CEPC injection and timing

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on behalf of CEPC AP group

Based on work and supports from different CEPC subsystems:

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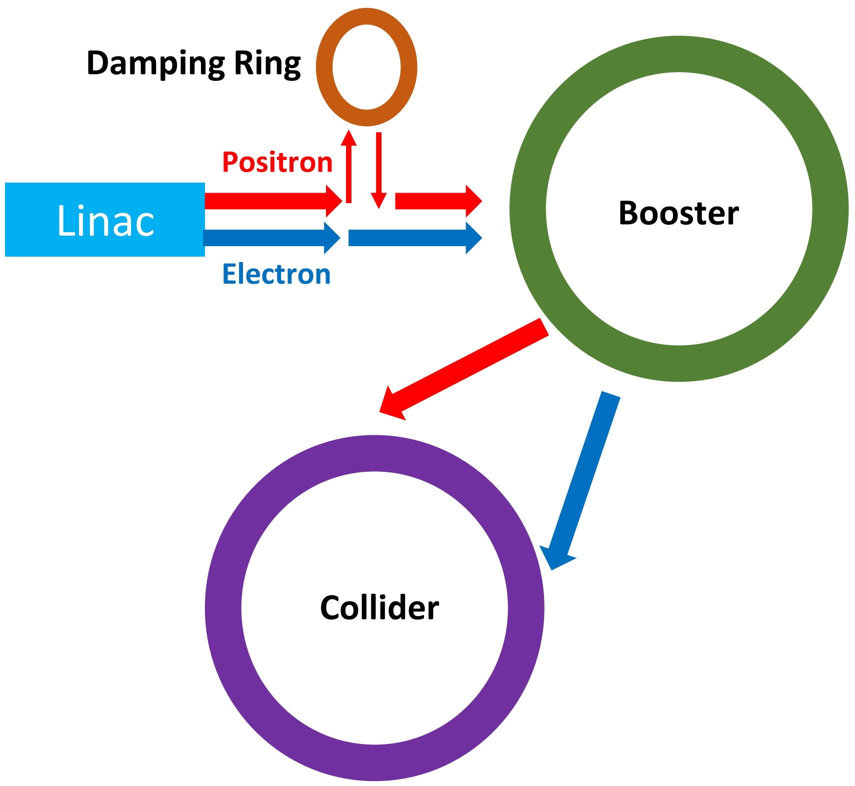
Introduction

1. Injection and extraction from: Linac, damping ring, booster, and collider;
2. Energy: tt (180 GeV), Higgs (120 GeV), W (80 GeV), Z (45.5 GeV);
3. Top-up and injection from scratch;
4. Off-axis and On-axis.



Introduction

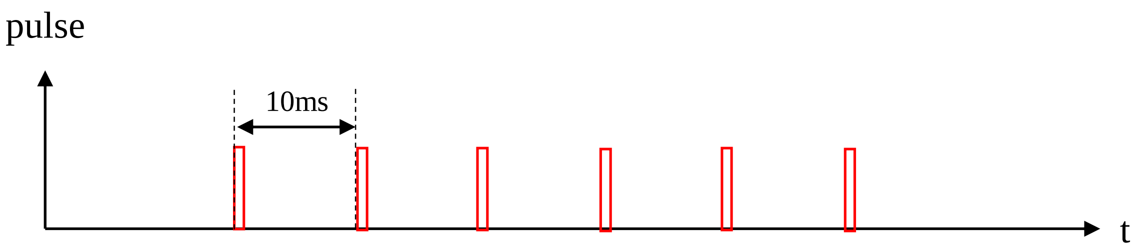
	tt	*Higgs*	*W*	*Z*
Bunch Number in collider	37	240	1230	11520
Bunch Separation	4.2μs	0.64μs	0.27μs	25ns
Bunch Number in booster	37	240	1230	3840
Lifetime (hour)	0.59	0.33	1.4	1.4
Interval for top up* (s)	65	38	155	153

* Beam current in collider decays by 3%.

- Z-mode is the most challenging operation in terms of charge flux delivered by the injectors.
- At Z mode, the bunch number in the booster is only 1/3 of that in the collider, so the booster need to be ramped up and down 3 times to inject into every bunch in the collider.

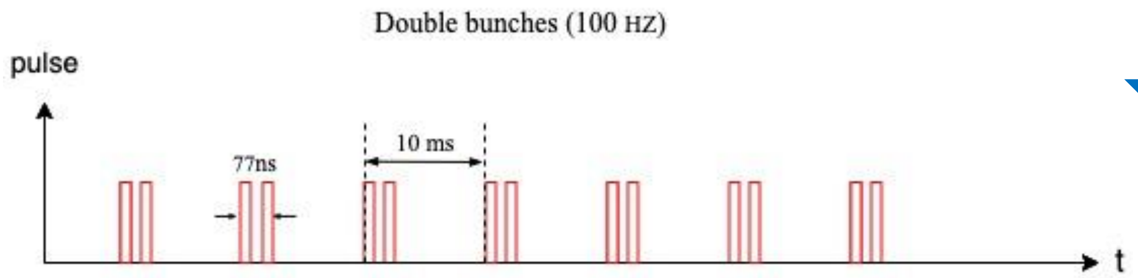
1. Linac

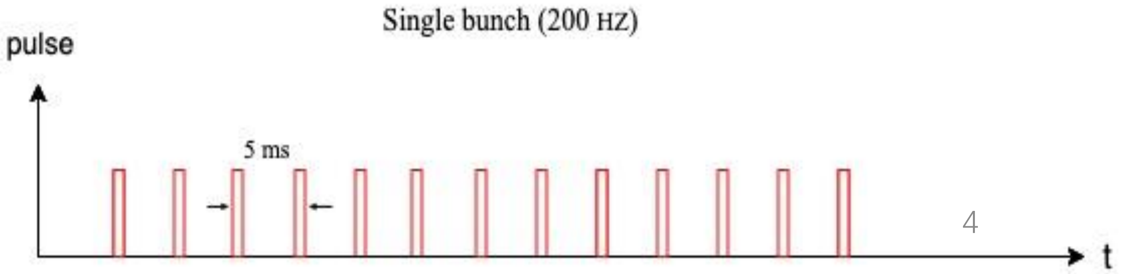
From the electron gun, bunches are generated in 100 Hz.



For High-Lum Z, more bunches are needed

It can be upgraded to double bunch (100Hz) or 200 Hz.



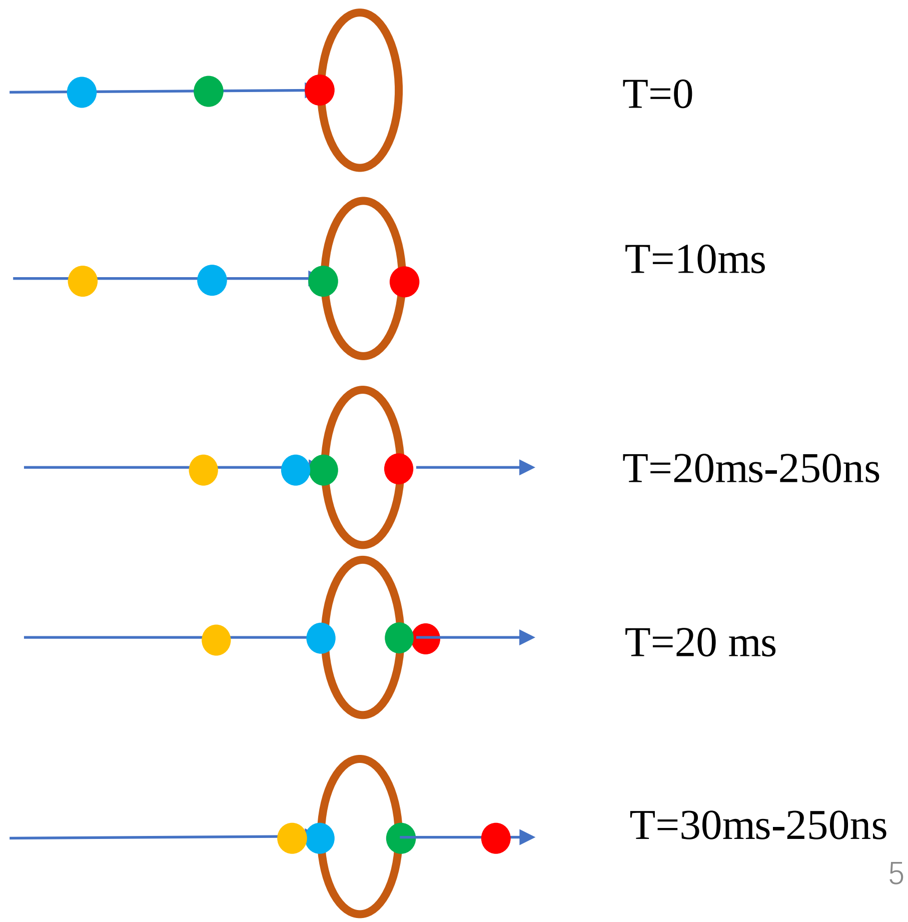


2. Damping Ring

Positron bunches will be injected into a damping ring at 1.1 GeV.

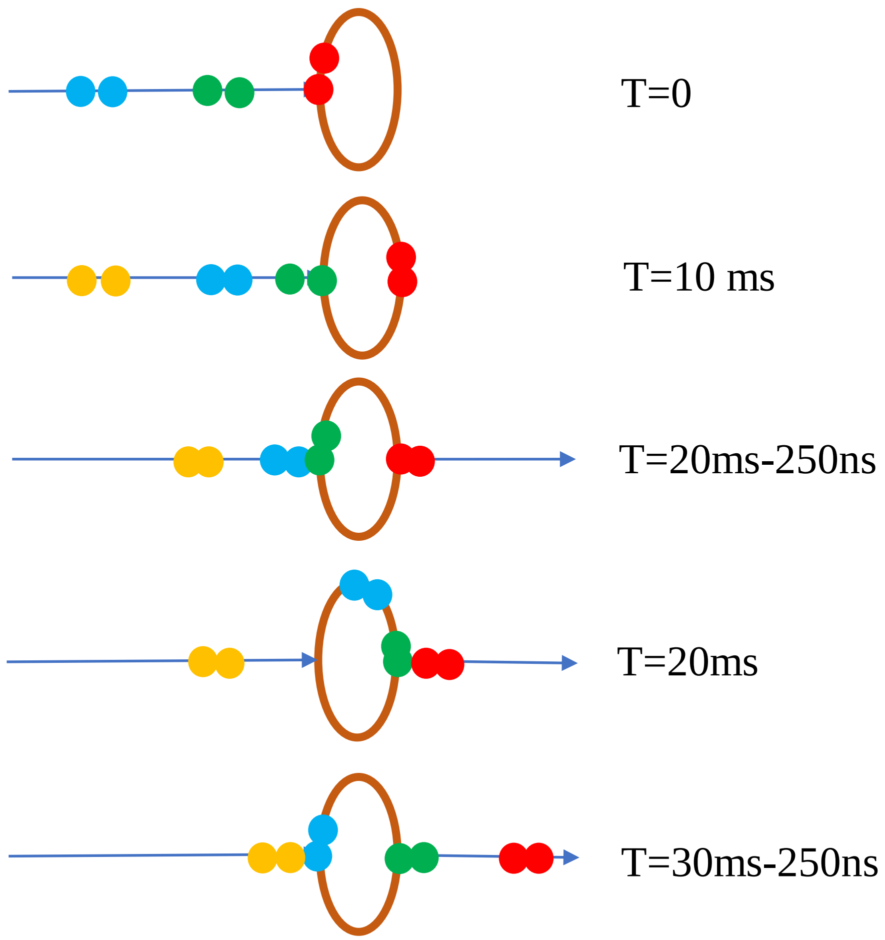
Damping ring circumference	150 m
Store time of the bunches:	20 ms

- The bunches are injected into the damping ring with the same frequency as bunches in the Linac;
- Each bunch which cooled for 20 ms will be extracted and re-injected into the linac.
- For 200 Hz or double-bunch mode, more bunches will be stored in the damping ring;
- With small changes, the cooling time of the bunches can be increased by holding more bunches in the damping ring.

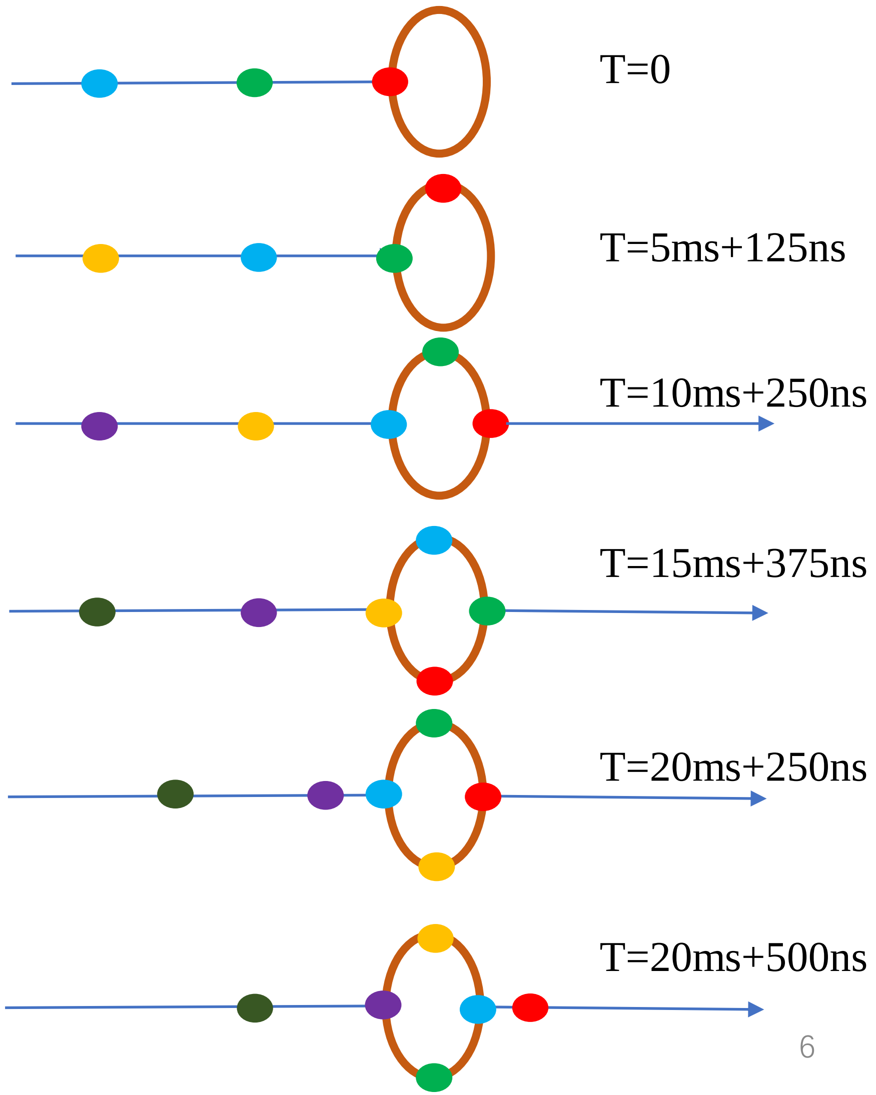


2. Damping Ring

Damping ring injection at Double bunch scheme

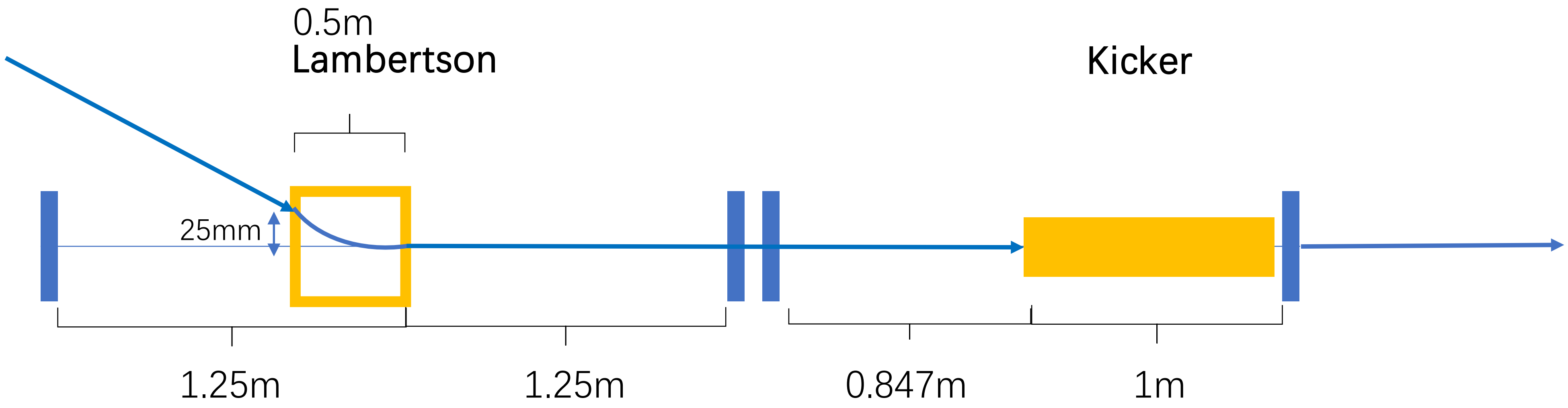


Damping ring injection at 200Hz scheme



2. Damping Ring

Top View:

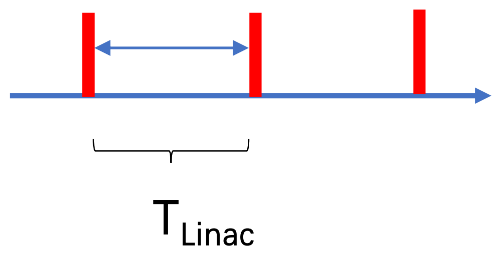


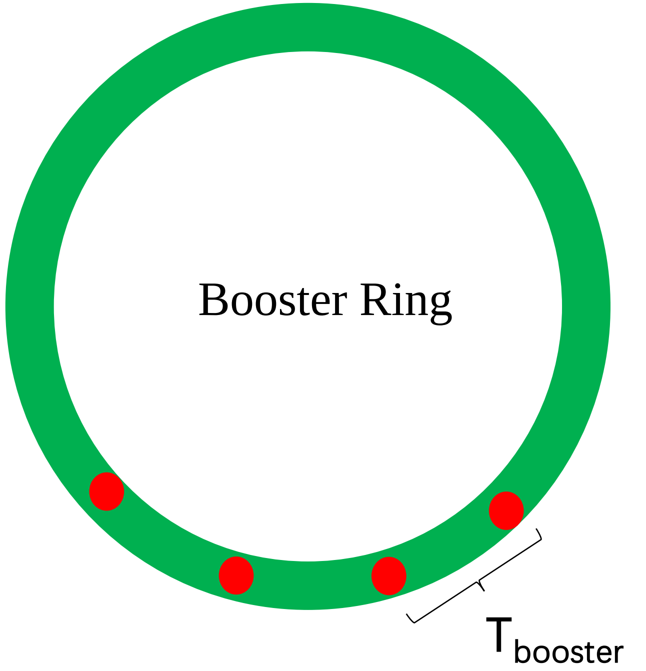
- Injection into the damping ring is a simple on-axis injection with 1 kicker;
- Extraction is similar to injection;

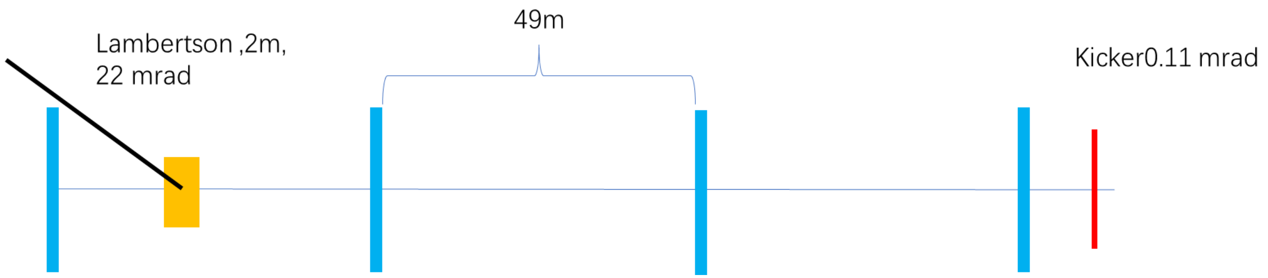
3. Injection to booster

Injection into the booster is a simple on-axis injection with 1 kicker

Bunches from the Linac will be in 100 Hz or 200 Hz





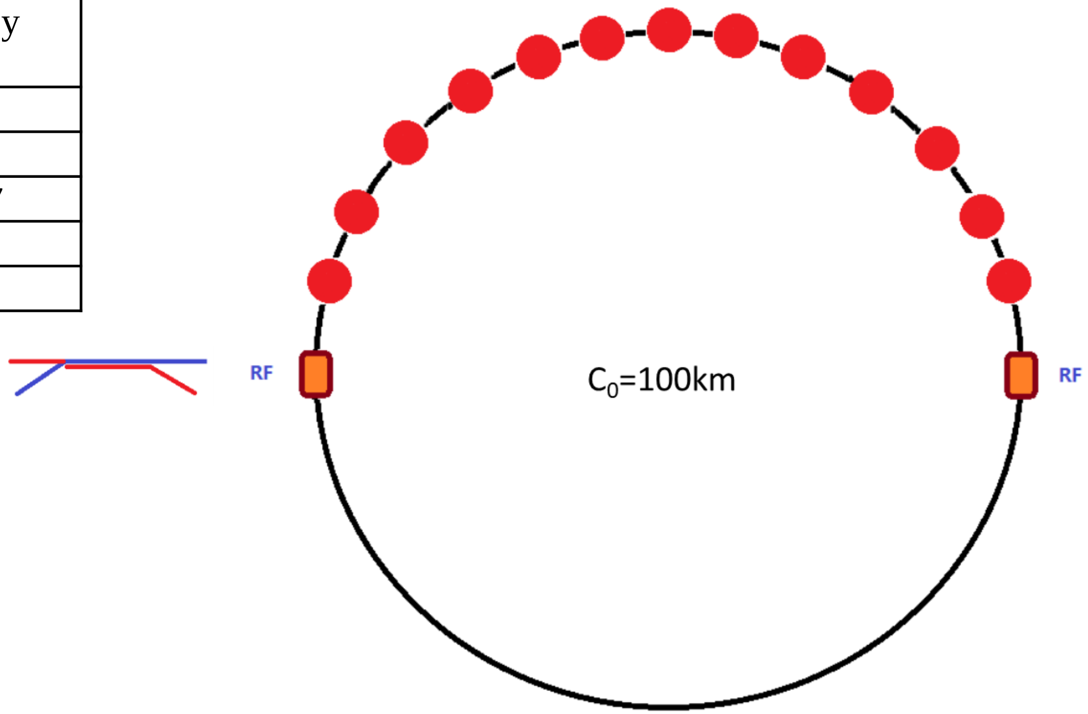


$$T_{Linac}=N*Turns+T_{booster}$$

By choosing the circumference of the booster and the Linac bunch separation, we can fill the booster with the pattern we needed.

3. Injection to booster (tt and Higgs)

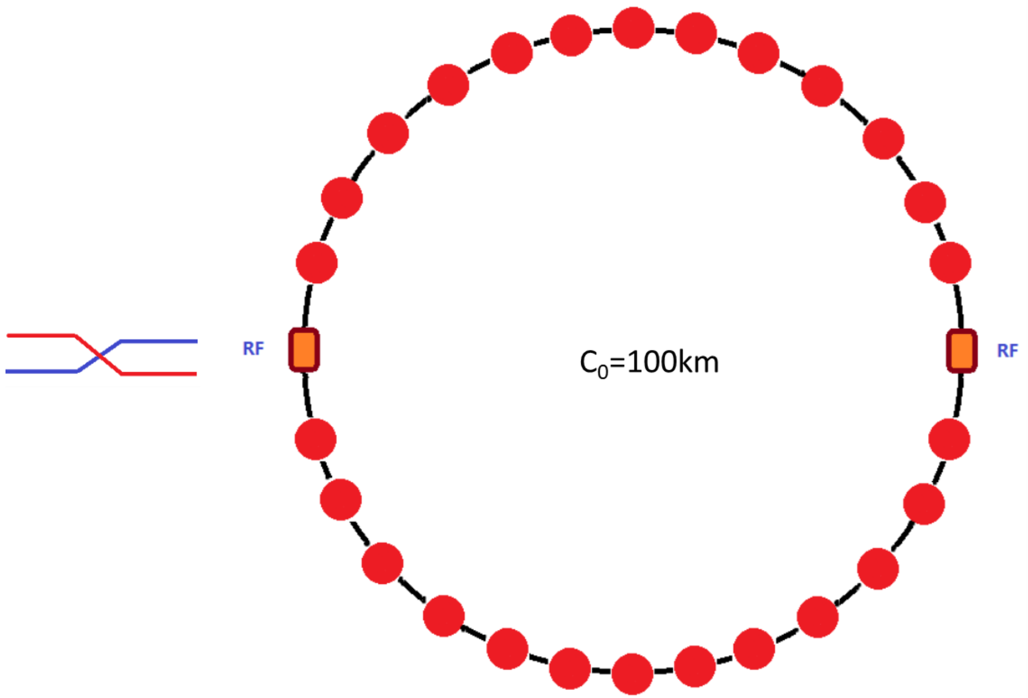
	tt	H
Energy（GeV）	20	20
Bunch number	37	240
Bunch seperation（us）	4.2	0.647
Injection scheme	bunch by bunch	bunch by bunch
Kicker frequency(Hz)	100	100
Kicker pules duration (us)	<8.4	<1.29
Kicker rise up/ fall down (us)	<4.2	<0.647
Timing delay(us)	4.2	0.647
Injection duration (s)	0.37	2.4



- To share the RF system, for tt and Higgs energy, bunches per beam are in the half ring both for booster and collider.

3. Injection to the Booster (W)

	W
Energy（GeV）	20
Bunch number	1230
Bunch seperation（us）	0.2677
Injection scheme	bunch by bunch
Kicker frequency(Hz)	100
Kicker pules duration (us)	<0.535
Kicker rise up/ fall down (us)	<0.2677
Timing delay(us)	0.2677
Injection duration (s)	12.3

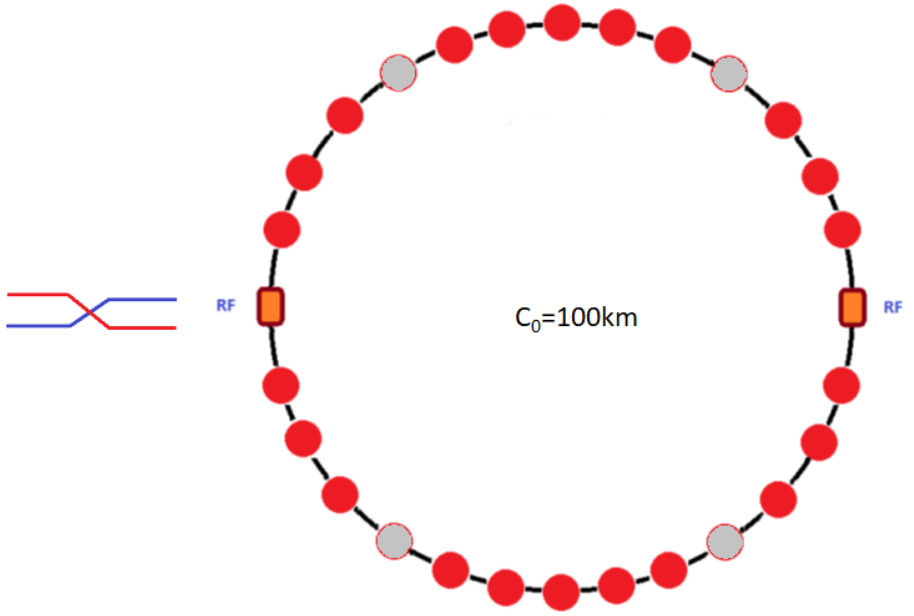


- For W mode, bunches are uniform in the whole ring both for booster and collider.

3. Injection to the Booster (Z)

	Z
Energy（GeV）	20
Bunch number/train	80
Bunch separation（ns）	23.076
Number of trains	48
Train separation (us)	5.11
Kicker frequency(Hz)	200 or 100 (double bunch)
Injection scheme	bunch by bunch or two by two
Kicker rise up/ fall down (ns)	<23.076
Flat top (ns)	23.1 for double bunch mode
Injection duration (s)	19.2

- bunches per beam are distributed train by train both in booster and collider. (This will be talked about in detail later)
- The number of train in the booster is 1/3 of that in the collider.



3. Injection to the Booster (Z)

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To have the flexibility of booster bunch patterns choice, some considerations on the electron gun or Linac frequencies are on going.

f (MHz)	SHB1	SHB2	Linac	DR	booster	collider
CEPC	143	572	2860	650	1300	650

- For CEPC, the common frequency is 13MHz, so the minimum time separation= 76.92ns.
- Max bunch number is limited by the common frequency of collider, booster and Linac.
- If the SHB1&SHB2 is cancelled, the minimum time separation=7.692ns.

➢2*11*n=N*m2*m1*k

- m1 = **11**
- m2=3~5, **4**
- N=4~6, **5**

➢T_{beam}=1/fbm=N*m2*m1*0.34965ns

@Cai Meng

2020.07.17

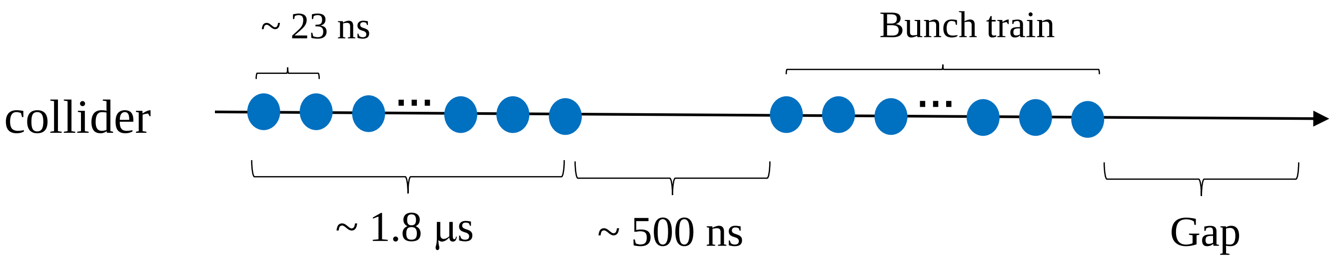
	frequency		Multiple	Preiod	
Common frequency	13	MHz	1	76.9231	ns
Two bunch	13	MHz	1	76.9231	ns
SHB1	143	MHz	11	6.9930	ns
SHB2	572	MHz	44	1.7483	ns
LINAC	2860	MHz	220	0.3497	ns
Booster	1300	MHz	100	0.7692	ns
Ring	650	MHz	50	1.5385	ns

- Subharmonic bunchers are cancelled and the thermionic gun is replaced by RF gun.

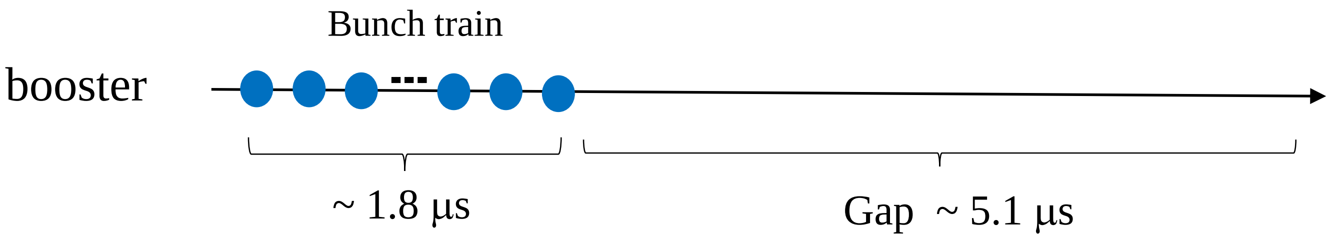
Bunch separation@Z=23.08ns

4. Extraction from the Booster

- For tt, Higgs, and W mode, bunch by bunch extraction is easy.
- For Z energy, more considerations are needed due to the large bunch number needed in the collider.
- the separation between bunches are only 20~30 ns. Considering the rise time of the kickers, bunches are arranged **train by train** in the collider.
- Due to the current limit in the booster, The bunch number in the booster is only **1/3** of that in the collider.



The bunches in the collider are arranged in bunch trains about **1.8 μs** and with gaps about **500 ns**. The kickers in the collider can rise and fall down in the gaps.



The bunches in the booster are arranged in the same bunch train structure. But the train number is **1/3**, so the gap is much longer.

4. Extraction from the Booster

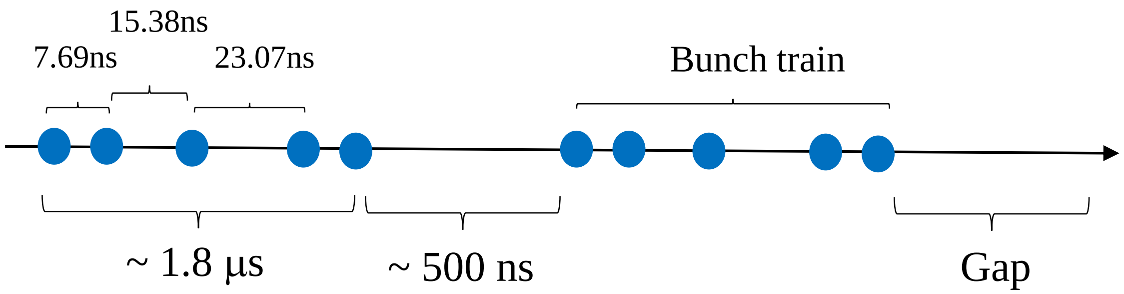
	tt	Higgs	W
Energy（GeV）	180	120	80
Bunch number	37	240	1230
Bunch seperation（us）	4.2	0.647	0.2677
Extraction scheme	bunch by bunch	bunch by bunch	bunch by bunch
Kicker frequency(Hz)	1000	1000	1000
Kicker pules duration (us)	<8.4	<1.29	<0.535
Kicker rise up/ fall down (us)	<4.2	<0.647	<0.2677
Timing delay(us)	4.2	0.647	0.2677
Extraction duration (s)	0.037	0.24	1.23

	Z
Energy（GeV）	45.5
Bunch number/train	80
Bunch separation（ns）	23.076
Number of trains	48
Train separation (us)	5.11
Extraction scheme	train by train
Kicker frequency(Hz)	1000
Flat top (us)	1.83
Kicker pules duration (us)	<12.05
Kicker rise up/ fall down (us)	<5.11
Timing delay(us)	6.94
Extraction duration (s)	0.048

4. Extraction from the Booster

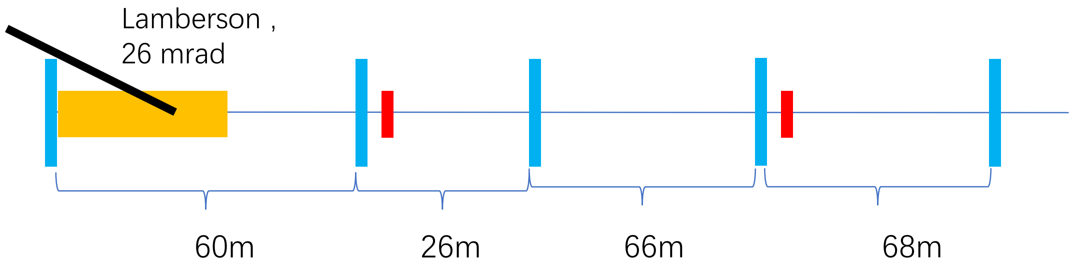
Some considerations on 50MW upgrade

- More bunches are needed in the collider and booster.
  - Min time separation=7.69ns
- Different bunch filling patterns considered.
  - Put more bunches in a bunch train
  - Free combination of 7.69ns, 15.38ns, 23.07ns, 30.76ns…



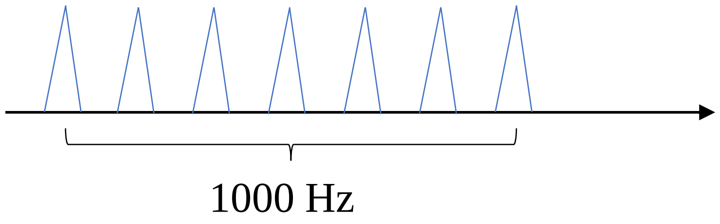
6. Injection to the collider

1. Considering the robustness of the design, the injection of the main collider ring is conventional off-axis injection. (Maybe an on-axis injection is needed for Higgs)
2. For tt, Higgs and W energy, injection into the collider is bunch by bunch; and for Z energy, injection is train by train.



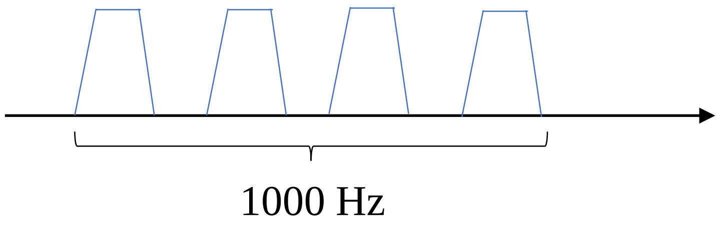
Kicker:

Bunch by bunch



The kickers rise up, inject one bunch into the collider, and fall down. This process repeated in 1000 Hz, to inject all bunches into the ring.

Train by train



The kickers rise up, stay there to inject a whole train into the collider, and fall down. This process repeated in 1000 Hz, to inject all bunches into the ring.

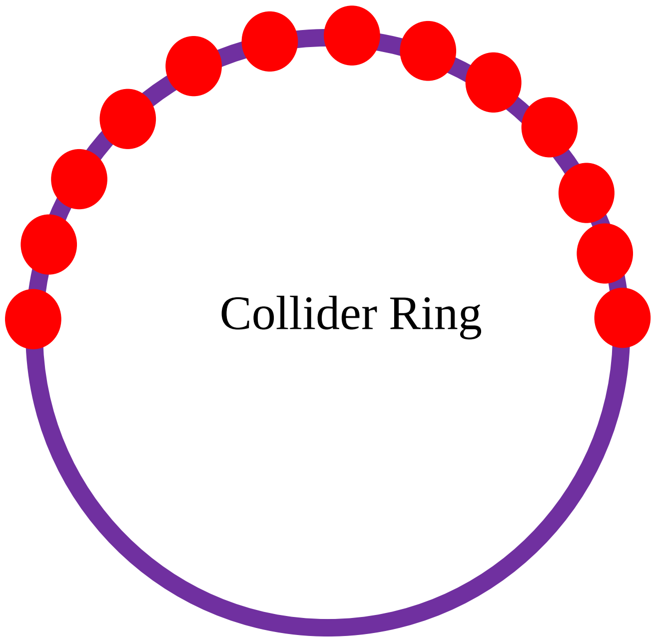
6. Injection to the collider

	tt	Higgs	W
Energy（GeV）	180	120	80
Bunch number	37	240	1230
Bunch seperation（us）	4.2	0.647	0.2677
Injection scheme	bunch by bunch	bunch by bunch	bunch by bunch
Kicker frequency(Hz)	1000	1000	1000
Kicker pules duration (us)	<8.4	<1.29	<0.535
Kicker rise up/ fall down (us)	<4.2	<0.647	<0.2677
Timing delay(us)	4.2	0.647	0.2677
Injection duration (s)	0.037	0.24	1.23

	Z
Energy（GeV）	45.5
Bunch number/train	80
Bunch separation（ns）	23.076
Number of trains	144
Train separation (us)	0.492
Injection scheme	train by train
Kicker frequency(Hz)	1000
Flat top (us)	1.83
Kicker pules duration (us)	<2.81
Kicker rise up/ fall down (us)	<0.49
Timing delay(us)	6.94 & 2.32
Injection duration (s)	0.144

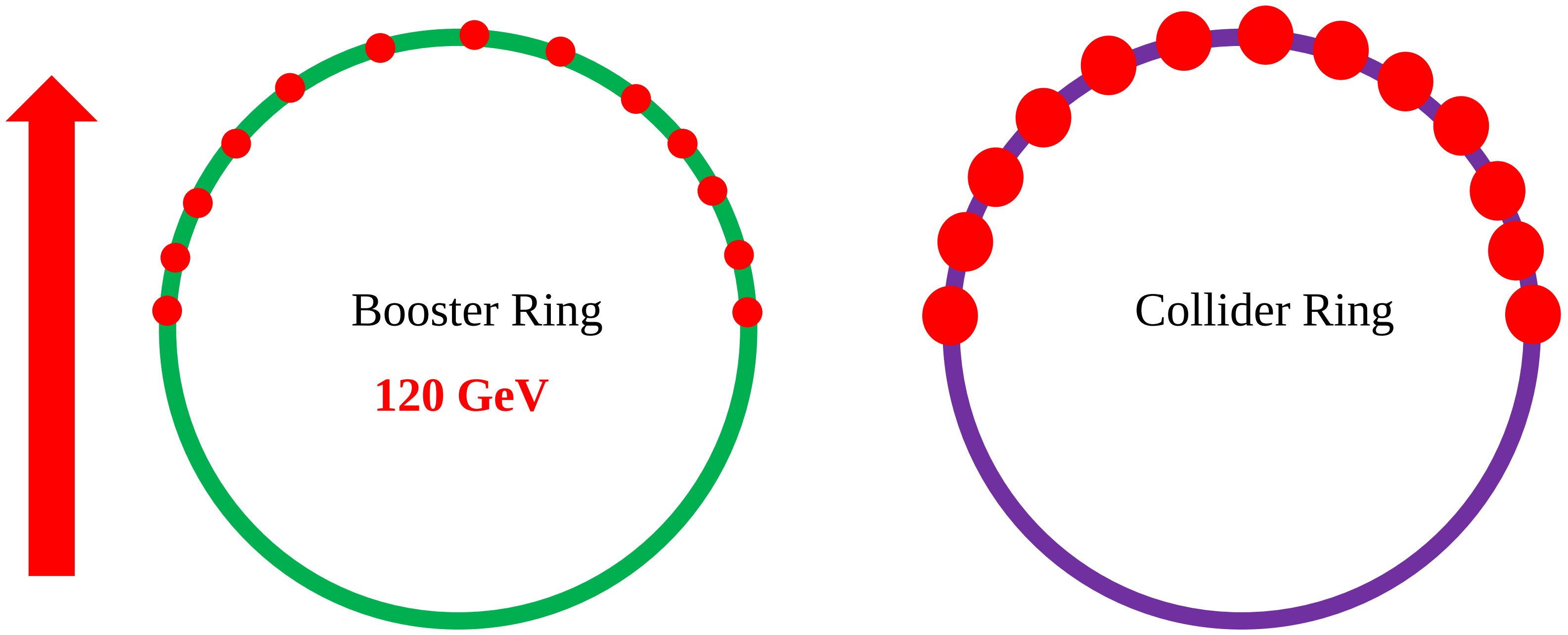
7. Injection to the collider- On-axis

There are 240 bunches uniformly in the half ring of the collider



7. Injection to the collider- On-axis

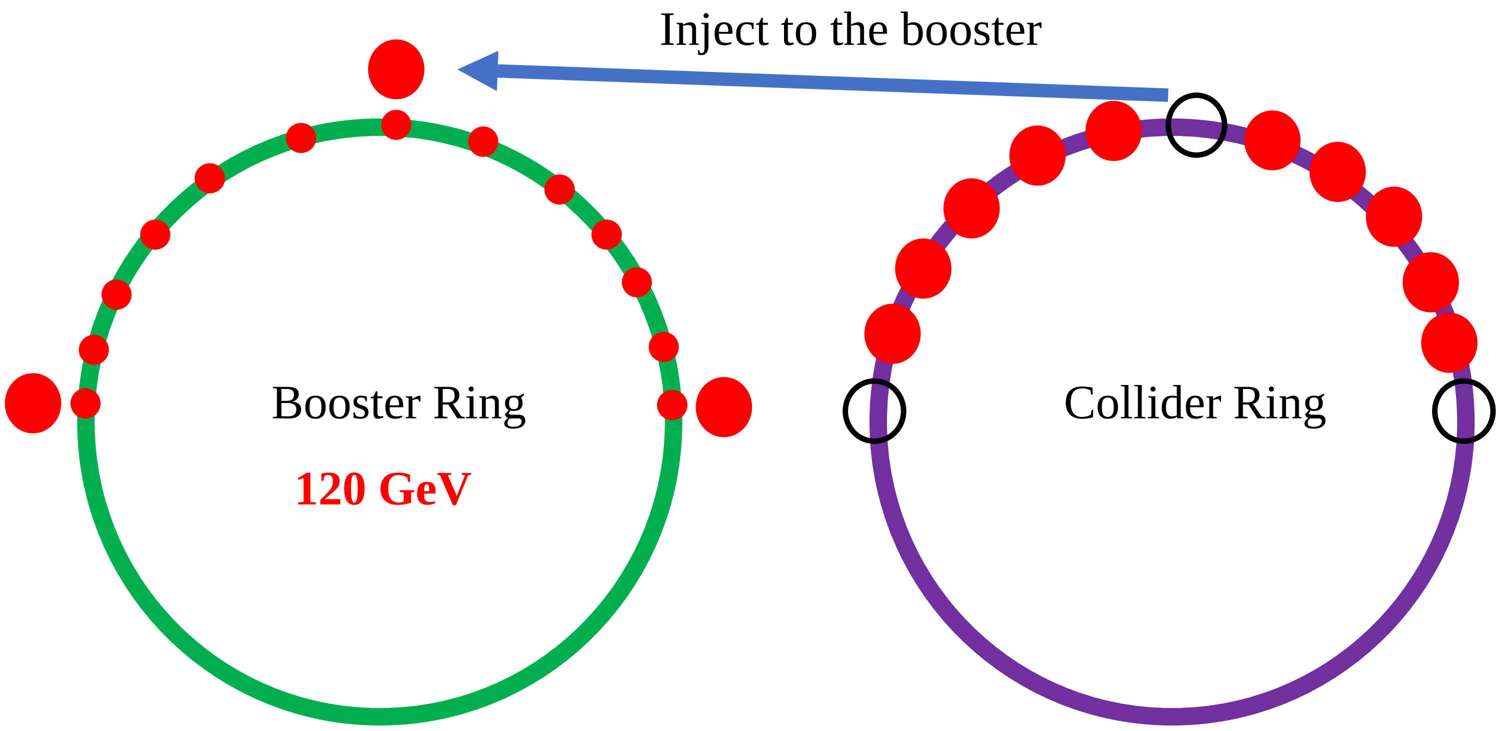
Step 1:
Inject 240 small bunches from Linac to booster, and ramp the booster up to 120 GeV.



7. Injection to the collider- On-axis

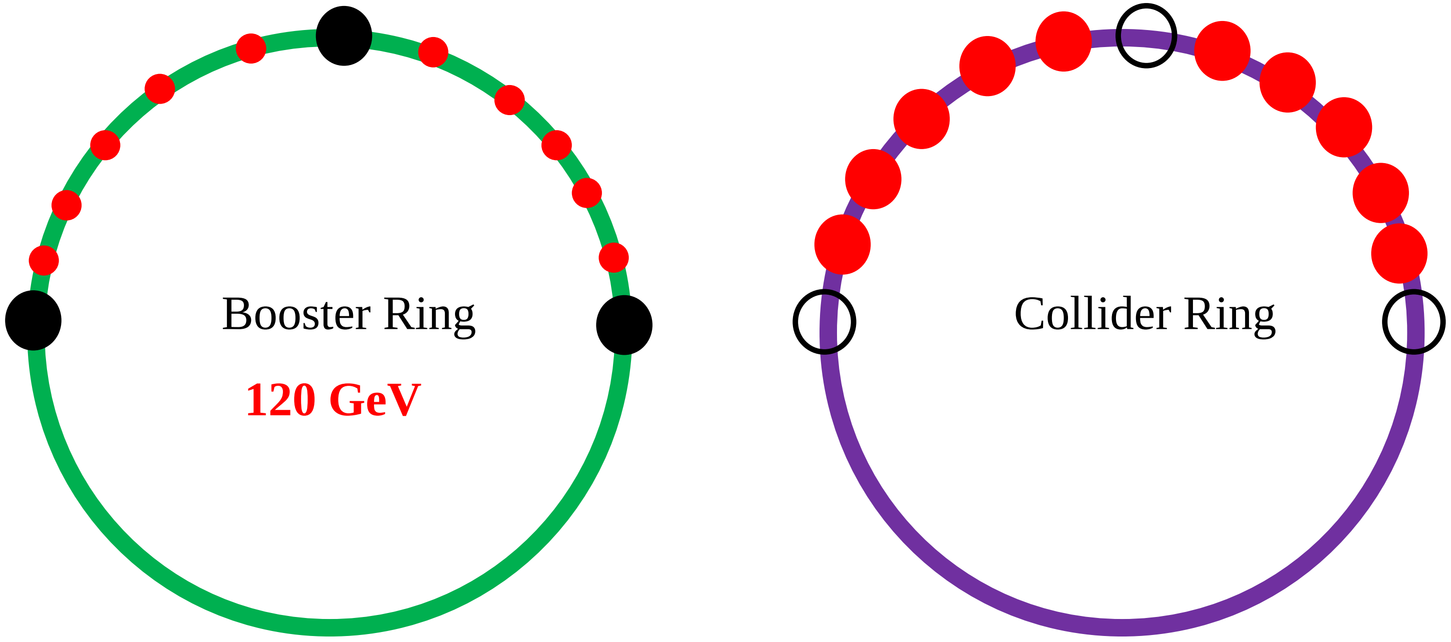
Step 2:
Inject N_{change} large bunches from the collider to booster, using off-axis injection method.

N_{change} is determined by the current limit in the booster, we can exchange 7 bunches in the beginning.



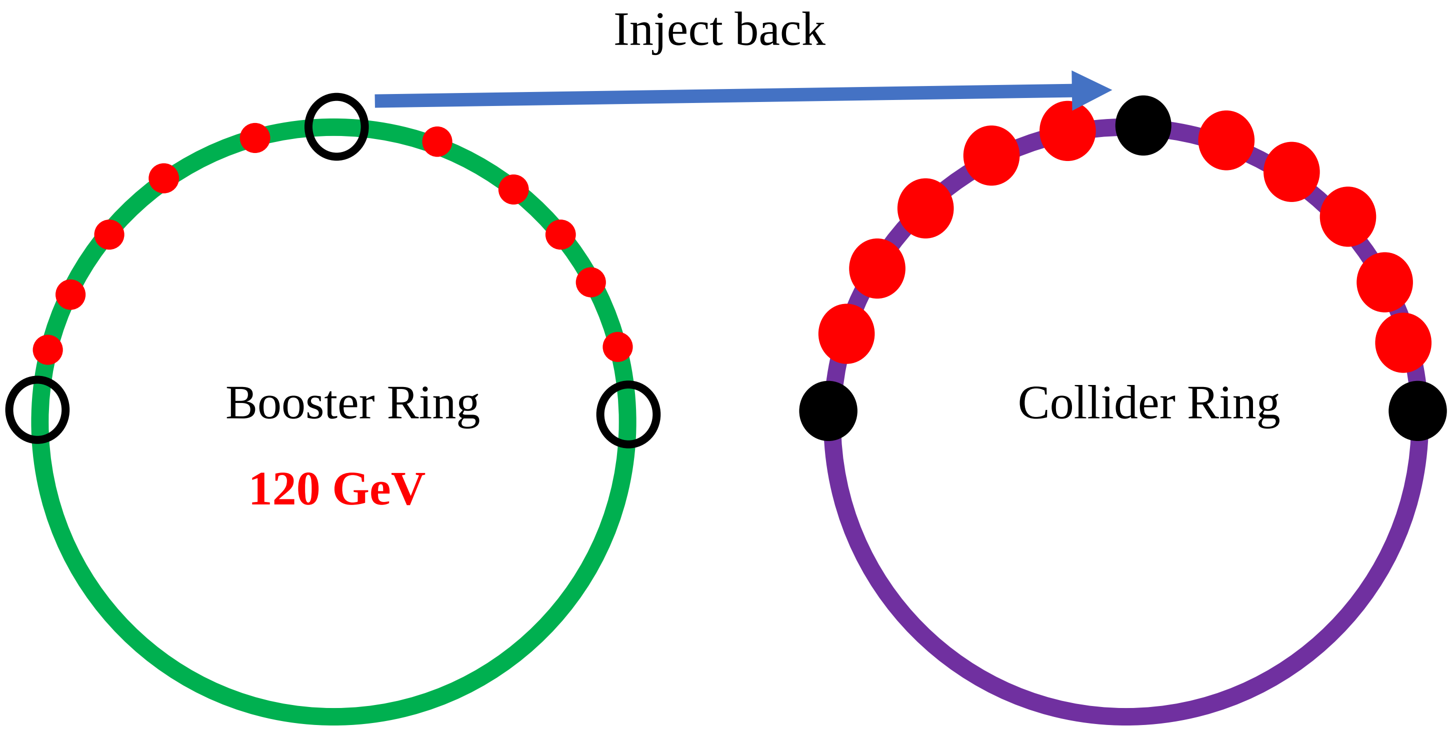
7. Injection to the collider- On-axis

Step 3:
After 4 damping time(~200ms), bunches from the collider will merge with small bunches in the booster



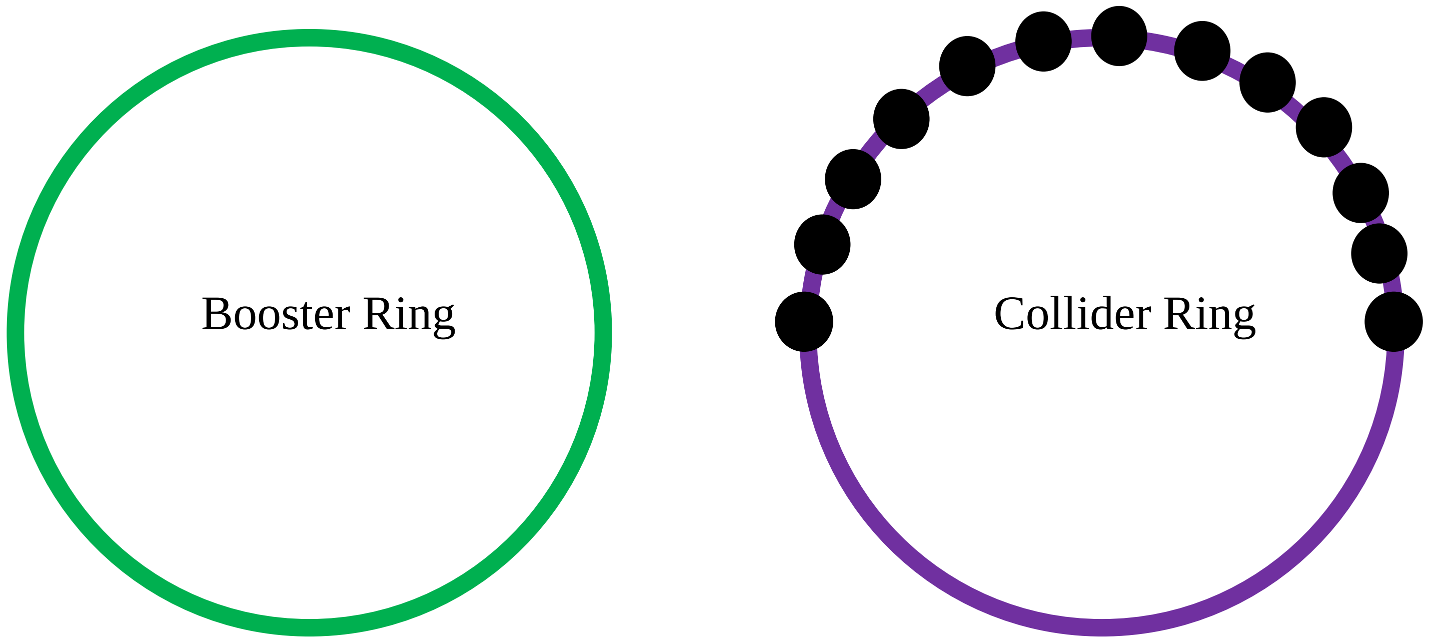
7. Injection to the collider- On-axis

Step 4:
Inject these bunches back to their original positions

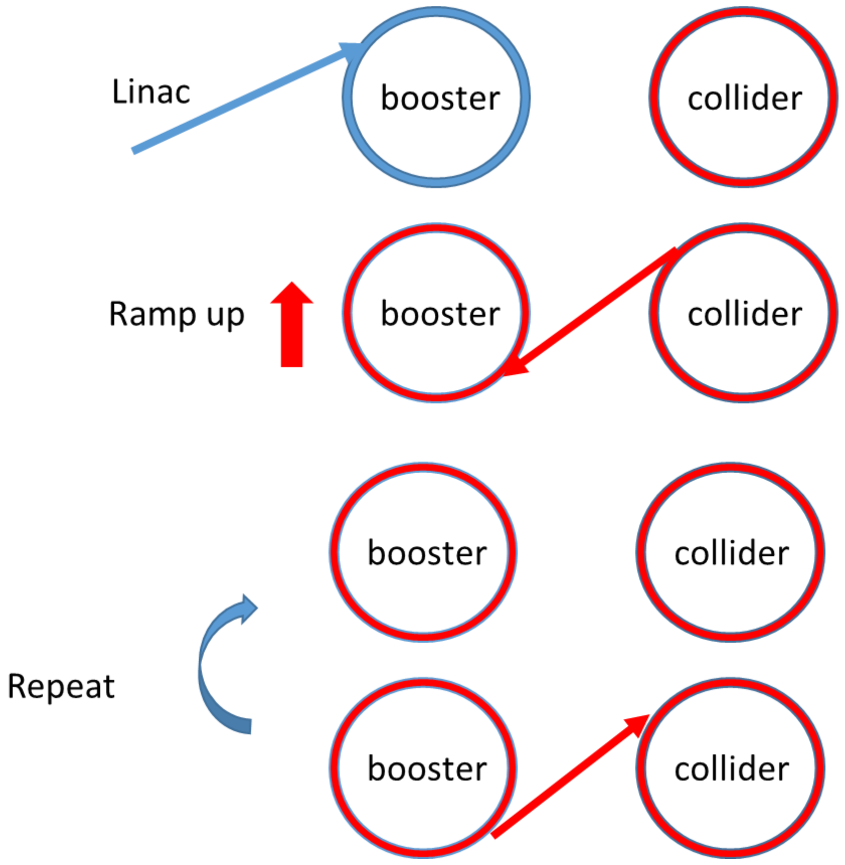


7. Injection to the collider- On-axis

Step 5:
Repeat the above steps until all bunches in the collider are renewed, and the booster is empty.



7. Injection to the collider- On-axis



1. Inject 240 small bunches into the booster.

2. Ramp the booster to high energy and inject several bunches from the collider into the booster.

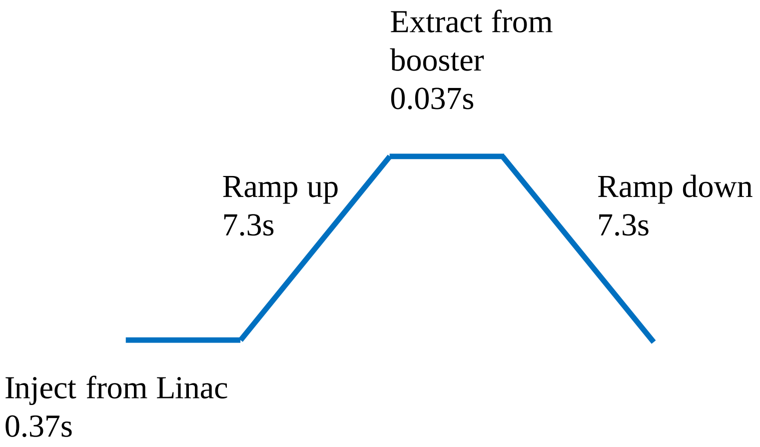
3. Booster stay at 120 GeV for 4 damping time(200ms), so that the injected large bunches merge with small bunches.

4. Inject the merged large bunches back to the same empty buckets left by the last step.

5. Repeat from last step.

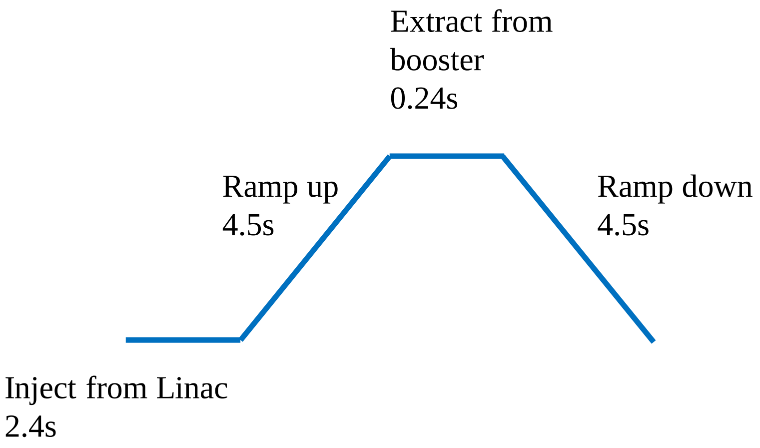
8. A diagram of the time structure

tt



0.37s+7.3s+0.037s+7.3s ~15s

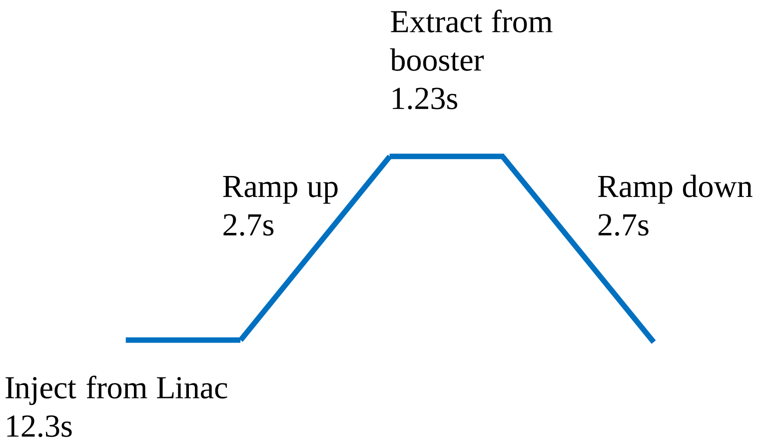
Higgs



2.4s+4.5s+0.24s+4.5s ~12s

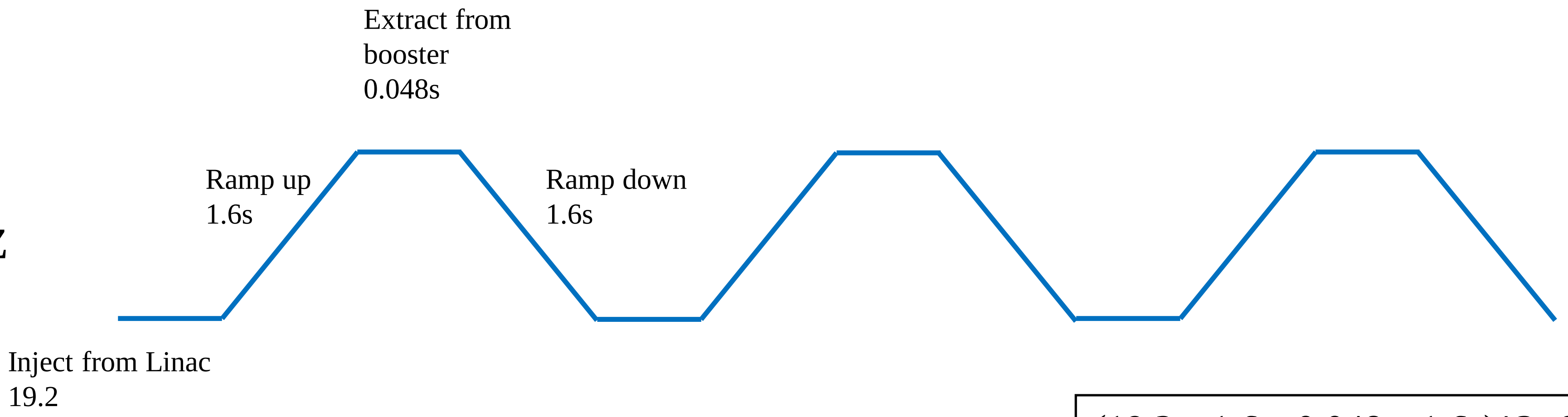
8. A diagram of the time structure

W



12.3s+2.7s+1.23s+2.7s ~18.9s

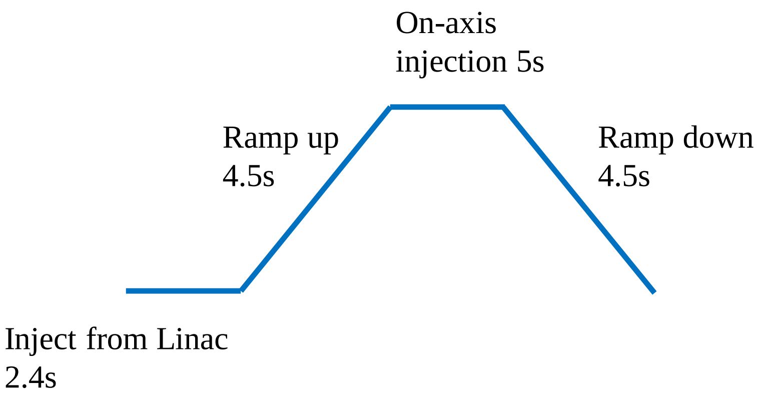
Z



(19.2s+1.6s+0.048s+1.6s)*3=67.3s

8. A diagram of the time structure

Higgs on-axis

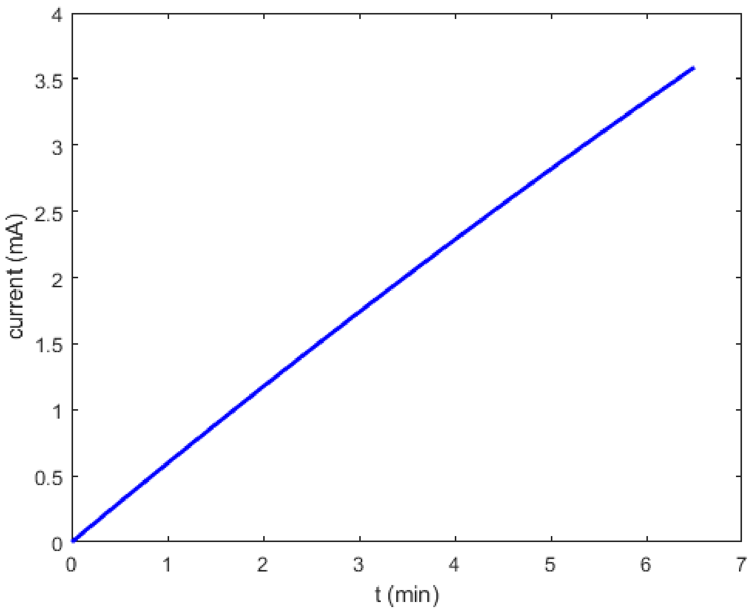


2.4s+4.5s+5.0s+4.5s=16.4s

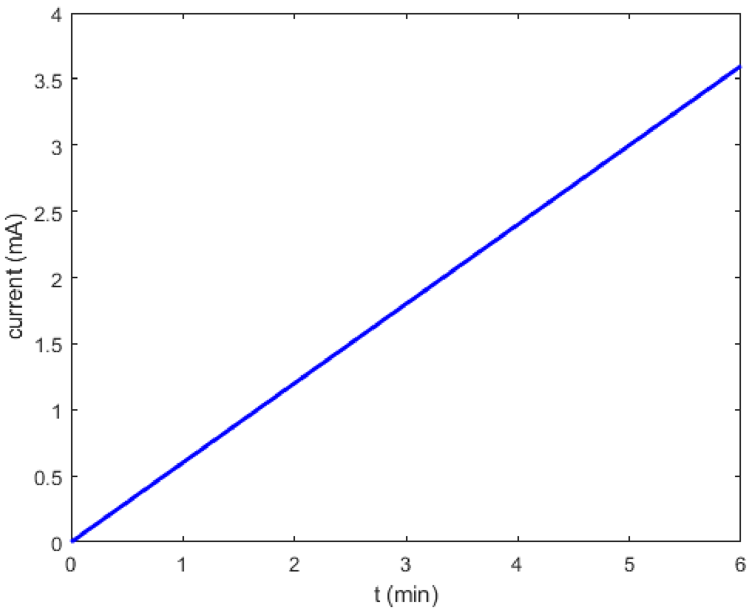
	tt	*Higgs*	*Higgs (on-axis)*	*W*	*Z*
Interval for top up* (s)	65	38	38	155	153
Injection time for both e^+/e^- (s)	30	24	32.8	37.8	134.6

9. Injection from empty- tt

- Design current in collider is 3.5mA.
- Total current in booster limited by RF system: < 0.3mA
- Collider lifetime (non-collision): ~2600 hours — dominated by Toucheck lifetime



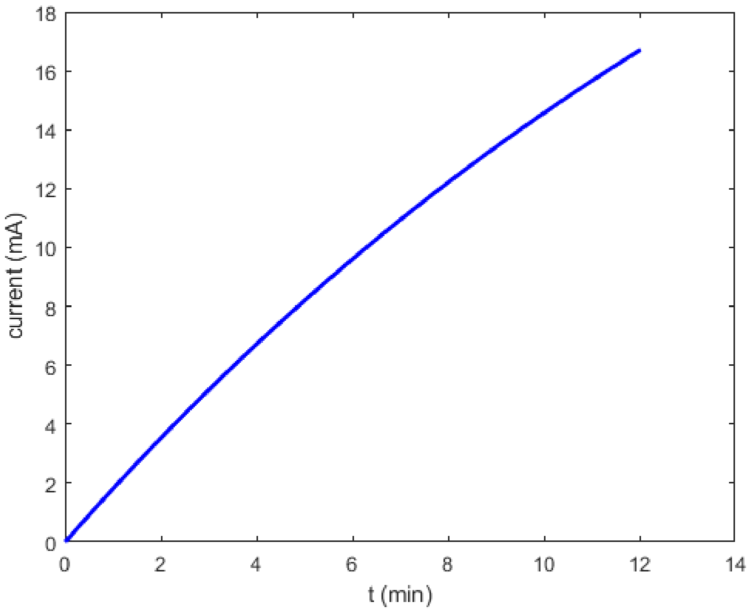
Full injection with collision



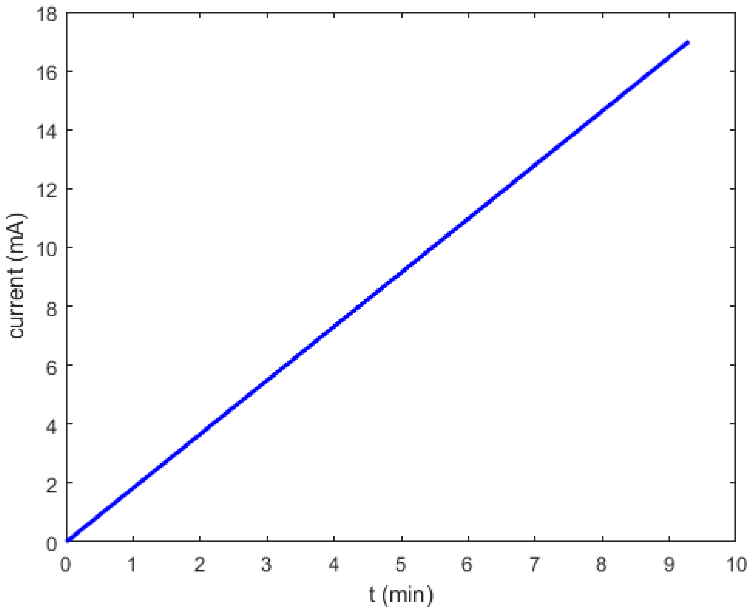
Full injection without collision

9. Injection from empty- Higgs

- Design current in collider is 16.7mA.
- Total current in booster limited by RF system: < 1mA
- Collider lifetime (non-collision): ~290 hours — dominated by Toucheck lifetime



Full injection with collision

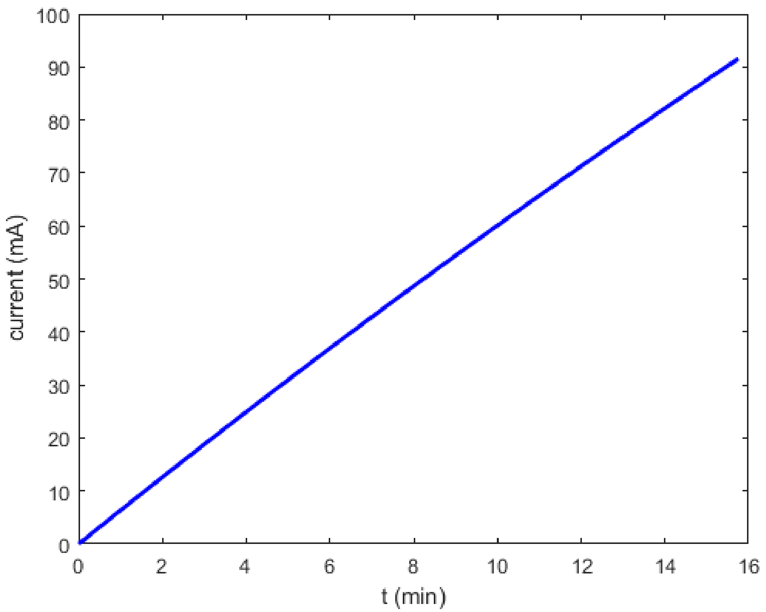


Full injection without collision

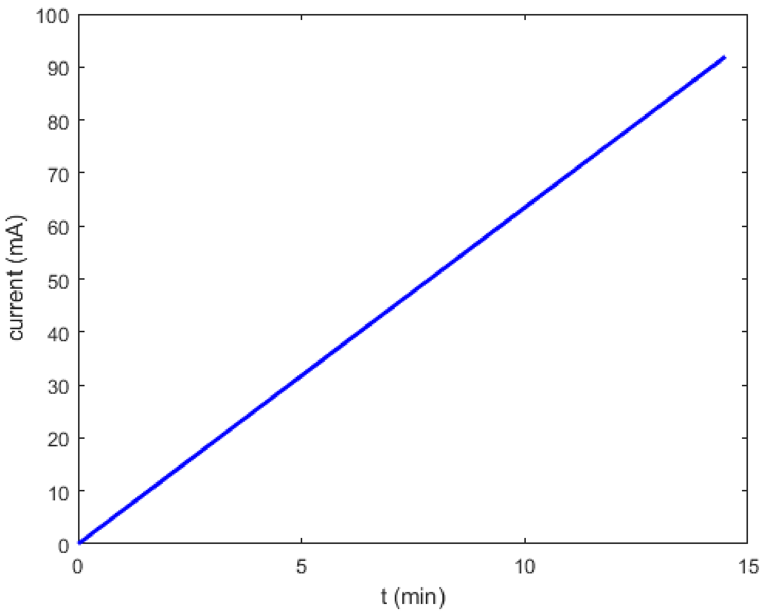
*on-axis injection for collider is assumed

9. Injection from empty- W

- Design current in collider is 88.6mA.
- Total current in booster limited by RF system: < 4mA
- Collider lifetime (non-collision): ~150 hours ─ dominated by Toucheck lifetime



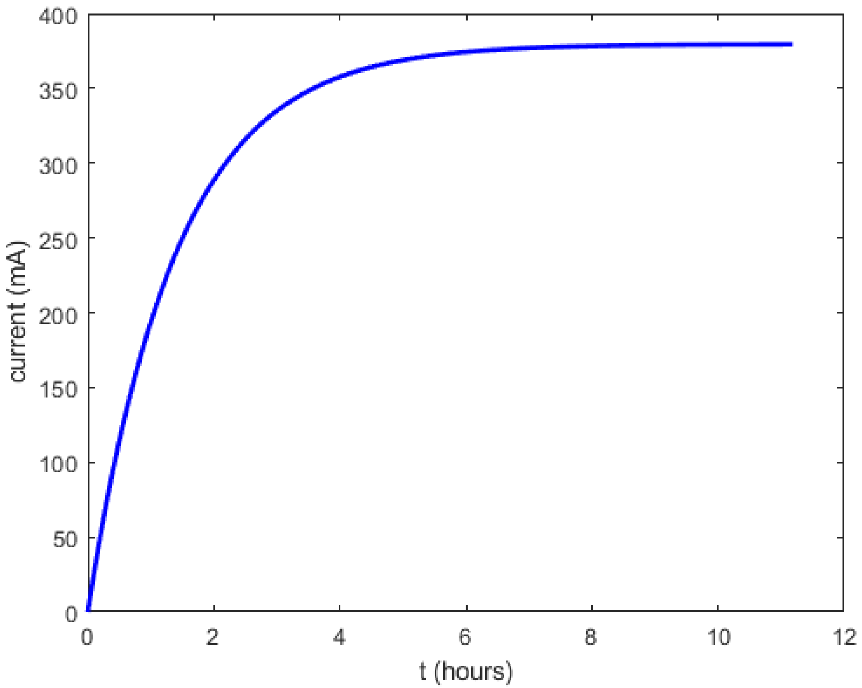
Full injection with collision



Full injection without collision

9. Injection from empty- Z

- Design current in collider is 840mA.
- Total current in booster limited by RF system: < 10 mA (will be increased to 16mA)
- Collider lifetime: ≥19 hours (non-collision), 1.9~1.4 hours (w. collision)
- The maximum current can’t be reached in a reasonable injection time.

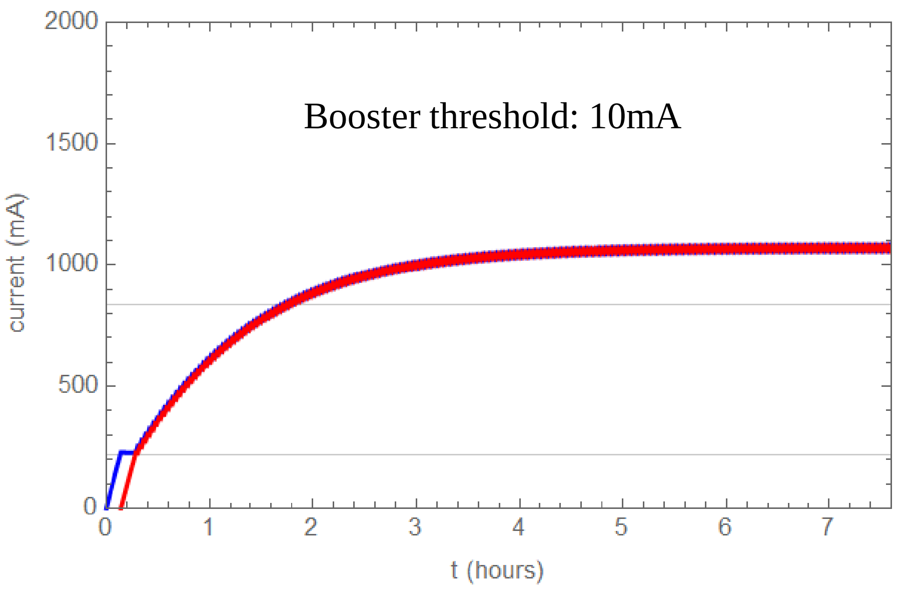


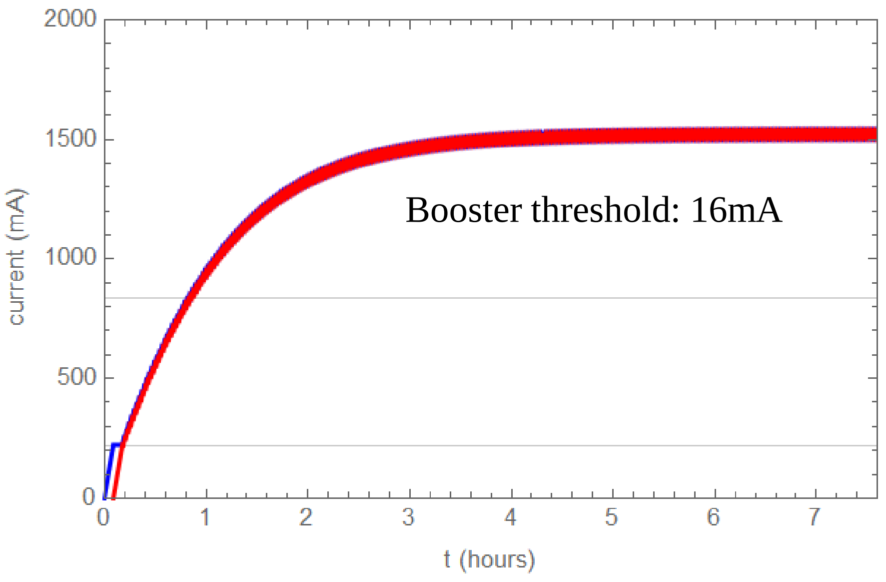
Full injection with collision

9. Injection from empty- Z

Yuan Zhang, Dou Wang

- Design current in collider is 840mA.
- Total current in booster limited by RF system: < 10 mA (will be increased to 16mA)
- Collider lifetime: ≥19 hours (non-collision), 1.9~1.4 hours (w. collision)*
- Bootstrapping from 220mA
- Full injection from empty for both beam → **2 hours (50min)**





*the beam lifetime with collision is related to the current.

Summary

- 1. This talk gives a general overview of the process of CEPC injection.
- 2. The timing structure of CEPC for different energy modes and different injection scheme are discussed.
- 3. Z mode is found to be the most challenging for the injection and extraction. Discussion about timing and filling scheme for Z continues.
- 4. Simulations and optimizations for the injection design are still going on.

Thank You

Back up

Requirement of timing system

Gang Li, Ge Lei

- Choose 130MHz as clock beat $\rightarrow$ minimum time separation=7.69ns (FPGA clock &EVG/EVR transmission can be realized)

- Circumference of damping ring:
  $(L*1000*10^9/(3*10^8))/(1000/650)$=integer

- Length of transfer line between DR and Linac:
  （（N*150+75+104*2-8.3）$10^9/(3*10^8))/(1000/2860)$=integer

  104m $\rightarrow$ 101.65m

- Circumference of collider/booster:
  $(L*1000*10^9/(3*10^8))/(1000/650)$=integer

- Length of transfer line between booster and collider:
  $(L*10^9/(3*10^8))/(1000/650)$=integer

  252m or 246m

Booster TDR parameters

- Injection energy: 10GeV → 20GeV
- Max energy: 120GeV → 180GeV
- Lower emittance — new lattice (TME)

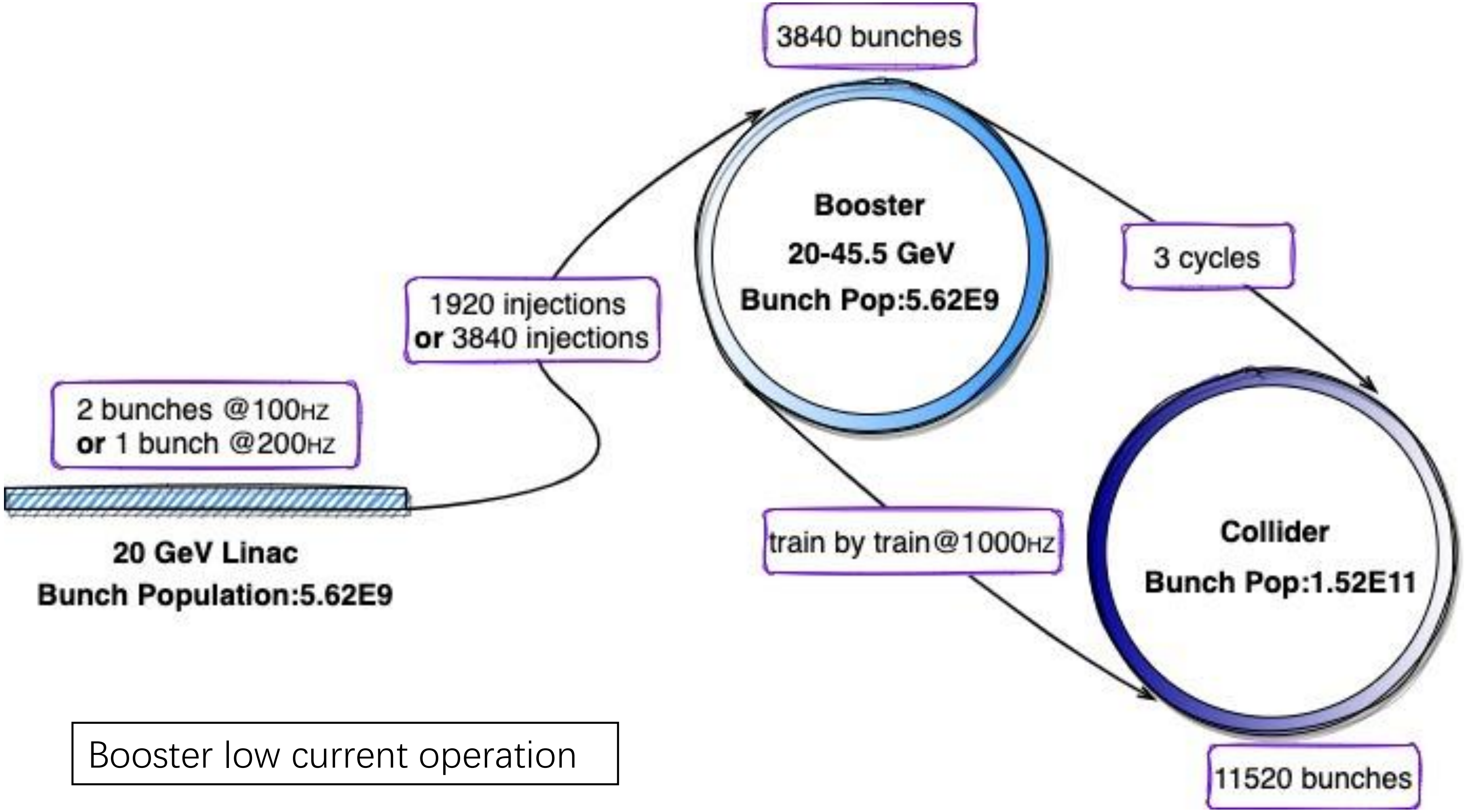
Injection		*tt*	*H*	*W*	*Z*	
Beam energy	GeV	20				
Bunch number		37	240	1230	3840	5760
Threshold of single bunch current	μA	7.18	4.58	3.8		
Threshold of beam current (limited by coupled bunch instability)	mA	27				
Bunch charge	nC	1.07	0.78	0.81	0.89	0.92
Single bunch current	μA	3.2	2.3	2.4	2.7	2.78
Beam current	mA	0.12	0.56	2.99	10.3	16.0
Energy spread	%	0.016				
Synchrotron radiation loss/turn	MeV	1.3				
Momentum compaction factor	10^{-5}	1.12				
Emittance	nm	0.035				
Natural chromaticity	H/V	-372/-269				
RF voltage	MV	438.0	197.1	122.4		
Betatron tune ν_x/ν_y		321.23/117.18				
Longitudinal tune		0.13	0.087	0.069		
RF energy acceptance	%	5.4	3.6	2.8		
Damping time	s	10.4				
Bunch length of linac beam	mm	0.5				
Energy spread of linac beam	%	0.16				
Emittance of linac beam	nm	10				

Extraction		*tt*	*H*		*W*	*Z*	
		Off axis injection	Off axis injection	On axis injection	Off axis injection	Off axis injection	
Beam energy	GeV	180	120		80	45.5	
Bunch number		37	240	233+7	1230	3840	5760
Maximum bunch charge	nC	0.96	0.7	23.2	0.73	0.8	0.83
Maximum single bunch current	μA	2.9	2.1	69.7	2.2	2.4	2.5
Threshold of single bunch current	μA	95	79				
Threshold of beam current (limited by RF system)	mA	0.3	1		4	10	16
Beam current	mA	0.11	0.51	0.99	2.69	9.2	14.4
Bunches per pulse of Linac		1	1		1	2	
Time for ramping up	s	7.3	4.5		2.7	1.6	
Injection duration for top-up (Both beams)	s	30. 0	23.3	32.8	39.3	134.7	128.2
Injection interval for top-up	s	65	38		155	153.5	
Current decay during injection interval		3%					
Energy spread	%	0.15	0.099		0.066	0.037	
Synchrotron radiation loss/turn	GeV	8.45	1.69		0.33	0.034	
Momentum compaction factor	10^{-5}	1.12					
Emittance	nm	2.83	1.26		0.56	0.19	
Natural chromaticity	H/V	-372/-269					
Betatron tune ν_x/ν_y		321.27/117.19					
RF voltage	GV	9.3	2.05		0.59	0.284	
Longitudinal tune		0.13	0.087		0.069	0.069	
RF energy acceptance	%	1.34	1.31		1.6	2.6	
Damping time	ms	14.2	47.6		160.8	879	
Natural bunch length	mm	2.0	2.0		1.7	0.96	
Full injection from empty ring	h	0.1	0.14	0.16	0.27	1.8	0.8

*Diameter of beam pipe is 55mm for re-injection with high single bunch current @120GeV.

Z mode injection (top-up)

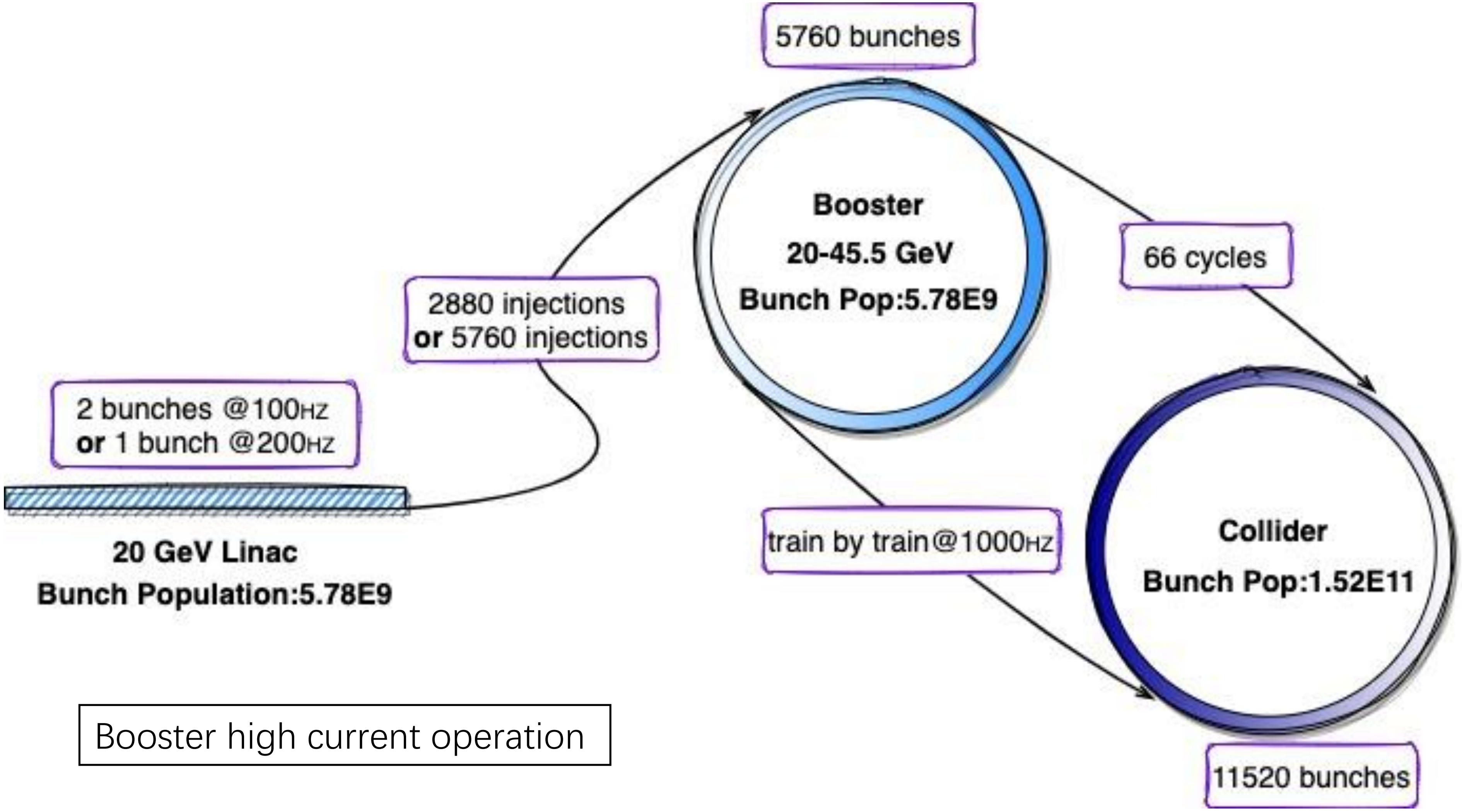
Meng Li



Booster low current operation

Z mode injection (full injection)

Meng Li



Booster high current operation