

中国物理学会高能物理分会，2022年8月

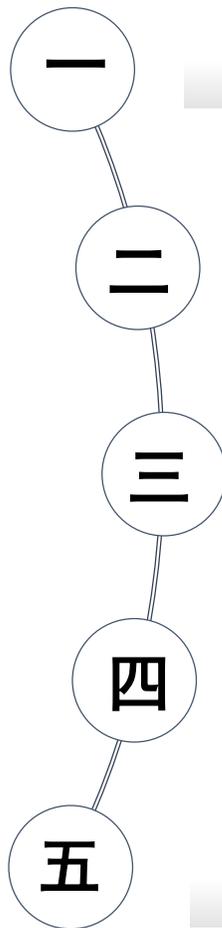
# 加速器最新原理和技术 研究进展

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2022年8月8日

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五	等离子体加速器

# 希格斯工厂与CEPC

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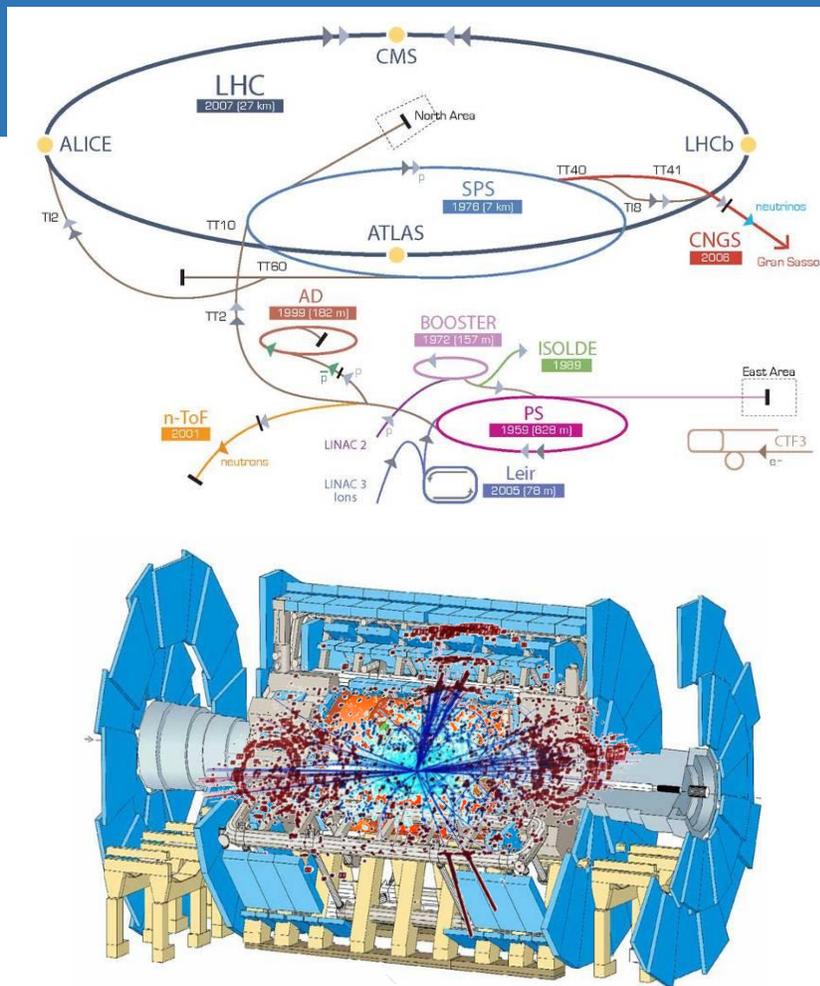
- Higgs工厂的能区与亮度
- CEPC的总体布局

# Higgs粒子被发现

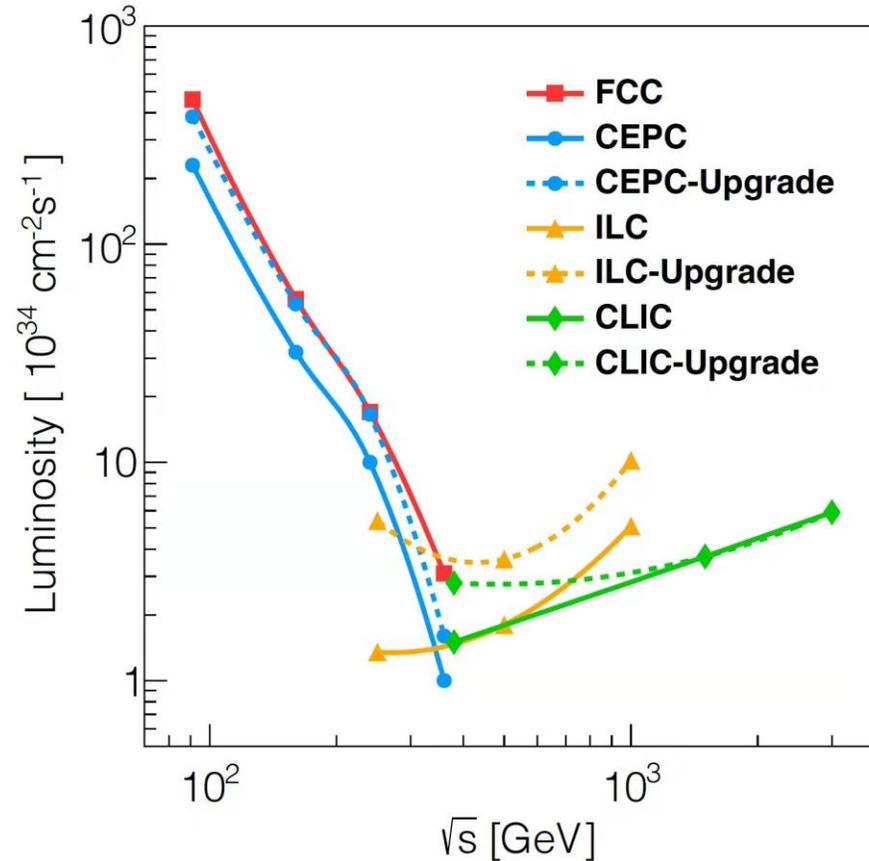
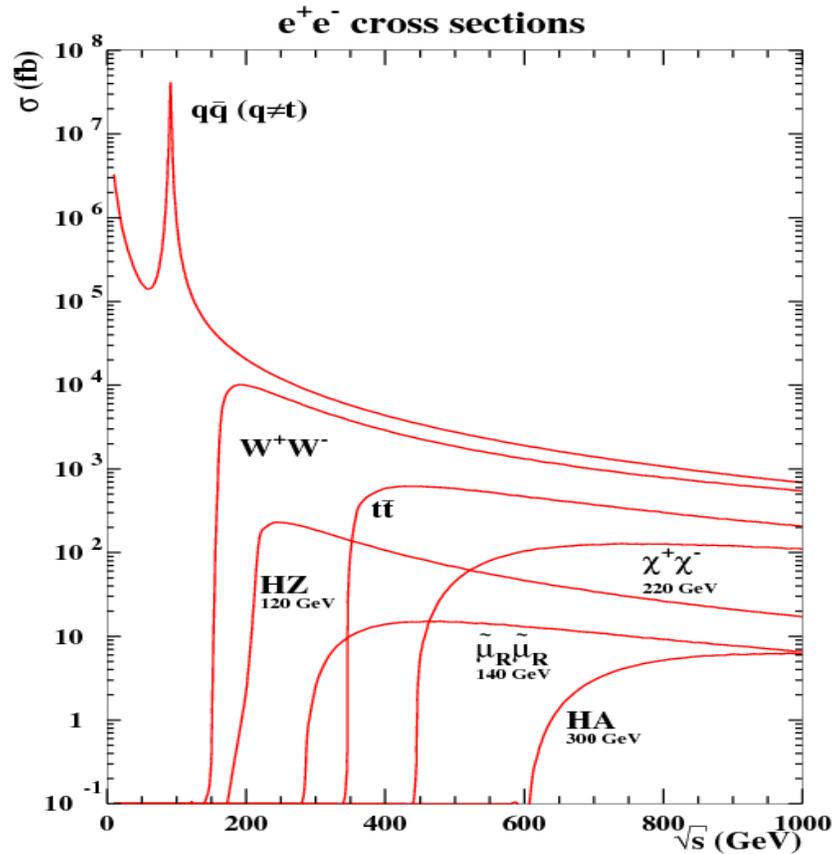
2012年7月4日，欧洲核子中心宣布，LHC上的CMS和ATLAS两个探测器，同时发现了质量为 $126.5\text{GeV}$ 的新玻色子，很可能就是科学家梦寐以求的希格斯玻色子。

比利时物理学家弗朗索瓦·恩格勒特和英国物理学家彼得·希格斯描述了粒子物理学的标准模型，其预测的基本粒子—希格斯玻色子，被欧洲大型强子对撞机通过实验发现，他们因此获得2013年诺贝尔物理学奖。

- 2012年欧洲核子中心（CERN）宣布发现了希格斯粒子，粒子物理的研究面临着一个重大的转折和发展机遇。
- 我国科学家于2012年9月率先提出建造下一代环形正负电子对撞机（CEPC）并可以适时改造为高能质子-质子对撞机（SppC）的方案。
- 国际上Higgs工厂的建设成为热点

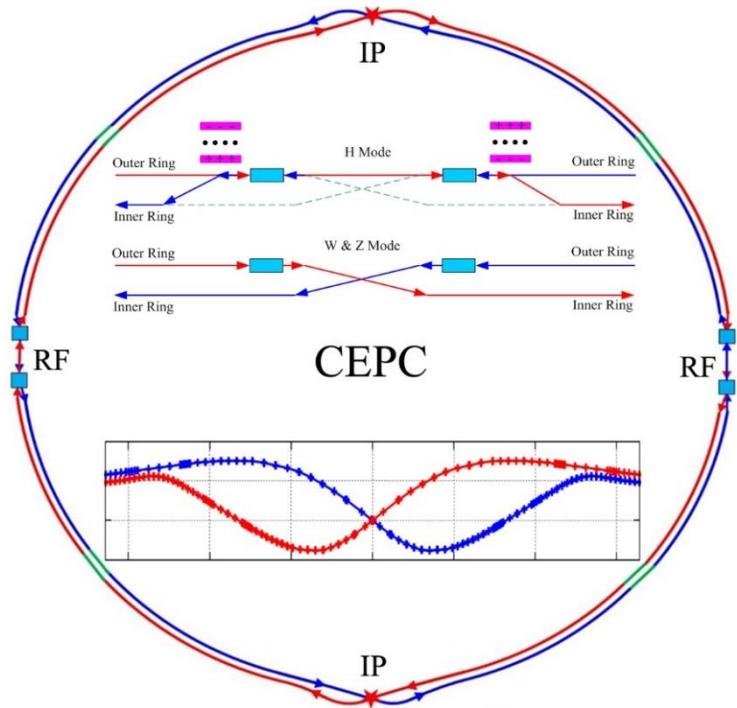


# $e^+e^-$ cross sections & luminosity

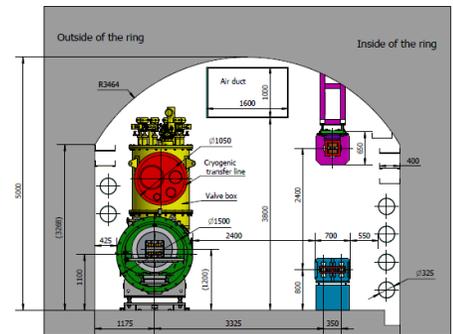
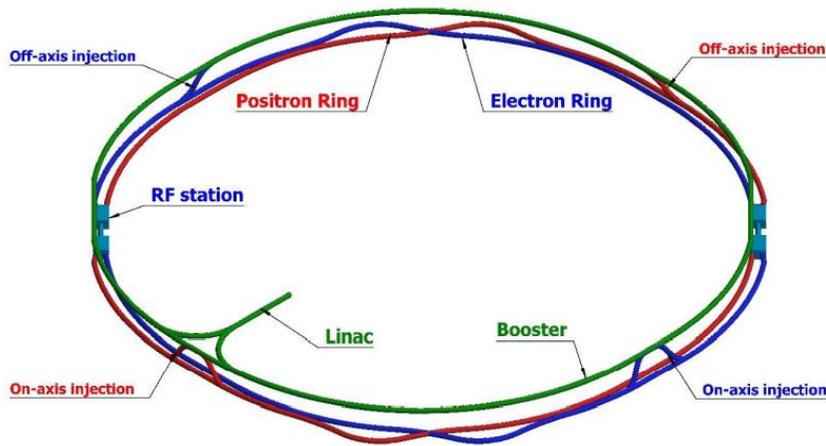
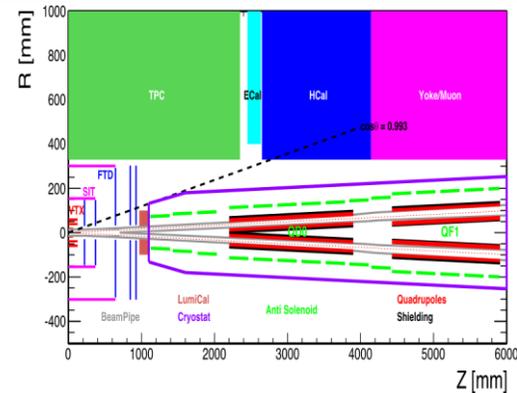


- 环形对撞机Higgs工厂主要有CEPC和FCCee;
- CEPC与FCCee均聚焦于z-ttbar能区对撞;
- 直线对撞机在Higgs能区亮度远低于环形对撞机;

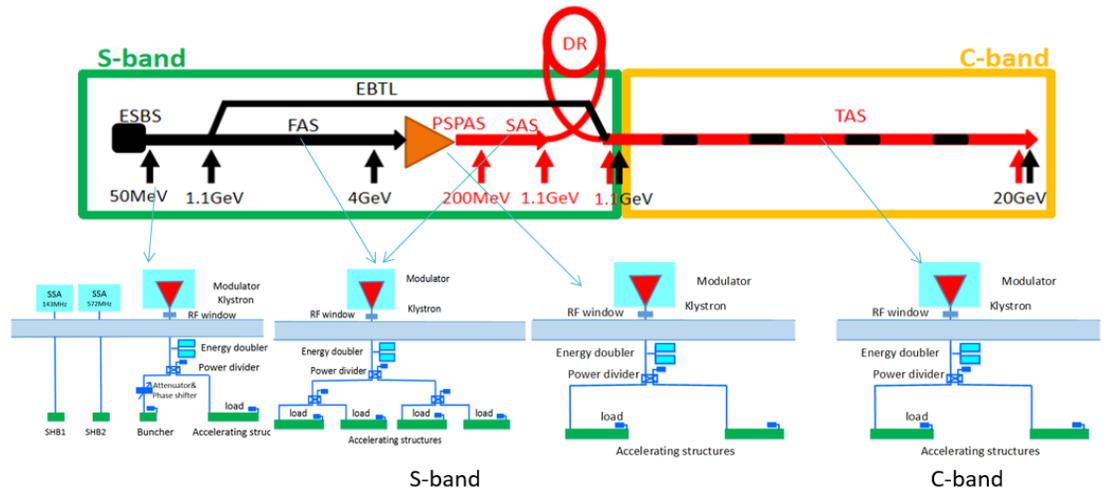
# CEPC的总体布局



- CEPC瞄准Higgs工厂
- 30MW初始方案, 可以升级为50 MW
- 可以升级为高亮度 Z & ttbar
- 后期可兼顾质子对撞 SPPC



- 对撞点: Crab-Waist对撞方案
- 对撞环高频系统: 650MHz超导高频
- 增强器高频系统: 1.3GHz超导高频
- 直线注入: 常温C波段(base line);  
牵引技术发展 1. 低温铜加速; 2. 等离子体加速



# Crab-waist 对撞

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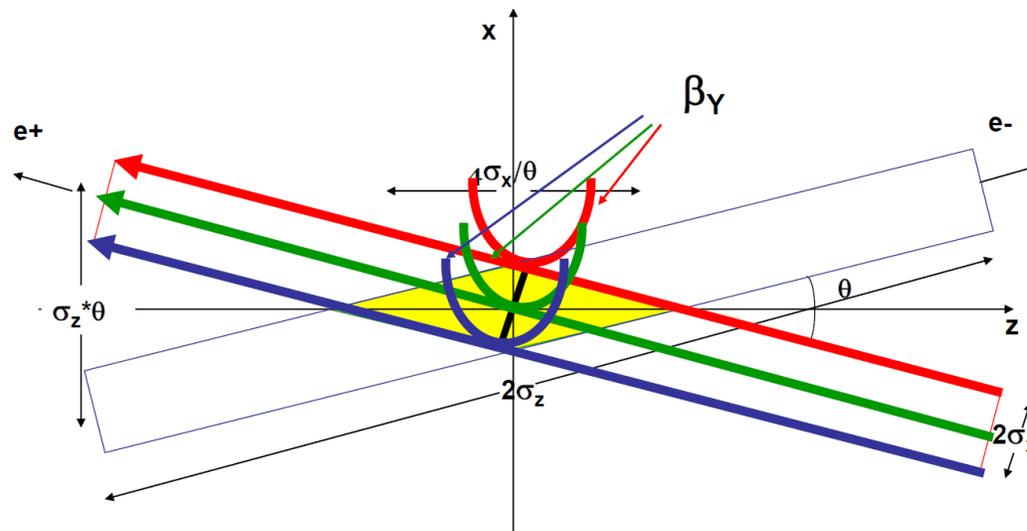
- 大Piwinski角对撞与亮度提高
- Crab-Waist模式
- CEPC的相关参数和物理设计

# 大Piwinski角对撞与亮度提高

- 与直线对撞机相比，环形对撞环亮度受到束-束作用影响，tuning shift  $\xi_y$  的最大值受到限制
- Head-on对撞 ( $\theta = 0$ )，由于 $\xi_y$ 的限制，导致束团数 $N$ 不能太大

$$L \propto \frac{N \xi_y}{\beta_y^*} R_{hg} \quad \phi = \frac{\sigma_z}{\sigma_x^*} \tan\left(\frac{\theta}{2}\right) \quad \xi_y \propto \frac{N}{\sigma_x^* \sqrt{1 + \phi^2}} \sqrt{\frac{\beta_y^*}{\epsilon_y}} \quad \xi_y \propto \frac{N}{\sigma_z \theta / 2} \sqrt{\frac{\beta_y^*}{\epsilon_y}}$$

- 保持较小 $\theta$ ，压缩 $\sigma_x^*$ ，提高Piwinski角， $\phi^2 \gg 1 \rightarrow N \propto \frac{\sigma_z \theta}{2} \rightarrow$  提高束团数 $N$ ，提高对撞亮度 $L$
- 大Piwinski角对撞进一步降低有效作用 $\beta_y^*$



P. Raimondi, Proc. of the 2nd SuperB Workshop, Frascati, March 2006.

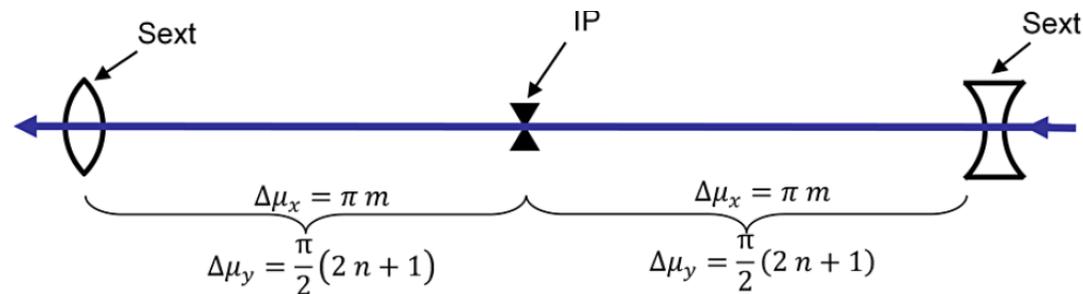
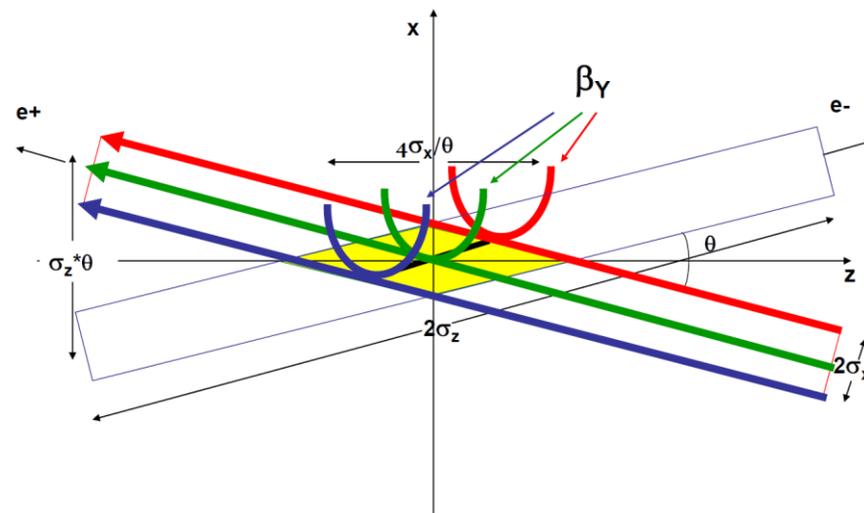
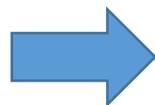
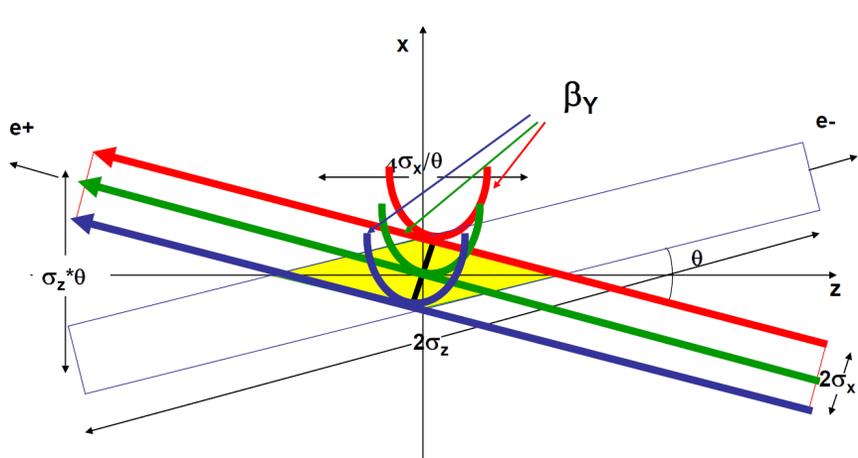
P. Raimondi, D. Shatilov, M. Zobov, arXiv:physics/0702033.

M. Zobov et al, PRL 104, 174801 (2010).

A. Bogomyagkov et al, PRAB 19,121005(2016).

# 六极铁产生Crab-Waist

- 大Piwinski角度也会产生较强束-束共振，限制最大的束-束参数  $\xi_y$
- 使用六极铁，在对撞点处使 $\beta$ -waist沿束流横向位置分布
- 通过降低X-Y耦合，抑制synchro-betatron共振



P. Raimondi, Proc. of the 2nd SuperB Workshop, Frascati, March 2006.

P. Raimondi, D. Shatilov, M. Zobov, arXiv:physics/0702033.

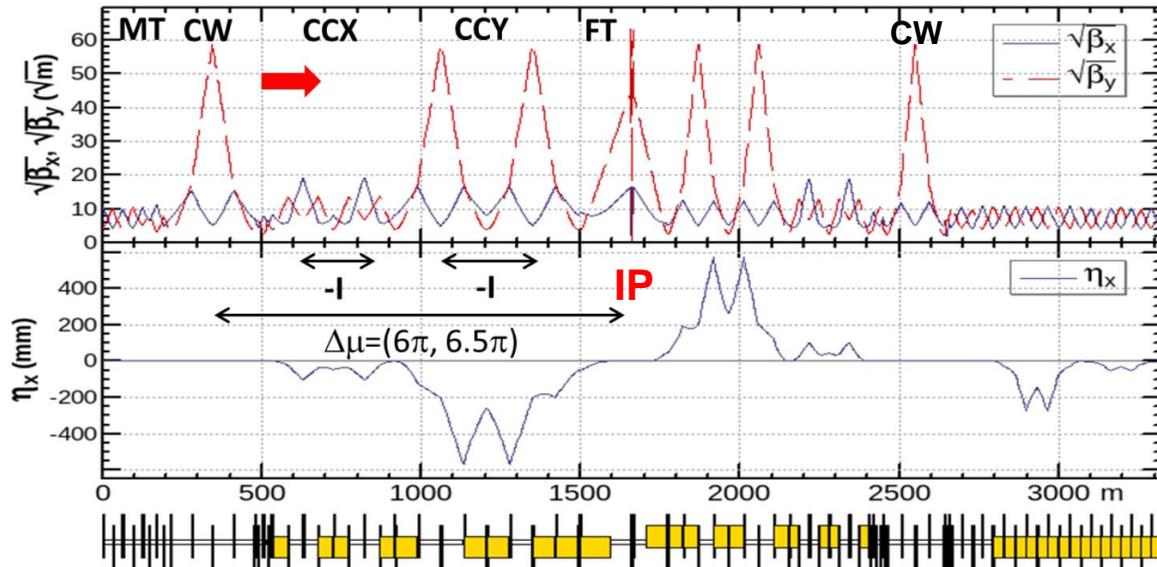
M. Zobov et al, PRL 104, 174801 (2010).

A. Bogomyagkov et al, PRAB 19,121005(2016).

# CEPC的主要参数和Crab-Waist对撞

- 采用crab waist亮度:  $5e34/cm^2/s/IP$  for Higgs
  - Piwinski 角  $\phi=5.9$ , 作用区  $L_i=0.7mm$ ,  $\beta_y^*=1mm$
- 不采用crab-waist, 亮度约  $1.4e34/cm^2/s/IP$  for Higgs
  - 需增大  $\sigma_x$  抑制 synchrotron-betatron resonances
  - 此时 Piwinski angle  $\phi=0.5$ , 作用区  $L_i=3.7mm$ , 导致  $\beta_y^*=3.7mm$

$$L = \frac{\gamma}{2er_e} \cdot \frac{I_{tot}\xi_y}{\beta_y^*} \cdot R_{HG} \quad \phi = \frac{\sigma_z}{\sigma_x} \tan\left(\frac{\theta}{2}\right) \quad L_i = \frac{\sigma_z}{\sqrt{1+\phi^2}}$$



	Higgs	Z	W	ttbar
Number of IPs	2			
Circumference [km]	100.0			
<b>SR power per beam [MW]</b>	<b>30</b>			
Half crossing angle at IP [mrad]	16.5			
Energy [GeV]	120	45.5	80	180
Energy loss per turn [GeV]	1.8	0.037	0.357	9.1
<b>Piwinski angle</b>	<b>5.94</b>	<b>24.68</b>	<b>6.08</b>	<b>1.21</b>
Bunch number	268	11934	1297	35
Beam current [mA]	16.7	803.5	84.1	3.3
<b>Beta functions at IP (<math>\beta_x/\beta_y</math>) [m/mm]</b>	<b>0.3/1</b>	<b>0.13/0.9</b>	<b>0.21/1</b>	<b>1.04/2.7</b>
Emittance ( $\epsilon_x/\epsilon_y$ ) [nm/pm]	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7
Beam size at IP ( $\sigma_x/\sigma_y$ ) [um/nm]	14/36	6/35	13/42	39/113
Bunch length (natural/total) [mm]	2.3/4.1	2.5/8.7	2.5/4.9	2.2/2.9
Beam-beam parameters ( $k_{sx}/k_{sy}$ )	0.015/0.11	0.004/0.12	0.012/0.113	0.071/0.1
RF frequency [MHz]	650	650	650	650
Longitudinal tune Qs	0.049	0.035	0.062	0.078
Beam lifetime [min]	20	80	55	18
Hour glass Factor	0.9	0.97	0.9	0.89
<b>Luminosity per IP [<math>1e34/cm^2/s</math>]</b>	<b>5.0</b>	<b>115</b>	<b>16</b>	<b>0.5</b>

# 国内外采用Crab-Waist方案的对撞环

<b>Colliders</b>	<b>Location</b>	<b>Status</b>
DAΦNE	<b>Φ-Factory</b> Frascati, Italy	In operation (SIDDHARTA, KLOE-2, SIDDHARTA-2)
SuperKEKB	<b>B-Factory</b> Tsukuba, Japan	Crab Waist optics in April 2020
SuperC-Tau	<b>C-Tau-Factory</b> Novosibirsk, Russia	Russian mega-science project
FCC-ee	<b>Z, W, H, ttbar-Factory</b> CERN, Switzerland	91 km, CDR released in December 2018
CEPC	<b>H, Z, W, ttbar-Factory</b> China	100 km, CDR released in August 2018
STCF	<b>2-7 GeV</b> China	CDR design under going

# Crab-waist 对撞小结

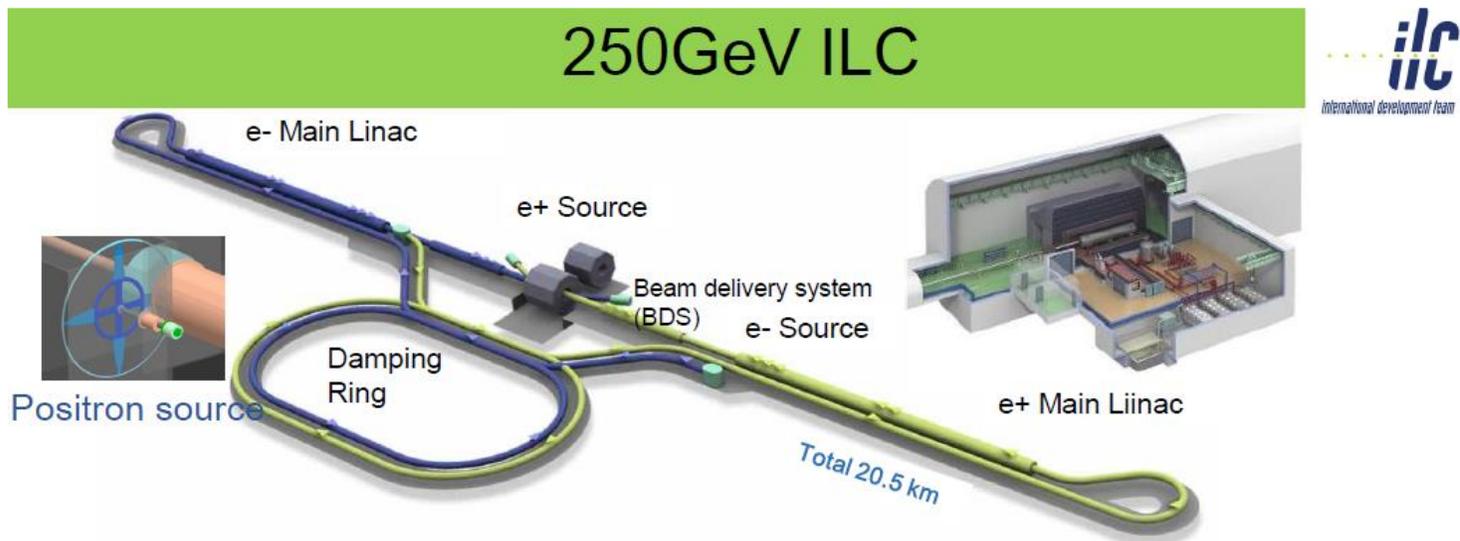
- 环形对撞机需要考虑束-束作用
- 大Piwinski角对撞和Crab-Waist模式有效提高亮度
- 环形对撞机比直线对撞机有更高的亮度

# 超导高频的研究进展

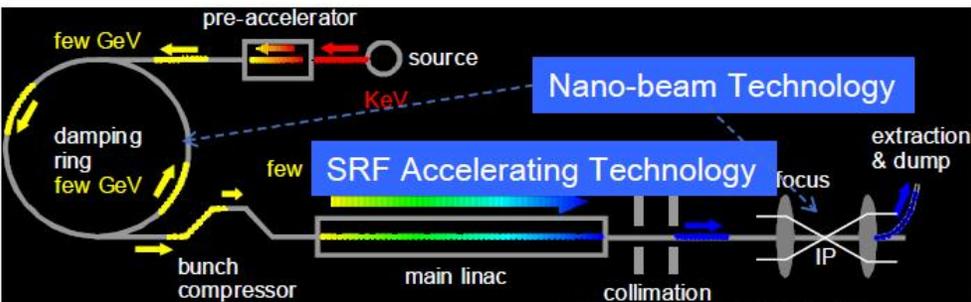
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- 国际直线对撞机ILC与1.3GHz SRF
- 高配版ILC：HELEN超导直线对撞机
- 高能所超导高频技术的研究现状

# ILC驱动1.3GHz超导高频的技术发展



## Key Technologies



ILCX2021 (Shin MICHIZONO)

Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	$1.35 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G.	31.5 MV/m (35 MV/m)
$Q_0$	$Q_0 = 1 \times 10^{10}$

2

- **需求**——由于其超导直线加速器绵延几十公里的巨大规模，ILC对高梯度（及高Q）超导腔有强烈需求
- **引擎**——直线对撞机在过去三十年（始于TESLA项目）带动了超导高频技术的快速发展（加速梯度提高5倍，造价降低2倍），并将催生下一代超导腔材料和技术
- **应用**——如，已成为全球科技竞争焦点的高重频自由电子激光装置

# 美国近期提出“高配版ILC”：HELEN超导直线对撞机

arXiv:2203.08211v1 [physics.acc-ph] 15 Mar 2022

FERMILAB-FN-1155-AD-PPD-SQMS-TD

## Higgs-Energy LEptoN (HELEN) Collider based on advanced superconducting radio frequency technology

S. Belomestnykh<sup>1,2</sup>, P.C. Bhat<sup>1</sup>, A. Grassellino<sup>1</sup>, M. Checchin<sup>1</sup>, D. Denisov<sup>3</sup>, R.L. Geng<sup>4</sup>, S. Jindariani<sup>1</sup>, M. Liepe<sup>5</sup>, M. Martinello<sup>1</sup>, P. Merkel<sup>1</sup>, S. Nagaitsev<sup>1</sup>, H. Padamsee<sup>1,6</sup>, S. Posen<sup>1</sup>, R.A. Rimmer<sup>6</sup>, A. Romanenko<sup>1</sup>, V. Shiltsev<sup>1</sup>, A. Valishev<sup>1</sup>, and V. Yakovlev<sup>1</sup>

<sup>1</sup>Fermi National Accelerator Laboratory, Batavia, IL, USA

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<sup>3</sup>Brookhaven National Laboratory, Upton, NY, USA

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<sup>5</sup>Cornell University, Ithaca, NY, USA

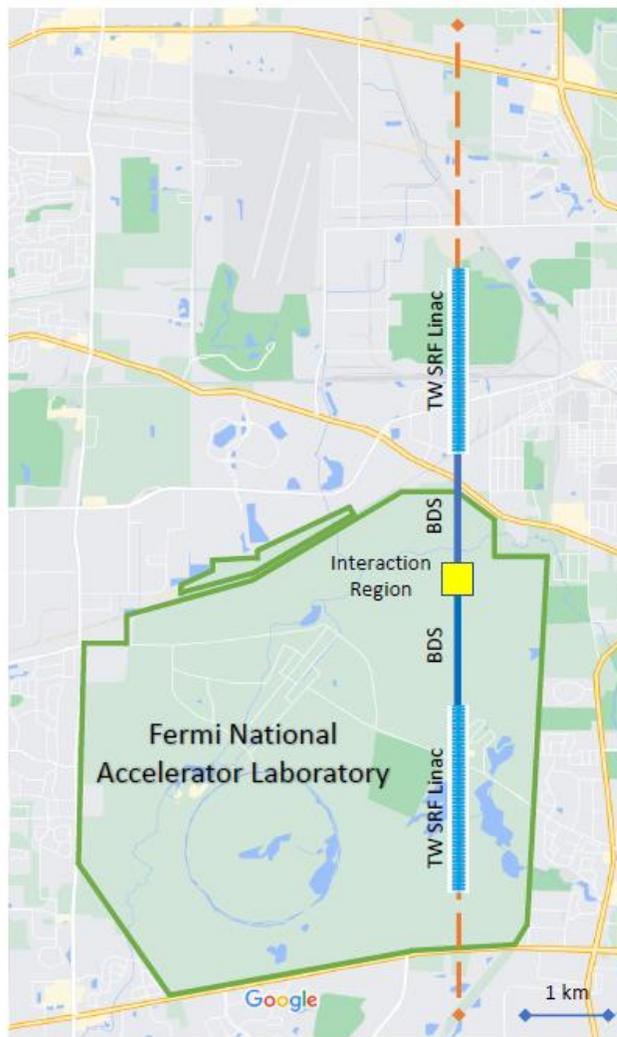
<sup>6</sup>Thomas Jefferson National Accelerator Facility, Newport News, VA, USA

March 17, 2022

Submitted to the Proceedings of  
the U.S. Particle Physics Community Planning Exercise (Snowmass 2021)

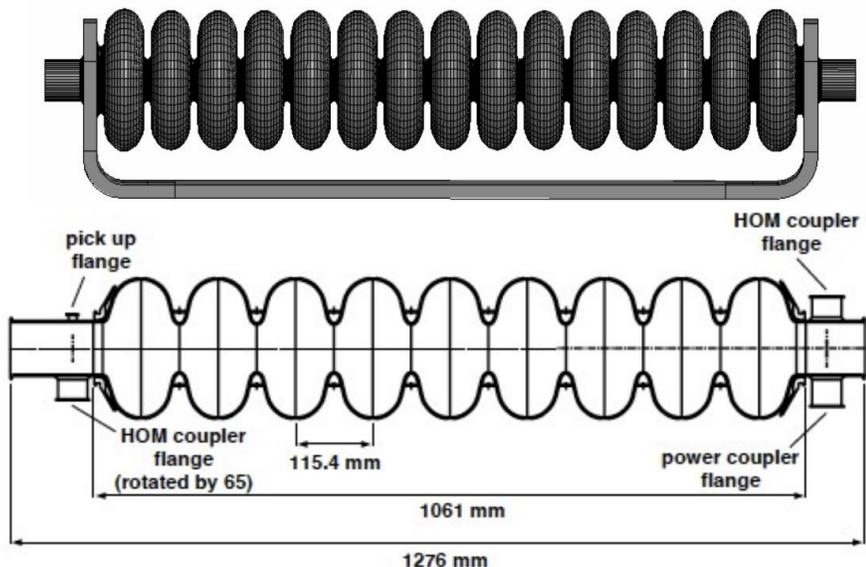
### Abstract

This Snowmass 2021 contributed paper discusses a Higgs-Energy LEptoN (HELEN)  $e^+e^-$  linear collider based on advanced superconducting radio frequency technology. The proposed collider offers cost and AC power savings, smaller footprint (relative to the ILC), and could be built at Fermilab with an Interaction Region within the site boundaries. After the initial physics run at 250 GeV, the collider could be upgraded either to higher luminosity or to higher (up to 500 GeV) energies. If the ILC could not be realized in Japan in a timely fashion, the HELEN collider would be a viable option to build a Higgs factory in the U.S.



- 解决ILC梯度过低（技术保守？）、**footprint太大的问题**，大致在 Fermilab site范围内建一台250 GeV的直线对撞机
- **基准方案**：采用**行波超导腔**把运行加速梯度从ILC的31.5 MV/m提高到 **70 MV/m**
- **备选方案**：采用新材料**铌三锡**及新腔型，运行梯度达 **90 MV/m**。或至少采用新腔型提高到55 MV/m
- **计划五年完成TDR（？）**

# 行波超导加速结构

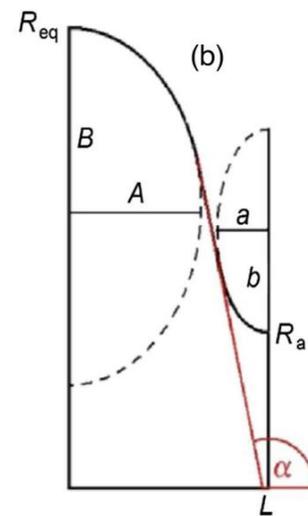


行波与驻波(TESLA)加速管比较



## 行波超导加速结构的优势:

- 极大降低峰值磁场 ( $H_{pk}/E_{acc}$ )  
28.8 vs. 42.6 Oe/(MV/m) (TESLA)
- 降低峰值电场比 ( $E_{pk}/E_{acc}$ )
- 更高的  $R/Q$ , 有效降低低温系统负载



Geometry of the TW half cell.

Optimization	120/200
Phase advance (deg.)	90
A (mm)	23.83
B (mm)	36.40
a (mm)	4.51
b (mm)	7.52
$E_{pk}/E_{acc}$	1.727
$B_{pk}/E_{acc}$ (mT/(MV/m))	2.878
$R_{sh}/Q$ (Ohm/m)	2,127
$\alpha$ (deg.)	90.91
$R_{eq}$ (mm)	98.95
$v_{gr}/c$	0.01831
$E_{acc}$ (MV/m)	69.5
$E_{acc} \cdot 2L$ MV	4.00

# HELEN与ILC对撞机的参数比较

Parameter	HELEN	ILC
CM energy $2 \times E_b$ (GeV)	250	250, 500
Length (km)	7.5	20.5, 31
Interaction points	1	1
Integrated luminosity ( $\text{ab}^{-1}/\text{yr}$ )	0.2	0.2, 0.3
Peak lumi. $\mathcal{L}$ ( $10^{34} \text{cm}^{-2} \text{s}^{-1}$ )	1.35	1.35, 1.8
CM energy spread $\sim 0.4\delta_{\text{BS}}$ (rms, %)	1	1, 1.7
Polarization (%)	80/30 ( $e^-/e^+$ )	80/30 ( $e^-/e^+$ )
Rep.rate $f_{\text{rep}}$ (Hz)	5	5
Bunch spacing (ns)	554	554
Particles per bunch $N$ ( $10^{10}$ )	2	2
Bunches per pulse $n_b$	1312	1312
Pulse duration ( $\mu\text{s}$ )	727	727
Pulsed beam current $I_b$ (mA)	5.8	5.8
Bunch length $\sigma_z$ (rms, mm)	0.3	0.3
IP beam size $\sigma^*$ (rms, $\mu\text{m}$ )	H: 0.52 V: 0.0077	H: 0.52, 0.47 V: 0.0077, 0.0059
Emittance, $\varepsilon_n$ (rms, $\mu\text{m}$ )	H: 5 V: 0.035	H: 5, 10 V: 0.035, 0.035
$\beta^*$ at interaction point (mm)	H: 13 V: 0.41	H: 13, 11 V: 0.41, 0.48
Full crossing angle $\theta_c$ (mrad)	14	14
Crossing scheme	crab crossing	crab crossing
Disruption parameter $D_y$	35	35, 25
RF frequency $f_{\text{RF}}$ (MHz)	1300	1300
Accelerating gradient $E_{\text{acc}}$ (MV/m)	70	31.5
Effective gradient $E_{\text{eff}}$ (MV/m)	55.6	21
Total beam power (MW)	5.3	5.3, 10.5
Site power (MW)	110	111, 173
Key technology	TW SRF	SW SRF

# 高能所1.3GHz超导腔研发历程

◆ CEPC增强器使用1.3GHz SRF；对撞环使用650MHz SRF

大晶粒低损耗型  
单-cell腔 BCP 40 MV/m  
(高能所后处理、KEK测试)



大晶粒低损耗型  
9-cell腔 EP 20 MV/m  
(FNAL后处理和测试)



PAPS和SHINE单/9-cell制造  
EP系统、真空退火炉、内窥镜、预调谐机等研制

12只中温退火单cell腔全部超过SHINE指标  
5只EP 9-cell腔平均33 MV/m, 最高36MV/m  
6只中温退火9-cell腔平均 3.8E10 @16-21MV/m,  
超过SHINE/LCLS-II及LCLS-II-HE指标



大晶粒低损耗型、无HOM  
9-cell腔 BCP 20 MV/m  
(高能所后处理, KEK/JLAB测试)



技术转移到高能锐新公司  
细晶粒TESLA型  
9-cell腔 24 MV/m  
(KEK后处理和测试)

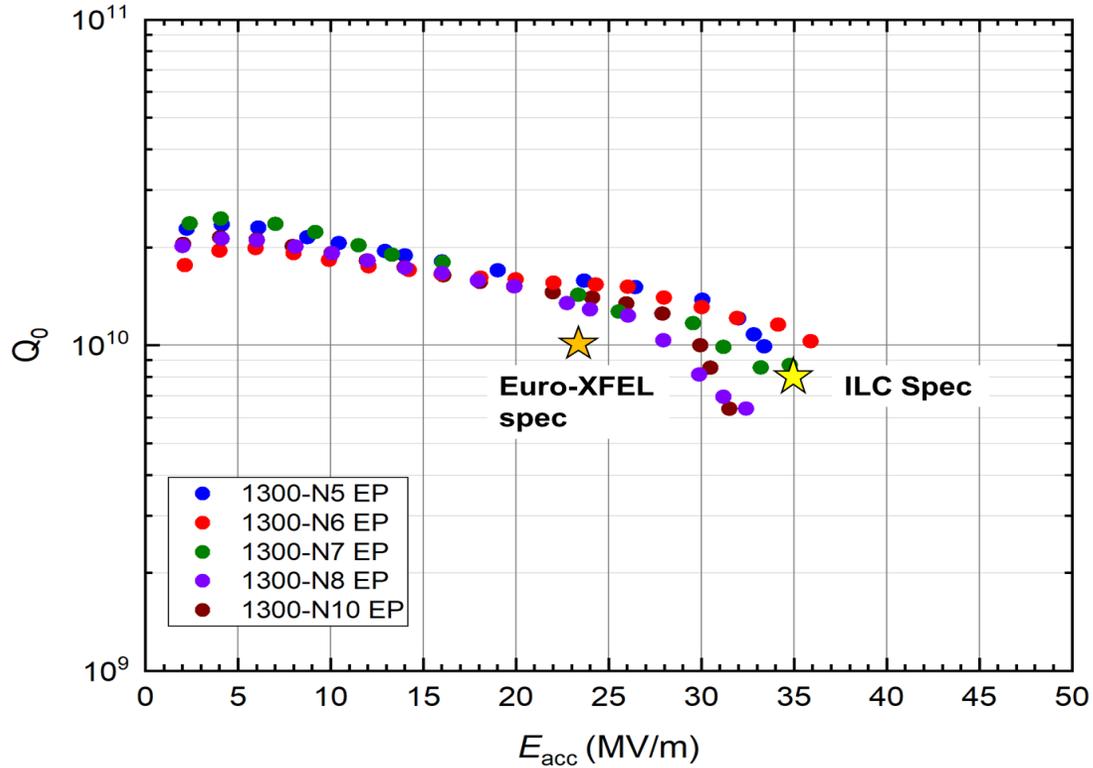


12只EP单cell腔  
全部超过 40 MV/m  
最高 46 MV/m

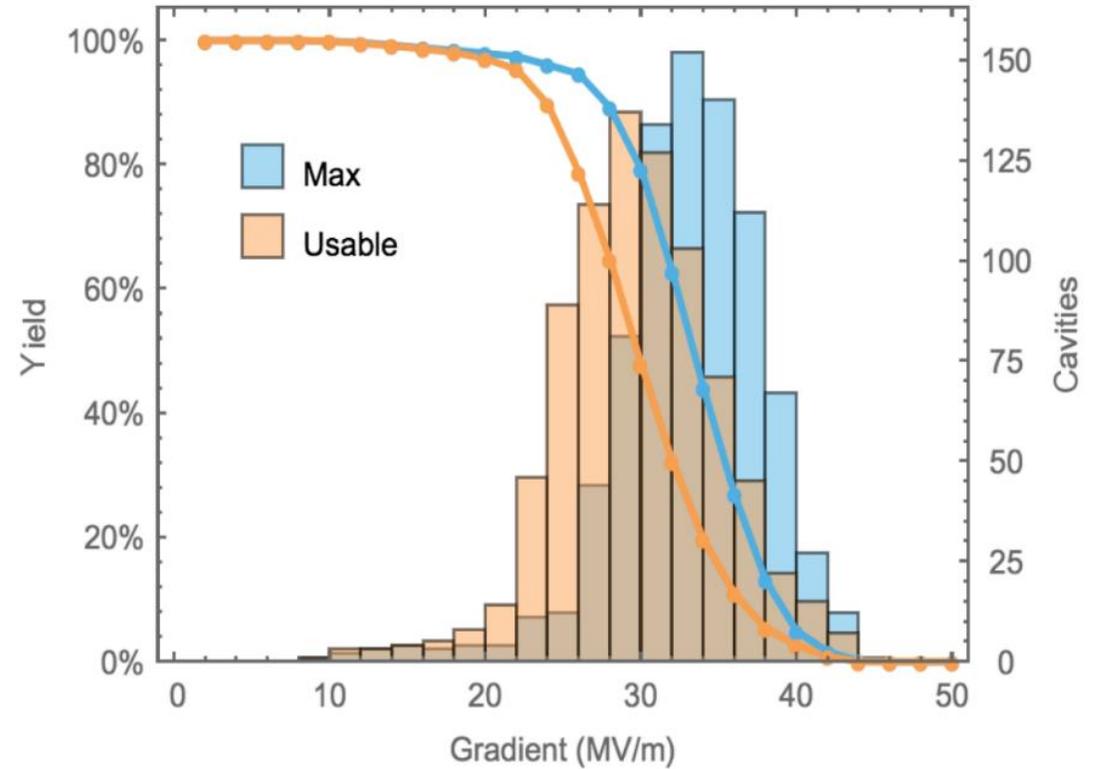


四只BCP 9-cell槽腔  
平均22 MV/m  
达标交付

# 高能所高梯度电抛光1.3GHz 9-cell超导腔与国际比较

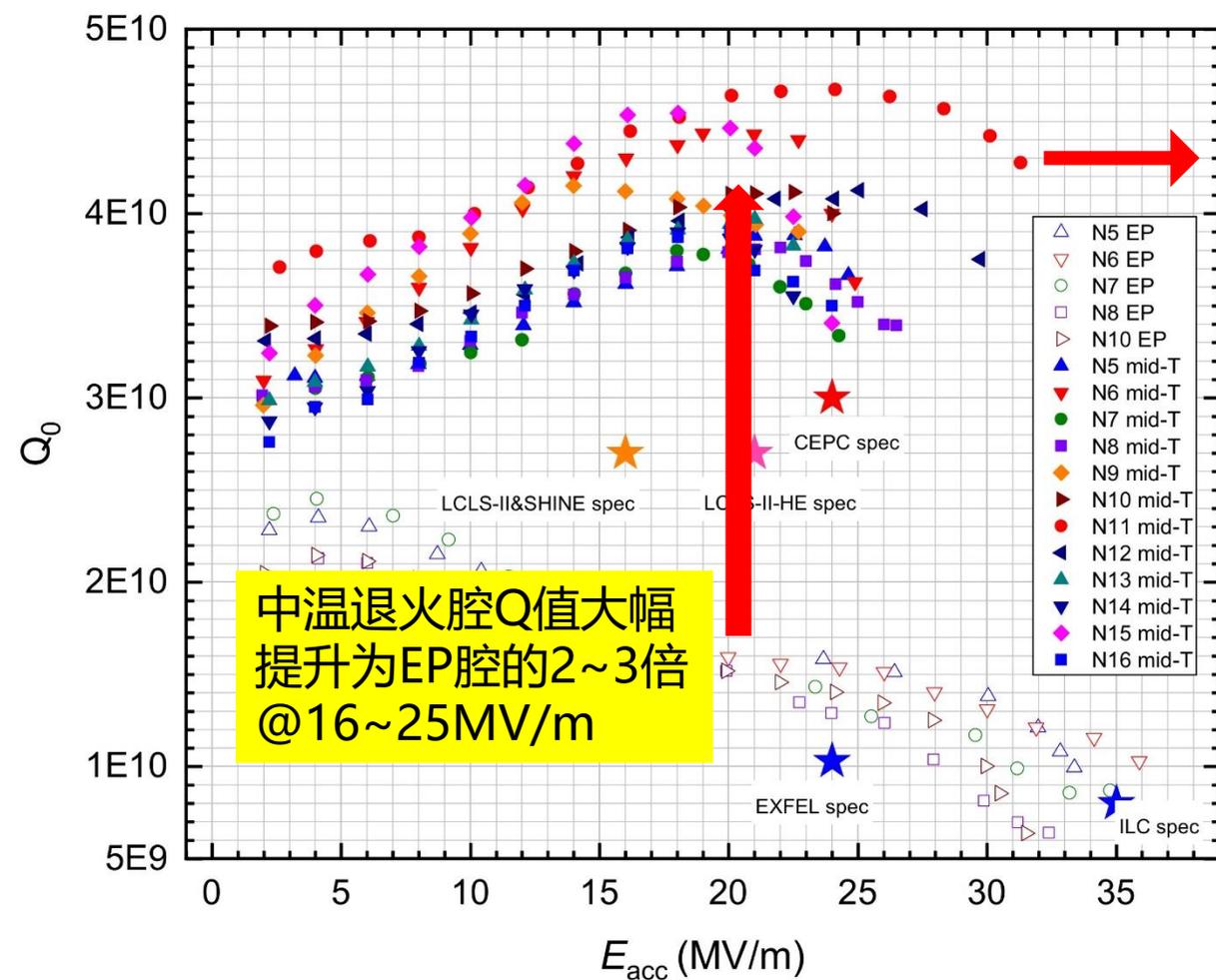


高能所5只电抛光9-cell腔加速梯度全部超过30 MV/m, 其中最高梯度36 MV/m, 超过 ILC 指标; 平均梯度33.4 MV/m, 与Euro-XFEL批量平均梯度相当。



Euro-XFEL 800只电抛光9-cell腔垂直测试加速梯度分布及对应成品率。平均加速梯度33 MV/m。

# 国际首次把中温退火工艺用于9-cell超导腔，Q值显著提升

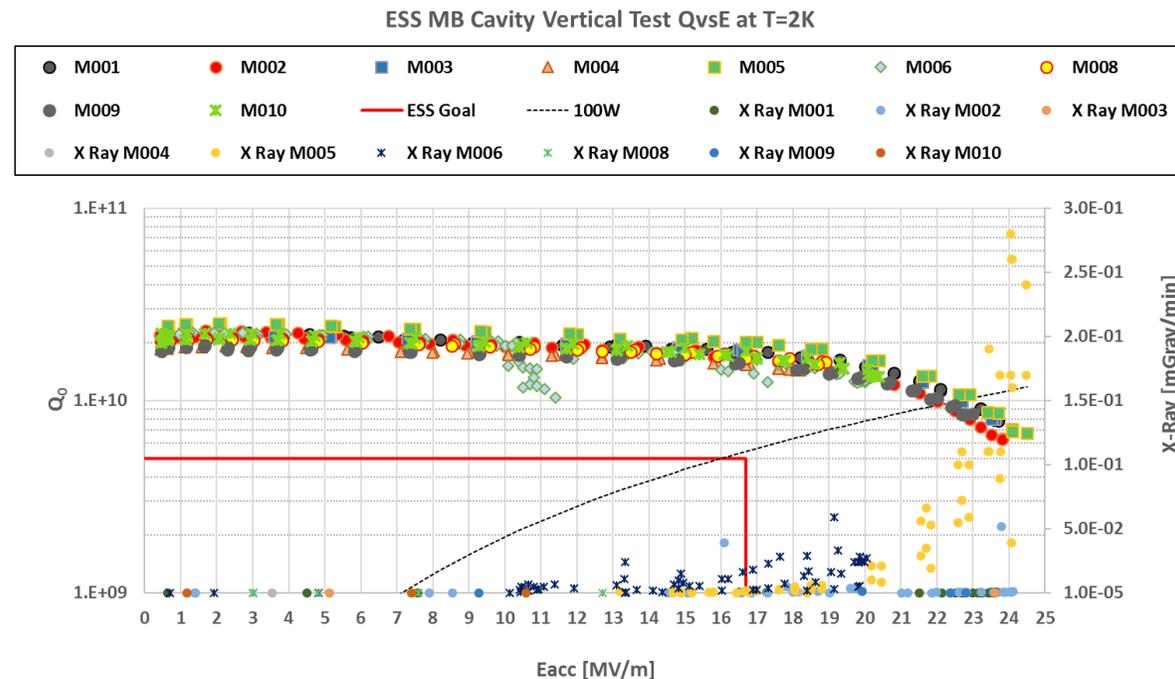
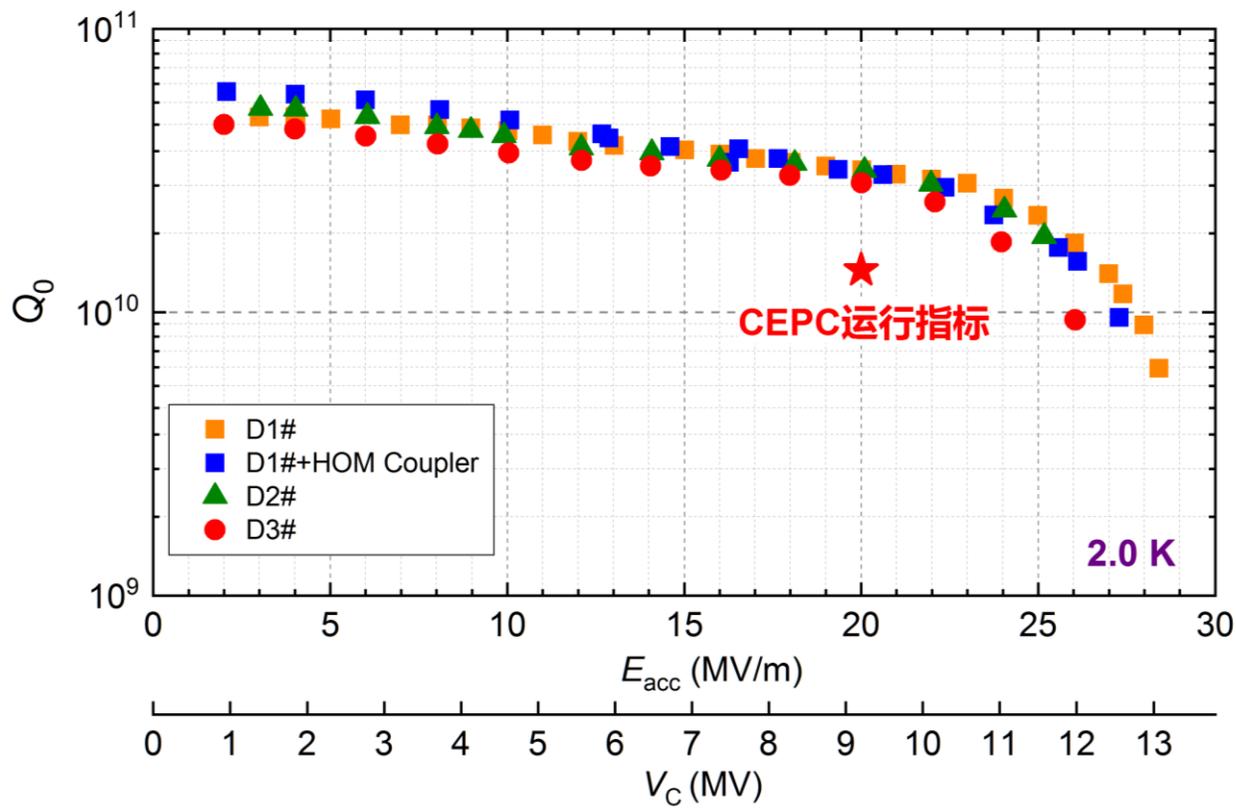


2020年高能所在国际上首次成功实现了1.3 GHz 9-cell超导腔的中温退火工艺和小批量试制，垂直测试和水平测试结果均处于1.3 GHz 9-cell超导腔的国际领先水平。

2022年研制成功世界性能最高的高Q高梯度9-cell腔（中温退火工艺）：**4.3E10@31 MV/m**。进一步改进工艺、提高梯度，有望实现3E10@45MV/m的超高梯度和Q（Q值高于现有国际水平2倍），达到纯铌腔热处理后的物理极限，**用于ILC**。

# 高能所2-cell 650MHz超导腔研究进展

- 650 MHz two-cell超导腔采用了化学抛光的成熟技术，垂测结果超过CEPC的运行指标，达到了世界先进水平。
- 与**ESS 704 MHz MB Cavity** ( $\beta=0.67$ , 化学抛光) 的垂测结果 ( $3\sim 4E10@17MV/m$ ) 相当



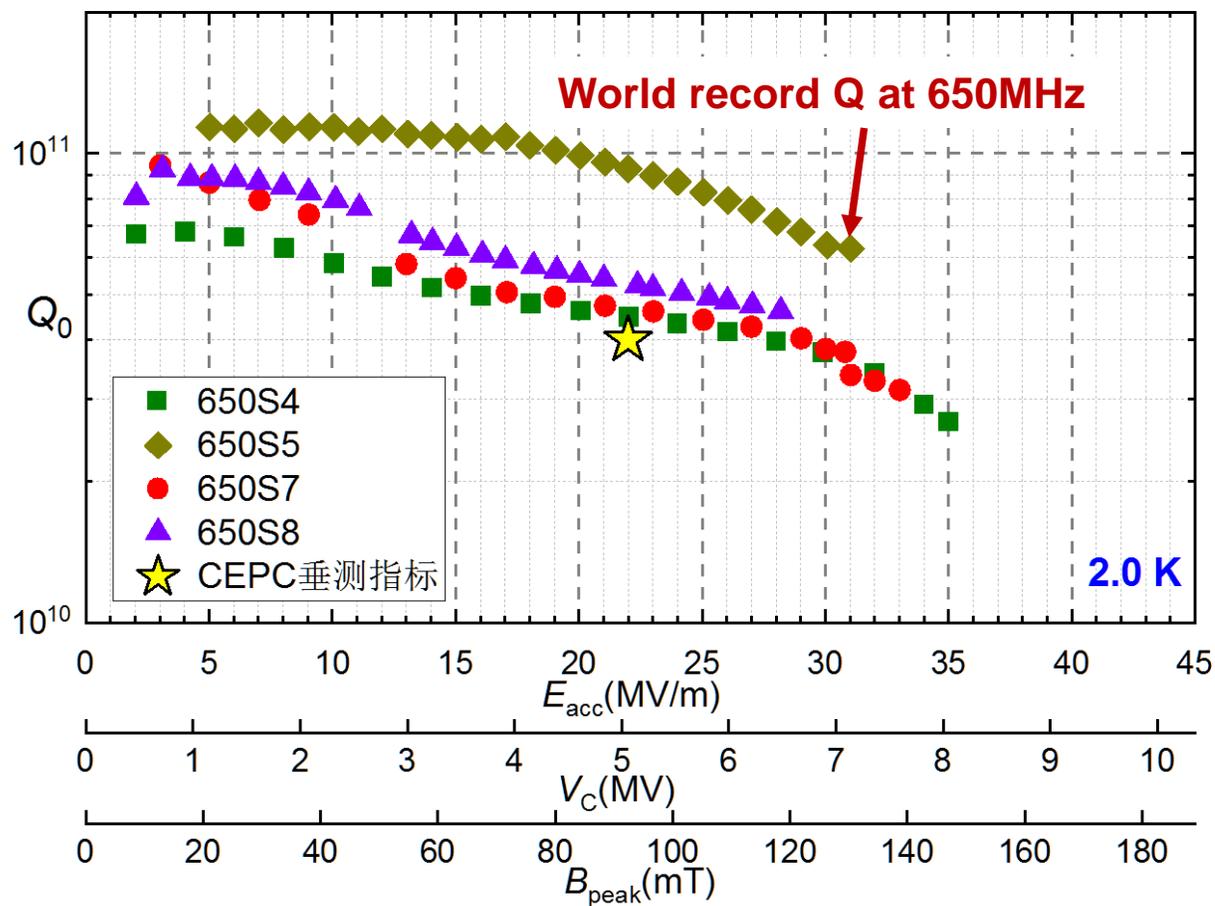
Scaling R/Q and frequency to CEPC 650 MHz @  $\beta=1$ :  $Q=3-4E10@17MV/m$

650 MHz test crymodule at PAPS

Carlo Pagani, CEPCWS 2019

# 650MHz 1-cell腔研究现状

- 650 MHz single-cell 超导腔采用了电抛光、中温退火、掺氮、大晶粒、柔性抛光等新技术，测试结果达到了 $6.4E10@30MV/m$ ，创造了国内大尺寸 (<1GHz) 超导腔的最高纪录，达到世界领先水平。



Congratulations for achieving such a high gradient (高加速梯度) and high Q value (高品质因数) in FG (细晶) and LG (大晶) 650 MHz cavities...

**Eiji Kako**教授  
(KEK SRF负责人, 世界射频超导协会 (TTC) 主席)

下一步目标: 高Q值下达到  $>41MV/m$  的高梯度 → 兼容Higgs 运行

650 MHz single-cell超导腔测试结果

# SRF下一代变革性超导腔材料：铌三锡 (Nb3Sn)

- 经40年发展，纯铌超导腔性能接近物理和工程极限。未来加速器高频腔技术向何处去？
- 铌三锡相比铌具有**2倍理论加速梯度（至100MV/m）**、**20倍品质因数@4.2K**，是下一代射频超导材料首选，未来加速器超导高频技术最重要方向（美国能源部射频加速器发展战略报告2017、美国高能物理战略规划Snowmass2021重点方向）

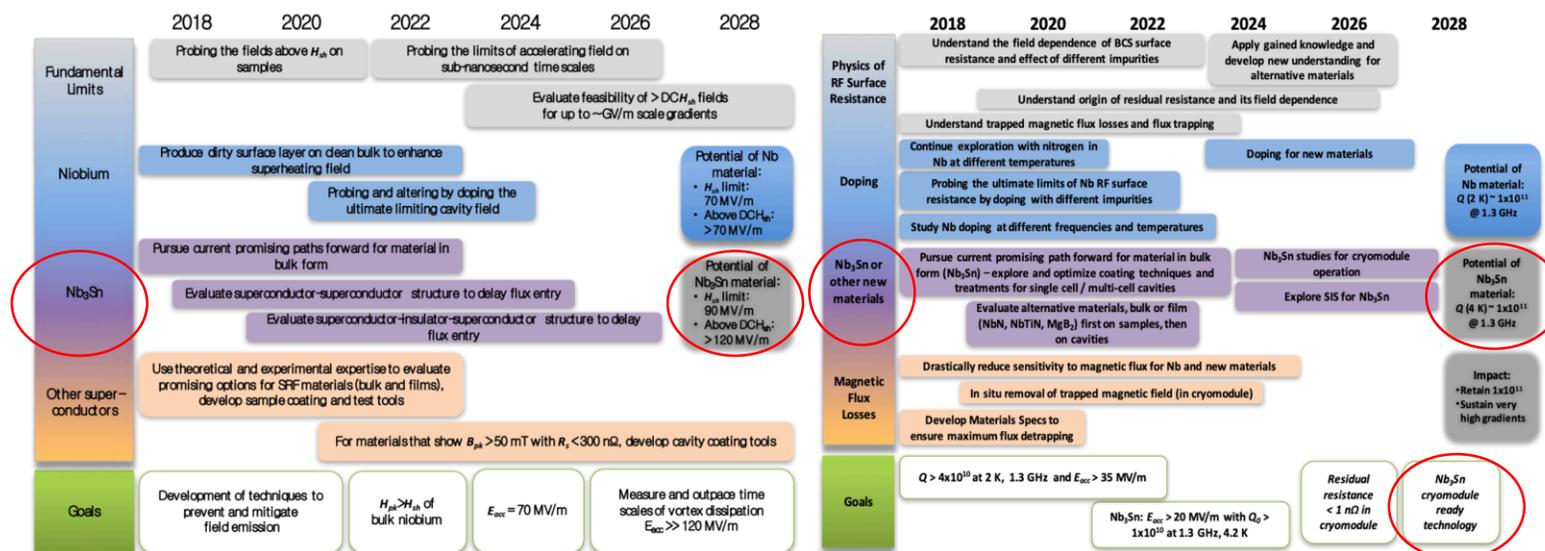
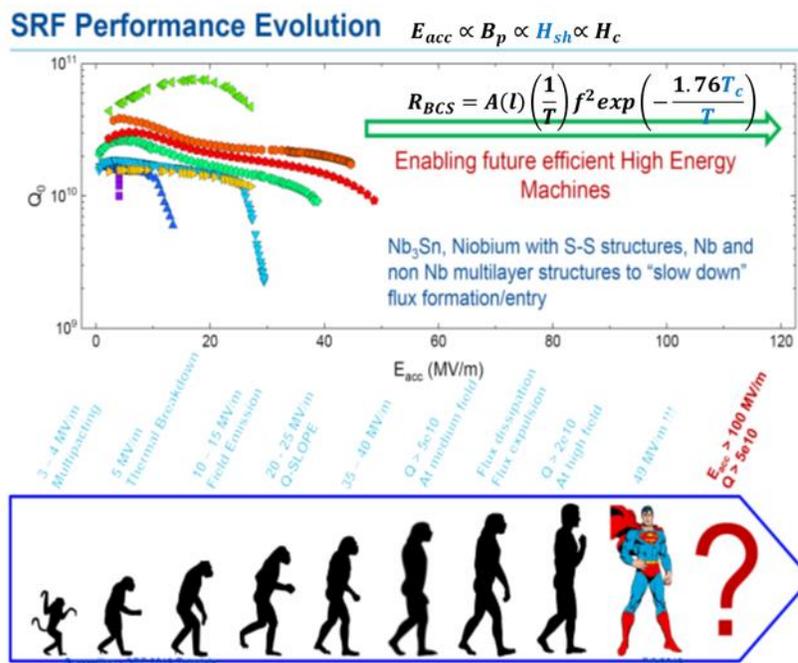


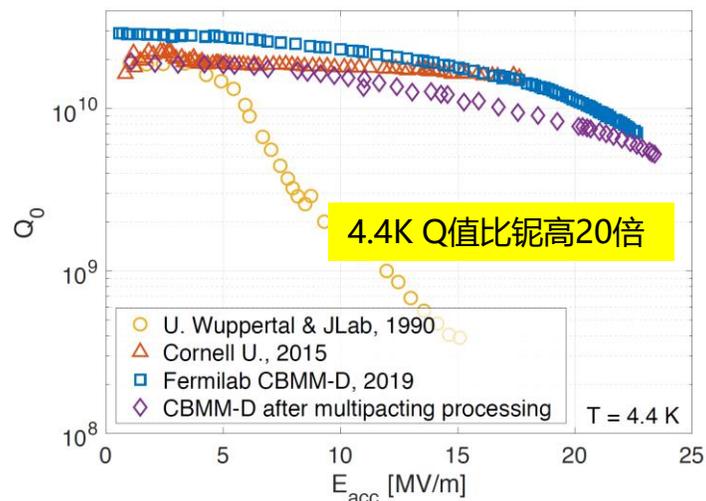
Fig. 2: Tables showing proposed directions over a decade of research and development towards pushing the accelerating gradients (left) and  $Q_0$  (right) of SRF cavities.

DOE GARD-SRF Roadmap Workshop, United States Department of Energy Office of High Energy Physics, <https://doi.org/10.2172/1631119> (2017)

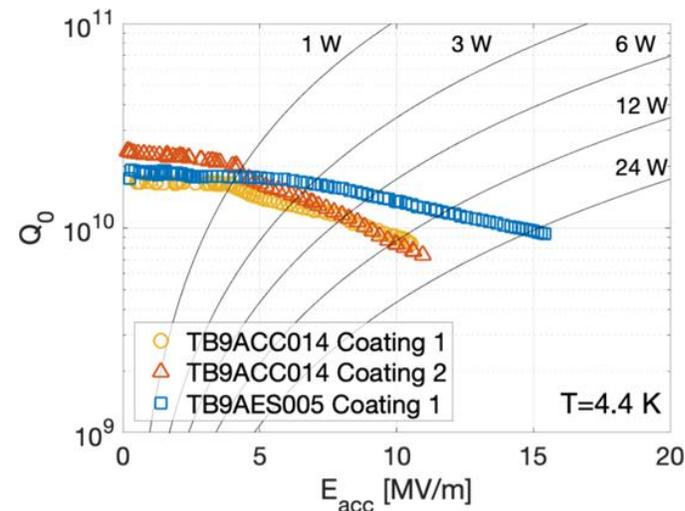
# Nb3Sn超导腔全球研究进展

全球铌三锡超导腔研究进展迅速，目前结果最好的是蒸镀法镀膜（磁控溅射等制备工艺仍在探索中），形成三个梯队：

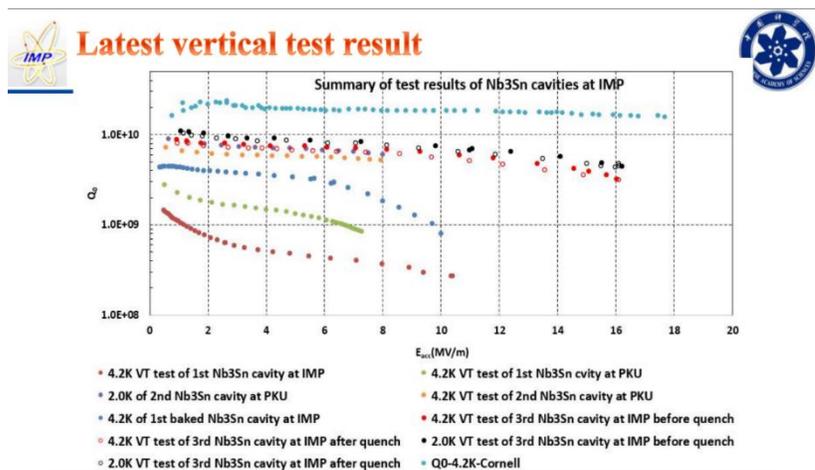
1. 美国FNAL、Cornell、JLAB
2. 中科院近物所
3. 日本KEK、中科院高能所



FNAL 1.3GHz 1-cell铌三锡腔



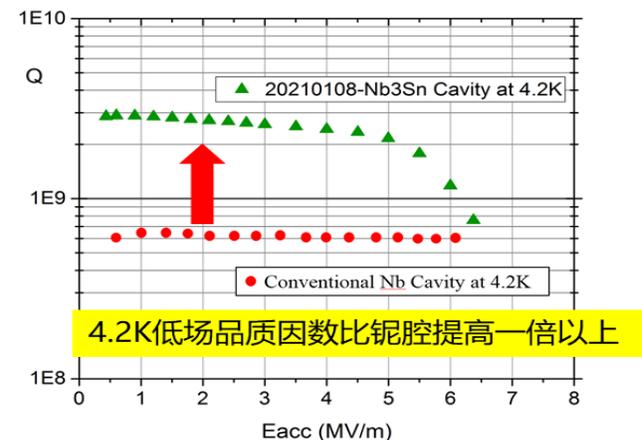
FNAL 1.3GHz 9-cell铌三锡腔



中科院近物所1.3 GHz 1-cell铌三锡腔



中科院高能所铌三锡超导腔蒸镀设备及1.3 GHz 1-cell铌三锡腔垂测初步结果



# 超导SRF小结

- 基于Nb材料的超导SRF技术发展日趋成熟，为对撞机建设提供有力支持
- 我国铌腔超导高频技术发展达到国际先进水平
- 腔型优化（行波）与新材料（Nb<sub>3</sub>Sn，不同材料镀膜）保持研究热点

# 低温铜加速结构

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- 基于低温铜直线对撞机  $C^3$  以及技术特点
- 低温铜加速技术驱动的其他应用
- CEPC直线注入器的  $C^3$  的初步方案

# 低温铜腔加速技术应用

■ C<sup>3</sup> (Cool Copper Collider) 以及相关的高梯度加速技术R&D得到SLAC, UCLA, INFN, LANL, Radiabeam, CERN, KEK, PSI, MIT等实验室的广泛重视

■ 依赖C<sup>3</sup>技术构建直线对撞机, 精确测量Higgs

■ 依赖低温铜腔加速技术建造XFEL自由电子

激光装置:

- 5-10GeV: 紧凑型XFEL装置
- 10-20GeV: 高光子能量XFEL, 50-100keV

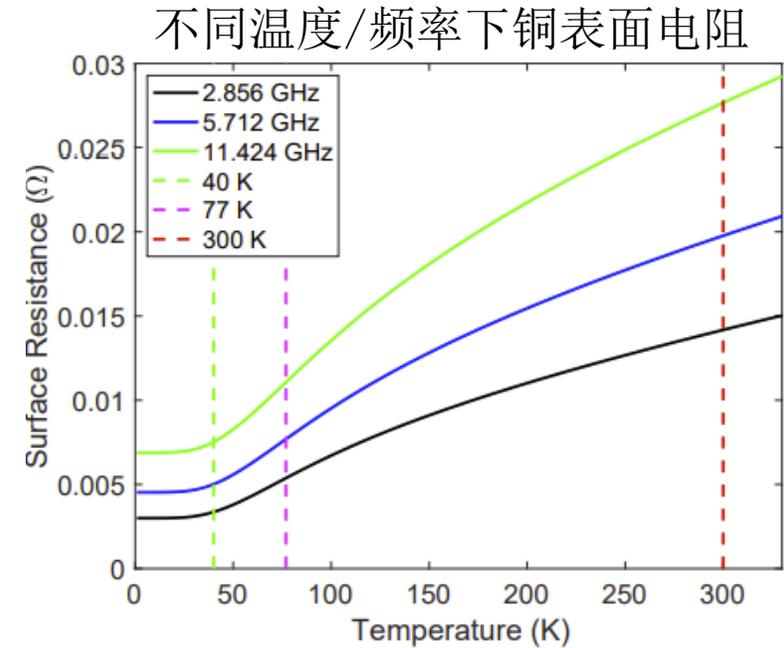
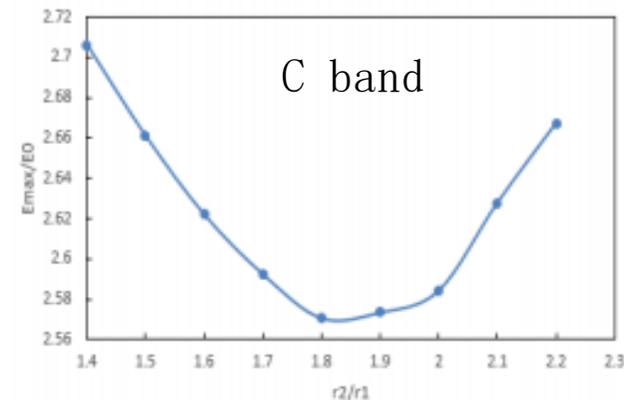
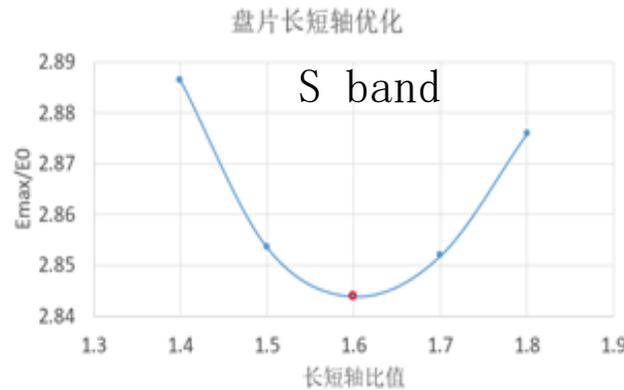
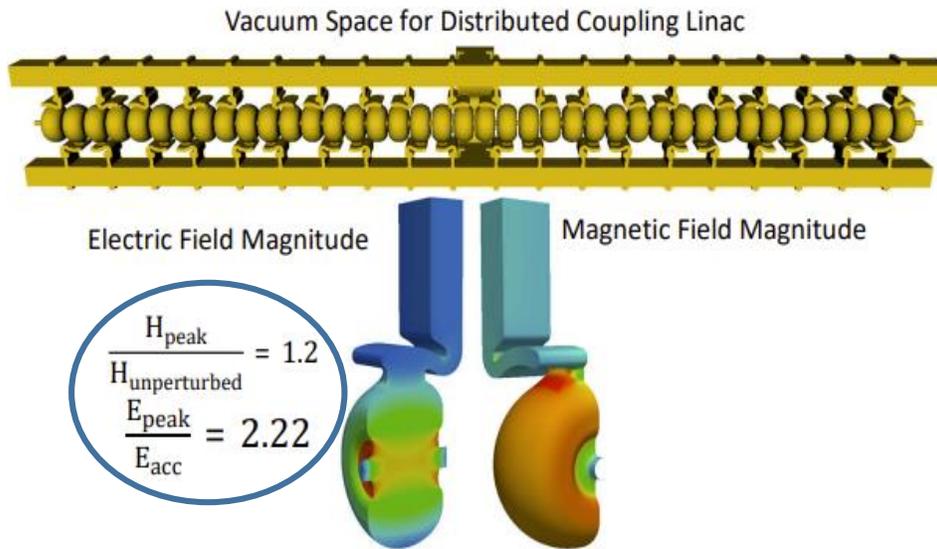
■ 其它应用:

- 工业与医疗
- 小型 $\gamma$ 源

Collider	CLIC[29]	ILC[5]	C <sup>3</sup>	C <sup>3</sup>
CM Energy [GeV]	380	250 (500)	250	550
$\sigma_z$ [ $\mu\text{m}$ ]	70	300	100	100
$\beta_x$ [mm]	8.0	8.0	12	12
$\beta_y$ [mm]	0.1	0.41	0.12	0.12
$\epsilon_x$ [nm-rad]	900	500	900	900
$\epsilon_y$ [nm-rad]	20	35	20	20
Num. Bunches per Train	352	1312	133	75
Train Rep. Rate [Hz]	50	5	120	120
Bunch Spacing [ns]	0.5	369	5.26	3.5
Bunch Charge [nC]	0.83	3.2	1	1
Beam Power [MW]	2.8	2.63	2	2.45
Crossing Angle [rad]	0.0165	0.014	0.014	0.014
Crab Angle	0.0165/2	0.014/2	0.014/2	0.014/2
Luminosity [ $\times 10^{34}$ ]	1.5	1.35	1.3	2.4
	(max is 4)			
Gradient [MeV/m]	72	31.5	70	120
Effective Gradient [MeV/m]	57	21	63	108
Shunt Impedance [ $\text{M}\Omega/\text{m}$ ]	95		300	300
Effective Shunt Impedance [ $\text{M}\Omega/\text{m}$ ]	39		300	300
Site Power [MW]	168	125	$\sim 150$	$\sim 175$
Length [km]	11.4	20.5 (31)	8	8
L* [m]	6	4.1	4.3	4.3

# C<sup>3</sup>高加速梯度：high field & low breakdown rate

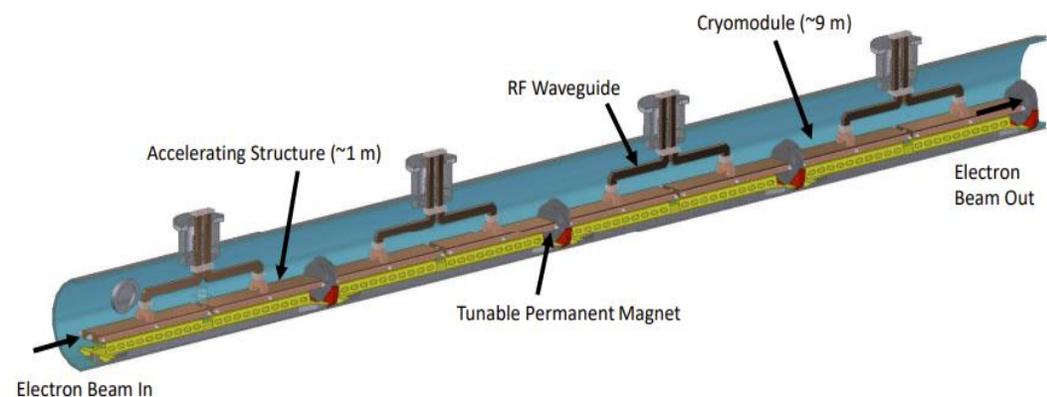
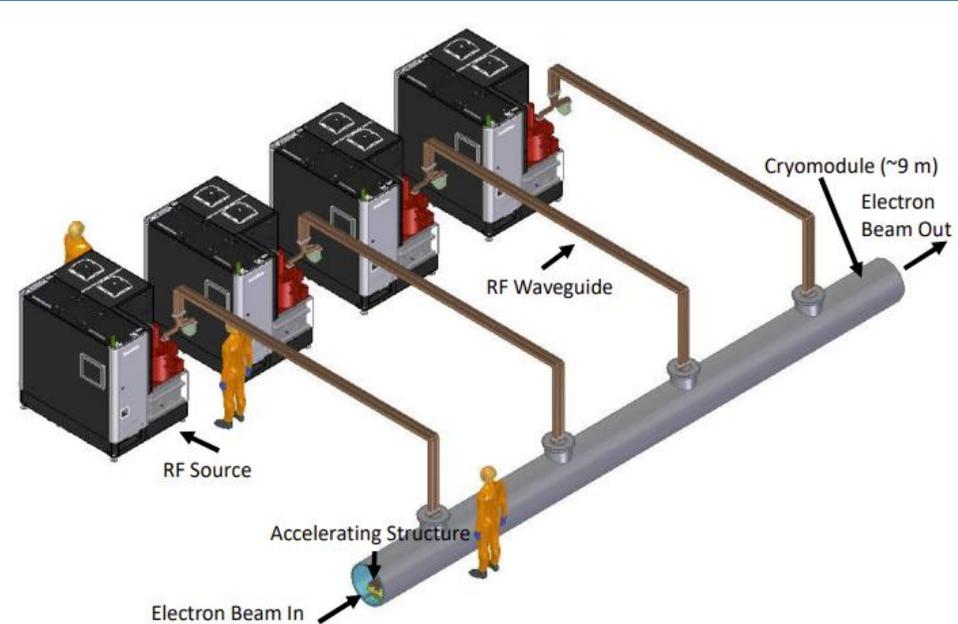
- C<sup>3</sup>主要的优势在于高加速梯度：120MV/m；常温S波段：~25MV/m；常温C波段：~45MV/m
- 采取的措施：
  1. 腔型优化，降低 $E_{peak}/E_{acc}$  → small iris → Blockage of fundamental frequency  
→ direct feed cavities → distributed coupling wave guide →  $H_{peak}$  raise 20%
  2. 降低温度到77K → 材料的屈服强度增高+损耗降低+热膨胀系数降低 → 提高gradient



加速梯度受射频击穿限制：射频击穿与材料的强度密切相关，如果材料不易变形，或者材料中的缺陷不易移动，在内表面形成小突起，则腔击穿率较低

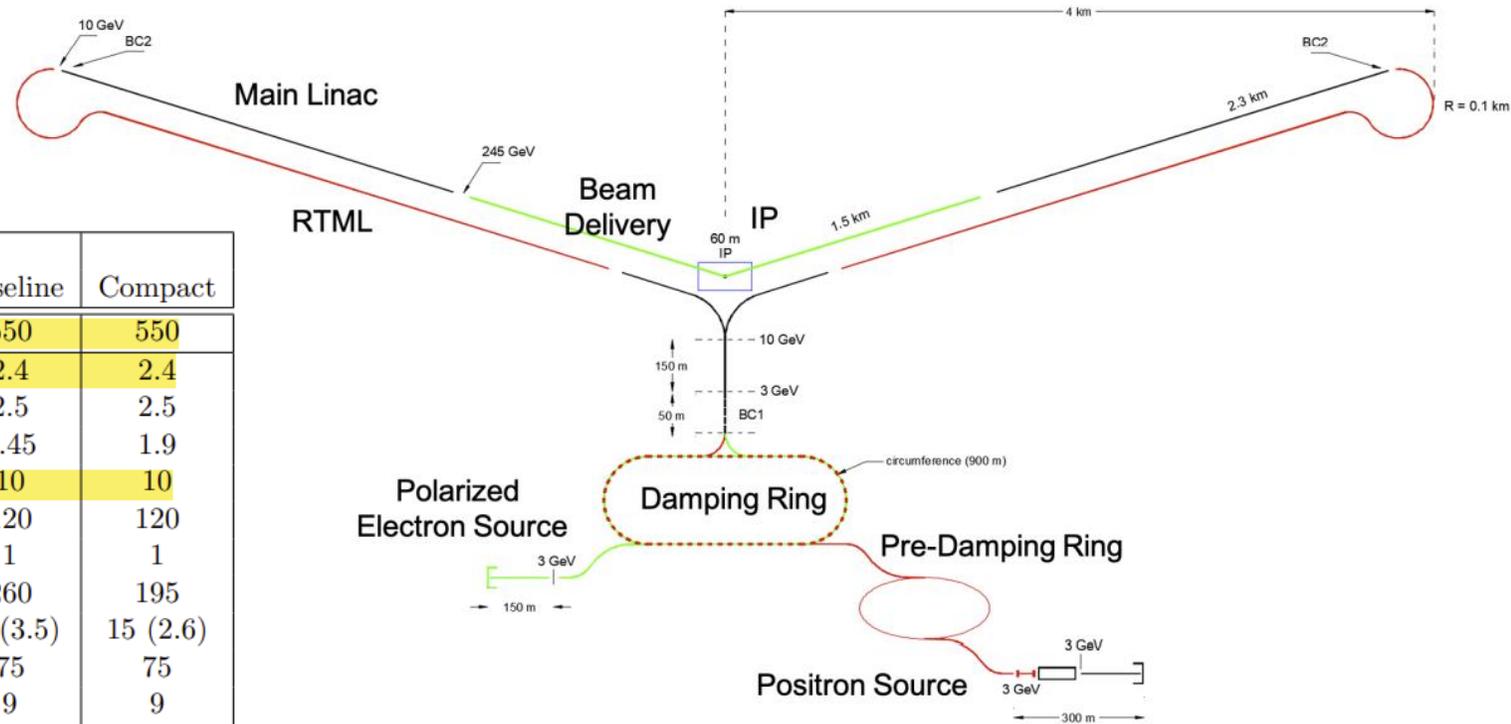
# C<sup>3</sup> 基本技术

- 加速腔/波导分两块1-m长铜材料整体加工(40 cell)
- 数字机床加工(CNC)
- 两部分拼接, 方向沿束流, 对RF性能影响小
- 高次模detune通过加工中微调每个cell形状
- Cell相移135°, 分路阻抗133MΩ/m



- 9m Cryomodule;
- 8 x 1m C<sup>3</sup> 加速结构
- 4 x 80MW C-band klystron, 1 to 2
- Flat top pulse

# 基于C<sup>3</sup>技术直线对撞机



Parameter Note	Unit			Baseline	Compact
Center of Mass Energy	GeV	91	250	550	550
Luminosity	$\times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	0.4	1.3	2.4	2.4
Single Beam Power	MW	0.7	2	2.5	2.5
Single Linac Active Length	km	0.56	1.83	2.45	1.9
Injection Energy Main Linac	GeV	10	10	10	10
Train Rep. Rate	Hz	120	120	120	120
Bunch Charge	nC	1	1	1	1
Flat-Top RF Pulse Length	ns	700	700	260	195
Bunch Spacing	Periods (ns)	30 (5.26)	30 (5.26)	20 (3.5)	15 (2.6)
Bunches per Train		133	133	75	75
Average Current	$\mu\text{A}$	16	16	9	9
Peak Current	A	0.19	0.19	0.3	0.385
Loaded Accel. Gradient	MeV/m	70	70	120	155
RF Power for Structure	MW/m	30	30	80	140

Parameter	Unit	Value	Value
Center of Mass Energy	GeV	250	550
Temperature	K	~80	~80
Pulse Length	ns	700	250
Cryogenic Load ~80 K	MW	9	9
Est. RF Power (Both Linacs)	MW	40	58
Est. Power for Cryogenic Cooling (Both Linacs)	MW	60	60
Total Est. Power (Both Linacs)	MW	100	118
RF Source efficiency (AC line to linac)	%	65	65

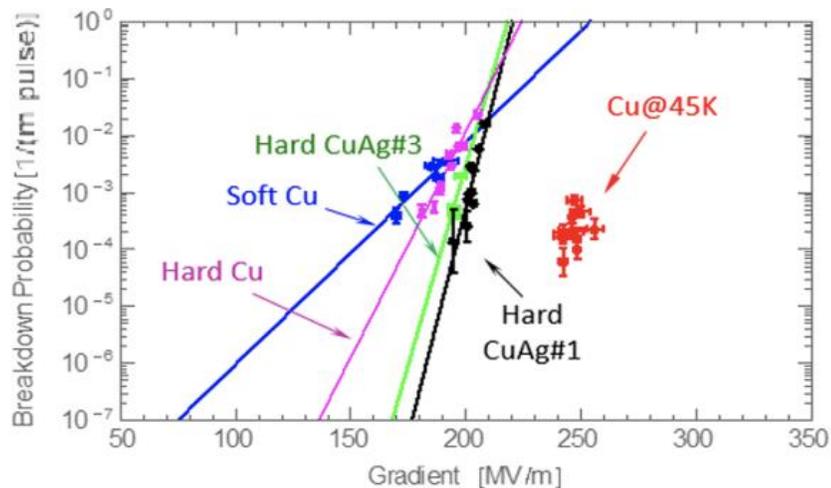
## • Low Cost RF Source

As the facility energy increases, RF source cost plays an ever larger role. To mitigate this, we can either make more efficient RF accelerator structures (at least until beam loading dominates) or reduce the cost of RF sources. Recognizing this need, the DOE General Accelerator R&D road-map for RF Accelerators calls out a goal of developing concepts which will be able to reduce the current large-volume unit cost of about \$7.5/peak-kW to \$2/peak-kW of RF. Many concepts are being pursued to achieve this goal [39], and the C<sup>3</sup> demonstration facility would be an excellent proving ground for maturing this technology and integrating it in a compatible way with the overall system's RF-only energy upgrade. There would be a 15 year-window from the start of the demonstration facility construction to the energy upgrade in order to develop these concepts and transition them to industry.

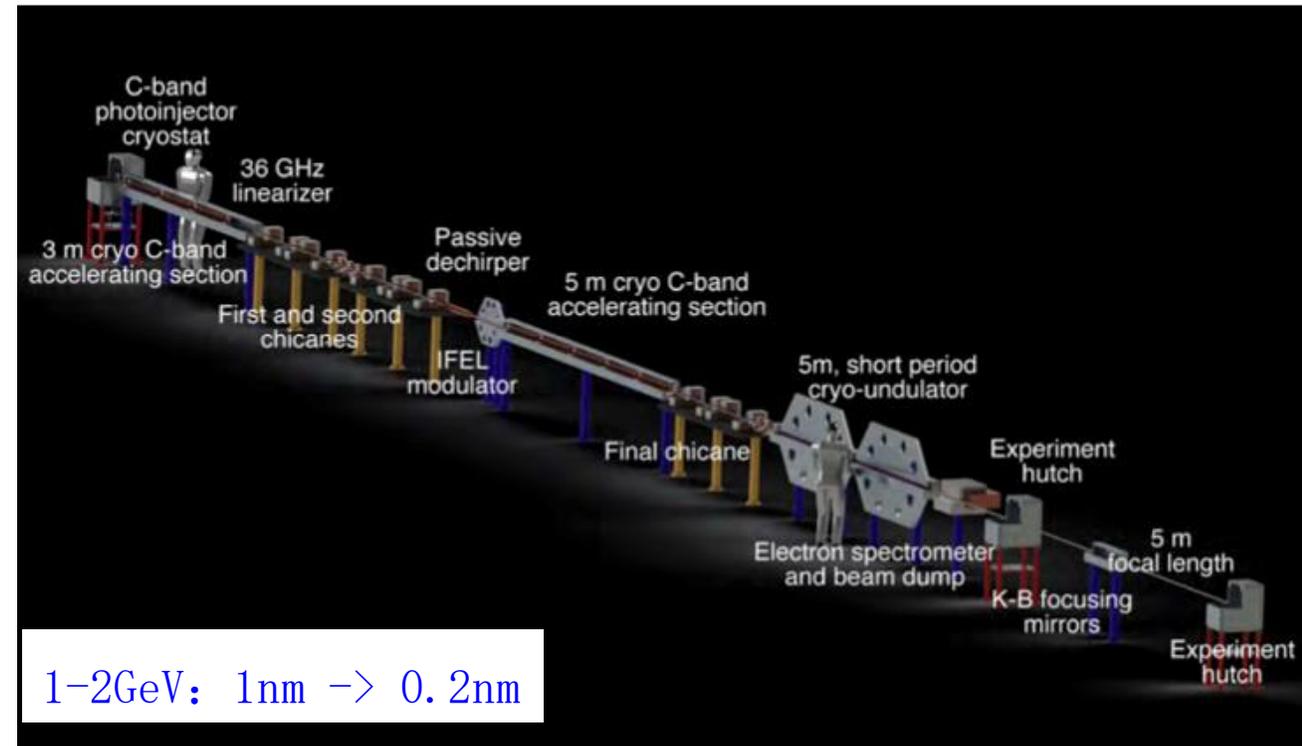
# C<sup>3</sup>技术驱动XFEL：紧凑型XFEL

- 低温gun, 极小发射度, ultra compact XFEL (UCLA proposal)
  - multi-kA electron beams, **50nm-rad** normalized emittances
    - High-gradient RF cryo-copper structure w/ surface electric fields 250~500MV/m
      - Photoinjectors with 6D beam brightness over one order beyond state-of-art
      - **GeV** scale electron beam in less than **10m**
    - Inverse free electron laser-based bunching technique
  - Short-period (**1-10mm**) undulators

液氮温区高  
梯度下铜材  
breakdown  
rate



photon production per pulse of **a few percent** of existing XFEL sources, in both soft & hard X-rays, less than **5% in costs** of existing XFELs, **scale < 50m**



# C<sup>3</sup>作为CEPC直线注入器的考虑

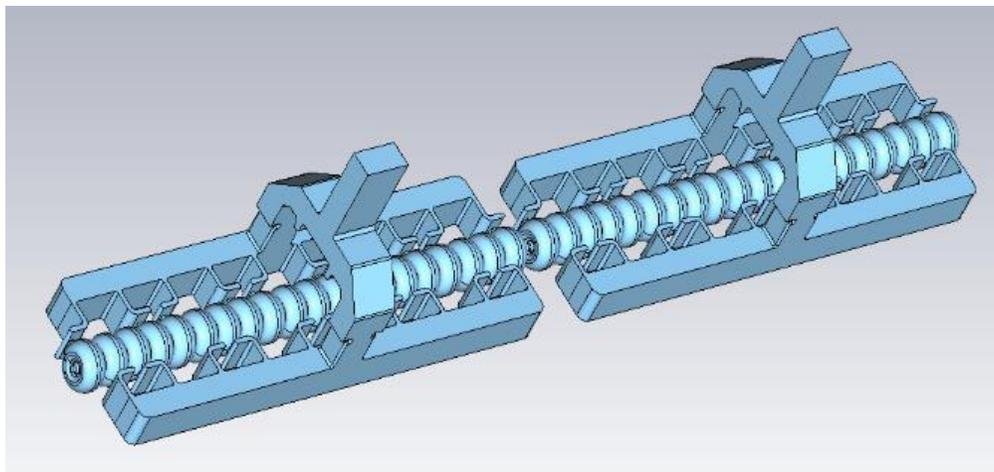
- 对于1nC bunch train, C<sup>3</sup> 技术优化频率在C波段（5.7GHz）：电荷量符合CEPC booster注入需求
- CEPC的直线升能方案（20-30GeV），1.1GeV → 20GeV加速拟采用C波段加速结构：C<sup>3</sup> 与CEPC直线加速器有共同的C波段功率源等技术需求

	CEPC baseline	C <sup>3</sup>	CEPC baseline 80MW
Klystron Power (MW)	50	80	80
Length/tube (m)	1.8	1	1.8
Iris aperture(2a) ( mm)	11.8~16	5.25!	11.8~16
Connection mode	1 to 2	1 to 2	1 to 4
Gradient (MV/m)	40	120	40
Total length(m) (only AS)	3.6	2	7.2
Total energy (MeV)	144	240	288
Pulse compressor	Y	N	Y
Load	Y	N	Y
Cryomodule	N	Y	N

# 高能所正在开展的 C<sup>3</sup> 技术相关工作

- 物理设计与样段研制：断耦合驻波结构、低温对加速梯度的贡献验证
- 分析 C<sup>3</sup> 技术对CEPC注入器的帮助：注入 C<sup>3</sup> 的能量, emittance compatibility, wakefield impedance effects
- C波段速调管 R&D
- C<sup>3</sup> 加速结构的短样加工与测试

Tentative work by Jingru Zhang: distributed coupling Acc.,  $\pi$  mode, simple manifold, ...

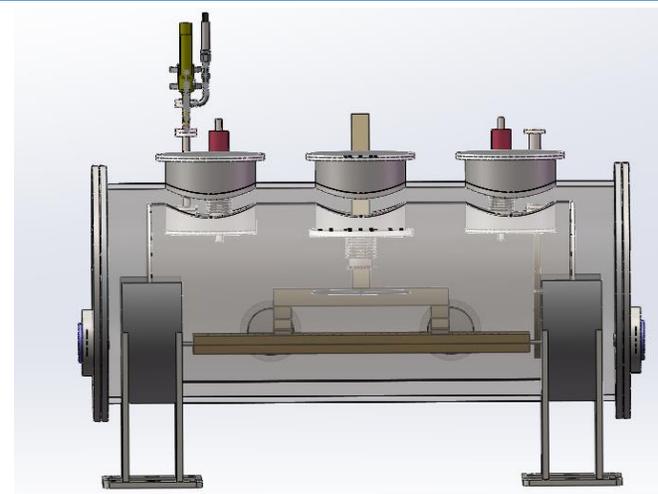
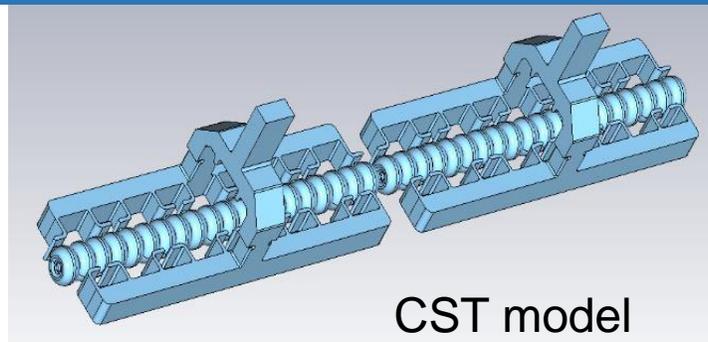


C波段速调管设计参数 by 周祖圣

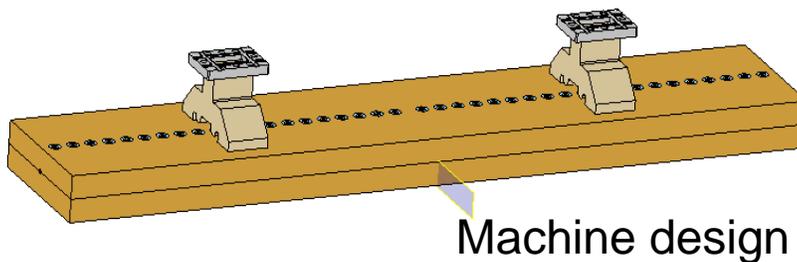
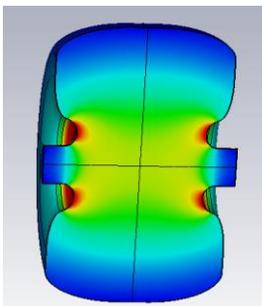
参 数	值
频率(MHz)	5720
脉冲高压(kV)	420
脉冲电流(A)	350
输出功率(MW)	80
脉宽(us)	3
效率(%)	55
重复频率	200
平均功率(kW)	48

# C<sup>3</sup>加速结构研究进展 @ IHEP

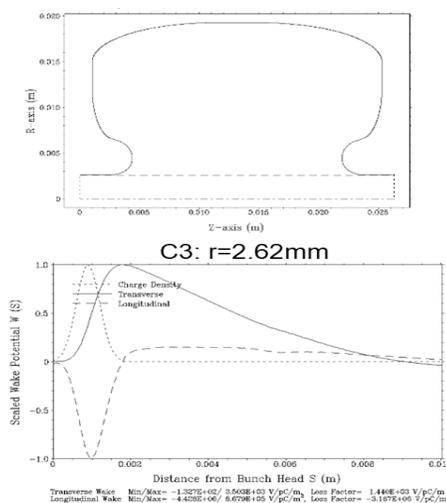
- Frequency: 5712MHz
- LN: 77k
- Cell number: 40
- Mode:  $\pi$



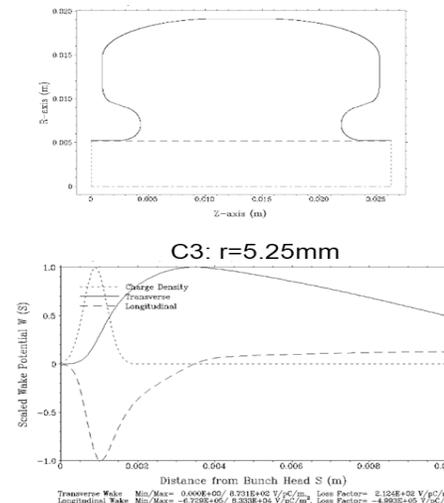
Cavity optimization  
 $E_{s\_peak}/E_0=2.16$



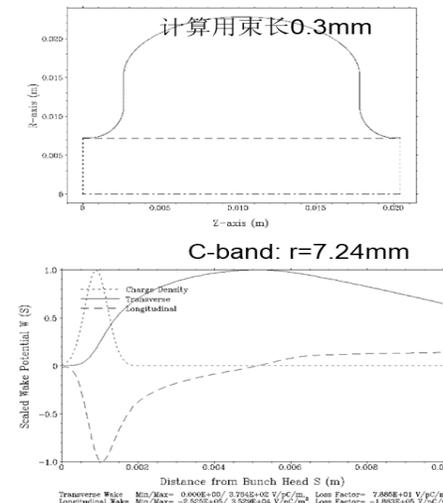
不同结构的尾场计算



Transverse Wake Max. = 3503 V/pC/m  
 Loss factor = -14.8 V/pC



Transverse Wake Max. = 873 V/pC/m  
 Loss factor = -7.2 V/pC



Transverse Wake Max. = 378 V/pC/m  
 Loss factor = -5.1 V/pC

# 低温铜加速器小结

- 低温铜腔（液氮温度）提供更高的加速梯度和宏脉冲宽度（实现bunch train）
- 采用新型的加速腔设计（驻波）与加工技术（整体加工）
- 基于C波段的低温铜加速器为直线对撞机Higgs工厂提供新的选择

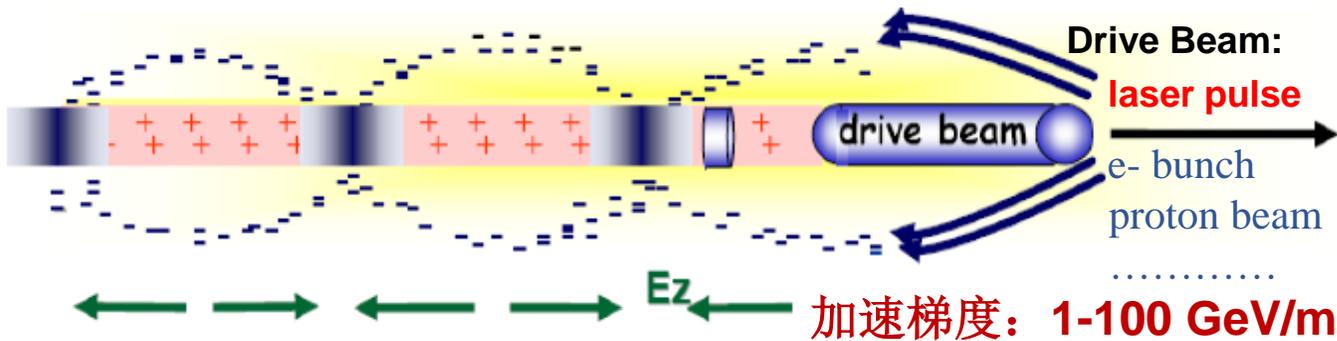
# 等离子体加速

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- 激光注入 (LWFA) 和粒子注入 (PWFA) 等离子体加速
- PWFA的国际发展情况
- PWFA技术用于CEPC注入器的研究

# 等离子体加速器的原理和分类

加速梯度:  $< 100\text{MeV/m}$

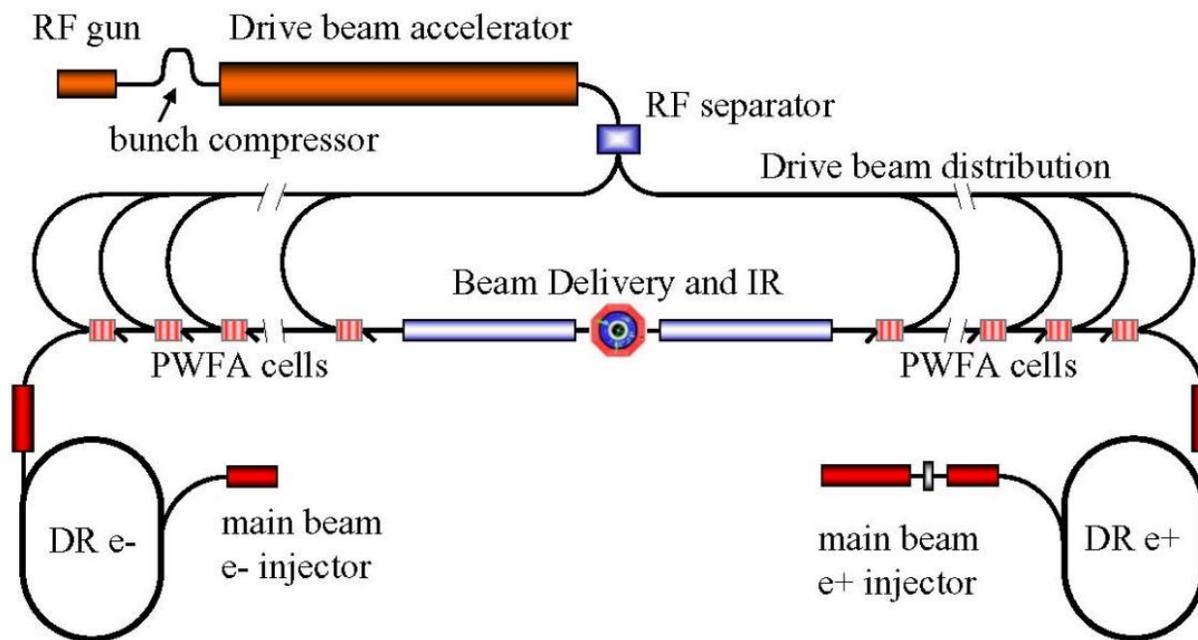
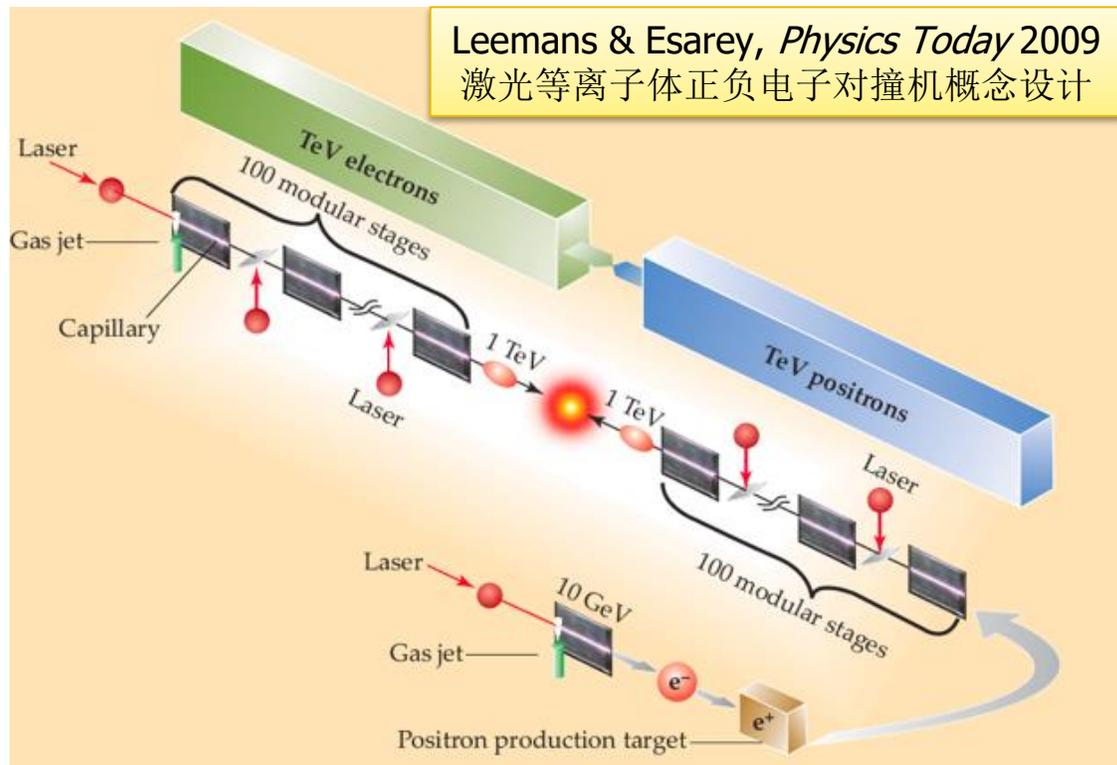


桌面型X/γ射线光源

强场物理研究平台

高能粒子对撞机

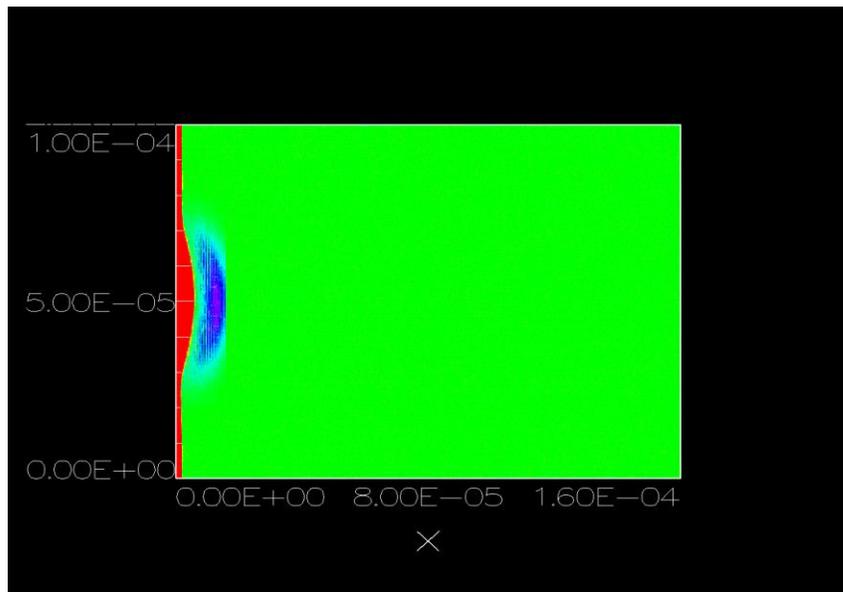
Leemans & Esarey, *Physics Today* 2009  
激光等离子体正负电子对撞机概念设计



基于PWFA的直线对撞机 ( $e^+e^-$ ) 概念设计



# 激光驱动与粒子驱动等离子体加速



能量

从零起步 Vs. 高能粒子

驱动源最大平均功率

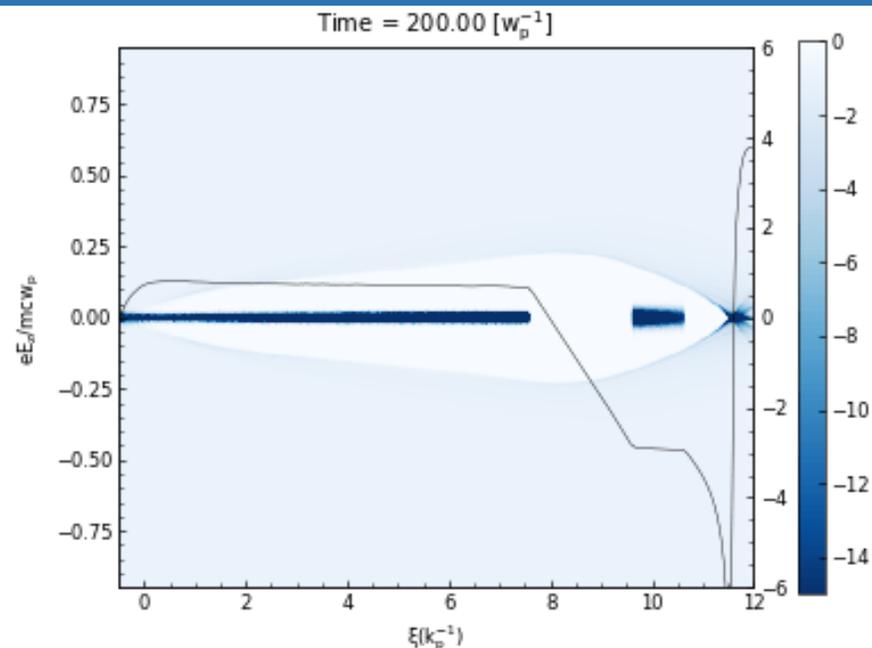
300 W (ELI-NP) Vs. 5.25 MW (ILC)

转换效率

~ 1% Vs. ~ 60%

最大有效加速距离

10 cm (失相) Vs. 10 m ( $\beta$ 函数)

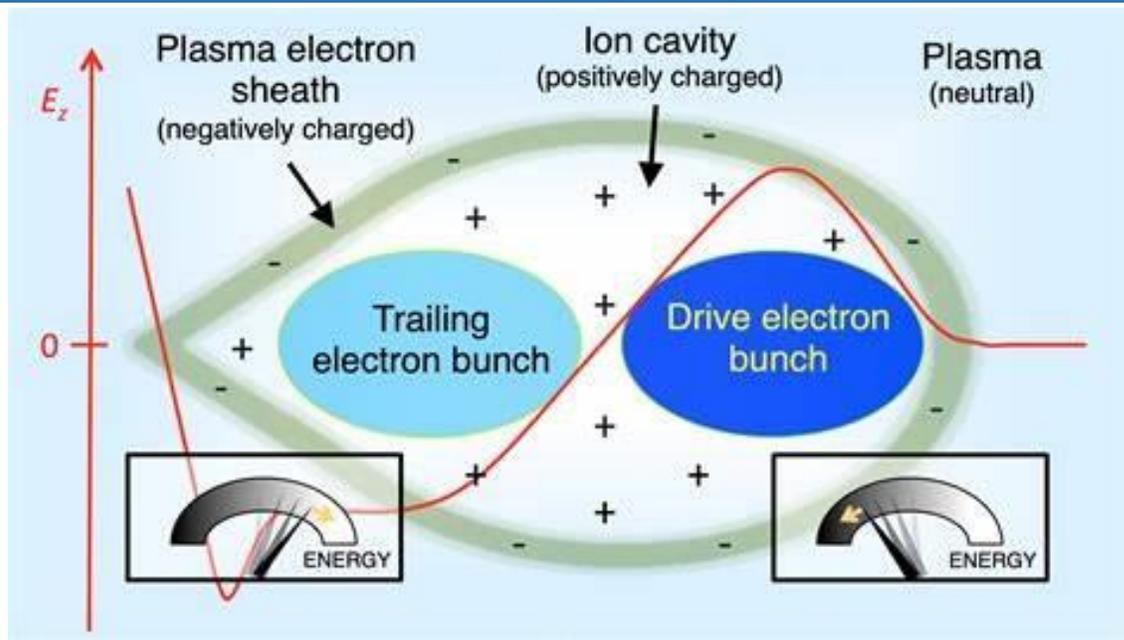


激光等离子体加速器特点:

- 无需前级加速器或电子源, 可实现真正的“桌面型”加速器/辐射源
- 开展研究门槛较低, 近年来广受国内外关注
- 失相制约加速距离, 单级能量有限, 需要级联以提升加速能量
- 研究热点: 电子束束流品质与稳定性的提升, 多级级联, 基于LWFA的桌面型光源实用化等
- 基于LWFA的桌面型光源在5-10年内有望成熟, 与基于传统加速器的同步辐射/FEL光源优势互补
- 目前驱动激光的平均功率和能量转换效率低, 暂不适合做高能对撞机



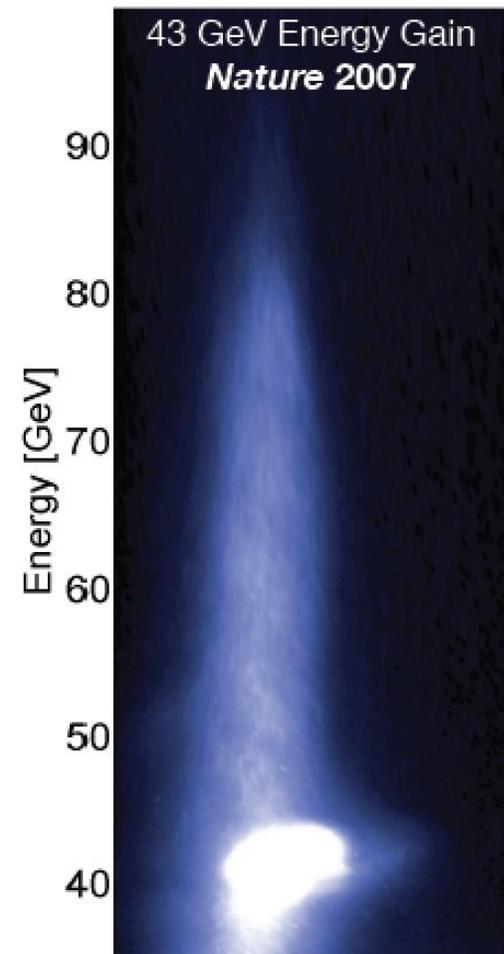
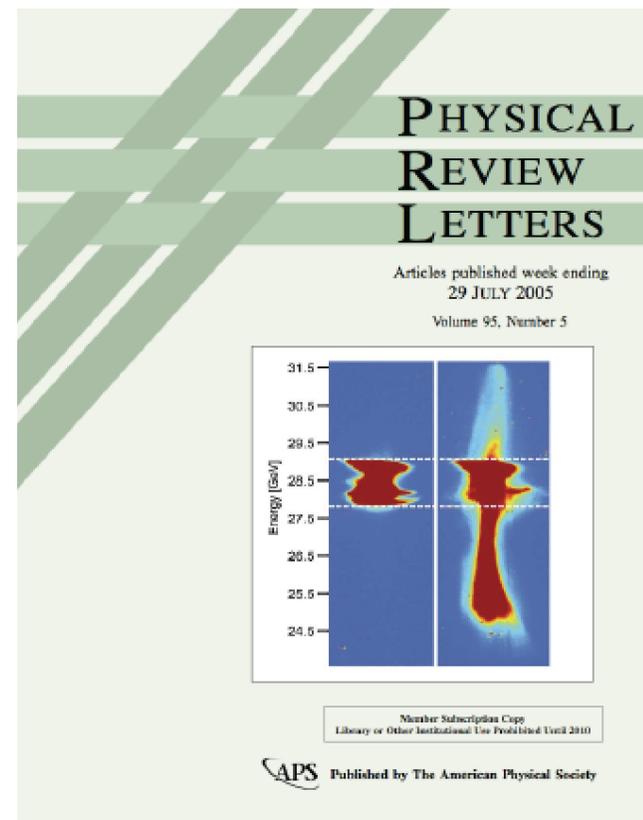
# 高能带电粒子束驱动的等离子体尾场加速器 (PWFA)



等离子体尾场加速器特点:

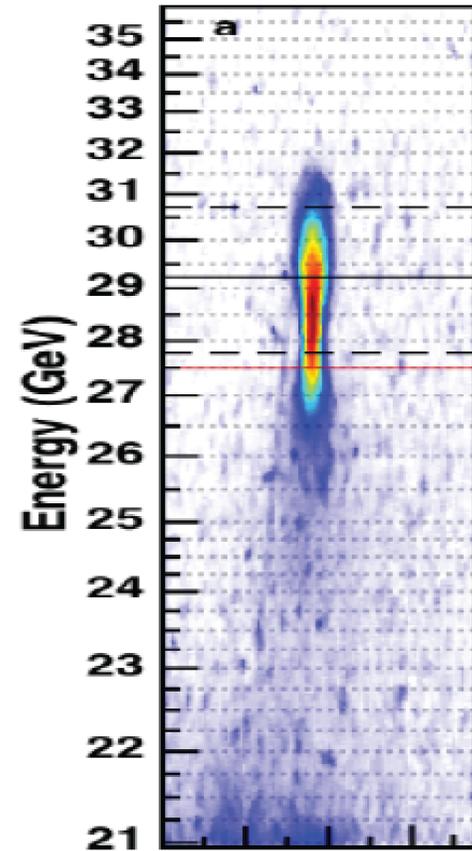
- 需要前级加速器及外注入电子源, 无法“桌面化”
- 无失相问题, 且能量转换效率高, 有望挑战高能前沿
- 实验研究门槛高, 仅在**FACET-II**, **FLASHForward**等装置上可开展相关研究
- 研究热点: 大电量、密度调制电子束产生, 不稳定性抑制, 正电子加速, 级联加速, 高精度束流操控等
- 以**PWFA对撞机**为目标, 还有很多待解决的问题, 尤其是迫切需要对关键的物理、技术问题进行实验验证

FFTb (FACET前身) 装置上的PWFA验证实验结果

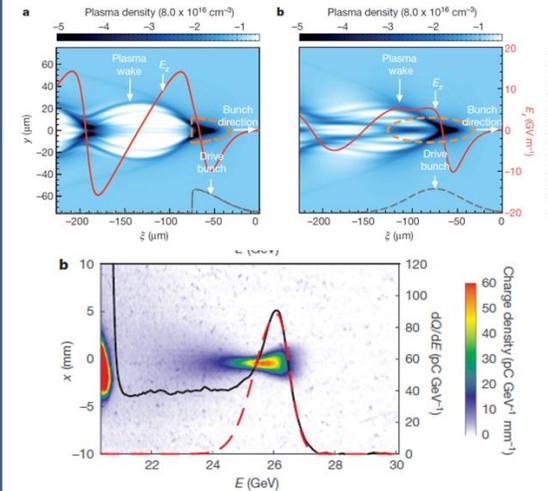


2007:  
Energy Doubling to 85 GeV

# Facility for Advanced Accelerator Experimental Tests at SLAC (2008-2016)



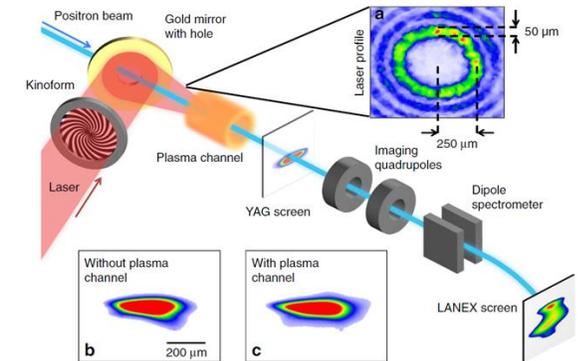
## Self-Loaded 正电子加速



实验结果:  $\Delta E = 5.76$  GeV with 1.3 m plasma

Multi-gigaelectronvolt acceleration of positrons in a self-loaded plasma wakefield, *Nature*, 14890,2015

## Hollow通道尾场加速



1. 成功演示无横向尾场hollow通道等离子体加速器，纵向尾场达230 MV/m;
2. 采用更小半径的通道和trailing正电子，GeV/m无发射度增长的加速将成为可能。

Demonstration of a positron beam-driven hollow channel plasma wakefield accelerator, *Nat. Commun.*,2016

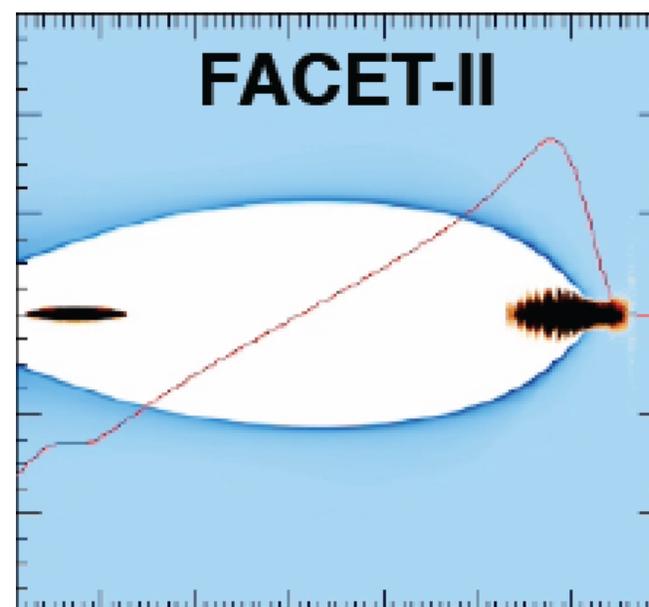
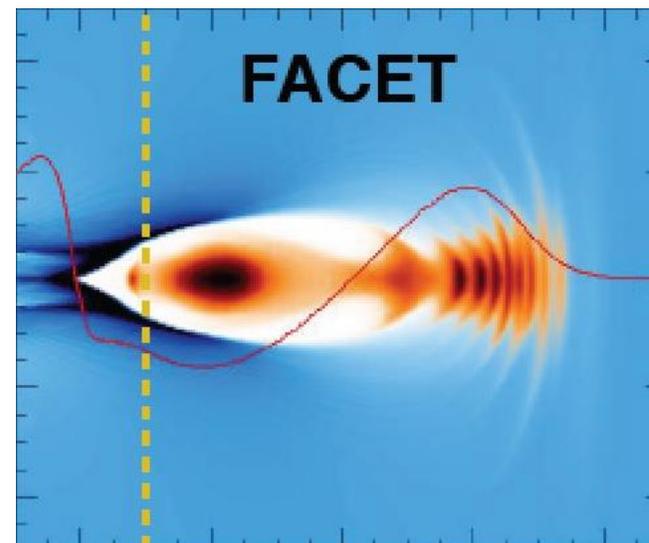
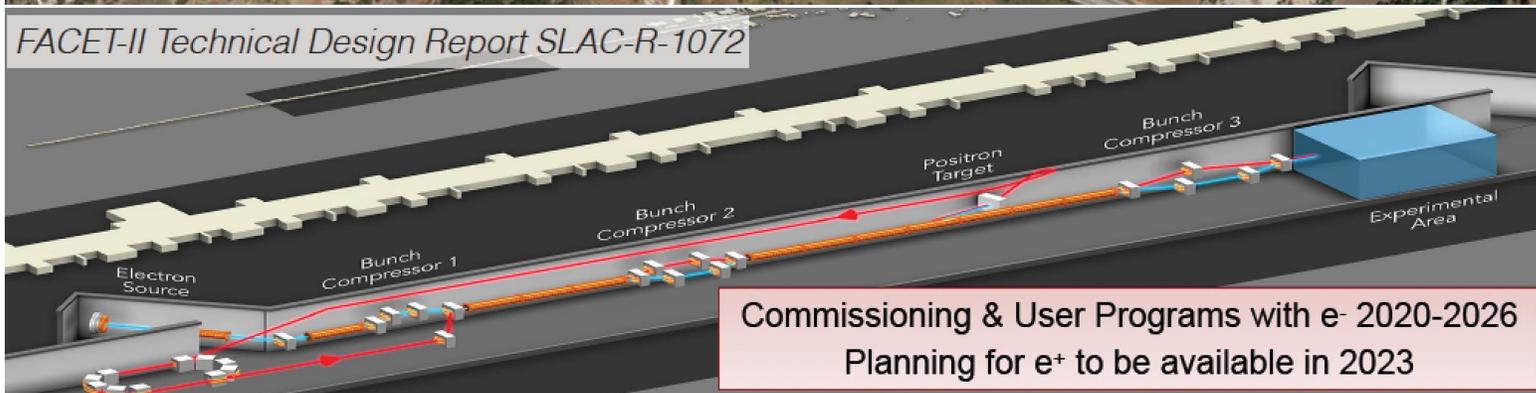
## Key PWFA Milestones @ FACET:

- 高效电子加速 (30%-50%)
- 能量增加9 GeV，能散好于2%

## Key PWFA Milestones @ FACET:

- 首次实现正电子加速 (self loaded)
- 加速效率有待提高

# FACET-II at SLAC: 更高品质、更高亮度的正负电子束

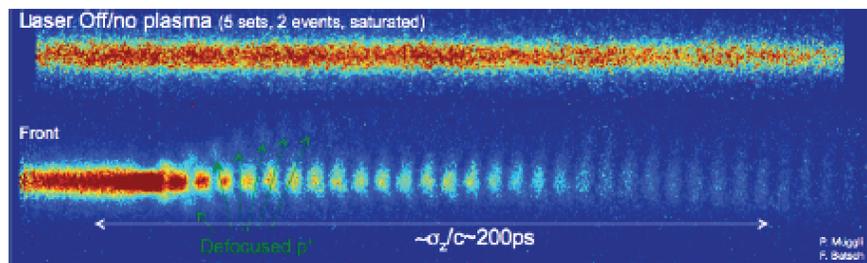


Electron Beam Parameter	Baseline Design	Operational Ranges	Positron Beam Parameter	Baseline Design	Operational Ranges
Final Energy [GeV]	10	4.0-13.5	Final Energy [GeV]	10	4.0-13.5
Charge per pulse [nC]	2	0.7-5	Charge per pulse [nC]	1	0.7-2
Repetition Rate [Hz]	30	1-30	Repetition Rate [Hz]	5	1-5
Norm. Emittance $\gamma\epsilon_{x,y}$ at S19 [ $\mu\text{m}$ ]	4.4, 3.2	3-6	Norm. Emittance $\gamma\epsilon_{x,y}$ at S19	10, 10	6-20
Spot Size at IP $\sigma_{x,y}$ [ $\mu\text{m}$ ]	18, 12	5-20	Spot Size at IP $\sigma_{x,y}$ [ $\mu\text{m}$ ]	16, 16	5-20
Min. Bunch Length $\sigma_z$ (rms) [ $\mu\text{m}$ ]	1.8	0.7-20	Min. Bunch Length $\sigma_z$ (rms)	16	8
Max. Peak current $I_{pk}$ [kA]	72	10-200	Max. Peak current $I_{pk}$ [kA]	6	12

# 欧洲的主要PWFA研究平台

## AWAKE @ CERN

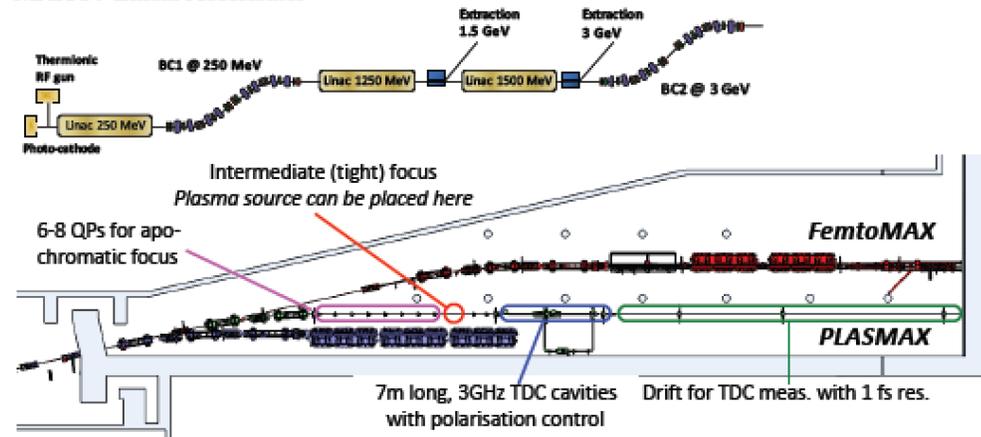
450GeV Proton Driven PWFA, Ongoing



## PLASMAX @ MAX IV

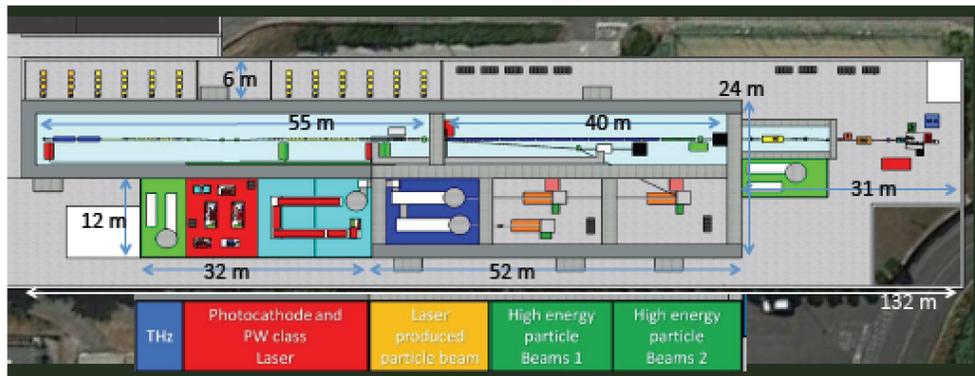
3GeV Electrons, Proposed for 2020+

MAX IV Linear Accelerator



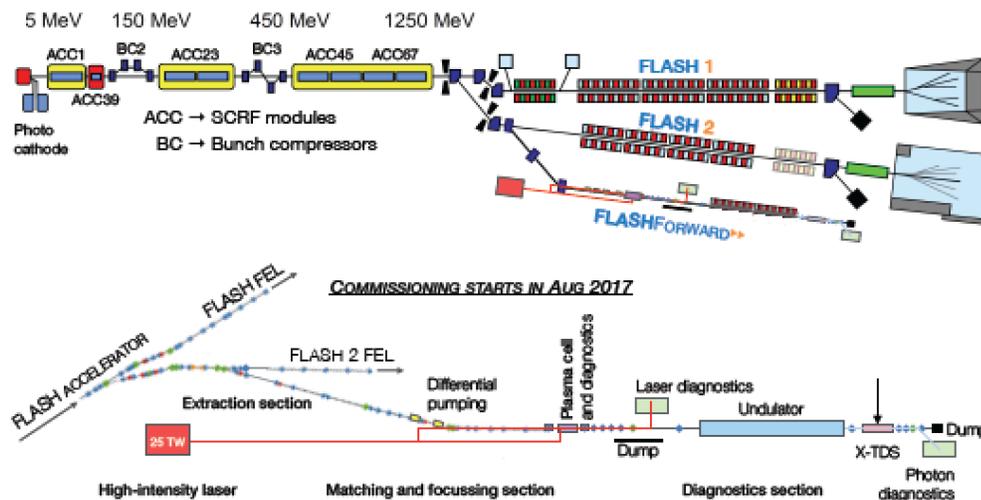
## EuPRAXIA @ SPARC\_LAB or DESY

1-5GeV Electrons, Proposed

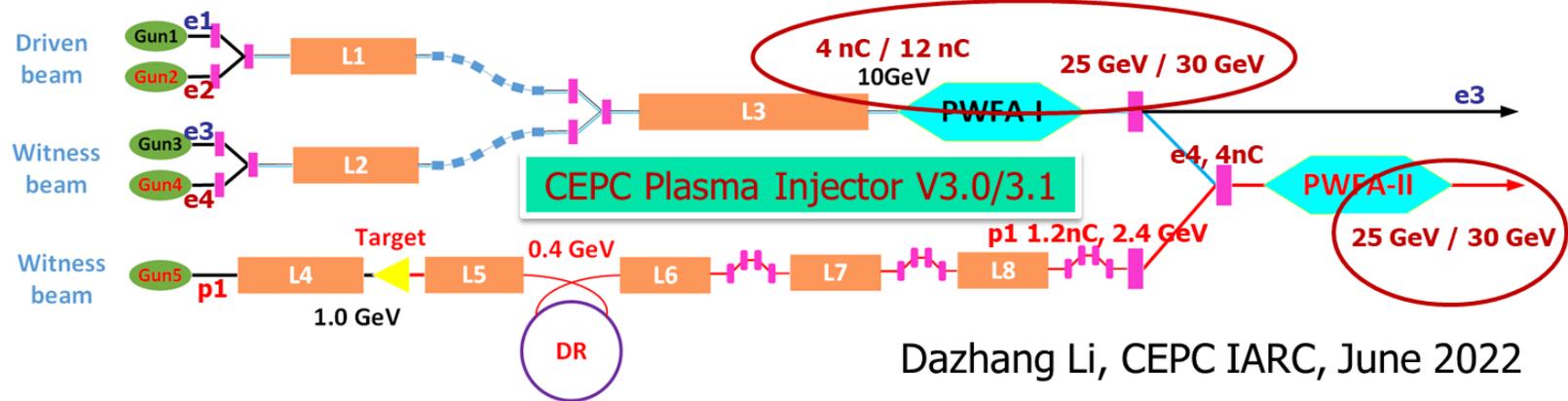
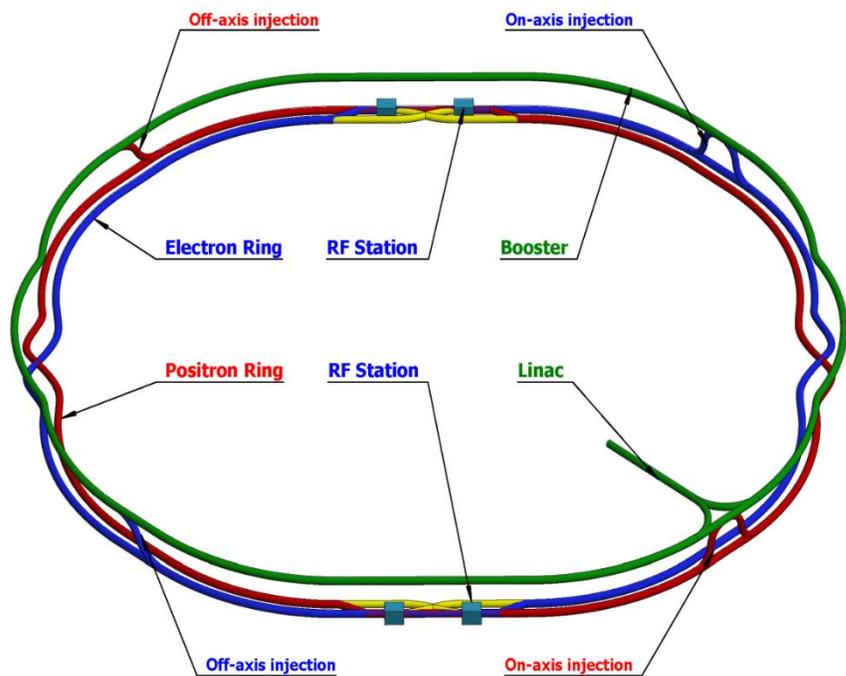


## FLASHForward @ DESY

1GeV Electrons, Commissioning



# CEPC等离子体注入器@IHEP



Dazhang Li, CEPC IARC, June 2022

## Booster dipole magnet challenges:

- Field error < 0.029Gs
- Field reproducibility < 0.015Gs
- The Earth field ~ 0.2-0.5 Gs, the remnant field of silicon steel lamination ~ 4-6 Gs.

V3.0 TR≥2	beam		Driver	Trailer
	plasma density $n_p (\times 10^{16}cm^{-3})$		0.50334	
	Driver energy $E (GeV)$		10	10
	Normalized emittance $\epsilon_n (mm mrad)$		20	10
	Length (um)		350	90
	(matched) Spot size(um)		3.89	2.75
	Charge (nC)		4.0	1.2
	Beam distance (um)		180	

Accelerating distance (m)	6.3
Trailer energy $E(GeV)$	30
Normalized emittance $\epsilon_n (mm mrad)$	10
Charge(nC)	1.2
Energy spread $\delta_E (%)$	0.32
Efficiency (%) (driver → trailer)	66.0

V3.1 TR≥1.5	beam		Driver	Trailer
	plasma density $n_p (\times 10^{16}cm^{-3})$		0.50334	
	Driver energy $E (GeV)$		10	10
	Normalized emittance $\epsilon_n (mm mrad)$		20	10
	Length (um)		305	80
	(matched) Spot size(um)		3.89	2.75
	Charge (nC)		4.63	1.5
	Beam distance (um)		184	

Accelerating distance (m)	4.8
Trailer energy $E(GeV)$	25
Normalized emittance $\epsilon_n (mm mrad)$	10
Charge(nC)	1.5
Energy spread $\delta_E (%)$	0.37
Efficiency (%) (driver → trailer)	52

# CEPC等离子体注入器：拟解决的关键问题及现状

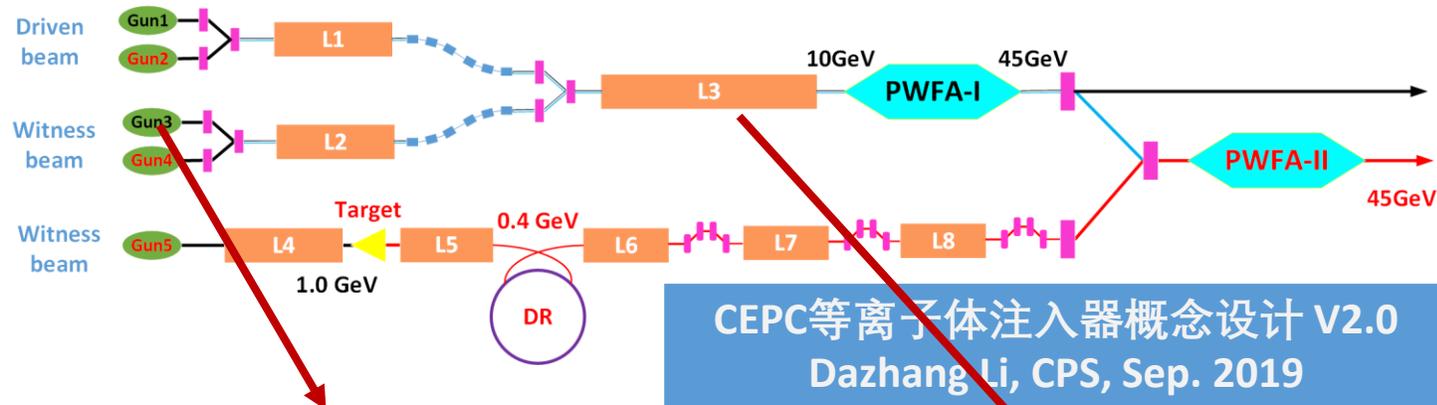
		初步理论分析	详尽数值模拟计算	初步实验验证
电子加速	高变压比 Vs. 不稳定性	√	√	
	加速效率及束流品质保持	√	√	
	误差容忍度分析	√		
正电子加速	稳定加速机制	√	√	
	能散及发射度控制	√	√	
	高效加速	√		
传统加速器设计与优化	L-band纵向密度可调的大电量电子枪	√		
	束流品质在直线加速器中的保持与优化	√		
	正电子的产生及发射度阻尼	√	√	
束流操控	等离子体能量补偿器	√	√	√
	完美外注入	√	√	√
	级联加速	√	√	√

- **CEPC**等离子体注入器研究是基于真实高能对撞机需求开展，提出新的要求
- 增强器的存在，大大降低了对等离子体加速器出口束流品质的要求（相比于**PWFA**对撞机）
- 国内亟需建设类似于**FACET-II**的专用**PWFA TF**装置，对关键的物理、技术问题进行实验验证

# CEPC等离子体注入方案：gun, 直线驱动加速器

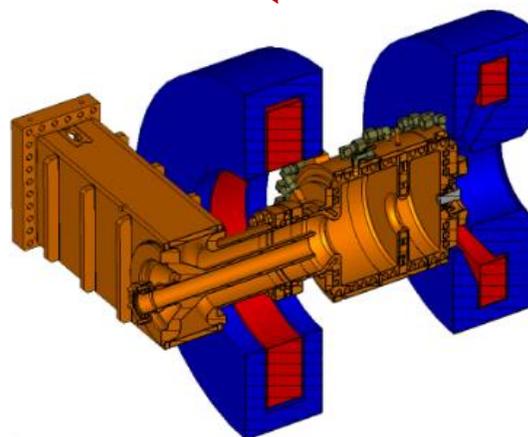
## CEPC Booster / Plasma Injector Requirement

Energy (GeV)	45.5
Bunch Charge (nC)	0.78
Bunch length(um)	<3000
Energy Spread(%)	0.2
$\epsilon_N(\mu\text{m}\cdot\text{rad})$	<800
Bunch Size(um)	<2000

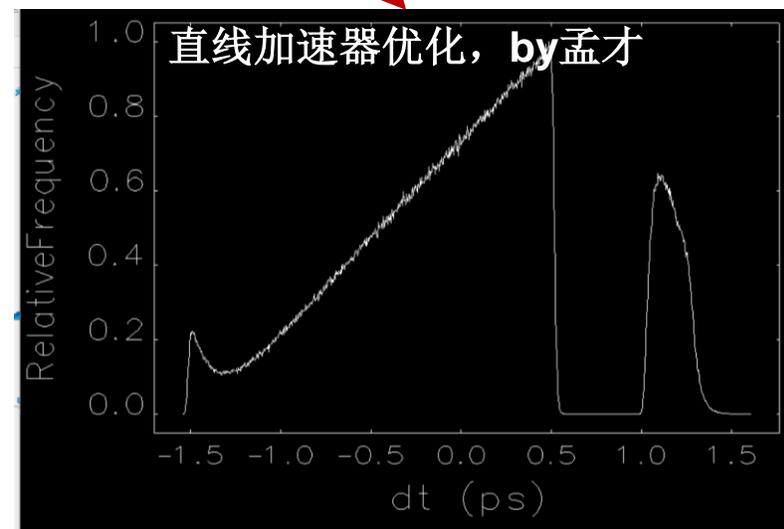
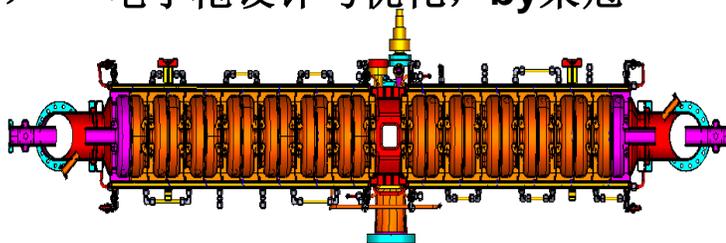


## CEPC等离子体注入器关键问题：

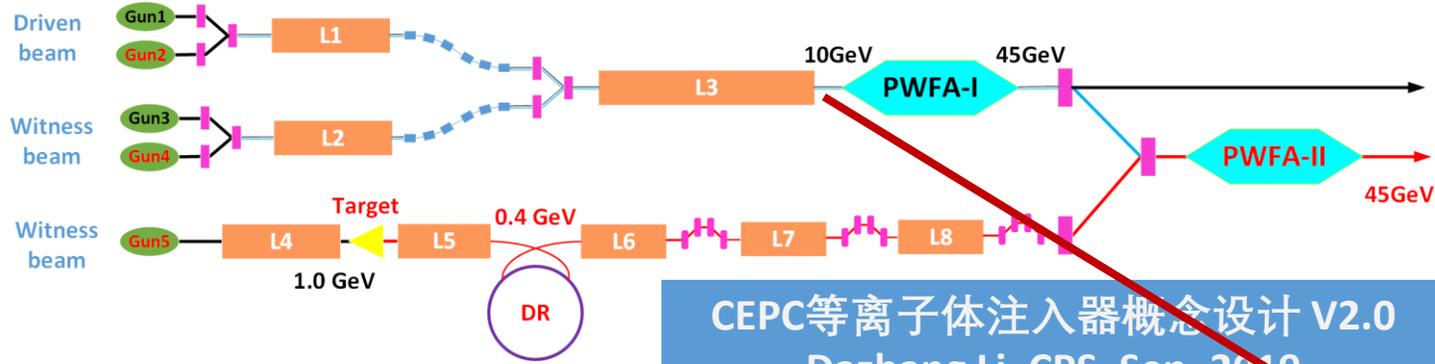
- 等离子体加速器与传统加速器的匹配
- 高变压比，以更好缓解booster压力
- 高效正电子加速
- 大电量、高平均功率驱动源
- 对束流参数的精细测量与操控（微米、飞秒）
- 级联加速



电子枪设计与优化, by束冠

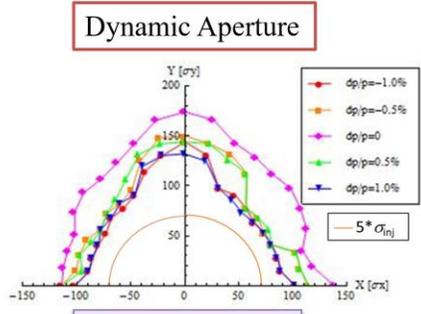
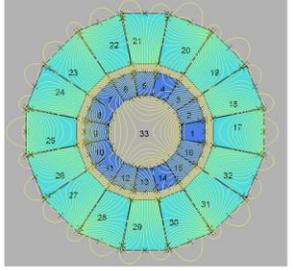
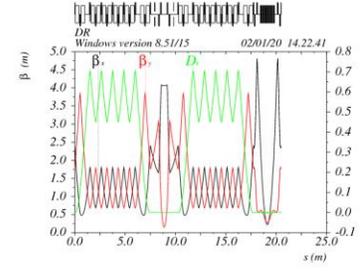
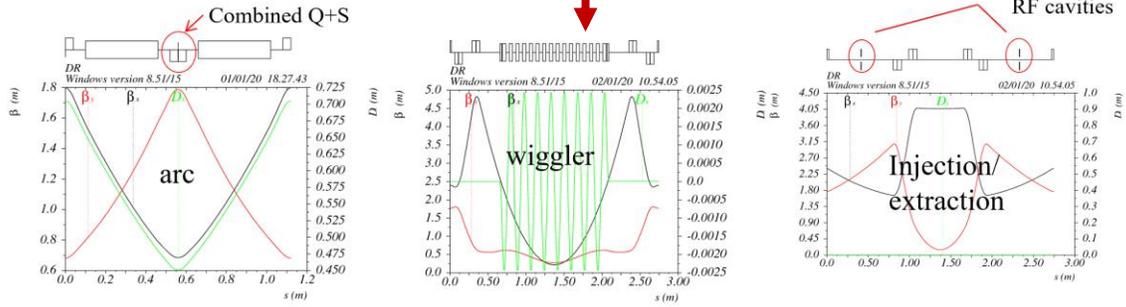


# CEPC等离子体注入方案：正电子源，等离子体注入



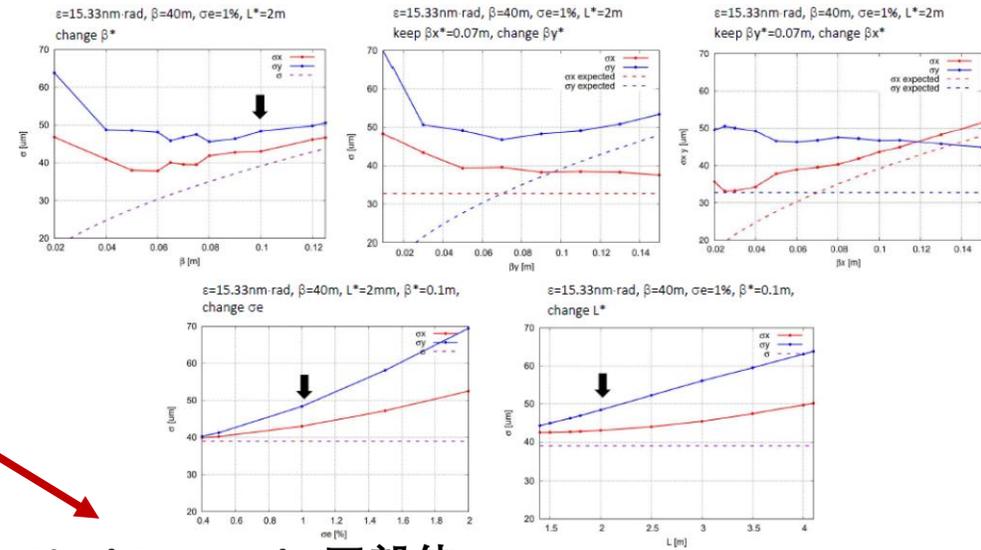
CEPC等离子体注入器概念设计 V2.0  
Dazhang Li, CPS, Sep. 2019

正电子束线, by王逗

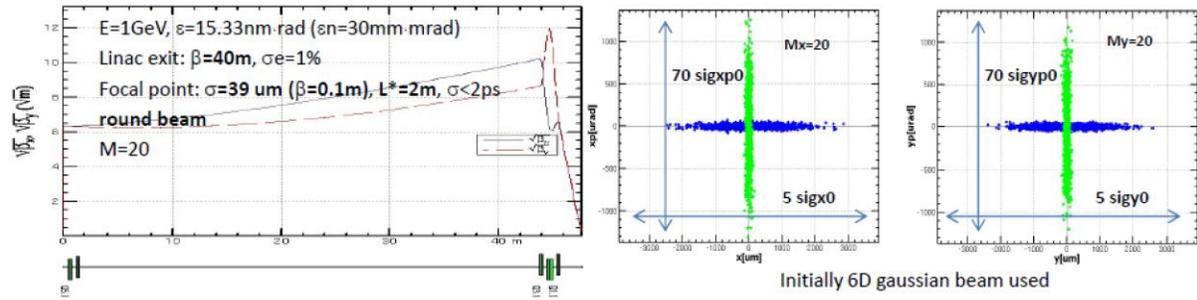


$$v_x / v_y = 3.16/3.21$$

- Combined quadrupole + sextupole (permanent magnet)
- Superconducting wiggler → shorter damping time & smaller equilibrium emittance

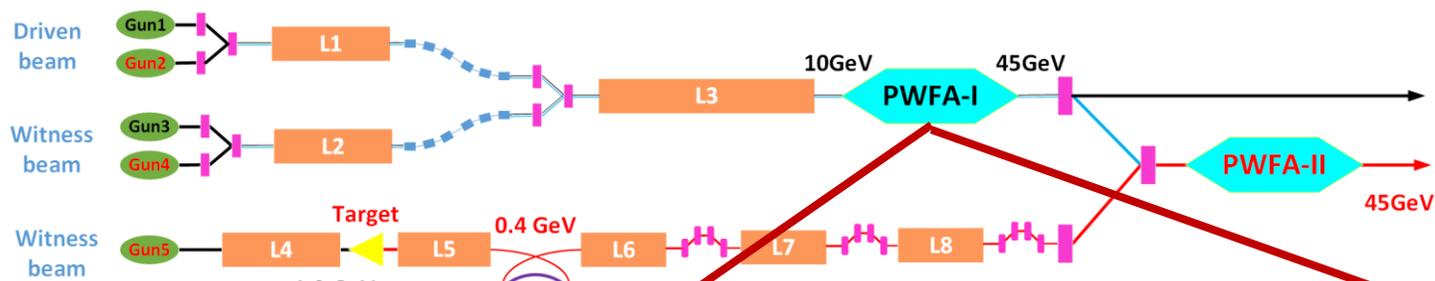


Final Focus, by王毅伟



	Gradient(T/m)	Length(m)	Beam stay clear region (mm)	Pole tip field (T) larger than
Q1	9.1	0.25	15	0.088
Q2	-7.6	0.50	23	-0.101
Q3	8.0	0.25	20	0.095

# CEPC等离子体注入方案：等离子体加速模拟 (IHEP CPI team)

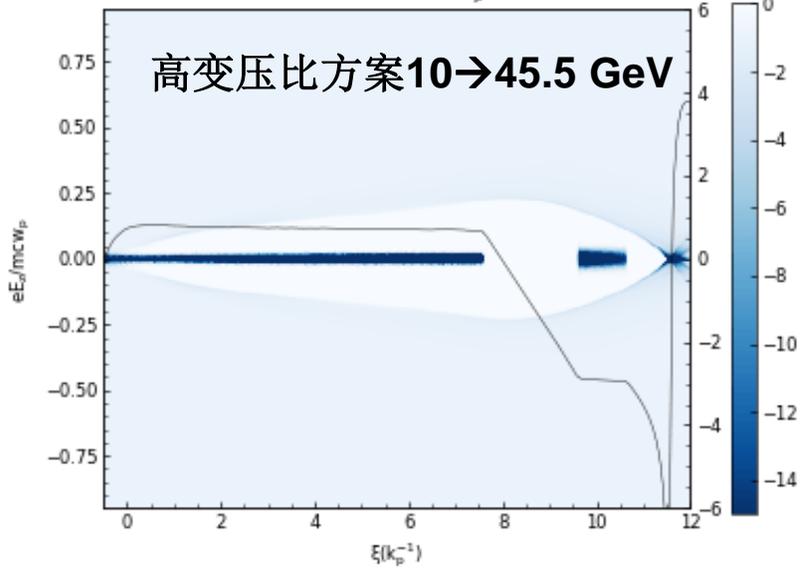


CEPC等离子体注入器概念设计 V2.0  
Dazhang Li, CPS, Sep. 2019

误差容忍度分析

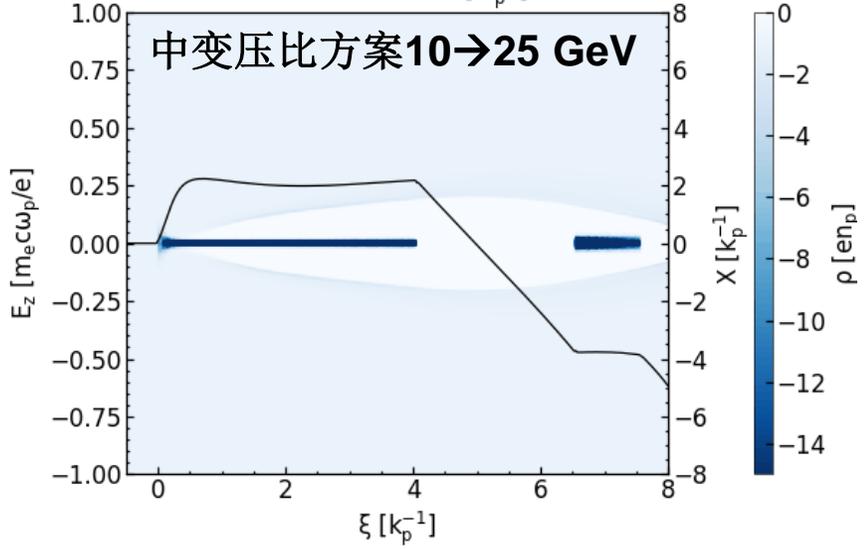
Perturbation	Limitation	limiting factor
beam charge	Driver	$[-1\%, 0.8\%]$ $E_t$
	Trailer	$[-0.24\%, 2\%]$ $E_t$
beam length	Driver	$\pm 1\%$ $E_t$
	Trailer	$\pm 5\%$ $E_t$
initial energy	driver	$[-1\%, 0.38\%]$ $E_t$
	trailer	$[-1.75\%, 0.37\%]$ $E_t$
initial energy spread		$3.9\%$ $E_t$
Spot size	driver	$[-40\%, 2\%]$ $E_t$
	trailer	$[8\%, 8\%]$ $E_t$

Time = 200.00 [ $\omega_p^{-1}$ ]

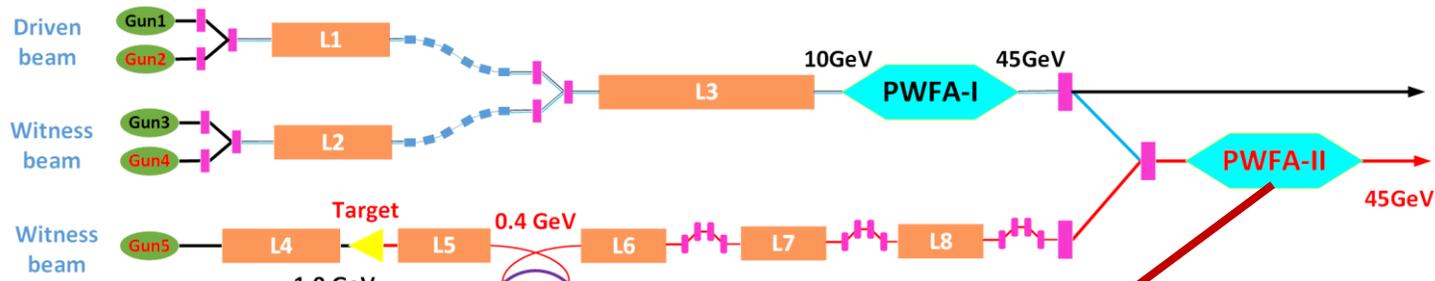


	V1.0 HTR	V2.0 NTR
Accelerating distance (m)	10.7	4.8
Trailer energy E(GeV)	45.5	25
Normalized emittance $\epsilon_n$ (mm mrad)	98.36	100
Charge(nC)	0.84	1.21
Energy spread $\delta_E$ (%)	0.40	0.40
TR	~ 4	~ 1.6
Efficiency(%) (driver -> trailer)	60.0	54.0

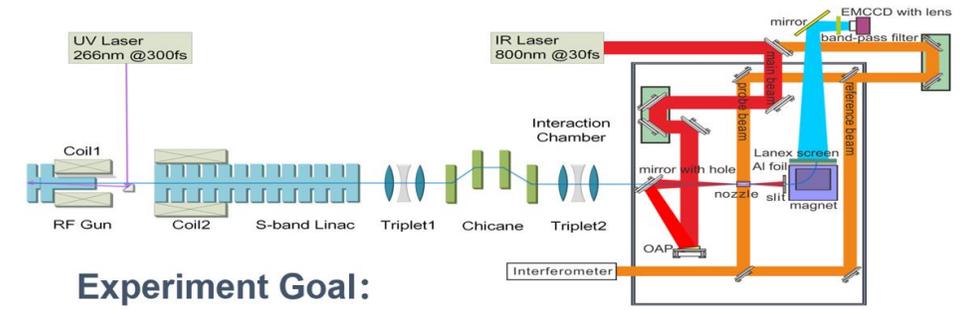
Time = 1000.00 [ $\omega_p^{-1}$ ]



# CEPC等离子体注入方案：正电子等离子体加速 (THU CPI)



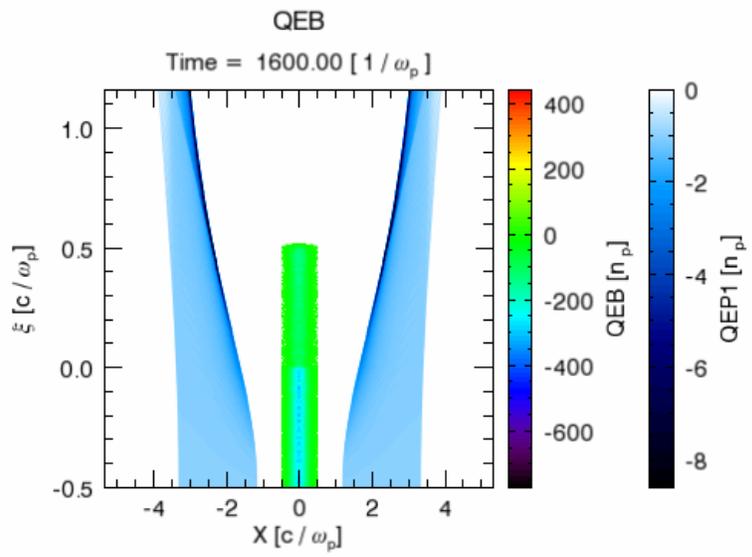
CEPC等离子体注入器概念设计 V2.0  
Dazhang Li, CPS, Sep. 2019



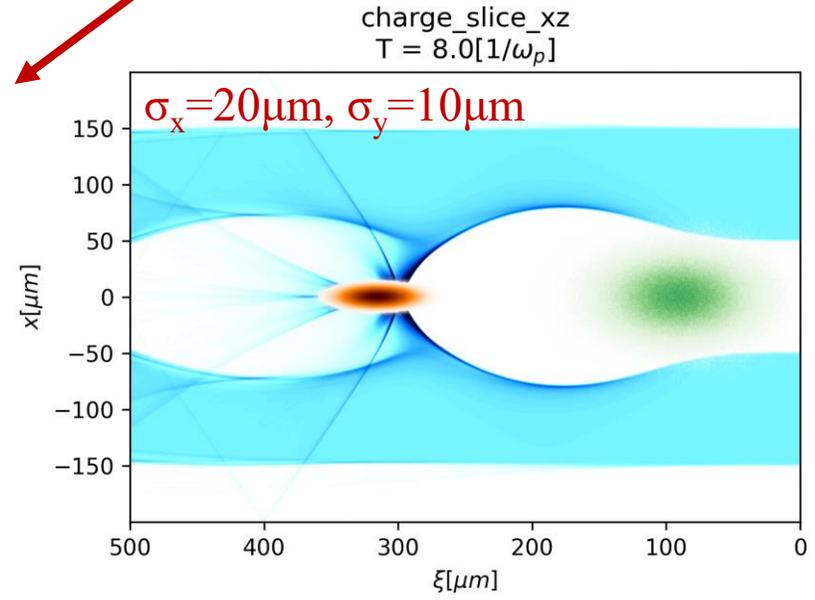
## Experiment Goal:

1. Decrease the energy spread from 1% to 0.1%
2. Study Hollow channel impact on beam quality

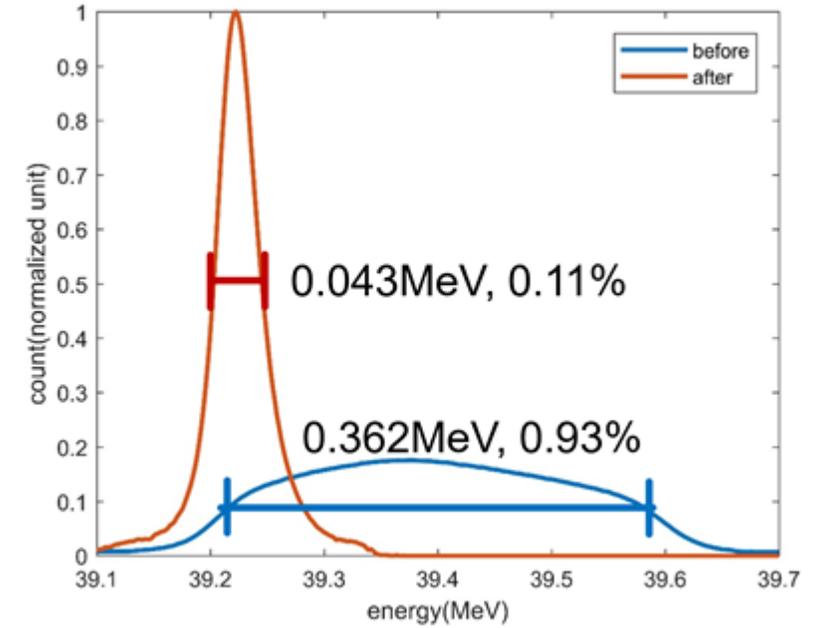
等离子体啁啾补偿器实验，能散1%→0.1%



正电子加速方案V1.0



正电子加速方案V2.0



# 等离子体加速器小结

- 激光等离子体（电子）加速在结果上已经有了非常大的进步，在关键参数的优化上也找到了继续优化下去的方法，接下来的重点是如何工程化，实用化
- 束流驱动的新加速原理天然和传统加速器（工程）相连，一旦关键原理（变压比，正电子加速等）得到实验的直接验证，就可以产生很好的应用
- CEPC 对等离子体加速提出新的要求：高能量、正电子、大电荷量。一旦成功可以有效提高CEPC的注入效率。技术可溢出到其它领域
- PWFA和LWFA在driver上的不同导致了用途和关键技术的差别。但是在等离子体源，加速结构，被加速束的不稳定性等方面还有很多相通之处，可以互为借鉴

谢 谢