to the highest luminosity and BEYOND...

Salim Ogur

Pre-compensation and Quasi-continuous Top-up Injection for FCC-ee at Z-pole

Many thanks to: K. Oide, Y. Papaphilippou, D.Shatilov, F. Zimmermann

Outline

1. Overview of Accelerators
2. The First Fill
3. Top up Injection
4. Conclusion
5. Further Discussion

to the highest luminosity and BEYOND …

Motivation

- ❖ We've needed to adopt a.s.a.p. to the changes made on ***Z*-**operation by D. Shatilov, K. Oide et. al. Mainly, Y. Papaphilippou's injector table are roughly preserved, for instance ramp-up times, current limits etc, yet the cycles are altered slightly.

- ❖ The new baseline foresees 20 mins of life time at ***Z***-mode (70 mins luminosity lifetime due radiative Bhabha, while beamstrahlung lifetime is 29 mins.)

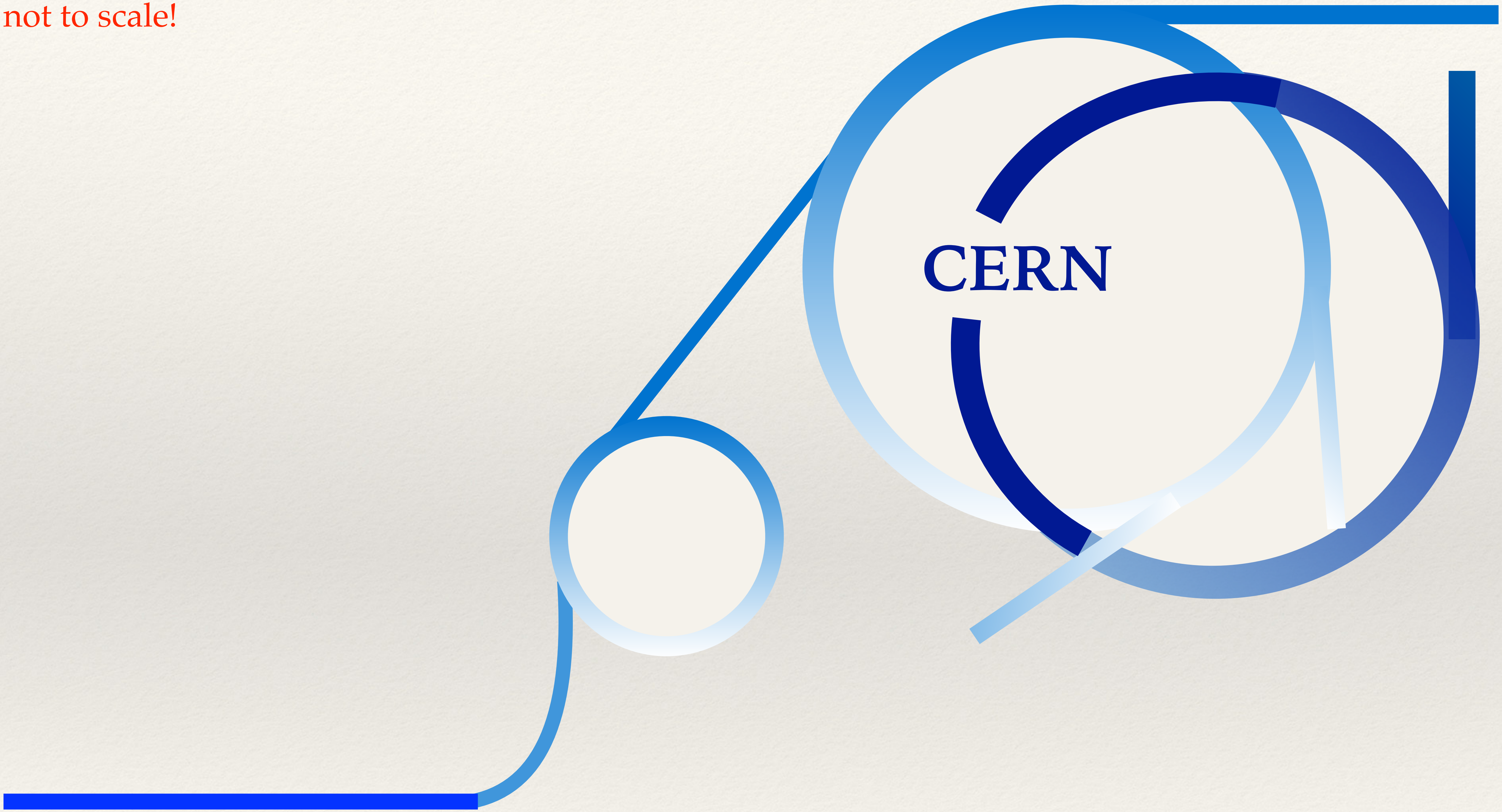
- ❖ Keeping at/around the peak luminosity is directly proportional to how often we inject into a bucket, rather than the amount of the charge injected. The top-up booster ring (BR) better have the same number of bunches, undoubtedly with a small fraction of full charge.

- ✓ First, each bucket in the collider will have the same fraction of full charge when the collisions start, a stepwise increase of the bucket charge will be performed until we reach the full charge in a collider bunch ("Bootstrapping" to keep the horizontal emittance fluctuations low, as suggested by D. Shatilov).

- ✓ A routine for the injector chain will be set as a quasi-continuous top-up such that the luminosity is kept effectively constant through the operation.

1. Overview of FCCe+e- Complex

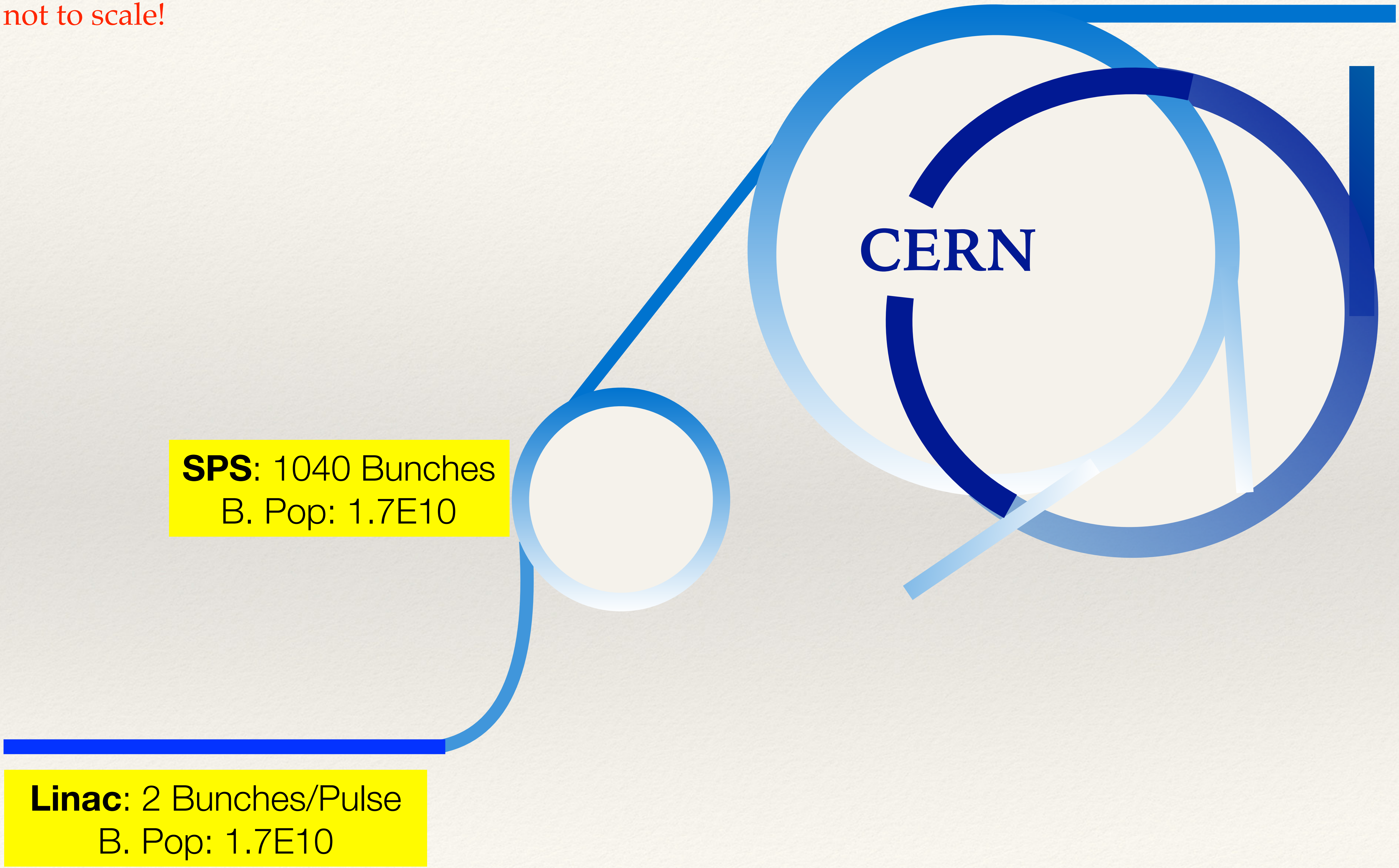
not to scale!



Linac: 2 Bunches/Pulse
B. Pop: 1.7E10

1. Overview of FCCe+e- Complex

not to scale!



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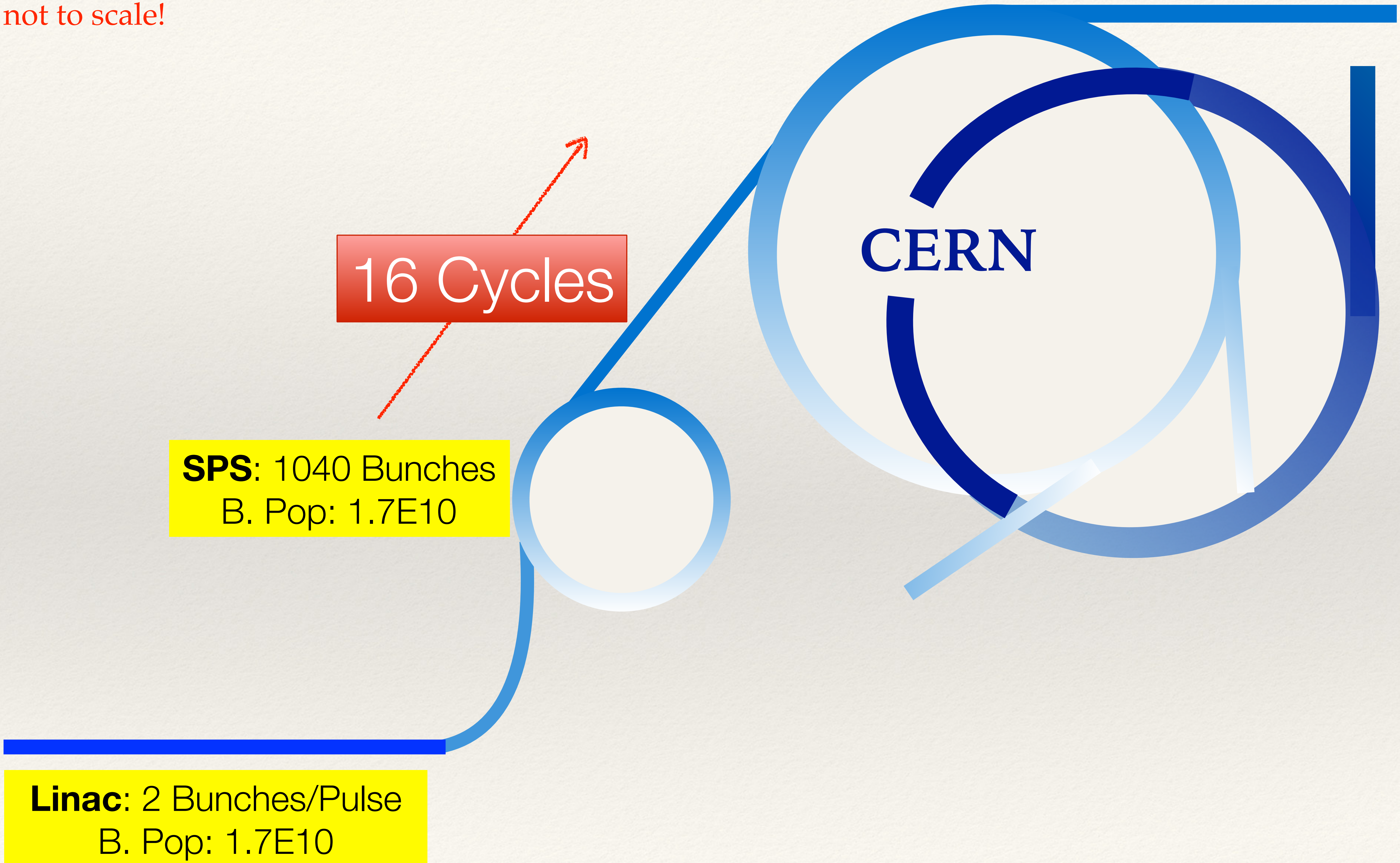

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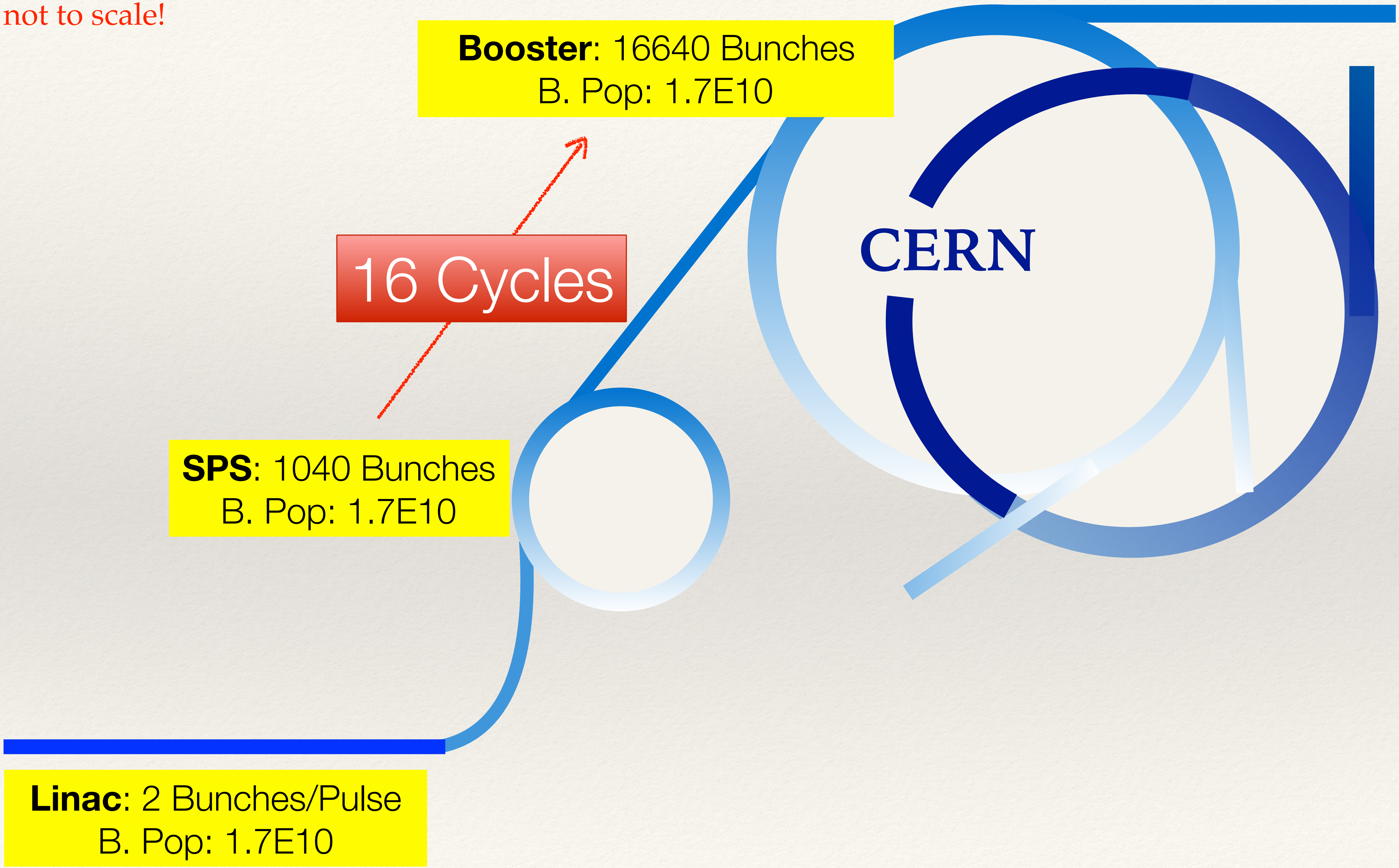

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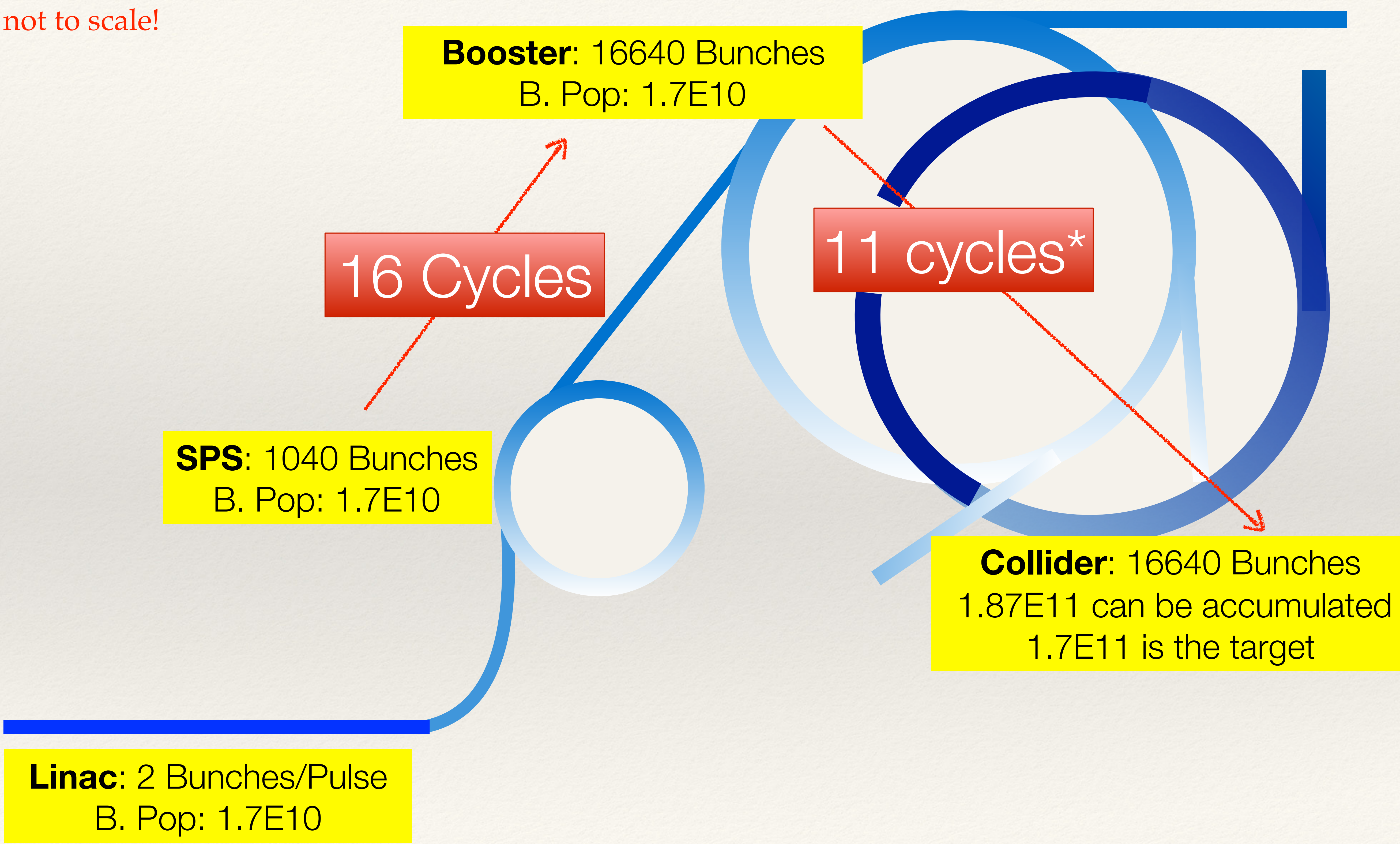

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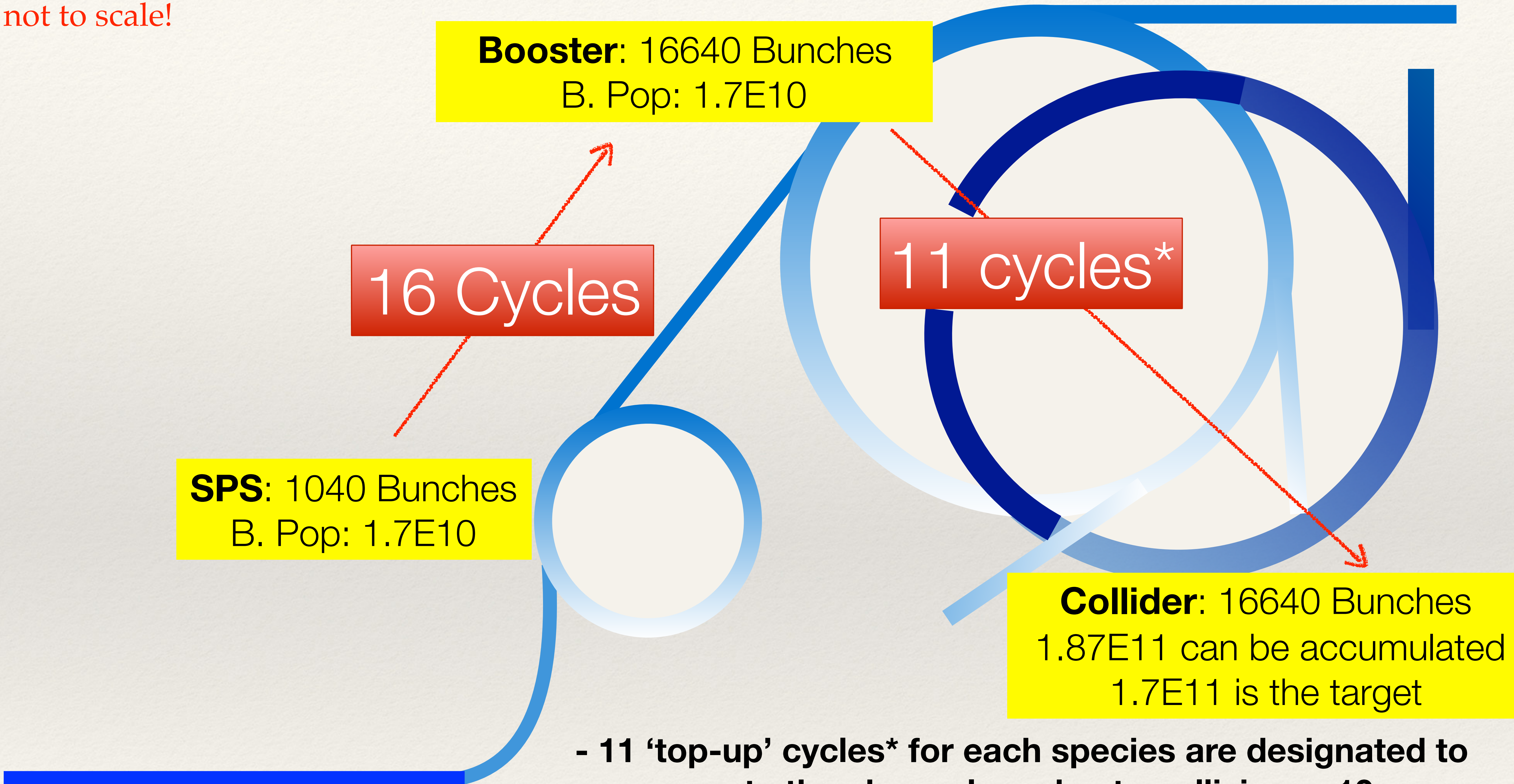


- 11 ‘top-up’ cycles* for each species are designated to compensate the charge loss due to collisions. 10 cycles* would correspond to 10% charge (± 5% fluctuations), with an additional 1 cycle* we would stay in the ± 5% restriction at the last injection

Injector Schedule at *Z*-pole

Linac Repetition [Hz]	200
Bunches per RF pulse*	2
Bunch Population **	1,70E+10
Linac Duty Factor [%]	80,0
Linac Injections to SPS	520
SPS Number of Bunches	1040
Current in SPS [mA]	123,0
SPS Ramp time [sec]	0,5
SPS Cycle Time [sec]	3,1
SPS Number of Cycles	16
SPS Duty Factor [%]	95,4
SPS Bunch charge **	1,70E+10
BR Bunch charge **	1,70E+10
BR Number of Bunches	16640
BR Ramp time [sec]	2,4
BR Cycle Time [sec]	52
BR Number of Cycles	11
BR Duty Factor [%]	93,8
Collider Number of Bunches	16640
Collider Bunch Charge	1,87E+11
Collider Bunch Target Aim	1,70E+11
Transmission Target [%] >	90,9
BR cycle for both species [sec]	104
Collider Fill time full charge (e-&e+)	1144
Collider Bunches	16640

- The duty factor is considered as the time that the corresponding accelerator has the beam inside scaled to one BR cycle.

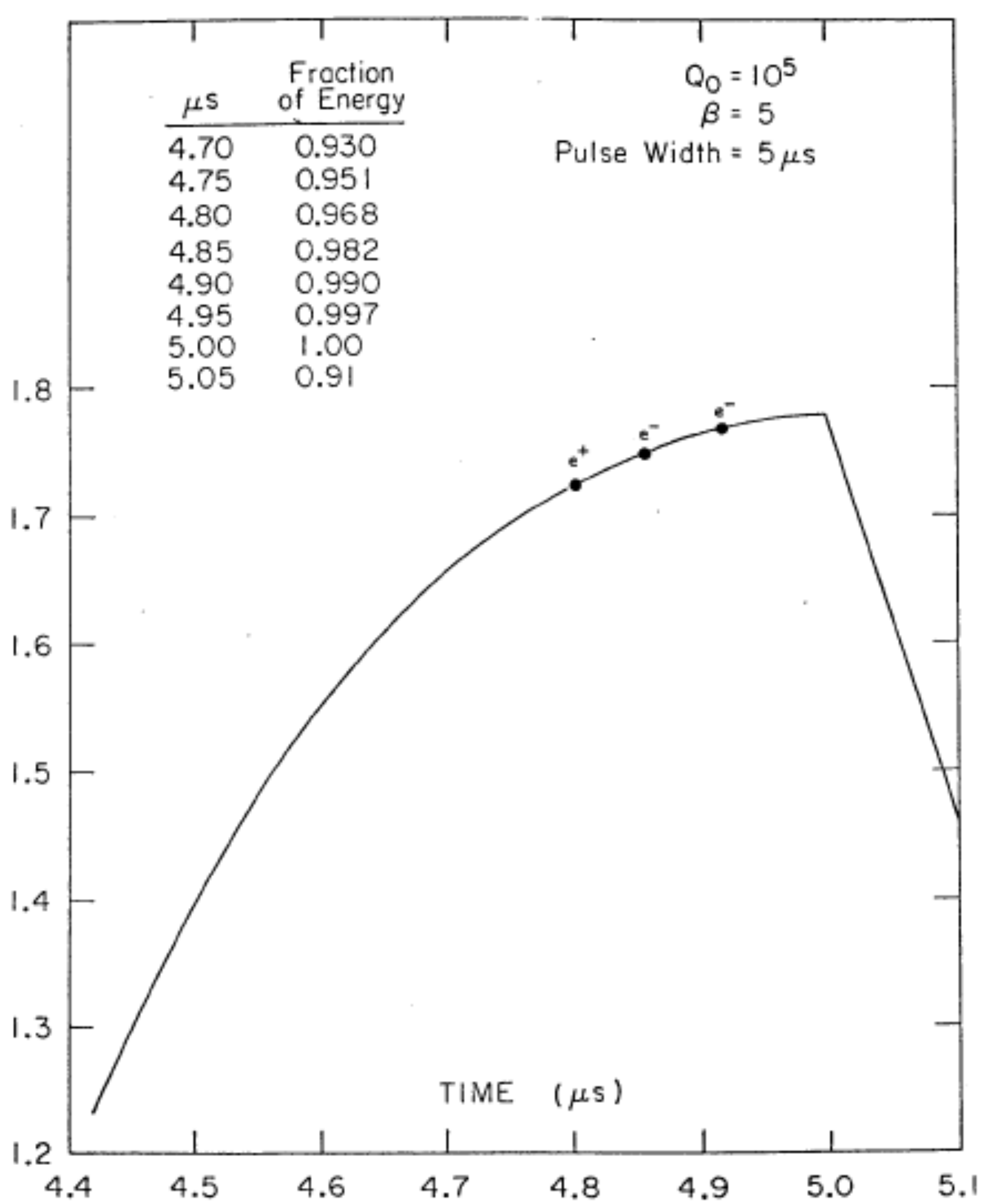
$$\frac{52 - 2.4 - 16 * 0.5}{52} = 80\%$$

where 2.4 seconds are due to BR ramp time, 16*0.5 seconds are due to SPS ramp times.

the full charge is the charge in 1 bucket of the collider with some extra charge due to the transmission loss.
the full charge as taken as 1.

[1]Bunches per RF Pulse

Figure 2.1.5 SLED II Energy Gain vs. Time



2–11

- ❖ K. Oide suggests 4 bunches per RF pulse during e+ creation, yet arising the question of hitting/moving the positron target between e- e+ bunch spacing.
- ❖ The second (unlikely due to additional cost) solution is to have two linacs.
- ★ These slides are prepared assuming either of the above statements is the case, and no additional delay during e+ delivery.

Ref: SLC Design Handbook, SLAC-R-714

[2]Cycles for the Fill from Scratch: Pre-compensation

Booster Cycle*	e- charge/bunch
1st	0.1043
2nd	0.1024
3rd	0.1006
4th	0.0990
5th	0.0974
6th	0.0960
7th	0.0948
8th	0.0936
9th	0.0926
10th	0.0917
11th	0.0909

1st: full charge/11 + charge lost in 1040 s

2nd: full charge/11+ charge lost in 936 s

.
.
.

9th: full charge/11+ charge lost in 208 s

10th: full charge/11 + charge lost in 104 s

11th: full charge/11

★ The charges are calculated with respect to the beam loss, which is dependent upon the amount of charge available (see next slide.)

★ If we first fill e-, then e+ should be filled a little bit more of charge which corresponds to the loss in 1 Booster Ring cycle.

²Cycles for the Fill from Scratch: Pre-compensation

Booster Cycle*	e- charge/bunch	e+ charge/bunch
1st	0.1043	0.1094
2nd	0.1024	0.1073
3rd	0.1006	0.1054
4th	0.0990	0.1036
5th	0.0974	0.1020
6th	0.0960	0.1004
7th	0.0948	0.0990
8th	0.0936	0.0978
9th	0.0926	0.0967
10th	0.0917	0.0957
11th	0.0909	0.0948

★ The charges are calculated with respect to the beam loss, which is dependent upon the amount of charge available (see next slide.)

★ If we first fill e-, then e+ should be filled a little bit more of charge which corresponds to the loss in 1 Booster Ring cycle.

[3]Dynamic Luminosity Lifetime

- Luminosity lifetime is not constant through the first fill. It depends on the bucket charges which is dynamically varying and the number of bunches, however the latter is set to be constant to 16640.

$$\frac{dN}{dt} \propto \mathcal{L} \propto N_1 N_2 n_{bunches}$$

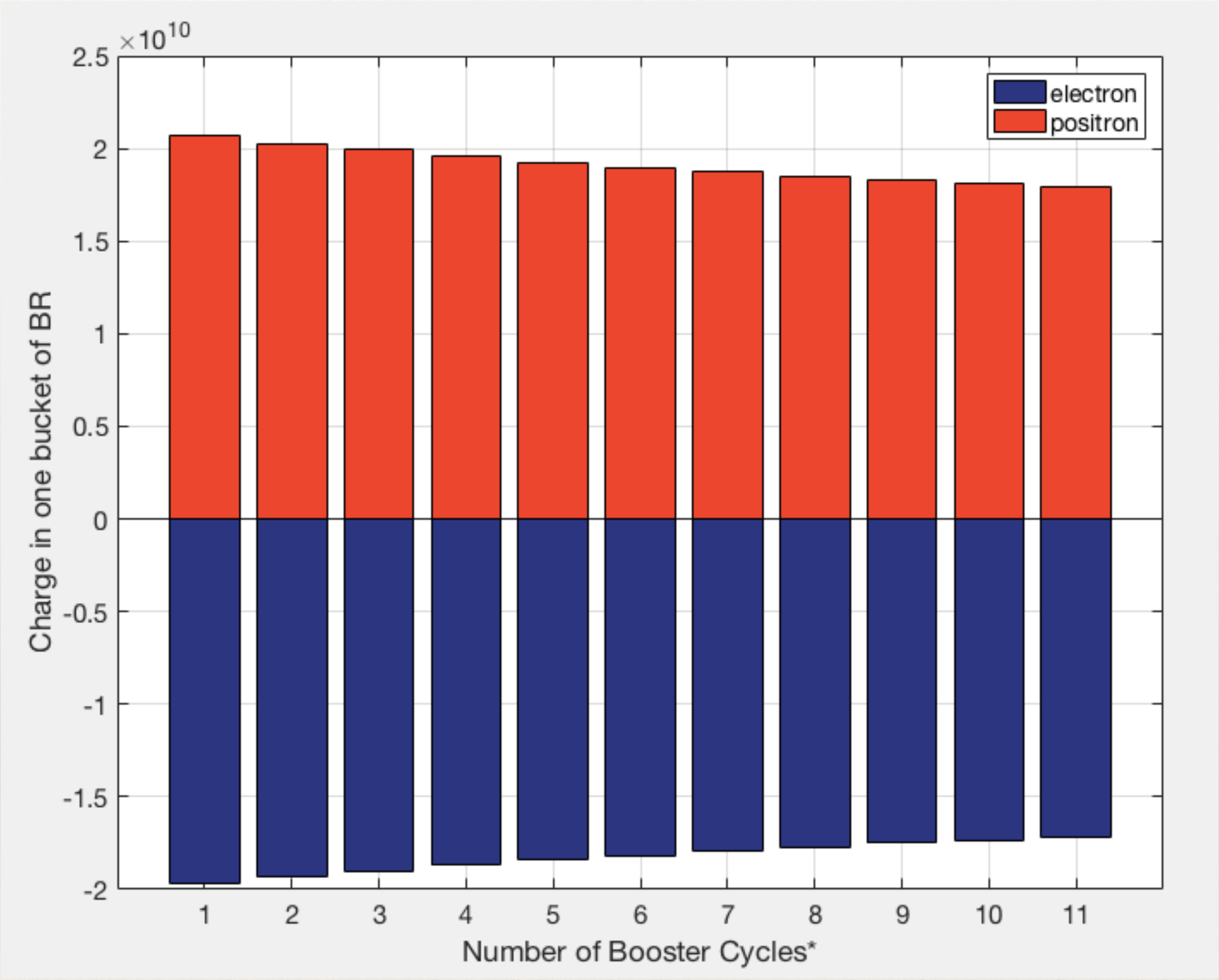
$$\frac{1}{\tau_{lifetime}} \propto \frac{1}{N}\frac{dN}{dt}$$

- Hence, the lifetime will depend on the charge ***N(t)*** at the time ***t*** as shown:

$$\tau_{lifetime}^{dynamic} \approx \frac{N_0}{N(t)} \tau_{lifetime}$$

- Therefore, the charge in one bucket of the injector for the cycle needs to be calculated recursively. Also equations are coupled, to illustrate, if we are injecting 10%+pre-compensation, we need to determine the tau using that charge, but the pre-compensation depends on the tau, too.

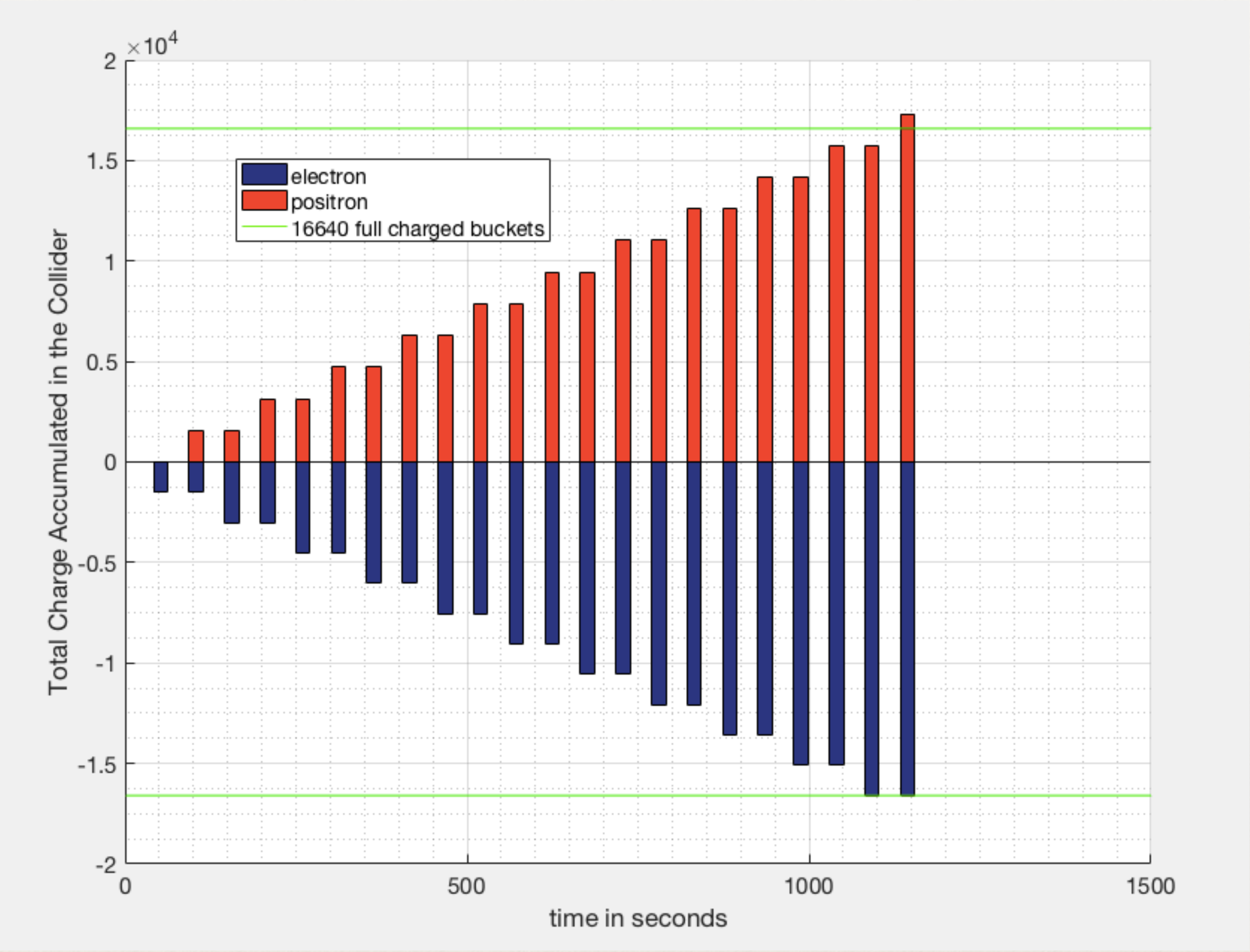
Booster Cycle* with charge Compensation



- ➡ This plot shows the bucket charge in the injector chain, in other words, the charge injected into the collider bucket.
- ➡ Notice that the e- and e+ charges are asymmetric, since e- will be topped up first, e+ is intentionally higher to pre-compensate 1 BR cycle time.

✓ S- Band linac can accelerate up to 6E10 in a bunch, meanwhile the SPS will have a varying current between 123-142 mA for the charges plotted above. Therefore, there should be no problem in terms of charge limits.

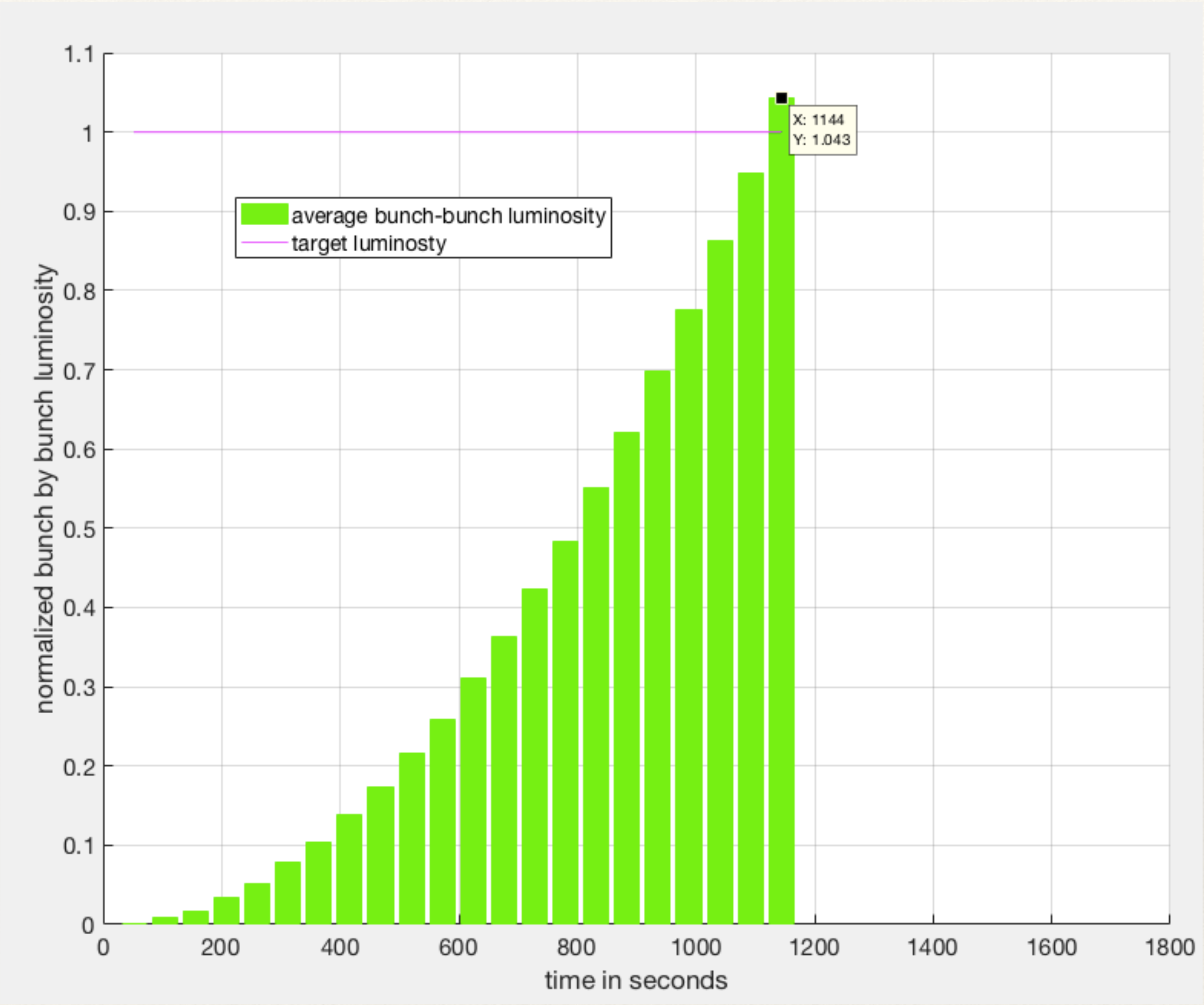
Collider Charge Accumulation



➡ Notice that the e- and e+ charges are asymmetric, e+ buckets of collider has 104% while e- buckets are with 100%. To obtain that configuration, for example, we add 9.5% to the e+ at the last cycle.

✓ Charge is distributed equally to all 16640 buckets. The full charge, taken as 1, in the collider is reached at 1154 s, as foreseen. The bootstrapping due to interleave and step-wise charge increase is achieved.

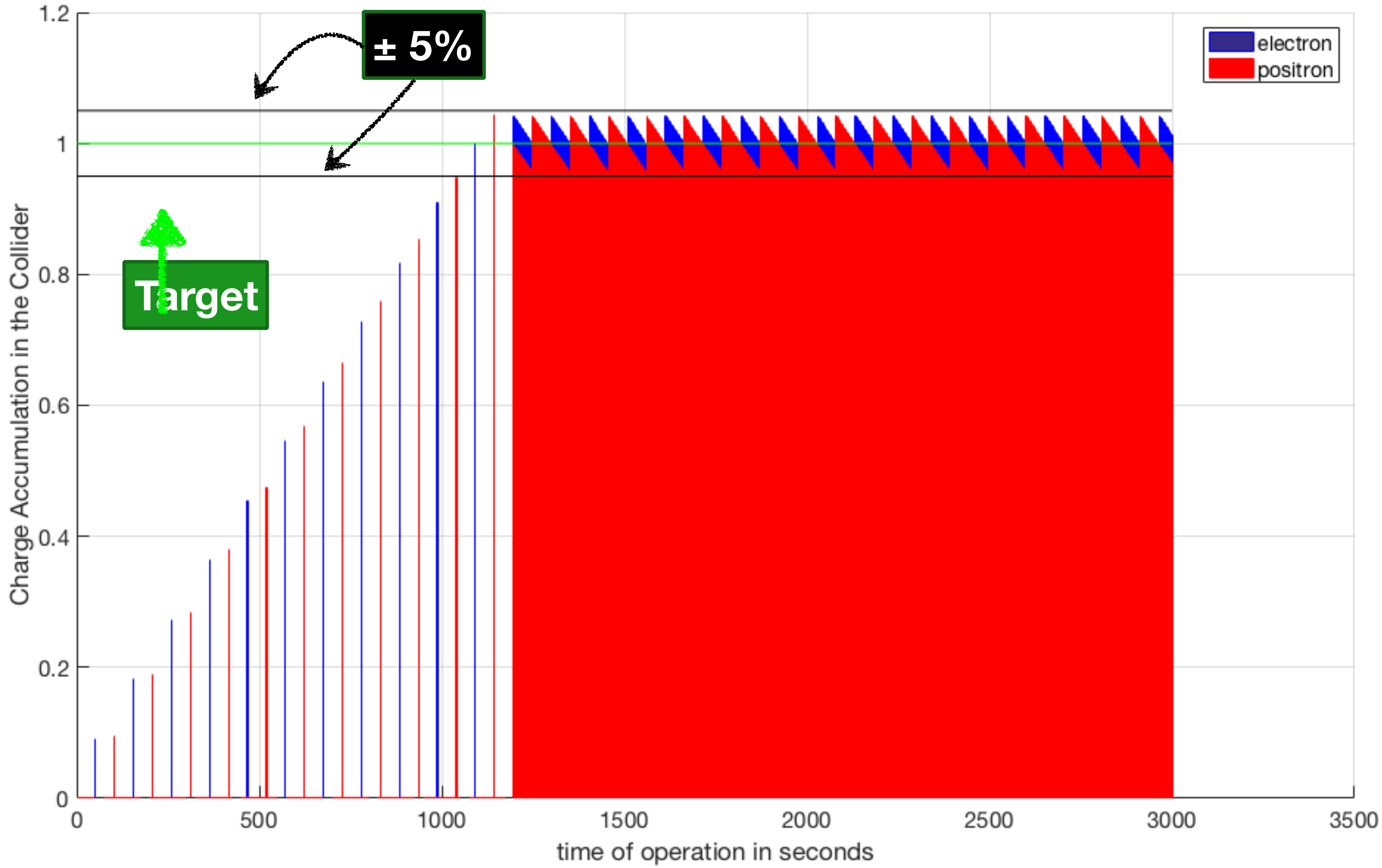
Luminosity through Fill from Scratch



- ❖ e+ over-charge results a higher luminosity by less than 5% at 1144 s.

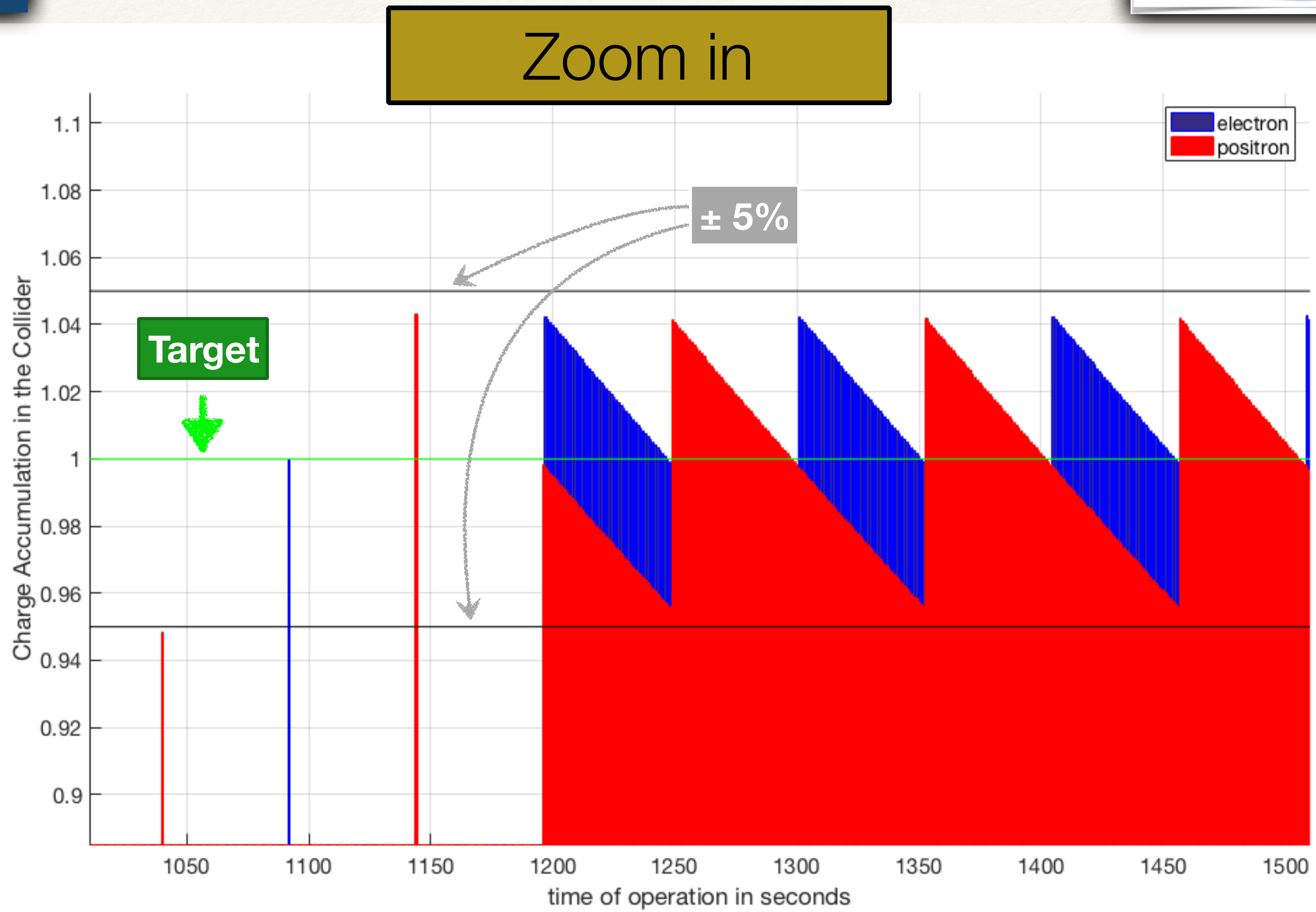
✓ Luminosity is calculated as 1 (i.e. target), when 1 full e- bunch collides with 1 full e+ bunch.

After First Fill:Quasi-continuous Top up

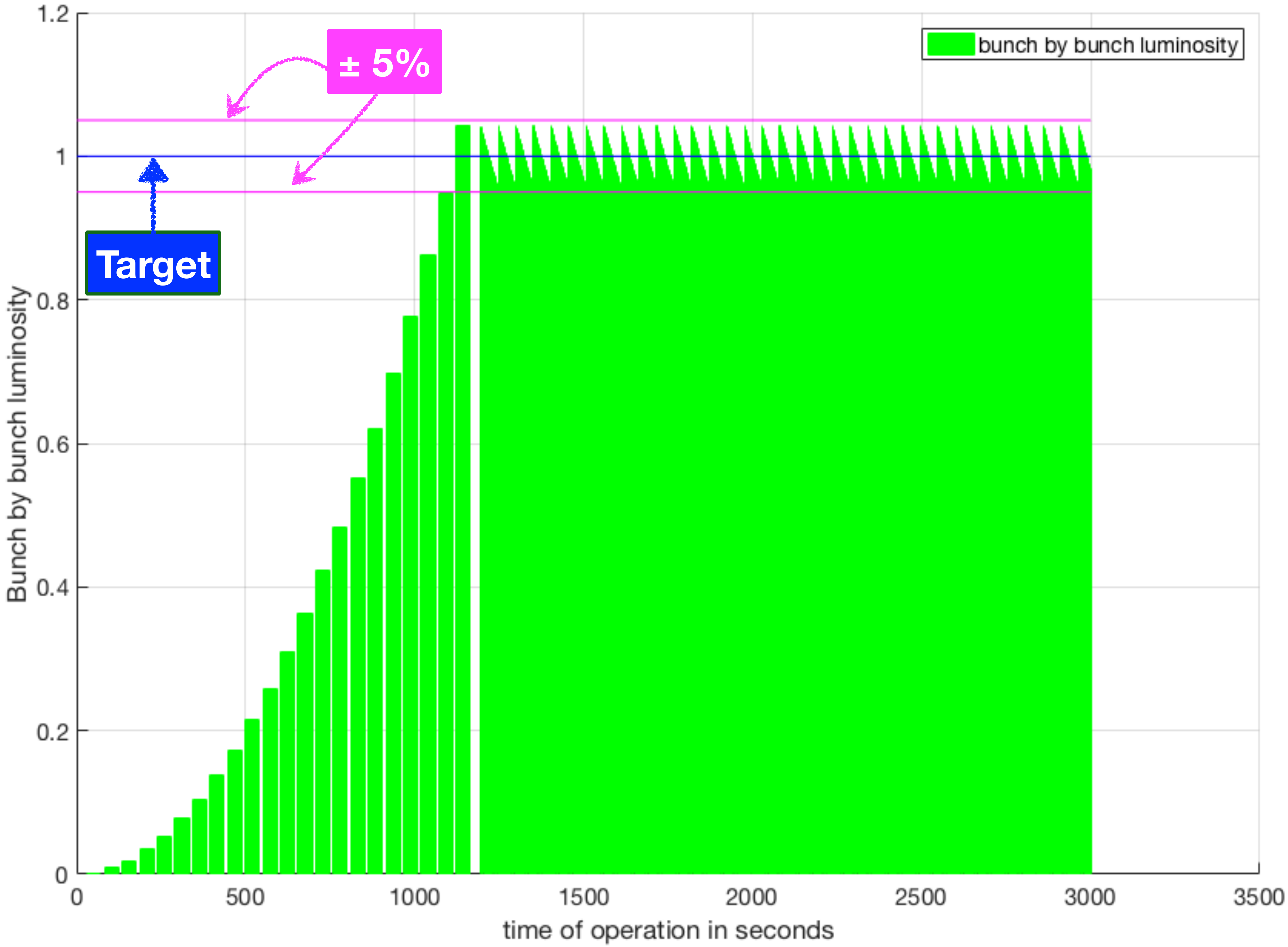


❖ The topped up charge for each species ~8.7% per cycle.

After First Fill:Quasi-continuous Top up

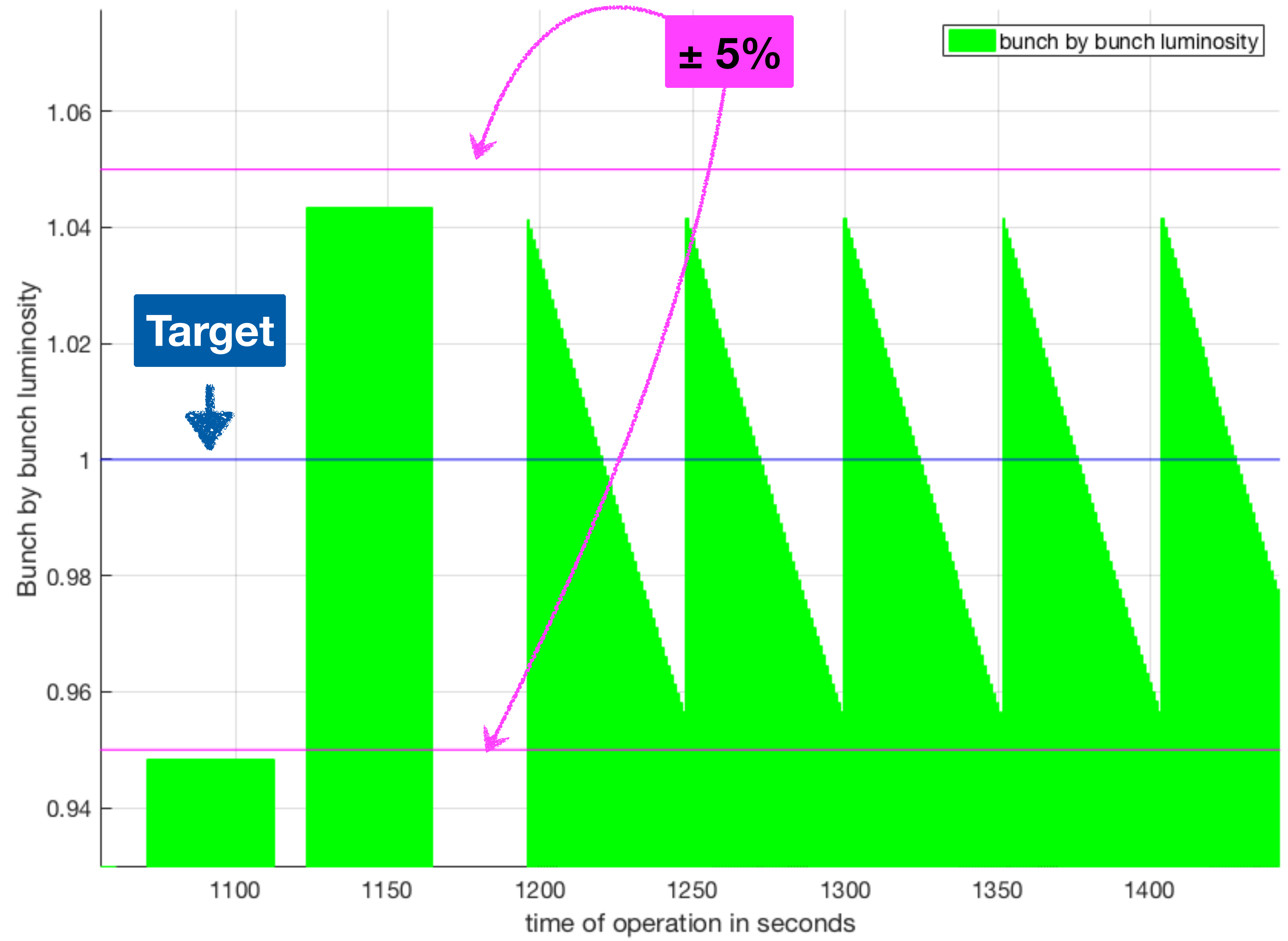


After First Fill:Quasi-continuous Top up



After First Fill:Quasi-continuous Top up

Zoom in



Conclusions

- ❖ This simulation code is written in MATLAB.
- ❖ Injector chain will keep the same routine (i.e. the same duty factors) for the first fill or the top up, with an only change of charge/bunch.
- ❖ Injectors need to provide 11+1 different charge portions varying between about ……… for continuous top up and charges varying between …….. particles per bunch for the first fill.

✓ Injectors can meet the requirements of the updated baseline for ***Z***-mode and provide full luminosity throughout top-up operation

Further Discussion

- A case with an injection to the BR with 20 GeV linac.

Linac Repetition [Hz]	200
Bunches per RF pulse*	2
Bunch Population **	1,70E+10
Linac Duty Factor [%]	94,5
BR Bunch charge **	1,70E+10
BR Number of Bunches	16640
BR Ramp time [sec]	2,4
BR Cycle Time [sec]	44
BR Number of Cycles	11
BR Duty Factor [%]	100,0
Collider Number of Bunches	16640
Collider Bunch Charge	1,87E+11
Collider Bunch Target Aim	1,70E+11
Transmission Target [%] >	90,9
BR cycle for both species [sec]	88
Collider Fill time full charge (e-&e+)	968
Collider Bunches	16640

- 44*22= 968 sec to reach full luminosity.
- No SPS, no conflicting schedules with hadron operations.
- Cost of 300-400 meter additional C-band (50 MV/m) linac compare to few km synchrotrons.
- Injected emittance to the BR can be below nanometer.