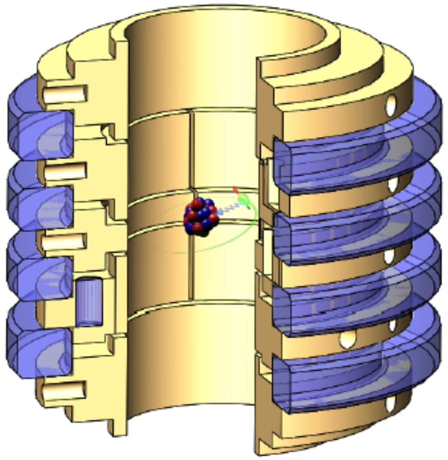
Recent progress on Shanghai Penning Trap



Bingsheng Tu

International Symposium on Stored Ions for Precision Measurements

Fudan University

2023-11-24

Penning Trap

<u>Eigen motions:</u>

- Reduced cyclotron frequency: $\sim 2\pi \cdot 25\ MHz$
- Magnetron drift frequency: $\sim 2\pi \cdot 8\ kHz$
- Axial frequency: $\sim 2\pi \cdot 650\ kHz$

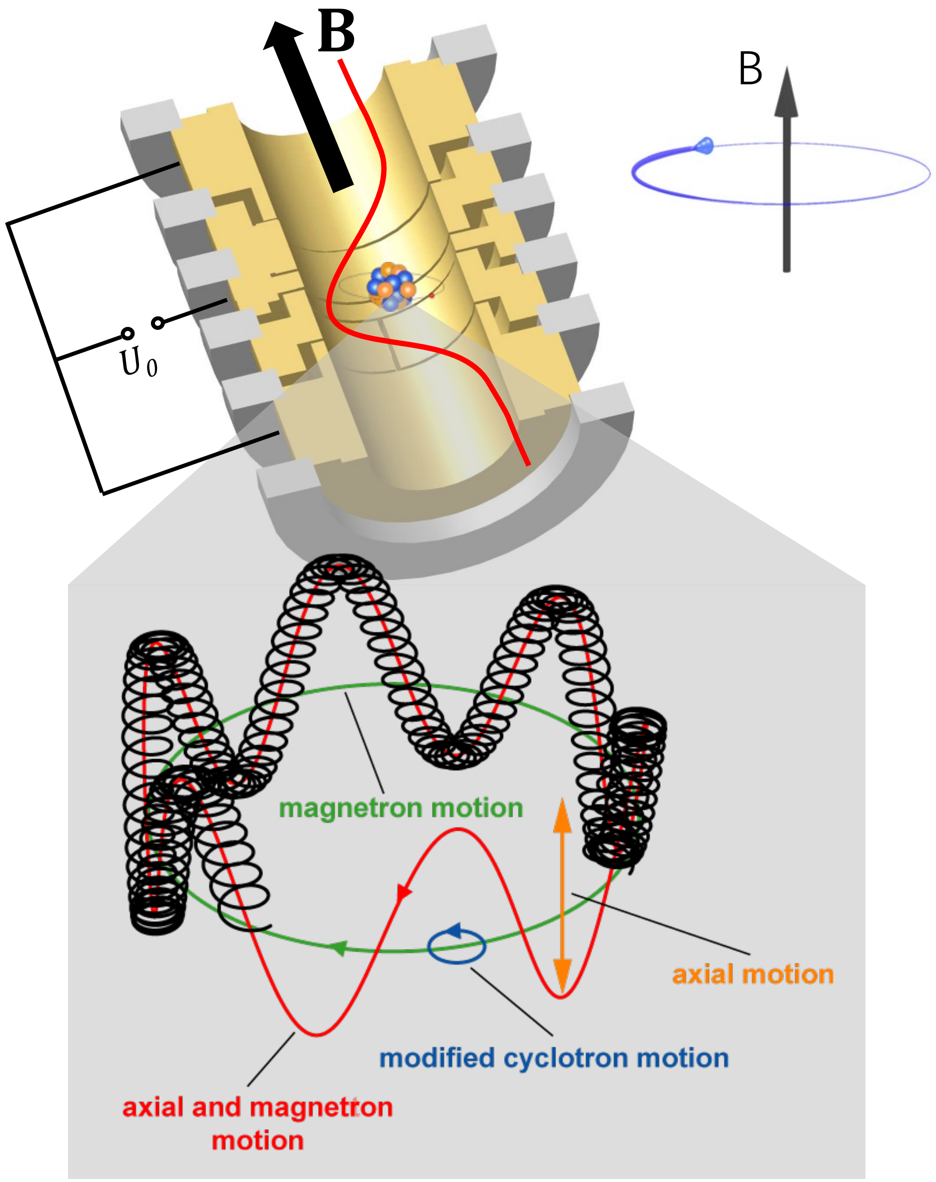
Free cyclotron frequency $\omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2$

(Brown-Gabrielse invariance theorem)

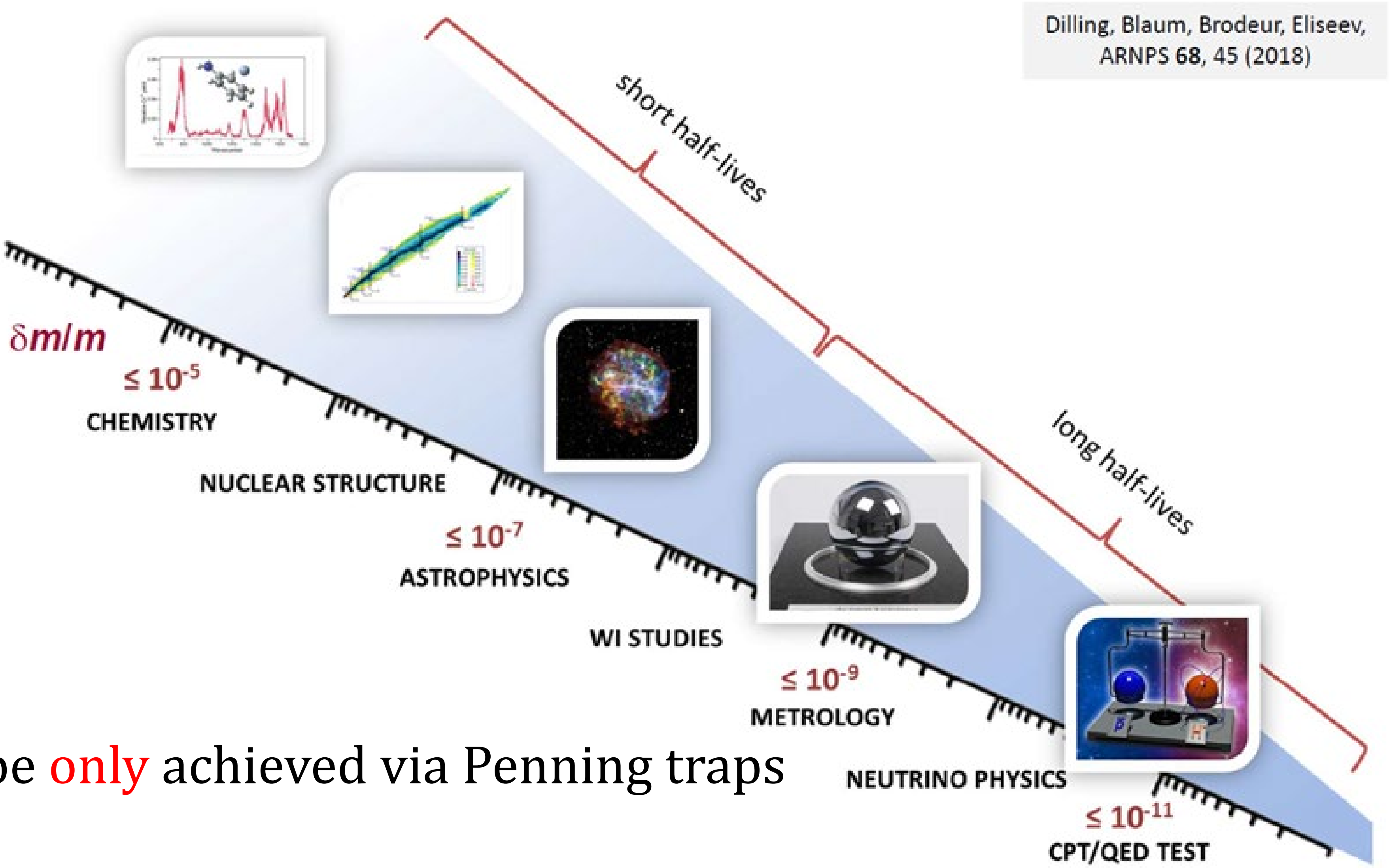
$$\nu_c = qB/(2\pi m_{ion})$$

Frequency → Atomic mass

Most precise mass spectrometry



Mass Spectrometry



$\frac{\delta m}{m} < 10^{-9}$ can be only achieved via Penning traps

Highest accuracy $\frac{\delta m}{m} \sim 10^{-12}$ for stable nuclei

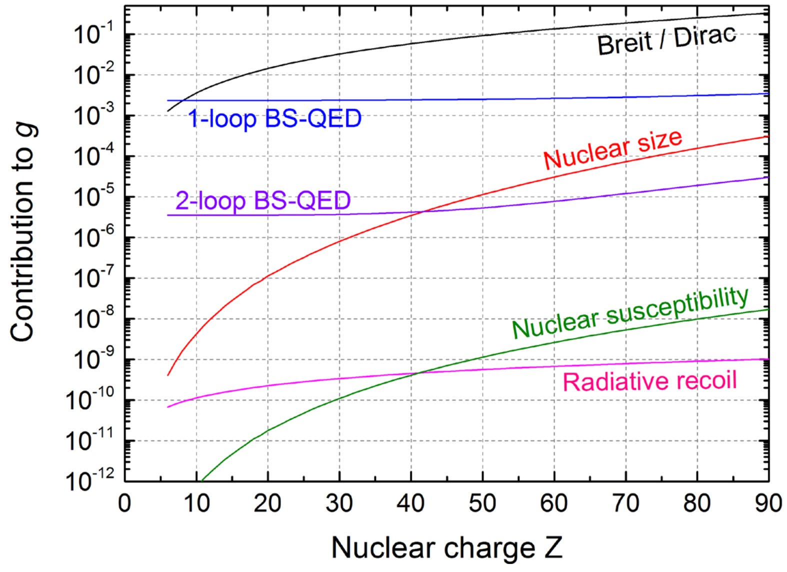
g-factor of fundamental particles

Free electron g factor
——most stringent QED test

$$\frac{g}{2} = 1.001\ 159\ 652\ 180\ 59(13)$$
$$\alpha^{-1} = 137.035\ 999\ 166\ \ (15)$$

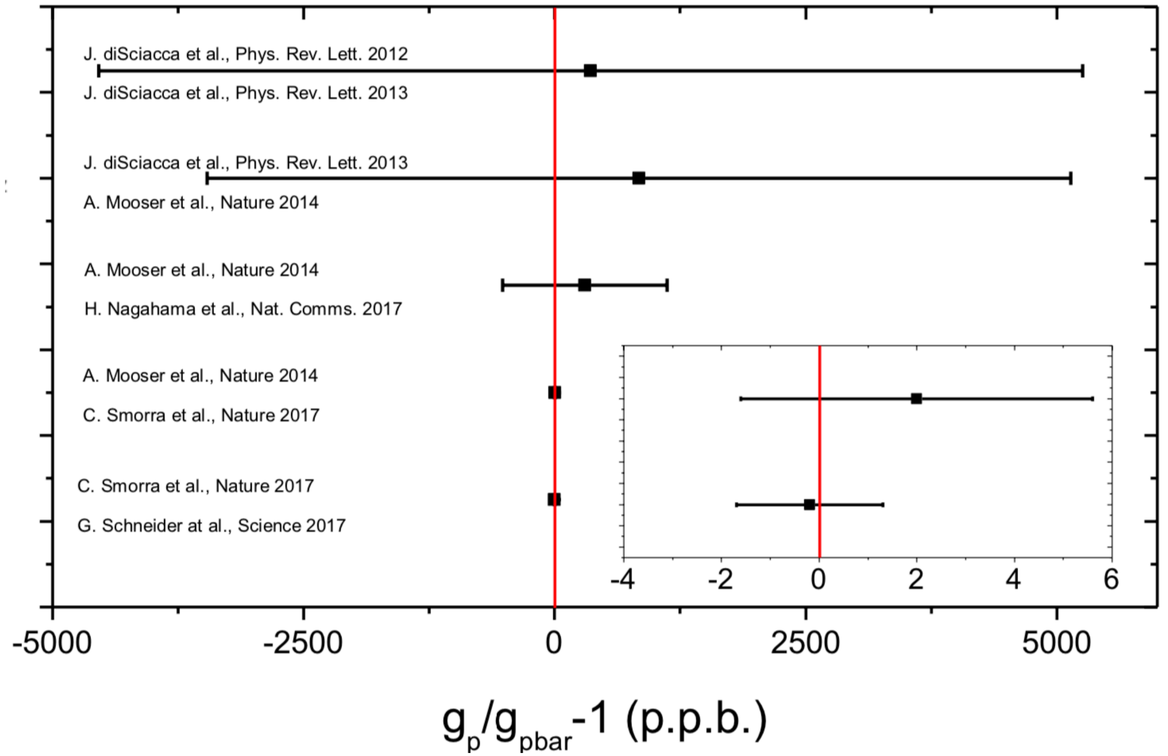
X. Fan et.al PRL **130**, 071801 (2023)

g factor of a bound-state electron
—— most stringent BS-QED test



S. Strum, *et al., Phys. Rev. Lett 107*,023002 (2011)
F. Koehler, *et al., Nat. Commun.* 7, 10246 (2016)

Proton and antiproton g *factors*
——most stringent CPT-invariance test



Year	Proton $g_p/2$	Antiproton $g_{pbar}/2$	CPT $\lvert g_p/g_{\bar{p}} \rvert - 1$	Collaboration
2011	2.792 847 353 (28)	2.786 2 (83)	0.002 4 (29)	Pask (ASACUSA)
2013	2.792 846 (7)	2.792 845 (12)	0.000 000 4 (49)	diSciacca (ATRAP)
2014	**2.792 847 349 8 (93)**	2.792 845 (12)	0.000 000 8 (43)	**Mooser(BASE)/**diSciacca (ATRAP)
2016	**2.792 847 349 8 (93)**	**2.792 846 5 (23)**	**0.000 000 30 (82)**	**Mooser/Nagahama (BASE)**
2017/1	**2.792 847 349 8 (93)**	**2.792 847 344 1 (42)**	**0.000 000 002 0 (36)**	**Mooser/Smorra (BASE)**
2017/2	**2.792 847 344 62 (82)**	**2.792 847 344 1 (42)**	**-0.000 000 000 2 (15)**	**Schneider/Smorra (BASE)**

ALPHATRAP @ MPIK

PENTATRAP @ MPIK

Shanghai Penning Trap @ Fudan

Motivation

Status

Technique foundations

Perspective

Shanghai Penning Trap - Motivations

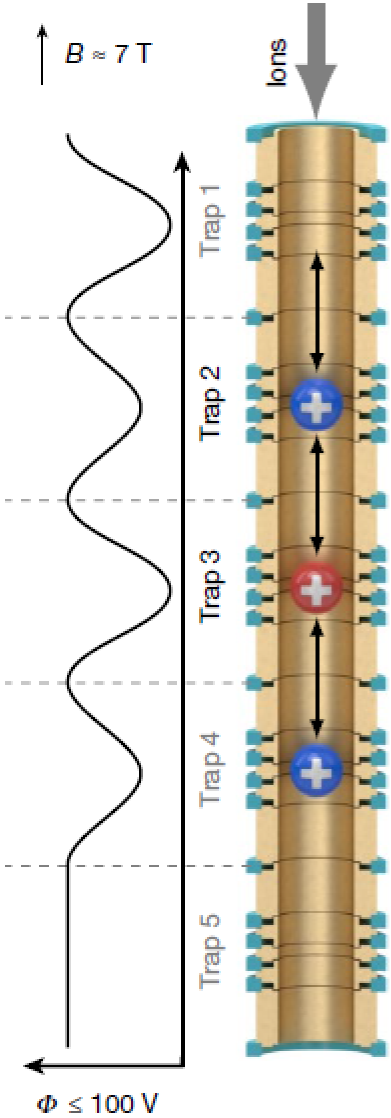
- **Develop the Penning trap techniques for ion trapping and precision measurement**

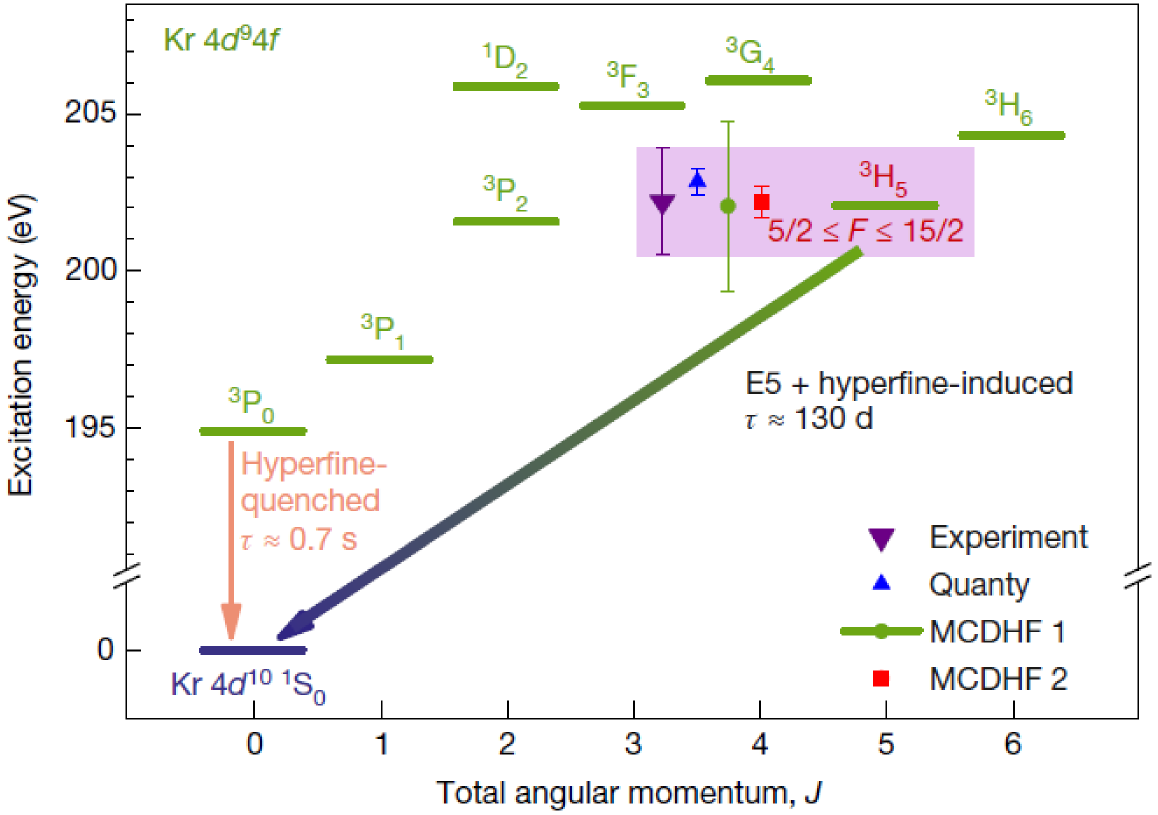
- **Cryogenic Penning trap + Highly charged ions + Precise mass measurement and spectroscopy**

- **Proposals: measurement of long-lived metastable states**

"See" long-lived metastable states

PENTATRAP @ MPIK



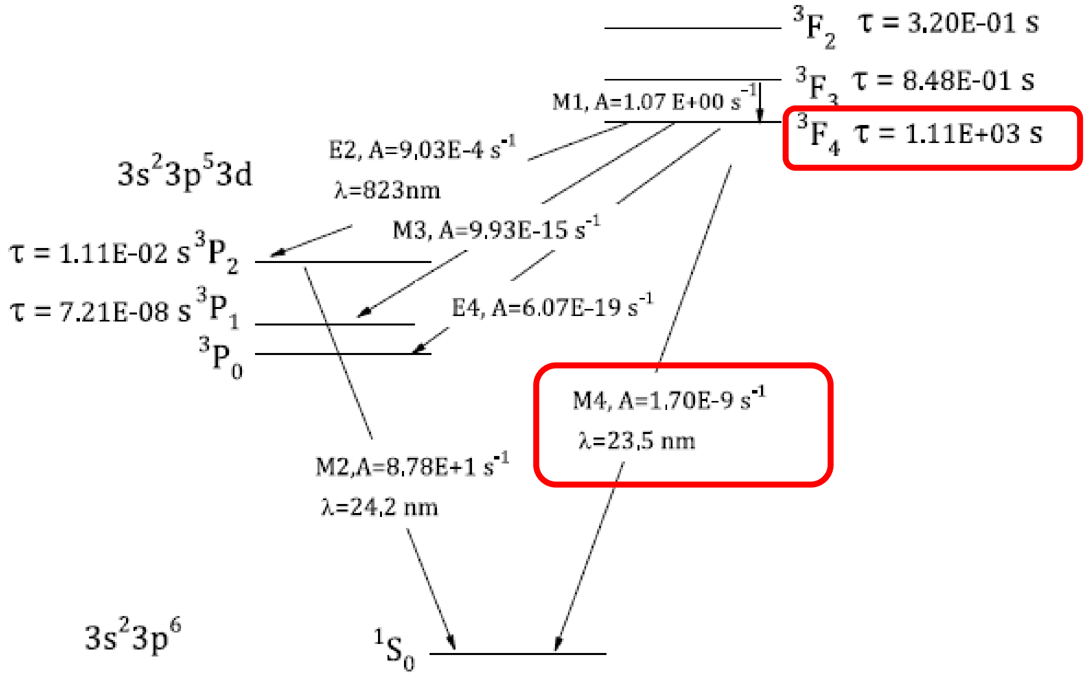


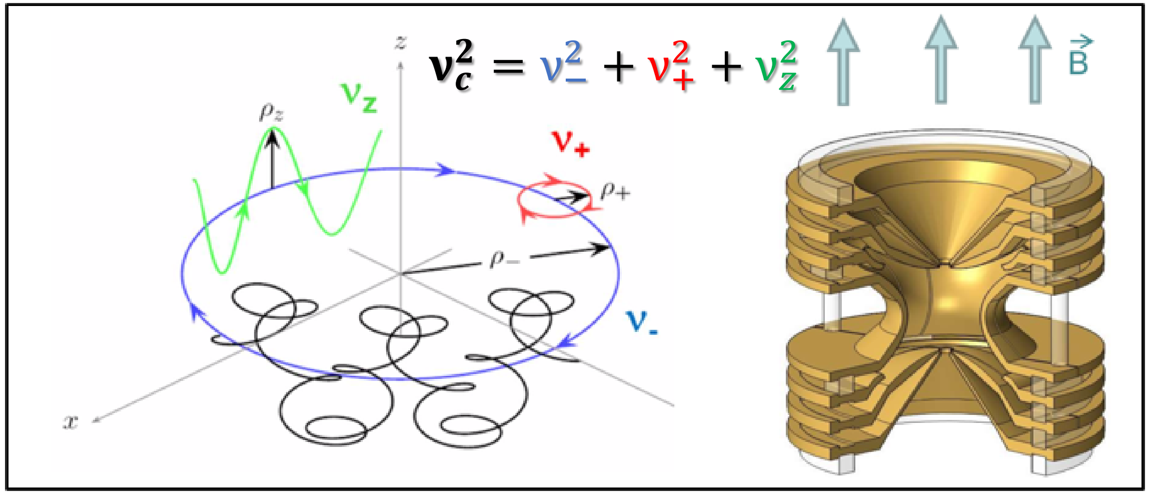
Nature **581**, pages 42–46 (2020)

“See” decays from long-lived metastable states

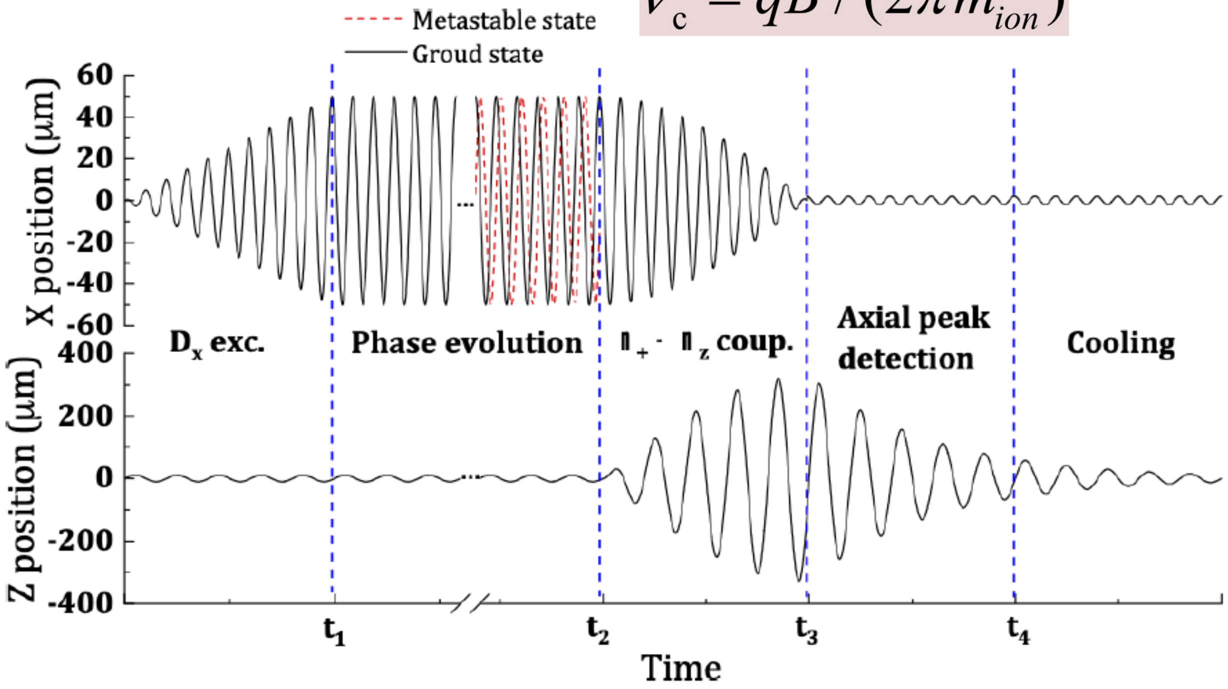
B. Tu, et. al., Physical Rev. Res. **5**, 043014 (2023)

$^{56}Fe^{8+}$ levels





$$\nu_c = qB/(2\pi m_{ion})$$

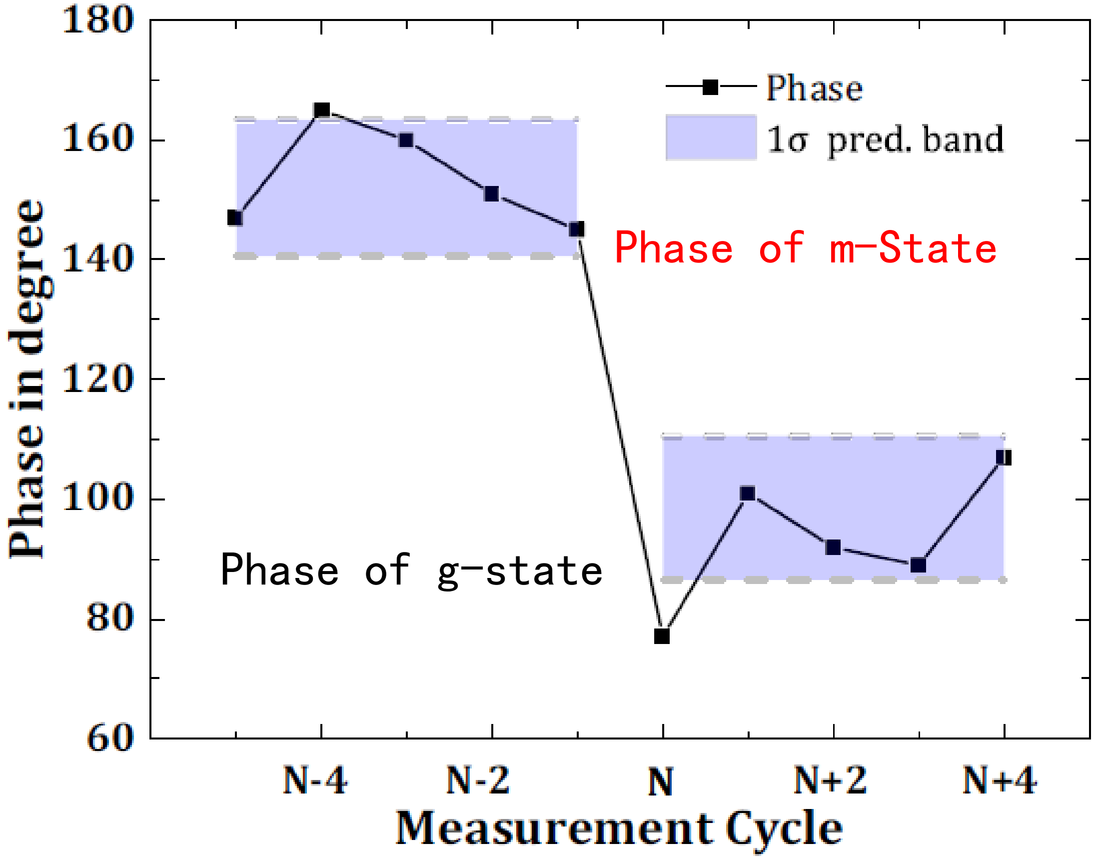


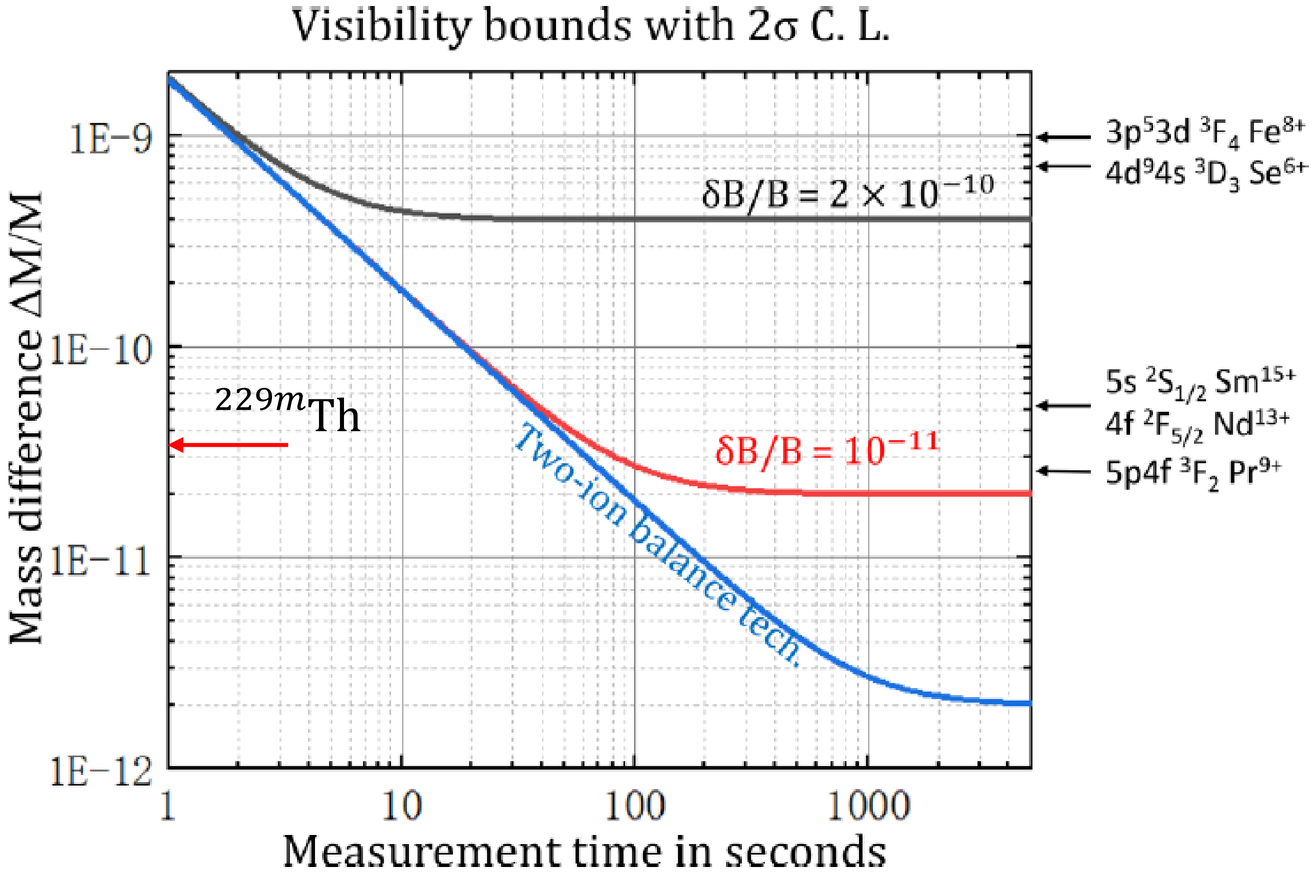
Hardly can see the high-order forbidden decays by conventional fluorescence detection

Precision Spectroscopy with Highly Charged Ion in the Dark -- **Reinhold Schuch**

“See” decays from long-lived metastable states

B. Tu, et. al., Physical Rev. Res. **5**, 043014 (2023)





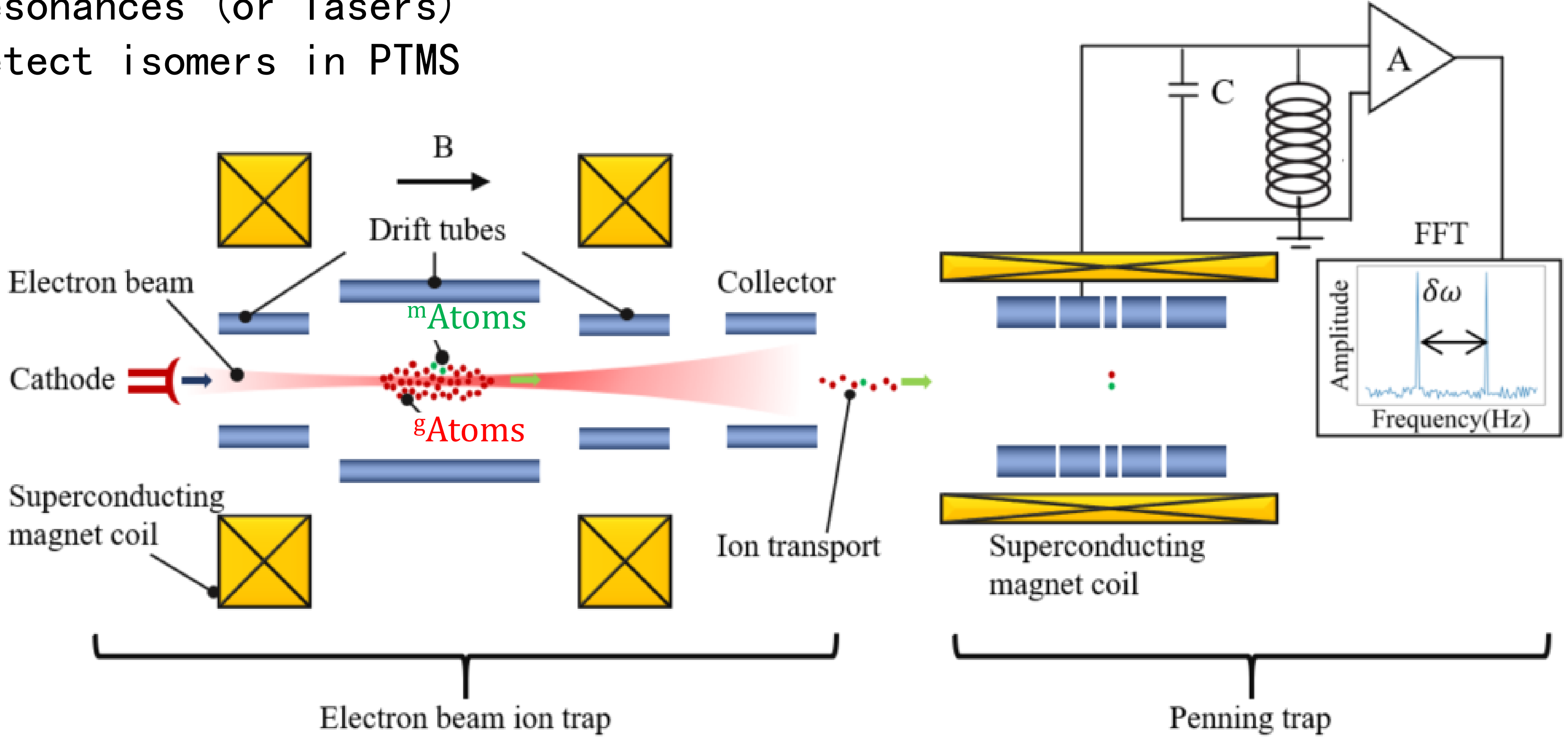
Mass ratio

$$R = \frac{\nu_{z1}^2}{2\nu_{c1}^2} + \left(1 - \frac{\nu_{z1}^2}{2\nu_{c1}^2}\right)\left(1 + \frac{\Delta\nu_+(\Delta\nu_+ - 2\nu_{+1})}{\left(\nu_{c1} - \nu_{z1}^2/2\nu_{c1}\right)^2}\right)^{1/2}$$

- Enable energy and lifetime measurements of long-lived metastable states

"See" long-lived nuclear isomeric state

i. Generate long-lived isomers via electron resonances (or lasers)
ii. Detect isomers in PTMS



$$\delta\omega = \omega_{iso} - \omega_0$$

- Search for NEEC, electron bridge and …

B. Tu, et. al., in preparation

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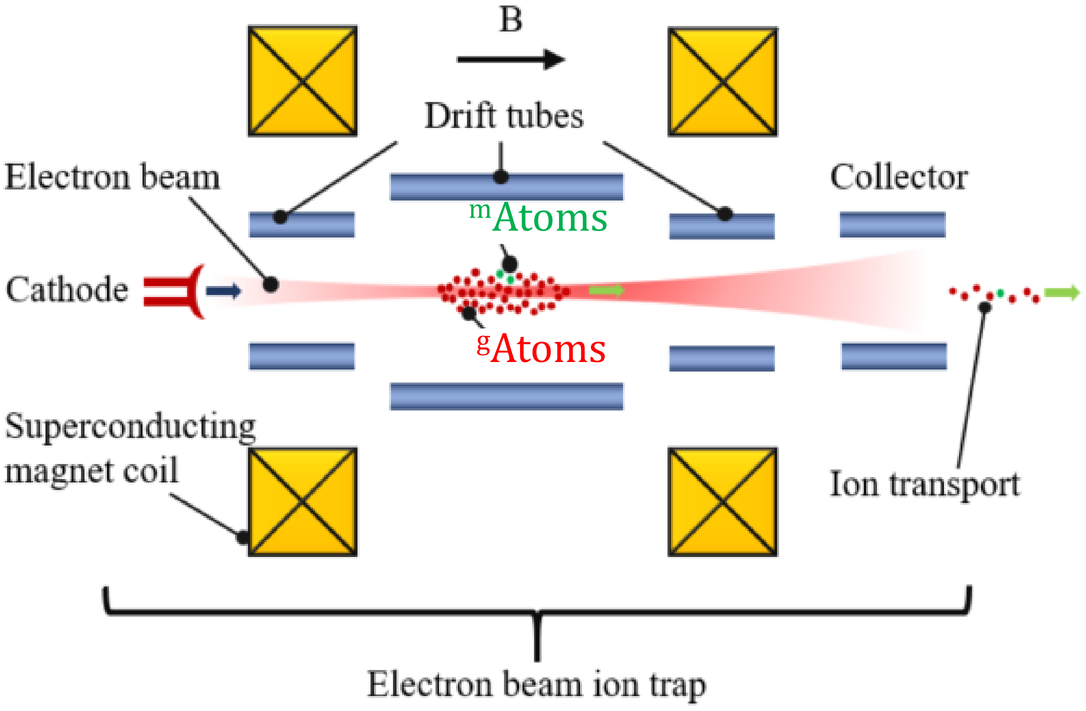

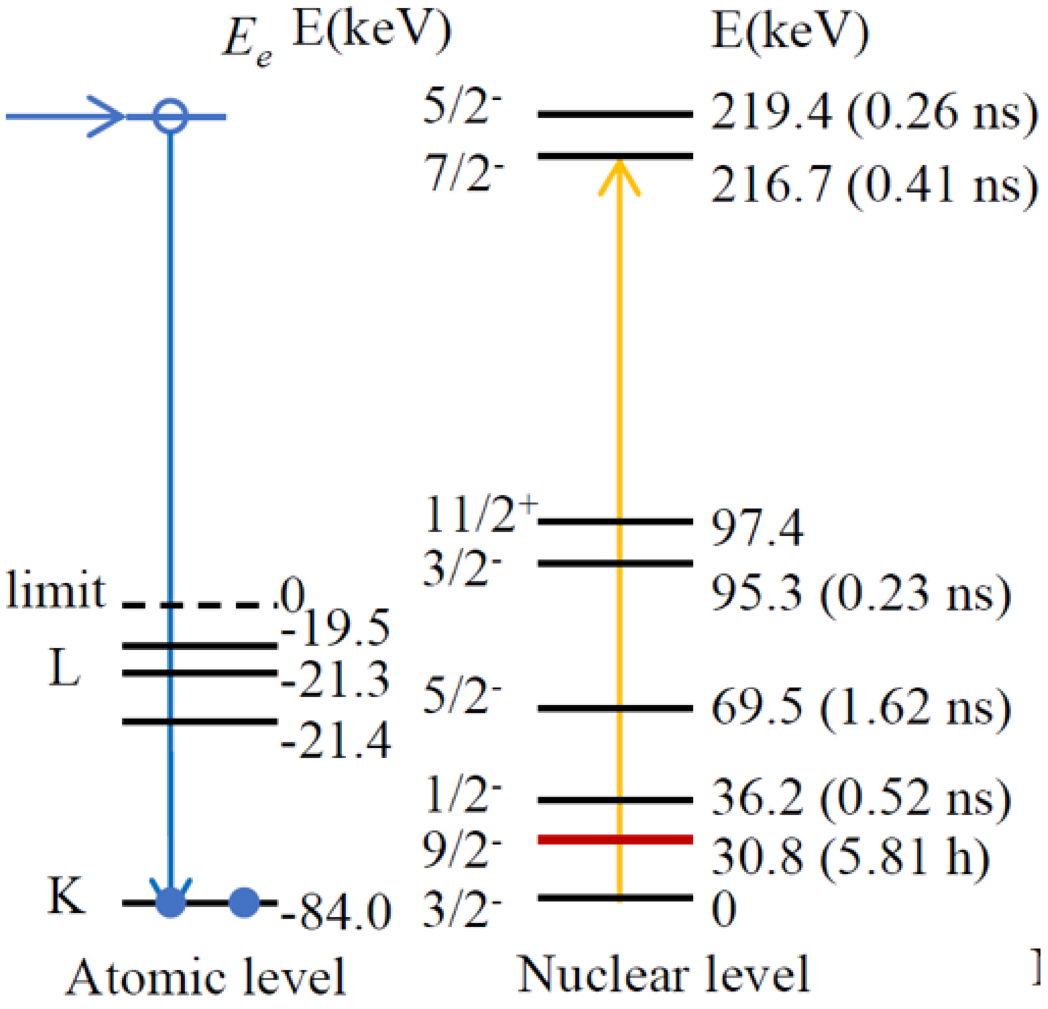

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B. Tu, et. al., in preparation

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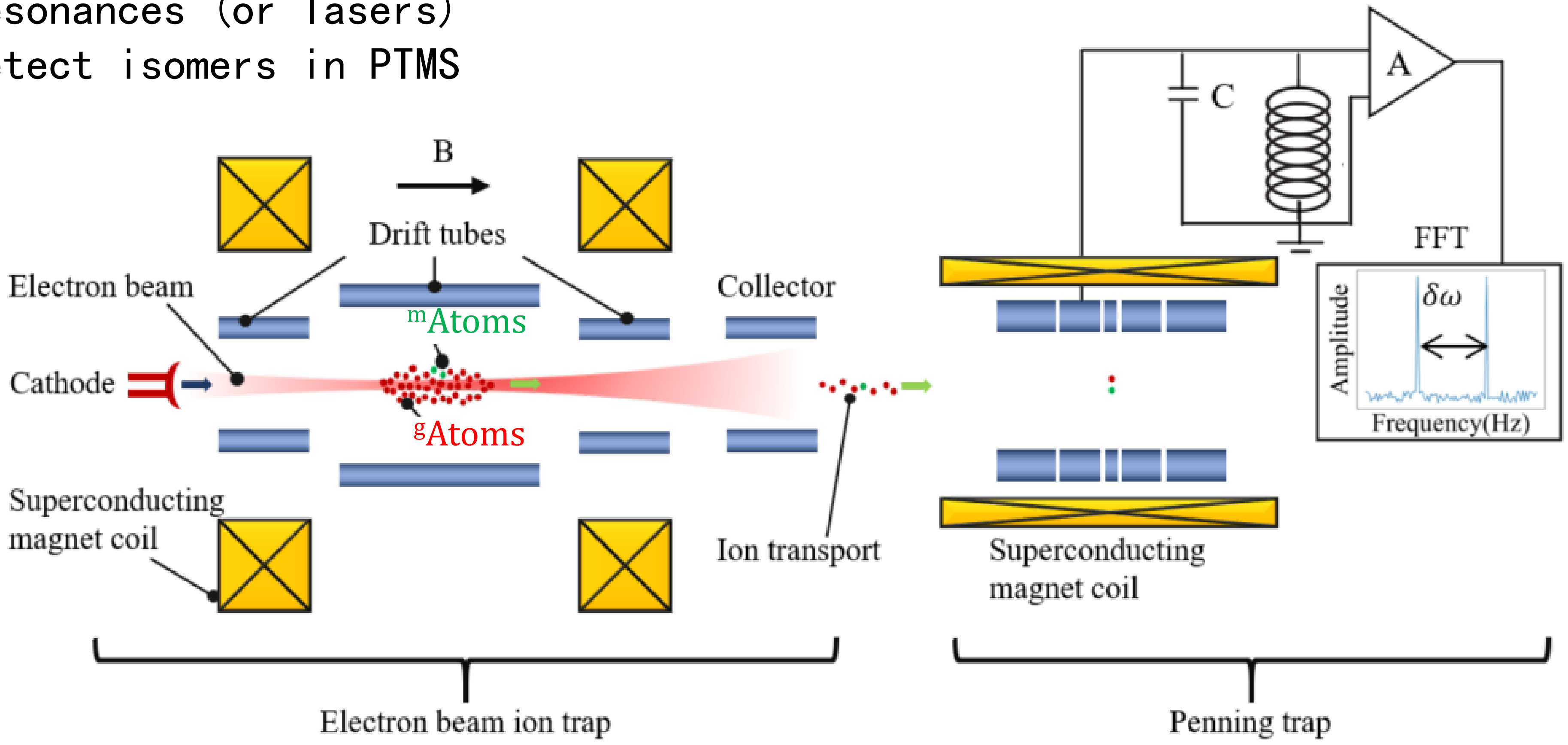

$\delta\omega = \omega_{iso} - \omega_0$

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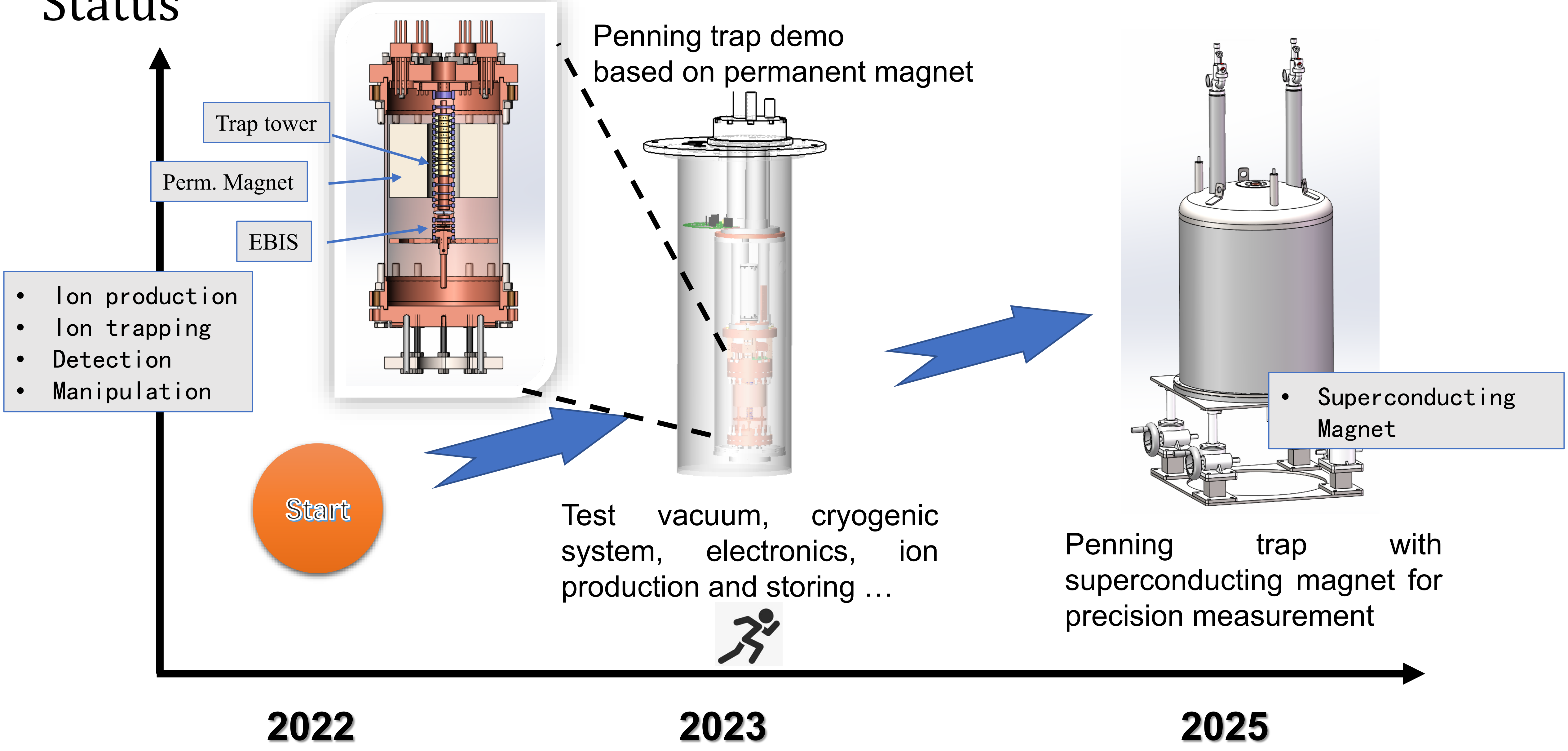
B. Tu, et. al., in preparation

Status



Trap tower
Perm. Magnet
EBIS
• Ion production
• Ion trapping
• Detection
• Manipulation
Start
Penning trap demo
based on permanent magnet
Test vacuum, cryogenic system, electronics, ion production and storing …
• Superconducting Magnet
Penning trap with superconducting magnet for precision measurement
2022
2023
2025

Development of 4K electronics

R&D route:

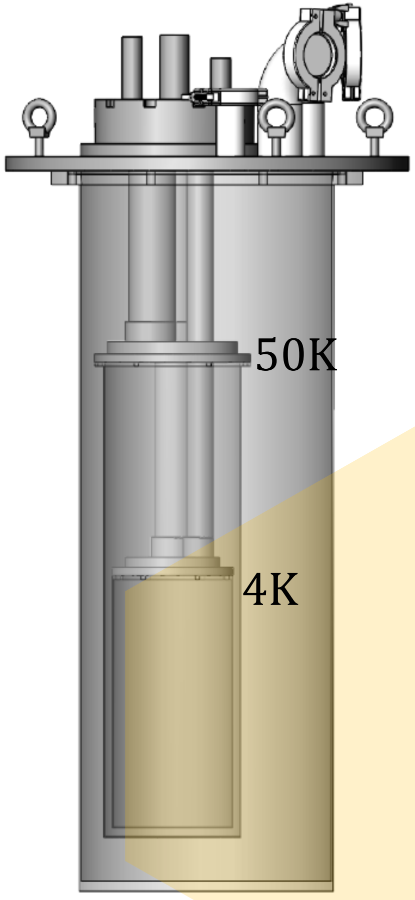
1. Setup 4K stage

2. Cryogenic Amp.

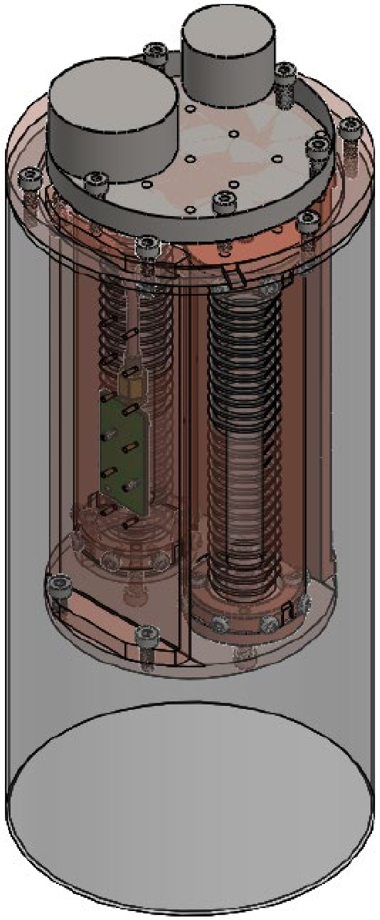
3. Tank circuit

4. Test at 4K

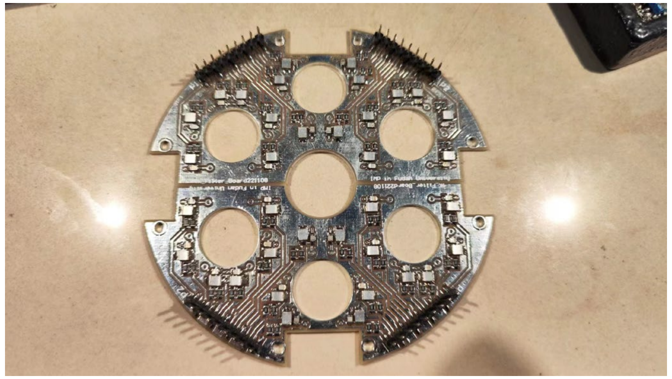
For image current detection



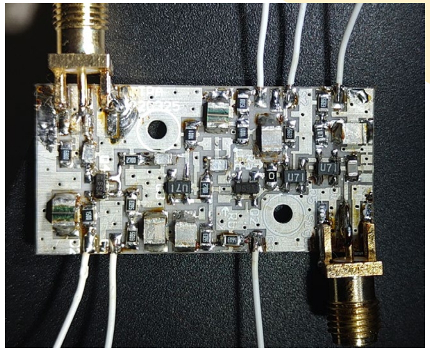
Cold-head based 4K stage



Filter board



Cryogenic Amplifier



Gain~24dB

Vn<0.8nV/$\sqrt{Hz}$

N = 900

L = 4.7mH

C = 5.7pF

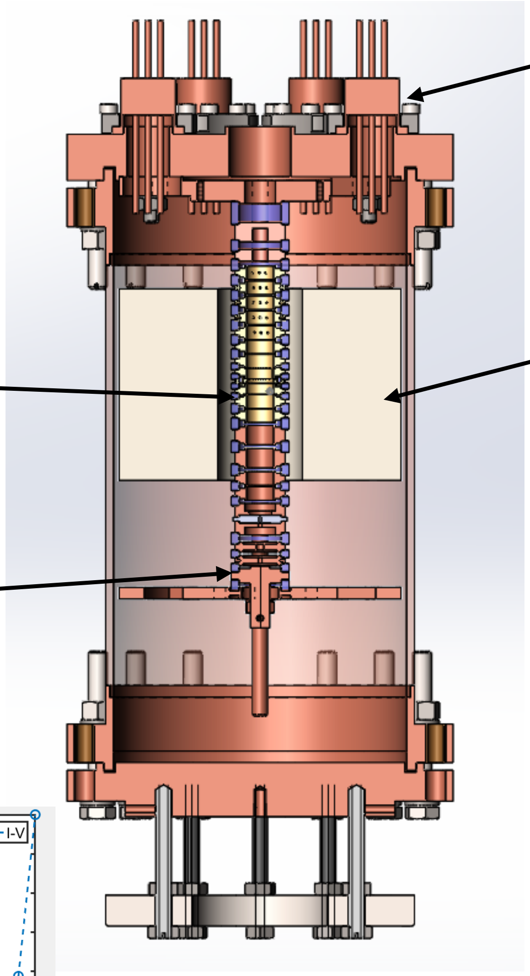
ω_R~1MHz

Q = 19,000

Trap tower building

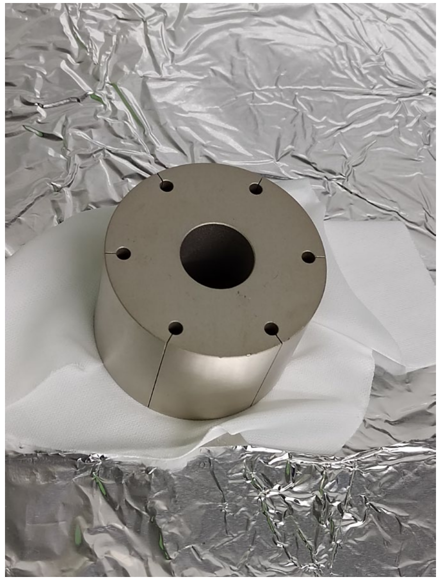
Trap tower

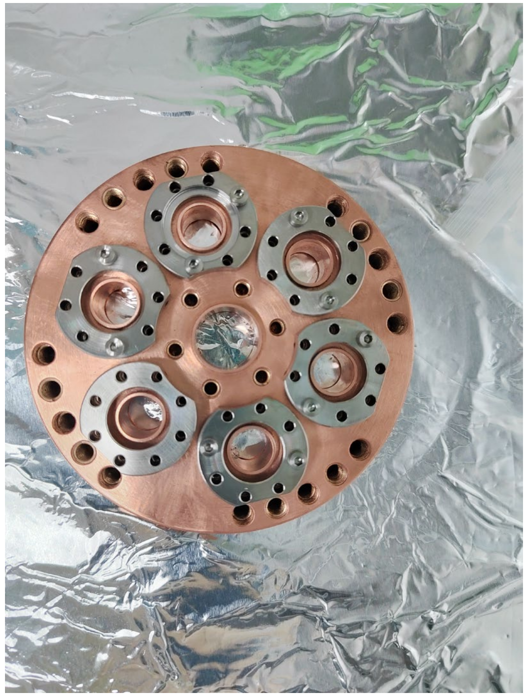
FEP

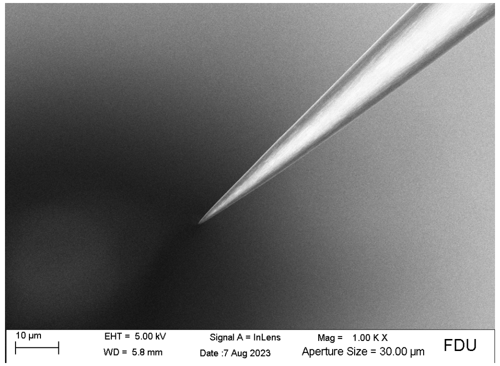


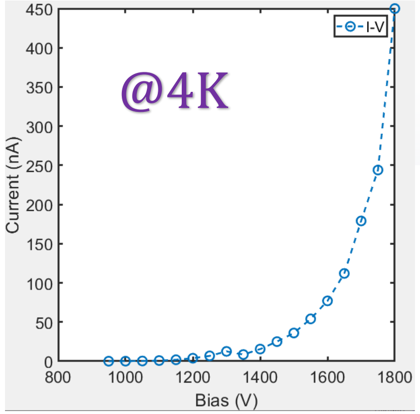
Feedthrough
Kyocera

SmCo

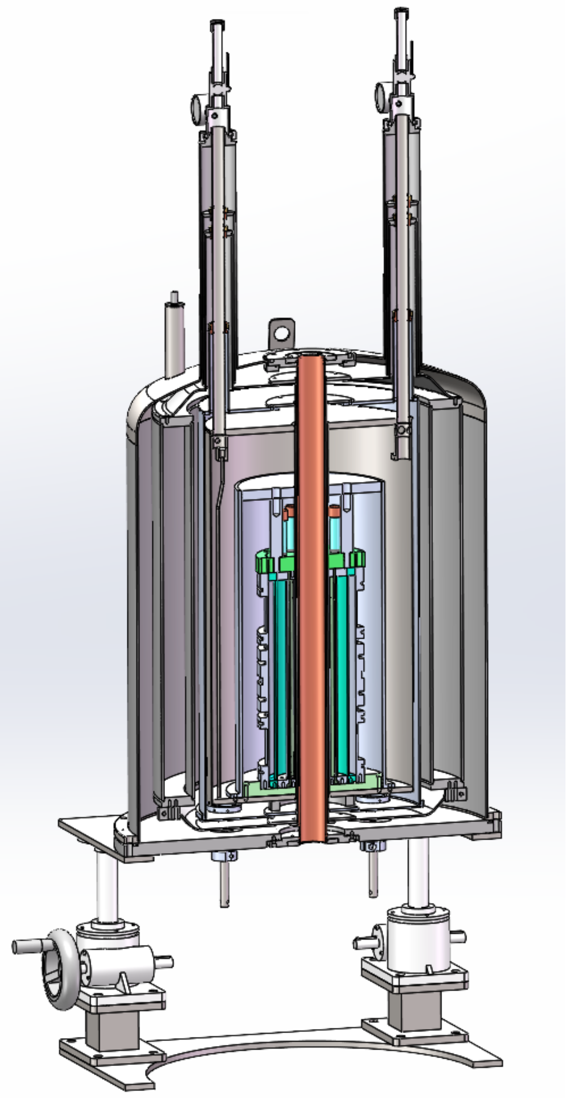


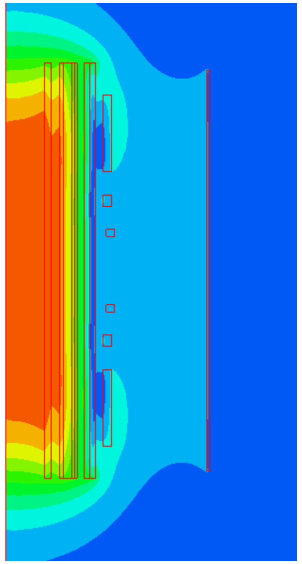


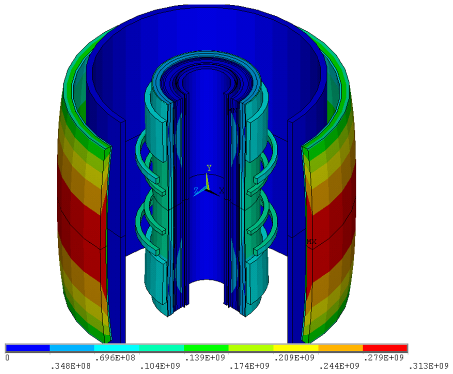


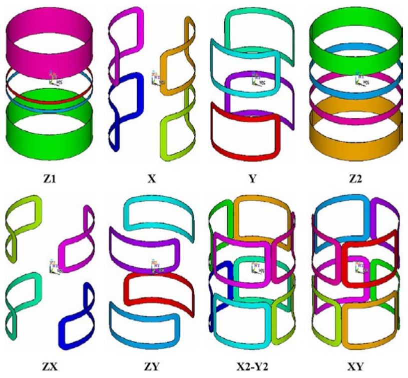


Magnet to be completed at 2025









B ≥ 7T

Type: Vertical

Warm bore size ≥130mm

Up to three-order shimming coils

Homogeneity：

better than 0.2 ppm at 1cm^3

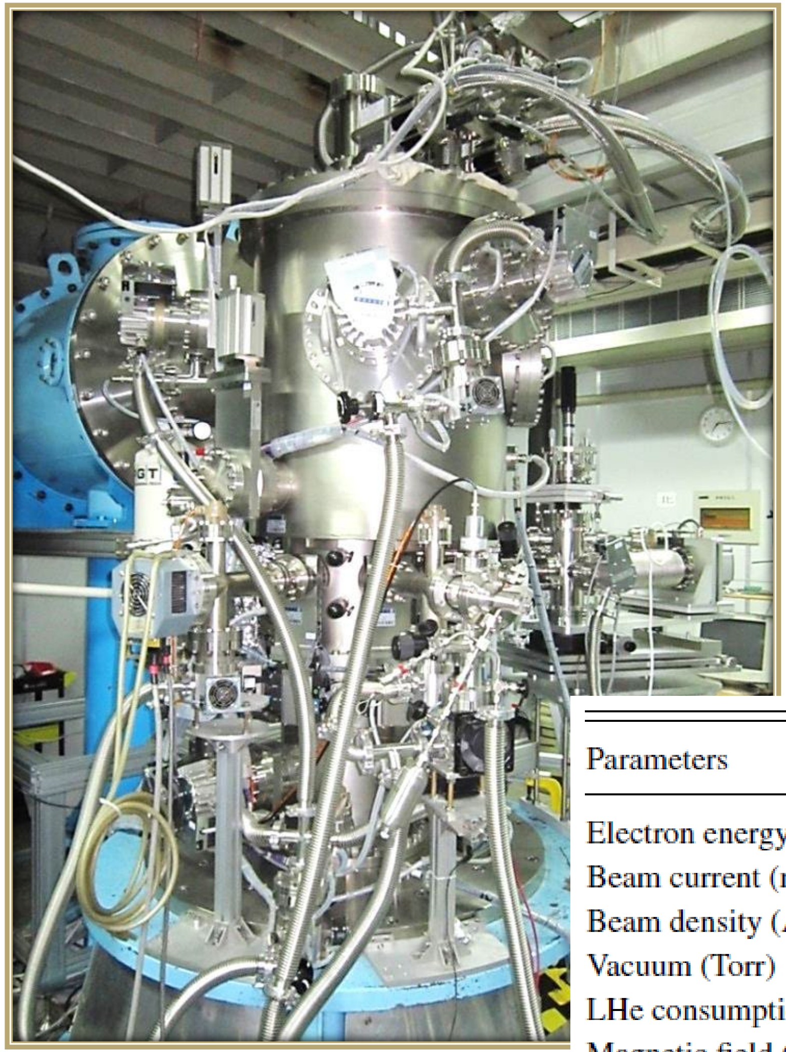
better than 0.5ppm at Φ2×5cm

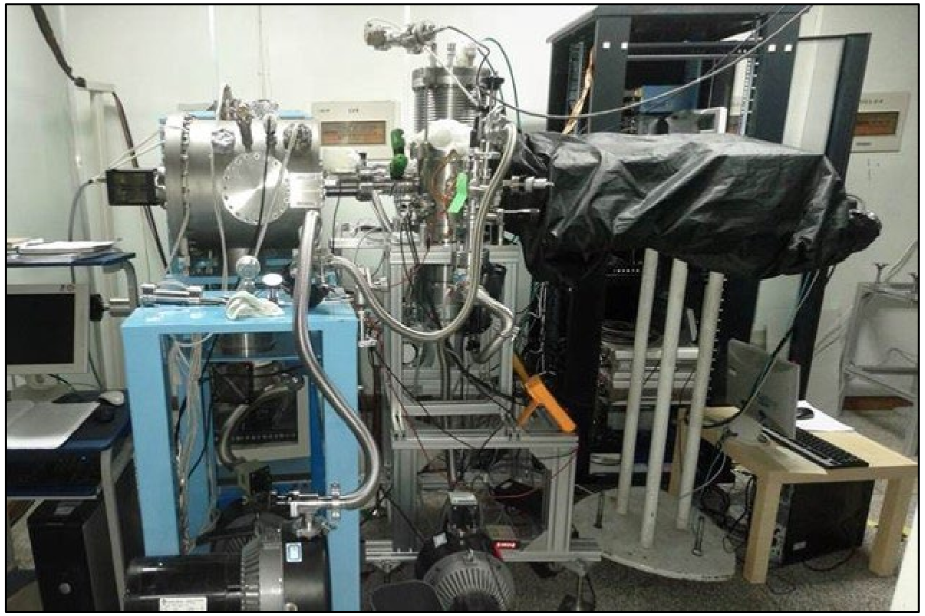
Stability：

Fluctuation better than 10^{-9}/h

Field strength decay better than 10^{-9}/h

Technique foundations





B= 0~0.25T
E_e=30~5000 eV
I_e=10 mA

Parameters	Upgraded
Electron energy (keV)	151
Beam current (mA)	218
Beam density (A/cm^2)	1793
Vacuum (Torr)	$\sim 7.5 \times 10^{-11}$
LHe consumption (l/h)	0
Magnetic field (T)	4.8

PRA 107, 062817 (2023)
Astro. Phys. J 937 48 (2022)
Opt. Exp. 30 25326 (2022)
Phys. Rev A. 105 032820(2022)
Phys. Rev A. 105, L030801 (2022)
Phys. Rev A. 103 022808(2021)
Phys. Rev A. 102 042817(2020)

Perspective

To setup an online Penning Trap facility

Expect collaborations with **HIAF** @ Huizhou and **XFEL** @ Shenzhen in the future

Thank you for your attention !

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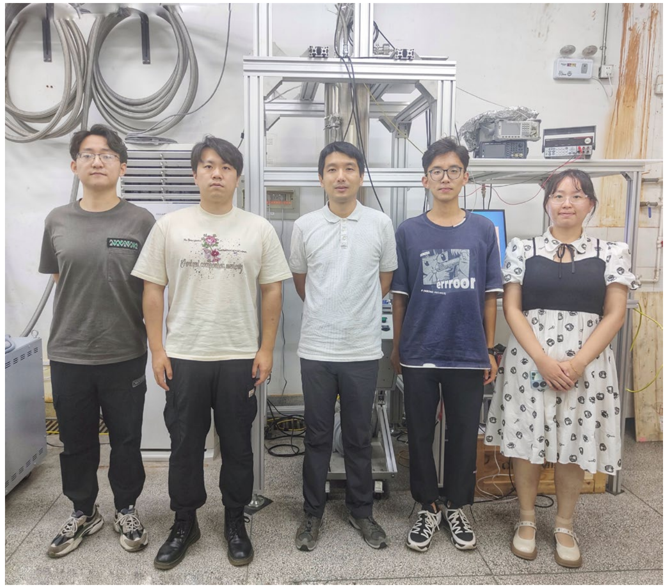
Max Planck Institute for Nuclear Physics

UNIVERSITY OF HEIDELBERG

Max-Planck-Partner Group

Humboldt Research Fellowship



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Baoren Wei

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IMP-CAS members: Yuhu Zhang, Meng wang, Zaiguo Gan, Wenxue Huang, Yulin Tian, Wenjia Huang, Xinliang Yan, Wei Wu(APACTRON)

IMP