FUTURE
CIRCULAR
COLLIDER

cnrs

Filling Schemes through Injector Chain

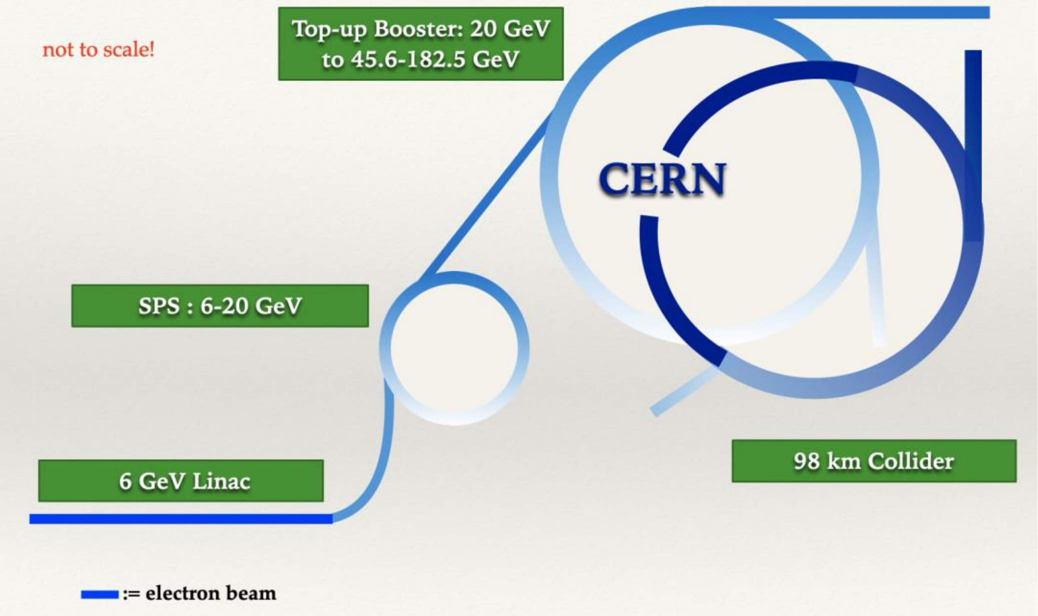
S. Ogur, I. Chaikovska (CNRS/IJCLab); D. Shatilov (BINP); M. Benedikt, A. Grudiev, K. Oide, Y. Papaphilippou, F. Zimmermann(CERN); P. Craievich (PSI)

IJCLab
Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 95175.

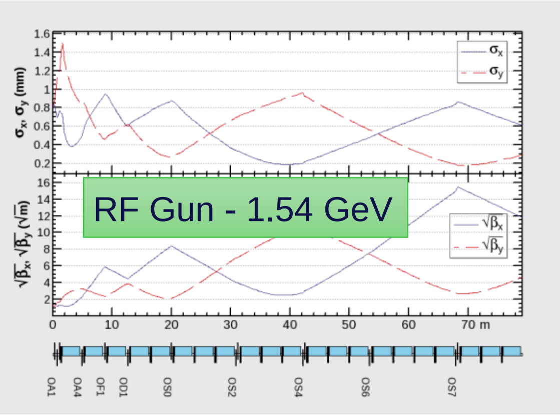
Table of content

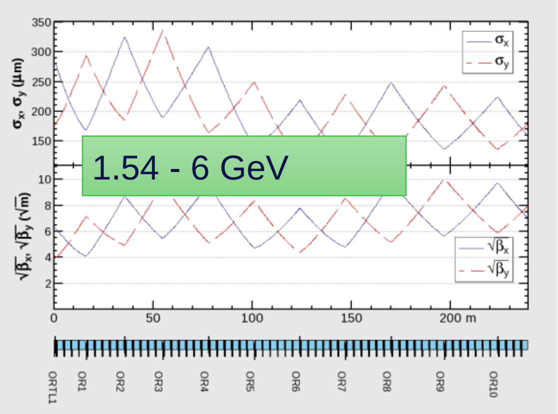
1. Conceptual Design Report



- SLAC/SuperKEKB like S-Band linac. 6 GeV is chosen assuming positron generation at 4.46 GeV and 1.54 GeV Damping Ring.
- The modified SPS was the intermediate booster to increase the energy to the *minimum possible injected energy* into the top-up booster.
- Top-up booster will share the same tunnel, and accelerate 20 GeV to the final energies. It would have the same number of bunches as the collider, yet with ~ $1/10^{th}$ of the collider bunch intensity.

1.1. S-Band Linacs in the CDR

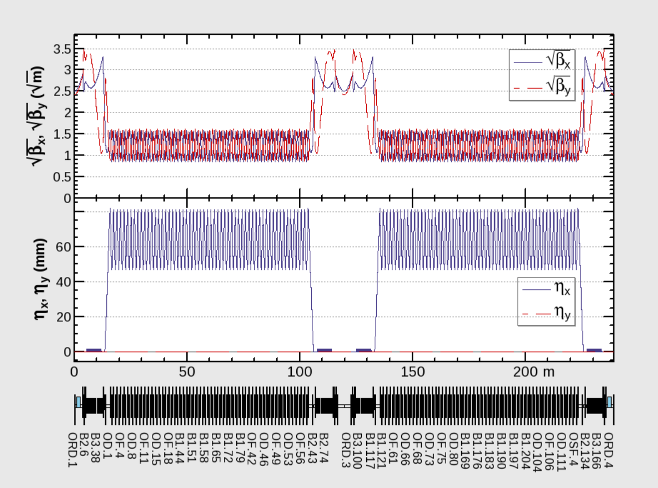




Cavities	S-Band
Repetition (Hz) and # of bunches	200 and 2 (4*)
Frequency (MHz)	2855.98
Length (m)	2.97
Cavity Mode	2π/3
Aperture Diameter (mm)	20
Unloaded Cavity Gradient (MV/m)	25

- In the CDR, 2 e- bunches per RF pulse were assumed to accelerate during e- delivery, and 2 e- bunches PLUS 2 e+ bunches during e+ delivery. In other words, the pre-booster would get 200 Hz of 2 bunches of a species each second.
- Bunch to bunch separation 50 ns (in the CDR was 100 ns).

1.2. Damping Ring in the CDR



Parameters	Value
Circumference	242 m
Energy	1.54 GeV
Bunch intensity	2.1E10
Number of trains x bunches in a train	8 x 2 bunches
Transverse Damping Time	10.5 ms
Store time for a train	40 ms
Energy loss per turn	0.225 MeV
SR Power loss	15.7 kW

- At each linac RF pulse (i.e. 5 ms) a train consisting of 2 e+ or e- bunches are injected into the DR.

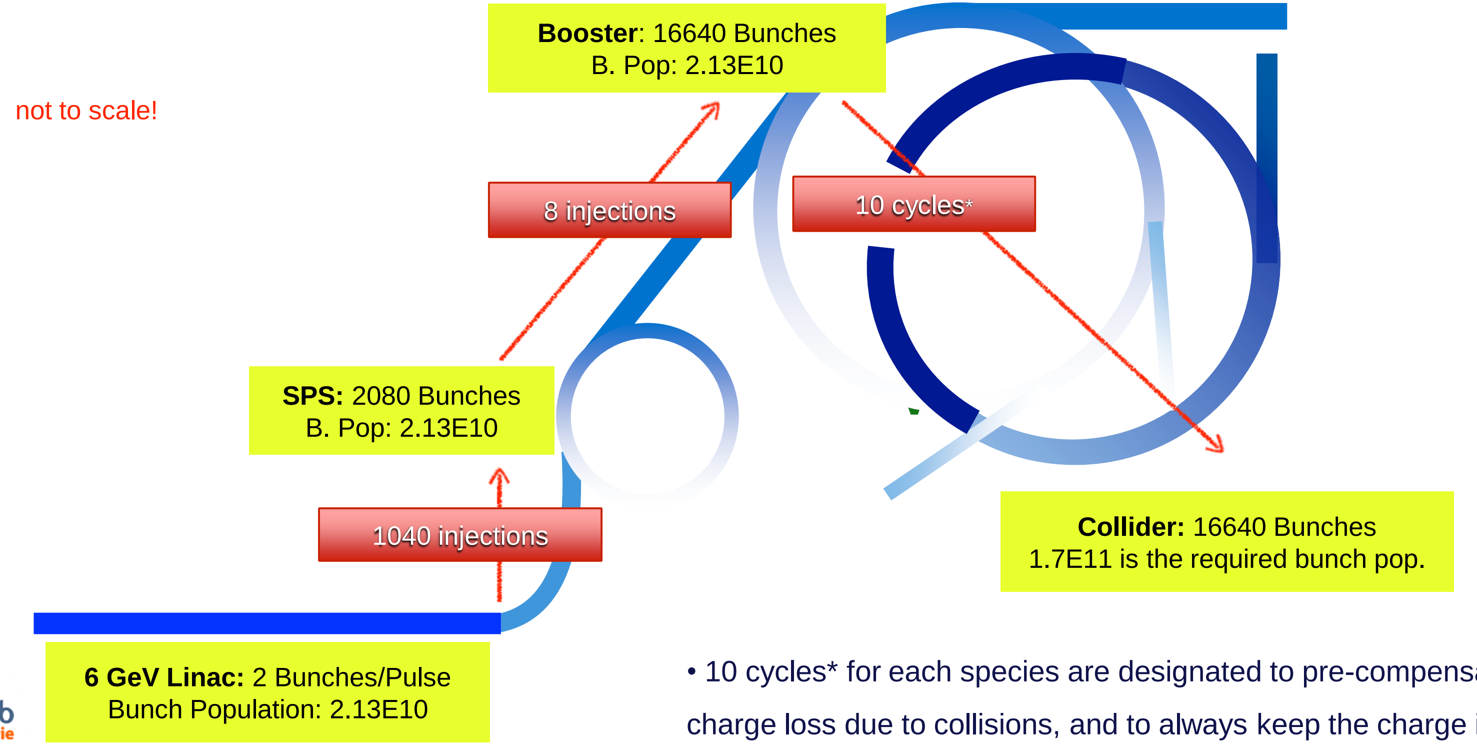
After 8 trains are stored, each train which cooled for 40 ms will be extracted and re-injected into the linac. The same RF pulse accelerating the extracted train from DR will carry the primary 2 e- bunches to generate the new e+ DR train.

1.3. Fill From the Scratch in the CDR

Operation Type	Final Energy [GeV]	Luminosity Lifetime [min]	Bunches/Beam	Bunch Population
Z	45.6	70	16640	1.7×10^{11}
W	80	50	2000	1.5×10^{11}
H	120	42	328	1.8×10^{11}
tt	182.5	39	48	2.3×10^{11}

- The highest accumulated charge will occur for the Z - operation. Now on, we will give the Z-mode fill which is the most challenging operation in terms of charge flux delivered by the injectors.

1.3. Fill From the Scratch in the CDR



- 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).

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

1.3. Fill From the Scratch in the CDR

- **Linac:**
  200 Hz 2 bunches per RF pulse

- **SPS:**

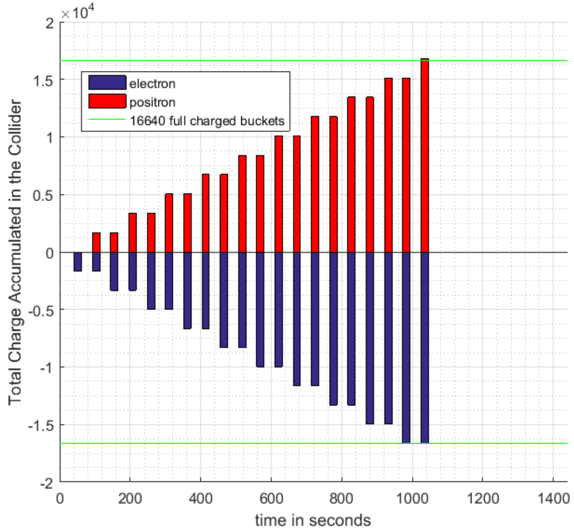
Accumulation of 2080 bunches	:	5.2 s
Emittance cooling (Damping time 0.1 s)	:	0.7 s
Ramp up time (6 - 20 GeV)	:	0.2 s
SPS Cycle time	**:**	**6.3 s**

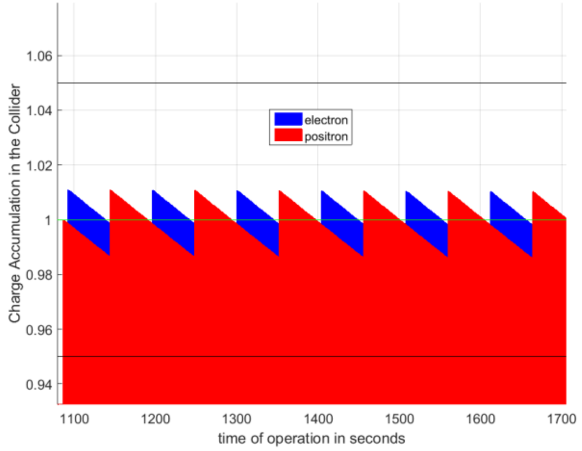
- **Top-up Booster:**

Accumulation of 8 SPS Trains	:	50.4 s
Emittance cooling (Damping time 0.1 s)	:	0.7 s
Ramp up time (20 - 45.6 GeV)	:	0.32 s
BR Cycle time	**:**	**51.74 s**

- **Collider:**
  10 BR Injections for each species will result the collider to be filled for Z- mode in 1035 seconds (17m15s)

1.4. Bootstrapping and Top-up in the CDR





- At each BR Cycle (51.7 s), we inject one species into the collider 1/10th of the nominal charge (normalised to 1).
- Pre-compensational charge for the last injected species.

- After the collider is fully filled, we need to keep e- and e+ charges within ±5% asymmetry for *Z*-mode.
- In this plot, we simply assume the bunch decays exponentially for the luminosity lifetime of 70 minutes.
- **At each booster cycle, we loose 1.2% by $N = N_0 e^{-t/\tau}$**
- **We top up by 2 x 1.2% to each species at each 2 BR Cycles.**

1.4. Bootstrapping and Top-up in the CDR

- **Z - operation:**
  First fill in 17m15s
  Allowed asymmetry is $\pm$ 5%
  Top up at each 51.74 s x 2 by 2.4% to each species
- **W - operation:**
  First fill in 4m26s
  Allowed asymmetry is $\pm$ 3%
  Top up at each 13.3 s x 2 by 1% to each species
- **H - operation:**
  First fill in 2m32s
  Allowed asymmetry is $\pm$ 3%
  Top up at each 7.58 s x 2 by 0.6% to each species
- **t - operation:**
  First fill in 12.56s
  Allowed asymmetry is $\pm$ 3%
  Top up at each 6.28 s x 2 by 0.5% to each species

- W, H and t operation requires 100 Hz linac repetition and 1 bunch/pulse for H, t!
- 200 Hz operation is only needed for Z!

- We can maintain the average luminosity at the peak!

2.1. Multi-bunch Linac Parameters

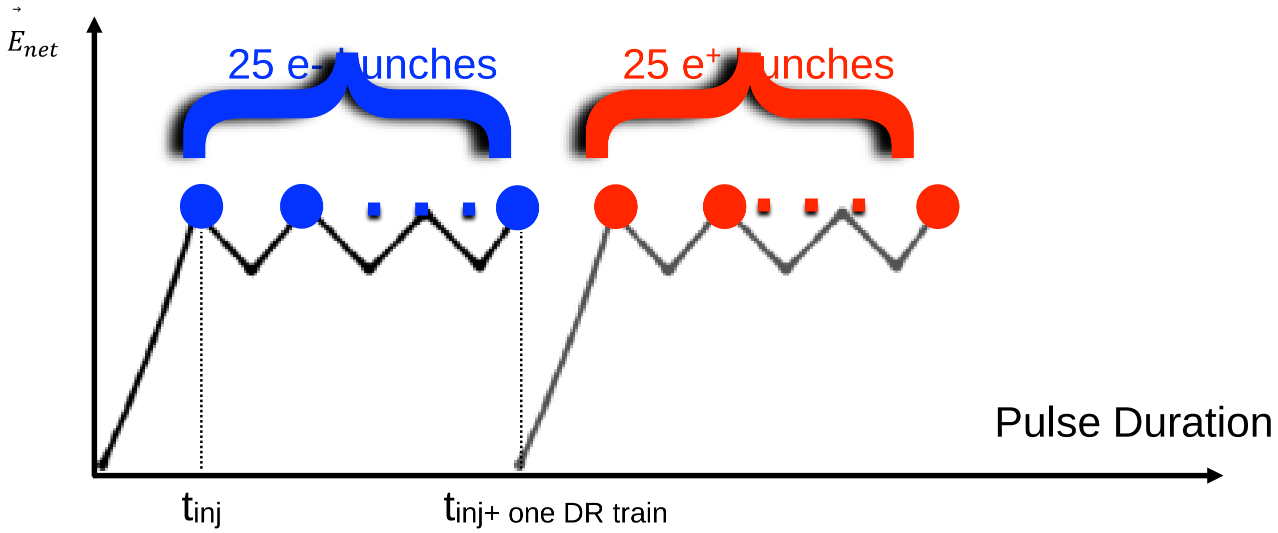
parameter	Baseline
Ring for injection	PBR
Injection energy [GeV]	6
Bunch population	2.1e10
Minimum bunch spacing [ns]	15, (17.5, 20)
Transverse emittances (RMS): ε_x,y [nm]	**5, 5 < 15**
Normalized transverse emittances (RMS): γε_x,y [um]	**60, 60**
Bunch length (RMS) [mm]	10
Energy spread (RMS) [%]	0.1
Injection scheme	Off axis injection:
Transverse acceptable emittances (RMS): ε_x,y [nm]	**15, 60 (12, 41)**

- Thus Damping Ring extraction emittance would be 2/8 nm if we leave factor ~2 as emittance blow-up budget in the transfer to the linac and in the linac for 1.54-6 GeV acceleration.
- Bunch to bunch spacing in the collider can be 17.5 ns at max, if 16640 bunches are stored. However this might be changed to space bunches at 20 ns (due to e- cloud2) and reduce number of bunches stored to ~16000 bunches if SPS not used (meaning no beam abort gaps nor injection gaps inherited from SPS).

2.1. Multi-bunch Linac Parameters

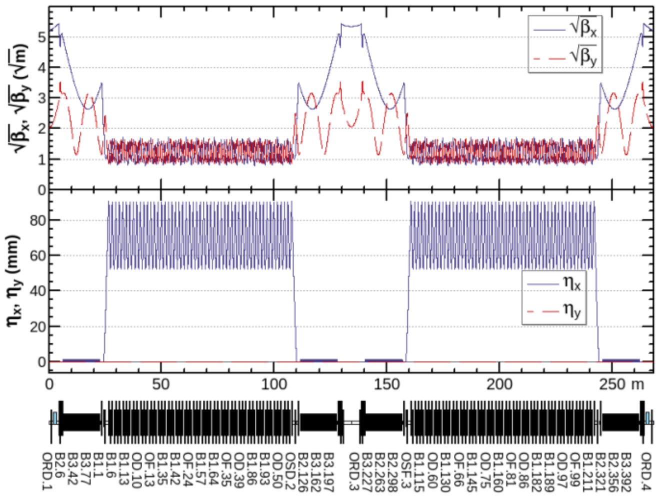
- Bunch to bunch spacing in the collider can be 17.5 ns at max, if 16640 bunches are stored. Since 16640 would span 291.2 μs of 325 μs collider.
- It may not feasible to stack if the linac spacing is not a harmonics of the rings.
  To illustrate, linac train with b-t-b spacing 35 ns can be stacked to reach 17.5 ns.
- So for now, let's assume that the collider b-t-b spacing is 17.5 ns, and all injectors have 17.5 ns b-t-b spacing.
- Positron study (link) puts limit at 100 Hz repetition with 25 bunches.

2.1. Multi-bunch Linac Parameters



- Not to create any delay due to positron generation, 1 linac pulse should accelerate 2 DR trains, 1 train to hit the target and be injected into the DR; while the other train to be sent into the SPS or (P)BR.
- Effectively, linac pulse accelerates 50 bunches per RF pulse.

2.2. Damping Ring for the Multi-bunches



Parameters	Value
Circumference	268.4 m
Energy	1.54 GeV
Bunch intensity	2.1E10
Number of trains x bunches in a train	2 x 25 bunches
Transverse Damping Time	5.6 ms
Store time for a train	20 ms
Energy loss per turn	0.461 MeV
SR Power loss	90.6 kW

- At each linac RF pulse (i.e. 5 ms) a train consisting of 2 e+ or e- bunches are injected into the DR.
- After 8 trains are stored, each train which cooled for 20 ms will be extracted and re-injected into the linac. The same RF pulse accelerating the extracted train from DR will carry the primary 2 e- bunches to generate the new e+ DR train.

2.2. Fill From the Scratch Multi-bunch

- **Linac:**
  100 Hz 25 bunches per RF pulse

- **SPS:**
  Accumulation of 1250 bunches : 0.5 s
  Emittance cooling (Damping time 0.03 s) : 0.12 s
  Ramp up time (6 - 20 GeV) : 0.175 s
  SPS Cycle time : 0.97 s

- **Top-up Booster:**
  Accumulation of 14 SPS Trains : 50.4 s
  Emittance cooling (Damping time 0.1 s) : 0.4 s
  Ramp up time (20 - 45.6 GeV) : 0.32 s
  BR Cycle time : 14.72 s

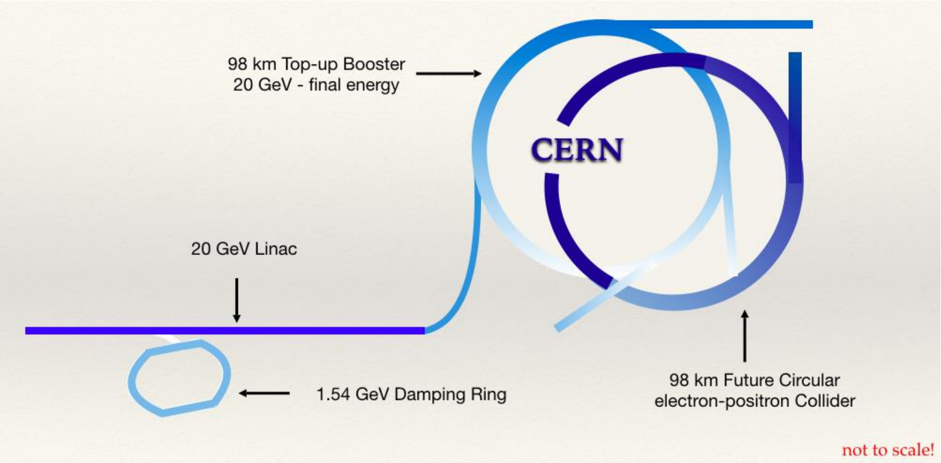
- **Collider:**
  10 BR Injections for each species will result the collider to be filled for Z- mode in 294.4 seconds (4m54s)

2.2. Fill From the Scratch Multi-bunch

- **20 GeV Linac:**
  100 Hz 25 bunches per RF pulse

- **Top-up Booster:**
  Accumulation of 16640 bunches. : 6.6 s
  Emittance cooling (Damping time 0.1 s) : 0.4 s
  Ramp up time (20 - 45.6 GeV) : 0.32 s
  BR Cycle time : 7.8 s

- **Collider:**
  10 BR Injections for each species will result the collider to be filled for Z- mode in 156 seconds (2m36s)



IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

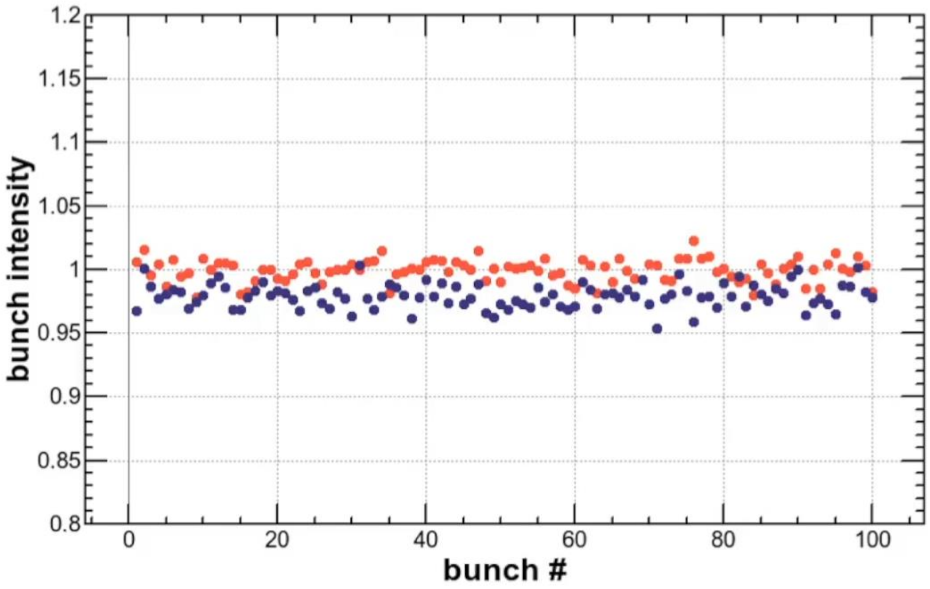
2.3. First Fill and Top-up for the Multi-Bunches

- **Z - operation with 6 GeV linac:**
  First fill in 4m54s
  Allowed asymmetry is ± 5%
  Top up at each 14.72 s x 2 by 0.7 % to each species

- **Z - operation with 20 GeV linac:**
  First fill in 2m36s
  Allowed asymmetry is ± 5%
  Top up at each 14.72 s x 2 by 0.4 % to each species

- **t - operation with 20 GeV linac with 25 bunches/pulse:**
  First fill in 9.2s
  Allowed asymmetry is ± 3%
  Top up at each 4.6 s x 2 by 0.4 % to each species

2.3. First Fill and Top-up for the Multi-Bunches



K. Oide

- A crude simulation of the bunch decay & refill

3. Discussion and Conclusions

- Multi bunches will decrease the first fill from 17m15s down to 4m54s for Z-operation.

- Assuming 10 beam aborts per day during the commissioning phases, multi-bunches will save 10*12 mins from the first fill, therefore higher integrated luminosity for Z-operation.

- The bunch-bunch luminosity during the top-up will not be dramatically effected from the multi-bunches. Disclaimer: no real luminosity and top-up injection are studied.

- Except the Z-operation, the fast repetition or multi-bunch acceleration may not be very beneficial.

Thank you for your attention.