Design studies on the ERL-Test Facility at IHEP

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IHEP, Beijing

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Outline

- Introduction of BAPS and ERL-TF
- ERL TF design
- Beam physics studies of ERL-TF
- Summary

“Beijing Comprehensive Research Center”

Planed with corporation between CAS & Beijing Govern.

CAS is proposing the

“Beijing Comprehensive Research Center”

to be built in North Suburb Beijing,

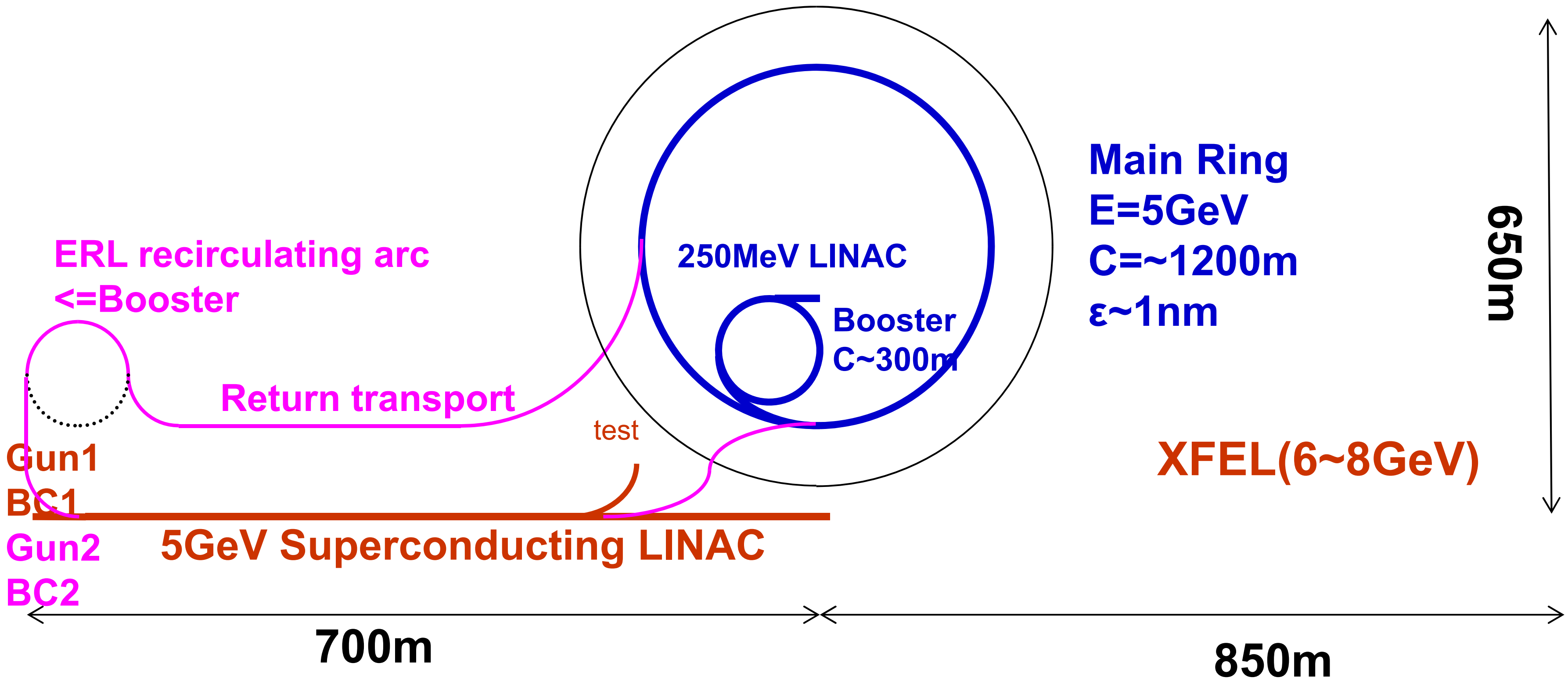
Huairou District,
~100 km from city center.

BAPS will be the central research facility of this Center.

A preliminary plan of the Beijing Advanced Photon Source

1st Phase: Small emittance synchrotron light source （2015-2020 ?）

2nd Phase : BX-ERL-FEL



BAPS Phase 1: 5GeV synchrotron light source

Main Parameters of BAPS

Parameter	Unit	Value
Energy	GeV	5
Circumference	m	~ 1200
Beam Current	mA	200
Emittance	nm·rad	~0.5 (with damping wiggler)
Bunch Length	ps/mm	~ 7.5/2.5(Vrf=6MV)
Critical Energy(Ec)	keV	~13.4(main bend) ~100(6T SC Wig.)
Number of Straight Section		48(DBA/DVB) 40(TBA) 32(QBA)
Peak Brightness	Photons/s/mm^2 /mrad^2/0.1%BW	~10^{21}

BAPS's 2nd phase: 5 GeV X-ERL (Preliminary !)

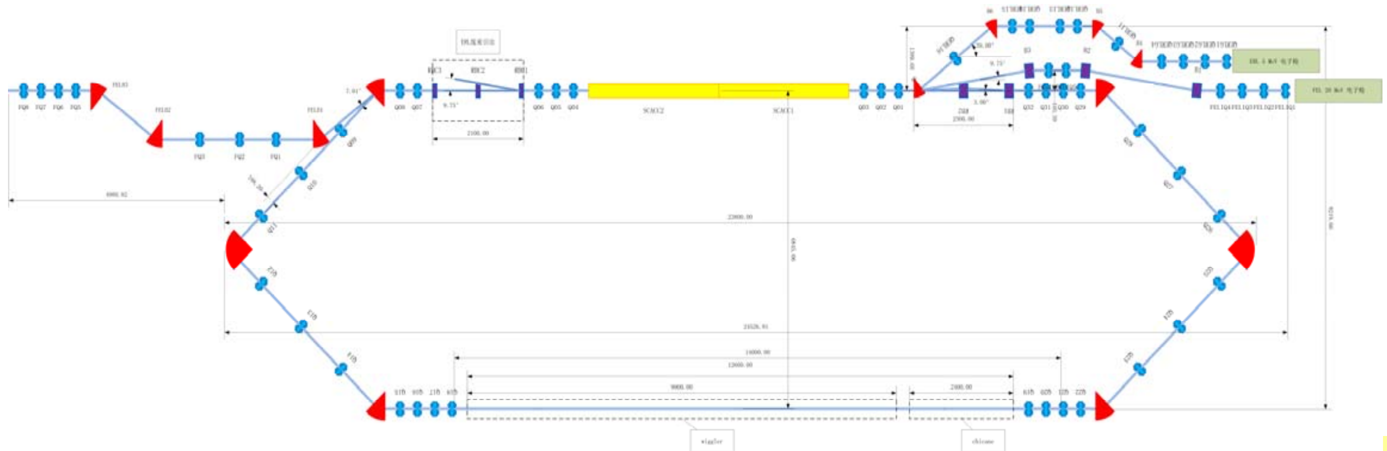
Parameters	Units	Values
Beam energy	GeV	5
Beam current	mA	10 ~ 100
Frequency	GHz	1.3
Bunch charge	pC	7.7 ~77
Injection energy	MeV	10
Nor. Emittance（rms）	mm-mrad	0.2 ~ 2
Energy spread（rms）	%	0.02 ~ 0.3
Bunch length	ps	0.1 ~ 1.0
Radiated power	kW	400
X-ray brilliance	$/(s.mm^2 .mrad^2 .0.1\%BW)$	10^{22}

XERL Key technologies

- Low emittance (0.1 mm-mrad) , High voltage DC Gun (500 KV);
- Low emittance ERL- Injector (5 MeV ~ 15 MeV);
- SC accelerating structures for CW operation, including Cavity, Coupler, HOM absorber and so on;
- ERL Beam physics;
  (Emittance dilution due to CSR, IBS, BBU, Merger, etc.)

XFEL-ERL has very attractive features, but the key technologies are very challenging, which need to be investigated and prepared by a test facility.

Layout of the ERL Test Facility at IHEP



Compact TF-- 35 MeV-10 mA

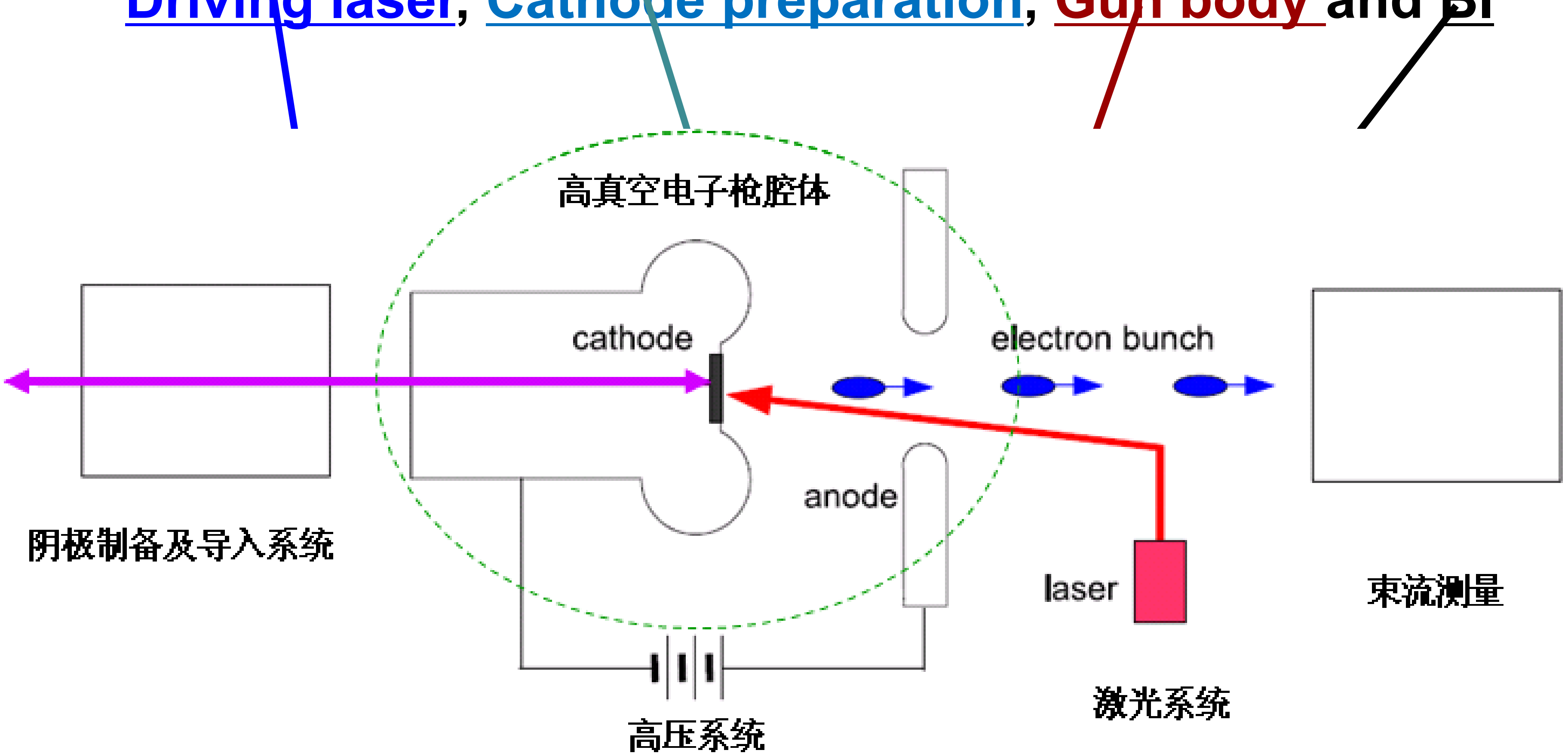
- **DC- and 5 MeV injector (2 x 2-cell CW SC cavity)**
- **L-band CW SC Linac: E = 15~20 MV/m、**
  35 MeV ~10 mA (2 x 7-cell CW SC cavity)；
- **ERL ring: 2 TBA arcs , 2 straight sections ；**
- **ERL -THz beam lines (from CSR or Oscillator).**

Main parameters of the ERL-TF

Energy	35 MeV
Current	10 mA
Bunch charge	77 pC
Nor. Emittance	(1~2) mm-mrad
Energy spread	0.5% ~ 1.0%
Bunch length	(2~4) ps
Bunch frequency	130 MHz

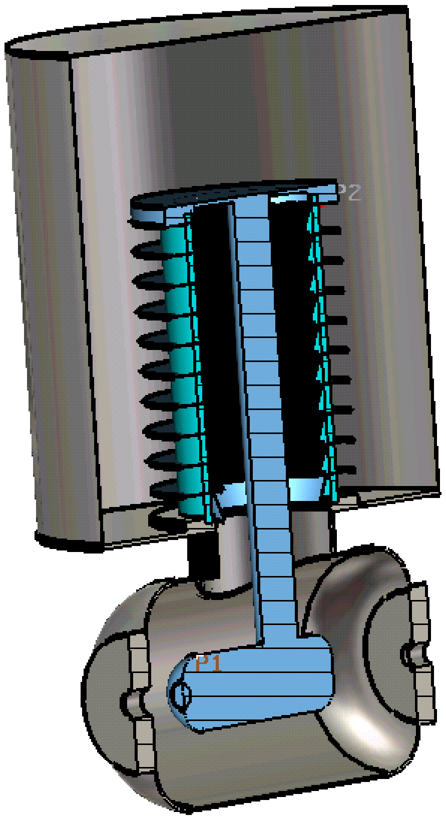
Layout of DC- Gun (500KeV, 10mA)

Driving laser, Cathode preparation, Gun body and BI

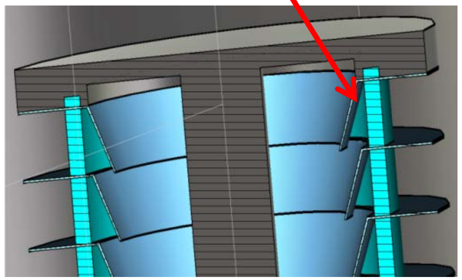


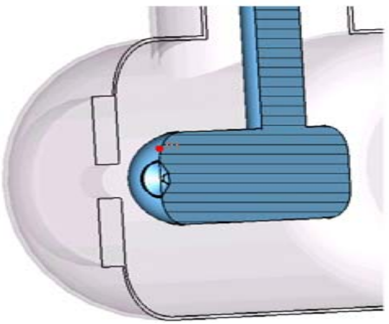
DC Gun Body (500 keV, 10 mA)

500-kV gun with a segmented insulator



guard ring against field emission





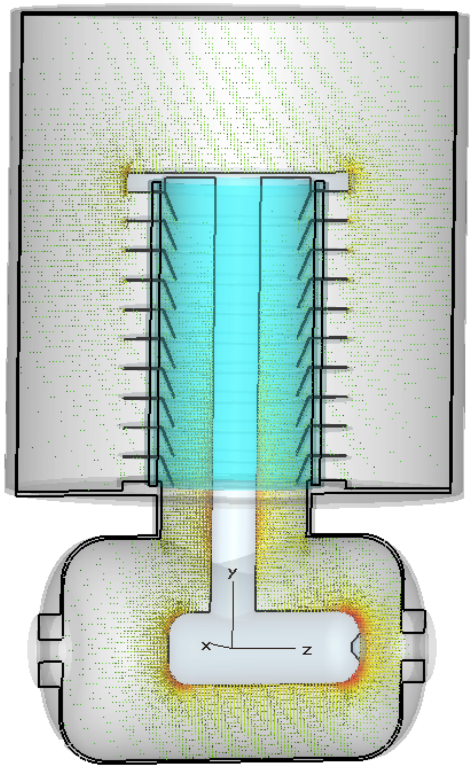
Gun body inner diameter	502 mm
Gun body material	Pure Ti
Gun length	800 mm
Ceramic insulator's material	99.8% Al_2O_3
Insulator's section number	10
Insulator's section length	65 mm
Insulator's outer diameter	400 mm
Insulator's thickness	20 mm
Cathode ball diameter	164 mm
Cathode support rod diameter	101.6 mm

We design the gun body and do lots of simulation on the field distribution, based on KEK/JAEA DC gun.

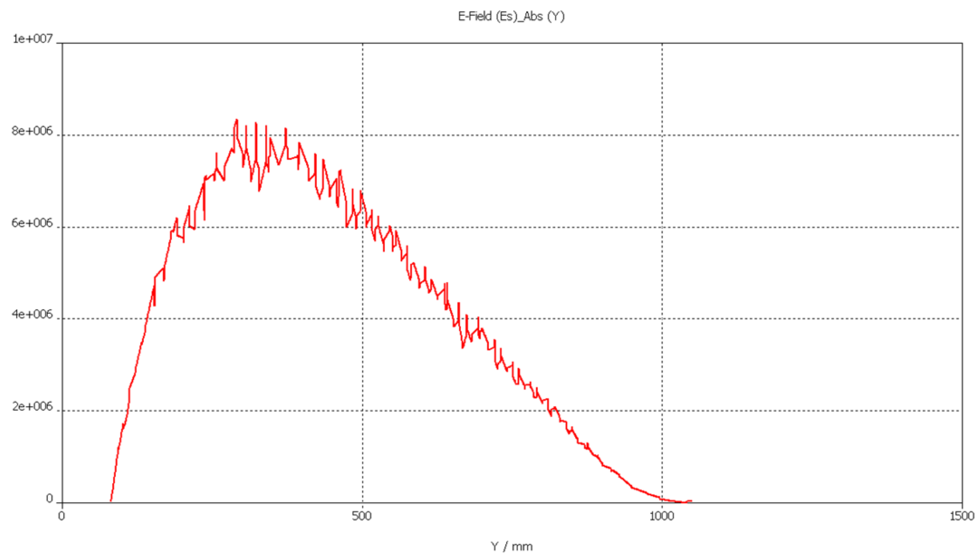
Gun field distribution simulation

The distance from the cathode to the pole is 10cm

With cathode ball

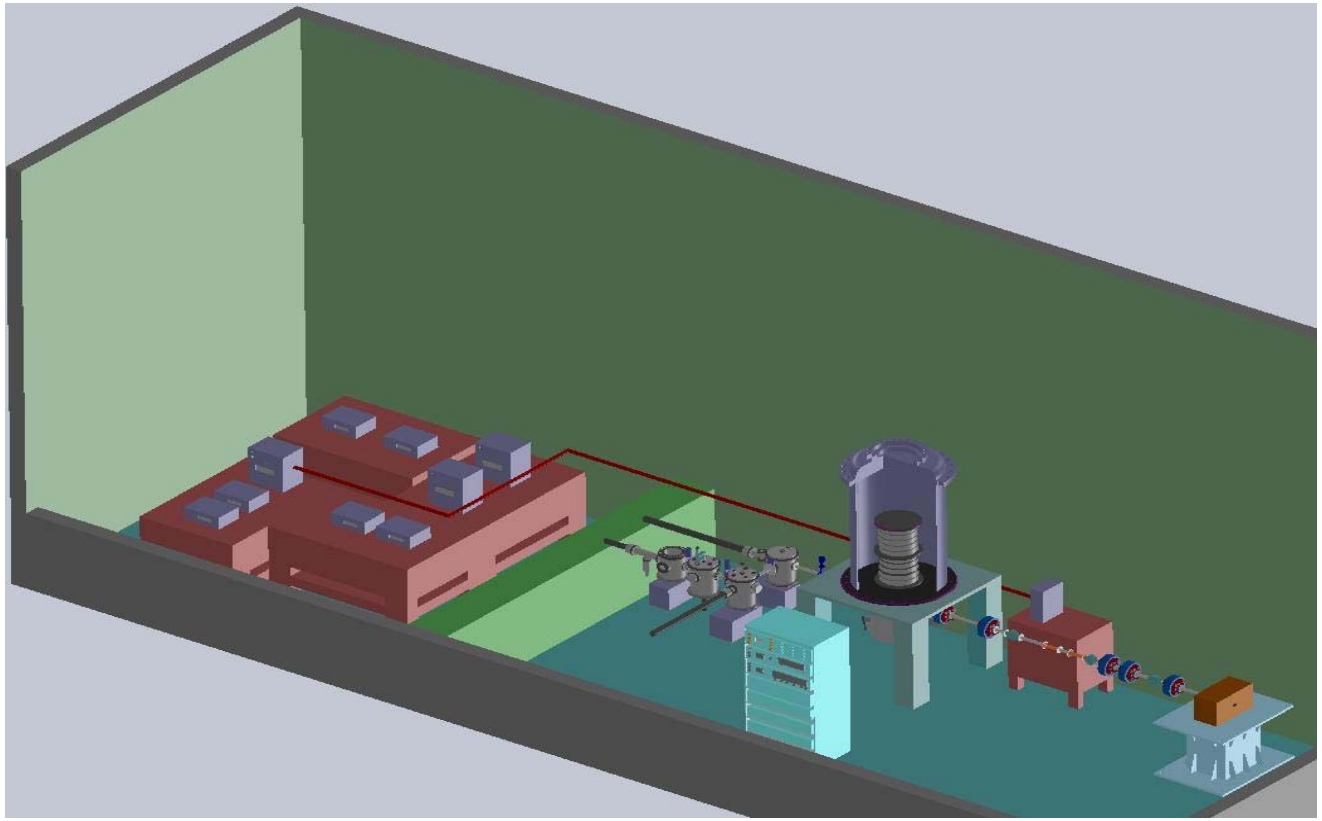


Type	E-Field
Plane at x	0
Maximum-2d	1.06115e+007 V/m at -3.48632e-013 / -66.0868 / 285.597



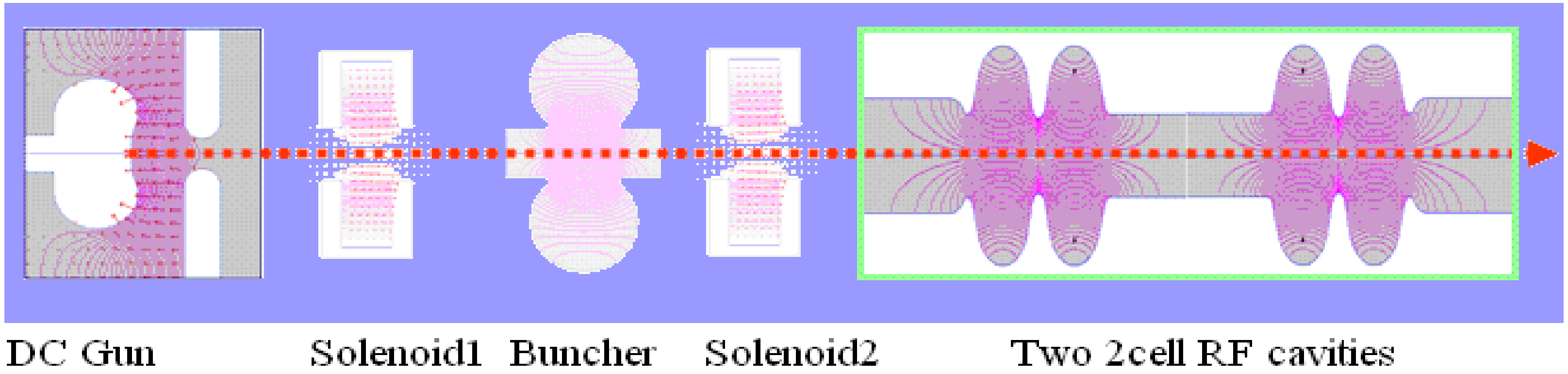
This is the field distribution in the gun cavity simulated by 3D code, the maximum surface field is 10.6 MV/m.

DC- Gun experimental setup in hall #2



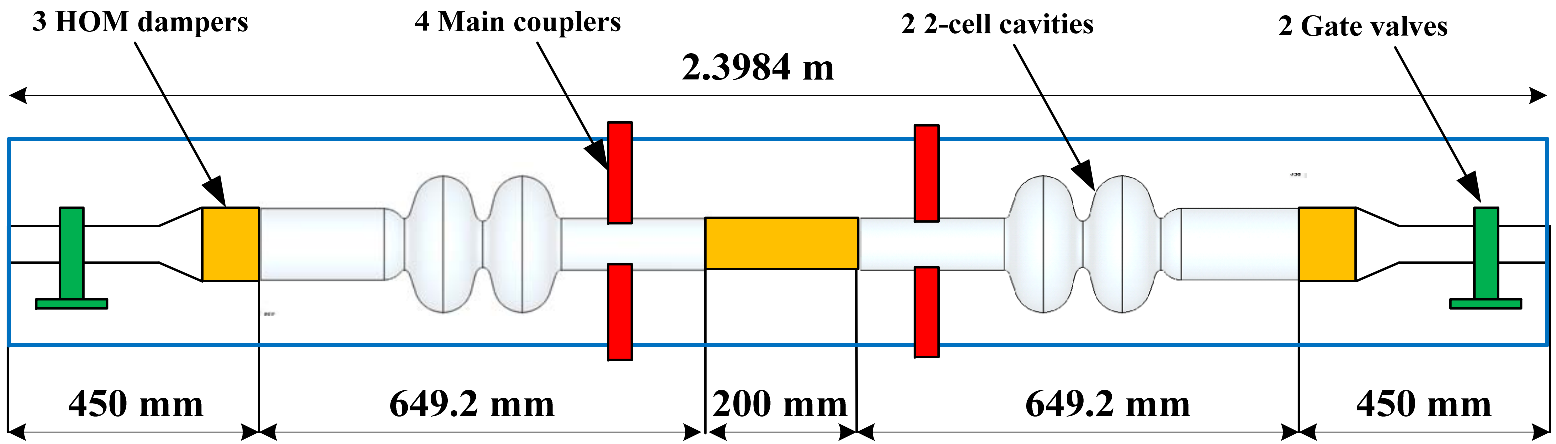
The Gun's preliminary design is ready and its funding is approved by IHEP.

5 MeV Injector



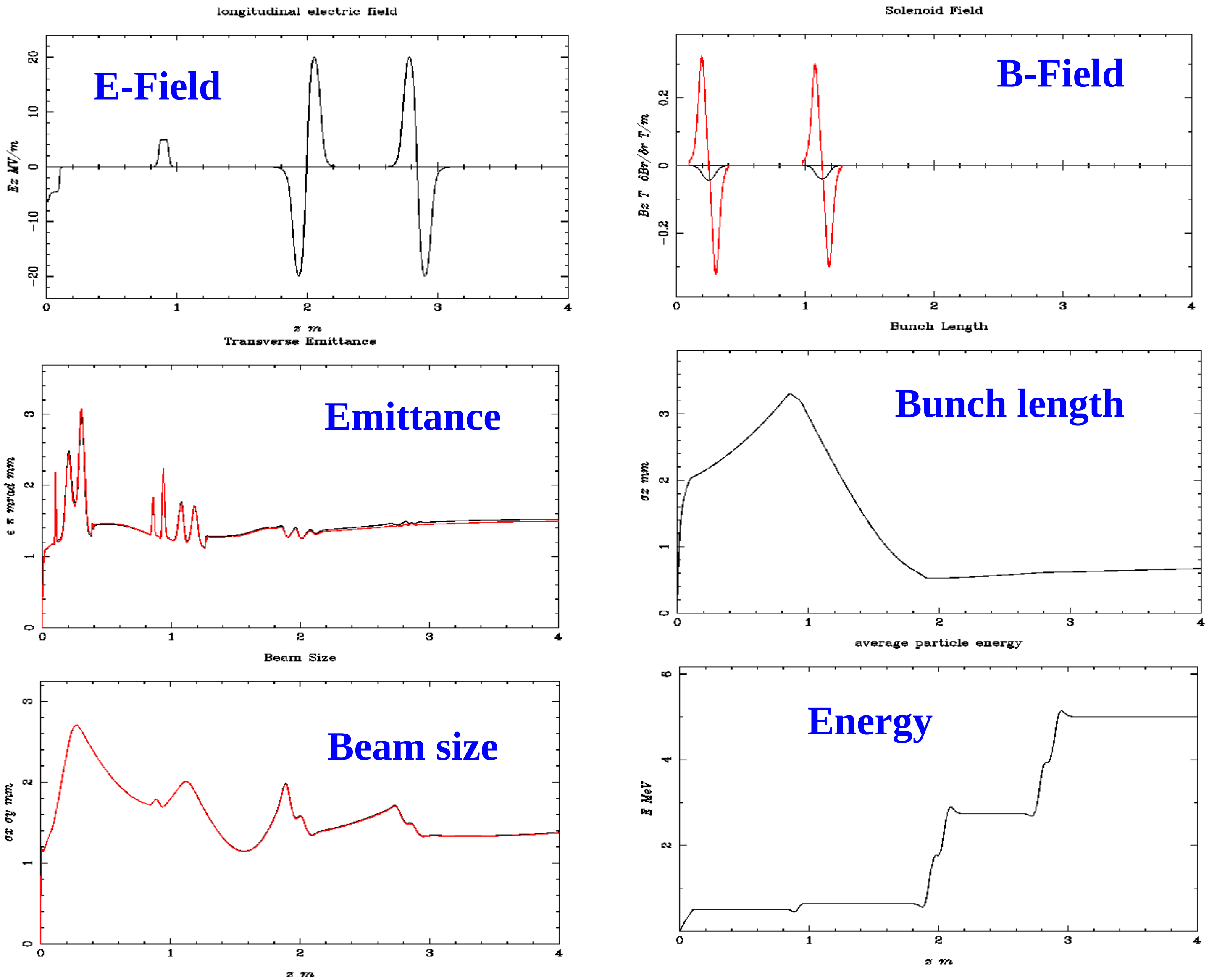
Buncher ~5 MeV/m

SC Cavity ~20 MeV/m



Two 2-cell SC Cavities in one Cryomodule

Injector beam simulation (1)



Injector beam simulation (2)

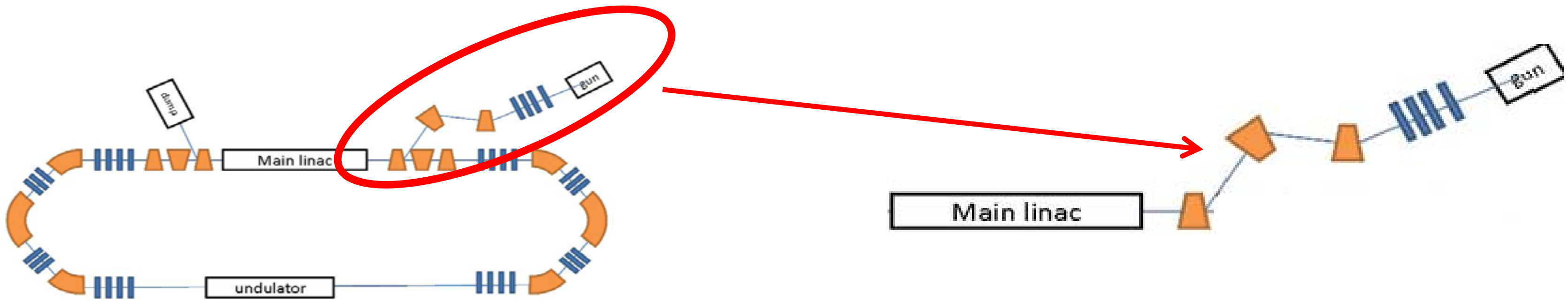
- **Simulation conditions：**

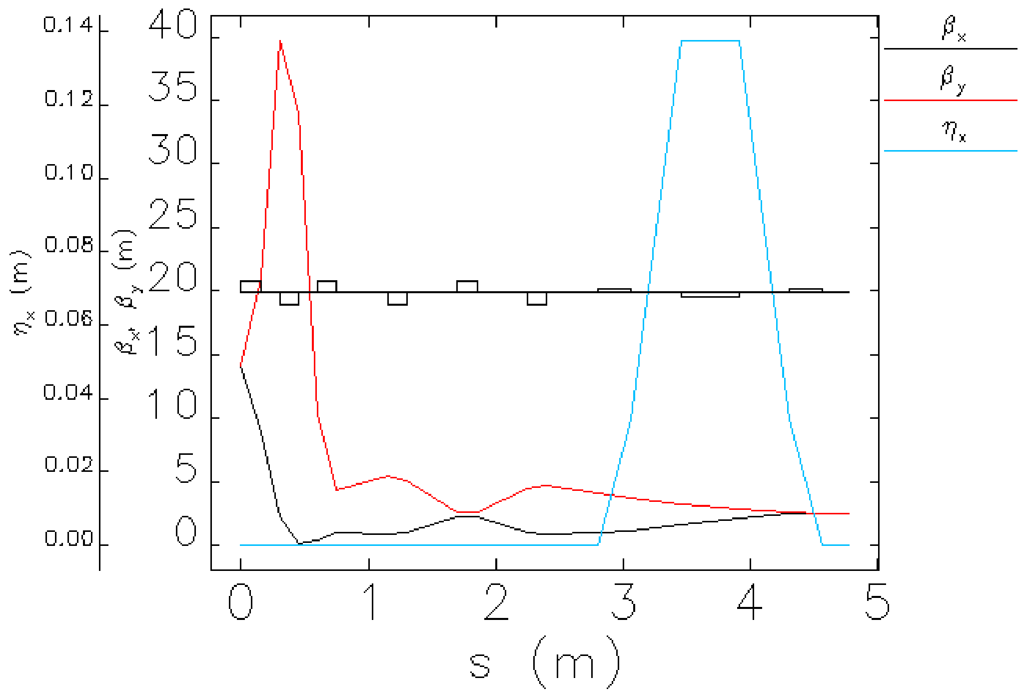
（1）Charge / bunch 77pC；
（2）Laser RMS beam size 1.2 mm； flat top laser, flat top 20ps， rise time 2 ps；
（3）initial kinetic energy is assumed to 0.2 eV；
（4）High voltage of the DC gun 500 kV,
maximum field gradient on z-axie is 6.45 MV/m；
maximum field gradient on the cathode surface 5.48 MV/m；
（5）Maximum B-field of solenoid 1 is 430 Gauss；
Maximum B-field of solenoid 2 is 400 Gauss；
（6）Buncher 1.3 GHz, Maximum e-field is 5 MV/m；
（7）two 2-cell SRF cavity，maximum e-field is 20 MV/m ；

- **Simulation results：**

Beam energy is 5 MeV，RMS energy spread is 0.72%，
RMS normalized emittance is 1.49 mm-mrad,
RMS bunch length is 0.67mm = 2 ps.

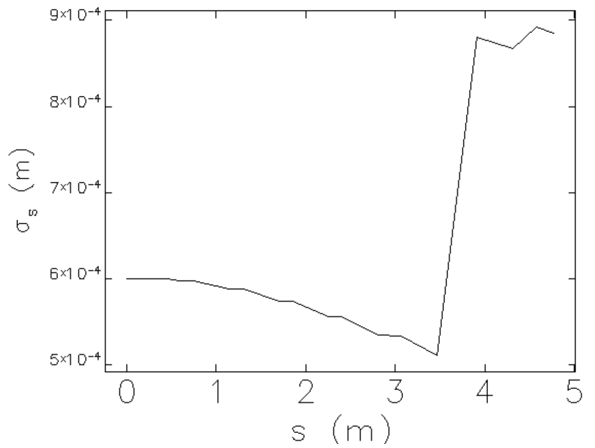
Beam injection

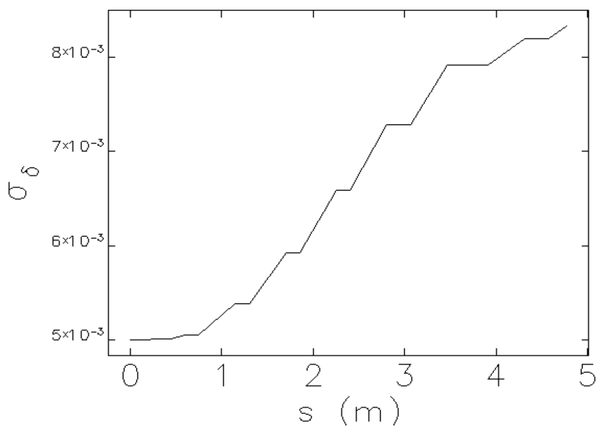




Primary lattice of the injection system

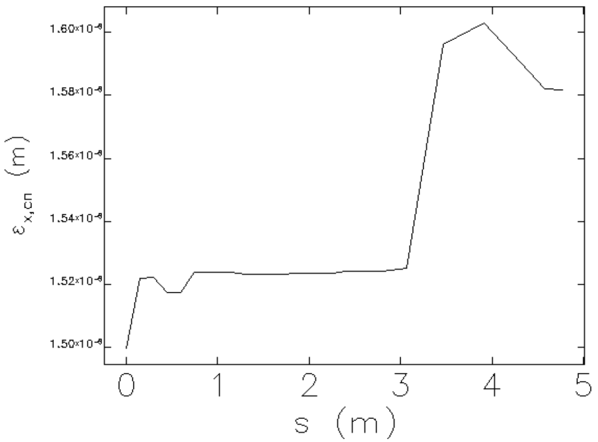
Preliminary results of injection simulation (not yet optimized)

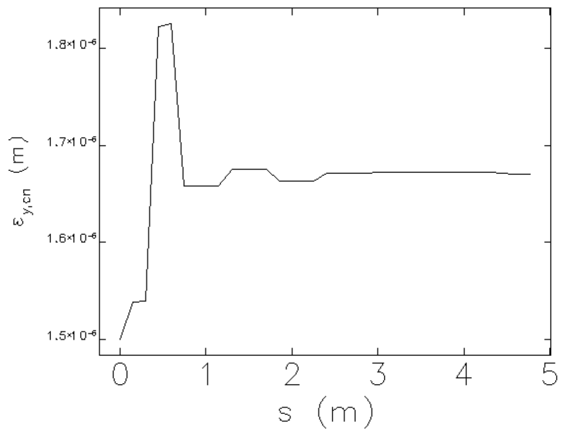




Bunch length 2.0→2.8 ps due to longitudinal space charge

Energy spread 0.5%→0.8%





ε_x 1.50 →1.58 um

ε_y 1.50 →1.68 um

Bunch compression with the 1st TBA arc

- **To avoid significant emittance growth and high-order-mode (HOM) effects, the bunches in merger and in main linac kept long enough.**
- **For high power THz-CSR or THz-oscillator, the bunch length should be compressed from 2ps to ~0.2ps.**
- Bunch compression **[T.Shiraga, et, al . NIM A 575 (2007) 315]**

Accelerating the beam in the linac at an off-creat phase Φ, to produce the additional energy spread:

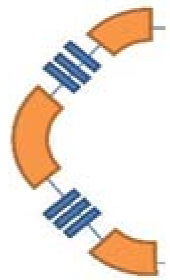
$$\delta = \frac{\Delta E}{E_f} = \frac{E_0}{E_f}\left\{\cos\left(\varphi + \frac{\omega Z}{c}\right) - \cos(\varphi)\right\}$$

then compress the bunch by 1st TBA arc with non-zero R_{56}:

$$\Delta Z = R_{56}\delta + T_{566}\delta^2 + U_{5666}\delta^3 + \cdots$$

X. Cui's poster PSP001

Bunch compression with the 1st TBA arc



- TBA consists of 45-90-45 degree dipoles and 3 families of quads.
- Preliminary results of the simulations with ELEGANT, [M. Borland, ELEGANT: APS LS-287, September 2000].

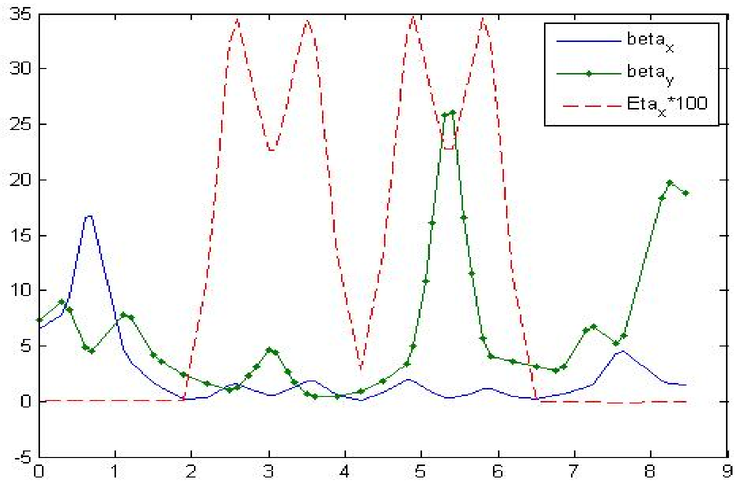
including CSR & S.C effects, initial bunch length = 2ps, Emitt.= 1.8 um.

Linac phase (degree)	Nor. Emittance (mm-mrad)	Bunch length (ps)	R_{56}
13.0	2.65	0.18	0.16
12.6	2.40	0.25	0.165
12.3	2.26	0.33	0.169
12.0	2.16	0.41	0.174
11.0	1.97	0.70	0.19

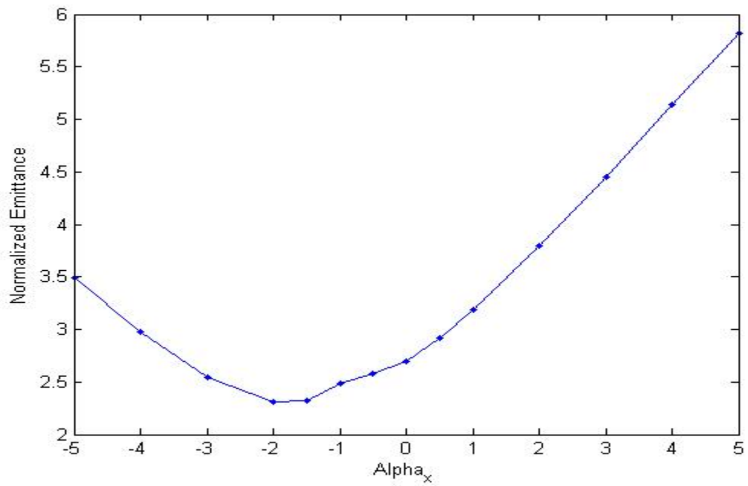
When bunch length compressed from 2 ps to 0.25 ps, then the nor. emittance is increased by a factor of 29% , caused by CSR Effect, even with emittance growth suppression.

Suppression of the CSR induced emittanc

- **Low emitt. at the undulator is one of the key requirement,**
- **The "envelope matching method" is used to suppress the CSR induced emittance increase, by adjusting the orientation of the phase ellipse parallel to the CSR kick** [R. Hajima, APAC 2004].
- **To scan the Twiss parameters at the arc exit, We set β_x = 0.202, and scan α_x in the range of $-5 < \alpha_x < +5$, and when $\alpha_x = -2$, the emittance growth due to the CSR is minimum.**



Lattice functions at the 1st arc,

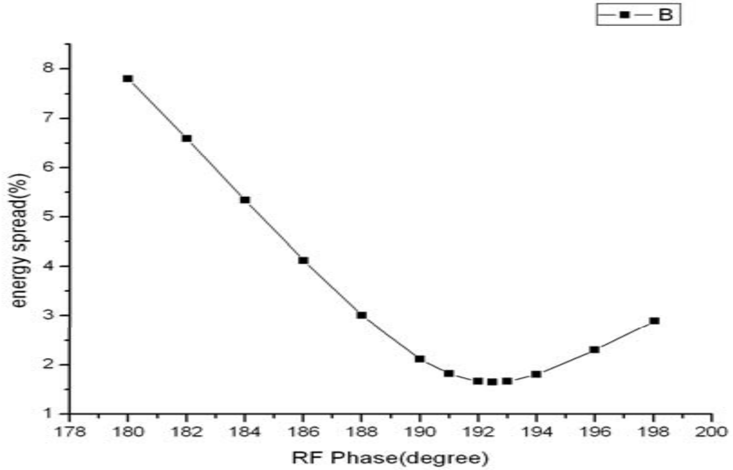


Emittance VS. α_x

Energy Compression with return ARC

- Downstream the undulator, the beam energy spread is enlarged. While decelerated through the Linac, relative energy spread increases.
- This energy spread can be reduced by rotating the bunch in the longitudinalphase space, as so called Energy Compression

  [P.Pilot, D.R.Douglas, G.A.Krafft, Phys.Rev.ST Accel.Beams 6(2003)0.0702].
- In our ERL-TF, energy compression is done by setting the return arc (2^{nd} TBA arc) non-isochronous, and tuning the deceleration phase in the linac.
- To stretch the bunch length, R_{56} =-0.16 in the return arc. RF Phase~ 193 degree , the energy spread could be down to ~ 1.5%.



About the BBU effect (Preliminary)

- **The BBU effect caused by HOMs in the SC cavity may be one of the most critical issues to limit the beam current.**

- **To suppress this effect, the most effective way is to well control the R/Q of the HOMs and well optimizes the beam optics.**

- **Our simulation results with a BBU-code for ERL** [JIAO Yi, A BBU code developed with C language implanted in Matlab environment]

  with HOM's parameters of Cornell 7-cell ERL SC cavities

  [Mayes C.E. and Hoffstaetter IPAC 2010],

  Preliminary results:

  The BBU current limitation could be about 260 mA.

About 7-cell 1.3 GHz SC cavity design

For the design of the SC cavities of the main linac, the following factors are considered:

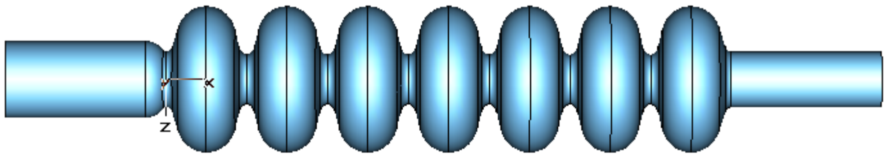
1) Lower the cryogenic loss with large $G \cdot R / Q$;

2) Lower the HOM impedance about one order of magnitude than the ILC and XFEL cavities, and to avoid HOM frequencies around the multiples of the fundamental mode;

3) Small electromagnetic surface field;

4) Large bandwidth of dipole modes, to decrease the frequency error due to fabrication error;

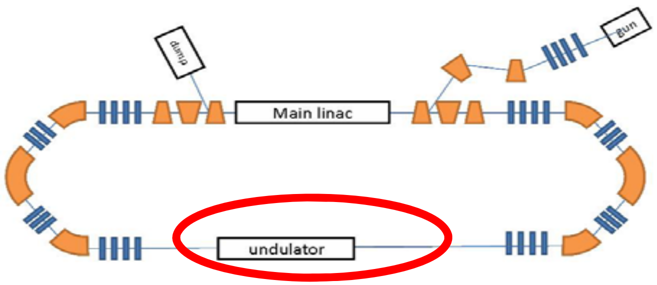
5) Magnetic field shielding (less than 10 mG).



J. Zhai's Talk WG3011

High average power THz @ the ERL-TF

Modes	Electron beam	Insertion device	THz wave performance
CSR	Energy 20MeV Bunch length 0.5ps Emittance 2um Energy spread 0.5% Peak current 62 A	Period 60 mm Gap (9-23) mm Length 1.5m	Wave length 0.15～1 mm (Frequency (0.3-2) THz) Peak power 2 MW Average power 270 W
Oscill -ator	Energy 35 MeV Bunch length 4ps Emittance 2 um Energy spread 0.5% Peak current 20 A	Period 60 mm Gap (23-32) mm Length 1.5m	Wave length 21～50 um Peak power 7 MW Average power 9 kW



Summary

1) A 5 GeV small emittance synchrotron radiation facility is planed @ IHEP. Its R@D is under way, and may be further upgraded to an 5 GeV ERL-FEL facility according to IHEP's planed road-map.

2) A (35 MeV-10 mA) ERL TF is proposed @ IHEP, its beam dynamics design and the key components design were preliminary done：

- ✓ **Beam dynamics design of the 5 MeV injector and the injection system.**
- ✓ **A lattice with 2 TBAs and 2 straight sections for the ERL-TF.**
- ✓ **A bunch compression (from 2 ps to 0.25 ps, 77 pC) with the 1st TBA arc is studied, cost by the nor. emittance growth of ~30% due to the CSR effect, even the CSR induced emittance growth suppression is employed. Further study to optimize this issue is under way.**
- ✓ **The BBU current limitation is about 260 mA as preliminary studied.**

3) A 500 keV DC-gun will be constructed soon for the ERL TF, funded (~2M USD) by IHEP. Its design and optimization are being done.

Thank you！

Light sources comparisons

Facilities	3rd GLS	XERL	XFEL
e- energy（GeV）	3 - 8	5 - 7	14 ~ 20
Current (mA)	100 ~ 300	10~100	(3.4 ~ 5.0) kA (peak)
Emitt.（nm）	2.1 ~3.9	0.015~0.15	0.05~0.02
Peak brilliance	$\sim 10^{19\text{-}22}$	$\sim 10^{25\text{-}26}$	$\sim 10^{32\text{-}33}$
Aver. brilliance	$\sim 10^{17\text{-}20}$	$\sim 10^{22\text{-}23}$	$\sim 10^{22\text{-}25}$
Pulse length	15~70 ps	1 ps ~100 fs	~100 fs
Coherency (Coher. photons)	Partial Transv. ($\sim 10^{13\text{-}14}$)	Partial Transv. ($\sim 10^{17}$)	Coherent ($\sim 10^{24}$)
Other features		Energy Recovering; Round beam with small emittance.	
Simultaneous users	≥ 50	~ 30	Not many
Feasibility	Feasible	Under R&D	Feasible

They can not be replaced each other !

Preliminary parameters of BAPS

	Spring-8	APS	ESRF	SSRF	DIAMOND	NSLSII	TPS	BAPS (preliminary)
Energy	8 GeV	7	6	3.5	3	3	3	5
No. periods	48	40	32	20	24	30	24	50
Emittance（nm）	6.9	7.6	6.8	11.8	6.5	2.09	4.9	1.11
Emittance w.wiggler	2.22	2.26	3.24	4.51	1.92	0.983	1.92	0.587
Circum. (m)	1436 m	1104	844.4	432	561.6	792	518.4	1218.4
Strait section L	44×6.6 4×30	40×6.7	32×6.3	16×5.3 4×10.8	18×5.0 6×8.0	15×6.6 15×9.3	18×7 6×12	45×6.4 5×14.6
ΣL/C	0.286	0.243	0.239	0.296	0.246	0.301	0.382	0.296
Dynamic Aper.（mm）						±15		

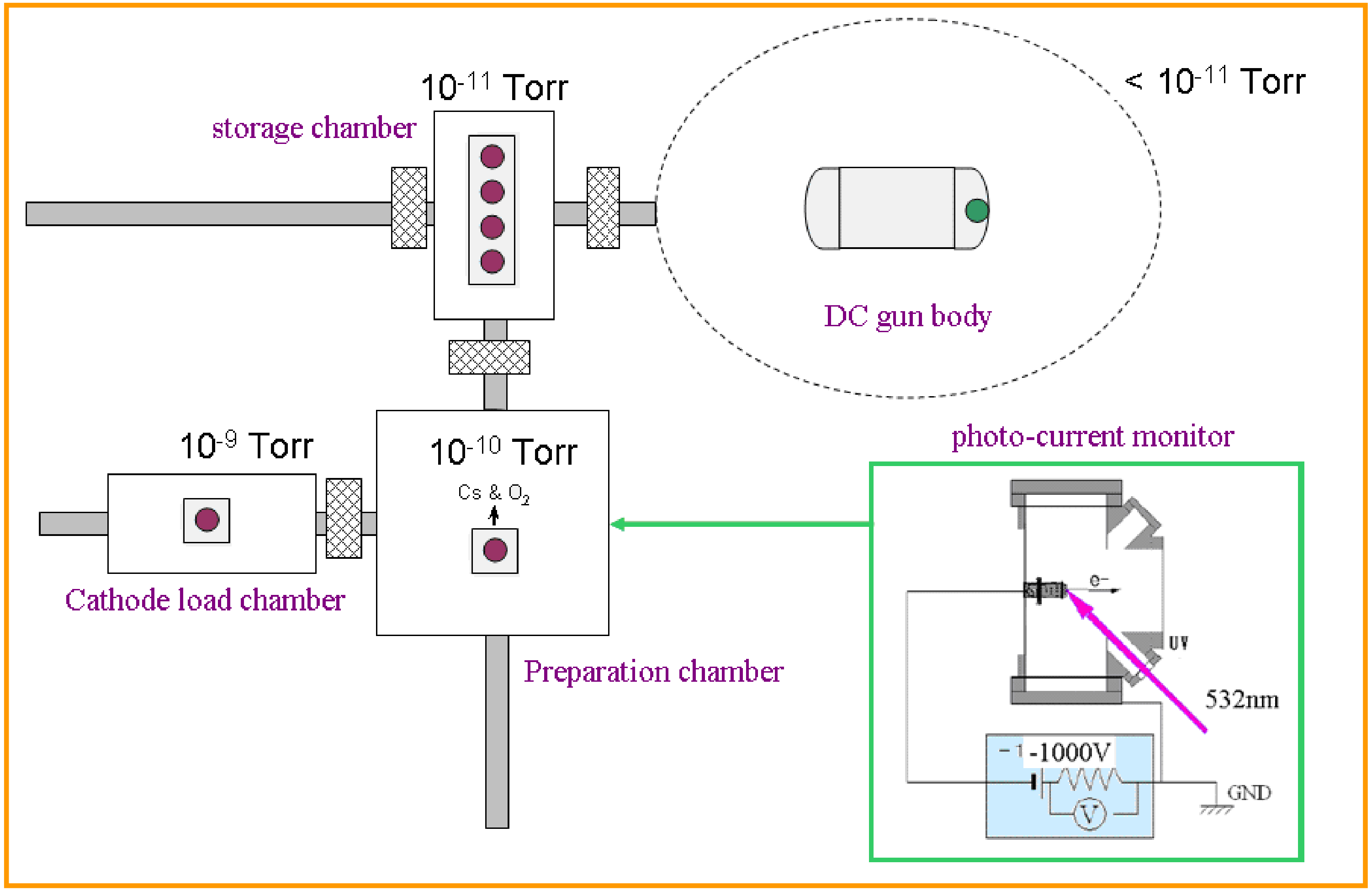
BAPS's 2nd phase: （6~ 8）GeV XFEL (Preliminary)

		LCLS	E-XFEL	SCSS	BXFEL
BEAM	Energy (GeV)	14.35	20.0	6 ~ 8	6 ~ 8
	Nor. Emittance (μm)	1.2	1.4	0.5	0.8 ~ 1.2
	Energy spread (rms, %)	0.008	0.0125	0.02	0.01
	Peak current (kA)	3.4	5.0	4.0	4.0
	Bunch length (fs)	230	200	250	230
	Repe. rate (Hz)	120	10	50	25
ID	Gap / Period（mm）	5 / 30	10 / 38	3.5/15 ~4/18	3.5/15 ~ 4/18
	B field (T)	1.32	1.06	0.94	0.94 ~ 1.14
	K value	3.71	3.8	1.32	1.32 ~ 1.9
FEL	Wave length (nm)	0.15	0.1	0.1	0.1
	Satua. gain length（m）	86	145	35	52 ~ 84
	Peak power（GW）	9	24	8	2.6 ~ 6.3
	Peak brilliance (10^{32})	12	54	10	5 ~ 8

BAPS's 2rd phase: 5 GeV BX-ERL (Preliminary)

Parameters	Units	Values
Beam energy	GeV	5
Beam current	mA	10 ~ 100
Frequency	GHz	1.3
Bunch charge	pC	7.7 ~77
Injection energy	MeV	10
Nor. Emittance （rms）	mm-mrad	0.2 ~ 2
Energy spread （rms）	%	0.02 ~ 0.3
Bunch length	ps	0.1 ~ 1.0
Radiated power	kW	400
X-ray brilliance	/(s.mm^2 .mrad^2 .0. 1%BW)	10^{22}

Cathode preparation system



Primary 7-cell 1.3 GHz SC cavity parameters

f_0	1.3 GHz
Cavity voltage V_c	15 MV
Effective length L_{eff}	0.8 m
Accelerating gradient E_{acc}	18.8 MV / m
Q_0	$> 10^{10}$
Q_L	2×10^7
Bandwidth	65 Hz
R / Q	800 Ω
Iris diameter	72 mm
Large beam pipe diameter	110 mm
Small beam pipe diameter	78 mm
Geometry factor (G)	270 Ω
E_{peak} / E_{acc}	2.06
B_{peak} / E_{acc}	4.2 mT / (MV / m)
Longitudinal loss factor*	13.1 V / pC
Transverse loss factor*	13.7 V/ pC / m