上海激光电子伽马源 (SLEGS)
光核物理研究进展

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内容

1 光核物理与γ源

2 SLEGS@SSRF

3 典型光核物理实验

4 总结&展望

1 光核物理与γ源

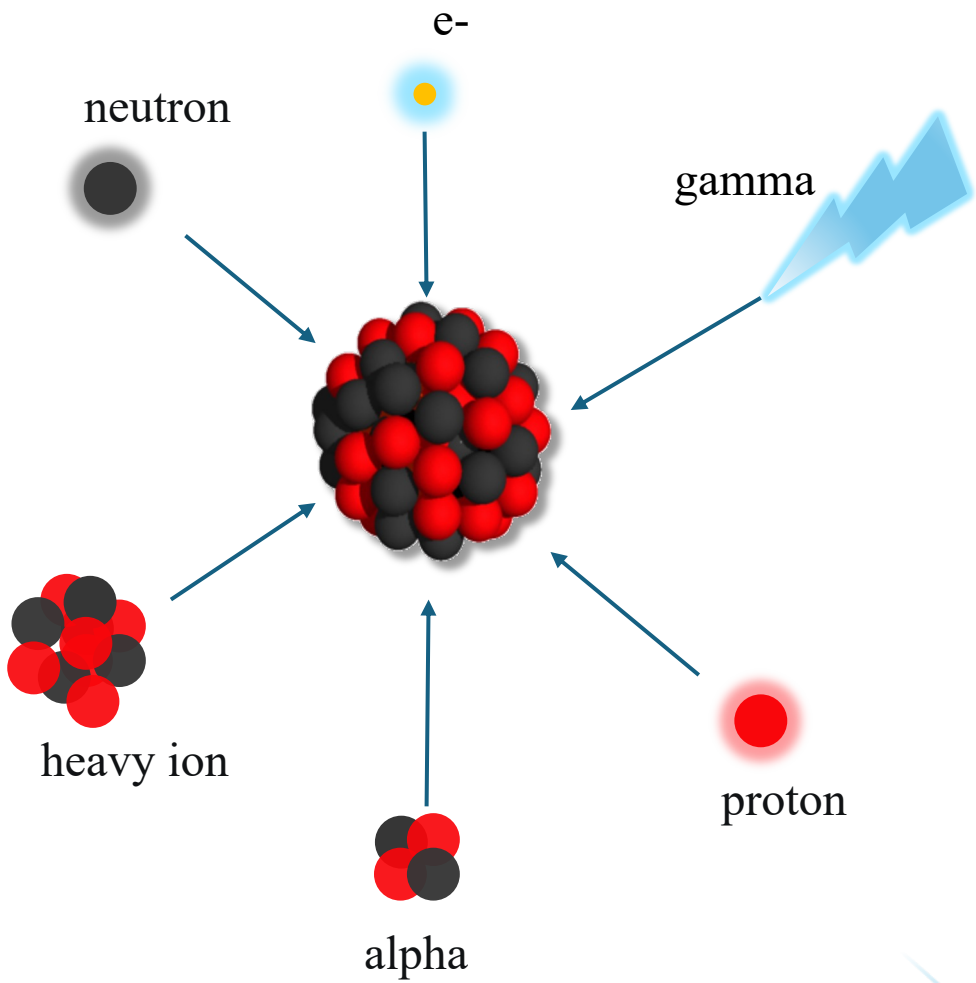
为什么用γ光子探针研究原子核/核子?

PROS-

- Interaction is understood(QED)
- Whole volum of nucleus probed
- Inerpretation clearer – probe unlikely to interact more than once

CONS:-

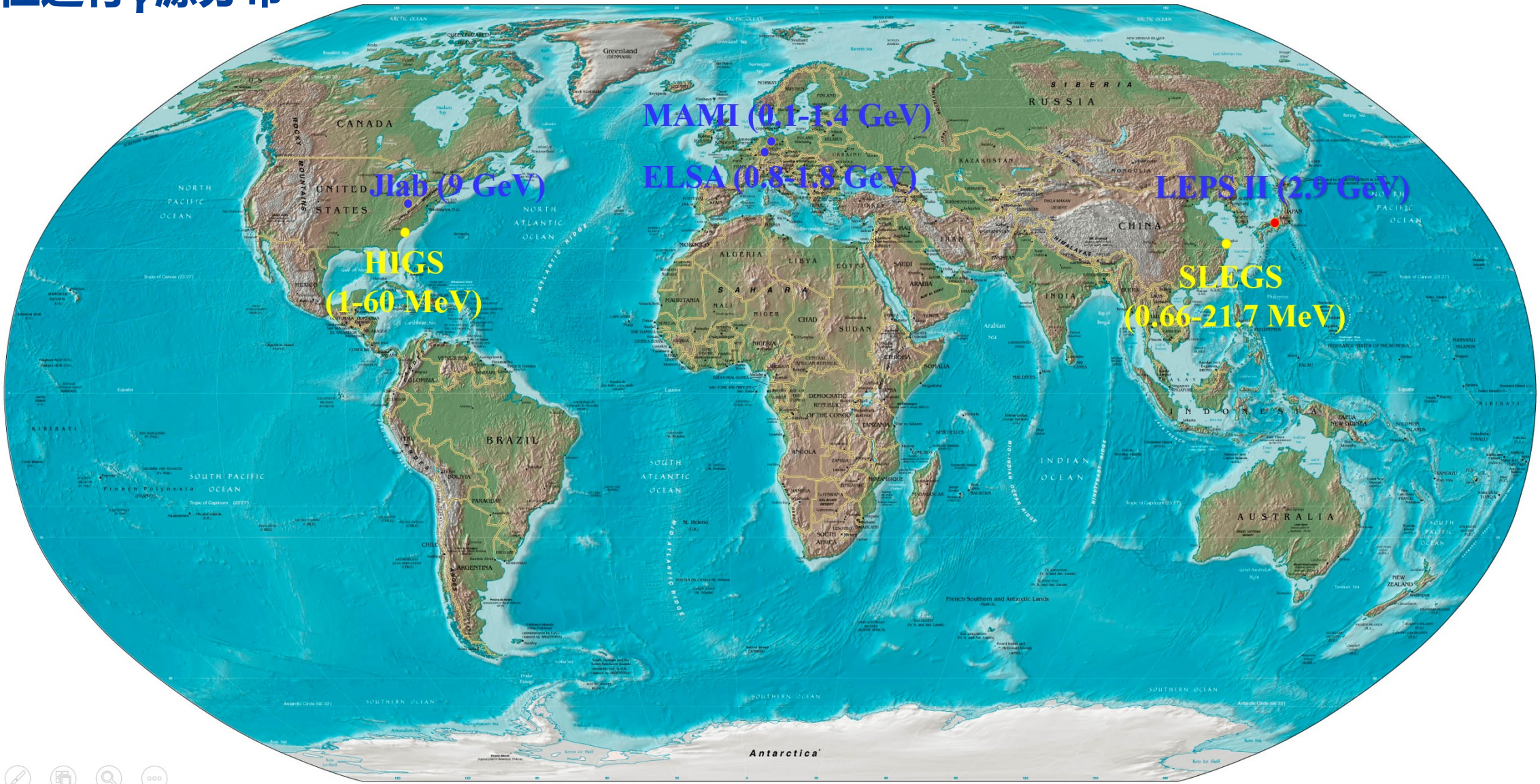
- Cross-sections are small
- High enery photo beam were challenging



Prog. Part. Nucl. Phys. 62, 1(2009). Prog. Part. Nucl. Phys. 122,103903 (2022).

1 光核物理与γ源

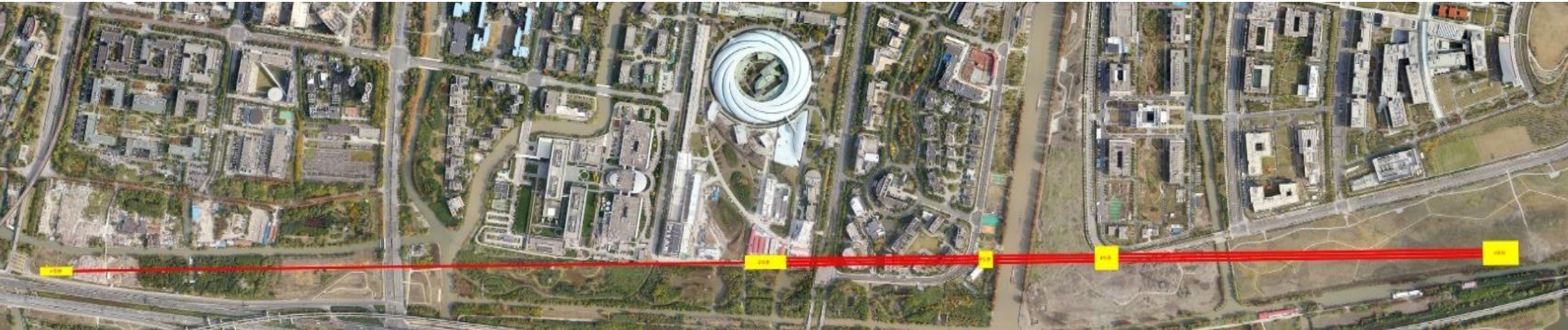
□ 在运行γ源分布



2 SLEGS@SSRF



Energy	3.5 GeV
Beam Sizeσ_x	276.9 um
Beam Sizeσ_y	12.24 um
Pulse RMS	3 mm
Current	**300 mA**
Q_e	1.44 nC
Emittance$\varepsilon_x/\varepsilon_y$	2.59 / 2.59E-2 nmrad
Divergenceη_x/η_y	0.207 / 0 m
β_x/β_y	14.86 / 5.78 m
Energy spread	0.944E-3
Pulse Number	500

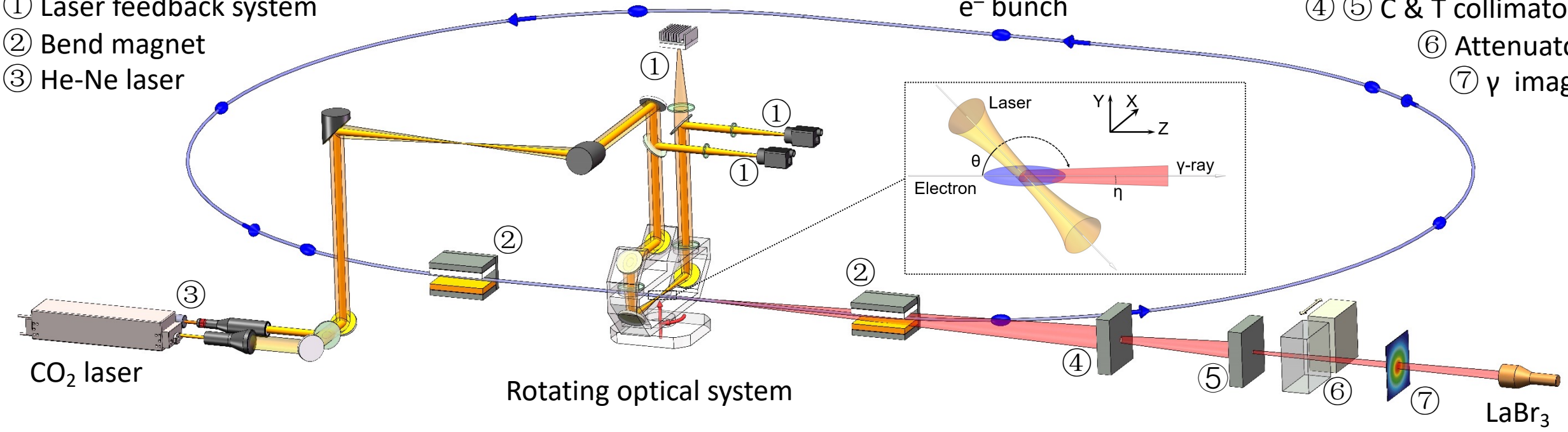


2 SLEGS@SSRF

① Laser feedback system
② Bend magnet
③ He-Ne laser

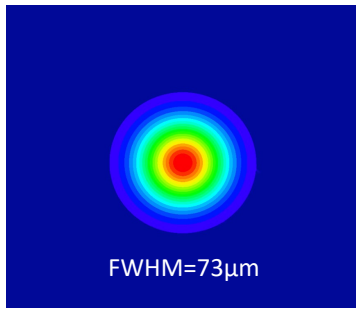
e⁻ bunch

④ ⑤ C & T collimators
⑥ Attenuator
⑦ γ image

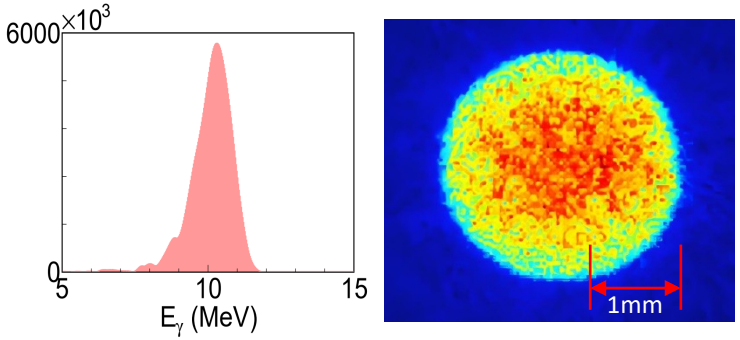


CO_2 laser

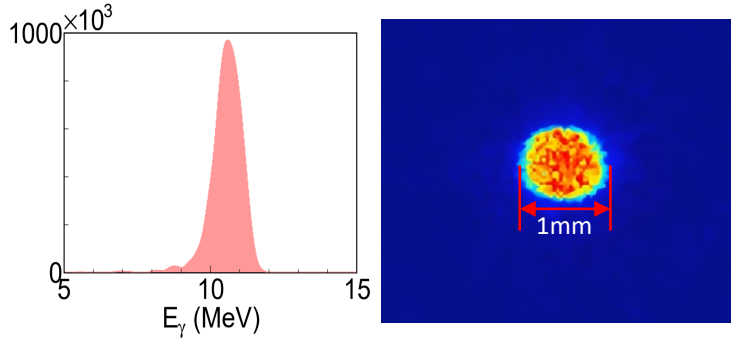
Rotating optical system



Laser focal spot



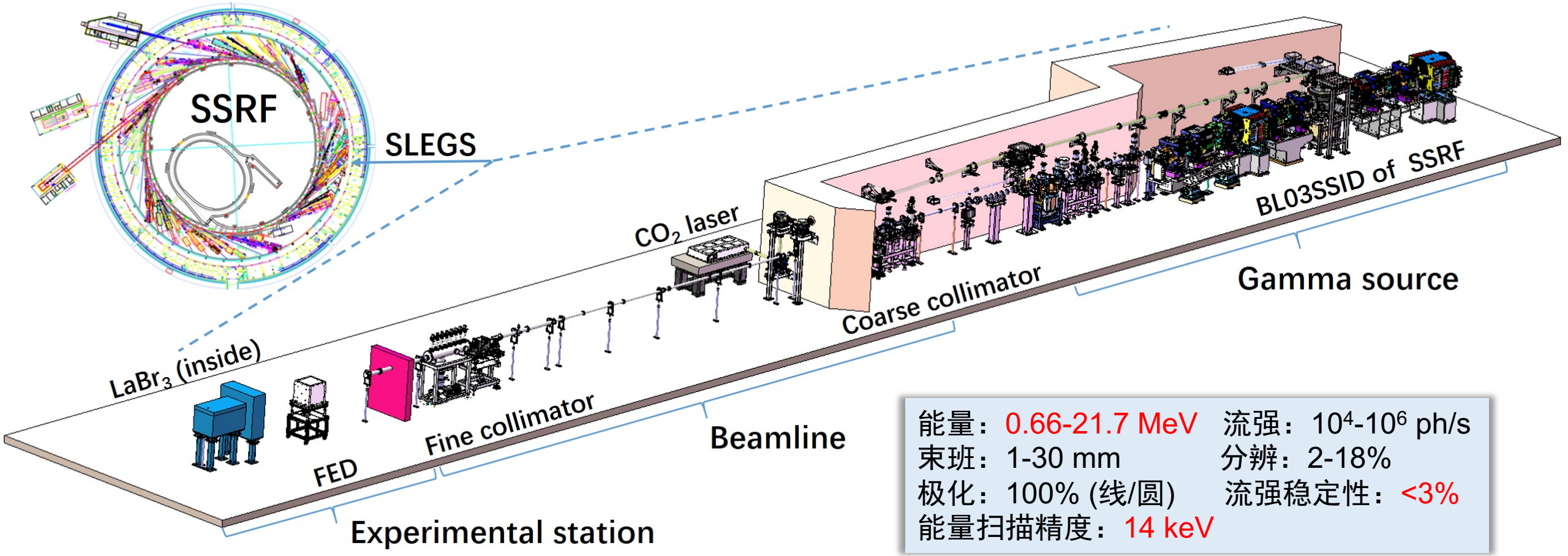
γ spot and spectrum @ C3



γ spot and spectrum @ C3T1

2 SLEGS@SSRF

Layout

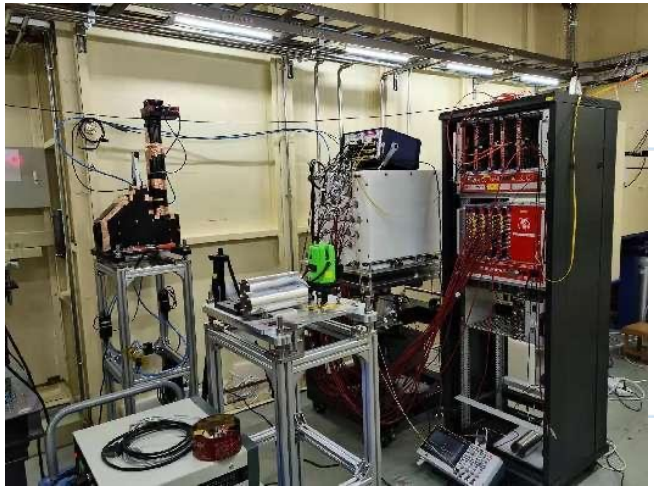


能量：0.66-21.7 MeV　流强：10^4-10^6 ph/s
束班：1-30 mm　分辨：2-18%
极化：100% (线/圆)　流强稳定性：<3%
能量扫描精度：14 keV

NIMA 1013,165638(2021), 1033, 166742 (2022), 1063,169314 (2024), 1073,170249 (2025), 1083,171075 (2026)
NIMB 519,9(2022), 559,165595 (2025) ; Proceedings of IPAC.(2021,2022,2023); Radiat. Meas. 174,107127(2024)

2 SLEGS@SSRF

口 实验能力-“带样品来，取数据回”便捷高效核物理实验模式

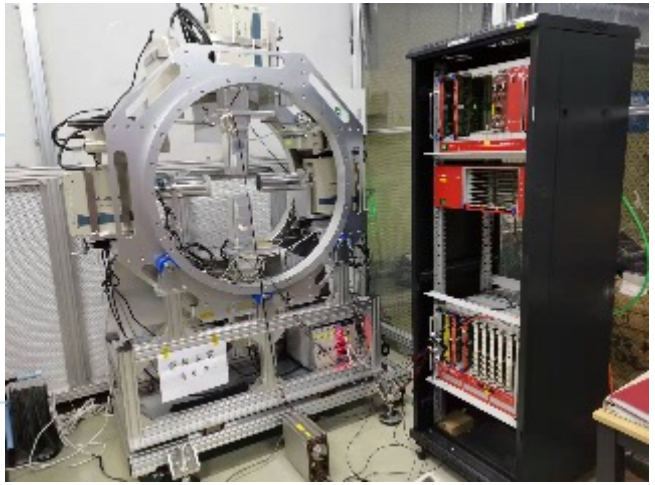


01 FED



02 TOF

03 NRF

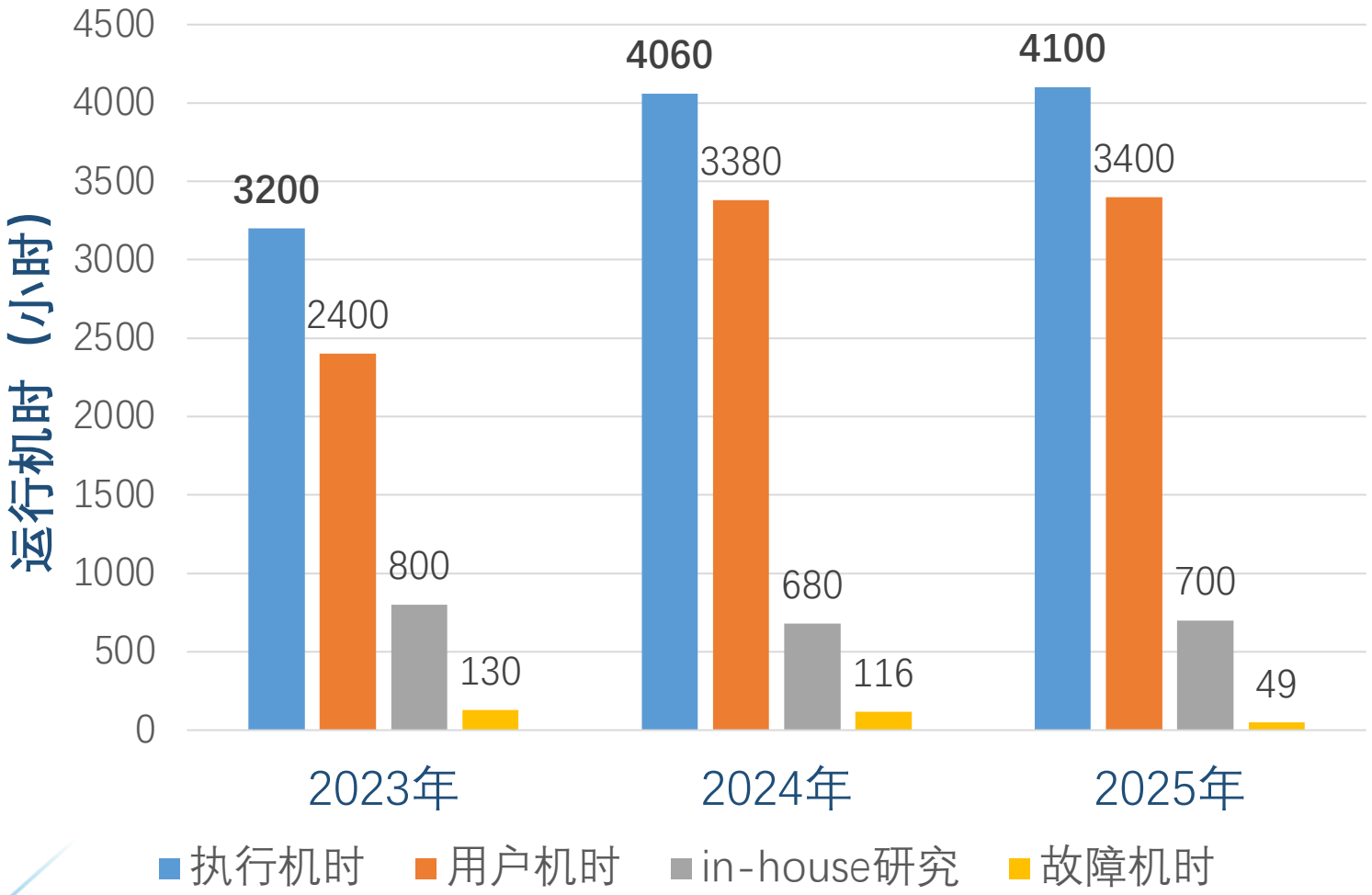


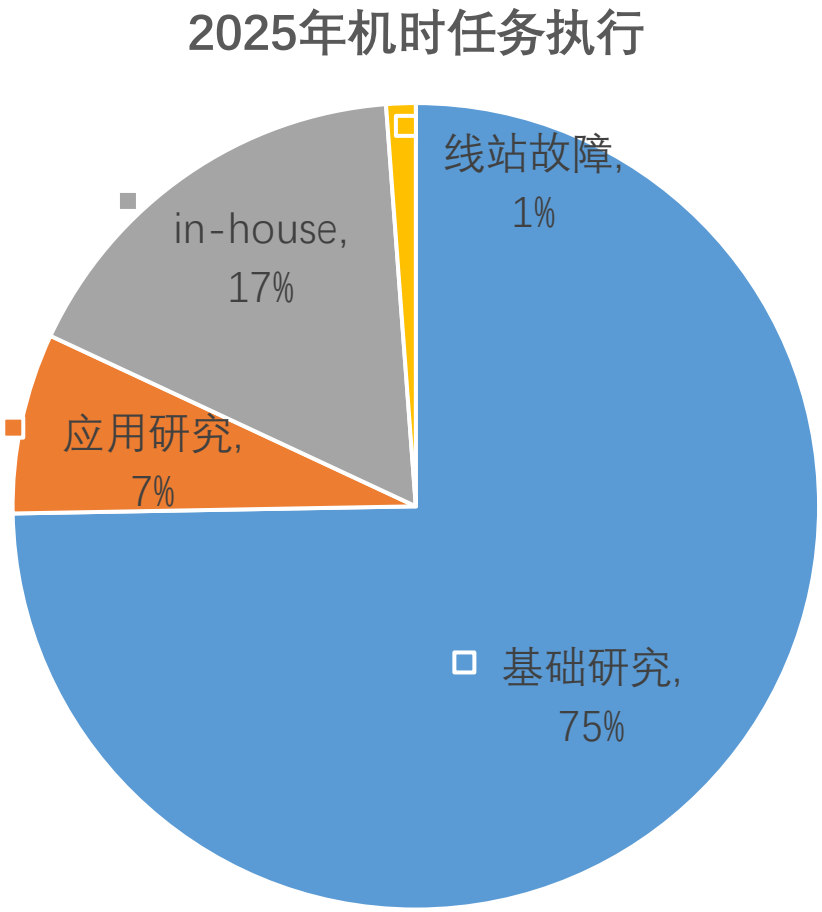
04 LCP



2 SLEGS@SSRF

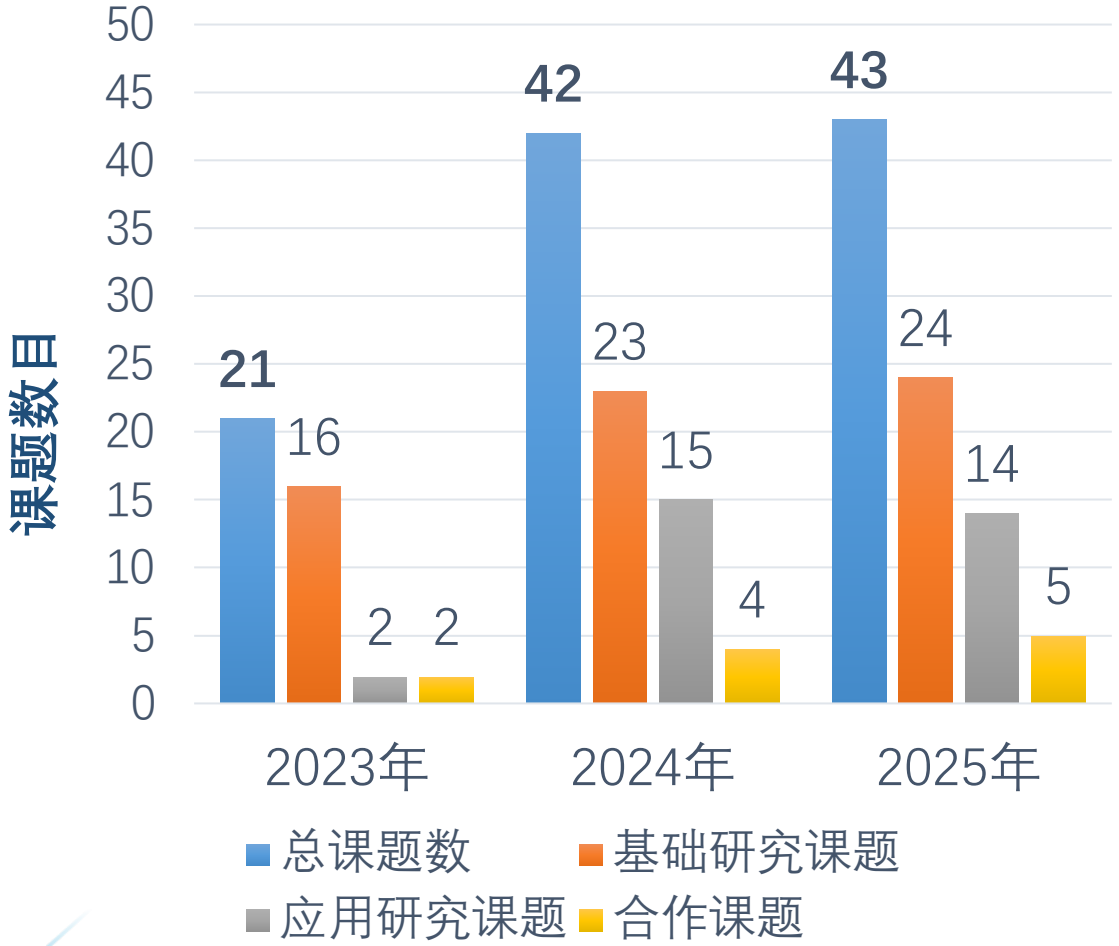
运行&开放





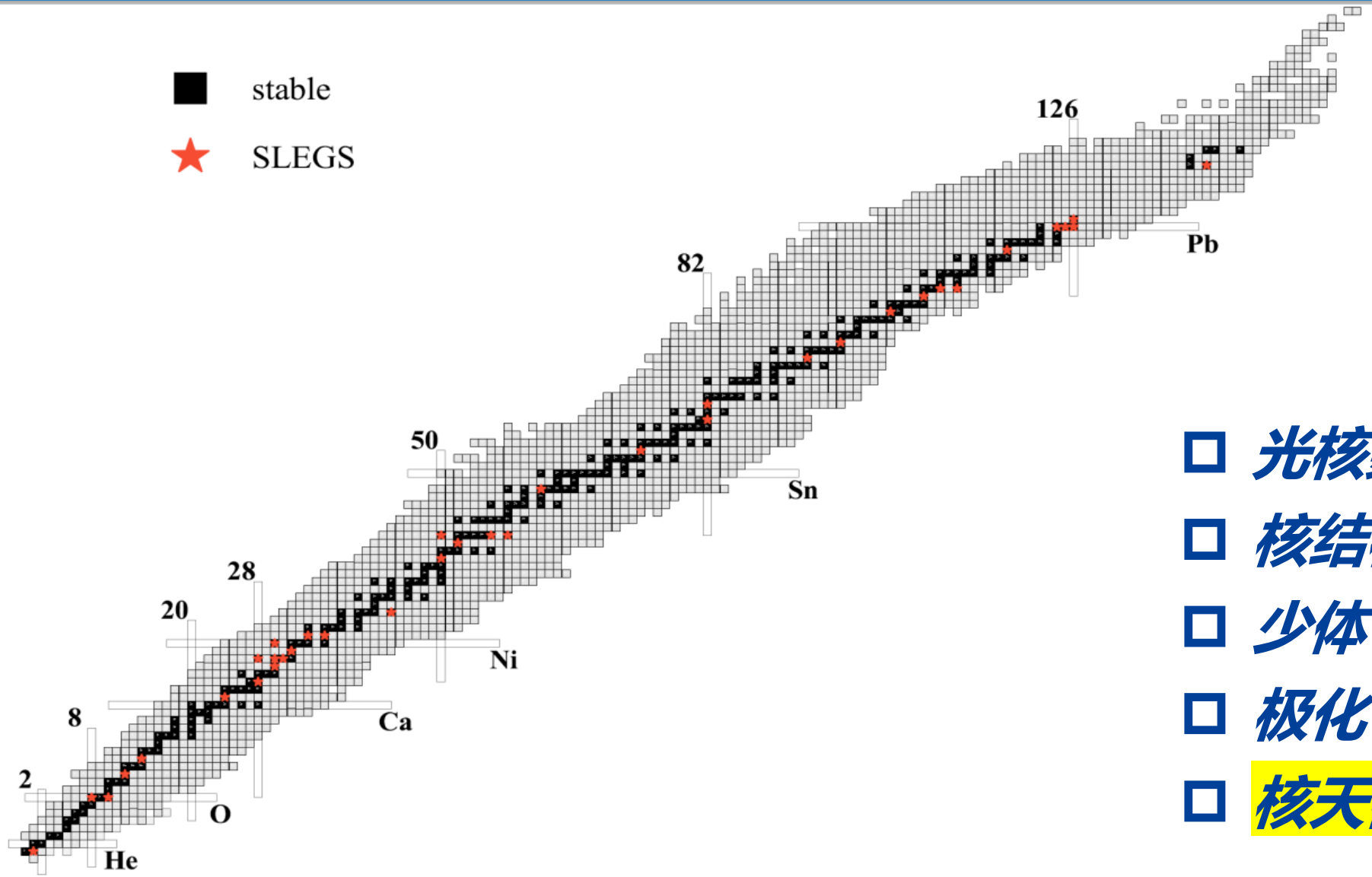
2 SLEGS@SSRF

口 支撑课题





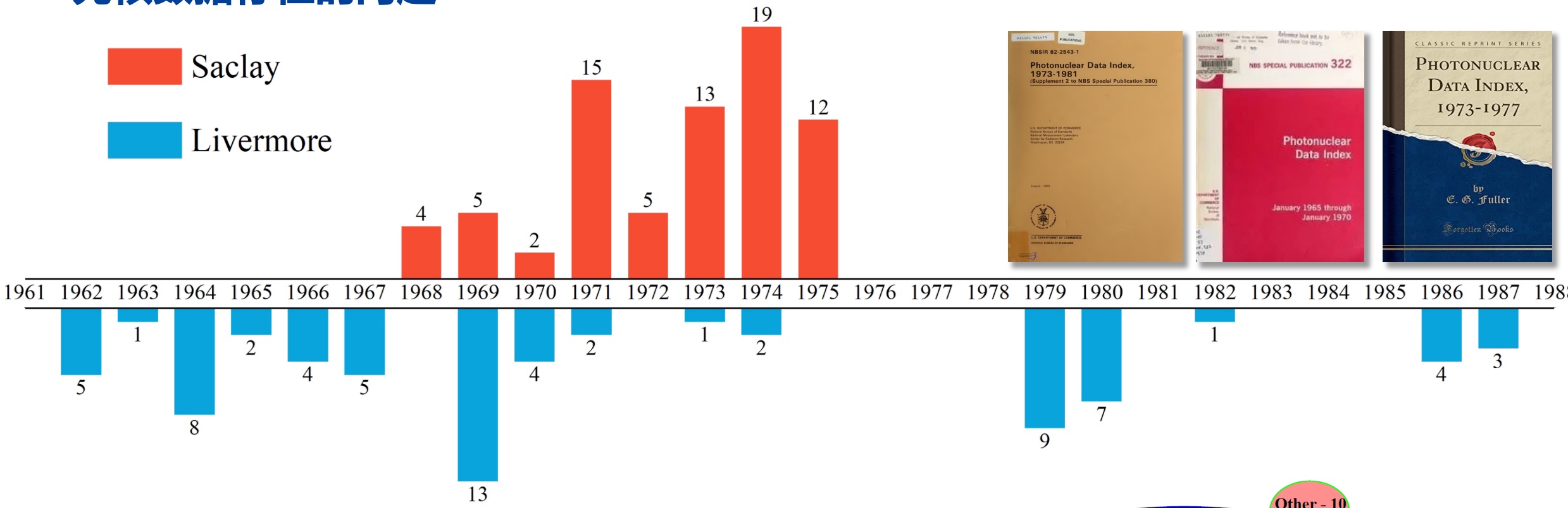
2 SLEGS@SSRF



- 光核数据
- 核结构
- 少体
- 极化
- 核天体

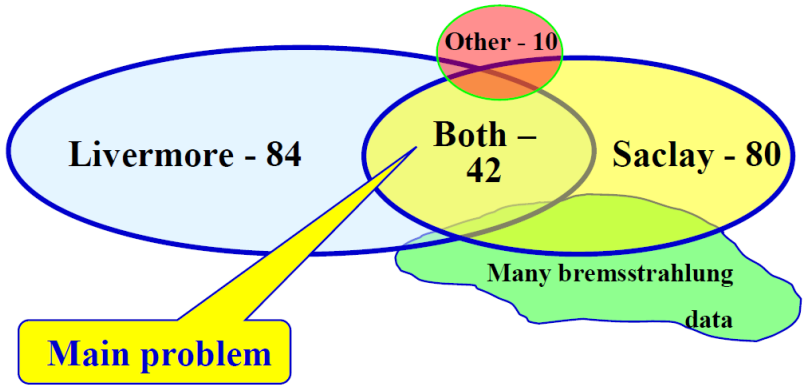
3 典型光核实验-光核数据

口 光核数据存在的问题



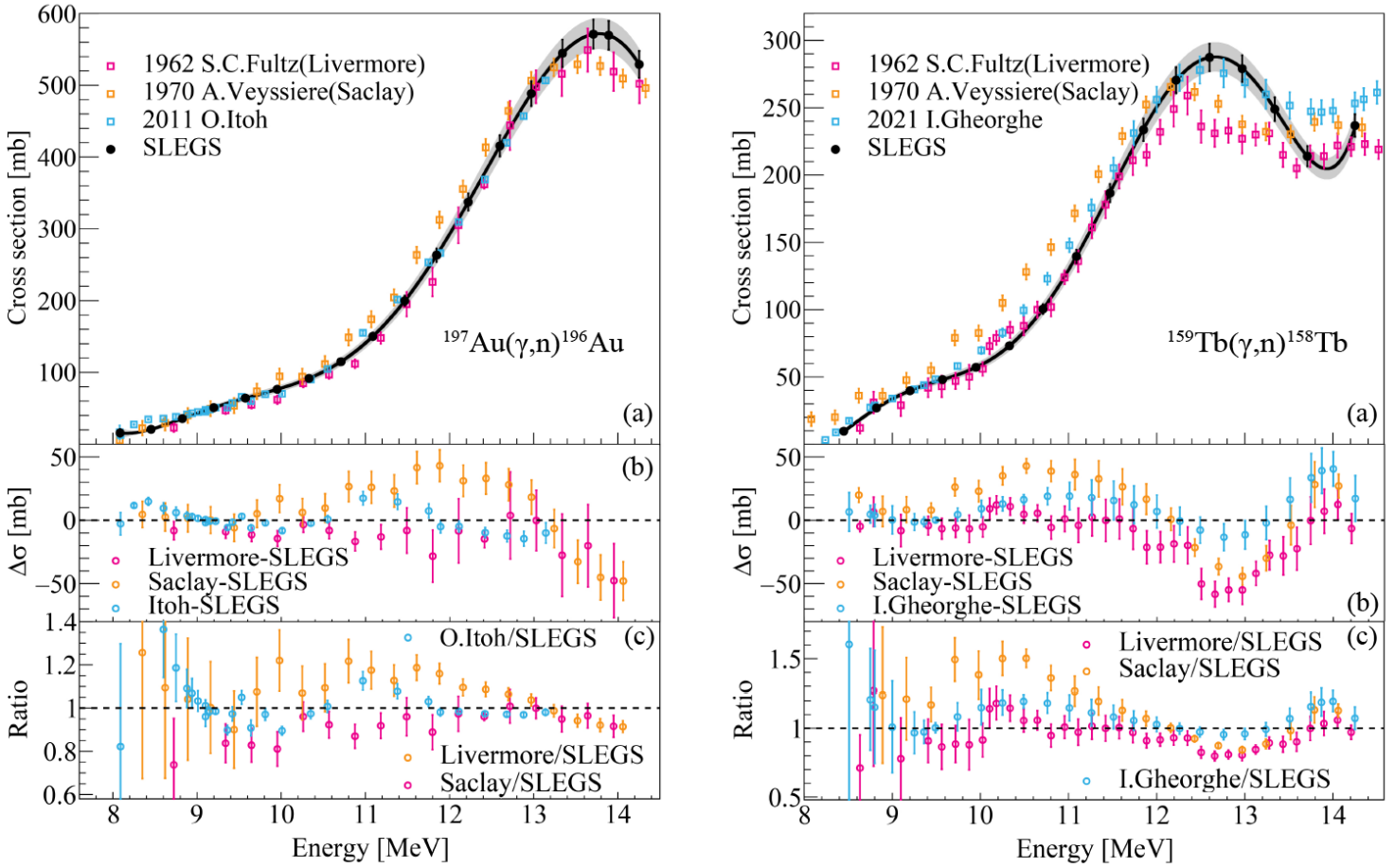
		^{51}V	^{75}As	^{89}Y	^{90}Zr	^{115}In	$^{116-124}$Sn	^{127}I	^{133}Cs	^{159}Tb	^{165}Ho	^{181}Ta	^{197}Au	^{208}Pb	^{232}Th	^{238}U
Saclay	统计误差	√	√	√	√	√	√	√	√				√		√	√
	系统误差		√	√	√											
	总误差															
Livermore	统计误差							√					√		√	√
	系统误差							√					√		√	√
	总误差	√											√			

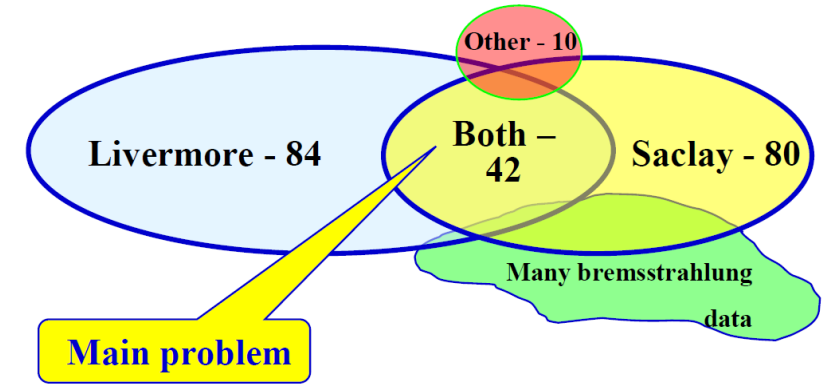
?

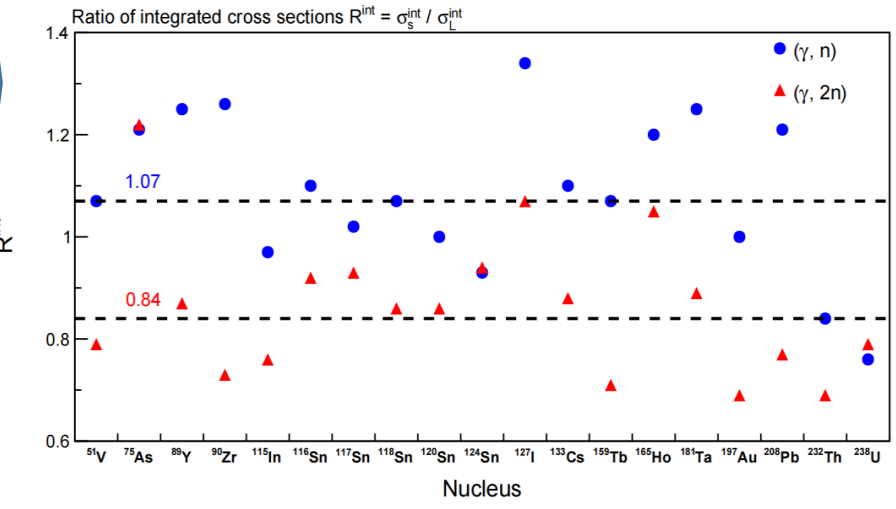


3 典型光核实验-光核数据

Day-one experiment at SLEGS



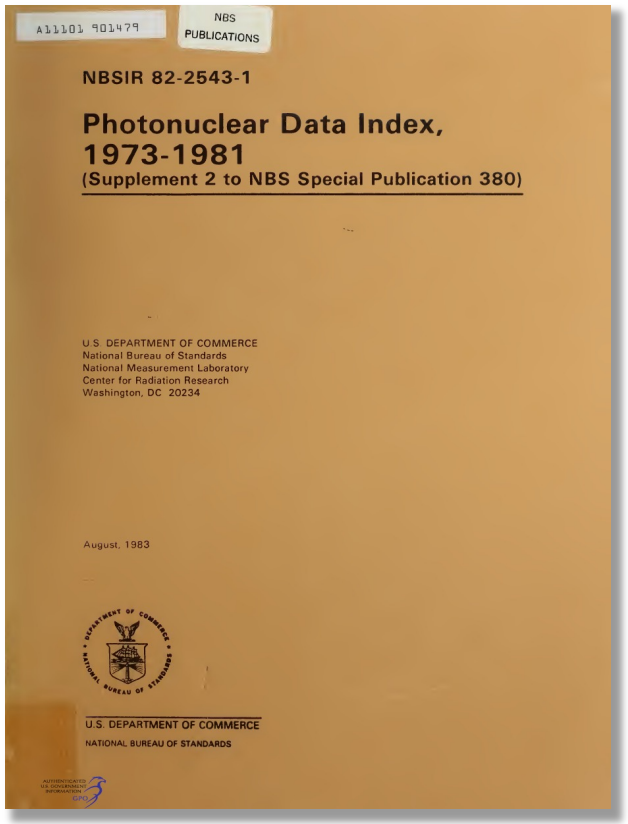


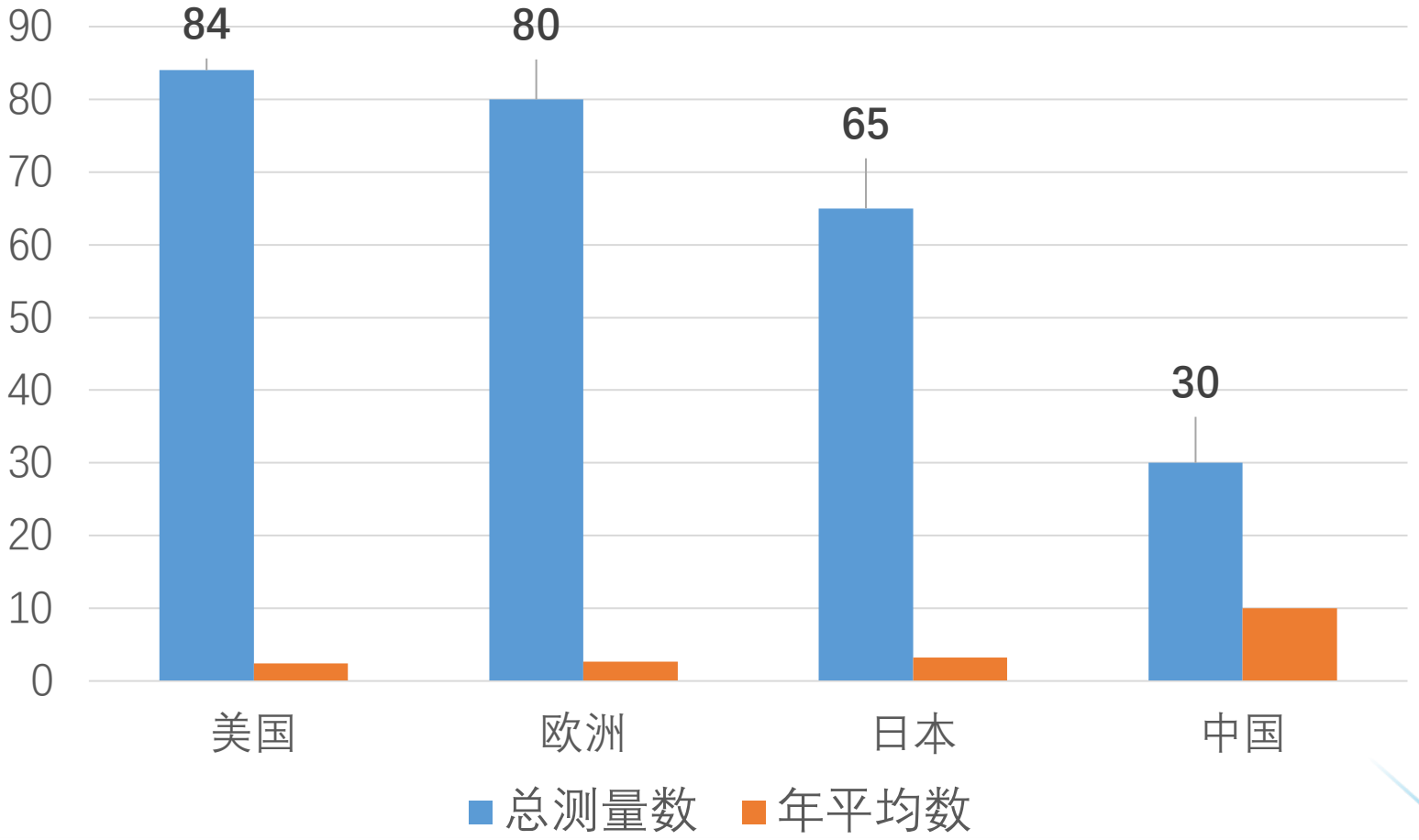


Hao Zirui, Fan Gongtao*, Wang Hongwei*,… Ma Yugang*, Science Bulletin , 70, 20252591 (2025)

3 典型光核实验-光核数据

- 完善光中子截面数据库，最终有望解决Livermore/Saclay光中子截面数据不一致这一世纪难题





3 典型光核实验-核结构(形变)

□ 准单能伽马束截面数据问题

准单能截面 $(\sigma_N)_{\mathrm{f}} = \int_{S_n}^{E_{\max}} n_\gamma(E_\gamma)\sigma_\gamma(E_\gamma)\mathrm{d}E = \dfrac{N_n}{N_\gamma N_t \xi \varepsilon_n g}$

$$\sigma_{\mathrm{f}} = \mathbf{D}\sigma$$

$$\begin{pmatrix}\sigma_1\\ \sigma_2\\ \vdots\\ \sigma_N\end{pmatrix}_{\mathrm{f}} = \begin{pmatrix} D_{11} & D_{12} & \cdots & D_{1M}\\ D_{21} & D_{22} & \cdots & D_{2M}\\ \vdots & \vdots & \ddots & \vdots\\ D_{N1} & D_{N2} & \cdots & D_{NM}\end{pmatrix}\begin{pmatrix}\sigma_1\\ \sigma_2\\ \vdots\\ \vdots\\ \sigma_M\end{pmatrix}$$

（1）令$\sigma_0 = 1$，计算folded cross section $\sigma_{\mathrm{f}} = D \cdot \sigma_0$，其中$D$为响应矩阵；

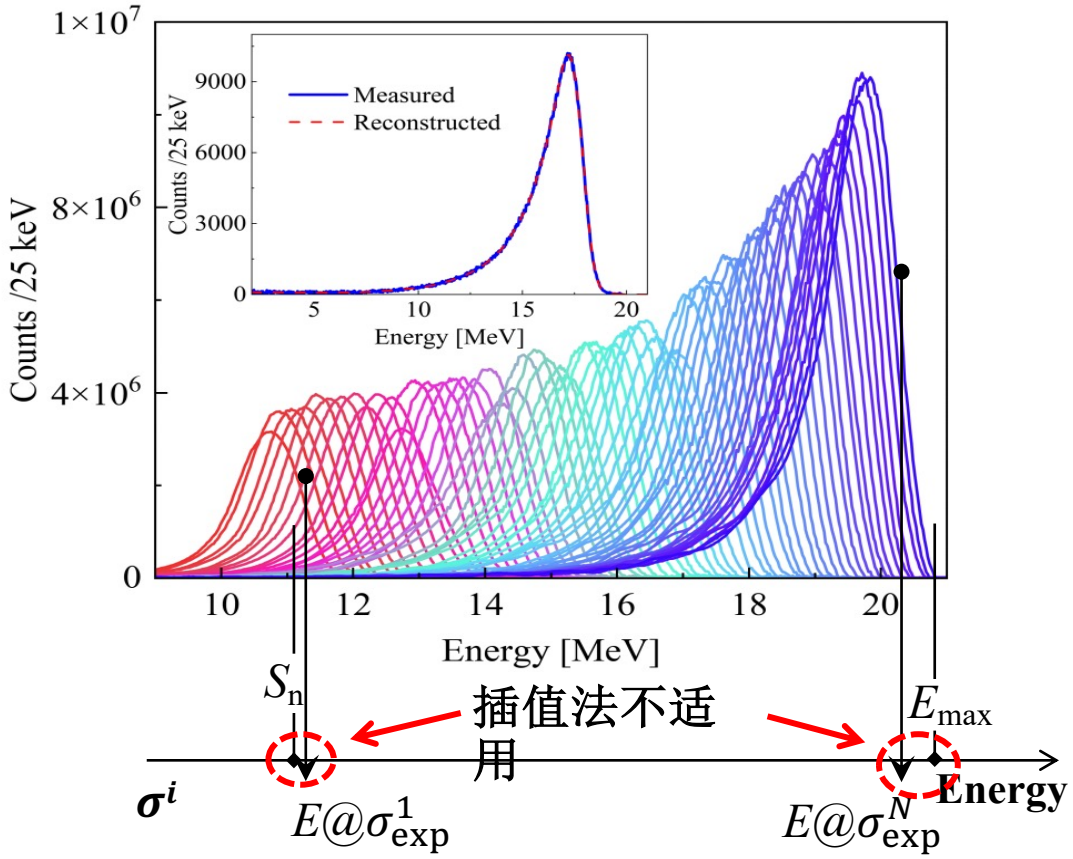
(59×390)

（2）$\sigma_1 = \sigma_0 + \sigma_{\exp} - \sigma_{\mathrm{f}}$，

$$\sigma_{\mathrm{f}}^{i} = D \cdot \sigma^{i}$$

$$\sigma^{i+1} = \sigma^{i} + (\sigma_{\exp} - \sigma_{\mathrm{f}}^{i})$$

（3）当$\sigma_{\mathrm{f}}^{i+1} \approx \sigma_{\exp}$**时**，结果收敛，结束迭代，最终计算的单能结果应为得到$\sigma_{\mathrm{f}}^{i+1}$的$\boldsymbol{\sigma_{\mathrm{f}}^{i}}$.



$\sigma_{\exp}$，σ_{f}^{i}维度为N，需要扩展为M以与σ^i相加

SLEGS常用的方法：多项式回归、支持向量机回归

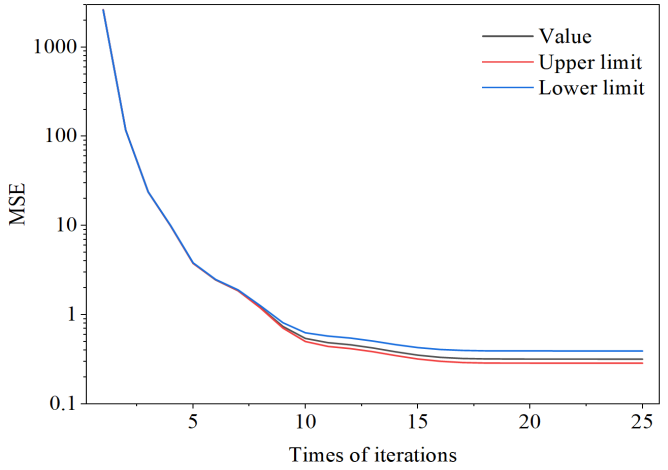
需要合理设置超参数

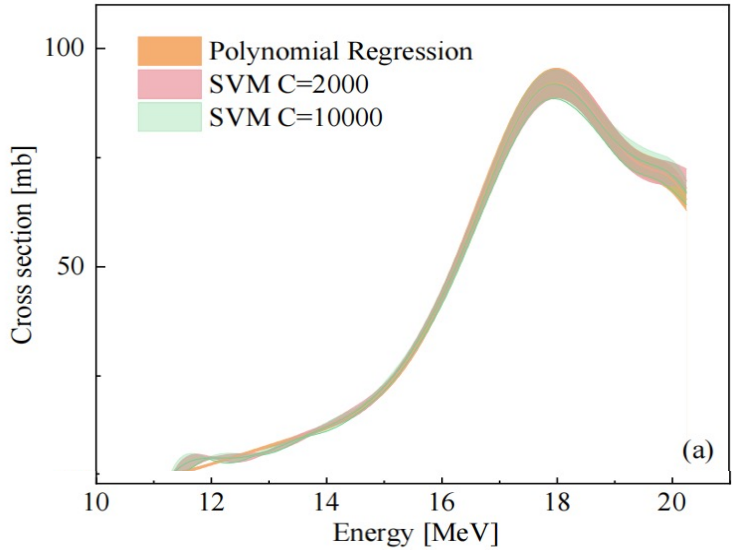
3 典型光核实验-核结构(形变)

□ 解决准单能伽马束截面数据问题

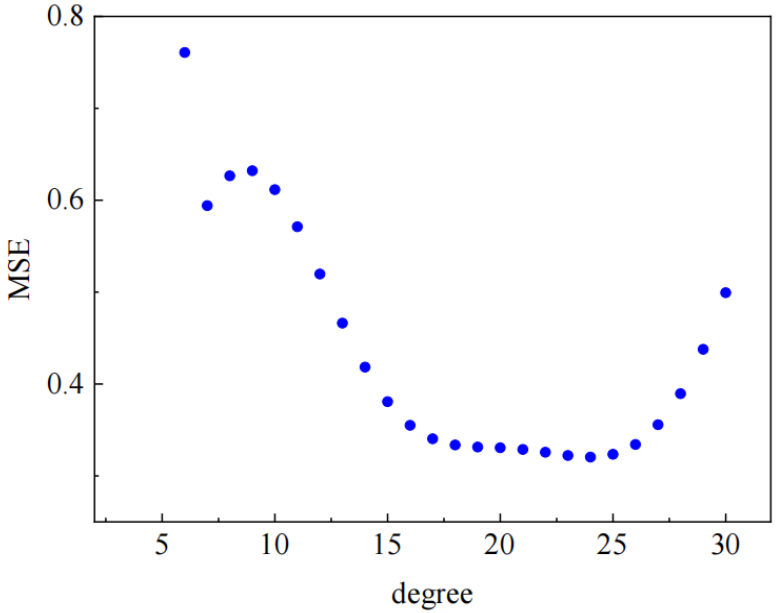
多项式回归
- ***degree*** 多项式次数

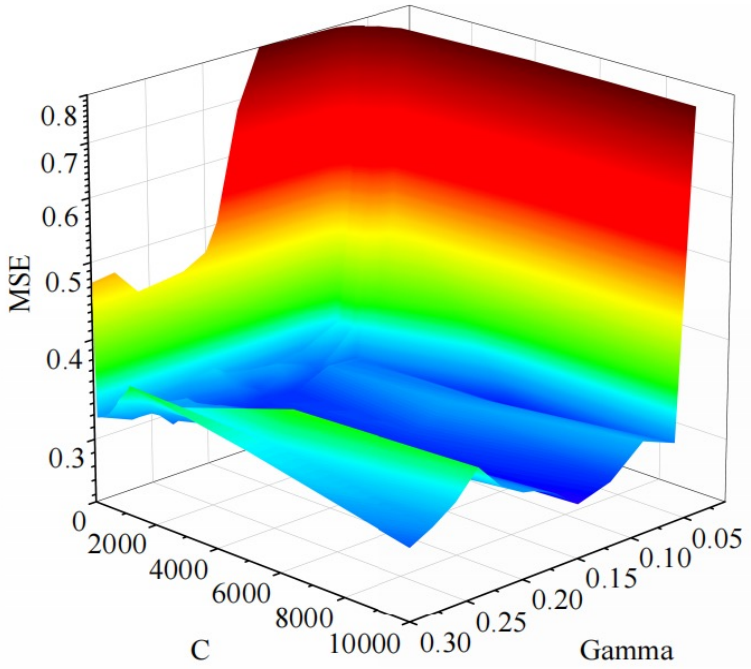
支持向量机回归
- ***C*** 正则化惩罚系数
- ***gamma*** 核系数
- ***kernel***通常为rbf





寻找能使得重建截面与实测截面
均方根误差(MSE)最小的超参数





使用多项式回归与支持向量机回归的单能截面求解算法，结果一致

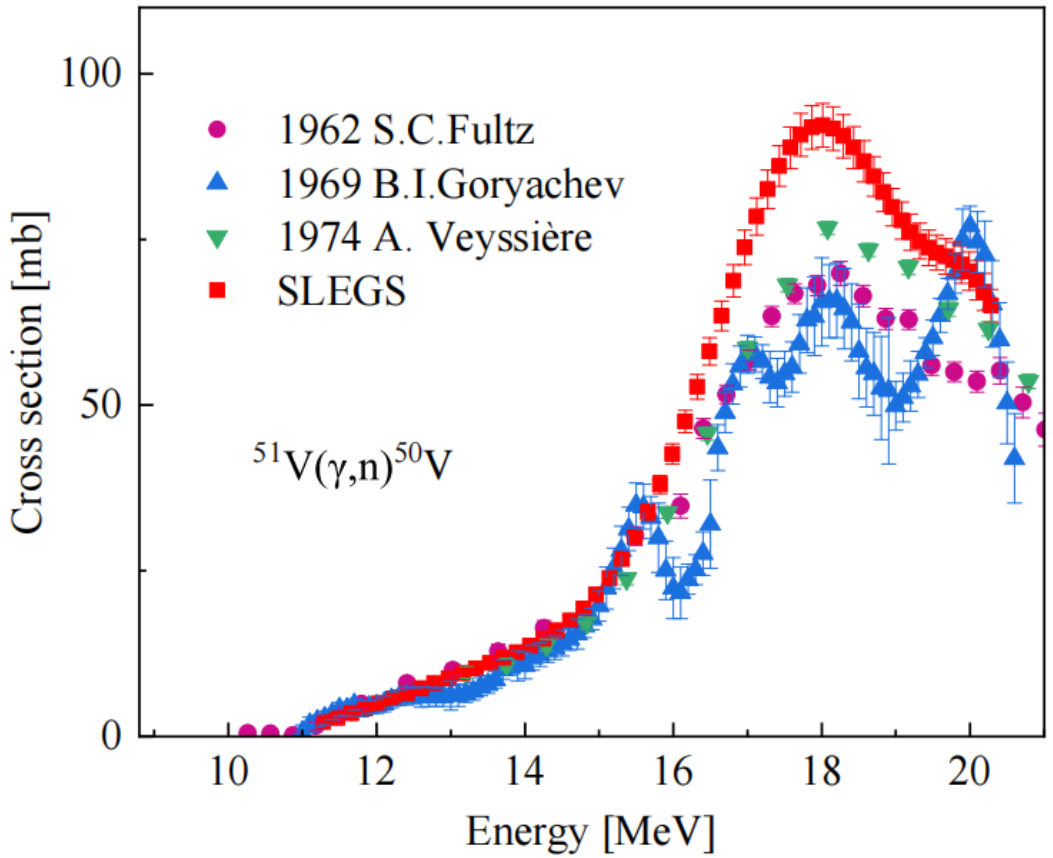
结果一致性（相对高度、宽度）

- □ 算法学习截面趋势**避免过拟合**
- □ 优化超参数使结果**避免欠拟合**

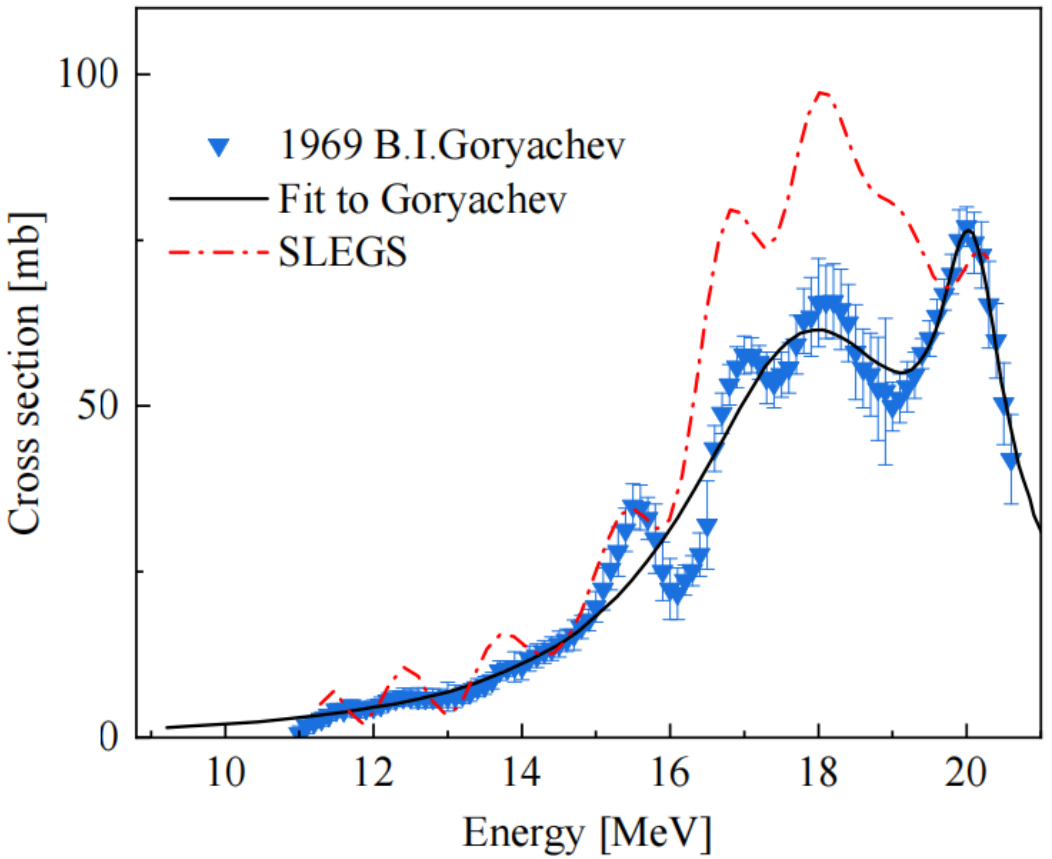
最终截面结果能够反应核结构

3 典型光核实验-核结构(形变)

□ 解决准单能伽马束截面数据问题



实验测量的$^{51}V(\gamma,n)^{50}V$截面

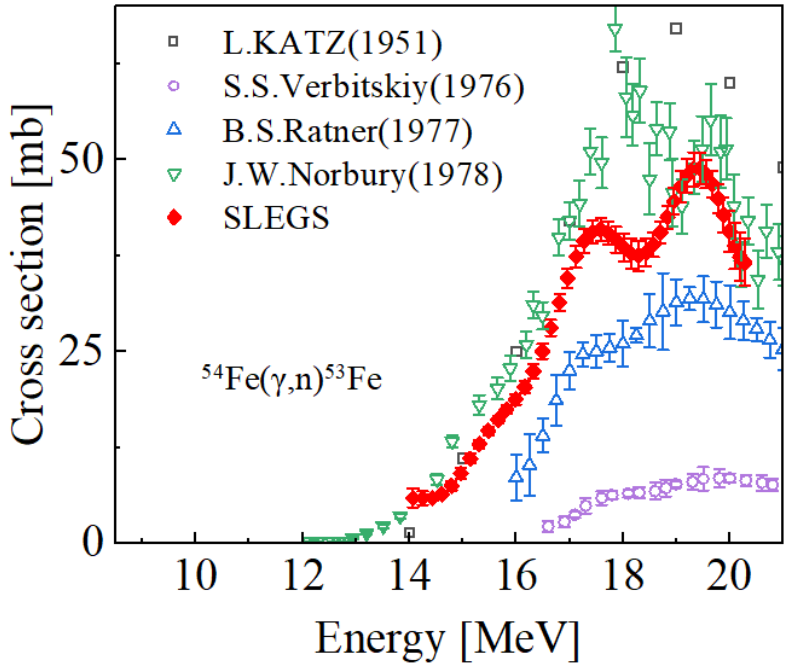


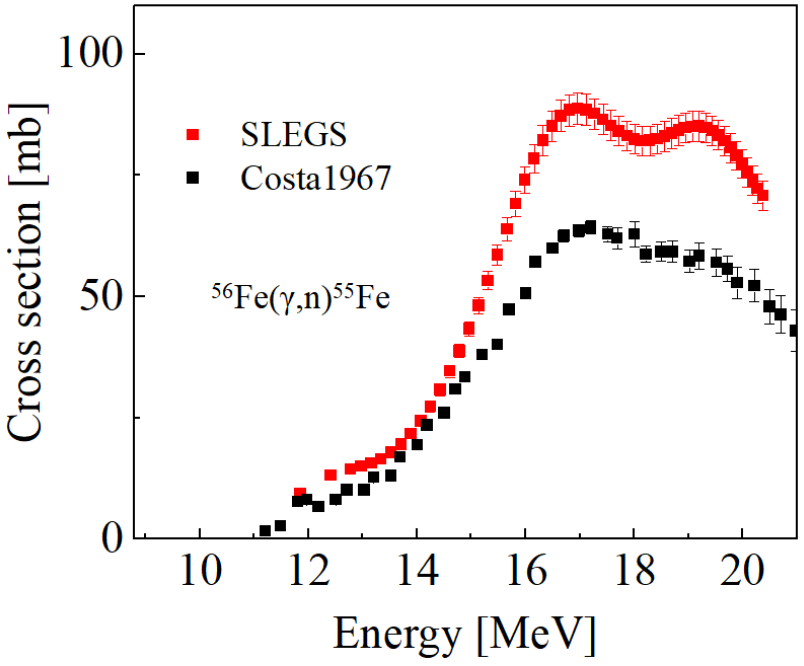
- 使用SVR，设置超参数**强制使模型过拟合**，提取的单能截面出现震荡。
- 推测某些韧致辐射伽马源测量截面的共振峰可能来源与单能截面提取算法。

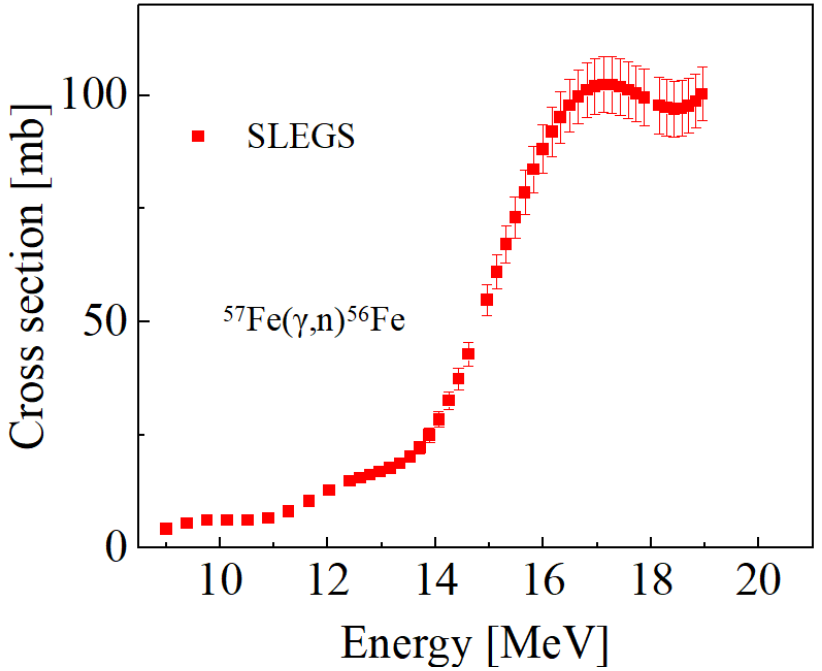
Hao Zirui, Fan Gongtao*,… Phys. Lett. B 876, 140445 (2026)

3 典型光核实验-核结构(形变)

Fe同位素光中子截面系统测量



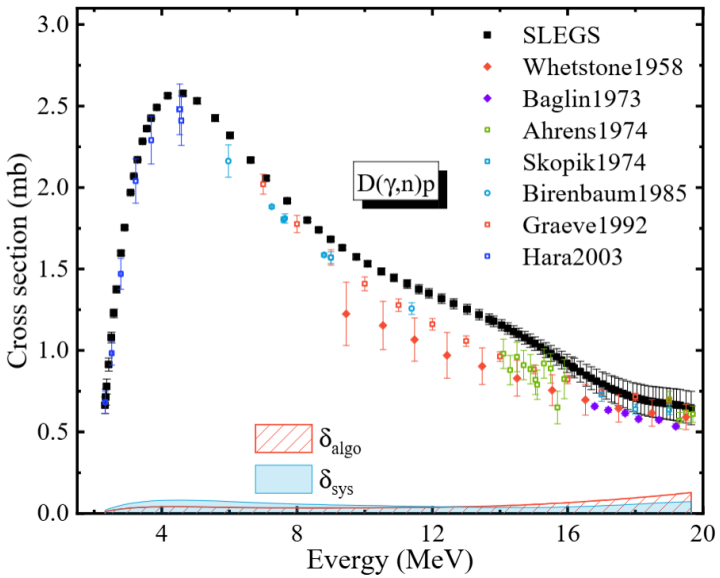


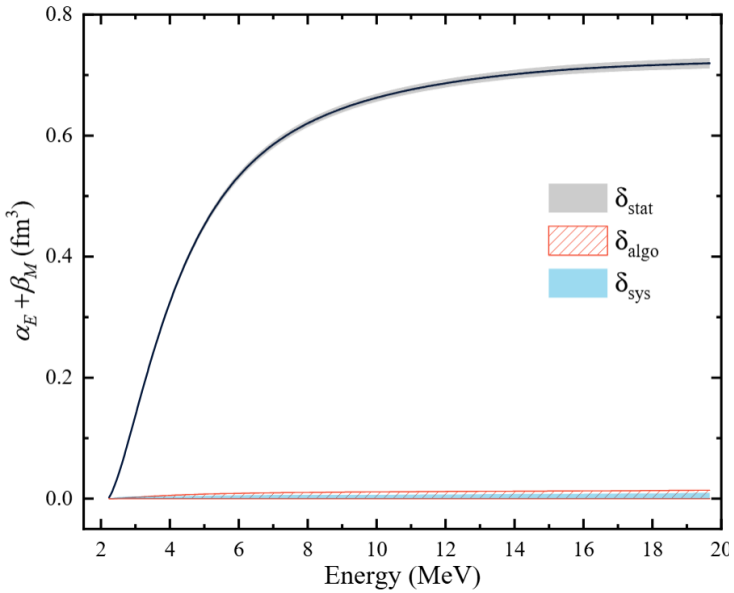


- ^{54}Fe(γ,n)已有的实验数据存在严重分歧，首次次精确测量了^{54}Fe由同位旋引起的GDR光中子截面劈裂，有望提取其形变。
- 首次次精确测量到了^{56}Fe由同位旋引起的光中子截面劈裂，峰位为17.9 MeV 和19.8 MeV，有望提取其形变。
- 首次测量了^{57}Fe(γ,n) 反应截面。

3 典型光核实验-少体(极化率)

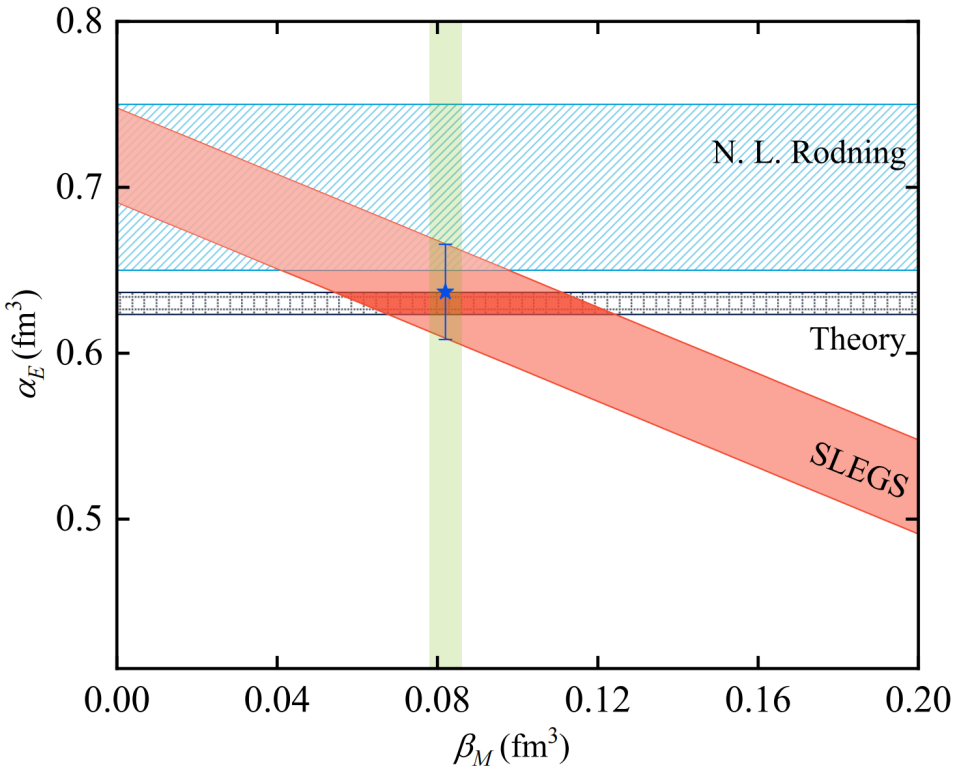
D电极化率精确测量





$$\alpha_E + \beta_M = \frac{1}{2\pi}\int_{S_n}^{19.65\,\mathrm{MeV}} \sigma(E)\frac{dE}{E^2} = 0.719\ \mathrm{fm}^3 + \Delta$$

$$\pm 0.009_{\mathrm{stat}} \pm 0.014_{\mathrm{algo}} \pm 0.023_{\mathrm{syst}}\ \mathrm{fm}^3$$

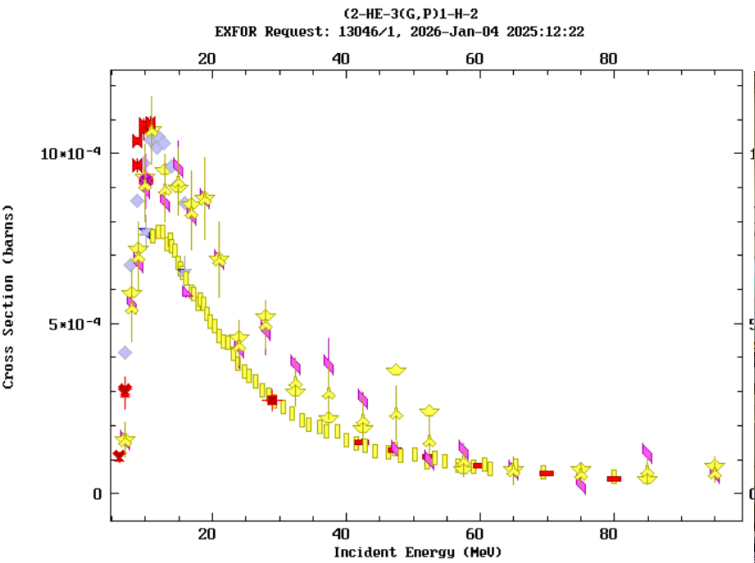


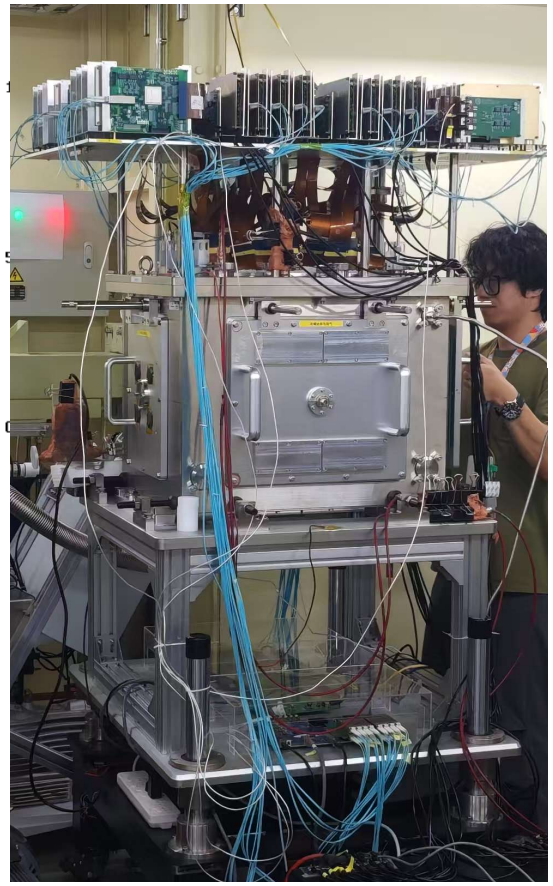
- The photodisintegration cross sections of the deuteron have been systematically measured over the photon energy range of 2.33–19.65 MeV.
- By applying the well-established Baldin sum rule to the newly obtained data, the sum of the electric and magnetic dipole polarizabilities of the deuteron is extracted for the first, yielding $\alpha_E + \beta_M = 0.719 \pm 0.009_{\mathrm{stat}} \pm 0.014_{\mathrm{algo}} \pm 0.023_{\mathrm{syst}}$ fm^3.
- This result resolves the previous discrepancy between experimental measurements from elastic scattering and theory, providing a high-precision benchmark for nuclear interaction models.

Hao Zirui, Fan Gongtao*,… Ma Yugang*, Phys. Rev. Lett. (2026)

3 典型光核实验-少体(极化率)

$\sigma^{abs}_{^3He}$ → $^3He(\gamma,p)d$ + $^3He(\gamma,pp)n$

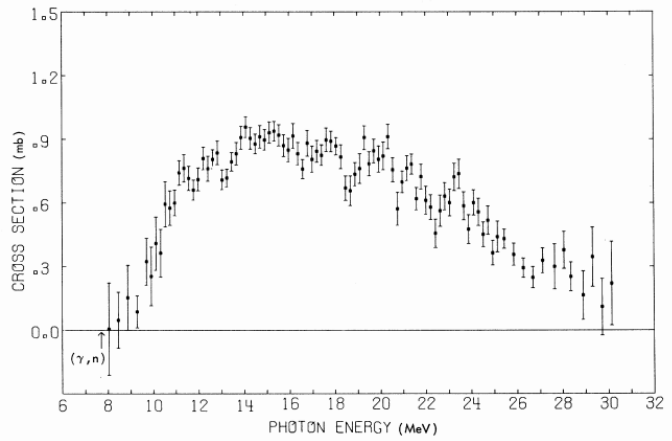




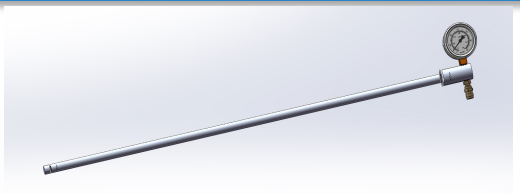
TPC

^{3}He气体；

成本高，探测器效率相对较低，需要长时间测量。







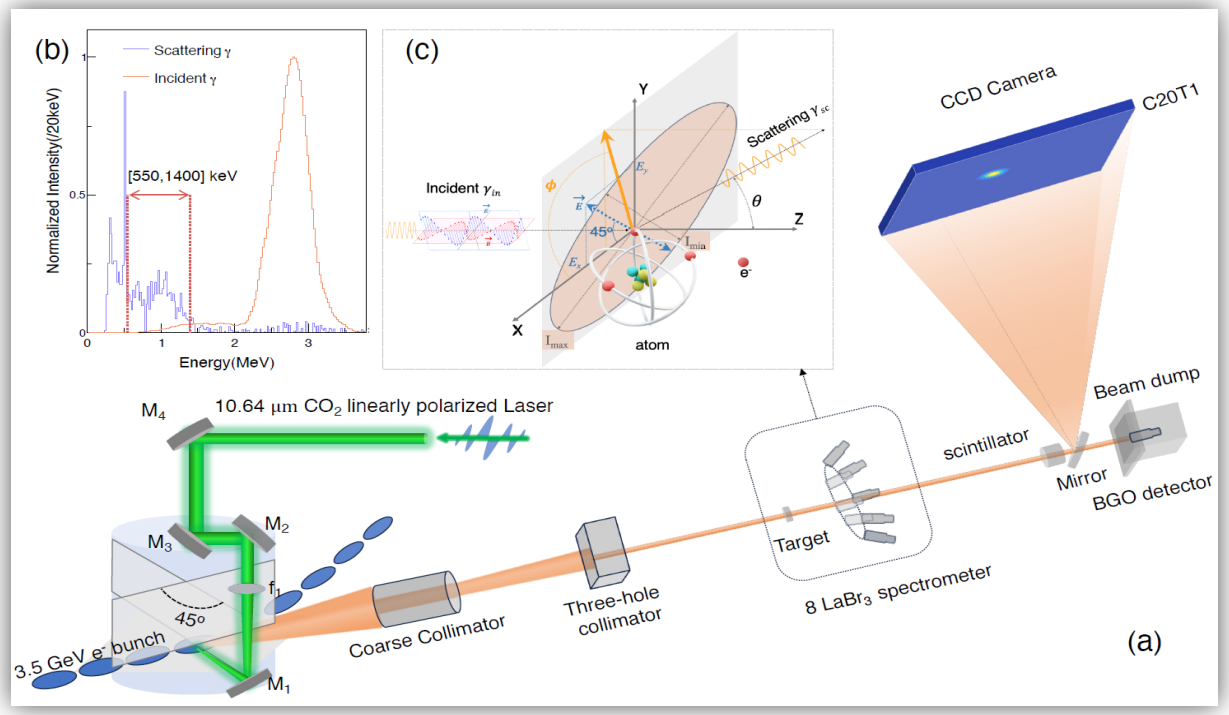
FED测量^{3}He(γ,pp)n截面使用的气体靶

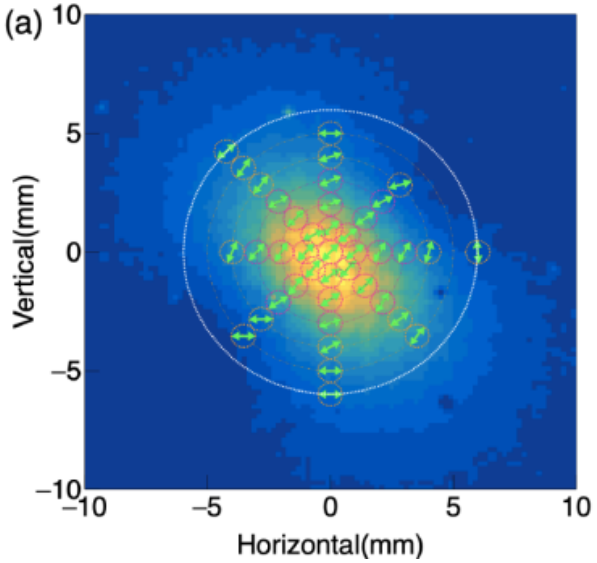
FED

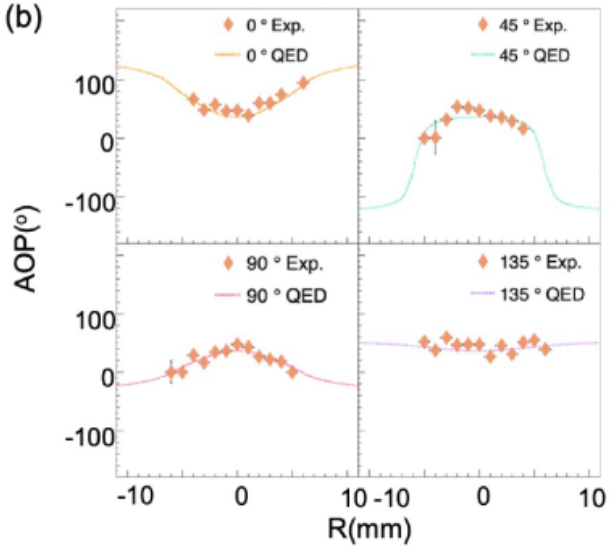
^{3}He气体靶，密度低，中子产额少；气体靶不易操作；靶的长度超出常规实验范围，FED效率需要重新修正。

3 典型光核实验-极化

斜入射Compton过程出射光子极化性质2D精确扫描







- 首次实现了对出射光子的强度、极化角与极化度的全二维精细测量。
- 极化方向展示出有规律的分布，与QED理论一致。
- 中心点处，极化度1.0±0.13，证明相对论电子与低能光子的康普顿散射过程中，极化的传递接近100%，与相互作用角度无关。

Chen Kaijie, Xu Hanghua*, Fan Gontao*…Ma Yugang*, National Science Review, 13: nwag073, (2026)

4 总结 & 展望

- SLEGS实现了国际最好的14 keV能量扫描精度、秒级快速能量调节速度、10^6/s/mm^{2}流强密度、好于3%的流强稳定性、100%极化，同时实现了与SSRF其他线站同步稳定运行。

- 自2023年1月向用户正式开放以来，装置在供束时长、服务用户数、高水平成果产出（等方面超过或达到美国HIGS装置，总体水平达到国际前列。



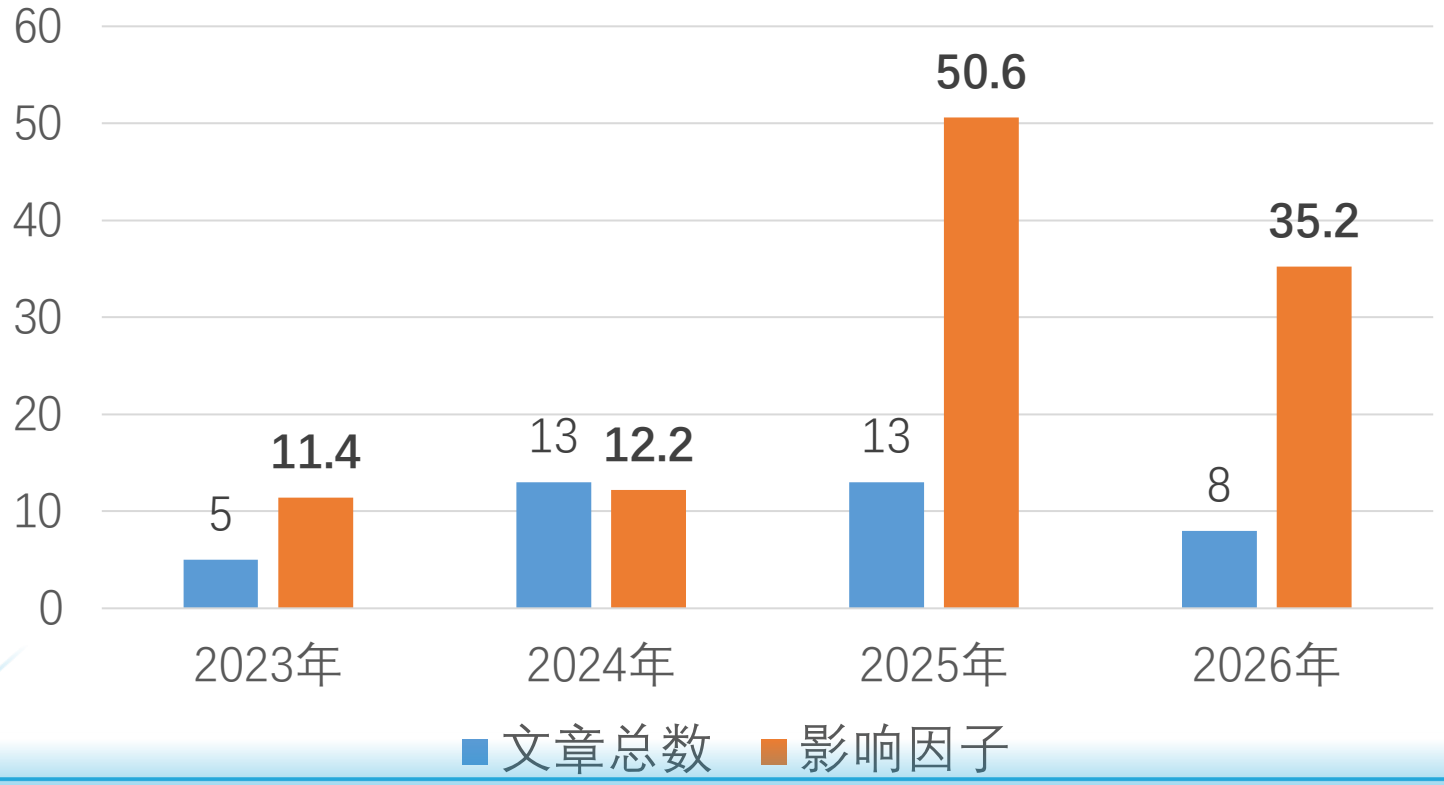


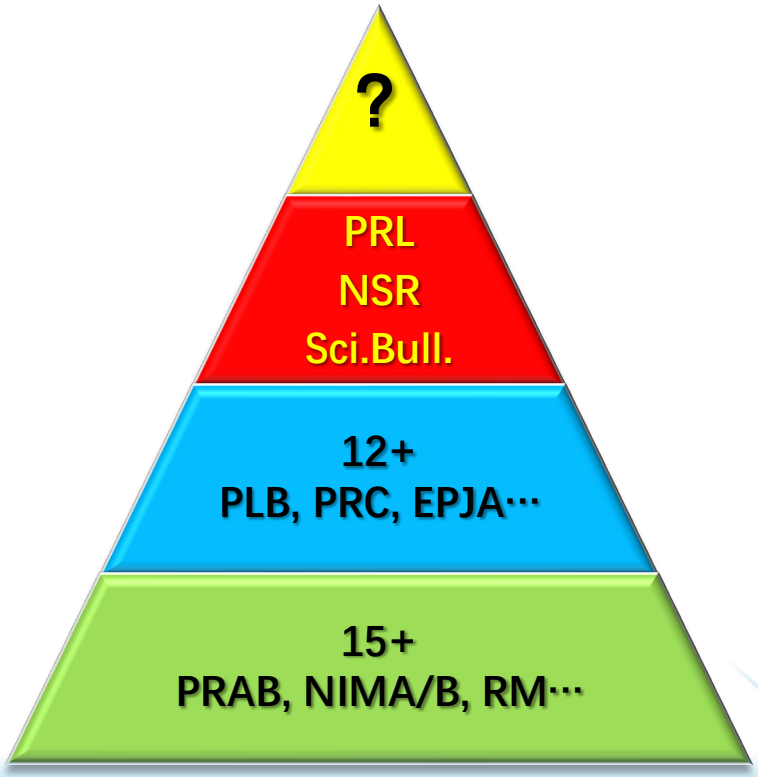


4 总结 & 展望

- 建成性能领先的FED、TOF、NRF等光核测量实验平台，开拓光核物理实验研究，在国内实现自主光核实验系统测量。

- 开放以来，在核数据、核结构、核天体等领域支撑了国际/国内100多个用户实验课题，完成了一批高水平的光核物理实验，发表一批光核物理实验文章，文章质量逐年提高。





4 总结 & 展望

- 目前，SLEGS的光核反应实验主要集中在光中子测量，进一步增加其他反应产物信号符合将能获得更丰富的核信息。另一方面，SLEGS伽马束的极化特性刚刚被研究清楚，基于极化伽马将开辟全新的实验领域。

- 基于SXFEL的20-128 MeV高亮度伽马装置已经开始建设，将提供光核物理新实验条件。

Facility/Project: SLEGS
Photon energy: 0.6 – 21.7MeV
Total flux : 10^5 ~ 10^7ph/s
Resolution: 2~15% (FWHM)
Research: Nuclear structure



SSRF

Facility/Project: SLEGSII
Photon energy: ~ 100MeV
Total flux : ~ 10^8ph/s
Research: Nuclear structure



SXFEL

Facility/Project: SLEGSIII
Photon energy: ~ GeV
Total flux : 10^6 ~ 10^{10}ph/s
Research: Particle



SHINE

4 总结 & 展望

SLEGS Team

建设运行团队

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邓先概，周波
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原子能科学院：续瑞瑞，
贺创业
北京航空航天大学：孙保华
应用物理研究所：胡继峰
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应用物理研究所：蔡翔舟，陈金根， 郭威，…

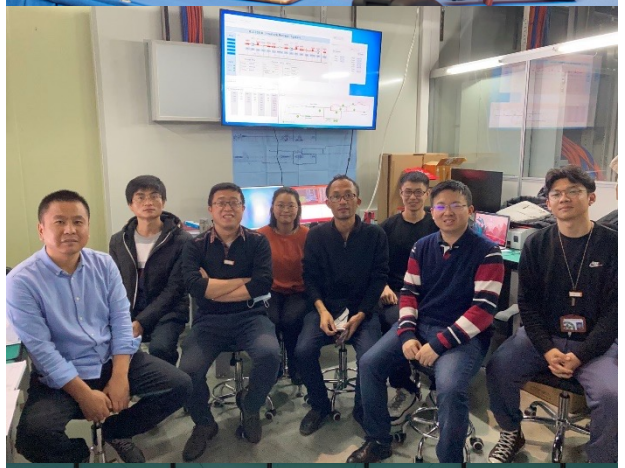
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线站咨询委员会

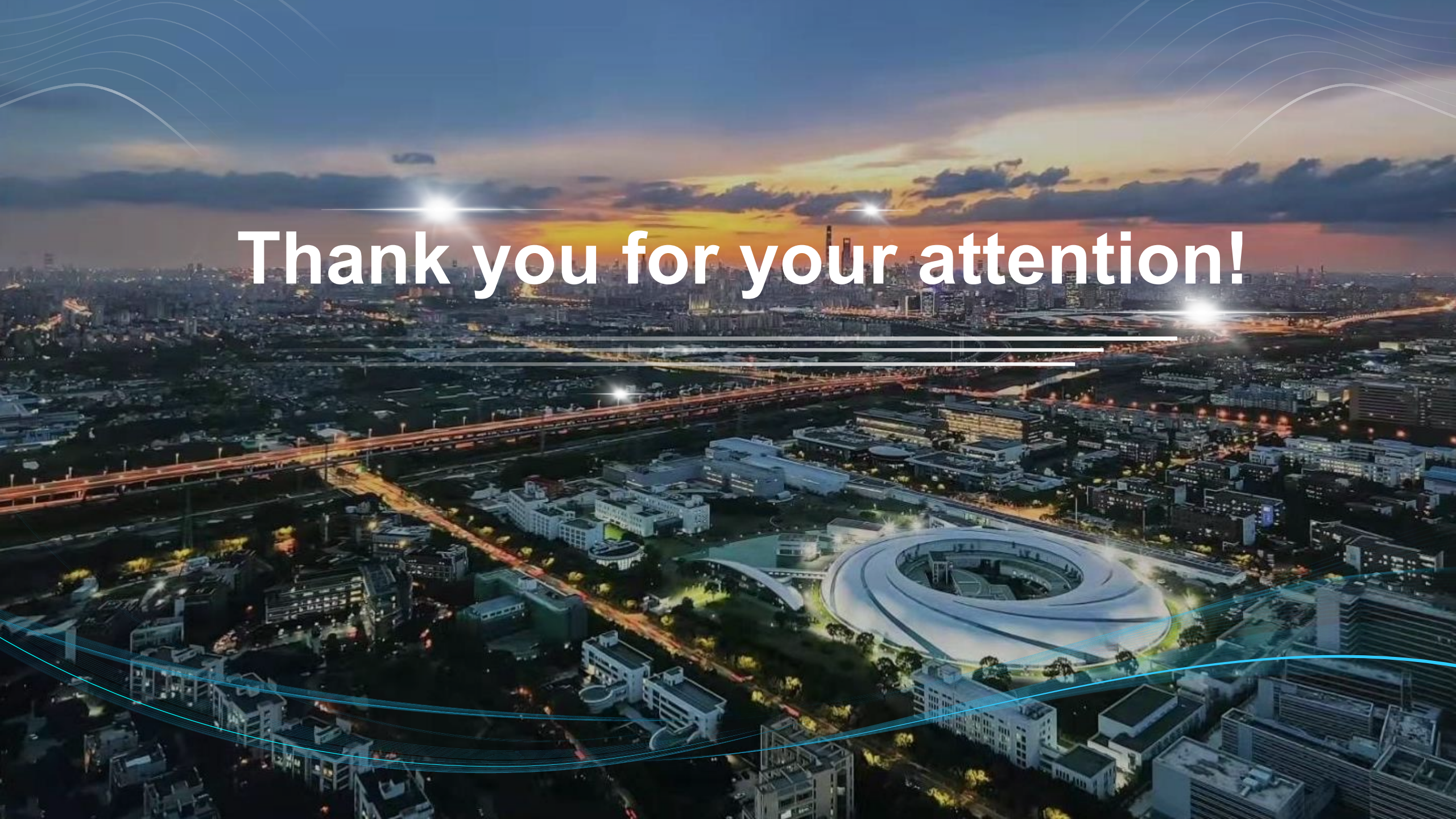
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Thank you for your attention!