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The Design Progress of STCF Injector

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OUTLINE

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Introduction

- The super high luminosity is main challenge for STCF
- To reach the required luminosity, the STCF will adopt:
  - Crab Waist collision scheme
  - Higher beam current
  - Better beam emittance (~5 nm·rad)
- Two injection schemes are under consideration:
  - Off-Axis injection
  - Swap-Out injection
- Two different injectors were designed for each injection scheme

Main parameters of the STCF injector

- Main parameters of injector for each injection scheme were studied
- Difference on bunch charge, emittance and injection frequency

Parameters	Value		Unit
Collider ring injection scheme	Off-axis	Swap-out	
E-gun type	Photo /Therm.	Therm. /Therm.	
E-gun charge	1.5/10	8.5/11.5	nC
Injection e- bunch charge	1.5	8.5	nC
Injection e+ bunch charge	1.5	8.5	nC
Injection energy	1.0-3.5	1.0-3.5	GeV
Optimal energy	2.0	2.0	GeV
MW frequency	2998.2	2998.2	MHz
Injection emittance (X/Y, Geo, rms)	≤6	≤30	nm-rad
Injection energy spread (rms)	≤0.1	≤0.5	%
Injection frequency e-/e+	30/30	30/30	Hz

Parameters	Value		Unit
e- linac energy for direct injection	1.0	1.0	GeV
e- energy for e+ production	1.0 + 0.5	2.5	GeV
e+ energy	1.0	1.0	GeV
Main linac energy for e-/e+	0-2.5	0-2.5	GeV
e+ DR/AR bunch numbers	5	5	
e+ DR/AR RF frequency	499.7	499.7	MHz
e+ DR/AR injection charge	1.5	2.5	nC
e+ DR/AR injection frequency	30	100	Hz
e+ DR/AR injection emittance (X/Y)	≤1400/1400	≤1400/1400	nm-rad
e+ DR/AR extraction emittance (X/Y)	≤11/0.12	≤30/30	nm-rad

Challenges

- For Off-Axis injection scheme：
  - Merger design for two beam generated by different guns, with different bunch charge, bunch length and emittance, share the 1st linac section
  - Positron generation and transportation (target material, capture efficiency…)
  - Damping ring design to reduce the positron emittance and energy spread
  - Beam transportation and emittance preservation
- For Swap-Out injection scheme：
  - Get enough electron bunch charge (up to 10 nC) for positron production
  - Injector repetition rate (Modulator limitation)
  - Direct injection of high bunch charge electron into collider ring
  - Get rid of the electron accumulator ring (AR)
  - and more …

Injector design for the Off-Axis injection scheme

Overview of Injector for off-axis scheme

- For off-axis injection scheme, the injector needs to provide at least 30Hz/1.5nC electrons and 30Hz/1.5nC positrons. Strict demands for beam qualities (emittance, energy spread)
- The required 1.5nC electron can be generated with Photo-cathode gun, further boosted and compressed then injected into the collider ring
- The required 1.5nC positron is generated when high charge (~10nC) electrons hit the motional target which is provided by Thermionic gun
- Damping ring is needed to reduce the positron emittance and energy spread

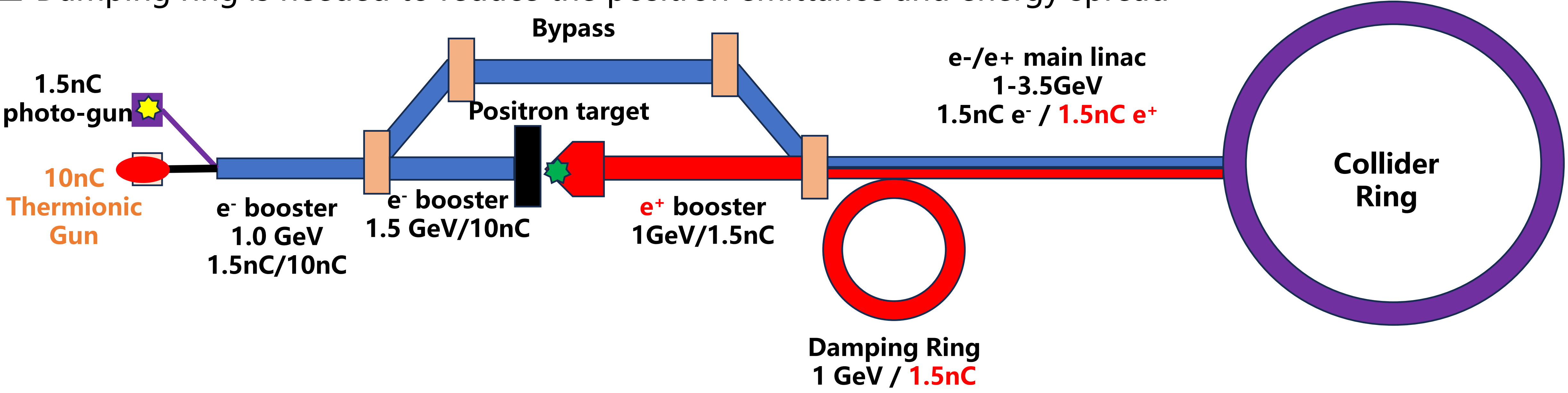
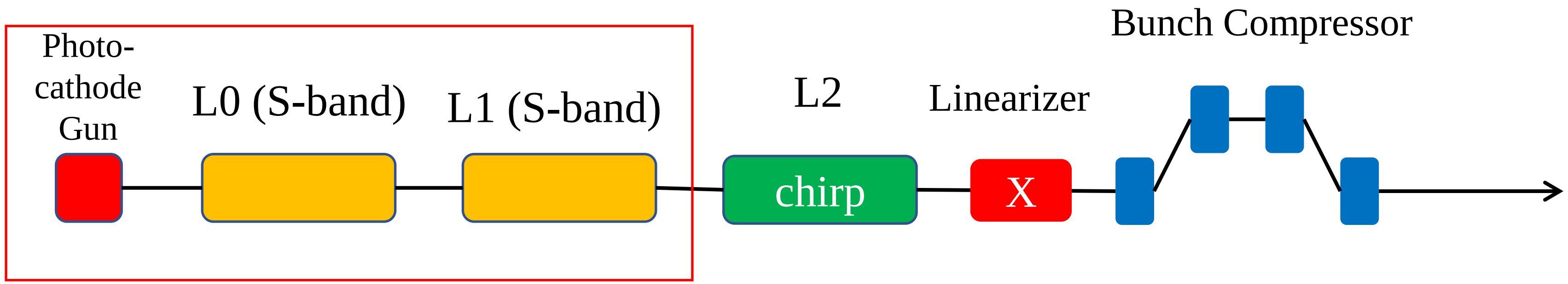
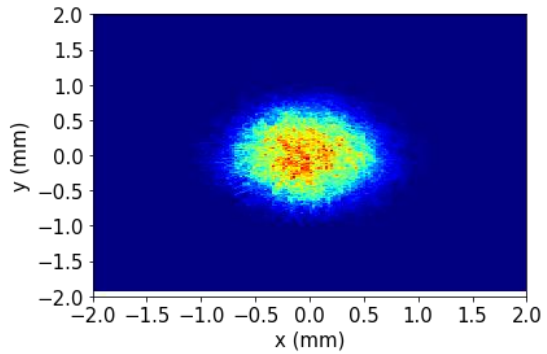
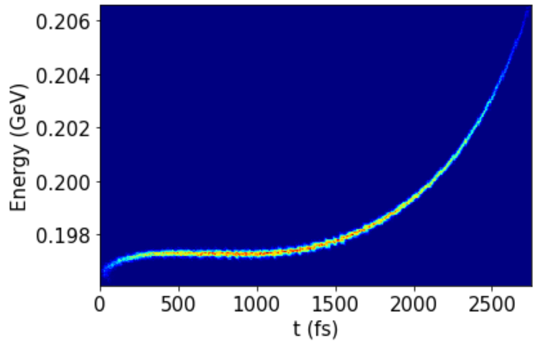


Photo-cathode gun line

- S-band photo-cathode gun, with gradient >100MV/m, beam energy ~4MeV at gun exit
- Lower energy part (L0&L1) consists of 2 S-band accelerating tube, 120MeV at exit
- L2 section consists of 2 S-band tube, powered by one klystron with SLED, further boost the beam to 200MeV and provide the energy chirp for compression
- One X-band (12 GHz) tube is used for phase space linearization
- One magnetic chicane is used to compress the beam to ~1 ps (S-band 1°)

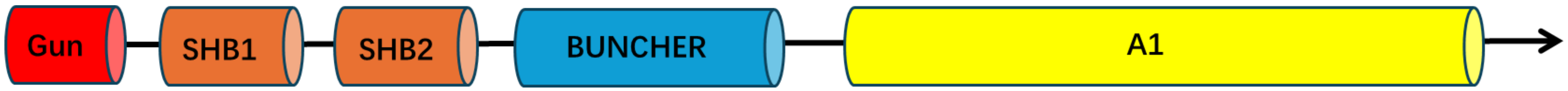






Thermionic gun line

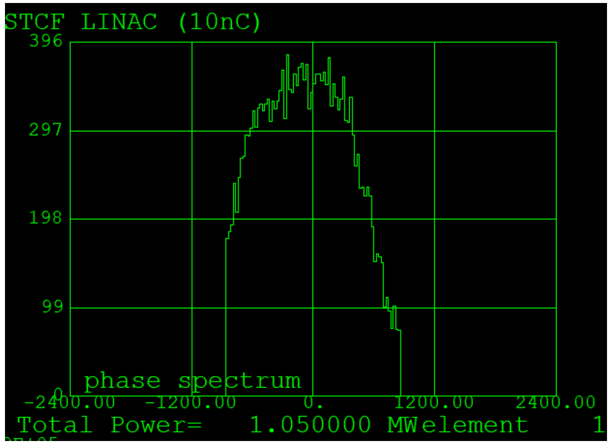
- The mature thermionic gun is used to provide at least 10nC electrons
- Consist of 2 sub-hormonic buncher, 1 buncher and S-band accelerating tube.
- Multiple solenoids are used to keep the beam envelope and emittance

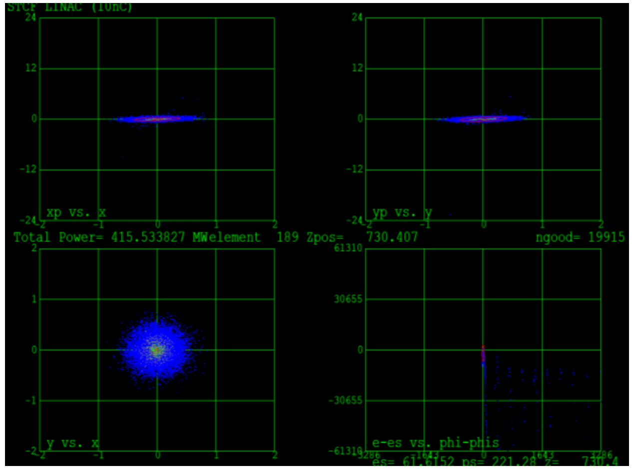


	Type/Frequency(MHz)	Length(m)	Distance(m)	Parameters
Cathode/grid	Y-796			150kV， 7A， 1.6ns
SOL1			0.182	
SHB1	166.56		0.667(center)	1/18th of fundamental wave period 6ns, compression ratio ~3.7
SHB2	499.7		2.03(center)	1/6th of fundamental wave period 2ns, compression ratio ~2.8
BUNCHER	2998.2	1.3144	2.26	fundamental wave period 333.6ps， energy gain~11MeV
ACC. Tube （A1）	2998.2	3.0667	4.10	fundamental wave period 333.6ps， energy gain~50MeV

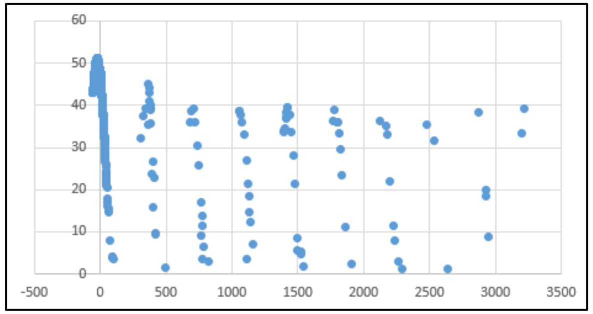
Thermionic gun line

- According to the start-to-end simulation, the charge in main bunch is >10 nC, the tailing bunch is ~0.1%，with emittance~41um and energy spread<1%



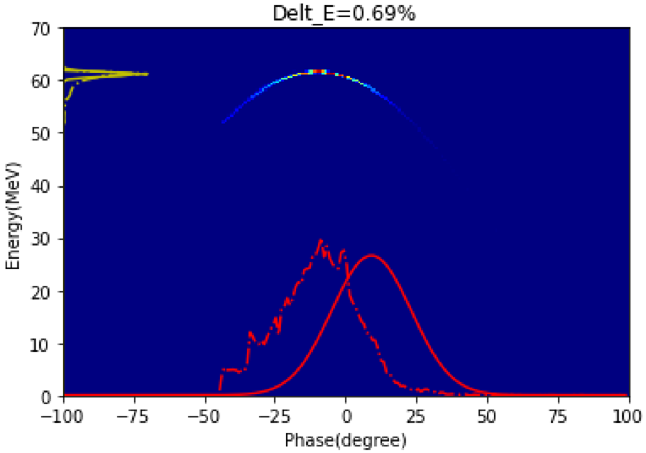


Phase space at exit



- Bunch distributions

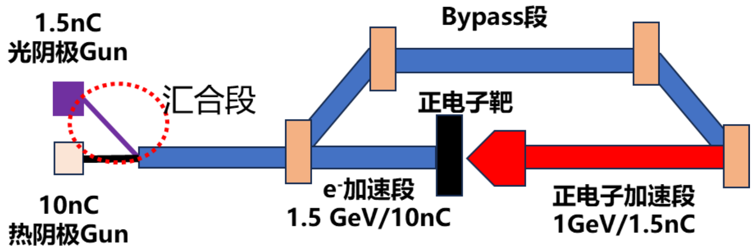
main bun	bun 1	bun 2	bun	bun 4	bun 5
99.11%	0.14%	0.06%	0.07%	0.04%	0.03%

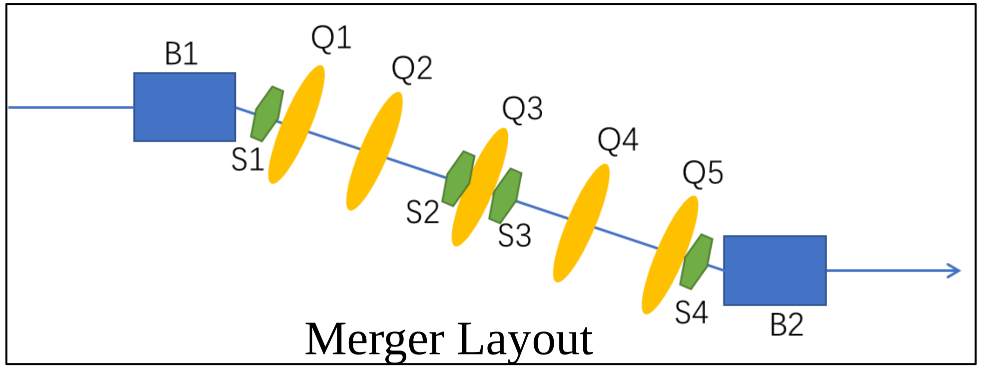


Main parameters of the thermionic gun booster	
Bunch charge, Q	10.9 nC
Energy, E	61.2 MeV
Transmission efficiency, η	99.6%
main bunch ratio, η	99.1%
Energy Spread, ΔE	0.69%
Bunch Length, σ	13 ps
Nor. projected emittance, ε	41 mm·mrad

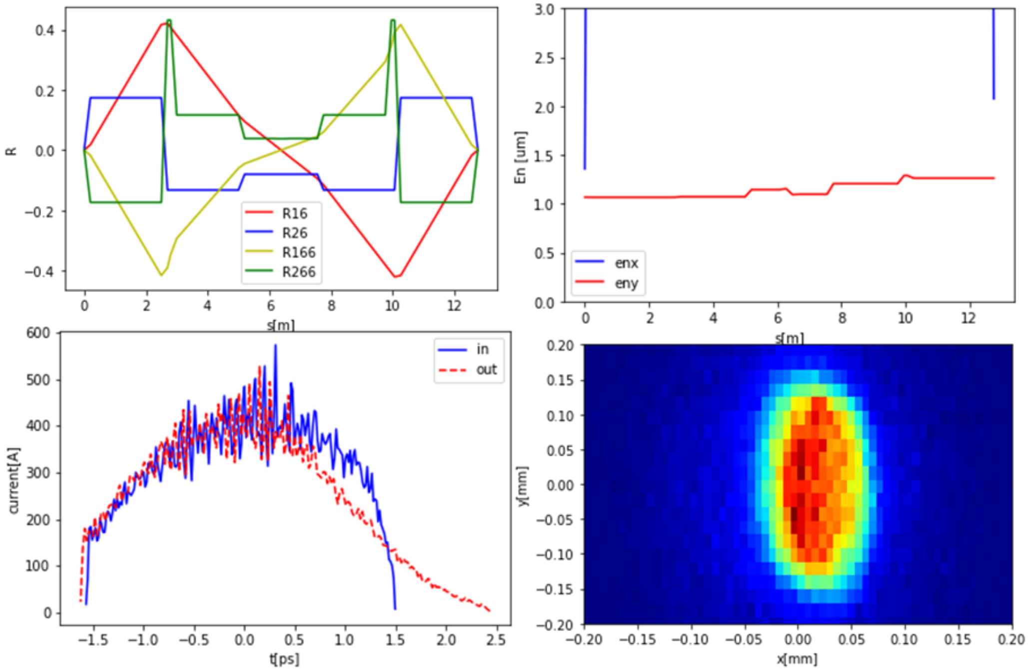
Merger

- Merger is used to combine the two electron beams from different guns, the merger need to guarantee the quality of the beam from photo-cathode gun.
- To eliminate the effects of CSR and high order effects when beam passes the merger, a double-bend-achromat (DBA) dogleg is designed. Bend angle <20°, vertical distance ~2.5 m, total length ~8 m
- 5 quadrupoles and 4 sextuples are used to cancel R16/R26/T166/T266, suppress the emittance growth
- S2E shows the emittance growth <20%, no significant change on energy spread or beam distribution



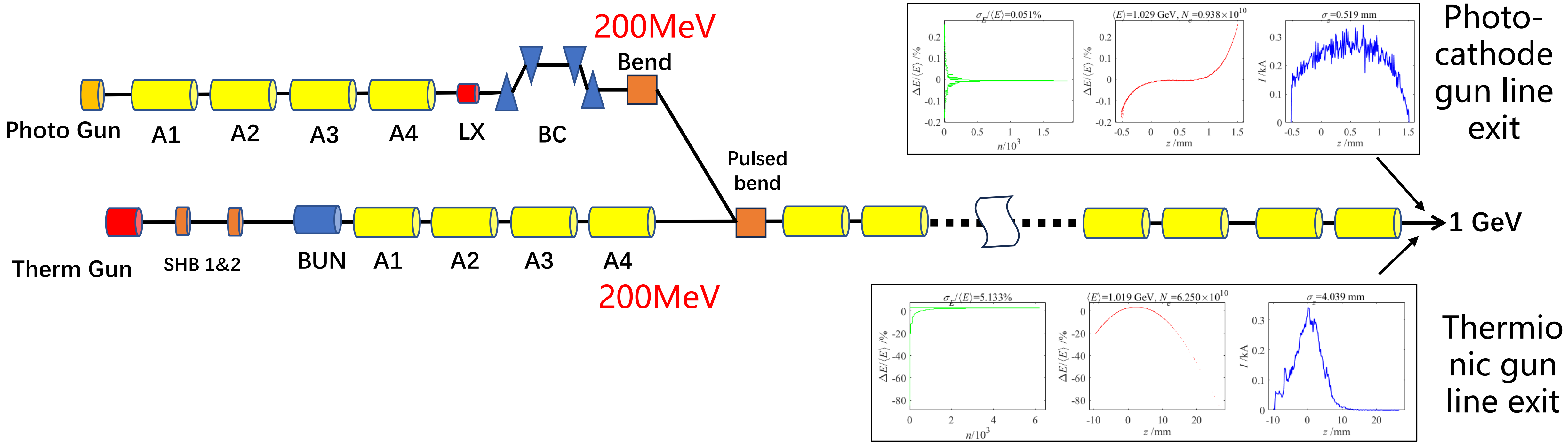


Merger Layout



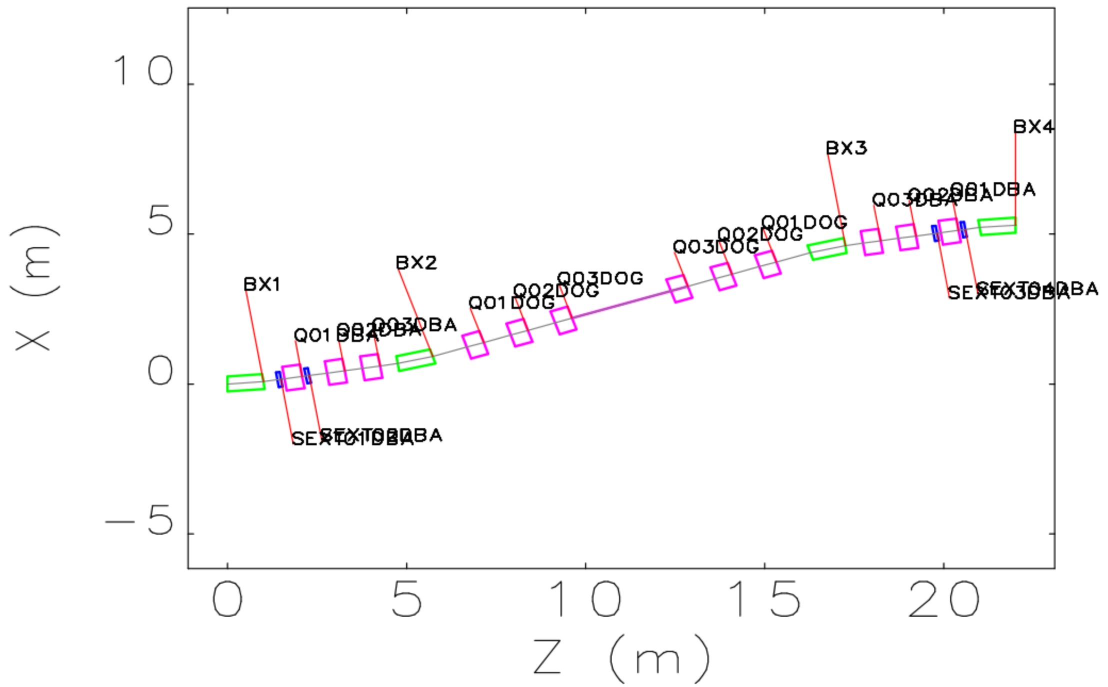
Merge point selection

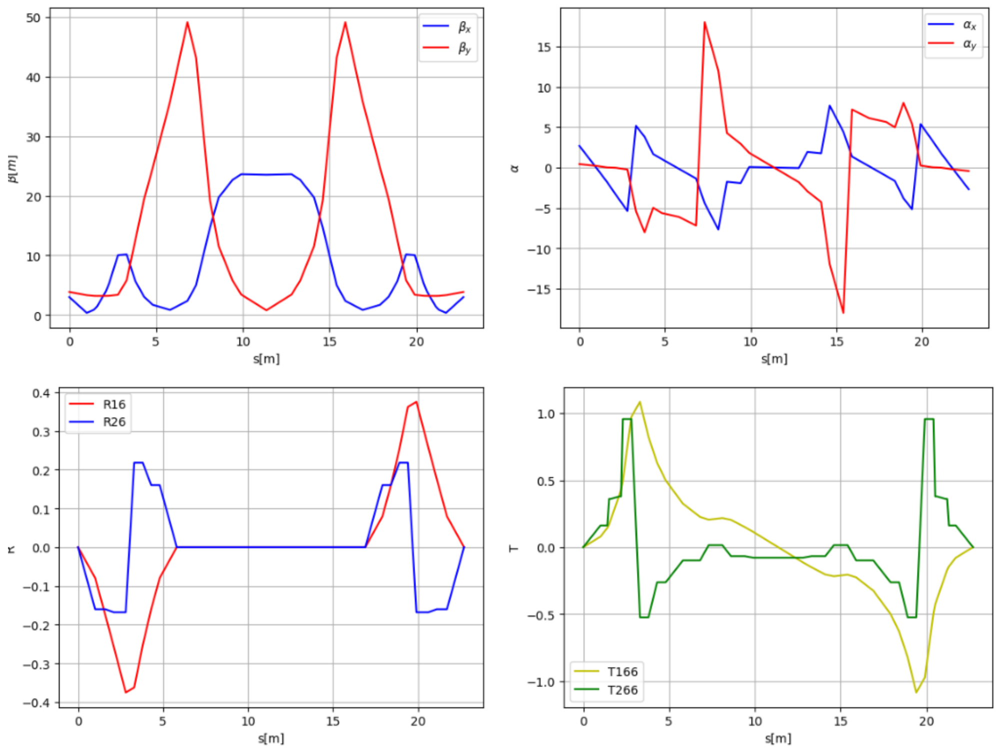
- Beams from two guns merger at same energy to facilitate the linac design such as lattice design
- According to optimization, the merge point is selected at 200MeV beam energy
- At Photo-cathode gun line exit, the normalized emittance <2 um, energy spread <0.1% @ 1.5nC
- At Thermionic gun line exit, the normalized emittance <50 um, energy spread <5 % @ 10 nC



Bypass Line

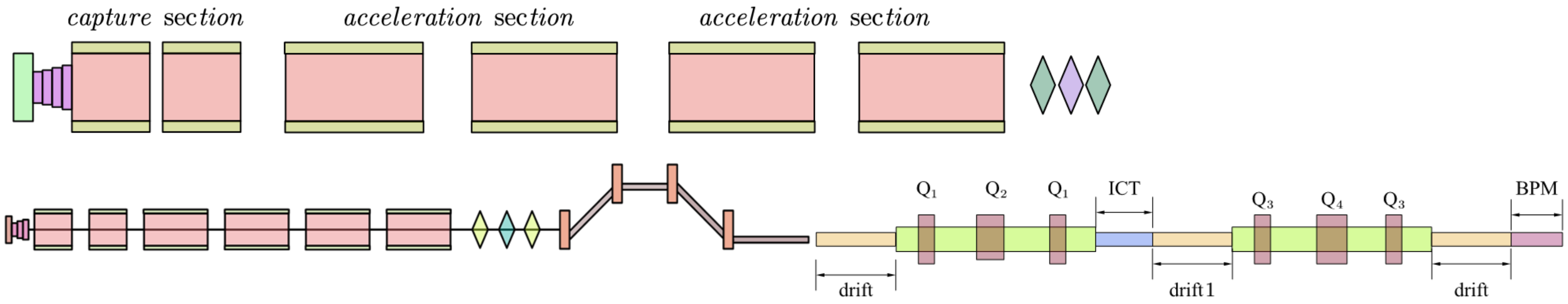
- Beam from the Photo-cathode gun goes to the bypass line, then further be accelerated in main linac
- The Bypass line design based on the double DBA dispersion-free scheme, 4 bends with each of 6° bend angle, the total length ~150 m
- At the exit of the second DBA, the R16/R26/T166/T266 are all eliminated to cancel the second order dispersion, the emittance growth is <10%

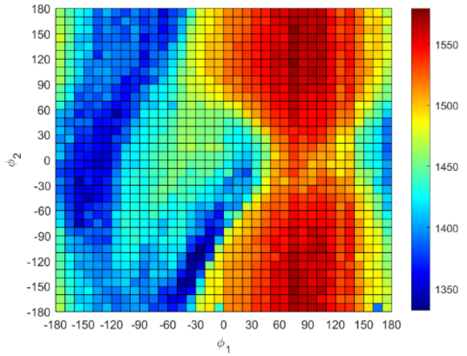




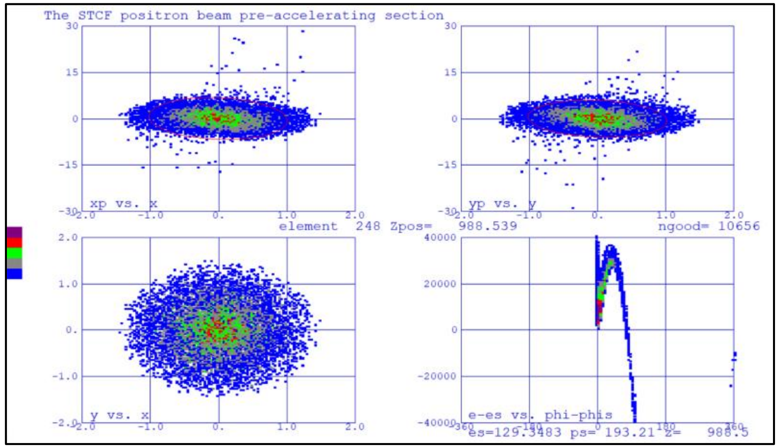
Positron generation and acceleration

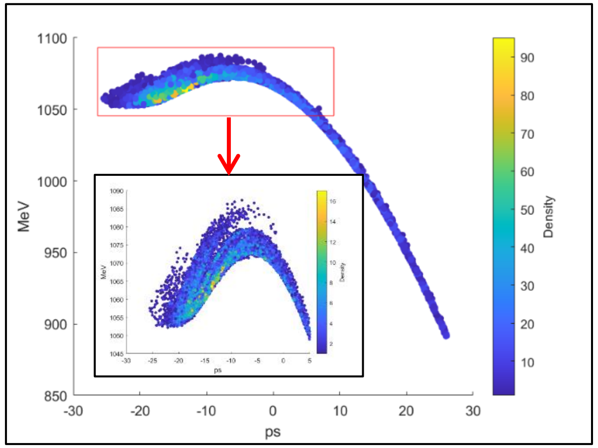
- Detailed studies were conducted on positron generation and acceleration (see Ailin's talk next)
- After positron generation, emittance and energy spread still large, a damping ring is needed





- Phase optimization of Capture Section



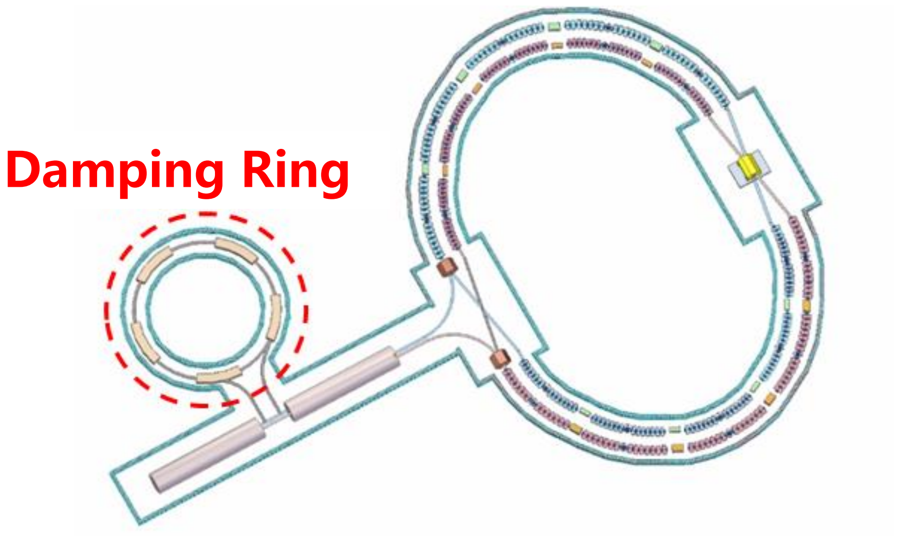


Parameter	Off-axis	Swap-out
yield	0.16	0.252
Energy spread	0.068%	0.068%
Bunch length	1.92mm	1.95mm
Beam size	1.2mm	1.2mm
$\varepsilon x/nm \cdot rad$	795	769
$\varepsilon y/nm \cdot rad$	1168	1185

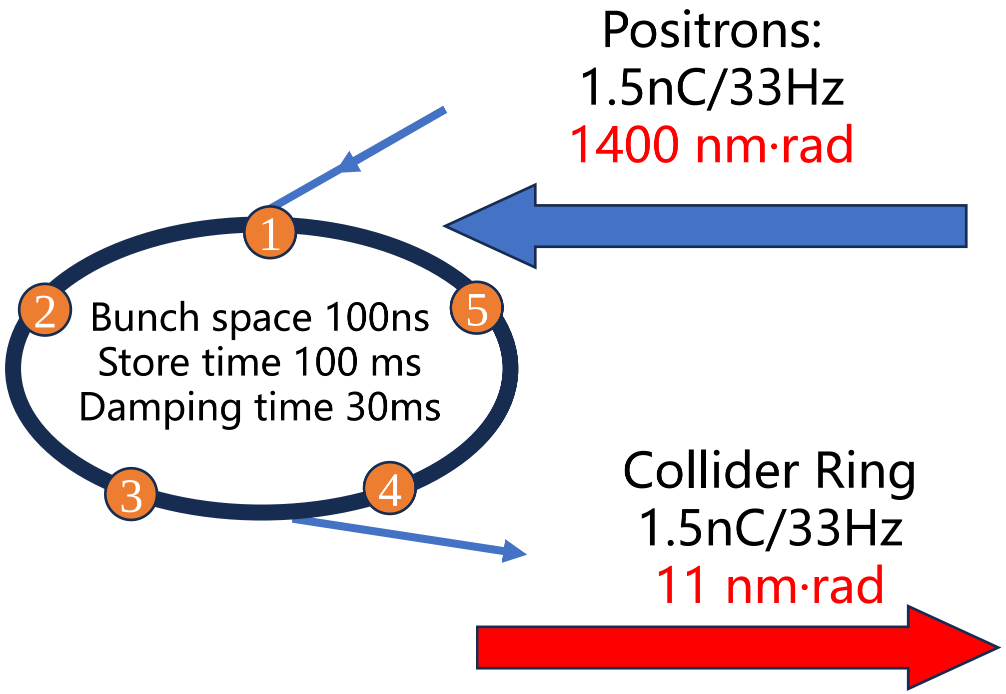
- Phase space of 1GeV positron beam
- Main parameter of positron beam

Damping Ring for positrons

- After positron generation, the beam qualities are poor, (ε_x >1400 nm·rad), the damping ring should reduce the emittance and energy spread to acceptable level ($\varepsilon_x \leq$ 11 nm·rad)

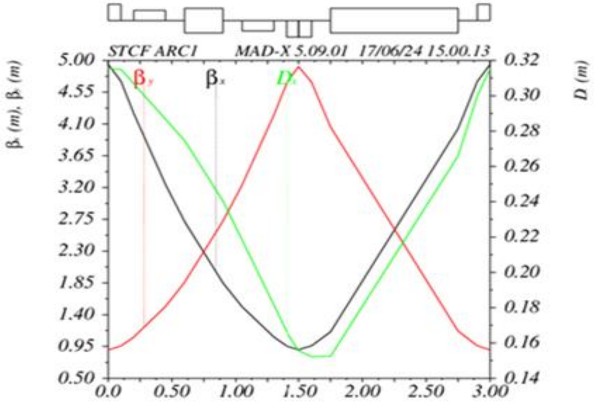


STCF Positron Damping Ring

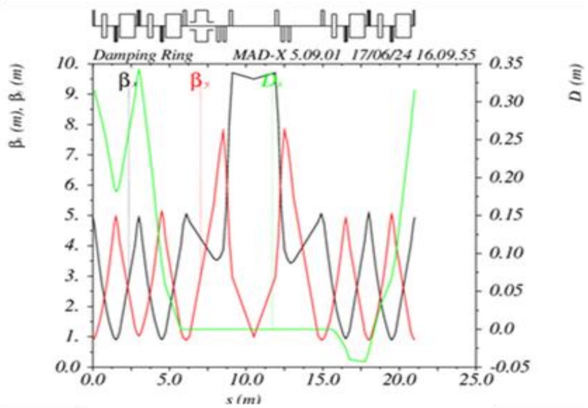


Damping Ring for positrons

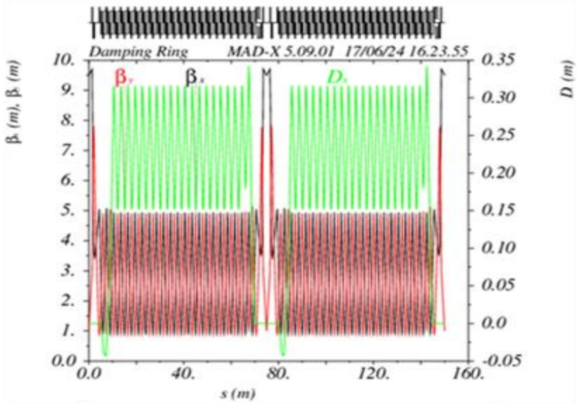
- Finish the lattice design for DR, circumference 150m， damping time~30ms, natural emittance~8nm·rad
- Reverse bends are uesd to reduce the damping time
- Preliminary results meets the requirements, more studies on DA is ongoing



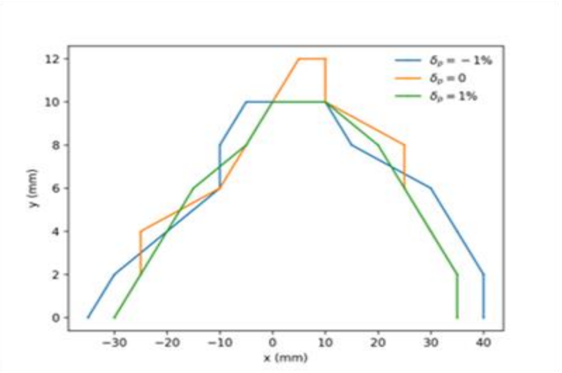
FODO section（3m)



ARC+RF（21m)



Total length 150m



Dynamic Aperture

Main Parameters of STCF DR	
Energy (GeV)	1.0
Circumference (m)	149.986
Number of bunches	5
Total current (mA)	15
Bending radius (m)	4.456
Dipole strength B0 (T)	0.749
Damping time τx/τy/τz (ms)	28.8/28.6/14.2
Natural emittance (nm·rad)	8.25
Natural energy spread (%)	0.031
Momentum compaction	0.0064
Chromaticity x/y	-15.0/-15.3

Summary of Injector Design for off-axis injection

- Two guns to generate different bunch charge:
  - ✓ P-gun line exit, Q~1.5nC, ε_{nx}<2 mm·mrad, σ_E <0.1%, fulfill the requirement of direct injection
  - ✓ T-gun line exit, Q~10 nC, ε_{nx}<50 mm·mrad, σ_E <5 %, fulfill the requirement of positron production
- Merger and Bypass line:
  - ✓ Dispersion-free DBA design to reduce emittance growth in bending section
- Positron generation:
  - ✓ Complete the design of 200MeV positron production and 1GeV acceleration
- Damping Ring:
  - ✓ Complete the design of positron damping ring

➢ In general, the injector design can meet the requirements of off-axis injection scheme

Injector design for the Swap-Out injection scheme

Overview of Injector for swap-out scheme

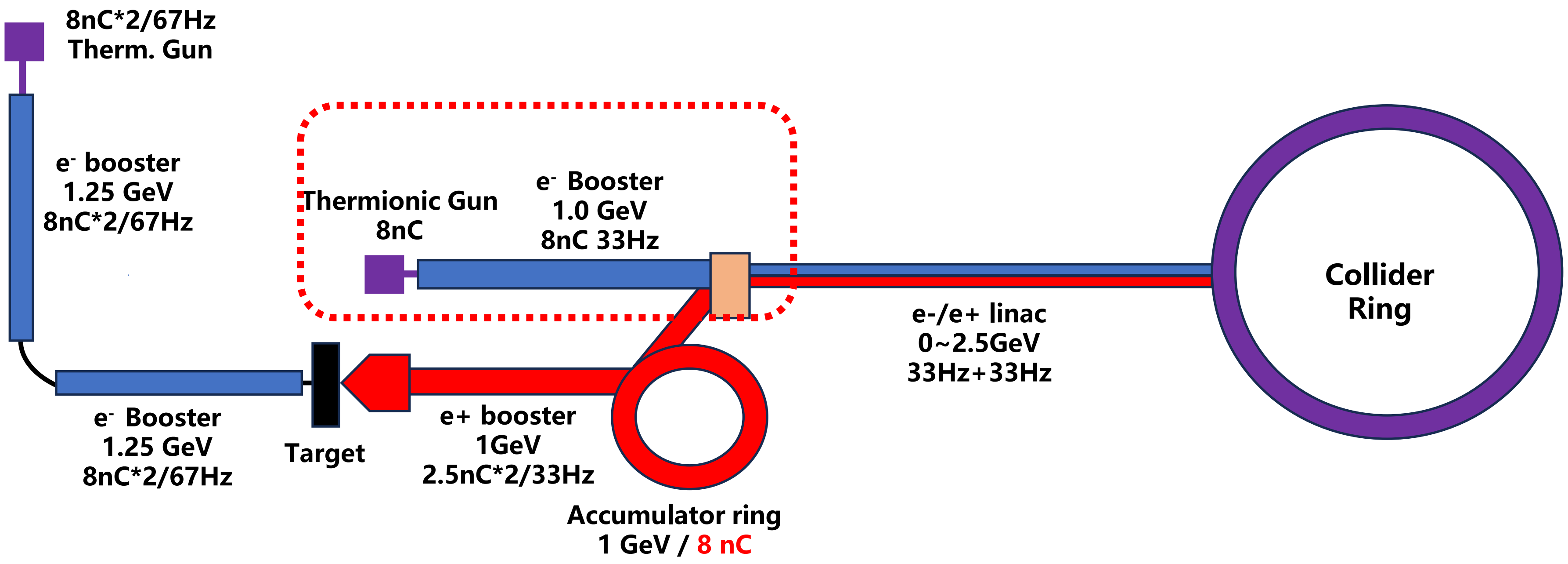
- For swap-out injection scheme, the injector need to provide at least 30Hz/8nC electron bunches and 30Hz/8nC positron bunches , which poses great challenges to the design of injector
- For positrons, it is almost impossible to produce high bunch charge around 8 nC, so an Accumulator Ring (AR) is needed which can store the positrons and damp the emittance simultaneously
- Even use the thermionic gun to generate high electron bunch charge for positron production, the repetition rate of main linac can be over 100Hz, which over the limitation of commercial klystrons, so a Double Pulse scheme is under consideration
- To improve the production of positrons, the electron beam energy is upgraded to 2.5GeV

Main parameters of injector for swap-out scheme		
Bunch charge	8	nC
Lifetime	200	s
Bunches	707	
Bunch charge in AR	2.5	nC
peak current	90	%

Refilling Charge %	Beam lifetime in CR τ(s)	Refilling time for 707 bunches (s)	Extraction freq of AR (Hz)	Injector freq of AR (Hz)	Injector freq of AR with 2 bunches (Hz)
90	100	10.54	67.1	268.4	134.2
	150	15.80	44.7	178.9	89.5
	200	21.07	33.6	134.2	67.1
	300	31.61	22.4	89.5	44.7

Injector Plan A

- To save the budget and reduce the complexity of design, we decide to get rid of the AR for electrons, proposed two plans to generate 8nC high quality electrons and then send them to collider ring directly
- Plan A: 8nC electrons with thermionic gun, direct inject into the collider ring



Injector Plan A

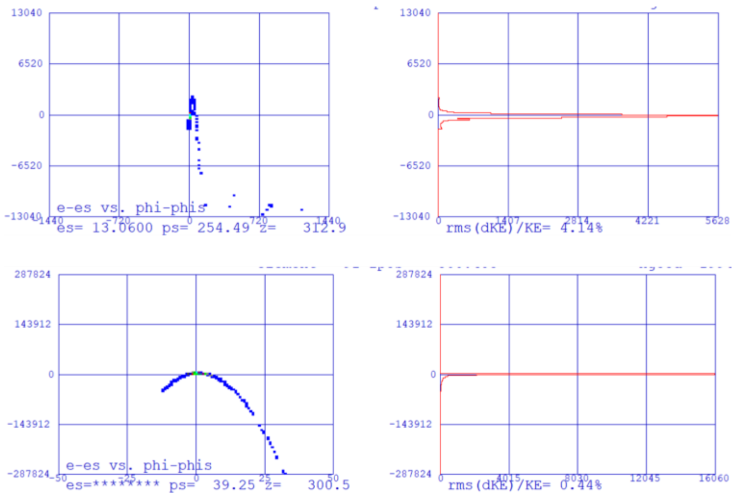
Advantage: Thermionic gun easy to produce electrons over 8nC

Disadvantage: Beam qualities are hard to control, emittance/energy spread need to be verified

- Based on the S2E, at the injector exit, the ε_n ~42 um, σ_E <0.5% (RMS), σ_E ~0.15% (within 6 σ), meet the requirements of swap-out injection

	Frequency	Voltage/Gain
Gun	DC	200 kV
SHB1	1/18 RF	100kV
SHB2	1/6 RF	100kV
TW Buncher	2.998GHz	12.8MeV
ACC*39	2.998GHz	51 MeV*39

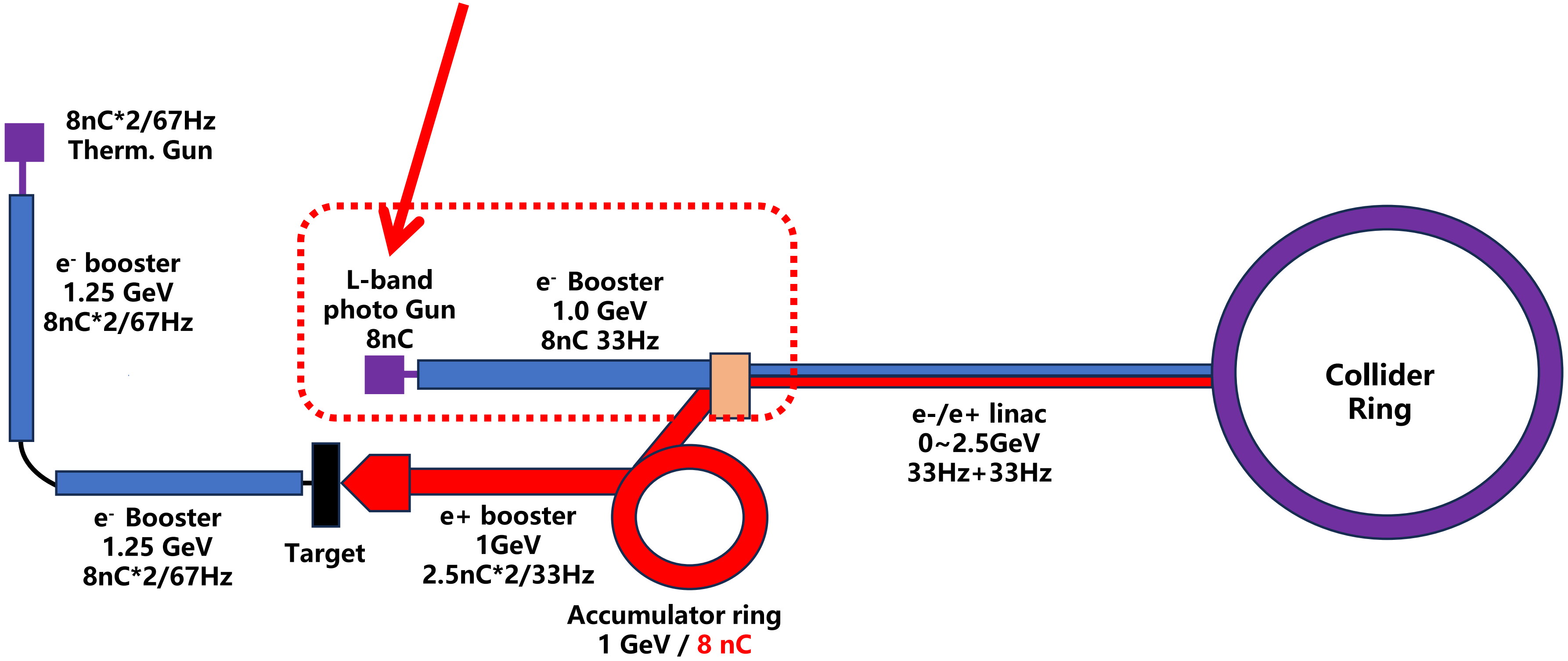
Position	Energy(MeV)	Charge(nC)	Energy Spread(%)
Gun	0.2	10	
ACC-1	63.84	99.74%	1.61
ACC-2	113.29	99.74%	1.61
ACC-3	163.41	99.74%	1.72
Injector End	2002.0	9.974	0.44



- Phase space as buncher and injector exit

Injector Plan B

- Although the emittance and energy spread almost meet the requirements, but they are still large, may be not good enough for higher luminosity
- Plan B: 8nC electrons with L-band photo-cathode gun, direct inject into the collider ring

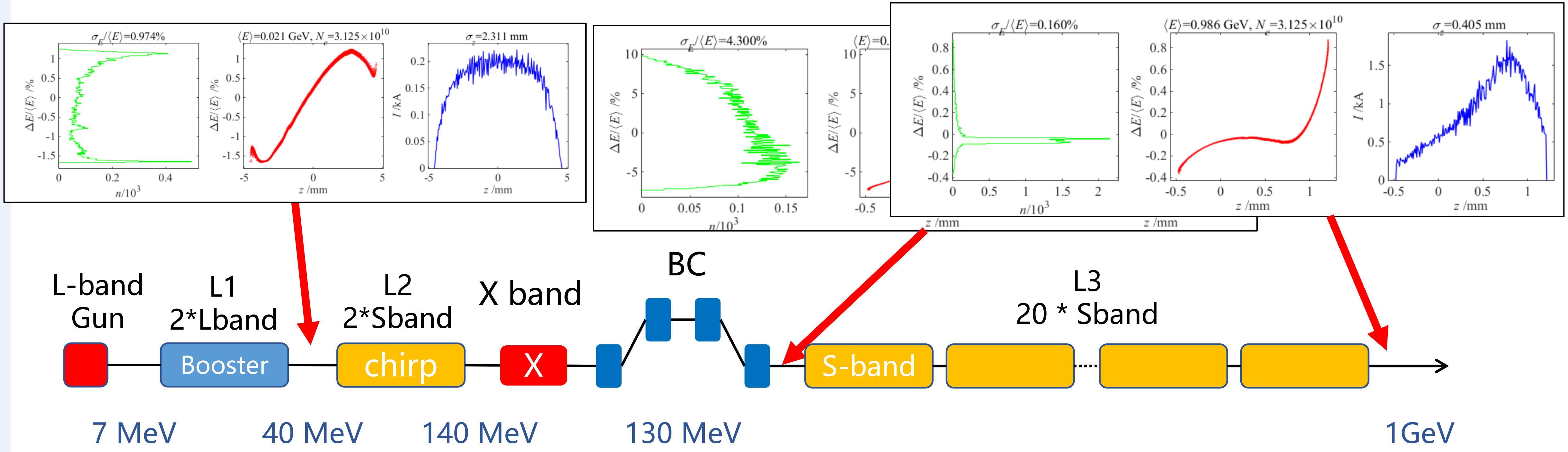


Injector Plan B

Advantage: L-band photo-gun can provide much better emittance and energy spread

Disadvantage: High demands on vacuum, laser, cathode and lack of experiences of large bunch charge generation, long term stability

- Based on the S2E, at the injector exit, the ε_n ~6 um, σ_E <0.16 % (RMS)
- Much better results compared with plan A (ε_n ~42 um, σ_E <0.5%) → higher luminosity!



Summary

- The performance of STCF relies on the beam qualities provided by injector and also put very high challenges on the injector design.
- According to the collider ring design, we proposed two injector designs for both off-axis and swap-out injection scheme.
- For off-axis scheme, the injector with two beams generated by two guns was studied, together with Damping Ring, both the electrons and positrons can meet the requirements.
- For swap-out scheme, we proposed two plans (thermionic gun / L band gun), which can save the electron Accumulator Ring.
- The L band scheme holds the potential for better luminosity, can be a choice for upgrade
- Further studies on Accumulator Ring is onging.

Thank you!

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