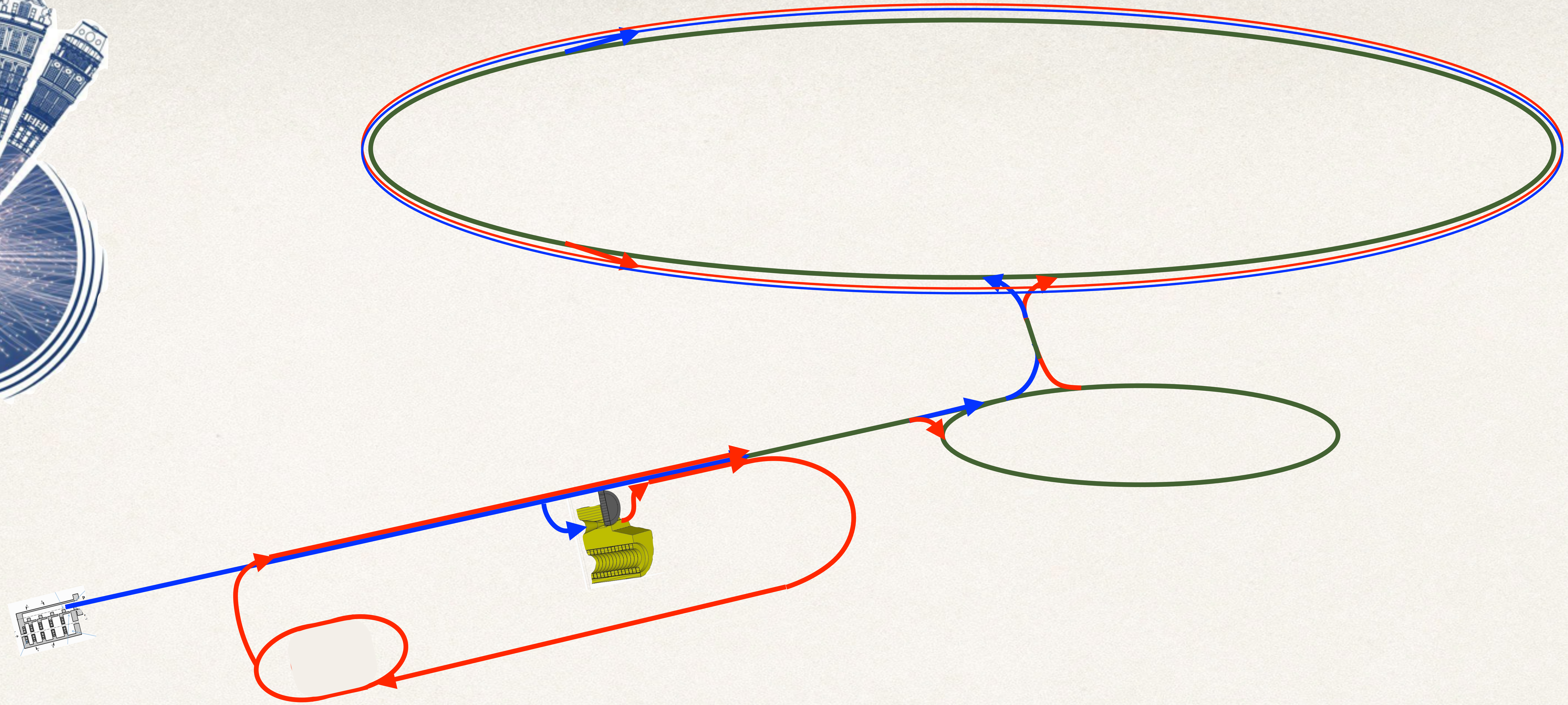


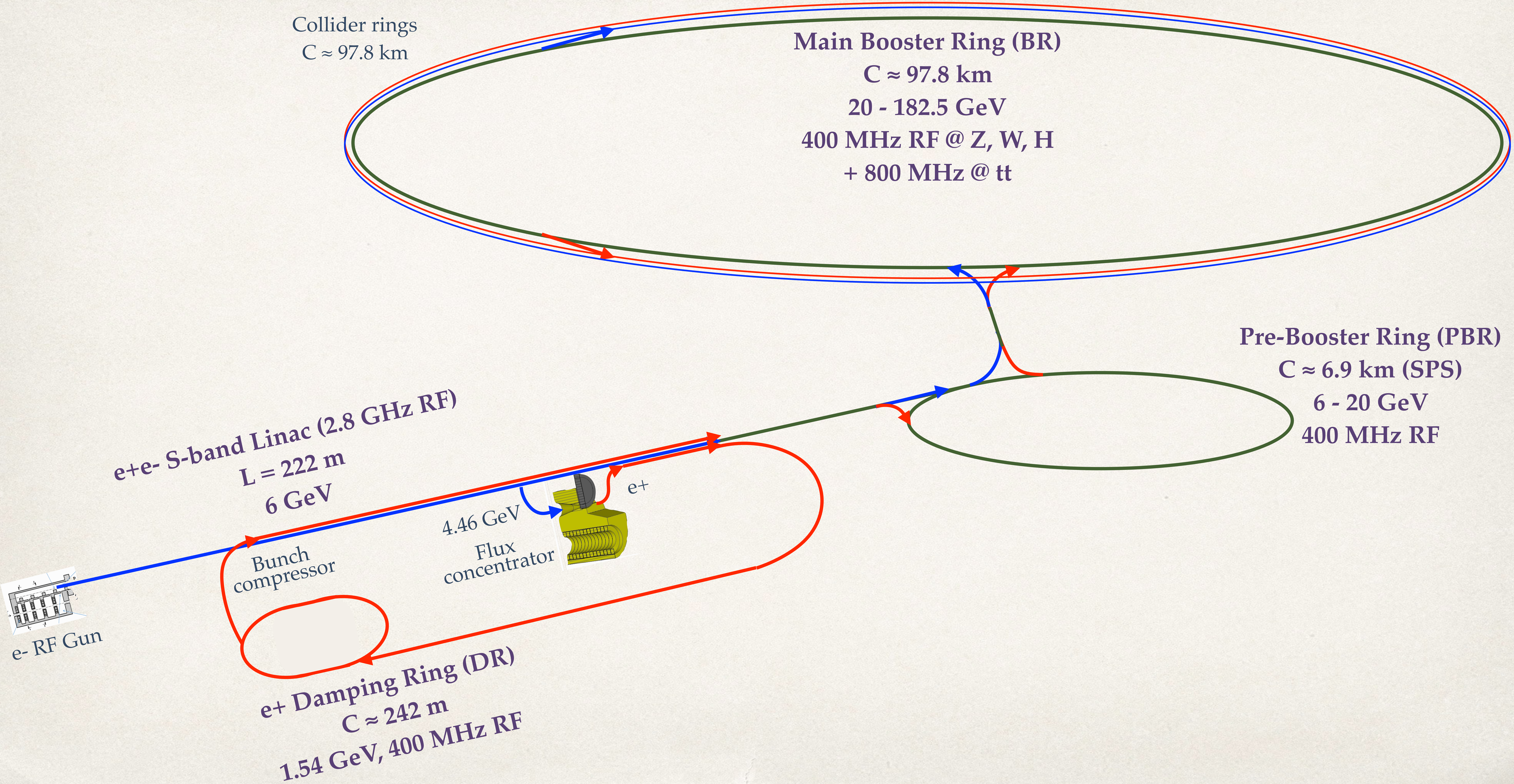
Baseline scheme for the FCC-ee injector

K. Oide (CERN)

Many thanks to A. Apyan, M. Benedikt, I. Chaikovska, T.K. Charles, O. Etisken, B. Härer, P. Martyshkin, S. Ogur, Y. Papaphilippou, D. Schulte, D. Shatilov, D. Teytelman, F. Zimmermann, and all contributors for the CDR.

June 26, FCC Week 2019 @ Brussels

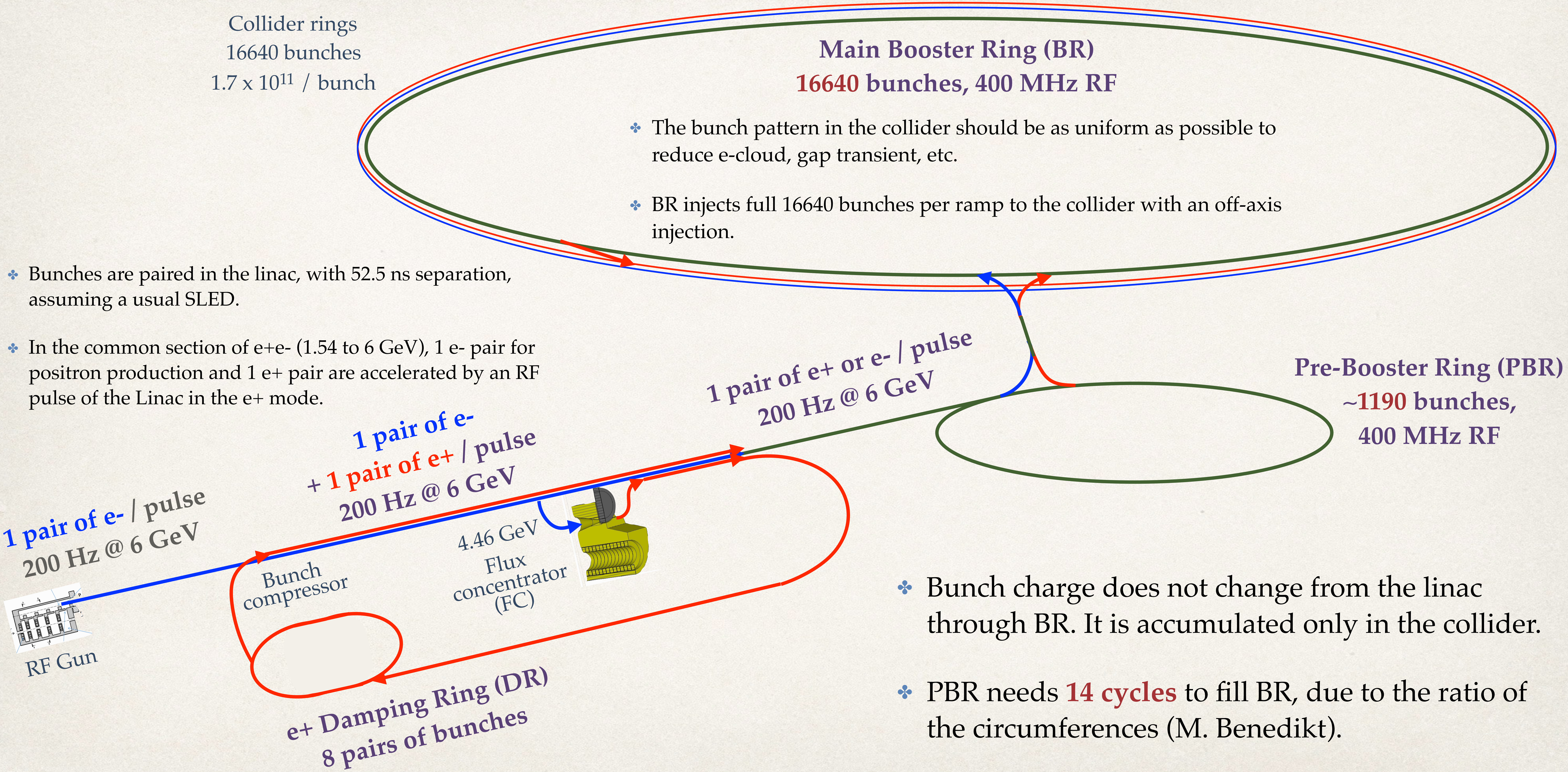
The baseline layout in the CDR



Injection scheme for Z

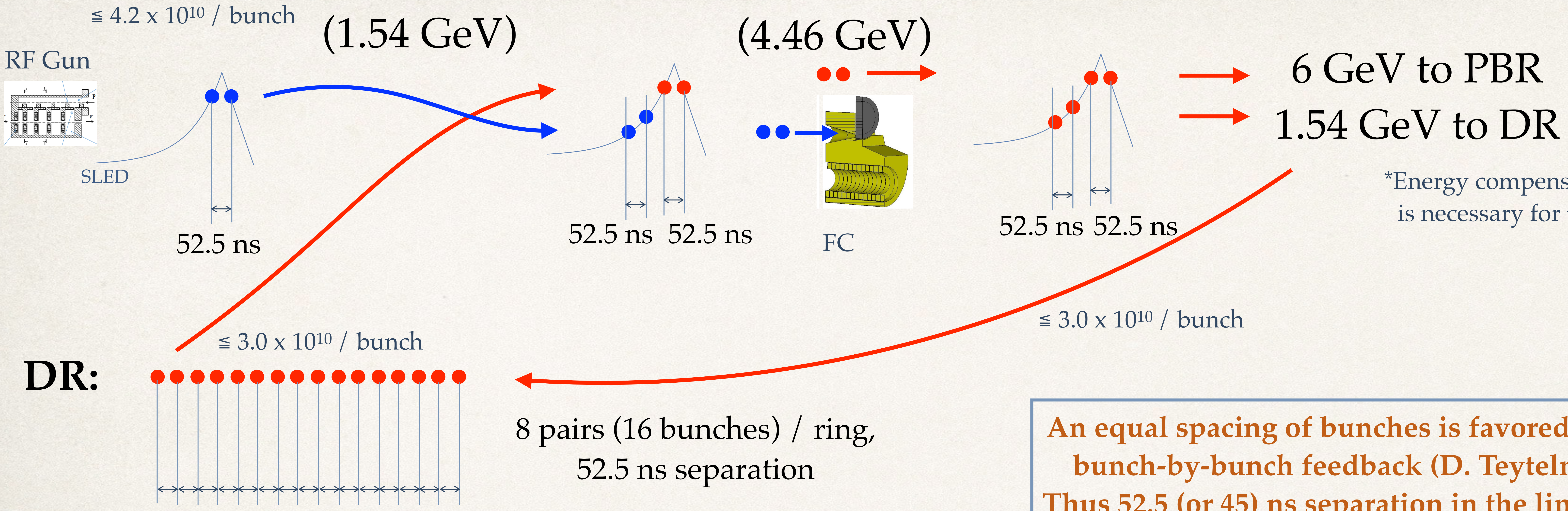
- The bunch pattern in the collider should be as uniform as possible to reduce e-cloud, gap transient, etc.
- BR injects full 16640 bunches per ramp to the collider with an off-axis injection.

- Bunches are paired in the linac, with 52.5 ns separation, assuming a usual SLED.
- In the common section of e+e- (1.54 to 6 GeV), 1 e- pair for positron production and 1 e+ pair are accelerated by an RF pulse of the Linac in the e+ mode.



- Bunch charge does not change from the linac through BR. It is accumulated only in the collider.
- PBR needs **14 cycles** to fill BR, due to the ratio of the circumferences (M. Benedikt).

Injection scheme for Z (e+ mode)

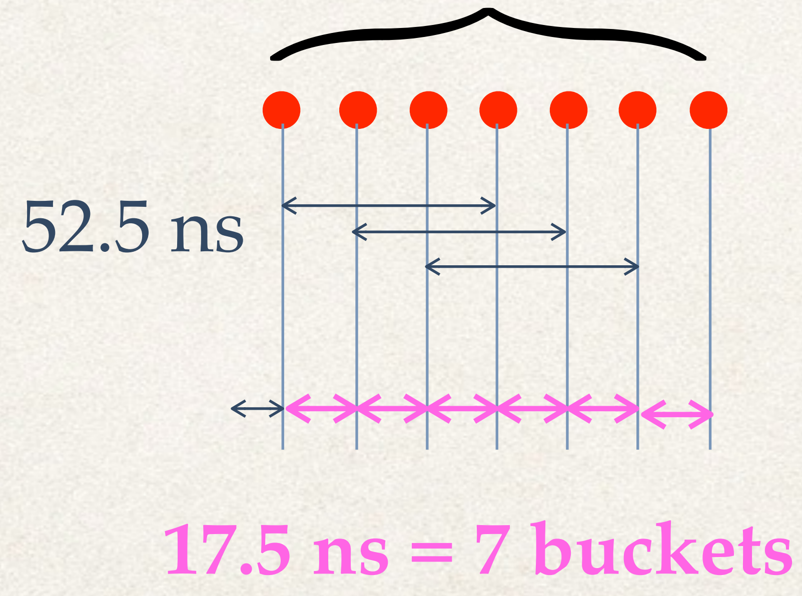


*Energy compensation or a flat SLED is necessary for the low-energy e+.

An equal spacing of bunches is favored by the bunch-by-bunch feedback (D. Teytelman). Thus 52.5 (or 45) ns separation in the linac, and 17.5 (or 15) ns in the PBR/BR can be chosen.

1 trainlet = 3 linac pairs interleaved
= 105 ns = 42 buckets

PBR:



200 trainlets (1200 bunches)
+ 806 buckets for kicker
= 9206 buckets / ring

BR: Same bunch pattern as the collider.

14 PBR trains = 16800 bunches
+ 1606 buckets for spare
= 130490 buckets / ring.

Bunch separation in the S-band linac

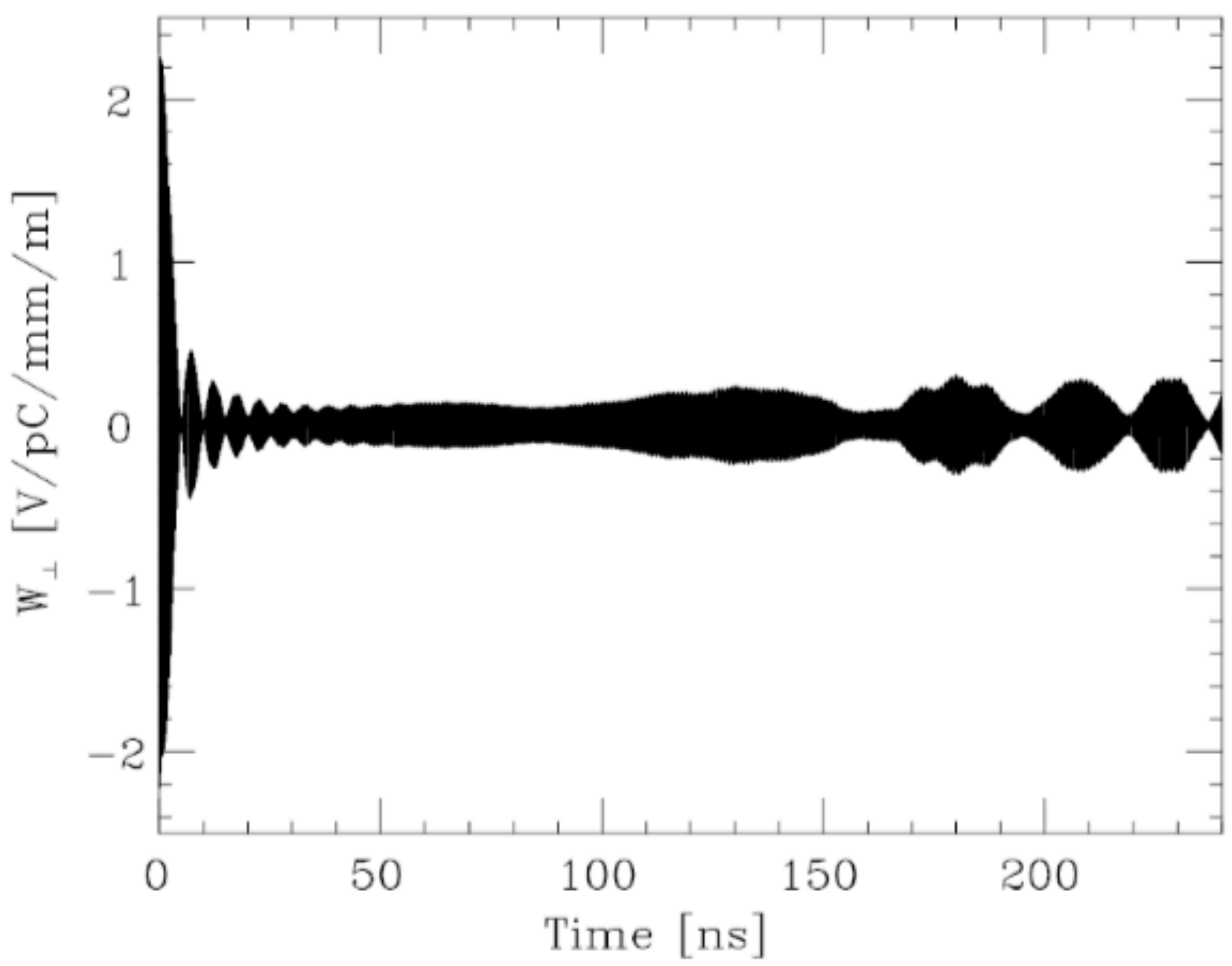


Figure 4.6. Theoretical long-range wakefield calculation of SLAC structure[28].

F.J. Decker et al.., “Long-Range Wakefields and Split-Tune Lattice at the SLC”, SLAC–PUB–7259, 1996.

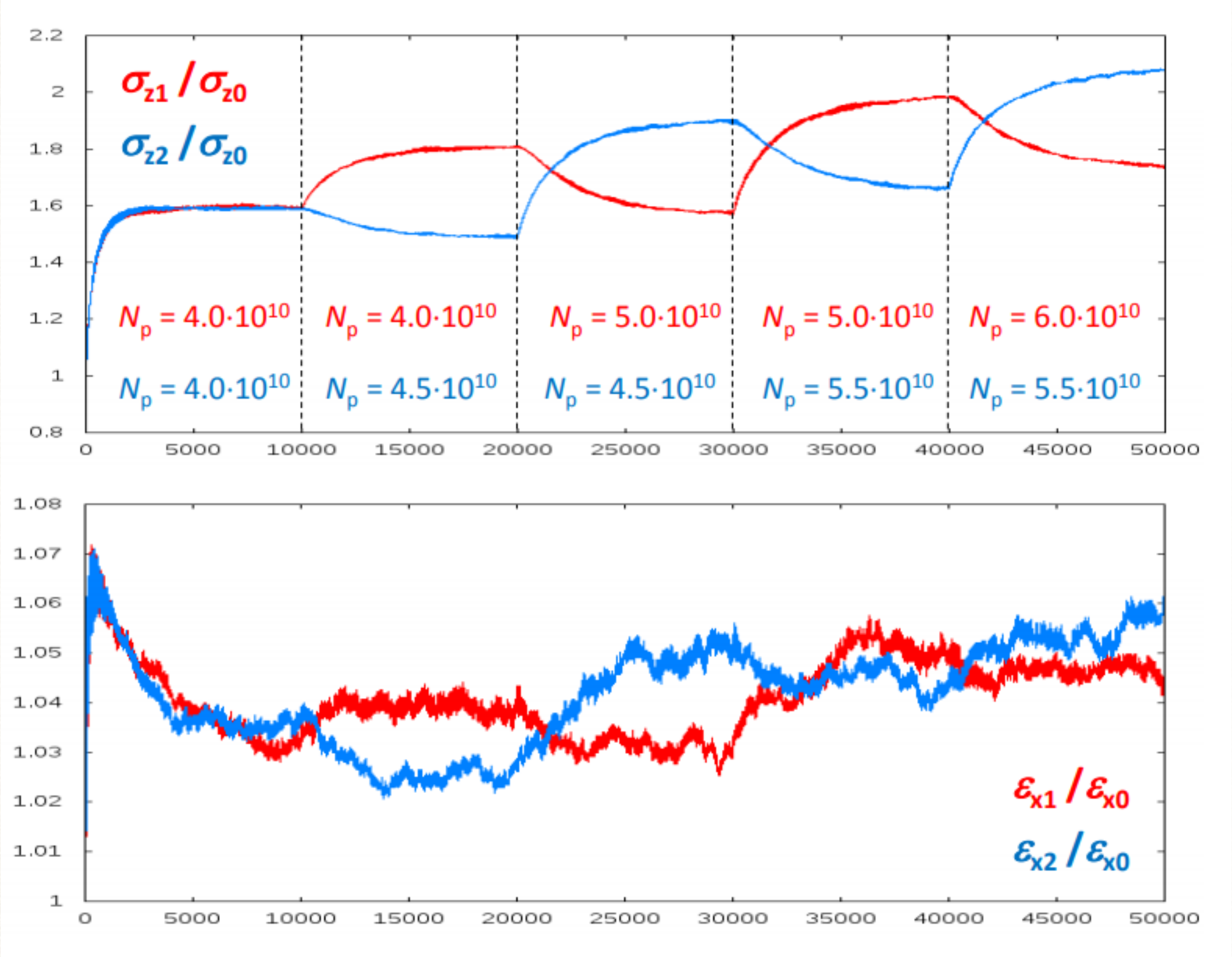
- $\Delta t \gtrsim 50$ ns is safe to avoid beam breakup due to long-range transverse wake of the S-band accelerating structure.

Injection time for each specie

	Z	WW	ZH	tt
Collider energy [GeV]	45.6	80	120	182.5
Collider & BR bunches / ring	16640	2000	328	48
Collider particles / bunch [10^{10}]	17	15	18	23
Injector particles / bunch [10^{10}]	≦ 3.0 *			
Bootstrap particles / bunch [10^{10}]	1.7	0.9	1.1	1.3
# of BR ramps (to 1/2 stored current)	3	3	3	4
# of BR ramps (bootstrap)	5	7	8	8
BR ramp time (up + down) [s]	0.6	1.5	2.5	4.1
# of PBR cycles	14			7
PBR ramp time (up + flat top + down) [s]	0.5			
PBR bunches / ring	1190	143	24	7
Linac pulses	595	71	12	4
Linac repetition frequency [Hz]	200			
PBR injection time [s]	3.0	0.36	0.06	0.02
Collider filling time from scratch [s]	396.8	135.4	113.7	92.9
Collider filling time for top-up [s]	49.6	13.5	10.3	7.7
Collider interval between top-ups (2 IP) [s]	< 400	< 212	< 44	< 44

* Although electron bunch intensity can be increased up to 4.2×10^{10}, it does not much reduce the injection time, as the bunch intensity is limited by the bootstrap injection anyway.

Bootstrap injection (D. Shatilov)



- The collider is filled with the maximum bunch intensity of the injector up to about a half of the design current. Then the injection bunch intensity is reduced to 10% (Z) or 6% (W,H,tt) of the design intensity of the collider.
- Then a higher bunch intensity in the injector than the baseline does not shorten the injection time so much.

RF Gun

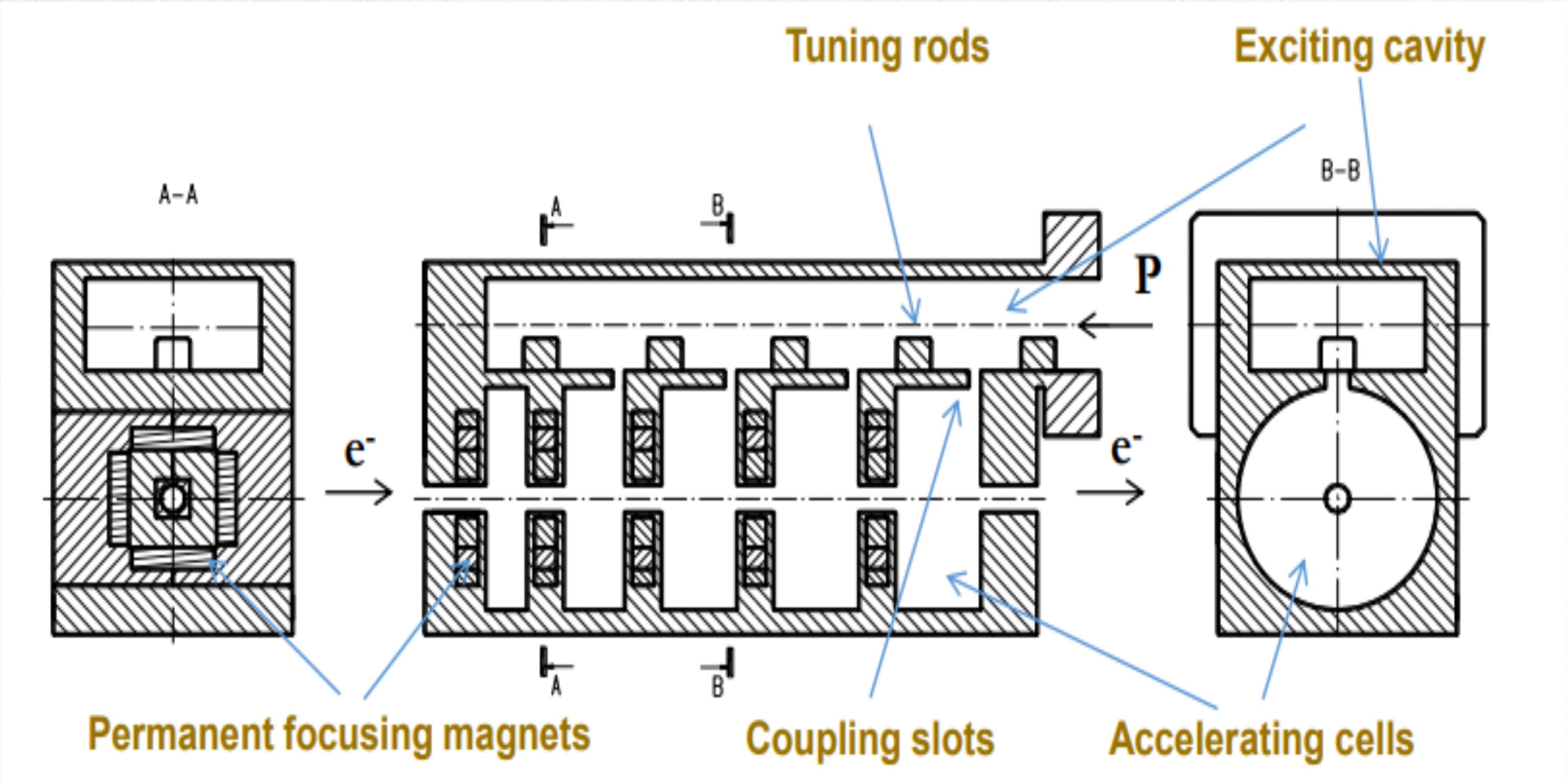


Figure 6.3: A schematic drawing of the RF gun.

Table 6.2: Design parameters of the RF gun.

Parameter	Value
Initial geometrical emittance	0.6 μm
Injection kinetic energy	11 MeV
Total charge	6.5 nC
Cathode spot size	5 mm
Initial distribution	Radially uniform
Laser pulse duration	8 ps
Laser injection phase	variable
Magnetic field on the cathode	0 T
Peak accelerating field	100 MV/m
Focussing solenoid field	0.5 T

I. Chaikovska et al., *Experimental Activities on High Intensity Positron Sources Using Channelling*, Proceedings of the IPAC'17, Copenhagen, Denmark (2017) 2910–2913.

- The RF gun in the CDR can produce 4.2×10^{10} e-/bunch, which generates 3.0×10^{10} e+/bunch via the flux concentrator.
- Higher e- bunch charge > 4.2×10^{10} for e+ production may be possible by a thermal gun, but it will not shorten the injection time due to bootstrap injection.

Flux Concentrator

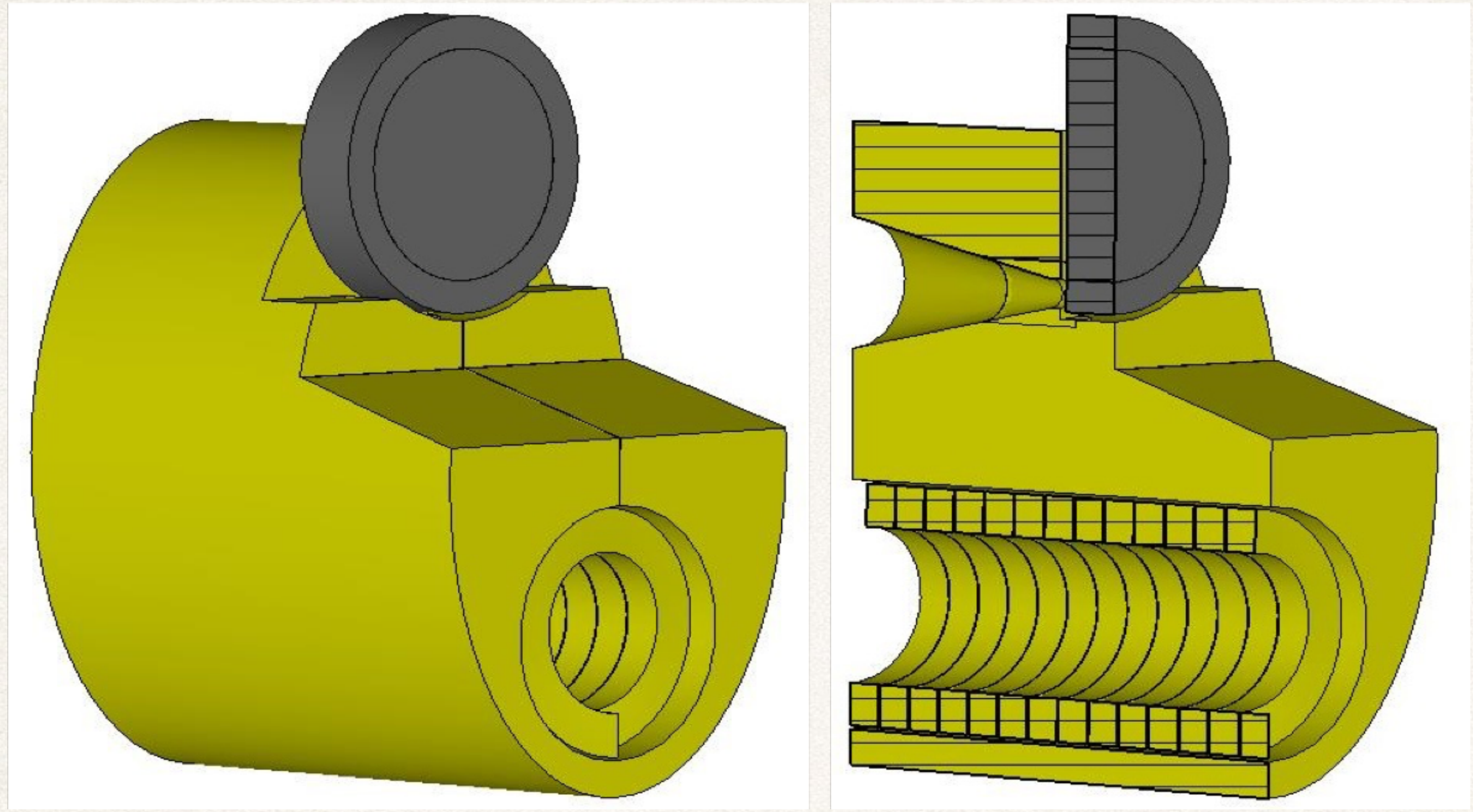


Figure 6.7: Model of the flux concentrator at the FCC-ee e^+ target; parameters are listed in Table 6.9.

Table 6.9: FCC-ee flux concentrator parameters.

Parameter [unit]	Value
Target diameter [mm]	90
Target thickness [mm]	15.8
Gap between target and FC [mm]	2
Grooving gap between target side face and FC body [mm]	2
Elliptical cylinder size [mm]	120×180
Total length [mm]	140
Conical part length [mm]	70
Min cone diameter [mm]	8
Maximm cone diameter [mm]	44
Cone angle [deg.]	25
Cylindrical hole diameter [mm]	70
Coil turns [-]	13
Current profile pulse length [μs]	25
Peak field [T]	7
Peak transverse field [mT]	135–157
Gap between coil turns [mm]	0.4
Gap between coil and FC body [mm]	1
Turns size	9.6×14 mm

P. Martyshkin

Table 6.10: Performance of other positron sources compared to a conventional source for FCC-ee.

Accelerator	SLC	LEP (LIL)	SuperKEB	FCC-ee (conv.)
Incident e^- energy [GeV]	33	0.2	3.3	4.46
e^-/bunch [10^{10}]	3-5	0.5 - 30	6.25	4.2
Bunch/pulse	1	1	2	2
Rep. rate [Hz]	120	100	50	200
Incident beam power [kW]	20	1	3.3	15
Beam size @ target [mm]	0.6 - 0.8	< 2	> 0.7	0.5
Target thickness [X_0]	6	2	4	4.5
Target size [mm]	70	5	14	>30
Deposited power [kW]	4.4	0.1	0.6	2.7
Capture system	AMD	λ/4 transformer	AMD	AMD
Magnetic field [T]	6.8→0.5	1→0.3	4.5→0.4	7.5→0.5
e^+ yield	1.6	0.003	0.5	0.7

Damping Ring

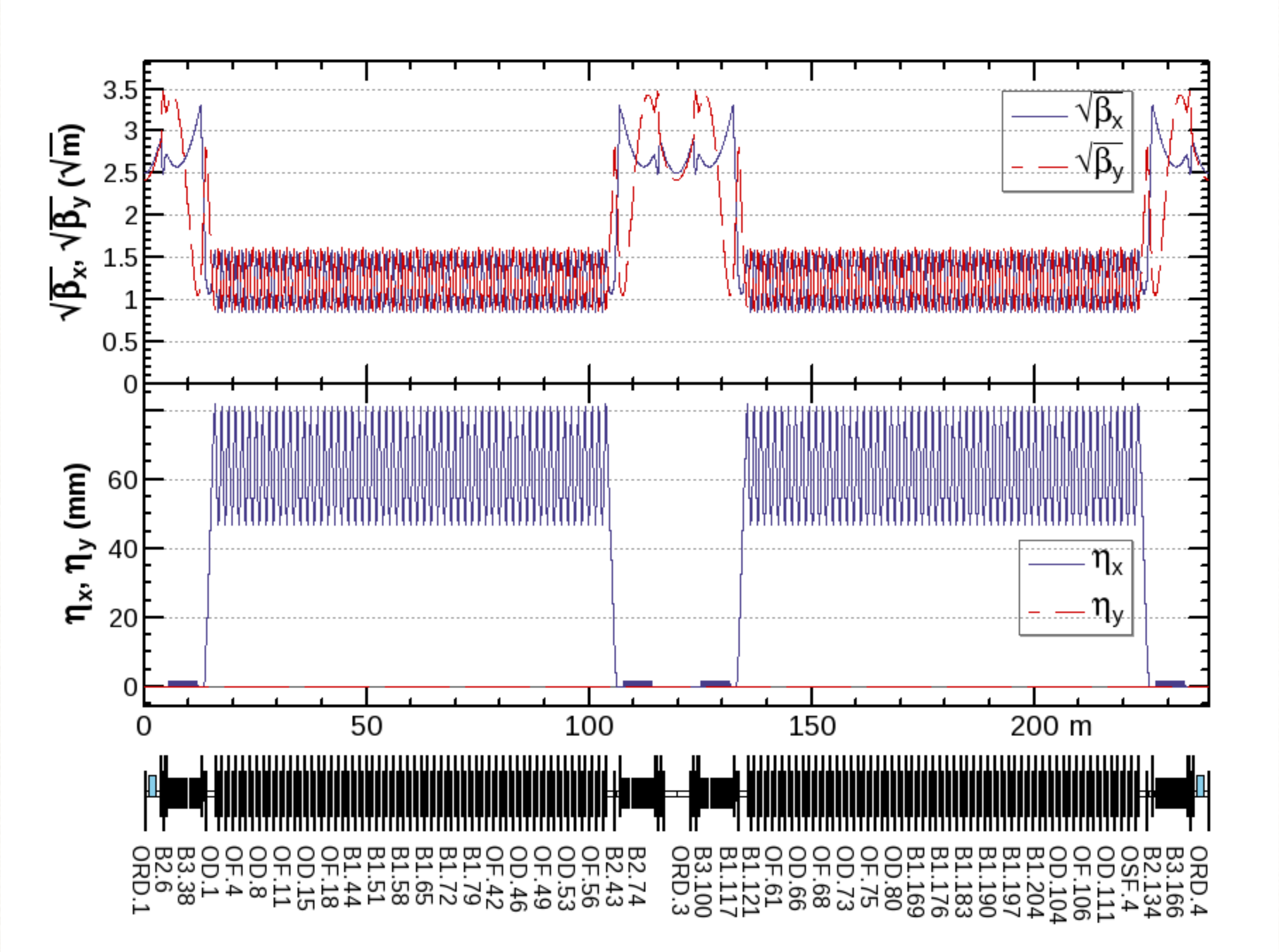


Figure 7.7. Damping ring optics.

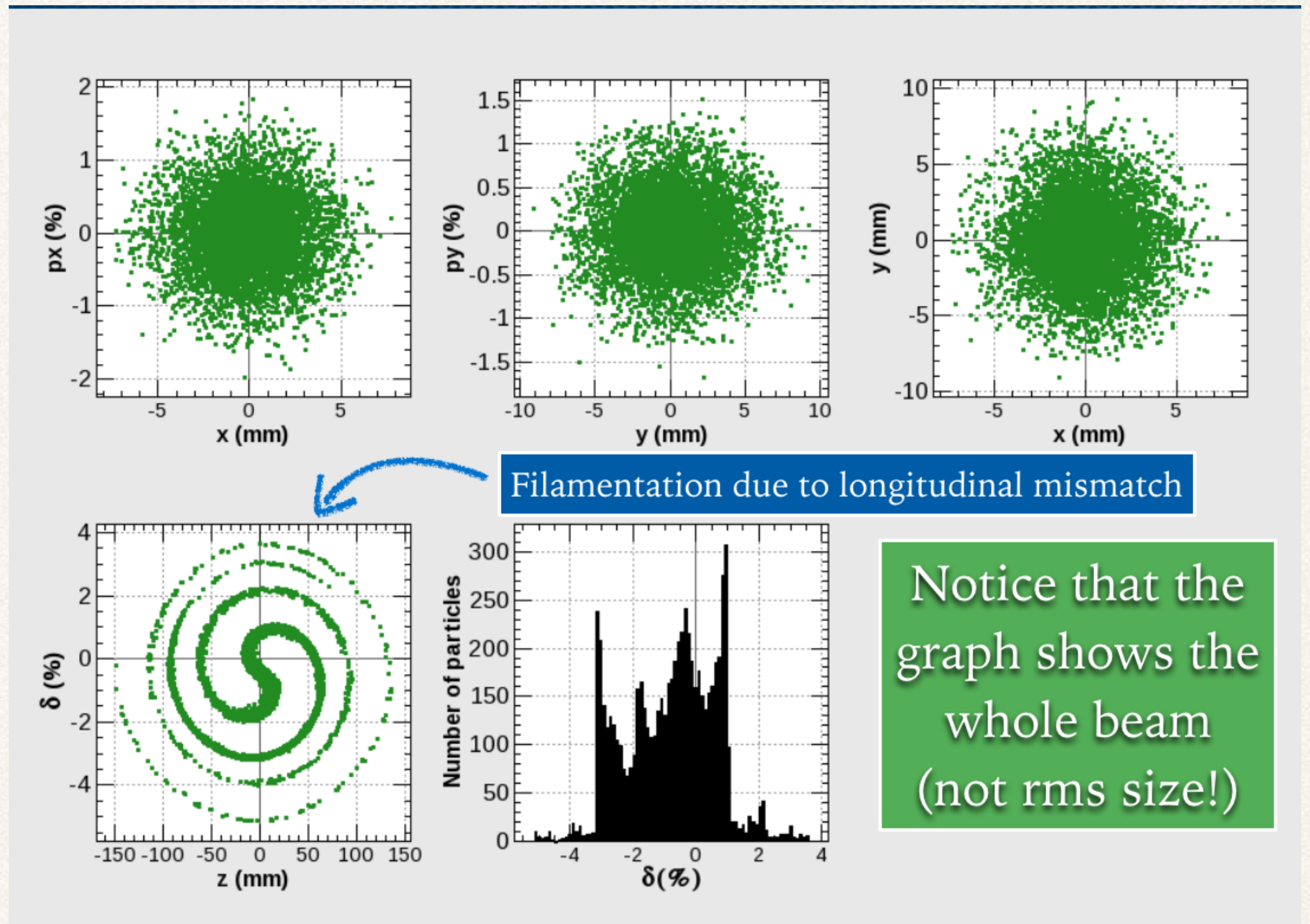


Figure 7.8. DR beam profile after tracking the positrons for 1000 turns with synchrotron radiation cooling.

Table 7.1. 1.54 GeV damping ring generic parameters.

parameter	value
circumference	241.8 m
no. trains, bunches/train	8, 2
train, and bunch spacings	51 ns, 50 ns
train store time	40 ms
energy loss per turn	0.225 MeV
RF voltage, frequency	4 MV, 400 MHz
no. of cells in an arc, cell length	57, 1.54 m
FODO cell phase advance (x, y)	69.5/66.1 deg
betatron tune (x, y)	24.19/23.58 rad
momentum compaction α_c	1.5 $\times 10^{-3}$

- The damping ring captures and damps the huge positron beam from the flux concentrator.
- The dynamic aperture and the momentum acceptance look OK.

S. Ogur, "LINAC AND DAMPING RING DESIGNS OF THE FUTURE CIRCULAR e^+e^- COLLIDER OF CERN"

Bunch compressor between DR and Linac

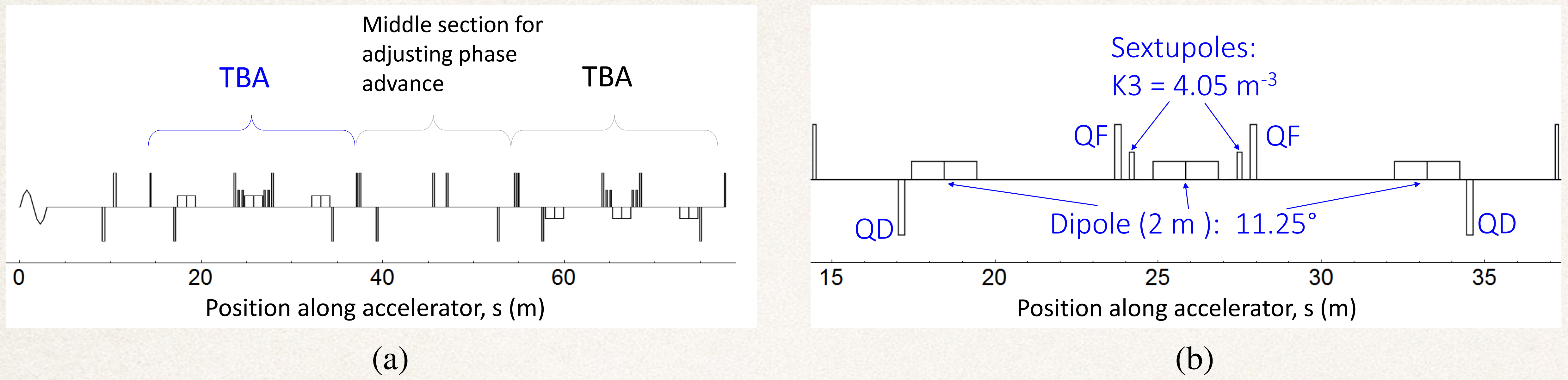


Figure 6.9: (a) Magnet layout of the dogleg bunch compressor. The TBAs are identical except that they bend in opposite directions. (b) Detailed layout of one TBA.

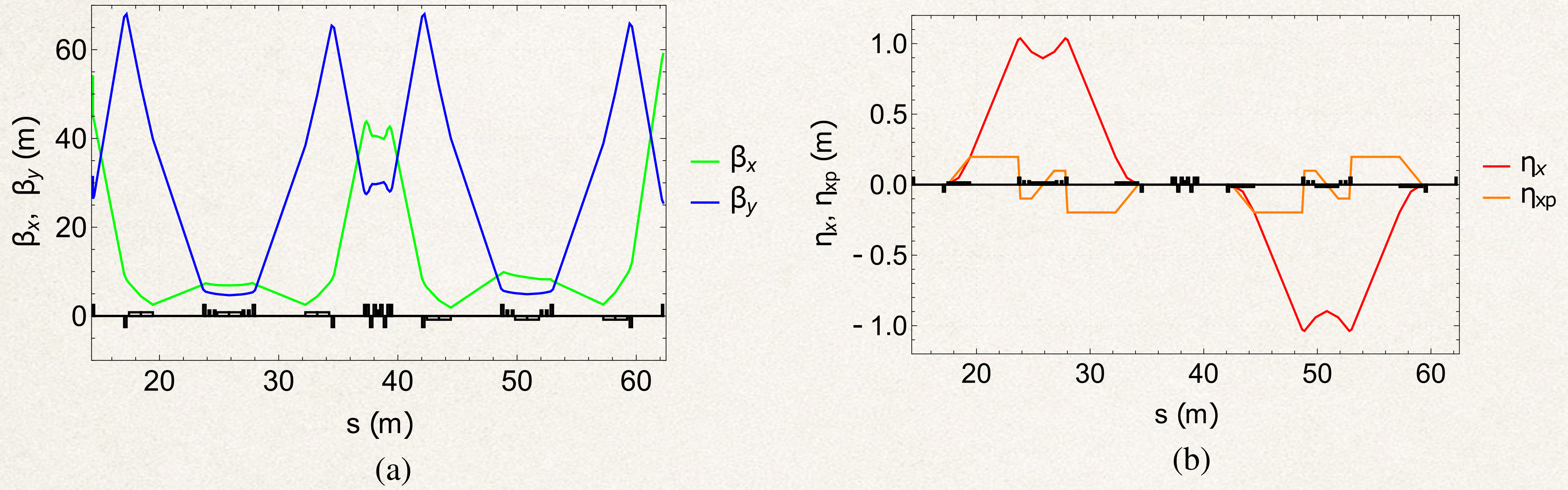


Figure 6.10: (a) Beta functions through the dogleg bunch compressor, where β_x is indicated by the green line, and β_y by the blue line. (b) Horizontal dispersion function, η_x, shown by the red line, and the horizontal angular dispersion function, η_{xp} shown by the orange line.

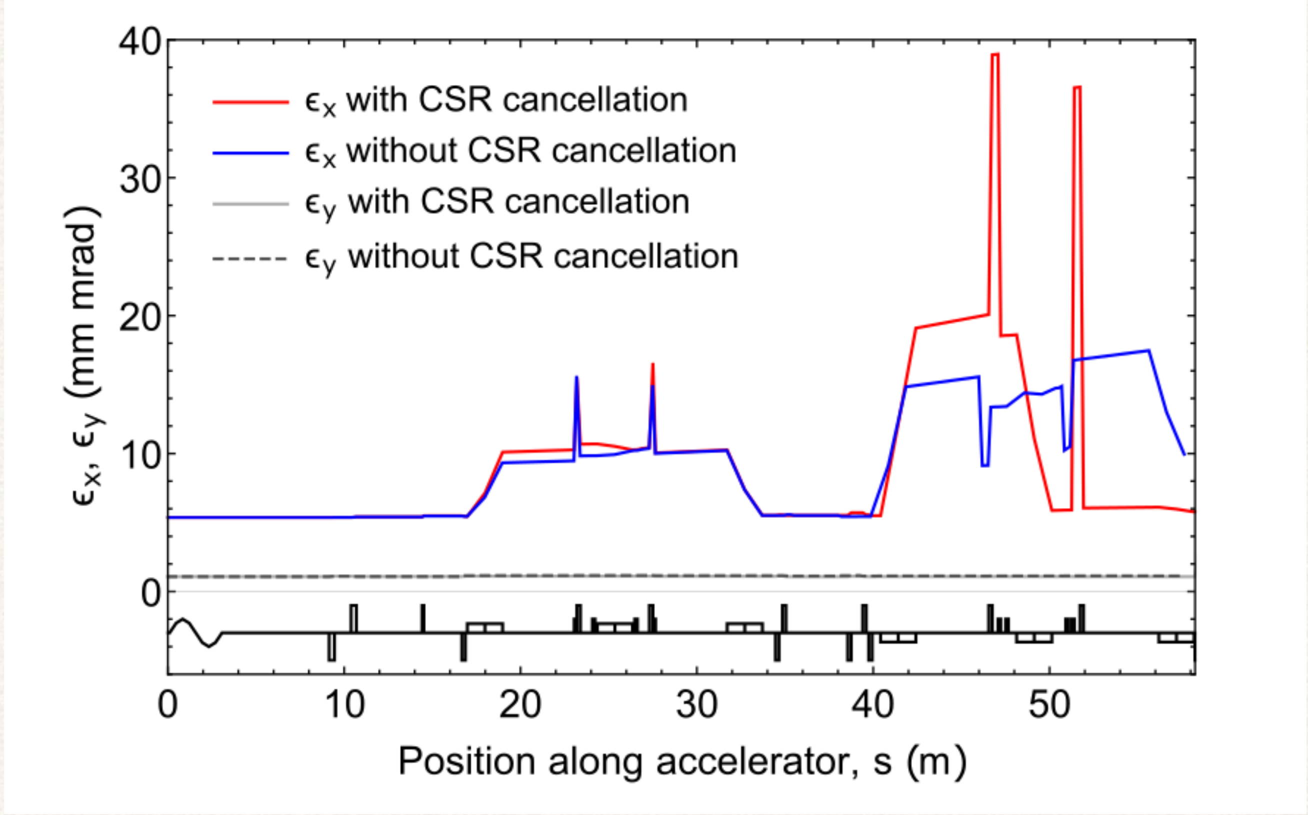


Figure 6.11: Emittance along the bunch compressor, before CSR cancellation techniques are applied (red) and after (blue).

- A bunch compressor has been designed to match the DR bunch the the linac.
- A CSR compensation has been implemented (T.K. Charles).

S-band Linac

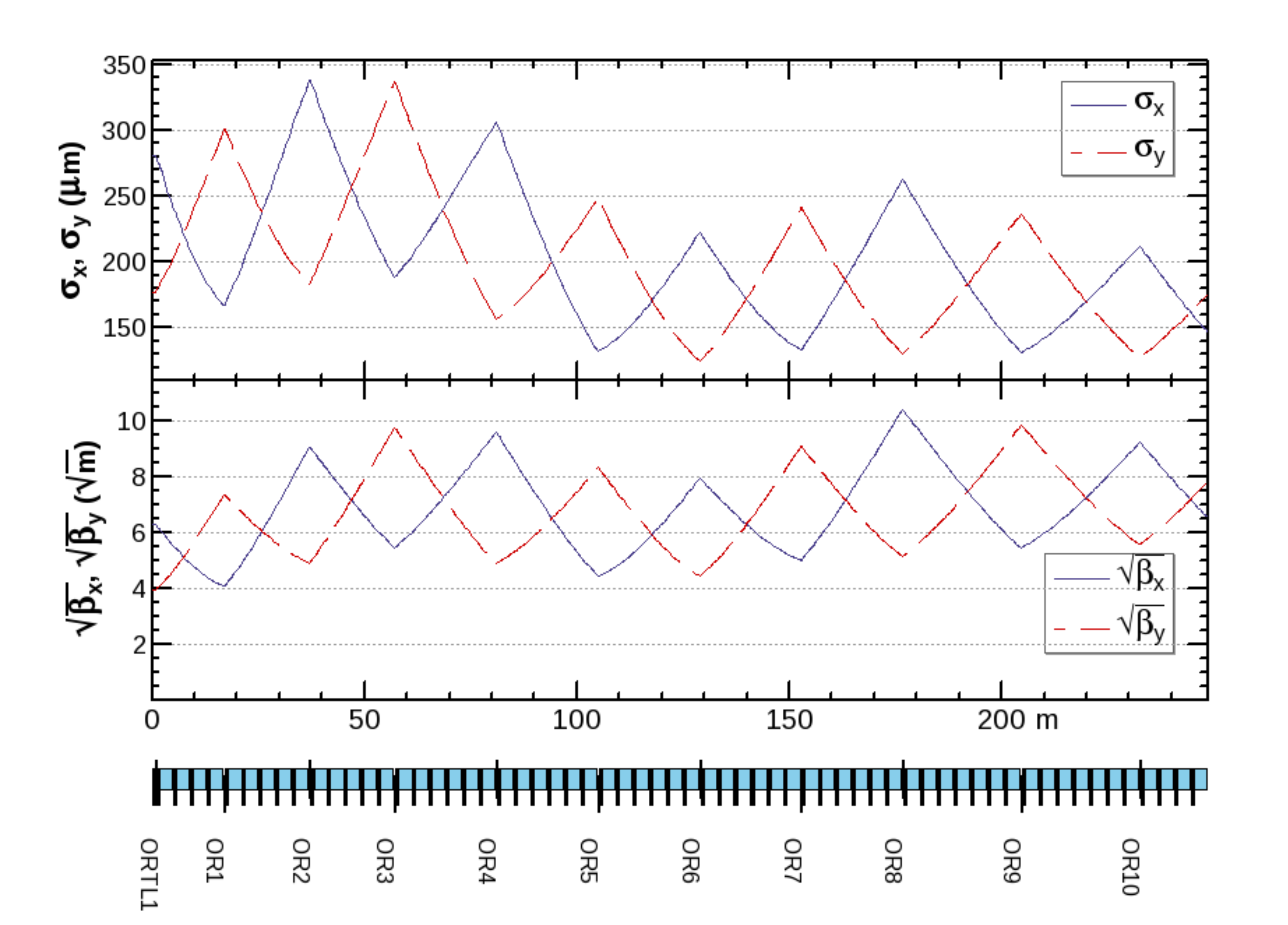


Figure 5.10. Optics of 1.54-6 GeV part of the linac.

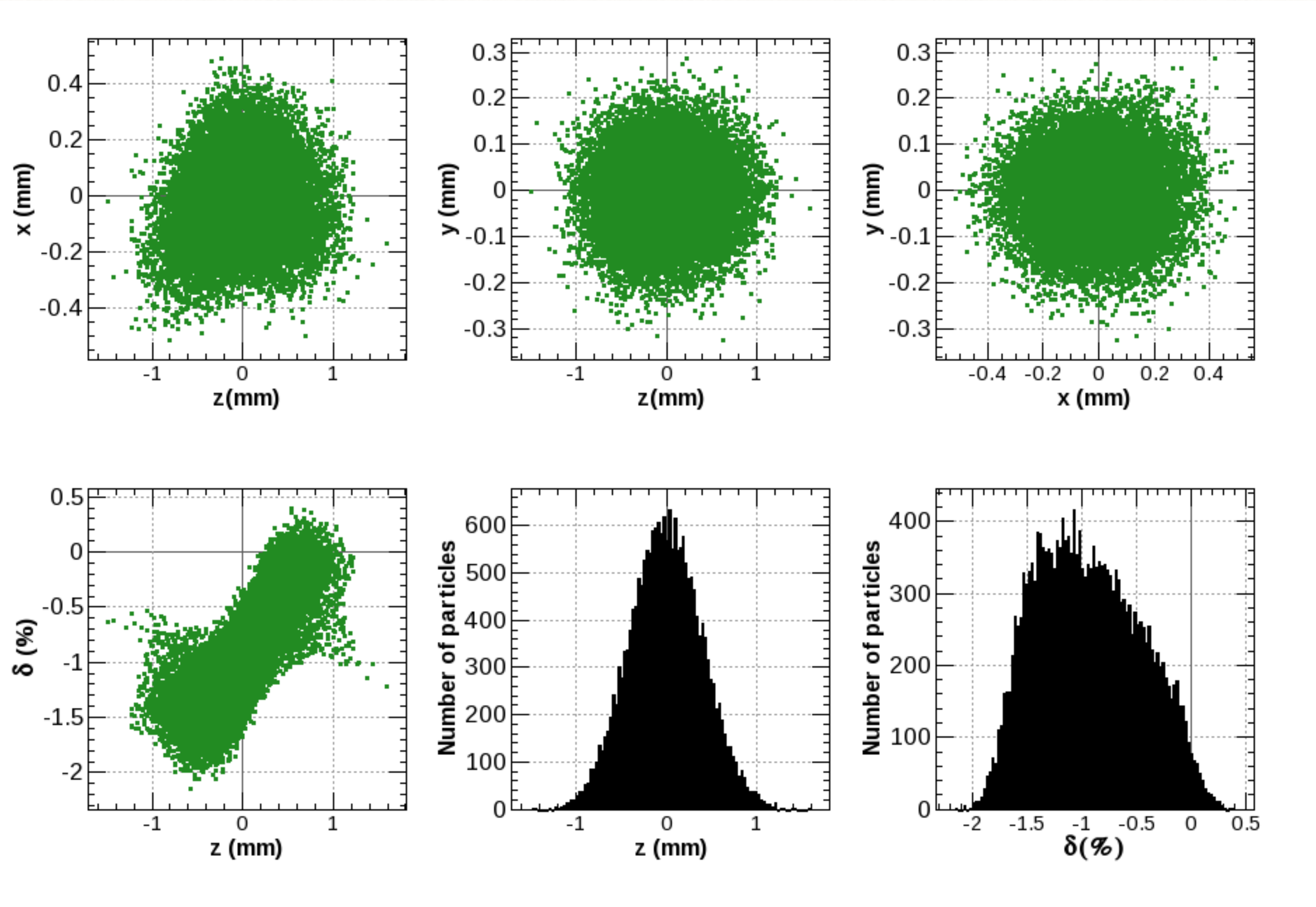


Figure 5.11. Beam Profile of 1.54-6 GeV part linac tracking with the positrons cooled in the DR.

- Beam has been simulated through the S-band Linac with misalignments and corrections, including long./trans. wakes of the accelerating structures.
- The emittance has been well preserved and the transmission reaches 100%.

S. Ogur, "LINAC AND DAMPING RING DESIGNS OF THE FUTURE CIRCULAR e^+e^- COLLIDER OF CERN"

Pre Booster (PBR) and Main Booster (BR)

Table 6.13: SPS Parameters with/without wiggler magnets.

	6 GeV (injection)		20 GeV (extraction)	
	Without wiggler	With wiggler	Without wiggler	With wiggler
ϵ_x (nm)	2.43	0.13	27	10
τ (s)	1.7	0.1	0.04	0.02
U_0 (MeV)	0.15	2.7	19	47

Arc SR loss @ 20 GeV: ~700 W / m (= 19 MeV*0.25 A / 6900 m).

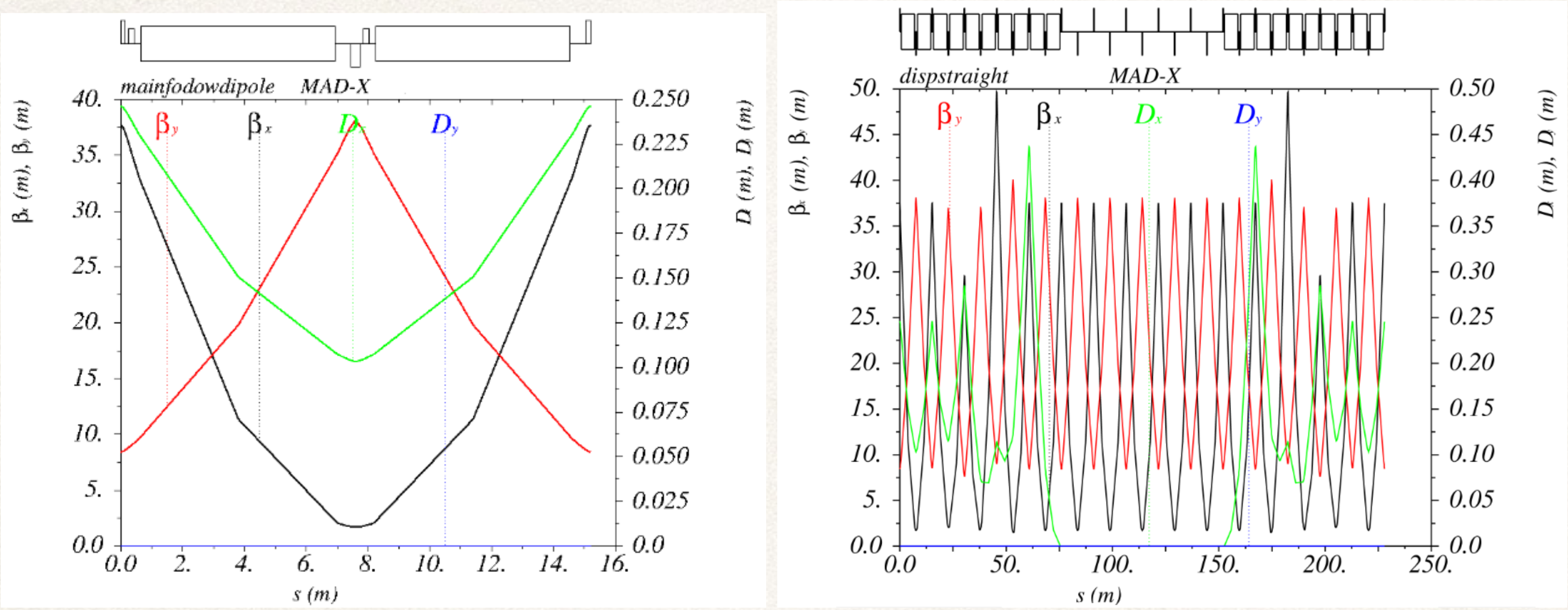


Figure 6.12: Beta functions and dispersion of the main cell (left) and straight section(right).

- PBR & BR designs are shown in the CDR (PBR: see O. Etisken's poster, BR: B. Härer). The lattices are basically done showing enough dynamic aperture for the off-axis injection.
- Further studies are needed for the low magnetic field (BR) and collective effects (see M. Migliorati's and F. Zimmermann's presentations for BR and PBR, respectively).

Table 6.14: Horizontal equilibrium emittances of the booster compared to the collider for all four beam energies. The 60° optics is used for 45.6 and 80 GeV; the 90° optics for 120 and 182.5 GeV.

Beam energy (GeV)	Booster emittance (nm.rad)	Collider emittance (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

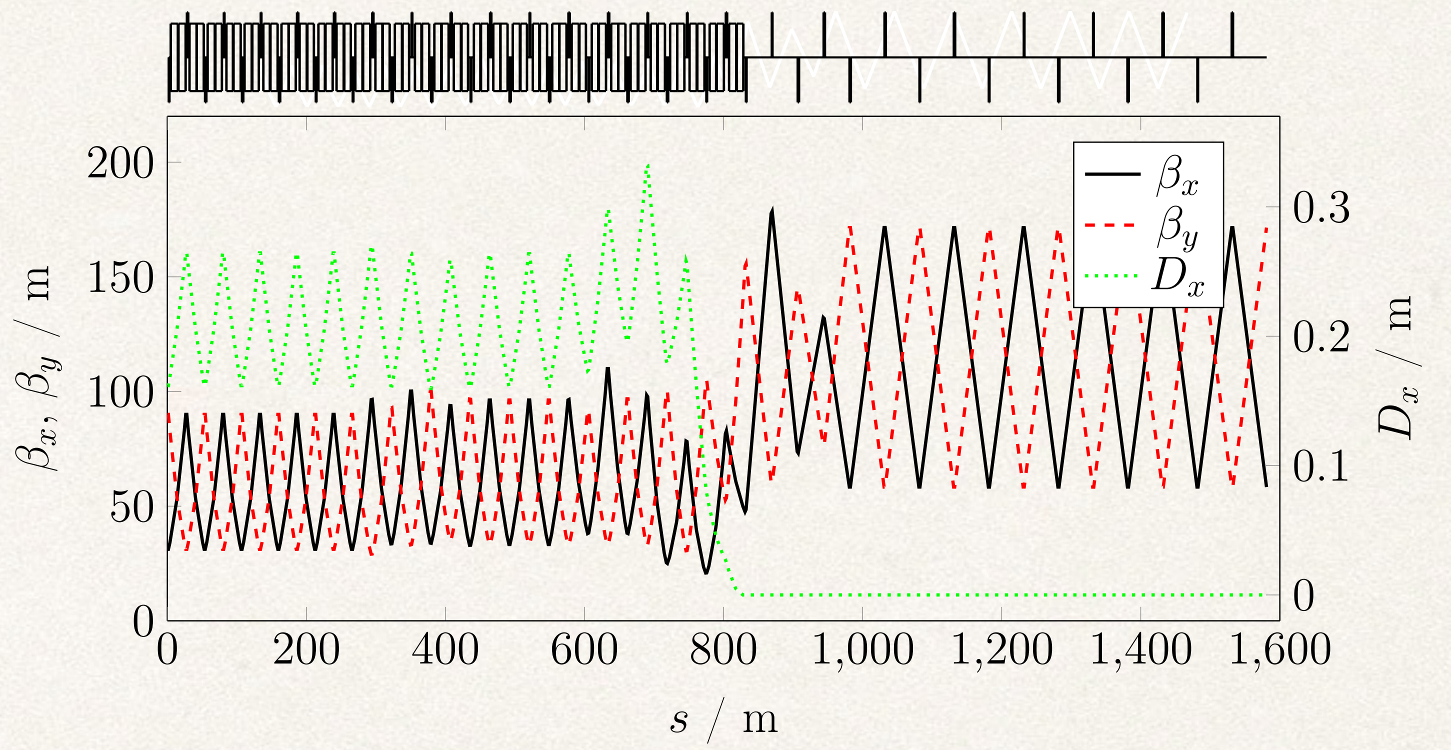


Figure 6.13: Beta functions and horizontal dispersion function of the transition from the arc lattice into a straight section with an RF installation. The first five cells are regular arc FODO cells with a length of 54 m. The following section of 566 m consists of ten FODO cells with a different bending angle to fit the geometry of the dispersion suppressor of the hadron collider. They also serve as quadrupole based dispersion suppressor and matching section to the optics of the 100 m long straight FODO cells.

Table 6.15: Booster cycle parameters.

Parameter	Unit	Z	W	H	$t\bar{t}_1$	$t\bar{t}_2$
Dipole field at injection	G			63.5		
Dipole field at extraction	G	144.8	254.1	381.1	555.6	579.7
Flat bottom duration	s	51.1	11.8	5.0	1.6	1.6
Cycle duration	s	51.7	13.3	7.5	5.5	5.7
Ramp rate up	G/s			254		

Possible options / alternatives

- C-band and/or X-band linac to > 20 GeV, eliminating the PBR.
- Separate linac for e+ to avoid two species in the same linac.
- Choice of RF structure (damped cavity, etc.), gradient, pulse compression scheme.
- An energy compressor before the DR.
- Use the DR also for e-, to mitigate the possible beam breakup in the low-energy section of the DR.
- Variants for the e+ production: hybrid target (see I. Chaikovska's presentation), coherent bremsstrahlung production of polarized e+ (see the poster by A. Apyan), etc.
- Polarized beam.

C-band linac from 6 to 20 GeV

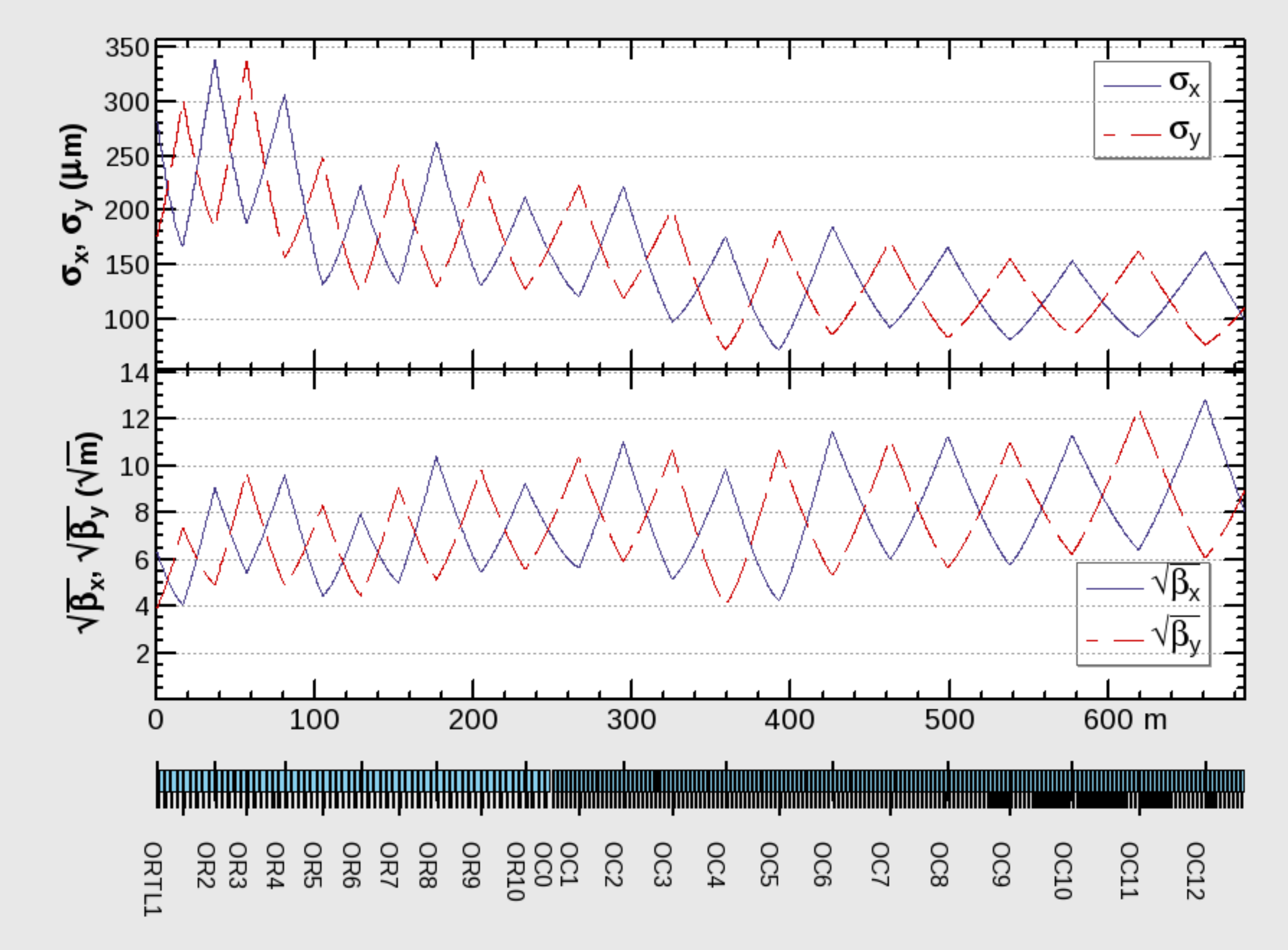


Figure 5.12. Optics of 1.54-20 GeV linac. Notice that the C-band structures start at QC0 where S-band structures ended which corresponds to 6 GeV.

Table 5.7. Some parameters of the 1.54-20 GeV linac.

Parameter	Value
length	685.9 m
number of S-band and C-band cavities	60 and 156
number of quadrupoles in the S-band and C-band sections	12 and 13
RF pulse repetition and bunches per RF pulse	200 Hz and 2 (4*)
injection-extraction energy	1.54 GeV-20 GeV
injected emittance at 1.54 GeV (h/v)	1.9/0.4 nm
final emittance w/o blow up at 20 GeV (h/v)	0.15/0.03 nm
average extracted emittance at 20 GeV (h/v)	1.18/0.05 nm
Transmission for 3.5 nC	100%

*During positron beam delivery.

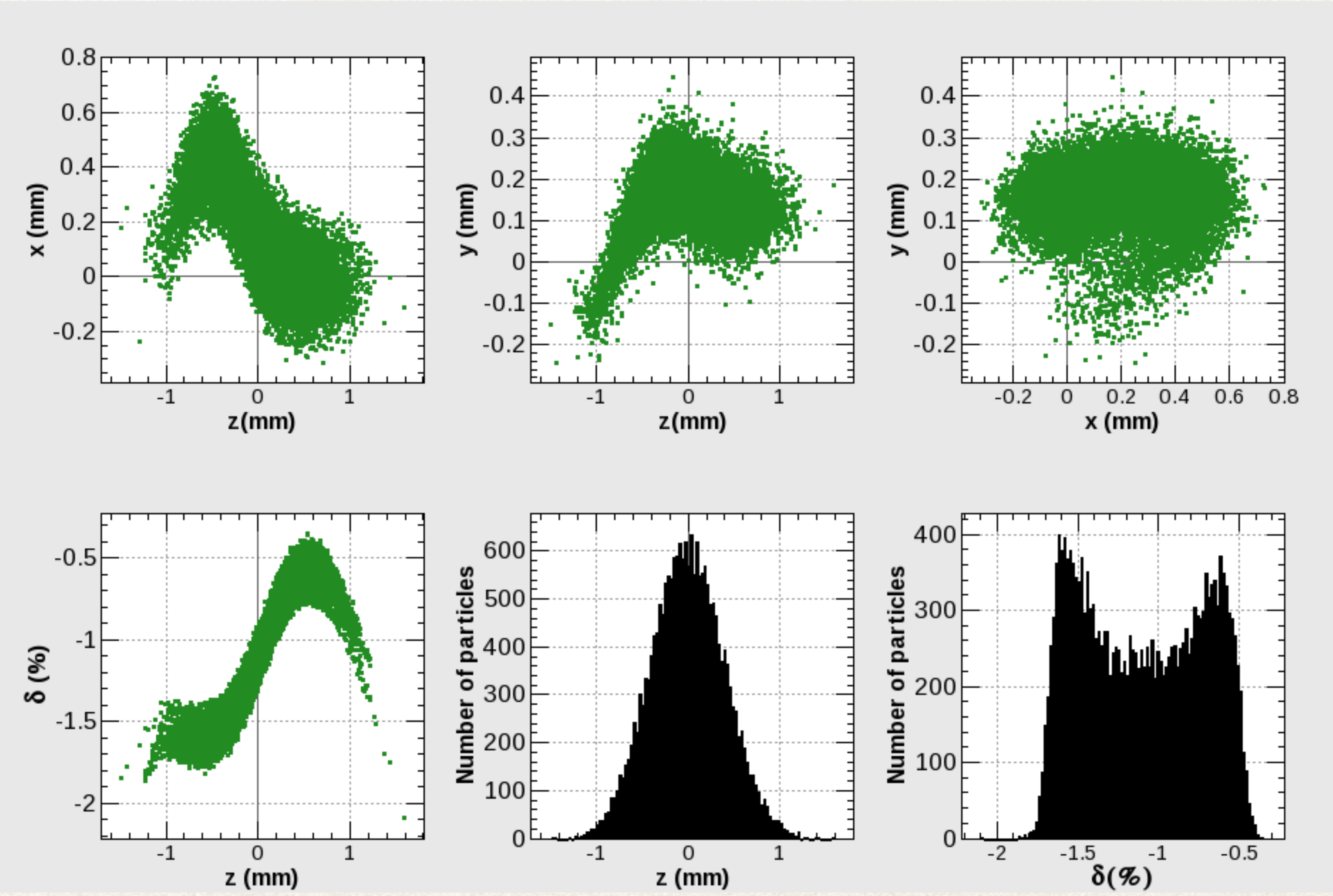


Figure 5.14. Beam Profile of 1.54-20 GeV part linac.

- A design of C-band linac from 6 to 20 GeV was made by S. Ogur for the CDR, showing a good emittance preservation with misalignments and correction.

S. Ogur, "LINAC AND DAMPING RING DESIGNS OF THE FUTURE CIRCULAR e^+e^- COLLIDER OF CERN"

Injection time with 20 GeV Linac

	Z	WW	ZH	tt
Collider energy [GeV]	45.6	80	120	182.5
Collider & BR bunches / ring	16640	2000	328	48
Collider particles / bunch [10^{10}]	17	15	18	23
Injector particles / bunch [10^{10}]	≦ 3.0			
Bootstrap particles / bunch [10^{10}]	1.7	0.9	1.1	1.3
# of BR ramps (to 1/2 stored current)	3	3	3	4
# of BR ramps (bootstrap)	5	7	8	8
BR ramp time (up + down) [s]	0.6	1.5	2.5	4.1
Linac pulses	8320	1000	164	24
Linac repetition frequency [Hz]	200			
BR injection time [s]	41.6	5	0.82	0.12
Collider filling time from scratch [s]	**337.6**	**65.0**	**36.5**	**50.6**
Collider filling time for top-up [s]	**42.2**	**6.5**	**3.3**	**4.2**
Collider interval between top-ups (2 IP) [s]	< 400	< 212	< 44	< 44

With PBR:

	Z	WW	ZH	tt
Collider filling time from scratch [s]	396.8	135.4	113.7	92.9
Collider filling time for top-up [s]	49.6	13.5	10.3	7.7

Summary

- The baseline scheme for the FCC-ee injector complex has been introduced, basically along the CDR.
- The design is based on technologies already experienced at SLC, SuperKEKB, and other machines.
- The design matches the requirements for the collider performance.
- Options and alternatives are going to be studied in several parts: high-energy linac extension, e+ production, separate linac, etc.