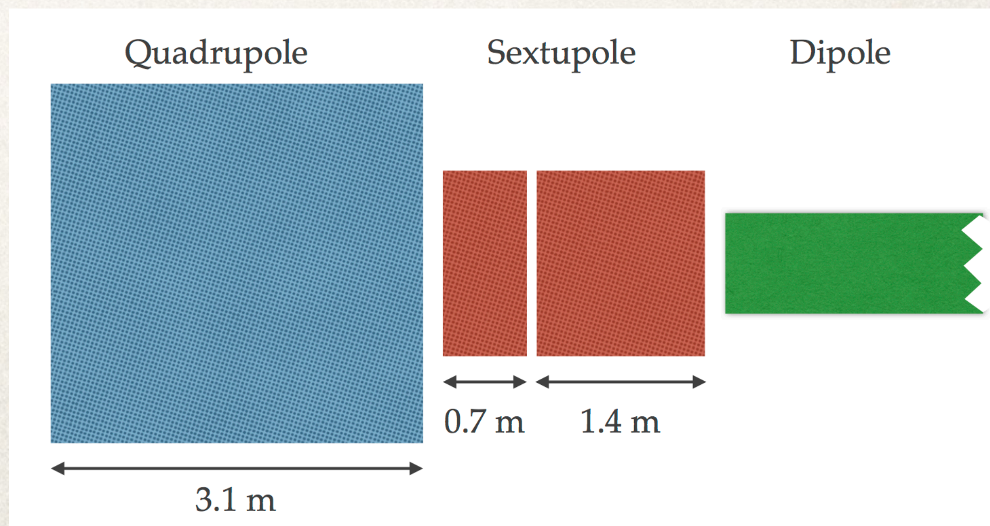
- By this split the chromaticity and the peaks of $\beta_{x,y}$ around the IP are suppressed for the reduction of $\beta_{x,y}^*$ at Z to (1/7, 1/2) at tt.

60°/60° Arc FODO Cell at Z



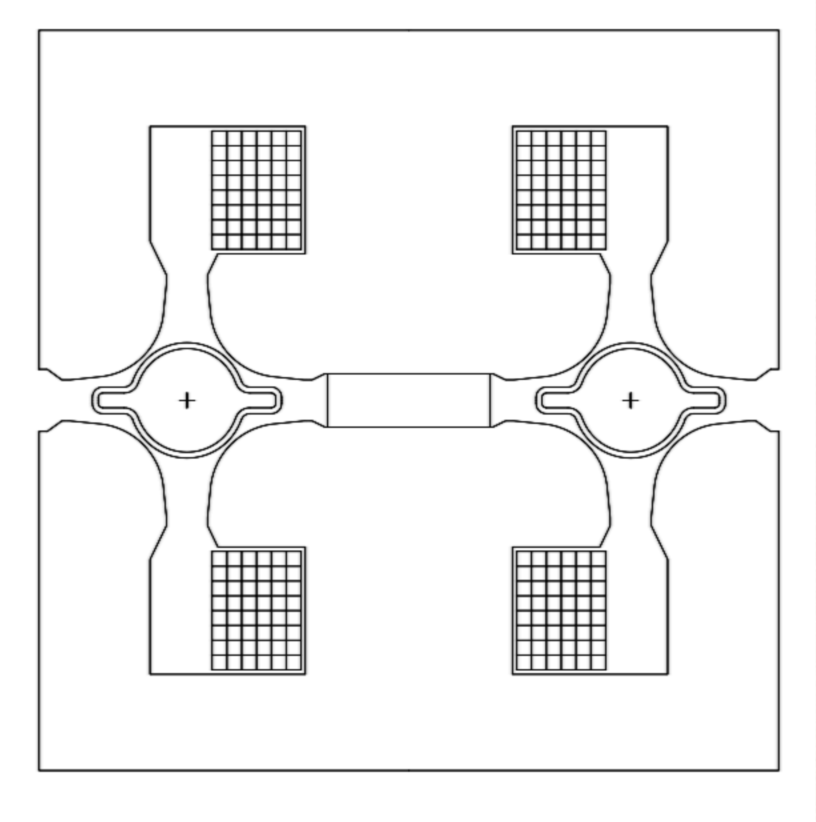


- There are two lengths for the space for sextupoles between quads and dipoles.
- The longer ones ↑ are used for sexts in the case of 90°/90° cell. Some of shorter ones are used in the 60°/60° cell, making *-I* transformation between a pair of sextupole.
- There are two lengths for the dipole, with the same field strength, thus a small irregularity is seen in the dispersion.
- The sextupole at the longer space consists of two slices.
- Only the shorter one is used/inserted at Z.



Twin Aperture Quadrupole

- An idea of "twin aperture quadrupole" has been developed by A. Milanese to save the power consumption of quadrupole magnets.
- The currents in the magnet are always surrounded by iron to maximize the usage.



An example of the cross section of a twin aperture quadrupole for FCC-ee (A. Milanese).

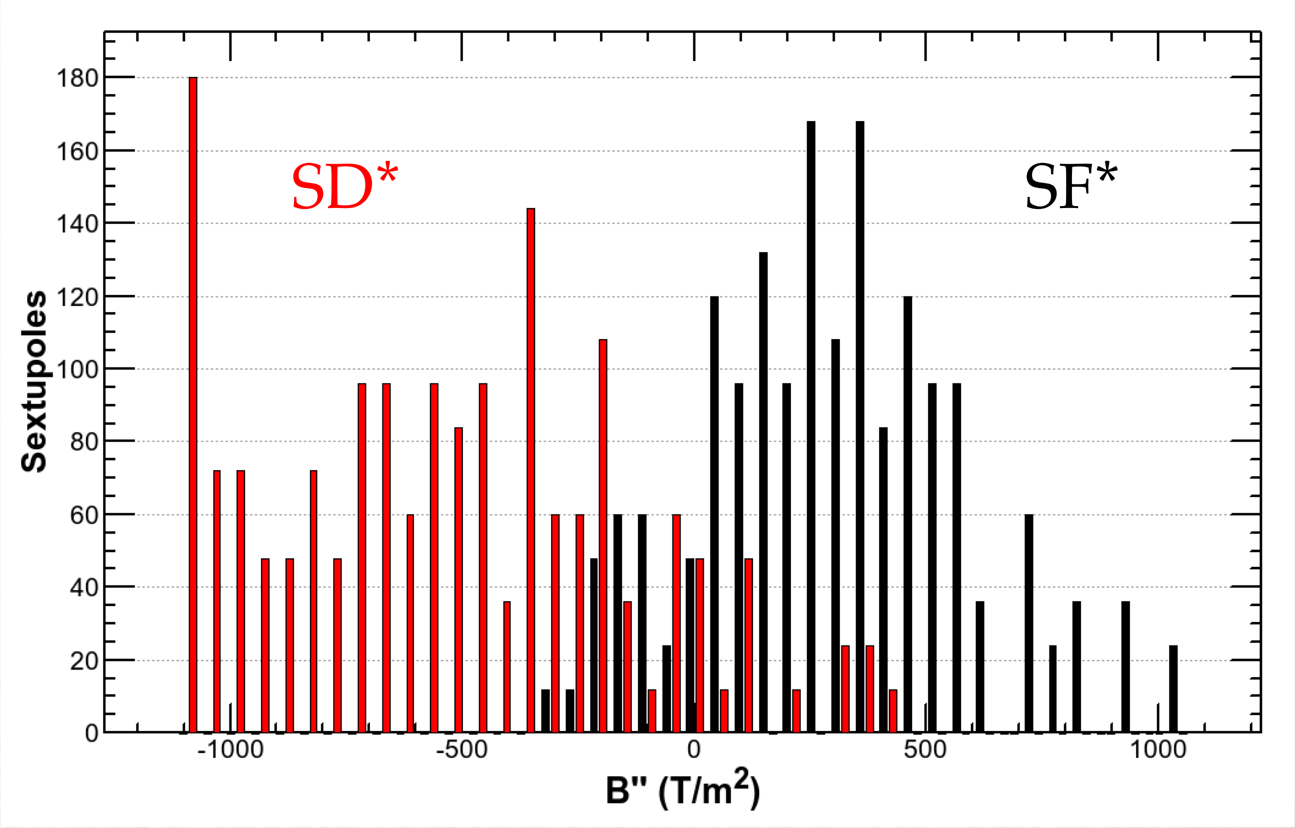
The separation between two beams is 30 cm.

- The power consumption of the twin aperture quad: 22 MW at 175 GeV with Cu coil = half of single-aperture quads.
- Dipoles are also "twin": power consumption = 17 MW at 175 GeV with Al bus bar.

Parameters for Arc Magnets

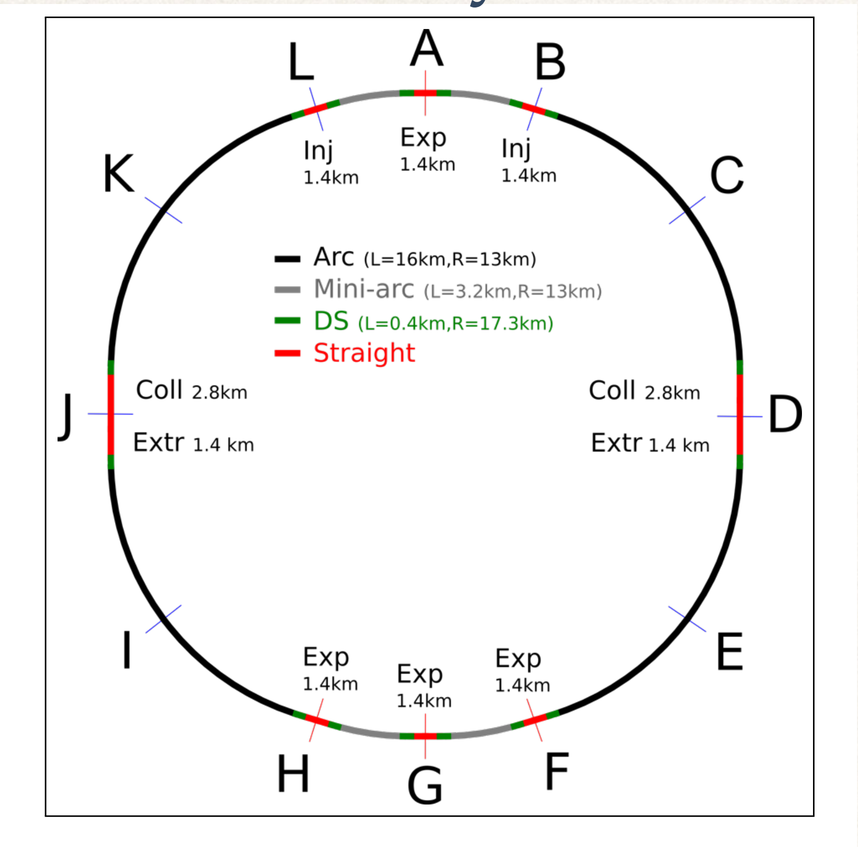
Beam Energy	[GeV]	175
Cell length	[m]	55.88
Length of dipole B1 / B1L	[m]	21.94 / 23.44
Bending angle/dipole	[mrad]	2.042 / 2.183
Dipole field	[mT]	54.3
Dipole packing factor in the arc	[%]	81.7
Number of arc dipoles / ring		2900
Arc quadrupole scheme		twin aperture
Quad length, QF/QD	[m]	3.1 / 3.1
Quad gradient, QF/QD	[T/m]	9.9 / −9.9
Number of quads / ring, QF/QD		1450 / 1450
Sext. length short (long), SF/SD	[m]	0.7 (1.4) / 0.7 (1.4)
Max. sext. $\|B''\|$, SF/SD	[T/m^2]	1117/ 1069
Number of sexts/ring, short (long), SF/SD		588 (588) / 588 (588)

- Although the sextupoles seem very strong, the average of them is still reasonable.
- ~10% of them may need a special dedicated architecture.

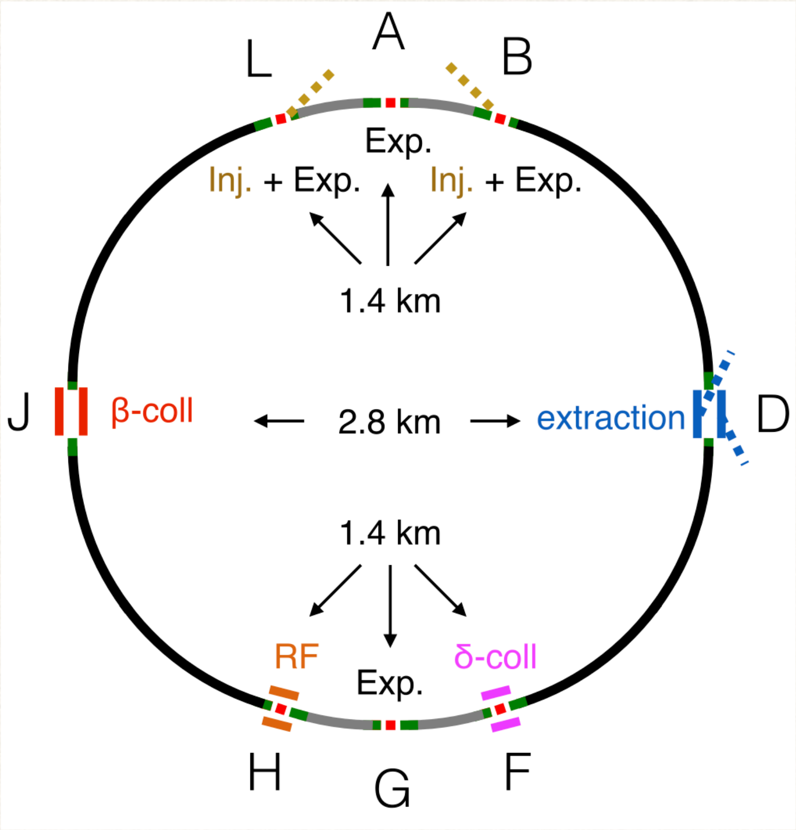


Fitting to the new geometry of FCC-hh

Old Layout



New Layout

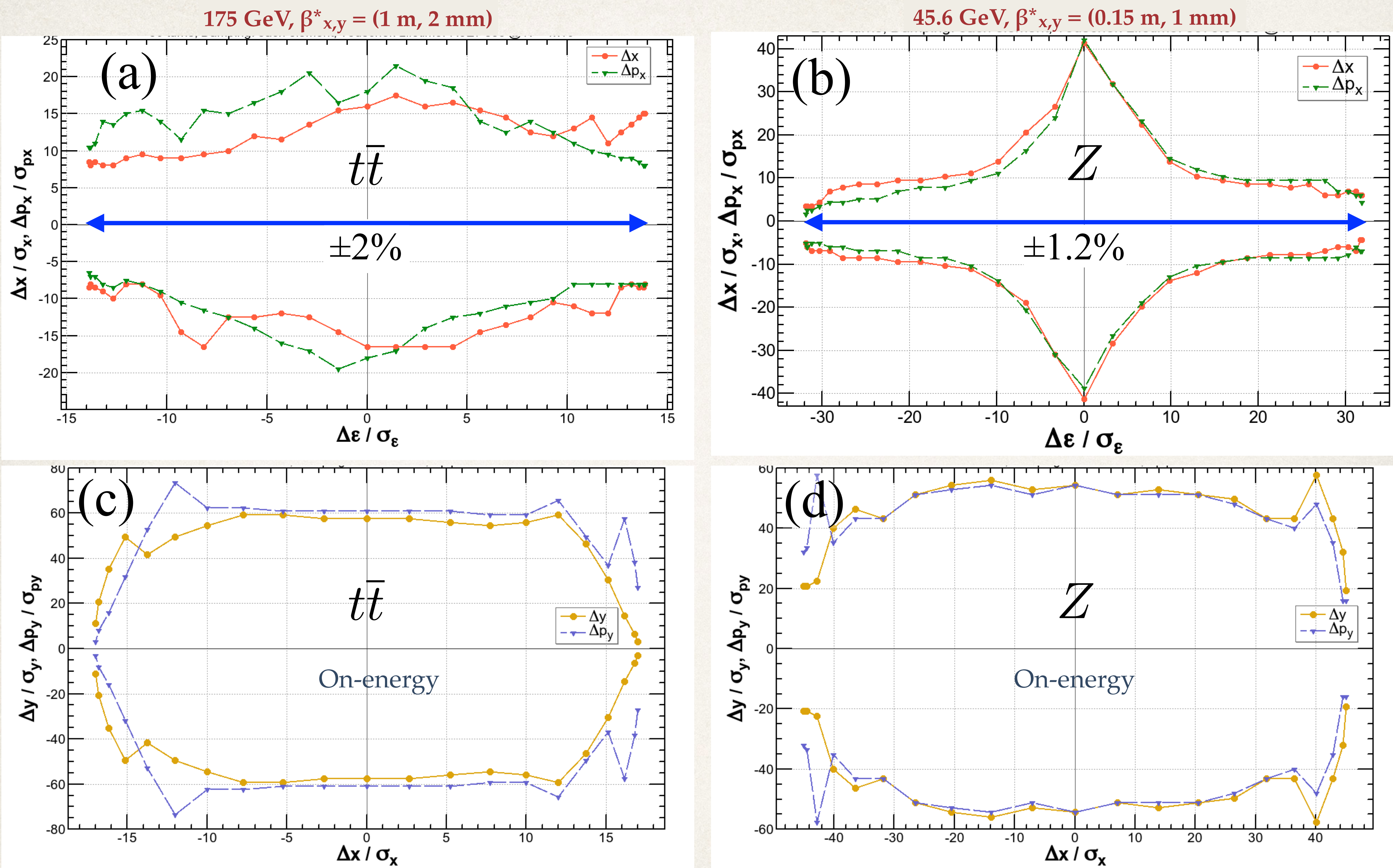


- The straight sections D&J have been shortened from 4.2 km to 2.8 km each.
- The circumference has shortened by 2.2 km.
- The location of sections B, F, H, L are slightly changed.

Parameters

Design		2017		2016	
Circumference	[km]	97.750		99.984	
Arc quadrupole scheme		**twin aperture**		single aperture	
Bend. radius of arc dipole	[km]	10.747		11.190	
Number of IPs / ring		2			
Crossing angle at IP	[mrad]	30			
Solenoid field at IP	[T]	± 2			
ℓ^*	[m]	2.2			
Local chrom. correction		y-plane with crab-sext. effect			
RF frequency	[MHz]	400			
Total SR power	[MW]	100			
Beam energy	[GeV]	45.6	175	45.6	175
SR energy loss/turn	[GeV]	0.0360	7.80	0.0346	7.47
Long. damping time	[ms]	414	7.49	440	8.0
Polarization time	[s]	9.2×10^5	1080	9.2×10^5	1080
Current/beam	[mA]	1390	6.4	1450	6.6
Bunches/ring		70760	62	30180(91500)	81
Particles/bunch	[10^{10}]	4.0	21.1	10 (3.3)	17.0
Arc cell		$60^\circ/60^\circ$	$90^\circ/90^\circ$	$90^\circ/90^\circ$	
Mom. compaction α_p	[10^{-6}]	**14.79**	7.31	6.99	
Horizontal tune ν_x		269.14	389.08	387.08	
Vertical tune ν_y		267.22	389.18	387.14	
Arc sext. families		208	292	292	
Horizontal emittance ε_x	[nm]	**0.267**	1.34	0.086	1.26
$\varepsilon_y/\varepsilon_x$ at collision	[%]	0.38	0.2	1.2	0.2
β_x^*	[m]	**0.15**	1	0.5 (1)	1 (0.5)
β_y^*	[mm]	1	2	1 (2)	2 (1)
Energy spread by SR	[%]	0.038	0.144	0.038	0.141
RF Voltage	[MV]	**255**	9500	88	9040
Bunch length by SR	[mm]	2.1	2.4	2.6	2.4
Synchrotron tune ν_z		-0.0413	-0.0684	-0.0163	-0.0657
RF bucket height	[%]	3.8	10.3	2.3	11.6
Luminosity/IP	[$10^{34}/\text{cm}^2\text{s}$]	**121**	1.32	210 (90)	1.3 (1.5)

Dynamic Aperture satisfies the requirements



Momentum acceptances: ±2% = 11σ_δ @ *tt*, ±1.2%=±14σ_δ @ *Z*, including beamstrahlung.
Tracking 50 turns @ *tt*, 2550 turns at *Z*. Synchrotron motion, synchrotron radiation damping in dipoles & quads, tapering, Maxwellian fringes, kinematical terms, crab waist are included.

Effects included in the dynamic aperture survey

Effects	Included?	Significance
Synchrotron motion	Yes	**Essential**
Radiation loss in dipoles	Yes	**Essential** – improves the aperture
Radiation loss in quadrupoles	Yes	**Essential** – reduces the aperture esp. at $t\bar{t}$
Radiation fluctuation	after optimization	**Essential**
Tapering	Yes	**Essential**
Crab waist	Yes	transverse aperture is reduced by $\sim 20\%$
Maxwellian fringes	Yes	small
Kinematical terms	Yes	small
Solenoids	Evaluated separately	minimal, if locally compensated
Beam-beam effects for stored beam	after optimization (D. Zhou)	affects the lifetime for $\beta_y^* = 1$ mm at $t\bar{t}$
Beam-beam effects for injected beam	Not yet	
Higher order fields / errors / misalignments	Not yet	**Essential**, development of correction/tuning scheme is necessary

Summary

- Modification of the beam optics for FCC-ee has been performed over the base line optics 2016:
  - Mitigation of the coherent beam-beam instability at Z
    - *By achieving smaller* β_x^*
    - *Applying 60°/60° cell in the arc, only at Z, compatible with 90°/90° cell at higher energies.*
  - Adopt the "Twin Aperture Quadrupole" scheme for arc quadrupoles
  - Fit the footprint to a new FCC-hh layout
- The resulting dynamic aperture is sufficient for the beamstrahlung and top-up injection.
- Please visit related posters:
  - Vertical Dispersion and Betatron Coupling Correction for FCC-ee, **MOPIK097**
  - Conceptual Design of a Pre-Booster Ring for the FCC e+e- Injector, **MOPVA029**
  - Beam Dynamics Simulation in Two Versions of New Photogun for FCC-ee Electron Injector Linac, **TUPAB011**
  - Optimisation of the Design of CERN's Future Circular Collider from a Civil Engineering Perspective, **TUPVA127**
  - Advanced Beam Dump for FCC-ee, **WEPIK001**
  - Challenges and Status of the Rapid Cycling Top-Up Booster for FCC-ee, **WEPIK031**
  - Progress in the FCC-ee Interaction Region Magnet Design, **WEPIK034**
  - Coupling Impedances and Collective Effects for FCC-ee, **THPAB020**
  - Coherent Beam-Beam Instability in Collision With a Large Crossing Angle, **THPAB021**