Dielectronic Recombination spectroscopy of Na-like Kr^{25+} at the cooler storage ring CSRm

Zhongkui HUANG & DR collaboration

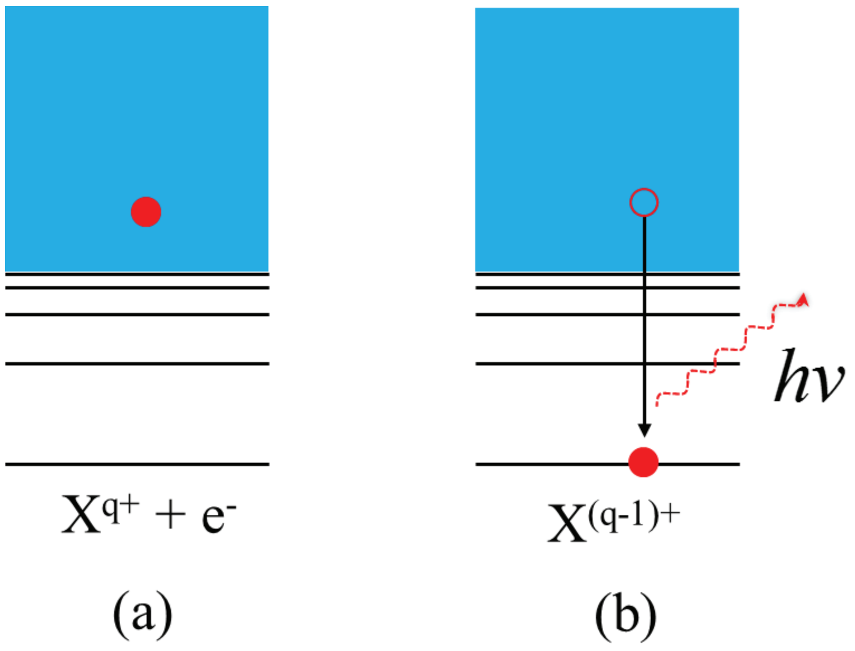
Institute of Modern Physic, Chinese Academy of Sciences

Content

1.Introduction and motivation

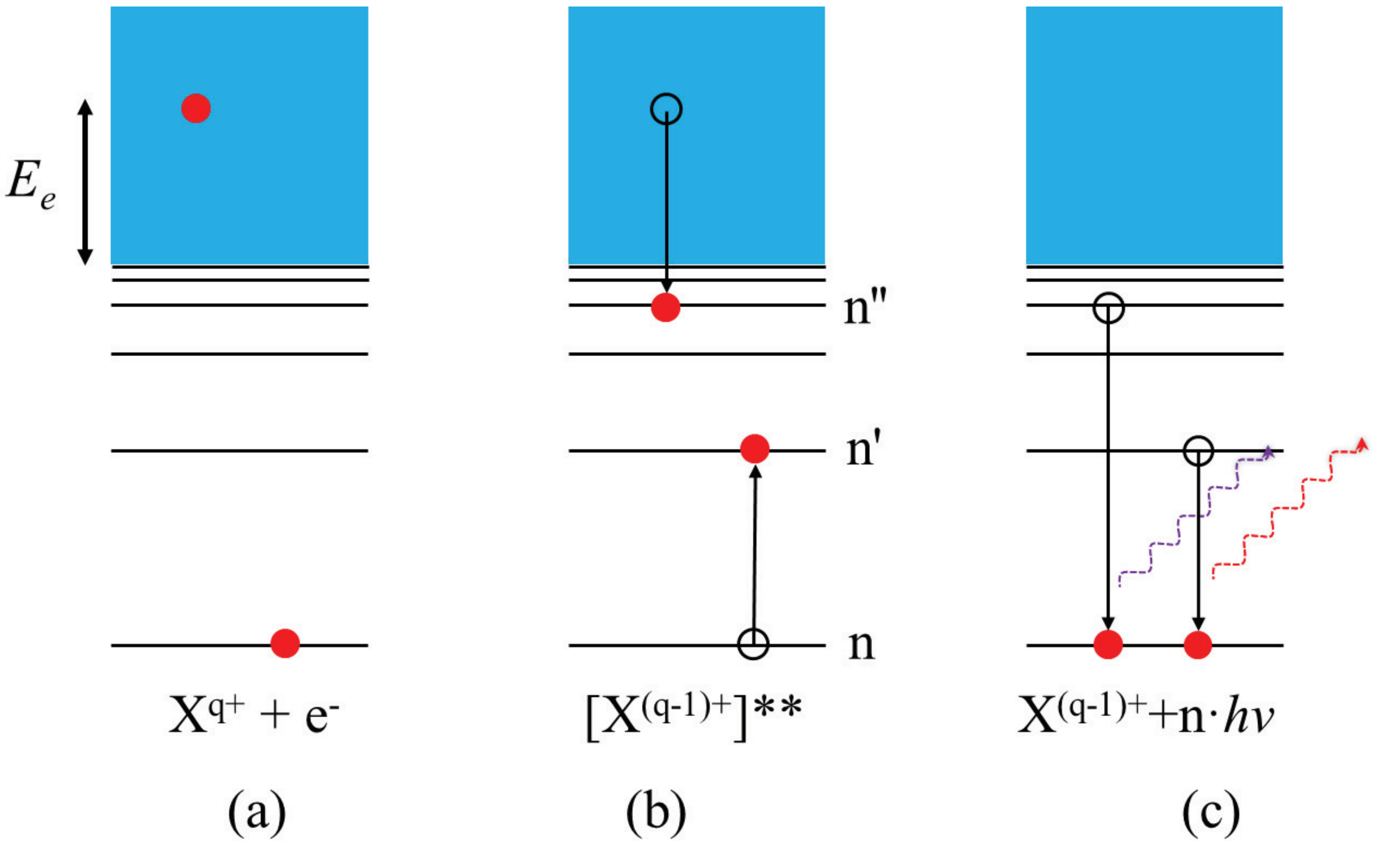
Introduction-RR and DR

Radiative Recombination(RR)



$$^{A}X^{q+} + e \longrightarrow {}^{A}X^{(q-1)+} + h\nu$$

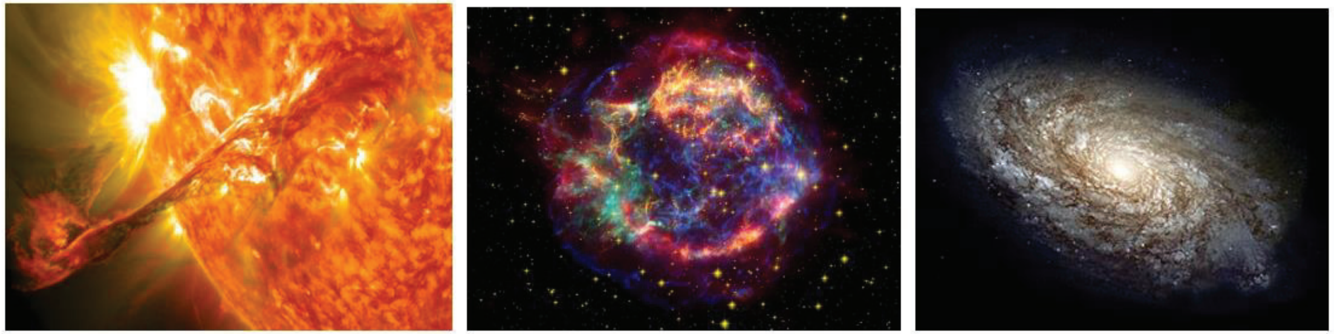
Dielectronic Recombination(DR)



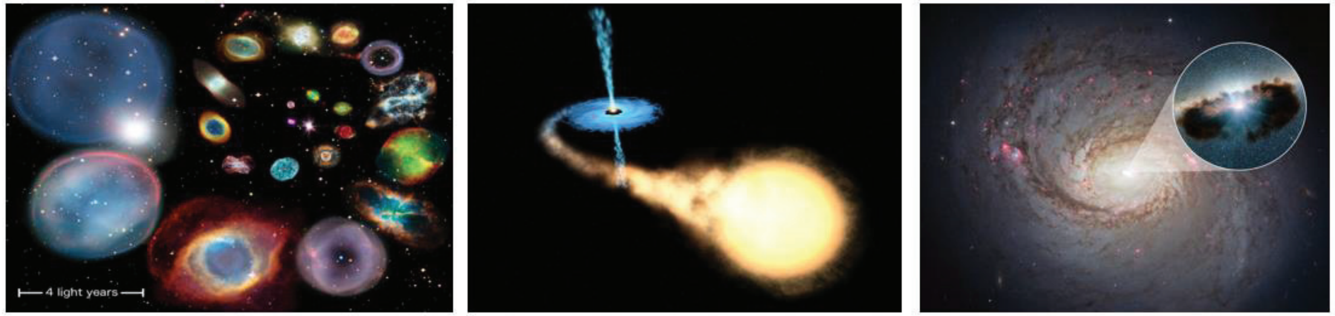
$$^{A}X^{q+} + e \longrightarrow ({}^{A}X^{(q-1)+})^{**} \longrightarrow {}^{A}X^{(q-1)+} + h\nu$$

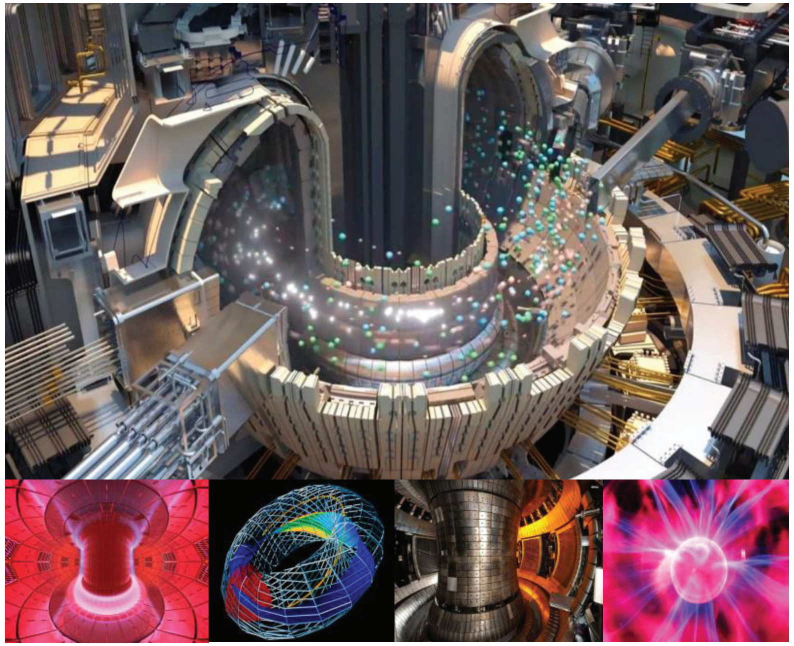
Motivation 1: astrophysical and fusion plasma

Collisionally ionized plasma formed in stars, supernova remnants, and galaxies



photoionized plasmas formed in planetary nebulae, X-ray binaries, and AGN





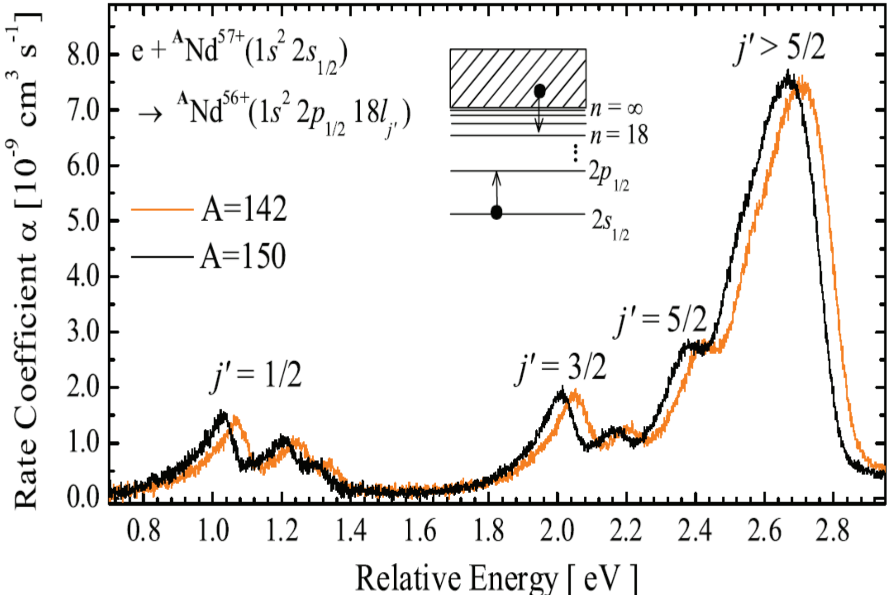
ITER

- ☐ **Diagnose status (T_e and n_e) of natural and man-made plasmas;**
- ☐ **Interpret the spectra from cosmic sources**
- ☐ **Benchmark the theory and model;**

Motivation 2: precision spectroscopy tool

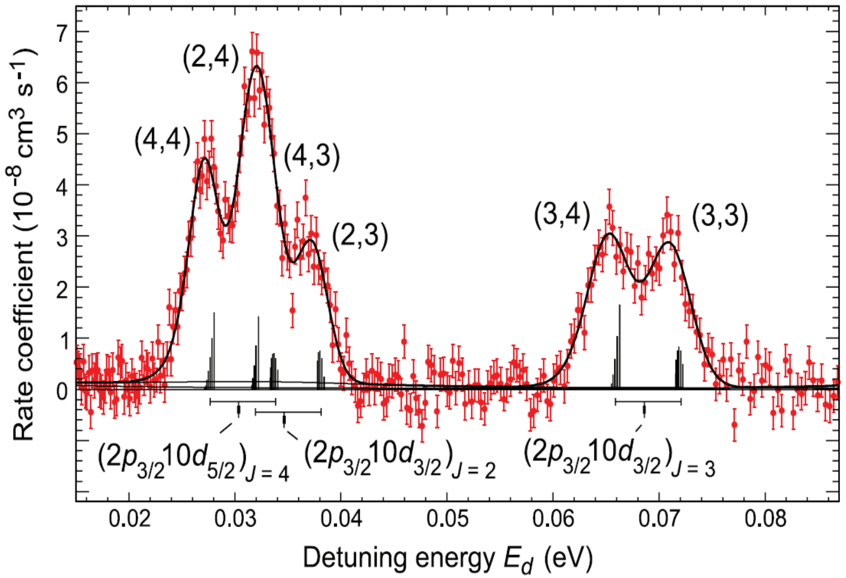
- **Test QED in strong field (*Au^{76+}, Pb^{79+}, U^{89+}*);**
- **Measure Isotope shift (*$^{142,150}Nd^{57+}$, $^{207,208}Pb^{53+}$*) and hyperfine splitting (*Sc^{18+}*);**

*Isotope shift of DR resonances in **$^{142,150}Nd^{57+}$***



*C. Brandau et al., PRL **100**, 073201(2008)*

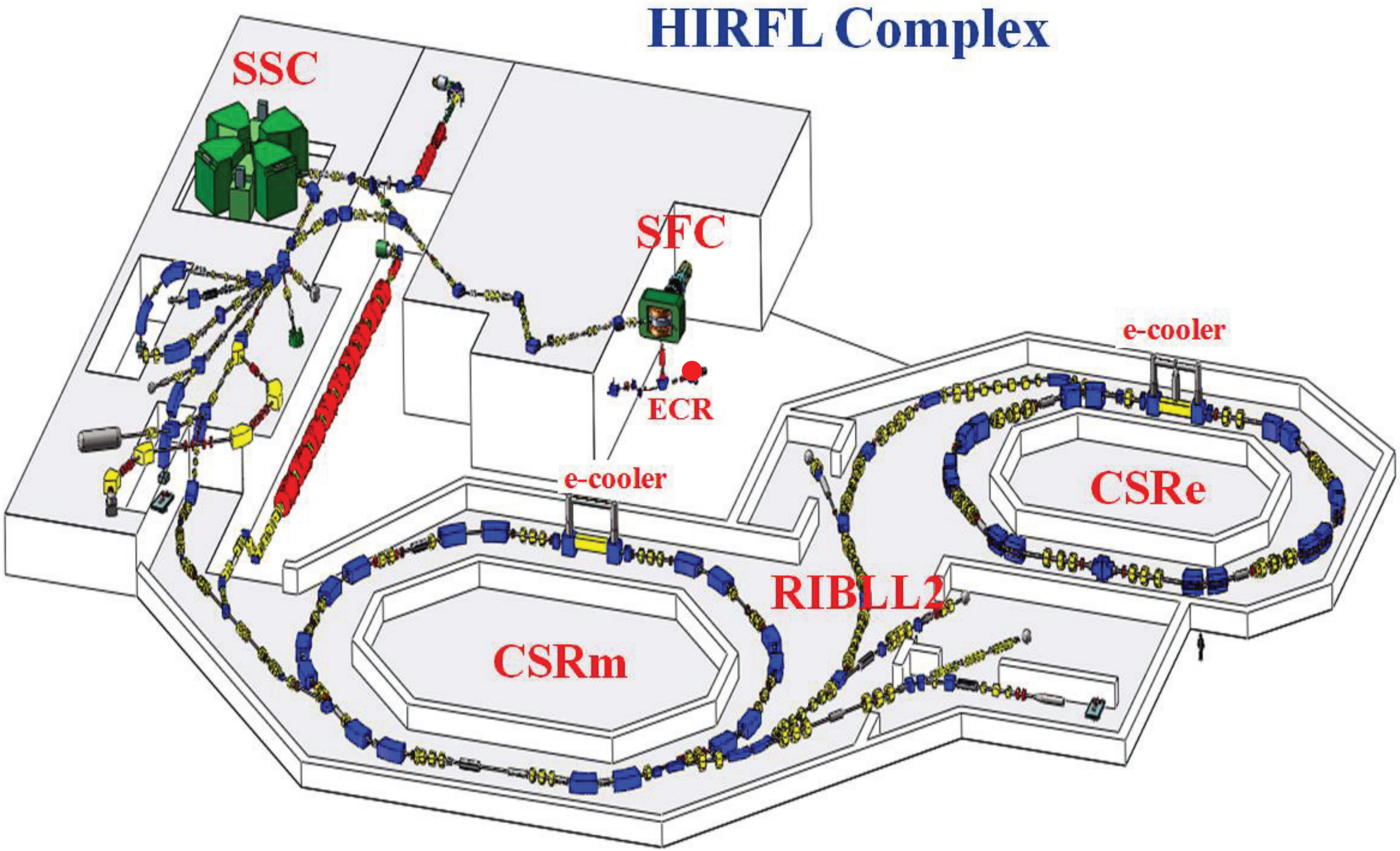
*Hyperfine splitting of DR resonances in **Sc^{18+}***



*M. Lestinsky et al., PRL **100**, 033001(2008)*

2. Experimental setup and technique

DR experimental setup at the HIRFL-CSRm



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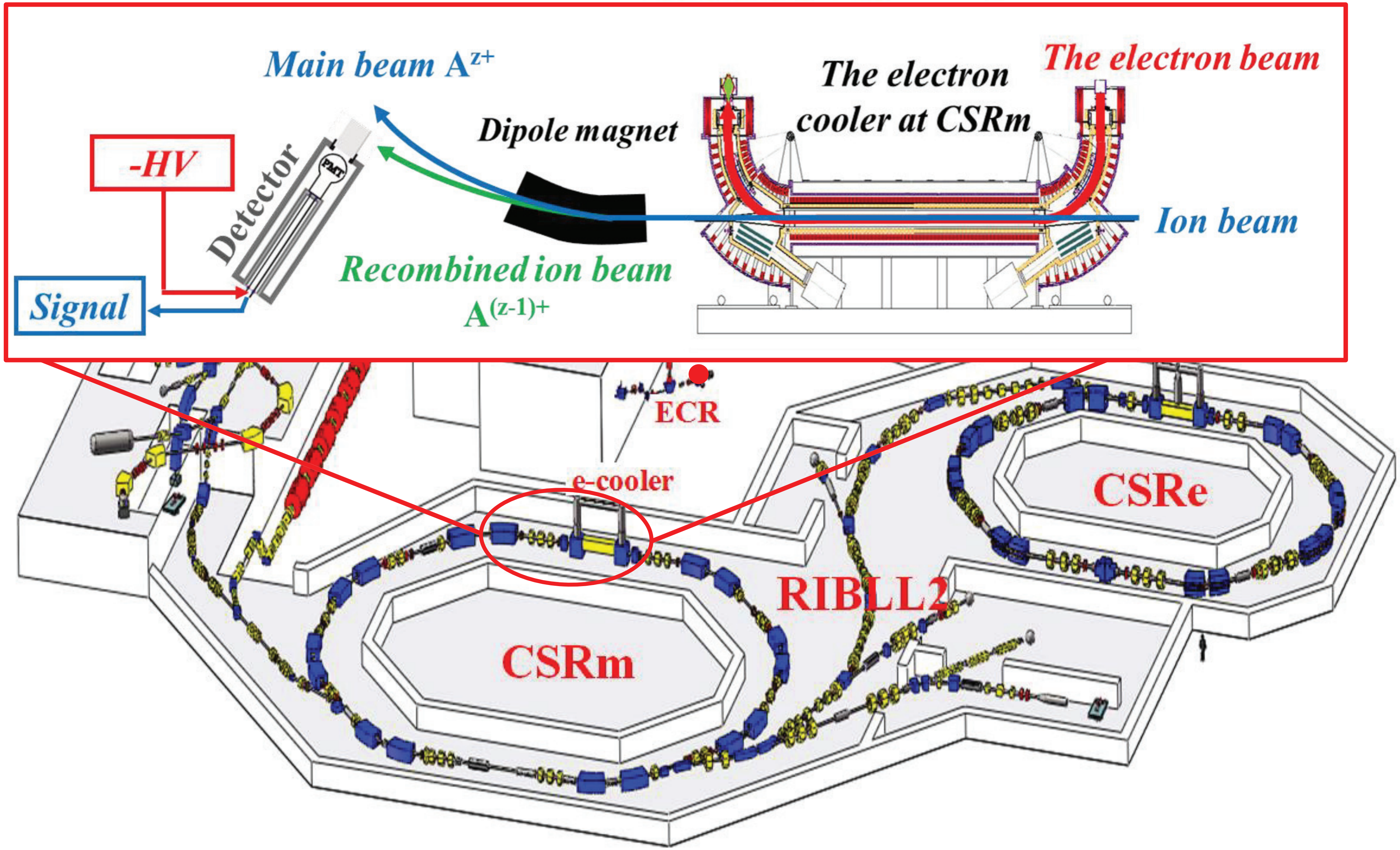

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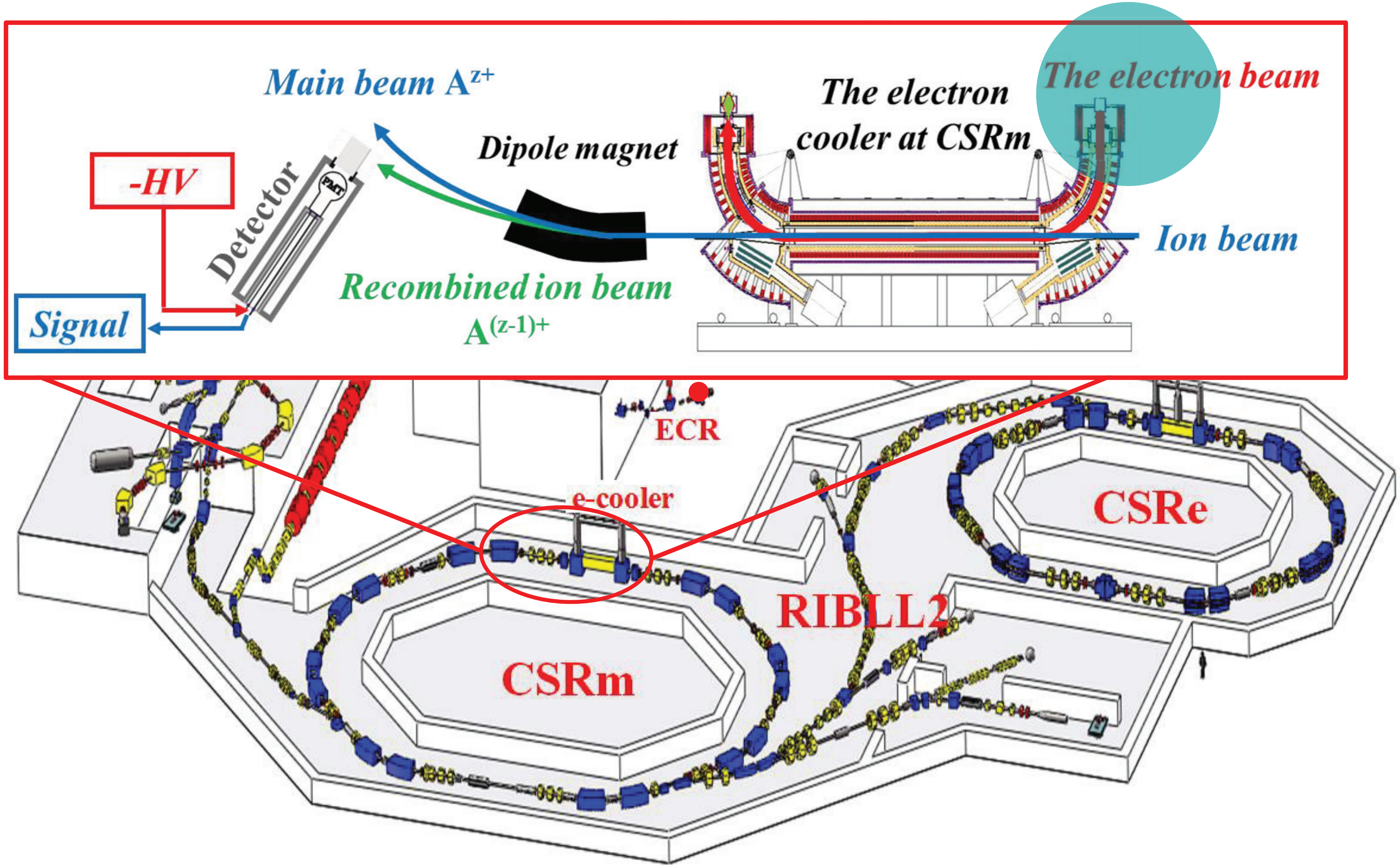

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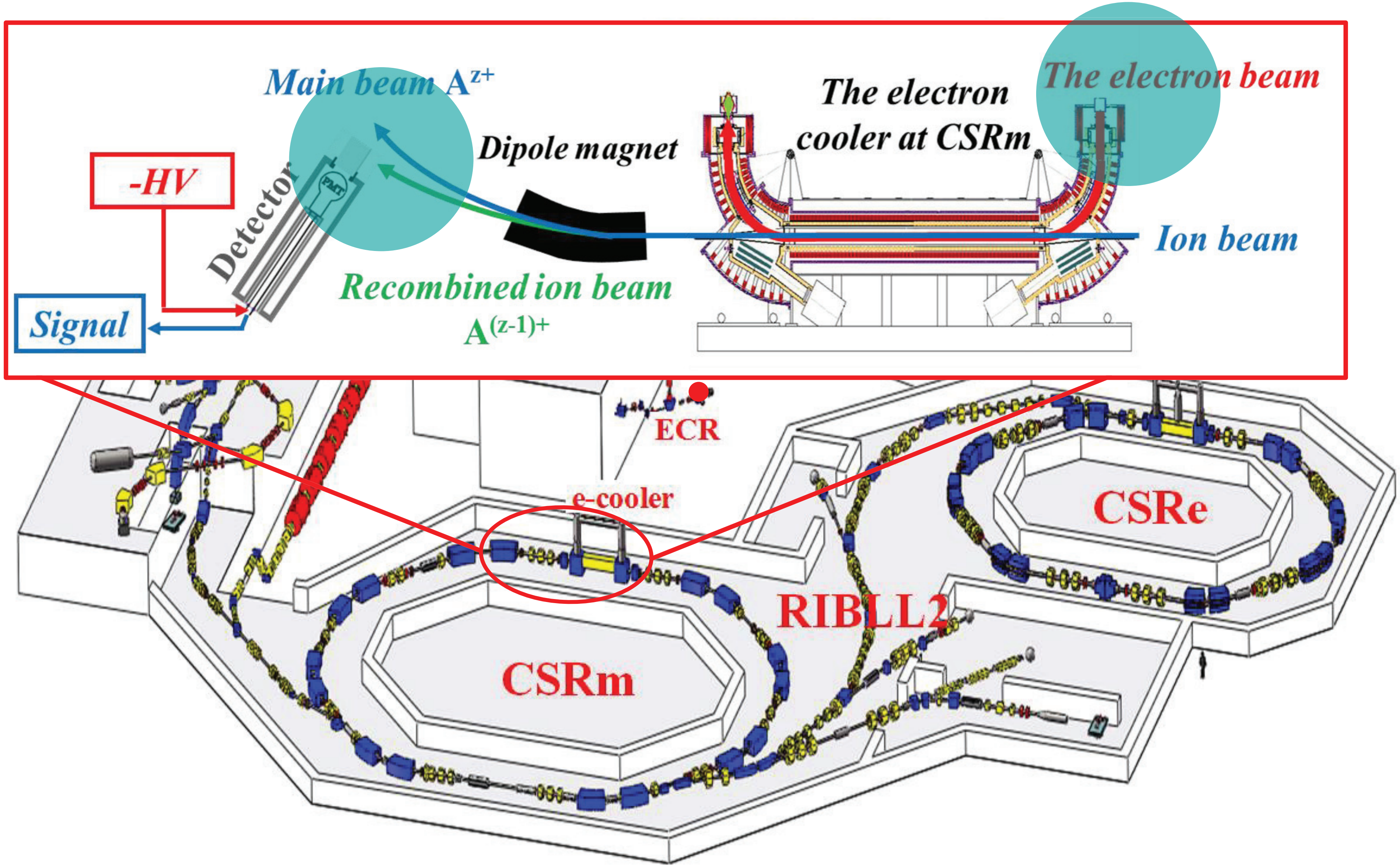

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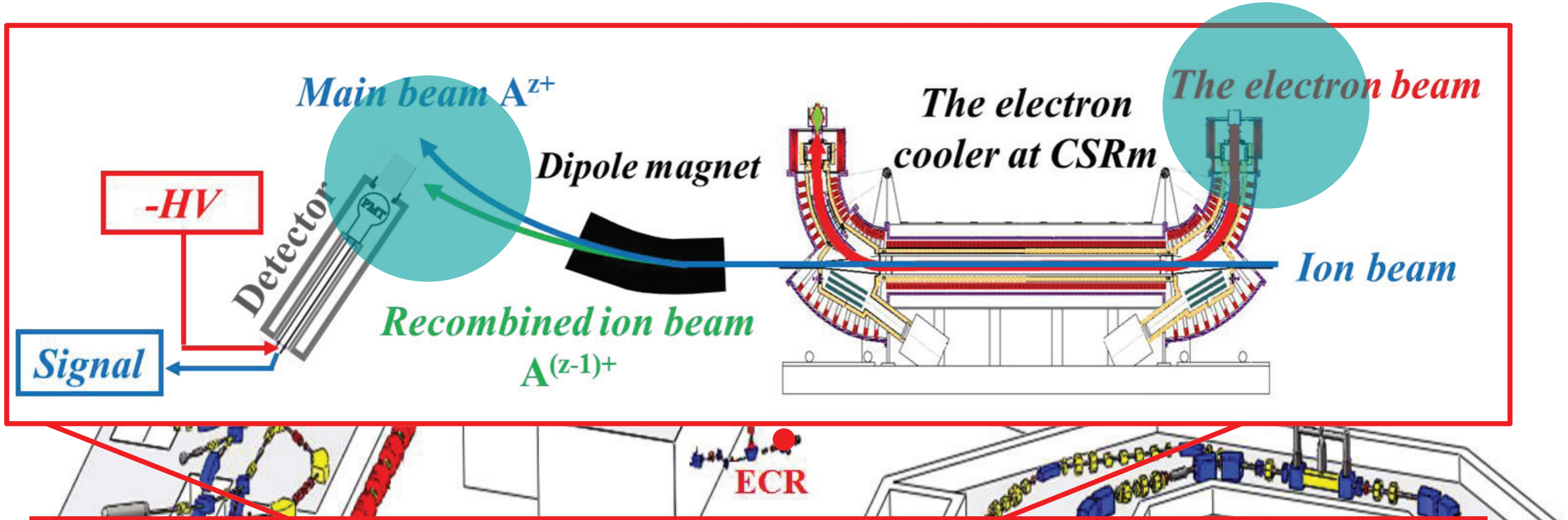

$$\alpha(E_{rel}) = \frac{R}{N_i n_e (1-\beta_e\beta_i)}\frac{C}{L}$$

R : *counts of recombined ions*
N_i : *strored ion beam in storage ring*
n_e : *electron density*
L : *effective interaction length*
C : *the circumstance of CSRm*

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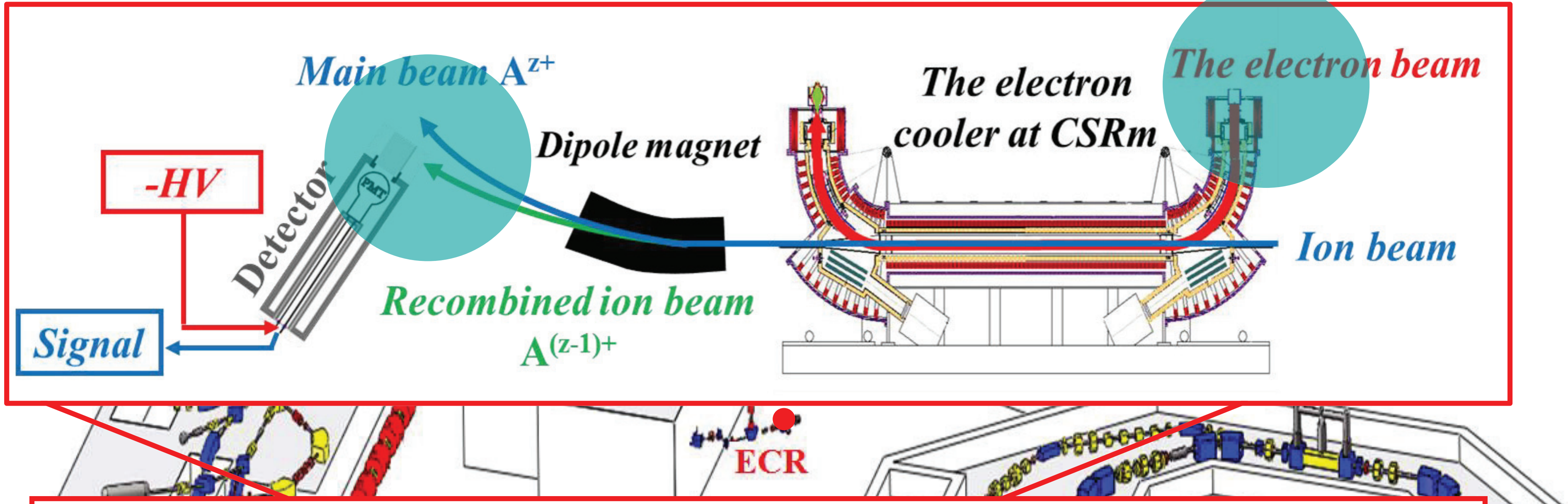

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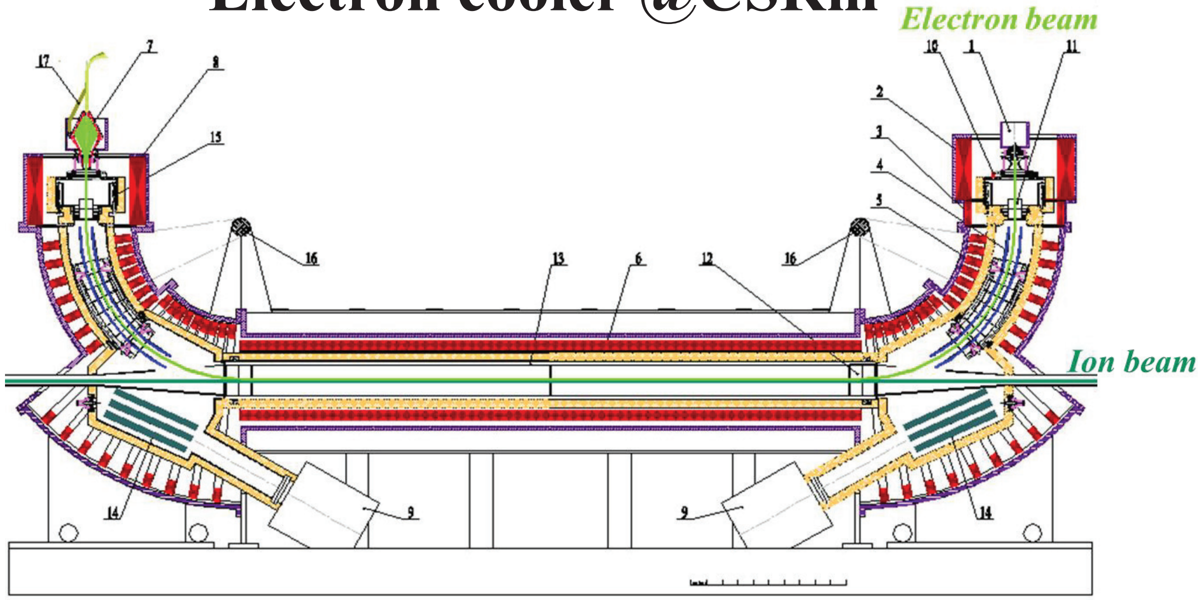
C : *the circumstance of CSRm*

-----*Advantages*-----

- *High vacuum Low background*
- *Broad detuning energy-range*
- *Ultra-high precision*
- *~100% detection efficiency*
- *Absolute rate coefficients*

Electron cooler and beam cooling

Electron cooler @CSRm



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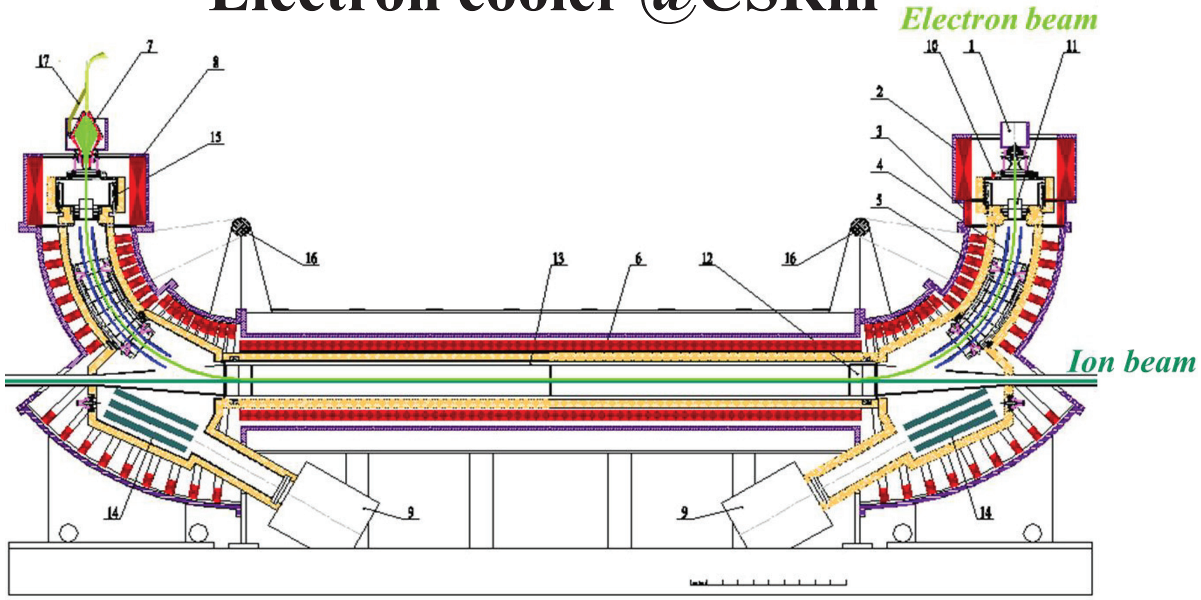


Electron-cooler:

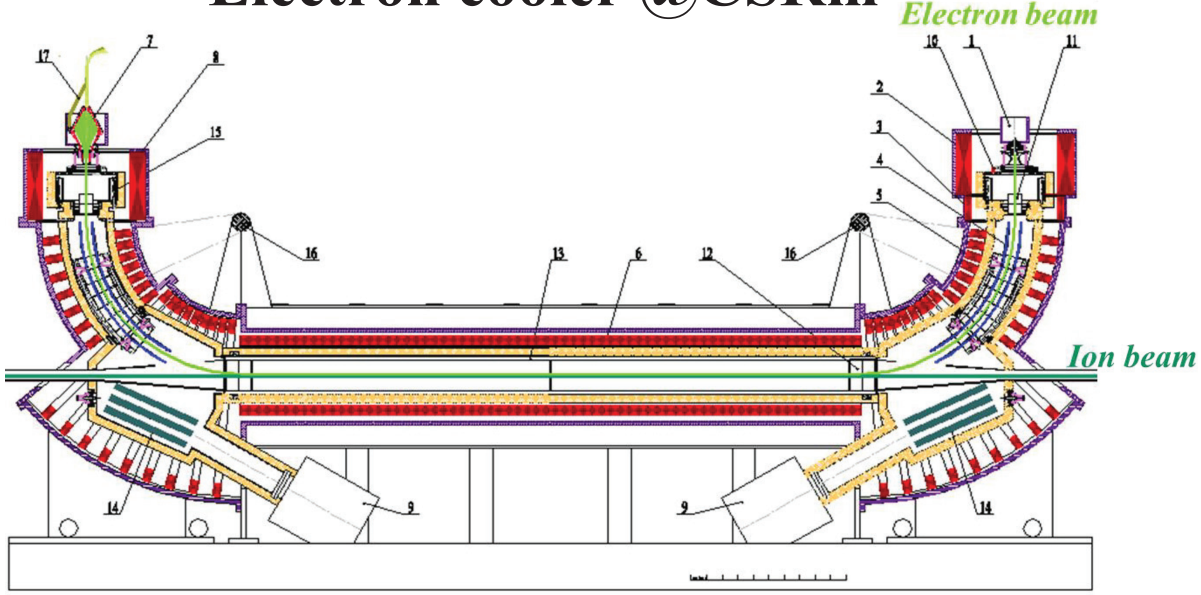
decrease the momentum spread, improve beam quantity;

Electron-target:

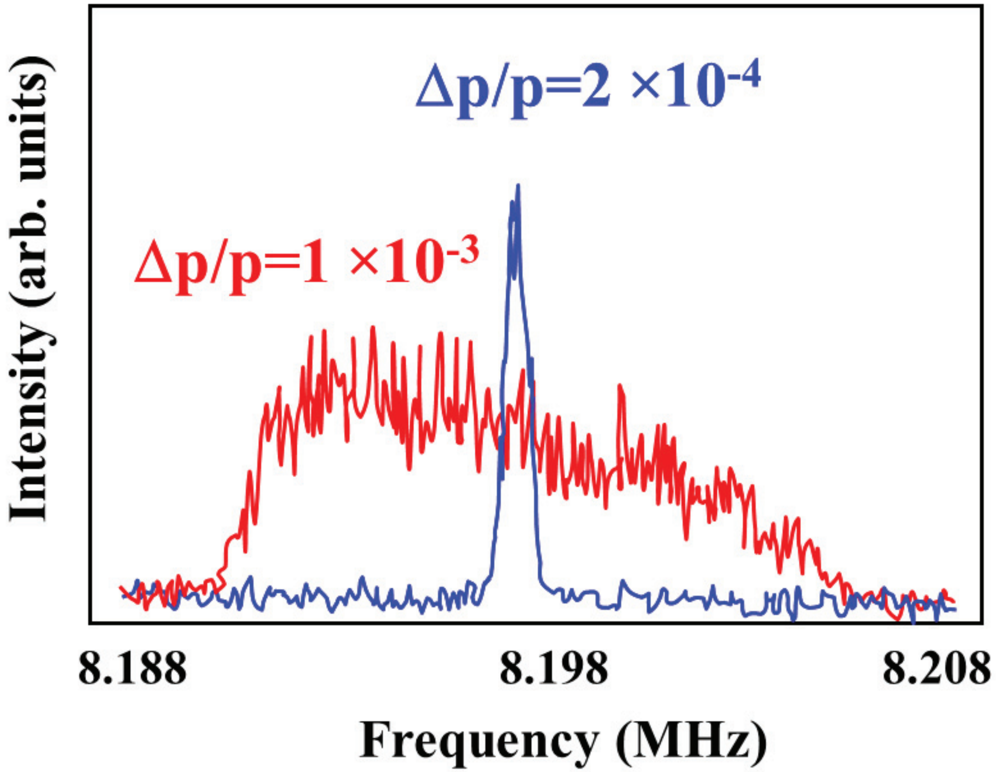
provide low-temperature electron beam;

Electron cooler and beam cooling

Electron cooler @CSRm



8.37 MeV $^{36}Ar^{15+}$@CSRm



Schottky noice spectrum analysis

Electron-cooler:
decrease the momentum spread, improve beam quantity;

Electron-target:
provide low-temperature electron beam;

Adiabatic transverse expansion of the electron beam

Flattened Maxwellian electron energy distribution [Storage Ring]

$$f(\upsilon_{rel},\vec{\upsilon}) = \left(\frac{m_e}{2\pi kT_{||}}\right)^{\frac{1}{2}} \exp\left[-\frac{m_e(\upsilon_{||}-\upsilon_{rel})^2}{2kT_{||}}\right] \times \frac{m_e}{2\pi kT_{\perp}} \exp\left(-\frac{m_e\upsilon_{\perp}^2}{2kT_{\perp}}\right)$$

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Adiabatic transverse expansion of the electron beam

Flattened Maxwellian electron energy distribution [Storage Ring]

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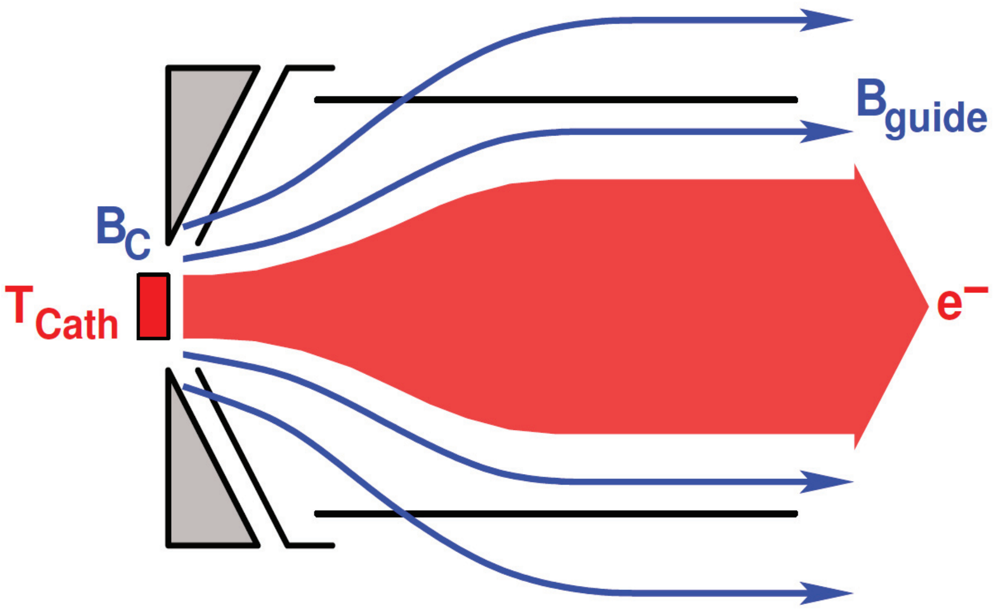
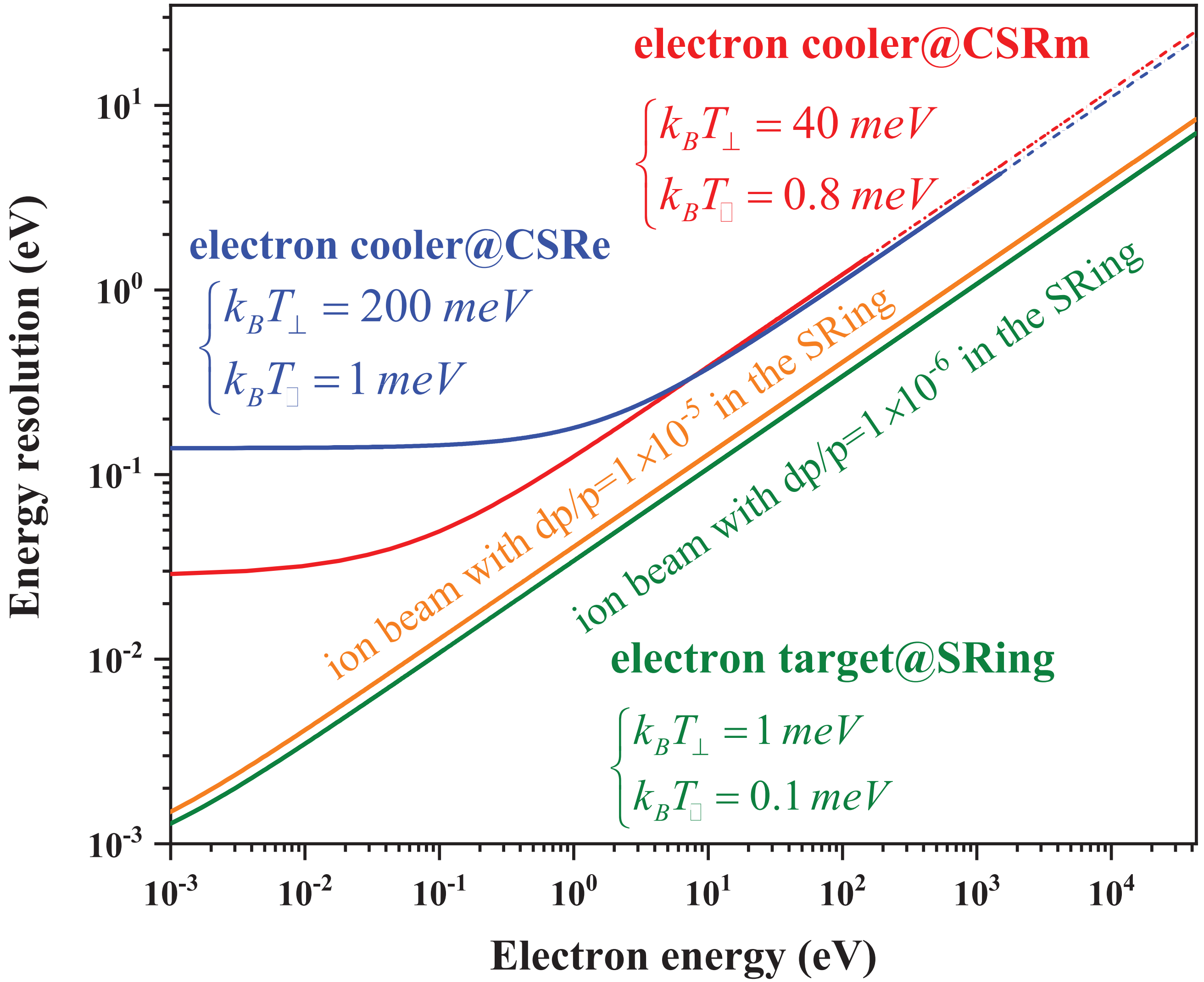


$$k_B T_{\perp} = \frac{k_B T_{\text{cath}}}{\xi} \qquad \xi = B_{\text{c}}/B_{\text{guide}}$$

$$k_B T_{\parallel} = k_B T_{\parallel}^{\text{kin}} + \frac{\partial \Delta E_{\text{TLR}}}{\partial x} dx + \Delta E_{\text{LLR}}$$

Energy resolution of DR resonances

$$\Delta E = \sqrt{(K_BT_{\perp} \cdot ln2)^2 + 16ln2 \cdot K_BT_{\parallel} \cdot E_{rel}} + \frac{\Delta p}{p} \cdot (\beta_{ion} - \beta_e)\gamma_{ion}\gamma_e$$



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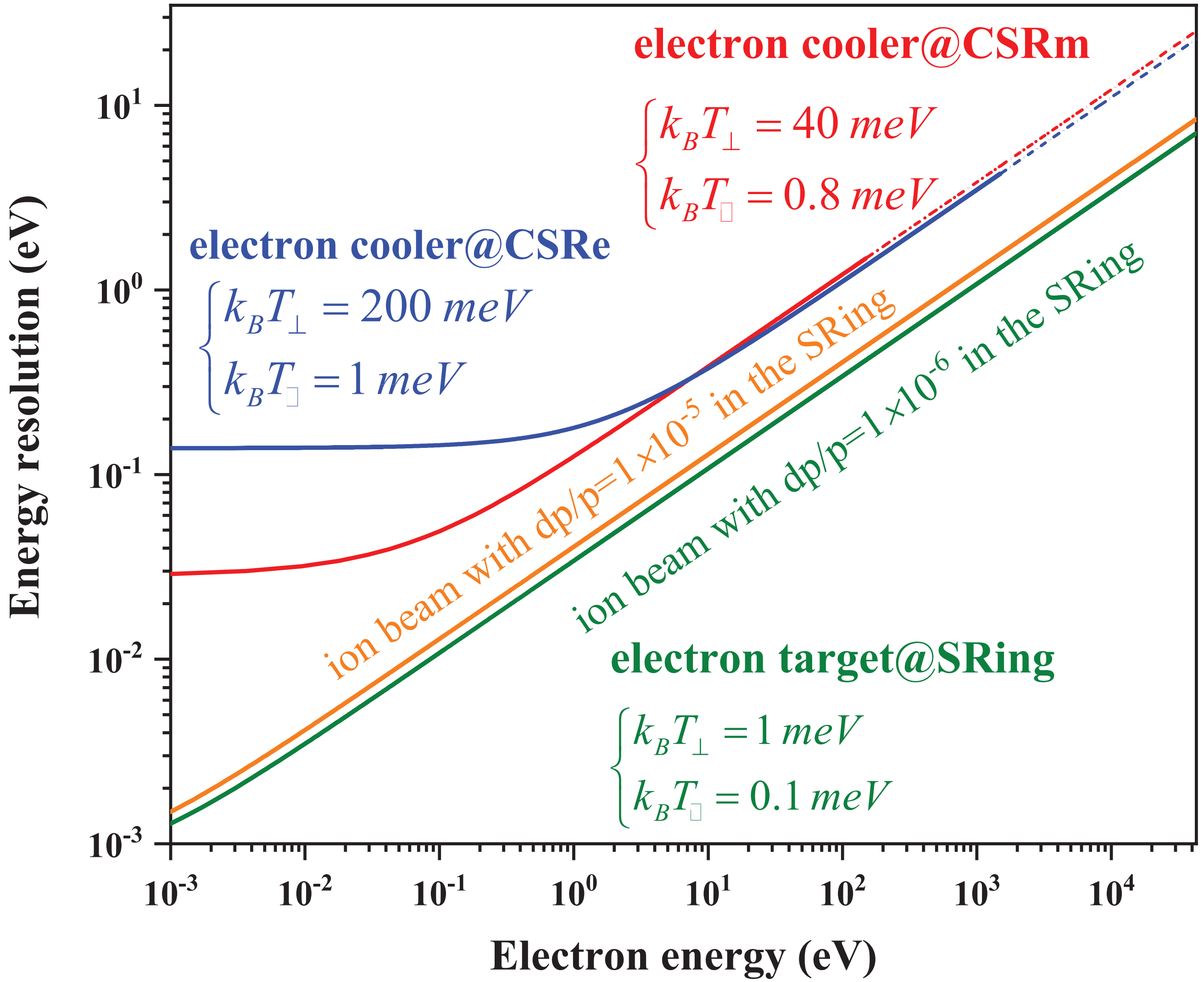
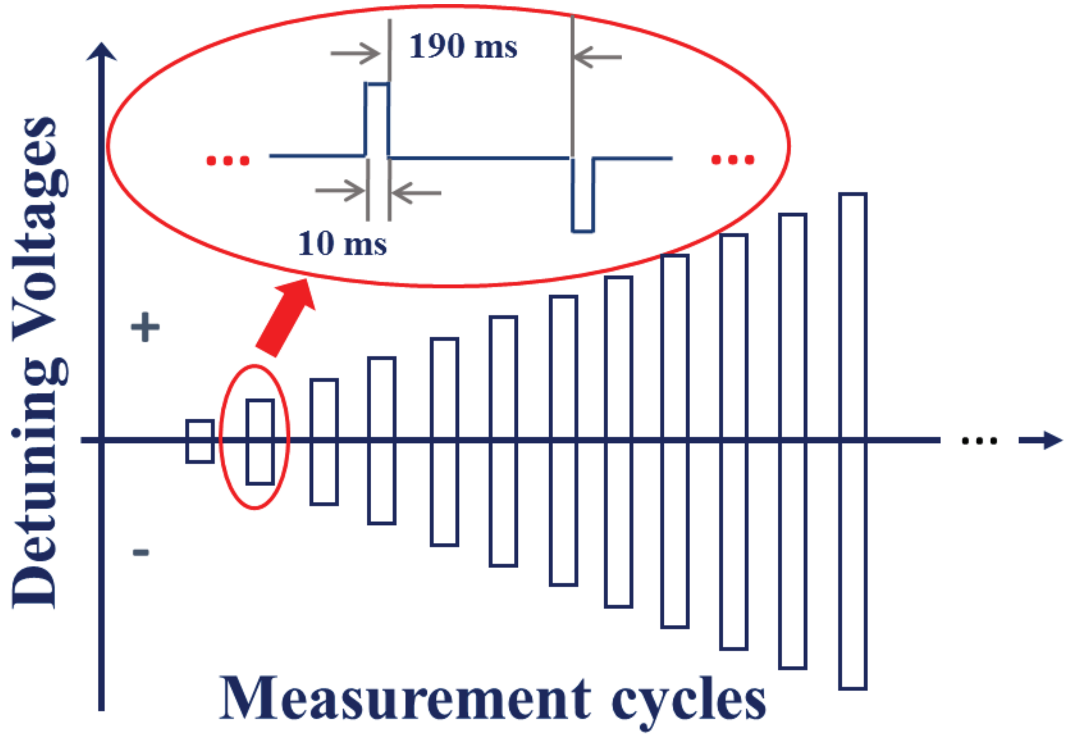
Lower electron temperature
Lower momentum spread

Higher energy resolution



Detuning timing sequence

Detuning timing scheme for DR experiments at the CSRm



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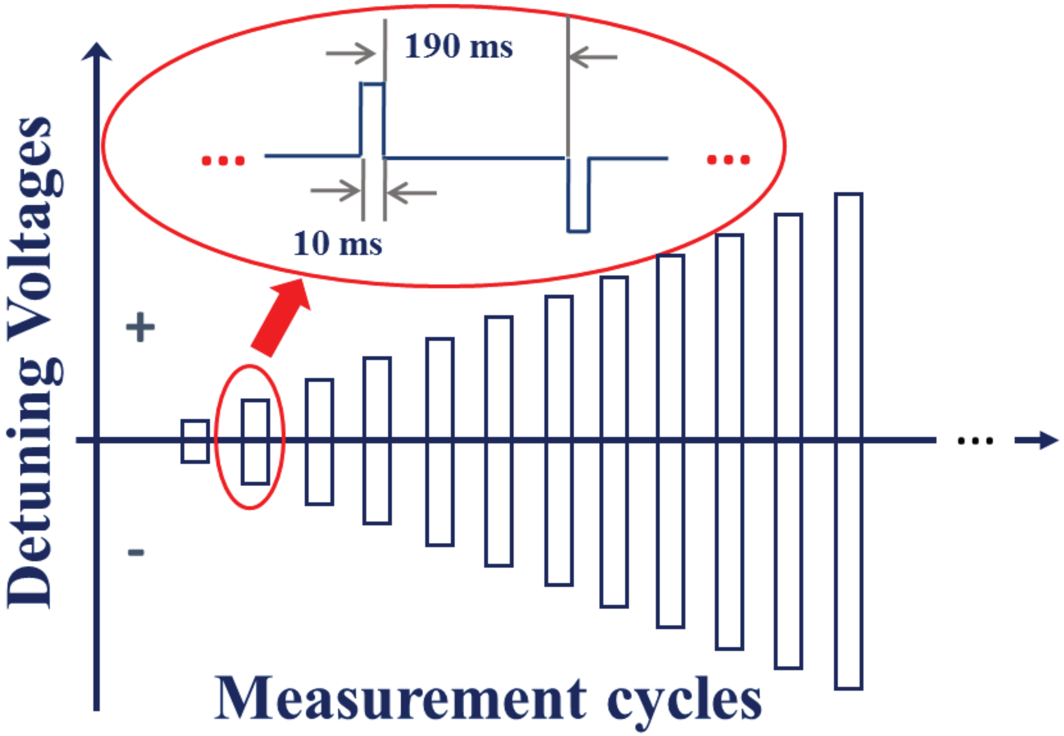

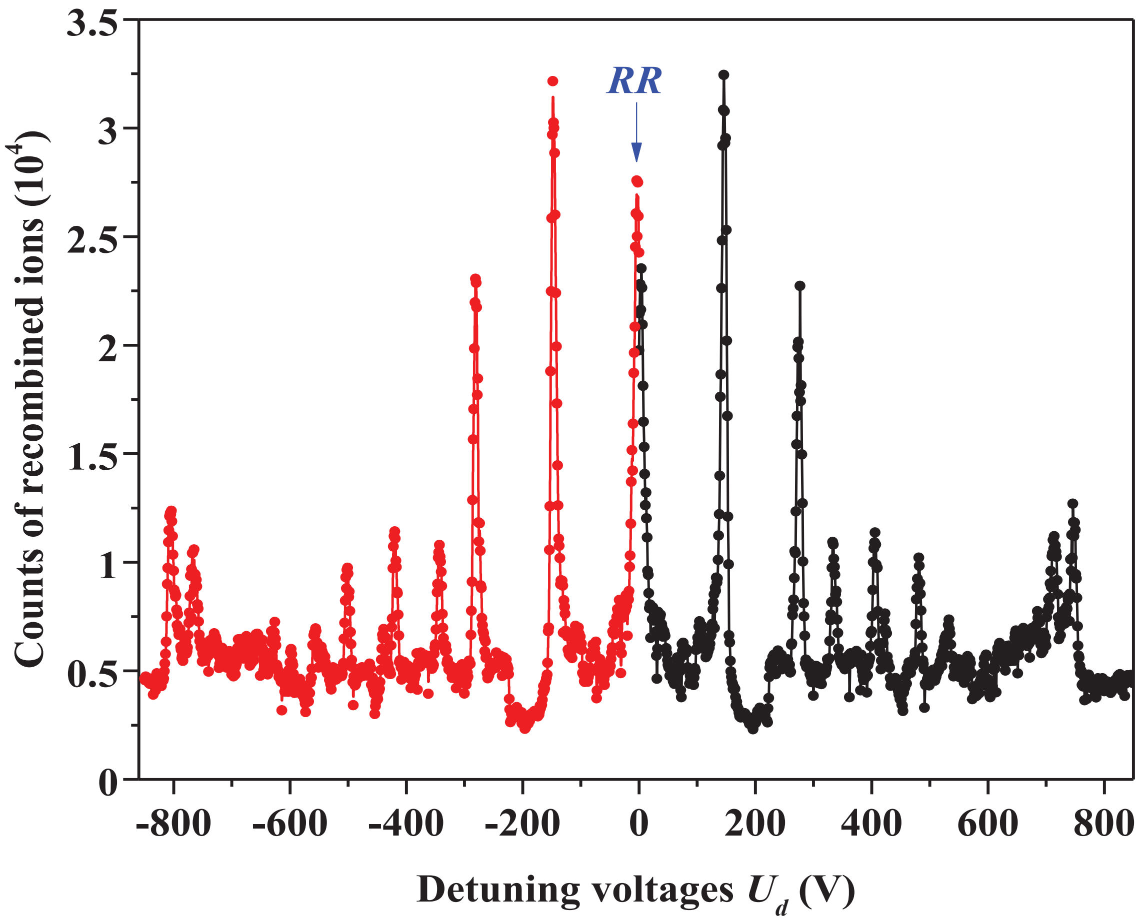

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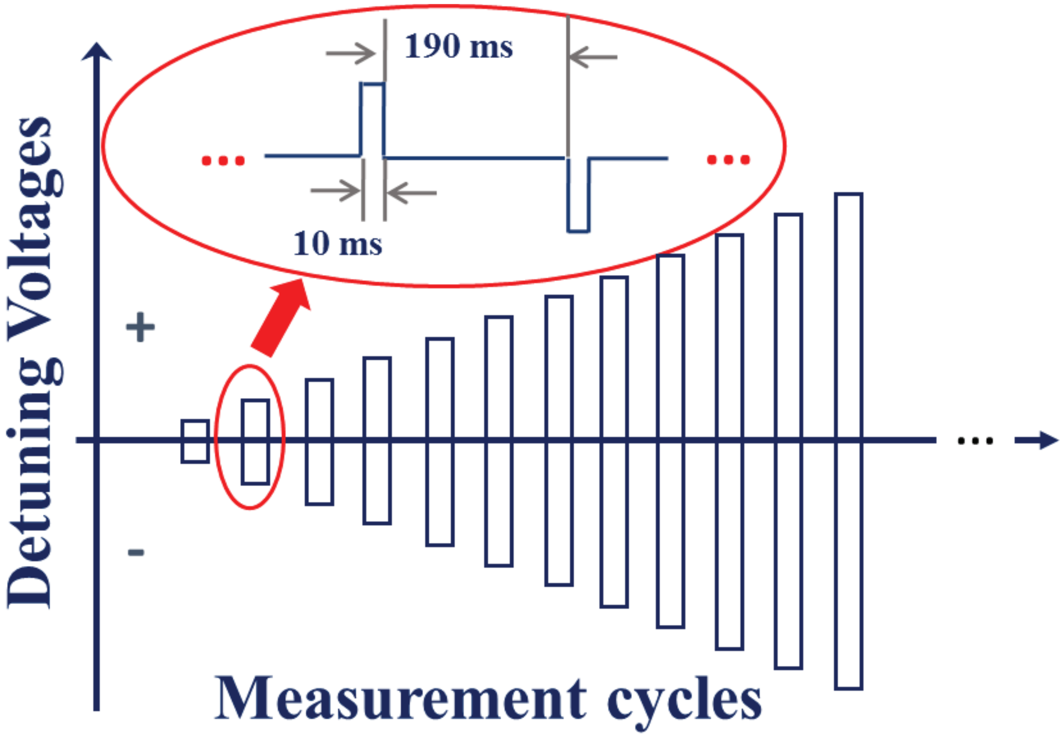

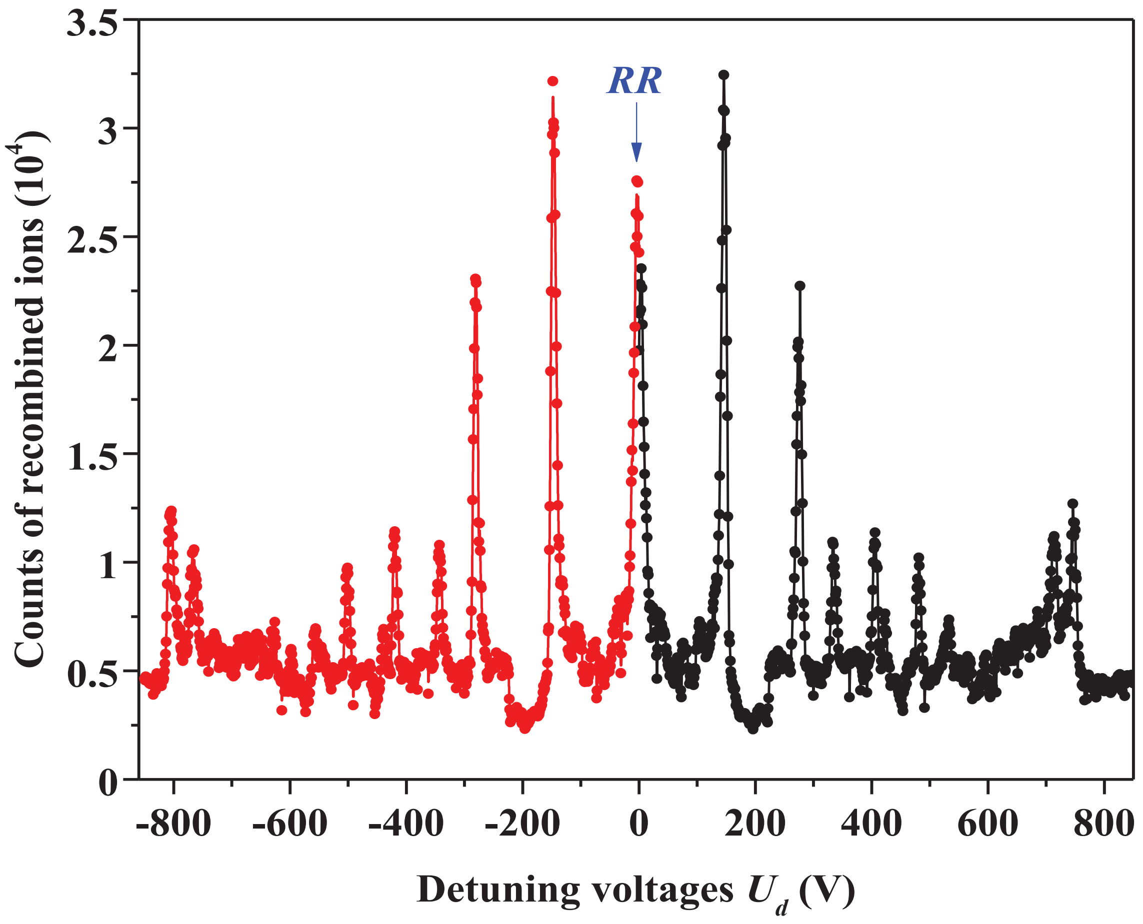

Counts of recombined ions vs. detuning voltages → DR spectrum

Data analysis

1. X axis：Detuning voltages → Electron –ion collision energy；

$$E_{rel}=\sqrt{m_e^2c^4+m_{ion}^2c^4+2m_em_{ion}\gamma_e\gamma_{ion}c^4(1-\beta_e\beta_{ion}cos\theta)}-m_ec^2-m_{ion}c^2$$

Under cooling: $\gamma_e=\gamma_i$

Detuning: $\gamma_e=1+\frac{E_{e-0}+\Delta E_e}{m_ec^2}=\gamma_i+\frac{\Delta E_e}{m_ec^2}$

2. Y axis：Counts of recombined ion → Rate coefficients；

$$\alpha(E_{rel})=\frac{R}{N_in_e(1-\beta_e\beta_i)}\frac{C}{L}=qe^2c^2\pi r_e^2\cdot\frac{\beta_e\beta_i}{1-\beta_e\beta_i}\cdot\frac{RL}{I_{ion}I_e}$$

Data analysis

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$$E_{rel} = \sqrt{m_e^2 c^4 + m_{ion}^2 c^4 + 2 m_e m_{ion} \gamma_e \gamma_{ion} c^4 (1 - \beta_e \beta_{ion} cos\theta)} - m_e c^2 - m_{ion} c^2$$

Under cooling: $\gamma_e = \gamma_i$

Detuning + Correlation

Detuning: $$\gamma_e = 1 + \frac{E_{e-0} + \Delta E_e}{m_e c^2} = \gamma_i + \frac{\Delta E_e}{m_e c^2}$$

2. Y axis：Counts of recombined ion → Rate coefficients；

$$\alpha(E_{rel}) = \frac{R}{N_i n_e (1 - \beta_e \beta_i)} \frac{C}{L} = q e^2 c^2 \pi r_e^2 \cdot \frac{\beta_e \beta_i}{1 - \beta_e \beta_i} \cdot \frac{RL}{I_{ion} I_e}$$

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→ **DR Spectrum**

3. DR experiment of Na-like Kr^{25+} at the CSRm

Program and parameters

1. **Preparation before experiment**
   (Parameters evaluate, Instrument status)
2. **Beam preparation**
   (Ion sources, Beam line, Injection, Cooling)
3. **Beam diagnostic and parameters**
   (Beam current, Profile, Momentum)
4. **Parameters Initialized**
   (Detector position, Injection event, Detuning)
5. **Last check before DAQ**
   (Trigger signal, Time sequence, Data format)
6. **Begin experiment and DAQ**
   (Parameters record, Online data process)

Parameters (unit)	value
CSRm circumstance (m)	161.00
Length of cooling section (m)	4.0
Radii of beam tube (cm)	25
Beam energy (MeV/u)	4.98
Max beam current (μA)	200
Momentum spread (dp/p)	2.2×10^{-4}
Beam life time (s)	50
Cooling point (kV)	-2.732
Electron beam current (mA)	~120
Electron density (cm^{-3})	3.85×10^{5}
Radii of electron beam (cm)	2.60
Magnet in cooling section (GS)	390
Magnet in gun section (GS)	1250

Atomic structure of Na-like Kr^{25+}

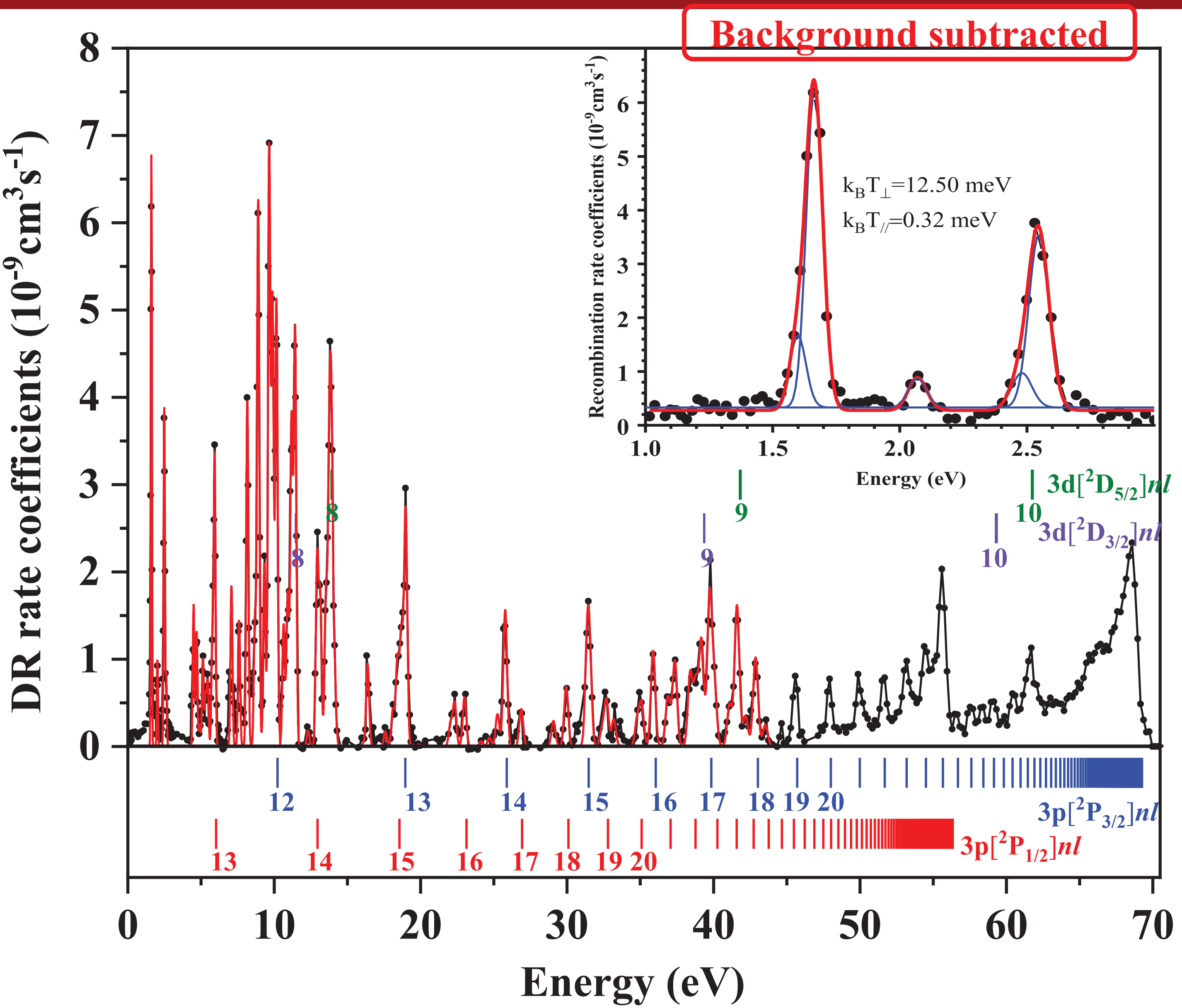
Dominate channels for DR of Na-like Kr25+

$$Kr^{25+}(3s\ ^2S_{1/2}) + e^- \rightarrow \left\{ \begin{array}{l} Kr^{25+}(3p[^2P_{1/2}]\,nl)^{**}(n \geq 13) \\ Kr^{25+}(3p[^2P_{3/2}]\,nl)^{**}(n \geq 12) \\ Kr^{25+}(3d[^2D_{3/2}]\,nl)^{**}(n \geq 8) \\ Kr^{25+}(3d[^2D_{5/2}]nl)^{**}(n \geq 8) \\ Kr^{25+}(4l\ nl)^{**} \end{array} \right. \rightarrow Kr^{24+} + \gamma$$

Energy levels for Na-like Kr^{25+}ions

Level configuration	Excitation energy(eV)[a]
$1s^22s^22p^63s\ [^2S_{1/2}]$	0
$1s^22s^22p^63p\ [^2P_{1/2}]$	56.340
$1s^22s^22p^63p\ [^2P_{3/2}]$	69.267
$1s^22s^22p^63d\ [^2D_{3/2}]$	144.340
$1s^22s^22p^63d\ [^2D_{5/2}]$	146.796
$1s^22s^22p^64s\ [^2S_{1/2}]$	557.147
$1s^22s^22p^64p\ [^2P_{1/2}]$	580.175
$1s^22s^22p^64p\ [^2P_{3/2}]$	585.285
$1s^22s^22p^64d\ [^2D_{3/2}]$	613.368
$1s^22s^22p^64d\ [^2D_{5/2}]$	614.463
$1s^22s^22p^64f\ [^2F_{5/2}]$	628.266
$1s^22s^22p^64f\ [^2F_{7/2}]$	628.708

Experimental results: Na-like Kr^{25+}



- The energy scale was recalibrated by a factor of 1.022 to achieve agreement with $3p[^2P_{3/2}]nl$ series limit at 69.267 eV.
- By fitting the resolved DR resonances with a flattened Maxwellian, electron temperatures of $k_BT_\parallel$=0.32 meV and $k_BT_\perp$=12.50 meV were obtained.

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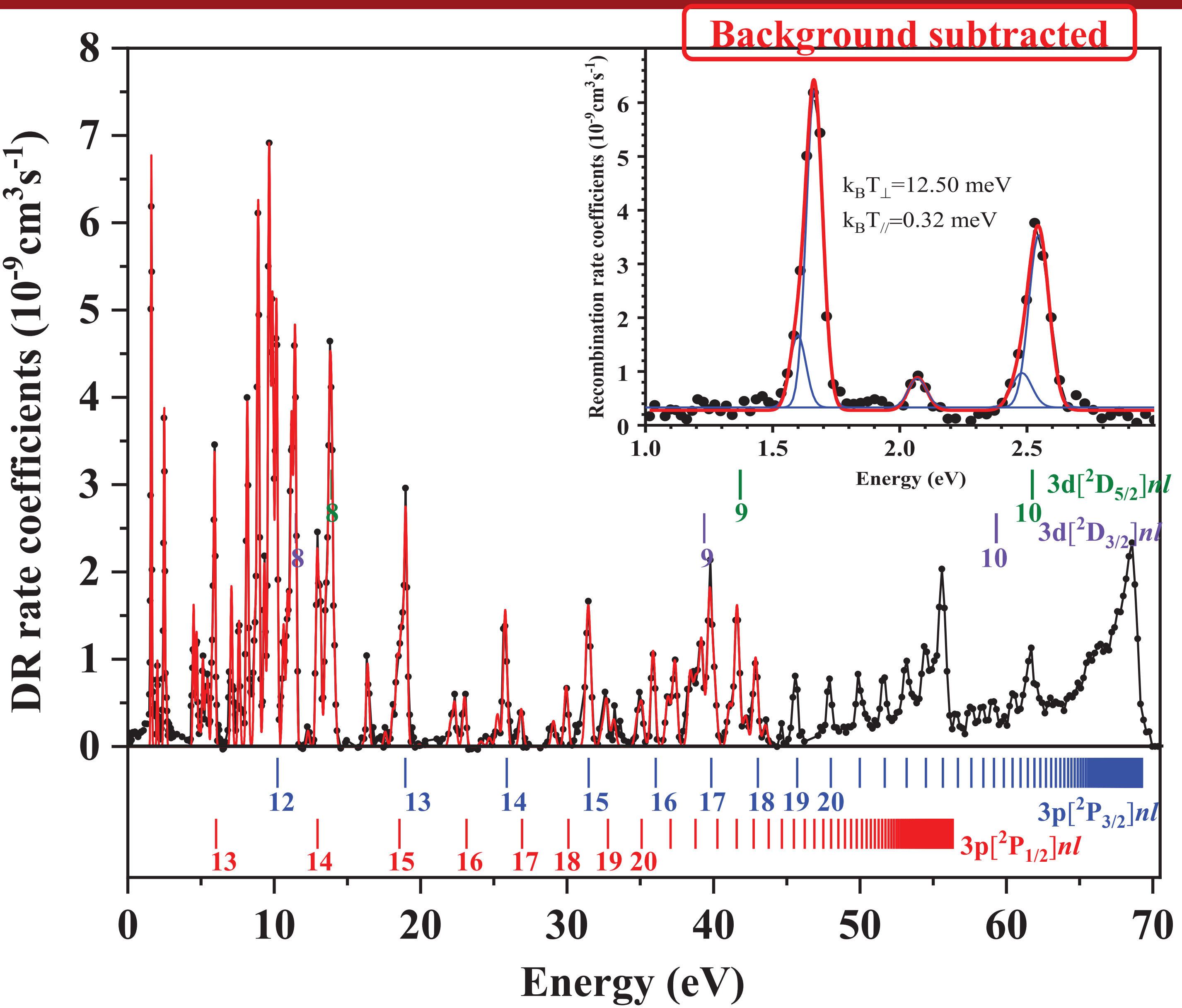

The vertical bar indicated in the figure is estimated by Rydberg formula :

E_{exc} donates the core excitation energy
R donates the Rydberg constant
Z_{eff} donates the charge state of ion

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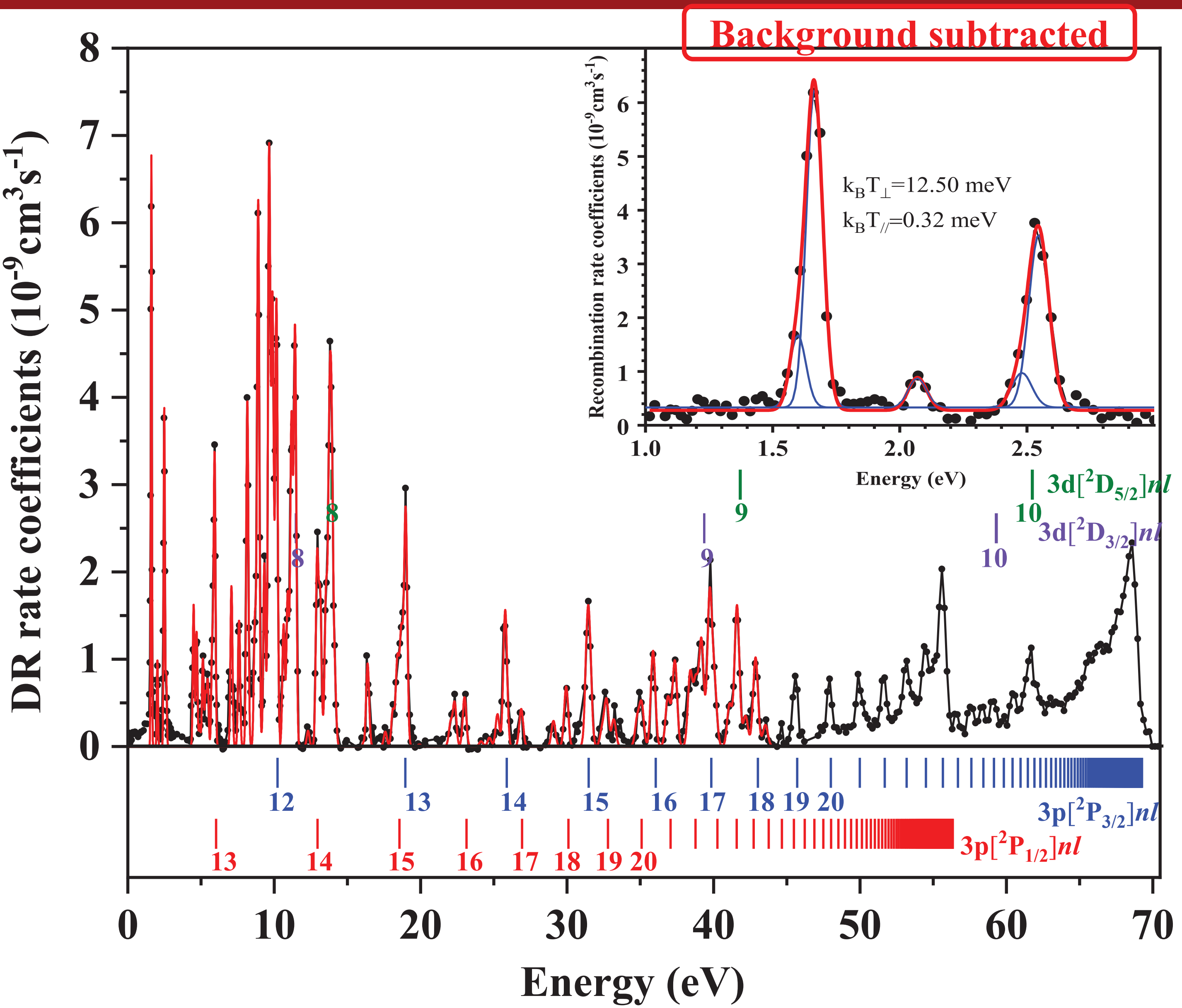

The vertical bar indicated in the figure is estimated by Rydberg formula :

$$E_{res} = E_{exc} - \frac{RZ_{eff}}{n^2}$$

E_{exc} donates the core excitation energy
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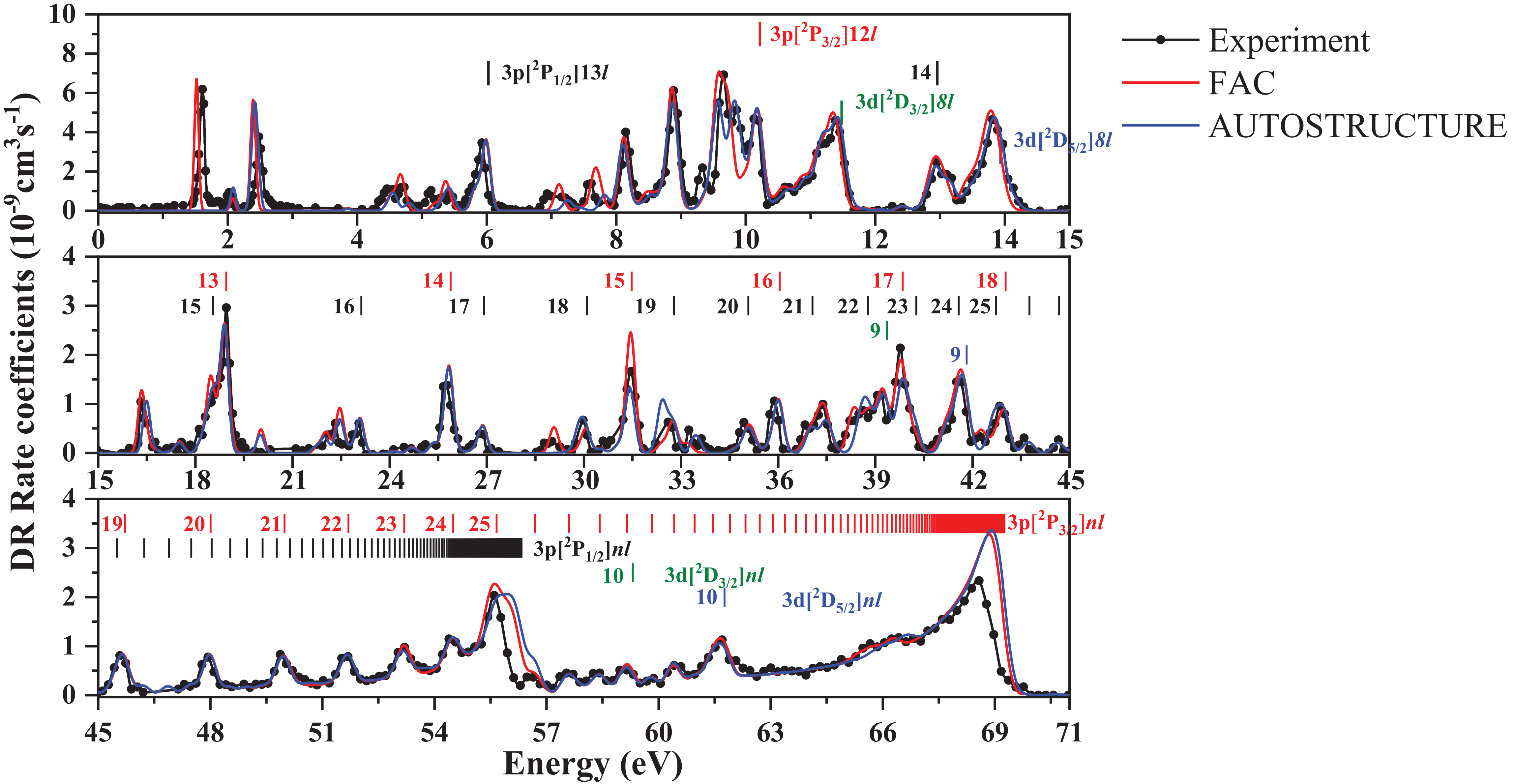

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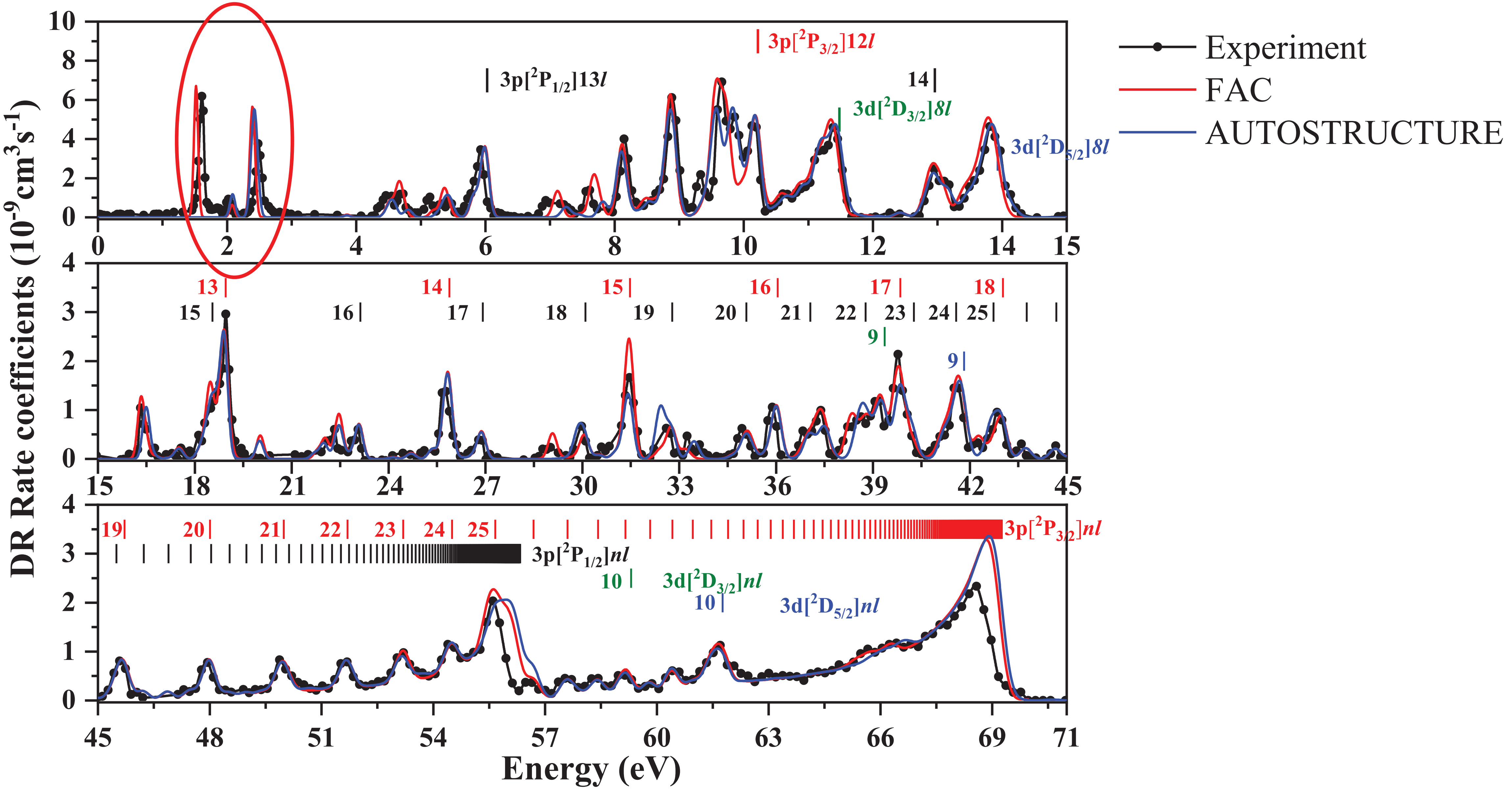

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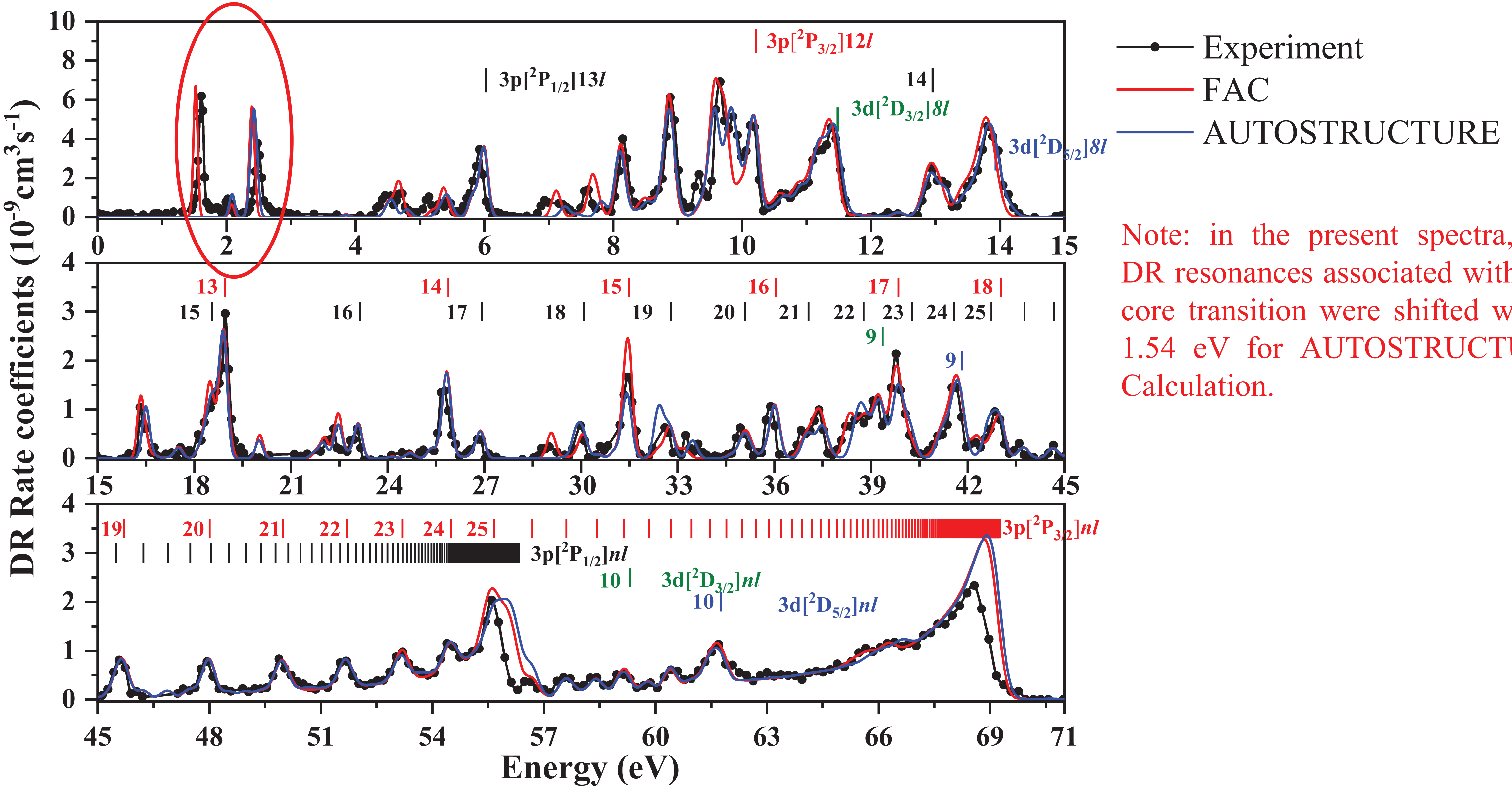
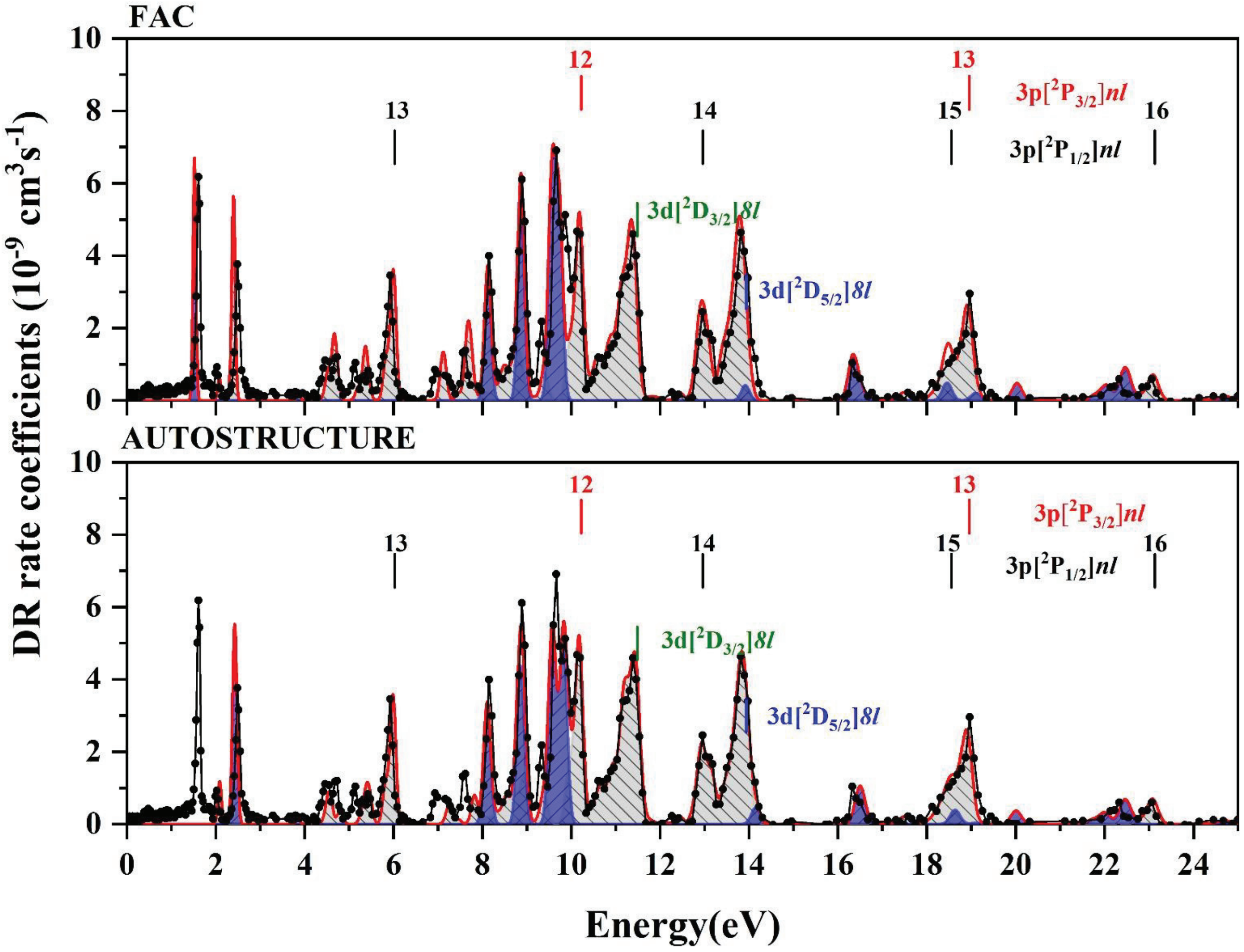


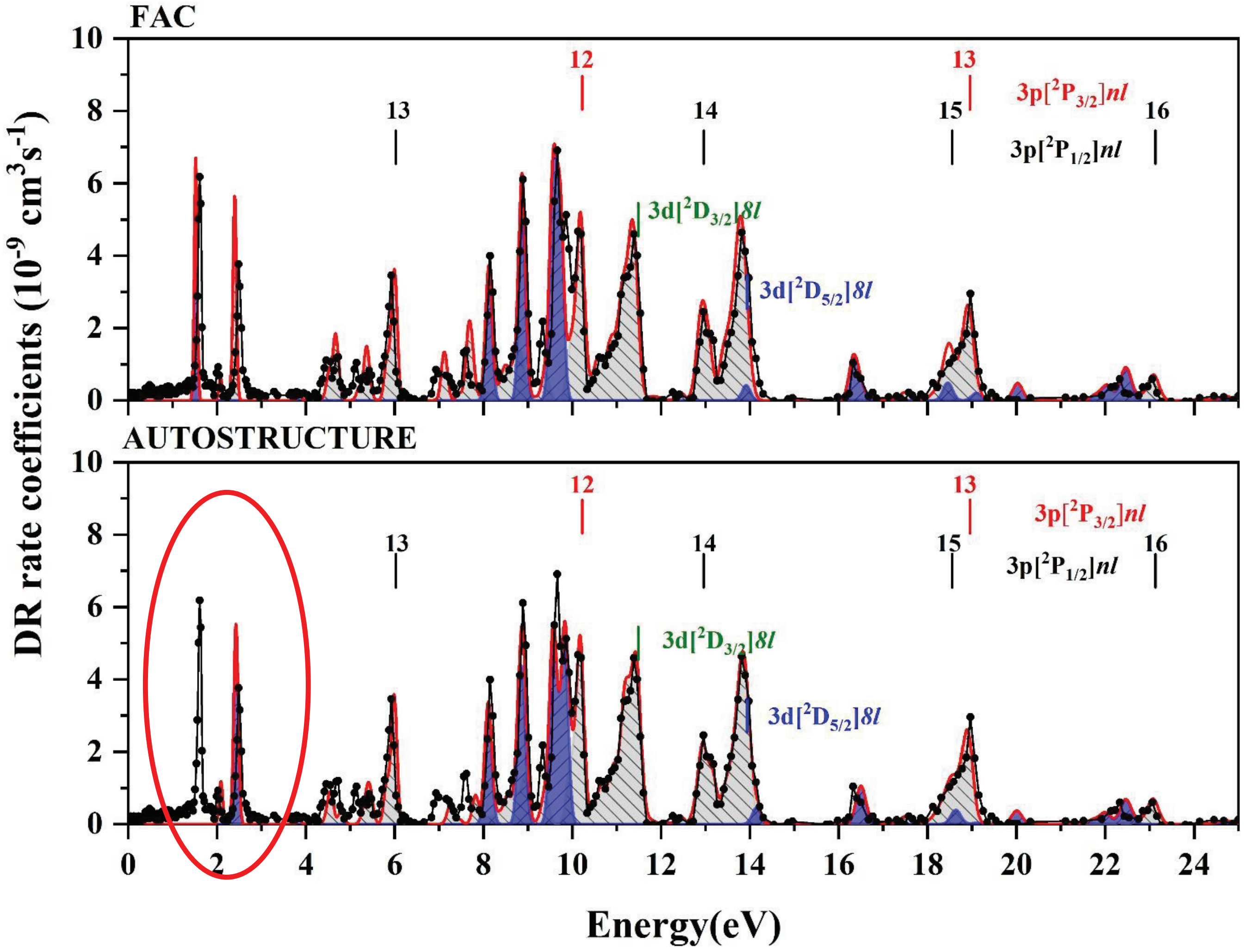
Note: in the present spectra, the DR resonances associated with 3-4 core transition were shifted with -1.54 eV for AUTOSTRUCTURE Calculation.

Experimental results: Na-like Kr^{25+}



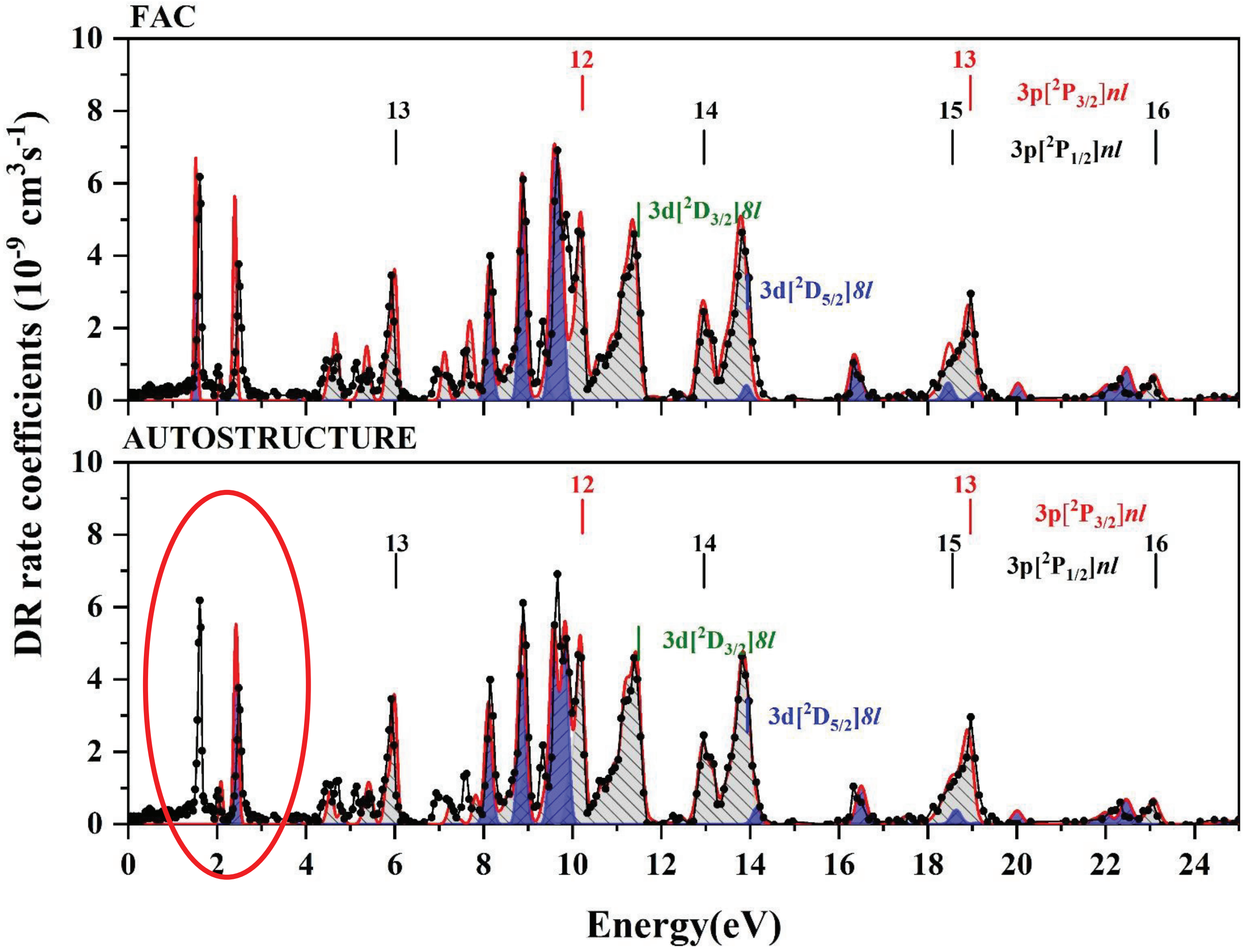
- The connected black dotted curve donates the measured background-subtracted DR spectrum.
- The red solid curve donates the FAC AUTOSTRUCTURE calculated total DR rate coefficient in each graph.
- The grey areas donate the DR rate coefficient associated with $3l \rightarrow 4l$ (ΔN=1) core excitation.
- The blue areas donate the DR rate coefficient associated with $3s \rightarrow 3l$ (ΔN=0) core excitation.

Experimental results: Na-like Kr^{25+}



- The connected black dotted curve donates the measured background-subtracted DR spectrum.
- The red solid curve donates the FAC AUTOSTRUCTURE calculated total DR rate coefficient in each graph.
- The grey areas donate the DR rate coefficient associated with $3l \rightarrow 4l$ ($\Delta N=1$) core excitation.
- The blue areas donate the DR rate coefficient associated with $3s \rightarrow 3l$ ($\Delta N=0$) core excitation.

Experimental results: Na-like Kr^{25+}



Note: the DR resonances associated with 3-4 core transition were shifted with -1.54 eV [AUTOSTRUCTURE]

- The connected black dotted curve donates the measured background-subtracted DR spectrum.
- The red solid curve donates the FAC AUTOSTRUCTURE calculated total DR rate coefficient in each graph.
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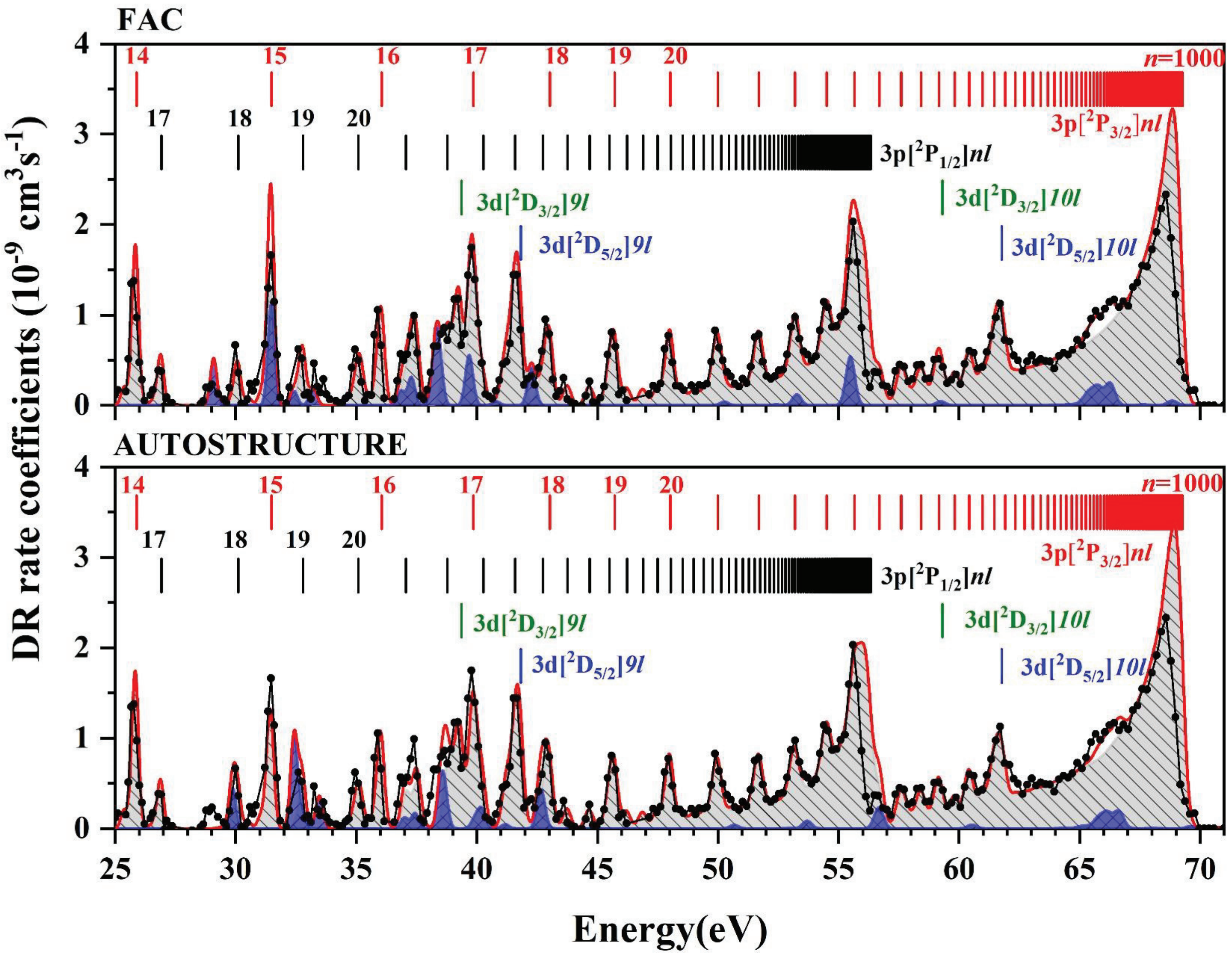
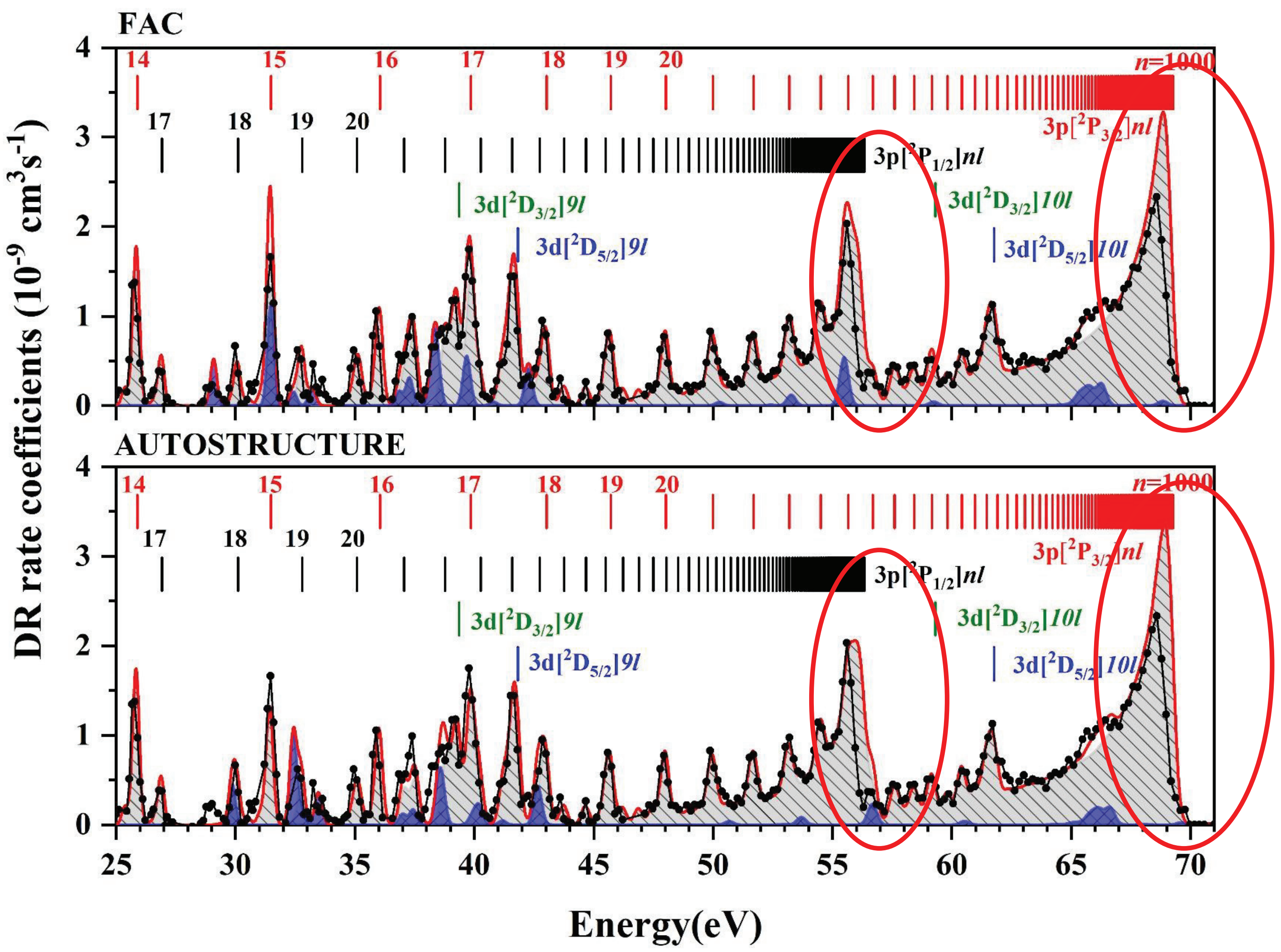
Experimental results: Na-like Kr^{25+}



- Same as last figure, but for the energy rage of 25-70 eV.

Experimental results: Na-like Kr^{25+}



Field- ionization

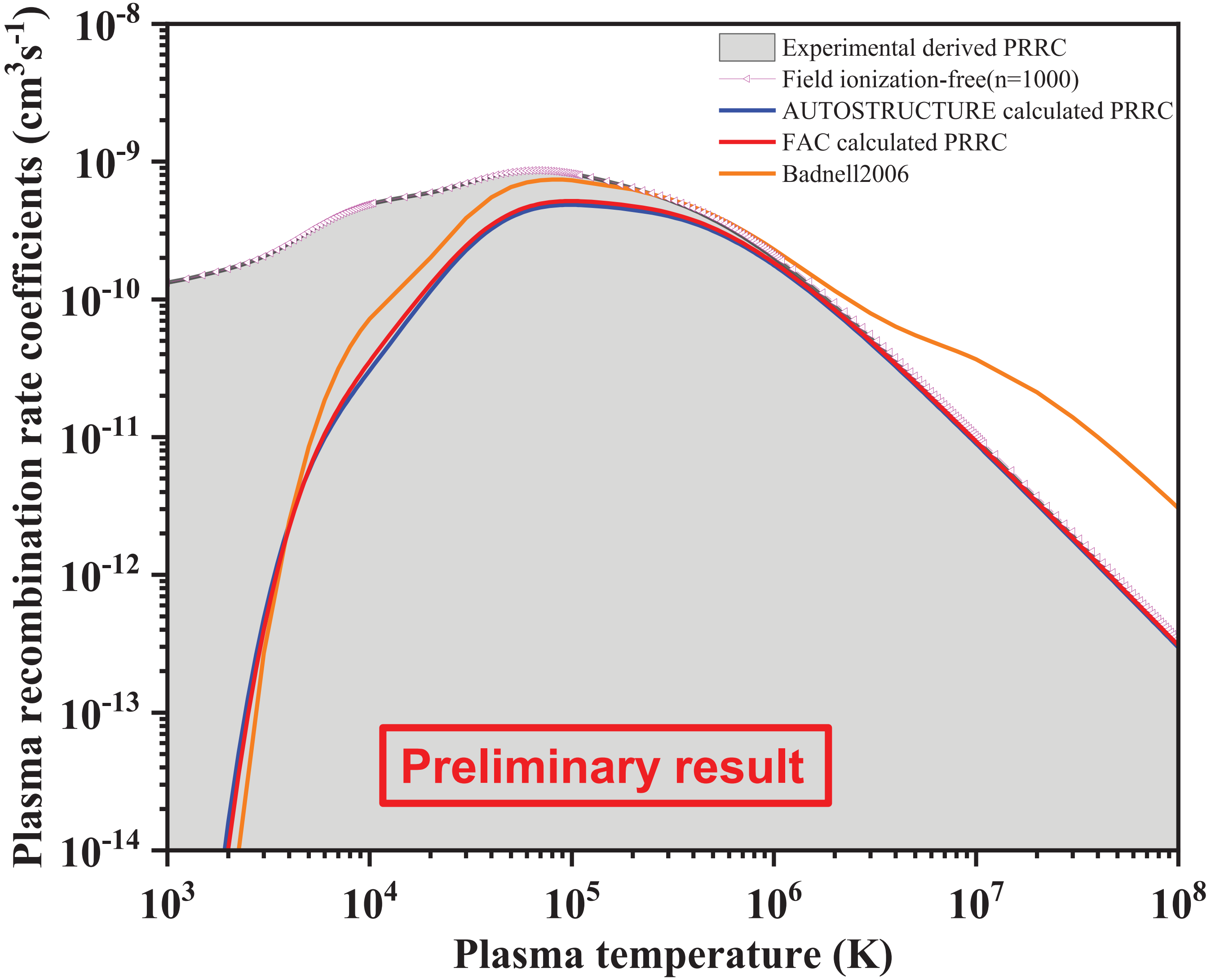
Field ionization of the loosely bound high Rydberg electron in the recombined ions can result from the **motional electric fields** that the ions experience inside the storage ring bending magnets

$$n_{cutoff} \approx \left[6.2 \times 10^8 \left(\frac{V}{cm}\right) \frac{q^3}{\nu_i \times B}\right]^{1/4}$$

q is the charge state of ion beam;
$\boldsymbol{\nu_i}$ donates the mean velocity of ion beam;
B is the magnet filed strength;

- Same as last figure, but for the energy rage of 25-70 eV.

Experimental results: Na-like Kr^{25+}



- The solid red curve denotes the plasma DR rate coefficients derived from the presently FAC code calculated DR rate coefficients.
- The solid blue curve denotes the plasma DR rate coefficients derived from the presently AUTOSTRUCTURE calculated DR rate coefficients.
- The solid orange denotes the previous data calculated by Badnell et al., which included both ΔN=0 and ΔN=1 DR rate coefficients.
- The pink triangle solid line is the filed-ionization-free resonant plasma DR rate coefficients.

Experimental results: Na-like Kr^{25+}

In order to facilitate the plasma modelers and astrophysicists to use our data, the presently experimentally derived and the theoretical calculated PRRC have been parameterized.

$$\alpha(T_e) = T_e^{-3/2} \sum_i^n c_i \cdot \exp\left(-\frac{E_i}{kT_e}\right)$$

No.	n_{cutoff}		n_{max}=1000	
i	c_i	E_i	c_i	E_i
1	0.173[0]	60.922[0]	1.454 [-4]	0.535[0]
2	0.071[0]	33.311[0]	1.702[-5]	0.127[0]
3	0.023[0]	7.562[0]	0.024[0]	7.627[0]
4	0.002[0]	1.539[0]	0.074[0]	33.806[0]
5	0.029[00]	3.101[0]	0.193[0]	61.738[0]
6	1.445[-4]	0.533[0]	0.003[0]	3.128[0]
7	0.048[0]	12.817[0]	0.048[0]	12.932[0]
8	1.692[0]	0.127[0]	0.002[0]	1.543[0]

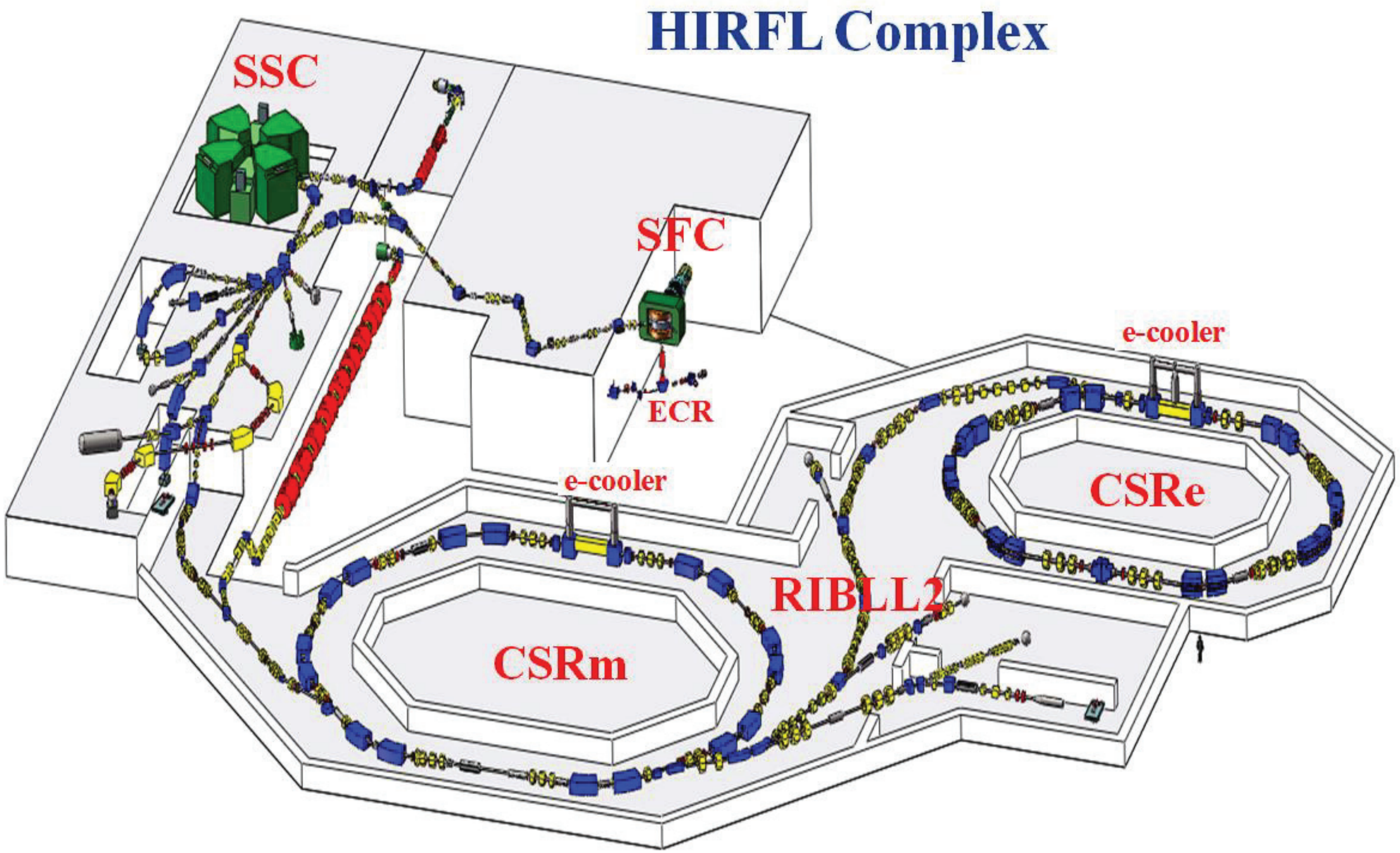
Note: Numbers in the squared brackets are powers of 10.

4. Summary and outlook

Summary

- DR spectrum of Na-like Krypton was measured first time;
- Both ΔN=0 and ΔN=1 resonances were observed in the measured spectrum;
- This work renewed the calculation of DR spectra forNa-like Kr^{25+} by AUTOSTRUCTURE.
- The plasma rate coefficients was derived and compared with the available theoretical calculation;
- The DR experiments at the CSRm pave the way for our upcoming DR experiments at the CSRe and also on the future facility HIAF;

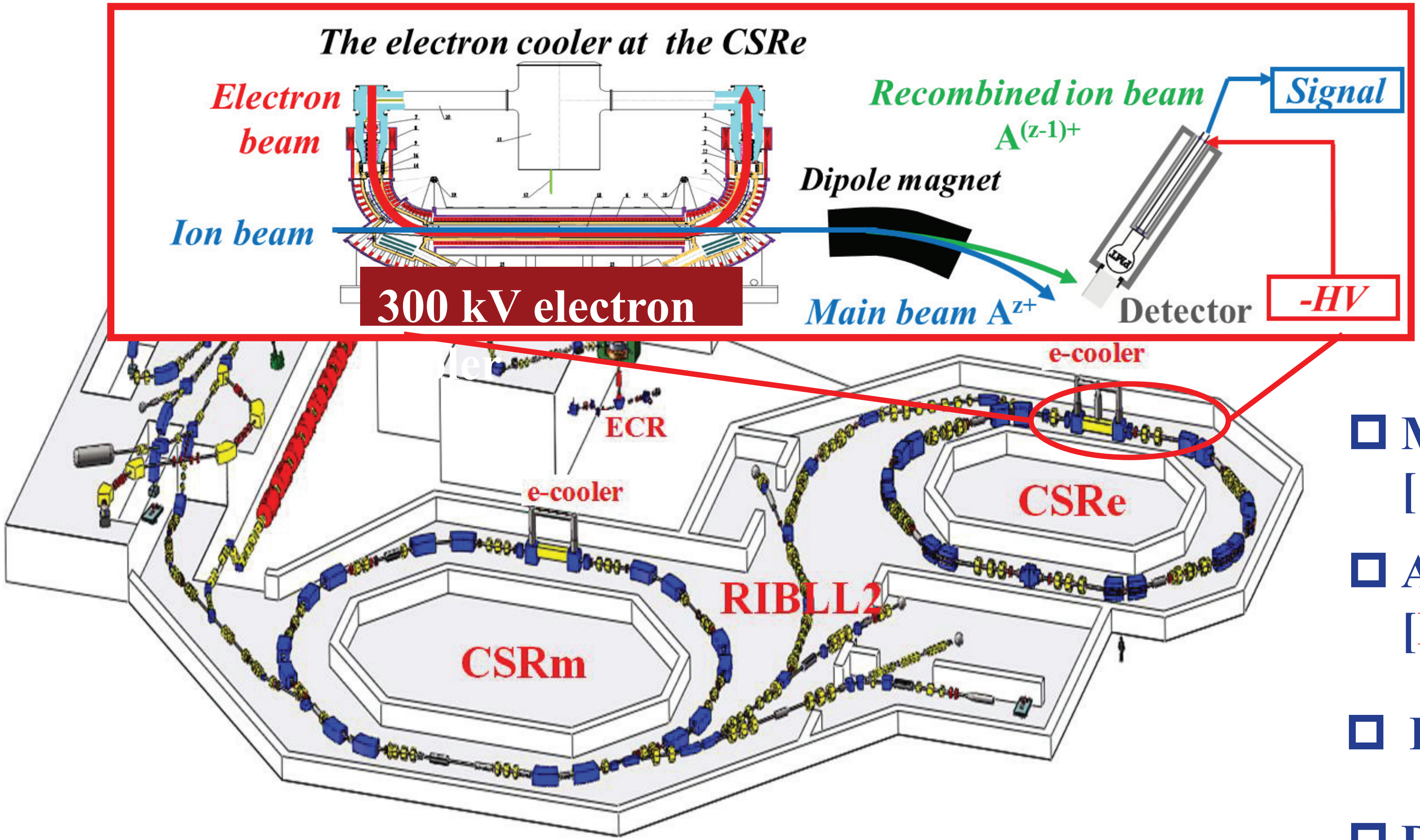
Outlook-upcoming DR experiment at the CSRe



Sketch wiew of DR experiment at the CSRe

- ☐ Much broader detuning energy range
  [±30 kV~1500 eV (U^{89+}@250MeV/u)]
- ☐ Astrophysics relevant DR spectroscopy
  [H-like, He-like, Li-like, Be-like]
- ☐ DR data of W^{q+} for the ITER project
- ☐ DR research on radioactive ion beams
  [CSRm + RIBLL2 + CSRe]

Outlook-upcoming DR experiment at the CSRe



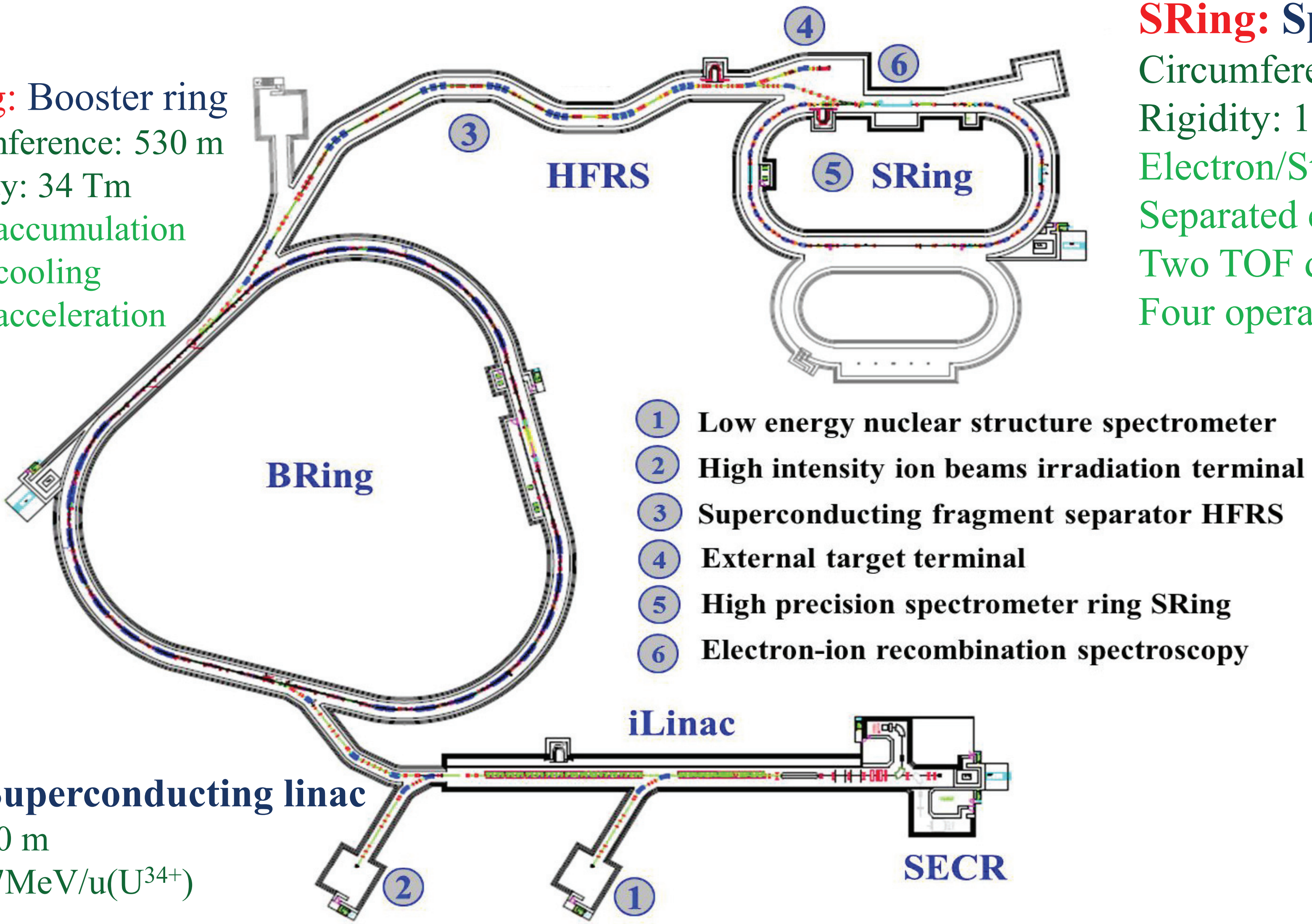
Sketch wiew of DR experiment at the CSRe

- Much broader detuning energy range [±30 kV~1500 eV (U^{89+}@250MeV/u)]
- Astrophysics relevant DR spectroscopy [H-like, He-like, Li-like, Be-like]
- DR data of W^{q+} for the ITER project
- DR research on radioactive ion beams [CSRm + RIBLL2 + CSRe]

Outlook-future DR experiment at the HIAF-SRing

BRing: Booster ring
Circumference: 530 m
Rigidity: 34 Tm
Beam accumulation
Beam cooling
Beam acceleration

SRing: Spectrometer ring
Circumference:290m
Rigidity: 13Tm
Electron/Stochastic cooling
Separated electron target
Two TOF detectors
Four operation modes



iLinac: Superconducting linac
Length:100 m
Energy: 17MeV/u(U^{34+})

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Outlook-future DR experiment at the HIAF-SRing

SRing: Spectrometer ring
Circumference:290m
Rigidity: 13Tm

BRing: Booster ring
Circumference: 530 m

The highlight of DR experiments at HIAF

electron-cooler & an ultra-cold electron-target
a unique research platform
electron-ion recombination spectroscopy!

iLinac: Superconducting linac
Length:100 m
Energy: 17MeV/u(U^{34+})

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DR international cooperation group

IMPCAS, Lanzhou	Z. K. Huang, W. Q. Wen, H. B. Wang, S. Mahmood, N. Khan, X. Y. Chai, L. J. Dou, X. L. Zhu, D. M. Zhao, L. J. Mao, Y. J. Yuan, J. Li, X. M, Ma, J. C. Yang, X. Ma;
USTC, Hefei	X. Xu, S. X. Wang, W. Q. Xu, L. F. Lin;
Uni. Fudan, Shanghai	T.H. Xu, K. Yao, Y. Yang;
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;
Uni. Strathclyde	N. R. Badnell, Simon Preval;

Thanks for your kind attention!

Thank You!

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