Main Injector Linac Parameters and Filling Schemes Overview*

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FCC-ee injector collaboration meeting #3

*with contributions from F. Antoniou, W. Bartmann, T. Charles, O. Etisken, B. Harer, B. Holzer, KT. Tydecks, L. Rinolfi; A. Barnyakov, A. Levichev, P. Martyshkin, D. Nikiforov (BINP); K. Furukawa, N. Iida, T. Kamitani, F. Miyahara (KEK); I. Chaikovska, R. Chehab (LAL); S. M. Polozov (MEPhI); M. Aiba (PSI)

references:

FCC-ee: The Lepton Collider, Eur. Phys. J. Spec. Top. 228, 261–623 (2019), https://doi.org/10.1140/epjst/e2019-900045-4

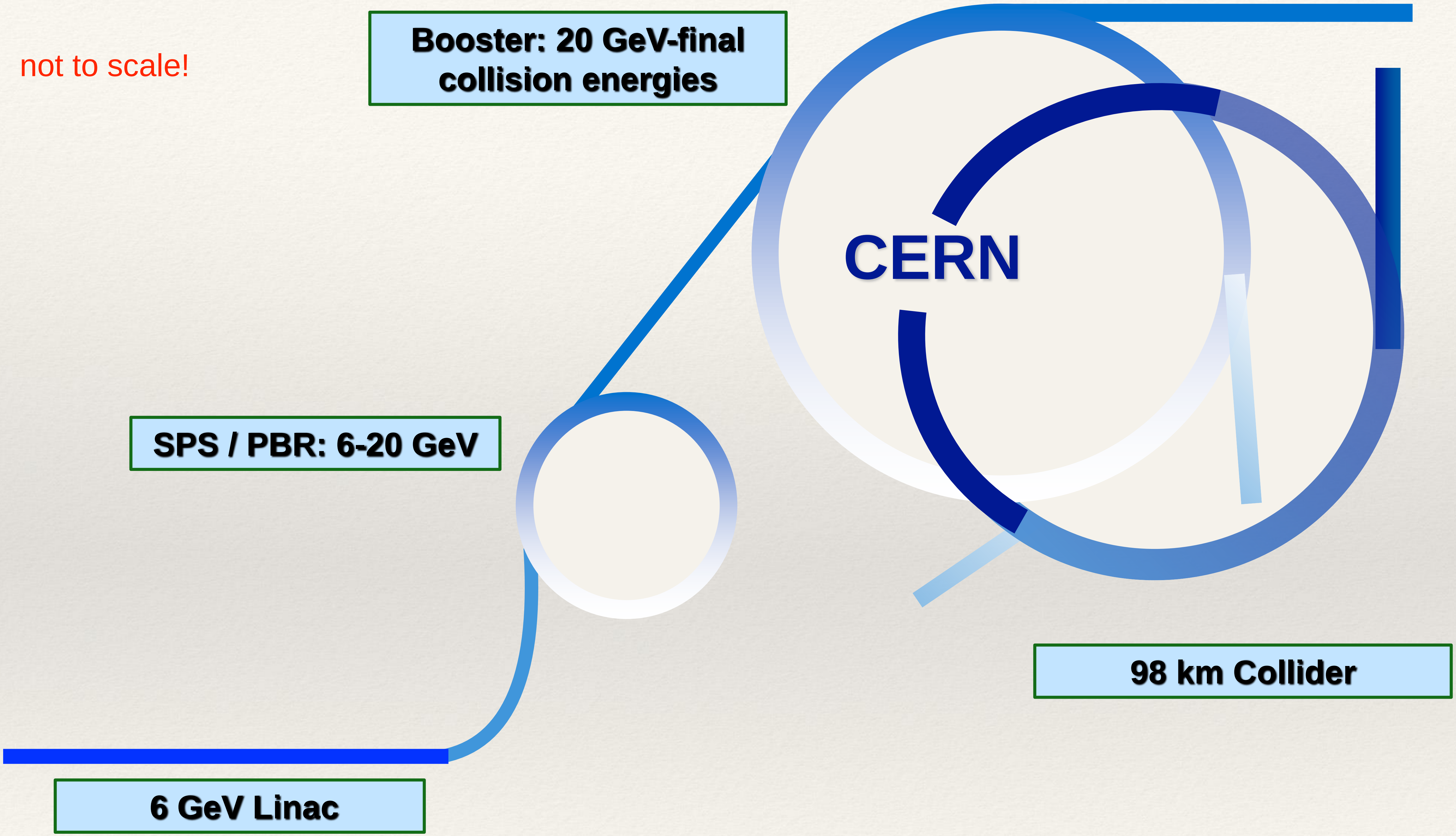
S. Ogur et al, *Linac and Damping Ring Designs for the FCC-ee*, IPAC'19, https://doi.org/10.18429/JACoW-IPAC2019-MOPMP002

S. Ogur, *Linac and Damping Ring Designs of the Future Circular e+e− Collider of CERN*, PhD thesis Bogazici U., CERN-THESIS-2019-099, http://cds.cern.ch/record/2685252?ln=en

Outline

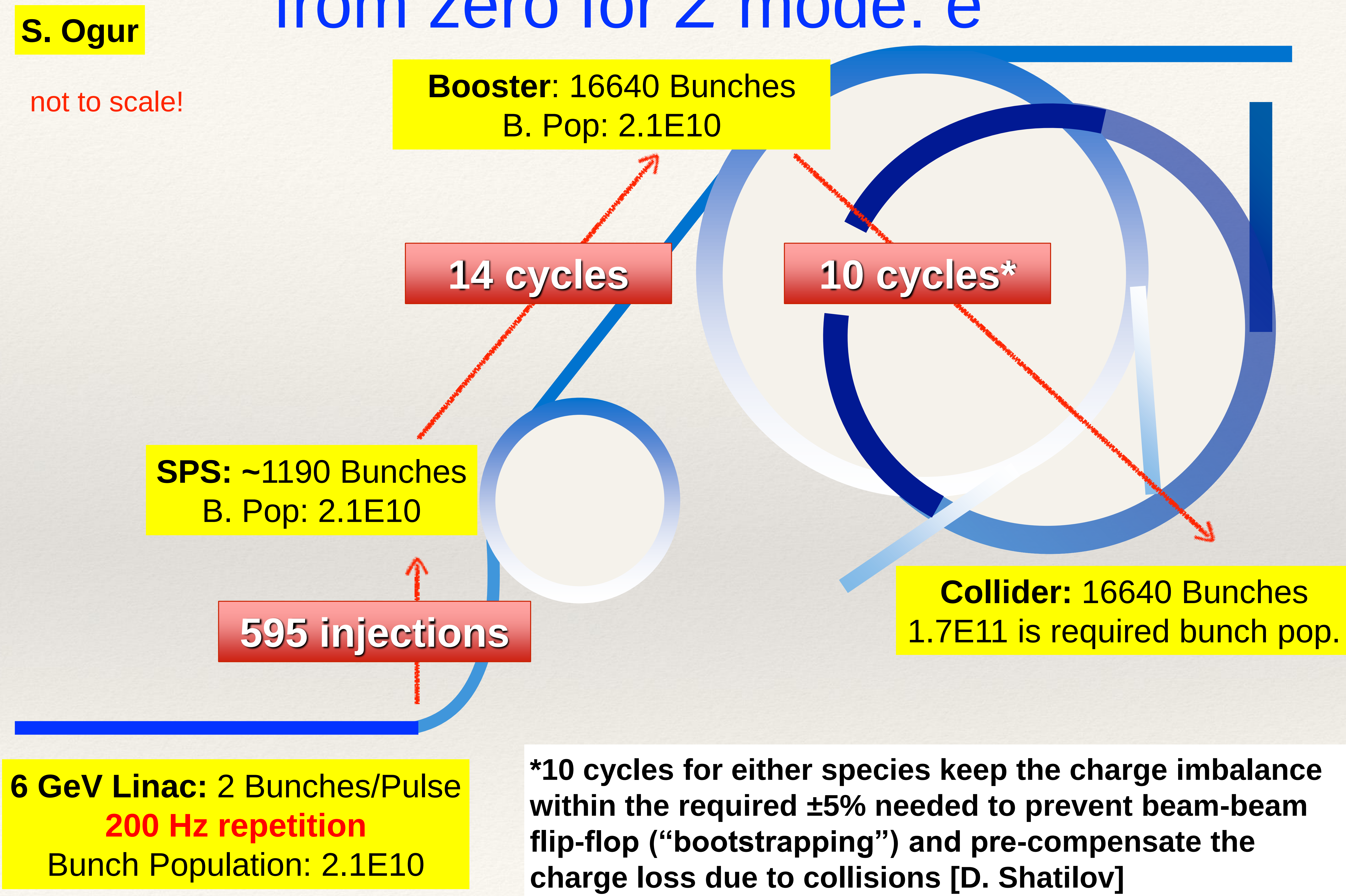
1. Filling the Collider from zero for Z-mode: baseline
2. The FCC-ee Injector Megatable
3. Filling the Collider from zero for Z-mode: alternative
4. Bootstrapping & top-up injection: interleaving e+/e-
5. Electron Gun
6. Linac
7. Positron Damping Ring
8. Bunch compressor

FCC-ee complex



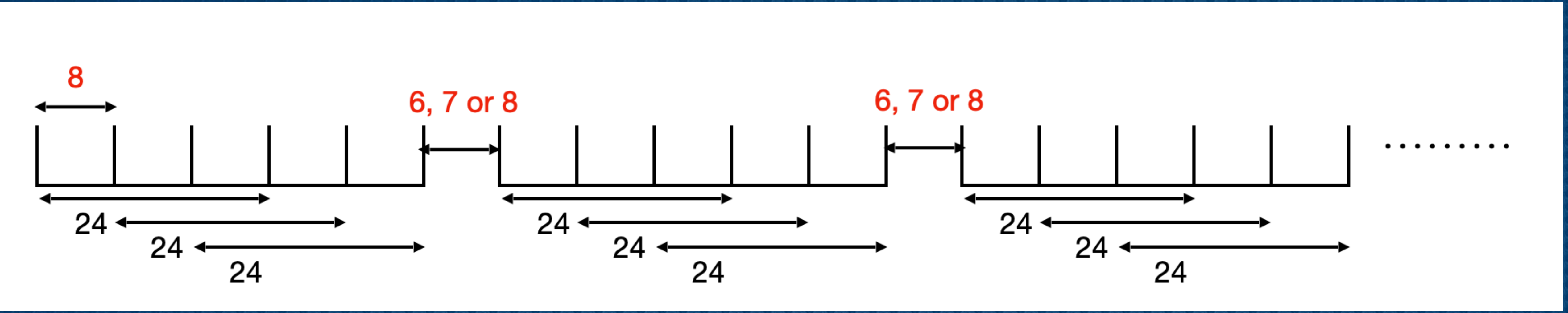
S. Ogur

biggest challenge: filling the collider from zero for *Z* mode: e^-



***10 cycles for either species keep the charge imbalance within the required ±5% needed to prevent beam-beam flip-flop ("bootstrapping") and pre-compensate the charge loss due to collisions [D. Shatilov]**

filling pattern for Z-mode (linac injecting into SPS/PBR)



Bunch spacing in a sub-train of 6 buckets is 20 ns. Yet sub-train spacing can be 15, 17.5 or 20 ns.   Abort gap is 120 ns. Totally 1188 or 1190 buckets are filled.

M. Benedikt, S. Ogur

The above means 60 ns spacing in linac.
Alternative would be 52.5 ns in linac, and 17.5 ns in collider.

SPS flat bottom time (accumulation of 1190 bunches from linac) = 2.975 s

SPS damping time 0.03 s (to reach equilibrium emittance) = 0.03 s x 7
SPS ramp time 6-20 GeV (acceleration + ramp down of mag) = 0.175 s
x 2

→ SPS cycle time for Z-mode = 3.535 s

linac duty factor ≥84%

O. Etisken, Y. Papaphilippou, S. Ogur *et al.*

filling the main booster ring (BR) for Z-mode

M. Benedikt

- ❖ 14 fills from SPS: 10 x 1188 +4*1190 bunches
- ❖ 1 fill from SPS = 1 BR train.

→ gap of 3.6 μs in BR for beam abort (more than necessary)

Comments:

- On-axis injection for BR could/should be considered.
- Each BR train has 120 ns abort gap inherited from SPS,; so we can enlarge the BR train spacing and/or have several abort gaps, by reducing the length of the abort gap.

BR flat bottom time (accumulation of 14 fills from SPS) = 3.535 s x 14

BR damping time 0.1 s (to reach equilibrium emittance) = 0.1 s x 7

BR ramp-up time 20-45 GeV (acceleration + ramp down of mag) = 0.37 s x 2

BR cycle time for Z-mode = 50.93 s

→ Filling collider with both species = 50.93 s x10x2= 1018.6 s (17 min)

S. Ogur, B. Harer, B. Holzer, Y. Papaphilippou

FCC-ee Injector Megatable

1	Accelerator	FCCee-Z		FCCee-W		FCCee-H		FCCee-tt	
2	Type of filling	Full	Top-up	Full	Top-up	Full	Top-up	Full	Top-up
3	Energy [GeV]	45,6		80		120		182,5	
4	luminosity Lifetime [min]	70	70	59	59	38	38	47	47
5	τinj [sec]	122	122	44	44	31	31	32	32
6	Linac bunches	2	2	2	2	1	1	1	1
7	Linac Repetition rate [Hz]	200	200	100	100	100	100	100	100
8	linac RF freq [MHz]	2800							
9	Linac Bunch population [10^10]	2,1263	1,0631	0,9375	0,5625	0,9375	0,5625	1,375	0,825
10	SPS circumference	6911,503838							
11	SPS bunch spacing [MHz]	400							
12	Harmonic number	9215							
13	SPS bunches/injection	2	2	2	2	1	1	1	1
14	SPS Bunch population [10^10]	2,1263	1,0631	0,9375	0,5625	0,9375	0,5625	1,375	0,825
15	SPS Damping time @ 6 GeV [s] (with wigglers)	0.03							
16	Number of linac injections	595	595	500	500	328	328	48	48
17	Number of SPS injections	14	14	2	2	1	1	1	1
18	SPS supercycle duty factor	0,81	0,81	0,32	0,32	0,28	0,28	0,10	0,10
19	SPS Number of bunches	1190	1190	1000	1000	328	328	48	48
20	SPS current [mA]	175,72	87,86	65,11	39,07	21,36	12,81	4,58	2,75
21	SPS injection time [s]	3,185	3,185	3,2	3,2	3,98	3,98	1,18	1,18
22	SPS ramp time [s]	0,175							
23	SPS Cycle length [s]	3,535	3,535	3,55	3,55	4,33	4,33	1,53	1,53
24	Minimum SPS bunch spacing [ns]	17,5	17,5	22,5	22,5	70	70	477,5	477,5
25	BR Number of bunches	16640	16640	2000	2000	328	328	48	48
26	BR Bunch population [10^11]	0,2129	0,1064	0,0938	0,0563	0,0938	0,0563	0,1375	0,0825
27	BR cycle time [s]	50,93	50,93	9,4	9,4	7,63	7,63	6,3925	6,3925
28	Booster ramp time	0,37	0,37	0,8	0,8	1,3	1,3	2,0813	2,0813
29	number of cycles per species	10	1	20	1	20	1	20	1
30	Transfer efficiency	0,8							
31	Number of injections/collider bucket	10	1	20	1	20	1	20	1
32	Total number of bunches	16640	16640	2000	2000	328	328	48	48
33	required FCCee bunch population [10^11]	1,701	0,0851	1,5	0,045	1,5	0,045	2,2	0,066
34	Filling time (both species) [sec]	1018,6	101,86	376	18,8	305,2	15,26	255,7	12,785

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Y. Papaphilippou,
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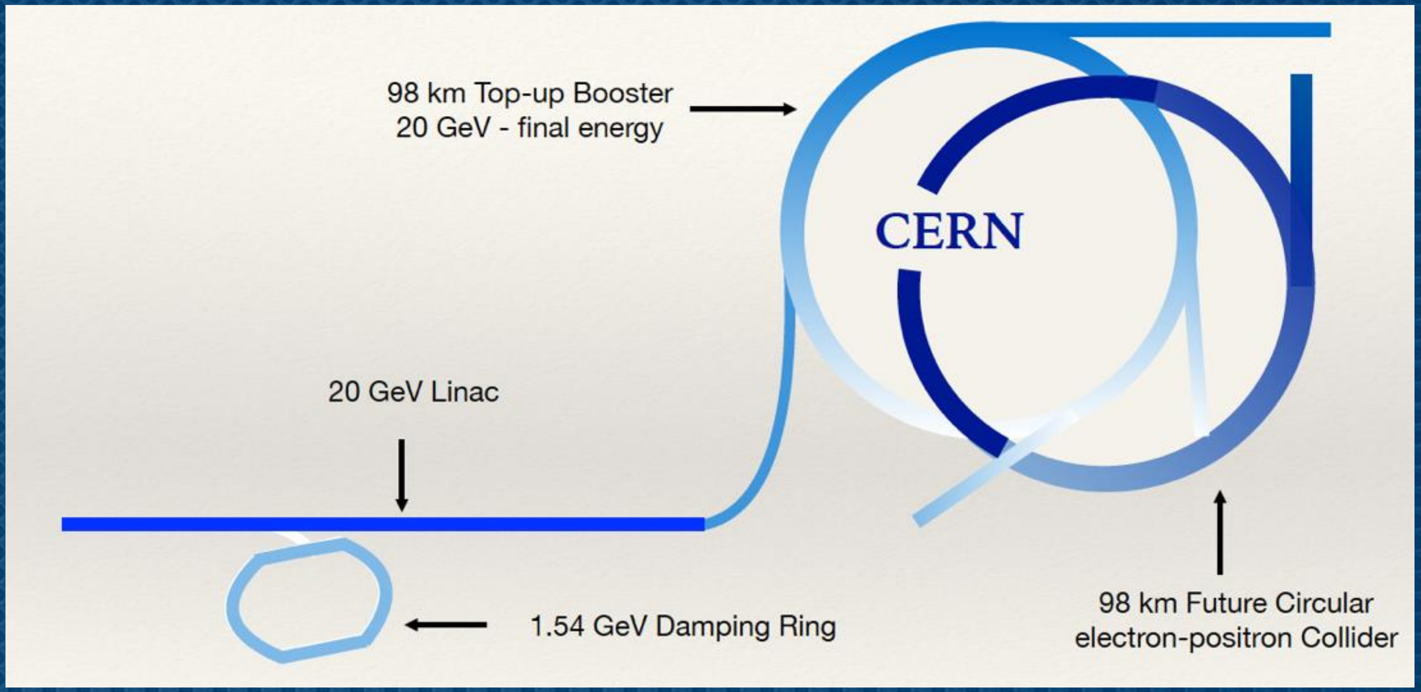
alternative filling directly into BR with 20 GeV Linac

20 GeV linac will directly feed the main booster ring



BR flat bottom time (accumulation of 16640 bunches from linac) = 41.6 s

BR damping time 0.1 s (to reach equilibrium emittance) = 0.1 s x 7

BR ramp-up time 20-45 GeV (acceleration + ramp down of mag) = 0.37 s x 2

BR cycle time for Z-mode = 42.94 s

Filling collider with both species = 42.94s x10x2= 858.8 s (~14 min)

with pre-booster: 17 min.

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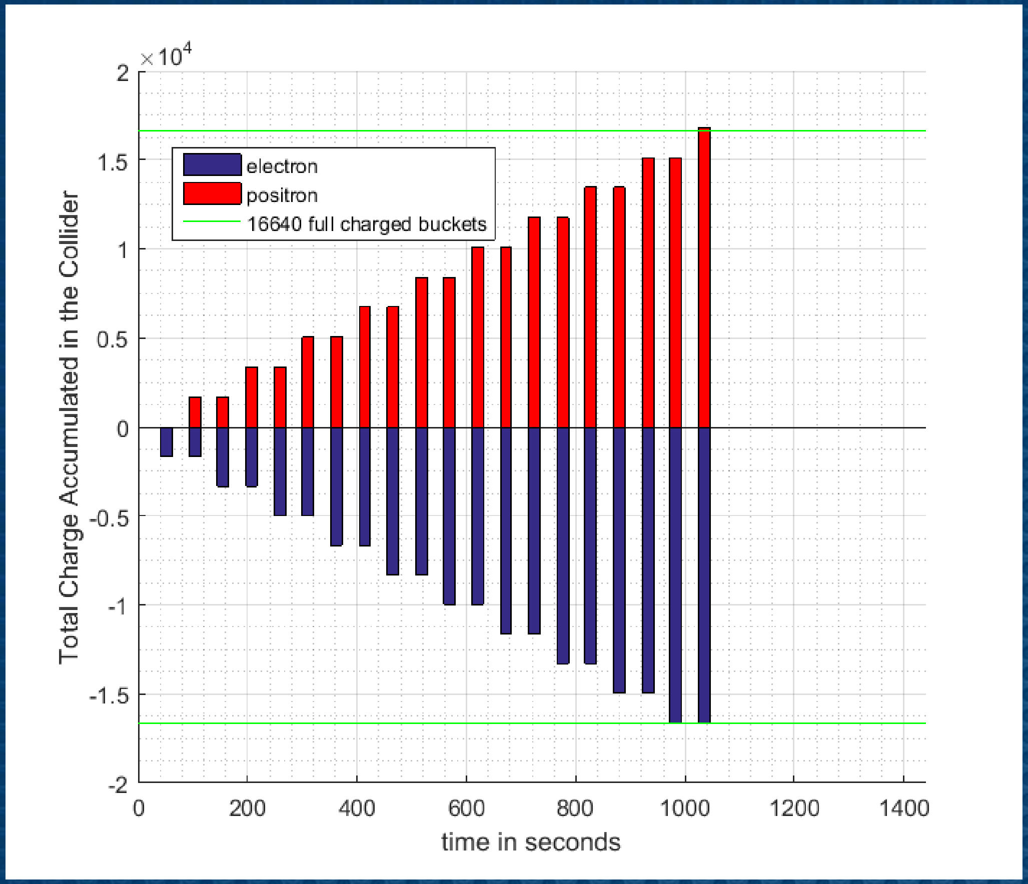
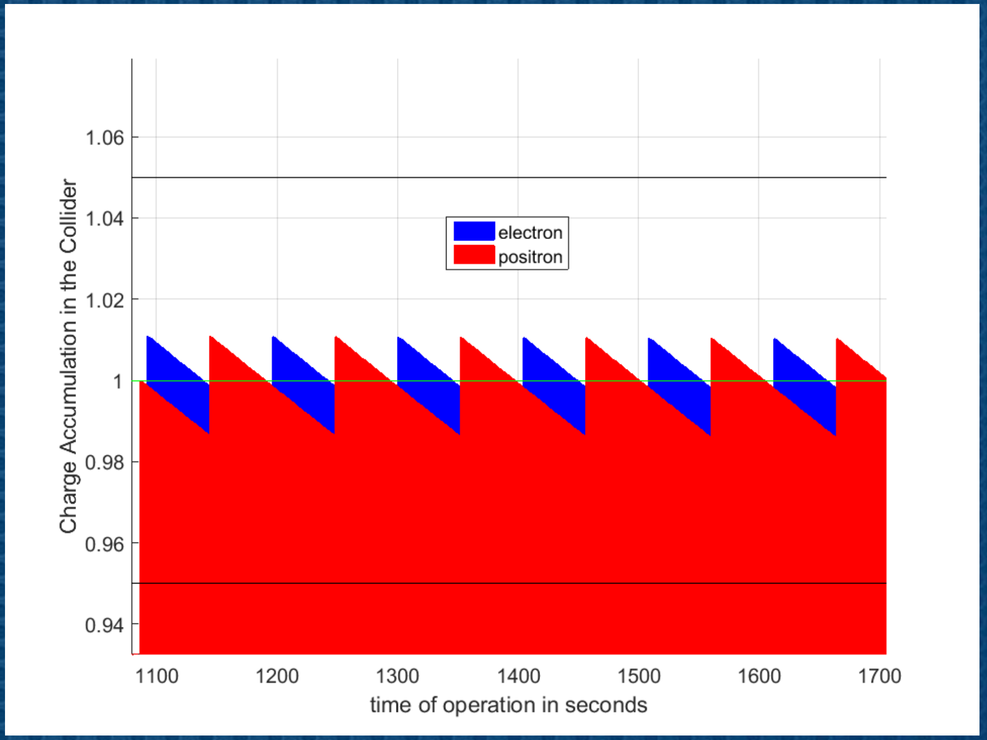
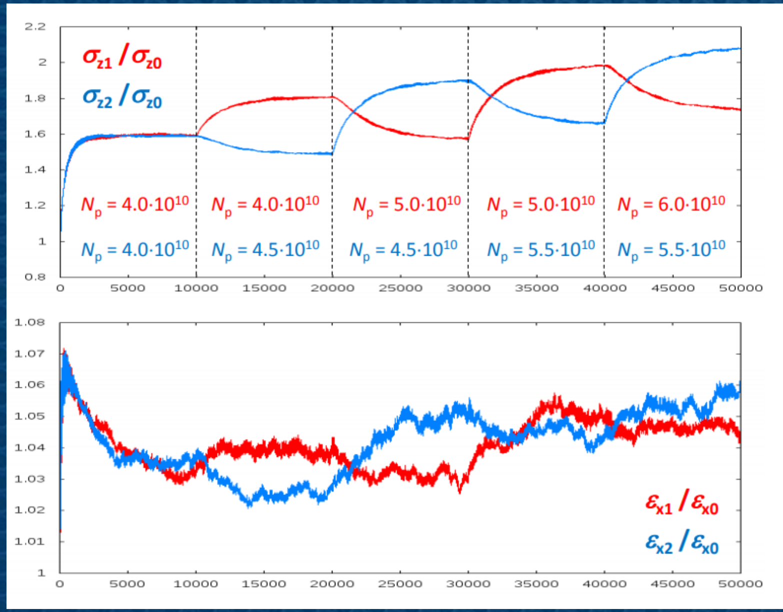
bootstrapping and top-up injection: interleaving e+/e-



Interleaved injection of species in the collider, **plus pre-compensation of the charge loss** due to collisions till next round. (The full target charge is normalised to 1.)



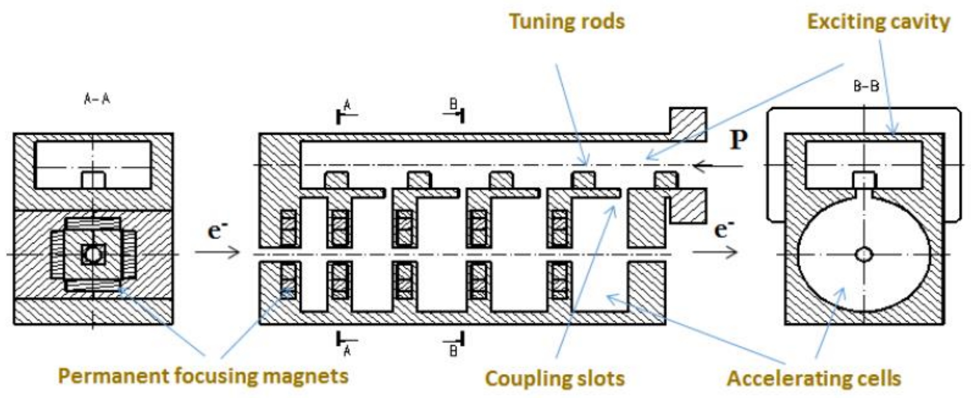


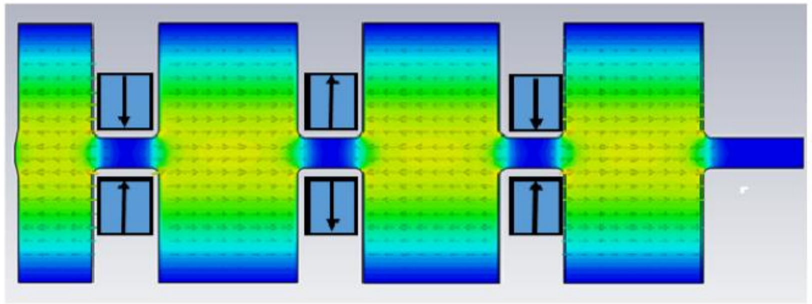
D. Shatilov

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

electron gun(s)

S. Ogur





Parameter	Value
total charge	6.5 nC
laser pulse duration	8 ps
peak accelerating field	100 MV/m
focusing solenoid field	0.5 T
beam length (σ_z)	1.5 mm
normalized transverse emittance	3 π.mm.mrad
energy	9.8 MeV
energy spread	0.6 %

RF gun can provide up to 4×10^{10} electrons, 2x more than we need for the e- collider bunches

For e+ production:
thermionic gun can generate up to 6.3×10^{10}

the 3 x higher value
supports e+ yield ≥0.3

A. Levichev, D. Nikiforov et al

linac assumptions in CDR

S. Ogur

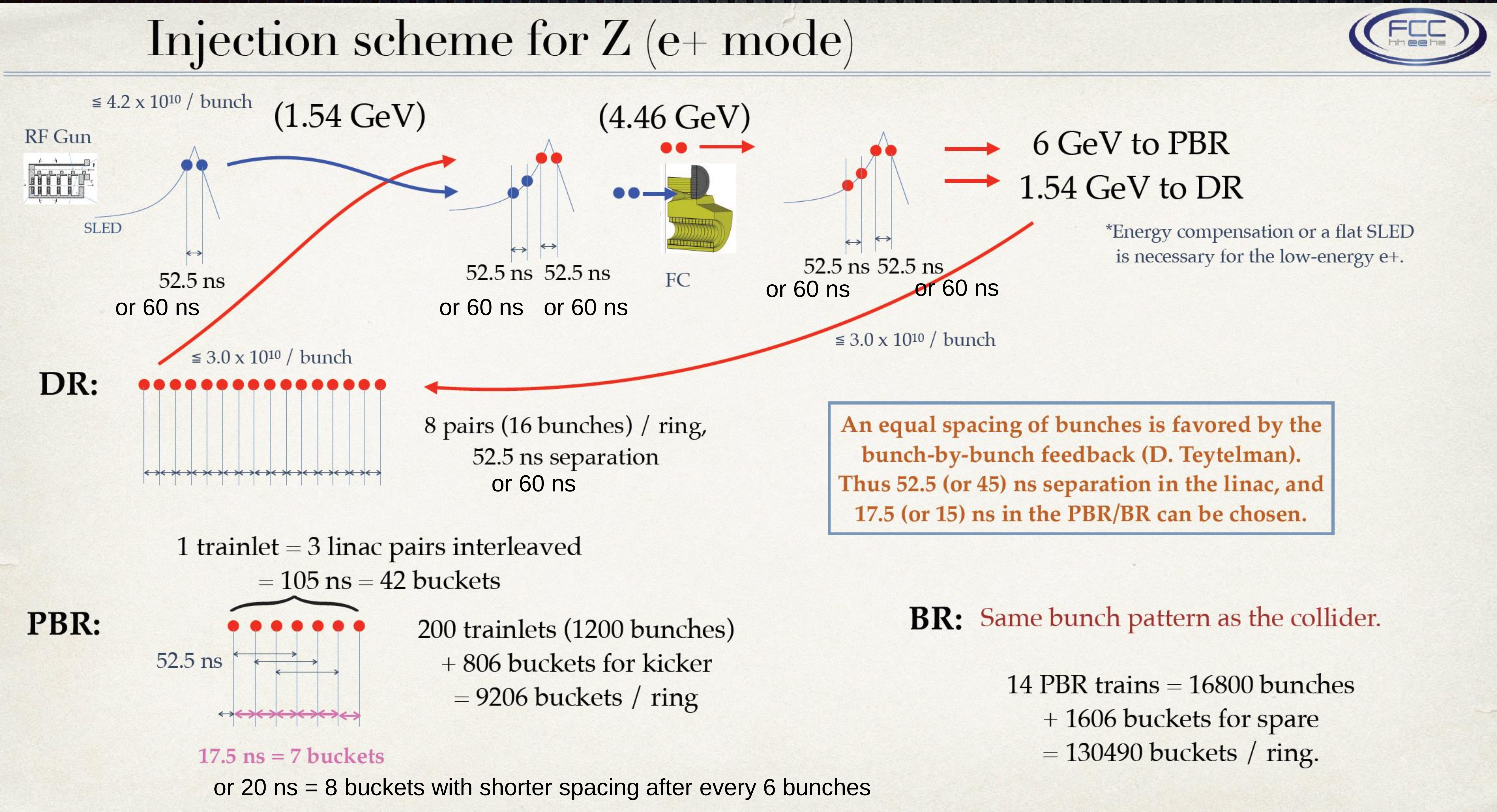
Cavities	S-Band	C-Band
Frequency (MHz)	2855.98 (or 2800 or 3000)	5711.96 (or 5600 or 6000)
Length (m)	2.97	1.8
Cavity Mode	2π/3	2π/3
Aperture Diameter (mm)	20	16
Unloaded Cavity Gradient (MV/m)	25	50

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

- ❖ Linac wakefields are included.
- ❖ Space charge included in the RF-Gun simulations and in the first 75 MeV part of the linac

lattice and tracking simulations: see appendix

linac during positron production (CDR configuration)



up to 1.54 GeV: 2 e^- bunches (from thermionic gun?)
1.54 to 4.46 GeV: 2 e^+ bunches and the 2 e^- bunches
4.46 GeV to 6 GeV: 4 e^+ bunches of different energy

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Positron Damping Ring

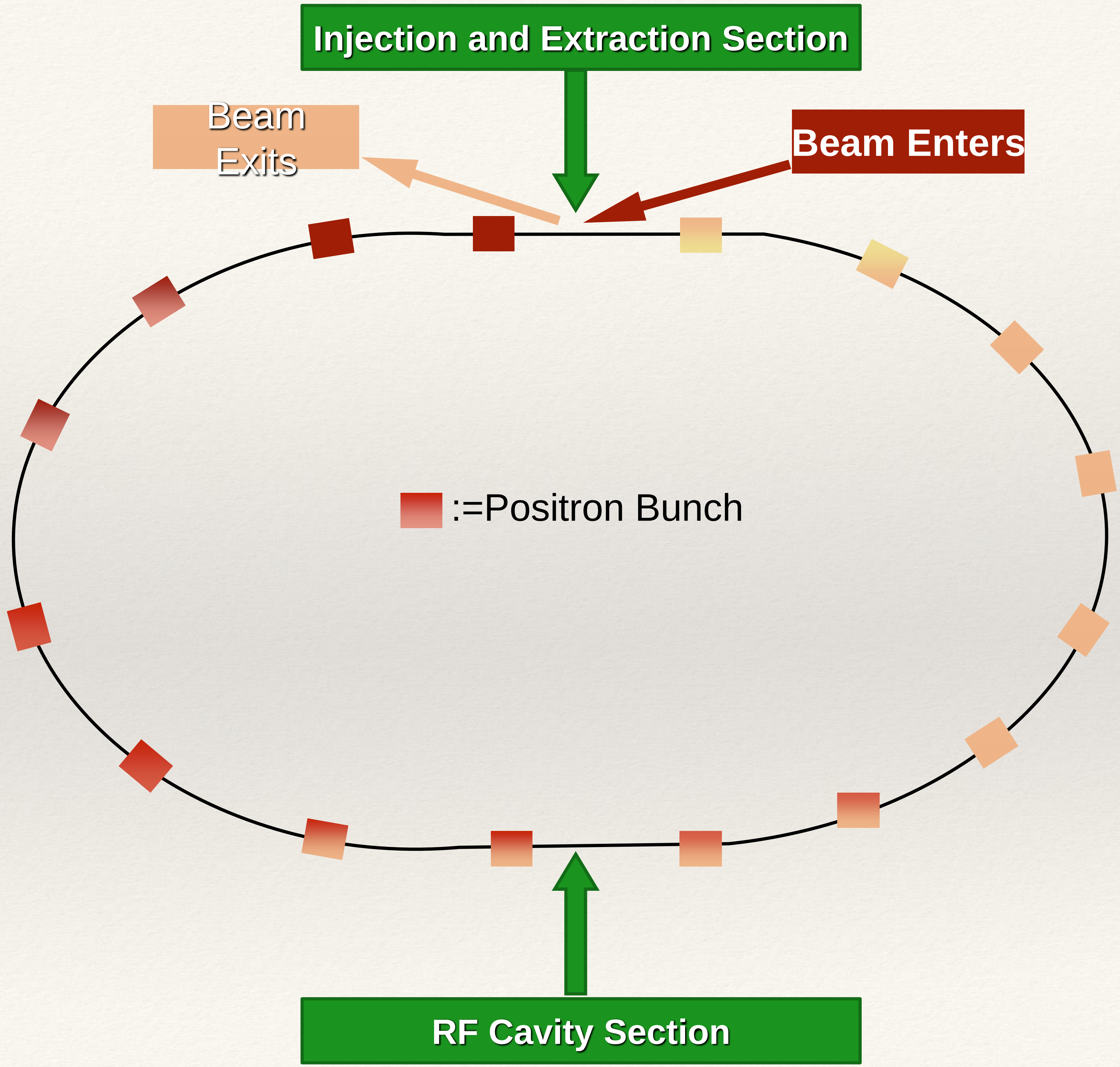
S. Ogur

the ring accommodates 8 bunch pairs

each bunch stays for 8 linac cycles (40 ms) in the damping ring

2 wigglers each in Straight Sections

400 MHz LHC like 2 SC cavities (1.5 + 2x1 meter long)



Damping Ring lattice and parameters

DR could be used only for e+ or for both species

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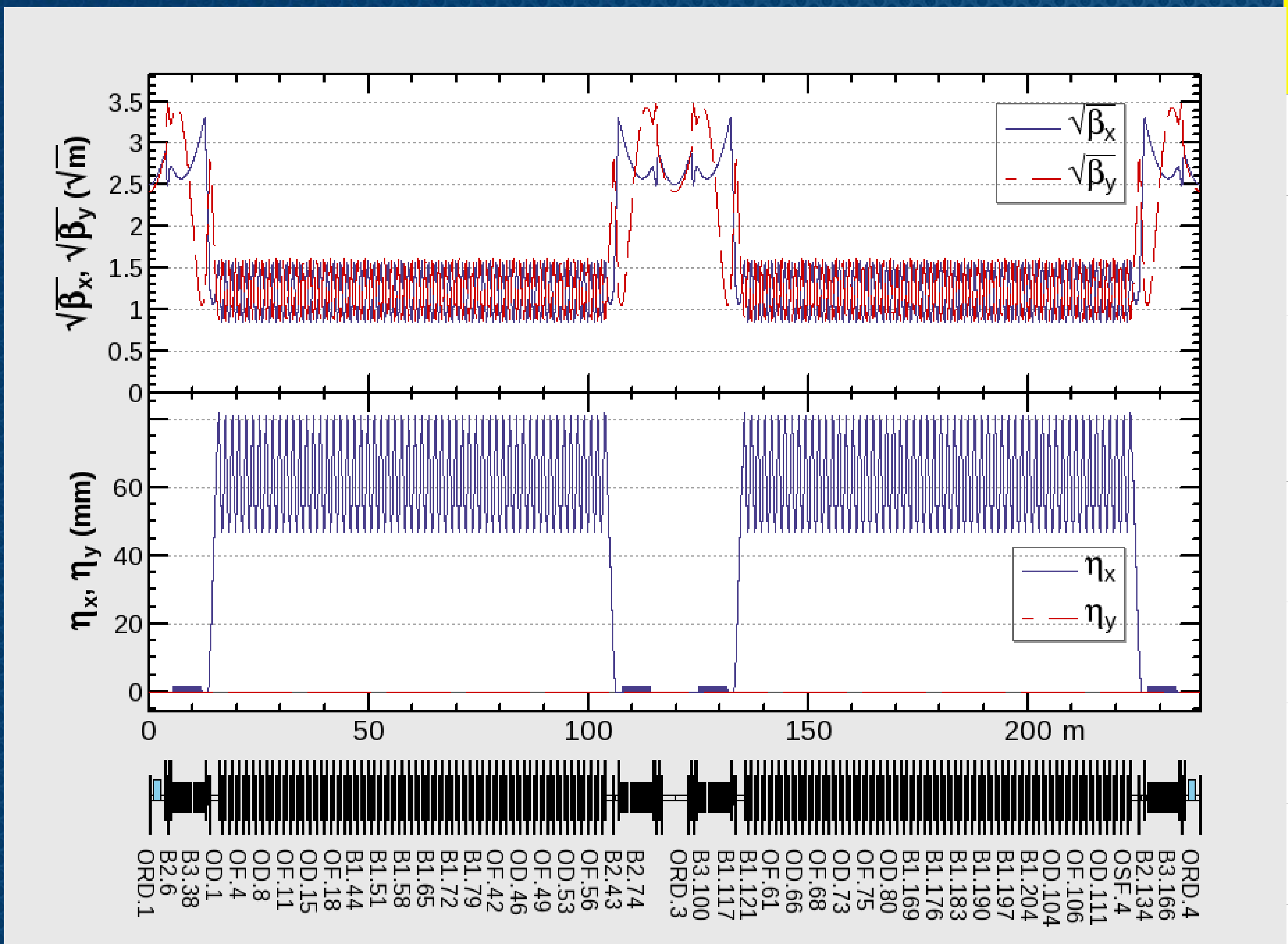


Parameter	Value
$\tau_x/\tau_y/\tau_z$	10.5/10.9/5.5 ms
equilibrium emittance (x/y/z)	0.96 nm/- /1.46 μm
circumference	241.8 m (for 50 ns) →≥320 m for 60 ns linac spacing
# of cells (FODO w/ sextupoles)	114
dipole field	0.66 T
no. of wigglers, field	4, 1.80 T
betatron tune (x/y)	0.193 rad/0.183 rad
ring tunes	24.189/23.580

studies of injection, emittance & dynamic aperture: see appendix

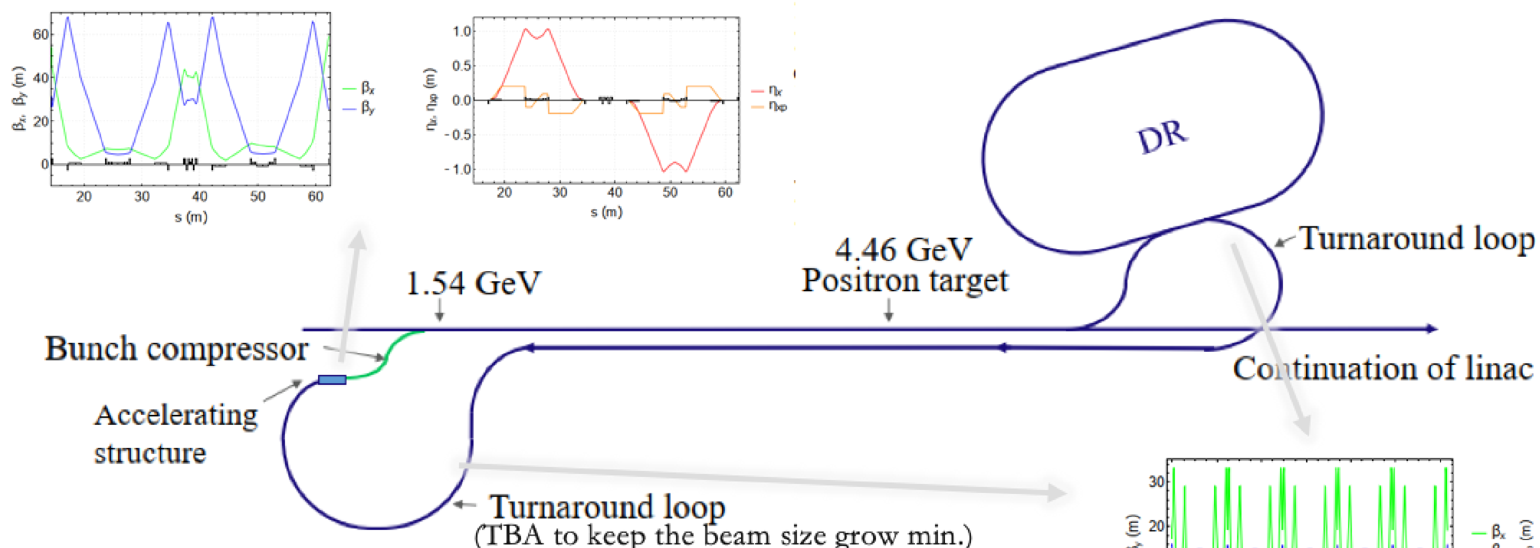
Bunch Compressor

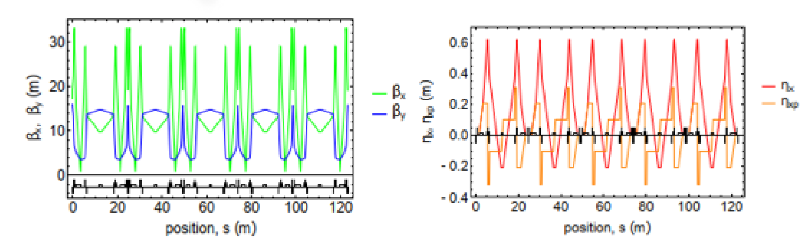
❖From DR back to linac at 1.54 GeV

T. K. Charles et al

FCC-e^+e^- injector requires two 180^0 turnaround loops to transport the positron beam from the damping ring to the lower energy section of the linac. In addition, bunch compression is required to reduce the RMS bunch length from 5mm to 0.5 mm, prior to injection into the linac.

Following the second loop, before the beam is injected back into the linac, is the location of the bunch compressor.





(a) (b)

Beam parameters at the damping ring exit

Property	Symbol	Value	Units
Beam energy	E_0	1.54	GeV
Bunch charge	Q	4.80	nC
Bunch length, initial	$\sigma_{z,i}$	5.00	mm
Energy spread	$\frac{\sigma_E}{E_0}$	0.10	%
Horizontal emittance	ϵ_x	1.81	nm rad
Vertical emittance	ϵ_y	0.37	nm rad

CSR cancellation techniques were applied to minimize the emittance growth across the compressor to 6.8%.

Damping Ring needs error study. Energy compressor may not be needed, if the current DA is preserved after introducing errors

Conclusions

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K. Oide,
Y. Papaphilippou,
D. Shatilov, et al.

Each of the FCC-ee injector components has been designed with alternative options. The injector baseline satisfies all known requirements, even with safety margins.

In particular, it 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 much faster at higher energies. The bunch schedules have been optimised for maximum average luminosity in operation.

Appendix

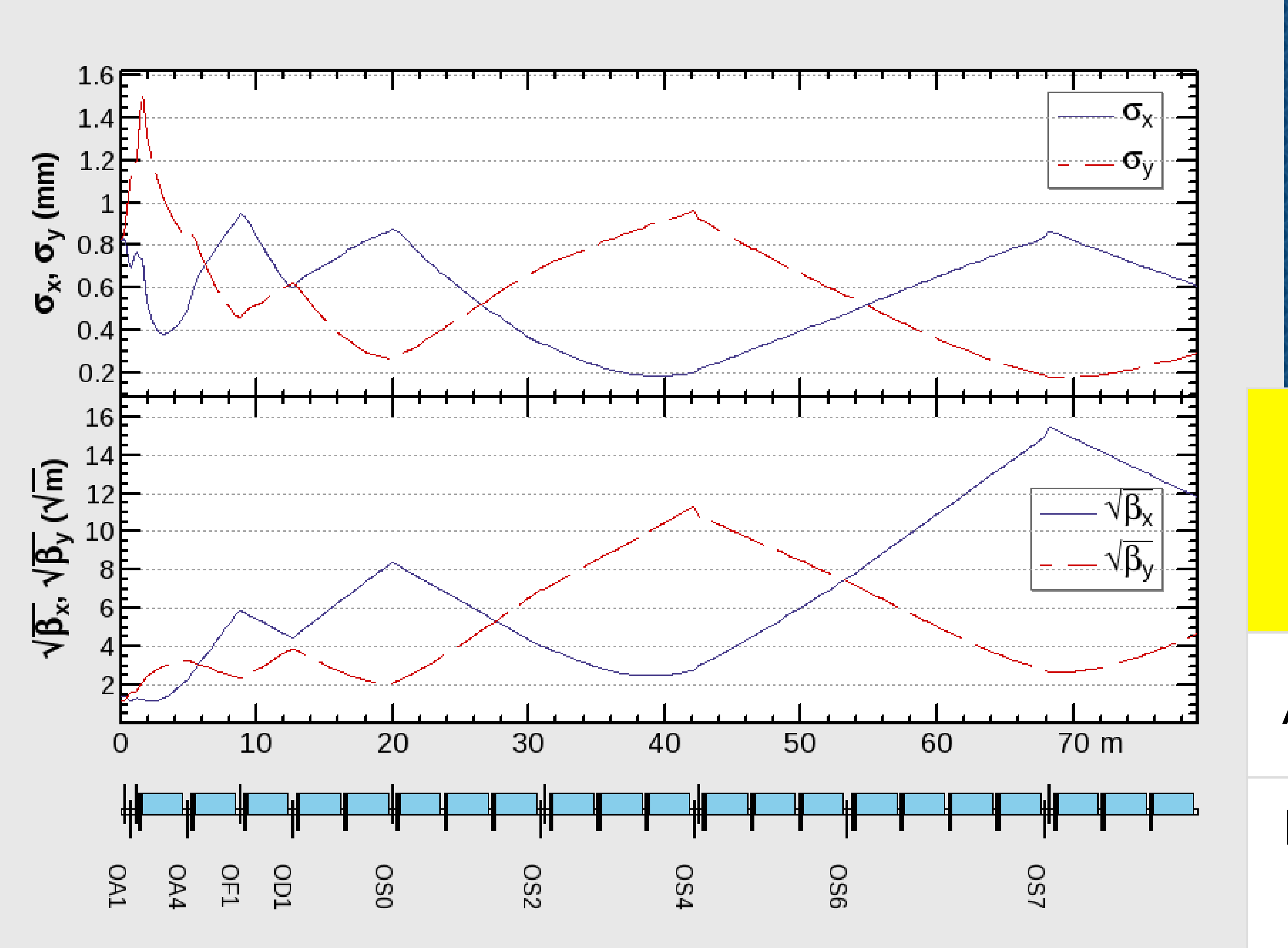
- Linac lattice design & beam dynamics simulations
- Damping ring beam dynamics simulations
- SPS as pre-booster
- New pre-booster synchrotron
- Main booster

S-band linac up to 1.54 GeV

S. Ogur

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

❖ We need 1.7E10 particles in a bunch (10 bunches -> 1 collider bucket for Z- mode), however 2.1E10 is chosen assuming above 80% transmission up to the collider.)



Some results for 12 different seeds averaged using 100k macro-particles for Gaussian random beam are presented below (all misalignments + BPM errors + SPACE charge are included):

Case	Horizontal Emit. (nm)	Vertical Emit. (nm)	Transmi ssion
Average	**9.4**	**6.0**	100%
No-blow up	**2.7**	**3.8**	100%

S-band linac from 1.54 to 6 GeV

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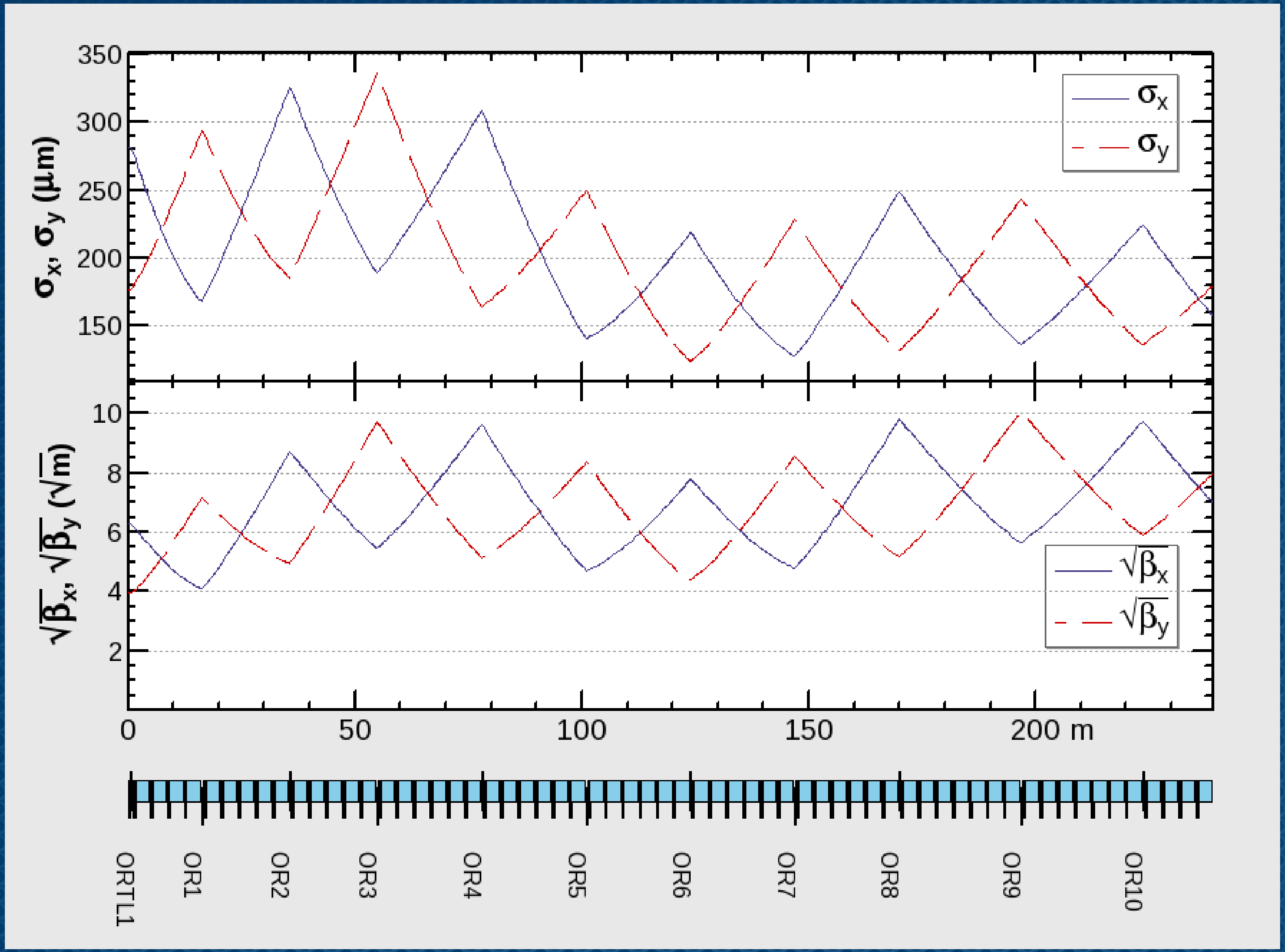
K. Oide

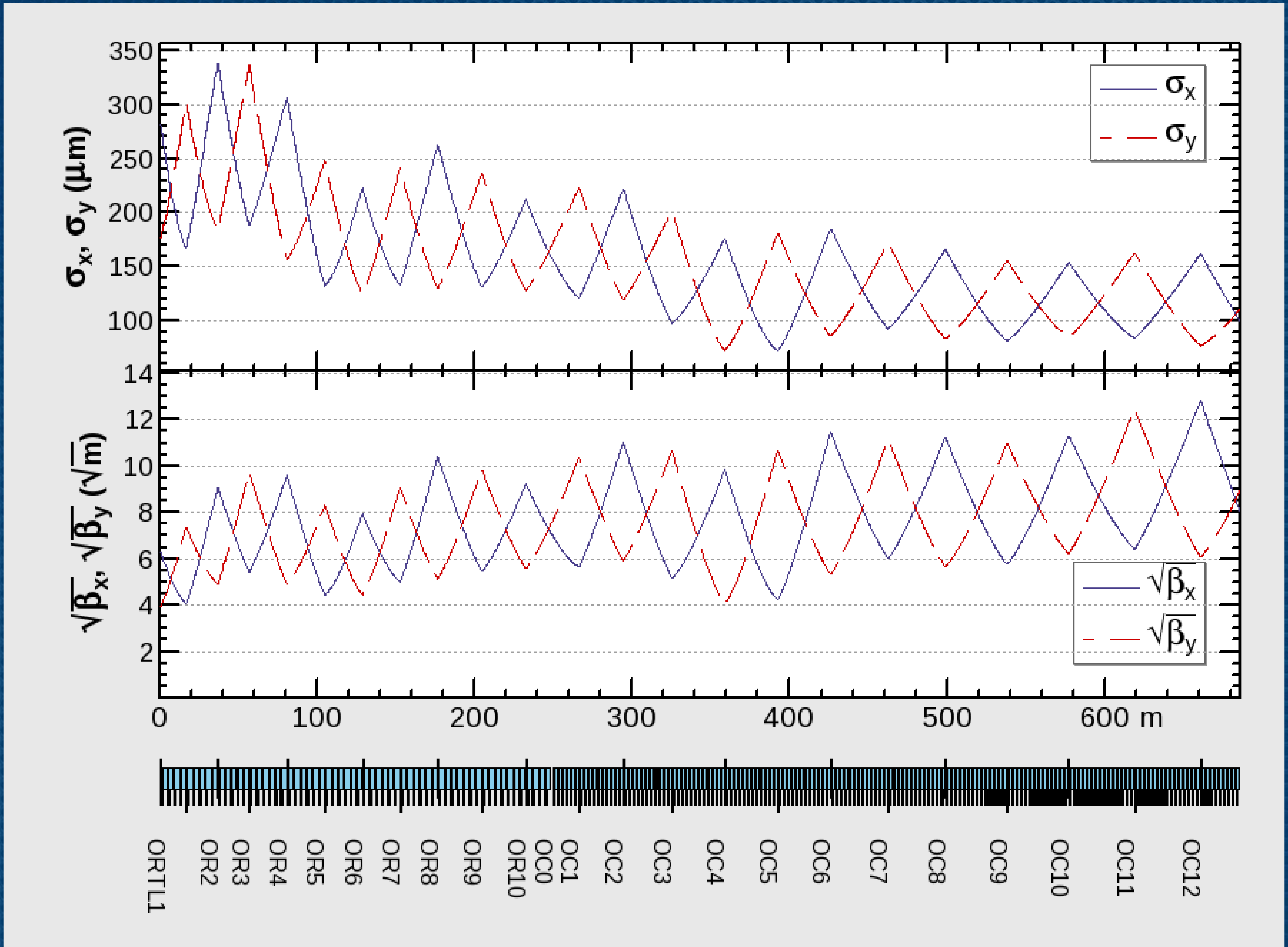


- ❖ S-Band structures.
- ❖ Results (averaged out of 12 different seeds) with all misalignments including BPM errors.

Trial ID	**Horizontal Emit. (nm)**	**Vertical Emit. (nm)**	Transmission
Average emit. at 6GeV	**0.55**	**0.11**	100%
Emittance without blow-up	**0.48**	**0.10**	100%

Linac from 1.54 to 20 GeV

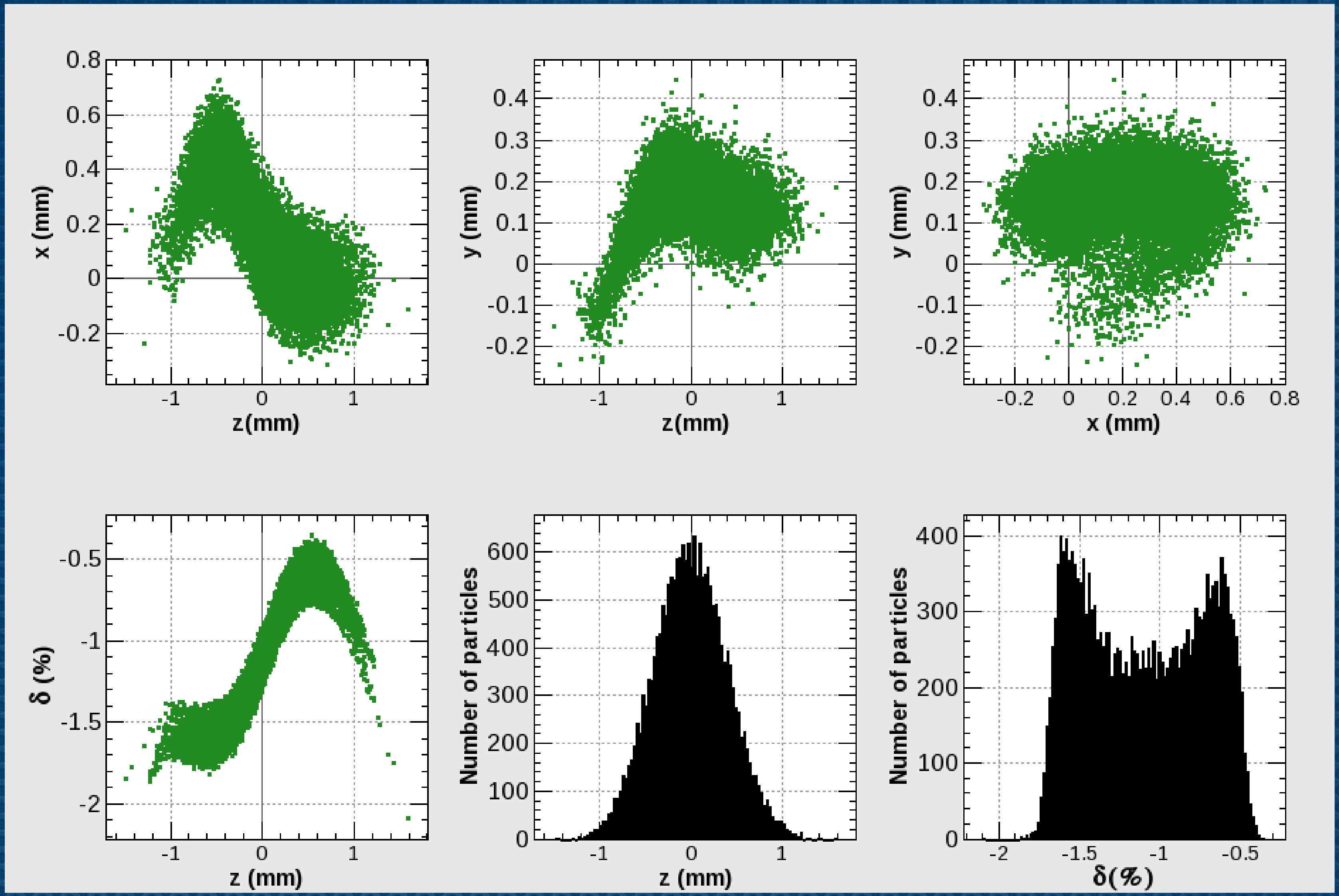
**S. Ogur,
K. Oide**



S-Band structures stop at 6 GeV (QC0 in the optics), then C-band structures start and contunie till 20 GeV.

Linac from 1.54 to 20 GeV

S. Ogur, K. Oide



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

Trial ID	Horizontal Emit. (nm)	Vertical Emit. (nm)	Transmission
Average	1.18	0.05	100%
Emittance w/o blow-up	0.15	0.03	100%

summary of linac simulation results

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.

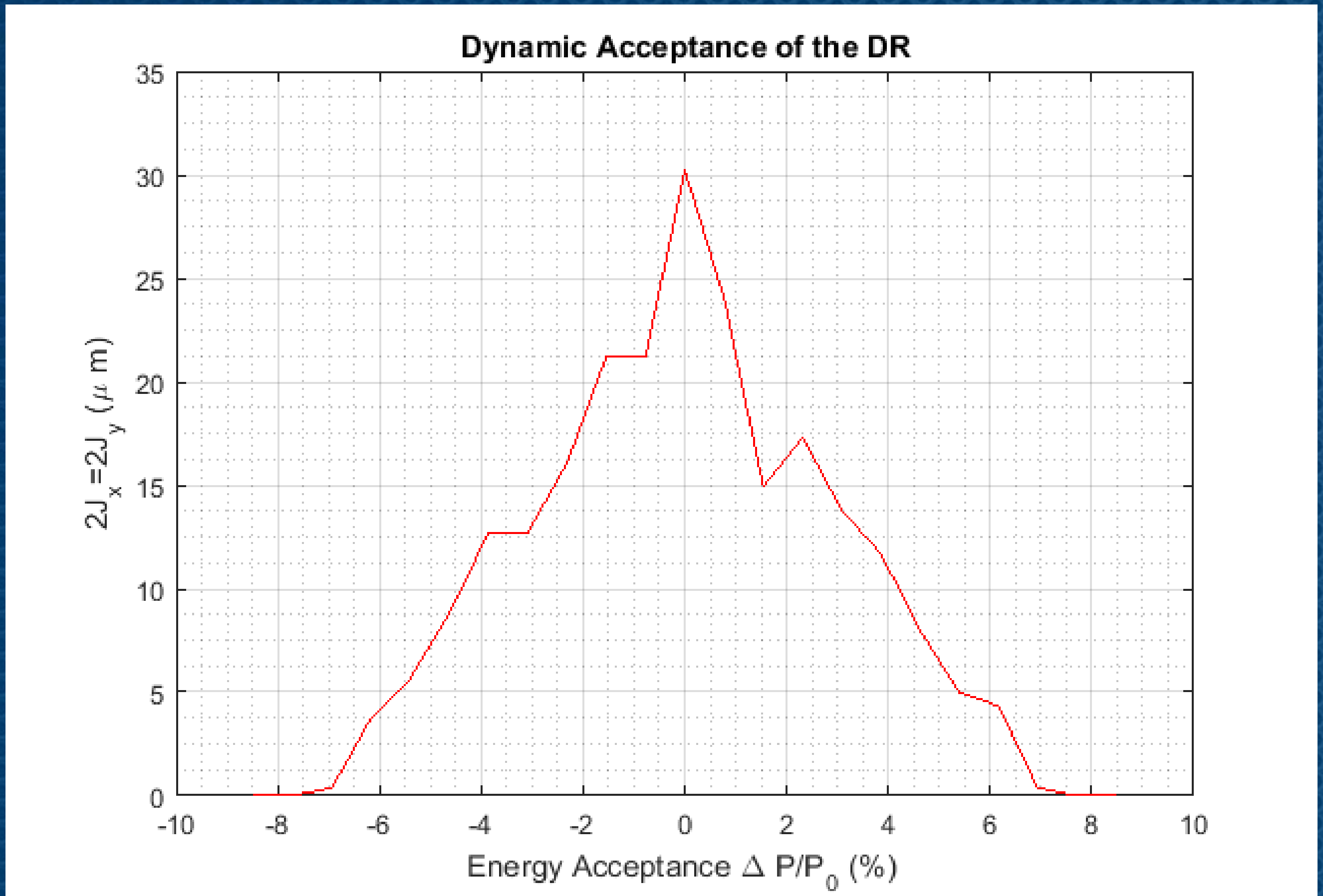
Meets the expectation of the Booster very safely.

†Excluding positron optics.

S. Ogur,
K. Oide

Damping Ring - Dynamic Aperture

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



parameter	value
natural emittance (x, y, z)	1.39 nm, 0.28 nm, 1.75 μm
damping time (τ_x, τ_y, τ_z)	10.6/11.0/5.6 ms
bending radius, wiggler field	7.75 m, 1.8 T
acceptance (x, y, z)	22.4 μm, 22.4 μm, 14.7 mm
energy spread	7.74×10^{-4}
bucket height	8.0 %
energy acceptance	±7.8 %
injected emittance (x, y, z)	1.29, 1.22, 75.5 μm
extracted emittance (x, y, z)	1.81 nm, 0.37 nm, 1.52 μm

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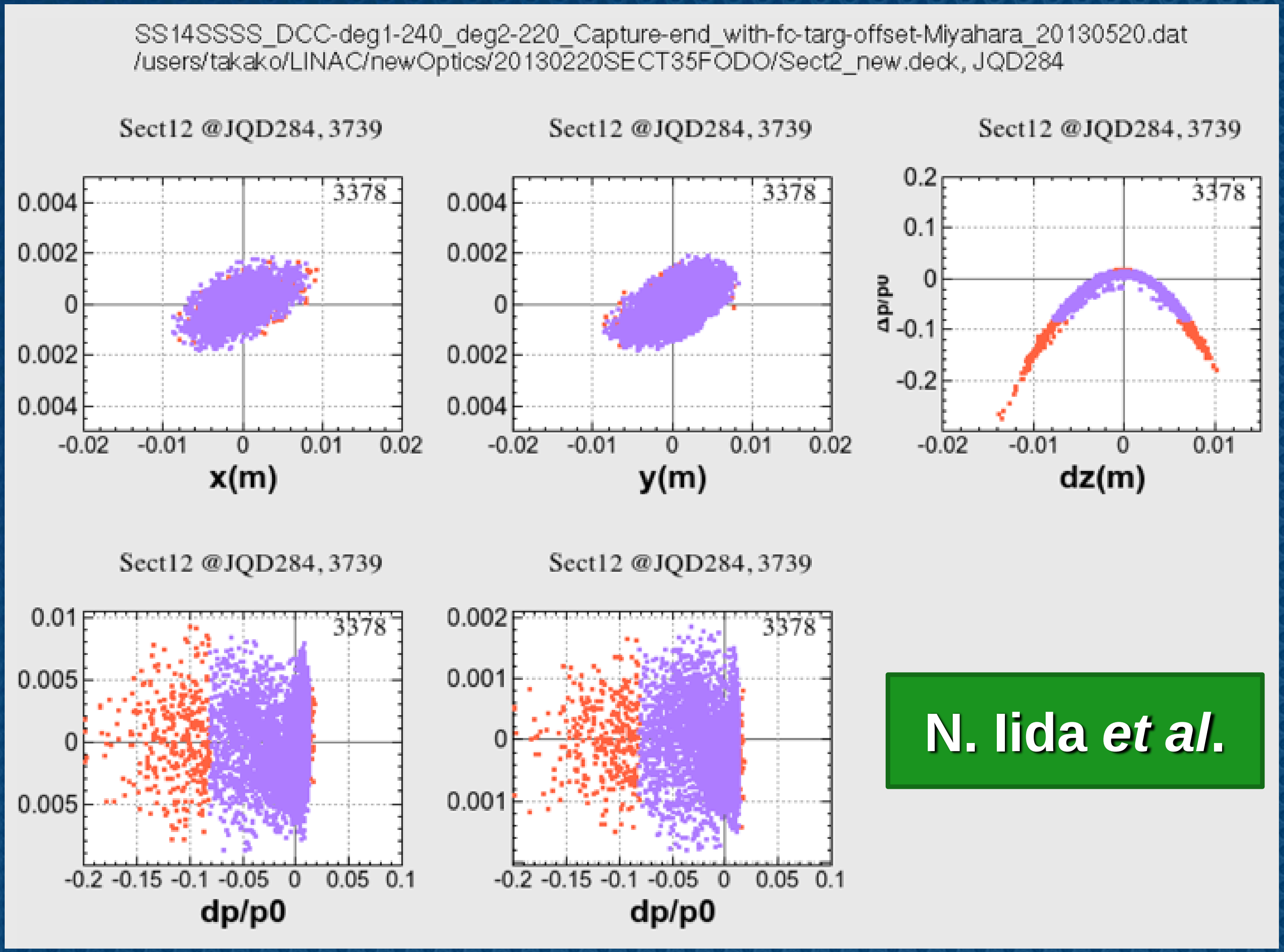
Damping Ring – injecting positrons

S. Ogur



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➞ 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.

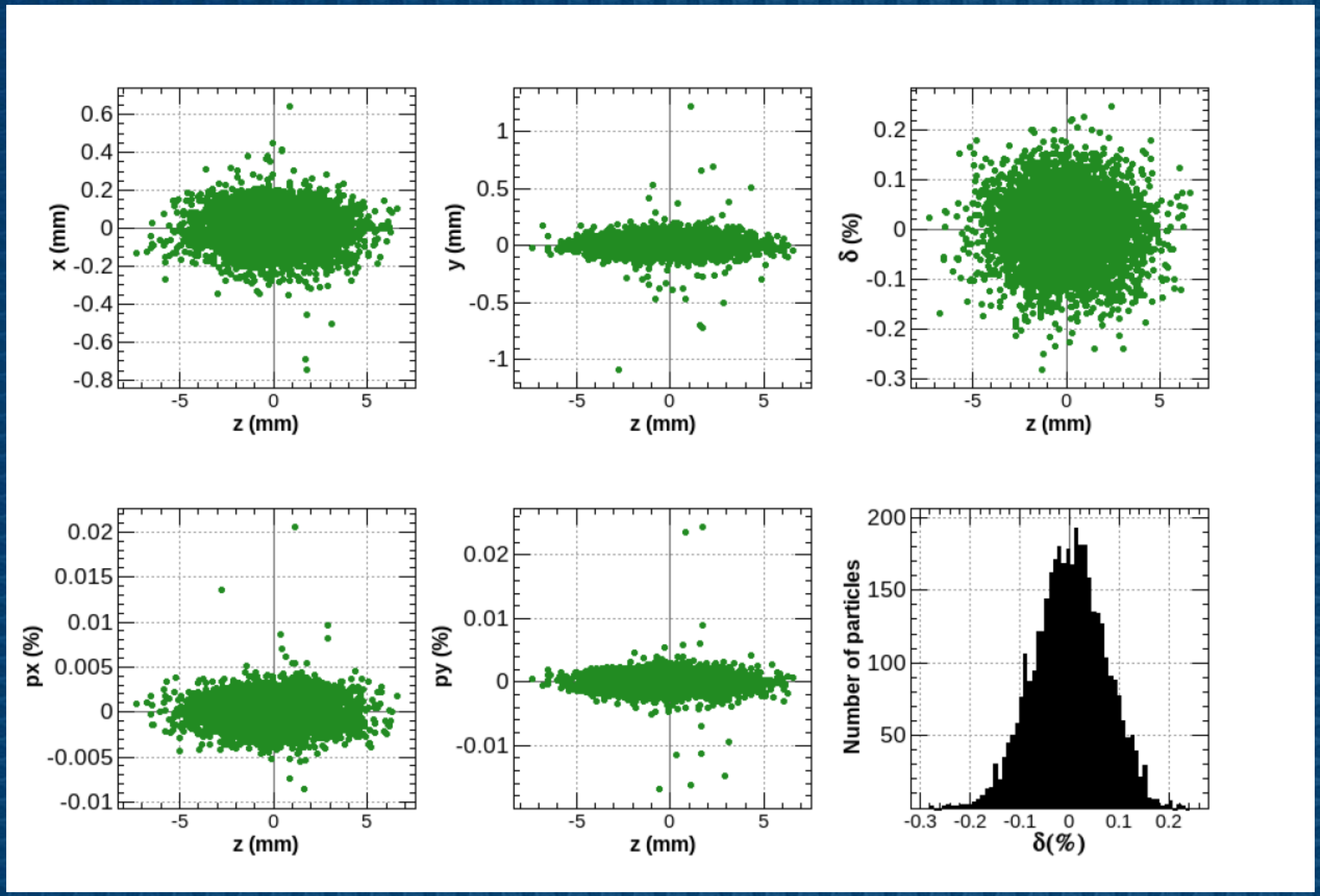
✓ KEK collimates e+, and inject the beam left with ±5% energy spread into the energy compressor.

✓ However FCC-ee damping ring has about ±7.8 % energy acceptance. Therefore, beam can directly be injected without collimation.

Damping Ring - tracking

S. Ogur

❖ Intra-beam scattering is assumed, the misalignment and error study has not been done yet. The beam profile for 40 ms (50k turns).



parameter	value
injected emittance (x, y, z)	1.29, 1.22, 75.5 μm
natural emittance of the ring (x, y, z)	1.39 nm, 0.28 nm, 1.75 μm
extracted emittance (x, y, z)	1.62 nm, 0.99 nm, 1.47 μm
injected bunch length (σ_z)	3.4 mm
extracted bunch length (σ_z)	2.1 mm

❖ The bunch length 2.1 mm can be a problem due to CSR.

Damping Ring - further studies

S. Ogur

- ❖ The bunch length 2.1 mm can be a problem due to CSR.

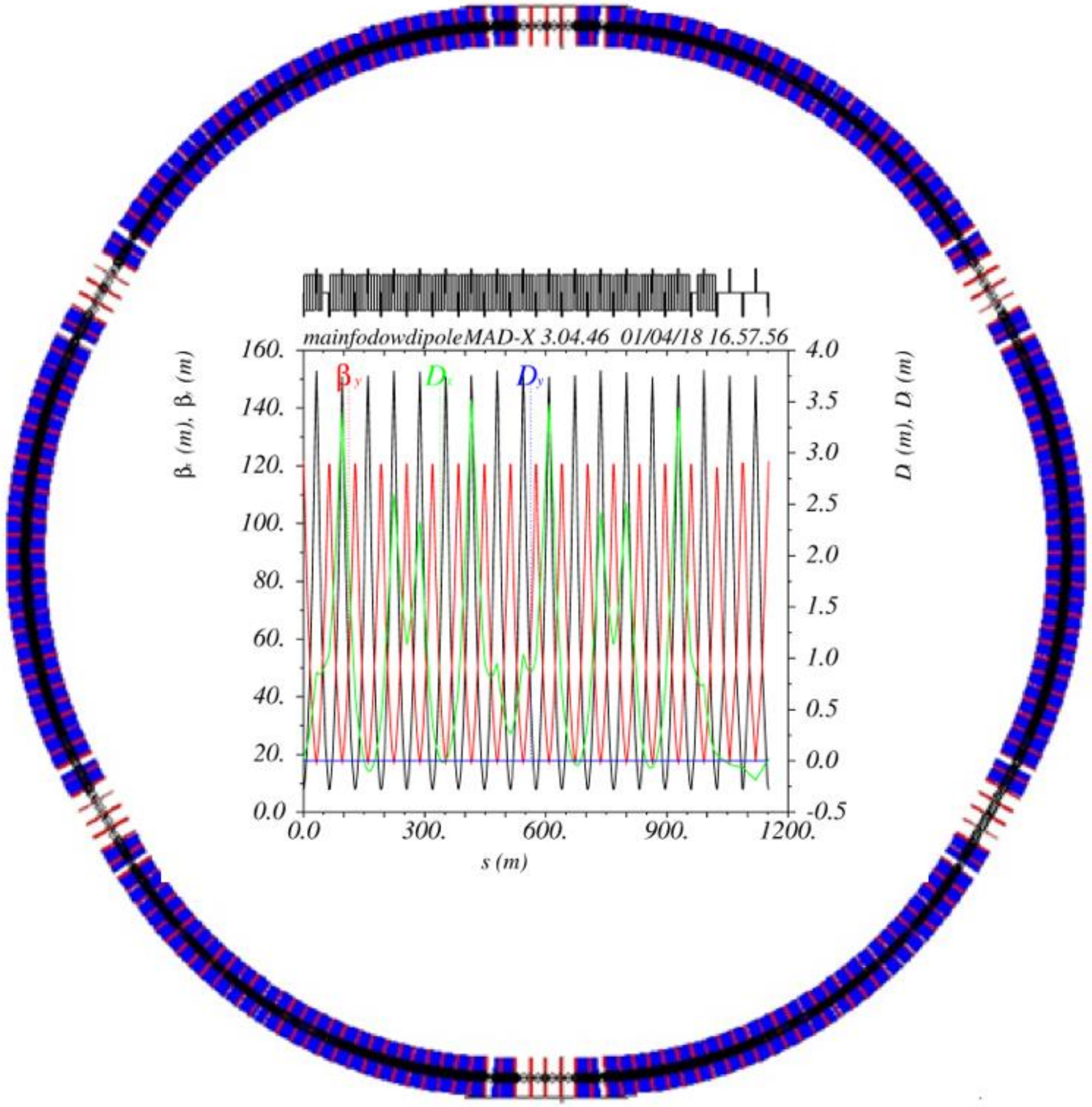
- ❖ The extracted/equilibrium bunch length can be elongated by reducing cavity voltage from
4 MV to 2 MV, so that beam bunch length becomes more than 4 mm.

- ❖ Momentum acceptance of the DR would shrink to 3.8%. Either we need to collimate the incoming positron beam or we need an energy compressor.

- ❖ Since this DR had been designed to host 5 pairs of positrons, the needed kicker was with rise time of 100 ns, now it has to be 50 ns, and bunch spacing should be 50 ns, as well. Yet, this means SPS fill has to be changed (PS: it was prepared for 60 ns bunch spacing in linac).

Pre-booster - SPS

Using the **SPS** as a pre-booster for the FCC e^+e^- imposes some **extra constraints**, as minimum modifications can be applied to the existing machine. The SPS lattice is designed with **FODO** cells and the dispersion suppression is achieved by keeping the total arc **phase advance a multiple of 2π**.



- The ring consist of **6 arcs and 6 straight** sections,
- 6 identical periods; each **super period** is composed of **18 FODO** cells,
- Each super-period is around **1.15 km,**
- The circumference is around **6.9 km,**
- **744 dipoles** with **6.26 m length.**

Main limitations for SPS as FCC e^+e^- PBR: the damping time at injection and the emittance at extraction. Thus, the proposals are:

- to move horizontal phase advance to **3π/4 (Q40)** (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**),
- to insert **wiggler** magnets.

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Pre-booster - SPS

Different extraction energy options are investigated and summarized parameter can be seen below.

	20 GeV option				**18 GeV option**				**16 GeV option**			
	@ injection		*@ extraction*		*@ injection*		*@ extraction*		*@ injection*		*@ extraction*	
	w/ wiggler	*w/ out wiggler*	*w/ wiggler*	*w/ out wiggler*	*w/ wiggler*	*w/ out wiggler*	*w/ wiggler*	*w/ out wiggler*	*w/ wiggler*	*w/ out wiggler*	*w/ wiggler*	*w/ out wiggler*
Emittance (nm.rad)	**1.03**	4.88	**5.92**	54.25	**0.95**	4.88	**5.60**	43.9	0.73	4.88	5.64	34.7
Energy loss per turn (MeV)	**9.96**	0.15	**128.0**	19.09	**6.97**	0.15	**73.9**	12.5	3.49	0.15	31.5	7.82
Damping time (s)	**0.012**	1.79	**0.003**	0.048	**0.01**	1.79	**0.005**	0.06	0.03	1.79	0.01	0.09
Energy spread (%)	**%0.3**	%0.01	**%0.60**	%0.06	**%0.35**	%0.01	**%0.5**	%0.05	%0.3	%0.01	**%0.38**	%0.05
RF Voltage (MV)	**35**		**160**		**30**		**90**		25		40	
Damping wiggler B[T] / L [m]	6 / 12.15				5 / 12.15				**3.5 / 12.15**			
Robinson wiggler B[T] / L [m]	0.5 / 12				0.5 / 12				0.5 / 6			

It becomes clear that the 16 GeV option provides a reasonable energy spread, energy loss per turn and emittance at the same time.

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Pre-booster alternative: New Synchrotron

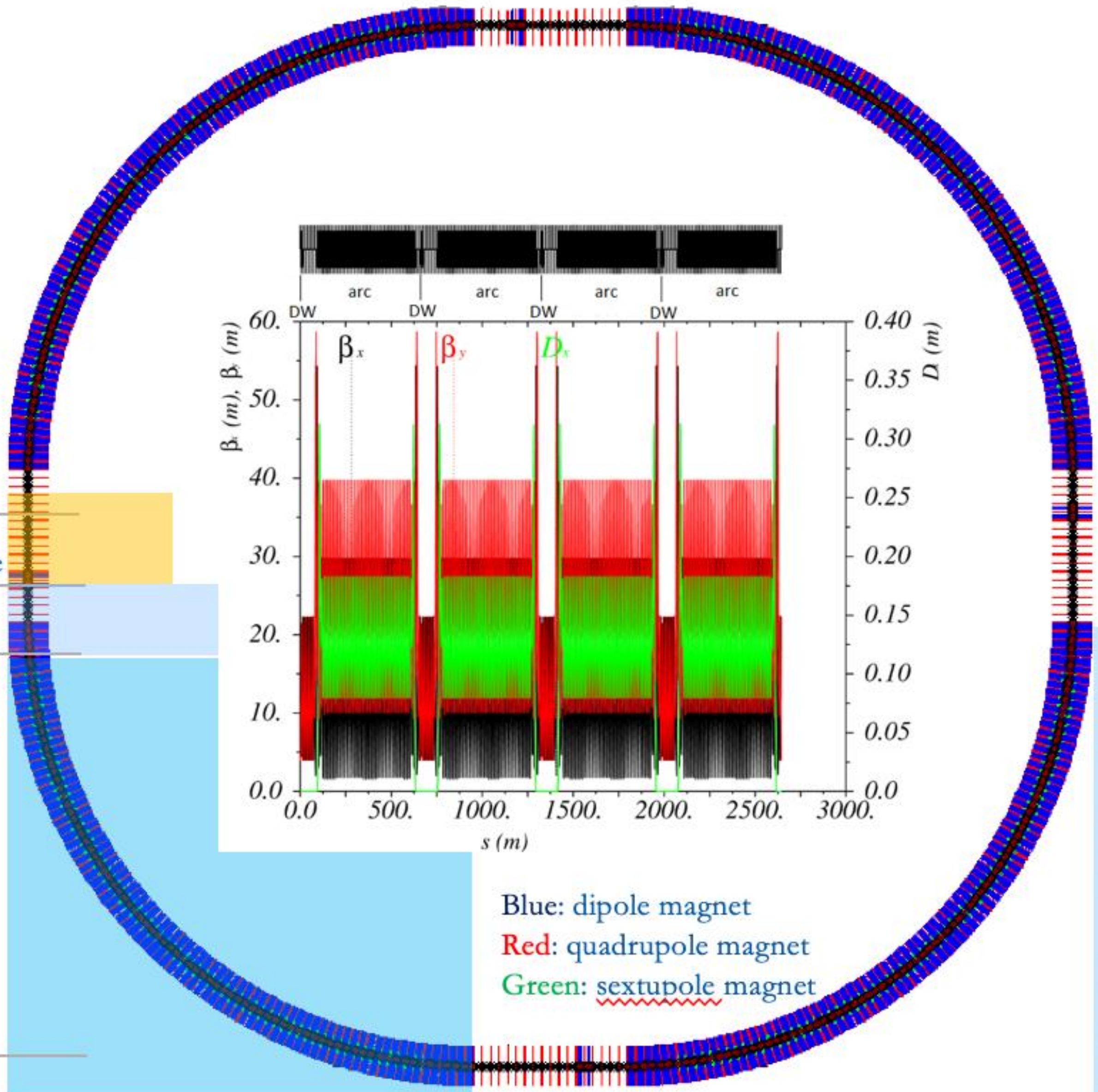
The design of the PBR composes of 4 arcs and 4 straight sections.

Straight sections:
- 5 cells,
- Allocated for
  - Wiggler magnets,
  - RF elements,
  - Injection and extraction elements.

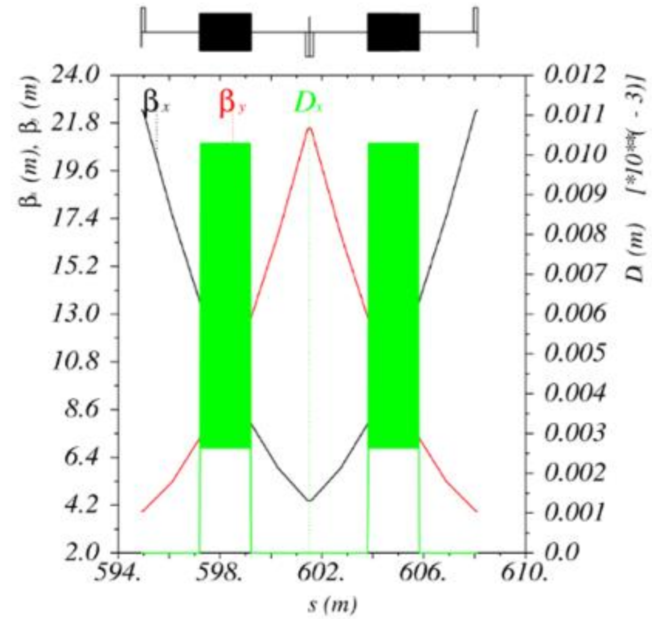
Zero-dispersion section
5 FODO cell with close to 90 degree phase advance

Dispersion suppressor and beta matching area

Arc: 35 FODO cells
Phase advance is
137.8 degree



Blue: dipole magnet
Red: quadrupole magnet
Green: sextupole magnet



Wigglers

1 FODO with wiggler magnet is used to reduce the damping time at the injection energy in each straight section.

Same wiggler structure with CLIC DR:
$B_w = 1.3\ T$
$\lambda_w = 0.05\ m$
$l_w = 2.025\ m$ x 8 wiggler = 16.2 m

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Pre-booster - New Synchrotron

The PBR basically needs to accept the beam from the linac (longitudinally and transversely) and increase the energy up to 20 GeV with the required beam parameters by main booster ring (BR). The **injected parameters** from linac and the **required beam characteristics**, defined by the BR and the linac, are summarized in tables below.

Injected Parameters	Value
Energy [GeV]	6
Emittance (h.) [nm.rad]	0.6
Emittance (v.) [nm.rad]	0.11
Emittance (l.) [μm]	1.1
Energy spread [%]	1.2
Bunch length [mm]	1 (10)

Design Requirements for PBR @Injection	
Energy [GeV]	6
Damping time [s]	0.1
Energy acceptance [%]	1.5
Dynamic aperture (hor.) [mm]	7
Design Requirements for PBR @Extraction	
Energy [GeV]	20
Emittance (hor.) [nm.rad]	5
Energy loss per turn [MeV]	50 (30)
Energy spread [%]	0.3

- ❖ The new synchrotron has 2664 m of circumference.
- ❖ It can satisfy all the requirements of the main booster.

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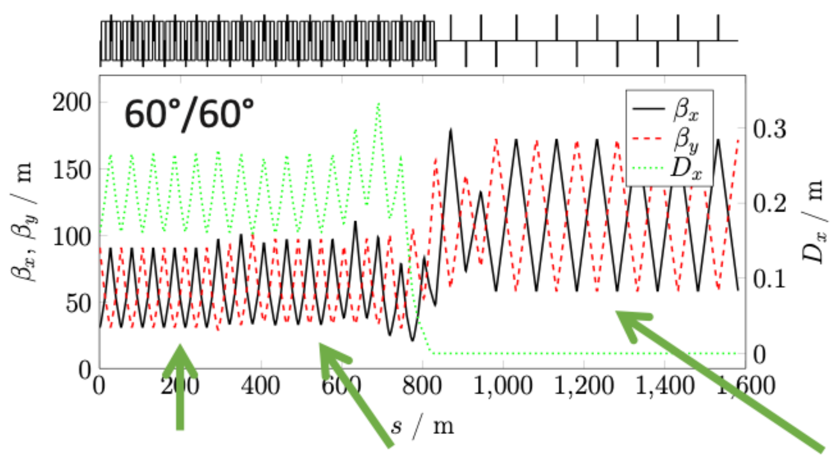
Main Booster

FCC-ee booster: lattice and optics



- 90°/90° optics for *H* an *tt*
- 60°/60° optics for *W* and *Z*

- Non-interleaved sextupole scheme, 1 family per plane

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

- 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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Main Booster

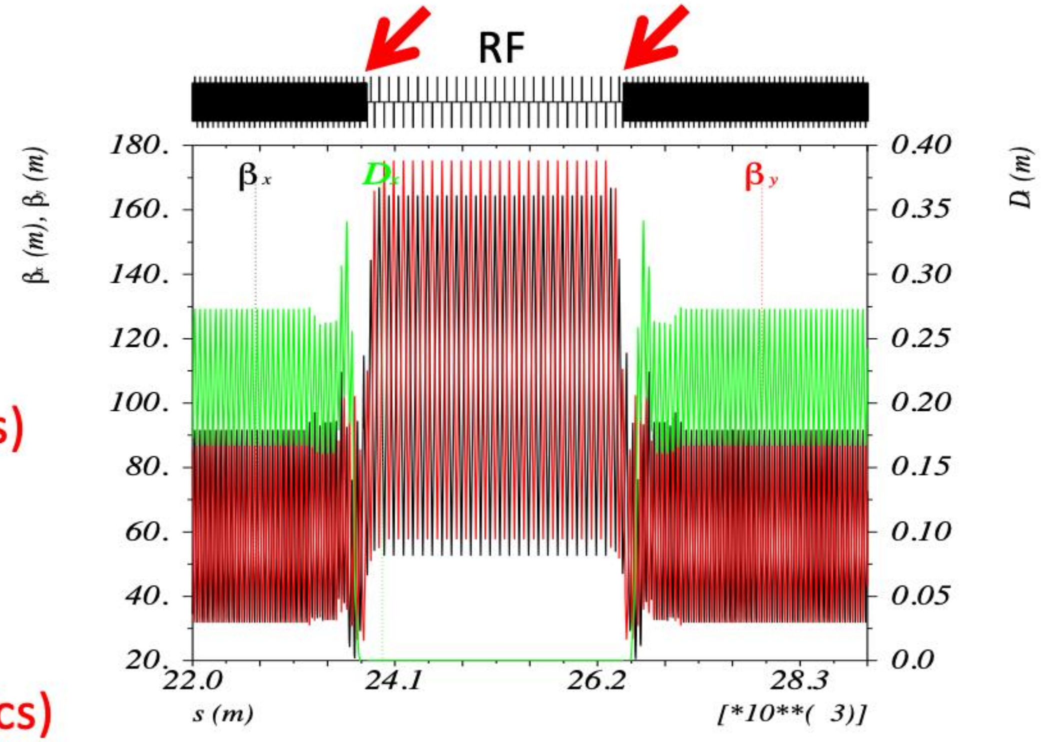
Wiggler magnets

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

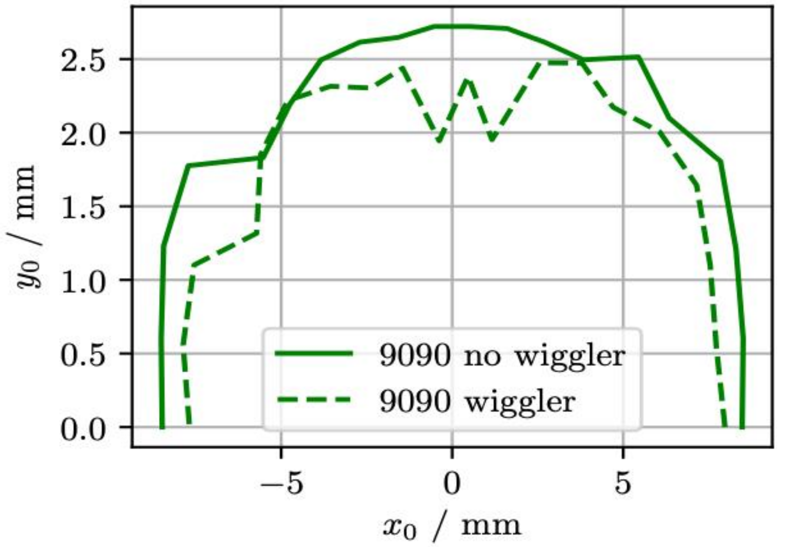
16 wigglers, L = 9.1 m, B = 1.8 T
→ ε_x = 196 pm rad (90°/90° optics)
τ_x = 0.1 s

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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status of ring designs

- Modified SPS with damping and Robinson wigglers is being designed
- Alternative new pre-booster synchrotron is also being designed, with 4 straight sections; satisfying the FCC-ee needs; instability studies are ongoing.
- Booster has large enough dynamic aperture; instabilities are under study.