Experimental advances using highly charged ions at CSR + Future Plans at HIAF

Xinwen Ma

Institute of Modern Physics, Chinese Academy of Sciences

IMPCAS, Huizhou, China, February 26 – 28, 2024

Outline

1. DR spectroscopy at CSR:

— F-like Ni, higher order QED test

2. Collision dynamics

— Fully differential cross sections

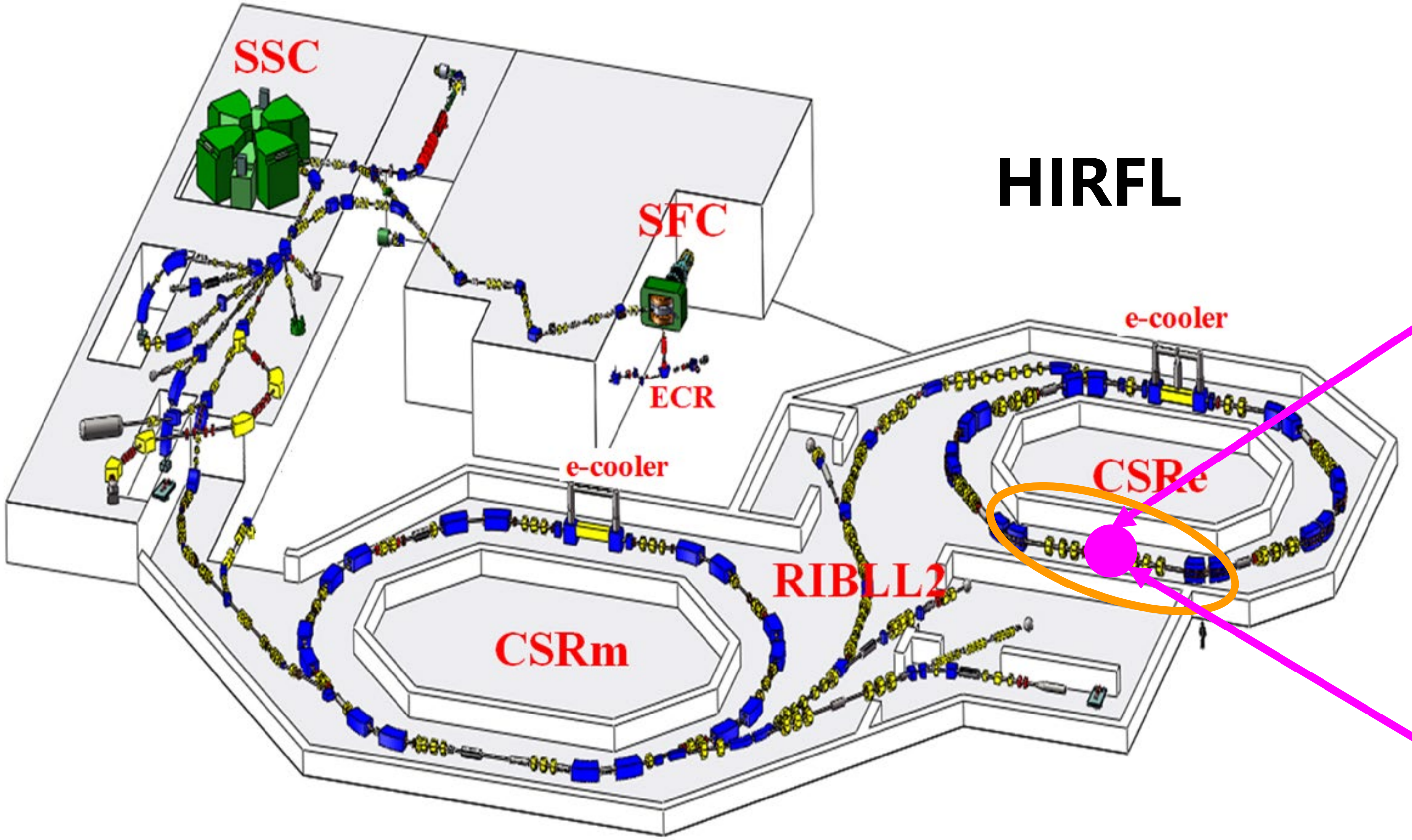
— High resolution, Q-value spectroscopy

4. Atomic Physics at HIAF

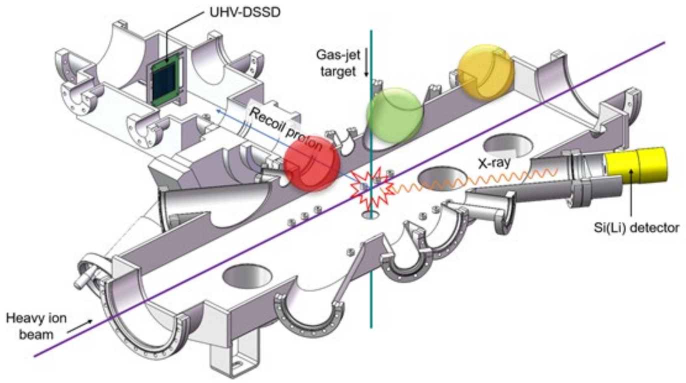
Upgrade of CSRe experimental setups

Multi-purpose internal target experimental setups

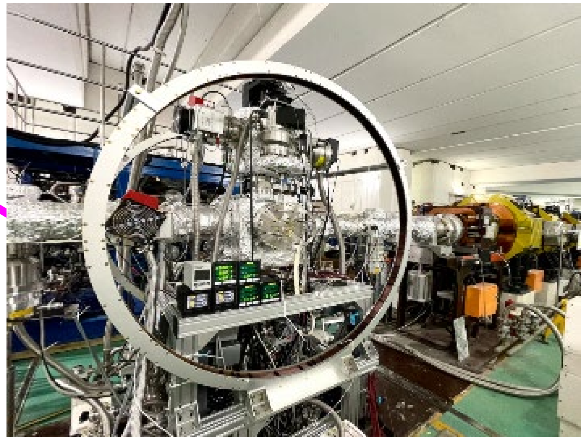
HIRFL



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

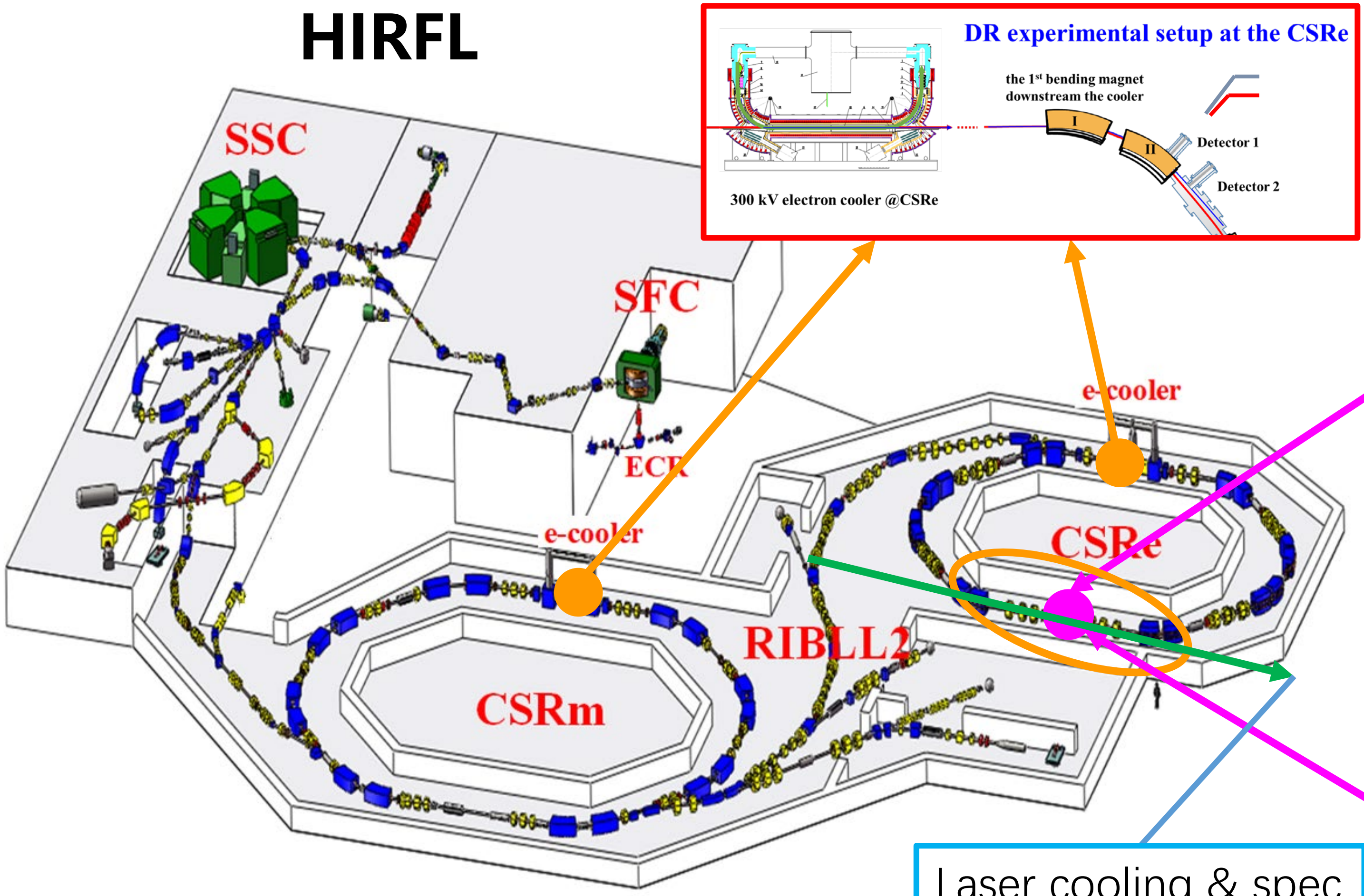


(3) Reaction microscope for relativistic ion-atom collisions



Upgrade of CSRe experimental setups

HIRFL



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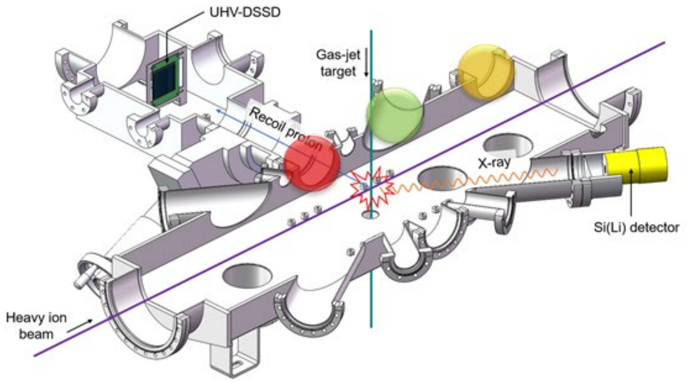
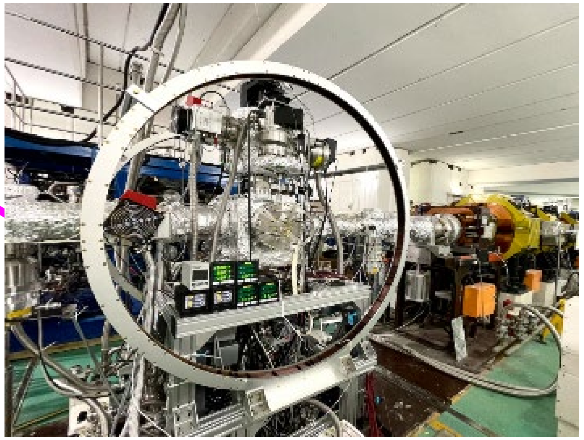
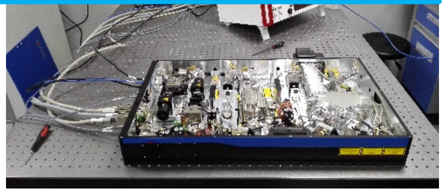


(3) Reaction microscope for relativistic ion-atom collisions



Laser cooling & spec



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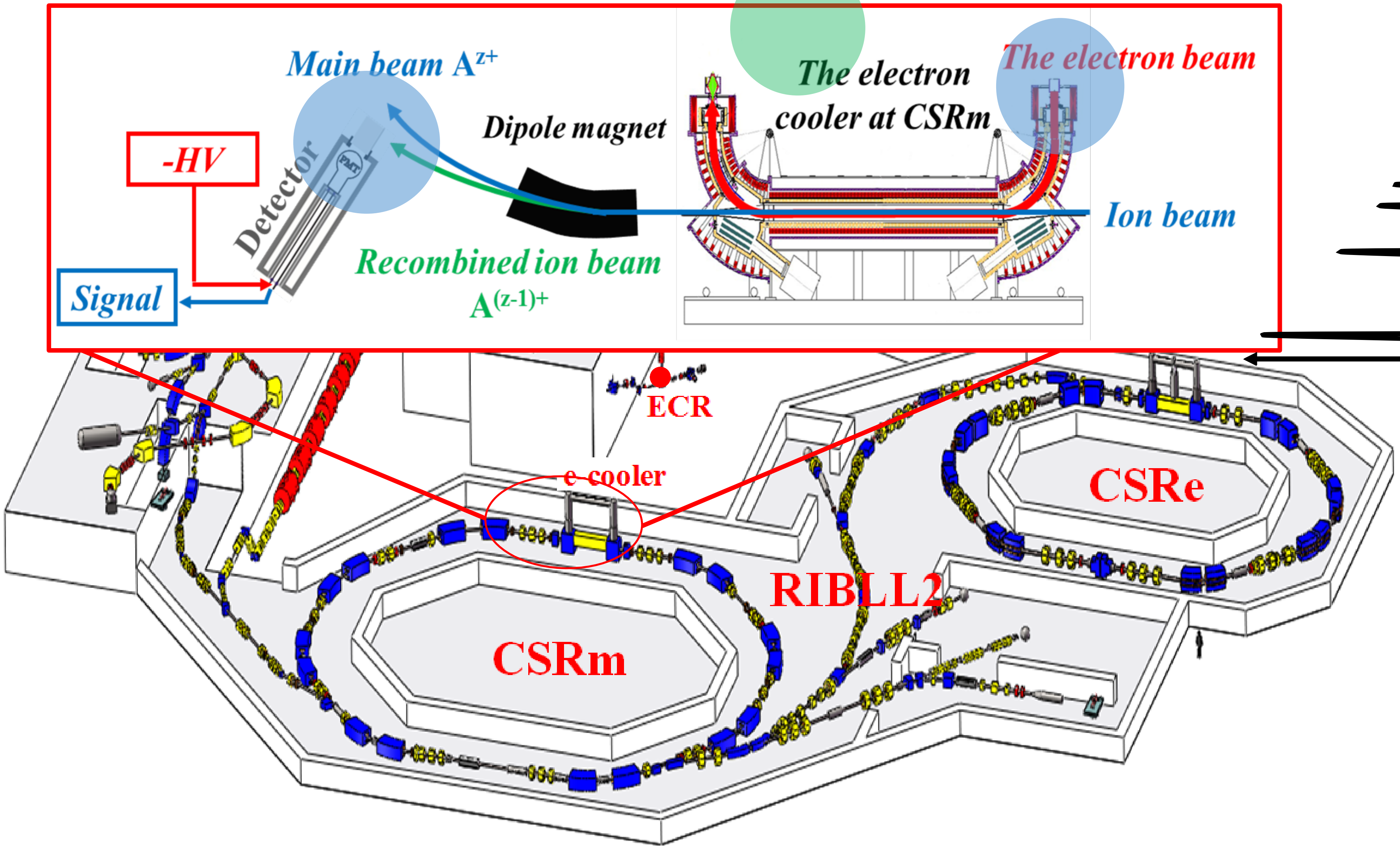
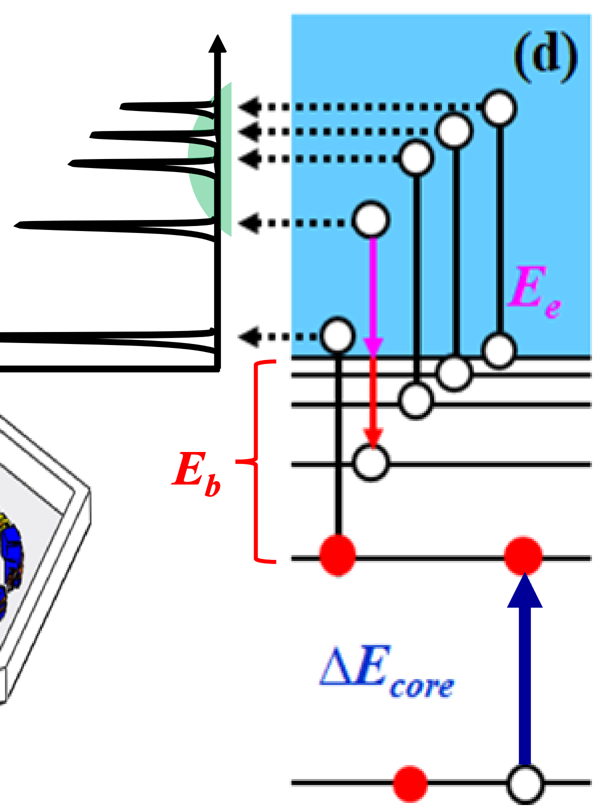
— F-like Ni, higher order QED test

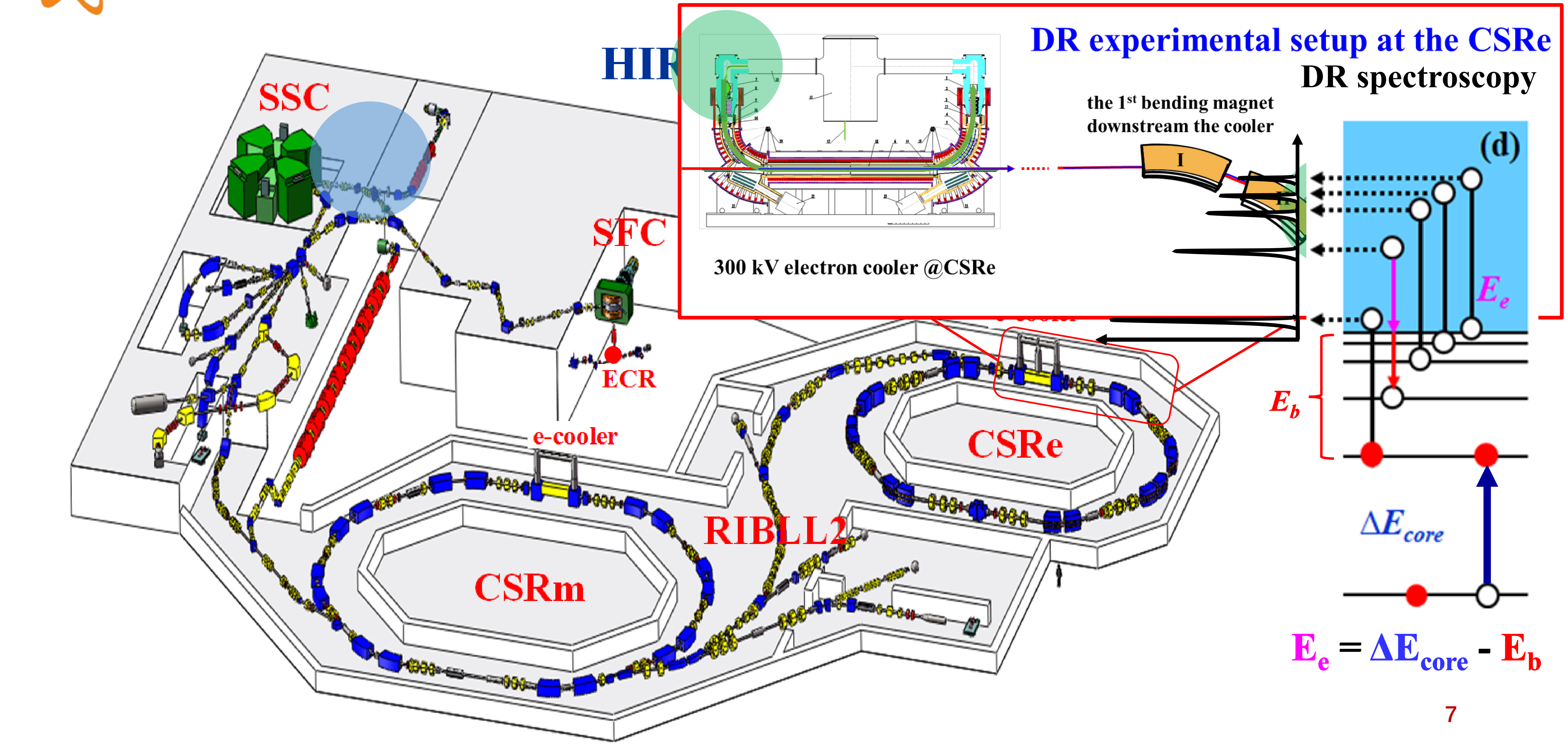
Storage ring DR spectroscopy technique



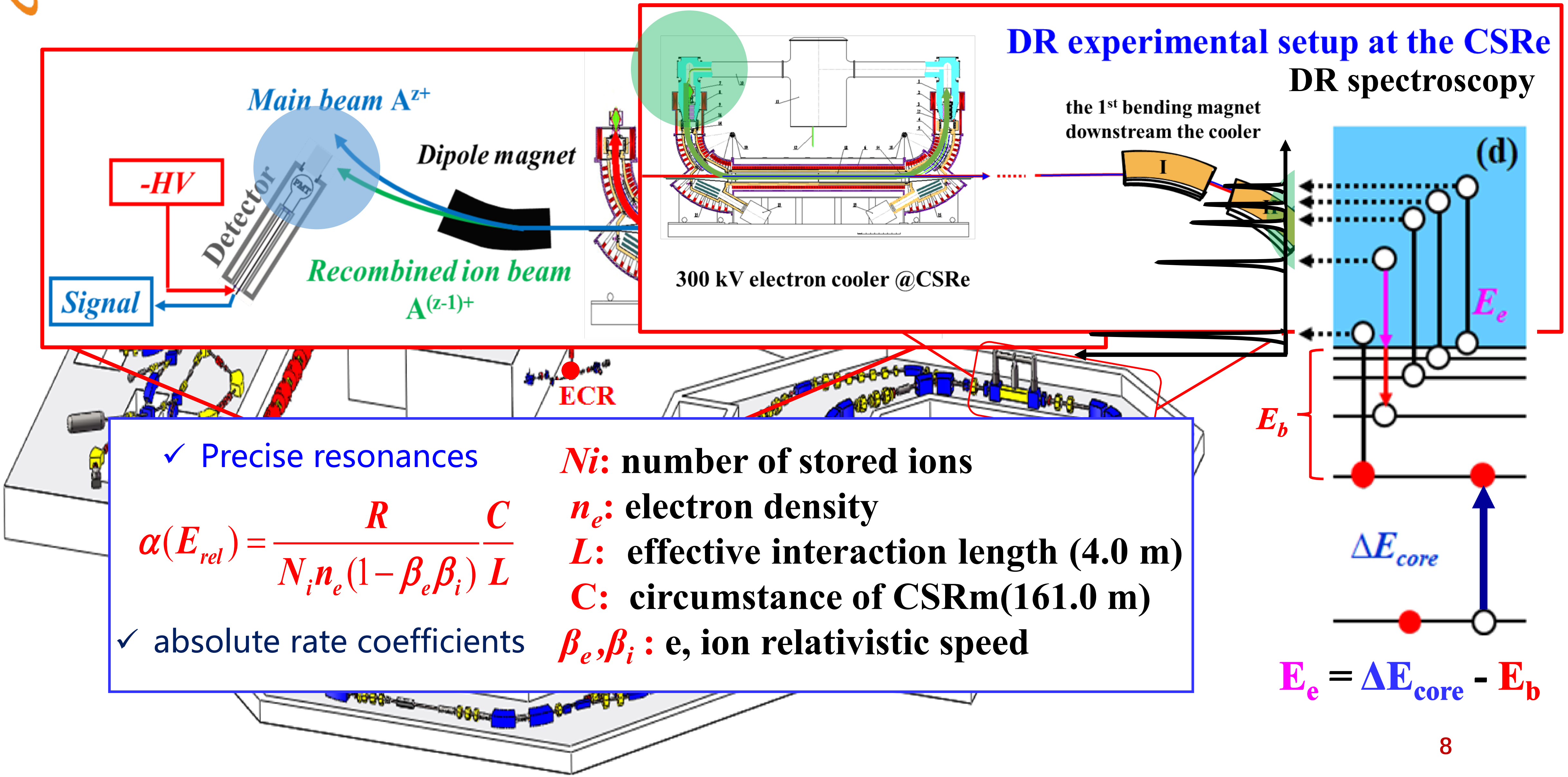


$$E_e = \Delta E_{core} - E_b$$

Storage ring DR spectroscopy technique



Storage ring DR spectroscopy technique



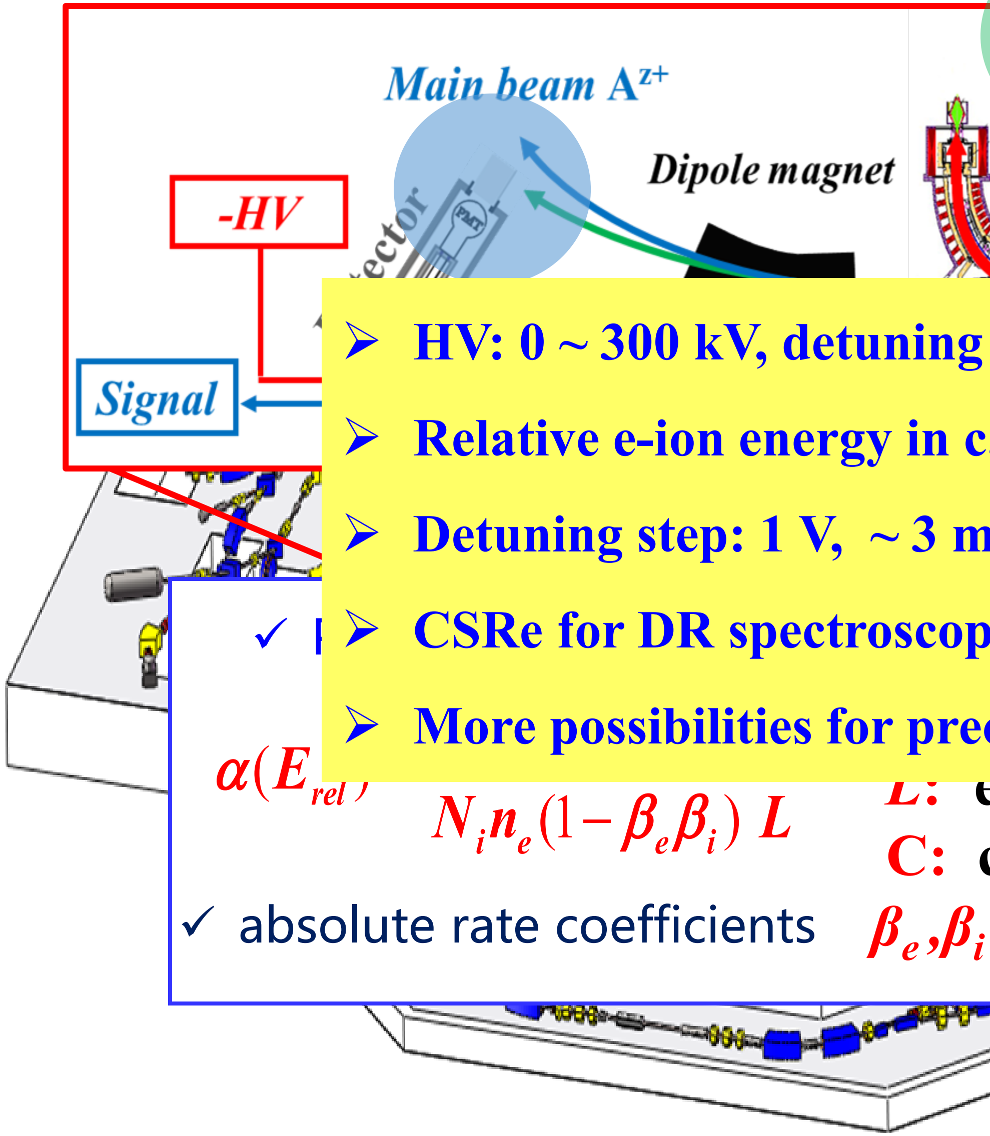
- ✓ Precise resonances

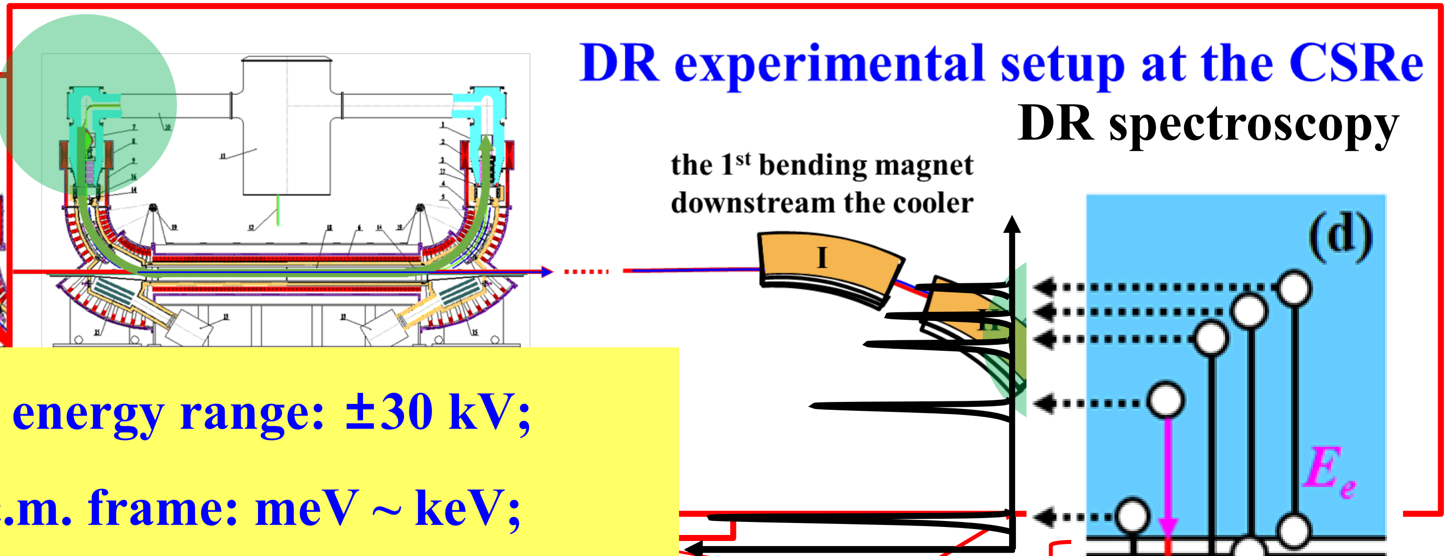
$$\alpha(E_{rel}) = \frac{R}{N_i n_e (1-\beta_e \beta_i)} \frac{C}{L}$$

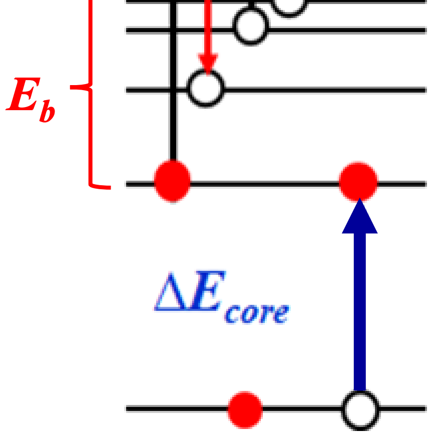
- ✓ absolute rate coefficients

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

Storage ring DR spectroscopy technique







$E_e = \Delta E_{core} - E_b$

- 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;

$\alpha(E_{rel})$ ... $N_i n_e(1-\beta_e\beta_i)\ L$

L: effective interaction length (4.0 m)

C: circumstance of CSRm(161.0 m)

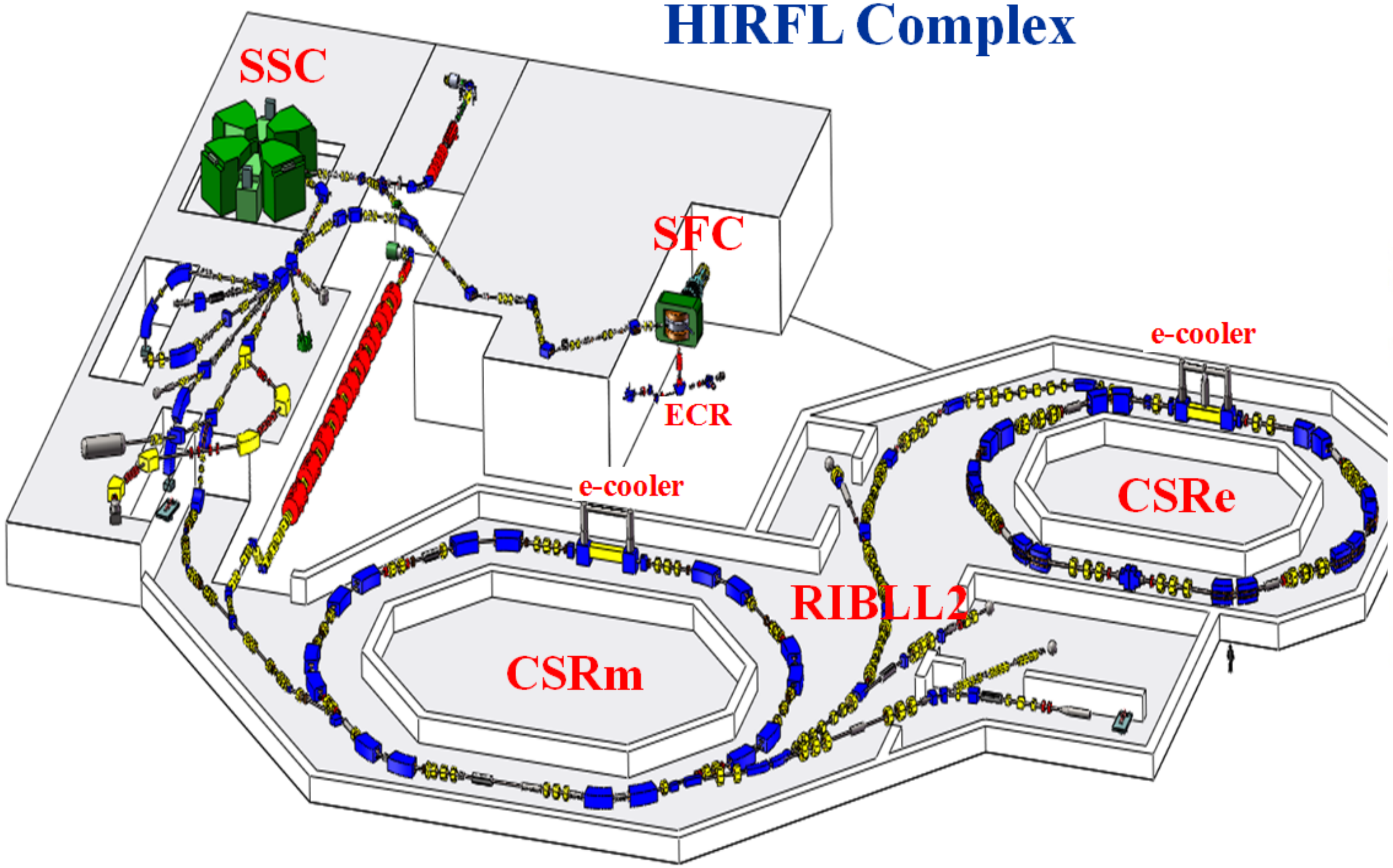
✓ absolute rate coefficients

β_e, β_i : e, ion relativistic speed

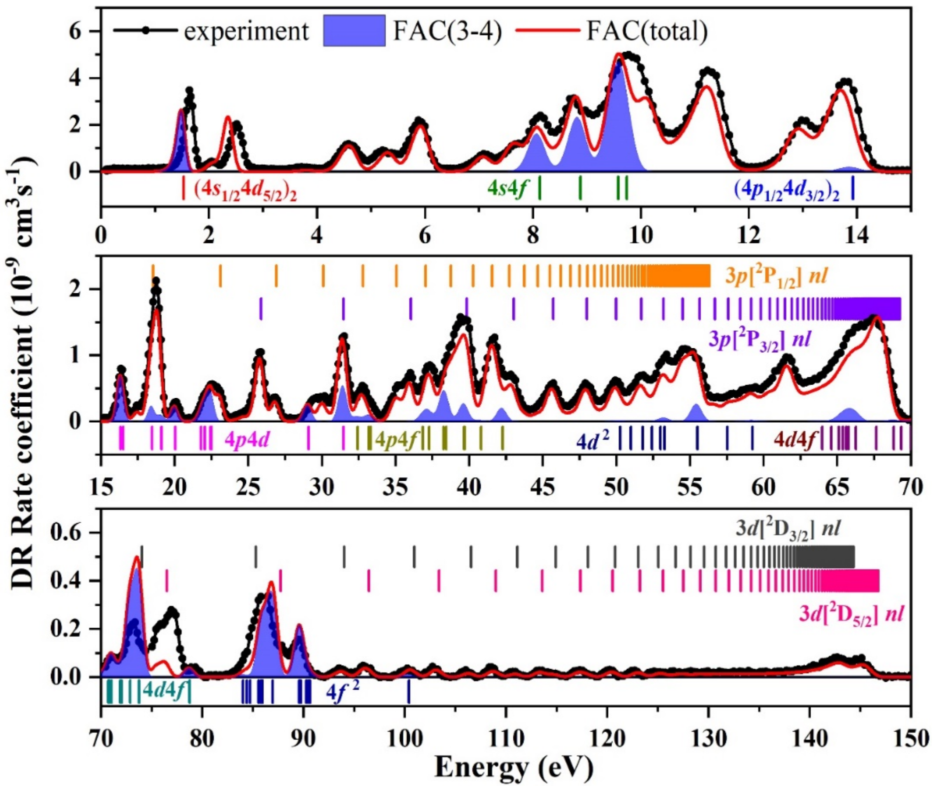
Progresses of DR spectroscopy at CSR

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

HIRFL Complex

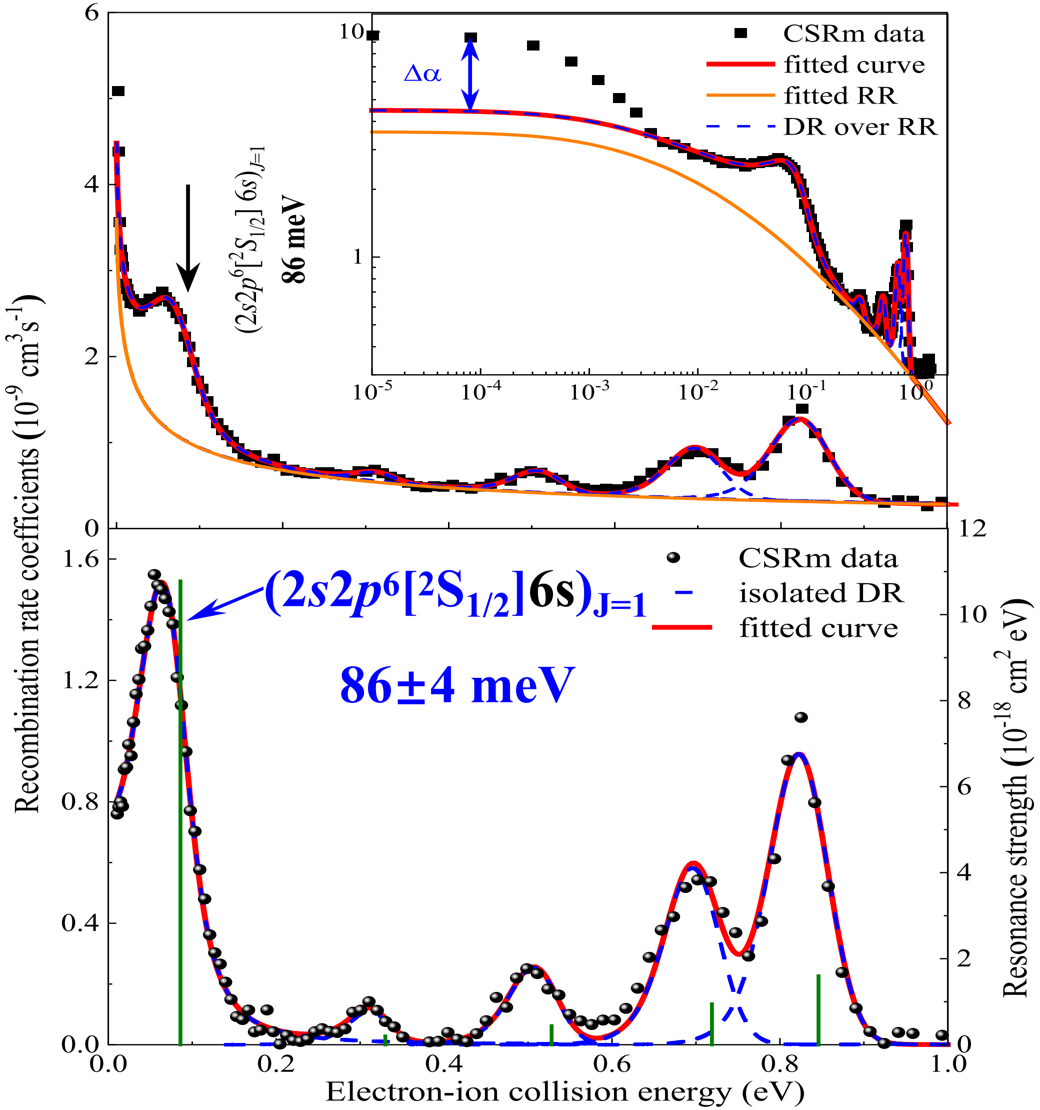


DR spectroscopy of Kr^{25+} ions at CSRe



DR spectroscopy of F-like ions: high order QED

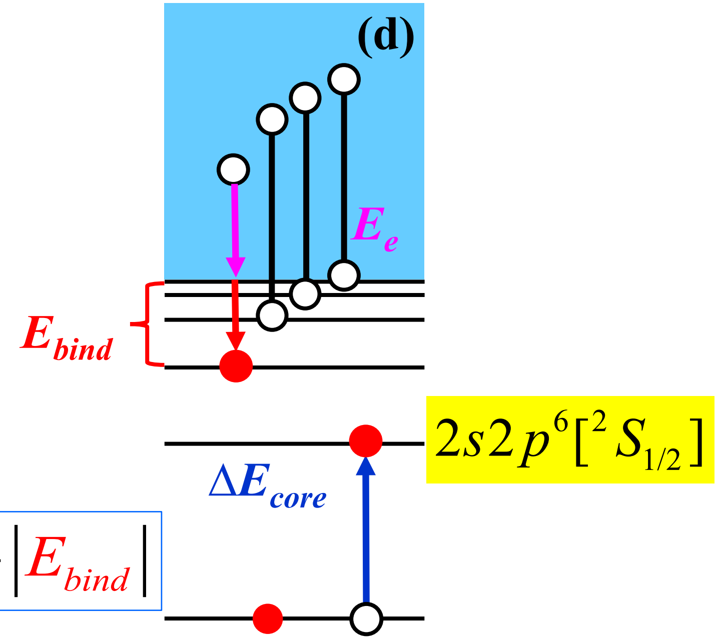
DR spectrum of Ni^{19+} in low energy



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

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

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

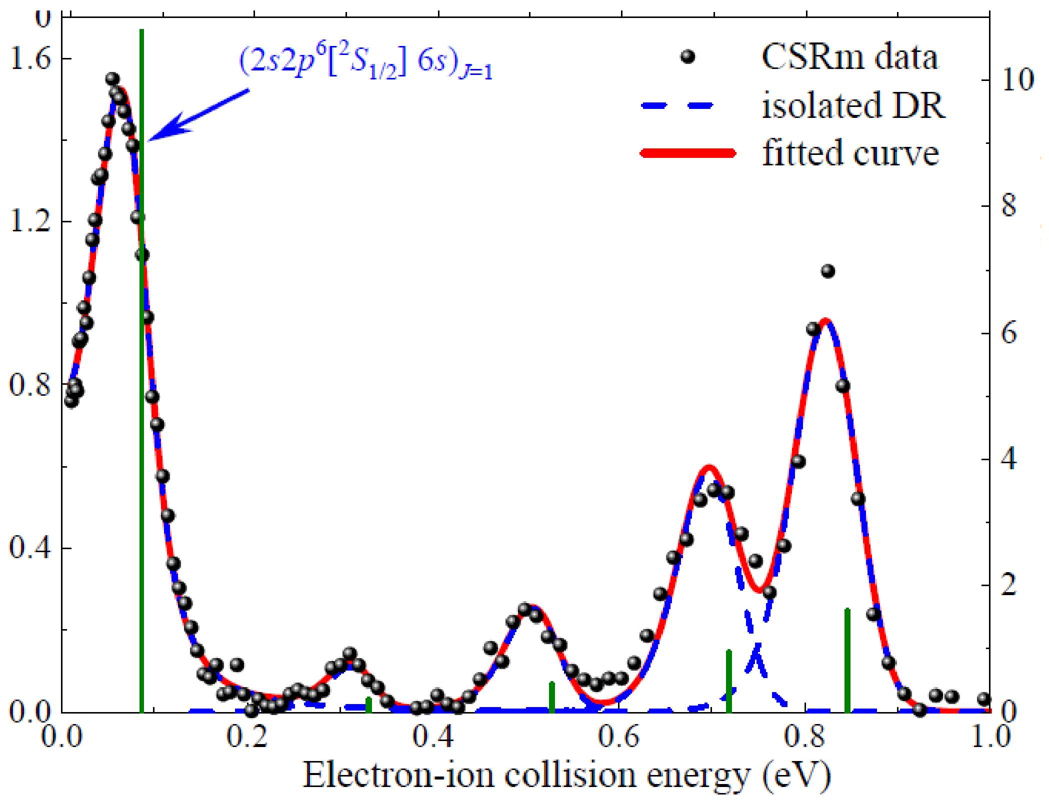


$$\Delta E_{core} = \mathrm{E_e} + |E_{bind}|$$

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).

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

ΔE_{core} of $2s^22p^5\ ^2P_{3/2} \rightarrow 2s2p^6\ ^2S_{1/2}$

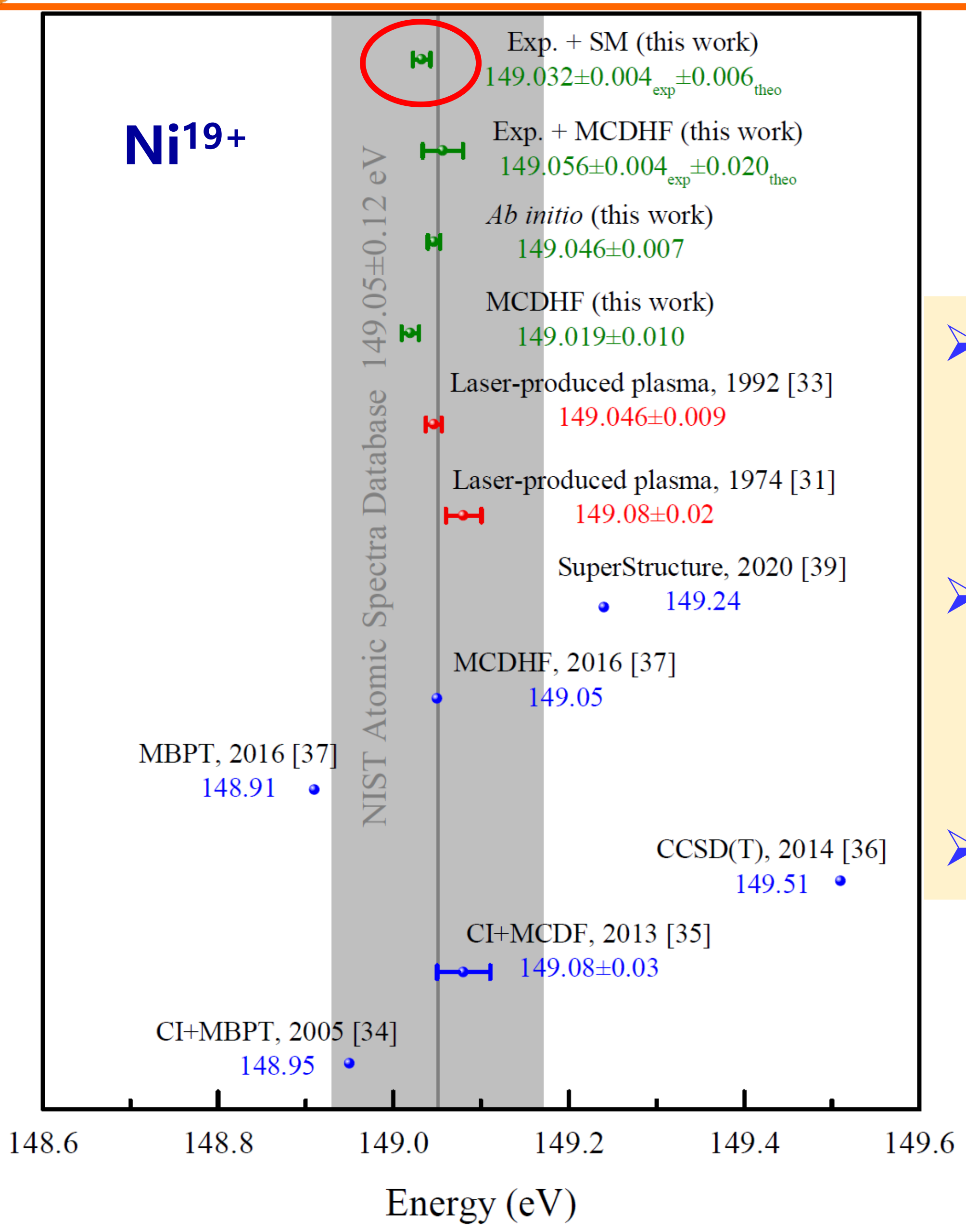
Individual contributions to transition energy of $2s^22p^5\ ^2P_{3/2} \rightarrow 2s2p^6\ ^2S_{1/2}$ in Ni^{19+} ion (in eV). *ab initio* calculations

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: $149.032 \pm 0.004_{exp} \pm 0.006_{theo}$ 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:** **$2s^2 2p^5[^2P_{3/2}] \rightarrow 2s2p^6[^2S_{1/2}]$=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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1. DR spectroscopy at CSR:

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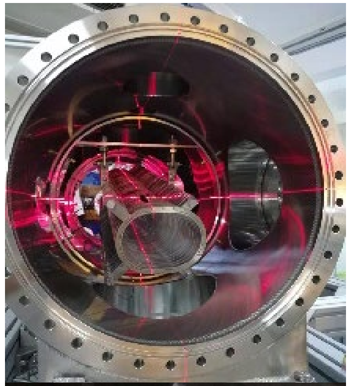
— Fully differential cross sections

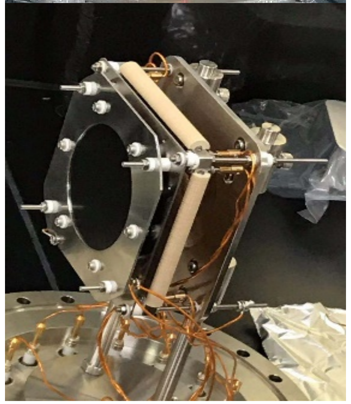
— High resolution, Q-value spectroscopy

High resolution reaction microscope

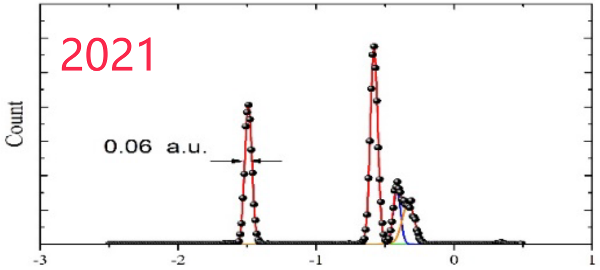
Study of Charge exchange reactions

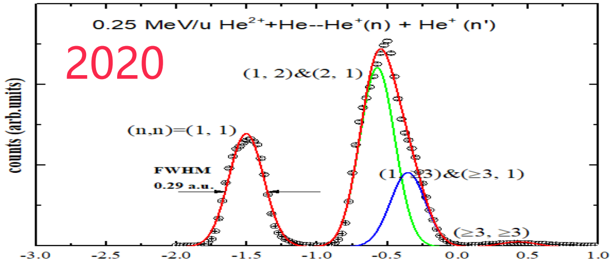
Experiments have been performed for State resolved charge exchange processes in ion-atom collision

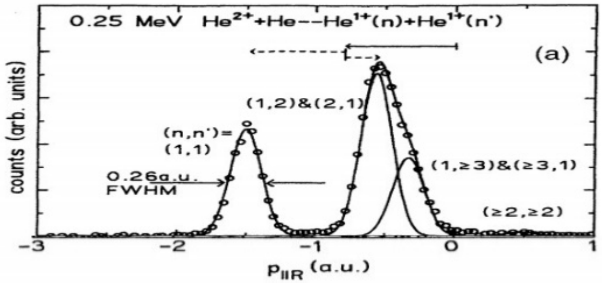




Momentum resolution
0.06a.u.







Benchmark measurements of charge exchange

nℓ-resolved Charge Exchange Cross Sections

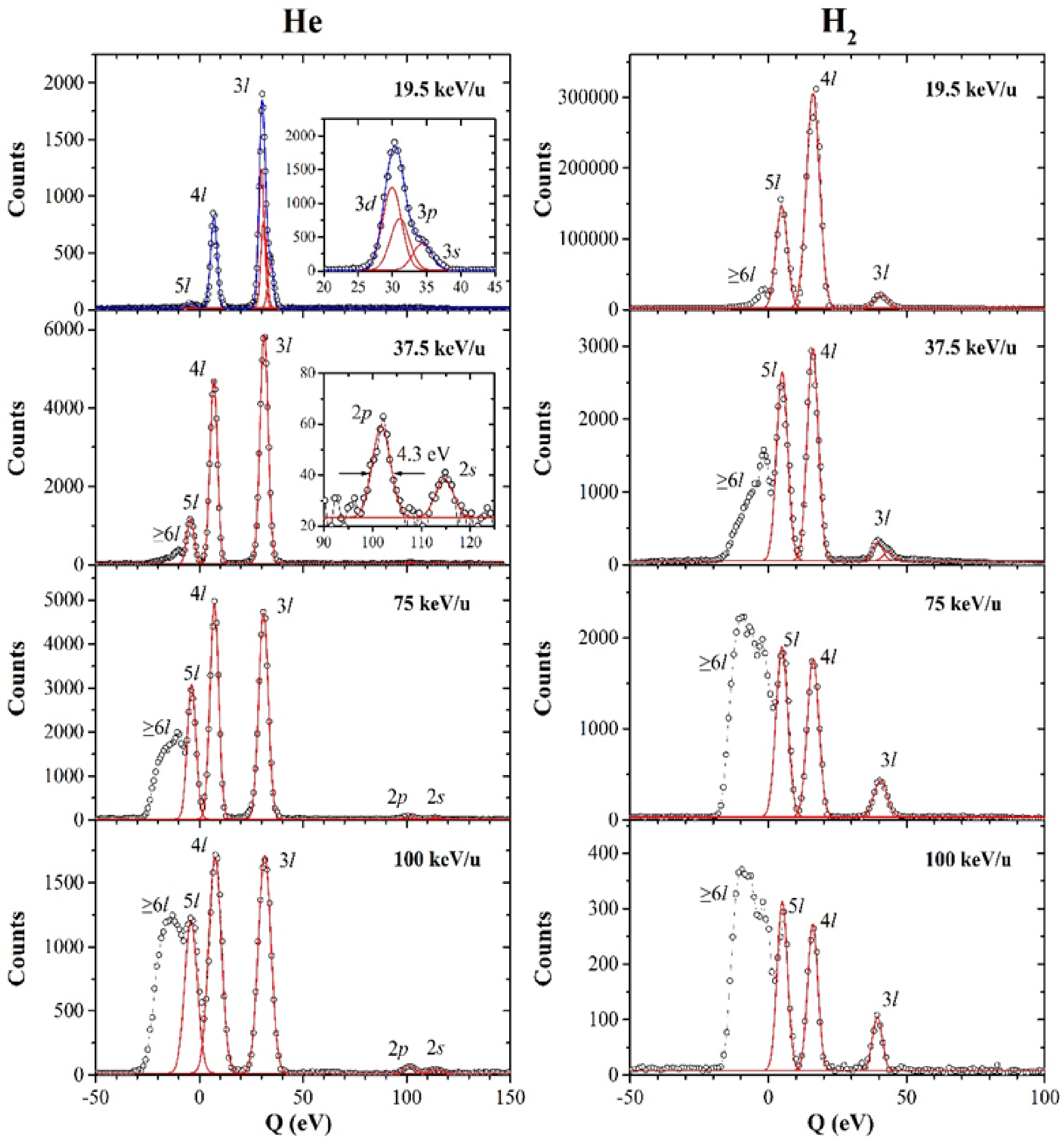
19.5, 37.5, 75, 100 keV/u

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

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

- **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.**



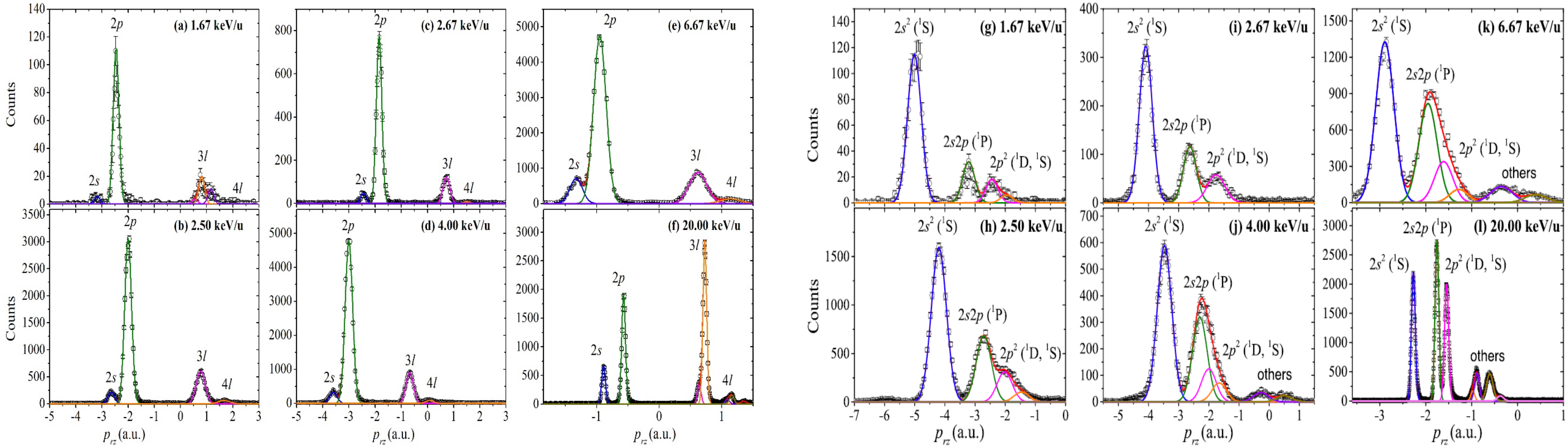
T. Cao *et al.*, ***Astrophys. J. Suppl. Series,*** 266, 20 (2023)

Benchmark measurements of charge exchange

nℓ-resolved Cross Sections of Single and Double Charge Exchange Processes

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

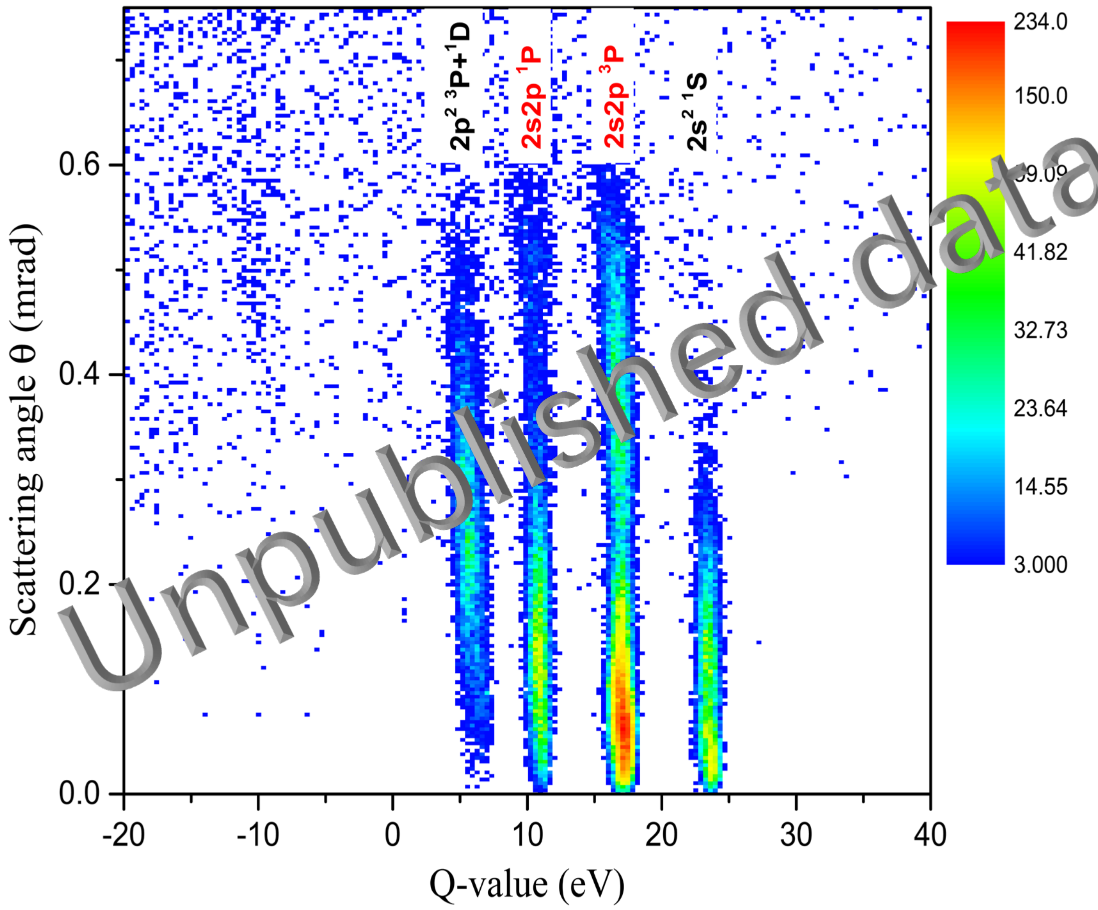
DC $C^{4+}(1s^2) + He \rightarrow C^{2+}(1s^2 nln'l') + He^{2+}$



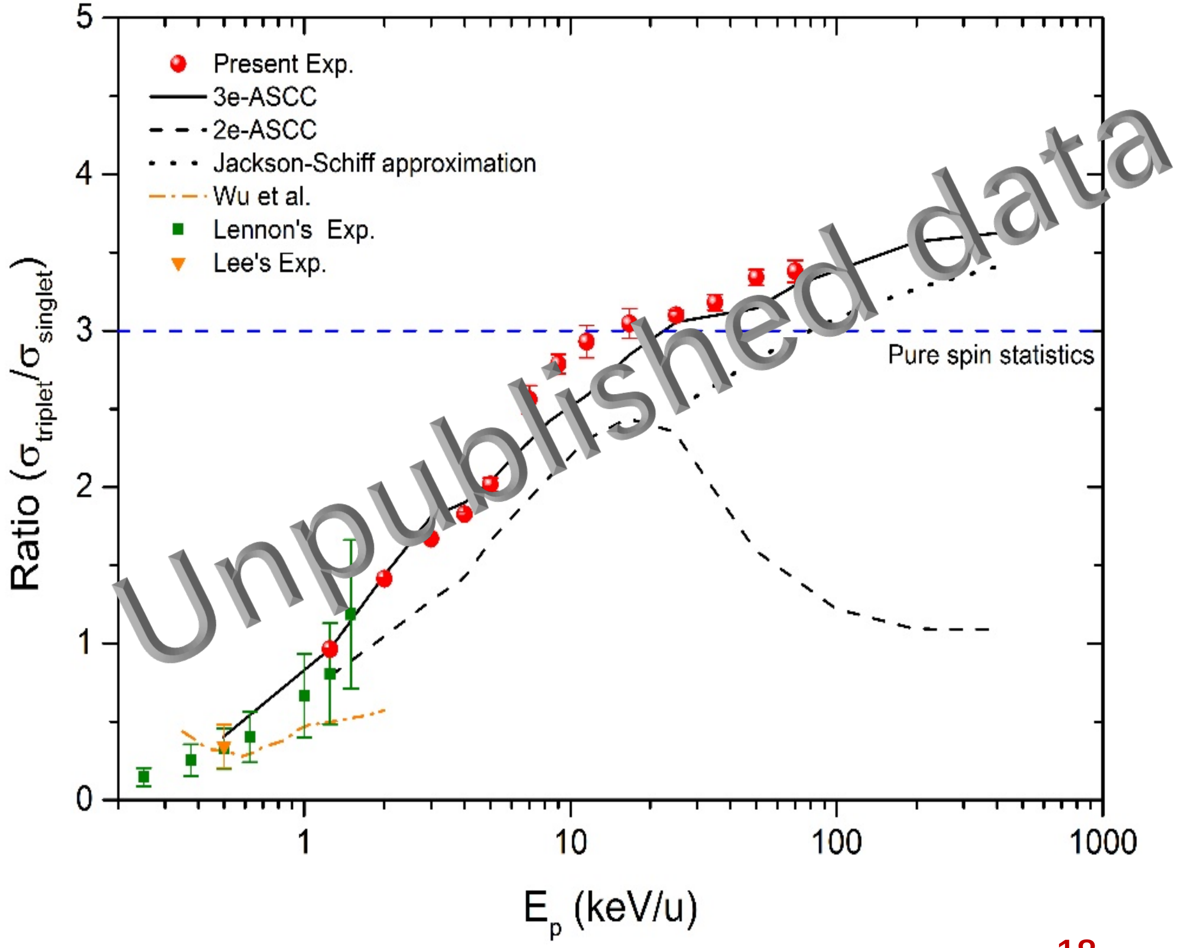
D. L. Guo *et al.*, ***The Astrophysical Journal***, 941, 31 (2022)

Breakdown of Spin Statistics in Ion-atom Charge Exchange Collisions

Correlation map of Q-value versus projectile scattering angle for single electron capture in C^{3+} + He at 7 keV/u impact energy.

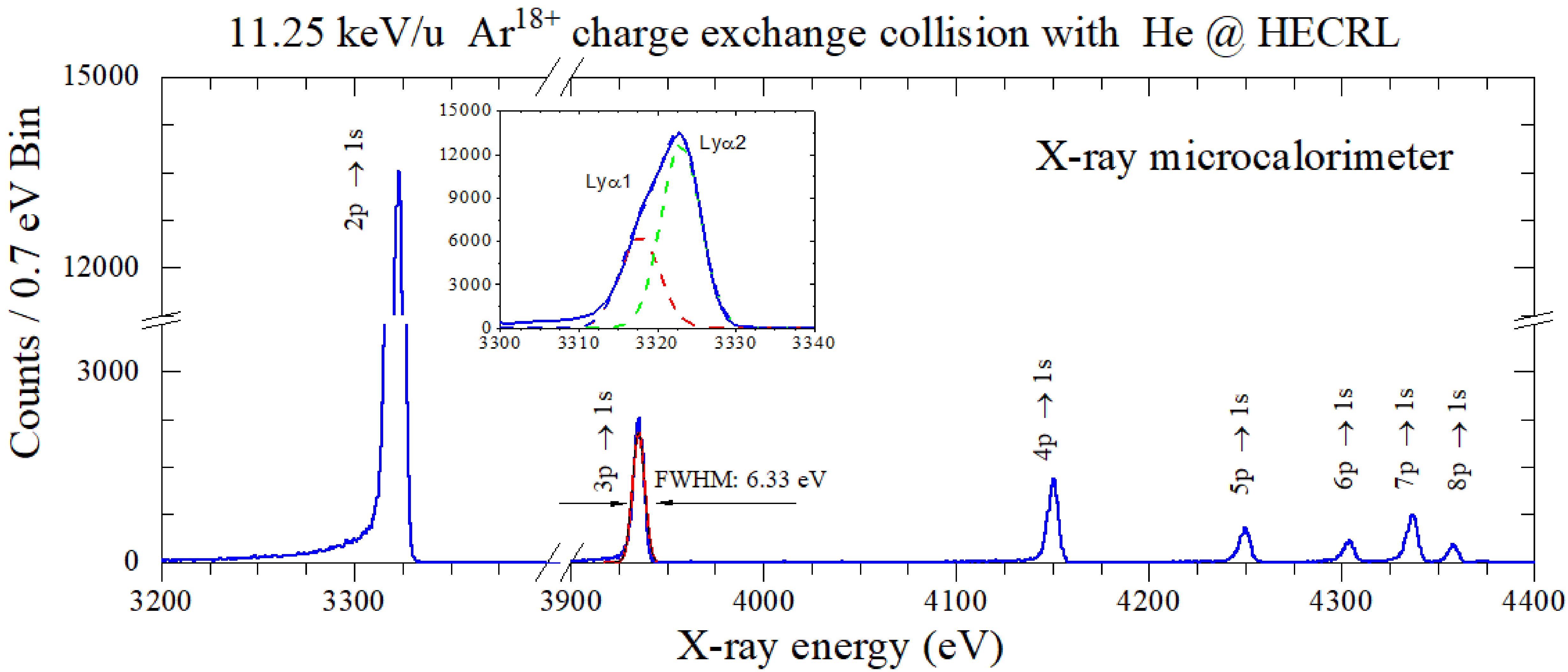


The ratios R of triplet to singlet states for SEC into $1s^22s2p\ ^{1,3}P$ as function of impact energy.



Submission to PRL

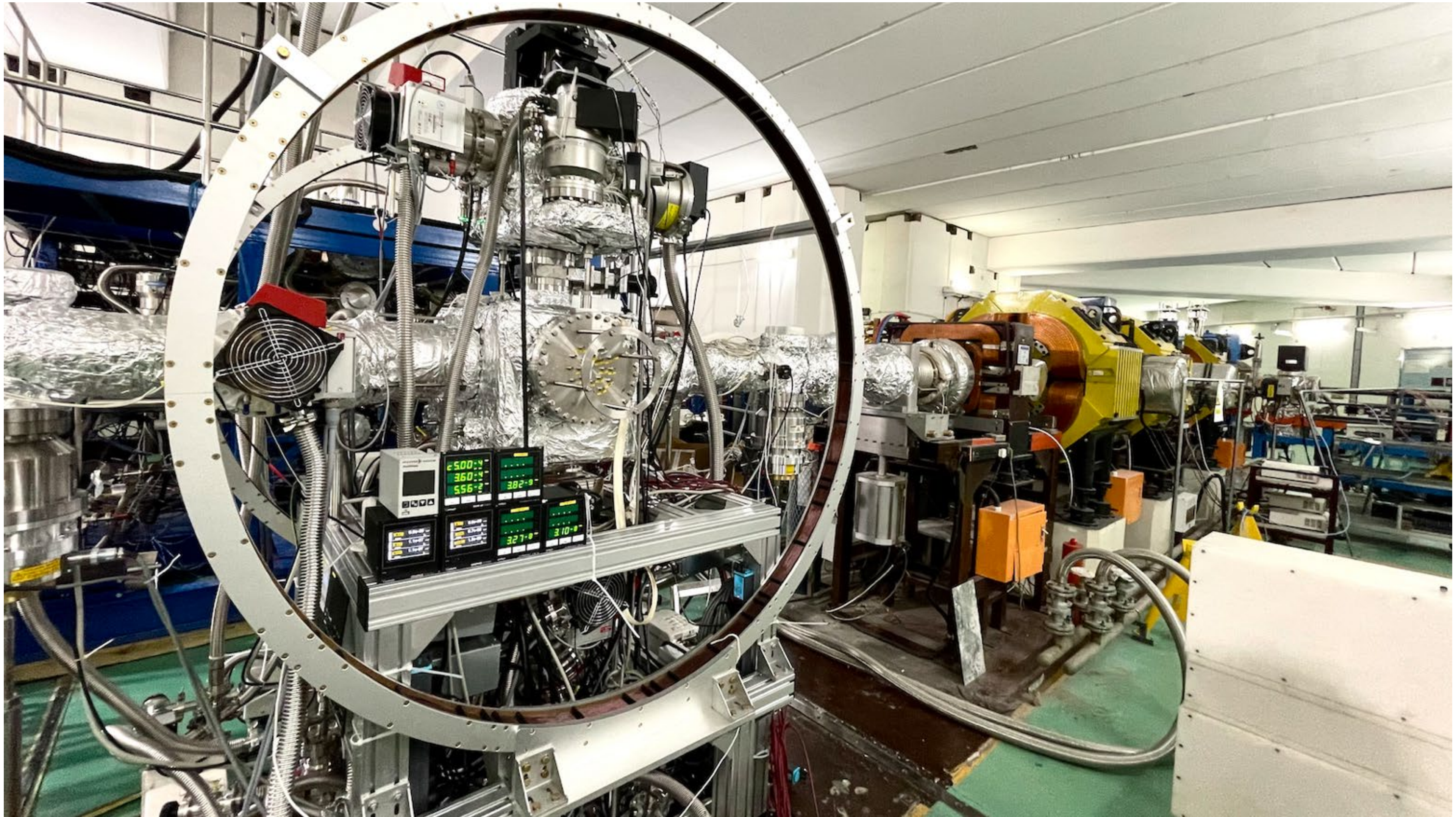
High precision X-ray spectroscopy of H-like ions



In collaboration with ShanghaiTech University, Dr S. Zhang

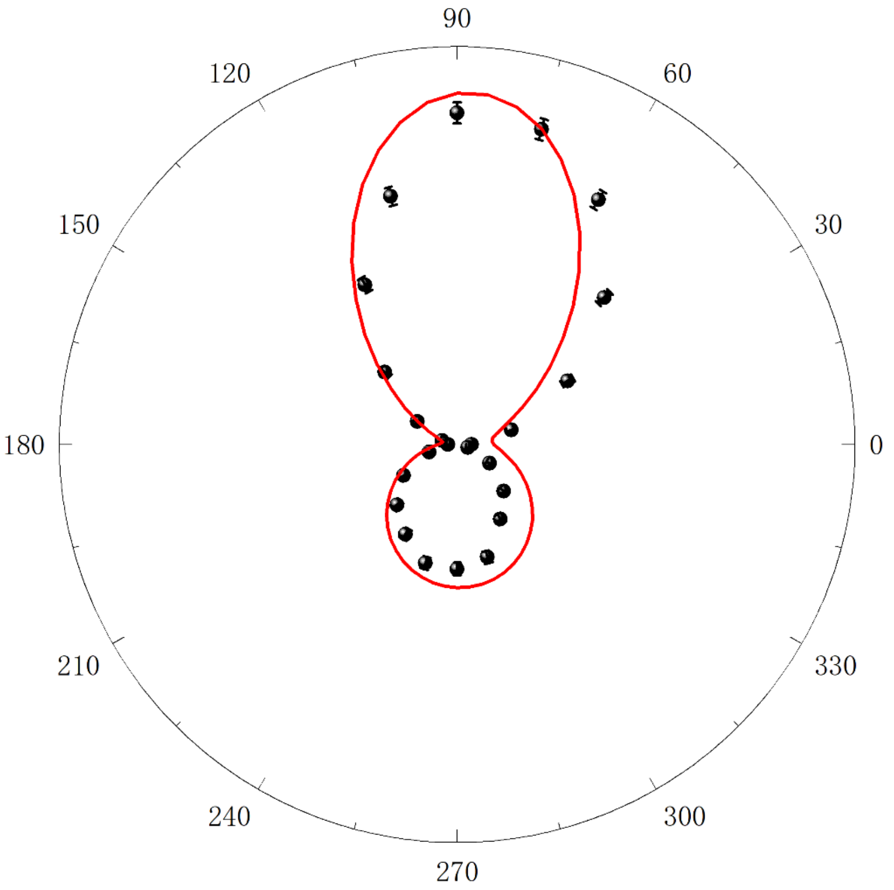
Q-value spectroscopy: electron capture + reaction microscope@ storage Ring

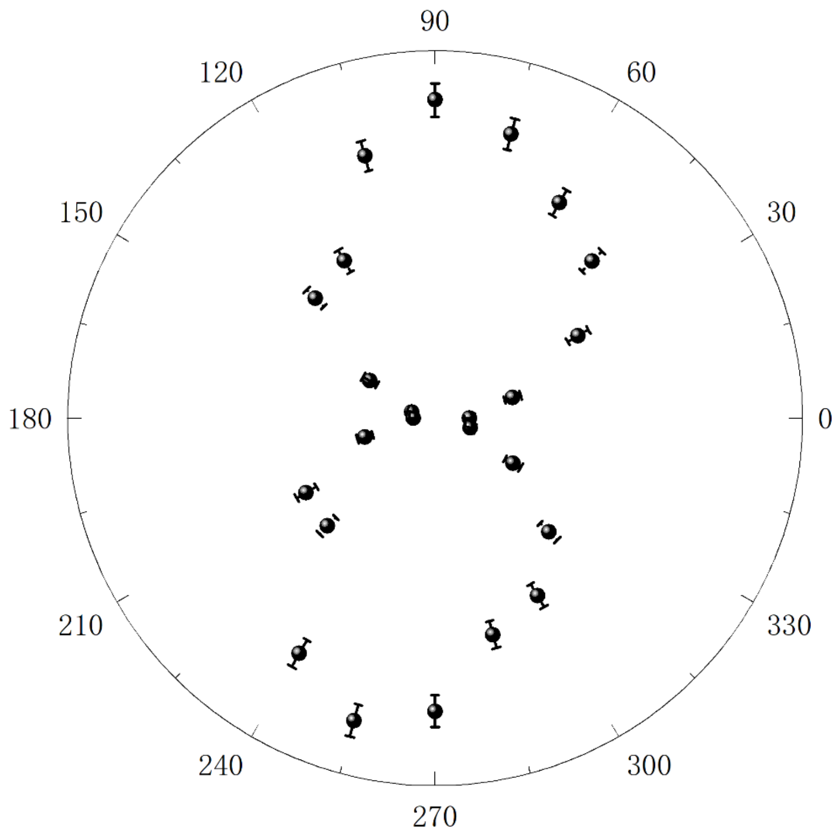
Reaction microscope Installed at CSRe internal target, commissioning with Fe^{26+} ions



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

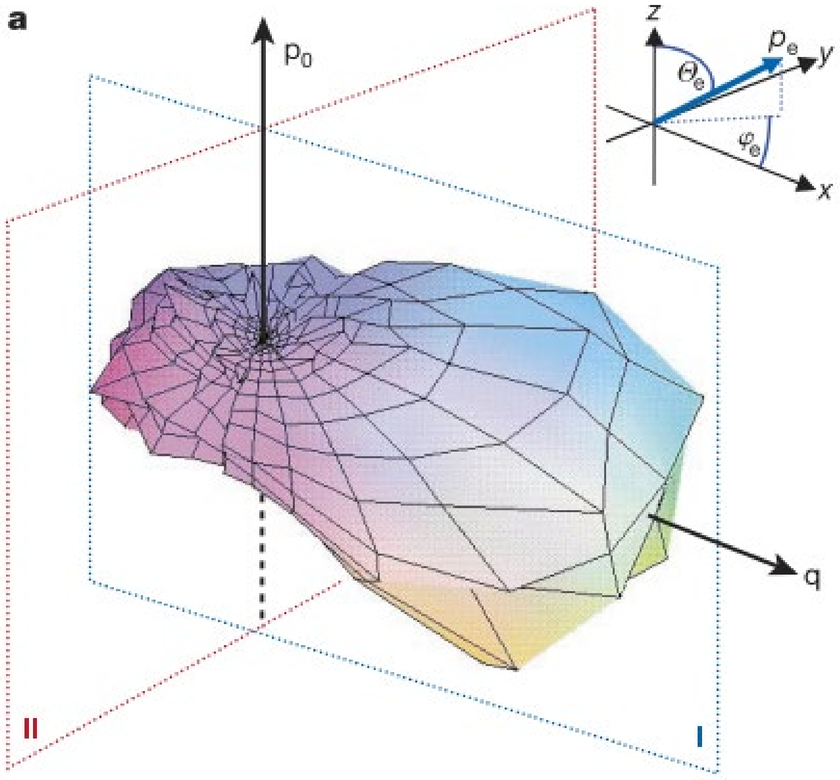
FDCS in polar coordinate: $q = 0.75 \pm 0.15\ a.u.$ $Ee = 3 \pm 0.5\ eV$, Polar presentation

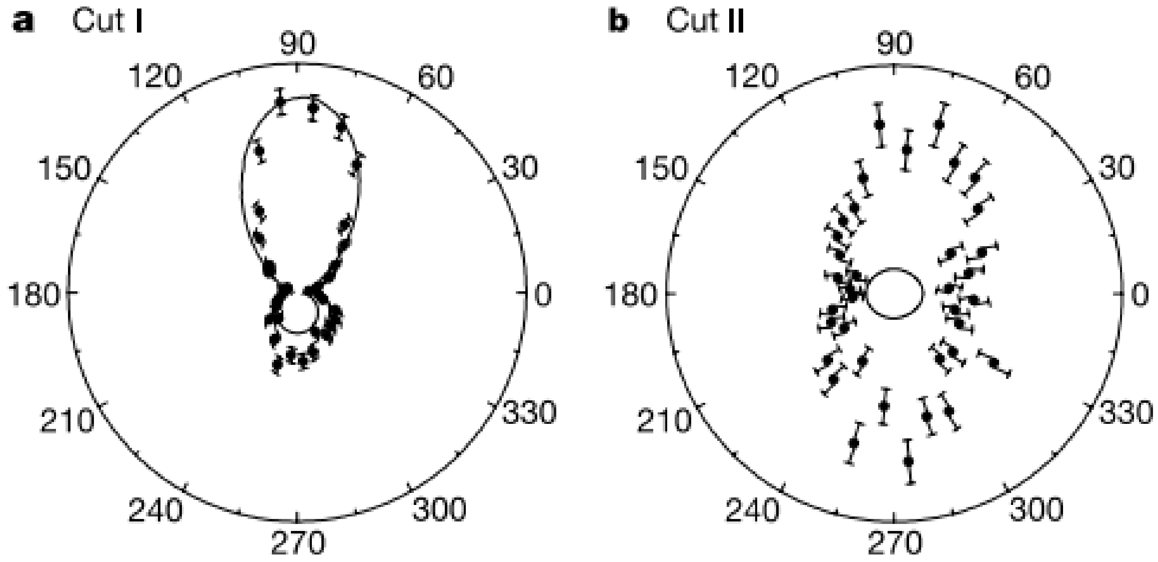




120 MeV/u Fe^{26+} on He, single ionization

The puzzle: theory @ experiments





$q = 0.75 a.u.$

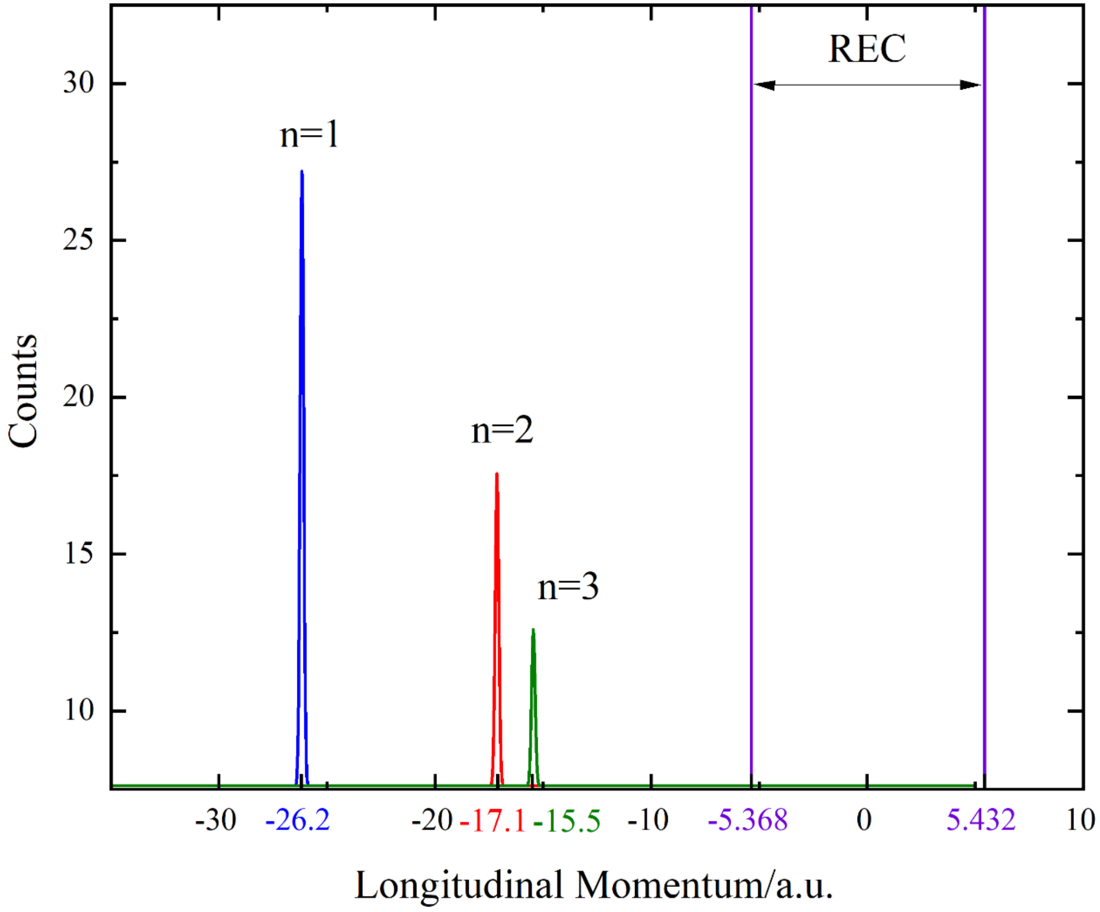
$Ee = 6.5\ eV$

M. Schulz, R. Moshammer, D. Fischer, H. Kollmus, D.H. Madison, S. Jones, and J.Ullrich,

Nature 422, 48 (2003).

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:

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

REC:

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

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

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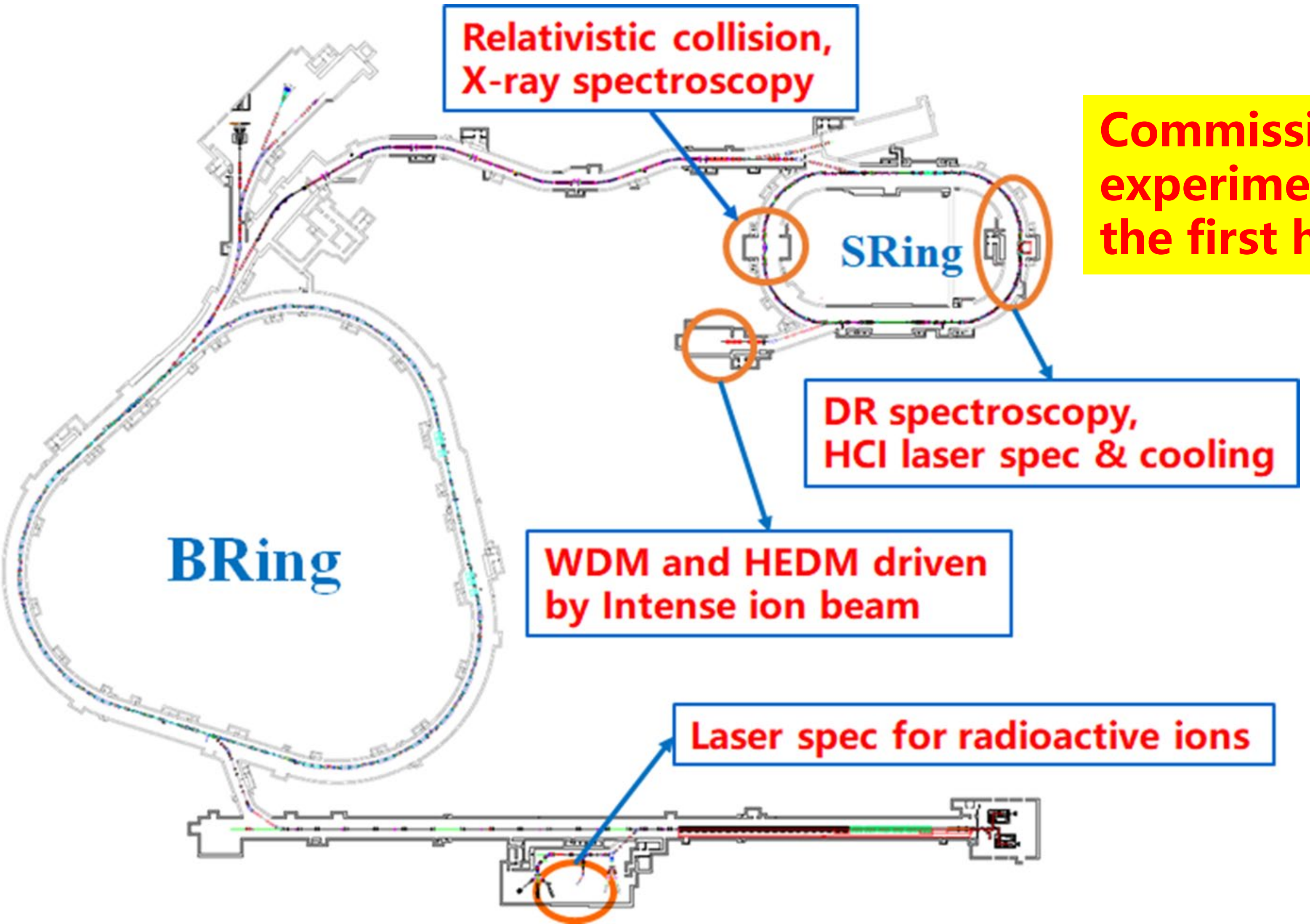
Atomic Physics of HCIs @HIAF

High Intensity heavy ion Accelerator Facility (HIAF)



Commissioning experiments will start in the first half of 2026

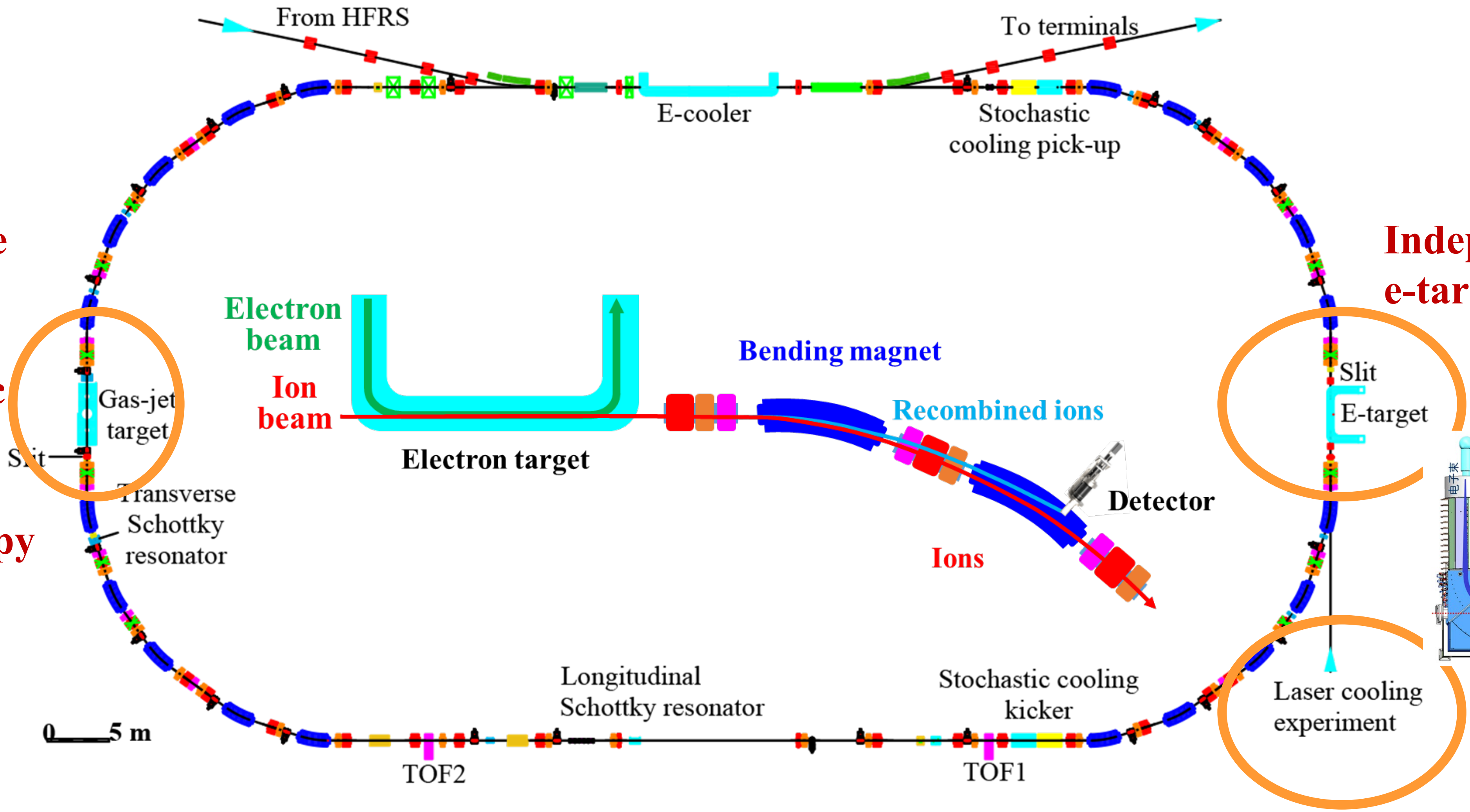
Atomic Physics of HCIs @HIAF

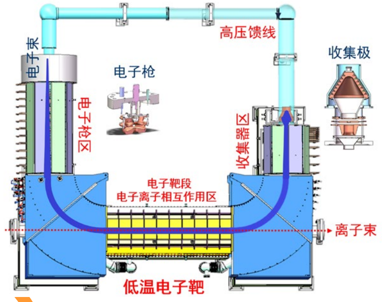
A closer look at SRing of HIAF

Multi-purpose internal-gas target area:

- Relativistic collision
- X-ray spectroscopy
- Nuclear reactions

Independent e-target





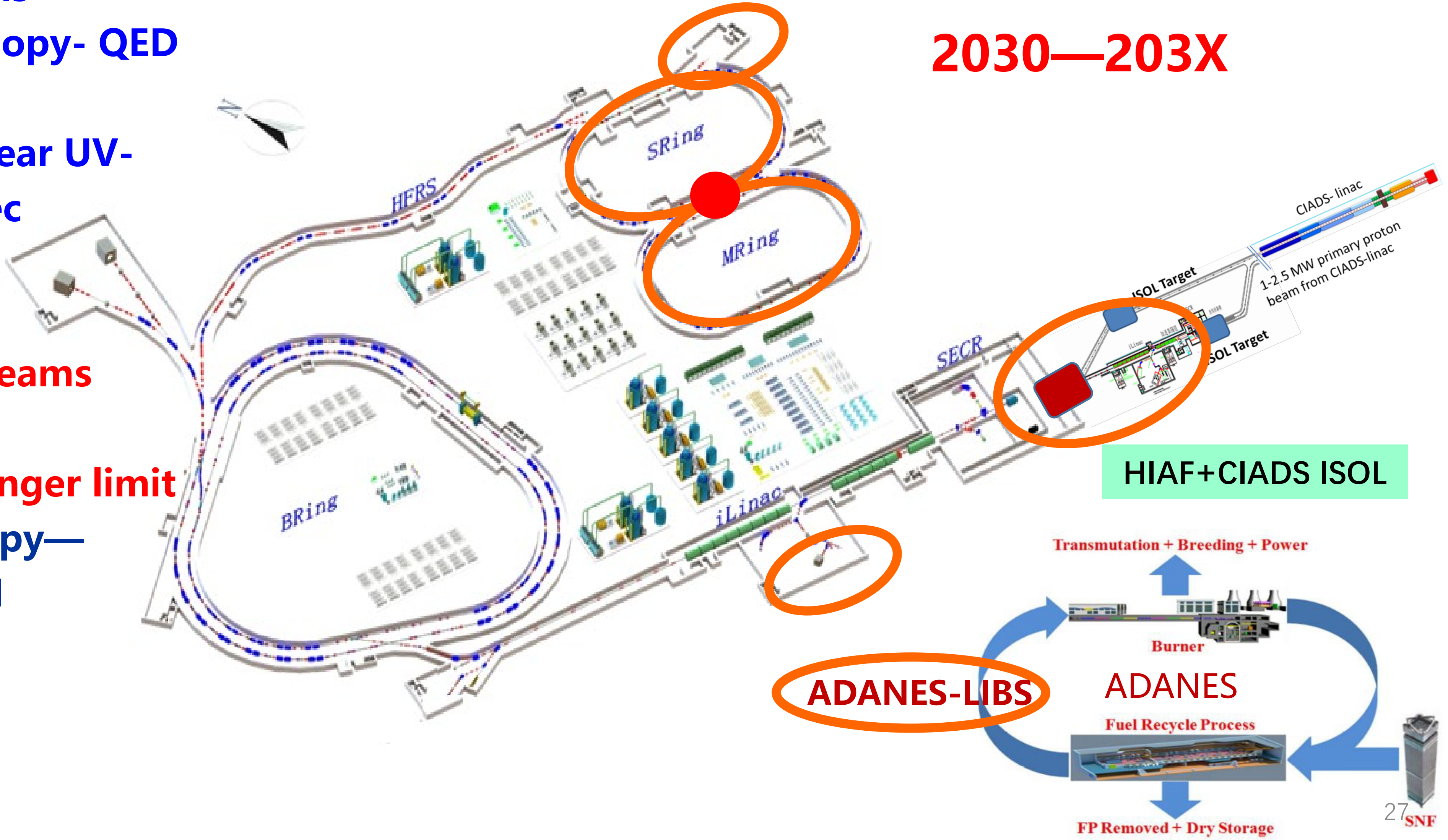
Spectrometer Ring

Atomic Physics of HCIs @HIAF, future

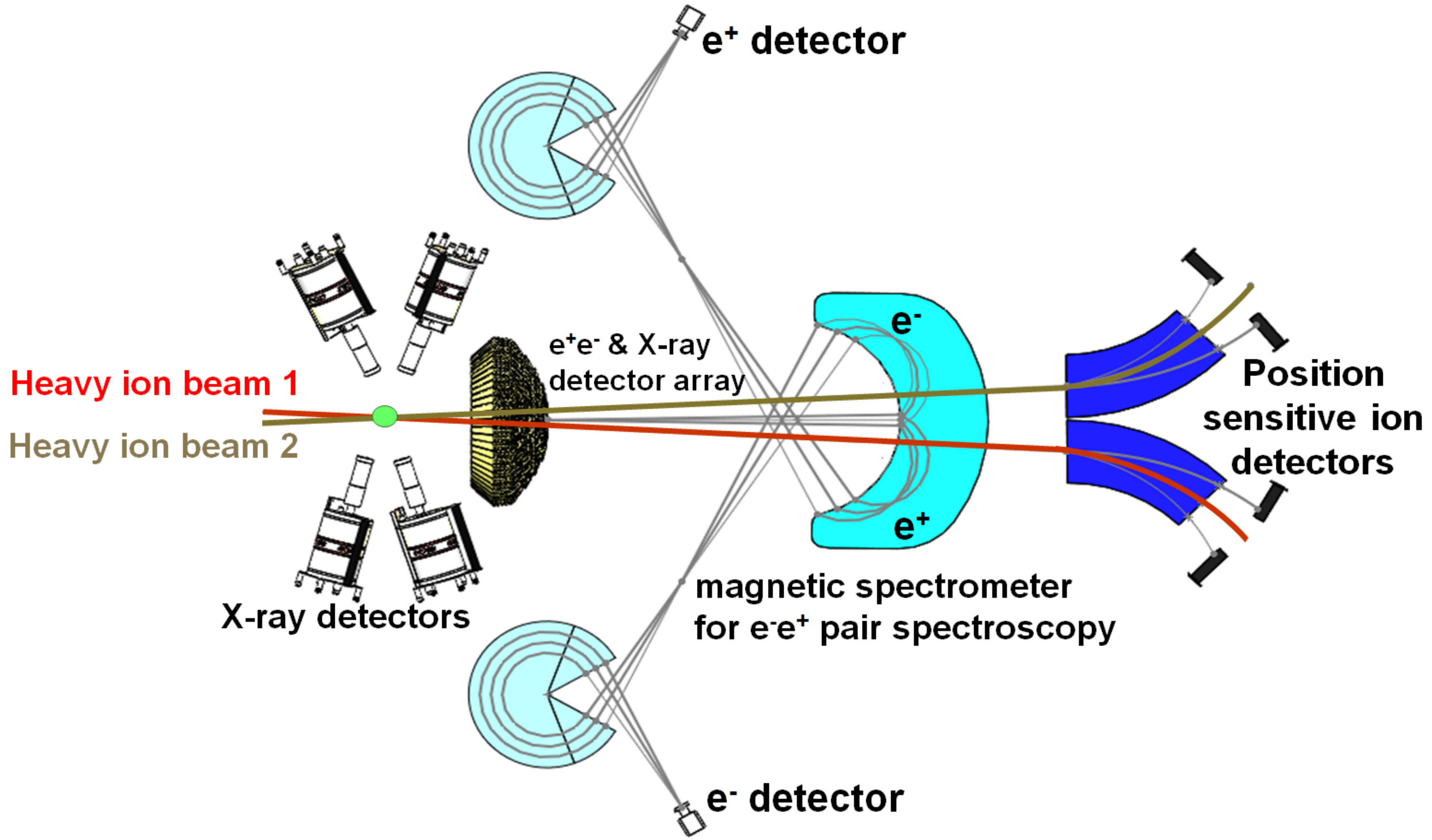
Relativistic collisions
Precision spectroscopy- QED in strong EM field
Application in nuclear UV-laser cooling & spec

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

2030—203X



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.

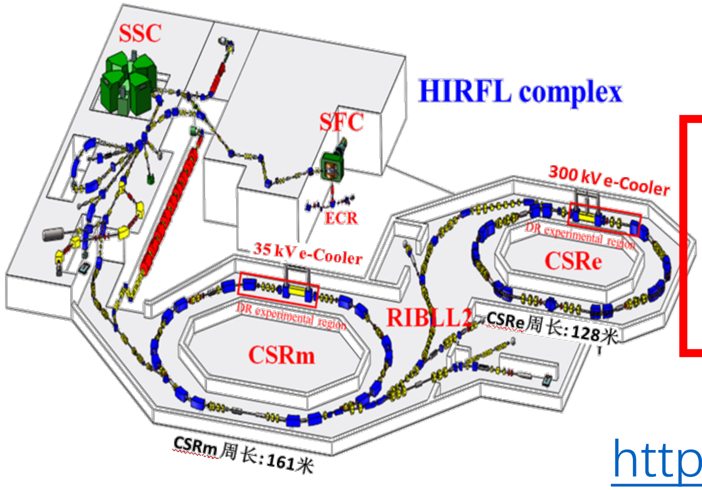
APEX Collaborations

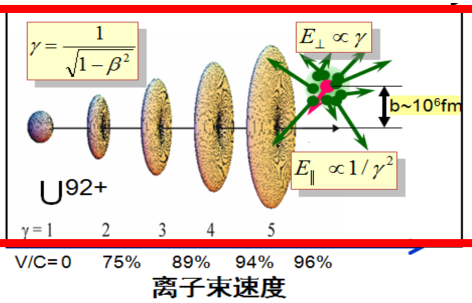
构建基于大科学装置HIRFL和HIAF的
极端条件原子过程研究国际合作组

APEX

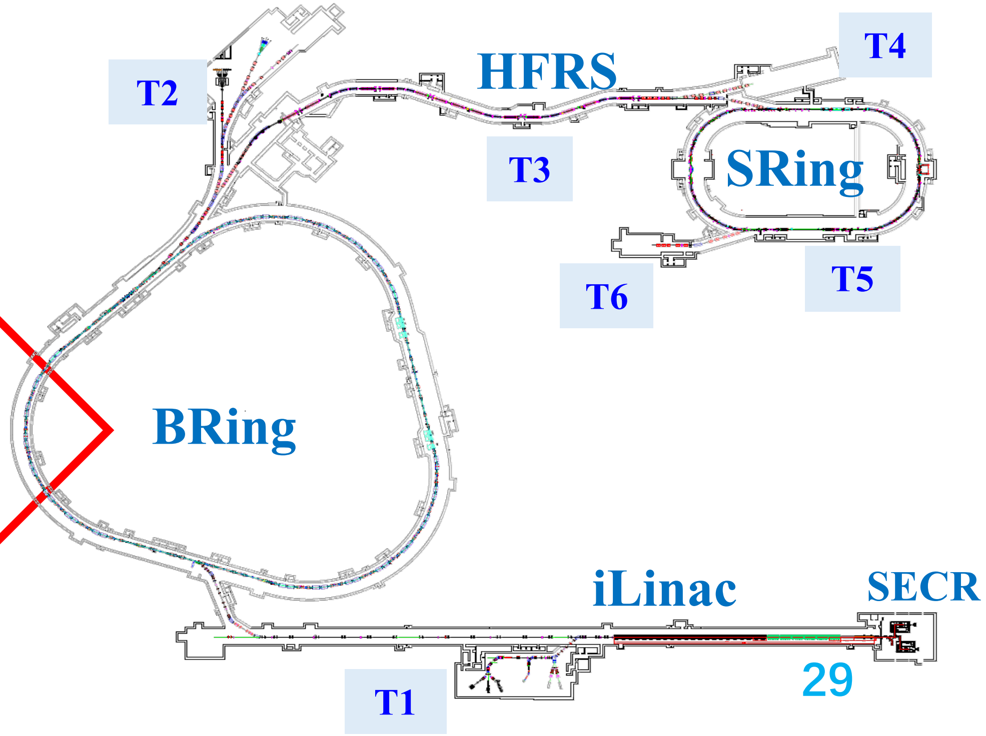
Collaborations on **A**tomic **P**rocesses at **Ex**tremes at HIRFL & HIAF

Collision dynamics + Spectroscopy+ HEDP + Instrumentation + Theory





https://apex.impcas.ac.cn/



Some considerations for polarized beams

- Polarization of ion beams:

  (1) Polarization of nuclear, bare ions

  (2) Polarization of non-bare heavy ions ??

- Experiments employing Polarized beam:

  Polarized electron beam

  Twisted electron beam: V A Zaytsev, et al. Journal of Physics: Conference Series 1412 (2020) 052013

  V A Zaytsev, et al. PHYSICAL REVIEW A 95, 012702 (2017)

  DR spectroscopy, APV

- Polarized atomic target, e.g. atomic hydrogen beam.

  X-ray spectroscopy, charge exchange processes, spin statistics

  Polarized ion beam on polarized target ??

  A. Surzhykov, et al., Proceedings of Science. PoS(STORI11)012; Th. Stöhlker, et al., Proceedings of Science, PoS(PSTP2022)028

- Double ionization of H_2 molecular target:

  Exploring in ultrashort timescale the entanglement between electron and nuclear.

Acknowledgements

Fundings:

NSFC (National Natural Science Foundation of China)
CAS (Chinese Academy of Sciences)
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

Thank you for your attention