Recent advances in QED and collision dynamics using highly charged ions at CSR

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Outline

1. DR spectroscopy at CSR:

— F-like Ni, higher order QED test

2. Collision dynamics

— Fully differential cross sections

— High resolution, Q-value spectroscopy

3. Laser cooling dynamics

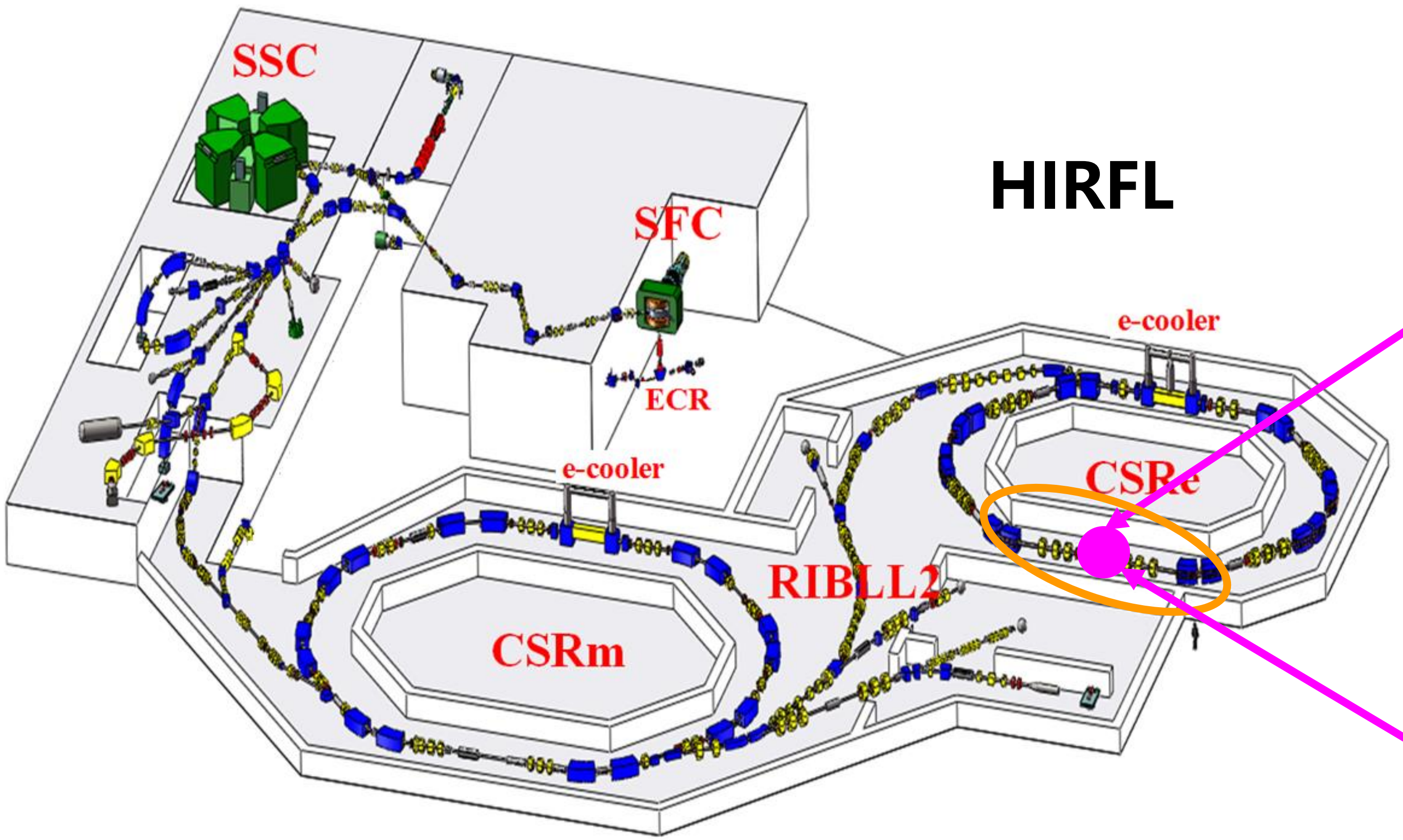
— Simulation of

4. Future plans and HIAF status

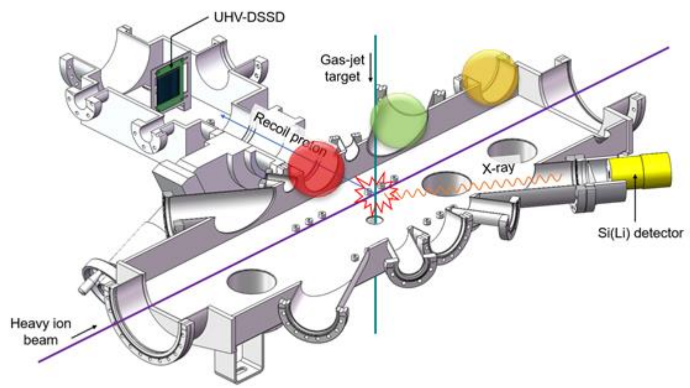
Upgrade of CSRe experimental setups

Multi-purpose internal target experimental setups

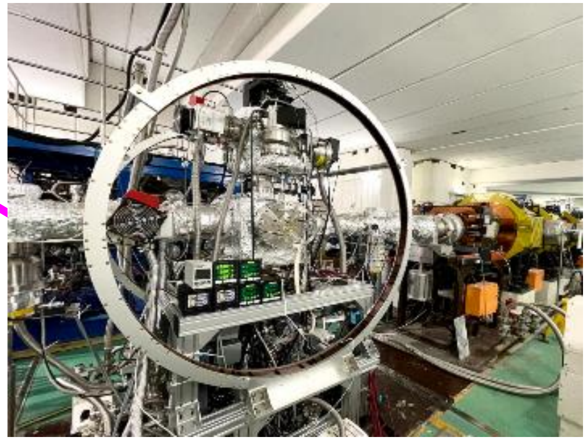
HIRFL



(1) X-ray Spectroscopy and
(2) Nuclear reaction chamber

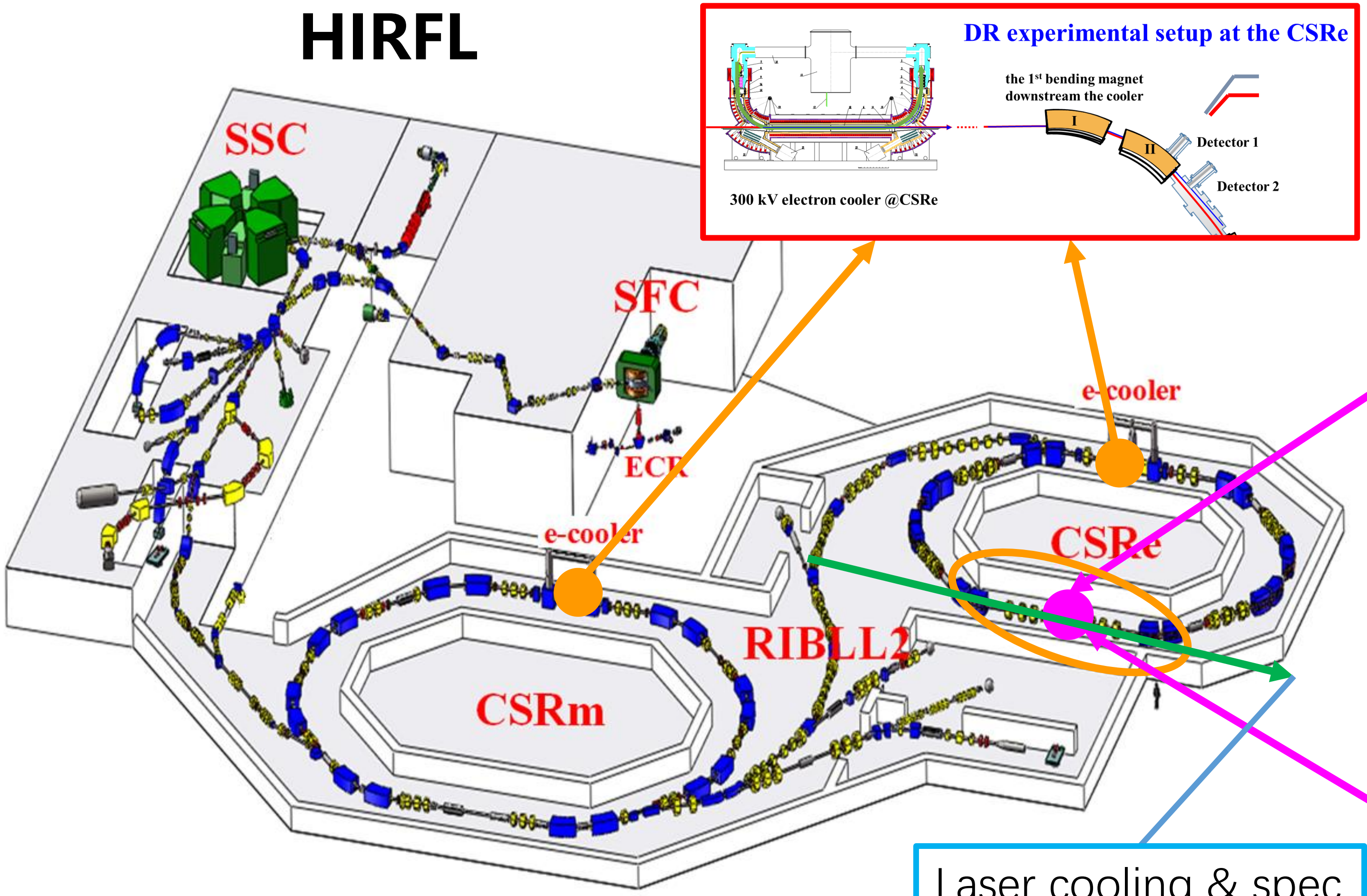


(3) Reaction microscope for
relativistic ion-atom collisions



Upgrade of CSRe experimental setups

HIRFL



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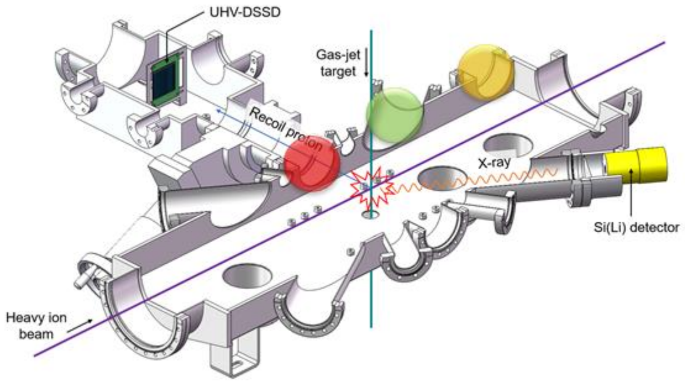

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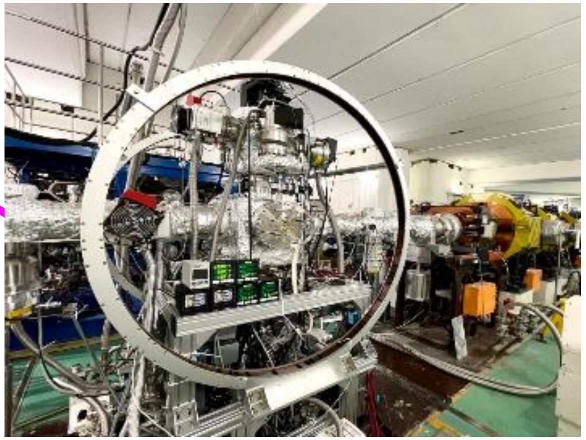
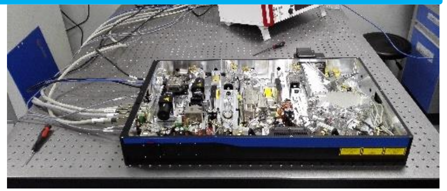


Laser cooling & spec



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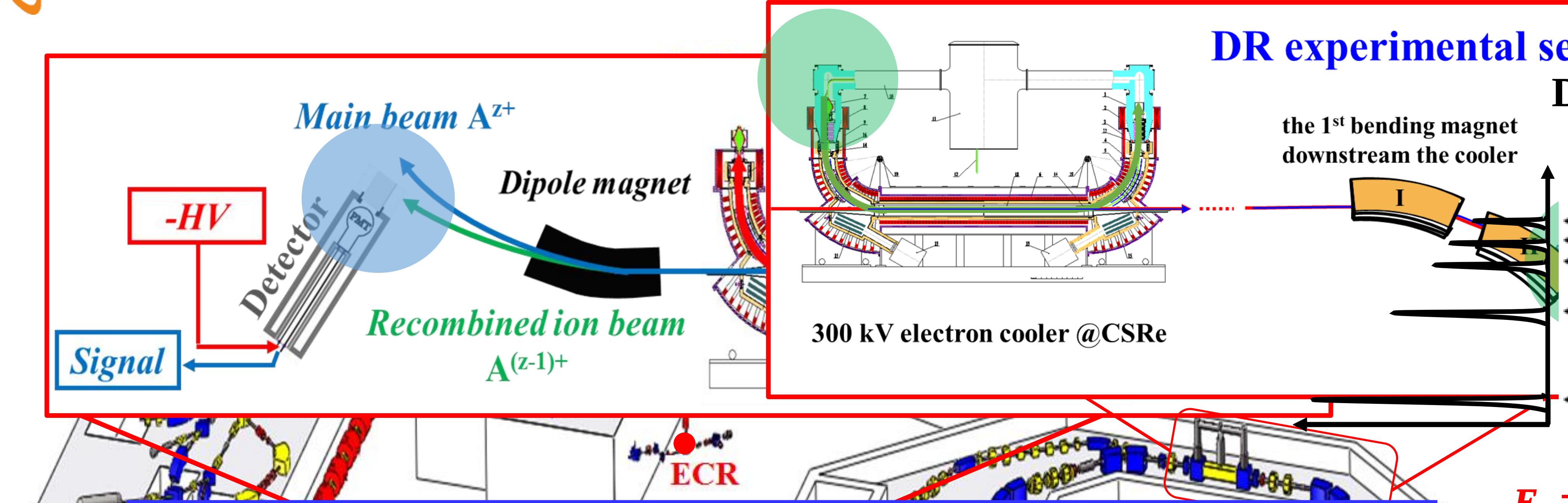
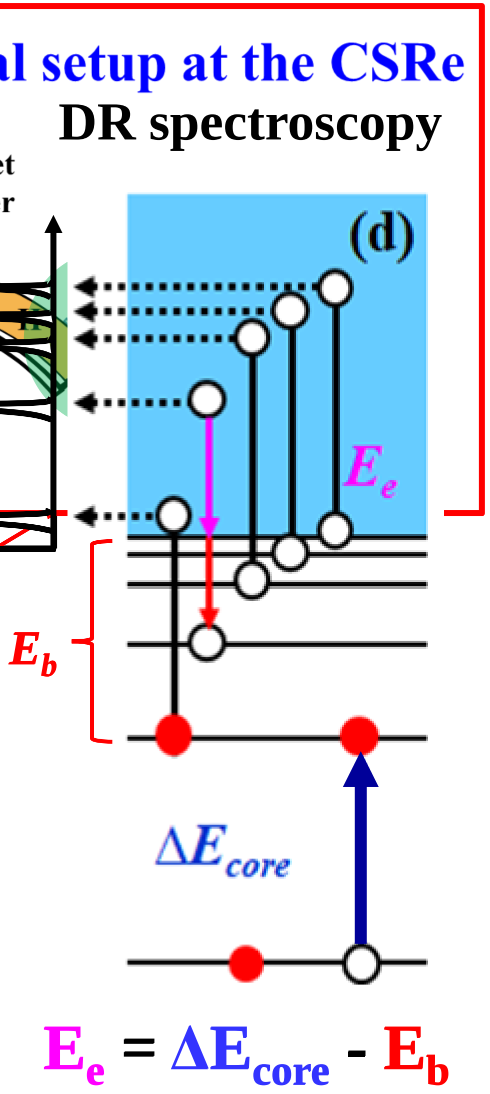
— F-like Ni, higher order QED test

Storage ring DR spectroscopy technique





- ✓ Precise resonances

$$\alpha(E_{rel}) = \frac{R}{N_i n_e (1-\beta_e \beta_i)} \frac{C}{L}$$

- ✓ absolute rate coefficients

Ni: number of stored ions

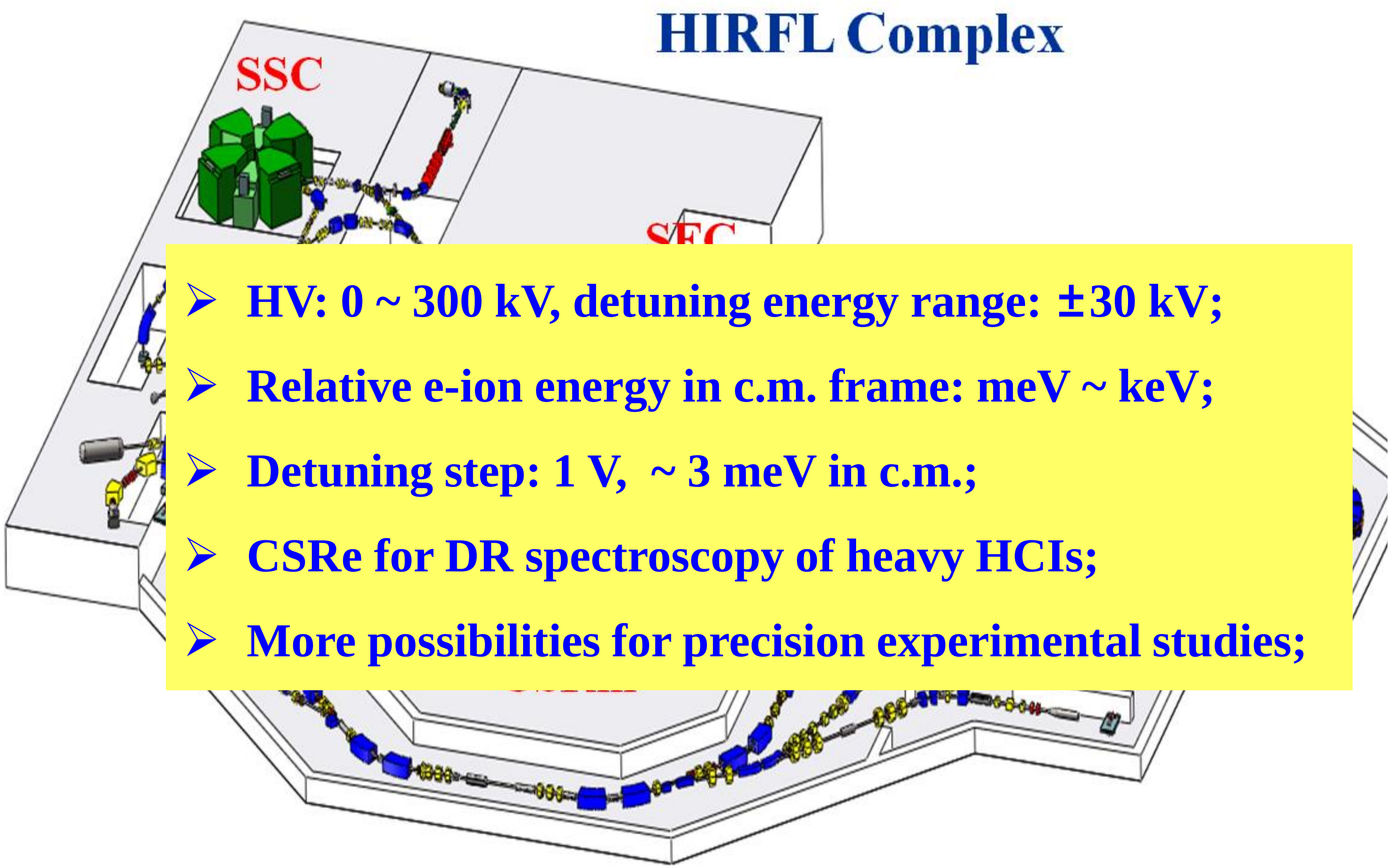
n_e: electron density

L: effective interaction length (4.0 m)

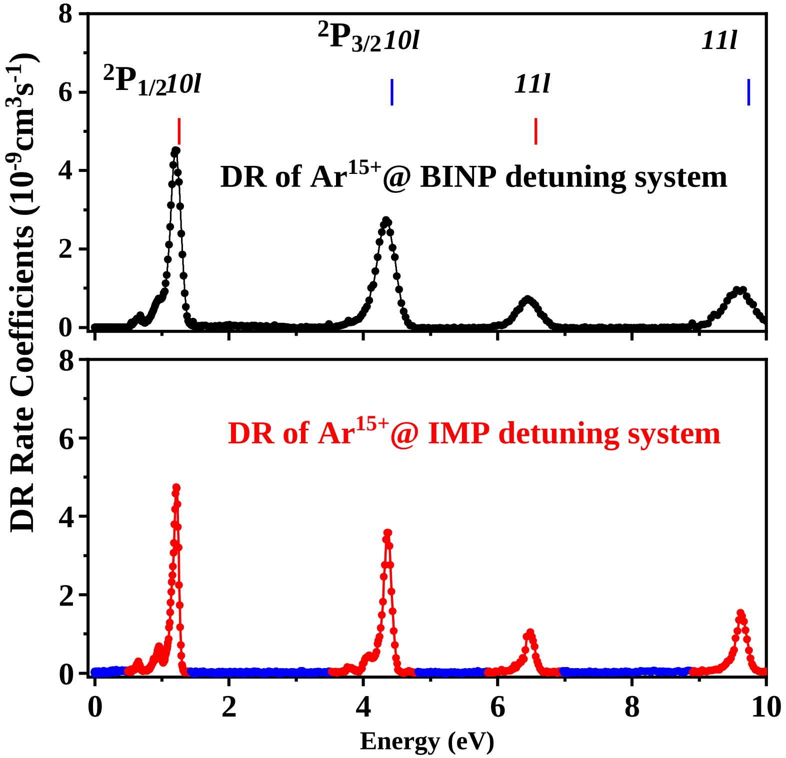
C: circumstance of CSRm(161.0 m)

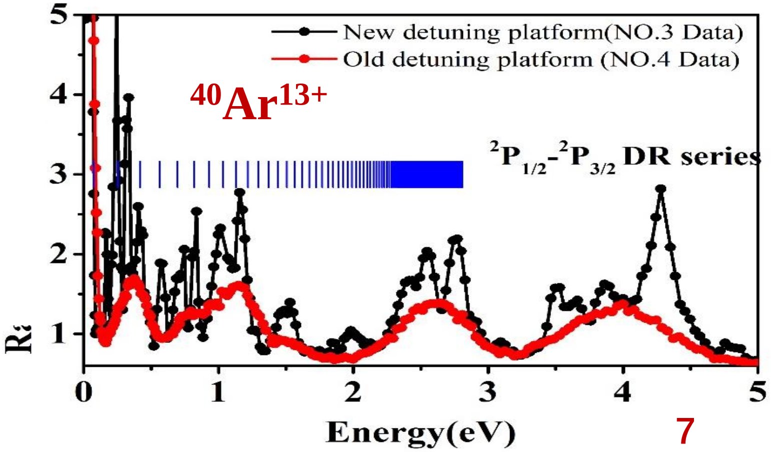
β_e, β_i : e, ion relativistic speed

Progresses of DR spectroscopy at CSR



- HV: 0 ~ 300 kV, detuning energy range: ±30 kV;
- Relative e-ion energy in c.m. frame: meV ~ keV;
- Detuning step: 1 V, ~ 3 meV in c.m.;
- CSRe for DR spectroscopy of heavy HCIs;
- More possibilities for precision experimental studies;

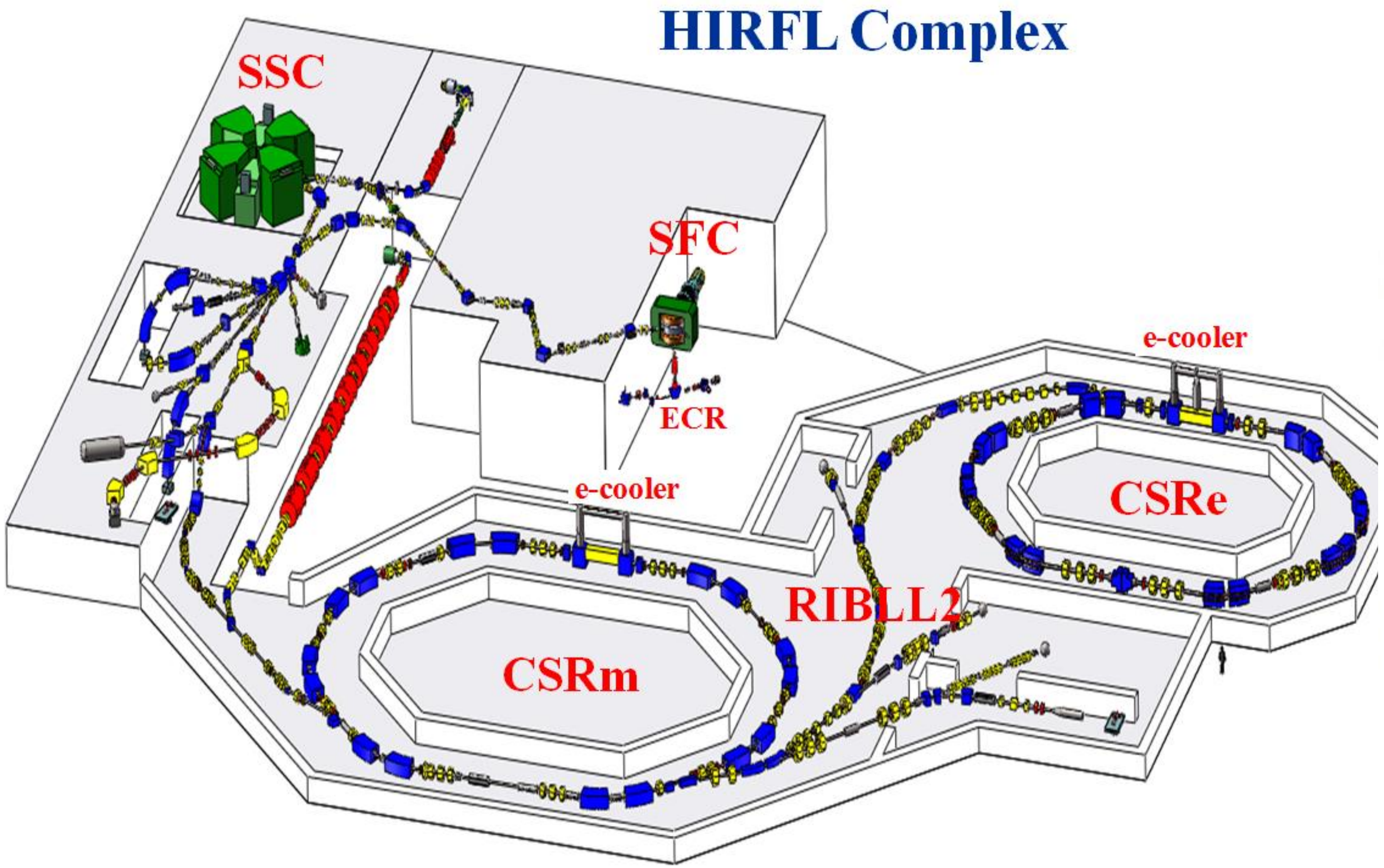




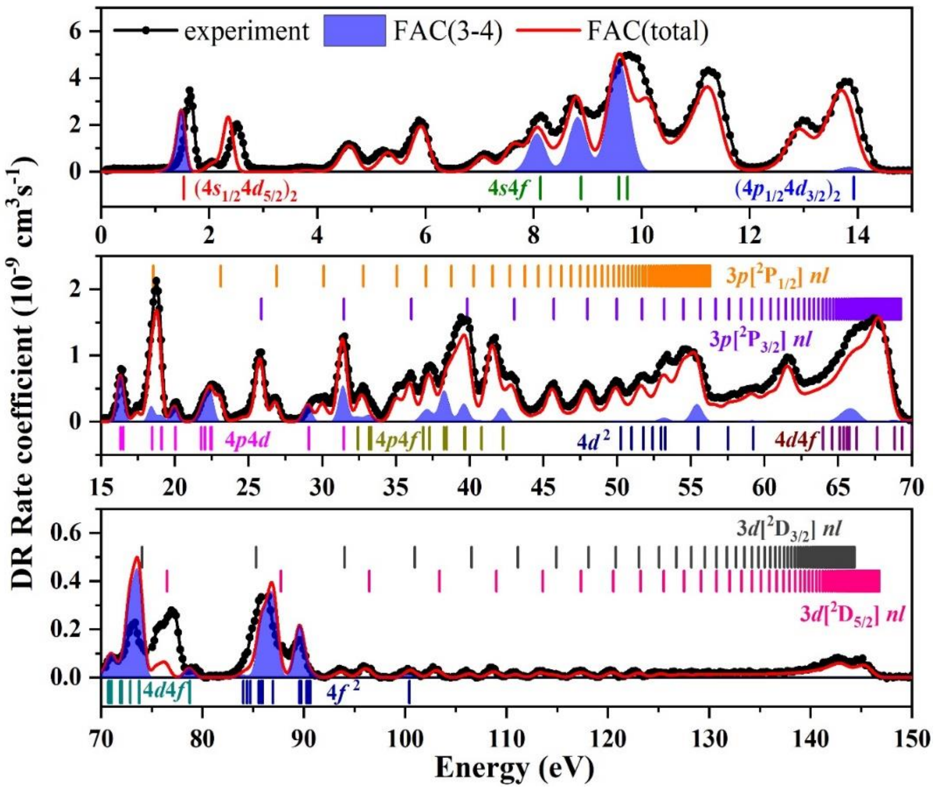
The upgrade has been completed, commissioning within two months

Progresses of DR spectroscopy at CSR

HCIs @DR at CSR: $^{36}Ar^{15+}$, $^{40}Ar^{12+,13+,14+,15+}$, $^{40}Ca^{14+,16+,17+}$, $^{56}Fe^{17+}$, $^{58}Ni^{19+}$, $^{86}Kr^{25+,30+}$, $^{112}Sn^{35+}$

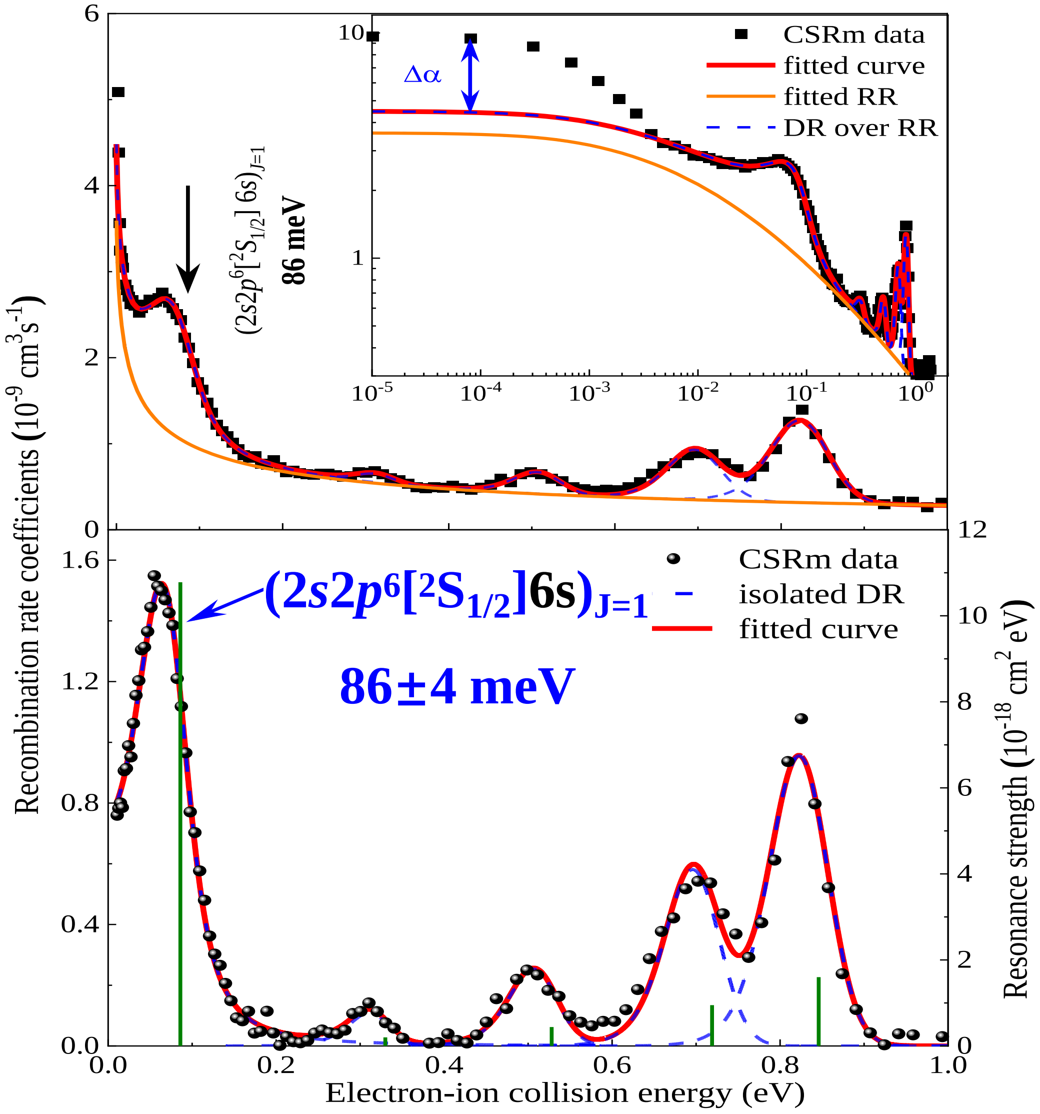


DR spectroscopy of Kr^{25+} ions at CSRe



DR spectroscopy of F-like ions: high order QED

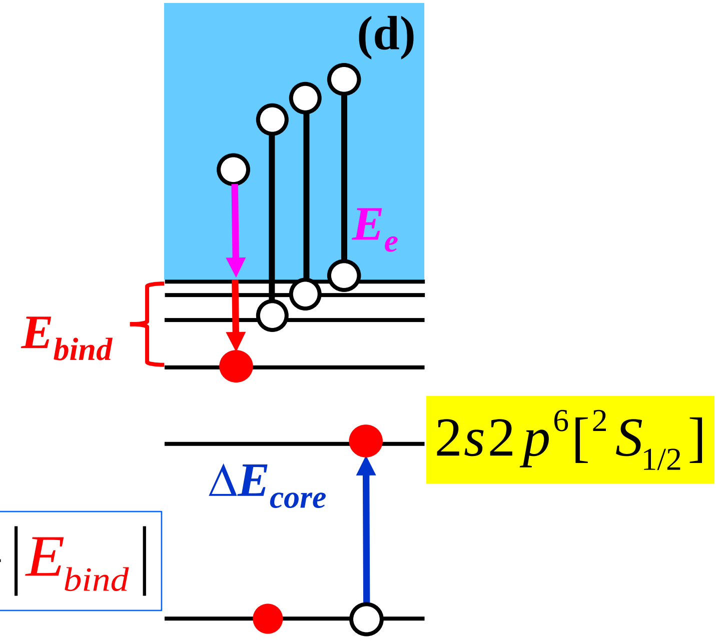
DR spectrum of Ni^{19+} in low energy



$$^{58}\mathrm{Ni}^{19+}(2s^2 2p^5[^2\mathrm{P}_{3/2}]) + e^-$$

$$\rightarrow \left\{ \begin{array}{l} ^{58}\mathrm{Ni}^{18+}(2s^2 2p^5[^2\mathrm{P}_{1/2}]nl)^{**} \\ \boxed{^{58}\mathrm{Ni}^{18+}(2s\ \ 2p^6[^2 S_{1/2}]nl)^{**}} \end{array} \right.$$

$$\rightarrow {}^{58}\mathrm{Ni}^{18+} + mh\nu$$

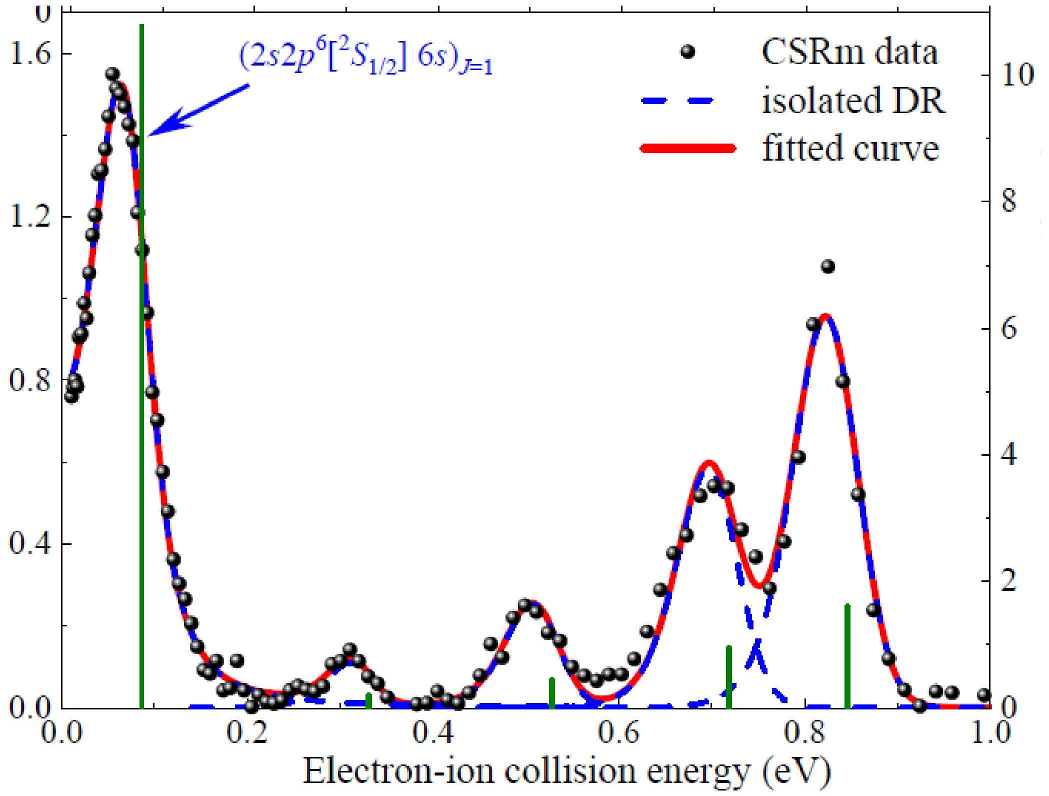


$$\Delta E_{core} = \mathbf{E_e} + |E_{bind}|$$

Transition energy of $2s^2 2p^5\ ^2P_{3/2} \rightarrow 2s2p^6\ ^2S_{1/2}$

S.X. Wang et al., PRA 106, 042808 (2022)

DR spectroscopy of F-like ions: high order QED



Multi-Configurational Dirac-Hartree-Fock (MCDHF)

Stabilization Method (SM).

$$\Delta E_{core} = \mathbf{E_e} + \left| E_{bind} \right|$$

ΔE_{core} of $2s^2 2p^5\ ^2P_{3/2} \rightarrow 2s2p^6\ ^2S_{1/2}$

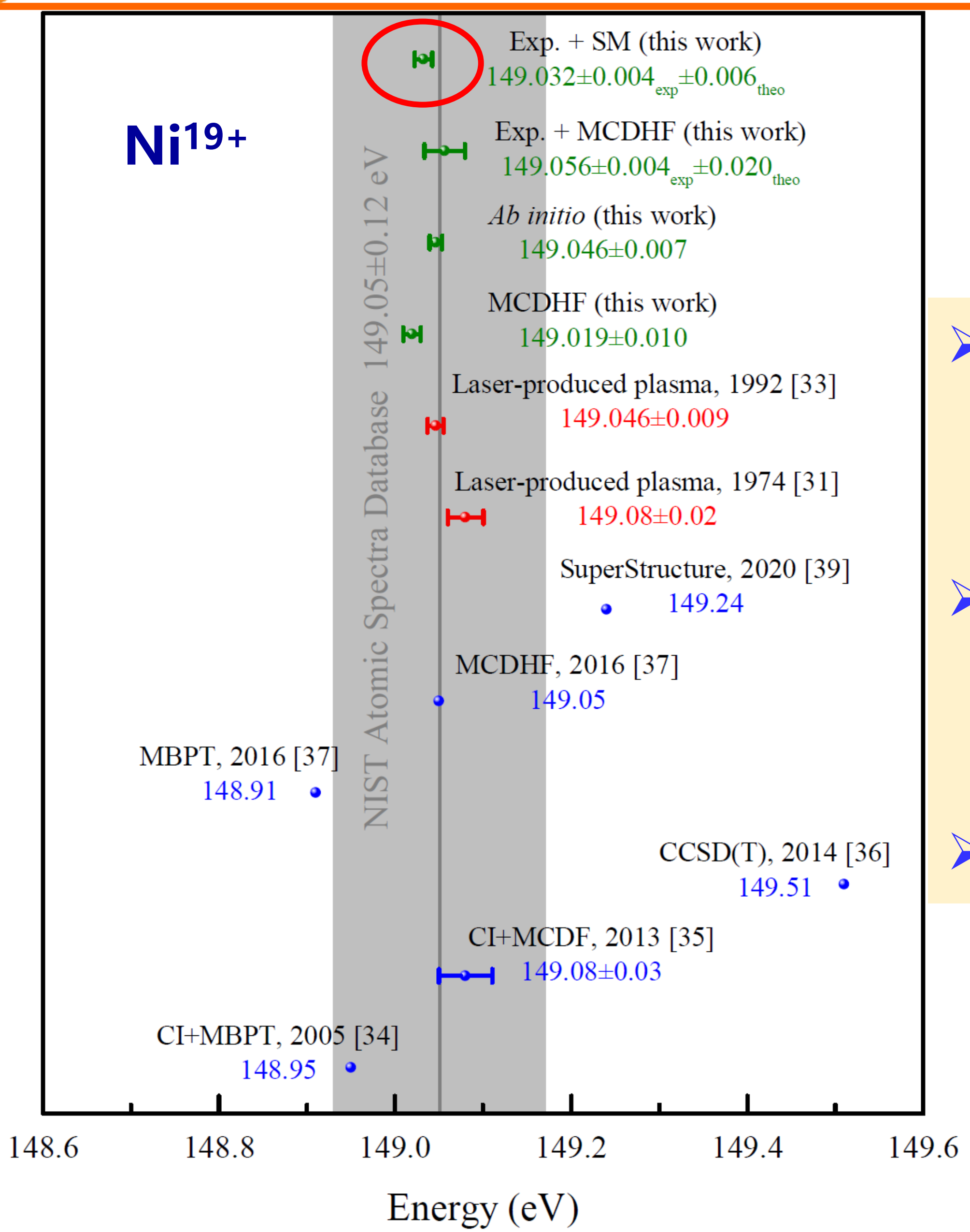
Individual contributions to transition energy of $2s^2 2p^5\ ^2P_{3/2} \rightarrow 2s2p^6\ ^2S_{1/2}$ in Ni^{19+} ion (in eV). *ab initio* calculations

Contribution	Core-Hartree	Kohn-Sham
Dirac	123.911	128.743
Correlation (1)	27.190	22.723
Correlation (2)	−1.536	−1.972
Correlation (3)	0.032(2)	0.102(2)
QED (1)	−0.506	−0.510
QED (2)	−0.033(6)	−0.028(6)
Recoil	−0.012(3)	−0.012(3)
Total	149.046(7)	149.046(7)

Experiment: 149.032± 0.004_{exp} ± 0.006_{theo} eV

S.X. Wang et al., PRA 106, 042808 (2022)

DR spectroscopy of F-like ions: high order QED



- **Transition energy of Ni^{19+} ion determined:**
  $2s^22p^5[^2P_{3/2}] \rightarrow 2s2p^6[^2S_{1/2}]$=149.032 $(4)_{exp}(6)_{theo}$ eV

- **Experimental precision at the level of test 2nd order QED and e-e correlation; the recoil contribution**

- **Approaching to test 3rd order QED**

S.X. Wang et al., PRA 106, 042808 (2022)

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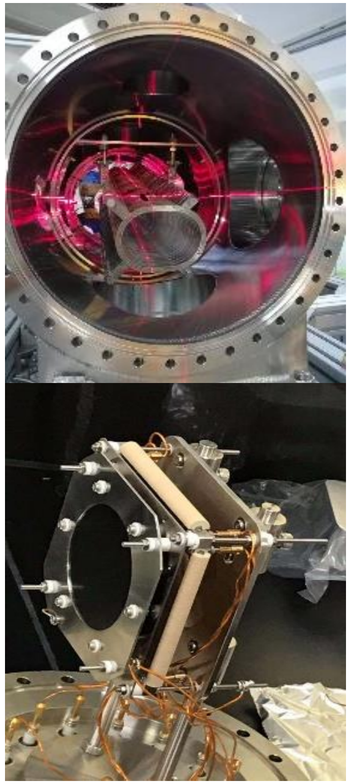
— High resolution, Q-value spectroscopy

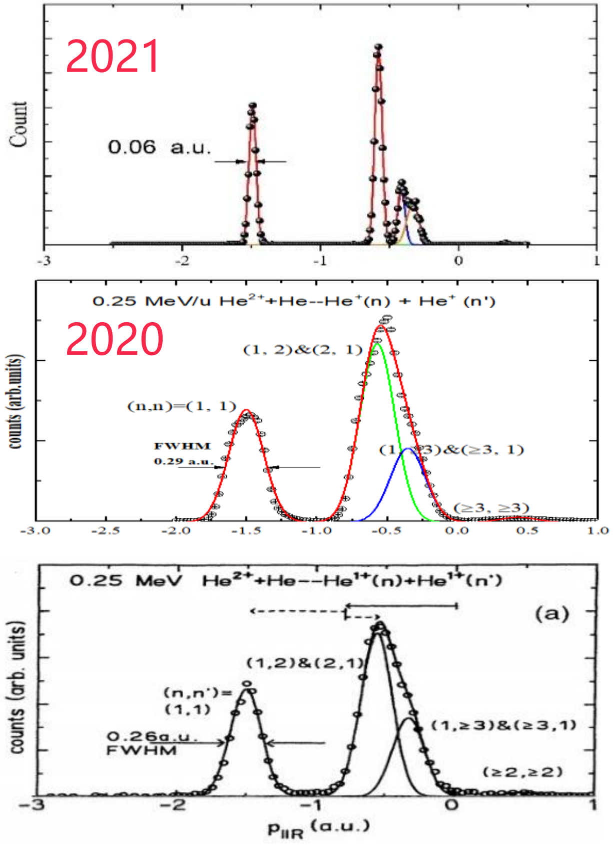
High resolution reaction microscope

Study of Charge exchange reactions

Experiments have been performed for State resolved charge exchange processes in ion-atom collision



Momentum resolution 0.06a.u.



Benchmark measurements of charge exchange cross sections

nℓ-resolved Charge Exchange Cross Sections

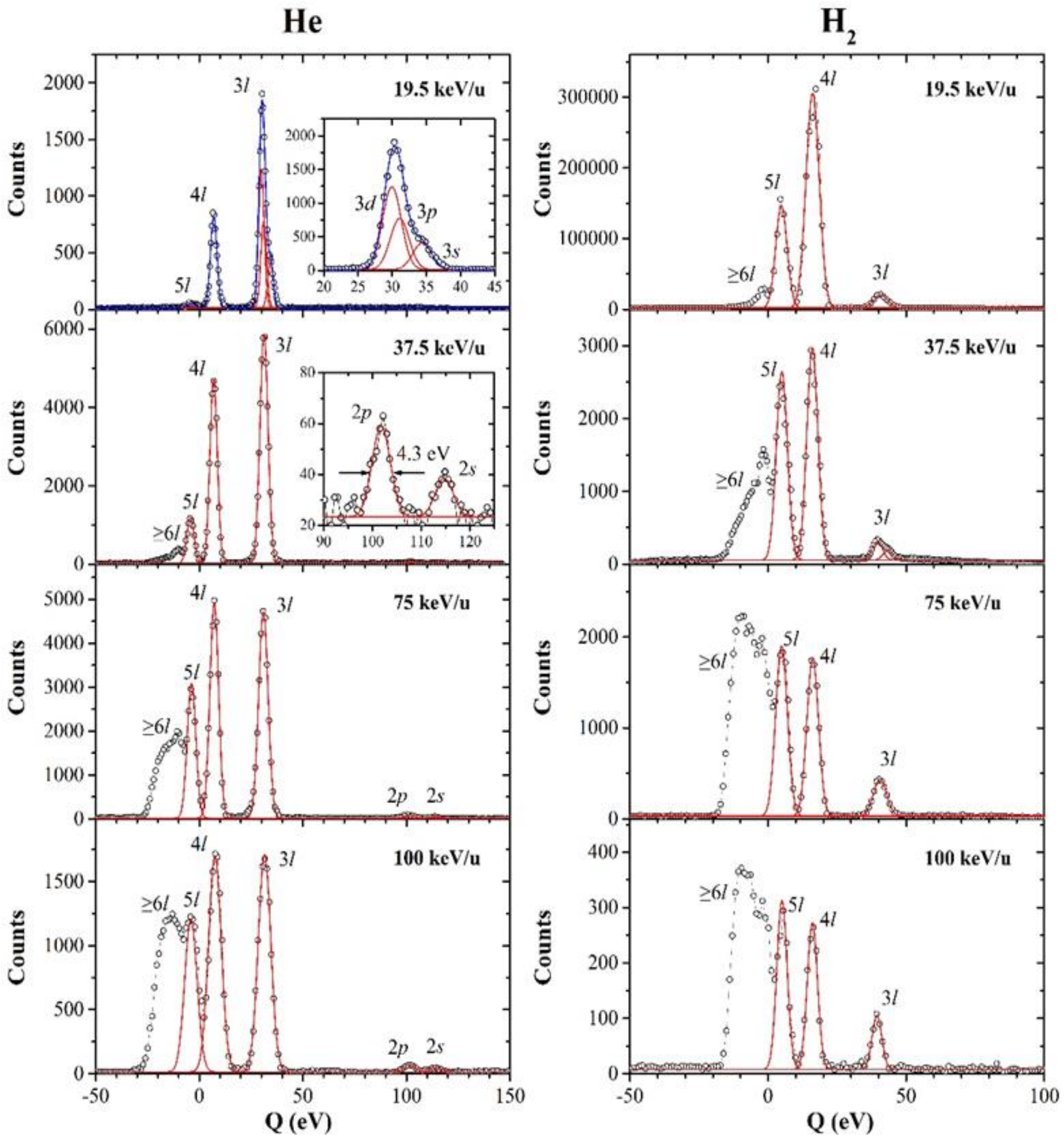
19.5, 37.5, 75, 100 keV/u

$$O^{6+} + He \rightarrow O^{5+}(1s^2 nl) + He^+$$

$$O^{6+} + H_2 \rightarrow O^{5+}(1s^2 nl) + H_2^+$$

- **He： mainly capture to n = 3**
- **H_2： mainly capture to n = 4**

- **with the collision energy increasing, the main capture shifts to channels with larger n and finally to n ≥ 6 for both targets.**



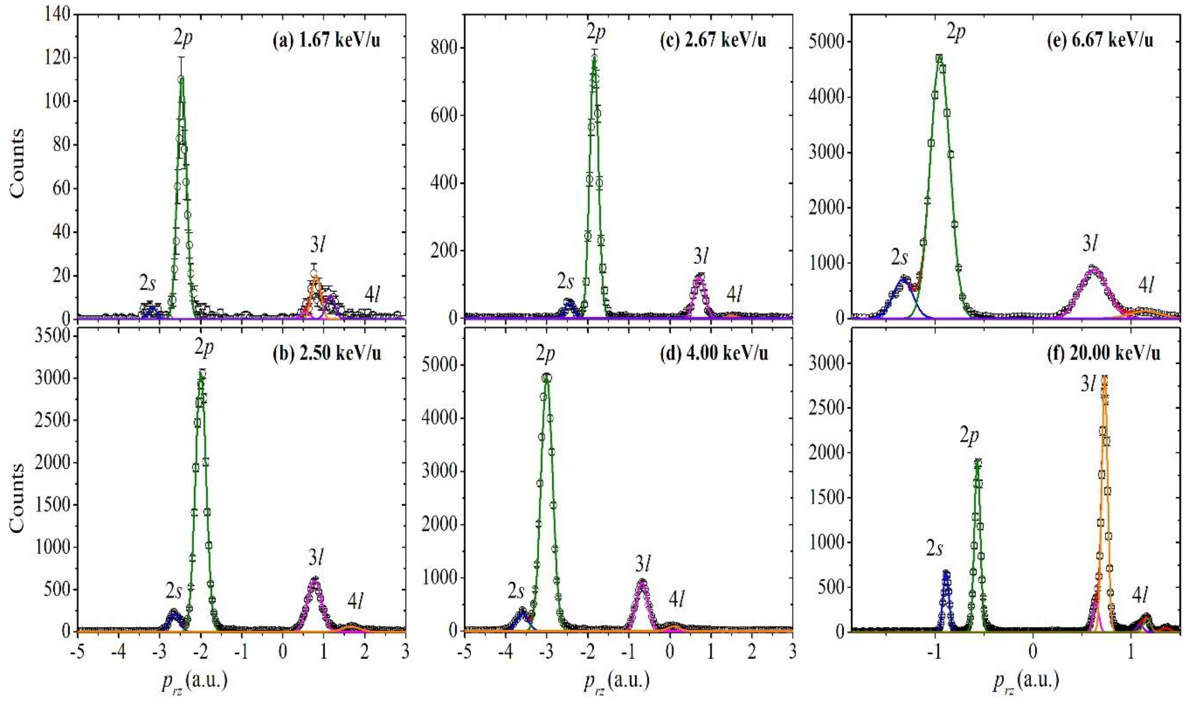
T. Cao *et al.*, ***Astrophys. J. Suppl. Series,*** 266, 20 (2023)

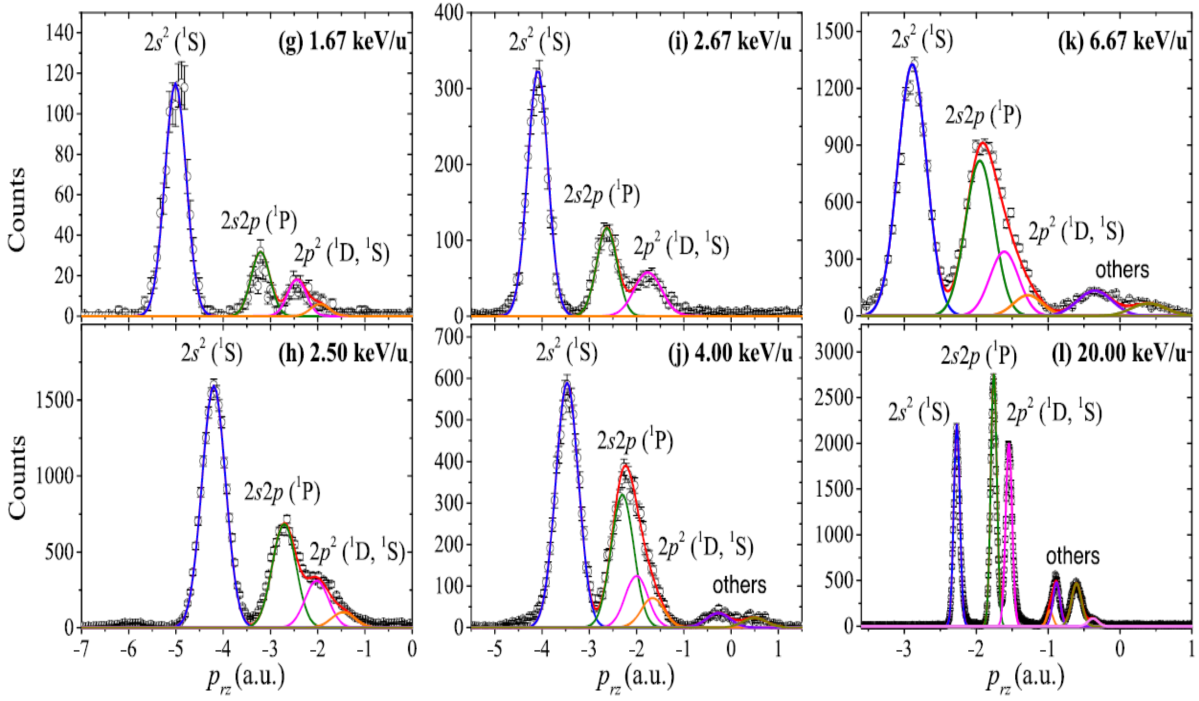
Benchmark measurements of charge exchange cross sections

$n\ell$-resolved Cross Sections of Single and Double Charge Exchange Processes

SC $C^{4+}(1s^2) + He \rightarrow C^{3+}(1s^2 nl) + He^{+}(1s)$

DC $C^{4+}(1s^2) + He \rightarrow C^{2+}(1s^2 nl n'l') + He^{2+}$

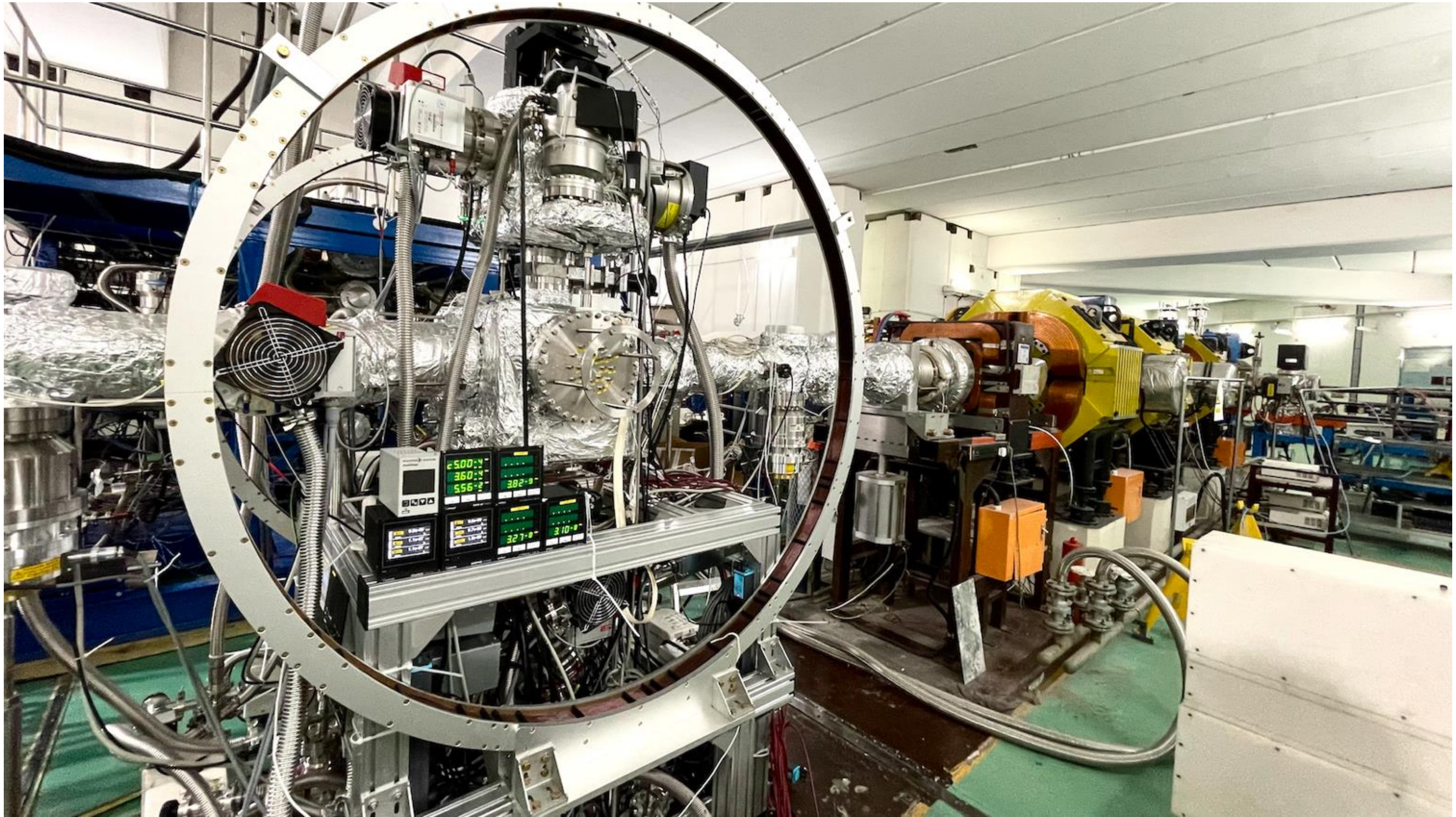




D. L. Guo *et al.*, ***The Astrophysical Journal,*** 941, 31 (2022)

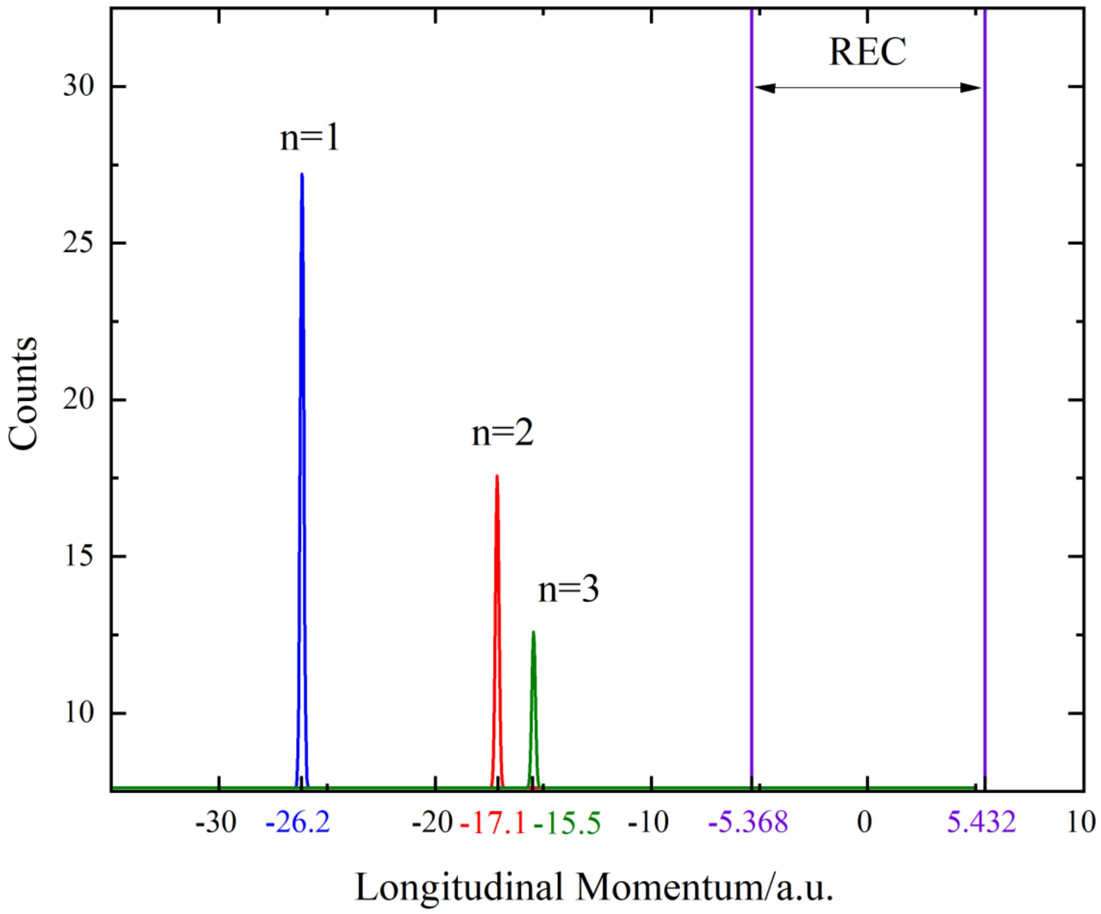
Q-value spectroscopy: electron capture + reaction microscope

Reaction microscope Installed at CSRe internal target



Q-value spectroscopy: direct measurement of binding energy of H-like ions

Take Fe^{26+} ion as an example, when an electron from helium atom is captured in to its inner orbitals, the corresponding longitudinal momentum can be separated clearly. ($FWHM = 0.1a.u.$) 1s binding energy @ QED, better than 1% expected.



$$Fe^{26+} + He(1s) \rightarrow Fe^{25+}(1s) + He^{+}$$

NRC:

$$P^{f}_{R\parallel} = \frac{Q}{v_p} - \frac{v_p}{2}$$

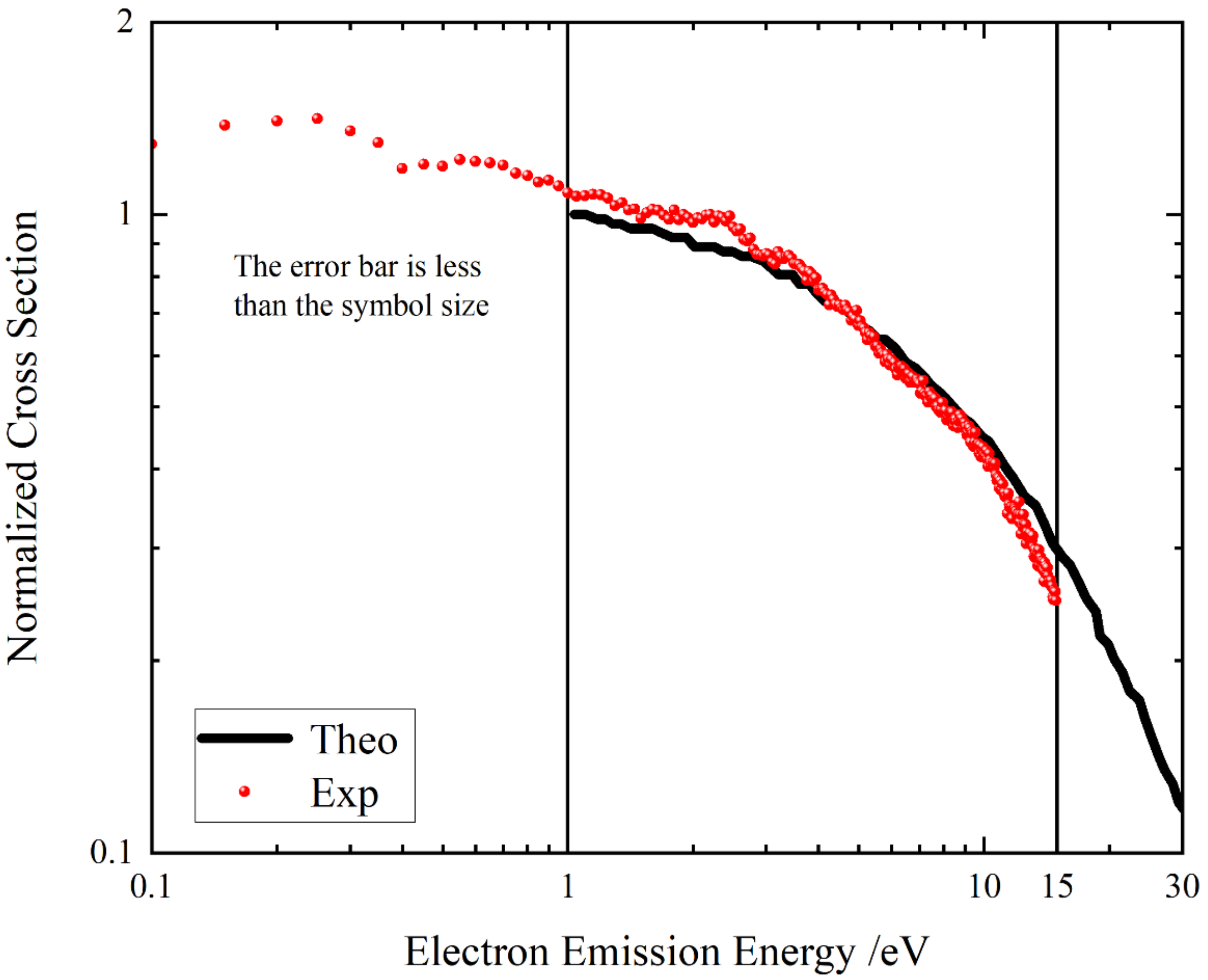
REC:

$$P^{f}_{R\parallel max} = -\frac{E^{i}_{bind}}{v_p} + \frac{E_\gamma}{c} = 5.432a.u.$$

$$P^{f}_{R\parallel min} = -\frac{E^{i}_{bind}}{v_p} - \frac{E_\gamma}{c} = -5.368a.u.$$

120 MeV/u Fe^{26+} on He: single ionization

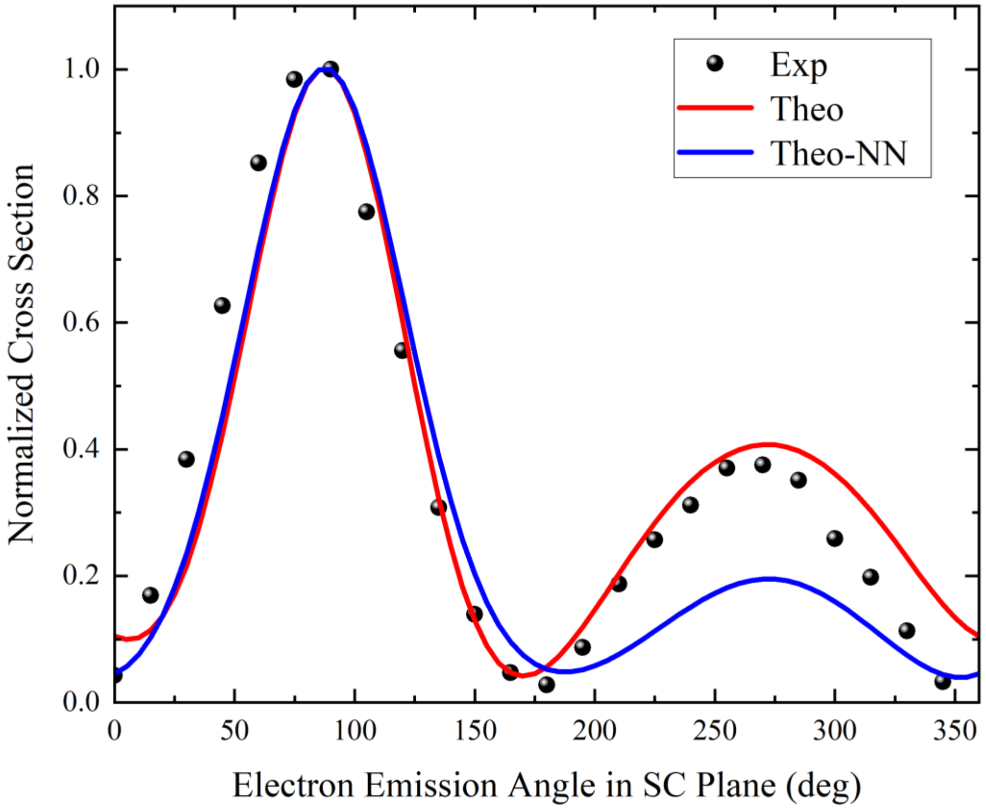
Electron energy spectrum of single ionization process

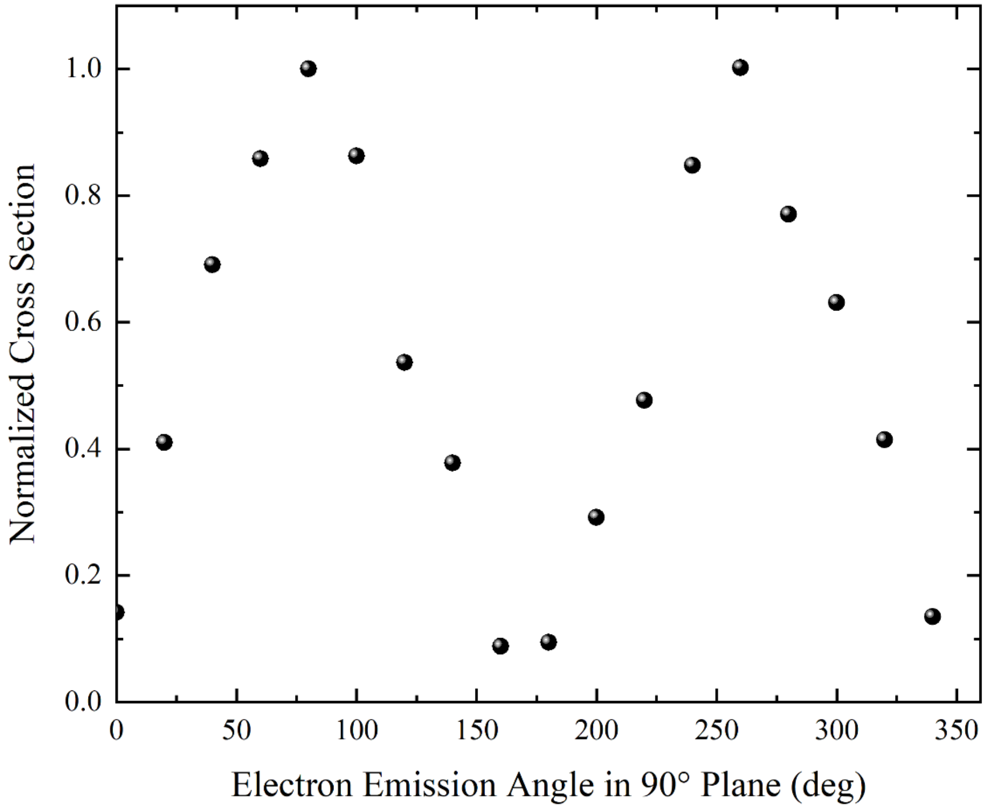


120 MeV/u Fe^{26+} on He: single ionization

Fully differential cross sections

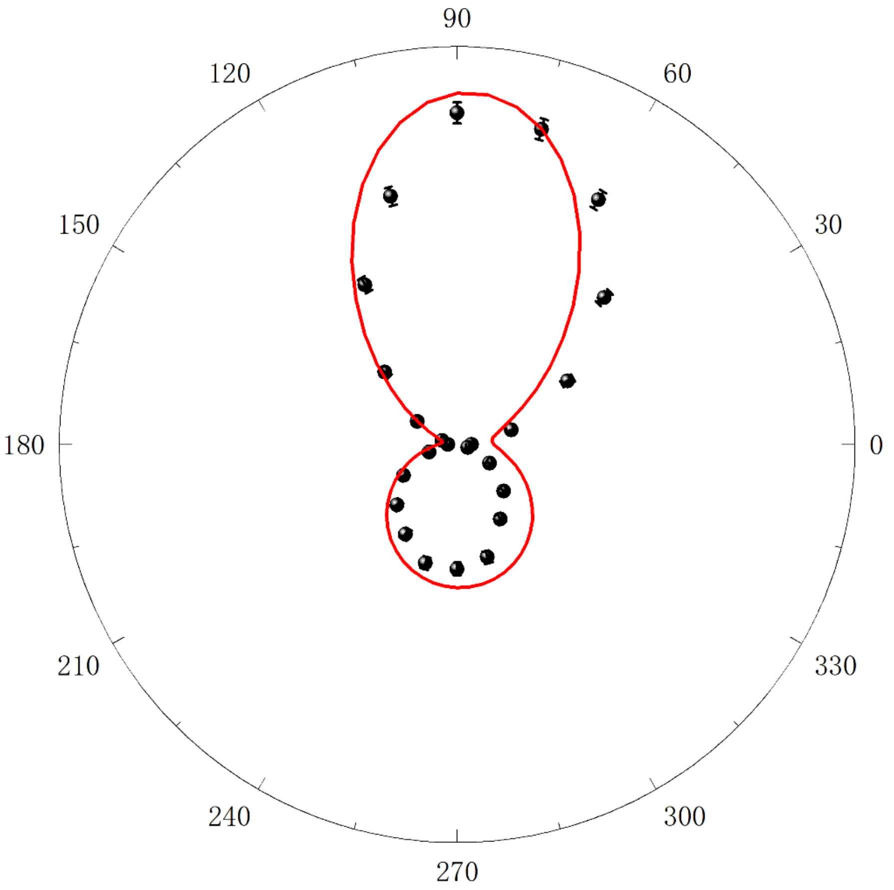
FDCS condition: $q = 0.75 \pm 0.15\ a.u.\ Ee = 3 \pm 0.5\ eV$

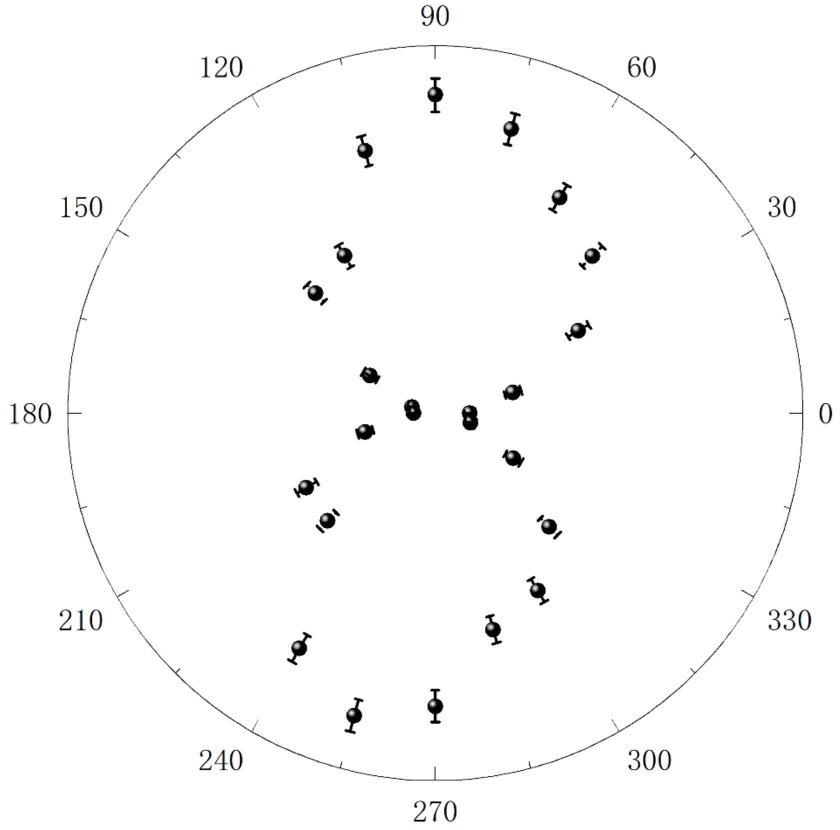




120 MeV/u Fe^{26+} on He, single ionization

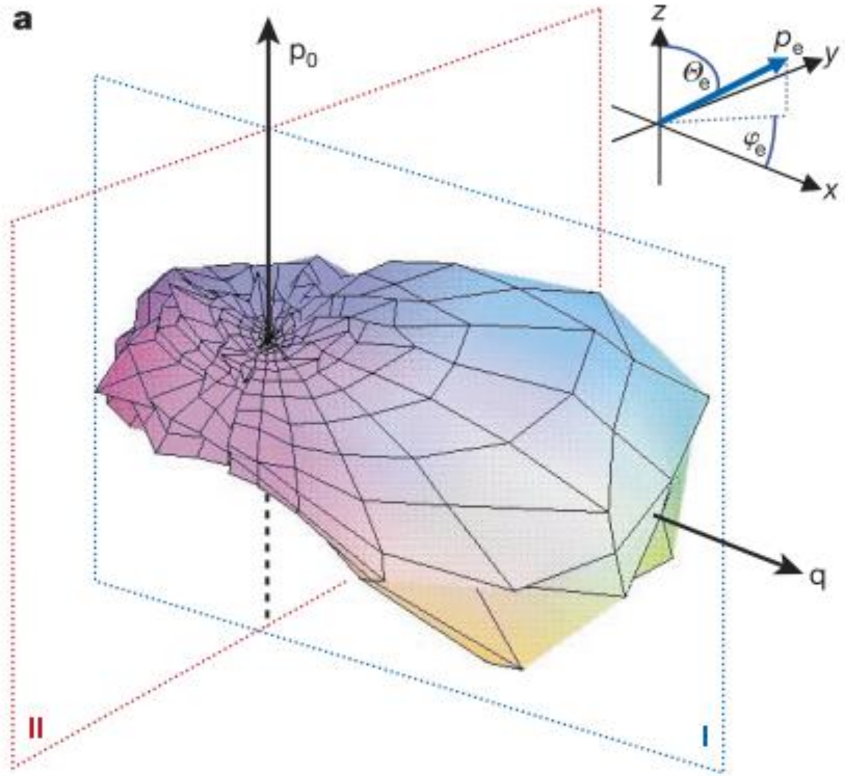
FDCS in polar coordinate: $q = 0.75 \pm 0.15\ a.u.\ Ee = 3 \pm 0.5\ eV$, Polar presentation

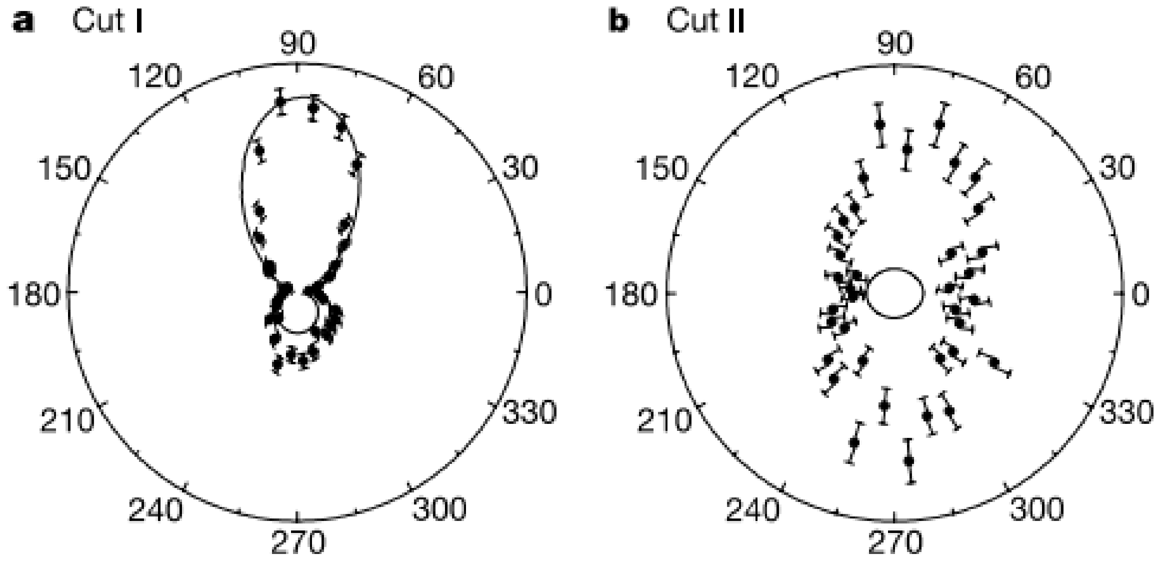




120 MeV/u Fe^{26+} on He, single ionization

Reminder comparison





$q = 0.75 a.u.$

$Ee = 6.5\ eV$

M. Schulz, R. Moshammer, D. Fischer, H. Kollmus, D.H. Madison, S. Jones, and J.Ullrich, **Nature** 422, 48 (2003).

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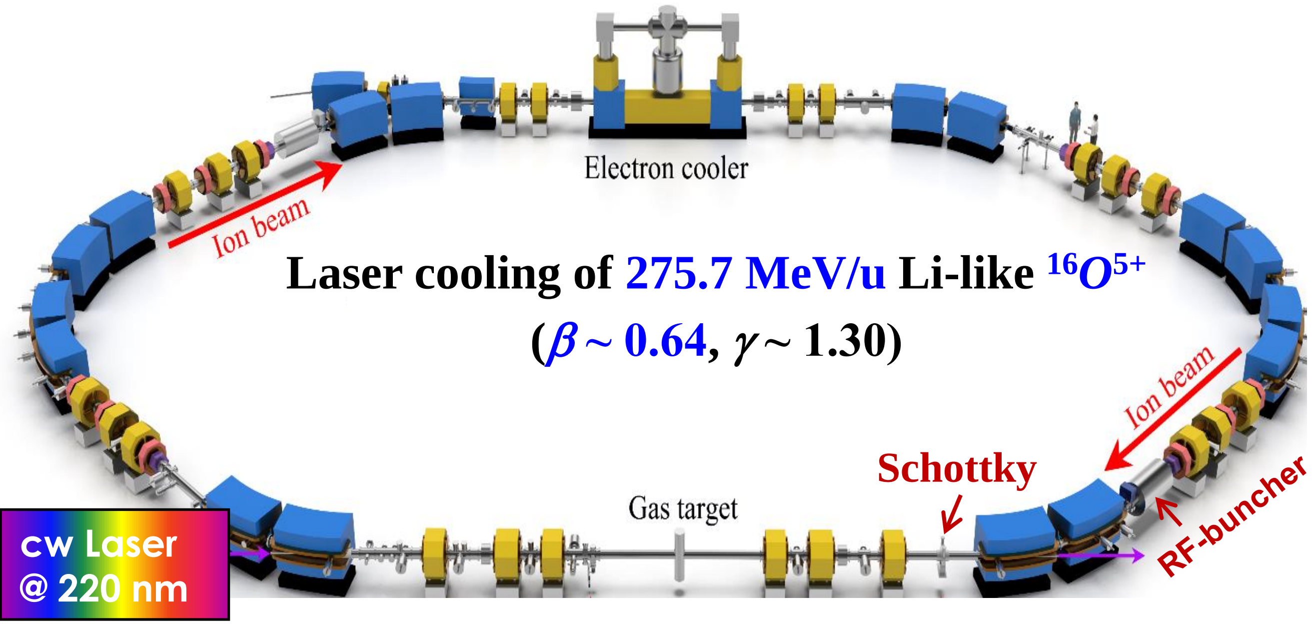
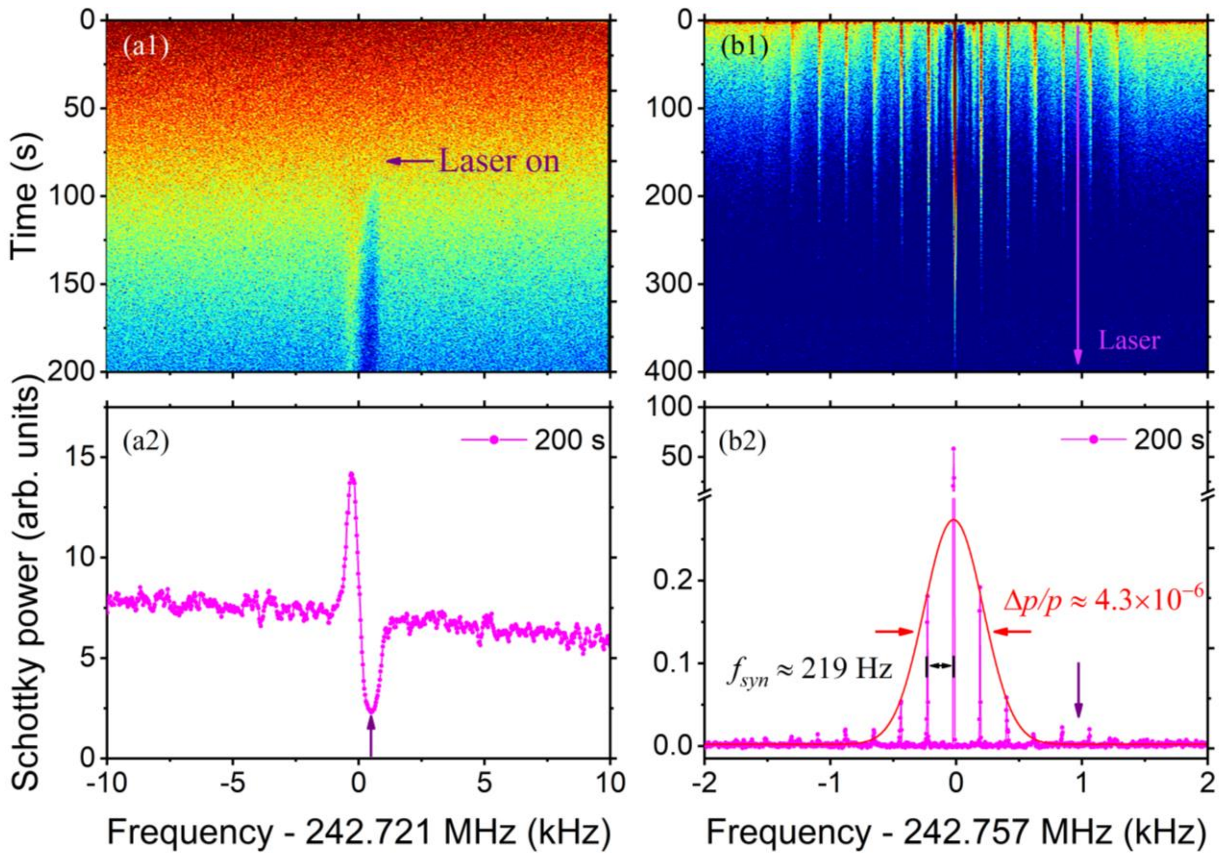
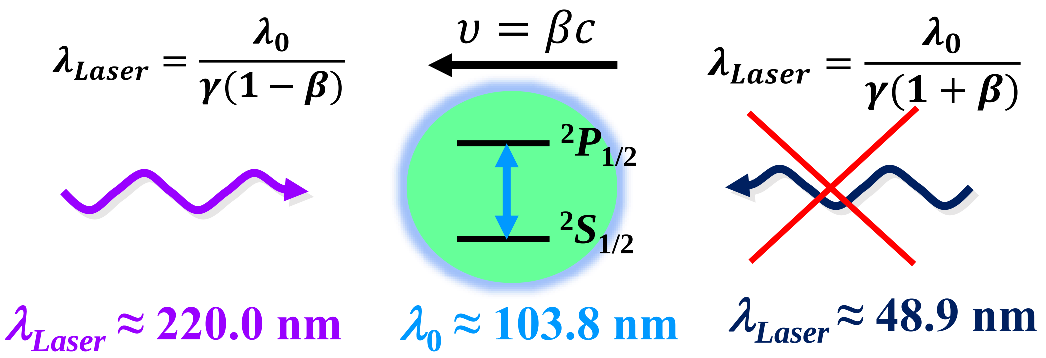
Laser cooling experiment at CSRe

$$\lambda_{Laser} = \frac{\lambda_0}{\gamma(1+\beta)}$$

Laser cooling @ HIRFL-CSRe



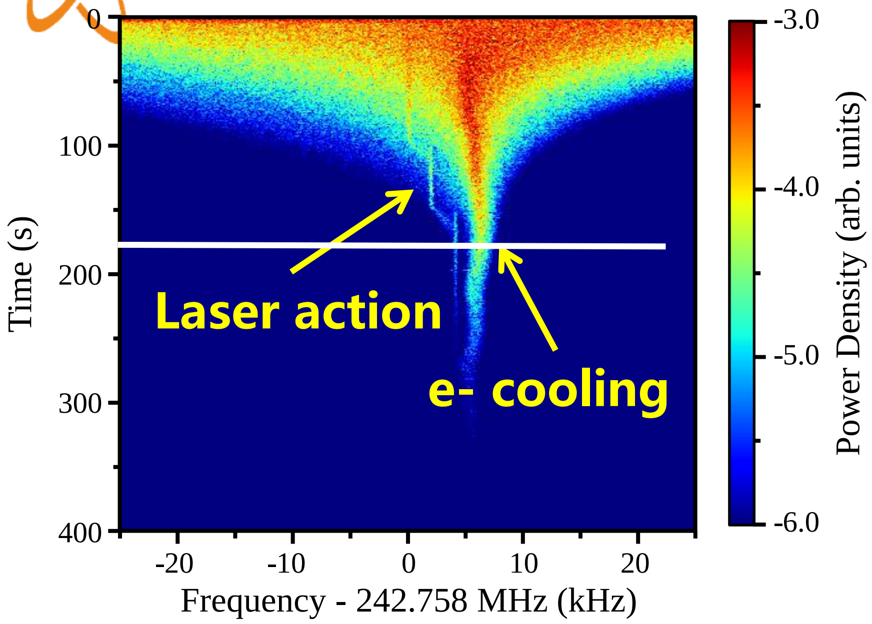


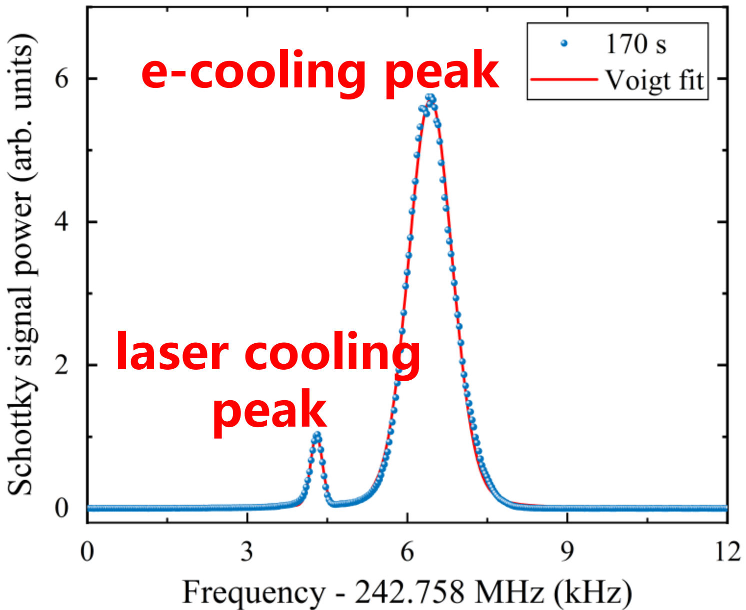


Realization of laser cooling of $^{16}O^{5+}$ ion beams:

- Highest charge state: $^{16}O^{5+}$
- Ion beam energy: 275 MeV/u
- Shortest transition wavelength: 103 nm

Cooling of $^{16}O^{5+}$ ion beam with laser + e-beam





Novel Spectroscopy technique

Error budget of $2s_{1/2} \rightarrow 2p_{1/2}$ transition of $^{16}O^{5+}$ ions

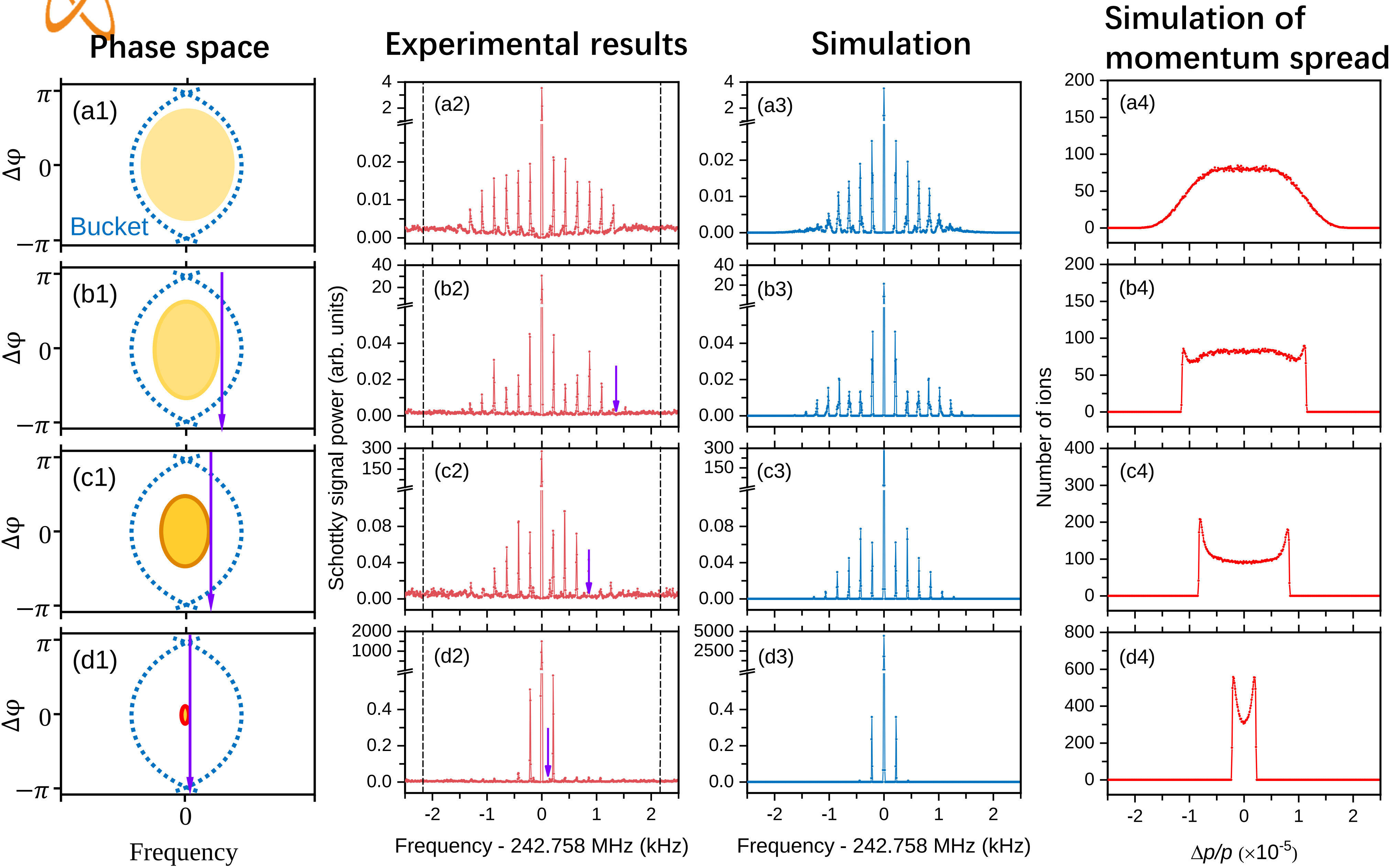
Source	Value	Unit	Correction (nm)	Uncertainty (nm)
Space charge effect	96.5	V	−0.024	−
Electron cooler voltage	1526	V	−	**0.373**
Laser wavelength	0.04	pm	−	1.8×10^{-5}
Angular deviation	3	mrad	−	8.2×10^{-4}
Line centroid of electron-cooled peak	0.65	Hz	−	3.0×10^{-7}
Line centroid of laser-acted peak	1.94	Hz	−	8.9×10^{-7}
Total uncertainty			−0.024	0.373
Final wavelength λ_0			103.453 (373) nm	

Novel Spectroscopy technique:

Laser + e-cooling + Schottky spec. High efficiency!

→→ （RI） isotope shift, hyperfine structure measurements

Simulation of laser cooling of $^{16}O^{5+}$ ion beam

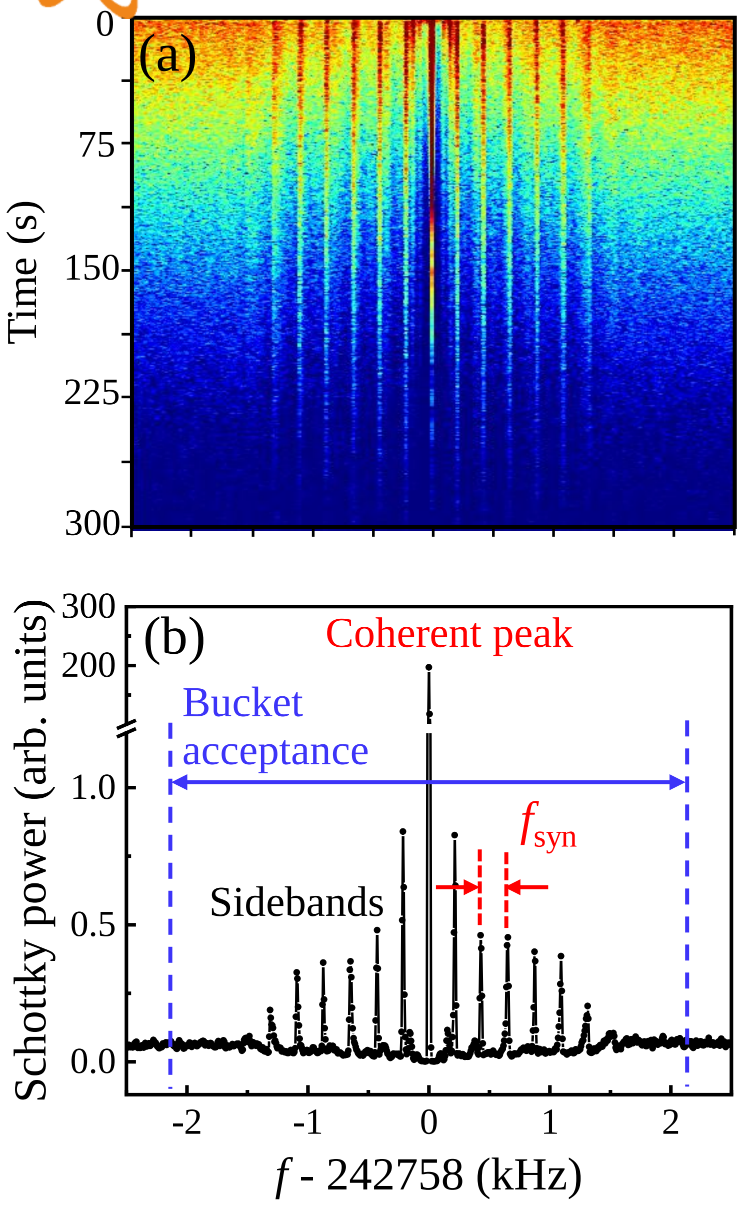


Established simulation program of laser cooling ion beams at CSRe, realization of $^{16}O^{5+}$ ion beams.

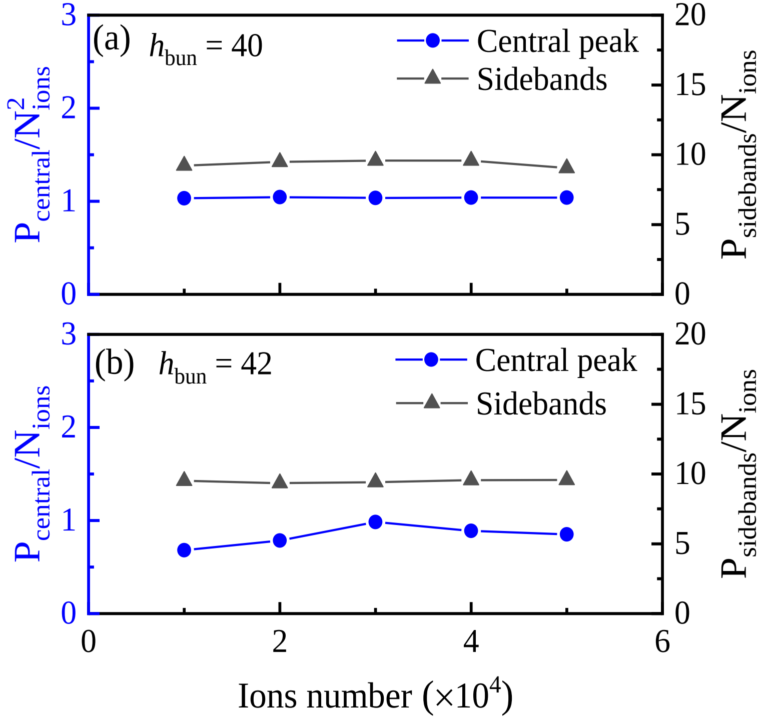
→ Deepen the understanding of laser cooling dynamics

→ Support the CERN Gamma Factory project

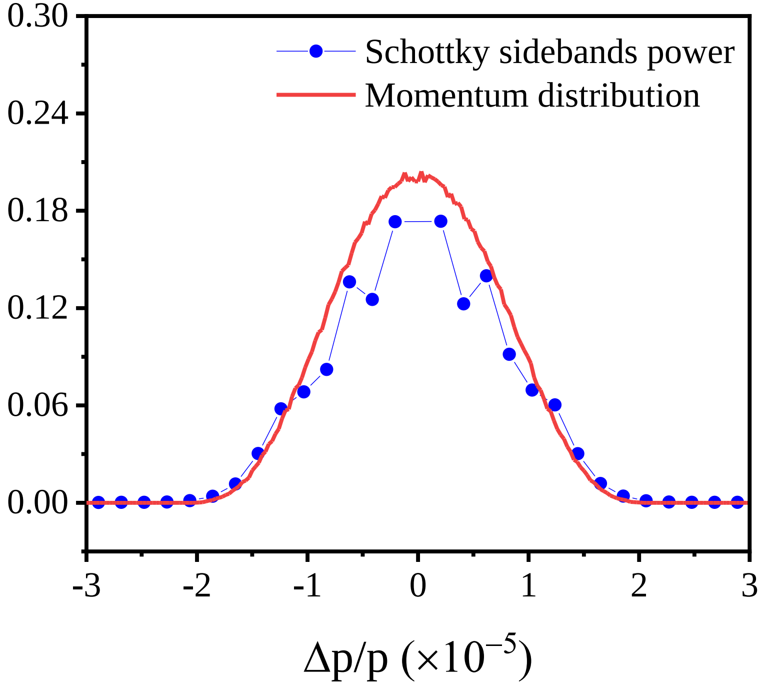
Study of Schottky spectra of Bunched ion beam



S-power vs ions number



Extraction of momentum spread of ion beam



Simulation of buched ion beam Schottky spectrum, interpreting the coherent phenomenon, conditions

→ 解决coherent引起的束团束随机冷却中功率饱和问题。

Developed a new method to extract momentum spread

→ 为储存环上束团束相关实验中实时提取离子束动量分散奠定了基础。

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Experimental plans in next 3 years at CSR in Lanzhou:

Relativistic collisions:

Single and multiple ionization of atoms, molecules

(e, 2e) mutual ionization, few electron ions – atoms

Q-value spectroscopy (Reaction microscope): QED test in strong EM field

DR spectroscopy:

Beryllium-like ions

Isotope shift measurements

Hydrogen-like light ions, e.g. Na10+, Mg 11+, Al12+, etc.

Laser cooling:

Simulation of laser cooling dynamics

Pulsed laser + continuum laser cooling: broadband laser cooling (‘white light’ laser cooling)

APEX Collaborations

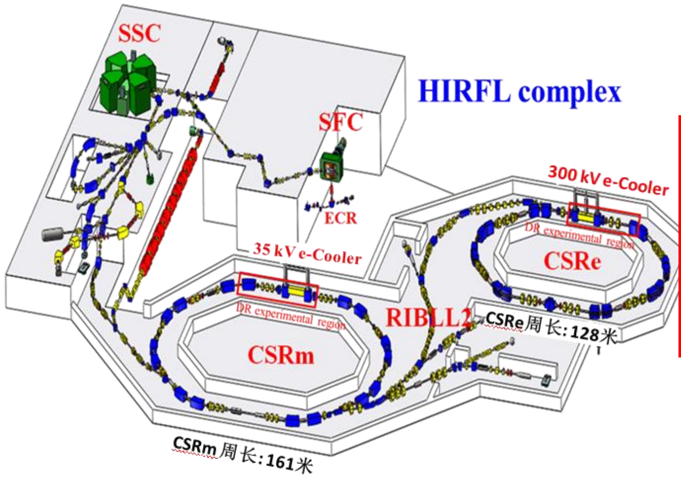
构建基于大科学装置HIRFL和HIAF的

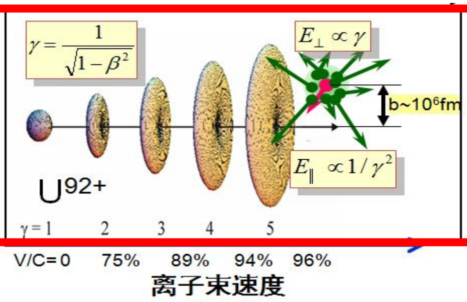
极端条件原子过程研究国际合作组

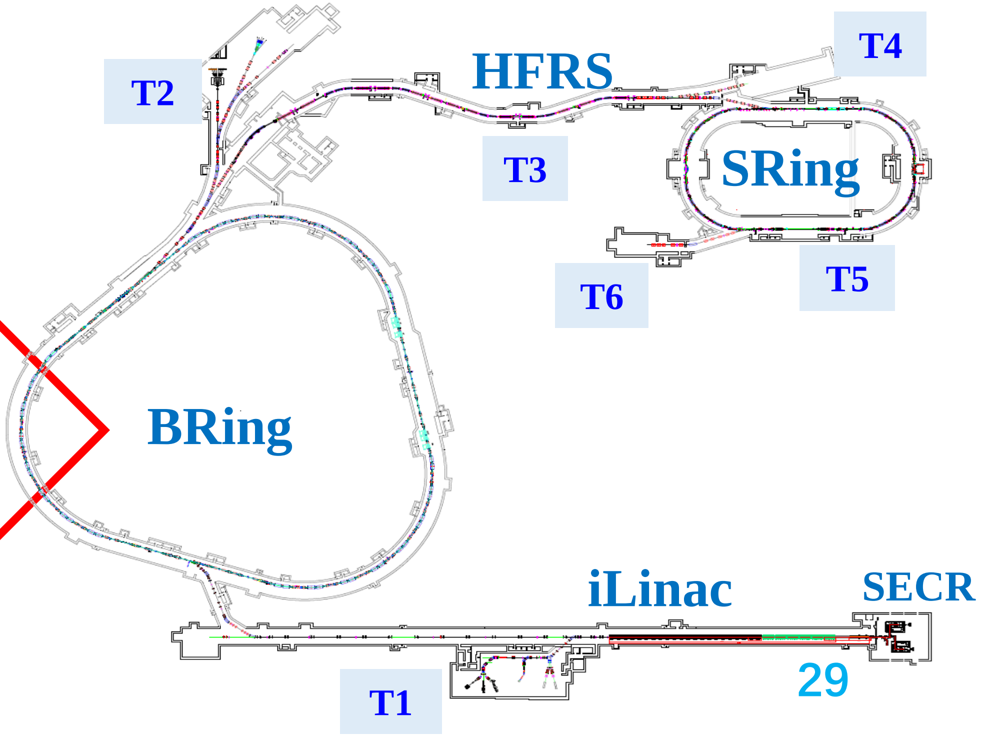
APEX

Collaborations on **A**tomic **P**rocesses at **Ex**tremes at HIRFL & HIAF

Collision dynamics + Spectroscopy+ HEDP + Instrumentation + Theory

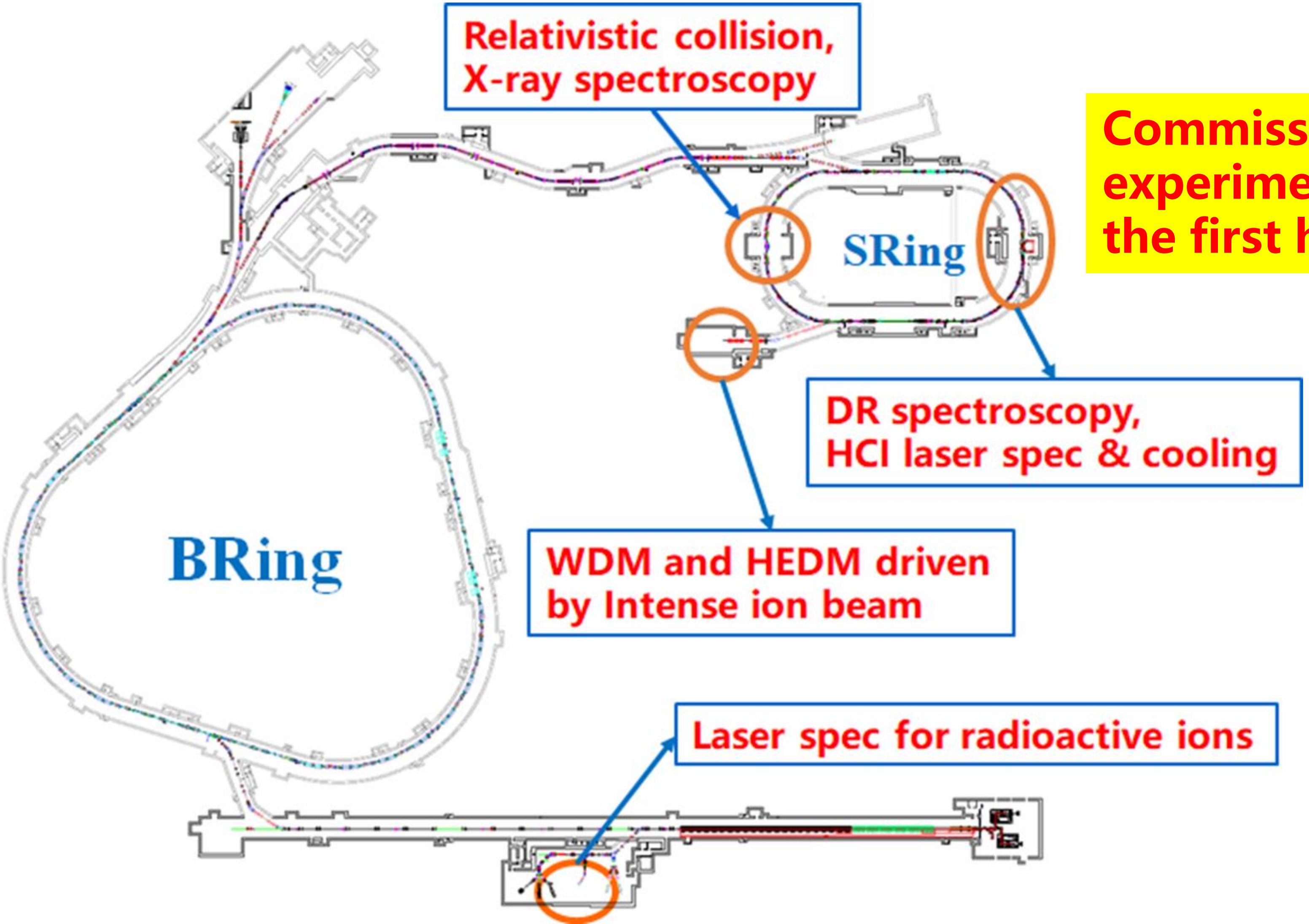






Atomic Physics of HCIs @HIAF

High Intensity heavy ion Accelerator Facility (HIAF)



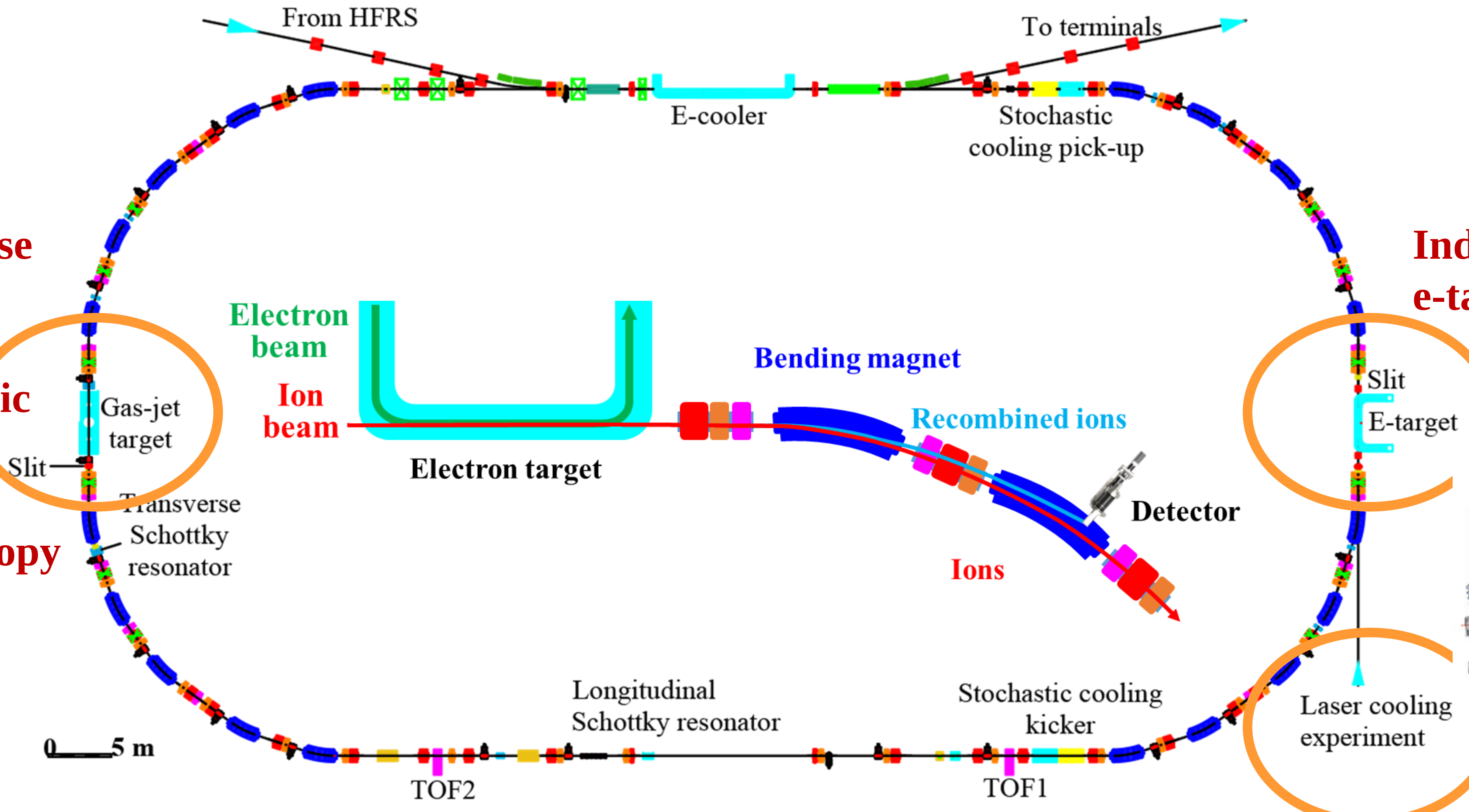
Commissioning experiments will start in the first half of 2026

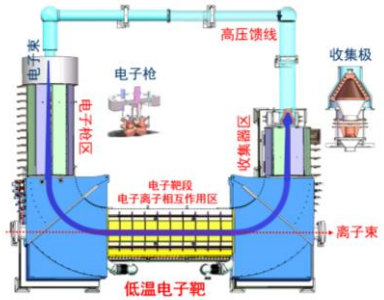
Atomic Physics of HCIs @HIAF

A closer look at SRing of HIAF

Multi-purpose internal-gas target area:
- **Relativistic collision**
- **X-ray spectroscopy**
- **Nuclear reactions**

Independent e-target





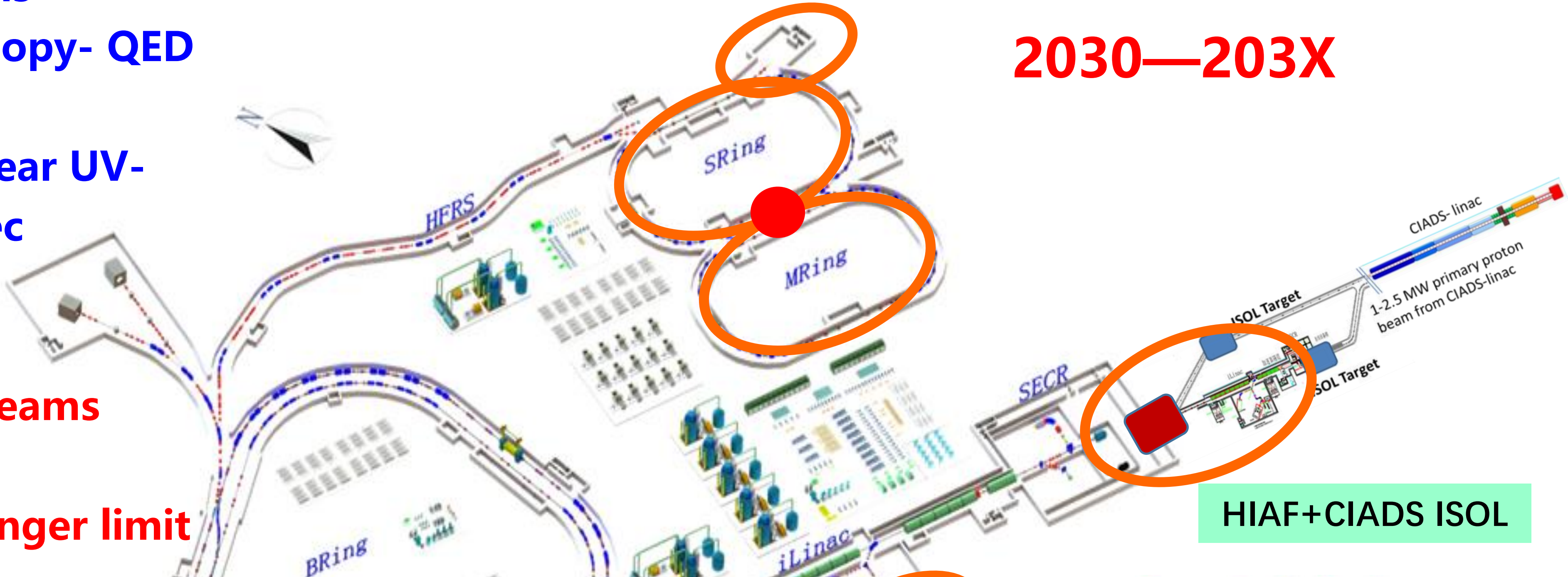
Spectrometer Ring

Atomic Physics of HCIs @HIAF, future

Relativistic collisions
Precision spectroscopy- QED in strong EM field
Application in nuclear UV-laser cooling & spec

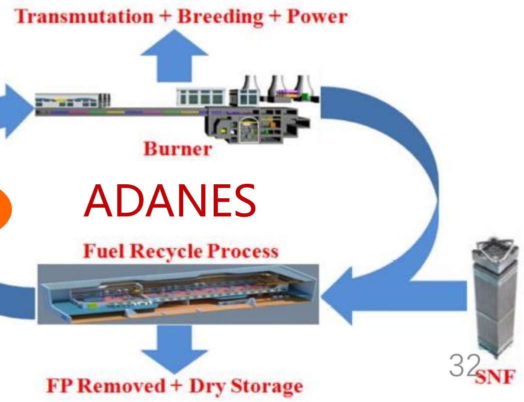
Laser spec of RI
HEDM @ intense beams
LIBS-ADANES
QED beyond Schwinger limit
μ–atom spectroscopy—physics beyond SM

2030—203X

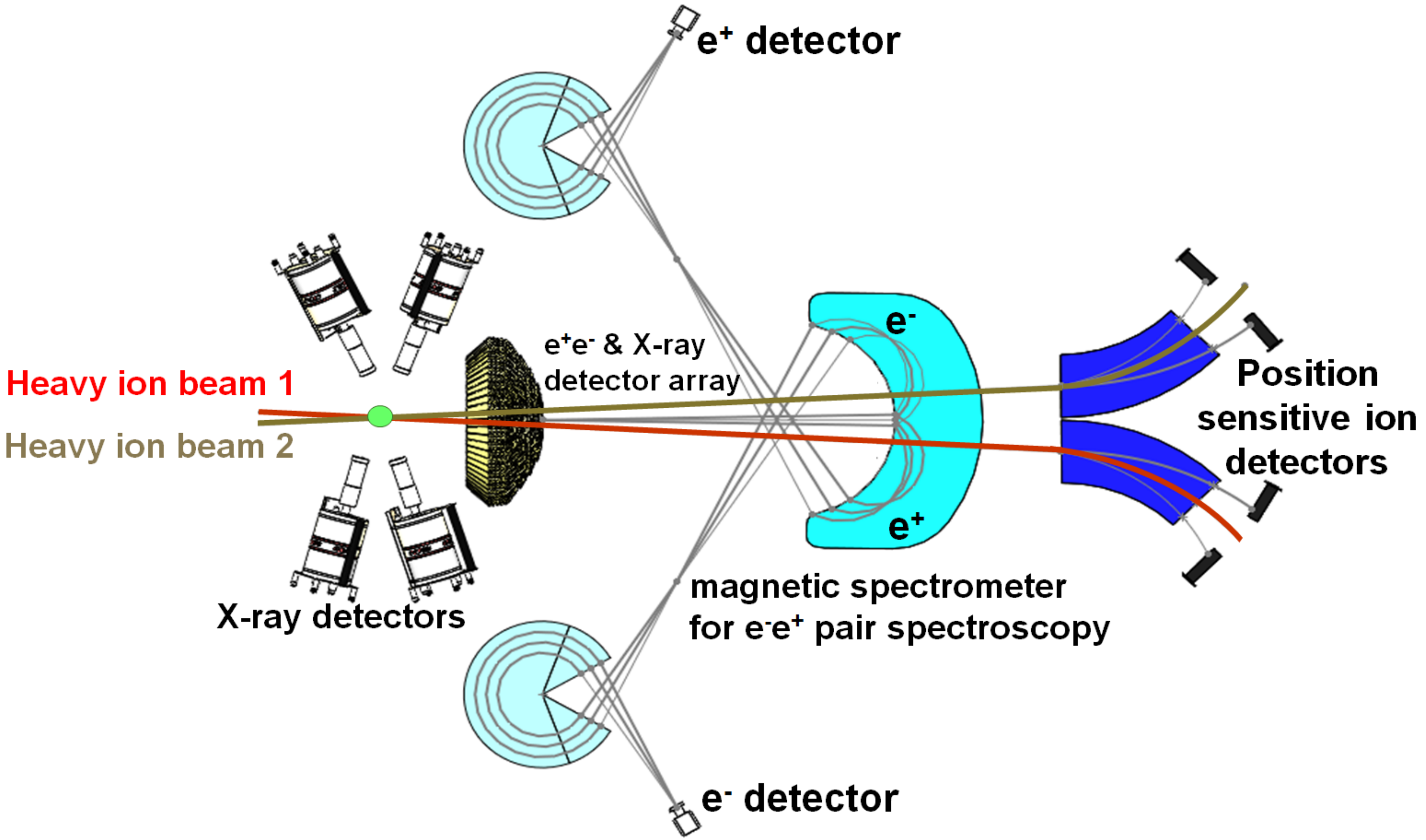


HIAF+CIADS ISOL

ADANES-LIBS



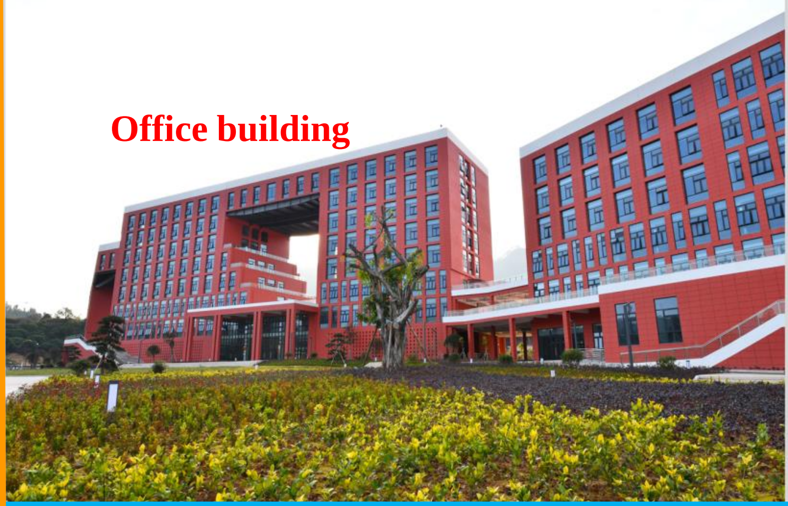
QED test experiments beyond Schwinger limit



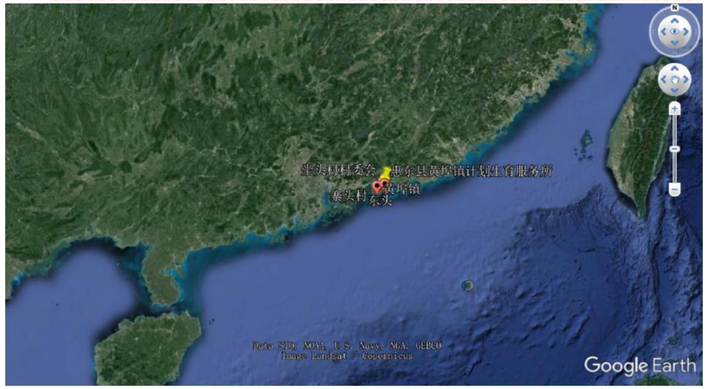
Conceptual design of detection of e+e- pair creation in critical field produced in bare/h-like heavy ion collisions.

Bird view of HIAF construction site

Institute new campus in Huizhou

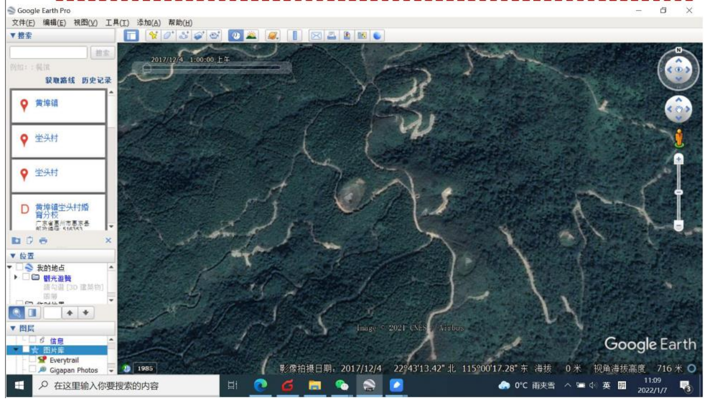


Construction progress of HIAF&CiADS

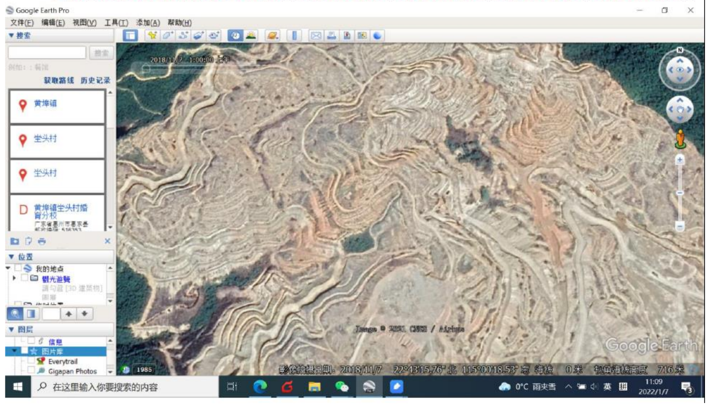


Address: Dongtou Village, Huangbu Town, Huidong County, Huizhou City.

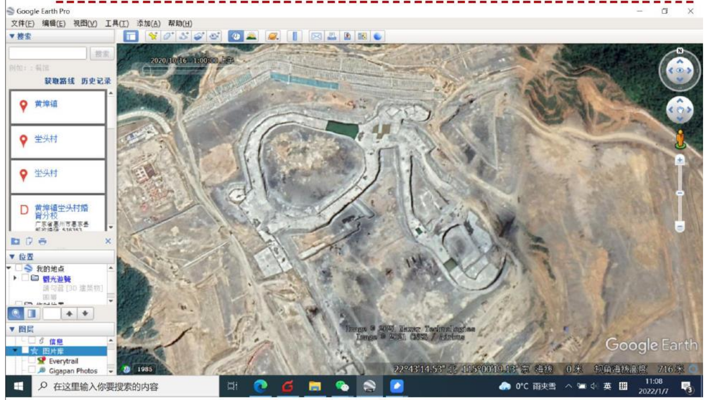
2017/12/4



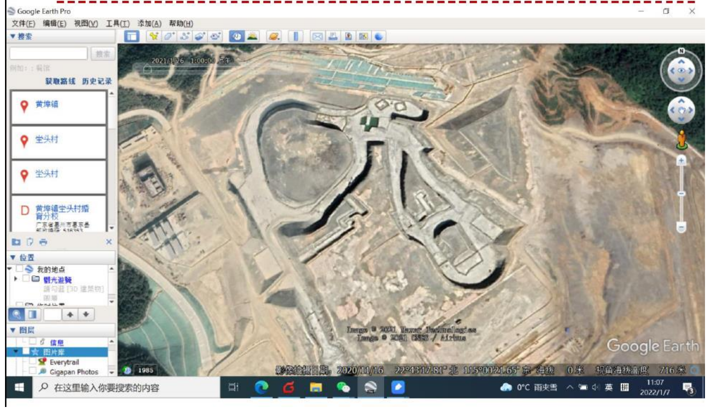
2018/11/7



2020/10/16



2021/1/26



2022/12/1

Overview map of HIAF&CiADS

2023.04.25

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NSFC (National Natural Science Foundation of China)
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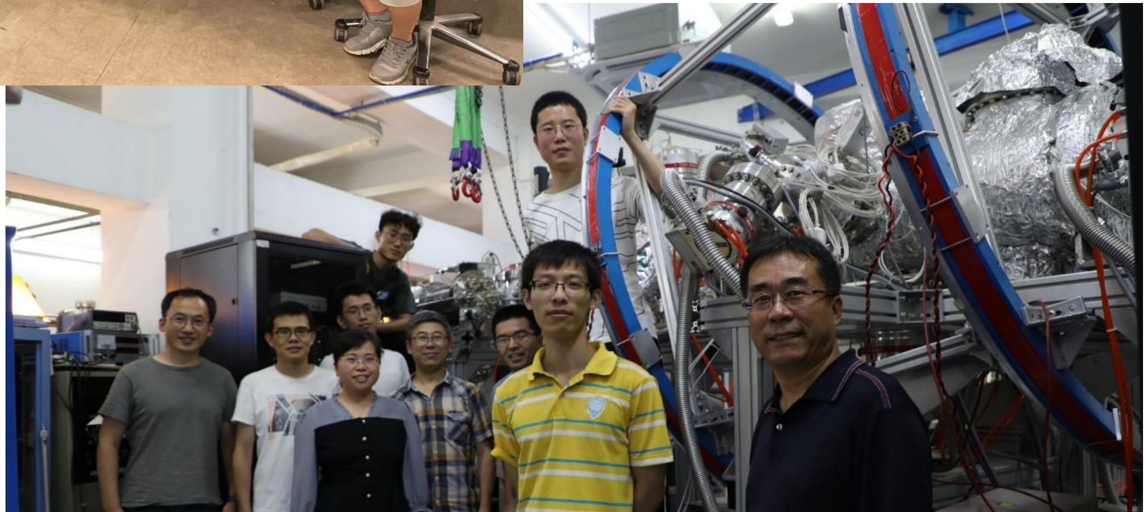
MOST (Ministry of Science and Technology)
NDRC (National Development and Reform Commission)

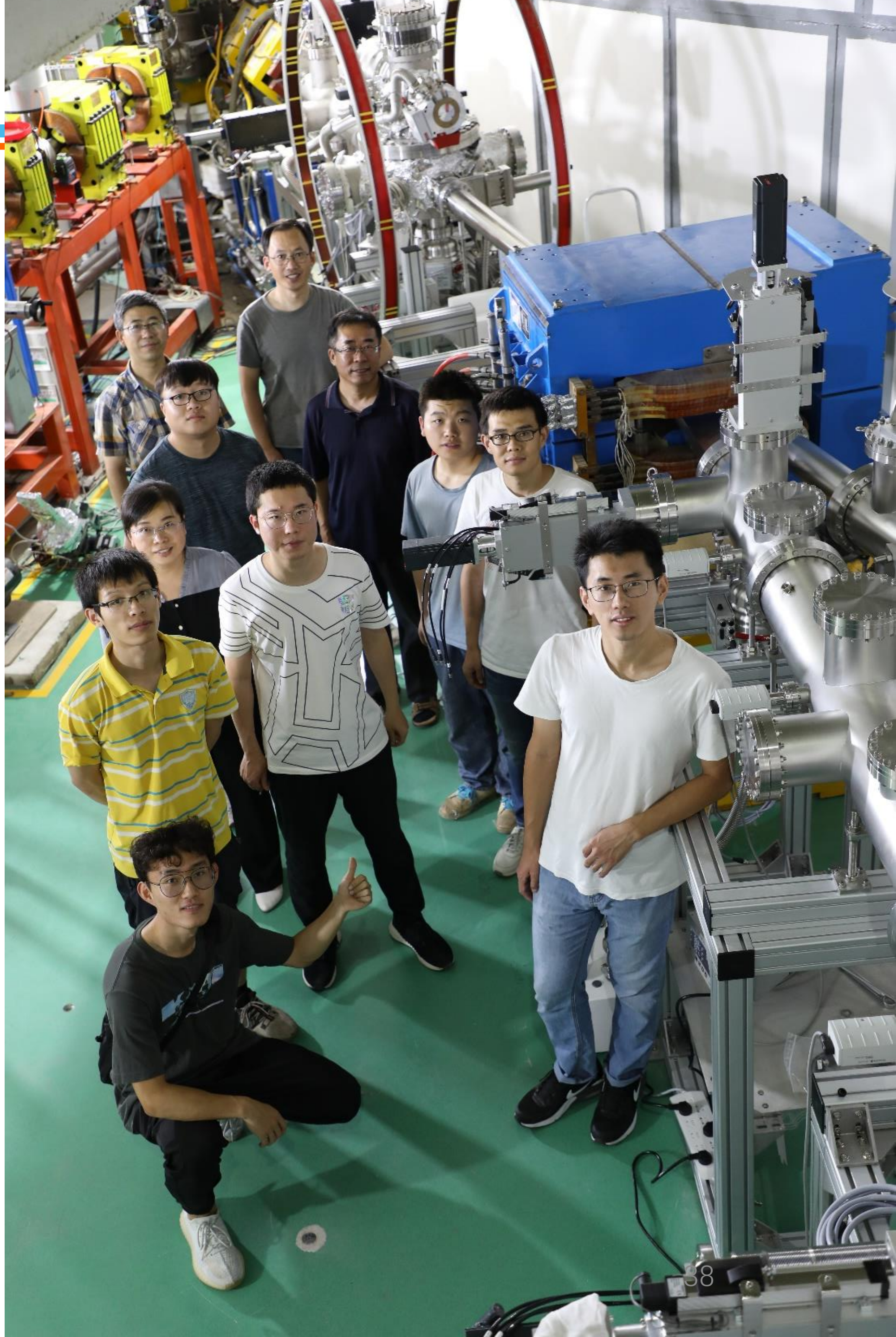
IMPCAS team and Collaborations:

CSRe laser cooling

CSRe collision experiment

Team for collisions
Reaction microscope



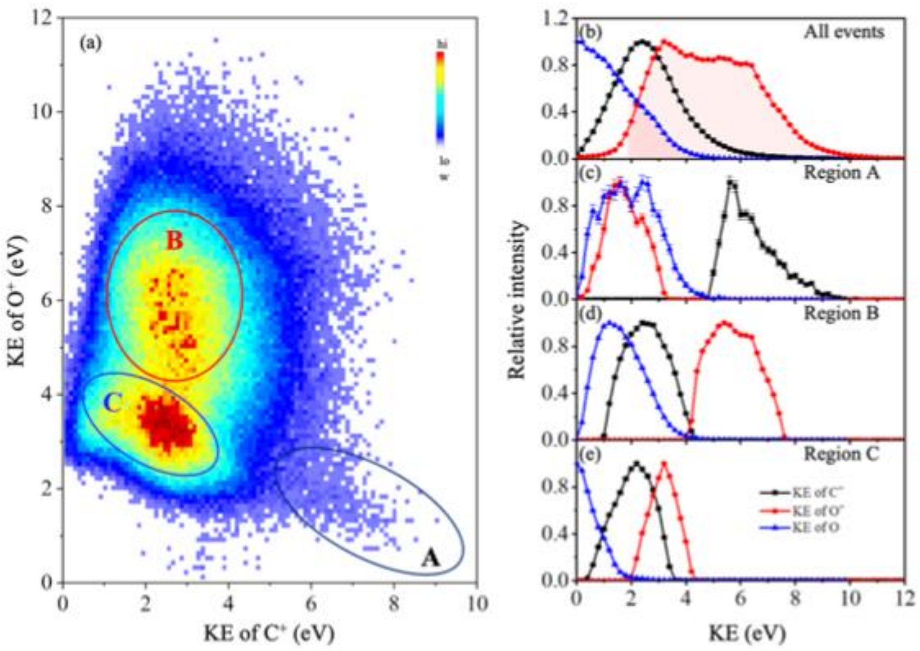


DR Collaboration of APEX

IMPCAS, Lanzhou	X. Ma, Z. K. Huang, W.Q. Wen, H. B. Wang, N. Khan, X. L. Zhu, D. M. Zhao, L. J. Mao, Y. J. Yuan, J. Li, X.M. Ma, J. C. Yang ;
USTC, Hefei	L. F. Zhu, S. X. Wang, X. Xu, W. L. Ma;
Uni. Fudan, Shanghai	C. Y Cheng, K. Yao, Y. Yang, R. Si;
GSI, Darmstadt	Th. Stöhlker, C. Brandau, A. Gumberidze, Yu. Litvinov, M. Steck;
Uni. Giessen	A. Müller, S. Schippers;
BINP, Novosibirsk	V. V. Parkhomchuk, V. B. Reva;
IAPCM, Beijing	C. Y. Li, X. Y. Han, J. G. Wang;
NWNU，Lanzhou	C. Z. Dong, L. Y. Xie, D. H. Zhang;
Uni. Strathclyde	N. R. Badnell, Simon Preval, Chunyu Zhang

Thank you for you

Dynamics of CO_2 fragmentation induced by ions



direct 61.7%

$CO_2^{2+} \rightarrow C^+ + O^+ + O$

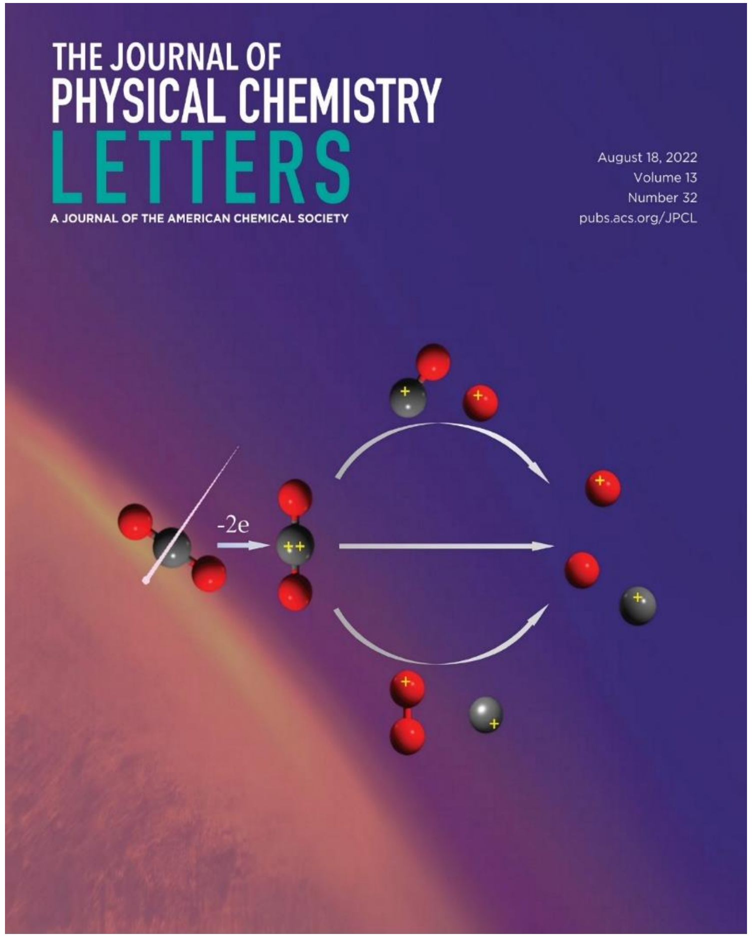
sequential 36.6%

$\rightarrow O^+ + CO^+ \rightarrow C^+ + O^+ + O$

isomerization 1.7%

$\rightarrow C^+ + O_2^+ \rightarrow C^+ + O^+ + O$

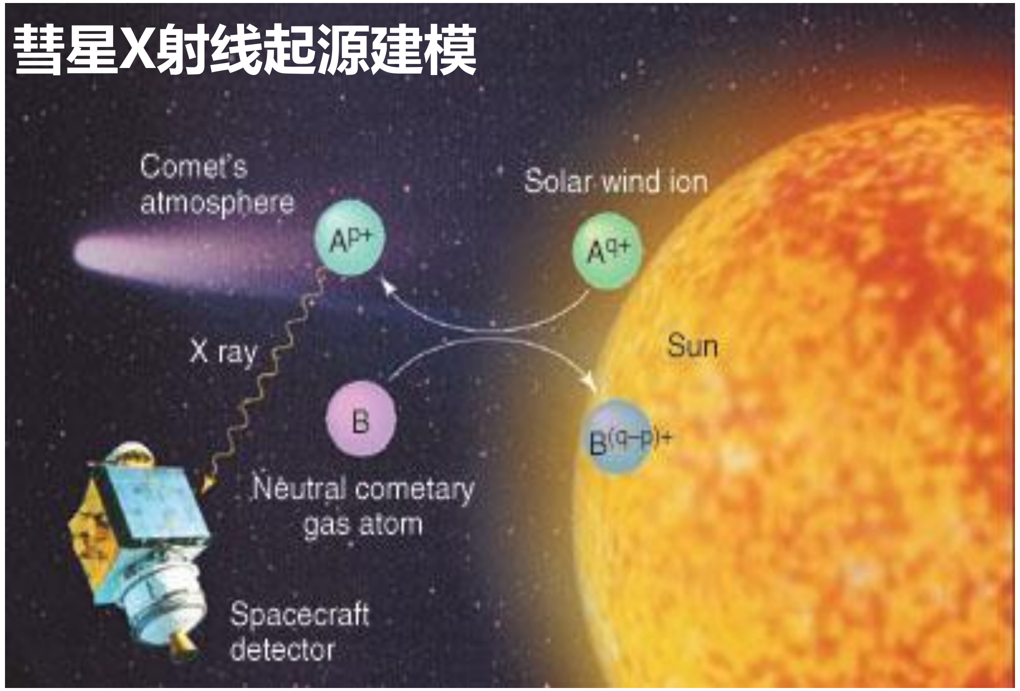
Part of the oxygen atom/ion get sufficient kinetic energy from fragmentation process, can escape the gravitation of Mars. Providing one possible mechanism of oxygen escape on Mars.

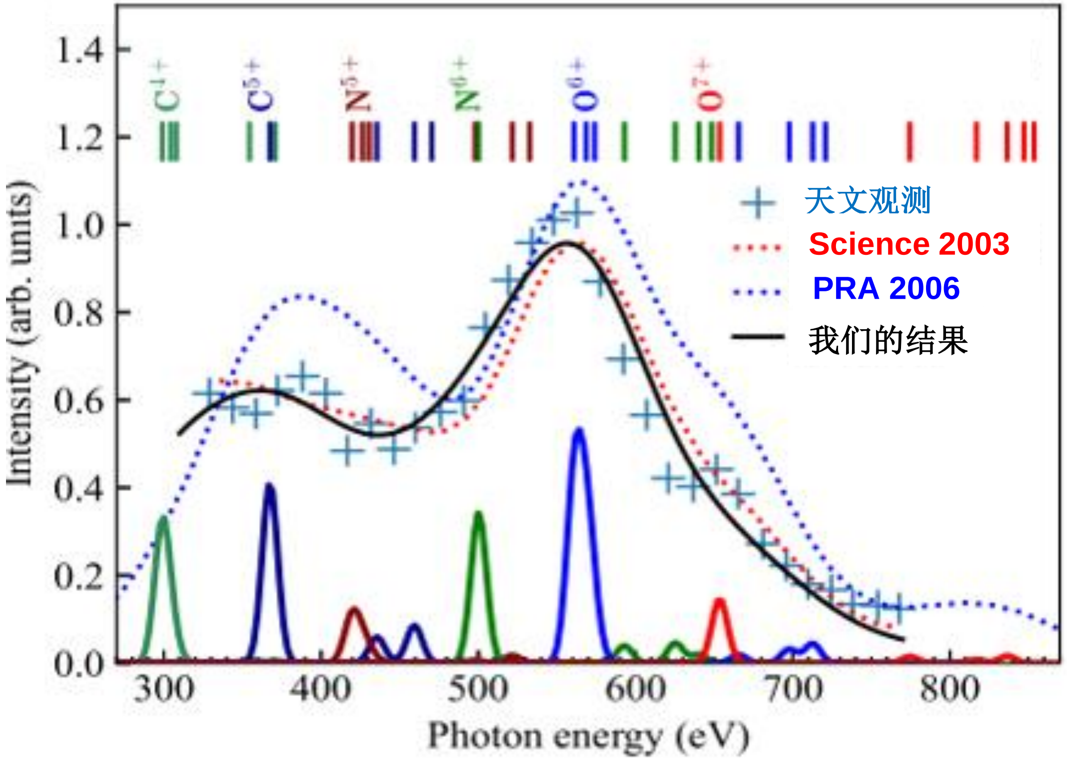


J. Phys. Chem. Lett. 13, 7594, 2022

成果产出：彗星大气X射线建模

太阳风高电荷态离子与彗星大气电荷交换是彗星X射线的主要来源。





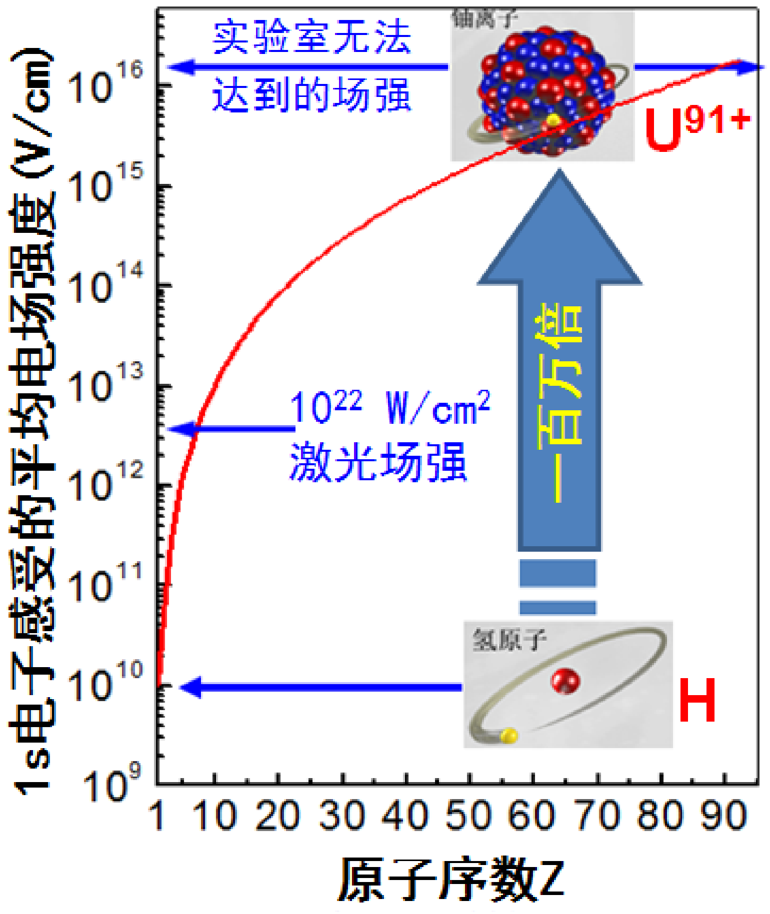
结合高分辨电荷交换原子数据，通过对彗星C/1994 S4 X射线的天文观测精准建模，获得了准确的太阳风高电荷态离子丰度，提供太阳活动以及其引发的空间天气的信息。

张瑞田等，MNRAS 2023

强库仑场量子电动力学效应@CSR

- 在弱场条件下QED得到了高精度的实验检验，**但是在极端强电磁场条件下，QED需要更高精度的实验检验！**

高电荷态离子强电场条件



检验精度 $\sim 10^{-2}$

$\Delta E_{QED} \approx 500$ eV

$Z\cdot\alpha \approx 1$

$\sim Z^4$

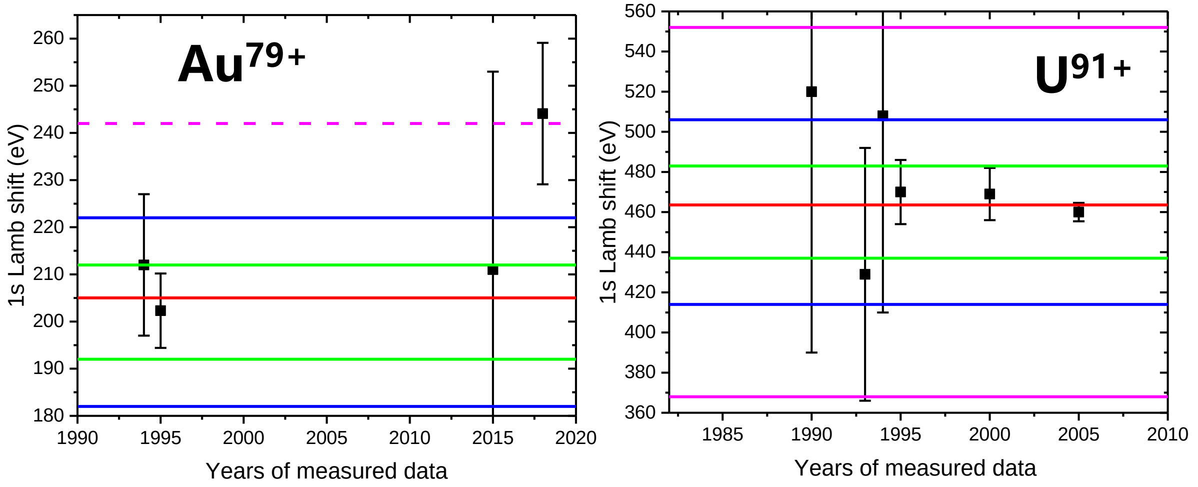
$\Delta E_{QED} \approx 10^{-6}$ eV

$Z\cdot\alpha \approx 0.01$

检验精度 $\sim 10^{-10}$

弱电场

类氢离子体系



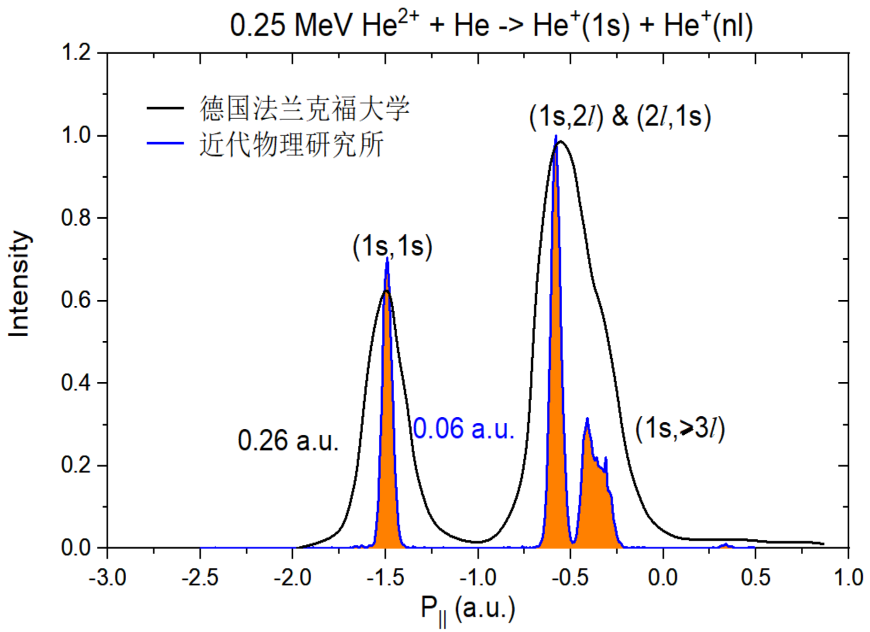
新方法

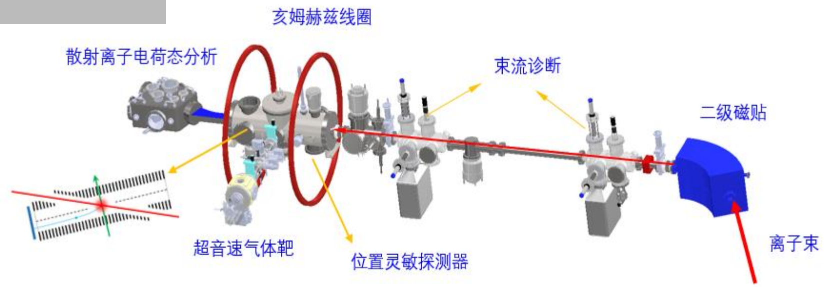
采用反应谱仪技术，直接获得1s电离能。

超越1%分辨

三、工作进展： 装置仪器建设

建成高分辨电荷交换实验测量装置

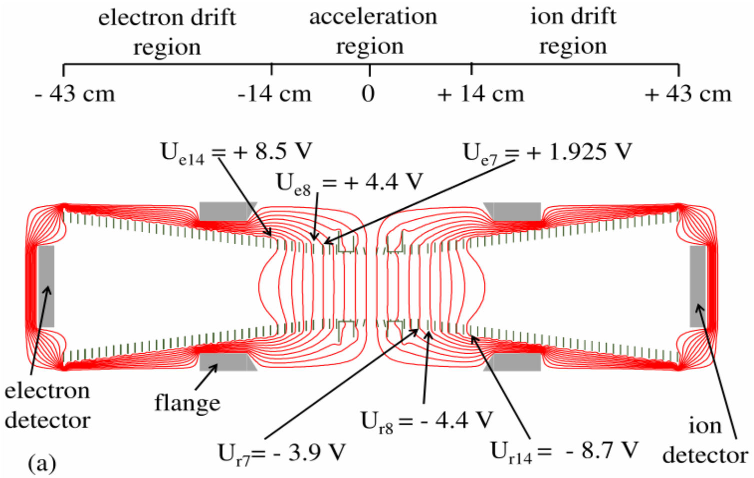


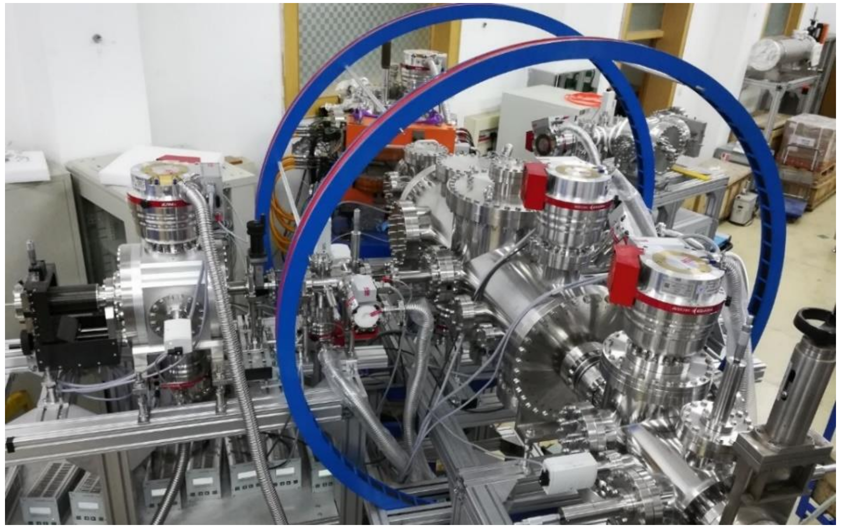


	我们团队	德国法兰克福大学	德国重离子物理研究中心	法国国家科学中心	美国克莱姆森大学
离子种类	H^{+} - Bi^{81+}	H+，He^{+}，He^{2+}	C^{6+} - U^{92+}	H^{+} - Xe^{30+}	H^{+} - Ar^{10+}
典型流强	1uA - 20 uA		10 – 20 mA		< 35 pA
能量范围	0.2 keV/u – 80 MeV/u	< 2 MeV/u	14.8 MeV/u - 24.7 MeV/u	eV/q - 20 keV/q	< 20 keV/u
实验分辨	0.06 a.u.	0.04 a.u.	在建	0.4 a.u.	在建

实验装置建设和性能提升(2)： 反应成像谱仪

发展了新的聚焦结构，建成纵向反应显微成像谱仪，反冲离子动量分辨达到0.05a.u.，实现自旋量子态分辨的碰撞动力学实验研究

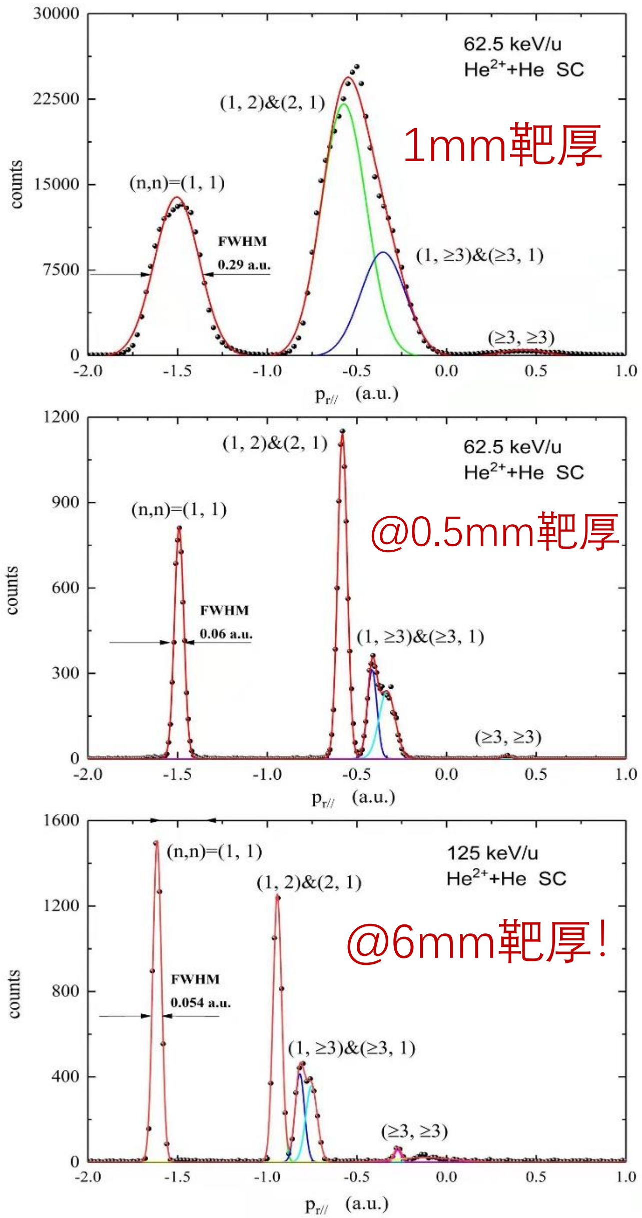




年初

年中

年末



抛弃传统聚焦方案，

气体靶反应谱仪精度的新纪录： 0.05a.u.

1. **逼近极限的动量分辨**
   （目前国际上气体靶反应谱仪动量分辨在0.2-0.3a.u.；磁光阱冷靶动量分辨0.03a.u.）
2. **高靶厚测量效率与精度的协调**
3. **采用冷头制冷，有望逼近磁光阱谱仪的动量分辨**

自主发展新技术
可应用到相对论谱仪


HIRFL-兰州重离子加速器
兰州重离子加速器国家实验室
HIRFL

Two aspects concerning the progresses at the cooler storage ring CSRe in Lanzhou will be reported. Firstly, the recent experimental results on QED test using F-like nickel ions via dielectronic recombination spectroscopy, fully differential cross section of helium ionization by 120 MeV/u Fe^{26+} ion using reaction microscope, and simulation of laser cooling dynamics at storage ring. Secondly, future aspects will be presented, including the experimental plans of precision spectroscopy and relativistic collisions dynamics at CSRe in next three years, and the progress of HIAF project in Huizhou, Guangdong province, and the atomic physics plans.

Construction progress of HIAF&CiADS

The current aerial photograph of HIAF.

2023/4/25