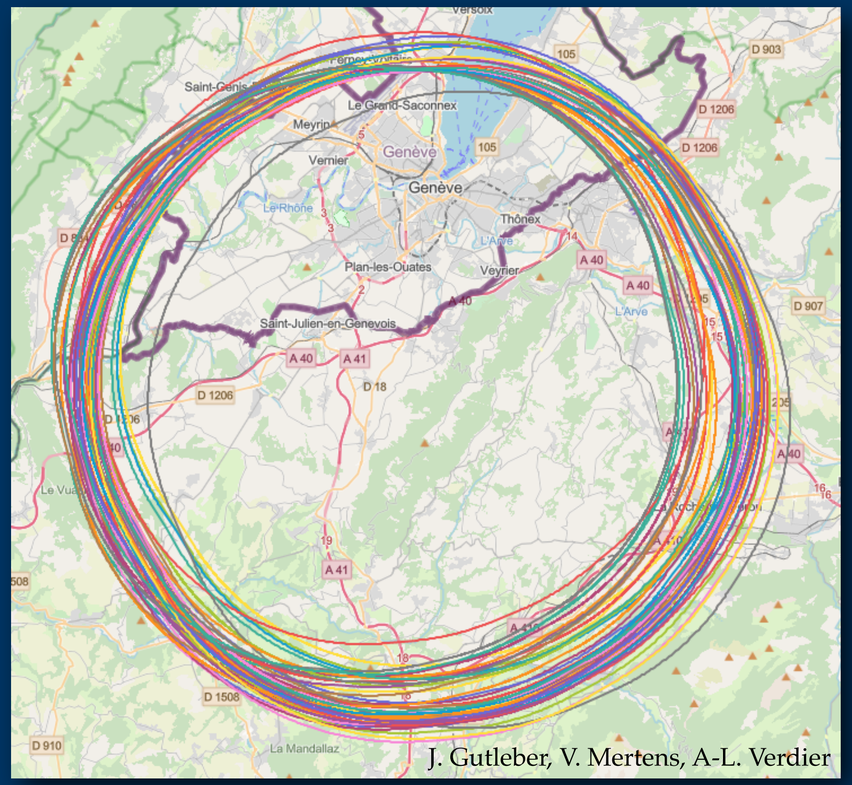


J. Gutleber, V. Mertens, A-L. Verdier

Evolution of optics for FCC-ee after CDR

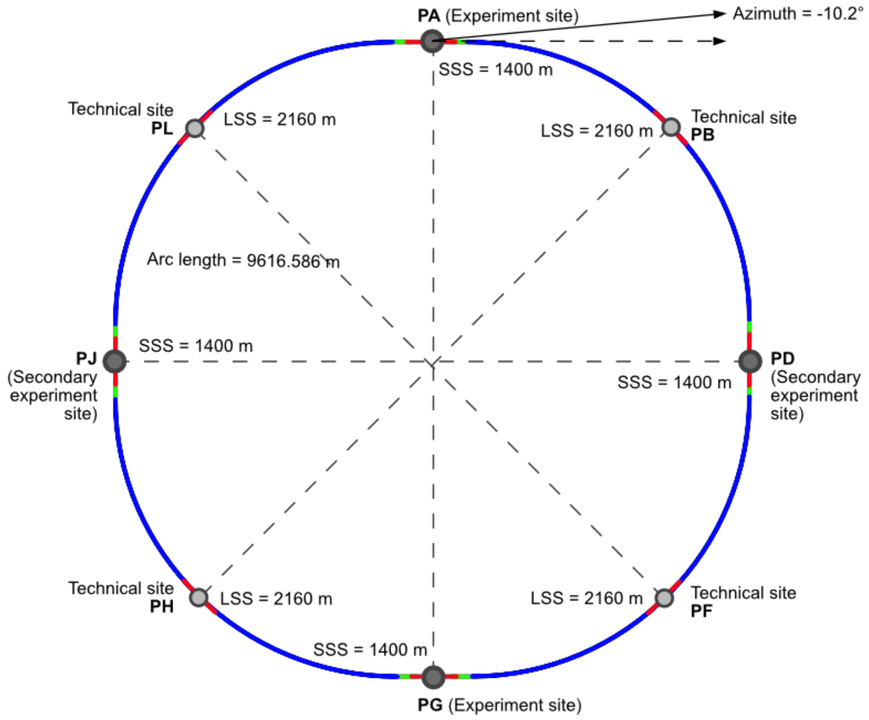
K. Oide

Nov. 29, 2021 FCCIS WP2 Workshop 2021

Many thanks to M. Benedikt, A. Blondel, T. Charles, J. Gutleber, K. Hanke, M. Hofer, M. Koratzinos, V. Mertens, T. Raubenheimer, D. Shatilov, F. Valchkova, F. Zimmermann, and all FCC-ee/FCCIS colleagues

The new layout

- The new layout “31” series has been presented by J. Gutleber in the last optics meeting.
  - 8 surface sites, 4 IP.
  - complete period-4 + mirror symmetries.
- Let us choose “PA31-1.0” for the baseline, for the time being.
  - The adaptation to other variants, if necessary, will be minor.



PA31-1.1 & 1.6 fallback alternatives

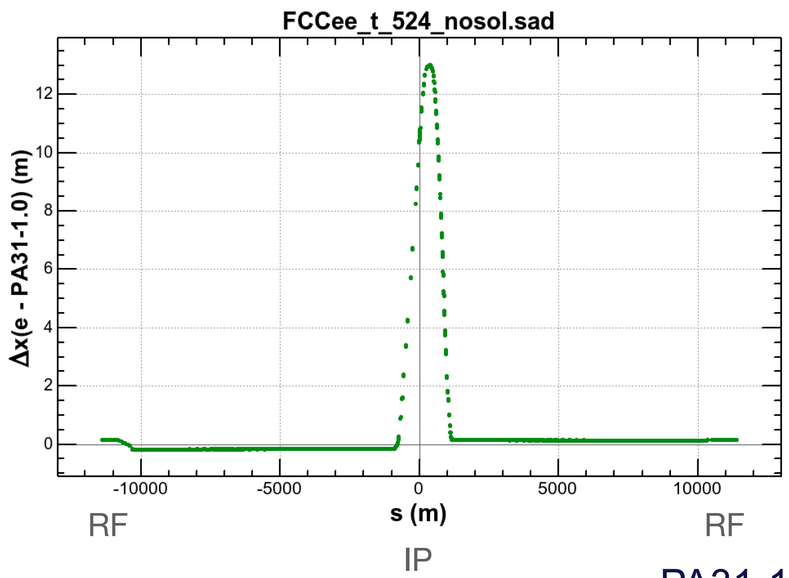
J. Gutleber

Scenario	PA31-1.0	PA31-1.1	PA31-1.6
Number of surface sites	8 (potential additional small access shafts at CERN or for ventilation at sites with long access tunnels, e.g. PF)		
Number of arc cells	42		
Arc cell length	213.04636573 m		
SSS@IP (PA, PD, PG, PJ)	1400 m	1400 m	1410 m
LSS@TECH (PB, PF, PH, PL)	2160 m	2100 m	2110 m
Azimuth @ PA (0 = East)	-10.75°	-10.45°	-10.2°
Sum of arc lengths	76 932.686 m		
Total length	91 172.686 m	90 932.686 m	91 052.686 m

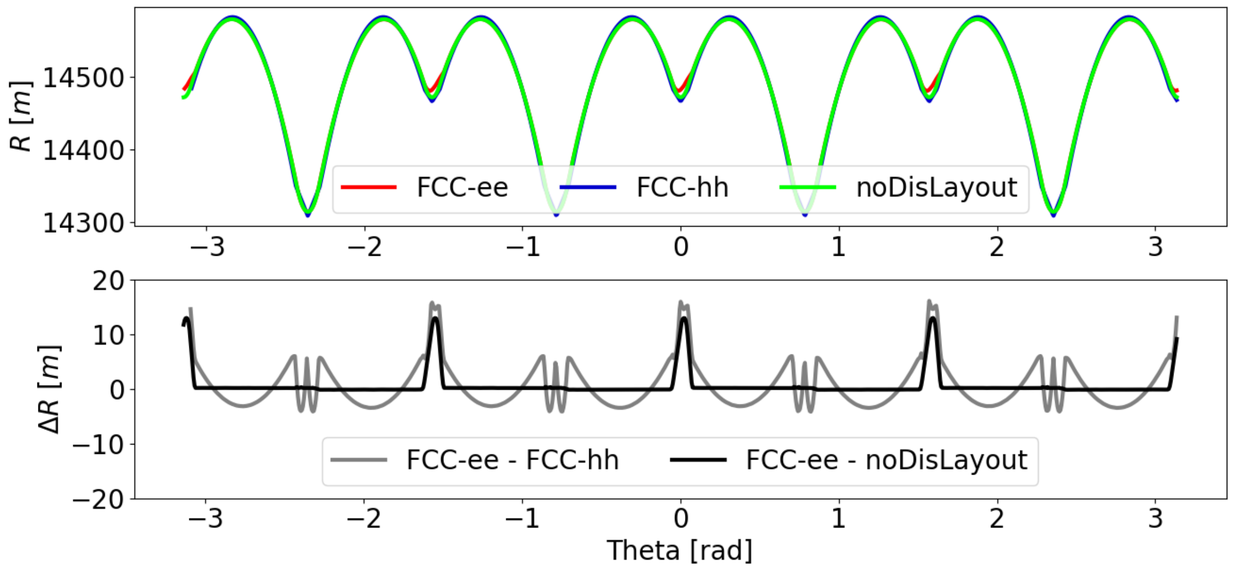
Fine adjustment to the layout “PA31-1.0”

FUTURE CIRCULAR COLLIDER

- Now the beam line fits within a few cm from the layout in the arc.
  - The resulting ring circumference is *1.42 m longer* than the layout, due to the IR excursion.
- However, some discrepancy has been found between hh’s beam line
  - Investigation is going on by M. Giovannozzi, M. Hofer, T. Risselada



M. Hofer



PA31-1.1 & 1.6 fallback alternatives

Scenario	PA31-1.0	PA31-1.1	PA31-1.6
Number of surface sites	8 (potential additional small access shafts at CERN or for ventilation at sites with long access tunnels, e.g. PF)		
Number of arc cells (FCC-hh)		42	
Arc cell length (FCC-hh)		213.04636573 m	
SSS@IP (PA, PD, PG, PJ)	1400 m	1400 m	1410 m
LSS@TECH (PB, PF, PH, PL)	2160 m	2100 m	2110 m
Azimuth @ PA (0 = East)	-10.75°	-10.45°	-10.2°
Sum of arc lengths		76 932.686 m	
Total length	91 172.686 m	90 932.686 m	91 052.686 m

If this number is strictly kept in the design of hh-arc, a discrepancy with the arc may happen?

The arc cell

- The most preferred phase advances of the FODO in the arc for luminosity: 90/90 @$t\bar{t}$, 60/60 @W, 45/45 (or long 90/90) @Z (D. Shatilov).
  - With 45/45, $\beta_{x,y}$ at SF/SD come close to each other: Long 90/90 is better.
- If we need a lattice structure compatible to all 90/90, 60/60, long 90/90, it will look like (**bold** letters show the sextupole locations. Only showing a half period):

```
          0         1         2         3         4         5         6
90/90S: FDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFD
60/60:  FDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFD
90/90L: F D F D F D F D F D F D F D F D F D F D F D F D F D F D F D F D F D F D F D F D F D F D F D F
```

  - Then 70 FODOs are necessary for the periodicity.
- Instead, if we can eliminate 60/60, the structure is simplified to:

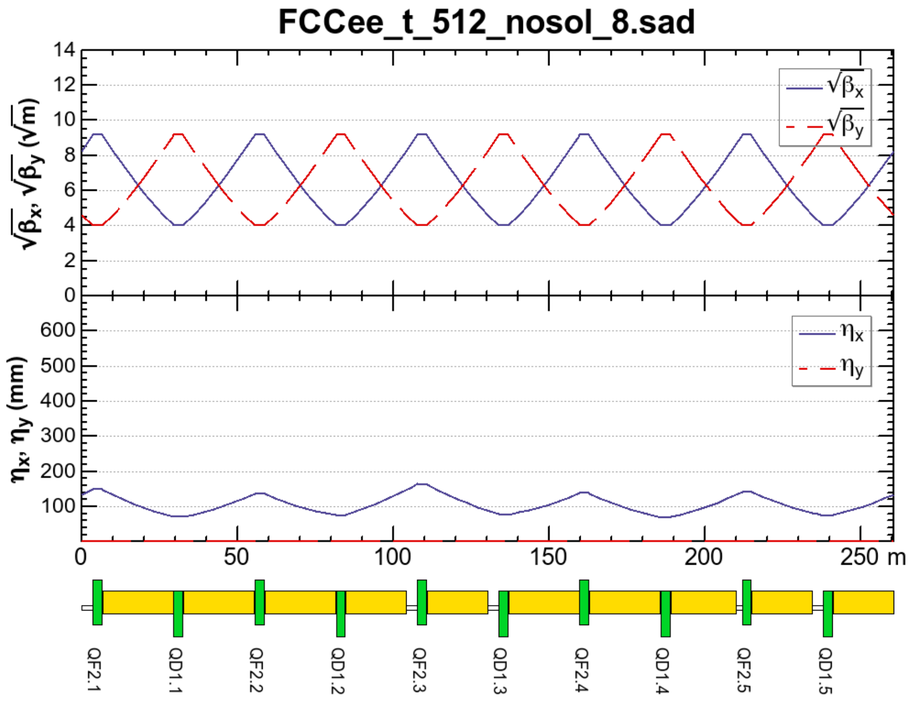
```
          0         1
90/90S: FDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFDFD
90/90L: F D F D F D F D F D F D F D F D F D F D F D F D F D F D F D F D F D F D F D F D F D F D F D F
```

- Nevertheless, as the 60/60 is only for W; the loss of luminosity at W can be compensated by:
  - The less tuning time on the transition from 90/90L to 60/60 (more integrated luminosity).
  - Slight increase of luminosity at other energies (D. Shatilov).
    - The filling factor of dipoles: with 60/60: 80.4%, without 60/60: 81.2%.
- **Thus we have chosen to eliminate 60/60, for the time being.**

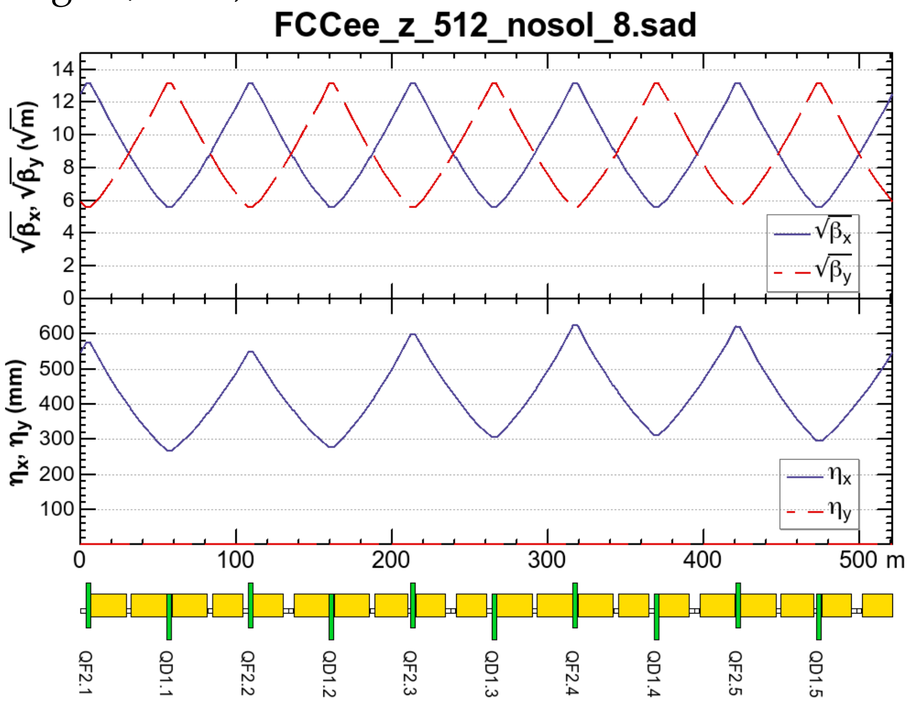
The arc cell optics (1 period = 5 FODOs)

FUTURE CIRCULAR COLLIDER

Short 90/90: $t\bar{t}$, Zh



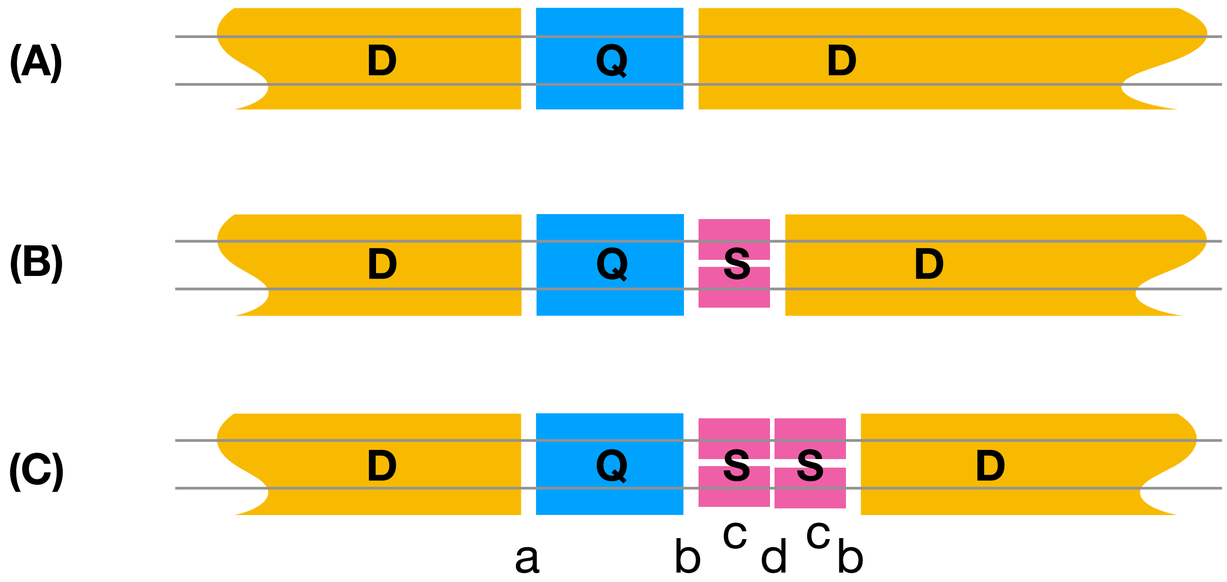
Long 90/90: Z, W



- For long 90/90:
  - The QDs for short 90/90 of the outer ring are turned off.
    - However, their BPMs and correctors are usable for additional orbit/optics correction power.
  - The polarity of QFs for short 90/90 are reversed alternatively to serve as QDs. These should have an easy mechanism in the wiring for switching.
- The arc dipoles should be divided into 3 pieces for installation. Then the field at their connection may matter.

Changes in the spacings & lengths

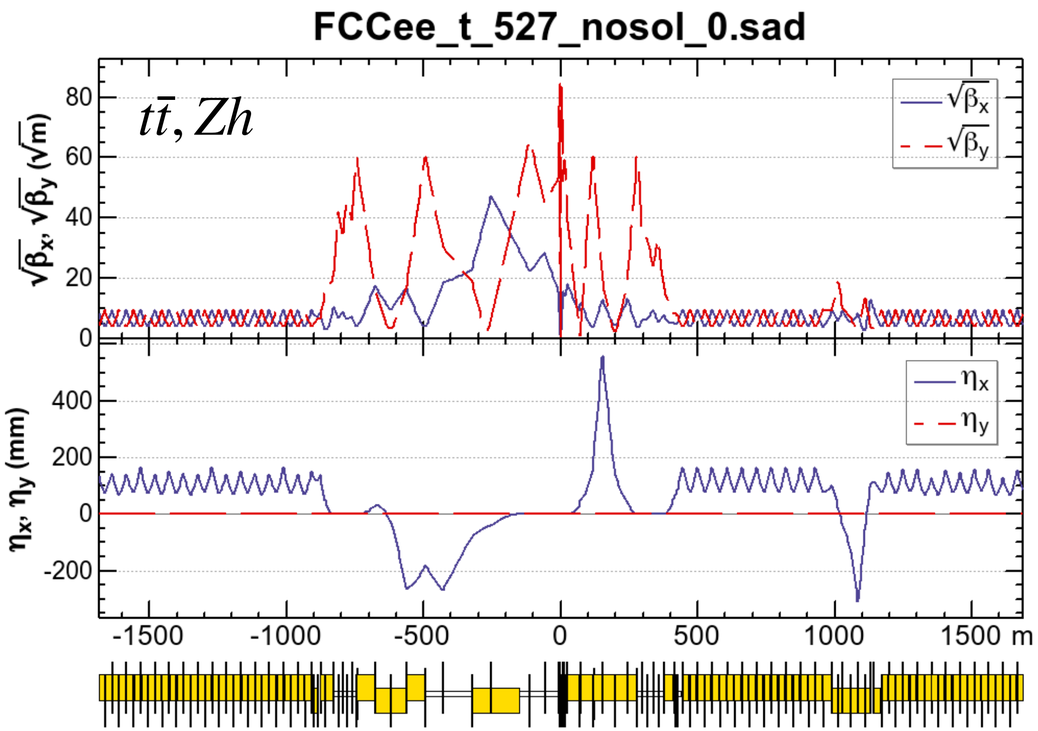
FUTURE CIRCULAR COLLIDER

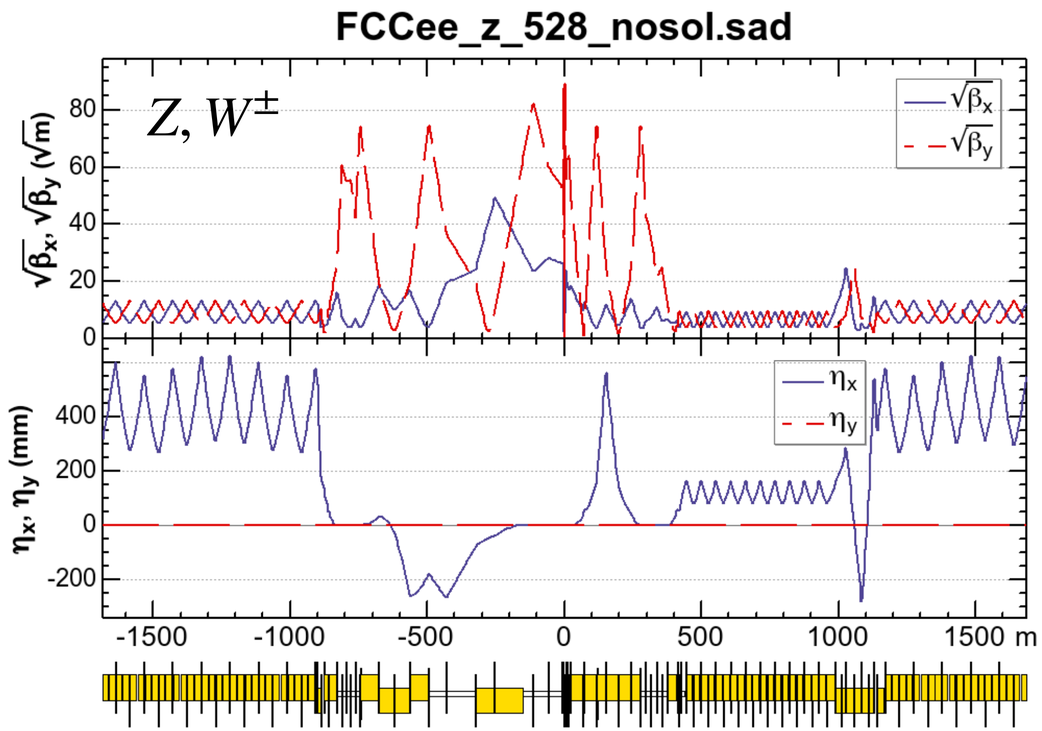


Label	Description	Length (m)	CDR (m)
a	• between quad and dipole, on the opposite side of sext. • usable for dipole correctors	0.3	0.3
b	• between quad and sext, dipole and sext	0.2	0.3
c	• sext thickness	1.5	1.4
d	• between sexts	0.15	0.1

- Need technical advices on the spacing and field profile of each magnet to finalize.
- Also for other sections.

IR optics

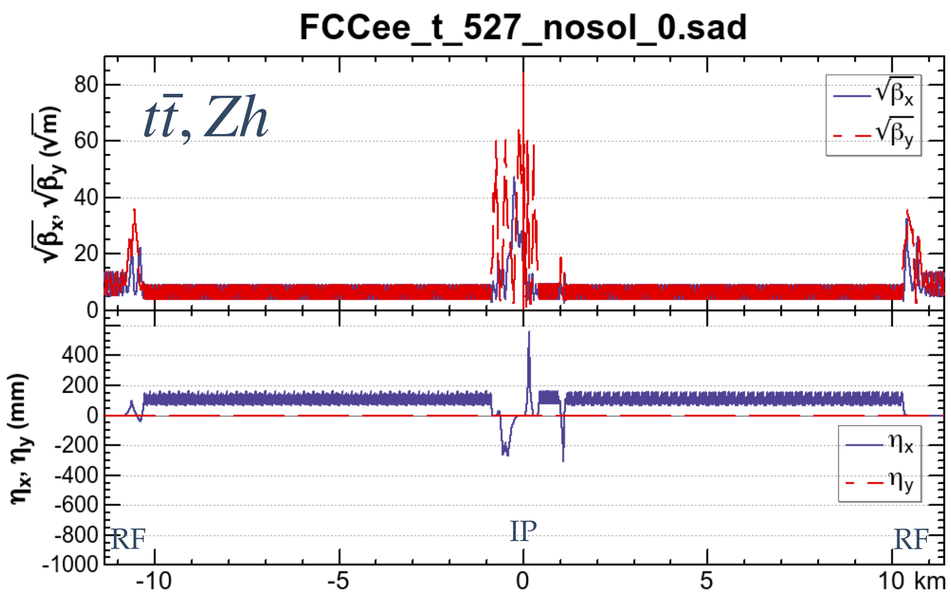


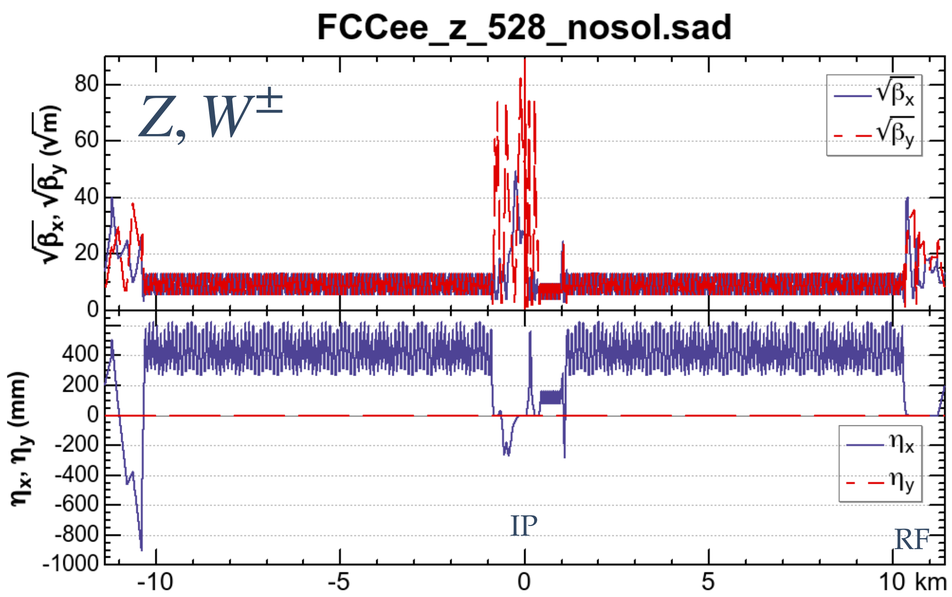


LA*

- The IR optics basically inherit conditions set at the CDR and later:
  - SR strengths
  - QC1/2 lengths
  - Now LA* are longer than 15.5 m for pol. wigglers (M. Hofer), shown in later page.
- Some dipoles have unrealistic lengths (> 100 m).

Ring optics (1/4 ring)

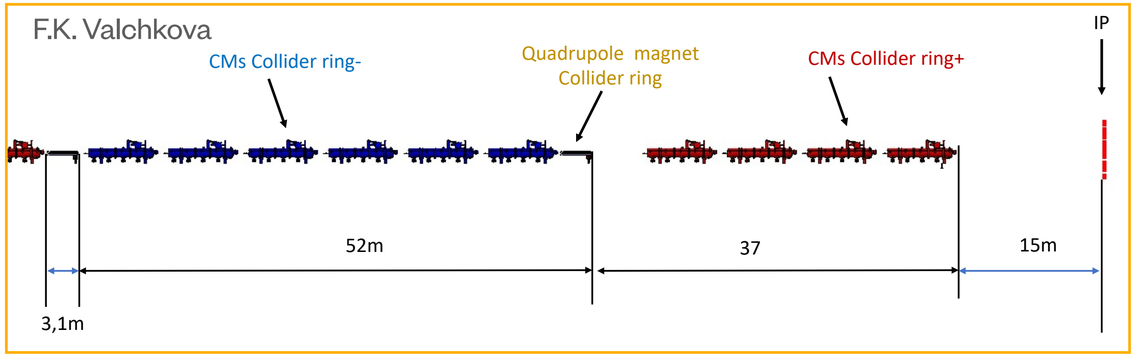




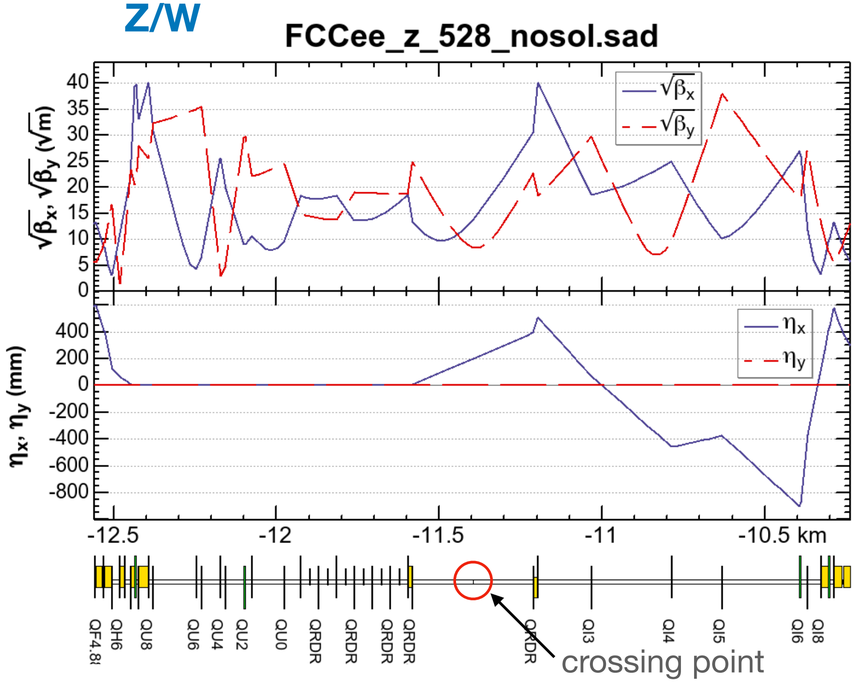
- Remarks:
  - Polarimeter, injection/extraction, collimation, BPMs, correctors are not included yet.
  - Details need technical advices for the actual requirements for spacing, field profile, etc.

Layout in the RF section ($t\bar{t}$)

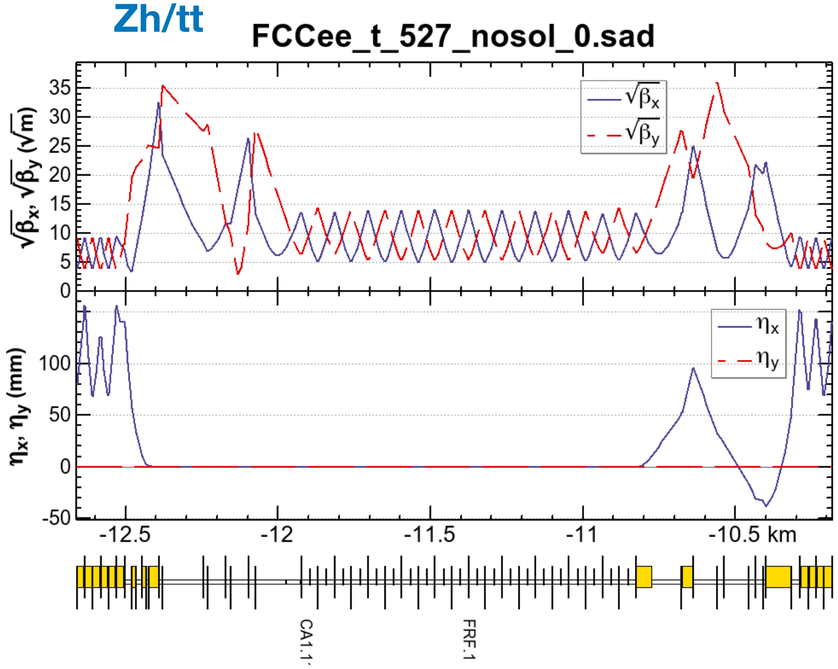
- Each space for RF is extended from 40 m to 52 m according to the request by F.K. Valchkova.
- The center of RF ("FRF") section is now shifted from the geometric center of the section to produce $\lambda_{\mathrm{RF400}}/2$ path difference from the IP between $e^{\pm}$, which is the condition of the common RF to ensure the collision at the IP.
  - The harmonic number for 400 MHz is 121648 with $f_{\mathrm{RF}} = 399.994627\,\mathrm{MHz}$ for Zh/tt.
- Designed an RF section for Z/W, which has a crossing point in the middle. The right part of the section is rebuilt at the transition to Zh/tt.



Z/W



Zh/tt



Optimum RF phase ($t\bar{t}$)

Suggested by T. Raubenheimer, D. Shatilov

FUTURE CIRCULAR COLLIDER

If we have two RF frequencies f_1 and f_2 with voltages $V_1$and V_2, the total accelerating voltage $V(z)$ and its potential energy $W(z)$ are written as:

$$V(z) = V_1 \sin(\phi_1 + k_1 z) + V_2 \sin(\phi_2 + k_2 z) - U_0 = -\frac{\partial W(z)}{\partial z}\,, \tag{1}$$

$$W(z) = -\frac{V_1}{k_1}\cos(\phi_1 + k_1 z) - \frac{V_2}{k_2}\cos(\phi_1 + k_2 z) + U_0 z\,, \tag{2}$$

where $\phi_{1,2}$ are the RF phases at the equilibrium $z = 0$, and $k_{1,2}$ are the wave numbers, respectively. The energy loss per turn is denoted by U_0. At the equilibrium, $V(z) = 0$, obviously.

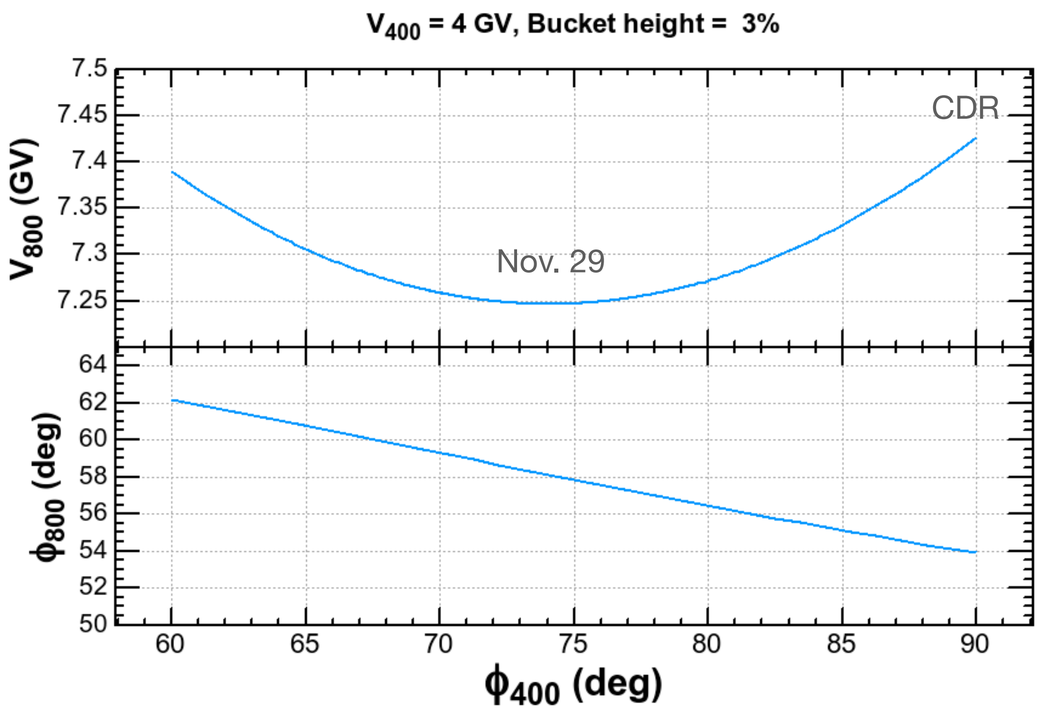
The bucket hight δ is obtained by energy conservation at the unstable fixed point $z_1 > 0$:

$$V(z_1) = 0\,, \tag{3}$$

$$W(z_1) = -\frac{\alpha C E}{2}\delta^2 + W(0)\,, \tag{4}$$

where α, C, and E are the momentum compaction, circumference, and beam energy, respectively. Note that the kinetic energy term above has negative sign.

Then once ϕ_1 and V_1 are given, we can obtain the solution for ϕ_2, V_2, and z_1 to satisfy the equations above, at least numerically.



I have once obtained the optimum for a given V' or bunch length, but D. Shatilov pointed out that an optimization for a fixed bucket height is suitable for FCC-ee.

Parameters

FUTURE CIRCULAR COLLIDER

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-1.0			
# of IPs		4			
Circumference	[km]	91.174117		91.174107	
Bending radius of arc dipole	[km]	9.937			
Energy loss / turn	[GeV]	0.0391	0.370	1.869	10.0
SR power / beam	[MW]	50			
Beam current	[mA]	1280	135	26.7	5.00
Bunches / beam		9600	880	248	36
Bunch population	[10^{11}]	2.53	2.91	2.04	2.64
Horizontal emittance ε_x	[nm]	0.71	2.16	0.64	1.49
Vertical emittance ε_y	[pm]	1.42	4.32	1.29	2.98
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.5		7.33	
Arc sextupole families		75		146	
$\beta^*_{x/y}$	[mm]	150 / 0.8	200 / 1.0	300 / 1.0	1000 / 1.6
Transverse tunes/IP $Q_{x/y}$		53.563 / 53.600		100.565 / 98.595	
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.130	0.069 / 0.154	0.103 / 0.185	0.157 / 0.229
Bunch length (SR/BS) σ_z	[mm]	4.37 / 14.5	3.55 / 8.01	3.34 / 6.00	2.02 / 2.95
RF voltage 400/800 MHz	[GV]	0.120 / 0	1.0 / 0	2.08 / 0	4.0 / 7.25
Harmonic number for 400 MHz		121648			
RF freuqeuncy (400 MHz)	MHz	399.994581		399.994627	
Synchrotron tune Q_s		0.0370	0.0801	0.0328	0.0826
Long. damping time	[turns]	1168	217	64.5	18.5
RF acceptance	[%]	1.6	3.4	1.9	3.1
Energy acceptance (DA)	[%]	±1.3	±1.3	±1.7	-2.8 +2.5
Beam-beam ξ_x/ξ_y [a]		0.0040 / 0.152	0.011 / 0.125	0.014 / 0.131	0.096 / 0.151
Luminosity / IP	[10^{34}/cm^{2}s]	189	19.4	7.26	1.33
Lifetime (q + BS)	[sec]	–		1065	2405
Lifetime (lum)	[sec]	1089	1070	596	701

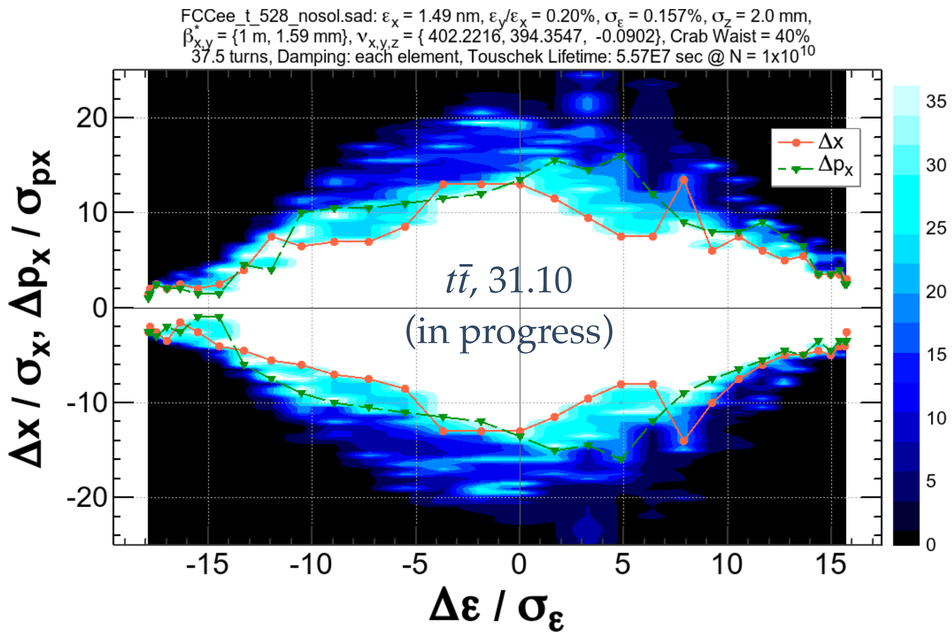
[a] incl. hourglass.

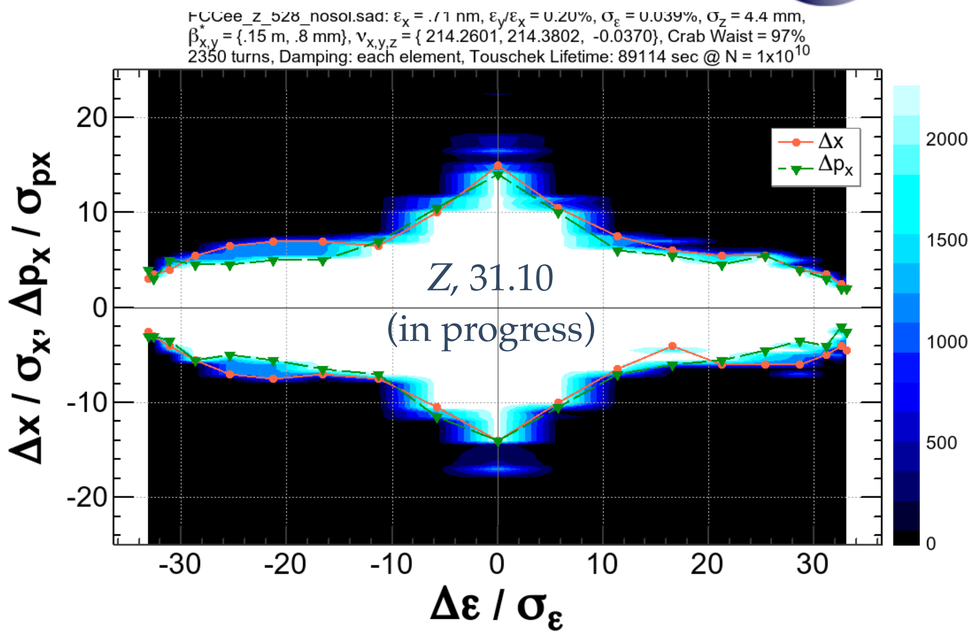
The luminosities and beam-beam related numbers are based on a simple model w/o beam-beam simulations.

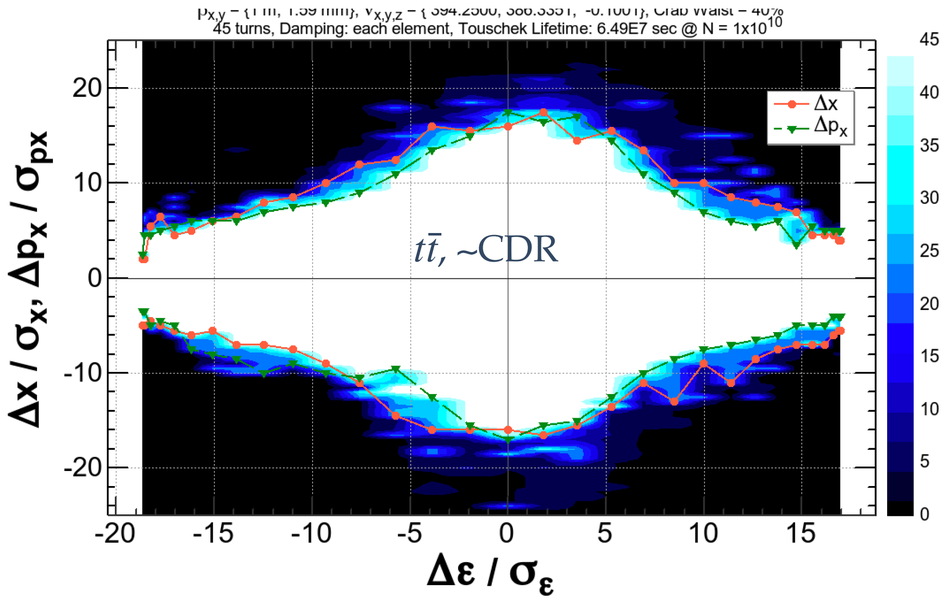
Dynamic aperture

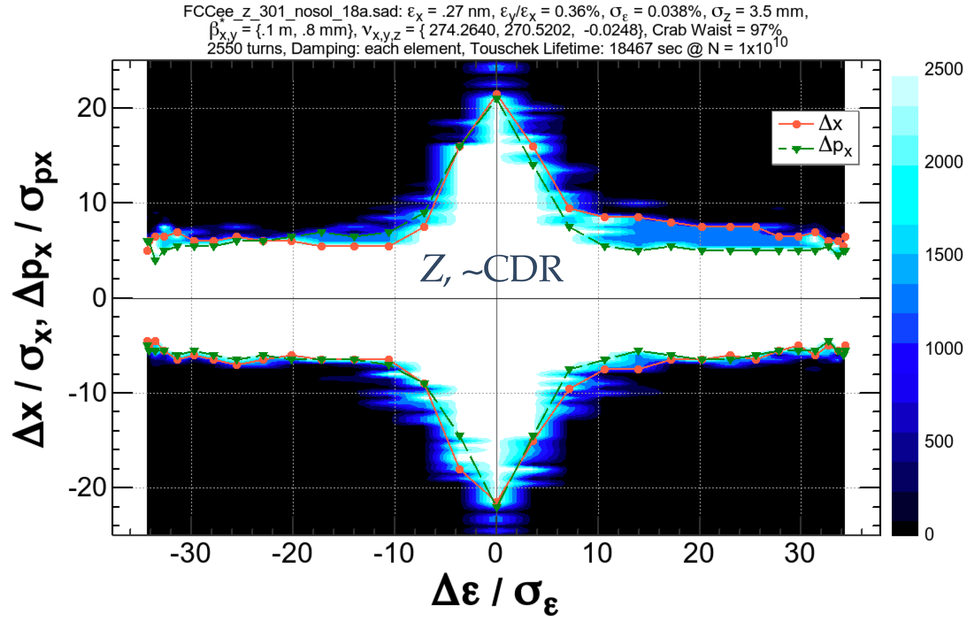
These are with the old RF sections and tunes.
DA with new RF sections and tunes are in progress…

FUTURE CIRCULAR COLLIDER

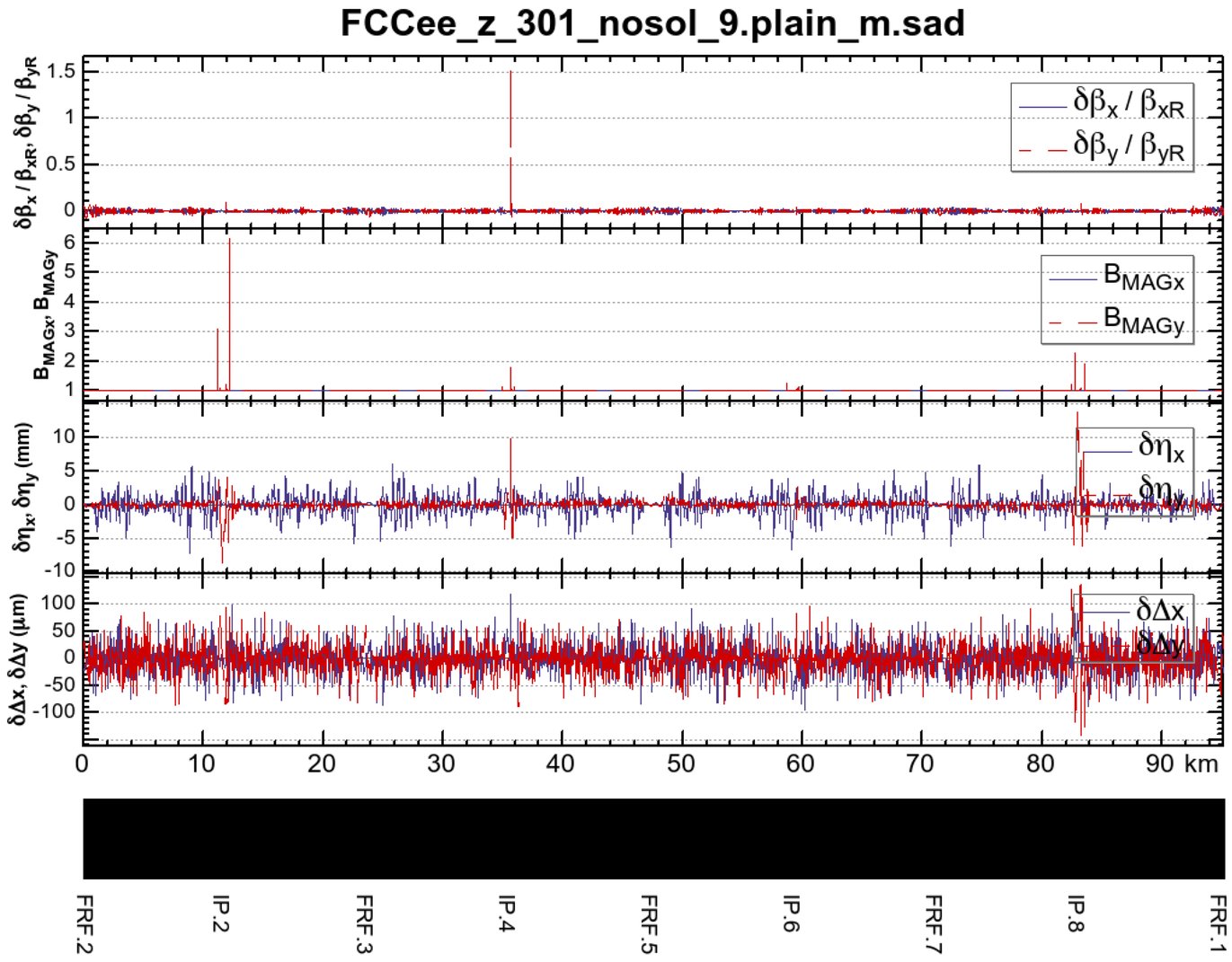








Impact of errors/corrections on DA



An example of errors and corrections by T. Charles, with an old 4IP lattice. New results will be in the next talk!

- The correction by T. Charles looks excellent!
  - Tunes are slightly shifted:
    - (274.26126, 270.52384) from (274.26400, 270.52000).
  - Emittances: (0.275 nm, 23.2 fm).

- Remarks:
  - The spike of $\Delta\beta_y/\beta_y$ at IP. 4 corresponds to a shift of waist.
  - If we look at B_{MAGy}, there are several locations with high B_{MAGy} esp. at crab sexts (see next page).
  - The residual orbit looks much smaller than the misalignment; probably the BPMs are placed on the ideal plane in this case?

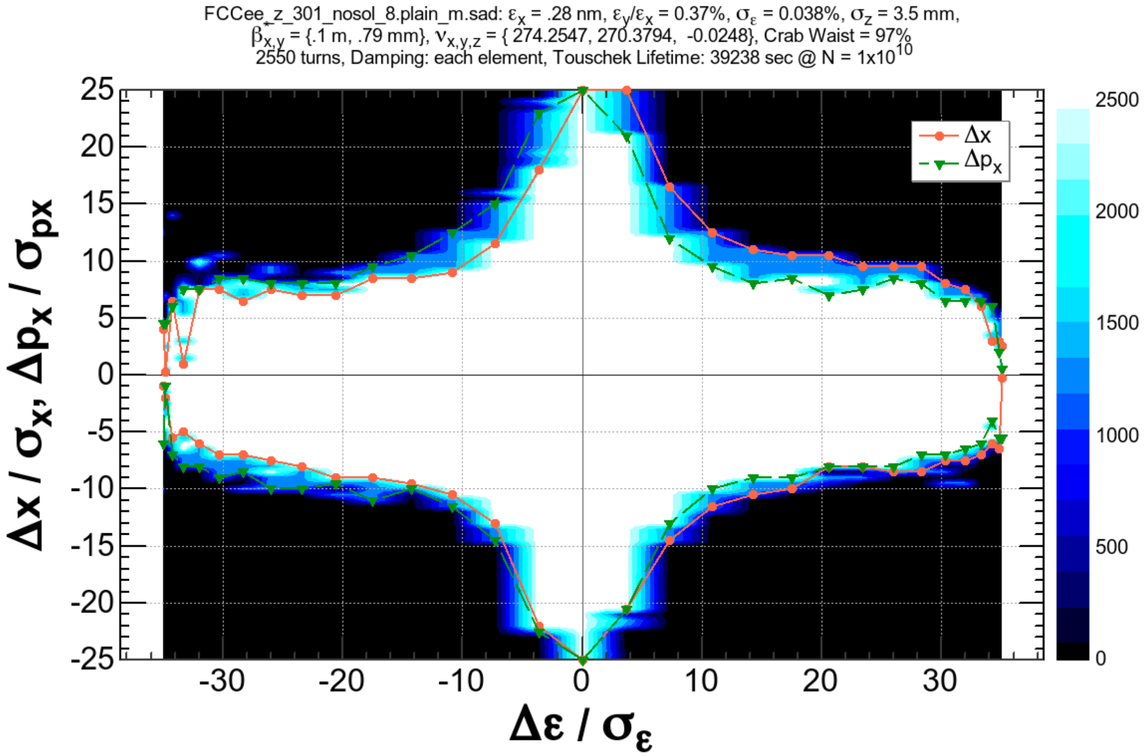
Reduction of DA by errors/corrections

FUTURE CIRCULAR COLLIDER

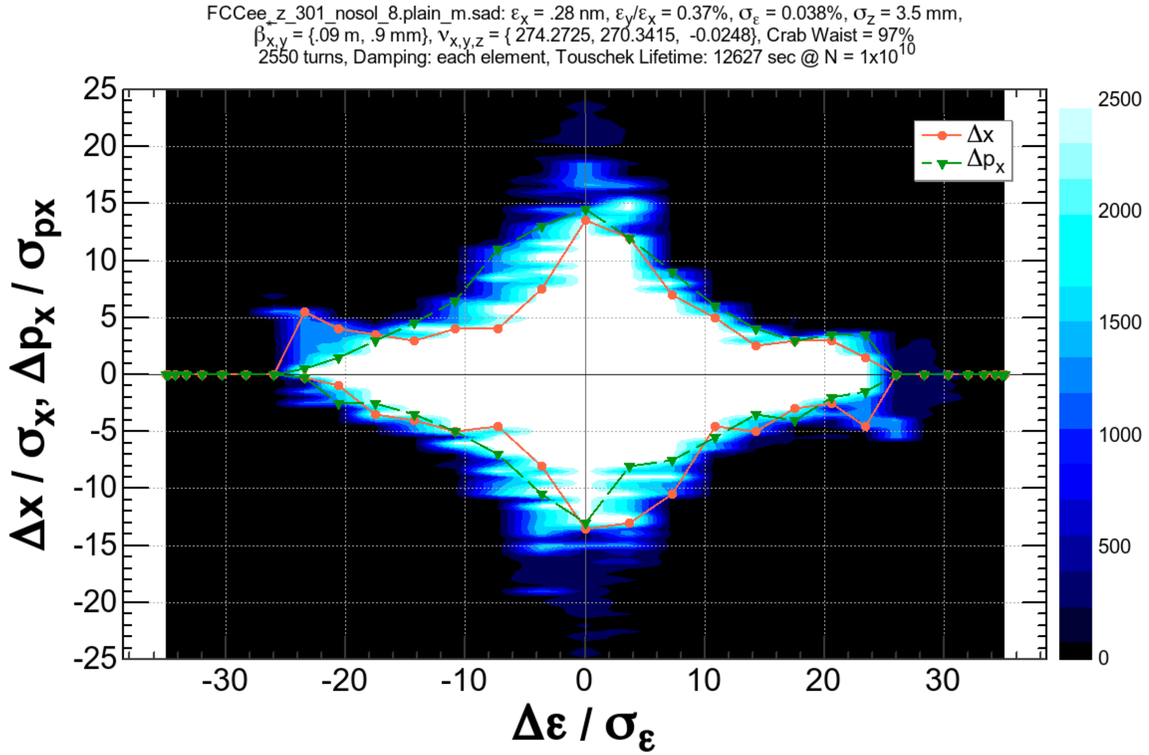
An example of errors and corrections by T. Charles, with an old 4IP lattice.

301_8

No error

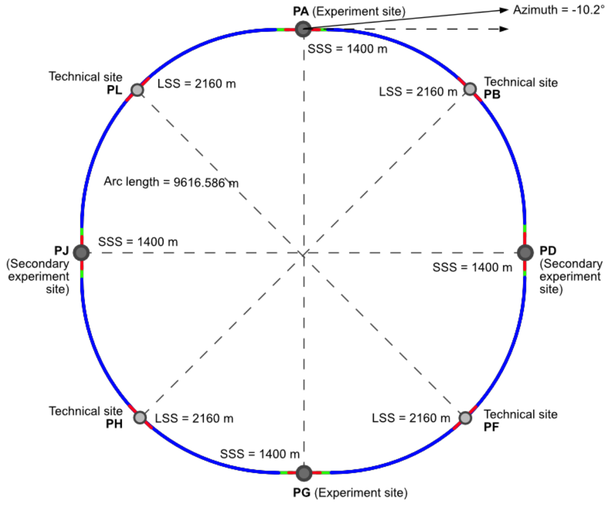


Errors + corrections ("seed 1")



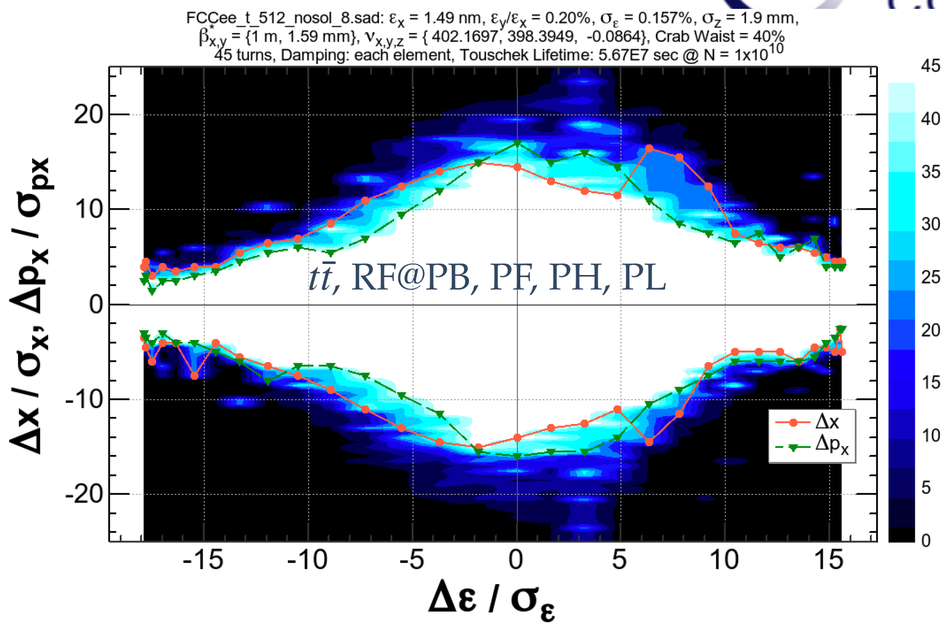
- The dynamic aperture shrinks with the errors and corrections ("seed 1") as seen in figures above.
  - The errors/corrections for 301_9 were simply applied on 301_8. The resulting vertical emittance raised to 0.2 pm.
- The corresponding momentum acceptance: ±1.3% (no error) → ±0.8%? (seed_1).
- Further optimization of sexts with errors/corrections may improve the DA

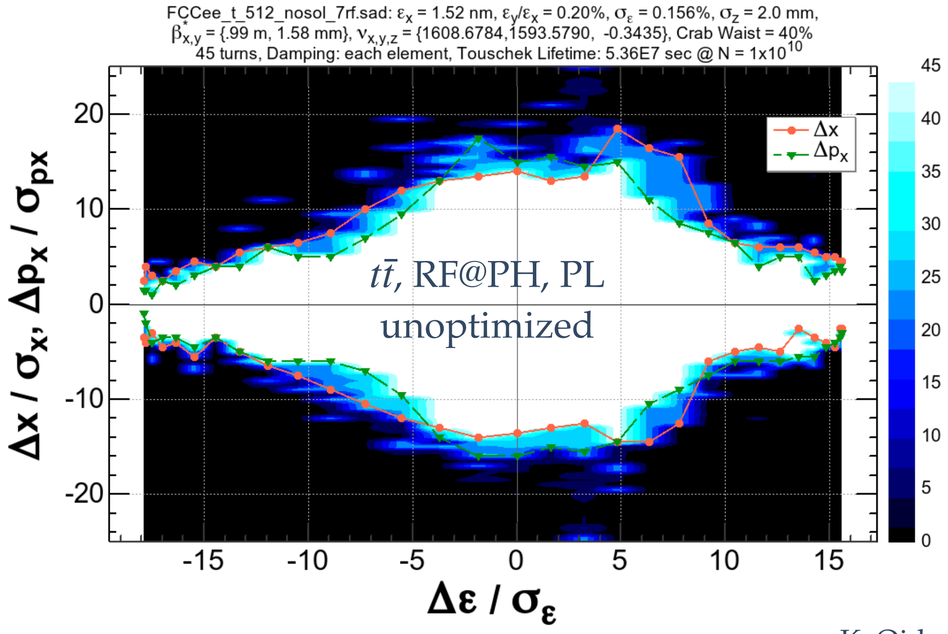
Non-periodic placement of RF



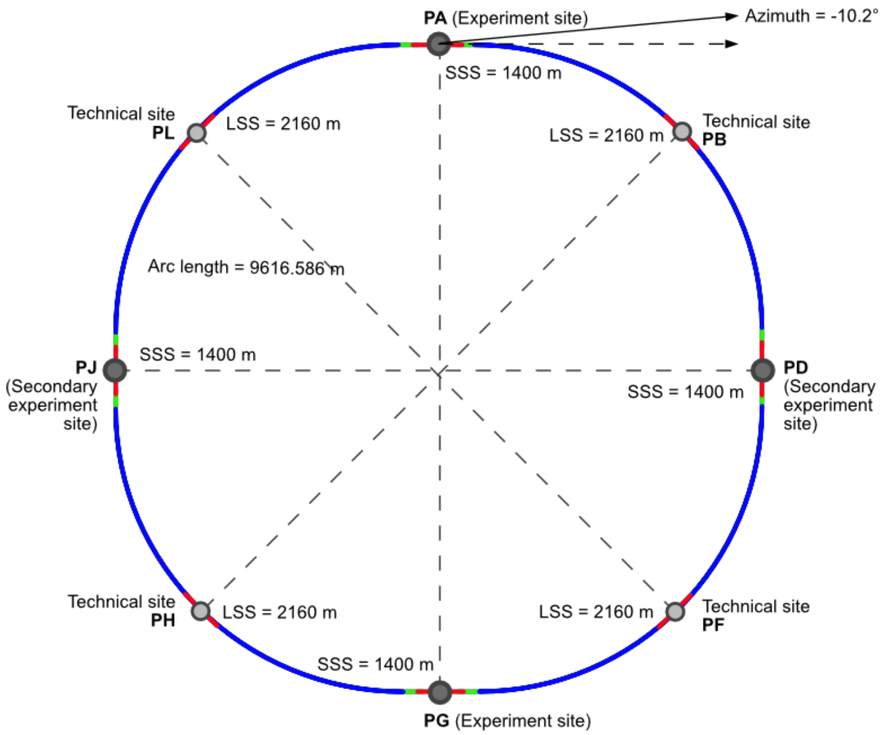
	e+	e-	power / station
Z, W	PL xor PH		100 MW
Zh, tt	PL, PH (common)		50 MW, in average
eeh	PL xor PH		100 MW

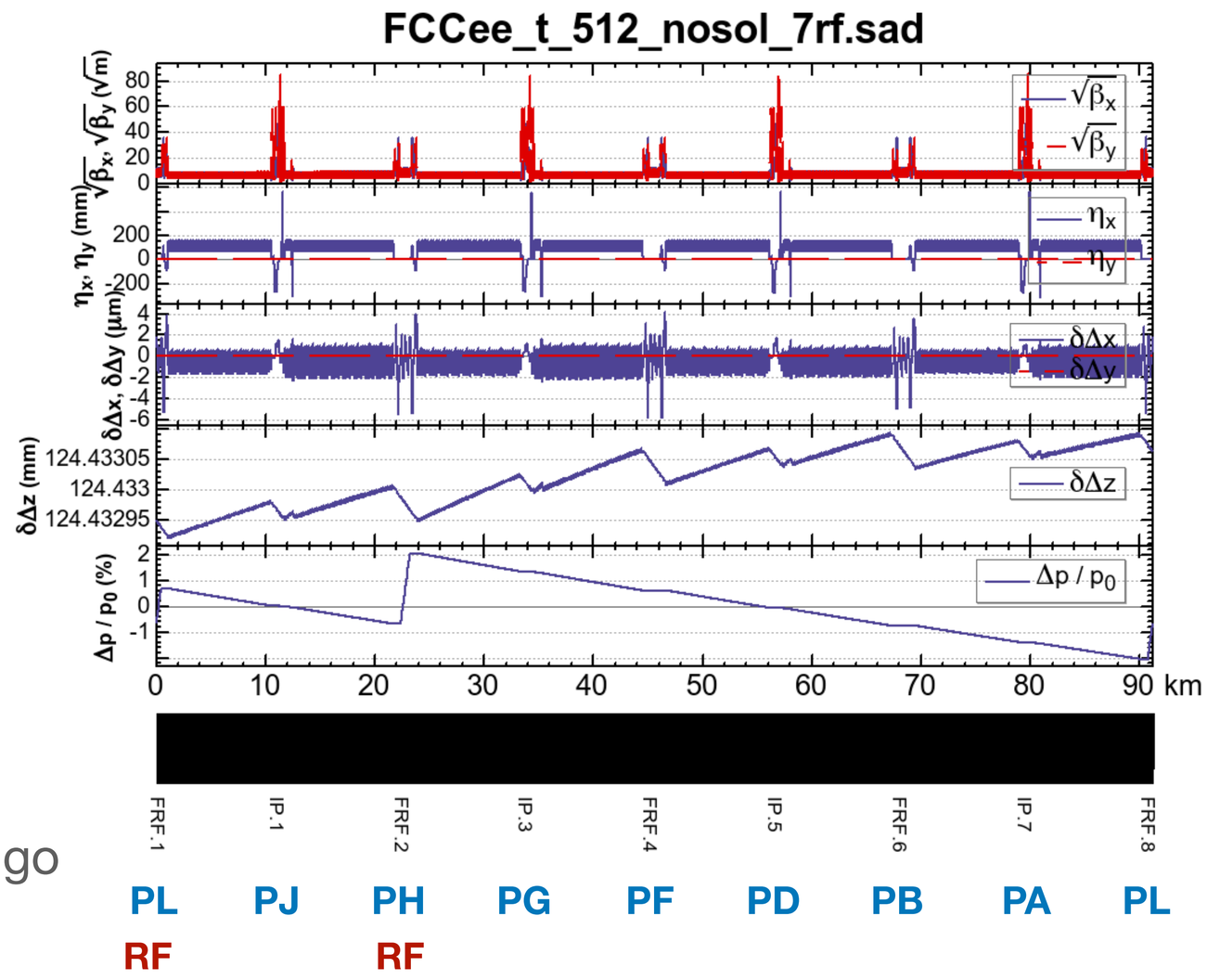
- For Z, W, eeh, placing all RF at one station, same for e+ and e-, is essential to the physics (A. Blondel).
- Placing the RF only at PL & PH, suggested by K. Hanke, for tt & Zh looks OK. The difference in the DA is small, within the range of further optimization.
- The possibility for common RF at Zh is under investigation (CEPC does so).





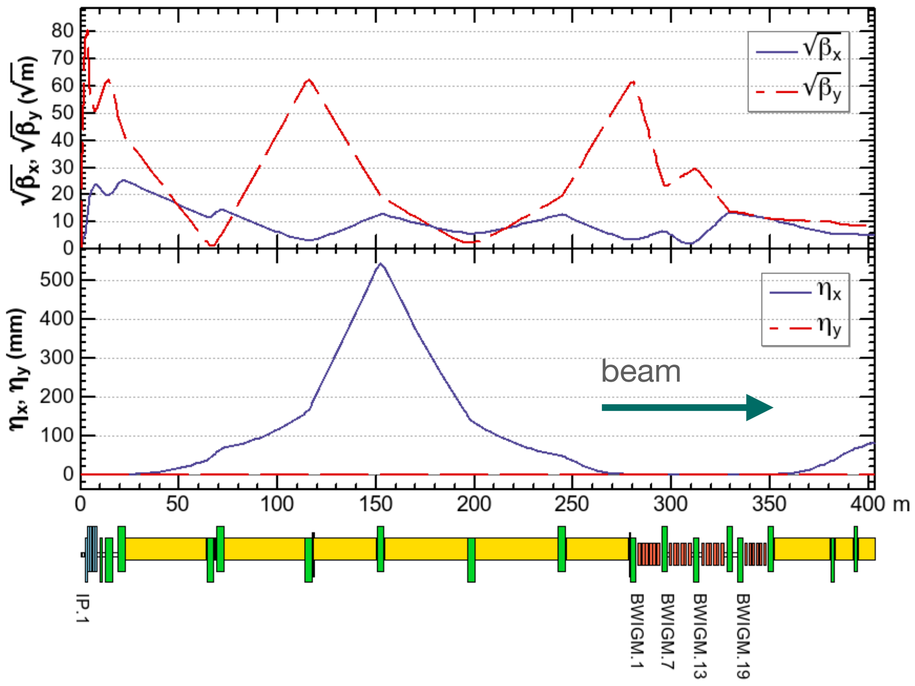
Energy sawtooth for RF@ PH,PL ($t\bar{t}$)

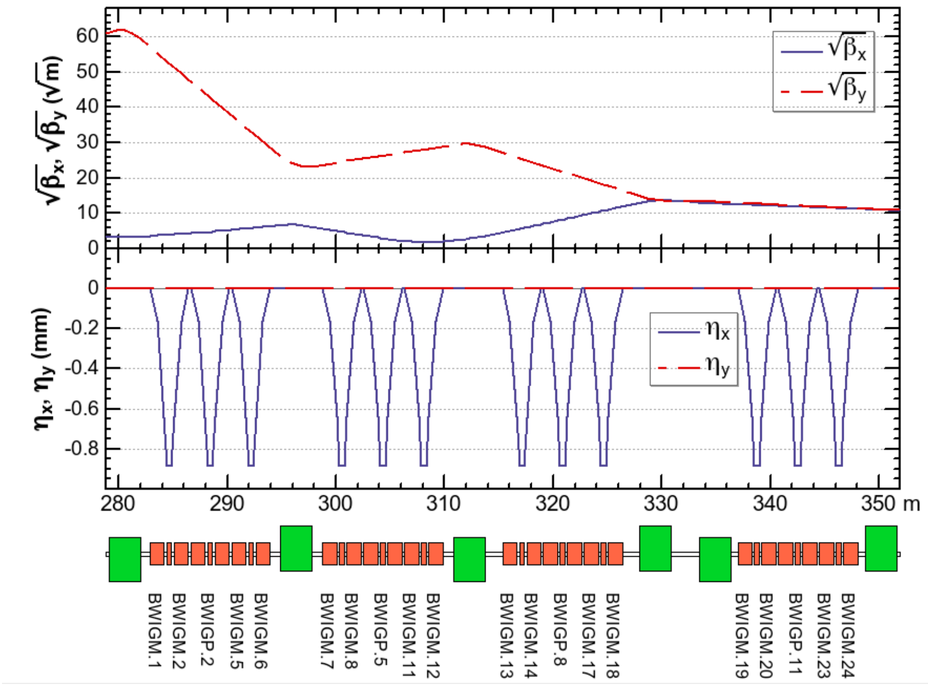




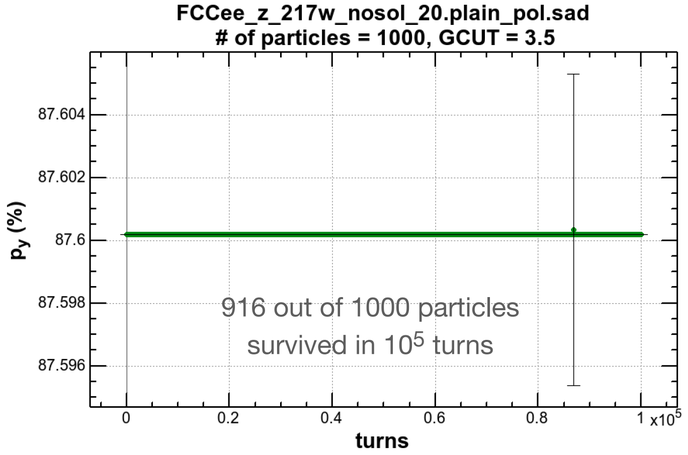
- What about the case of *2IP*?
  - PD&PJ (CDR) is the best, but we cannot go back after the work started at PL/PH…

Polarization wigglers (M. Hofer)





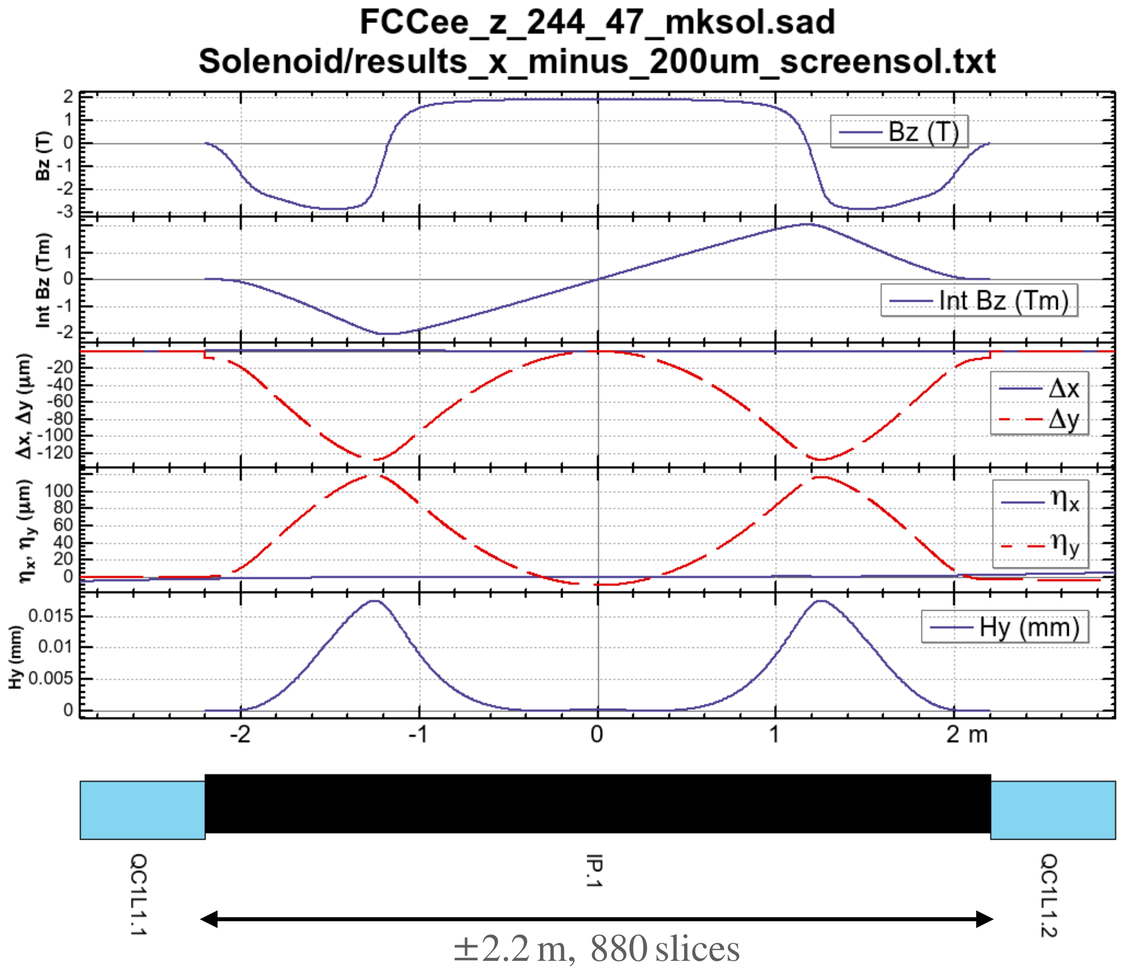
- Polarization wigglers can be placed at the straight section “LA*”, lcated at downstream of each IP.
  - A preliminary calculation of the polarization by tracking with SAD, without machine errors, seems OK…
- The location for polarimeters must be identified & designed.
  - “RF section without RF” can be a candidate.

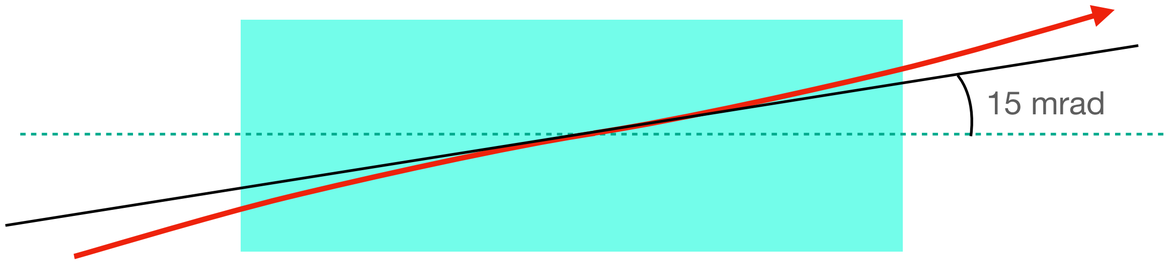


Including a realistic solenoid (M. Koratzinos)

- A realistic solenoid field model can included in the optics.
- The right plot is an example based on the solenoid + multipoles given by M. Koratzinos.
  - The L* region (IP±2.2 m) is divided into ~5 mm slices, *along the tilted straight line (±15 mrad),* not along the solenoid axis.
  - The optics and leaked hor. dispersions are corrected to the no-solenoid case by outer quads.
  - The resulting equilibrium vertical emittance is 0.23 pm.
- Thus the solenoid has been ready on SAD side, waiting for MADX (for years).

~CDR, 2IP optics





Summary

FUTURE CIRCULAR COLLIDER

- Beam optics for $t\bar{t}$ & Z with the new layout "31.10" have been generated.
  - Arc cells are "short" 90°/90° ($t\bar{t}, Zh$) and "long" 90°/90° ($Z, W^{\pm}$) FODOs.
  - Small changes are made for some spacings and sext thickness.
- RF sections are redesigned taking the transition from $Z/W^{\pm}$ to $Zh/t\bar{t}$ into account.
  - The length of the RF section follows the requirment from the RF group.
  - Placement of the RF has been considered with the collision condition of the common RF and the harmonic number at $Zh/t\bar{t}$.
  - The optimum phase for the mixed frequency at $t\bar{t}$ has been considered.
  - Having non-periodic RF at straight sections PH&PL at $Zh/t\bar{t}$ seems OK for the DA.
- The dynamic apertures (DA) are optimized up to some extent. The results look acceptable for $t\bar{t}$ & Z.
  - The reduction of DA with errors/corrections has a significant impact.
- The luminosity performances basically follow the change in the ring circumference or the bending radius, due to the SR loss.
- The polarization wigglers have found the place.
- A realistic solenoid can be implemented in the lattice.
- (Too) many details in the optics design remain, and require more technical inputs…