

C波段光阴极及高梯度加速结构研究平台 平台及初步束流测试

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Institute of High Energy Physics Chinese Academy of Sciences (CAS)

散裂中子源科学中心

Spallation Neutron Source Science Center

WHY

我们为什么要搭建这么一个平台

HOW

平台现在什么样

WHAT

我们在做些什么

国内第四代先进光源



极限衍射环

自由电子激光

HEPS (Beijing)

- 6GeV SR facility
- 0.06nm-rad emittance
- 1360m storage ring



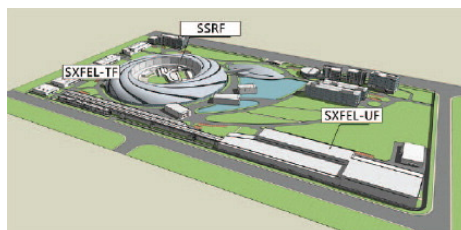
HALS (Hefei)

2.4GeV SR facility
0.03nm-rad emittance
672m storage ring



SXFEL (Shanghai)

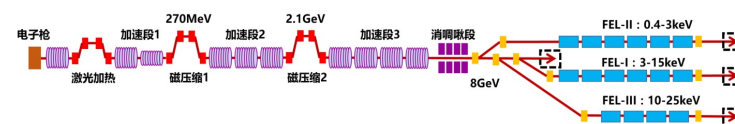
1.6 GeV, 10 Hz
530 m



SHINE (Shanghai)

8 GeV, 1 MHz
3 km

Shanghai High repetition rate XFEL and Extreme light facility (SHINE)



中能

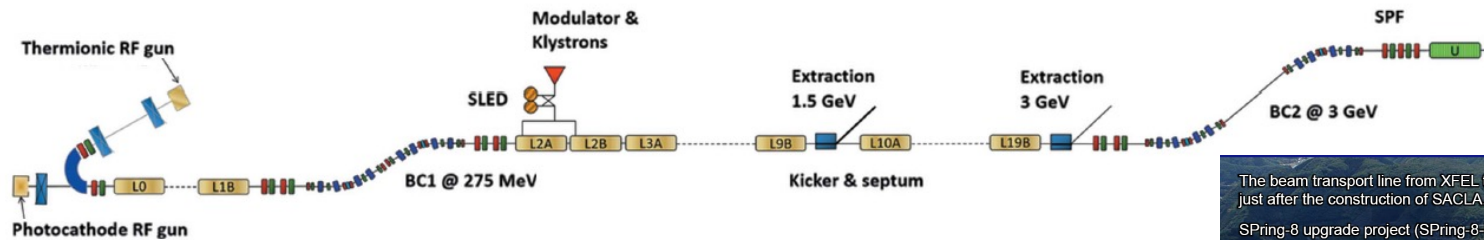
3.5 GeV SR
0.06 nm.rad
<1000 m

SAPS (Great Bay Area)

全能量直线注入方式
极限衍射环 + 自由电子激光

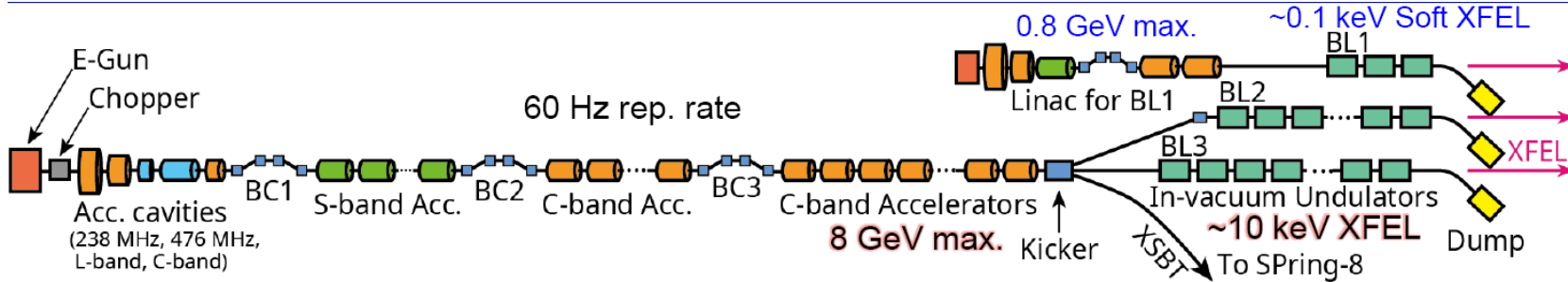
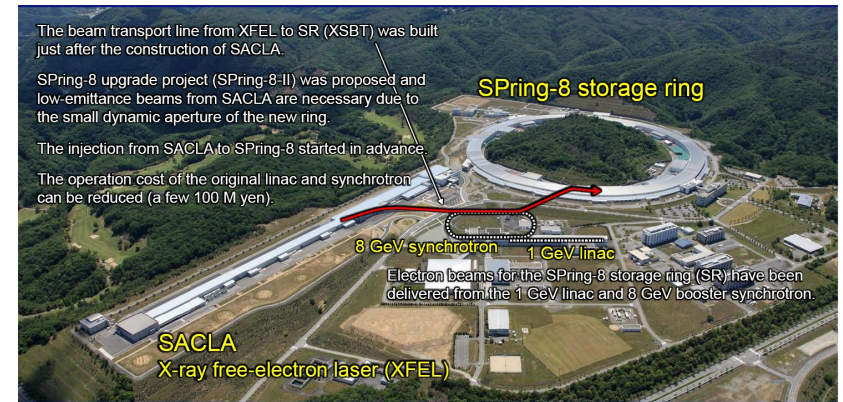
3.5~5.5 GeV FEL, 100 Hz
~700 m (加速器200~300m)

全能量直线注入的衍射极限环



MAX-IV & SXL Project

Spring8-U & SACLA



南方先进光源规划图

集**散裂中子源**与**同步辐射**，**自由电子激光**为一体的综合性光学研究平台

❖ 中国散裂中子源二期工程 - “十四五”规划

❖ 南方先进光源预研



南方先进光源预研

电子枪测试平台

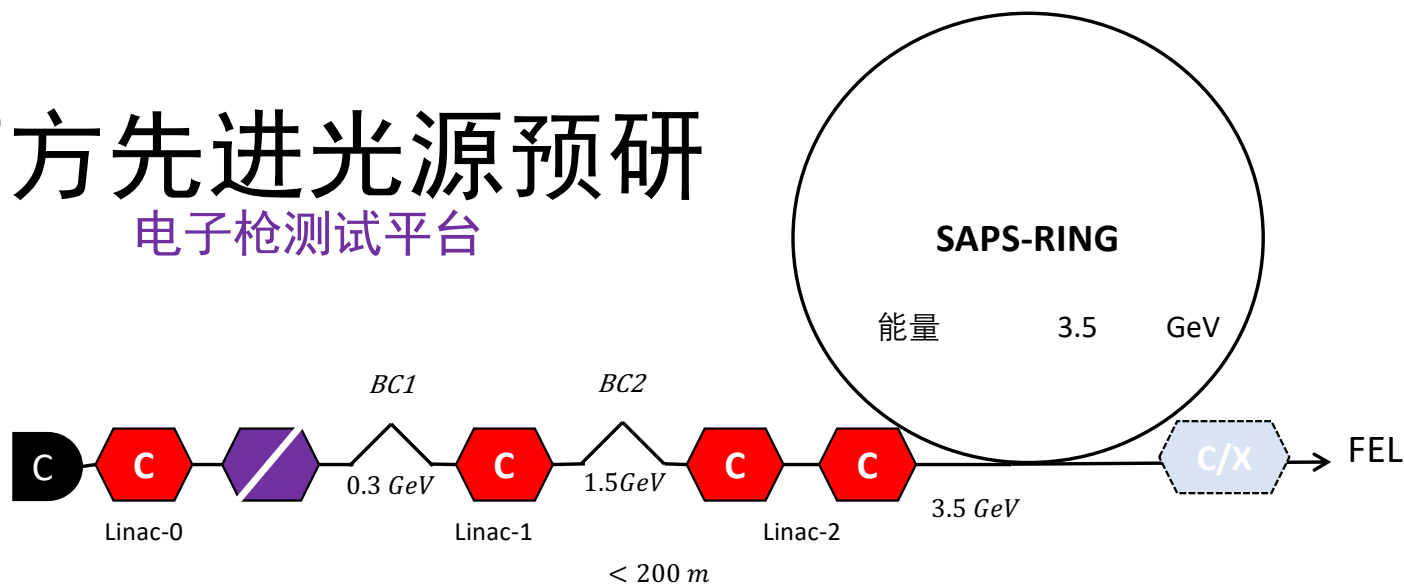
FEL直线出口束流需求:

$$\epsilon_n < 0.25 \text{ mm.mrad},$$

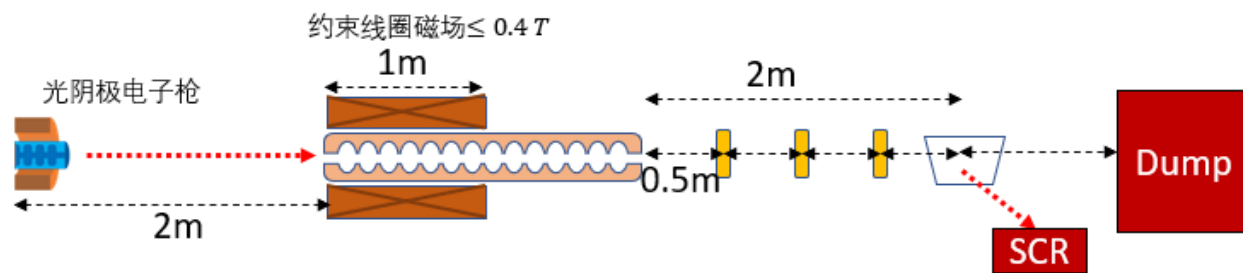
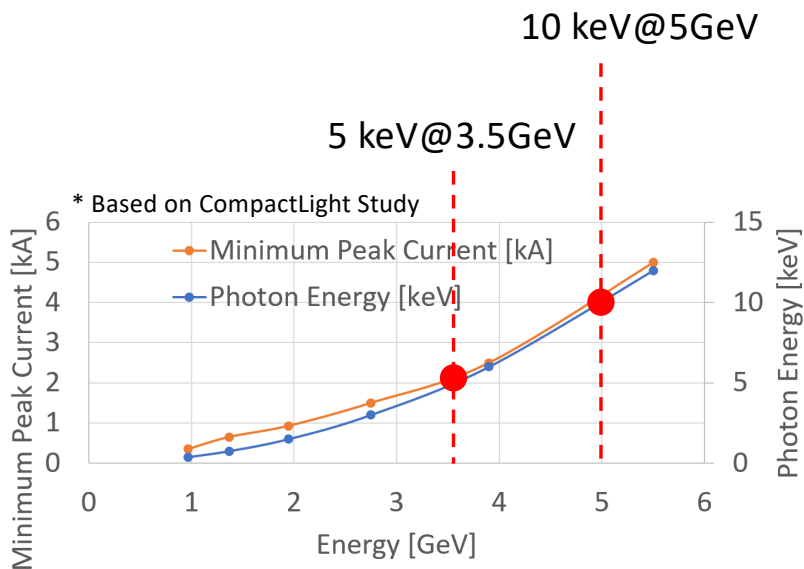
$$\frac{\Delta E}{E} < 0.05\%,$$

$$I_{peak} \sim 2 \text{ kA} (@3.5 \text{ GeV})$$

$$I_{peak} \sim 4 \text{ kA} (@5 \text{ GeV})$$



全能量直线注入+DSLIR

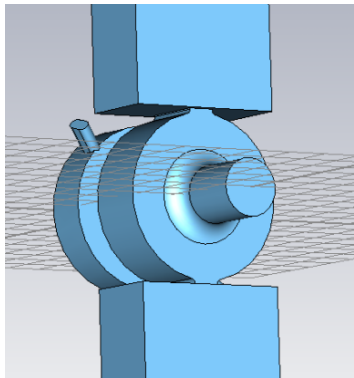


测试平台示意图

关键技术验证: 高品质电子枪、高梯度加速管

常温C波段光阴极电子枪现状

THU(2010)



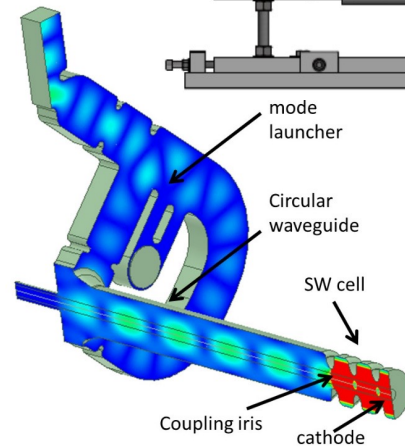
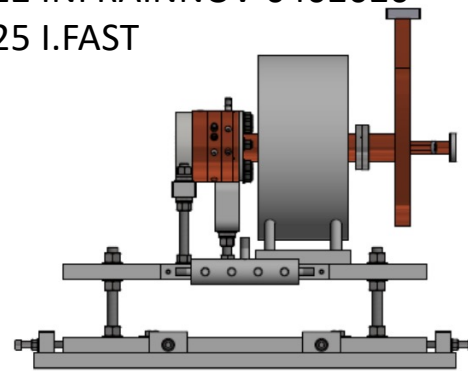
CompactLight & EuPRAXIA related

(2018-2021)

Prototyping

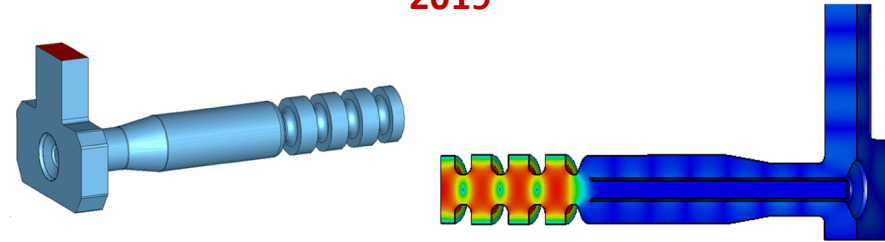
2020-2022 INFRAINNOV-0402020

2021-2025 I.FAST

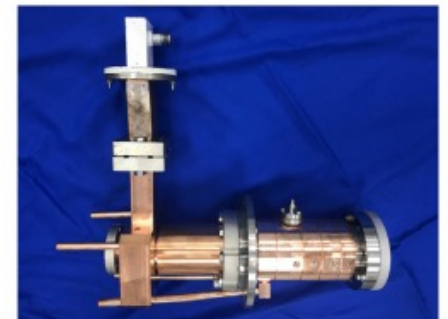
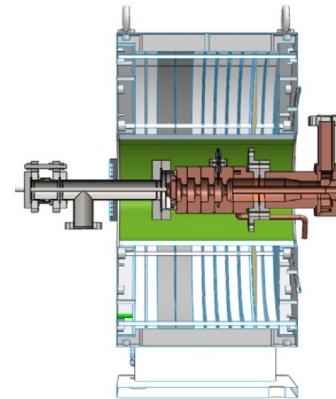


上海高研院

2019

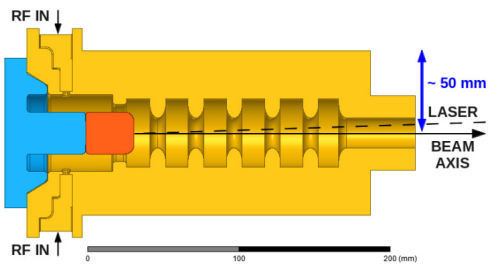


2021



SwissFEL

Injector Test Facility(2014)



2021.9 初步提案
 2022.1 项目启动
 2022.4 外部评审
~~2022.12 硬件到位~~
~~2023.1 安装调试~~
 2024.7 高功率测试
 2024.11 安装改造
 2024.12 束流测试

电子枪研制目标

电荷量/nC	重频	归一化发射度
0.1	100 ^{*1}	<0.2
1.0	10	<1 π .mm.mrad

常规C波段加速管研制目标*

梯度	长度	孔径
40 MV/m	1.8~2m	>6.4 mm

C-band Gun (~7.5MeV)

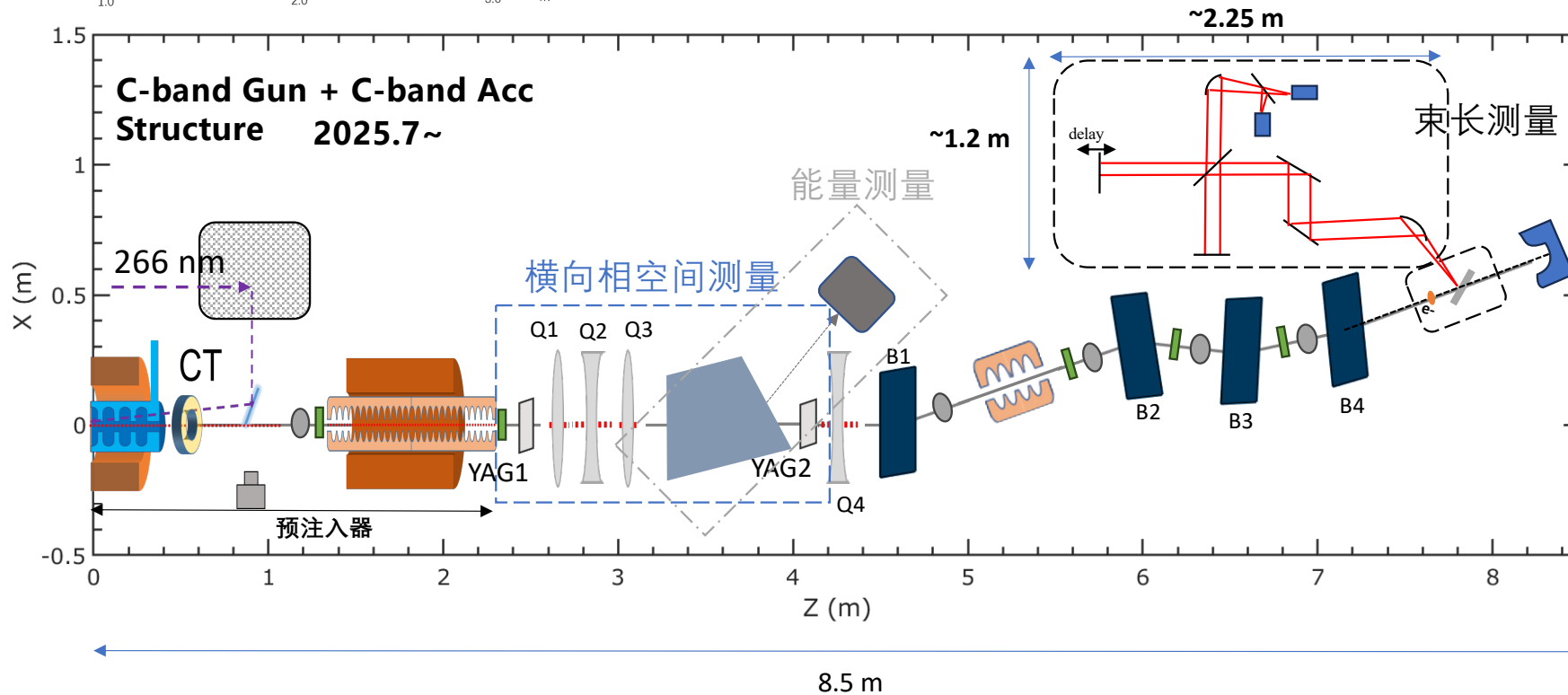
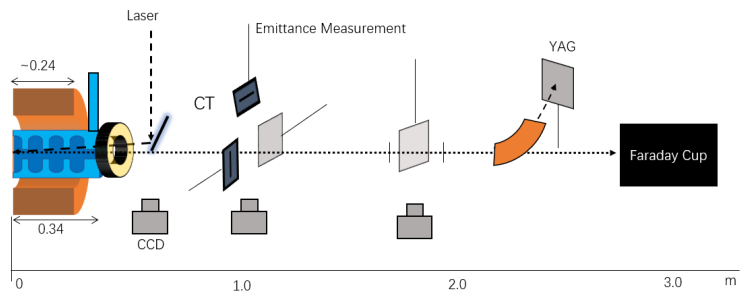
分阶段布局

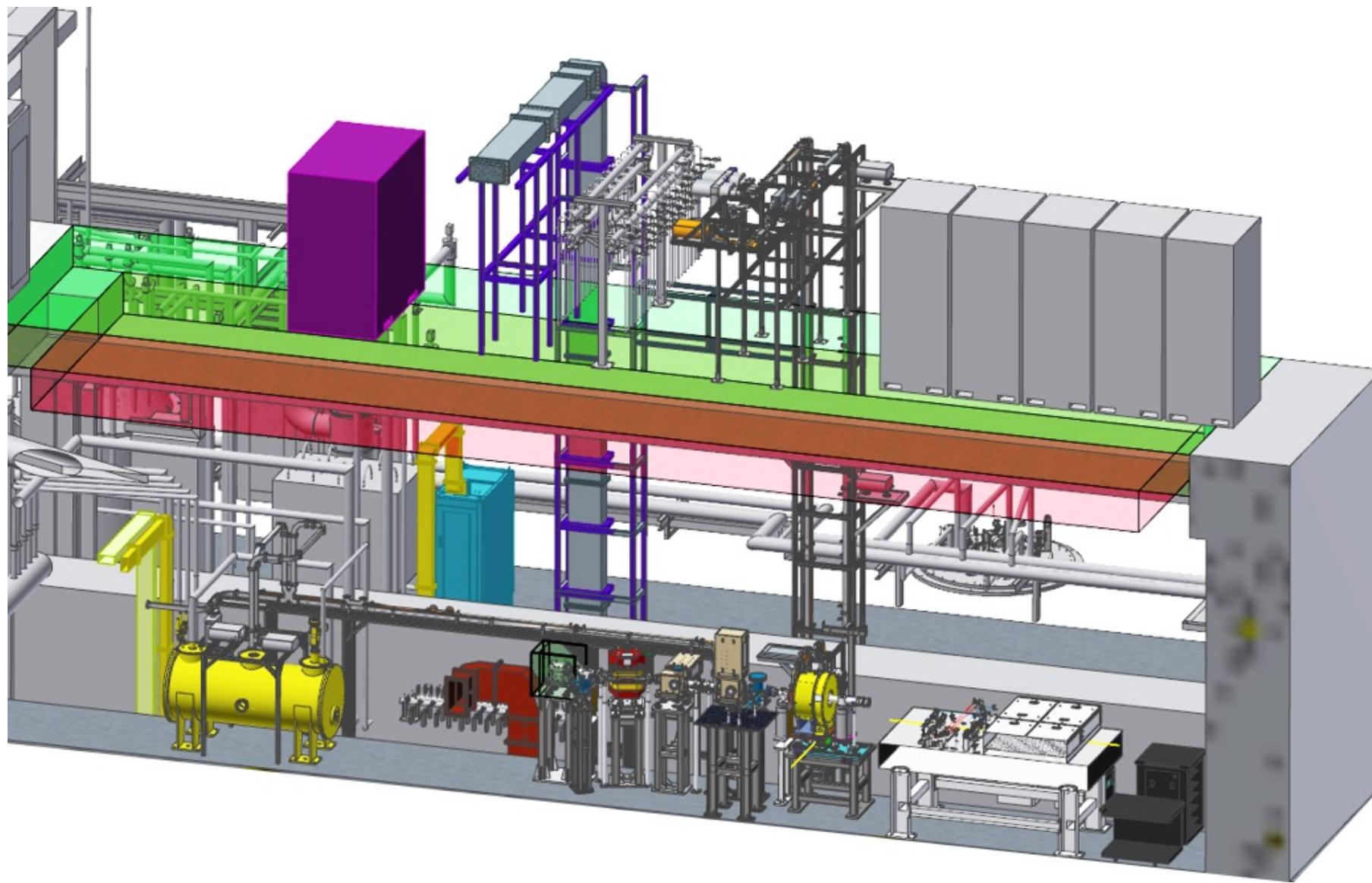
2023.1~

2023.5~

2025.7~

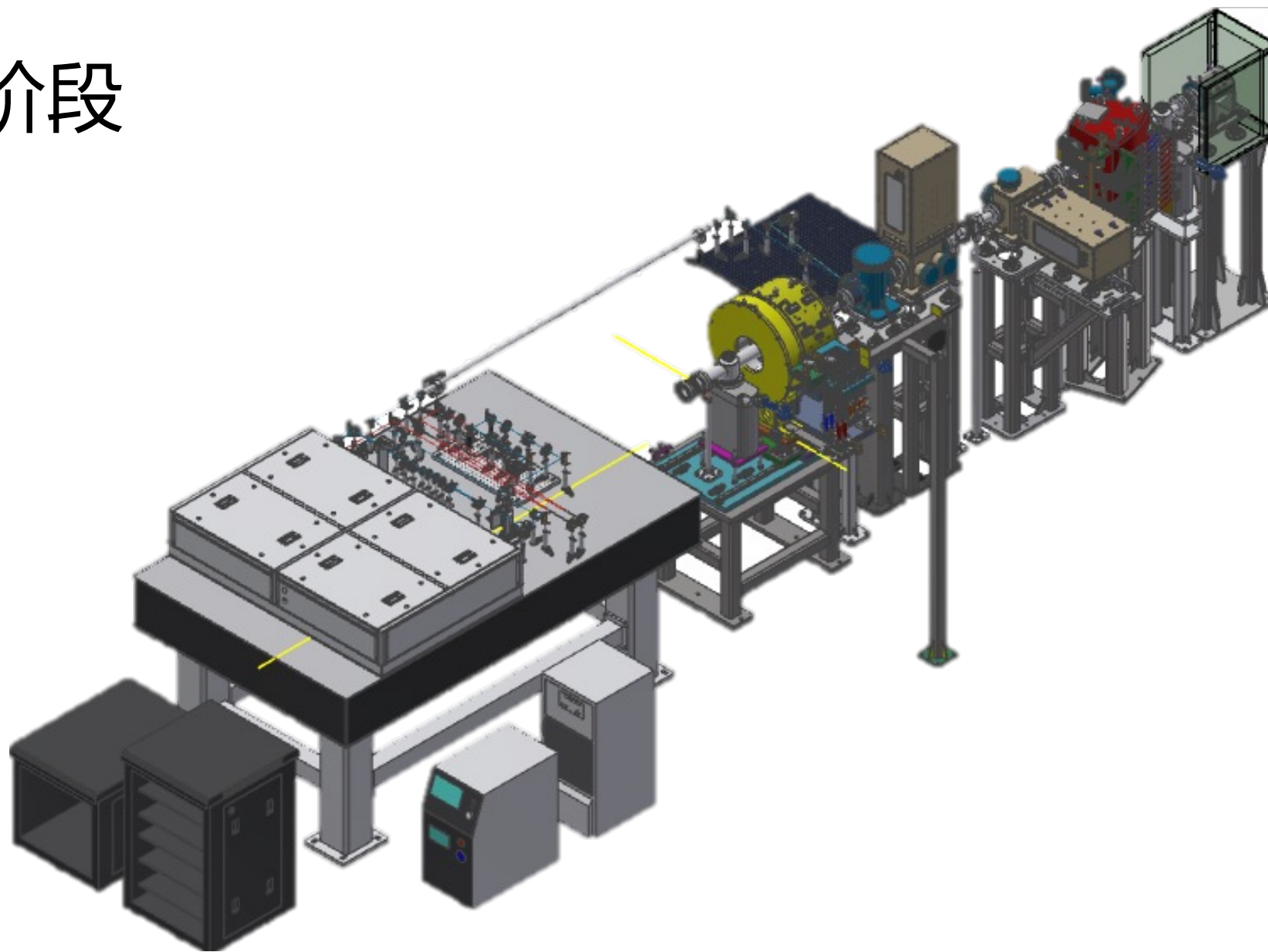
ADM原理验证实验布局





←
屏蔽门

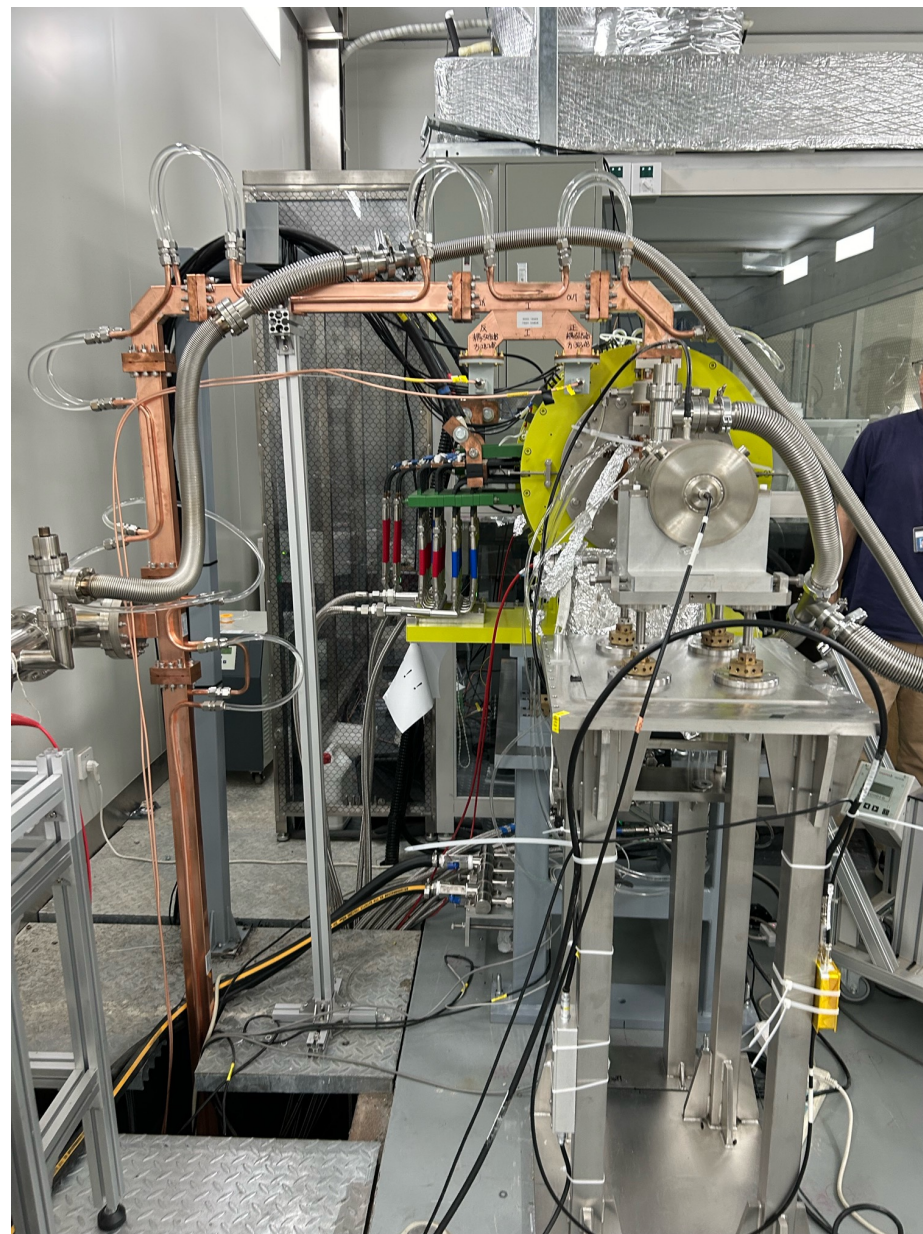
第一阶段



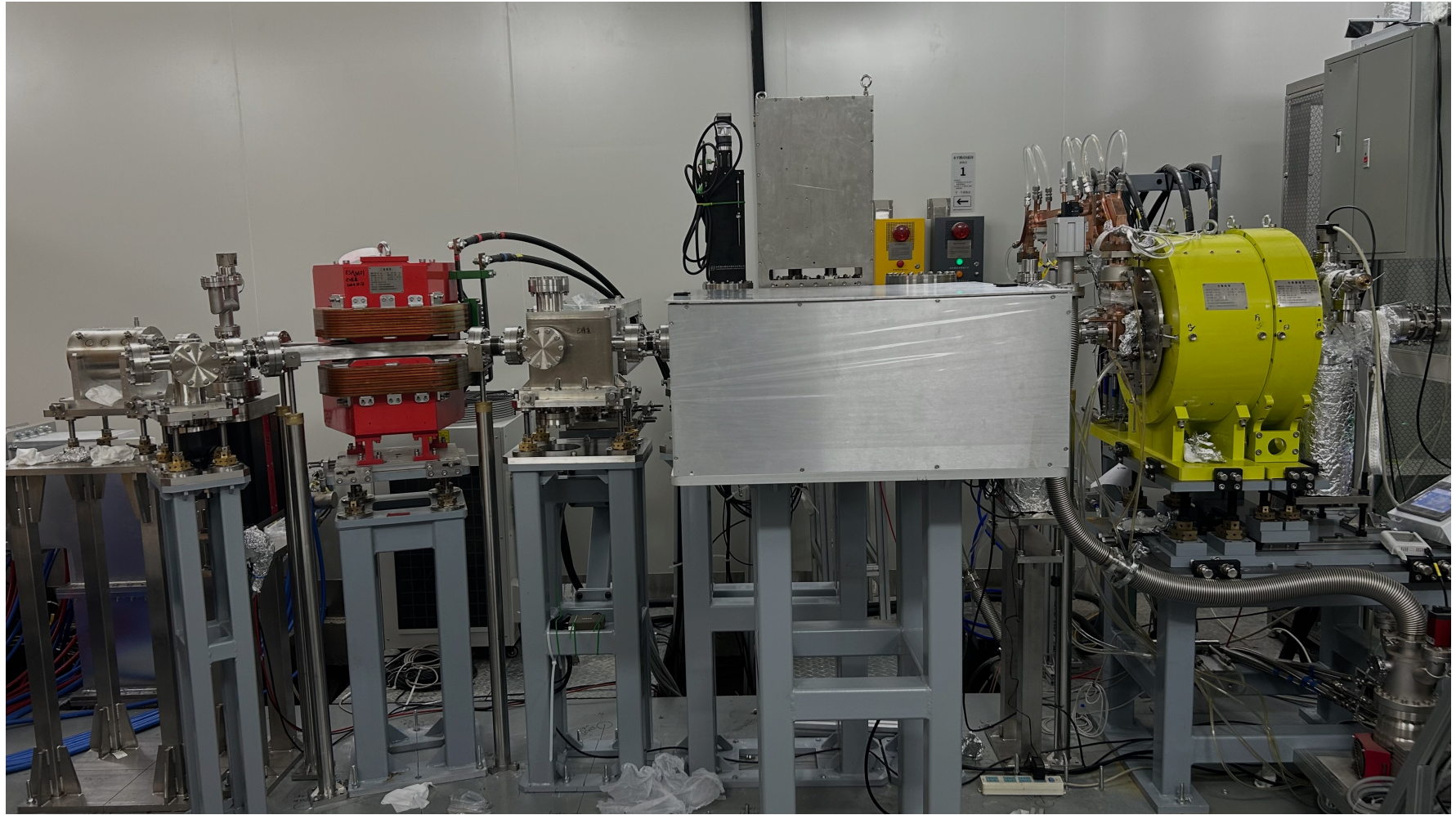
2022.7



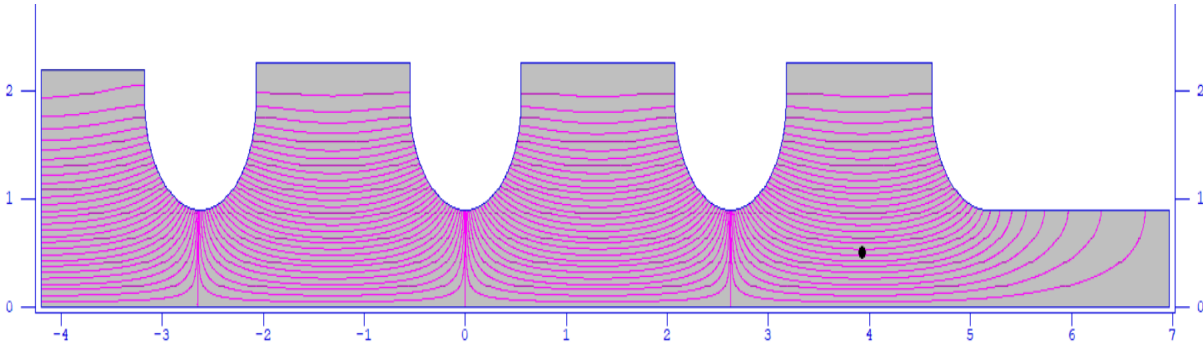
2023.10



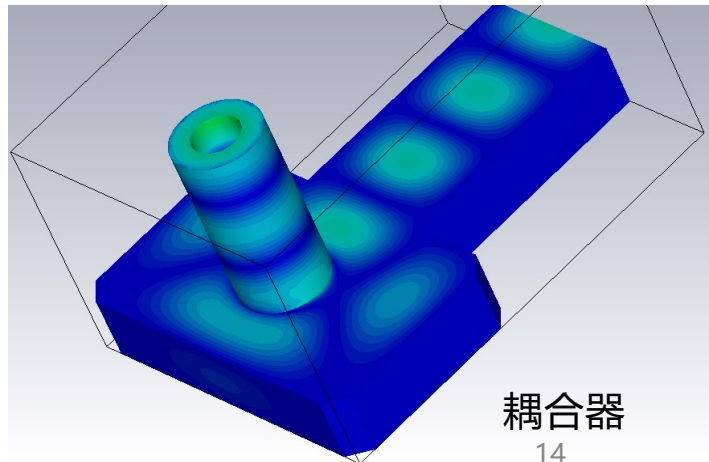
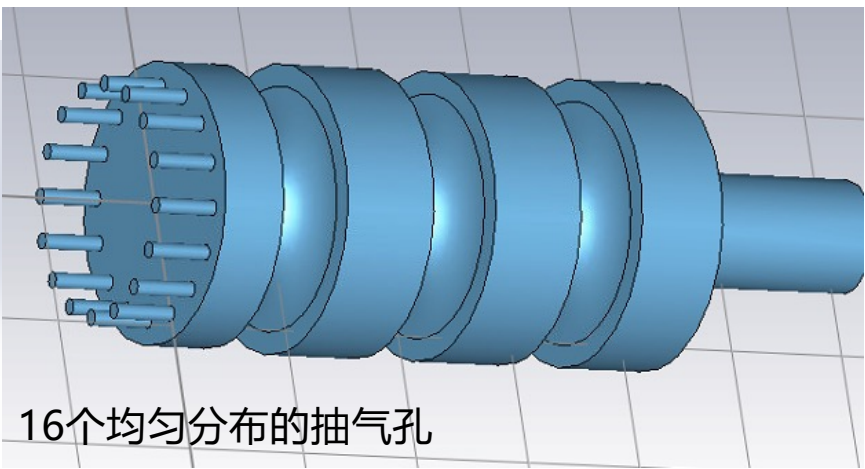
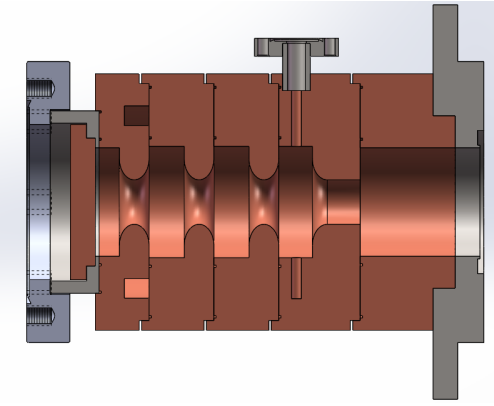
2024.11



电子枪



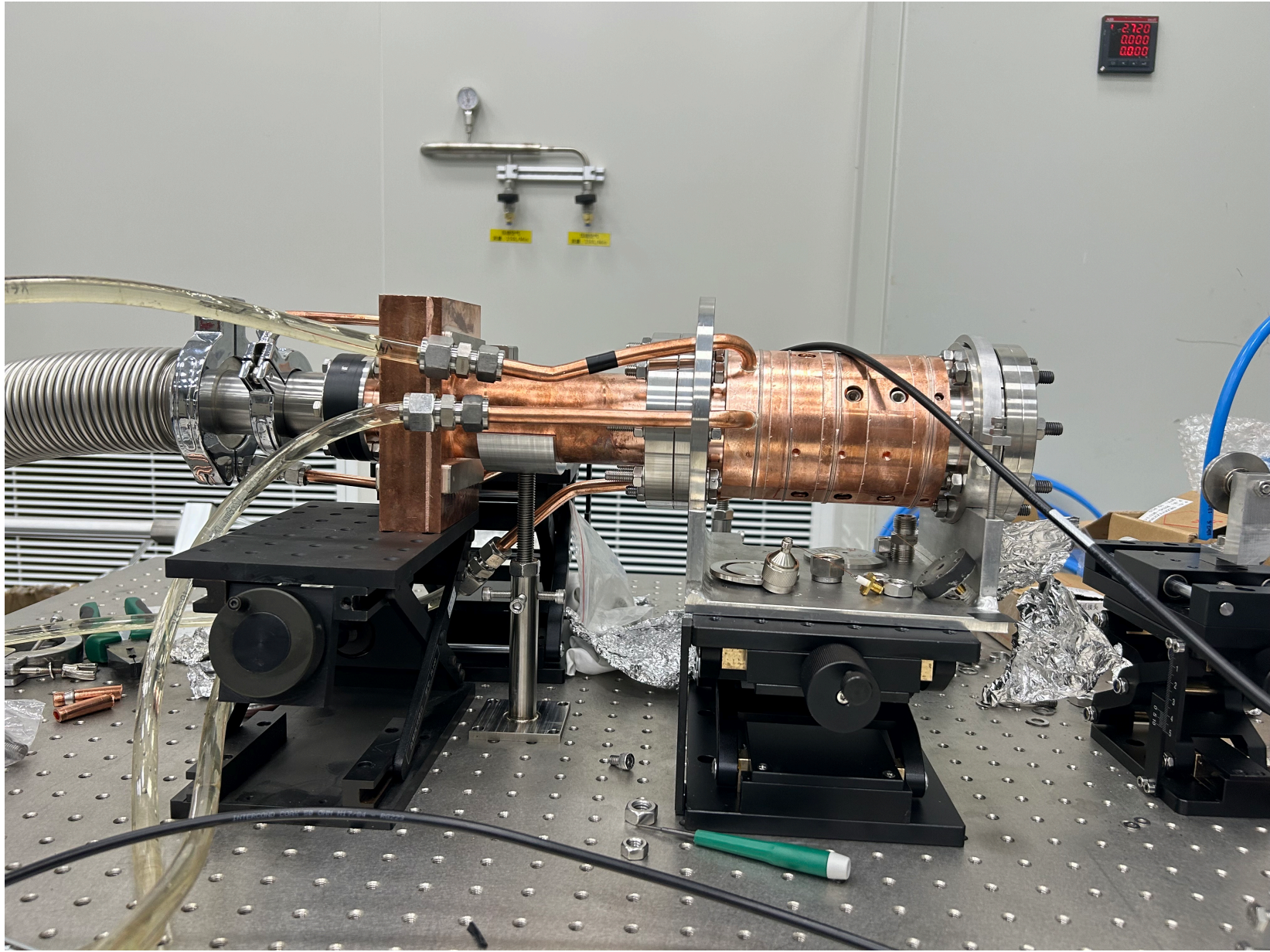
	频率 (MHz)	场平整度 (%)
Superfish	5711.92	0.355
CST	5711.978	0.4





"#0"

零号腔



"#1"

壹号腔

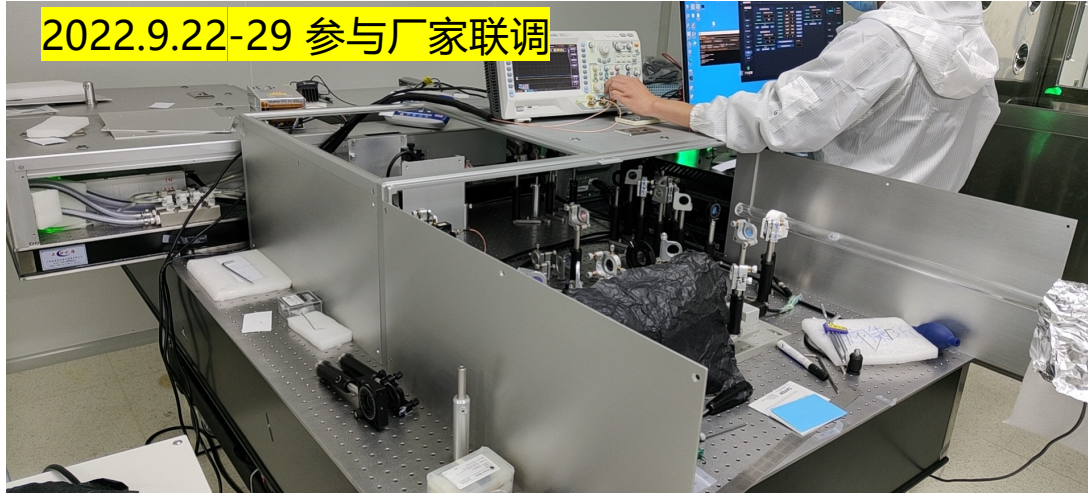


阴极面 Sa-10nm/13 nm

驱动激光

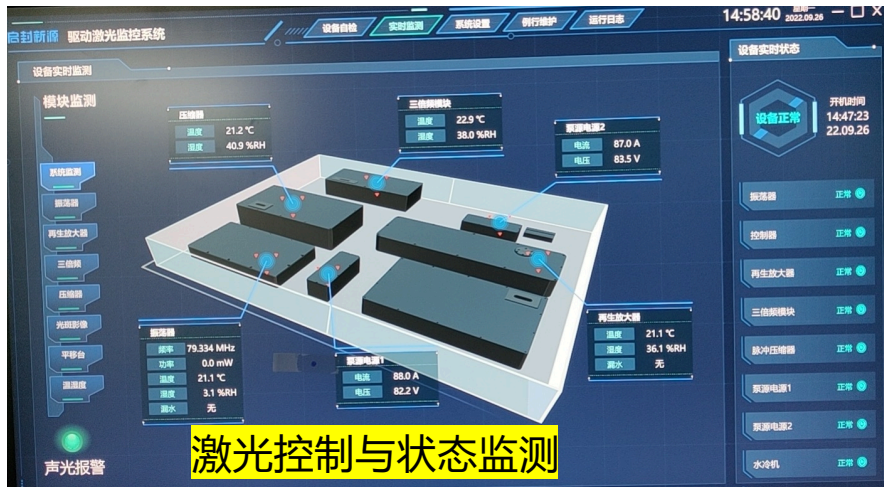
- *2022.9 在厂家完成联调
- *2023.1 完成出厂验收
- *2023.3 现场安装调试

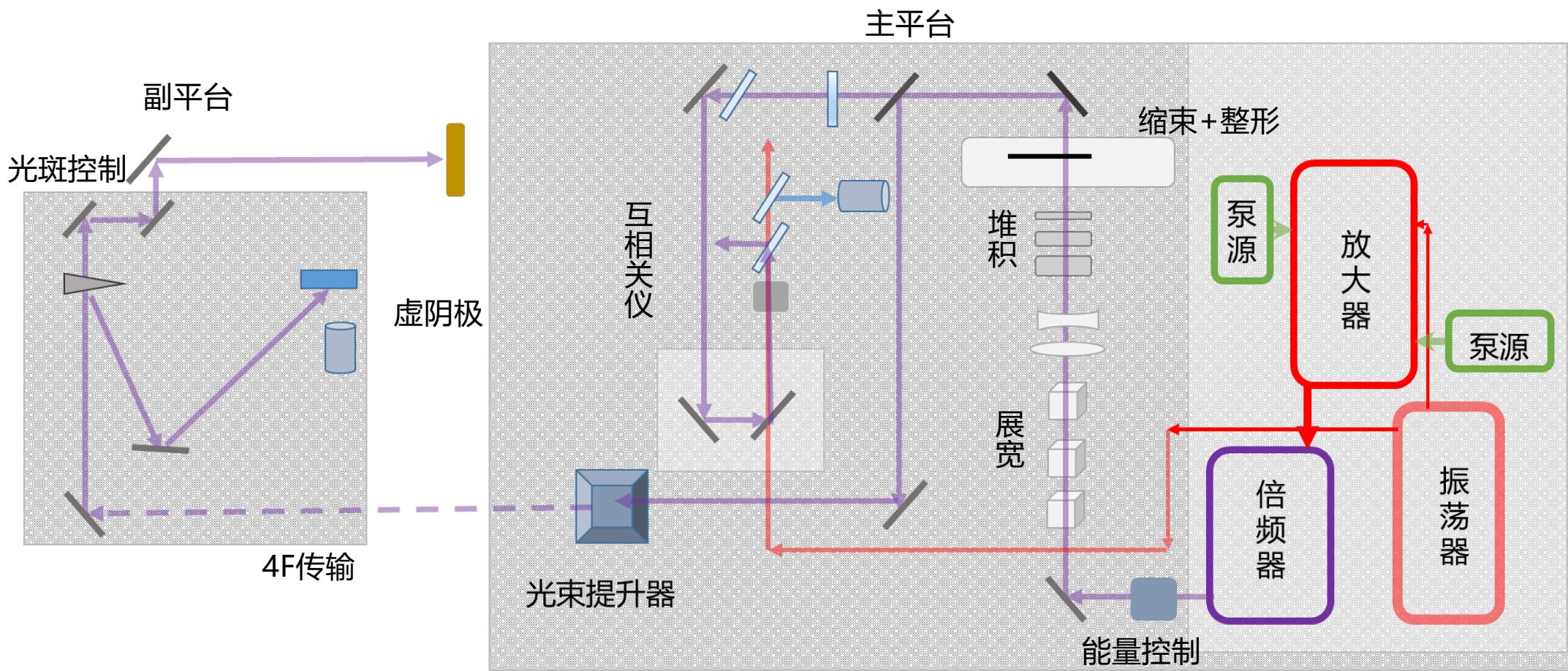
2022.9.22-29 参与厂家联调



驱动激光出厂检验

检验项目	出厂验收	单位	验收检验设备
中心波长	265.7±1.76	nm	光谱仪
脉宽	0.24	ps	单次互相关仪
能量	2.62±0.02	mJ	能量计
功率抖动 (RMS)	0.6% (短) 0.71% (长)	-	功率计
重频	1/10/20/50/100	Hz	光斑分析仪
指向稳定性	8	μrad	光斑分析仪
光斑直径	10	mm	光斑分析仪
锁相抖动	77.2 (RMS)	fs	相噪分析仪

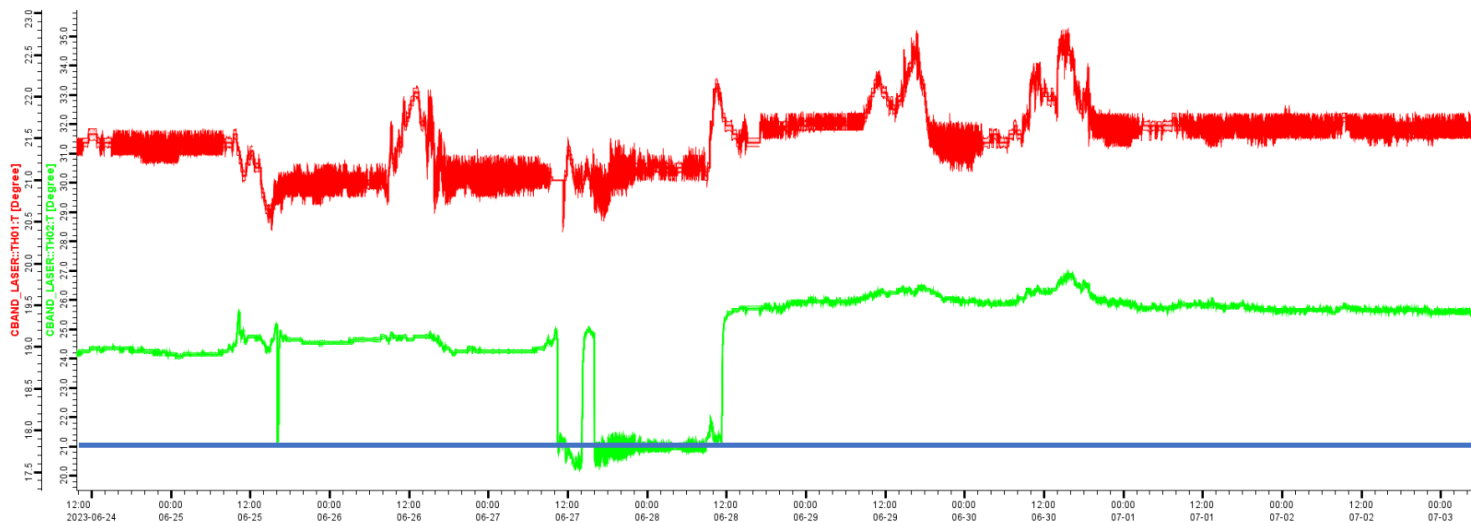




265.8 nm, 出口处2.1mJ
(到虚阴极) 传输效率为~14%

激光调试布局

温度变化

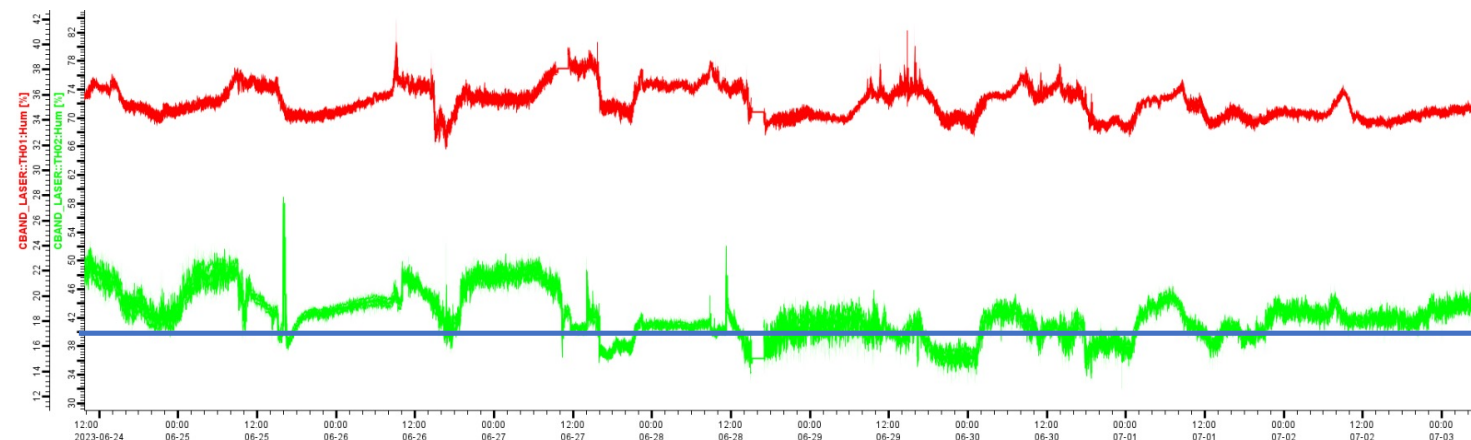


外

内

期望值

湿度变化

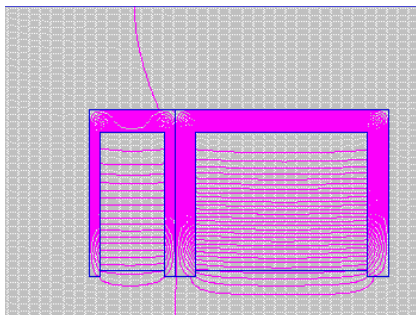


期望值

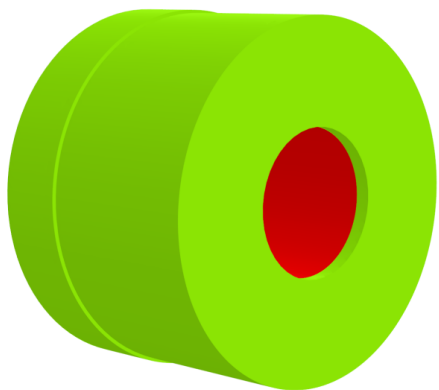
磁铁

2023.3 主/副螺线管已完成磁测
2023.7 螺线管组合测试, 二极磁铁测试

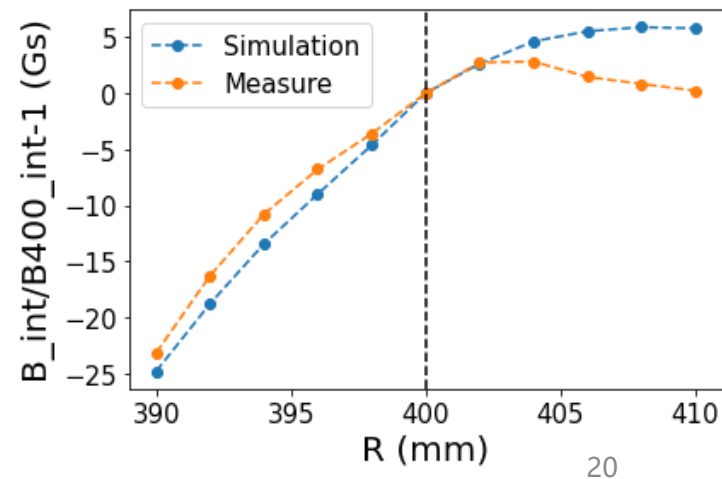
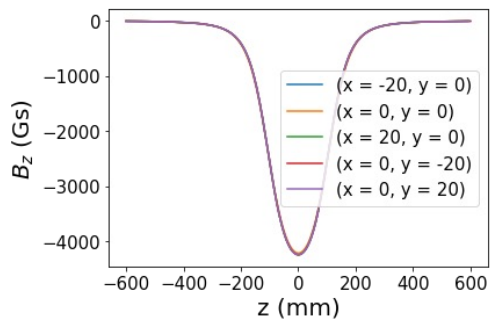
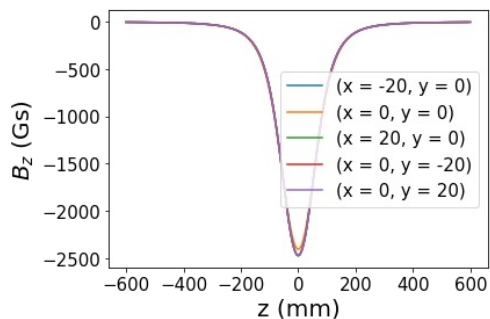
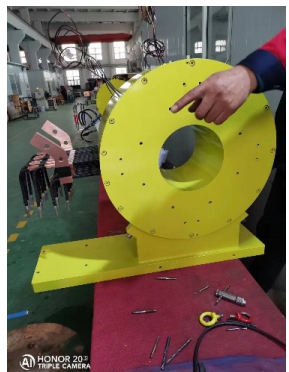
二维设计



三维设计

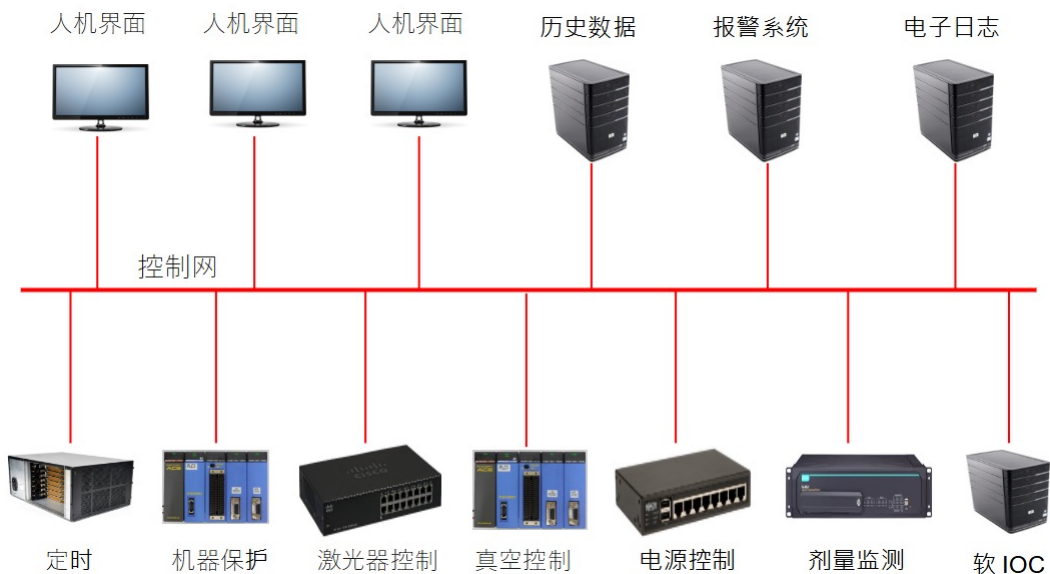


制作



控制

电子枪测试平台控制总体架构

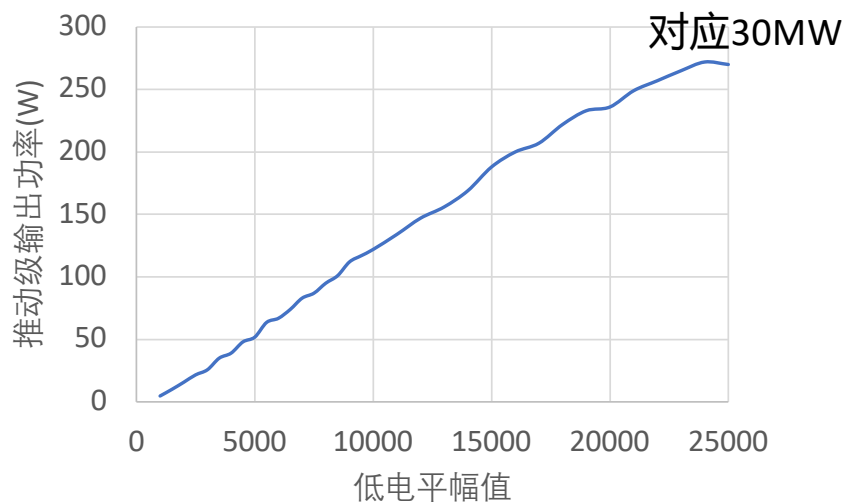


C波段速调管功率源联锁保护系统

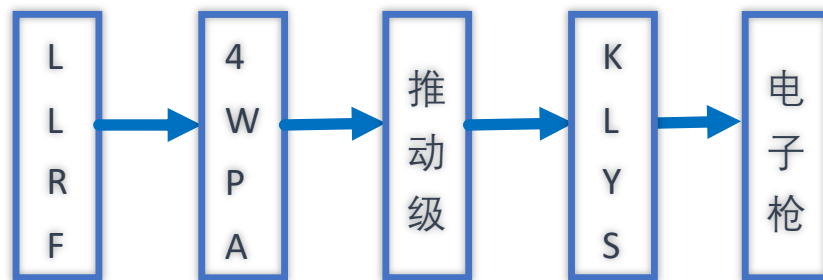
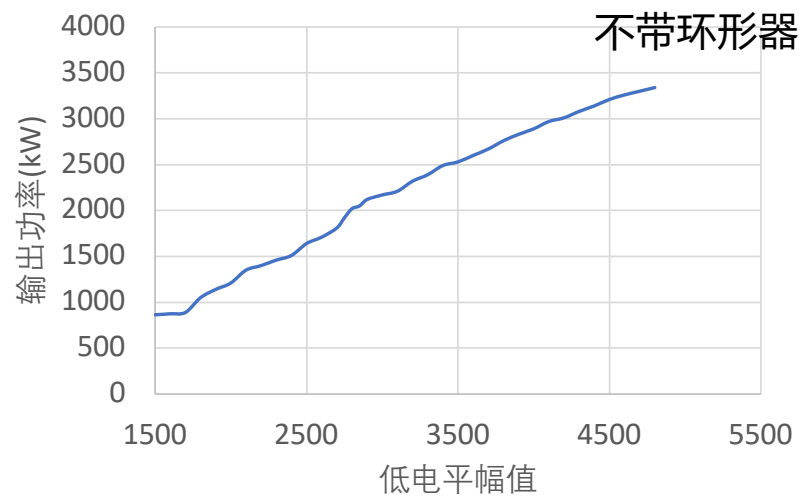


高频系统

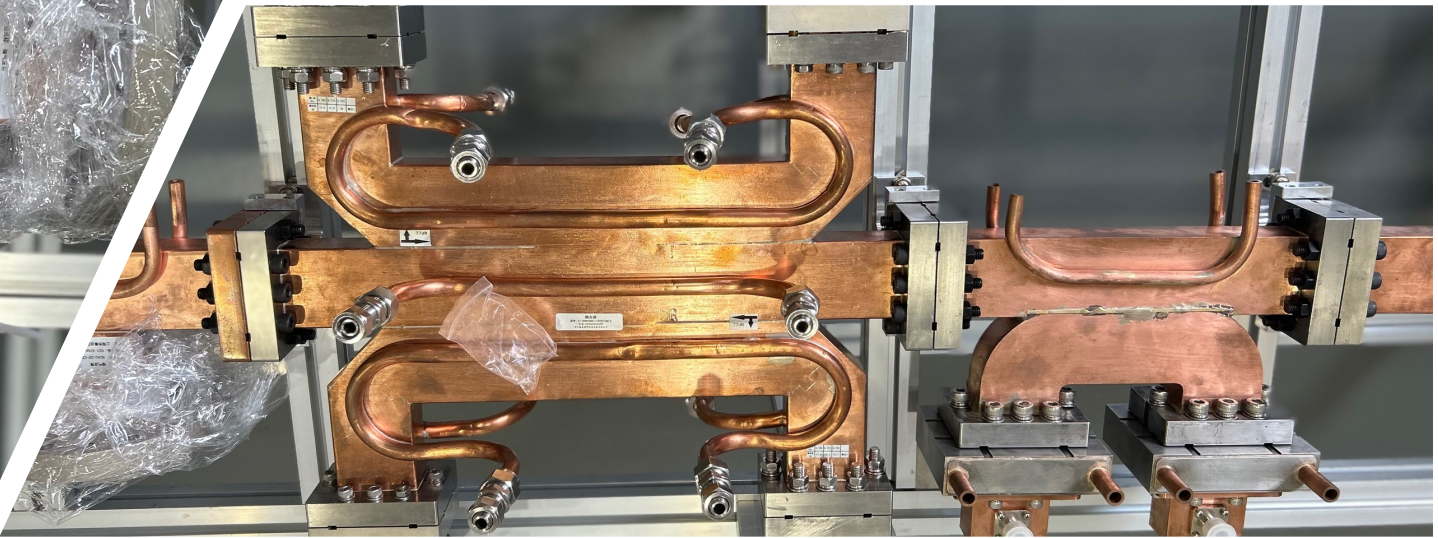
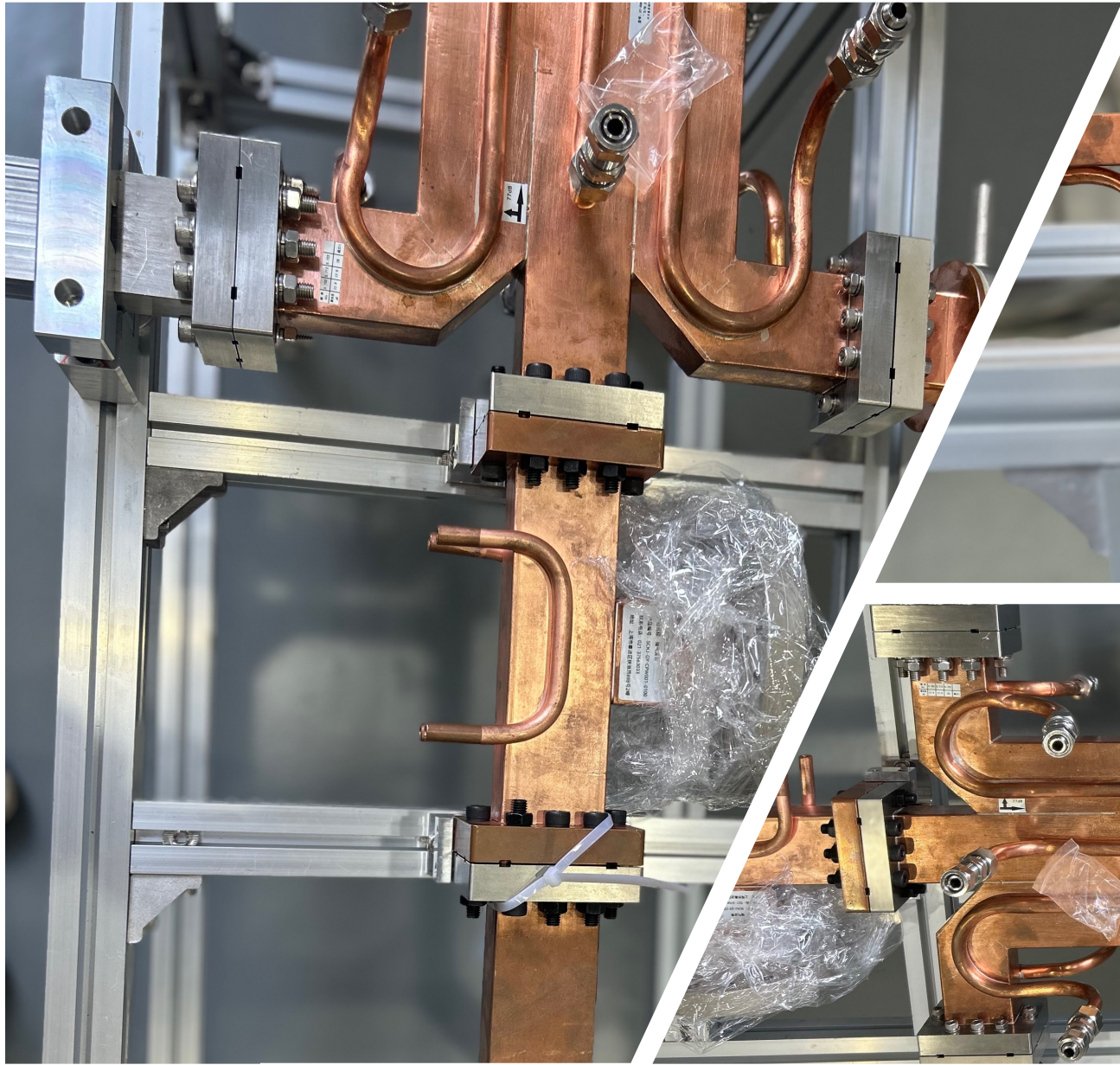
推动级输出测试

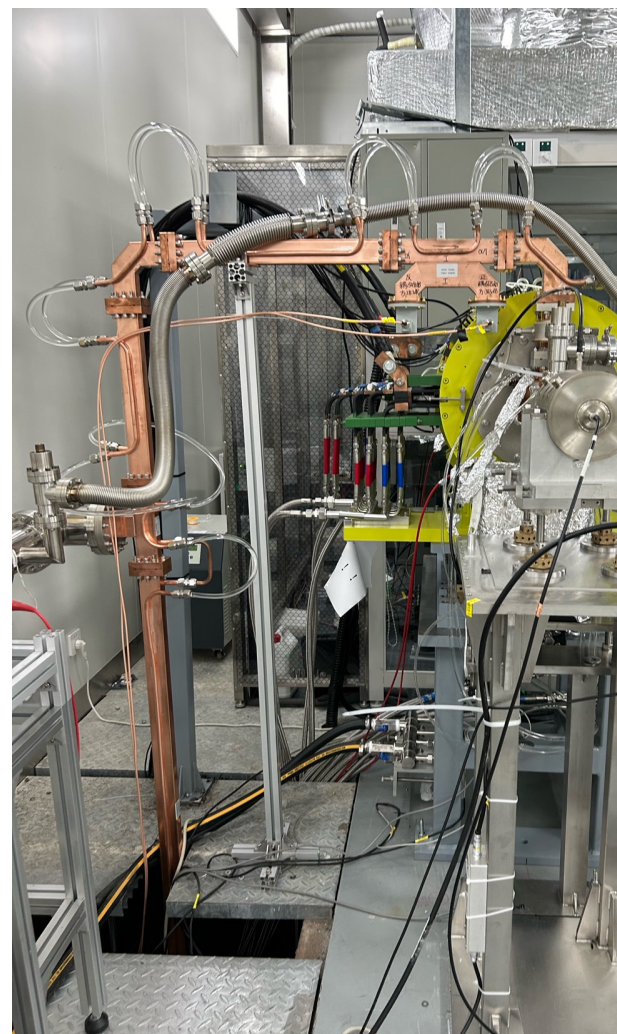


KLYS功率输出曲线

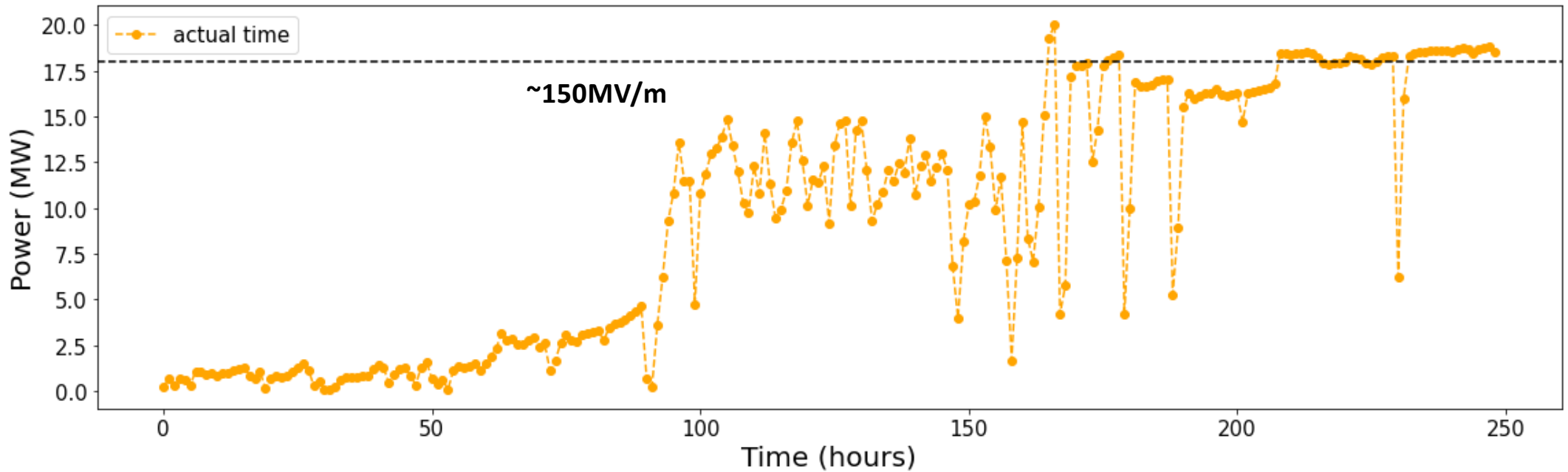


2023.10 入腔功率0.8MW





高功率测试2024.7

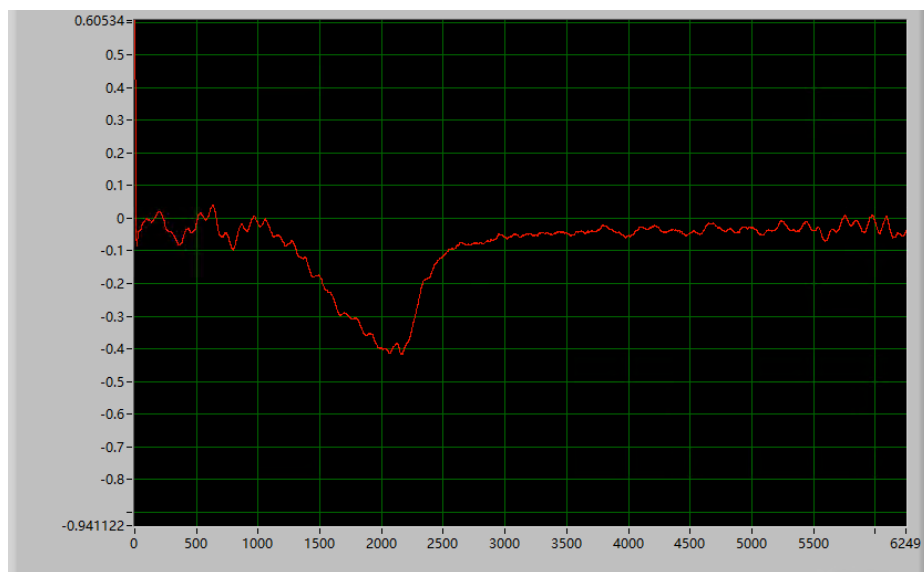


- 高功率测试达到预期（略晚于INFN/PSI）
- FC对暗电流进行了初步测量

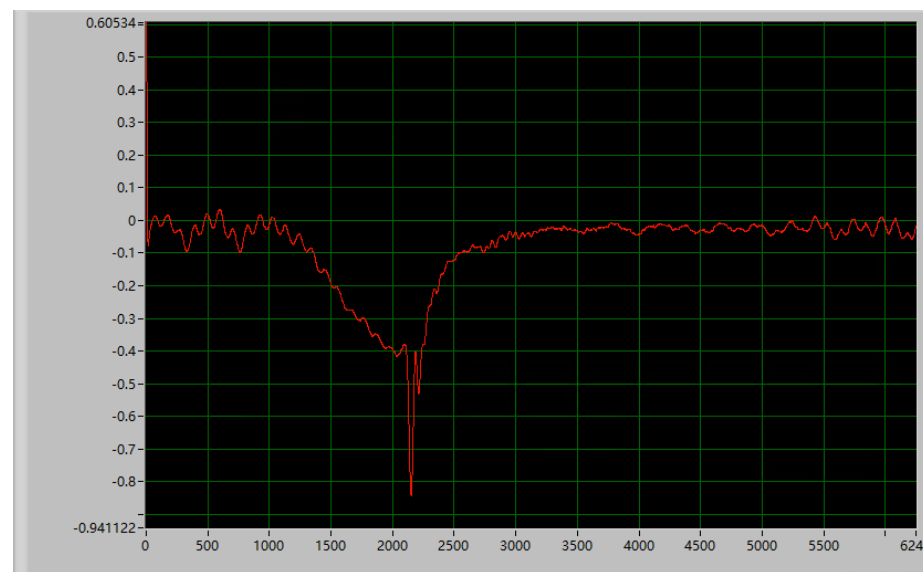
初步束流测试结果

首次观测到光电流信号 (ICT) 2024.12.13

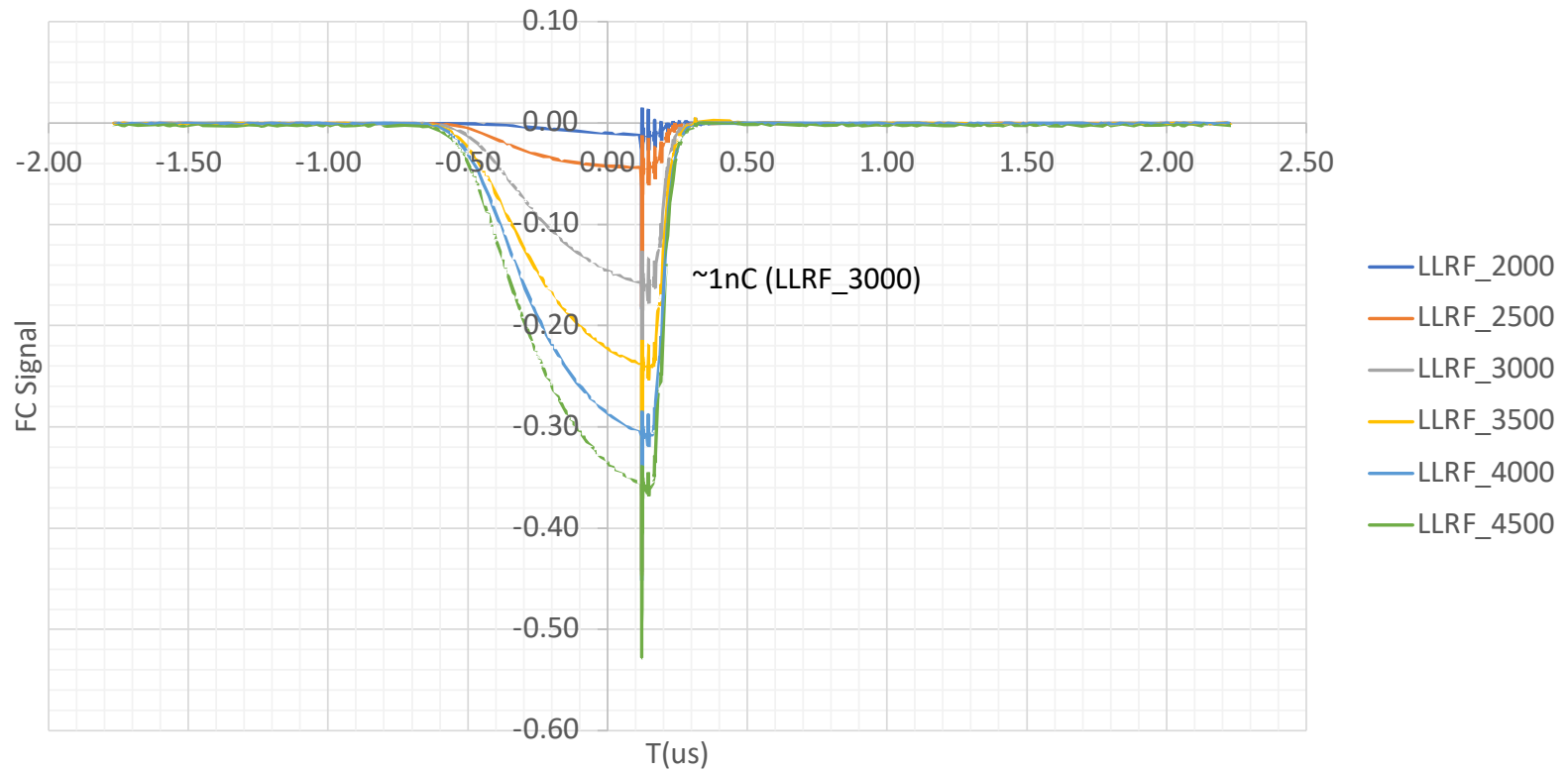
暗电流



暗电流+光电流



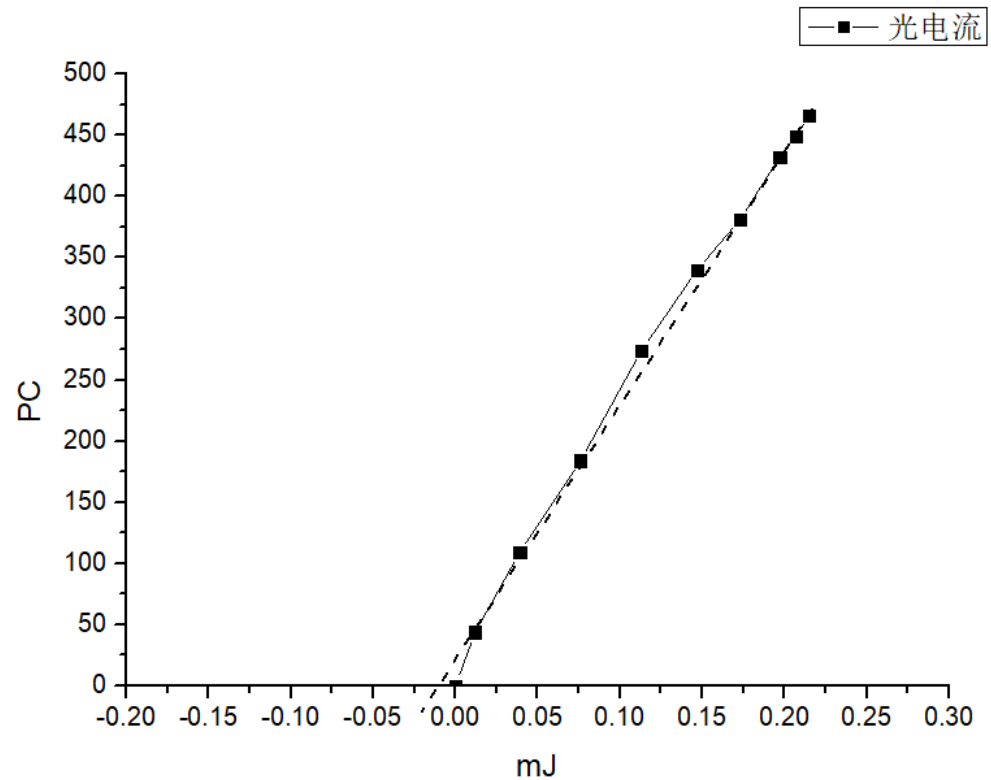
不同馈入功率下暗电流测量



束流电荷量与激光脉冲能量的关系

- 调整激光能量
- FC测量暗电流
- FC测量暗电流+光电流

激光能量: 4000	法拉第筒积分:	光电流 109 (192-83) (螺线管: 119-170)
3500		光电流 184 (268-84) (螺线管: 112-160)
3000 ???		光电流274 (382-108) (螺线管: 112-160)
2500		光电流 340 (426-84) (螺线管: 119-170)
2000		光电流 381 (469-88) (螺线管: 119-170)
1500		光电流432 (522-90) (螺线管: 119-170)
1000		光电流449
500		光电流466
4700		光电流 12

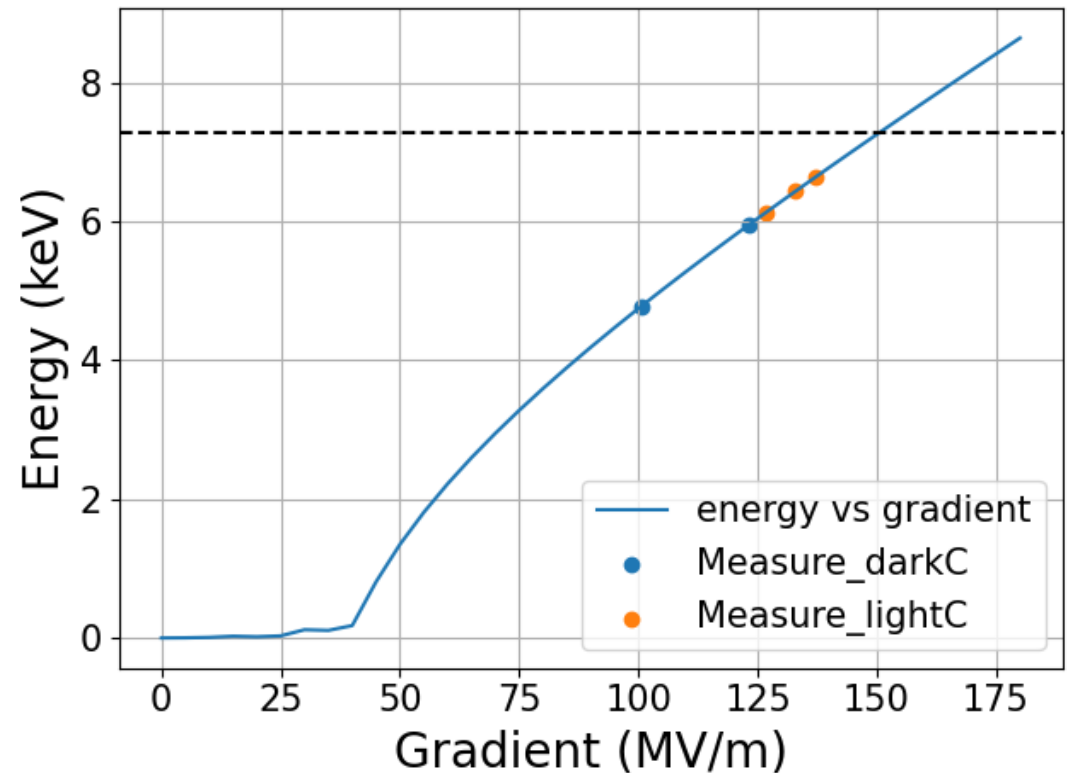


束流能量与梯度之间的关系

- 通过扫描可得到阴极梯度与束流能量的关系
- 能量测量的公式将二极铁边缘场也计算入内后，修改如下：

$$W = \sqrt{0.18166I^2 - 0.511^2} - 0.511$$

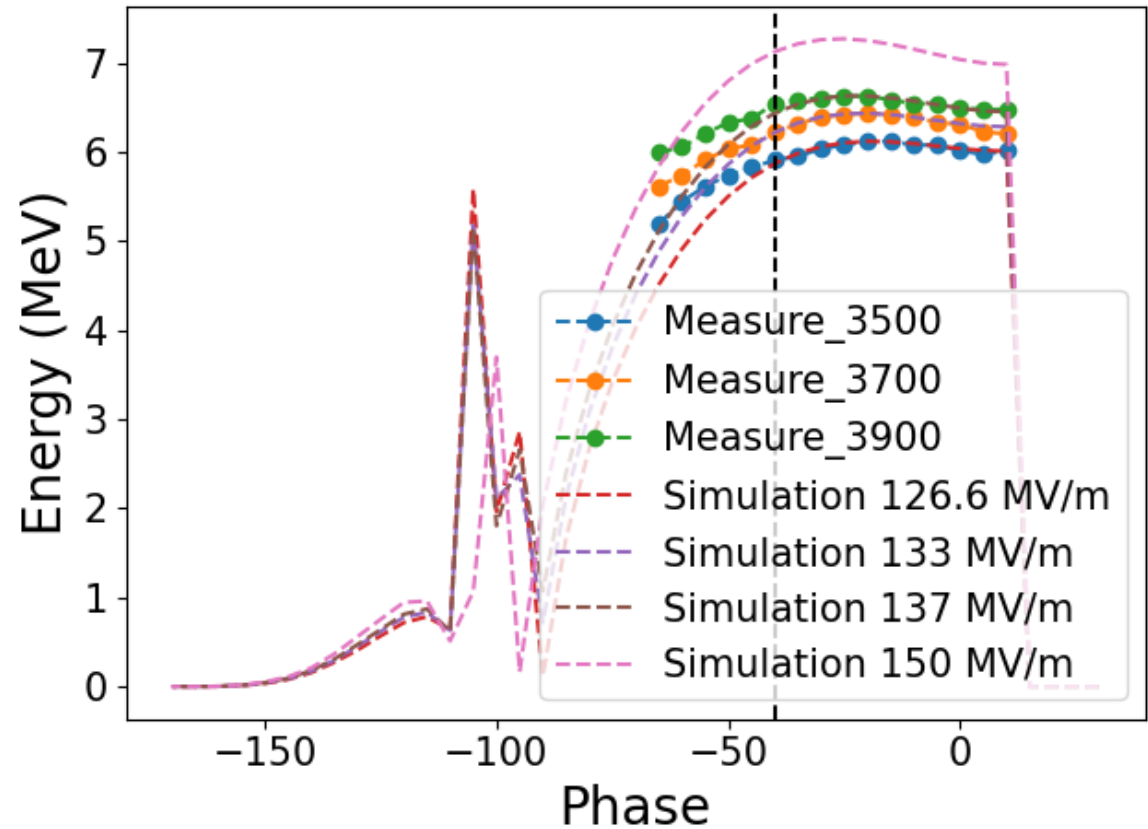
- 目前测到的最大束流能量时 6.63 MeV，对应137 MV/m



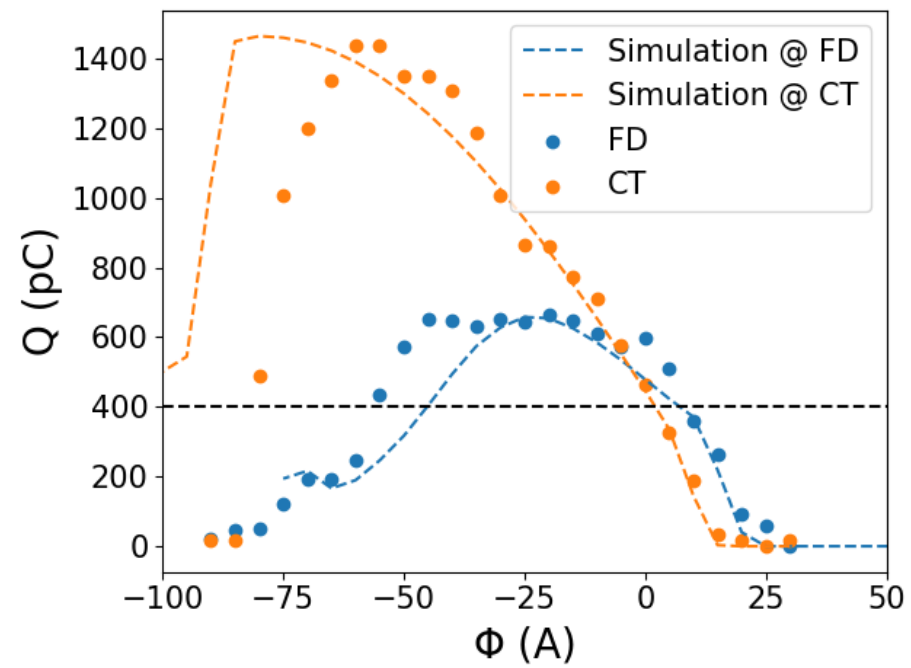
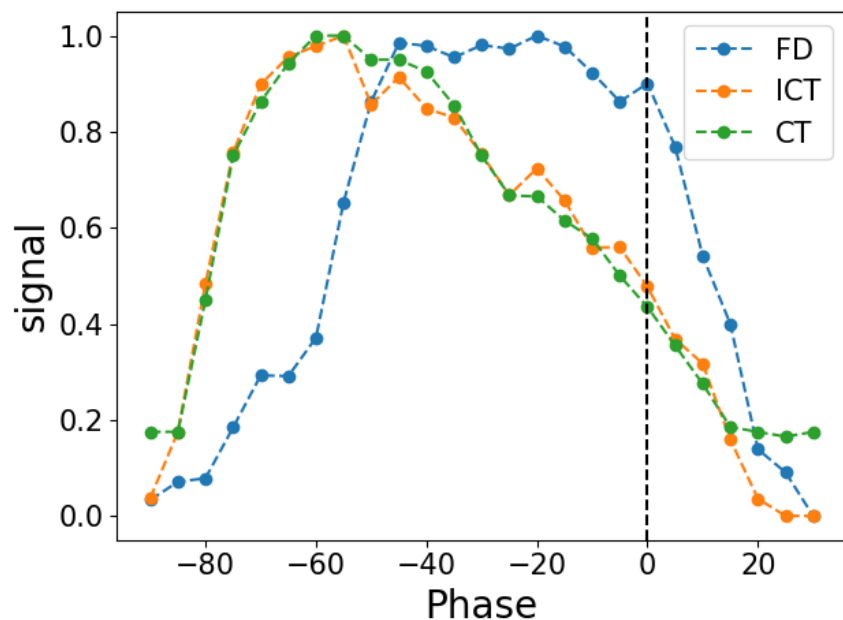
束流能量扫相

- 高压285 kV，分别对比低电平3500，3700，3900条件下的能量变化
- 在低于-40度的情况下，由于能散偏大，测到的能量不是中心能量，所以结果偏高

-50度时的
能量分布



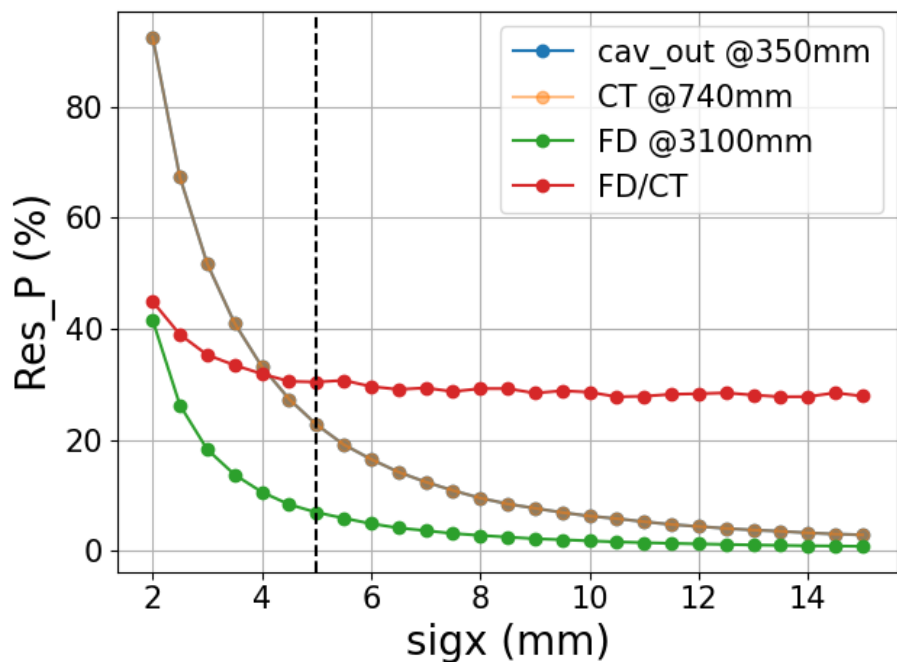
电荷量扫相结果



- 经过对比，发现测量得到的CT电荷量扫相范围会比模拟的大约20度，而且CT没有绝对标准值
- FD的模拟扫相结果将管道的束流损失考虑进去，会与CT的模拟扫描有较大的差别，说明光电子束中间即便加上螺线管磁场（是155A，约0.27 T）也有较大的束损

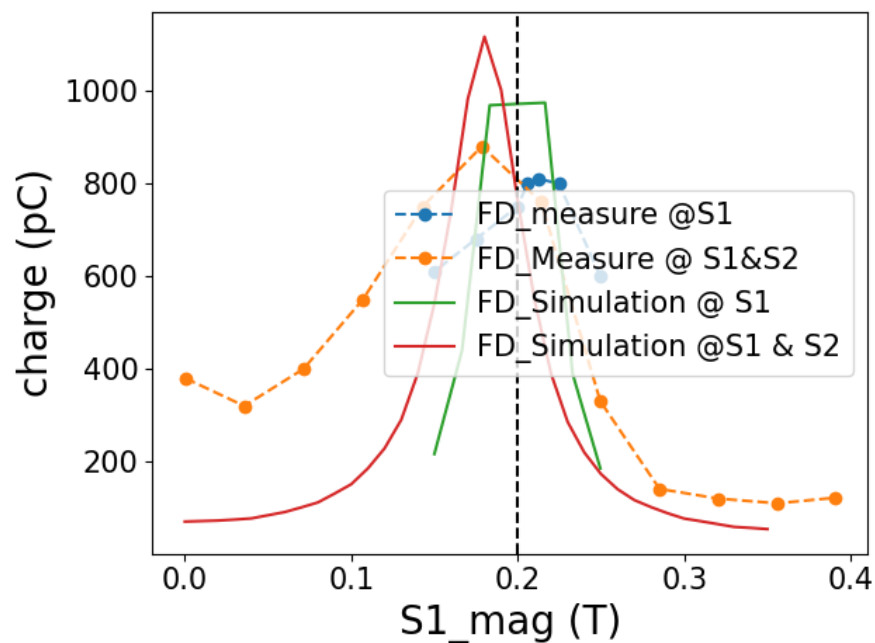
暗电流计算

- Cav_out与CT的结果相互重合，说明电子枪出口到CT是无电荷损失的



FD/CT 代表两个位置的剩余电荷量比例，维持在30%附近

暗电流与螺线管磁场的变化趋势一致，需要进一步修正暗电流模型来使得计算结果和模拟结果一致



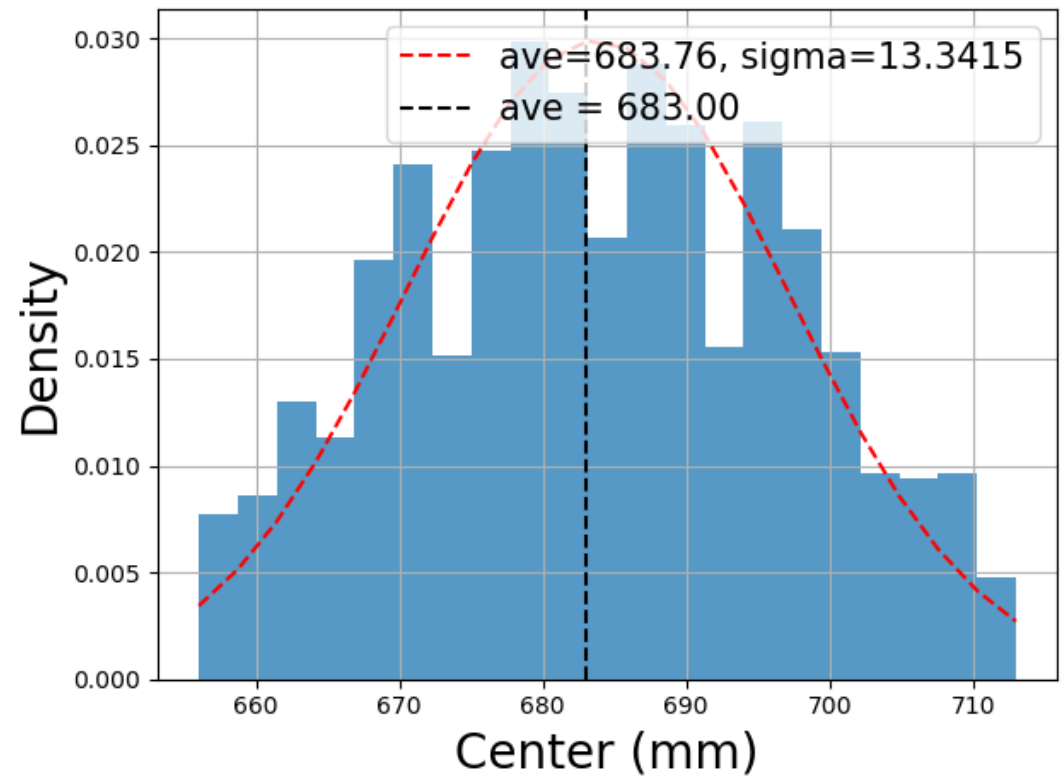
测量结果当中，可以看到聚焦趋势是倾斜的，原因是束流轨迹是倾斜的

调试过程中遇到的一些问题

功率源稳定性

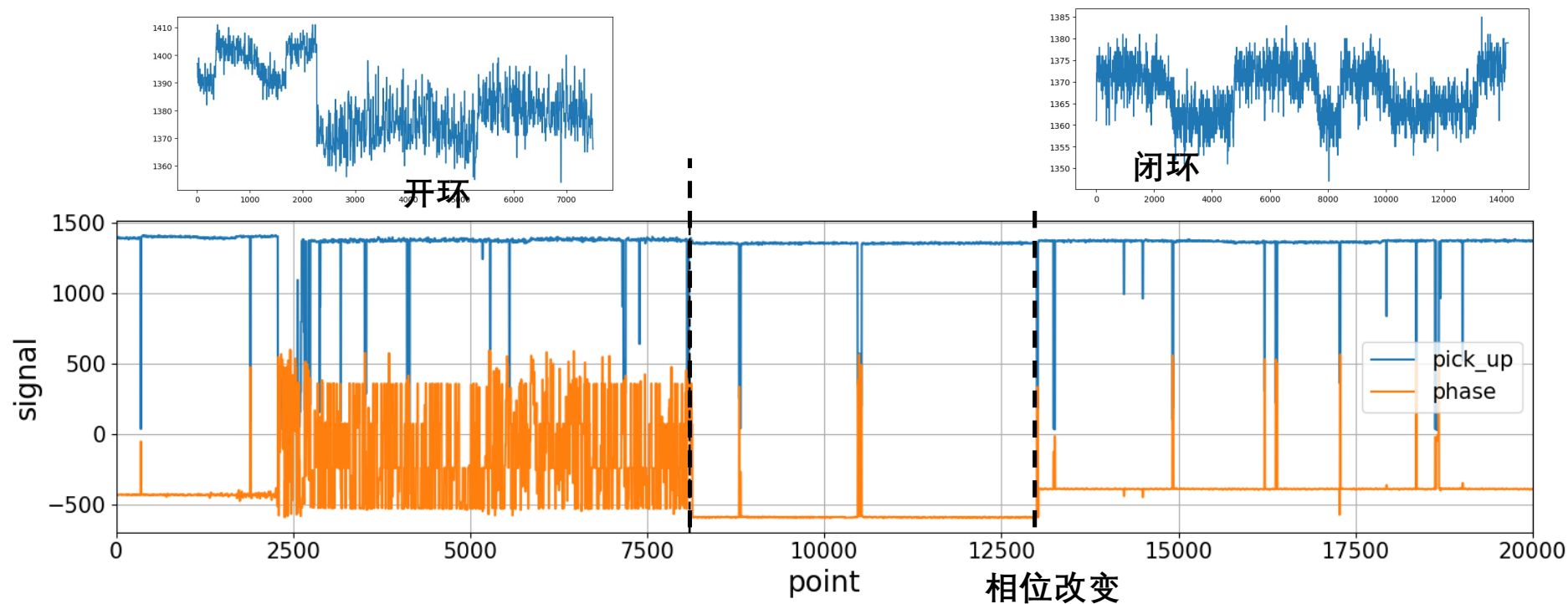
- 根据功率源的使用状态有如下困难：
 - 打火统计尚未具备功能
 - 稳定性偏差，同时会带动电荷量和能量也会大幅度抖动（法拉第桶处的暗电流电荷量抖动范围约为 $\pm 100\text{pC}$ ）
- 建议：
 - 希望稳定性能够达到0.1%左右（上海是0.04%）

低电平2000时，pick_up信号的分布情况，其幅值稳定性约为1.8%，峰峰值达到了约10%



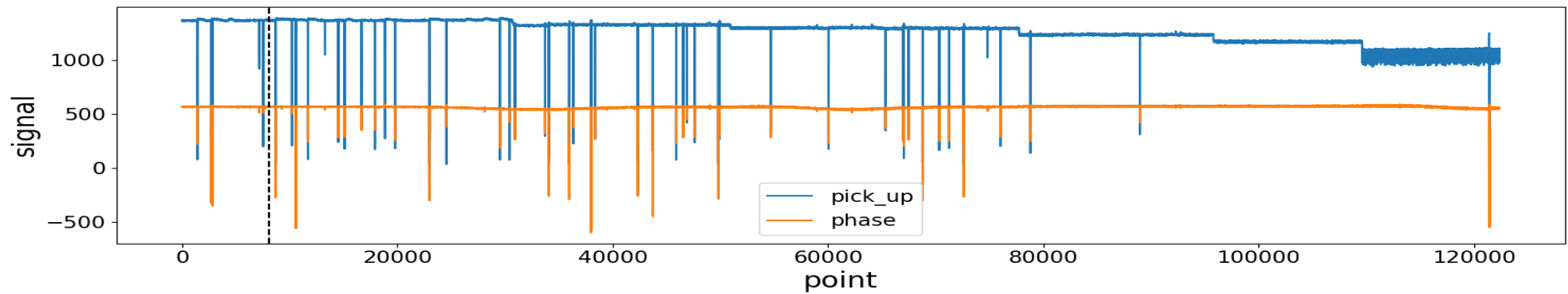
开环和闭环比较

	打火概率/%	幅值稳定性/ %	相位稳定性/%	功率稳定性/%
开环	7.2	0.87@1383	66@77	1.05@17.5 MW
闭环	2.2	0.44@1368	0.5@117.43	0.36@16.9 MW



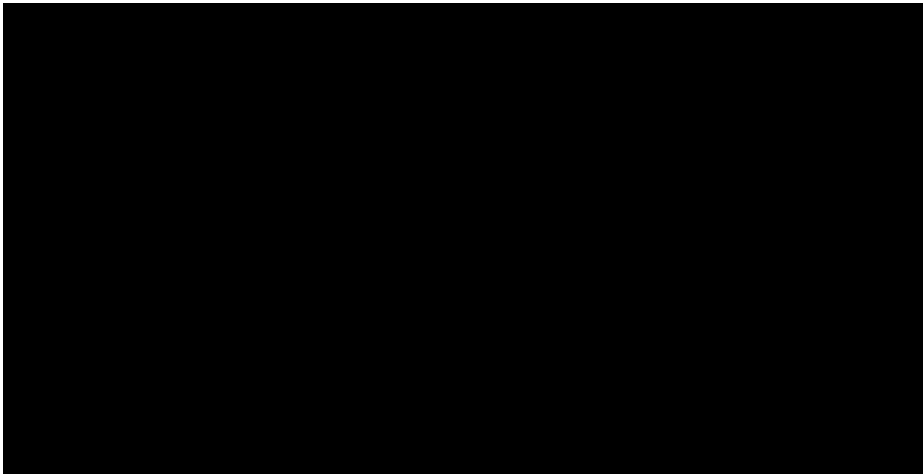
不同功率下稳定性分析

低电平	入腔功率/MW	反射功率/MW	打火概率/%	功率稳定性 σ /%	幅值稳定性 σ /%	相位稳定性 σ /%
4200	17.088	2.6	0.896	0.47	0.46	1.08
4000	15.5	2.16	0.534	0.67	0.48	1.7
3900	14.736	1.928	0.284	0.7	0.4	1.66
3700	13.26	1.638	0.047	0.8	0.43	0.6
3500	11.863	1.402	0.0	1.1	0.52	0.64
2000	3.878	0.414	0.0	2.82	1.98	1.79

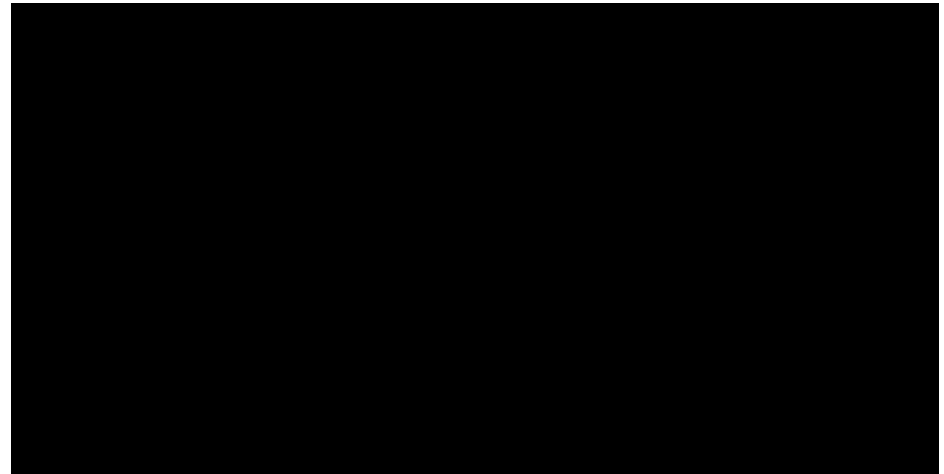


偏转铁后屏幕所测束团位置抖动比较

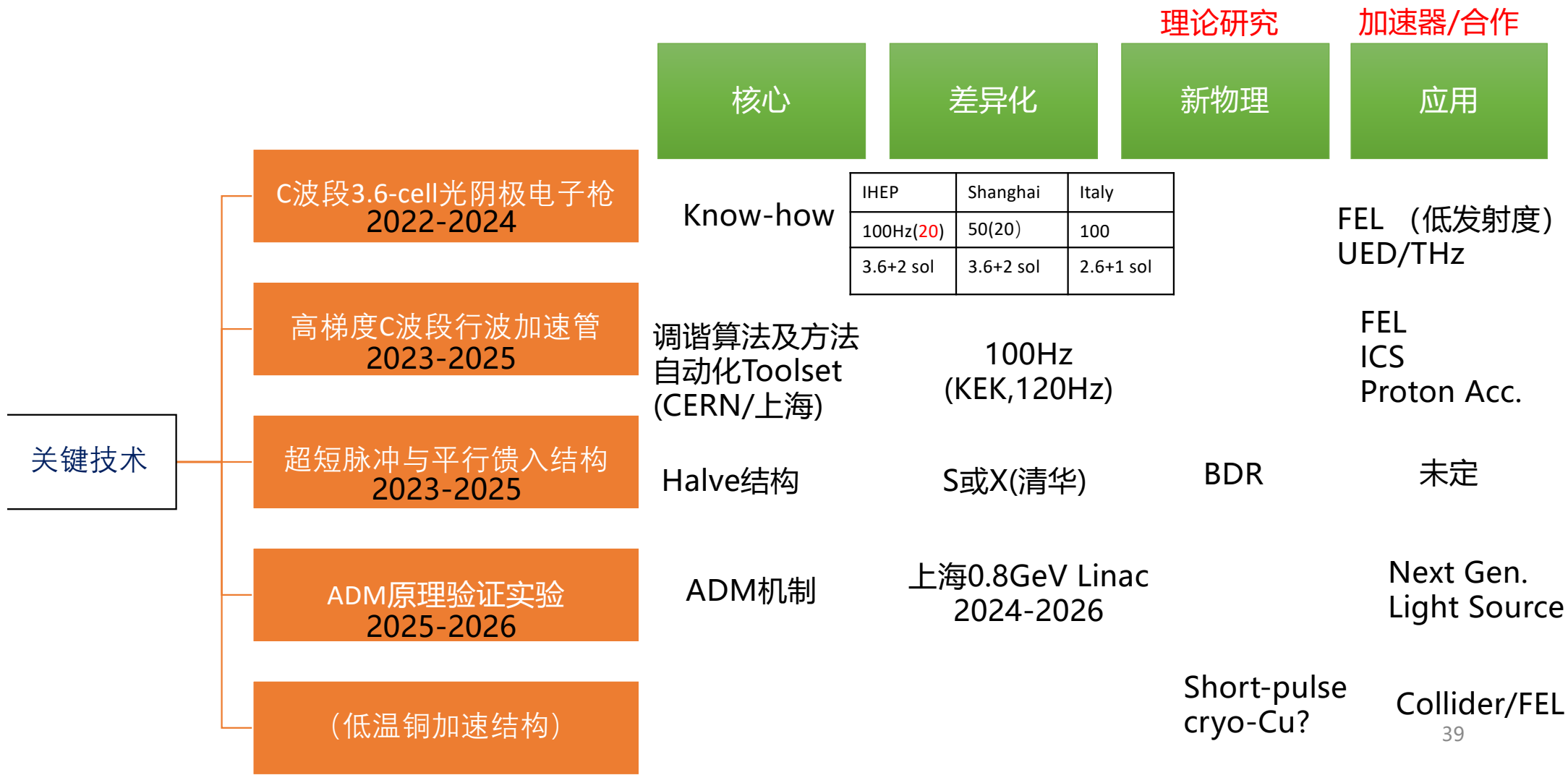
2000 (能量较低)



4500 (能量较高)

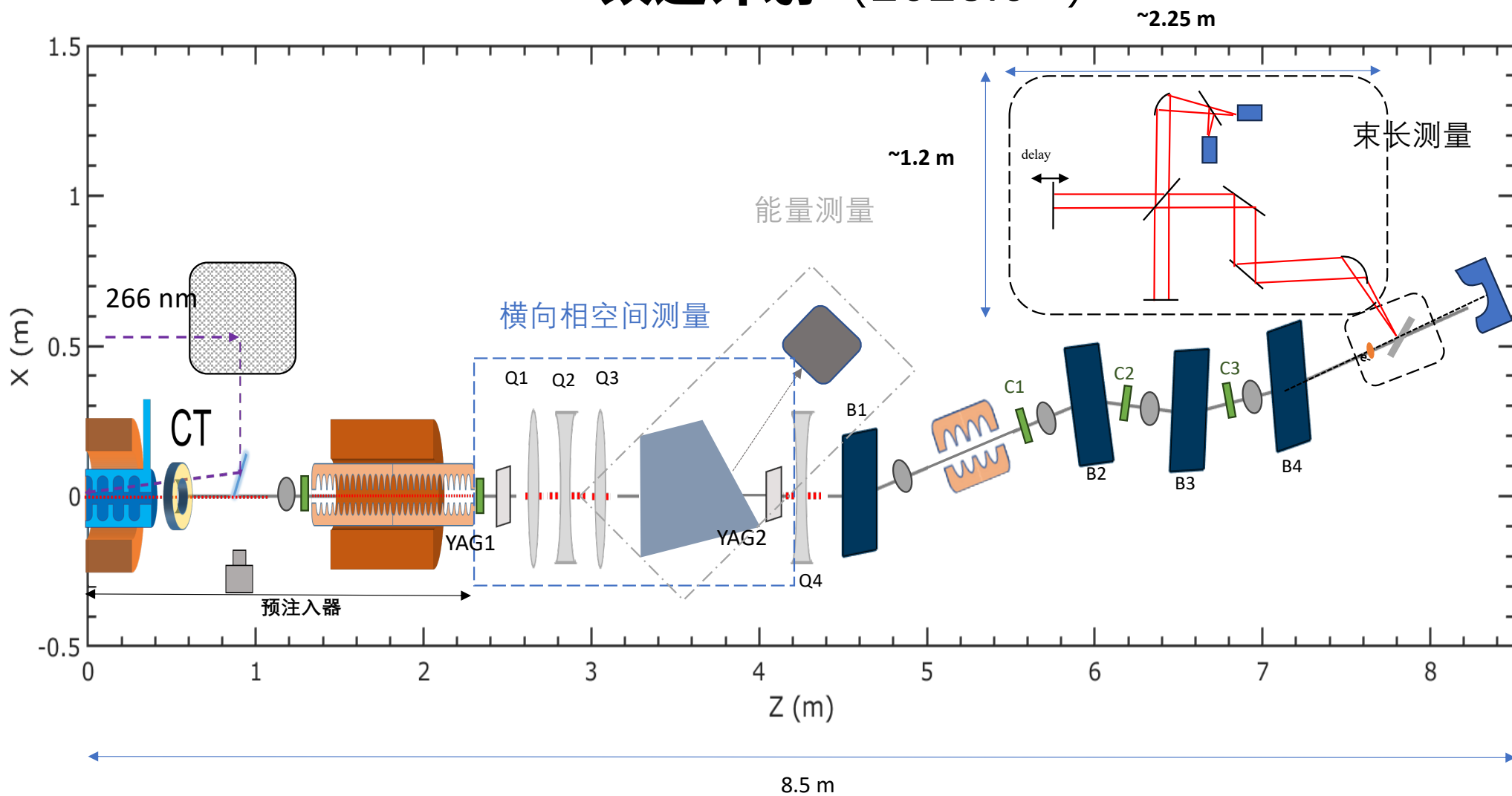


整体研究布局 全C/高梯度



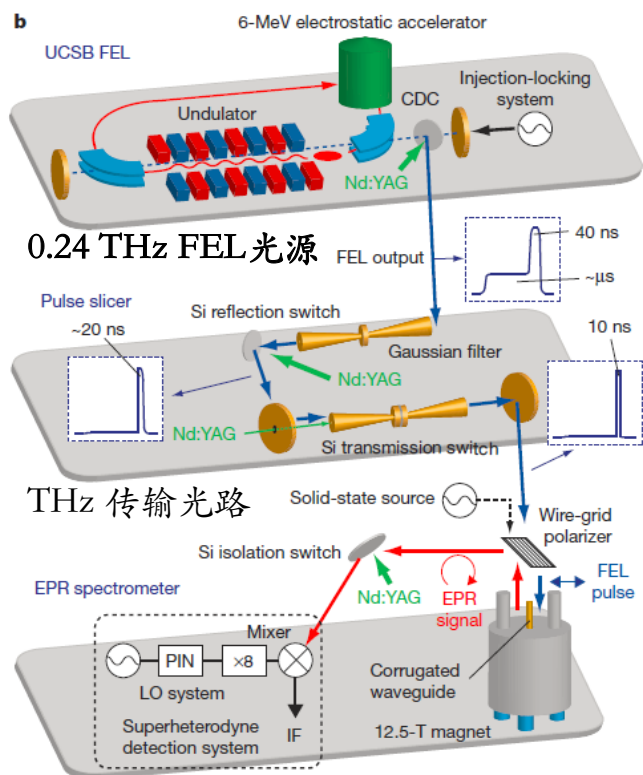
平台应用

ADM改造计划 (2025.6~)



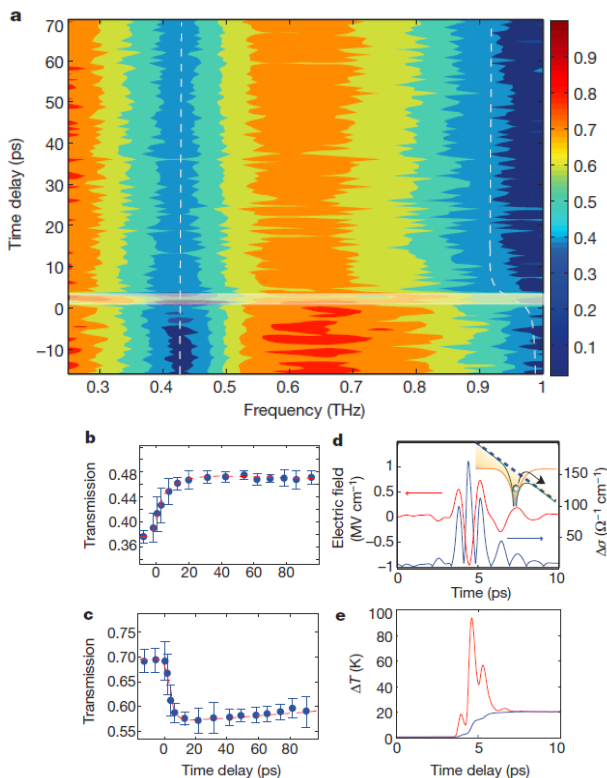
太赫兹相关应用研究

THz FEL做谱学测量



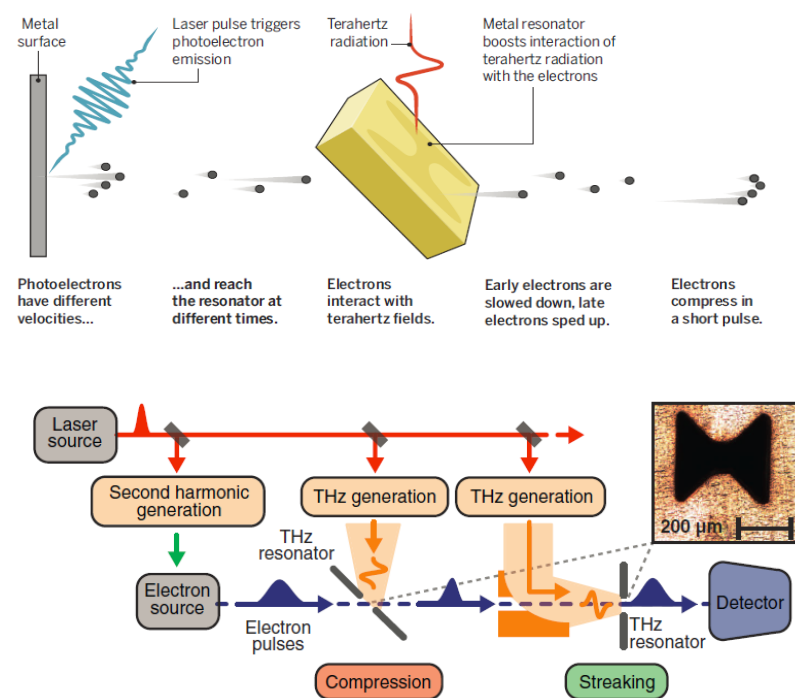
S. Takahashi, et al., Nature, 489, 409 (2012)

THz驱动的VO2的相性变化



Mengkun Liu, et al., Nature 487, 345 (2012)

THz波+电镜做成像

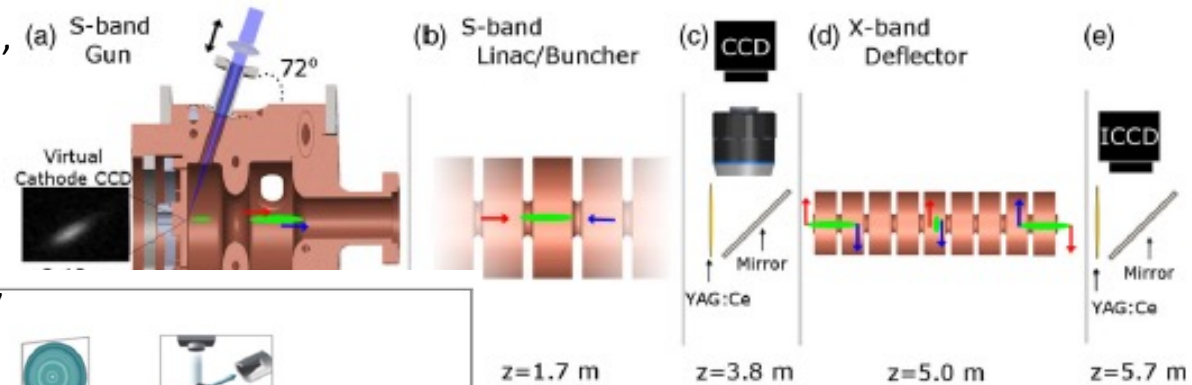


1. Claus Ropers, Science, 352, 410 (2016)

2. C. Kealhofer, et al., Science, 352, 429 (2016)

基于光阴极电子枪的UED

UCLA, Jared Maxson, et al., PRL 118, 154802 (2017)



BNL, Pengfei Zhu, et al., New J. Phys. 17 (2015) 063004

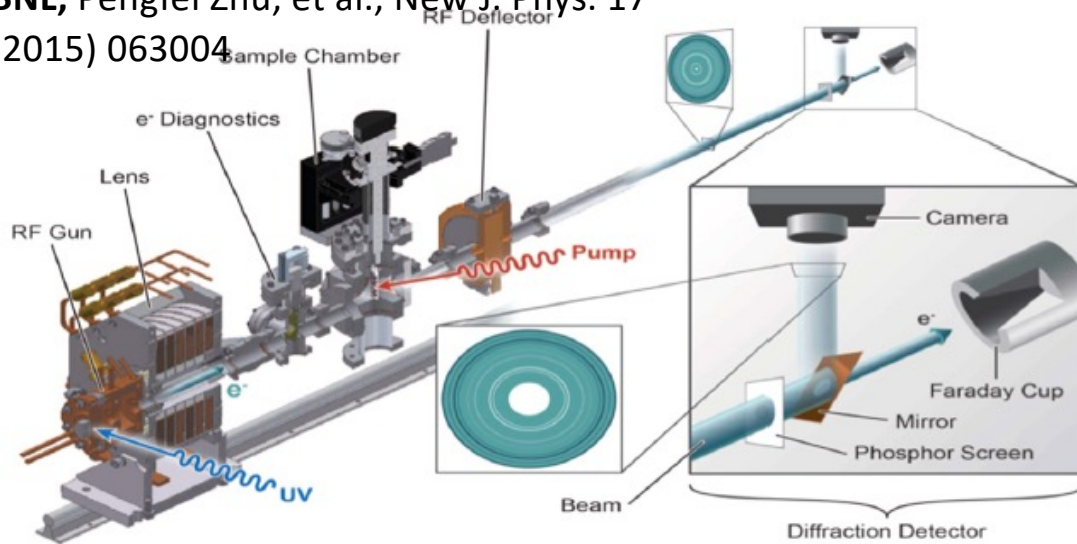


Figure 1. Schematic of the experimental set-up. UV photons from a Ti-sapphire laser are used to generate electrons in the RF gun. A solenoid magnet focuses the beam onto the detector screen 4 m downstream of the sample. Near-IR pulses from the same Ti-sapphire laser are used to optically pump the sample.

SLAC, Hastings *et al.* Appl. Phys. Lett. 89, 184109 (2006)

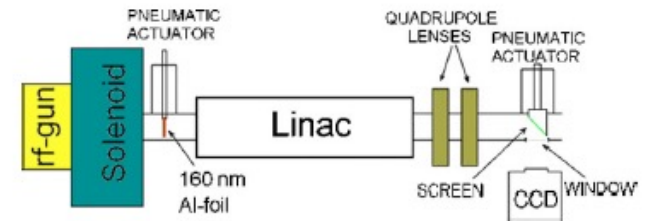
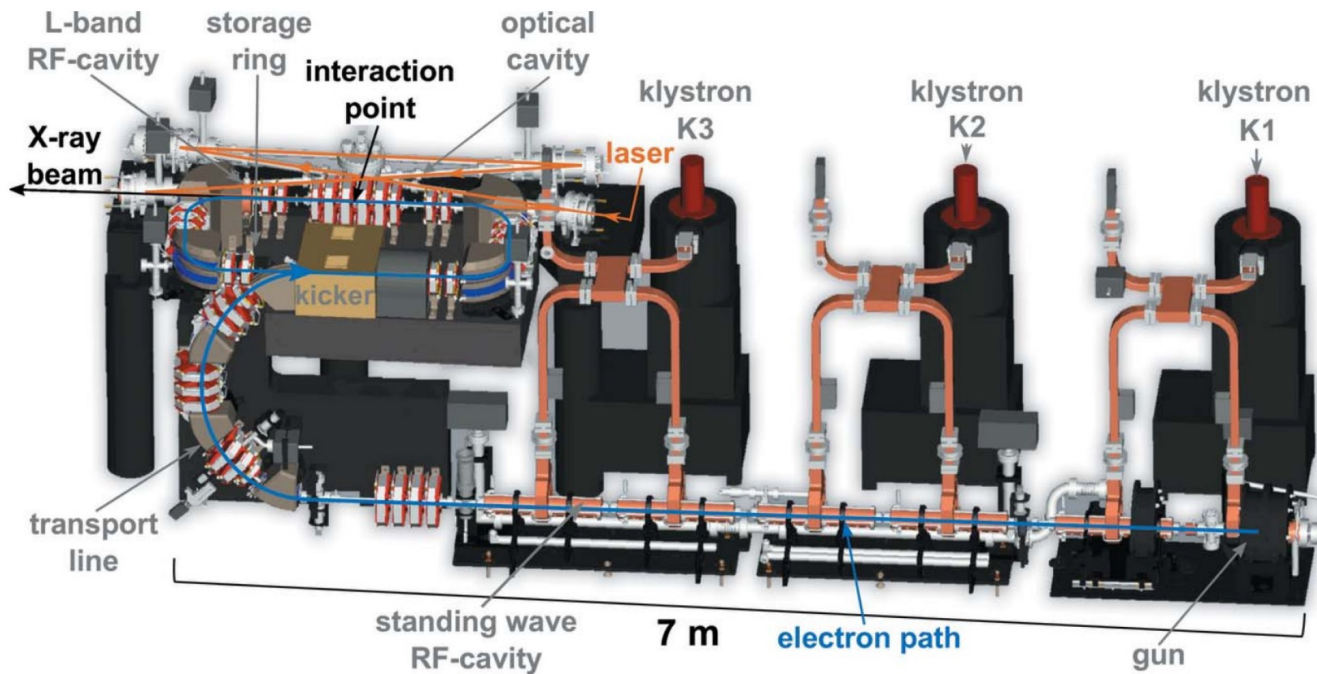


FIG. 1. (Color online) Layout of the GTF beamline and the electron diffraction experiment.

紧凑型光源/ICS

The X-ray source of the MuCLS



$$\mathcal{L}_0 = f_{\text{coll}} \frac{N_l N_e}{4\pi\sigma_r^2}$$



Günther et al., J. Synch. Rad. 27, 1395 (2020), underlying CAD drawing provided by Lyncean Technologies Inc.



谢谢!

欢迎大家合作开展基于MeV~数十MeV电子束流的研究!