FCCee filling schemes

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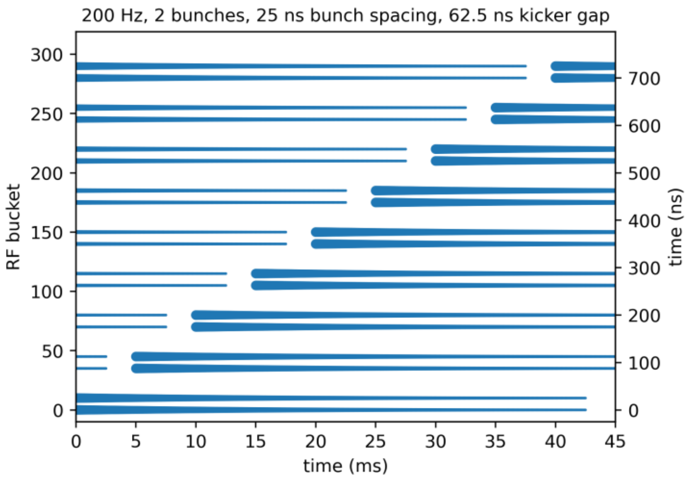
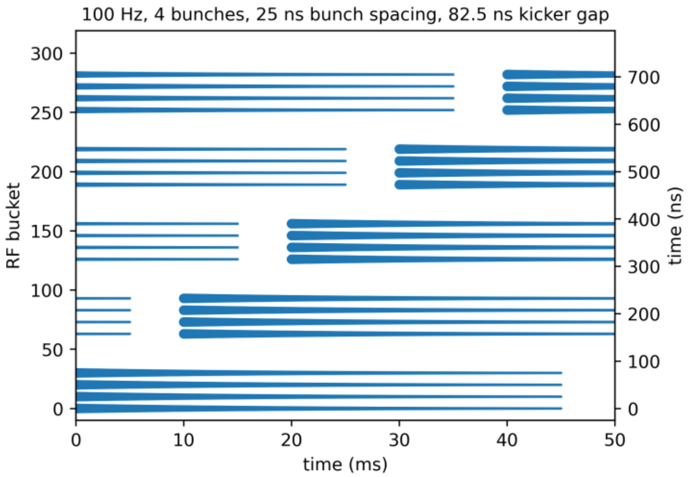
Outline

- Quick introduction to beam production scheme for FCCee
- Refining the filling scheme for Z-pole operation
  - CDR filling scheme
  - New proposal with 1/10th of bunches at each booster-to-collider transfer
- Filling schemes for WW, H, ttbar
- Summary & conclusions

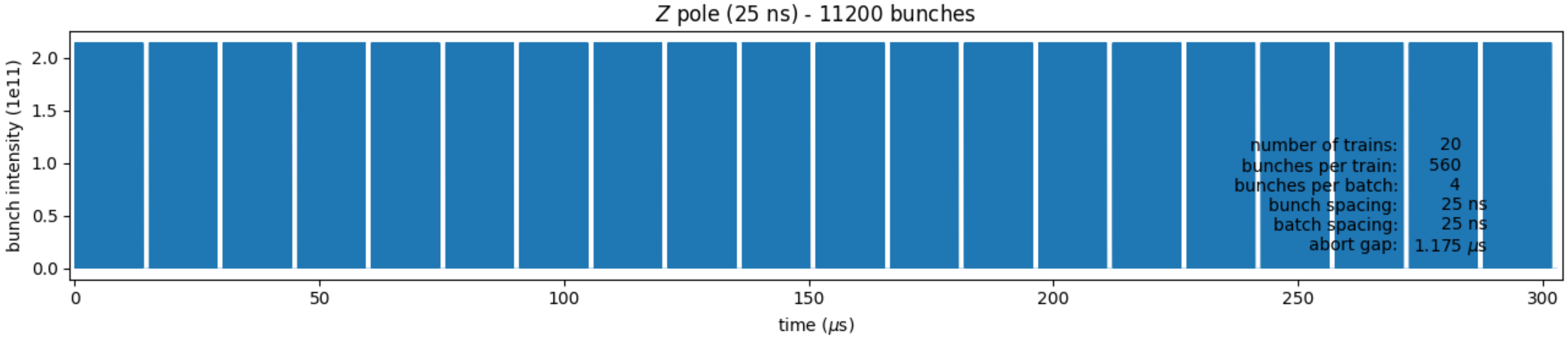
Pre-injector

- CDR scheme is based on Linac producing 2 bunches (25 ns spacing) at 200 Hz
  - **Damping ring at 1.54 GeV used for e^+ only**
  - Staggered injection, storage for ~42.5 ms (4 damping times), staggered extraction (first in first out)
- New proposal with Linac producing 4 bunches (25 ns spacing) at 100 Hz
  - **Damping ring at 2.86 GeV used for both e^+ and e^-** (see presentation of P. Craievich)



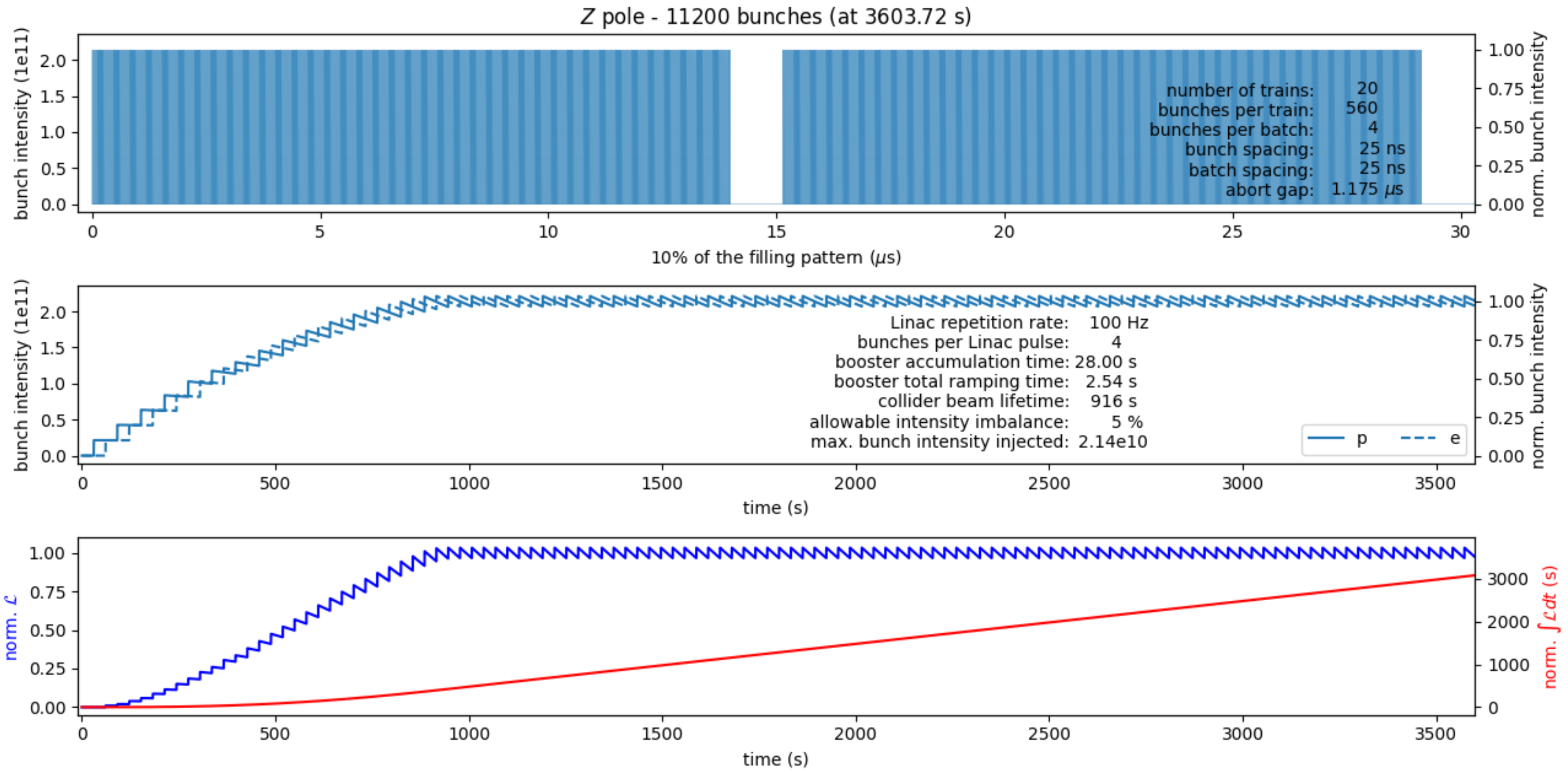


Z-pole collider filling pattern (baseline 25 ns)



- **20 gaps of 1175 ns** (abort gaps, non-colliding witness bunches for energy calibration)
  - Machine protection requires more than 1 gap for fast abort – maybe 4? … to be defined
  - **Non-colliding bunches for energy calibration** through depolarization: 10 per gap with 100 ns spacing (10-16 gaps available → **100-160 bunches**)
- **CDR scheme**
  - Filling pattern of booster is a mirror of the collider filling scheme
  - Booster is alternating between e^+ and e^- cycles

CDR scheme: all bunches at each transfer



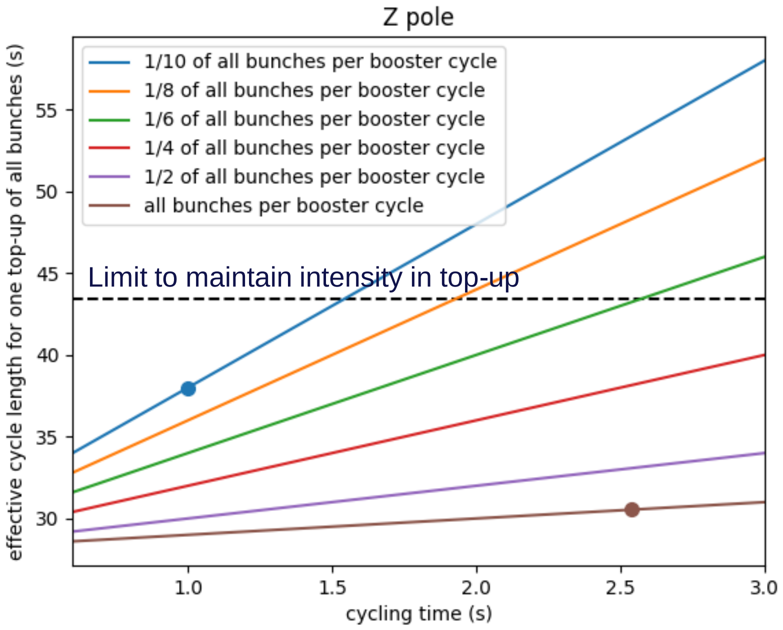
New scheme: transferring 1/10th of all bunches

- **A smaller number of bunches in each booster cycle has several advantages:**
  - **Machine protection considerations only allow for about 1/10th of all bunches, i.e. 1120** (each with max. 1/10th of nominal collider bunch intensity) injected into collider at once **at Z energy**
  - **Shorter booster injection plateau**
    - **relaxes required vacuum quality** for tolerable emittance growth from **rest gas collisions**[1)]
    - **reduces the impact of IBS on early injected bunches, less time needed for damping at high energy in the booster**[2)]
  - Allows to **distribute bunches along booster circumference**
    - **relaxes fast beam ion instability** and tune shifts for electron beam[1,3)]
    - **relaxes required RF power for beam loading compensation**[4)]
    - **Can also be exploited to optimize filling of collider to mitigate e-cloud for positrons**
  - **Smaller variation of average luminosity** of all bunches
  - Allows for **faster reaction time for topping up critical bunches** in case needed

1) F. Zimmermann, presentation at FCCee booster meeting
2) presentation of A. Ghribi
3) L. Mether, FCC week 2023
4) presentation of A. Vanel

Impact on effective booster cycle length

- Booster ramping time affects time required for top-up of all bunches ("effective cycle length")
- **We aim at 1/10th of all bunches in each booster cycle, with a total ramping time of 1 s**



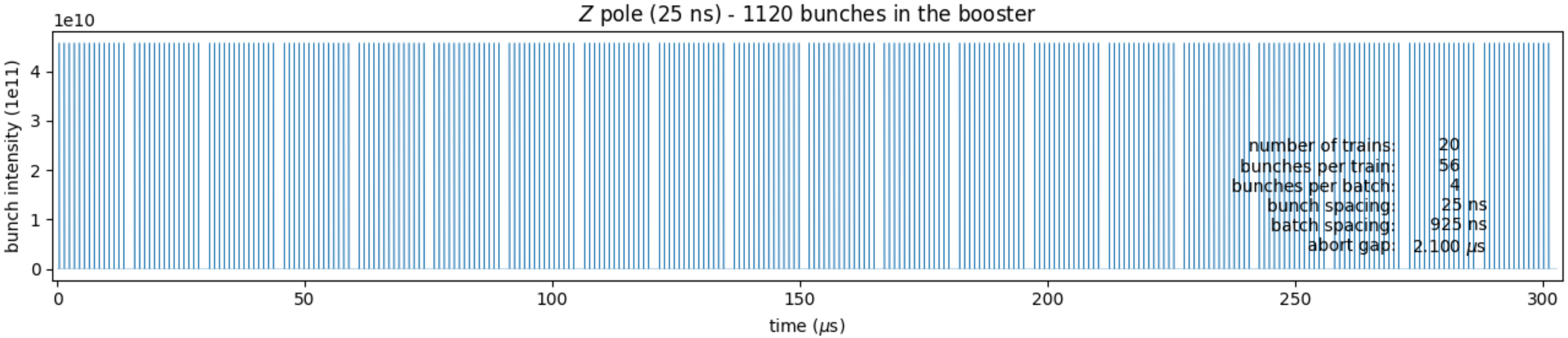
Original scheme

- all bunches transferred at once
- Ramping 0.64 s + flat top 1.9 s
- Cycle length of 28 s + 2.54 s
- **Effective cycle length of 30.54 s**

New scheme

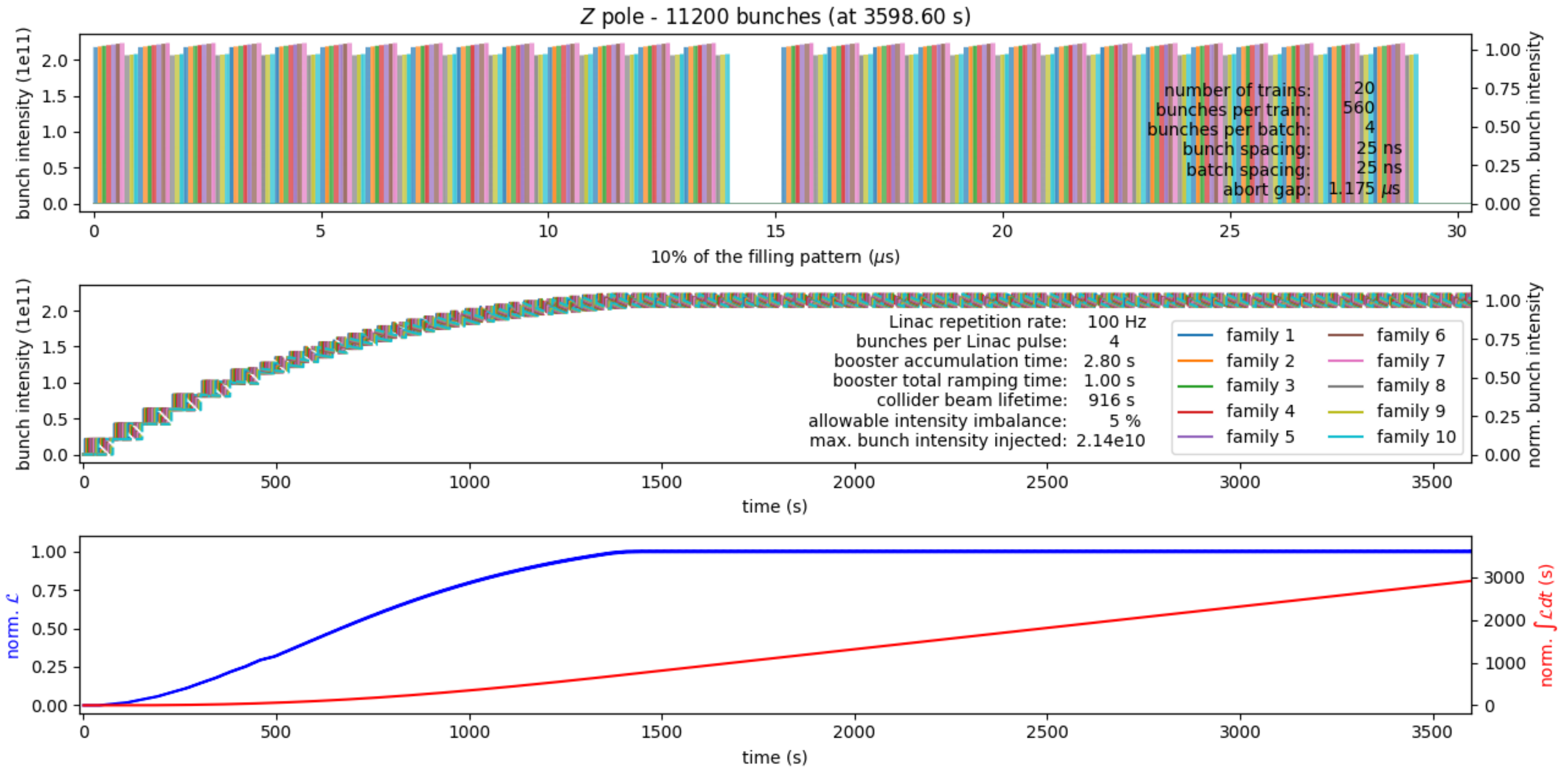
- 1/10th of all bunches transferred
- Ramping + flat top within 1 s
- Cycle length of 2.8 s + 1 s
- **Effective cycle length of 38 s**

Booster filling pattern



- Example of one of the booster filling patterns (corresponding to one "family" of bunches)
- Booster to collider transfer **still requires "full circumference" flat top** of extraction kicker and collider injection bump for off-momentum on-axis injection of distributed bunches (see presentation of Y. Dutheil)

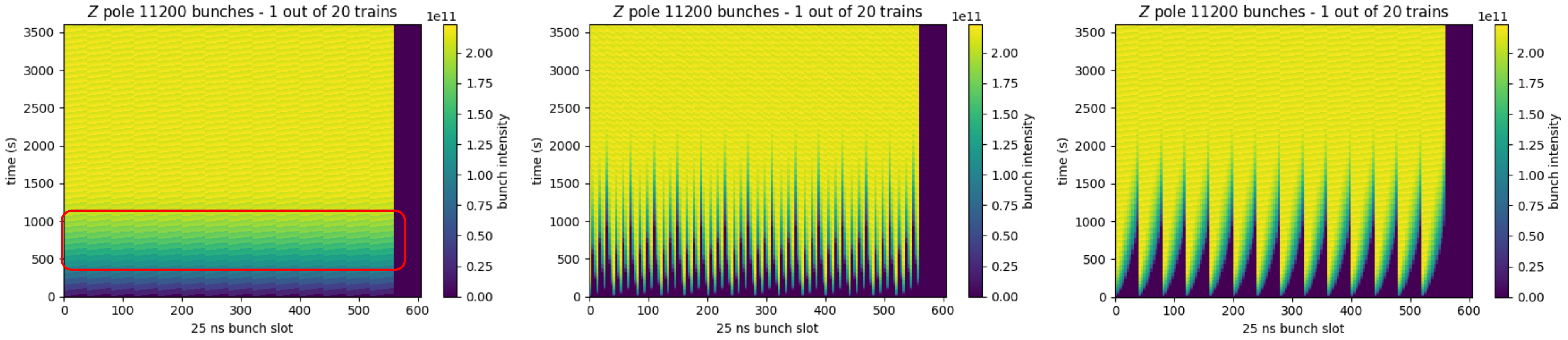
Transferring 1/10th of the bunches each time



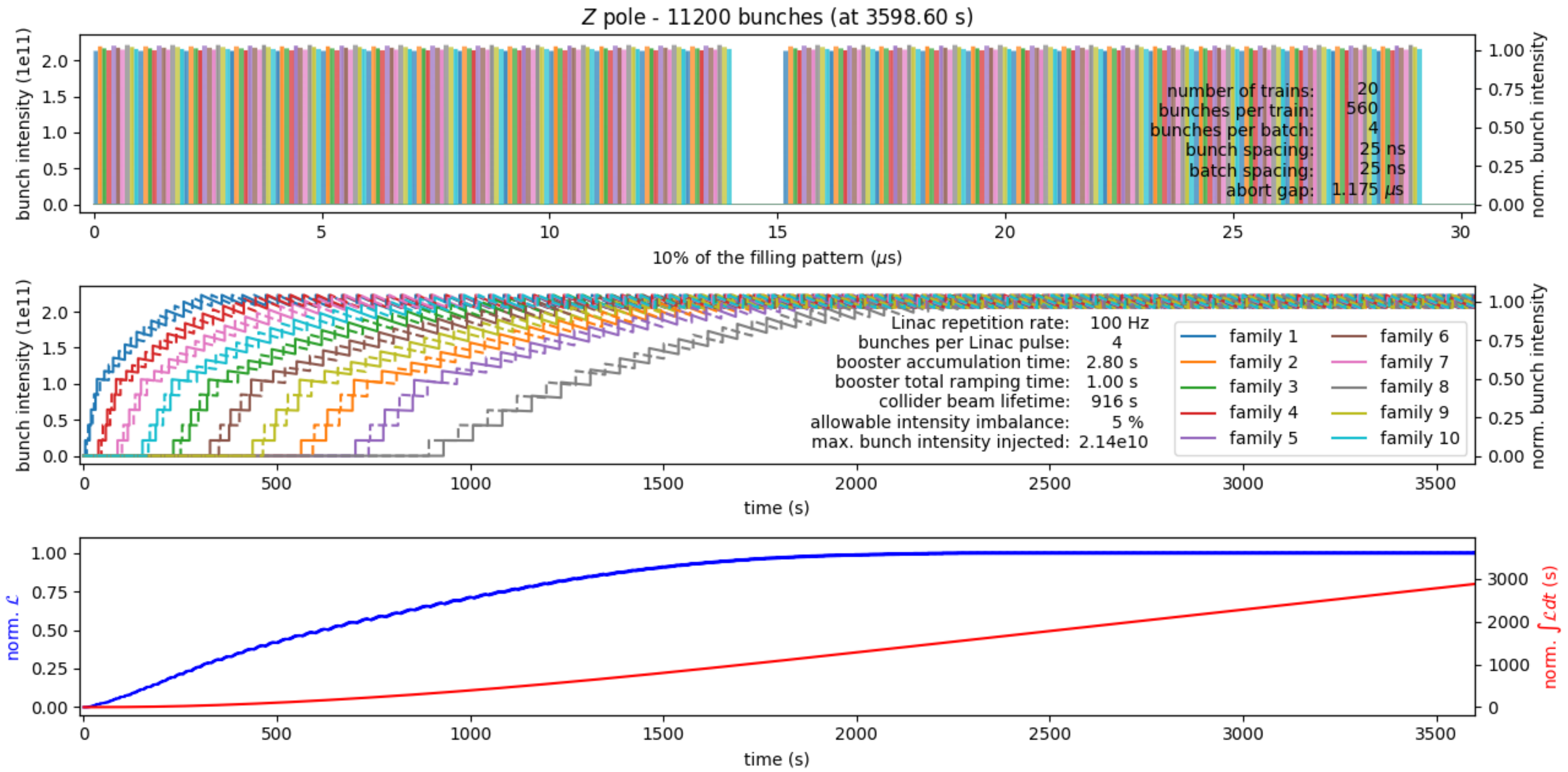
Optimization for e-cloud mitigation

- Simulations indicate that the **intermediate intensities (0.5-1.5e11 ppb)** are **the most critical** for e-cloud instabilities, i.e. during accumulation phase in the collider (see slides of L. Sabato)
- **Injecting each time only a subset of bunches provides flexibility in the accumulation phase** of the collider to **create gaps** in the bunch train as suggested by C. Carli
- L. Sabato and L. Mether are checking if one of the proposed new schemes mitigates the e-cloud instability

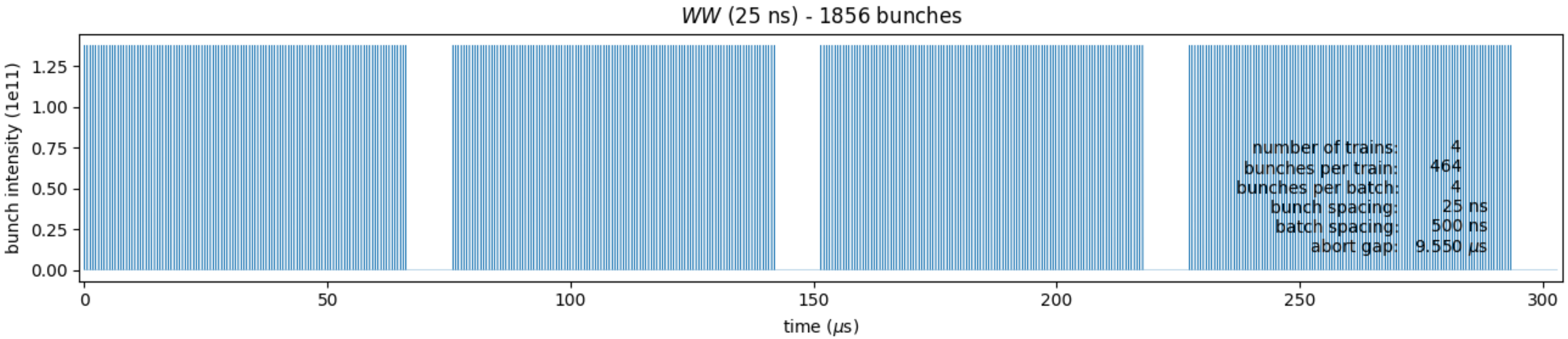
Filling schemes aiming at minimizing e-cloud effects during accumulation



Potential e-cloud mitigation scheme

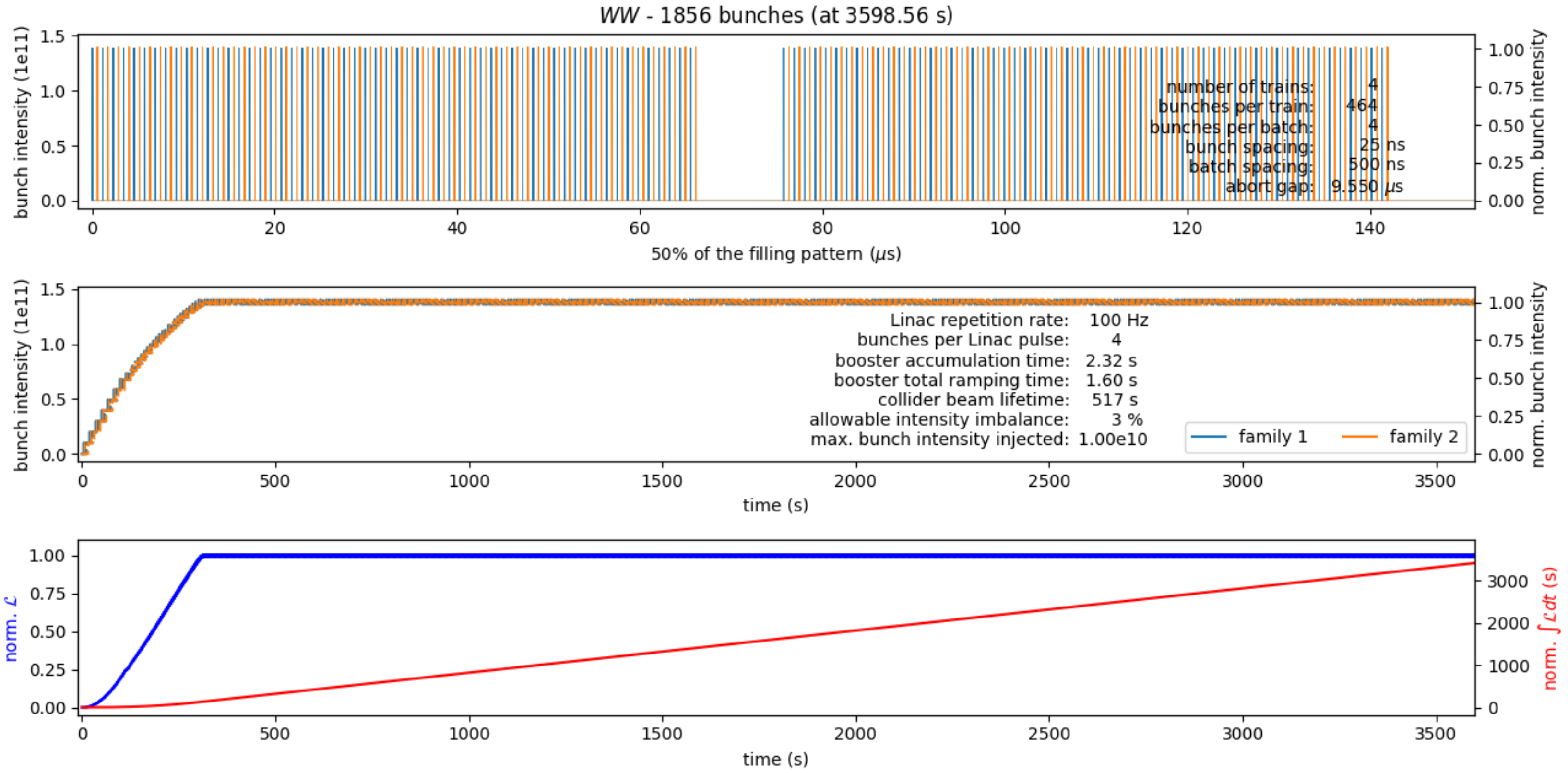


WW

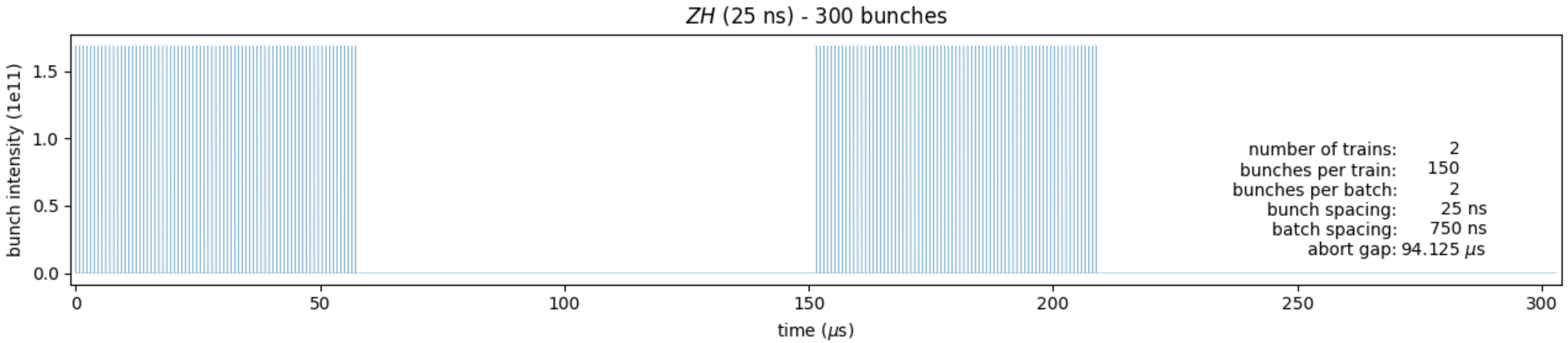


- **Remarks**
  - Smaller number of bunches and lower bunch intensity compared to Z
  - Consider **transferring half of bunches each injection** to limit length of booster injection plateau
  - **Lower bunch intensity required compared to Z pole**
  - Longer abort gaps, partly occupied by **non-colliding bunches for energy calibration**
  - **Margin to reduce injection rate (i.e. pausing between cycles)** for energy saving in top-up mode or increased booster cycle length (e.g. if beam injection in the collider needs to be done in chunks)

WW – filling illustration

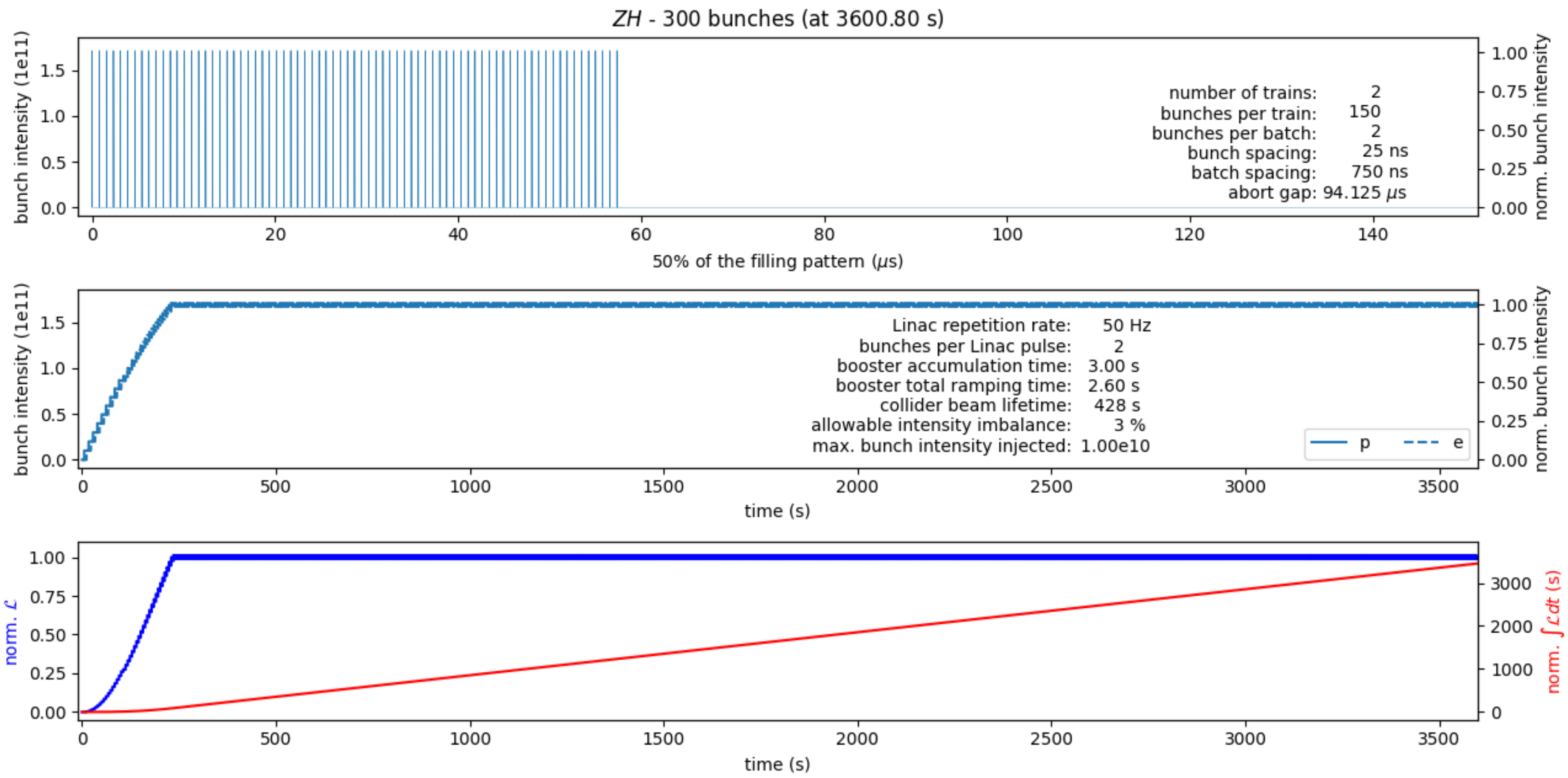


ZH

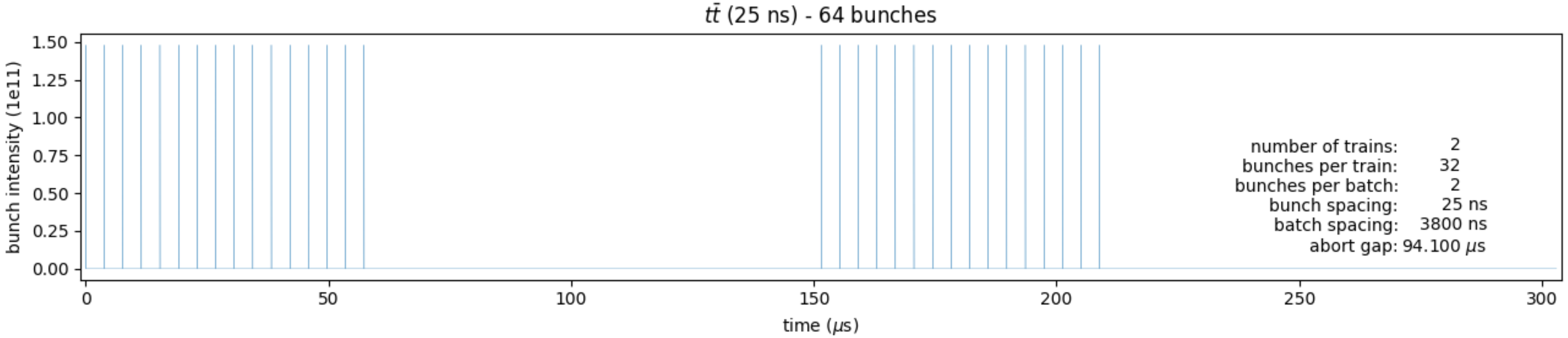


- **Remarks**
  - Filling scheme such as to have **always only one beam present in common RF section**
  - Small number of bunches – sufficient to run injector complex at 50 Hz with 2 bunches
  - **Low bunch intensity from injector needed** (<1e10) – **resolves TMCI limitation in the booster**
  - **Margin to reduce injection rate (i.e. pausing between cycles)** for energy saving in top-up mode or increased booster cycle length (e.g. if beam injection in the collider needs to be done in chunks)

ZH – filling illustration



ttbar



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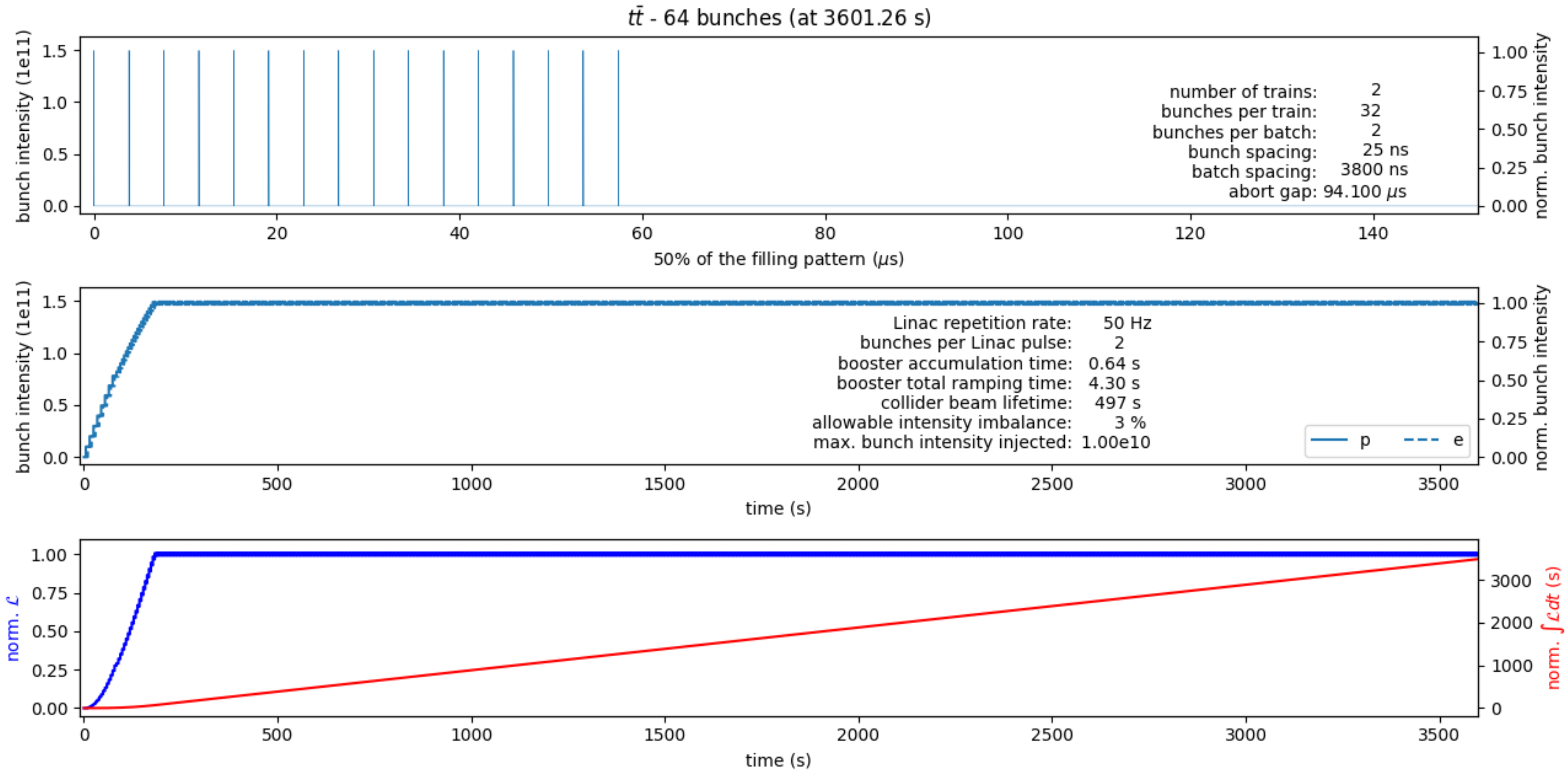
ttbar – filling illustration



Summary table

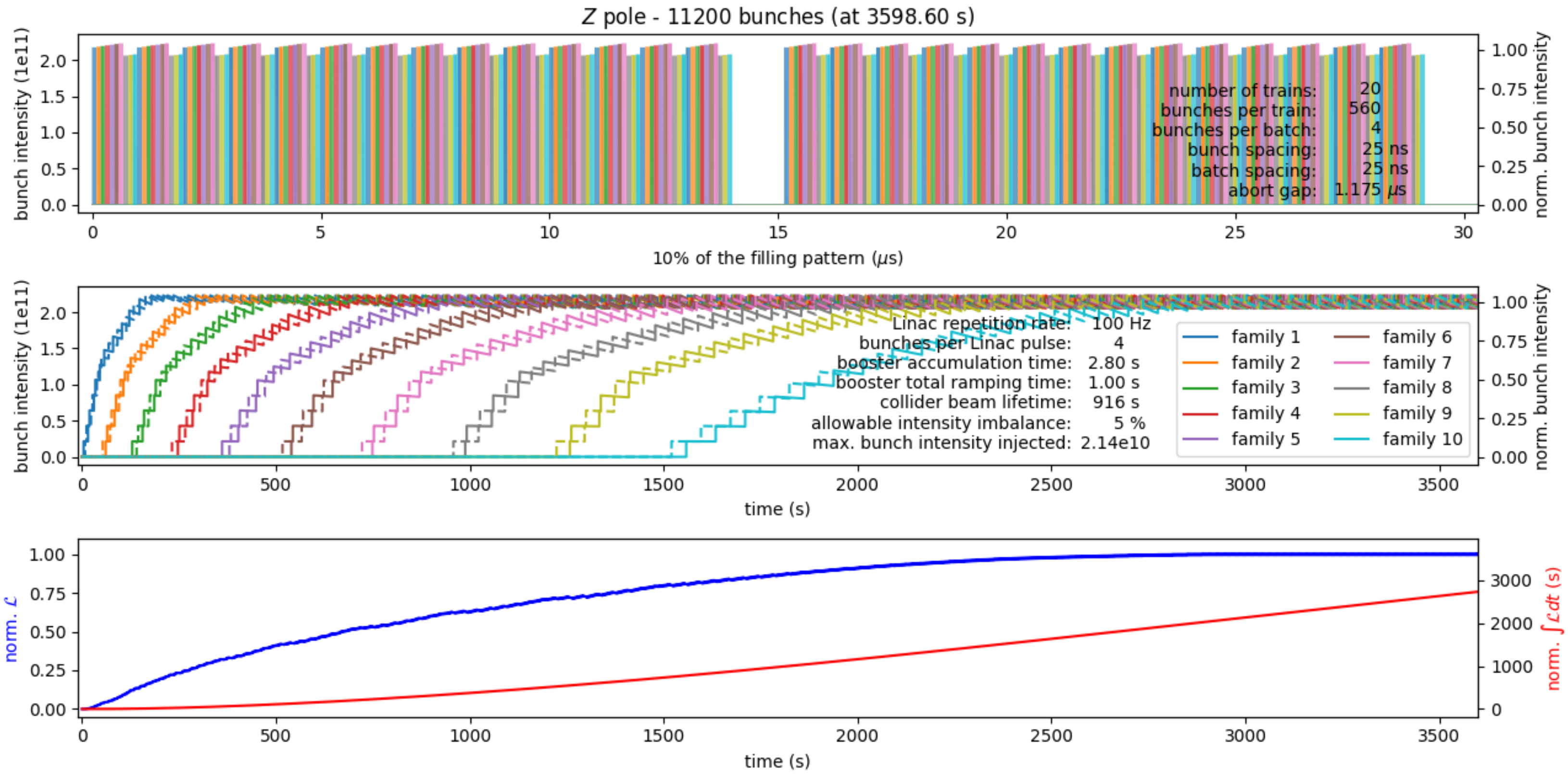
	Z	WW	ZH	ttbar
Linac repetition rate [Hz]	100	100	50	50
Bunches per Linac pulse	4	4	2	2
Linac bunch spacing [ns]	25	25	25	25
Booster accumulation time [s]	2.8	2.32	3.0	0.64
Booster total ramping time [s]	1.0	1.6	2.6	4.3
Booster cycle length [s]	3.8	3.92	5.6	4.94
Bunches per booster cycle	1120	928	300	64
Number of bunches in collider	11200	1856	300	64
Max. bunch intensity injected in collider	2.15e10	1.0e10	1.0e10	1.0e10
Nominal bunch intensity in collider	2.15e11	1.38e11	1.69e11	1.48e11
Allowable charge imbalance [%]	5	3	3	3
Beam lifetime: lumi 4 IPs, (q,BS,lattice)/4 [s]	916	517	428	497

Conclusion & Outlook

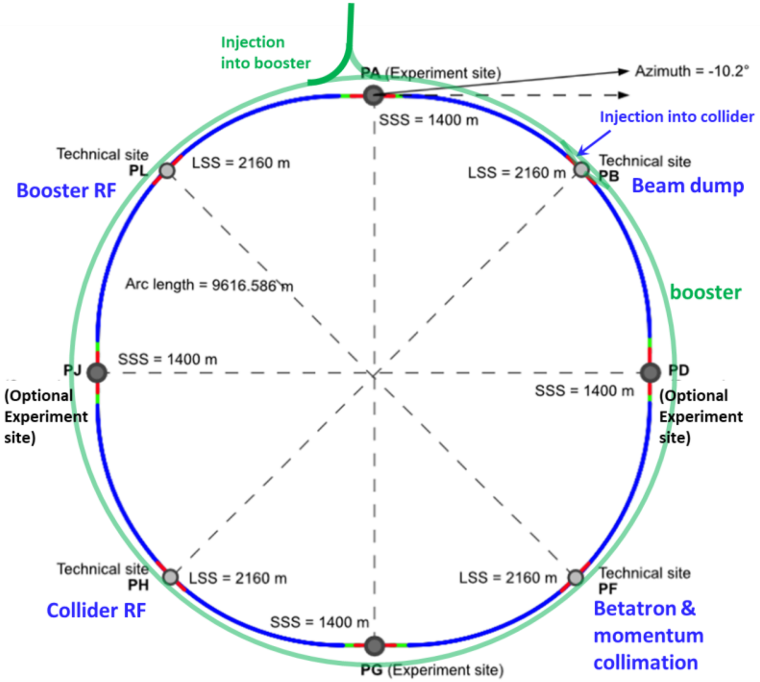
- **For Z-pole**, propose a scheme transferring only 1/10th of all bunches at each collider injection
  - To become compatible with machine protection requirements
  - To relax vacuum requirements, required RF power for beam loading compensation and fast beam ion instability in the booster
  - This scheme allows flexibility in the accumulation phase in the collider, which can be exploited to mitigate e-cloud for intermediate intensities (ongoing studies), without compromising luminosity
- **Other modes are more relaxed**
  - Lower bunch intensity in the booster required, resolves TMCI limitation in the booster for ZH and ttbar modes
  - Margin to reduce injection rate (i.e. pausing between cycles) for energy saving in top-up mode
- Next steps include the **study the robustness to short unavailability of the injector** (e.g. RF trips in the Linac)

BACK-UP

Z pole


Z pole - 11200 bunches (at 3598.60 s)
bunch intensity (1e11)
norm. bunch intensity
number of trains: 20
bunches per train: 560
bunches per batch: 4
bunch spacing: 25 ns
batch spacing: 25 ns
abort gap: 1.175 μs
10% of the filling pattern (μs)
Linac repetition rate: 100 Hz
bunches per Linac pulse: 4
booster accumulation time: 2.80 s
booster total ramping time: 1.00 s
collider beam lifetime: 916 s
allowable intensity imbalance: 5 %
max. bunch intensity injected: 2.14e10
family 1
family 2
family 3
family 4
family 5
family 6
family 7
family 8
family 9
family 10
time (s)
norm. ℒ
norm. ∫ℒdt (s)
time (s)

FCCee schematics



Latest FCCee collider parameters

FCC-ee collider parameters for the GHC lattice as of May 29, 2024.

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658728			
Bend. radius of arc dipole	[km]	10.021			
Energy loss / turn	[GeV]	0.0390	0.369	1.86	9.94
SR power / beam	[MW]	50			
Beam current	[mA]	1283	135	26.8	5.0
Colliding bunches / beam		11200	1852	300	64
Colliding bunch population	$[10^{11}]$	2.16	1.38	1.69	1.48
Hor. emittance at collision ε_x	[nm]	0.70	2.16	0.66	1.51
Ver. emittance at collision ε_y	[pm]	1.9	2.0	1.0	1.36
Lattice ver. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.87	1.20	0.57	0.94
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	$[10^{-6}]$	29.2nx		7.52	
Arc sext families		75		146	
$\beta^*_{x/y}$	[mm]	110 / 0.7	220 / 1	240 / 1	900 / 1.4
Transverse tunes $Q_{x/y}$		218.158 / 222.220	218.185 / 222.220	398.150 / 398.220	398.148 / 398.215
Chromaticities $Q'_{x/y}$		0 / +5	0 / +5	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.110	0.069 / 0.105	0.102 / 0.176	0.152 / 0.184
Bunch length (SR/BS) σ_z	[mm]	5.57 / 15.6	3.46 / 5.28	3.26 / 5.59	1.91 / 2.32
RF voltage 400/800 MHz	[GV]	0.079 / 0	1.00 / 0	2.09 / 0	2.1 / 9.20
Harm. number for 400 MHz		121200			
RF frequency (400 MHz)	MHz	400.787129			
Synchrotron tune Q_s		0.0289	0.0809	0.0334	0.0881
Long. damping time	[turns]	1171	218	65.4	19.4
RF acceptance	[%]	1.06	3.32	2.06	3.06
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.9	-2.8/+2.5
Beam crossing angle at IP θ_x	[mrad]	±15			
Crab waist ratio	[%]	70	55	50	40
Beam-beam ξ_x/ξ_y[a]		0.0022 / 0.0977	0.013 / 0.129	0.0108 / 0.130	0.065 / 0.136
Piwinski angle $(\theta_x \sigma_{z,\mathrm{BS}})/\sigma^*_x$		26.6	3.6	6.6	0.94
Lifetime (q + BS + lattice)	[sec]	11800	4500	6000	7700
Lifetime (lum)[b]	[sec]	1330	960	600	670
Luminosity / IP	$[10^{34}/\mathrm{cm}^2\mathrm{s}]$	143	20	7.5	1.38

May 29, 2024, K. Oide

Parameter table for the FCCee collider filling

March 5, 2024, K. Oide

	Z		WW	ZH	tt
Collider energy [GeV]	45.6		80	120	182.5
Collider bunches / ring	11200		1780	380	56
BR bunches / ring	11200	5600			
Collider particles / bunch N_b [10^{10}]	21.4		14.5	13.2	16.4
Allowable charge imbalance Δ [±%]	5		3		
Injector particles / bunch N_{max} [10^{10}]	≤ 2.5				
Bootstrap particles / bunch [10^{10}] $= 2N_b\Delta$	2.14		0.87	0.792	0.984
# of BR ramps (up to 1/2 stored current, with N_{max})	3	6	3	3	4
# of BR ramps (bootstrap with $2N_b\Delta$)	5	10	4	4	5
BR ramp time (up + down) t_{ramp} [s]	0.6		1.5	2.5	4.1
Linac bunches / pulse	2 / 4 / 8		2 / 4		
Linac pulses needed n_p	5600		890	190	28
Linac repetition frequency [Hz] f_{rep}	200 / 100 / 50		100 / 50	50	
Collider filling time from scratch [s]	228.8	457.6	72.8	30.8	39.42
Collider filling time for top-up [s] $= n_p/f_{rep} + t_{ramp}$	28.6	29.2	10.4	6.3	4.66
Lum. lifetime (4 IP) [s]	1330		970	660	650
Lattice+BS lifetime (4 IP) [s]	10000		4000	3500	3000
(real lattice lifetime)/(design lattice lifetime)	0.25		0.25	0.25	0.25
Collider lifetime (4 IP) τ_2 [s]	868.1		492.4	376.2	348.2
Collider top-up interval (between e+ and e-)(4 IP) [s] $= \tau_2\Delta$	43.4		14.8	11.3	10.4

Parameter table for the FCCee booster

Running mode		Z	W	ZH	$t\bar{t}$
Injection option		LINAC/SPS			
Circumference	[km]	91.174			
Injection energy	[GeV]	20/16			
Extraction energy	[GeV]	45.6	80	120	182.5
Number bunches / ring		11200	1780	440	60
Maximum particle number / bunch Nmax	[10^{10}]	≥ 2.5 (4 nC)			
Particles / bunch in top-up	[10^{10}]	2.14	0.87	0.69	0.93
RF frequency	[MHZ]	800			
Arc optics FODO		60°/60°		90°/90°	
Momentum compaction		14.9×10^{-6}		7.34×10^{-6}	
Coupling		2×10^{-3}			
Injection horizontal emittance (norm.)	[µm]	10/190			
Injection vertical emittance (norm.)	[µm]	10/4			
Extraction horizontal equilibrium emittance (RMS)	[nm]	0.26	0.81	0.63	1.45
Extraction vertical equilibrium emittance (RMS)	[pm]	0.53	1.62	1.25	2.90

Running mode		Z	W	ZH	$t\bar{t}$
Extraction horizontal equilibrium emittance (RMS)	[nm]	0.26	0.81	0.63	1.45
Extraction vertical equilibrium emittance (RMS)	[pm]	0.53	1.62	1.25	2.90
Injection Energy loss / turn	[MeV]	1.514/0.6203			
Extraction Energy loss / turn	[MeV]	40.93	387.7	1963	10500
Injection bunch length	[mm]	4/5.5			
Extraction bunch length	[mm]	4.38	3.55	3.34	1.94
Injection RMS energy spread	[10^{-3}]	1/4			
Extraction RMS energy spread	[10^{-3}]	0.38	0.67	1.01	1.53
Injection Maximum relative energy acceptance	[%]	3			
Extraction Maximum relative energy acceptance	[%]	0.36	0.76	0.49	2.39
Injection RF voltage	[MV]	104.9/82.97		52.85/41.36	
Extraction RF voltage	[MV]	49.48	458.6	2015	11533
Filling time	[s]	28/31.5	8.9/9.6	4.4/4.75	0.6/0.95
Ramp time	[s]	0.32/0.37	0.75/0.8	1.25/1.3	2.03/2.08
Flat top	[s]	1.9	0	0	0
Total cycling time	[s]	30.54/ 34.14	10.4/11.2	6.9/7.35	4.66/5.11

A. Chance