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& on behalf of the FCC-ee Injector Team†

Overall Injection Strategy for FCC-ee

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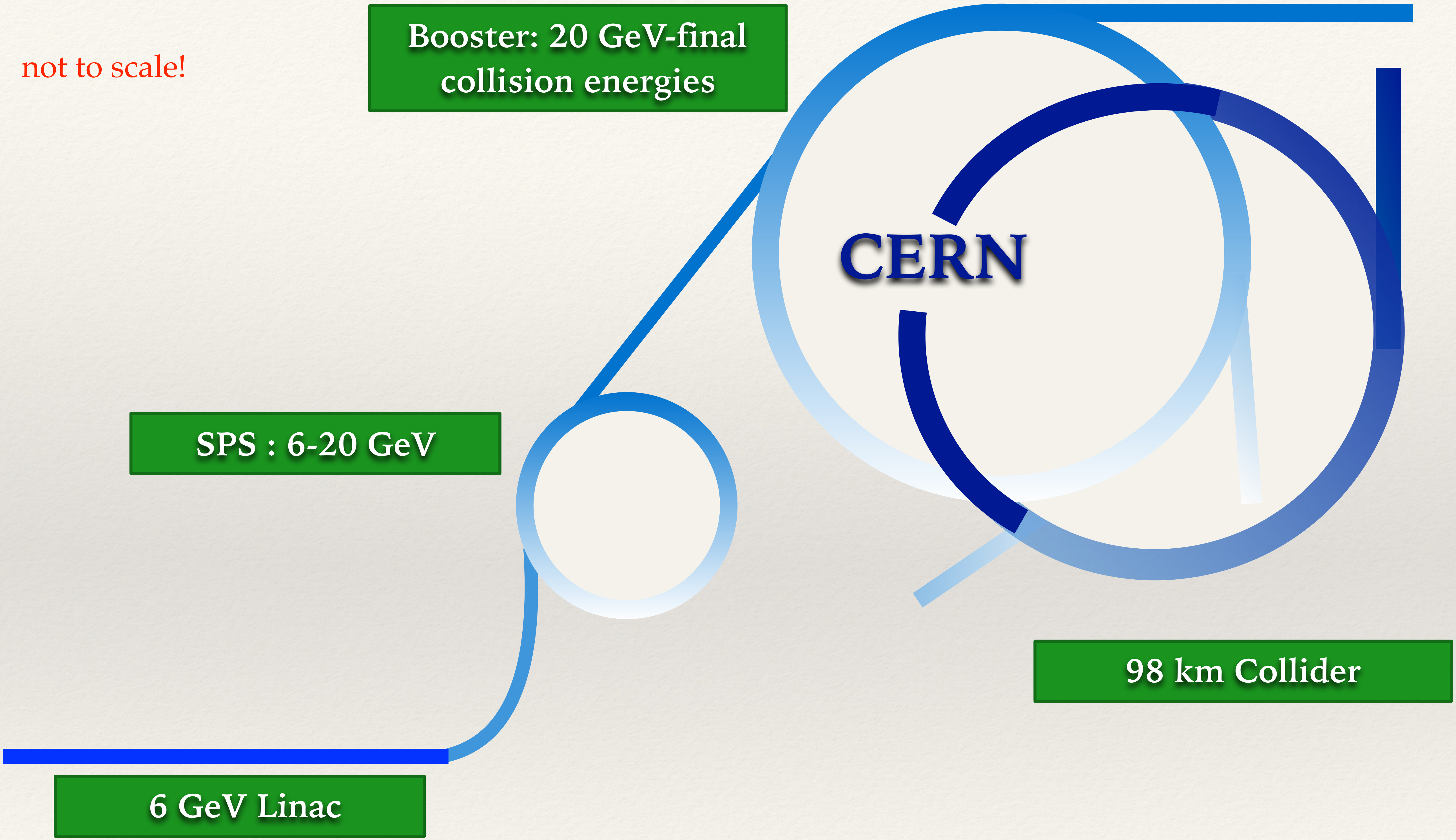
Outline

1. Overview
2. Linac
   - S-Band (up to 6 GeV)
   - C-Band (6-20 GeV)
3. Damping Ring
   - Positrons
4. Pre-booster Synchrotron (6-20 GeV)
5. Top up Booster (20 GeV - to final collision energies)
6. Fill of the Collider
7. Conclusion

1. Overview of FCCe+e- Complex



2. Linac- Basics

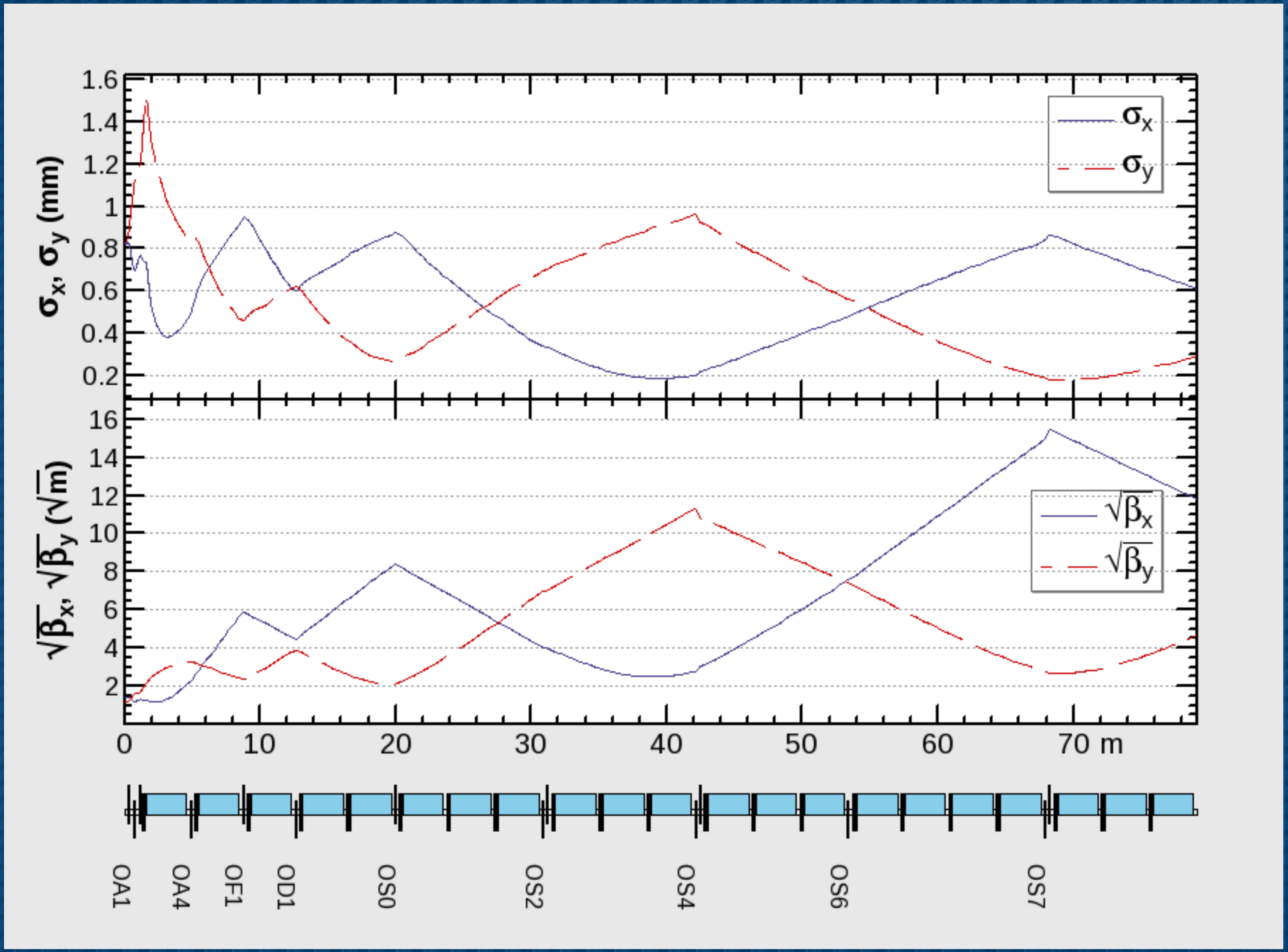
Cavities	S-Band	C-Band
Frequency (MHz)	2855.98	5711.96
Length (m)	2.97	1.8
Cavity Mode	2π/3	2π/3
Aperture Diameter (mm)	20	16
Unloaded Cavity Gradient (MV/m)	25	50

Element	Simulated Error
Injection Offset (h/v)	0.1 mm
Injection Momentum Offset (h/v)	0.1 mrad
Quadrupole Misalignment (h/v)	0.1 mm
Cavity Misalignment (h/v)	0.1 mm
BPM’s Misalignment w.r.t. Cavity (h/v)	30 μm

- Field errors are ignored, because we can always perform QuadBPM method in the linac throughout operation. The wakefields [K. YOKOYA] are ON.
- Space charge is included in the RF-Gun simulations and in the first 75 MeV part of the linac.

2.1 Linac up to 1.54 GeV

❖ An S- Band Linac has been simulated starting from an RF- Gun which provides a 2E10 particles* in a bunch at 10 MeV with 0.35/0.5 μm of geometric emittance (i.e. 8/12 μm normalised). The initial beam is created with 1% energy spread and sigma_z=1 mm Gaussian randomly **.



* normally we may need 1.7E10 particles in a bunch, 2E10 is chosen for pre-compensation, and safety.

** Currently, waiting for the macroparticle beam from RF gun simulations.

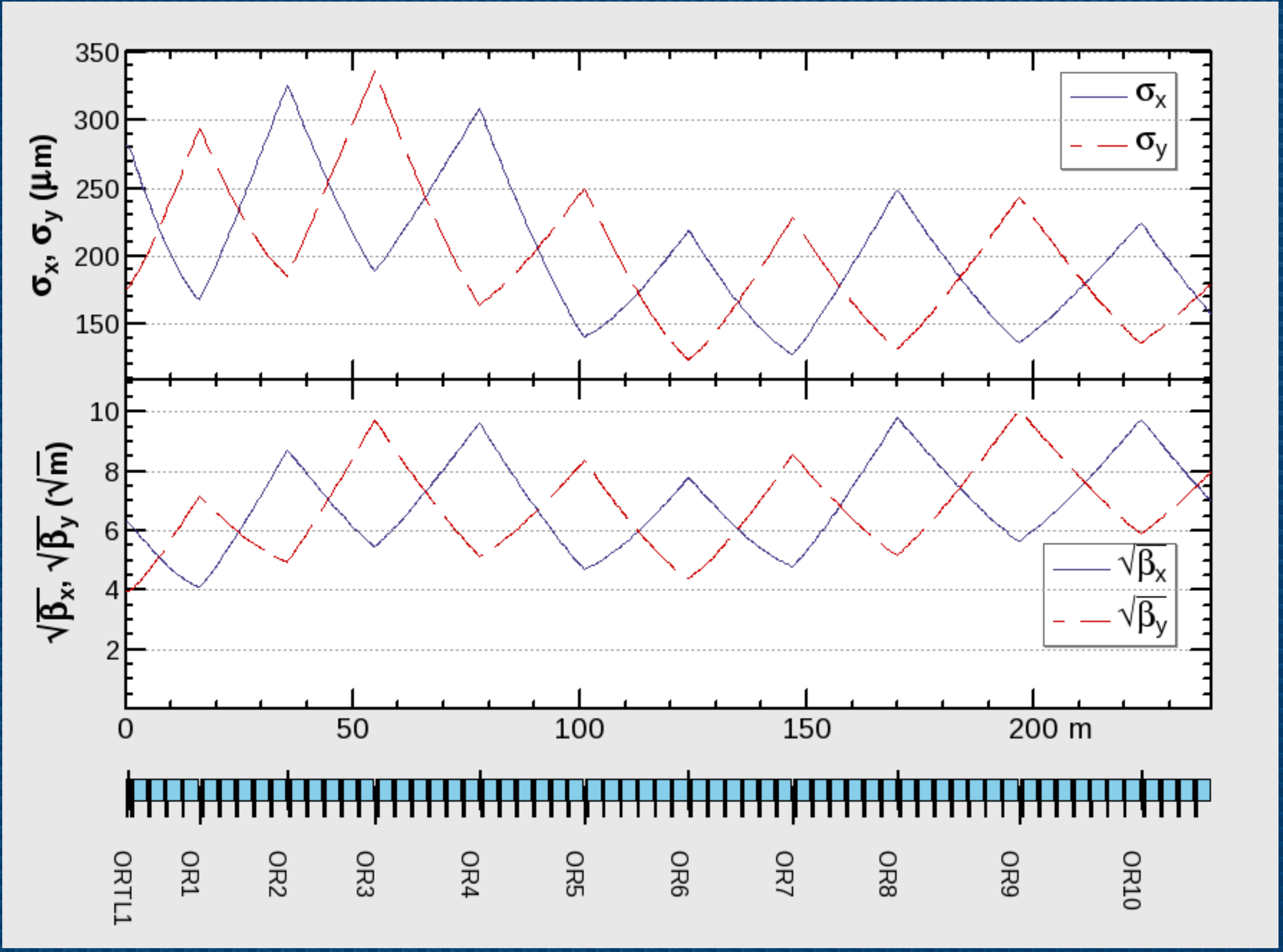
2.1 Linac up to 1.54 GeV

Some results for different seeds using 100k macro-particles for Gaussian random beam are presented below (all misalignments + BPM errors + SPACE charge are included):

Trial ID	Horizontal Emittance (nm)	Vertical Emittance (nm)	Transmission
1	10.4	6.8	100%
2	12.4	4.7	100%
3	9.8	5.6	100%
4	11.6	9.0	100%
5	6.3	4.7	100%
6	16.7	4.9	100%
7	5.7	4.9	100%
8	5.1	9.2	100%
9	11.6	5.2	100%
10	4.7	7.5	100%
11	11.7	4.4	100%
12	6.6	5.4	100%
AVERAGE	**9.4**	**6.0**	**100%**
No-Blow	**2.7**	**3.8**	**100%**

2.2. Linac from 1.54 to 6 GeV

- S-Band structures.

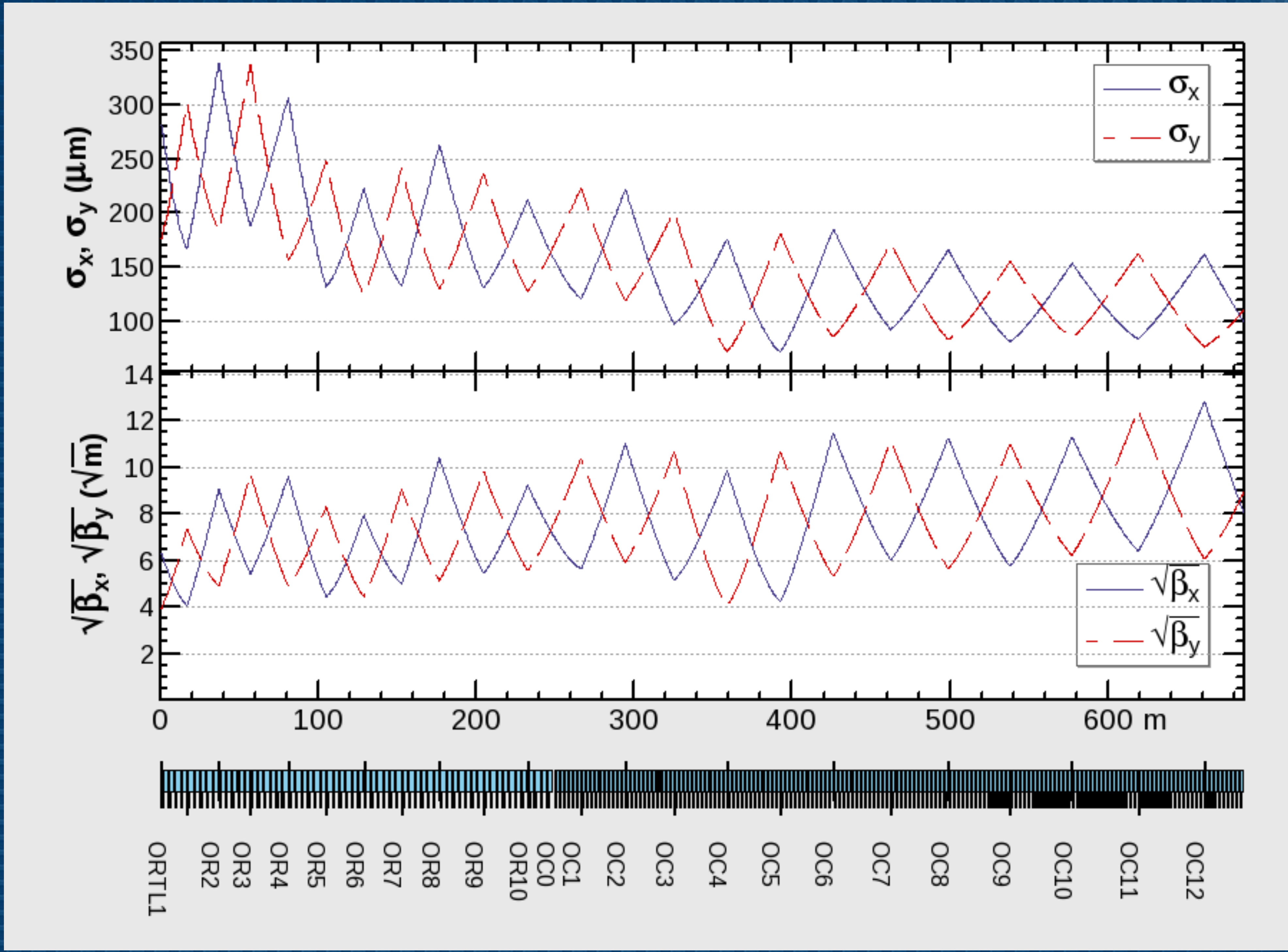


2.2. Linac from 1.54 to 6 GeV

❖ Results with all misalignments including BPM errors.

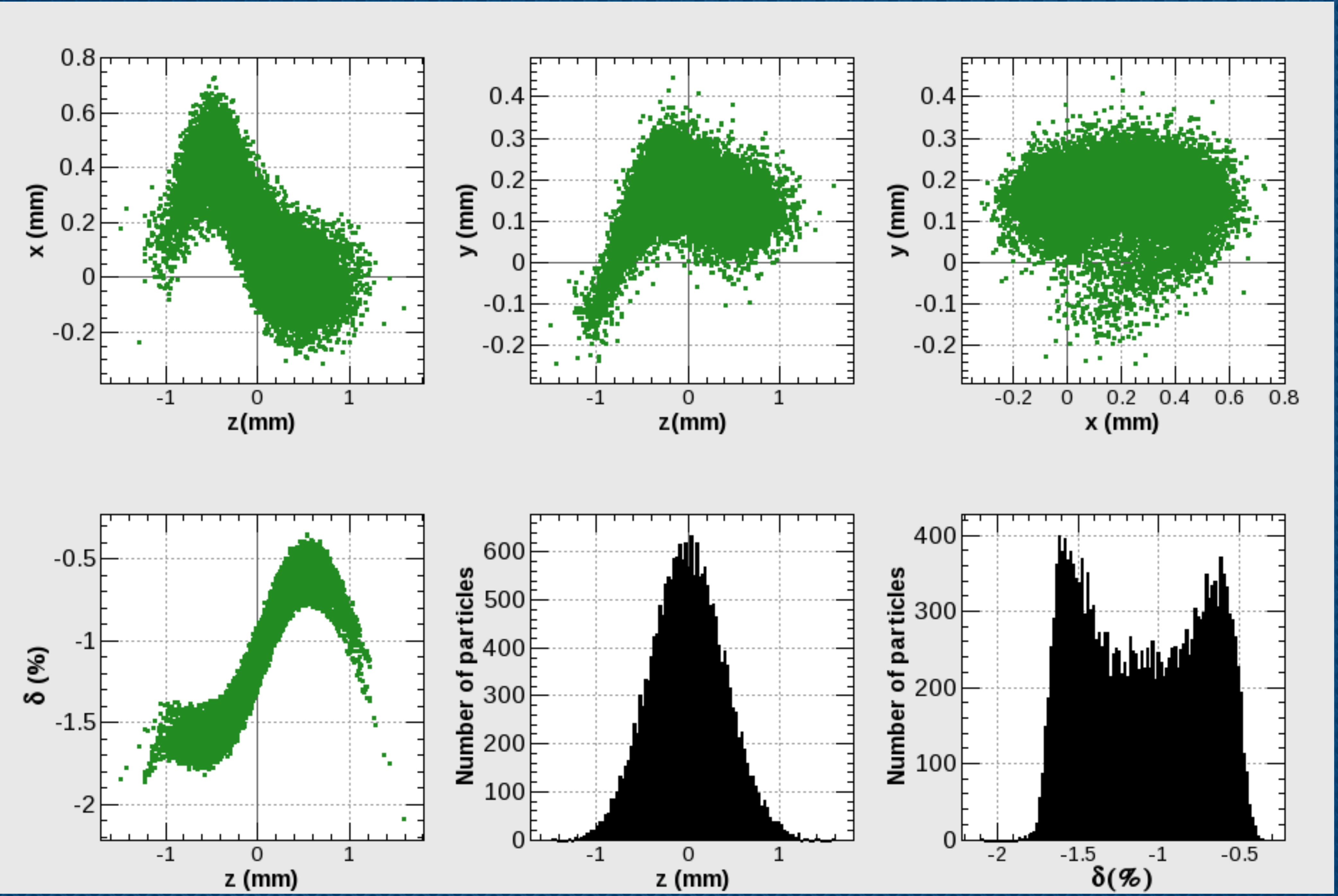
Trial ID	Horizontal Emittance (nm)	Vertical Emittance (nm)	Transmission
1	0.57	0.11	100%
2	0.52	0.12	100%
3	0.49	0.11	100%
4	0.56	0.10	100%
5	0.62	0.12	100%
6	0.53	0.11	100%
7	0.66	0.11	100%
8	0.53	0.10	100%
9	0.52	0.10	100%
10	0.59	0.10	100%
11	0.48	0.11	100%
12	0.54	0.10	100%
Average emit. at 6GeV	**0.55**	**0.11**	**100%**
Emittance without blow-up	**0.48**	**0.10**	**100%**

2.1 Linac from 1.54 to 20 GeV



- ❖ S-Band structures finish at 6 GeV (QC0 in the optics), then C-band structures start.

2.3. Linac from 1.54 to 20 GeV



K. Oide

- ❖ Beam profile at 20 GeV for a random seed.
- ❖ No beam loss has been seen and automatic orbit steering works well.

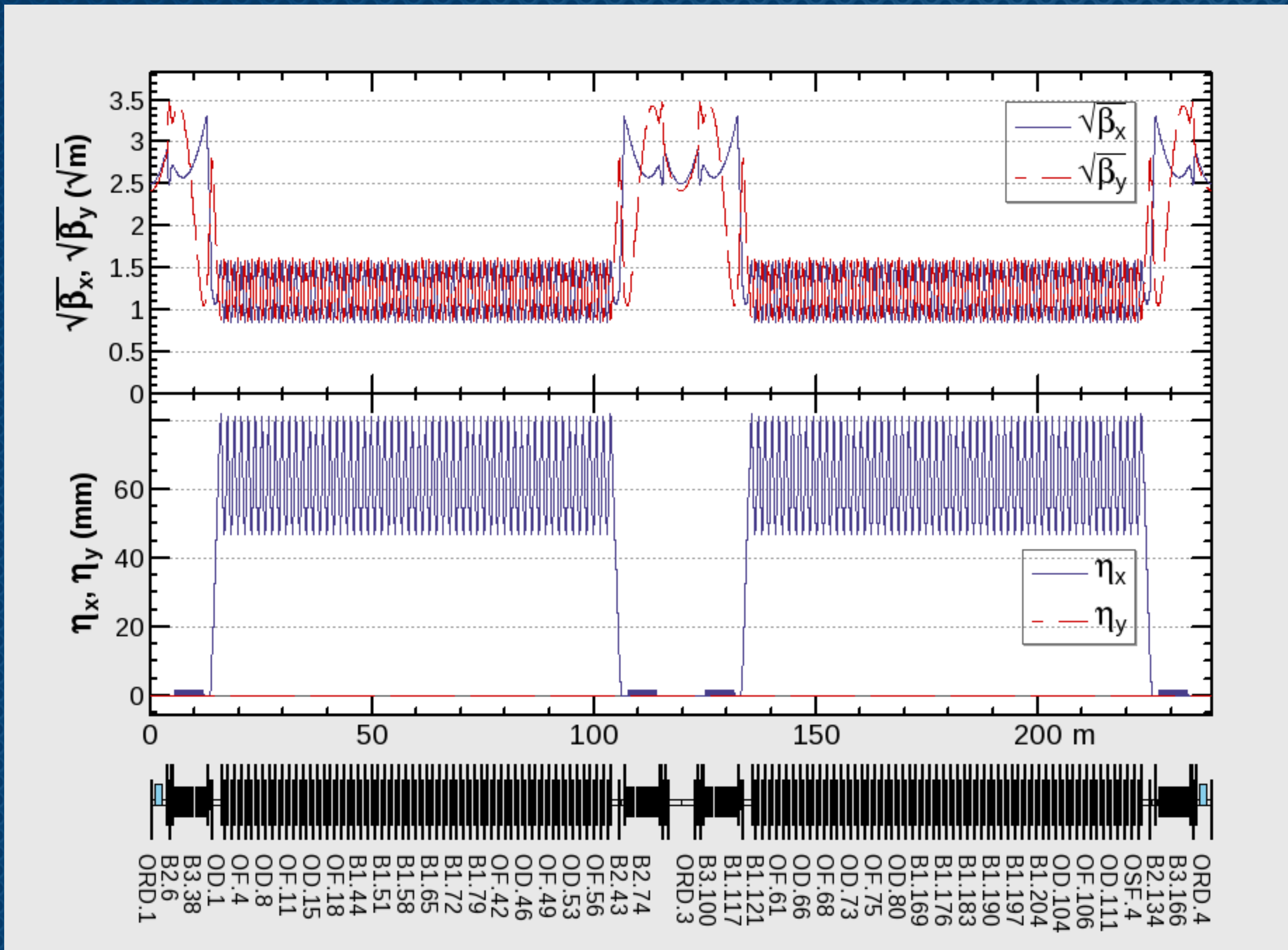
2.3. Linac from 1.54 to 20 GeV

- Some results with all misalignments (including BPM's) for different seeds using the e+ beam simulated through BC and BTL:

Trial ID	Horizontal Emit. (nm)	Vertical Emit. (nm)	Transmission
1	1.23	0.03	100%
2	1.09	0.04	100%
3	1.12	0.08	100%
4	1.18	0.09	100%
5	1.31	0.06	100%
6	1.15	0.05	100%
7	1.22	0.04	100%
8	1.33	0.04	100%
9	1.05	0.05	100%
10	1.15	0.06	100%
11	1.17	0.03	100%
12	1.11	0.03	100%
AVERAGE at 20 GeV	**1.18**	**0.05**	**100%**
Emittance w/o blow-up	**0.15**	**0.03**	**100%**

3. Damping Ring

❖ DR will be used for both species.



Parameter	Value
$\tau_x/\tau_y/\tau_z$	10.5/10.9/5.5 ms
equilibrium emittance (x/y/z)	0.96 nm/- /1.46 μm
circumference	241.8 m
# of cells (FODO w/ sextupoles)	114
dipole field	0.66 T
no. of wigglers, field	4, 1.80 T
betatron tune (x/y)	0.193 rad/0.183 rad
ring tunes	24.189/23.580

❖ The positron bunches have 45 milliseconds, while the electrons have 25 ms to spend in the DR !

3. Damping Ring - Dynamic Aperture

❖ Intrabeam scattering has been included in simulations. In order to overcome emittance blow in horizontal, 20% coupling has been assumed:

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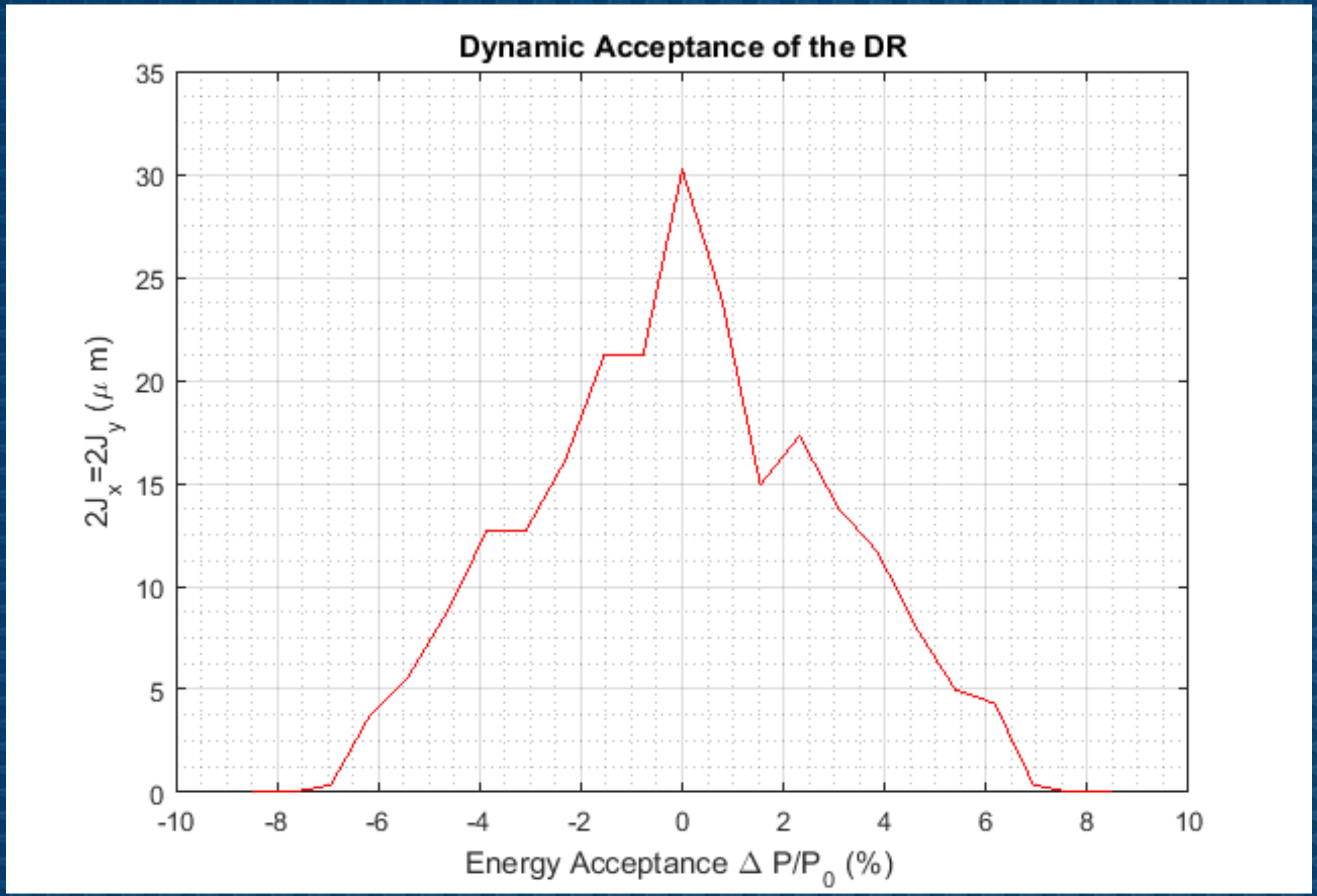
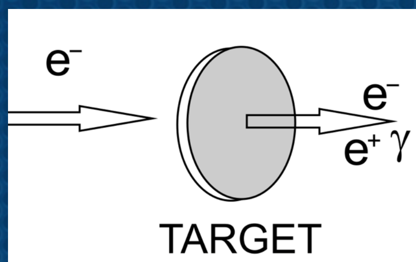


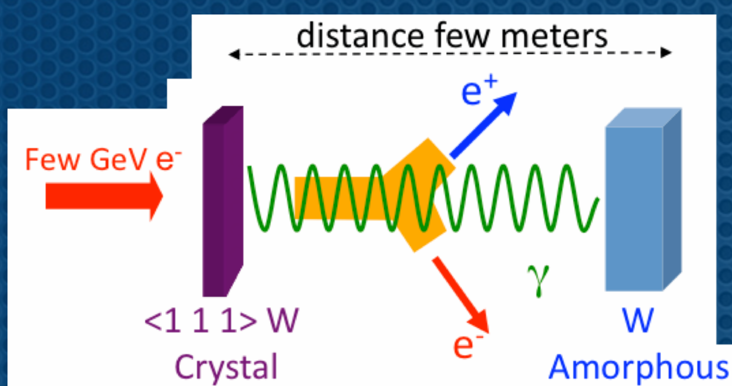
Parameter	Value
equilibrium emittance w/o IBS (x/y/z)	0.96 nm/- /1.46 µm
equilibrium emittance with IBS (x/y/z)	1.38 nm/0.28 nm/1.73 µm

3. Damping Ring - Positrons



1) **Conventional positron target:** bremsstrahlung and pair conversion

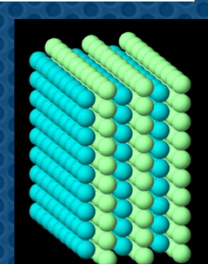
- Classical e+ source.
- It was employed to produce e+ beam at the existing machines (ACO, DCI, SLC, LEP, KEKB…).



2) **Hybrid positron target:** Two-stage process to generate positron beam. Channeling (crystal target) and pair conversion (amorphous target)

- Use the intense radiation emitted by high energy (some GeV) electrons channeled along a crystal axis => *channeling radiation*.
- Charged particles are swept off after the crystal target => the deposited power and PEDD (Peak Energy Deposition Density) are strongly reduced.
- Granular target can provide better heat dissipation associated with the ratio Surface/Volume of the spheres and the better resistance to the shocks.

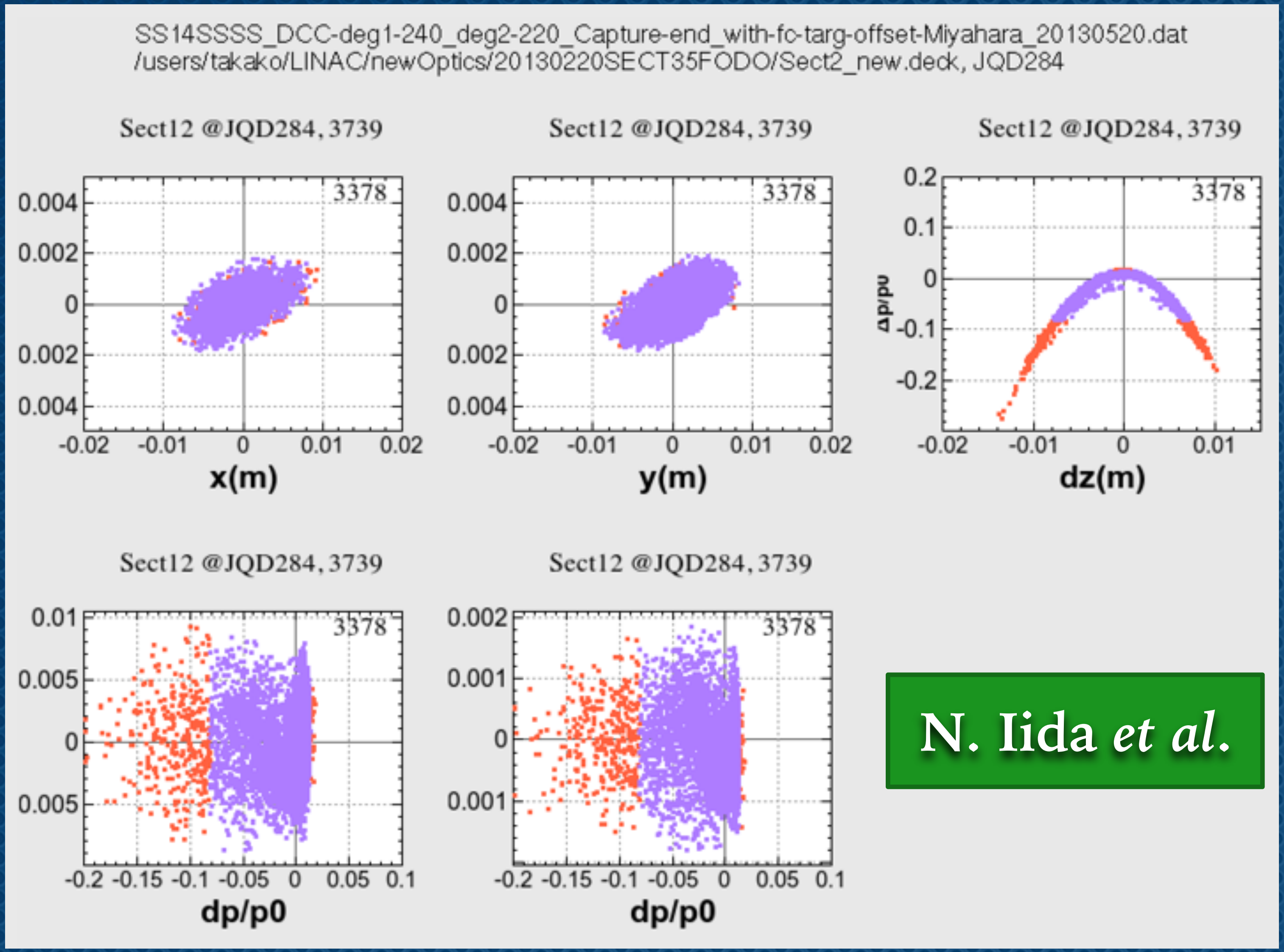
Recent idea: to replace the bulk target-converter by a **granular** one made of **small spheres**.



Several experiments had been conducted to study the hybrid e+ source (proof-of-principle experiment in Orsay, experiment @ SLAC, experiment WA 103 @ CERN and experiments @ KEK).

I. Chaikovska, R. Chehab, P. Martyshkin

3. Damping Ring - Positrons



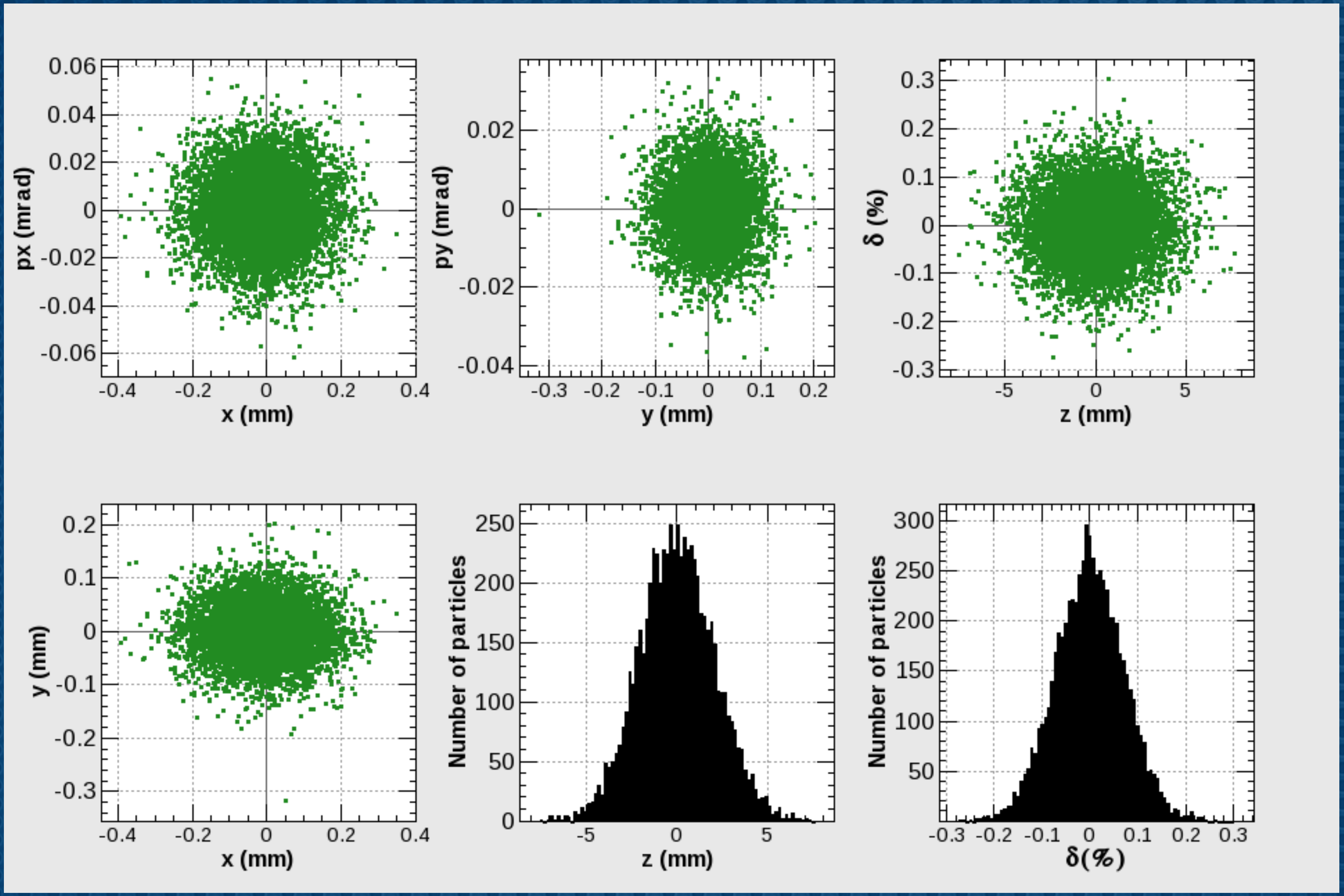
➡ The purple particles are safely injected into the DR. The orange particles are cut by the collimators at LTR because they can not enter the separatrix of DR.

✓ KEK collimates e+, and inject the beam left with ±5% energy spread into the energy compressor.

✓ However FCC-ee damping ring has about ±7% energy acceptance. Therefore, the collimated beam can directly injected.

3. Damping Ring - Tracking

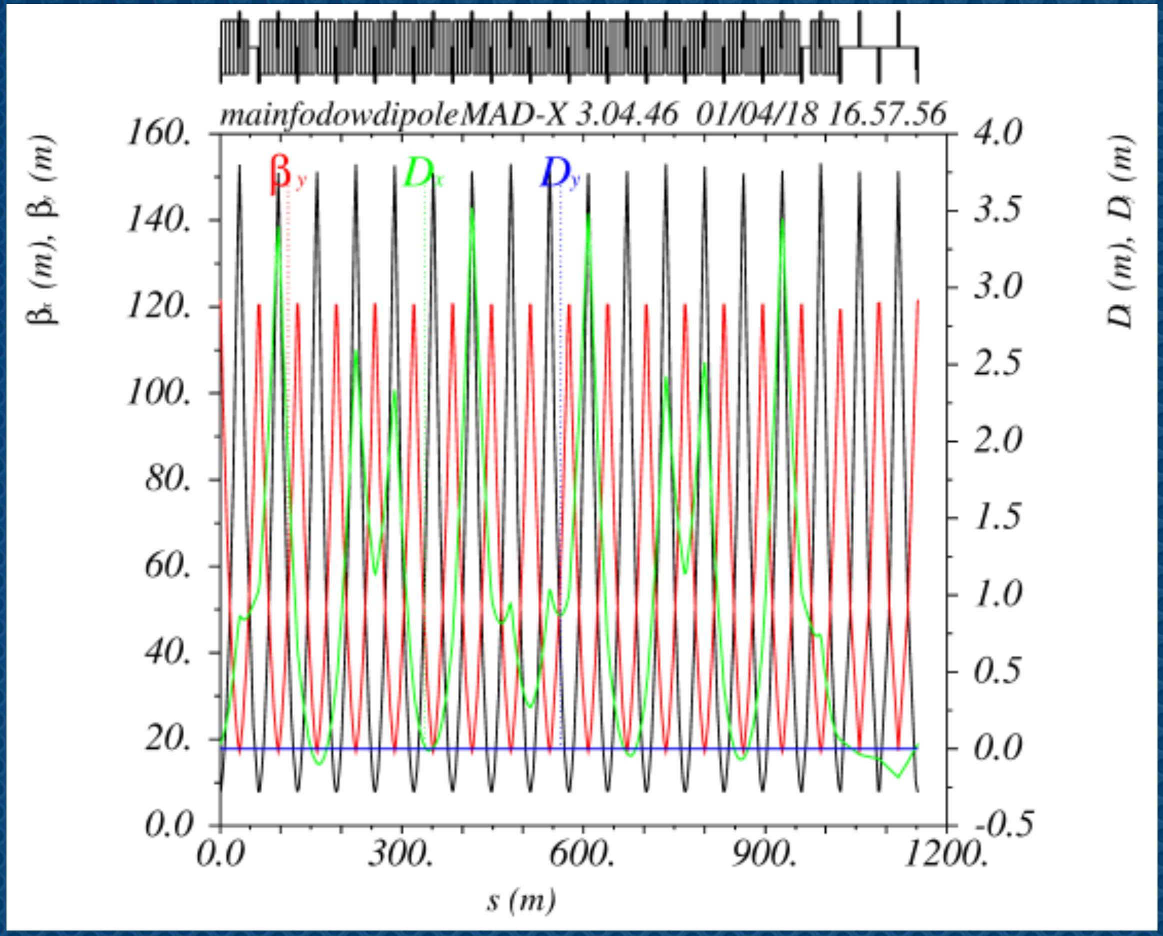
❖ Intra-beam scattering is assumed, the misalignment and error study has not been done yet.



Parameter	Value
Injected positron emittance (x/y/z)	1.26 μm/1.21 μm/75.5 μm
Extracted positron emittance (x/y/z)	1.48 nm/0.38 nm/1.48 μm

4. Pre-booster - SPS

- Using the SPS as pre-booster for the FCC-e^+e^- injector chain imposes various constraints, as minimum modifications can be applied to the existing machine. The SPS is constructed by FODO cells and the dispersion suppression is achieved by keeping the total arc phase advance a multiple of 2π. Main targets for this study is to reduce the emittance to 5 nm.rad at 20 GeV and shorten the damping time to 0.1 s at 6 GeV.



- SPS, usually tuned to π/2 phase advance for fixed target beams with integer tune of 26 (Q26) and since 2012 to 3π/8 (Q20) for LHC beams and considering even Q22,

- Move horizontal phase advance to 3π/4 (Q40);

- Geometrical emittance with nominal optics @ 20 GeV of about 48 nm.rad
- Natural chromaticities of -71,-39 (from -20,-27)
- Damping times of 1.7 s

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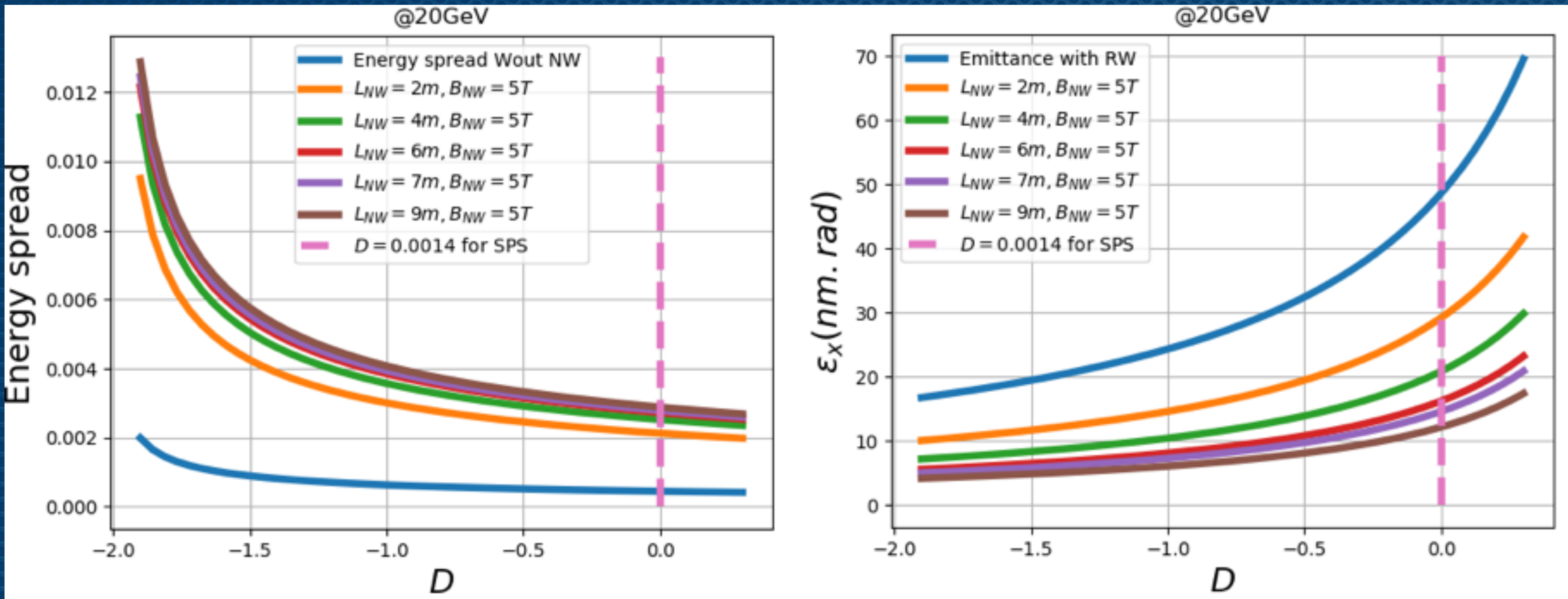
4. Pre-booster - SPS



- In order to keep the energy loss per turn much lower while having the required emittance, **Robinson wiggler** magnet is considered for the SPS. According to the first calculations, the emittance is estimated to reduce to 12 nm.rad from around 48 nm.rad, by using damping wiggler magnet with 9 m and 5 T. It is further reduced to 5 nm.rad by using a Robinson wiggler of 1 to 2 m with around 1 T.

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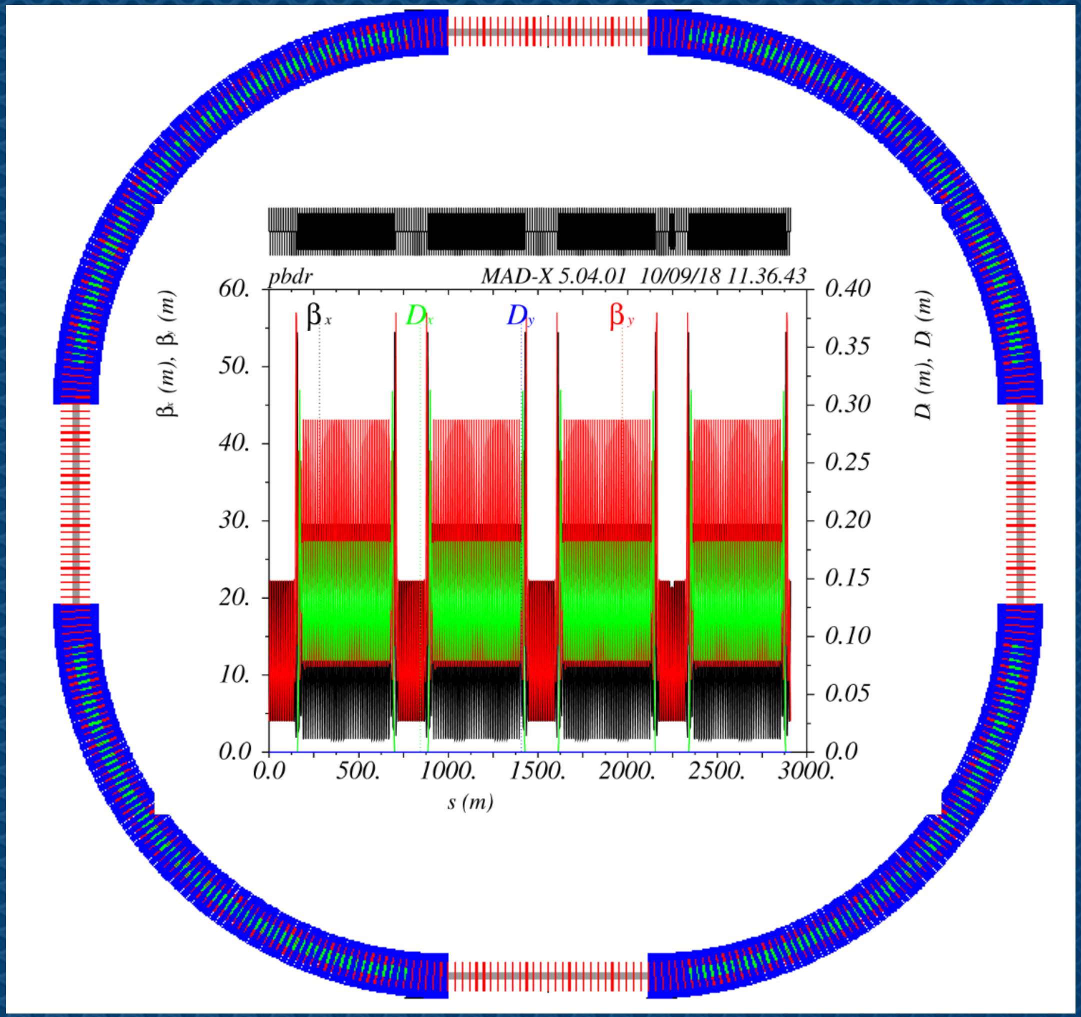
4. Pre-booster - New design

Parameters	Values	
Energy [GeV]	20	6
Circumference [m]	2908	
Emittance [nm.rad]	4.88	0.19
Energy loss / turn [MeV]	57.8	1.12
Natural h/v chromaticity	-123/-68	
Horizontal damping times [ms]	6	96



- μ_x, μ_y = 0.363/2π, 0.1/2π are chosen for achieving minimum emittance in the arc.

- For the phase advance in the straight section, it is planned to be chosen around 90 degree since it provides minimum beta function and maximum efficiency for injection and extraction elements.

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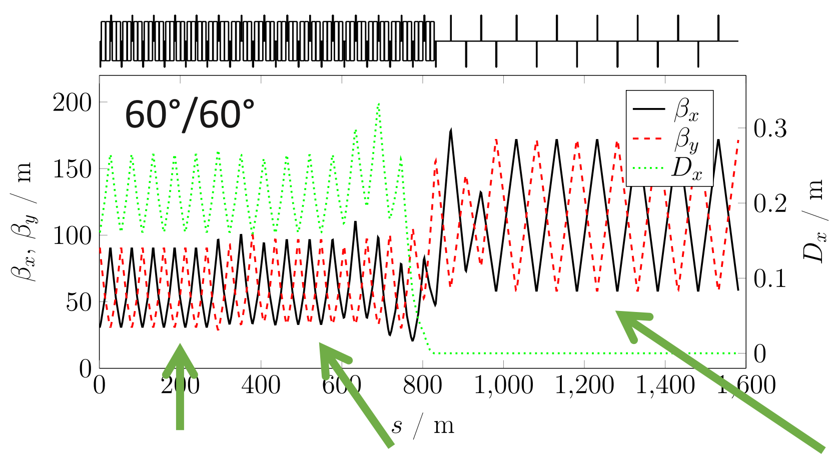
5. Booster

FCC-ee booster: lattice and optics



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!

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	

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5. Booster

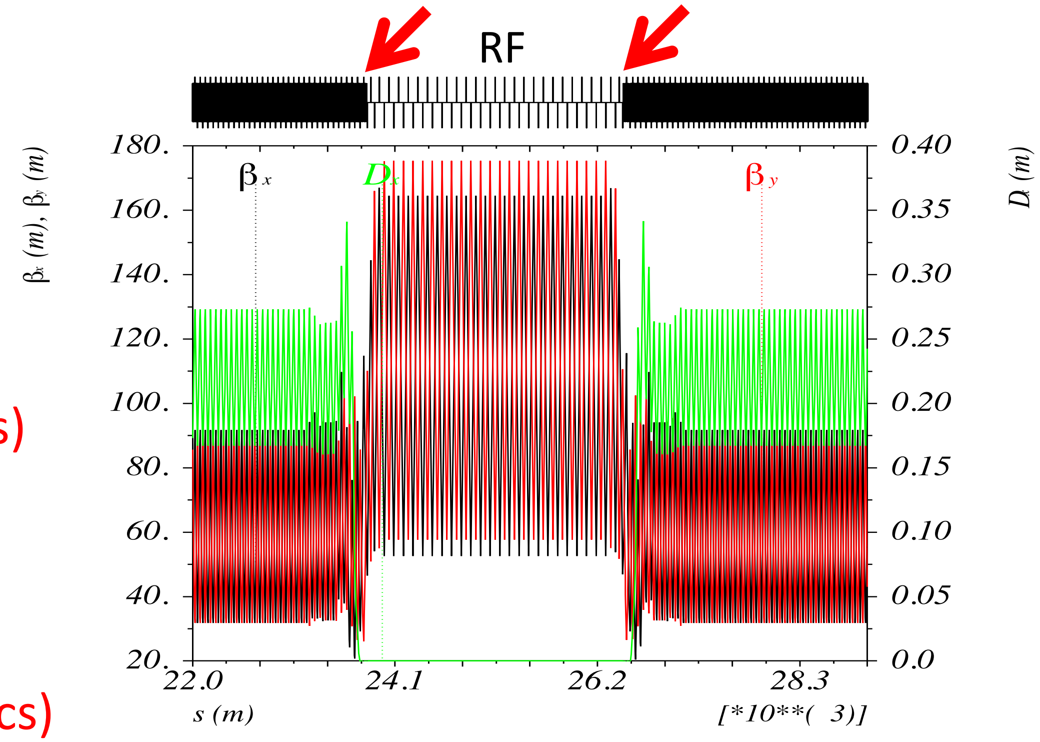
Wiggler magnets

Low synchrotron radiation at
20 GeV beam energy:
→ ε_x = 15 pm rad (90°/90° optics)
τ_x = 10.05 s

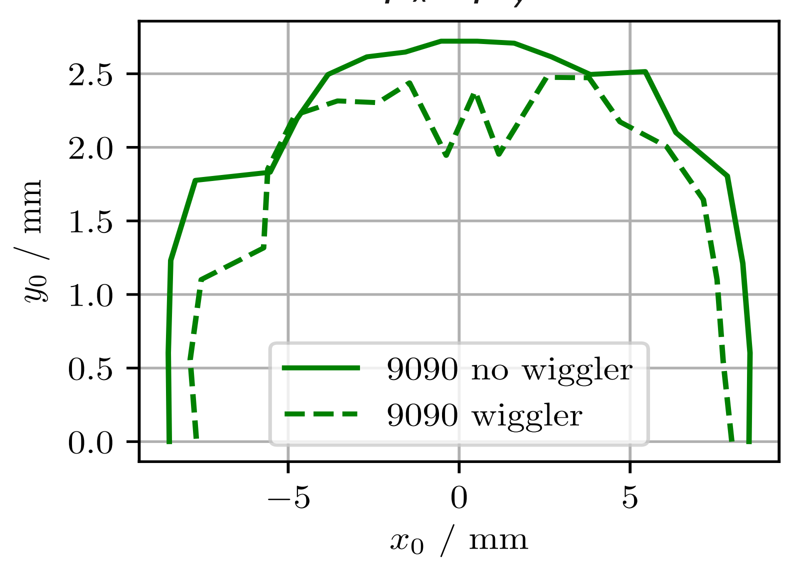
16 wigglers, L = 9.1 m, B = 1.8 T
→ ε_x = 196 pm rad (90°/90° optics)
τ_x = 0.1 s

Wigglers are needed to reduce the damping time and mitigate IBS

Only little effect on DA
Comprehensive studies with wiggler, quadrupole misalignments and realistic RF scheme under way



for $\beta_x = \beta_y$ = 100 m



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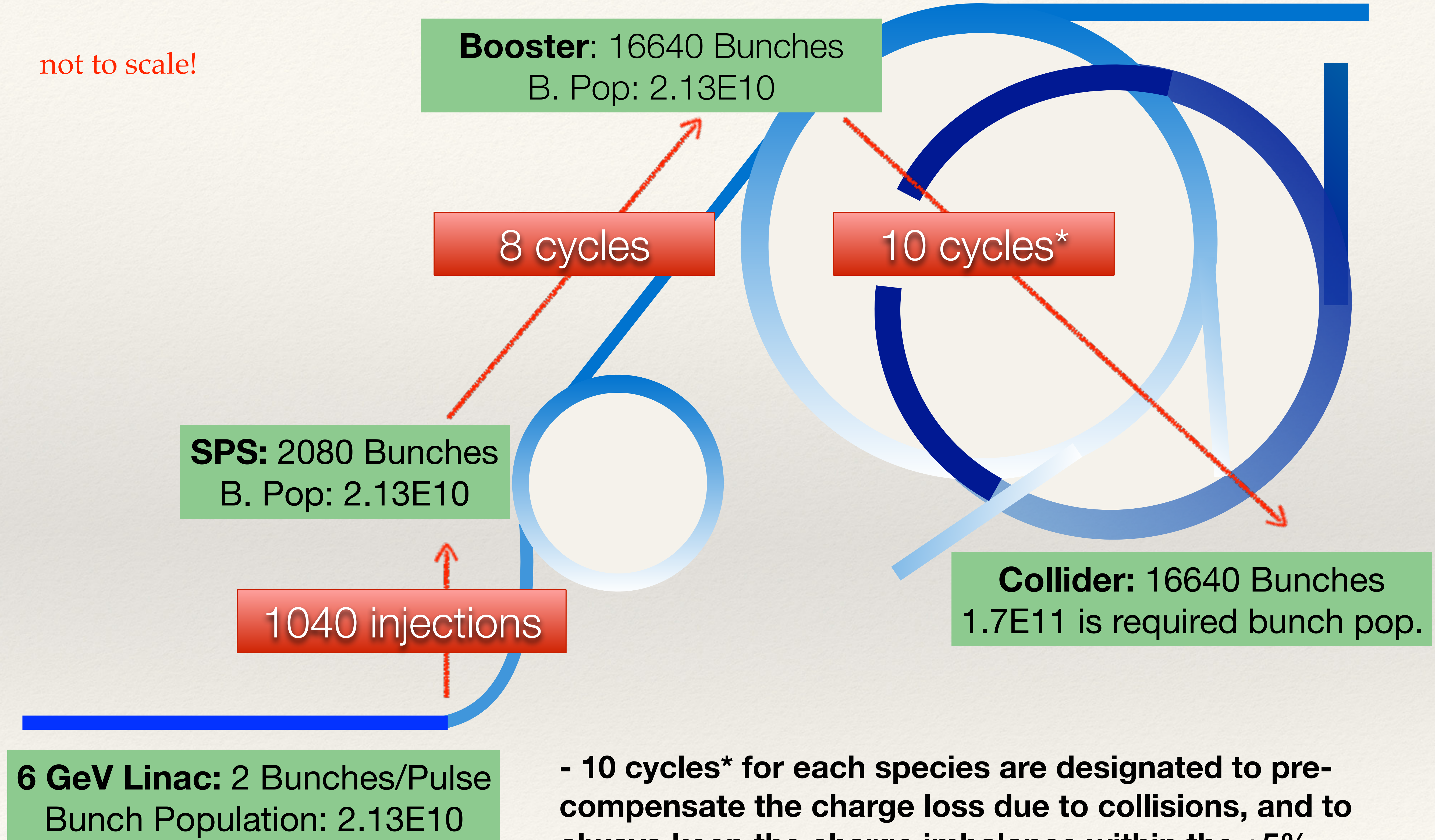
6. Injector Baseline

operation mode	FCCee-Z		FCCee-W		FCCee-H		FCCee-tt	
type of filling	Full	Top-up	Full	Top-up	Full	Top-up	Full	Top-up
energy [GeV]	45.6		80		120		182.5	
lifetime [min]	70	70	50	50	42	42	47	47
τ_{inj} [sec]	122	122	44	44	31	31	32	32
linac bunches	2	2	2	2	1	1	1	1
linac repetition rate [Hz]	200	200	100	100	100	100	100	100
linac RF frequency [MHz]	2856							
linac bunch population [10^{10}]	2.13	1.06	1.88	0.56	1.88	0.56	1.38	0.83
SPS bunch spacing [MHz]	400							
SPS bunches/injection	2	2	2	2	1	1	1	1
SPS bunch population [10^{10}]	2.13	1.06	1.88	0.56	1.88	0.56	1.38	0.83
number of linac injections	1040	1040	500	500	393	393	50	50
number of SPS injections	8	8	2	2	1	1	1	1
SPS supercycle duty factor	0.84	0.84	0.62	0.62	0.35	0.35	0.08	0.08
SPS number of bunches	2080	2080	1000	1000	393	393	50	50
SPS current [mA]	307.15	153.57	130.22	39.07	51.18	15.35	4.77	2.86
SPS injection time [s]	5.9	5.9	5.7	5.7	3.93	3.93	0.5	0.5
SPS ramp time [s]	0.2							
SPS cycle length [s]	6.3	6.3	6.1	6.1	4.33	4.33	0.9	0.9
BR bunch spacing [MHz]	400	400	400	400	400	400	400	400
BR number of bunches	16640	16640	2000	2000	393	393	50	50
BR bunch population [10^{11}]	0.21	0.11	0.19	0.06	0.19	0.06	0.14	0.66
BR cycle time [s]	51.74	51.74	14.4	14.4	7.53	7.53	5.6	5.6
booster ramp time	0.32	0.32	0.75	0.75	1.25	1.25	2	2
number of cycles per species	10	1	10	1	10	1	20	1
transfer efficiency	0.8							
no. of injections/collider bucket	10	1	10	1	10	1	20	1
total number of bunches	16640	16640	2000	2000	393	393	50	50
filling time (both species) [sec]	1034.8	103.48	288	28.8	150.6	15.06	224	11.2
required bunch population [10^{11}]	1.70	0.085	1.5	0.045	1.5	0.045	2.2	0.066

❖ *Z*-mode is the most challenging operation in terms of the injector since it requires the highest total charge accumulated in the collider with the lowest geometric emittance.

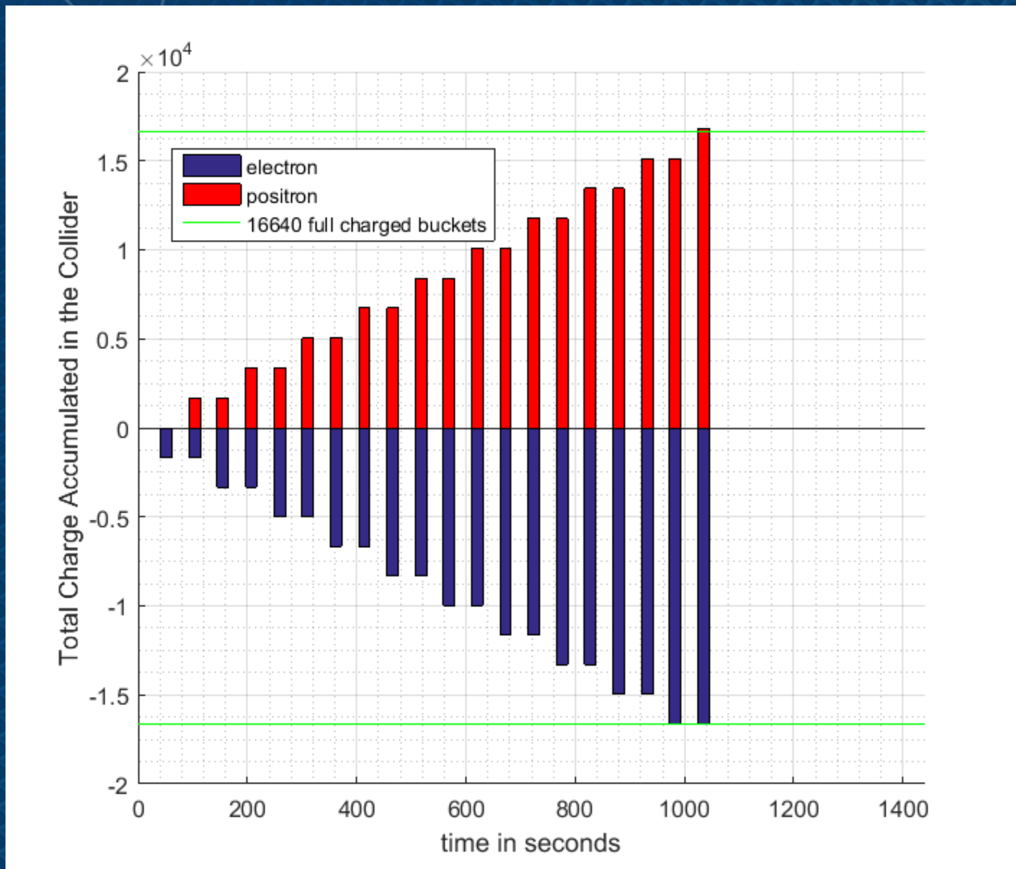
Y. Papaphillippou *et al.*

6. Fill from Scratch for Z-mode

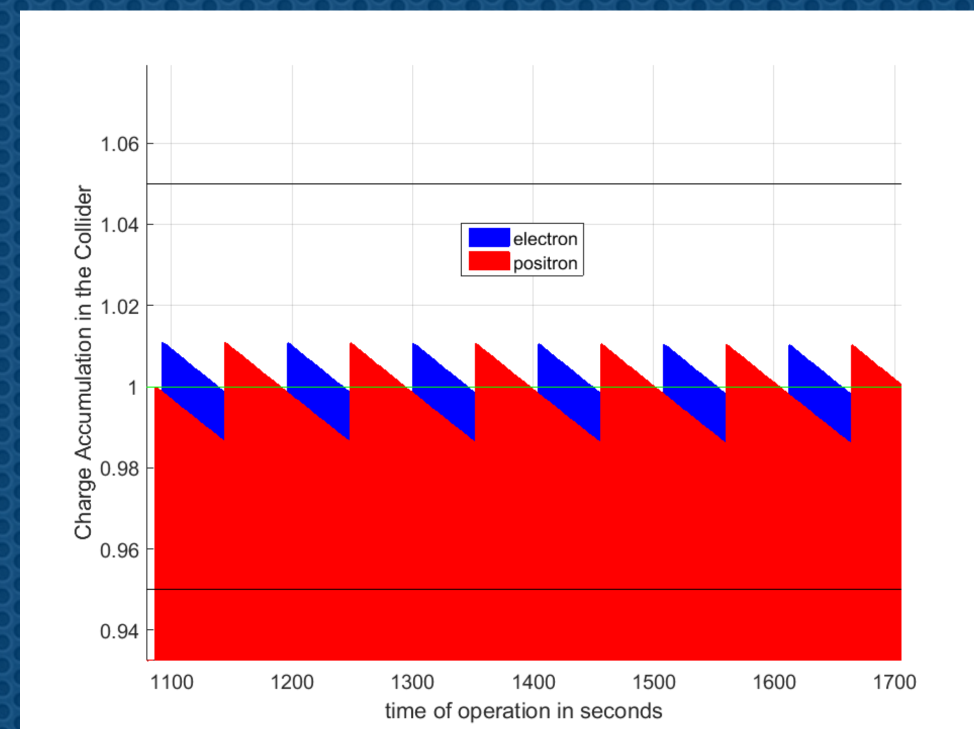


- 10 cycles* for each species are designated to pre-compensate the charge loss due to collisions, and to always keep the charge imbalance within the ±5% (BOOTSTRAPPING).

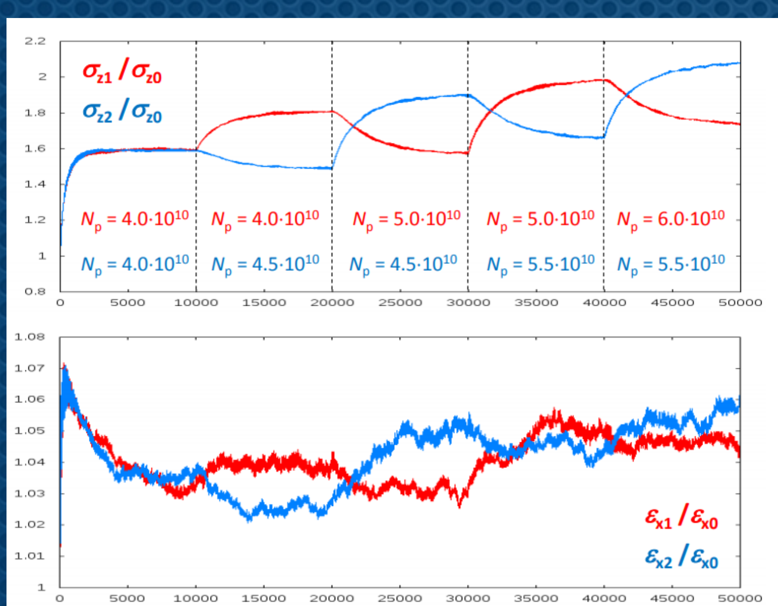
6. Fill from Scratch, Top-up, Bootstrapping for *Z*-mode



➡ Interleaved injection of species in the collider with pre-compensation of the charge loss due to collisions till next round. PS: the full charge is taken as 1.



Preliminary



D. Shatilov

➡ Bootstrapping of the charges while topping up in order to control bunch lengthening and emittance fluctuations due to beamstrahlung.

7. Conclusions

Linac Results	S-Band up to 1.54 GeV	S-Band 1.54 -> 6 GeV	C-Band 6 -> 20 GeV
Length (m)	79.1	239.1†	446.9
Transmission for 2.2E10 part.	100%	100%	100%
Number of Cavities	21	60	156
Number of Quadrupoles*	14	12	13
Emit. with no blow	2.7/3.8 nm	0.48/0.10 nm	0.15/0.03 nm
Avg. Extracted Emit.	6.4/5.0 nm	0.55/0.11 nm	1.18/0.05 nm

Meets the expectation of the DR very safely.

Meets the expectation of the SPS very safely.

Meets the expectation of the Booster very safely.

†Excluding positron optics.

7. Conclusions

- Positron production using conventional or hybrid targets are under study.
- Damping Ring needs error study. Energy compressor may not be needed, if the current DA is kept after errors.
- SPS with damping and Robinson wigglers are being designed.
- Pre-booster synchrotron is being designed with 4 straight sections, satisfying the FCC-ee needs, yet DA, instability studies are ongoing.
- Booster has large enough dynamic aperture, instabilities are under study.
- Each of the FCC-ee injectors has been designed with alternative options. The injector baseline satisfies all requirements, even with large safety margins. In particular, supports the proposed bootstrapping injection mode of the collider. With the proposed injector, the collider can be filled from zero in about 17 minutes at the Z pole, and even much faster at higher energies. The bunch schedules have been optimised for maximum average luminosity in operation.