Update on FCC-ee filling schemes

H. Bartosik, X. Buffat, C. Carli, A. Chance, P. Craievich,
H. Damerau, A. De Santis, A. Grudiev, W. Höfle, I. Karpov, J. Keintzel,
A. Latina, L. Mether, C. Milardi, Y. Papaphilippou, K. Oide,
T. Raubenheimer, L. Sabato, L. Valle, A. Vanel, F. Zimmermann

Latest FCC-ee collider parameter table

- Updated number of bunches for all modes (apart from W-mode)

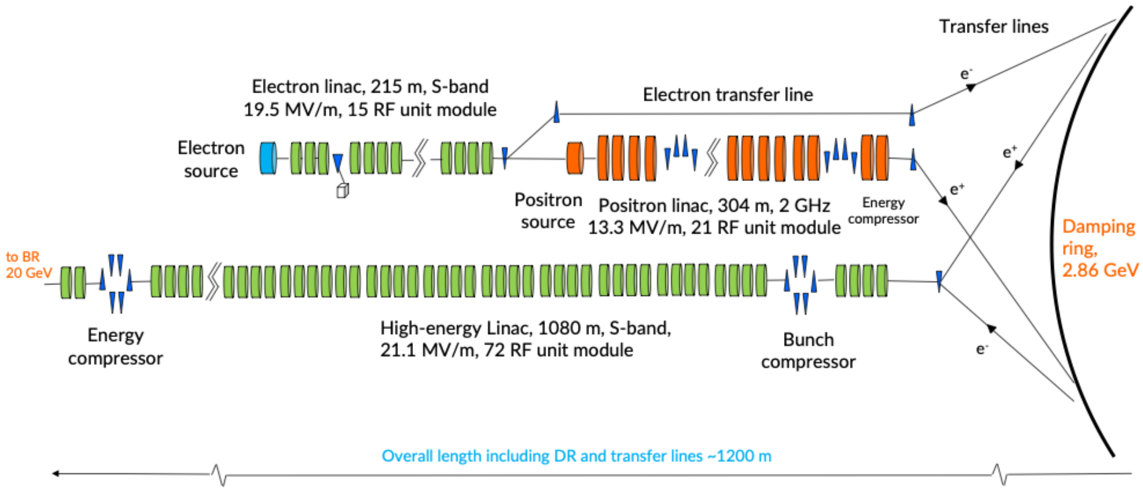
FCC-ee collider parameters for the GHC lattice. May 20, 2025.

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658499		90.658526[a]	
Bend. radius of arc dipole	[km]	10.021			
Energy loss / turn	[GeV]	0.0390	0.370	1.86	9.99
SR power / beam	[MW]	50			
Beam current	[mA]	1281	135	26.8	5.0
Colliding bunches / beam		12000	1852	292	60
Colliding bunch population	[10^{11}]	2.02	1.35	1.74	1.57
Hor. emittance at collision ε_x	[nm]	0.74	2.25	0.75	1.69
Ver. emittance at collision ε_y	[pm]	1.84	1.96	1.05	1.39
Lattice v. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.64	1.17	0.56	0.81
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.55		7.31	
Arc sext families		73		144	
$\beta^*_{x/y}$	[mm]	90 / 0.7	220 / 1	240 / 1	900 / 1.4
Transverse tunes $Q_{x/y}$		214.168 / 214.200	218.179 / 222.241	394.150 / 390.221	394.148 / 390.218
Chromaticities/ring $Q'_{x/y}$		+12 / +5	0 / +3	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.0395 / 0.1133	0.070 / 0.106	0.102 / 0.180	0.158 / 0.192
Bunch length (SR/BS) σ_z	[mm]	5.22 / 15.0	3.42 / 5.19	3.18 / 5.56	1.86 / 2.26
RF voltage 400/800 MHz	[GV]	0.0885 / 0	1.00 / 0	2.10 / 0	2.10 / 9.18
Harm. number for 400 MHz		121200			
RF frequency (400 MHz)	MHz	400.788075		400.787954	
Synchrotron tune Q_s		0.0310	0.0807	0.0338	0.0873
Long. damping time	[turns]	1168	217	65.5	19.2
RF acceptance	[%]	1.20	3.32	2.14	2.94
Energy acceptance (DA)	[%]	±1.0	±1.0	±2.0	-2.8/+2.5
Beam crossing angle at IP θ_x	[mrad]	±15			
Crab waist ratio	[%]	55	45	45	40
Beam-beam ξ_x/ξ_y[b]		0.0018 / 0.0955	0.0132 / 0.131	0.0108 / 0.130	0.067 / 0.140
Piwinski ang. $(\theta_x \sigma_{z,\mathrm{BS}})/\sigma^*_x$		27.6	3.5	6.5	0.87
Lifetime (q + BS + lattice)	[sec]	4500	3600	4600	9400
Lifetime (lum)[c]	[sec]	1320	960	600	650
Luminosity / IP /10^{34}	[/cm^{2}s]	141	20	7.5	1.43

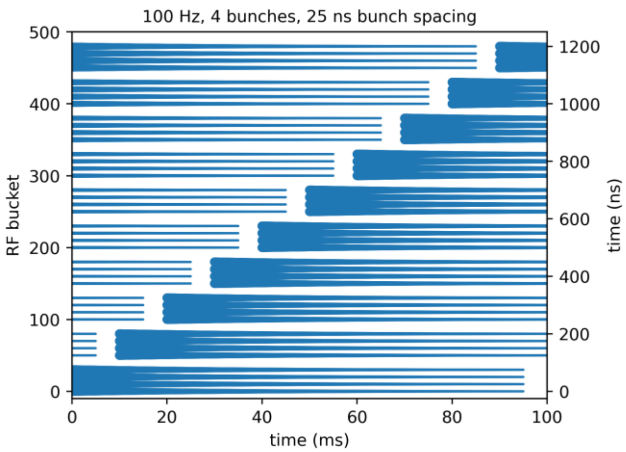
See presentation of K. Oide

Sketch of the pre-injector complex

- **FSR baseline: Pre-injectors** (linacs and damping ring) provide pulses of **4 bunches with 25 ns bunch spacing, at 100 Hz repetition rate** (see presentation of P. Craievich and for damping ring design presentation of A. De Santis)



Beam preparation in damping ring

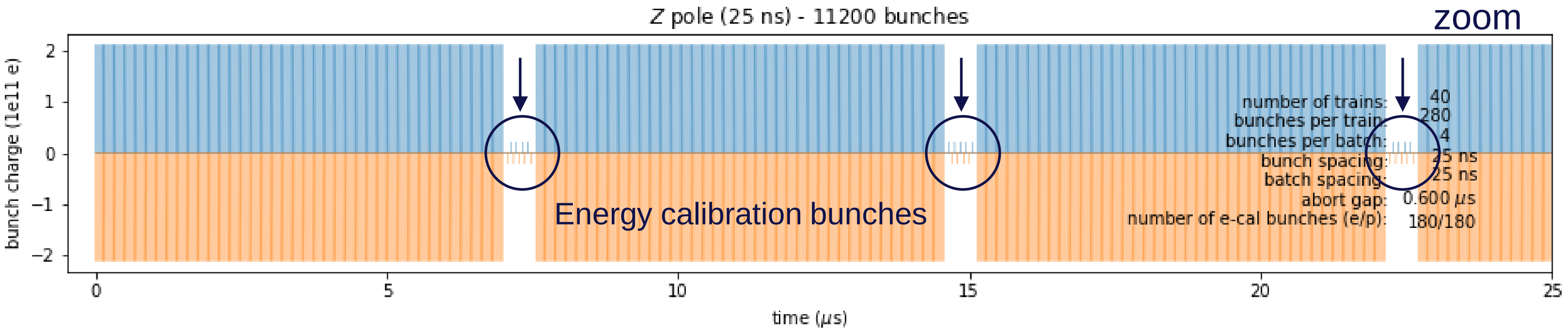


Filling scheme requirements and assumptions

- **Harmonic number** $h_{25} = 12\,120 = 2^3 \cdot 3 \cdot 5 \cdot 101$ (in terms of 25 ns slots)
  - Not yet considering exotic schemes with bunch spacings down to 5 ns (from e-cloud studies)
- High intensity **physics bunches colliding in all four experiments**
  - Filling pattern with periodicity of at least two (any pair number of equal trains works)
- **Large number of trains** with minimum length of gaps (kicker) **for Z-mode**
  - Minimizes beam loading transients leading to bunch length and synchrotron tune variations
- **No collisions in common RF section for ZH and $t\bar{t}$ mode** (smallish number of bunches)
- **Batches from injector containing four bunches for Z and W and two for high energies**
- **Energy calibration low intensity bunches for Z and W** (in gaps of lumi production bunches)
  - Not colliding in IPs, minimum spacing of 100 ns (excitation of depolarization on individual bunches)
- **Lower intensities in the Booster synchrotron**
  - Cures many collective effects (instabilities, electron cloud …)
  - Mitigation of machine protection issues (transfer Booster to Collider)

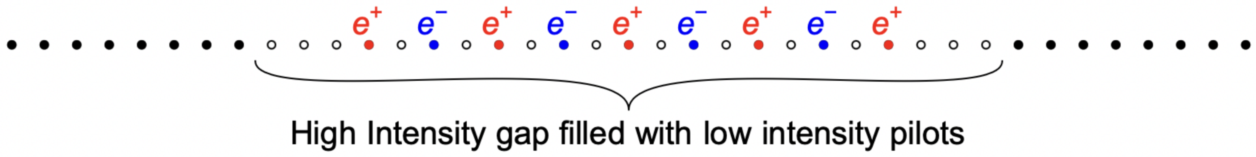
Z-pole: filling pattern

Update from scheme presented at last FCC week with 40 instead of 20 trains and shorter gaps to mitigate beam loading transients



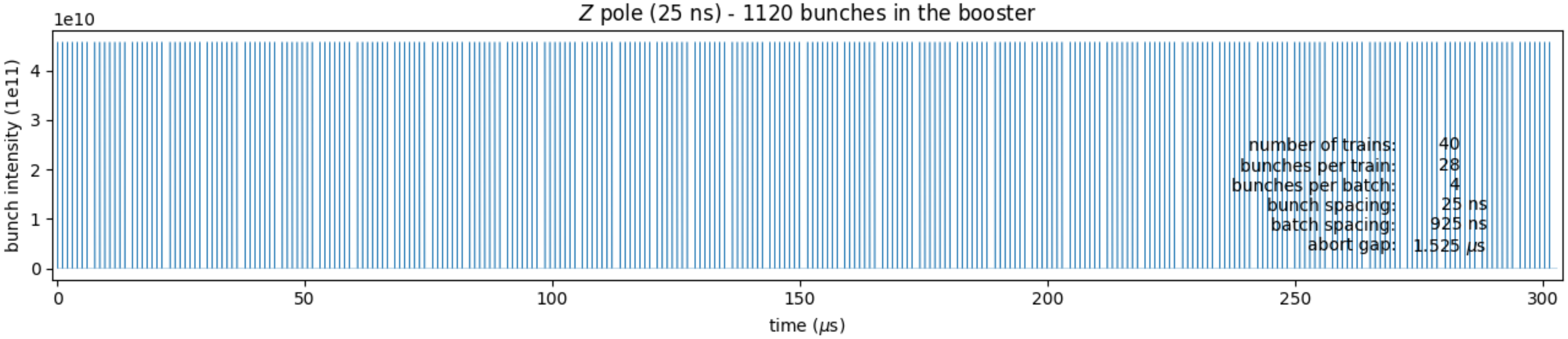
- Latest parameter table (see presentation of K. Oide) assumes $N_B = 12\,000$ bunches, filling scheme still to be updated (impact of shorter kicker gap on kicker design to be addressed)
- Number of bunches assumed here: $N_B = 11\,200 = 2^6 \cdot 5^2 \cdot 7$
  - Number of trains: $N_T = 2^3 \cdot 5 = 40$ each containing $N_T = 2^3 \cdot 5 \cdot 7 = 280$ high intensity bunches
  - Gaps with 23 empty positions, i.e. $600\ \mathrm{ns}$, for kickers (work on-going on shorter rise and fall times)
  - Most of these gaps used for energy calibration bunches

Z-pole: energy calibration bunches

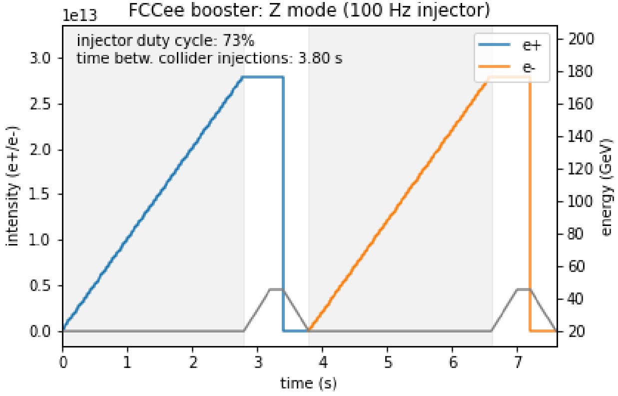


- **Filling gap with low intensity bunches for energy calibration**
  - Five bunches of one type (say e^+) and four bunches of other type (say e^-) per gap
  - **Alternating gap filling pattern** and filling all gaps allow to have $20 \cdot 5 + 20 \cdot 4 = 180$ bunches of either type
  - **Not filling four equidistant gaps** would allow, e.g., $18 \cdot 5 + 18 \cdot 4 =$ **162 bunches of either type**

Z-pole: beam from the booster

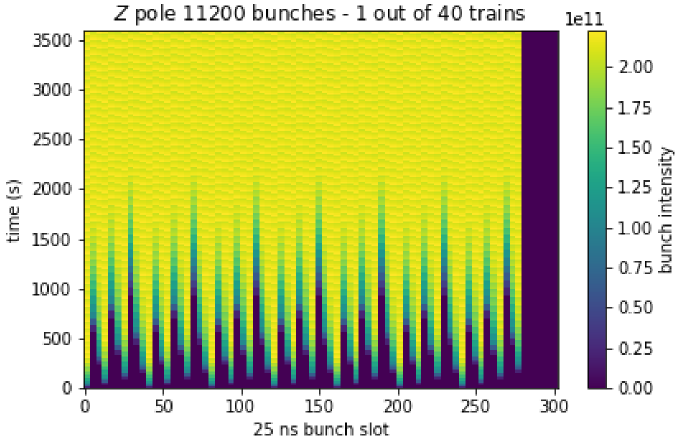


- **Booster filling pattern** (example)
  - **1/10th of bunches, with 1/10th intensity w.r.t. collider to** respect **machine protection constraints**
  - **Distribute bunches to minimize beam loading & collective effects** (e.g. e-cloud)
- Alternating booster cycles for top-up of e^+/e^- beams

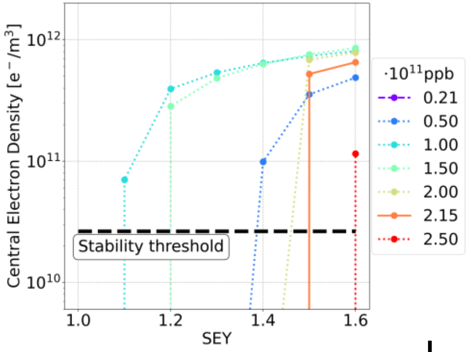


Z-pole: non-uniform bootstrap injection

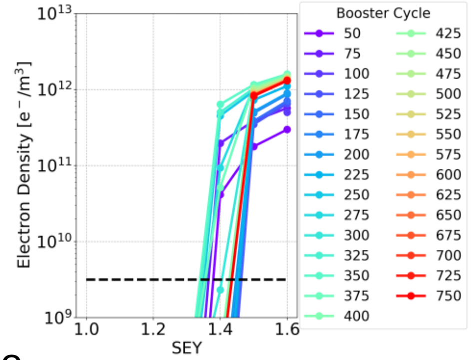
- **The present baseline scheme accumulates bunch families in non-uniform way**
  - Optimized to mitigate e-cloud effects for 25 ns bunch spacing encountered at critical intermediate bunch population (see presentation of L. Sabato)
  - However, avoiding X-Z instabilities is challenging as the stable horizontal tune changes significantly as function of bunch population (see presentation of R. Soos) + tune shifts from impedance (see presentation of C. Zannini)



Long trains with 25 ns bunch spacing: intermediate bunch population unstable

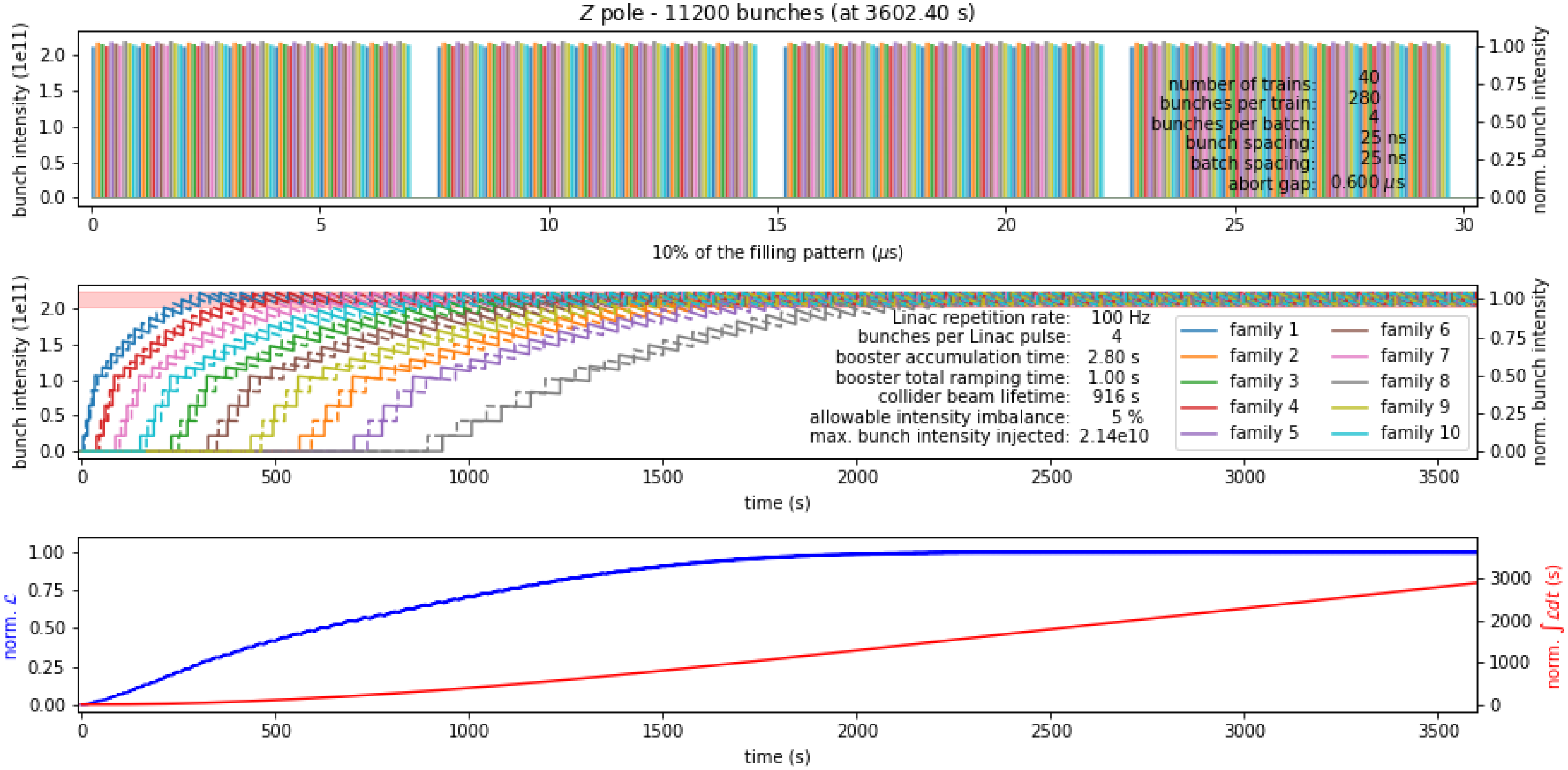


e-cloud instability avoided by special accumulation scheme



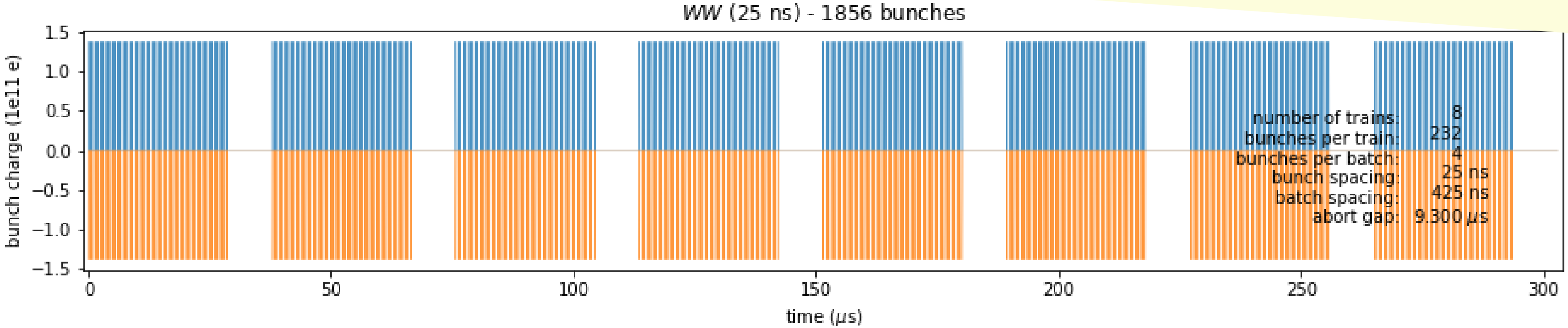
L. Sabato

Z-pole: boot-strap and top-up injection

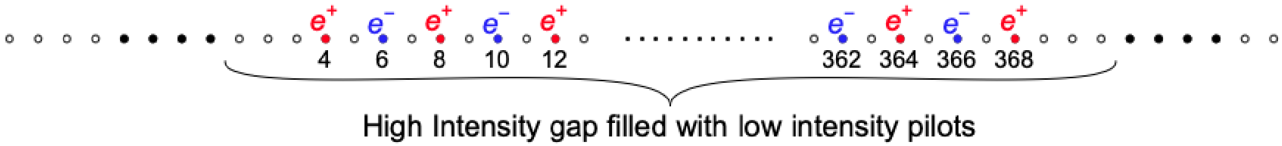


W-mode: filling pattern

Different from scheme pattern presented at the FCC week (eight instead of four trains) and equally possible

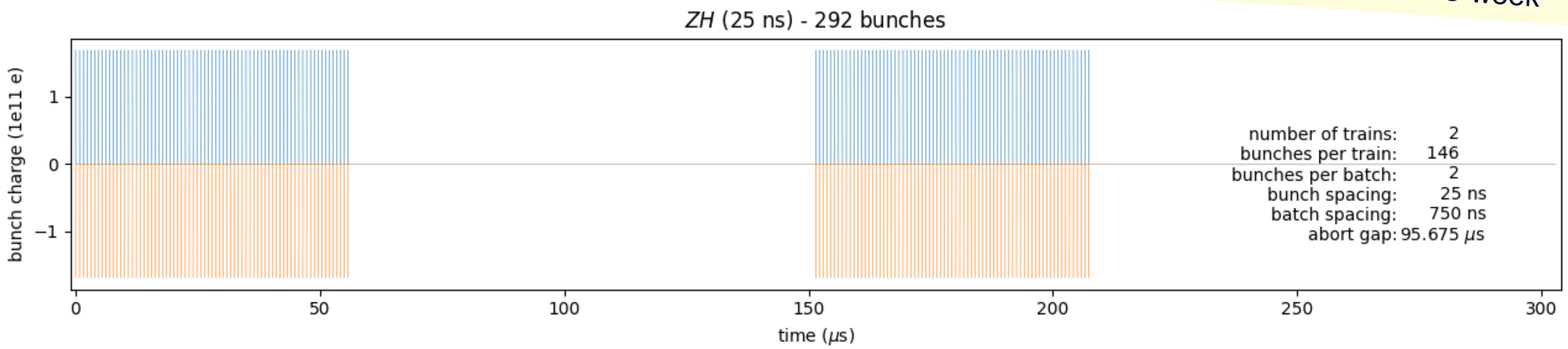


- **Number of bunches:** $\boldsymbol{N_B = 1\,856 = 2^6 \cdot 29}$ (four more bunches than in parameter list)
  - Number of trains: $\boldsymbol{N_T = 2^3 = 8}$ **each containing each** $\boldsymbol{2^3 \cdot 29 = 232}$ **high intensity bunches (**58 batches containing four bunches with 16 empty positions between them)
- **Many options to place low intensity energy calibration bunches,** e.g. two opposite gaps filled with below pattern gives 184 e^+ and 182 e^- bunches



ZH-mode: filling pattern

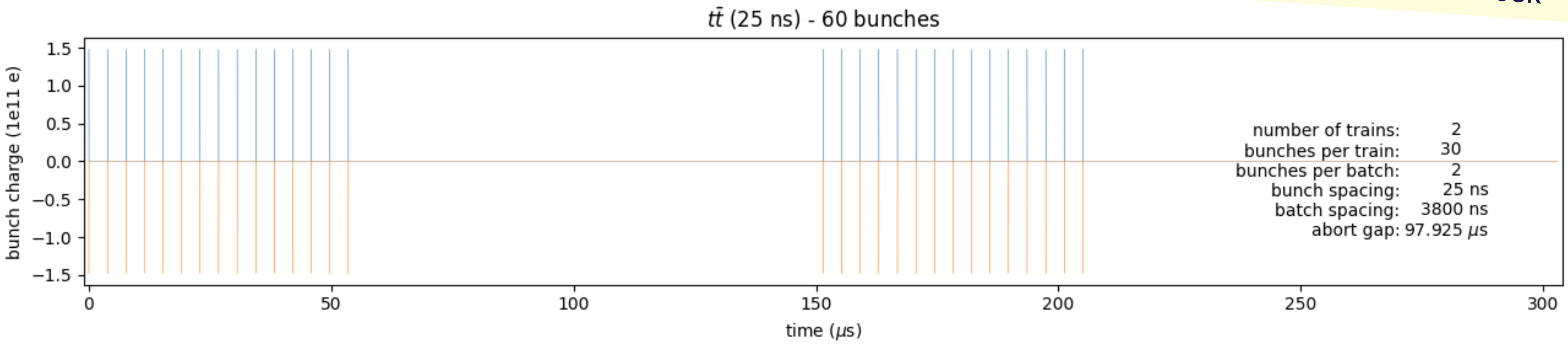
Updated number of bunches compared to last FCC week



- **Injector running with 50 Hz and 2 bunches per cycle**
- **No bunch crossings in RF section!**
- **Number of bunches:** $\boldsymbol{N_B = 292} = 2^2 \cdot 73$
  - Number of trains: $N_T = 2$ each containing each $2 \cdot 73 = 146$ high intensity bunches
  - 73 batches containing two bunches with 29 empty positions between them
- Filling and top-up for all 292 bunches (of one species) using the same booster cycle

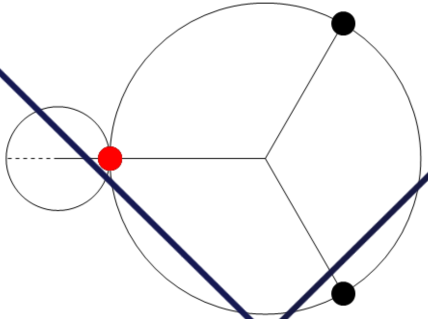
$t\bar{t}$ -mode: filling pattern

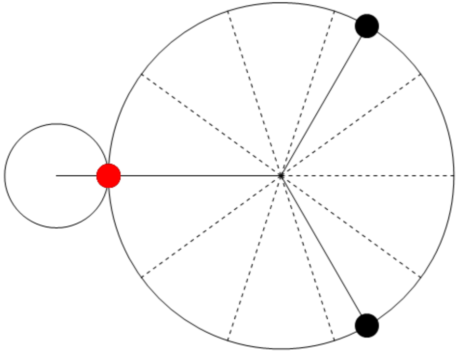
Updated number of bunches compared to last FCC week



- **Injector running with 50 Hz and 2 bunches per cycle**
- **No bunch crossings in RF section!**
- **Number of bunches: $N_B = 60 = 2^2 \cdot 3 \cdot 5$**
  - Number of trains: $N_T = 2$ each containing each $2 \cdot 3 \cdot 5 = 30$ high intensity bunches
  - 15 batches containing two bunches with 151 empty positions between them
- Filling and top-up for all 60 bunches using one and the same booster cycle

Ongoing studies on injector synchronisation (1)





H. Damerau

Integer ratio, $r = C_{booster}/C_{DR}$ of circumfs.

→ Due to cog-wheeling, only r azimuthal booster positions can be reached

→ Transfer possible at each booster turn

→ Required flexibility of positioning batches in damping up to ± 180° (only single batches are possible), or performing cogging (rephasing through energy variation in damping ring)

Rational ratio, $r = C_{booster}/C_{DR} = m/n$ of circumfs.

→ n times more azimuthal positions can be reached at expense of transferring within range of n booster turns

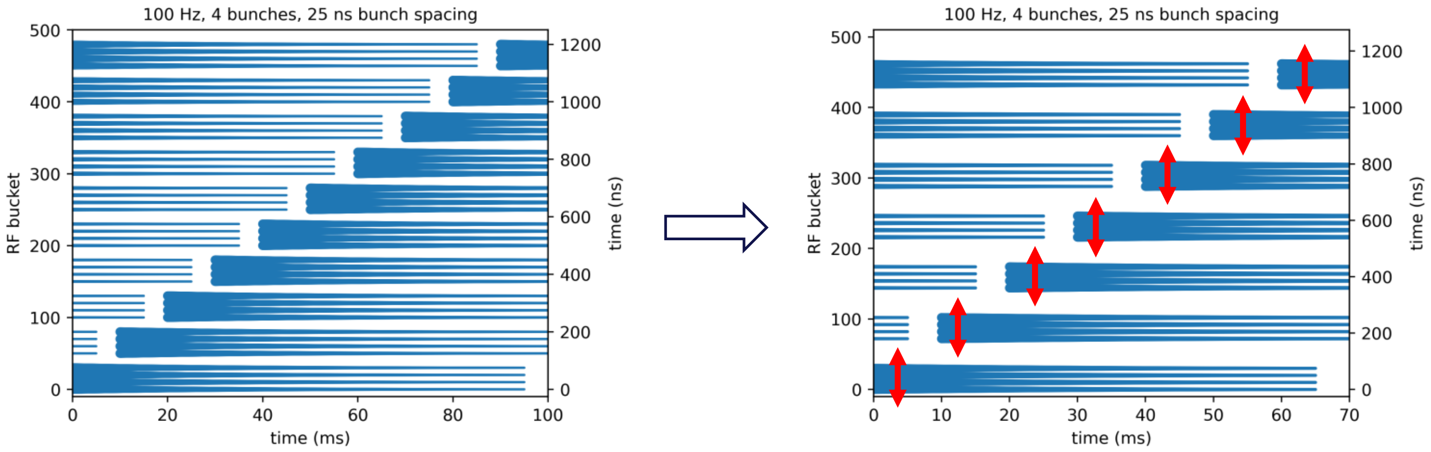
→ Requires pulsing Linacs and pre-injector complex non-periodically (from zero to n booster turns)

→ Required flexibility of positioning batches in damping ring reduced to ~ ±180°/n (assuming fixed RF frequency in damping ring)

Ongoing studies on injector synchronisation (2)

- **Choice of $r = C_{booster}/C_{DR} = m/n$ is extremely constrained close to targeted C_{DR}**
- **Possible choice: $r = C_{booster}/C_{DR} = 4040/17$ → $h_{25,DR} = 51$ (FSR had $h_{25,DR} = 50$)**
  - **Injection into booster over 17 booster turns (corresponding to time window of ~5 ms)**
  - **Only 7 trains can be stored** to accommodate required **flexibility of bunch slots offset from 0 to 2 (with kicker risetime of 55 ns) → faster damping required**

To be studied in more detail



Summary and conclusions

- **The present filling scheme for the Z-pole assumes non-uniform bootstrap injection to mitigate e-cloud instabilities**
  - Not yet updated to latest FCC-ee parameter table (7% more bunches)
  - This scheme is challenging for tune shifts and X-Z instabilities due to large range of bunch populations present in the machine (not possible to find a suitable working point for all bunches)
  - Alternative schemes with bunch spacings down to 5 ns have not yet been studied (this has strong implications for injector complex)
- **Updated filling patterns for W, ZH and tt – no particular issues**
- **Started looking into synchronisation between pre-injectors and booster**
  - **Preferred option** is careful choice of rational ratio $C_{booster}/C_{DR} = m/n$
  - To be able to guarantee full flexibility of generating filling patterns, **transfer from pre-injectors to booster within a time window (e.g. 5.2 ms)** resulting in **modulation of Linac pulsing** (with average pulsing every 10 ms = 100 Hz)