An Update on High Energy Plasma Based Injector for CEPC

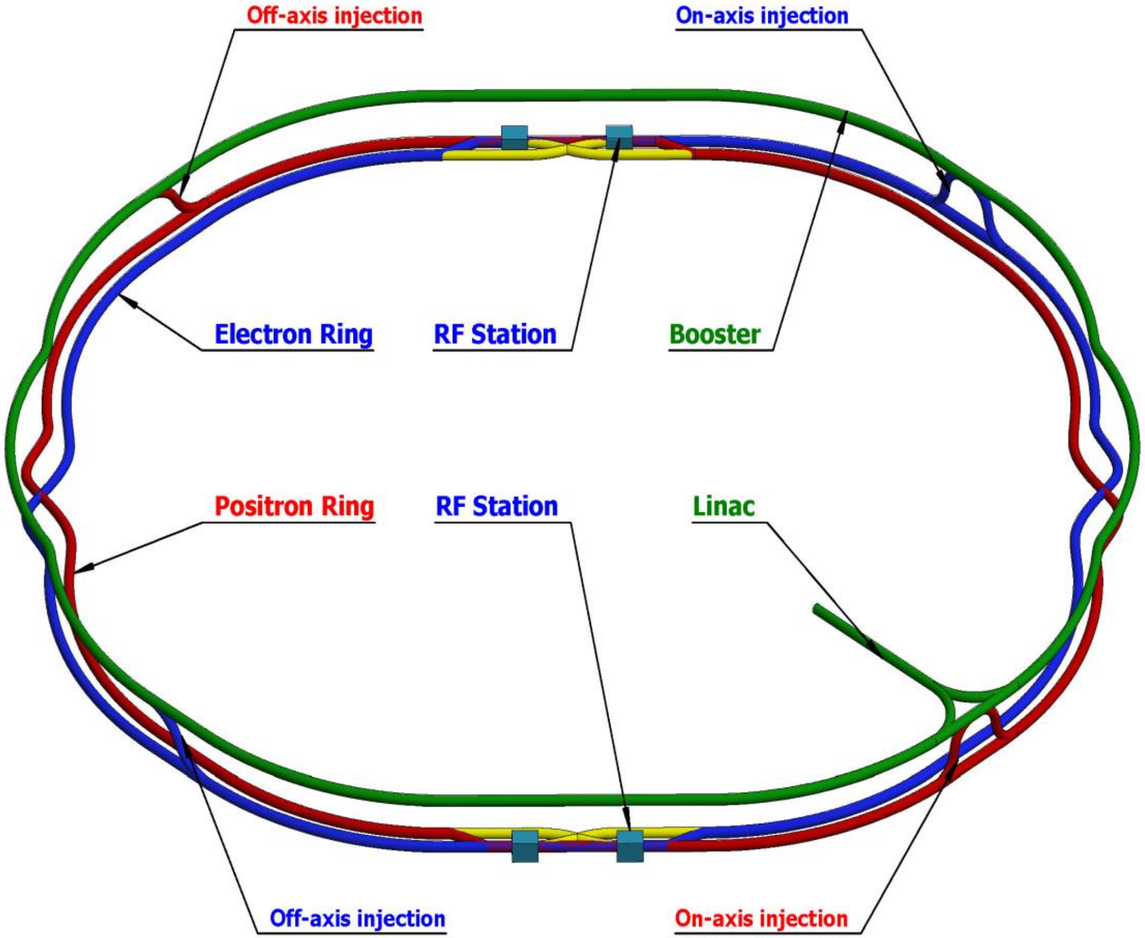
Wei Lu
Tsinghua University
On behalf the IHEP-THU-BNU AARG team
Jan 14, 2021

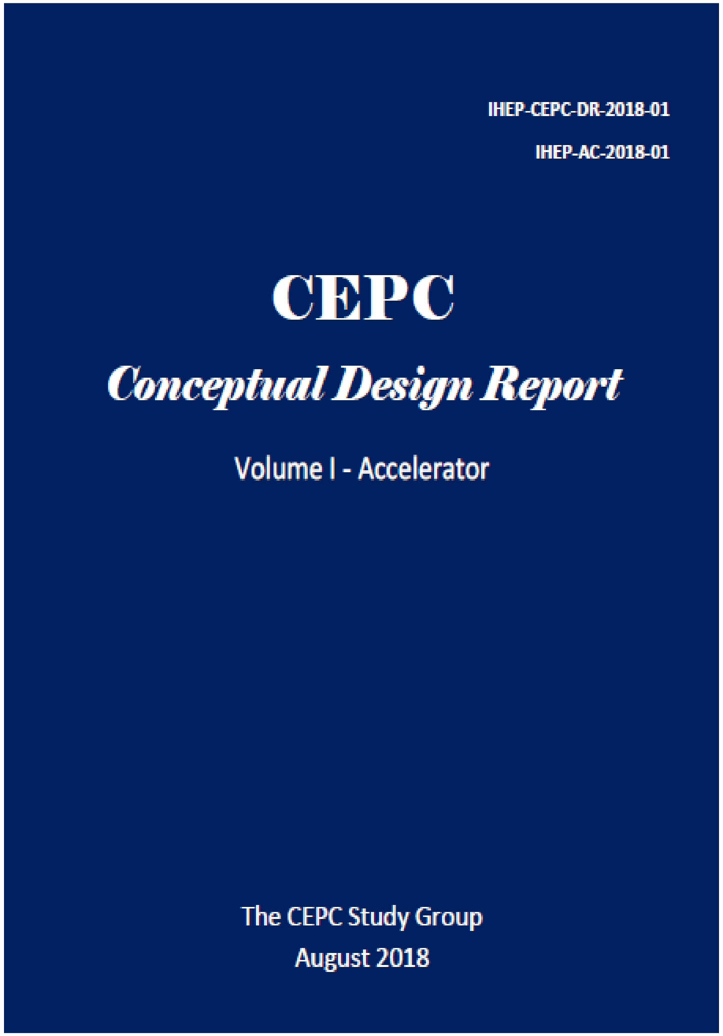
Mini-workshop on Accelerator: Plasma Acceleration
IAS Program on High Energy Physics 2021

Outline

- **Background: CEPC/CEPC plasma injector**
- **Preliminary Design v2**
- **Current status: Physics and experiments**
- **Outlook: Future experiments**

Background: CEPC





CDR (Acc.) International Review @ 2018.6.28-6.30 & Final Released @ 2018.9.2

CEPC Accelerator System

10 GeV

1) Injector

L=1.2km

Electron

Positron

2) Booster

C=100km

Booster Energy Ramp
10GeV→45/120GeV

LOW FIELD DIPOLE PROBLEM! !

Three rings in the sane channel:
- **CEPC & booster**
- **SppC**

3) Collider

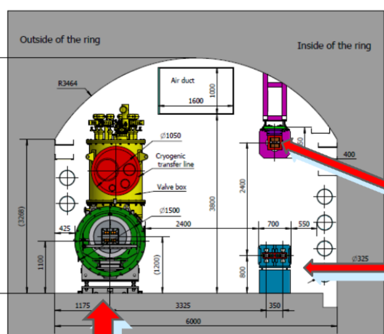
C=100km
2IP

45/120 GeV

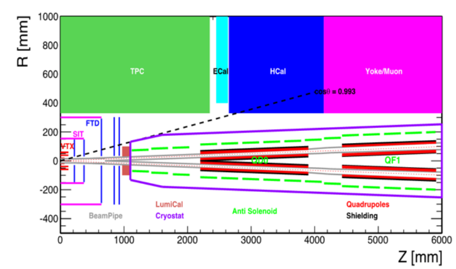
The key systems of CEPC:
1) Linac Injector
2) Booster
3) Collider ring
4) MDI
5) Civil Eng.

5) Civil Eng.

TUNNEL CROSS SECTION OF THE ARC AREA



CEPC Booster
CEPC Collider
SppC



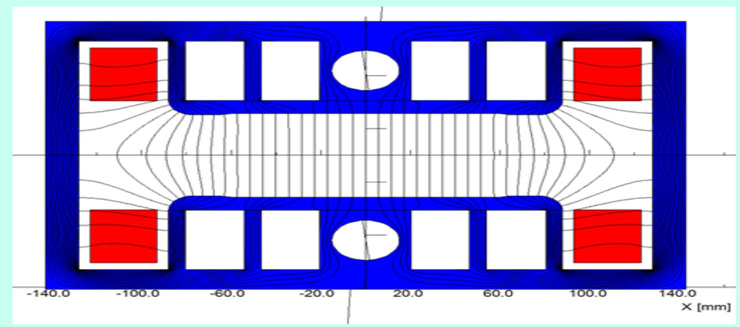
4) Detector Machine Interface (MDI)

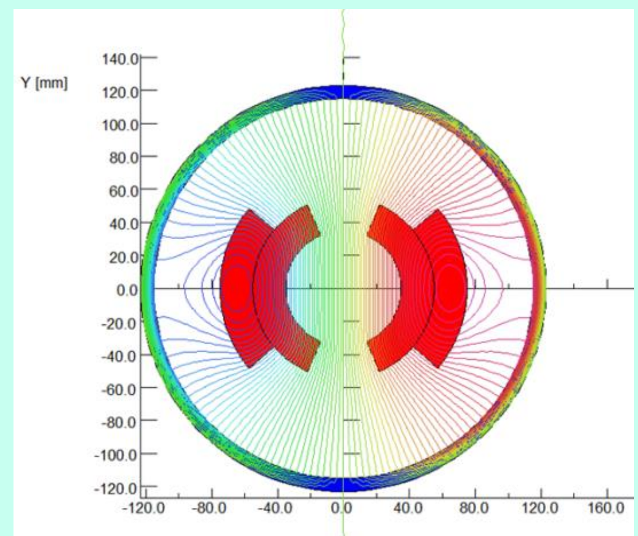
CEPC Low field Dipole in Booster Ring

Can we using a 10m scale plasma accelerator to boost the energy of the injector to about 45GeV?

- to design
- Field reproducibility <29Gs*0.05%=0.015Gs → how to measure
- The Earth field ~0.2-0.5 Gs, the remnant field of silicon steel lamination ~ 4-6 Gs.

(Twice excitation current)



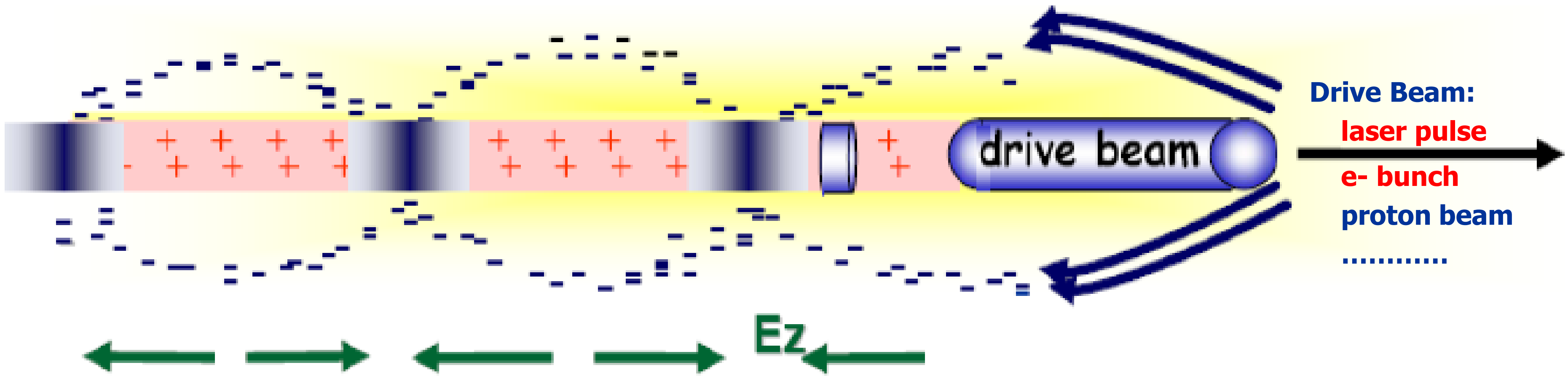


➢ Thinking beyond CDR

- Nominal field error: ~0.1%
- Uniformity requirement: ~0.05%
- Eddy current effect

  - Sextupole coils outside vacuum chamber

Plasma-based wakefield acceleration



Tajima & Dawson, PRL (1979)
Chen et al., PRL (1985)

$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_0} = -\omega_p^2\frac{n_{\mathrm{beam}}}{n_0} + c^2\nabla^2\frac{a^2}{2}$$

Plasma wave: electron density perturbation

Space-charge force of particle beam

Ponderomotive force (radiation pressure)

$$a = \frac{eA}{mc^2} \propto \lambda I^{1/2}$$

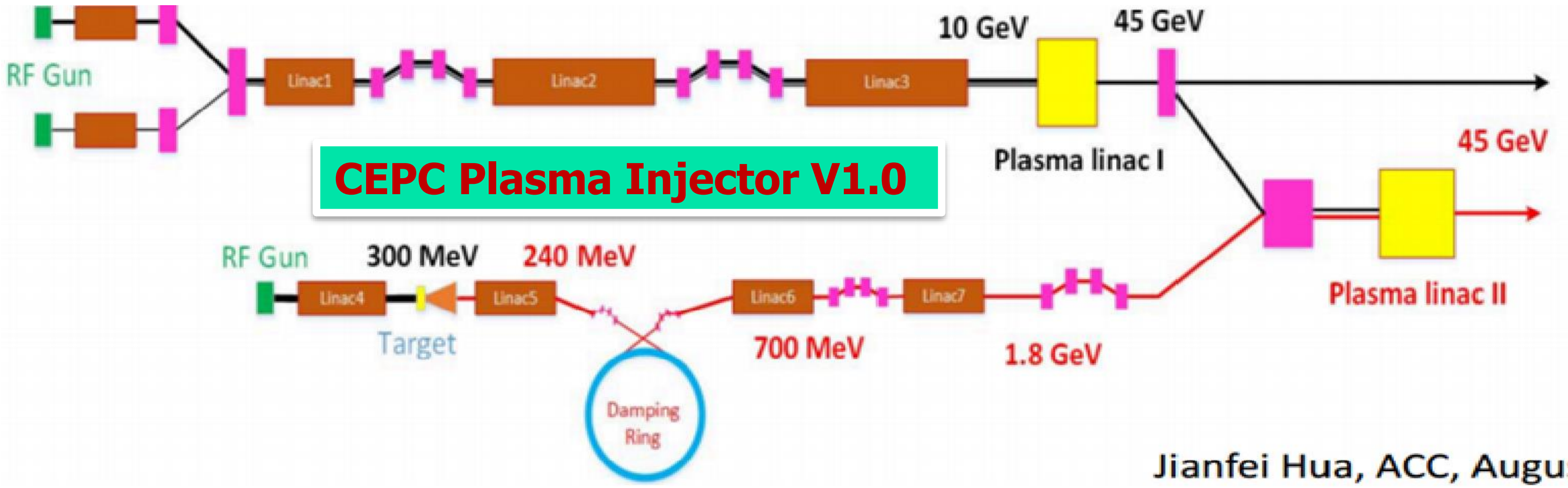
Plasma wave excitation

>10GeV/m acceleration

CEPC plasma injector & THU-IHEP AARG

IHEP-THU joint group on Advanced Accelerator Research

- Foundation：March 2017
- THU Member：Wei Lu, Jianfei Hua, Shiyu Zhou, Yue Ma, Shuang Liu, Bo Peng, ……
- IHEP Member：Jie Gao, Dazhang Li, Guan Shu, Cai Meng, Dou Wang, Jingru Zhang, Xiaoning Wang ……



Jianfei Hua, ACC, August 2018

Outline

- **Background: CEPC/CEPC plasma injector**
- **Preliminary Design v2**
- **Current status: Physics and experiments**
- **Outlook: Future experiments**

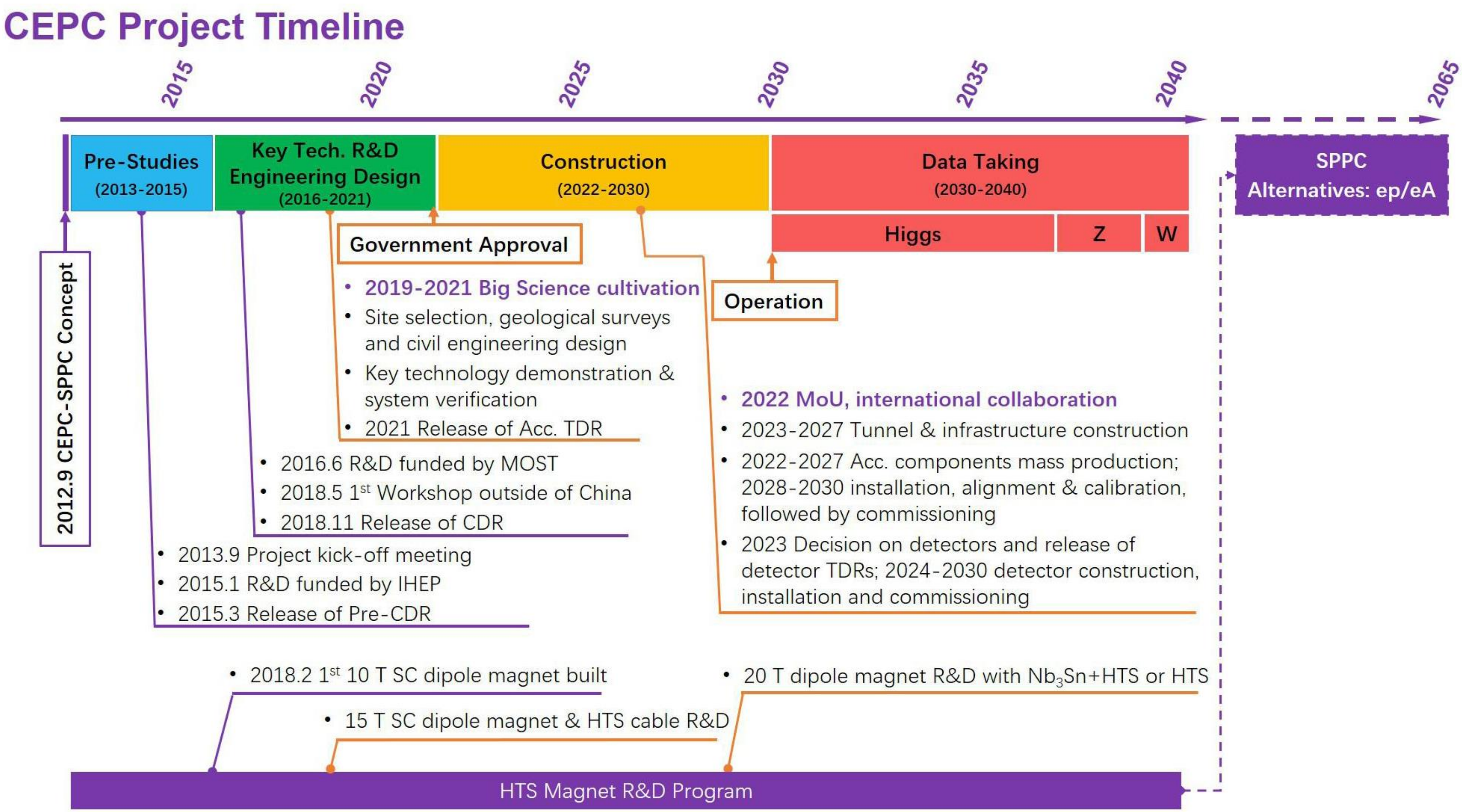
CEPC Plasma Injector/Overall Goal

- Working out a conclusion on the feasibility of plasma injector for 45GeV energy.
- If feasible, presenting a technology design with as much as possible details.
- Meantime, also working on the feasibility study of a full energy plasma injector at 120-180GeV

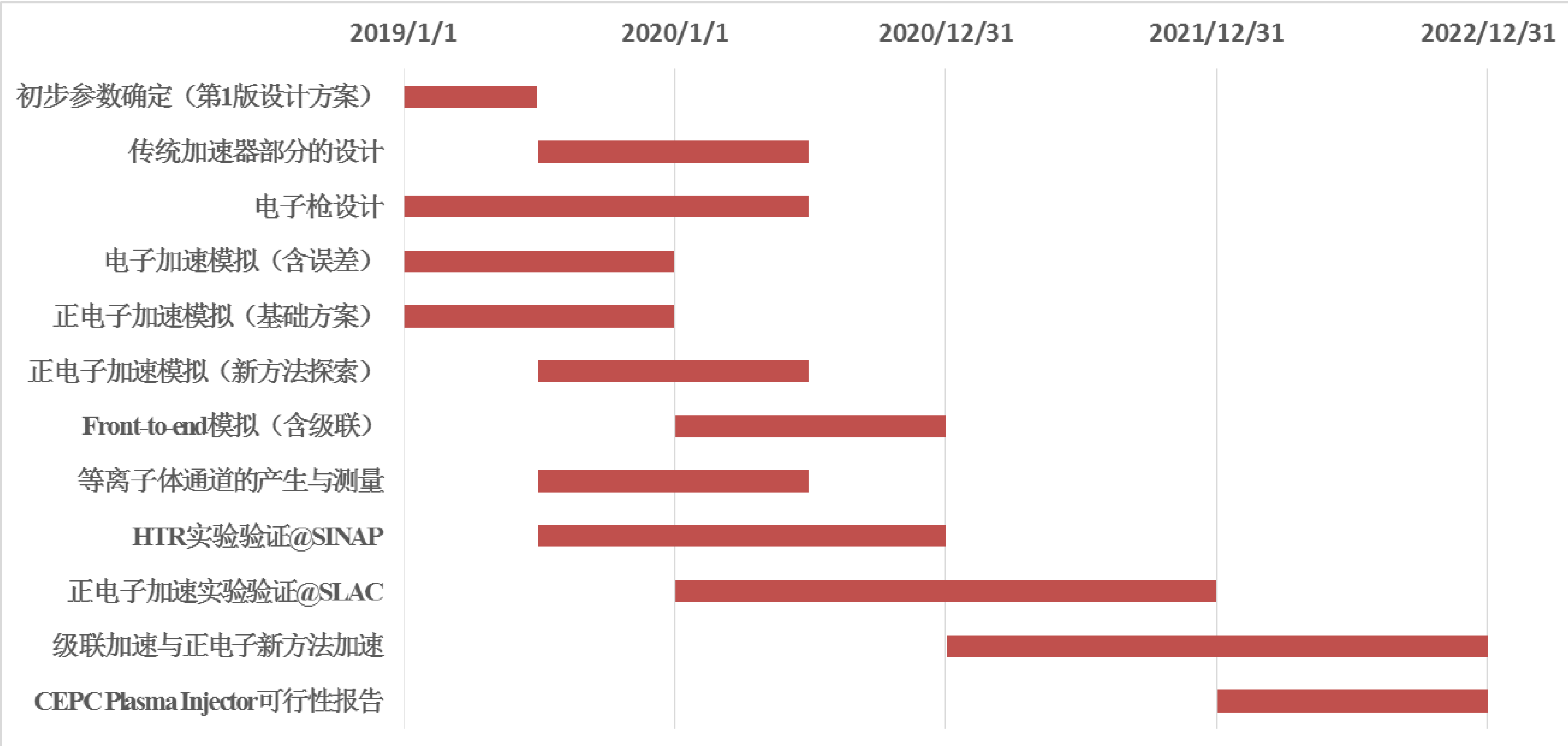
Key Issue to address：

- ✓ Driver/ Trailer design：large charge(10+ nC) shaped bunch generation
- ✓ Plasma source：meter-10meter scale uniform/hollow plasma source
- ✓ High transformer ratio high efficiency electron acceleration
- ✓ Stable high efficiency positron acceleration in electron beam driven PWFA
- ✓ Staging between different accelerators

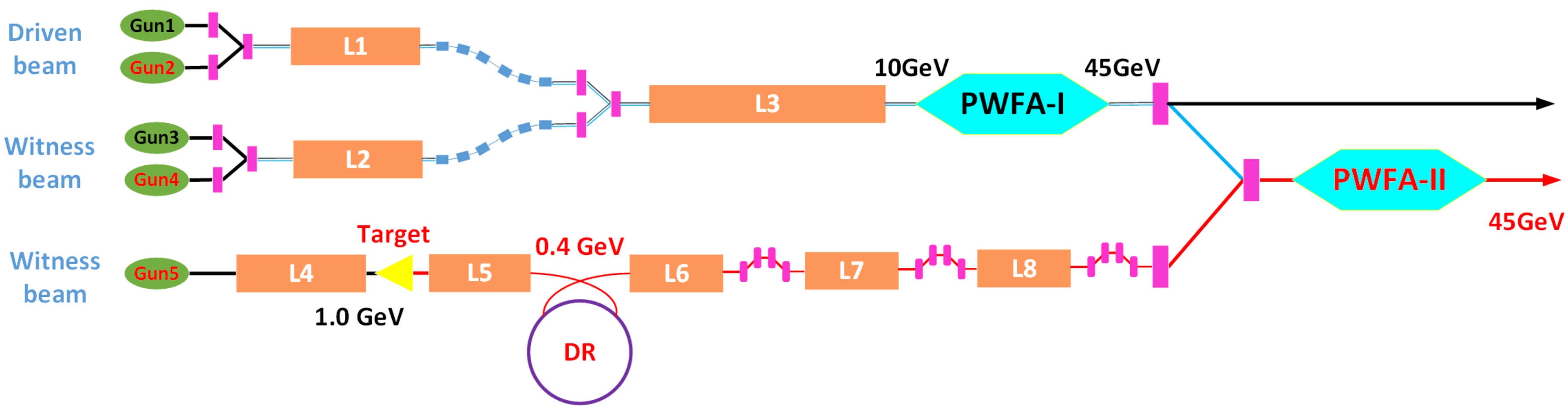
CEPC Project timelines



CEPC plasma injector timeline



CEPC plasma injector concept design （V2.0）



Parameter	Symbol	Unit	Requirement	Achieved(in sim.)
Energy	E_e	GeV	45.5	45.3(e-) / 45.2(+)
Energy Spread	σ_e		< 0.2%	0.2%(e-) / 0.14%(e+)
Frequency	f_{rep}	Hz	100	100
Bunch Charge	N_e	nC	> 1.0	1
Emittance	ε_r	nm·rad	< 30	1.89(e-) / 1.0(e+)
Bunch Length	σ_l	mm	< 3	0.3(e-) / 0.3(e+)
Energy Stability			< 0.2%	
Longitudinal Stability		mm	< 2	
Orbit Stability		mm	< 5(H) / 3(V)	

Outline

- **Background: CEPC/CEPC plasma injector**
- **Preliminary Design v2**
- **Current status: Physics and Technology**
- **Outlook: Future experiments**

Key Physics and Technology

- **Electron Acceleration**
  - High transformer Ratio， High efficiency, Stability
- **Positron Acceleration**
  - Stable acceleration (different schemes)， energy spread control, efficiency enhancement……
- **Conventional Accelerator design and optimization**
  - Photon-guns、Linac、Positron generation and damping ring……
- **Beam manipulations:**
  - dechirper， external injection， staging and cascading ……

I. Electron Acceleration

- **Goal：Stable High Transformer ratio Acceleration (3-4)**

- **To Do：**more realistic simulations，experimental demonstration，scaling verification

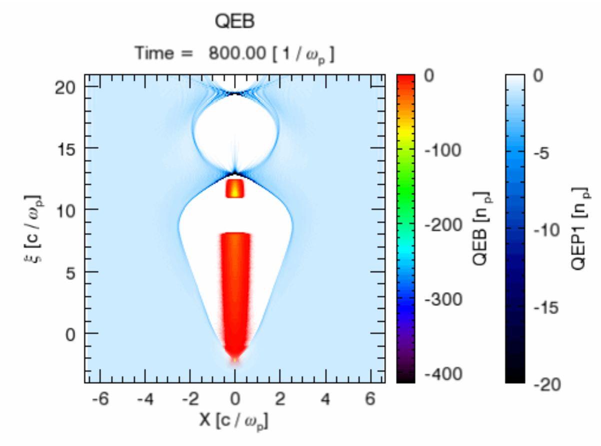
- **Tech：**
  - ✓ High fidelity 3D simulations with real parameters, tolerance analysis
  - ✓ Cross-checking between different codes, combining PIC with beam line dynamics simulations
  - ✓ Experimental verification on Tsinghua and SXFEL facilities, and scaling test
  - ✓ FACET-II high charge experimental test

- **How to Check：**
  1. Finishing front-to-end simulations, code cross-checking, tolerance analysis
  2. Preliminary experimental results from Tsinghua and SXFEL facilities
  3. Collaboration on FACET-II High energy High charge experiments

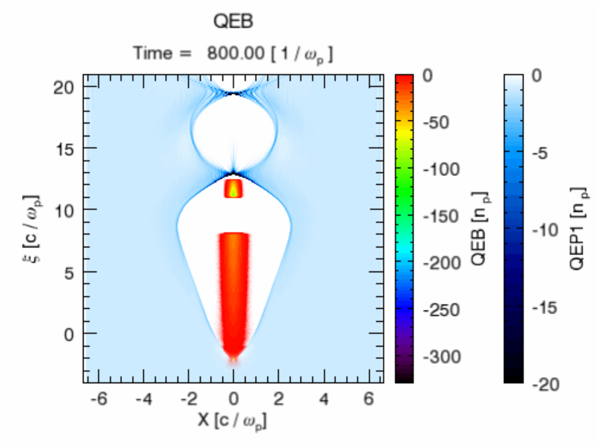
- **Expecting timeline：**1） 2021.12；2） 2021.12；3） 2022.12？

High TR Electron Acceleration:

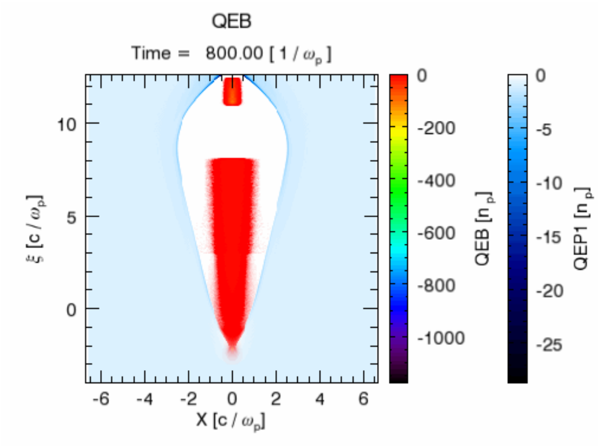
tolerance check



Without tilt, perfect injection



With 1μm tilt



With 1μm tilt, wide beam

Tolerance analysis for HTR e- acc.

<table>
<tr><th colspan="4">Perturbation No.</th><th>Error Source</th><th>Sensitivity</th></tr>
<tr><td>1</td><td rowspan="2">Beam energy</td><td colspan="2">Driver</td><td rowspan="10">the error of phase and amplitude of Linac accelerating structure, wakefield effect in Linac and orbit errors of Linac</td><td>E_t</td></tr>
<tr><td>2</td><td colspan="2">Trailer</td><td>E_t</td></tr>
<tr><td>3</td><td rowspan="2">Bunch charge</td><td colspan="2">Driver</td><td>E_t</td></tr>
<tr><td>4</td><td colspan="2">Trailer</td><td>E_t</td></tr>
<tr><td>5</td><td rowspan="2">Bunch length</td><td colspan="2">Driver</td><td>E_t & δ_{Et}</td></tr>
<tr><td>6</td><td colspan="2">Trailer</td><td>E_t</td></tr>
<tr><td>7</td><td rowspan="2">RMS spot size</td><td colspan="2">Driver</td><td>E_t</td></tr>
<tr><td>8</td><td colspan="2">Trailer</td><td>E_t</td></tr>
<tr><td>9</td><td colspan="3">Beam energy spread</td><td>E_t</td></tr>
<tr><td>10</td><td colspan="3">Beam distance</td><td>E_t</td></tr>
<tr><td>11</td><td colspan="3">Plasma density</td><td>plasma source</td><td>E_t</td></tr>
<tr><td>12</td><td rowspan="3">Offset</td><td colspan="2">Transverse position</td><td rowspan="5">the misalignment error of Linac elements and wakefield effect in Linac</td><td>Q_t & ϵ_{Nt}</td></tr>
<tr><td>13</td><td rowspan="2">Transverse velocity</td><td>Driver</td><td>E_t</td></tr>
<tr><td>14</td><td>Trailer</td><td>E_t</td></tr>
<tr><td>15</td><td rowspan="2">Tilt</td><td colspan="2">Driver</td><td>E_t</td></tr>
<tr><td>16</td><td colspan="2">Trailer</td><td>E_t & Q_t & ϵ_{Nt}</td></tr>
<tr><td>17</td><td rowspan="4">Slice jitter</td><td rowspan="2">Transverse position</td><td>Driver</td><td rowspan="4">transverse-longitudinal coupling in Linac</td><td>E_t</td></tr>
<tr><td>18</td><td>Trailer</td><td>E_t</td></tr>
<tr><td>19</td><td rowspan="2">Transverse velocity</td><td>Driver</td><td>E_t</td></tr>
<tr><td>20</td><td>Trailer</td><td>E_t</td></tr>
</table>

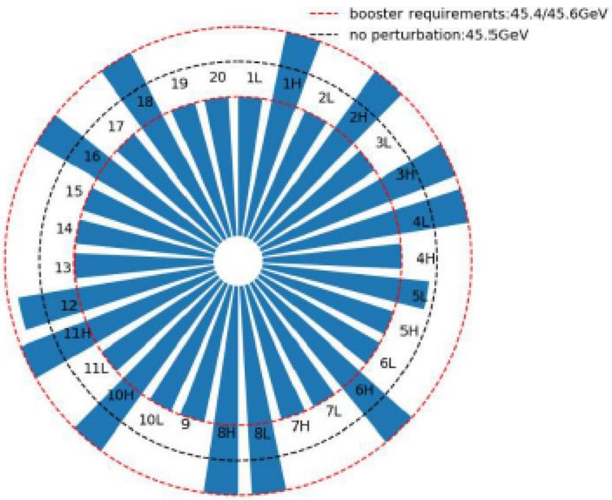
Error analysis for HTR e- acc.

Perturbation			Limitation	Linac output data
offset	Transverse position		±2.3um	——
	Transverse velocity	Driver	<0.05nrad	35nrad/68.8nrad
		Trailer	<10urad	
Tilt	Driver		±0.038urad	2.7urad
	Trailer		±180mrad	0.9mrad
Slice jitter	Transverse position	Driver	±0.025nm	1.4um
		Trailer	±3.7um	4.4um
	Transverse velocity	Driver	<0.1nrad	12nrad
		Trailer	<5urad	~0.1mrad
Beam distance			±0.16%	——
Plasma density			±0.26%	——

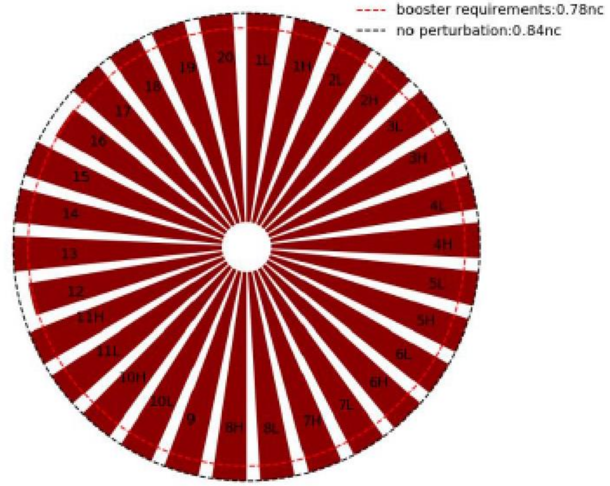
On going process

See Dr. Xiaoning Wang's talk

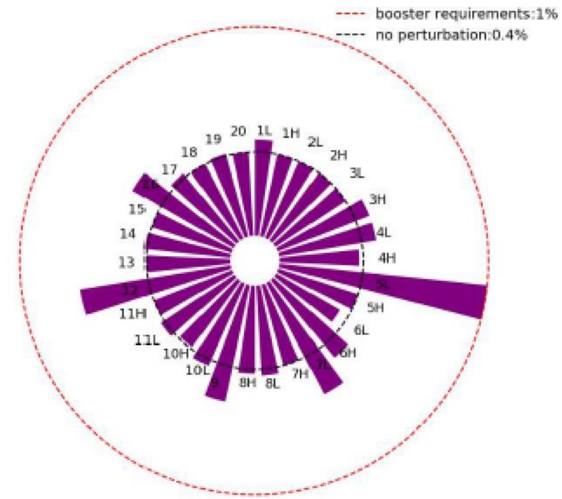
Error analysis for HTR e- acc.



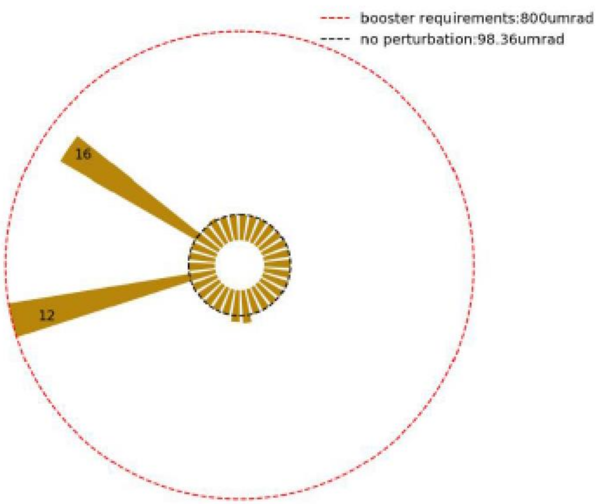
The sensitivity of trailer energy to perturbations



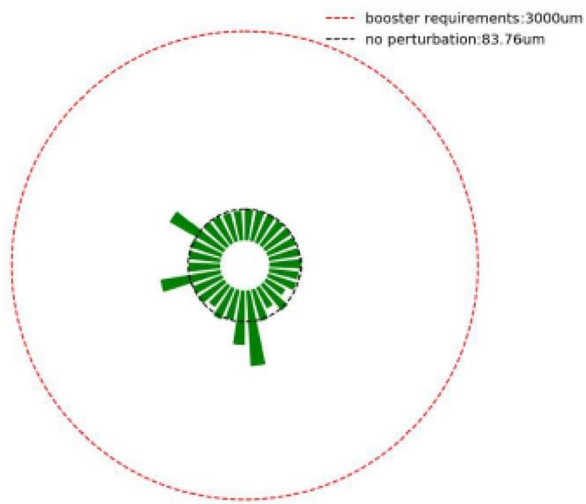
The sensitivity of trailer charge to perturbations



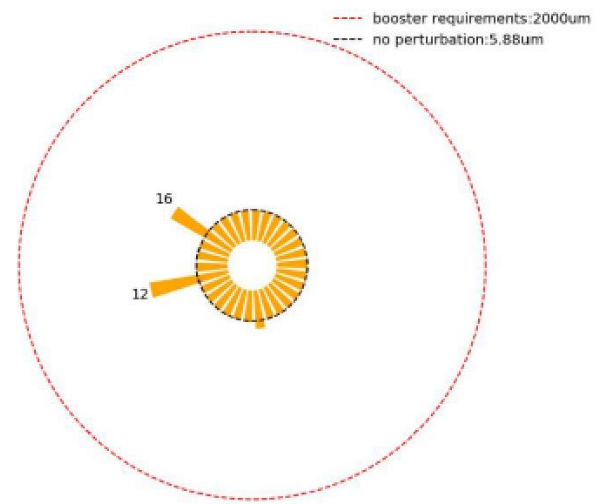
The sensitivity of trailer energy spread to perturbations



The sensitivity of trailer emittance to perturbations



The sensitivity of trailer length to perturbations



The sensitivity of trailer RMS spot size to perturbations

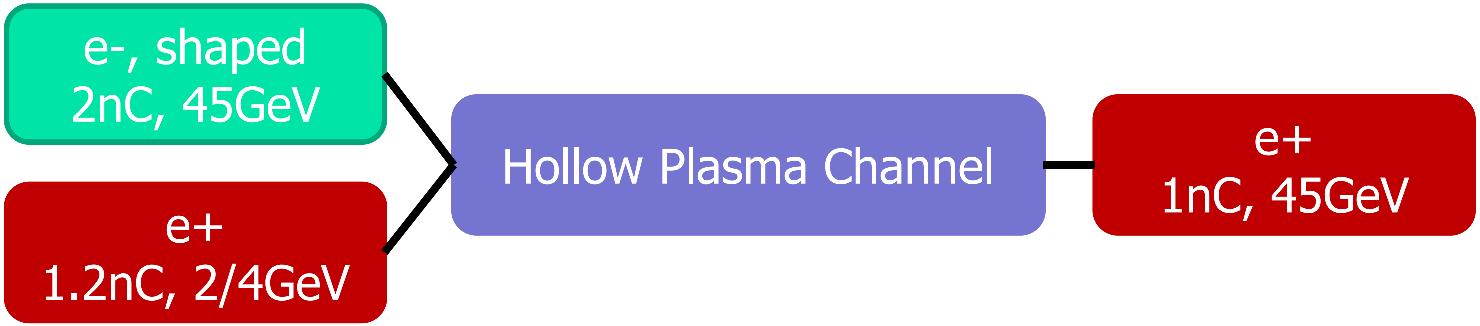
II. Positron Acceleration

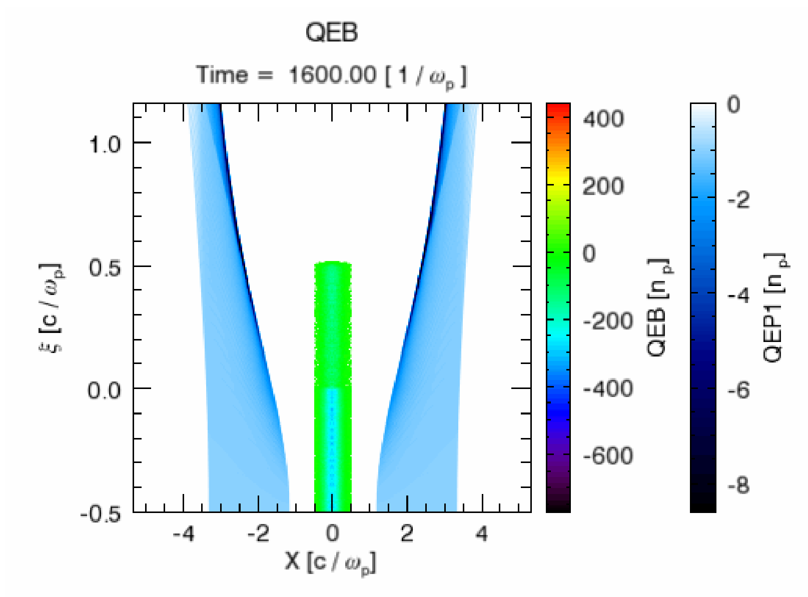
- **Goal：Stable high efficiency positron acceleration in an electron beam driven PWFA (with low energy spread)**

- **To Do：**check the feasibility of three (or more) possible schemes, stability and parameter tolerance
- **Tech：**
  - ✓ High fidelity 3D simulations with real parameters for three schemes, tolerance analysis
  - ✓ Explore new possible schemes
  - ✓ Experimental verification on Tsinghua and SXFEL facilities for stable possible acceleration modes
  - ✓ Collaboration on FACET-II positron experiments
- **How to Check：**
  1. Finishing front-to-end simulations, code cross-checking, tolerance analysis
  2. Preliminary experimental results from Tsinghua and SXFEL facilities
  3. Collaboration on FACET-II positron experiments

- **<u>Expecting timeline</u>**<u>：1） 2021.12；2） 2022.06；3） 2022.12？</u>

Positron Acceleration Scheme 1 (in CDR)





- High efficiency 60%
- Low energy spread ~0.5%
- Small emmitance growth
- Tight tolerance on injection parameters to control transverse instability （beam tilt or offset ~ 0.1μm）

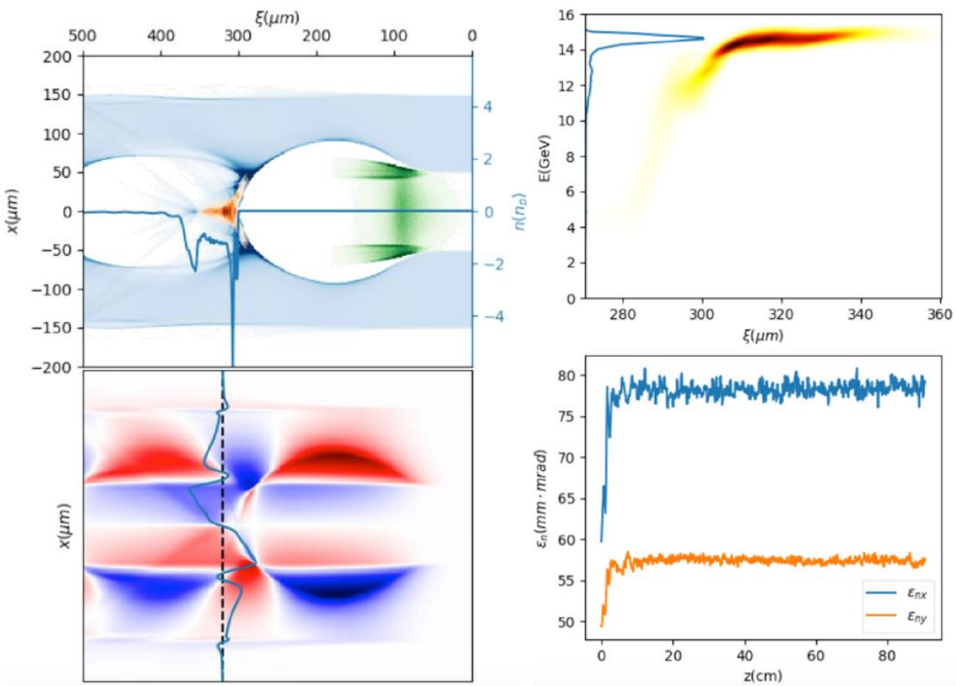
Positron Acceleration Scheme 2 (Stable mode)

e-, shaped & evolved
3-4nC, 45GeV

e+
1.2nC, 2/4GeV

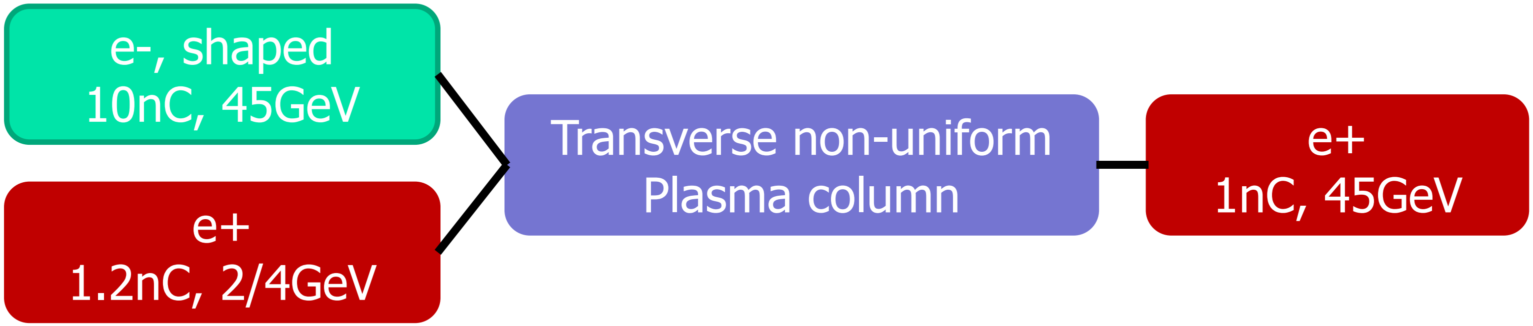
Hollow Plasma Channel

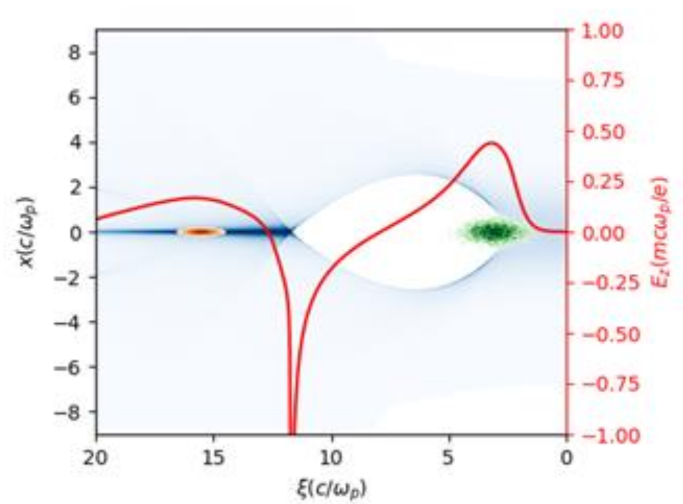
e+
1nC, 45GeV



- Energy efficiency ~ 40%
- Slice energy spread ~1%（to be optimized）
- Tolerable emittance growth
- High tolerance on beam tilt and offset
- debuncher + dechirper to reduce energy spread down to 0.2%

Positron Acceleration Scheme 3





- Relative low efficiency ~10% (to be optimized)
- Slice energy spread ~0.2%
- Tolerable emittance growth
- High tolerance on beam tilt and offset

■III. Accelerator design and optimization

- **Goal：Generation of 15nC (or more) 10GeV shaped bunches for driving HTR PWFA; Generation of positron beam with 1nC charge, 10mm mrad or less normalized emittance, short bunch (~100fs)**

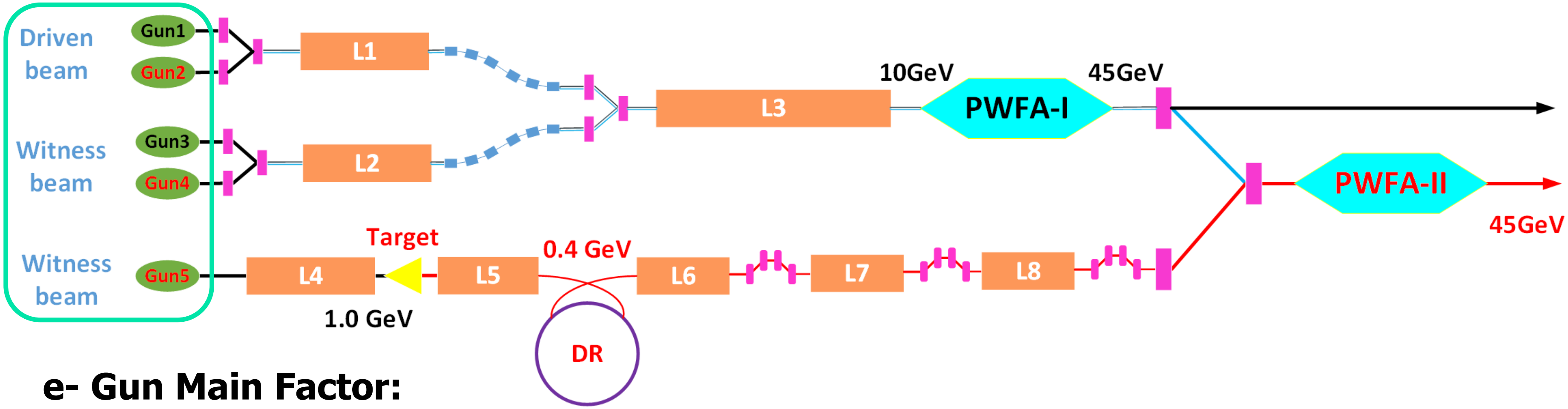
- **To Do：** to determine the beam and accelerator parameters, design of gun, Linac, and positron beam line

- **Tech：**
  - ✓ Detailed beam line simulations with tolerance check
  - ✓ Iteration loop: Booster→plasma injector→Linac→gun
  - ✓ Collaboration with FACET-II design

- **How to Check：**
  1. Giving detailed design of gun, Linac and positron beam line with tolerance check.

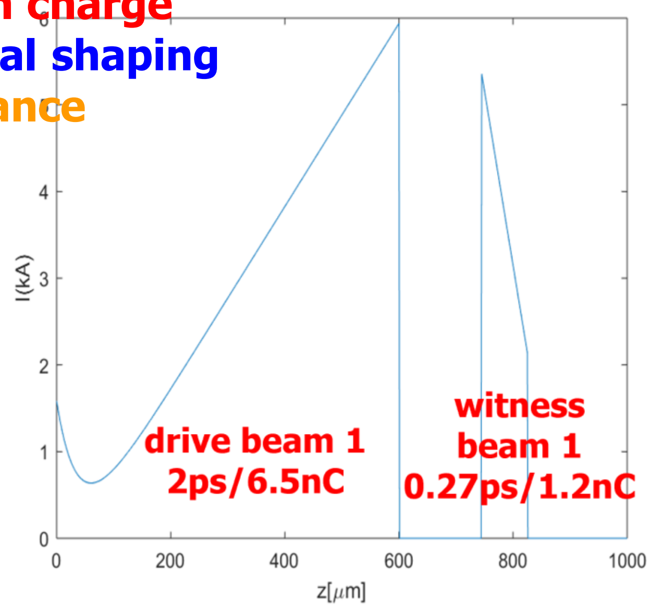
- **Expecting timeline：** 1） 2019.12 (V1) ；2） 2021.12 (V2, final)

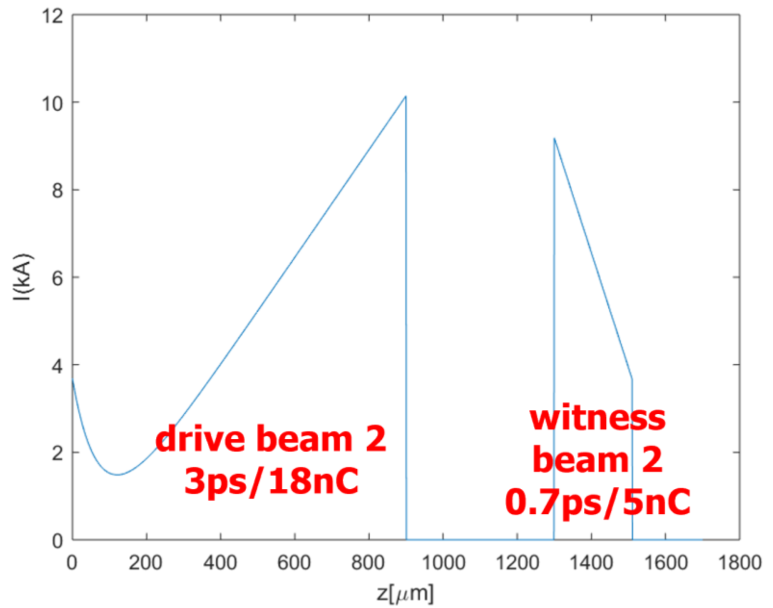
CEPC Plasma Injector beam requirements



e- Gun Main Factor:

- **High bunch charge**
- **Longitudinal shaping**
- **Low emittance**





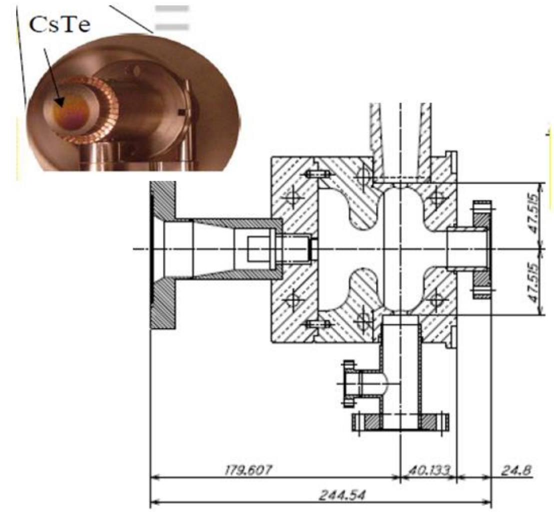
Large Charge Photon gun —KEKB, S-band

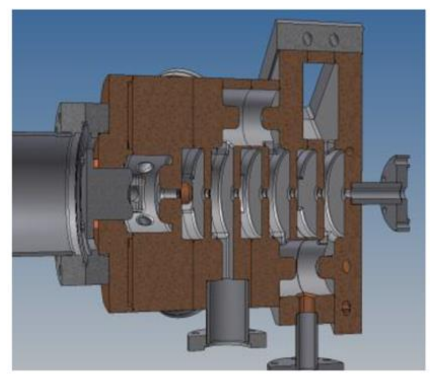
S band RF gun (highest bunch charge to my knowledge)

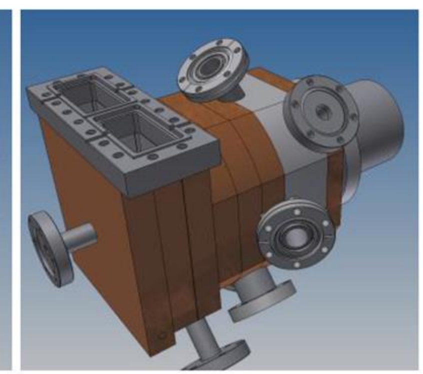
- Installed at KEK ATF facility for the X-rays based inverse Compton scattering*
  - S band (2856MHz), 1.6 cell
  - **5 nC** / 15 mm mrad
  - Cs_2Te (QE>3%)
  - Laser width (FWHM) 10 ps
  - Ecathode=140 MV/m, 6 MeV @ 15 MW
- SuperKEKB RF gun**
  - S band side coupled structure, 7 cells
  - **5 nC** / 5.5 mm mrad (simulation)
  - Ir5Ce (QE ~ $2*10^{-4}$)
  - strong focusing field at cathode
  - Ecathode ~100 MV/m, ~13 MeV @ 20 MW

transverse focusing

6MeV 1.6 cell gun





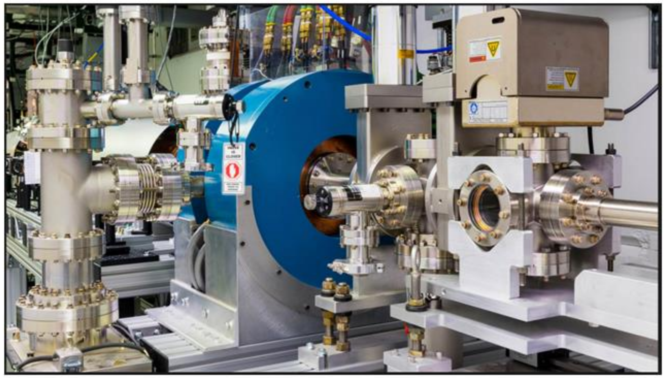


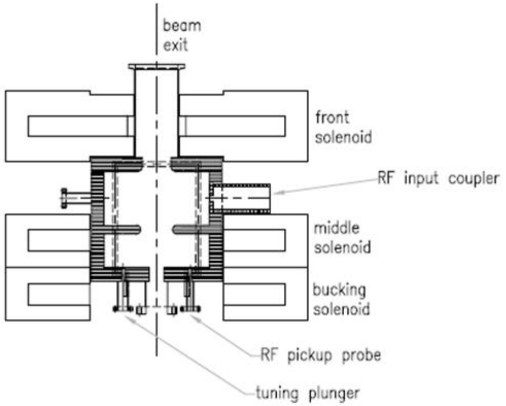
*Hirano. K et al., *Proc. of 9th EPAC*, 2004.
***T. Natsui et al., proceedings of IPAC 2013, TUOCB103*

Large Charge Photon gun:Argonne, L-band (√)

L band RF gun

- Installed in Argonne wakefield accelerator facility*
  - Wakefield acceleration application, high peak current, short beam length (2~5 ps)
  - Drive gun
    - L band 1.5cell RF photocathode gun (1.3 GHz)
    - Single bunch operation 10 pC~100 nC (**world record**)
    - Bunch train operation, 1~32 bunches/s, with up to 600 nC/s
    - Cs2Te photocathode, diameter > 30 mm (QE~3%)
    - **Ecathode > 80 MV/m** (14 MW, 8 MeV)
  - Witness gun
    - Mg photocathode
    - 10 pC to 10 nC
  - 20~100 nC, BSA=20 mm, logitudinal Gaussian laser, rms pulse length 2~5 ps (w/o bunch compressor), normalized rms emittance 30~108 mm mrad



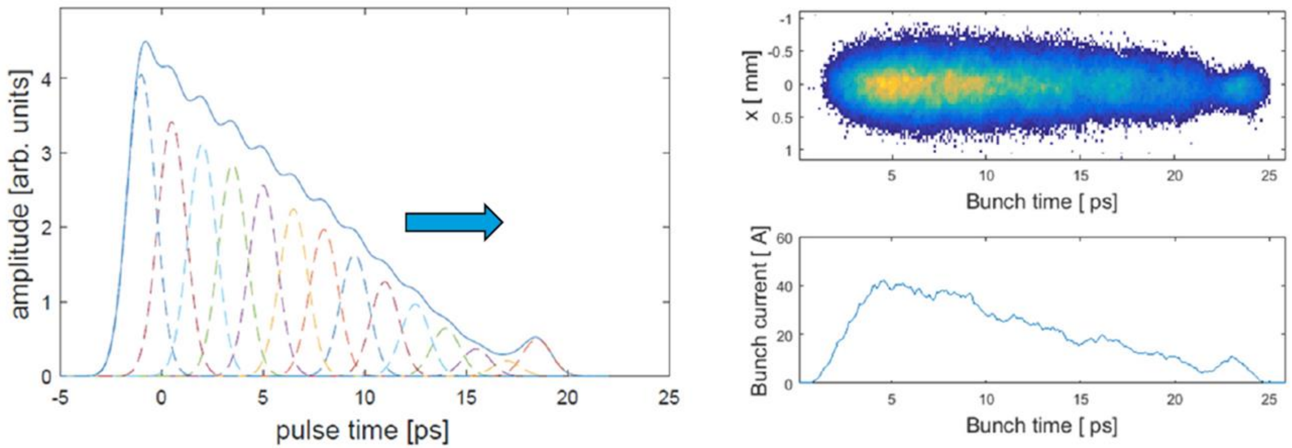


*Wei. G et al., *NIM A* 410.3 (1998). pp. 431-436.

Shaped bunch —Laser Shaping （√）

- Laser shaping on photocathode + beam line optics
  - Shaping by adding Gaussian quasi-pulses
    - Gaussian pulse relative delay is given by crystal thickness, relative amplitude can be varied by adjusting crystal angle
  - Powerful but complicated tuning
  - High bunch charge (~18 nC) means **strong space charge effect** → difficulty in longitudinal shaping preservation

Laser pulse simulation ***Bunch measurement***

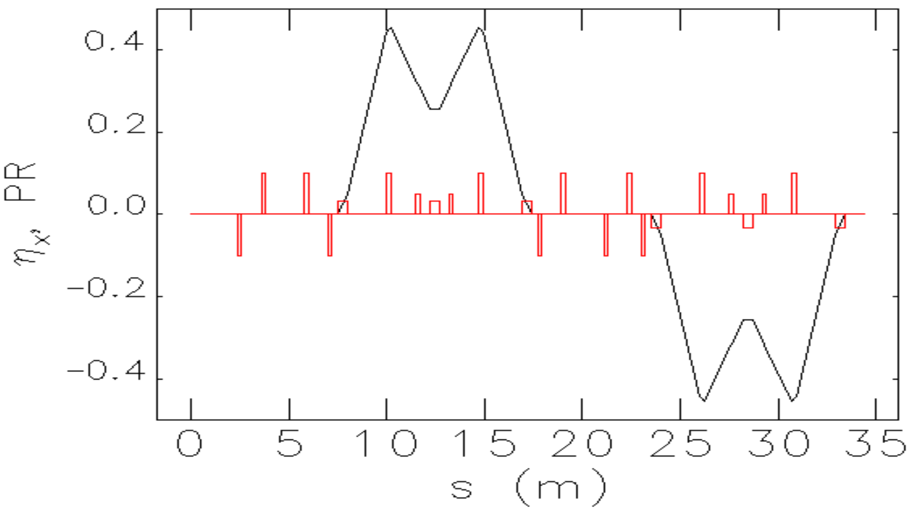


DESY PITZ laser shaping experiment (**500pC**)*

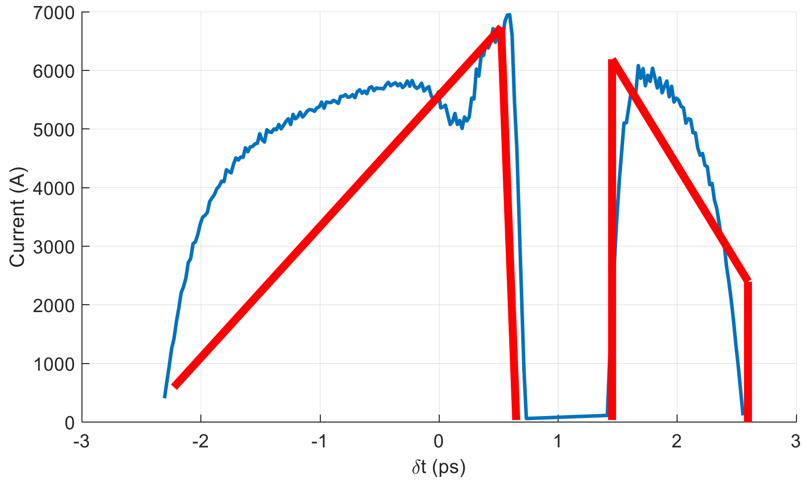
*G. Loisch *et al.*, *NIM A* **909**, pp. 107-110 (2018)

e- Gun requirement and preliminary design

Linac	Gun	Gun type	Bunch	Bunch charge (nC)	Bunch length (ps)		
					Requirement	RF Gun	Compression ratio
Electron	Gun1	L-band	Drive	6.5	2	30	~15
	Gun3	L-band	Witness	1.2	0.27	8	~30
Positron	Gun2	L-band	Drive	18	3	33	~11
	Gun4	L-band	Witness	5	0.7	13.5	~20

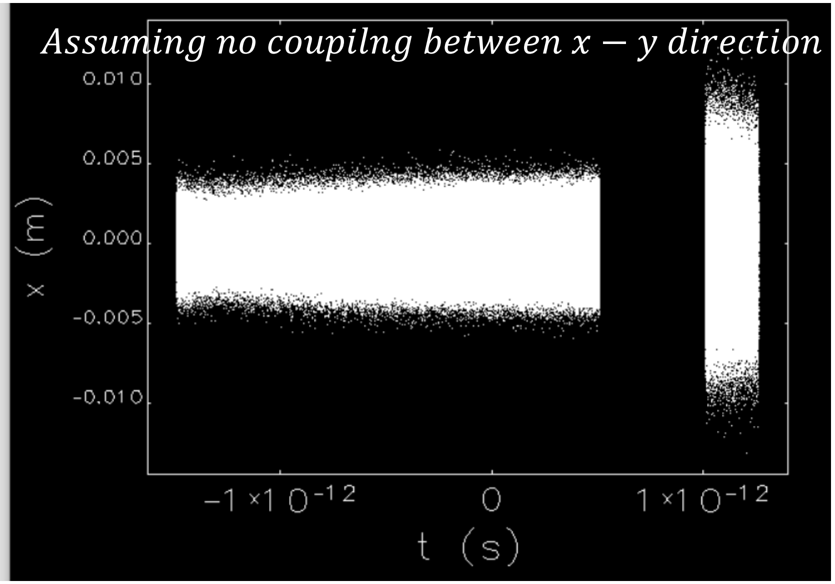


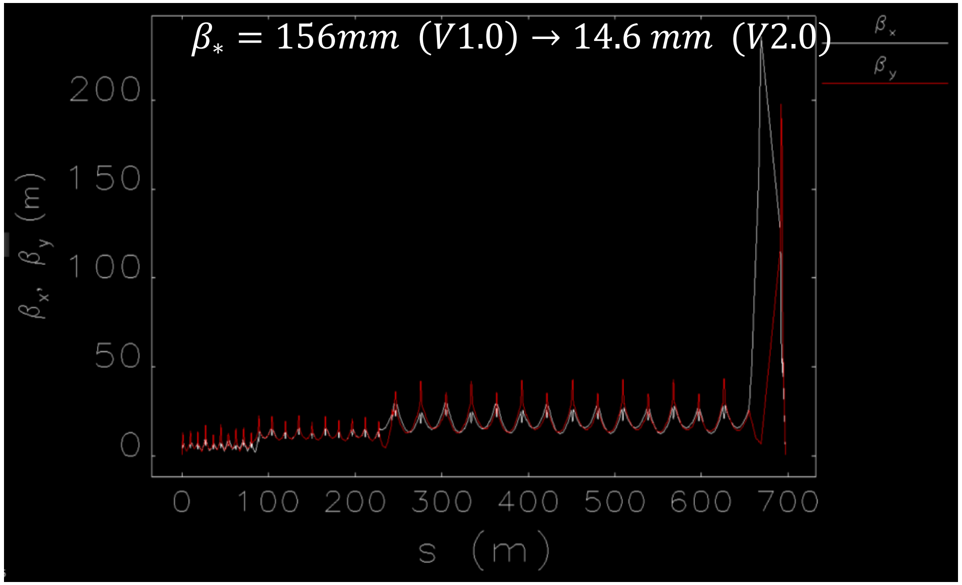
Bunch compressor lattice before main linac

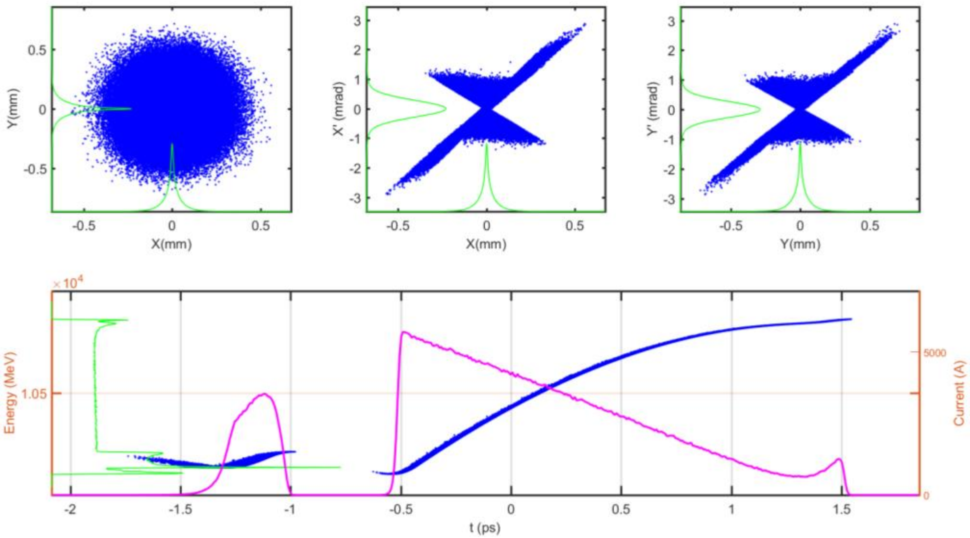


Required (red) and simulated (blue) beam profile

Linac optimization for ideal beams







L-band photocathode rf gun under design.

Finished the preliminary linac design and the end-to-end simulation (e- gun → FFS). Beam distribution improved but can not meet the requirements yet.

NEED MORE OPTIMIZATIONS

Optimized by Dr. Cai Meng (2020)

Preliminary design for e+ damping ring

	DR V2.0	current
Energy (MeV)	400	400
Circumference （m）	20	29.62
Bunch number	2	2
Bending radius (m)	1.5	1.375
B0 (T)	0.89	0.97
U0 (keV/turn)	5.0	1.65
Damping time x/y/z (ms)	10.7/10.7/5.3	47.7/48.0/24.1
δ0 (%)	0.05	
ε0 (mm.mrad)	5	
Nature σz (mm)	4.4	
Extract σz (mm)	4.4	
εinj (mm.mrad)	2400	
εext x/y (mm.mrad)	62/57	
δinj /δext (%)	0.6 /0.05	
Storage time (ms)	20	

Wiggler parameters	
Dipole strength (T)	4.8
Magnetic period (m)	0.2
Total length (m)	1.5
average βx (m)	1.3

RF parameters	
RF frequency (MHz)	500
RF voltage (MV)	1.5
Energy acceptance by RF(%)	2.1
harmonic	33

Conceptual design was finished, further lattice optimization is ongoing. Error study and correction are needed. Impedance and stability study are also required.

IV. Beam Manipulations

- **Goal：Carry out dechirper，hollow plasma channel generation，external injection experiments on Tsinghua and SXFEL facilities, verify their feasibilities**

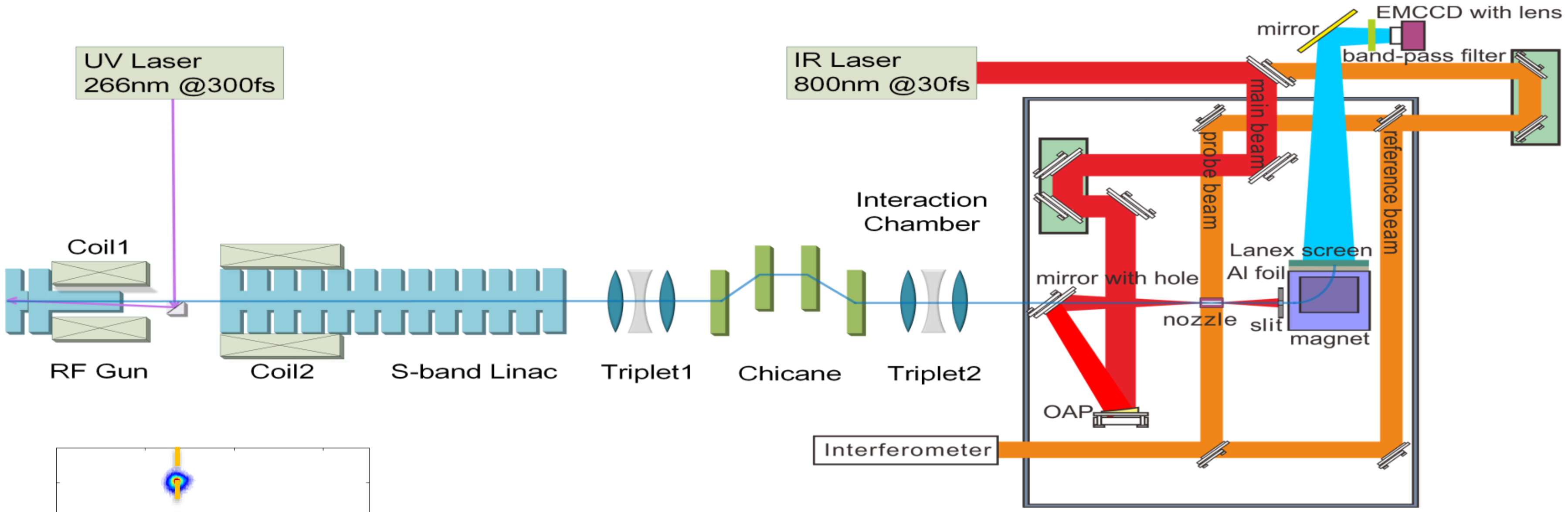
- **To Do：** Prepare and perform systematic experiments on dechirper, hollow plasma channel, and external injection to verify their feasibilities for plasma injector
- **Tech：**
  - ✓ Plasma dechirper experiments with uniform and hollow channel plasma
  - ✓ External injection from Linac to wakefield accelerator
- **How to Check：**
  1. Generating long uniform hollow plasma channel
  2. performing dechirper experiments to reach 0.1% level energy spread
  3. External injection experiments to show the feasibility of high efficiency high quality staging

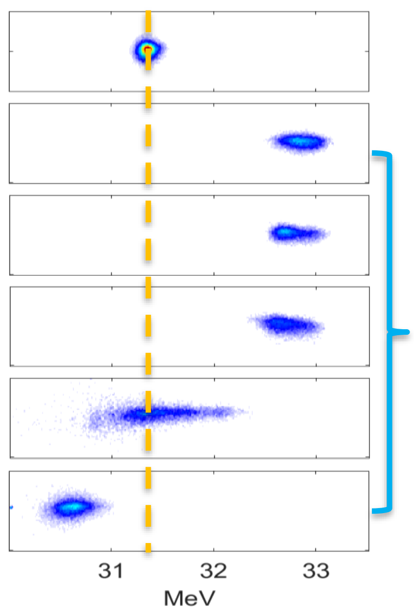
- **Expecting timeline：** 1） 2020.6；2） 2020.12; 3) 2021.12

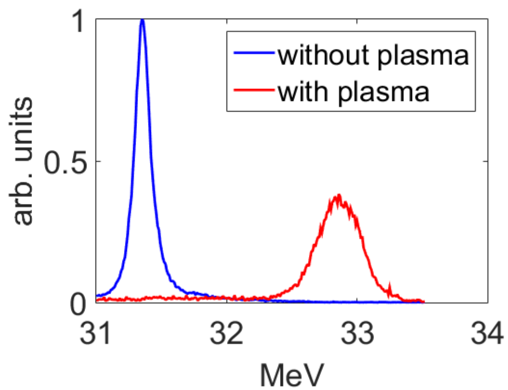
Outline

- **Background: CEPC/CEPC plasma injector**
- **Preliminary Design v2**
- **Current status: Physics and Technology**
- **Outlook: Future experiments**

Current External Injection Experiment



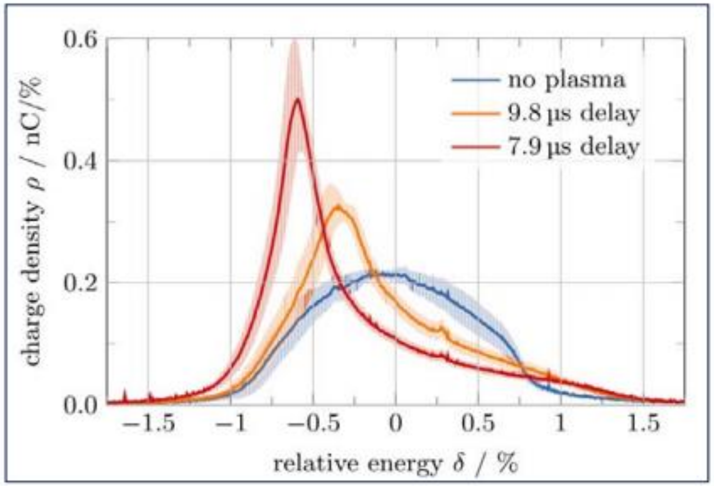


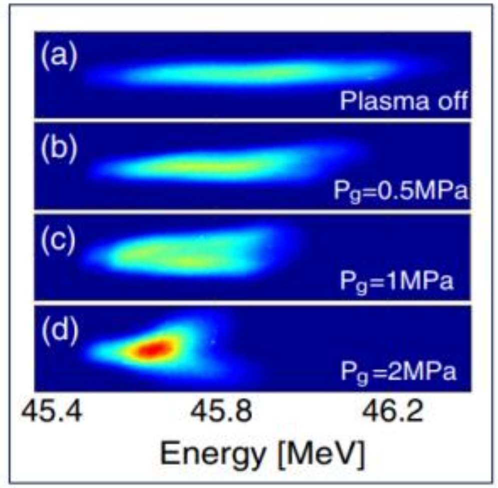


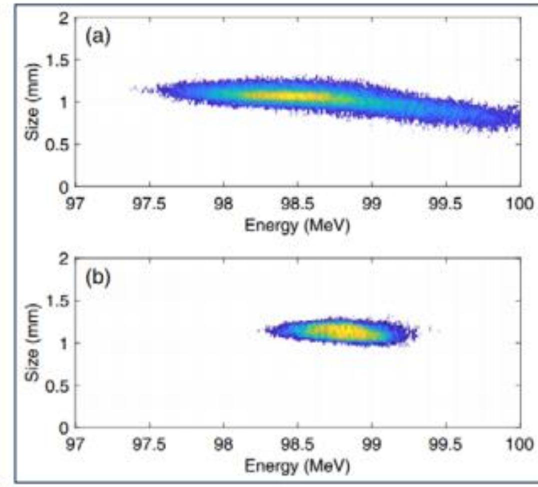
external injection with ~100% capture efficiency

AAC 2018, Plenary

Current Plasma dechirper @ THU lab







PHYSICAL REVIEW LETTERS **122,** 204804 (2019)

Phase Space Dynamics of a Plasma Wakefield Dechirper for Energy Spread Reduction

Y. P. Wu,[1] J. F. Hua,[1,*] Z. Zhou,[1] J. Zhang,[1] S. Liu,[1] B. Peng,[1] Y. Fang,[1] Z. Nie,[1] X. N. Ning,[1] C.-H. Pai,[1] Y. C. Du,[1] W. Lu,[1,†] C. J. Zhang,[2] W. B. Mori,[2] and C. Joshi[2]
[1]*Department of Engineering Physics, Tsinghua University, Beijing 100084, China*
[2]*University of Los Angeles, Los Angeles, California 90095, USA*

(Received 20 January 2019; revised manuscript received 19 April 2019; published 24 May 2019)

Plasma-based accelerators have made impressive progress in recent years. However, the beam energy spread obtained in these accelerators is still at the ~1% level, nearly one order of magnitude larger than what is needed for challenging applications like coherent light sources or colliders. In plasma accelerators, the beam energy spread is mainly dominated by its energy chirp (longitudinally correlated energy spread). Here we demonstrate that when an initially chirped electron beam from a linac with a proper current profile is sent through a low-density plasma structure, the self-wake of the beam can significantly reduce its energy chirp and the overall energy spread. The resolution-limited energy spectrum measurements show at least a threefold reduction of the beam energy spread from 1.28% to 0.41% FWHM with a dechirping strength of ~1 (MV/m)/(mm pC). Refined time-resolved phase space measurements, combined with high-fidelity three-dimensional particle-in-cell simulations, further indicate the real energy spread after the dechirper is only about 0.13% (FWHM), a factor of 10 reduction of the initial energy spread.

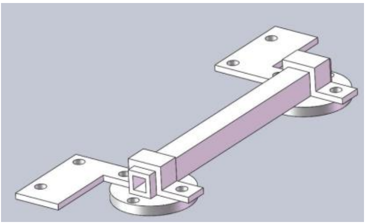
DOI: 10.1103/PhysRevLett.122.204804

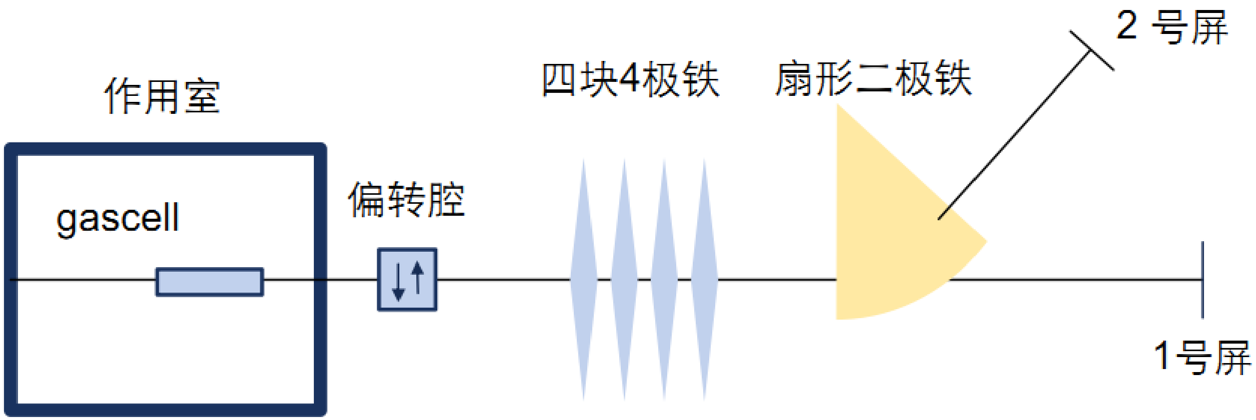
Energy spread reduction down to 0.2% level

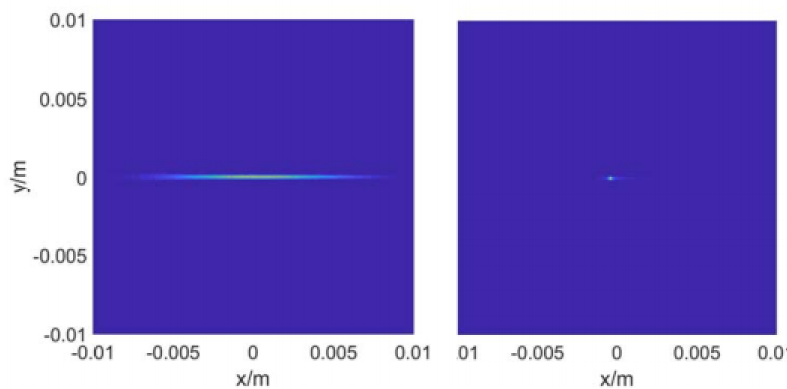
AAC 2018, Plenary

- The experimental resolution on energy spread is limited, refined experiments is planned
- The effects on emmittance and slice energy spread needs to be quantified
- Hollow channel dechriper seems to be a better solution

2nd round plasma dechirper experiment







经过hollow channel plasma dechirper 前后的束斑

以前的布局:

ΔE~0.17MeV

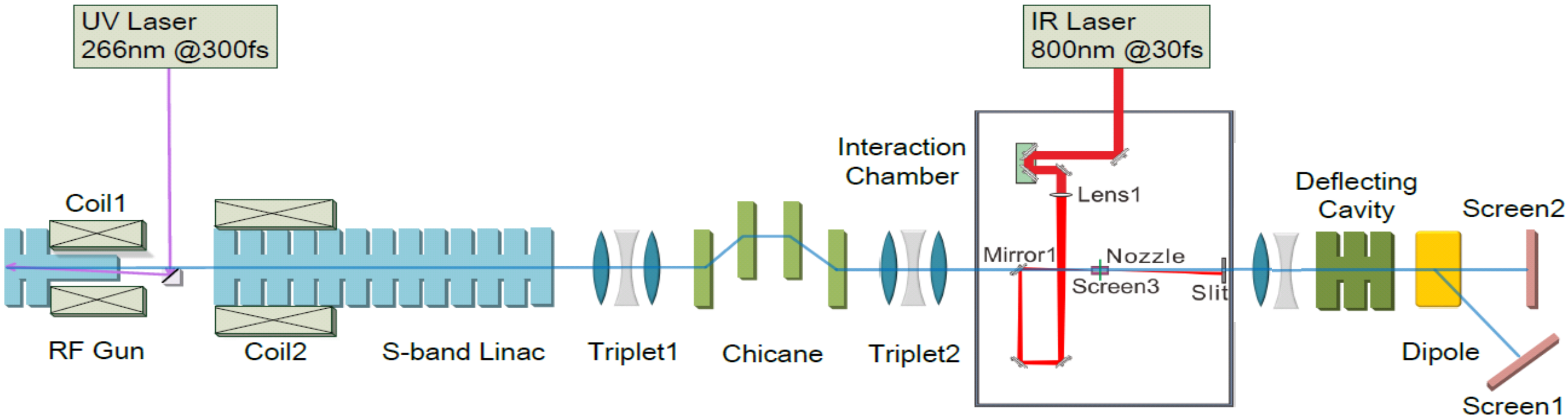
能谱仪屏幕上的光斑尺寸: ~mm

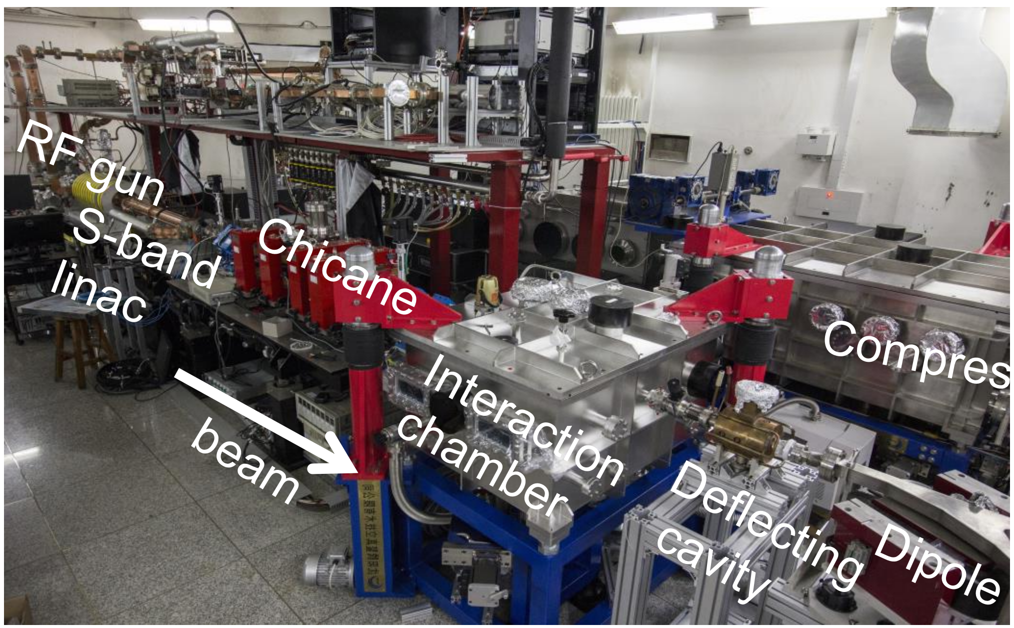
升级后的布局:

ΔE~0.01MeV

束斑尺寸 < 100μm

Hollow Channel experiment preparation at THU Lab





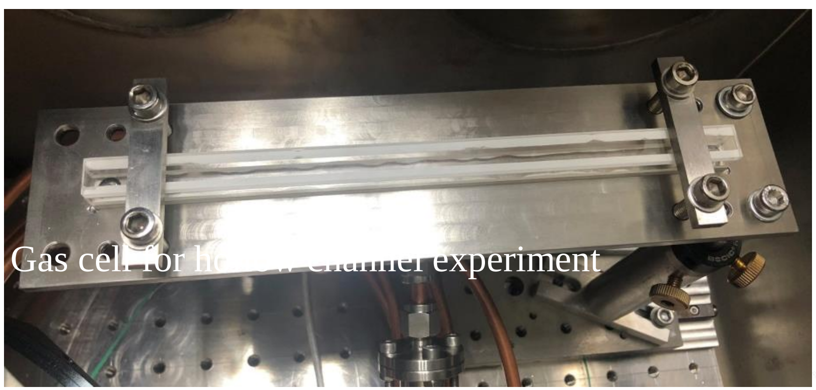
Estimated Start Time: 2019.12

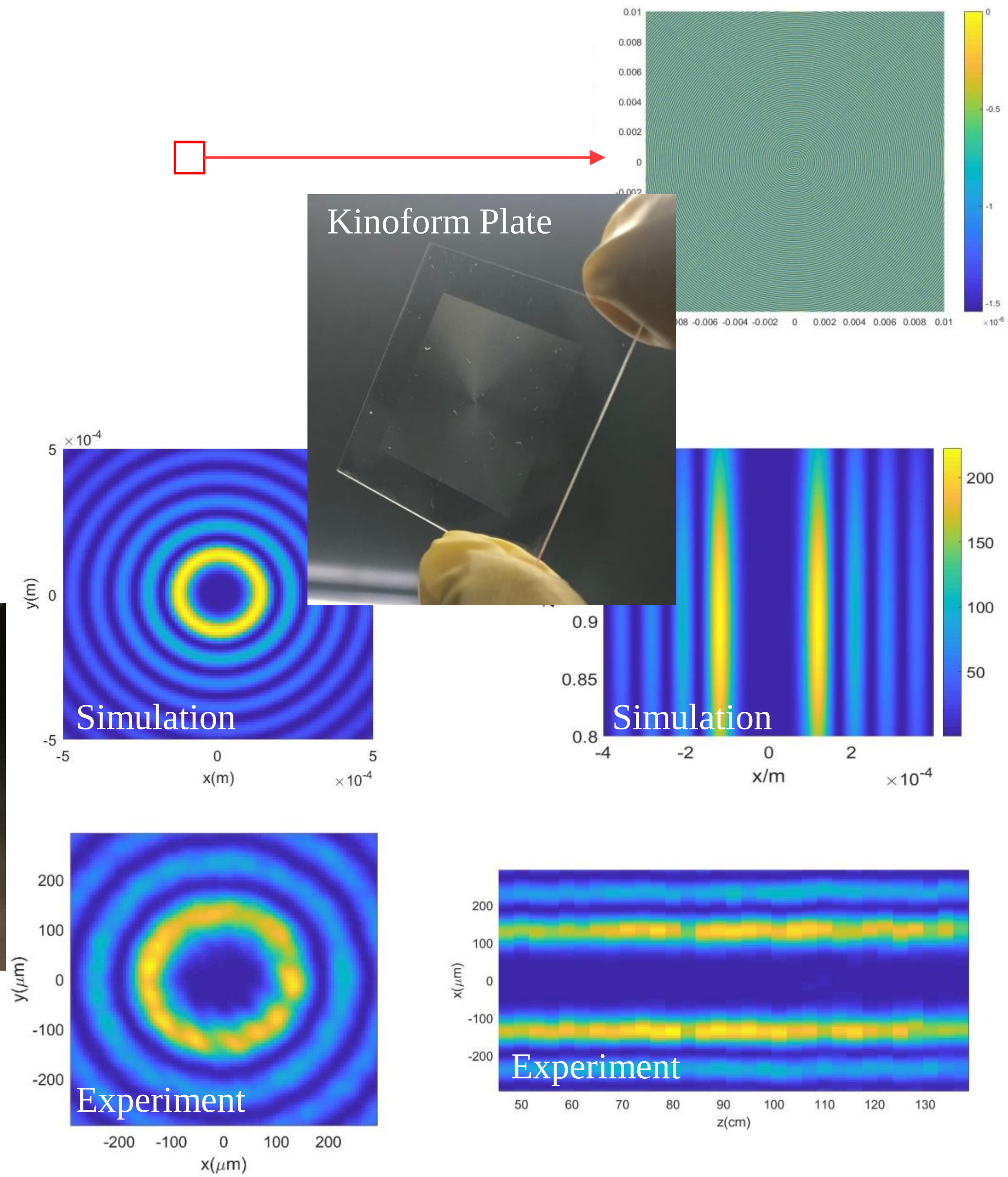
- Diagnostic system upgrade(1~2 weeks)
  - Assembling quadrupoles (1 week)
  - Online test (1 week)
- Offline test (4 weeks)
  - Optical layout (1 week)
  - Bessel beam profile measurement(1week)
  - Plasma density measurement(2 week)
- Dechirper experiment (8 weeks)
  - Optical layout (2 week)
  - Debugging (3 weeks)
  - Accessing data (3 weeks)

Hollow Channel experiment preparation at THU Lab

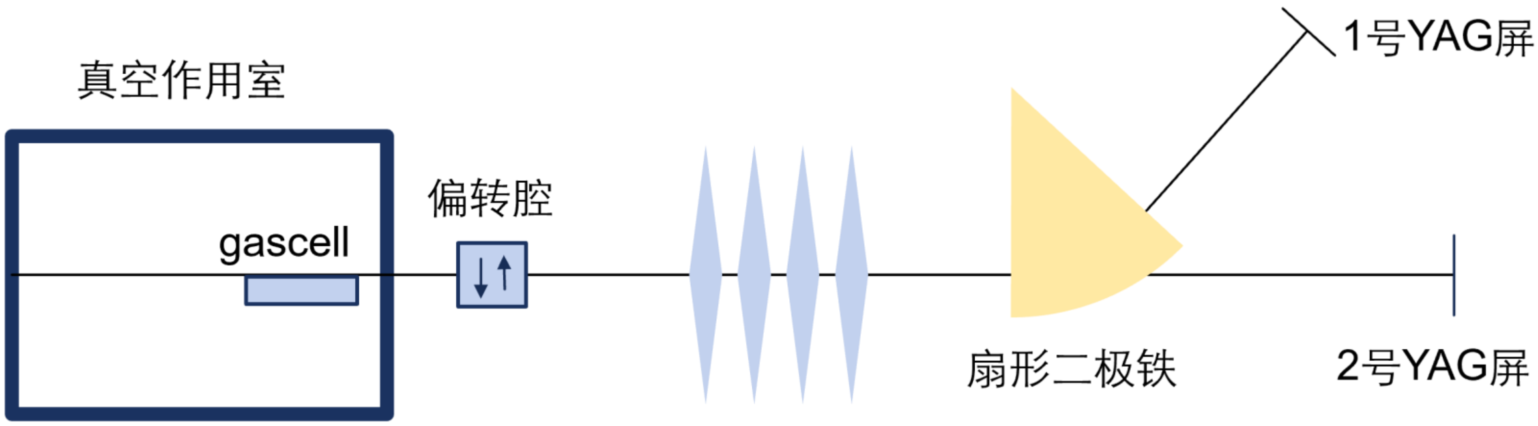
清华实验平台束流参数:

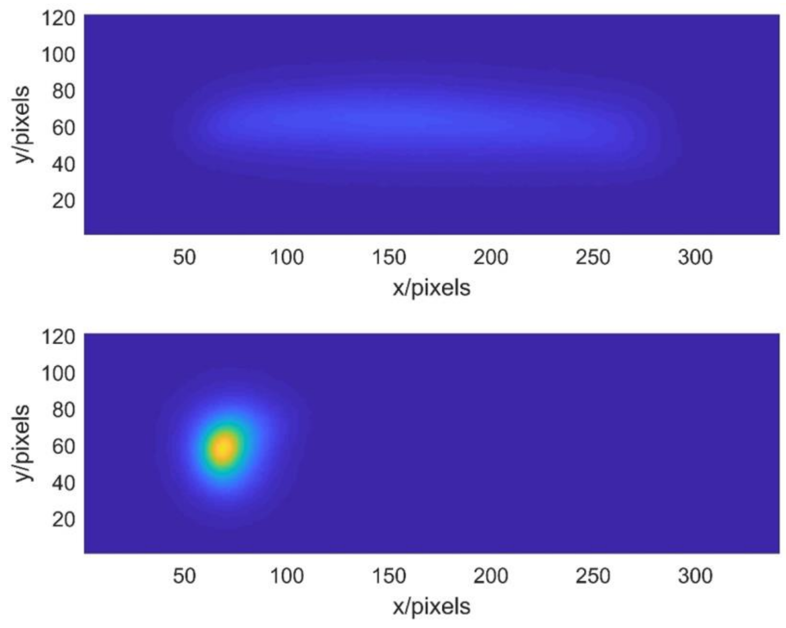
横向尺寸	σr=40um
纵向分布	parabolic
切片能散	0.01MeV
束长	~1.6ps(FWHM)
电荷量	100pC
归一化发射度	2mm*mrad
能量	46MeV
能散	~0.9MeV (2%)
等离子体密度	2.5e14 cm-3
Hollow channel长度	20cm

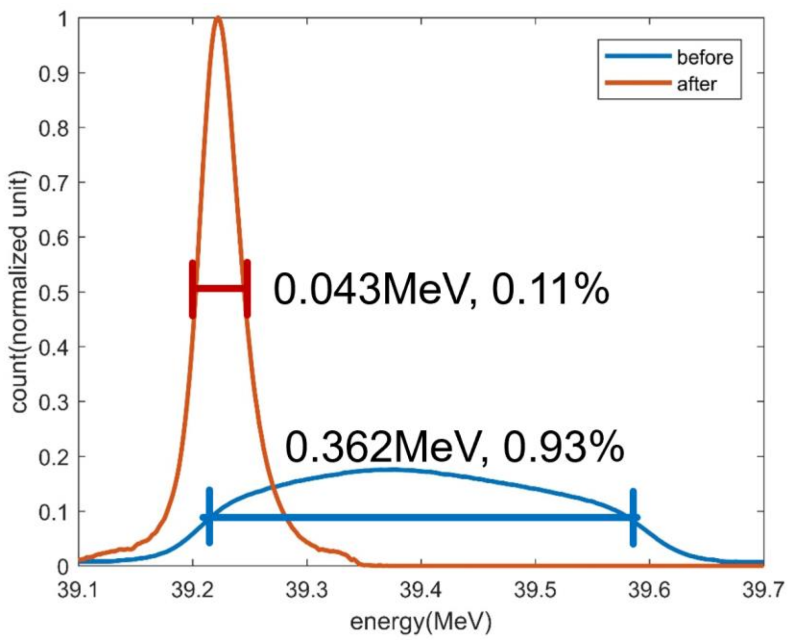




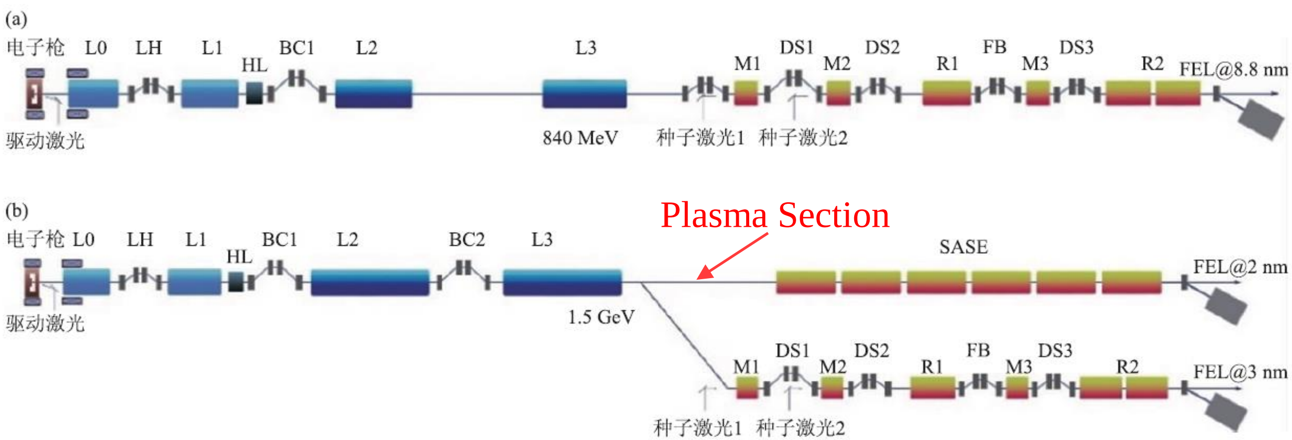
Energy spread measure: ~1%→~0.1%

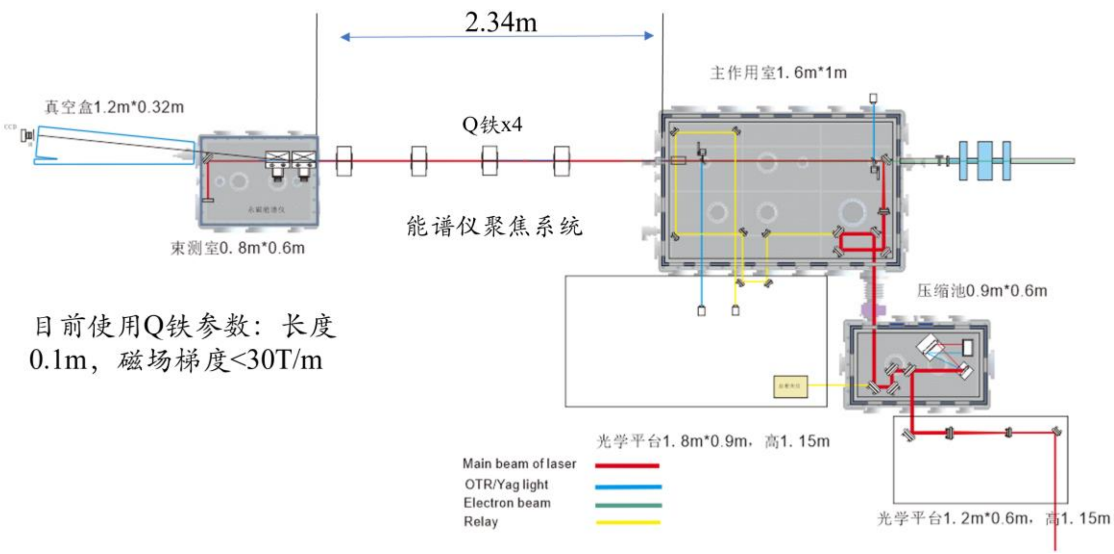






Plasma dechirper & HTR experiment Preparation@ SXFEL



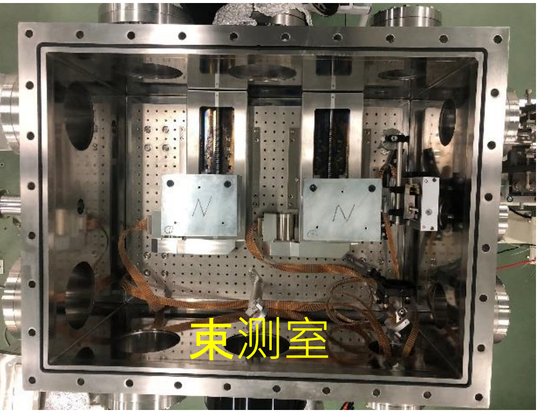


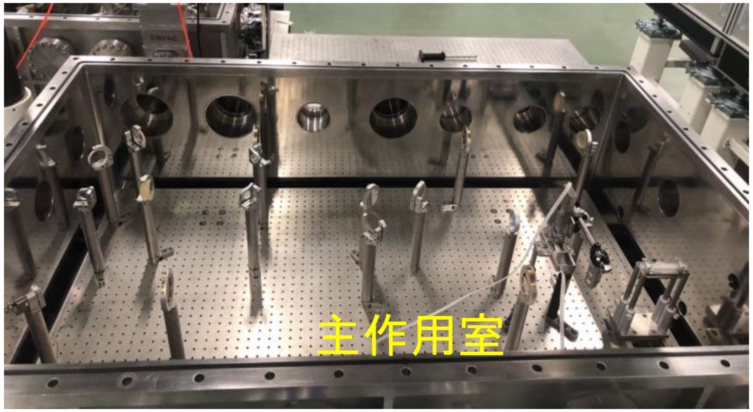
Parameter	Value
Energy	0.8GeV
Charge	50pC
Emittance	0.8μm
Beam size	10μm
Peak current	2.4kA
Energy Chirp	~8MeV

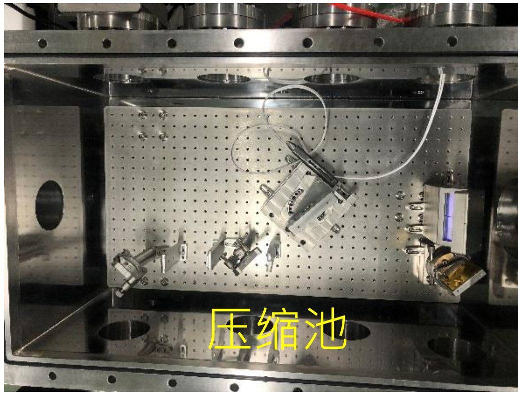
Dechirper experiment schedule

- First step: Obtaining a stable positively-chirped beam with few percent energy spread
- Second step: Post-processing the beam using a passive dechirper

Experiment preparation @ SXFEL





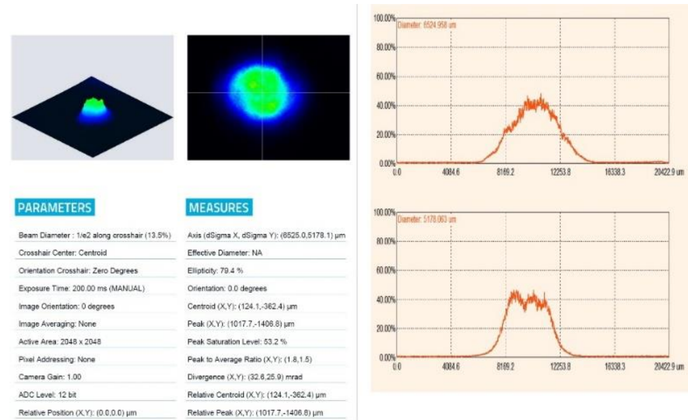


Slides from Dr. Bo Peng (2020)

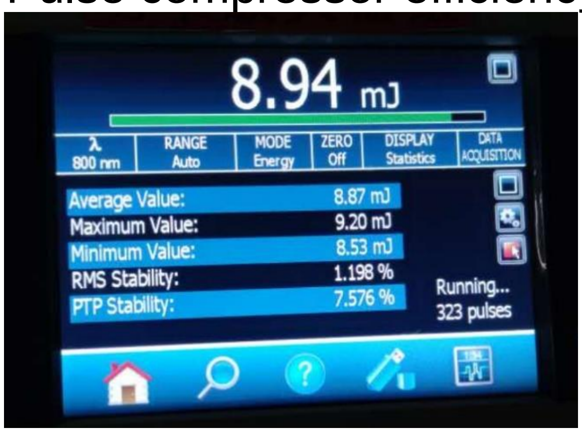
Experiment preparation → laser system

Amplifier energy performance

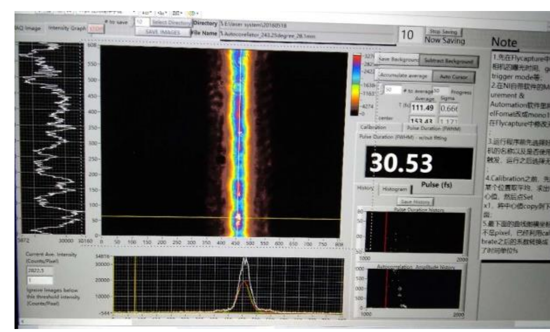
Amplifier output profile before expander



Pulse compressor efficiency: 72%

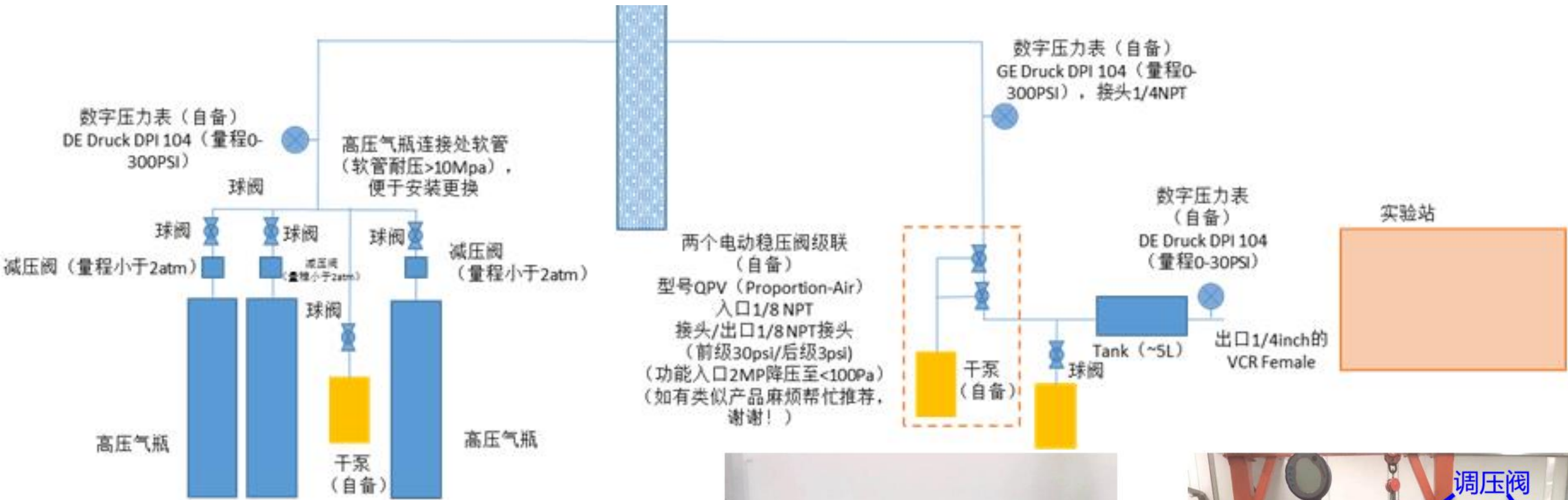


Pulse duration



Slides from Dr. Bo Peng (2020)

Experiment preparation → gas loop



高压气瓶为混合气体（He：N2混合的摩尔比=90:10或者99:1）

Requirement：

200 ~ 10^5 pa (Negative pressure)

Summary

- **CEPC Plasma Injector is a possible innovative solution to address the low field issue in CEPC booster ring**

- **A preliminary design for CEPC plasma injector at 45GeV has been carried out, and a step by step plan to verify its feasibility has also been mapped out**

- **Key experiments are planned to be carried out in future on several available facilities**

- **It is expected that a conclusion on the feasibilities of CEPC plasma injector should be reached in about 5 years study period**