Polarized Ion Source at IMP

Polarized ion beam team

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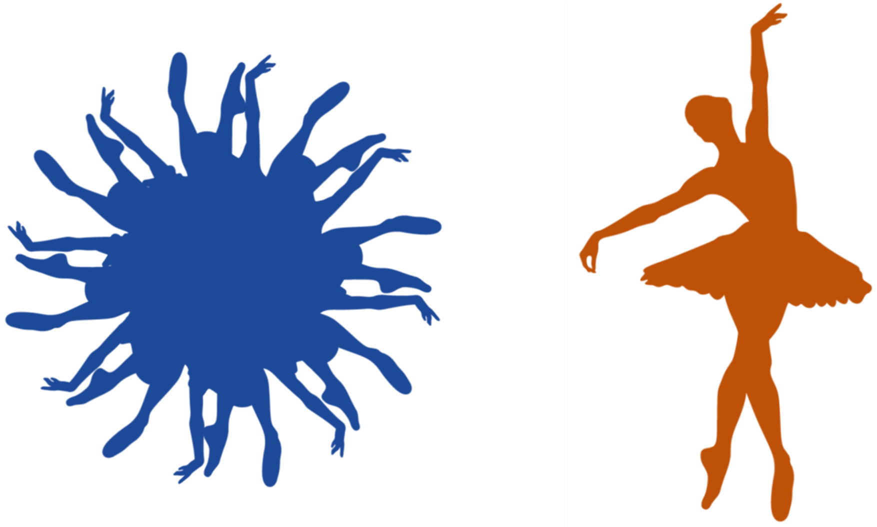
Outline

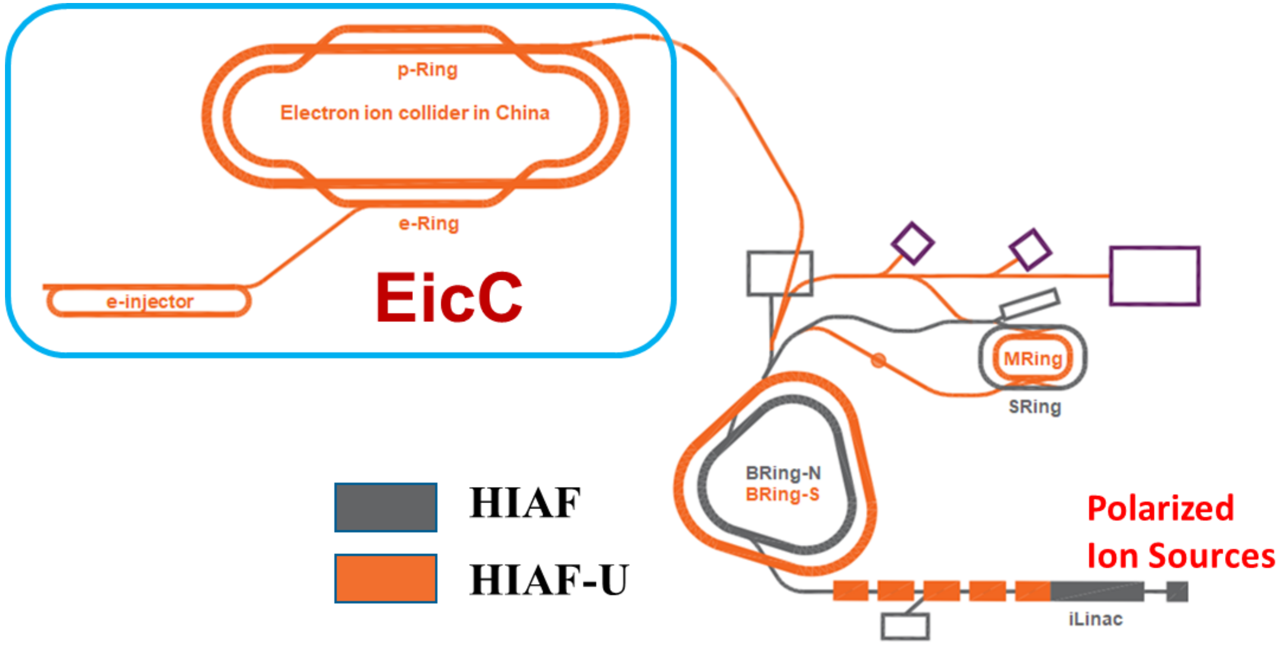
- Introduction: Polarized ion beams
- Status of SPIS at IMP
- Acceleration of polarized ions with HIAF and the challenges
- Summary

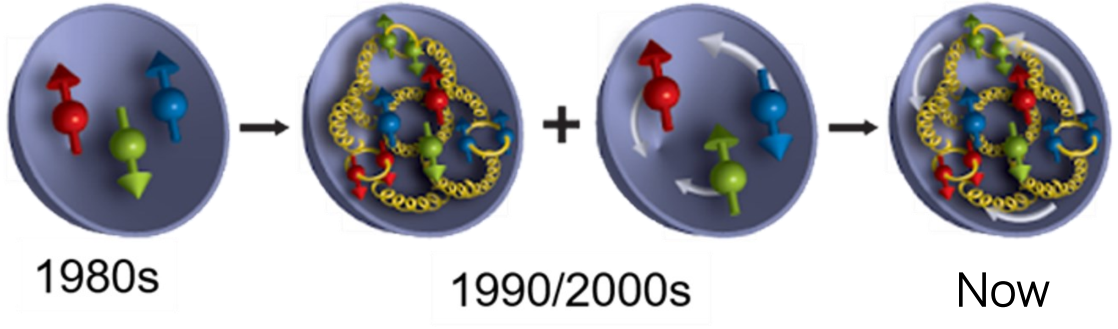
Introduction



Unpolarized　　Polarized

- Spin is an intrinsic property of particles
- Polarized particle beams (targets) utilize the degree of freedom of spin
- Investigating the important role of spin in nuclear structure and interactions
- Testing parity and time reversal symmetry

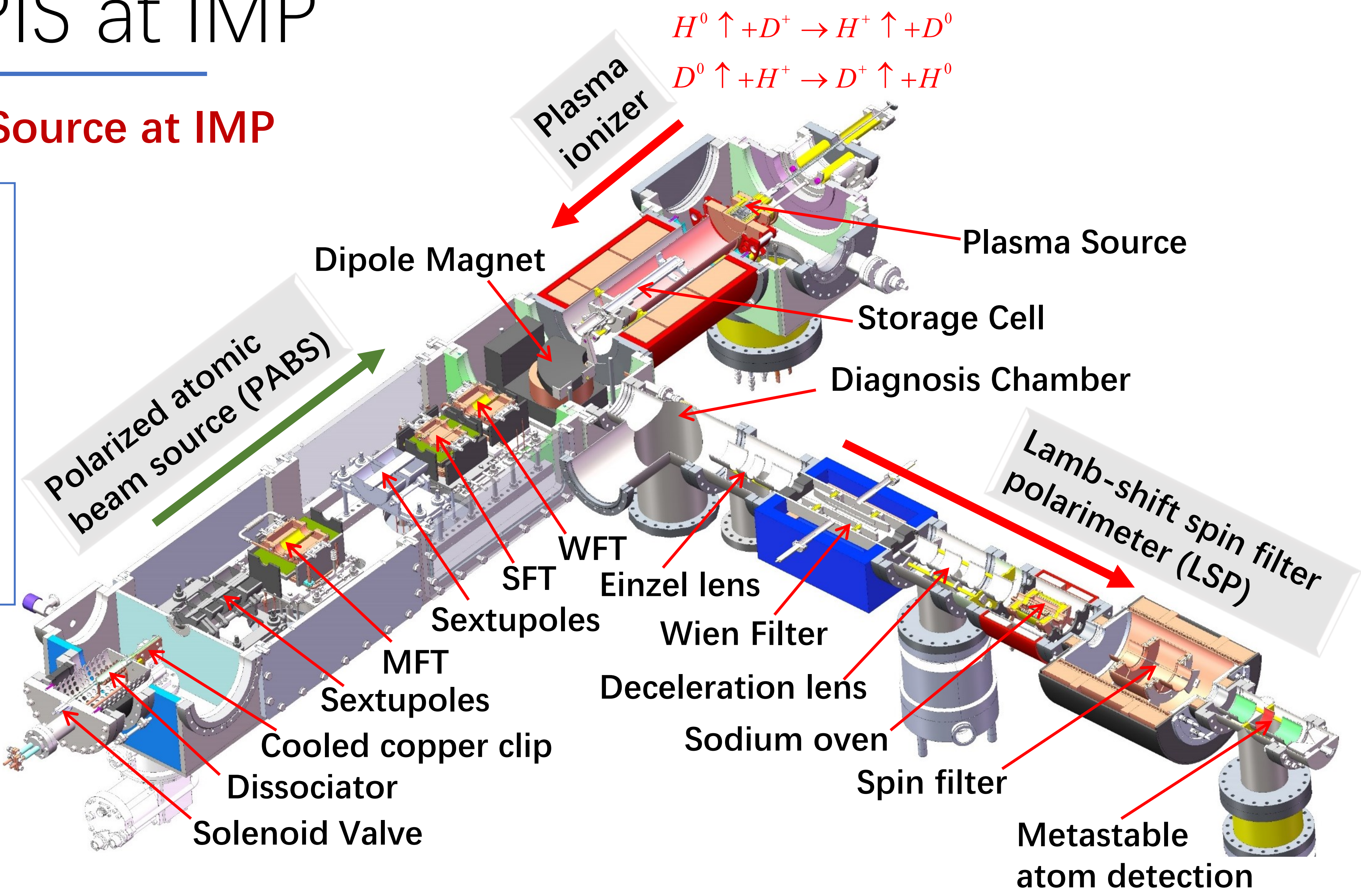




Status of SPIS at IMP

Spin Polarized Ion Source at IMP

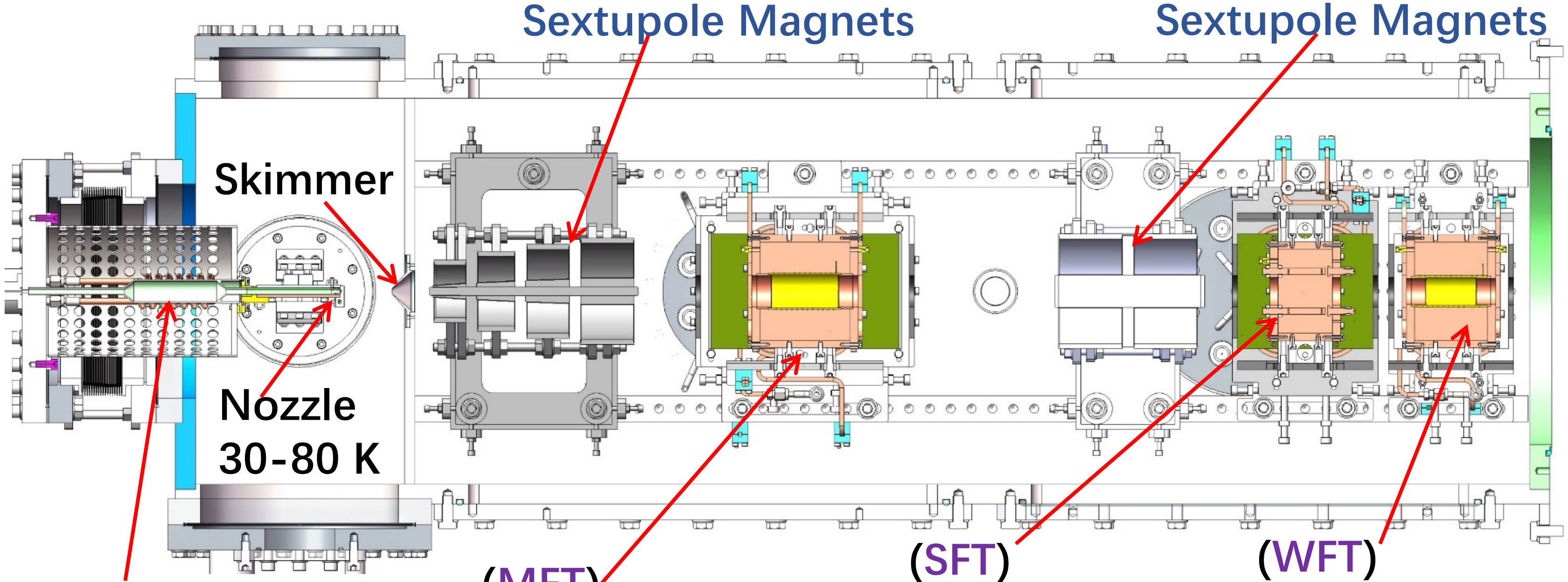
- Start from 2020.06
- Design Goals
  - Polarized H^+/D^+
  - Intensity: > 1 mA
  - Polarization: > 80%
  - 2-5 Hz, > 100 μs

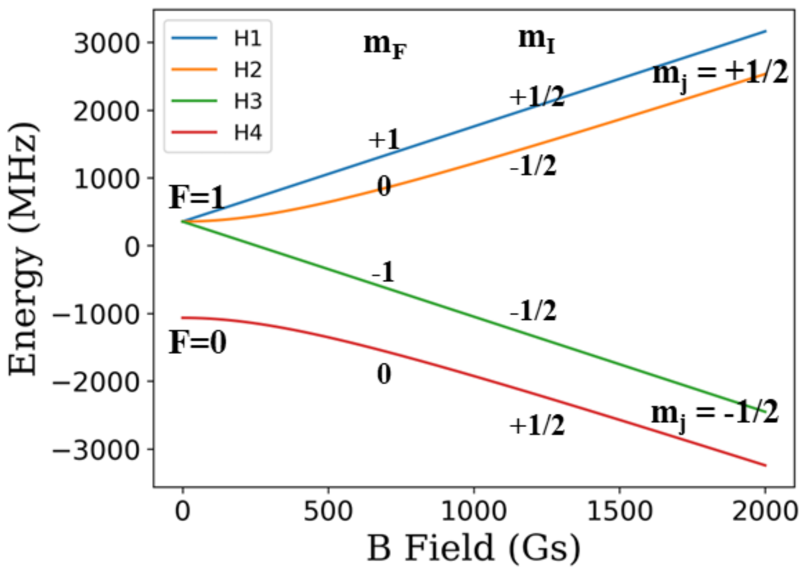


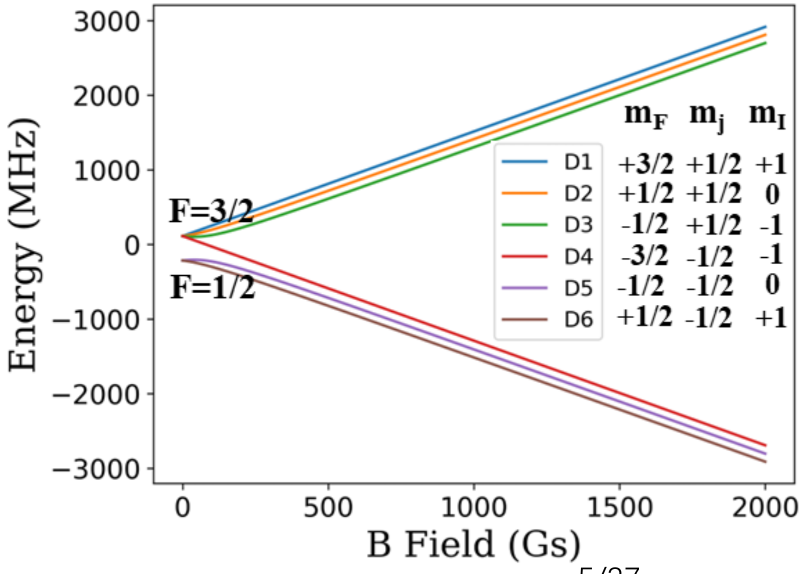
Status of SPIS at IMP

Polarized Atomic Beam Source - Principle

- ➢ Sextupole magnets:
  - focus the atoms $m_j = 1/2$; defocus others $m_j = -1/2$
  - Electron spin polarized atomic beam





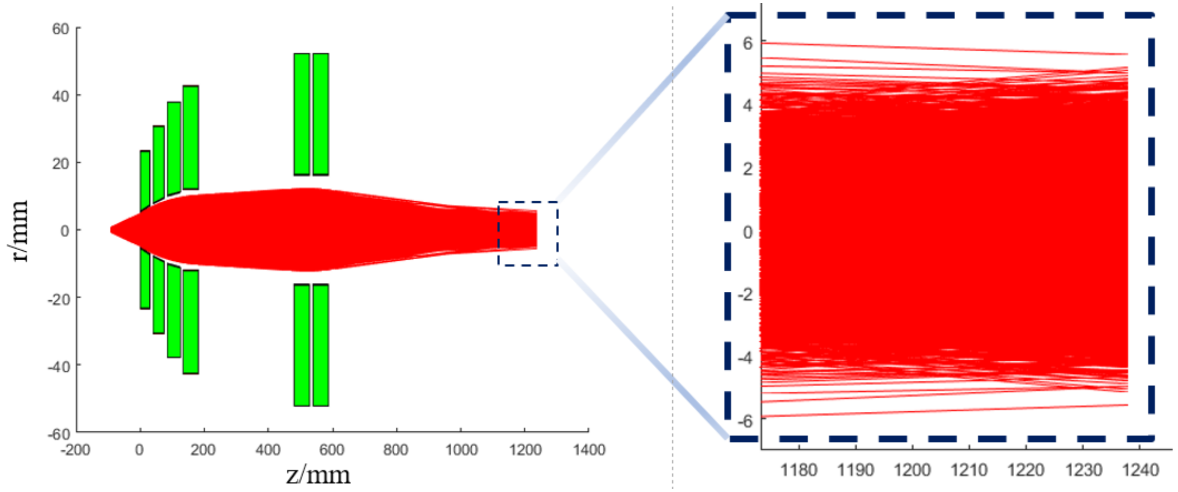


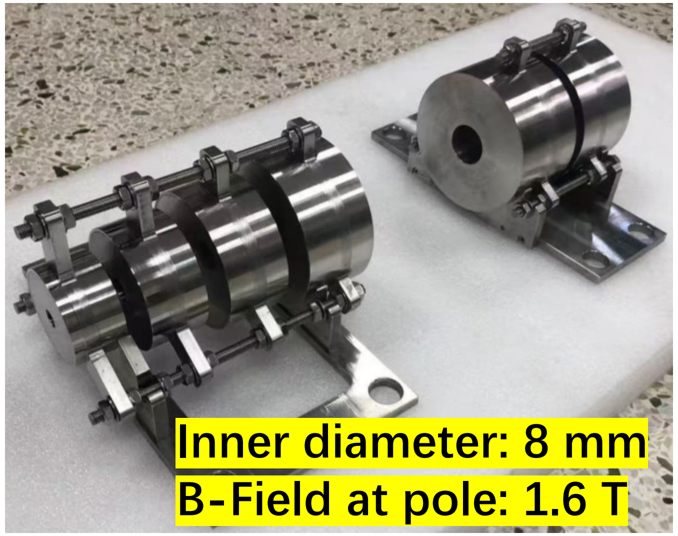
- ➢ Medium (Strong, Weak) Field Transition
  - Transfer the polarization from electron to nucleus
  - Nuclear spin polarized atomic beam

Status of SPIS at IMP

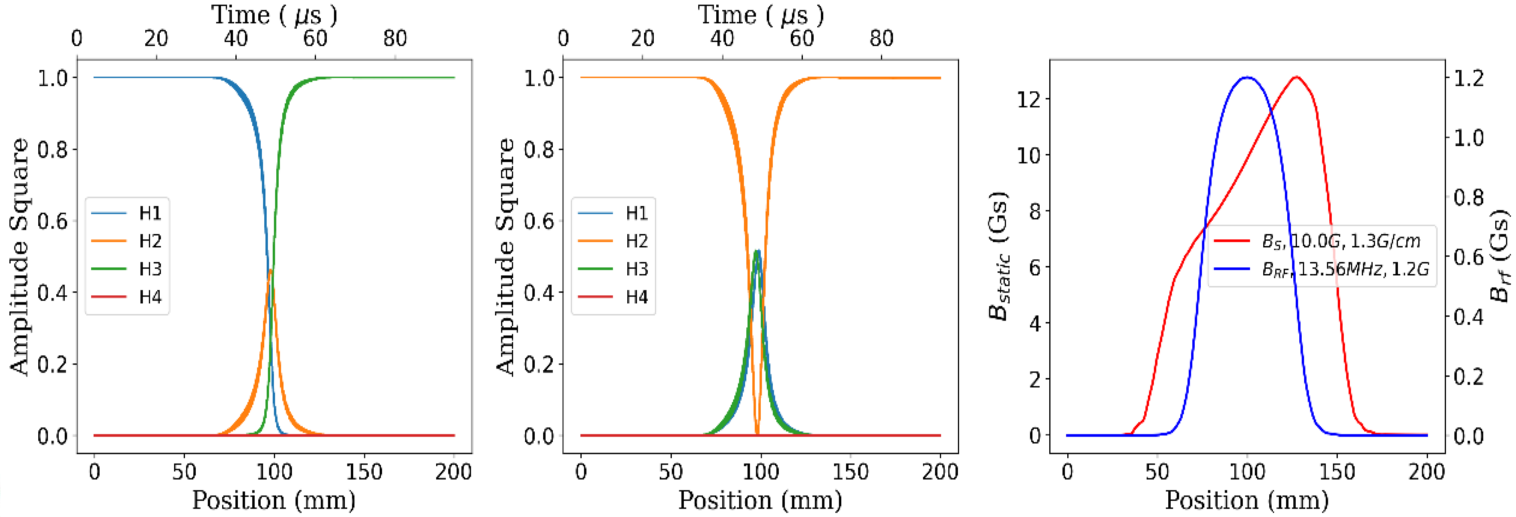
Polarized Atomic Beam Source - Design

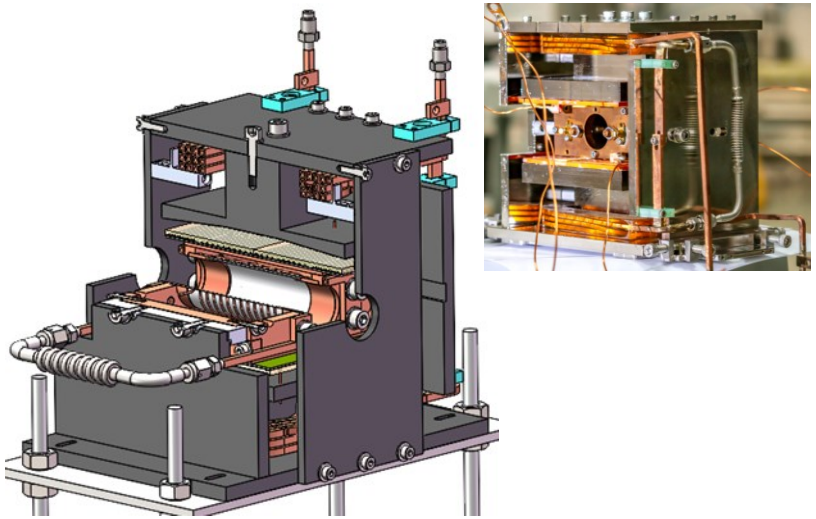
- Atoms with m_j = 1/2 are focused by sextupole magnets



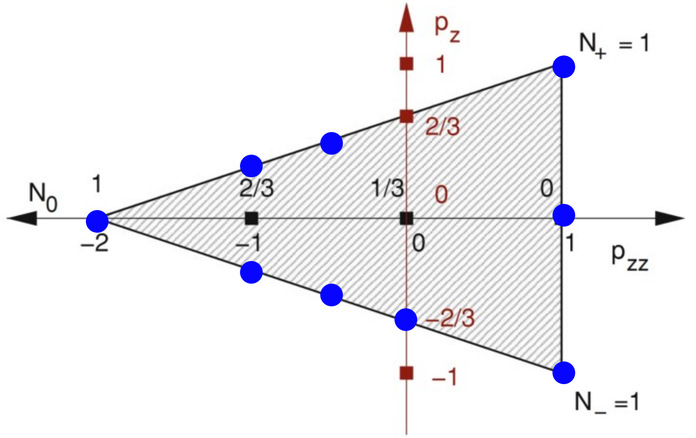


- Atoms staying in H1 state transition to H3





Status of SPIS at IMP



Polarized Atomic Beam Source – Polarized Mode

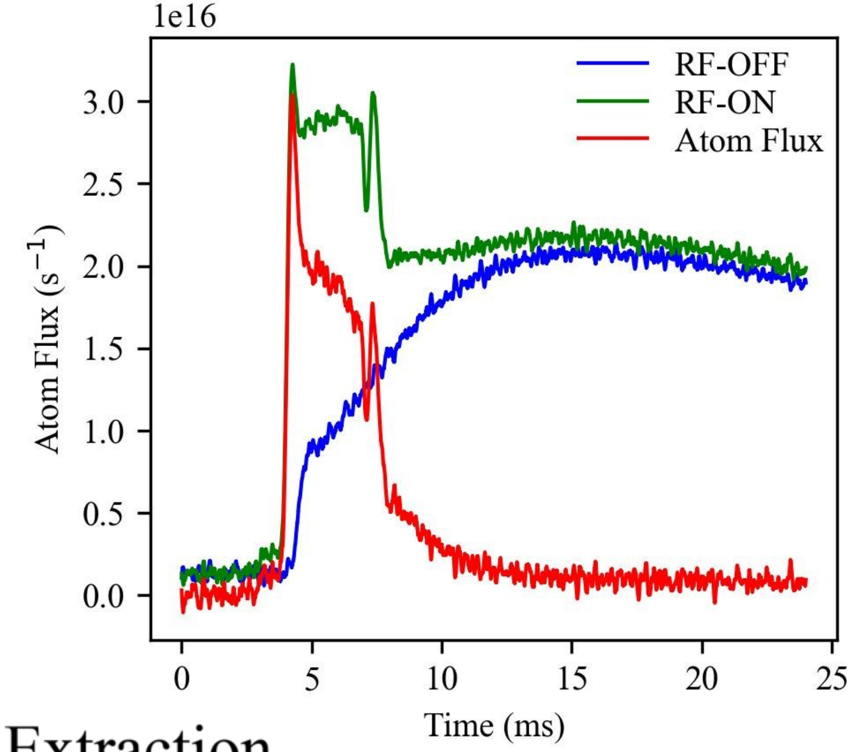
- **Switching on one or two transitions, vector and tensor polarized atomic beams can be obtained.**

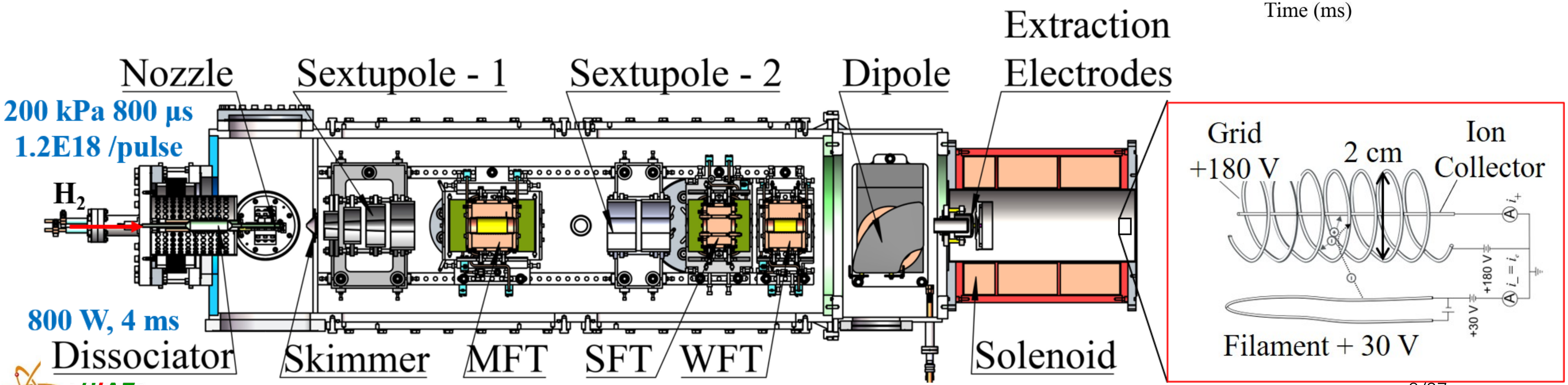
1	2	Polarization mode	3	4	5	6	7	8	9	10	11
H			D								
1+2+3+4		Atomic beam state	1+2+3+4+5+6								
1+2		After the 1st sextupole	1+2+3								
-	-	Transition in MFT	-	1↔4	1↔4	3↔4	3↔4	3↔4	1↔4	-	-
1+2	1+2	Statse after MFT	1+2+3	2+3+4	2+3+4	1+2+4	1+2+4	1+2+4	2+3+4	1+2+3	1+2+3
-	-	After the 2ed sextupole	1+2+3	2+3	2+3	1+2	1+2	1+2	2+3	1+2+3	1+2+3
2↔4	-	Transition in SFT	-	2↔6	3↔5	2↔6	-	-	-	2↔6	3↔5
1+4	1+2	States after SFT	1+2+3	3+6	2+5	1+6	1+2	1+2	2+3	1+3+6	1+2+5
-	1↔3	Transition in WFT	1↔4 2↔3	-	-	-	1↔4 2↔3	-	-	1↔4 3↔2 6↔5	-
1+4	2+3	States after WFT	2+3+4	3+6	2+5	1+6	3+4	1+2	2+3	2+4+5	1+2+5
1+4	2+3	Final states in ionizer	2+3+4	3+6	2+5	1+6	3+4	1+2	2+3	2+4+5	1+2+5
1	-1	Vector polarization	- 2/3	0	0	1	-1	1/2	- 1/2	- 1/3	1/3
-	-	Tensor polarizationz	0	1	-2	1	1	- 1/2	- 1/2	-1	-1

Status of SPIS at IMP

Polarized Atomic Beam Source – Pretest

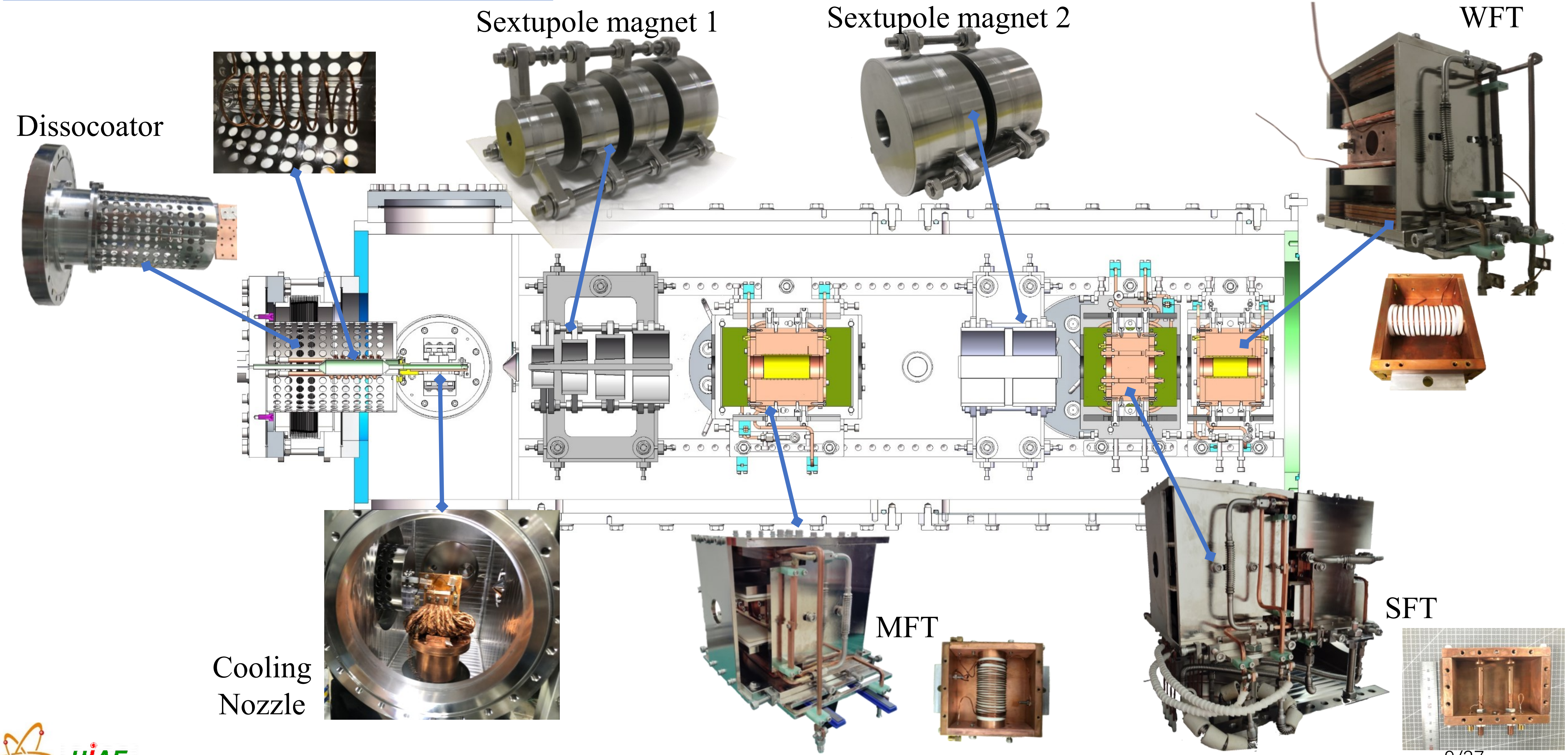
- Monitor the ion collector current of an ionization gauge
- The atom flux injected into ionizer was about 3 x 10^{16} /s
- Low level, potential to reach 1~2 x 10^{17} /s





Status of SPIS at IMP

Polarized Atomic Beam Source – photos



Status of SPIS at IMP

Plasma Ionizer - Principle

★ High-efficiency

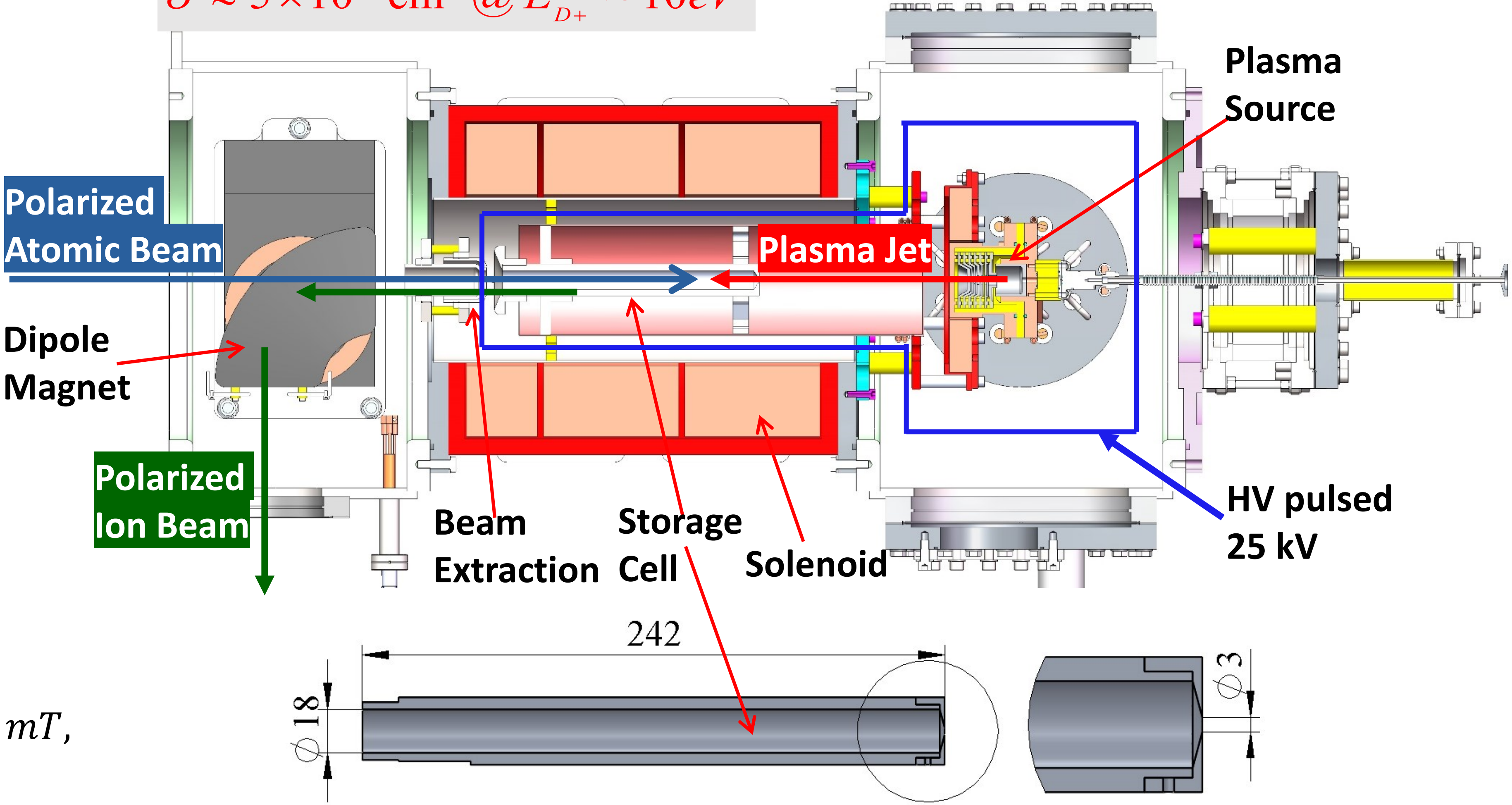
- Arc source produces plasma jet with high density
- Storage cell to increase the density of polarized atoms
- Strong magnetic field ($\gg B_c$) avoid depolarization during the charge exchange

$$B_{c,H}^{1S} = 50.7\ mT, B_{c,D}^{1S} = 11.7\ mT,$$

$$H^0 \uparrow + D^+ \rightarrow H^+ \uparrow + D^0$$

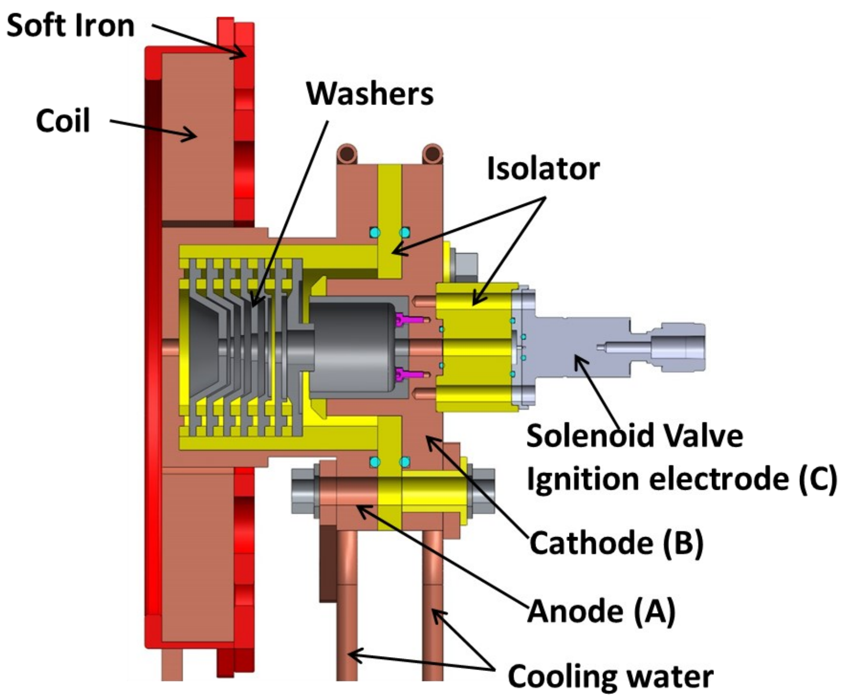
$$\sigma \approx 5 \times 10^{-15} \mathrm{cm}^2 \ @\ E_{D+} \sim 10eV$$

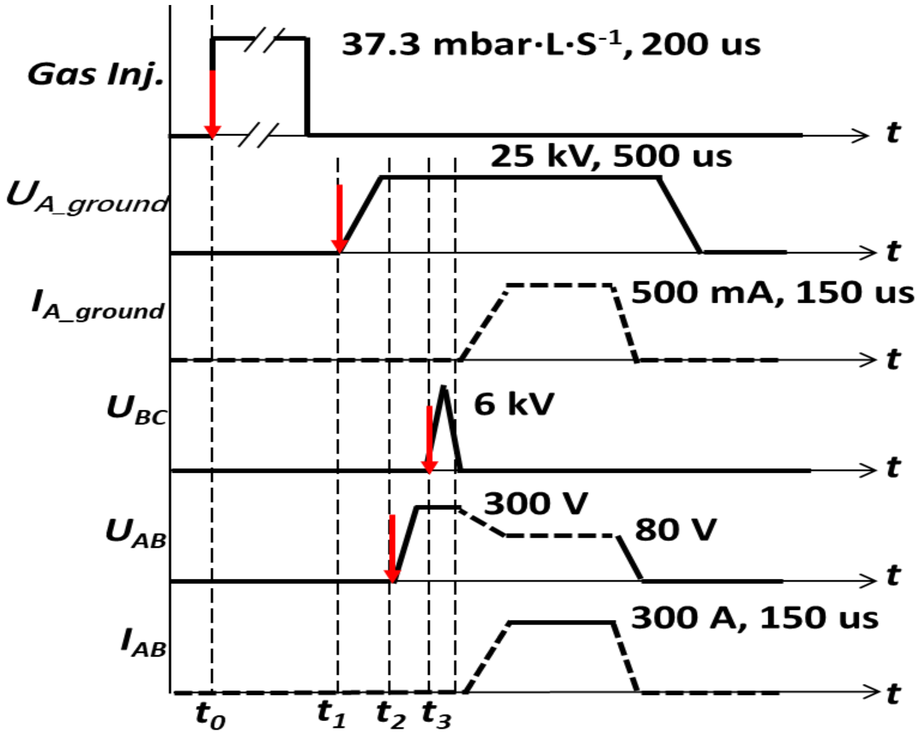
Quasi-resonant charge exchange



Status of SPIS at IMP

Plasma Ionizer – Plasma Generator



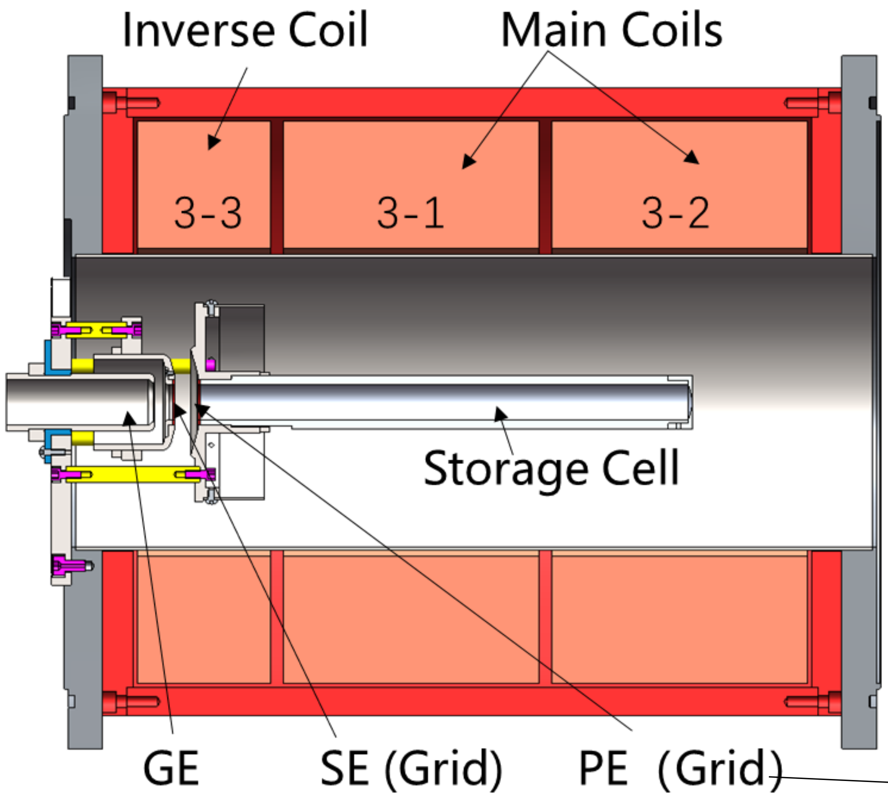


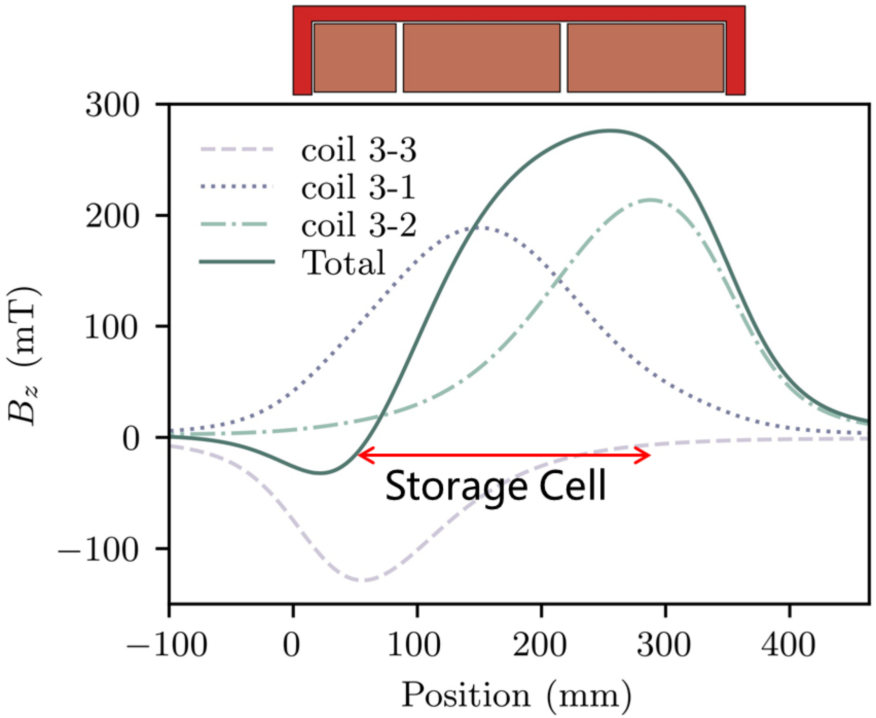
- **Pulsed gas injection (200 μs)**
- **Ignition with a HV spark**
- **Arc discharge (300 A) at the narrow washer canal (ID ~ 7mm)**
- **Instantaneous power 25 kW**

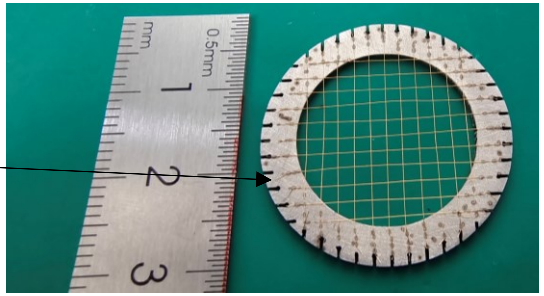
Status of SPIS at IMP

Plasma Ionizer
Ionization Region & Beam Extraction

- **Strong B-Field: avoid depolarization, confine plasma jet**
- **Beam extraction system for intense ion beam**



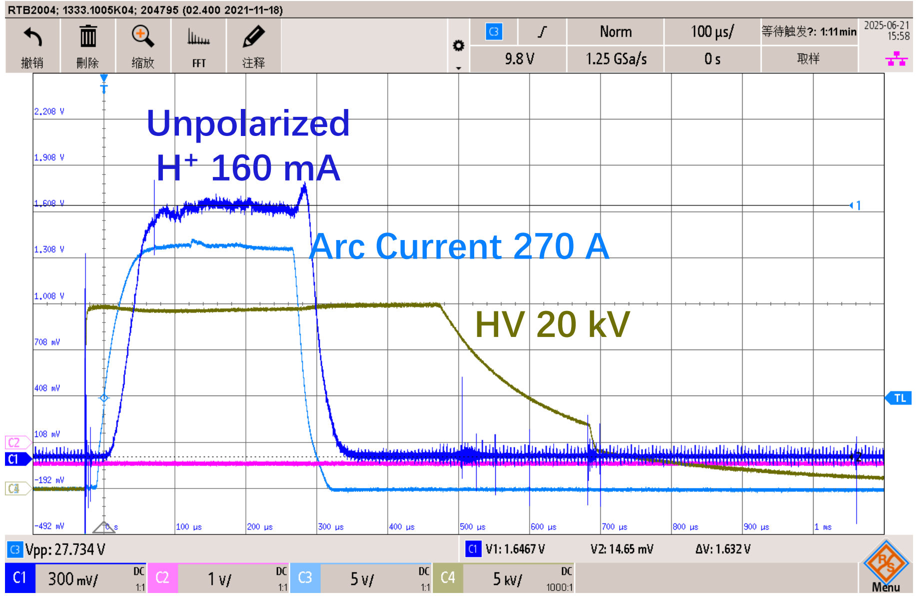


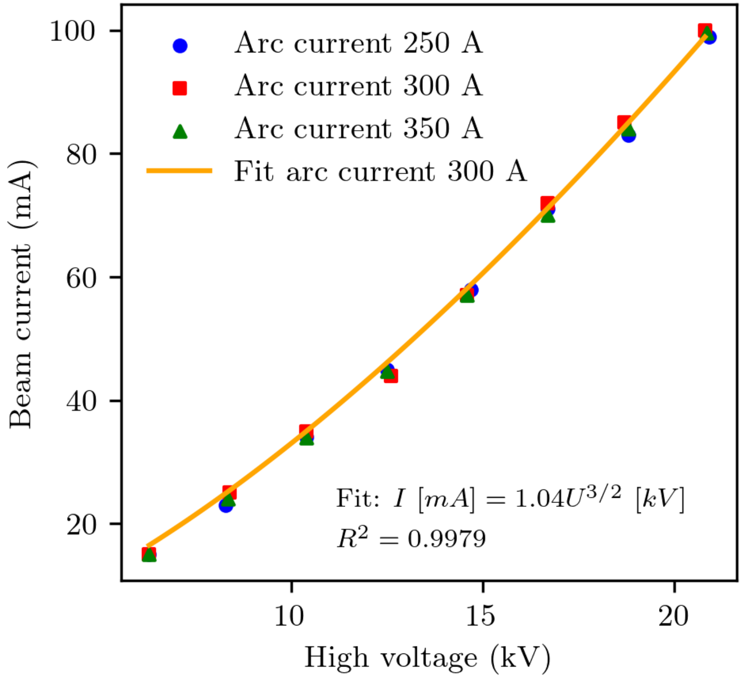


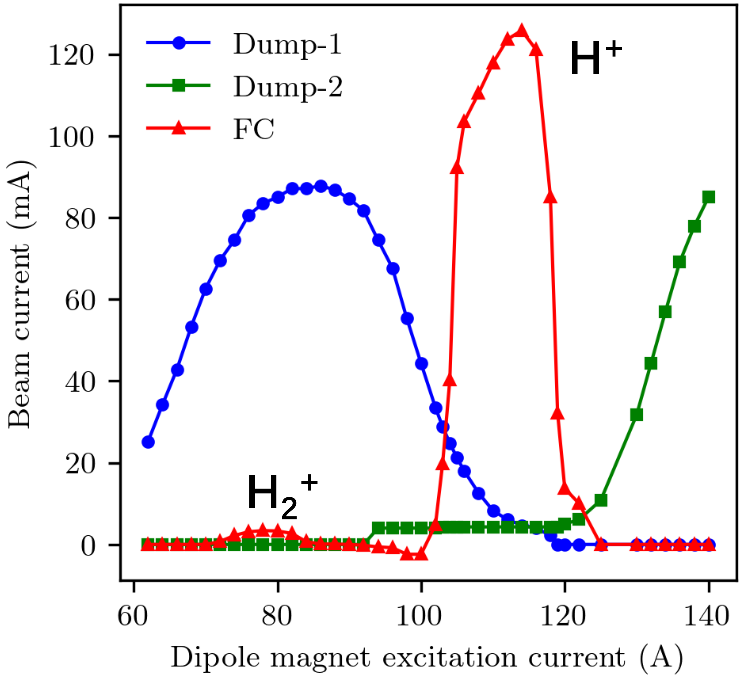
- **Tungsten wire 0.1 mm**
- **Period 2.0 mm**
- **Transparency 90%**

Status of SPIS at IMP

Plasma Ionizer – Pretest







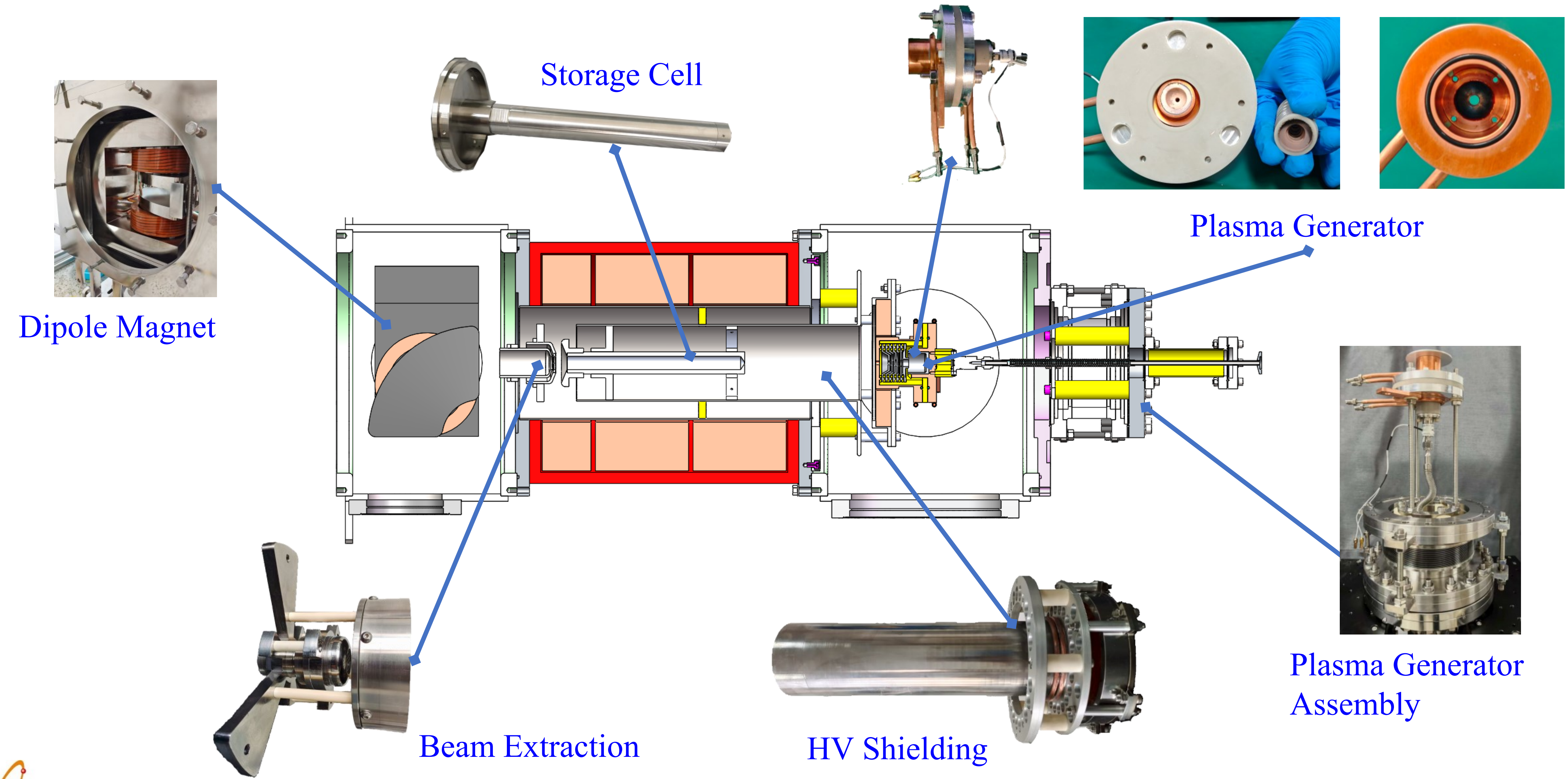
- High-density plasma generation and confinement
- High-intensity ion beam extraction

- Optimized beam current as a function of extracted HV obeys the Child-Langmuir law
- Extraction system works in space charge limited mode

- Beam composition analysis by scanning dipole magnet excitation current
- Proton/deuteron fraction 90%

Status of SPIS at IMP

Plasma Ionizer – Photos

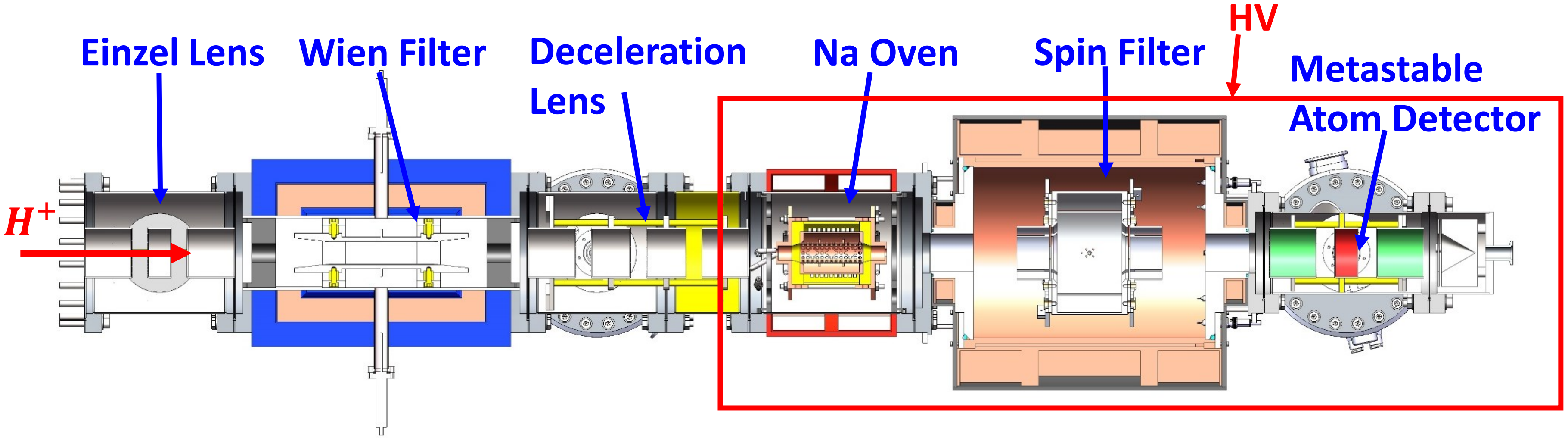


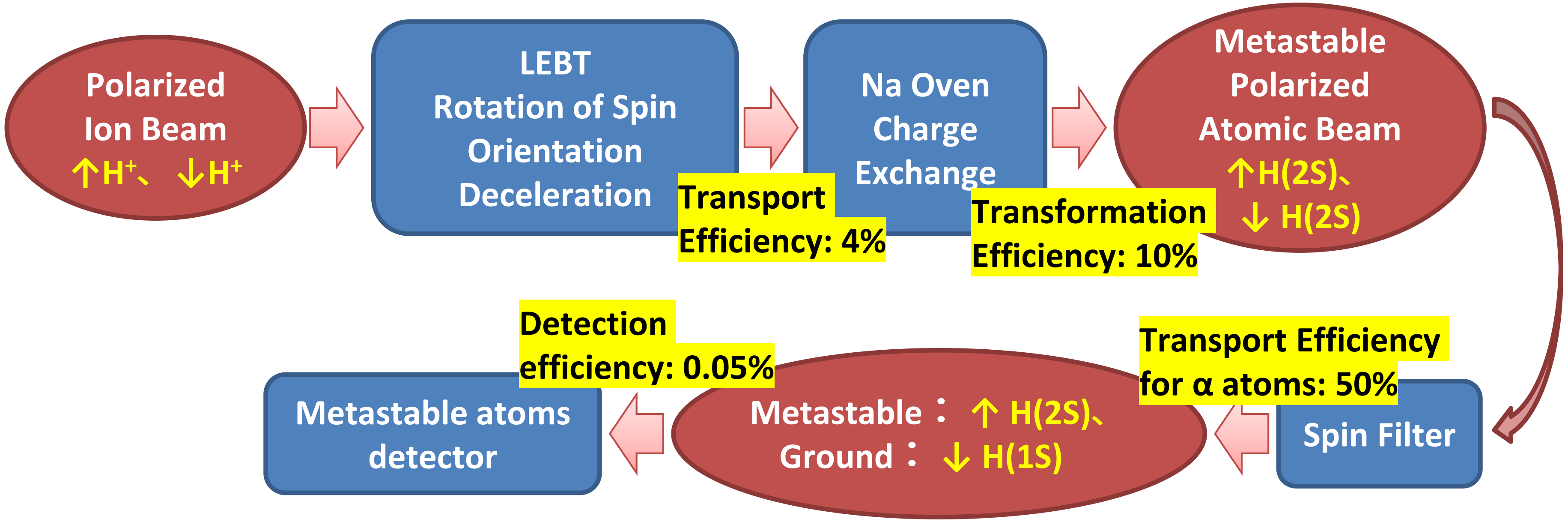
Status of SPIS at IMP

Lamb Shift Polarimeter – Principle

★ Measure polarization quickly and precisely

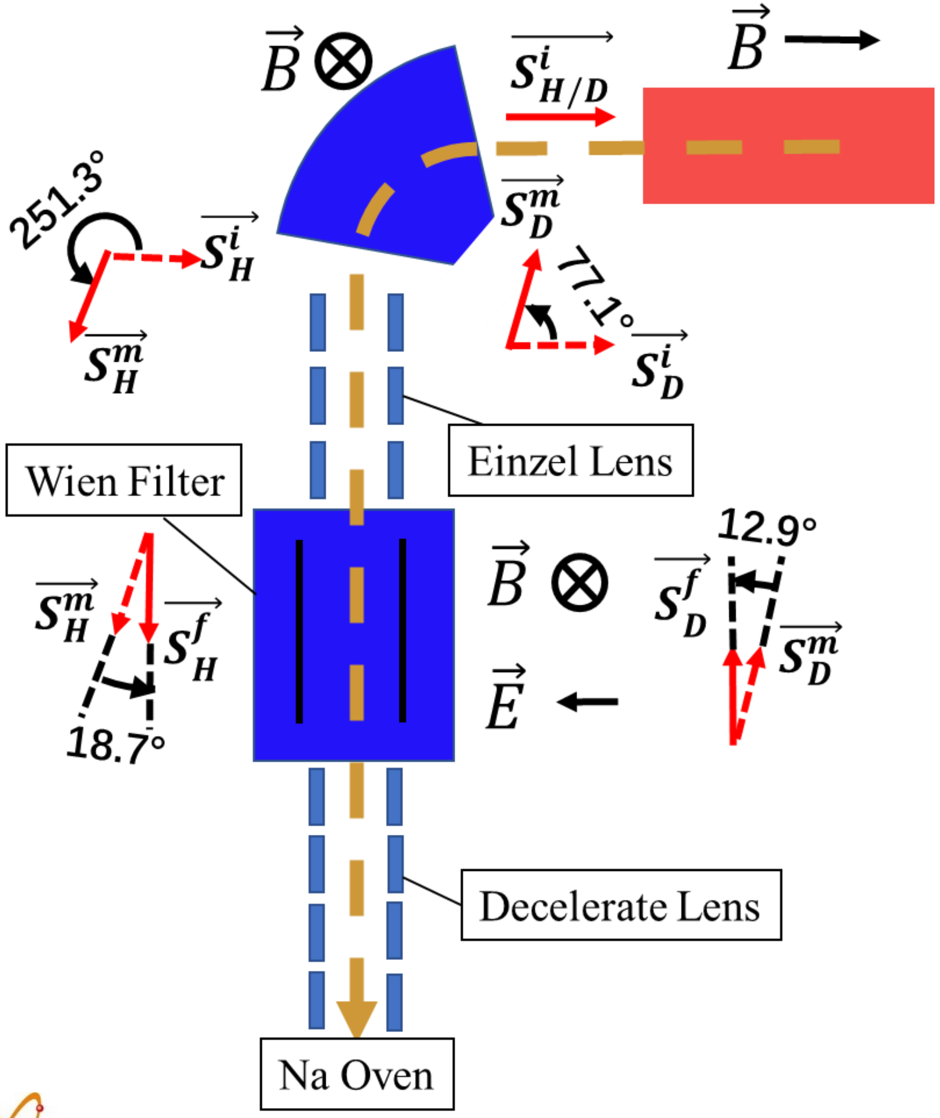
- Directed measurement downstream of SPIS
- No need for further acceleration
- Immunity to mixed H_2^+ in polarization measurement for D^+
- More sensitive and intuitive

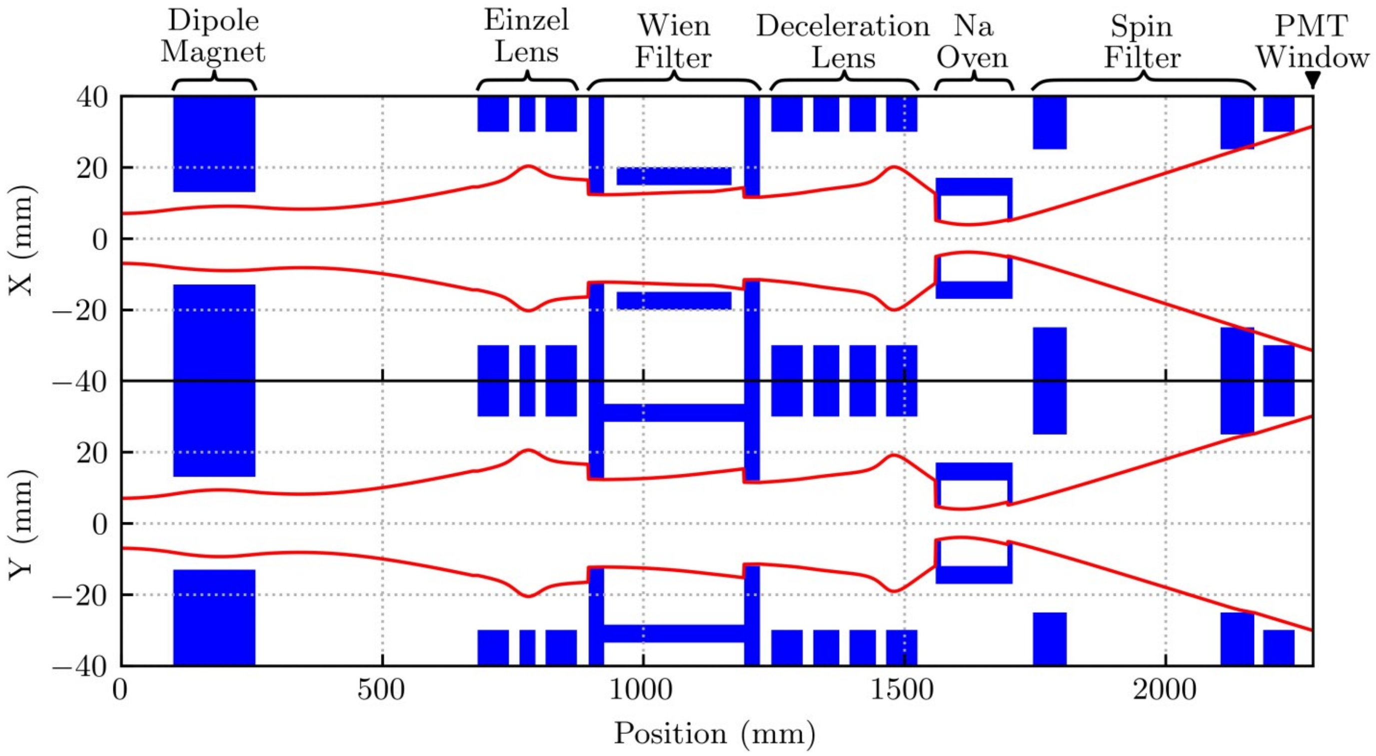




Status of SPIS at IMP

Lamb Shift Polarimeter – LEBT





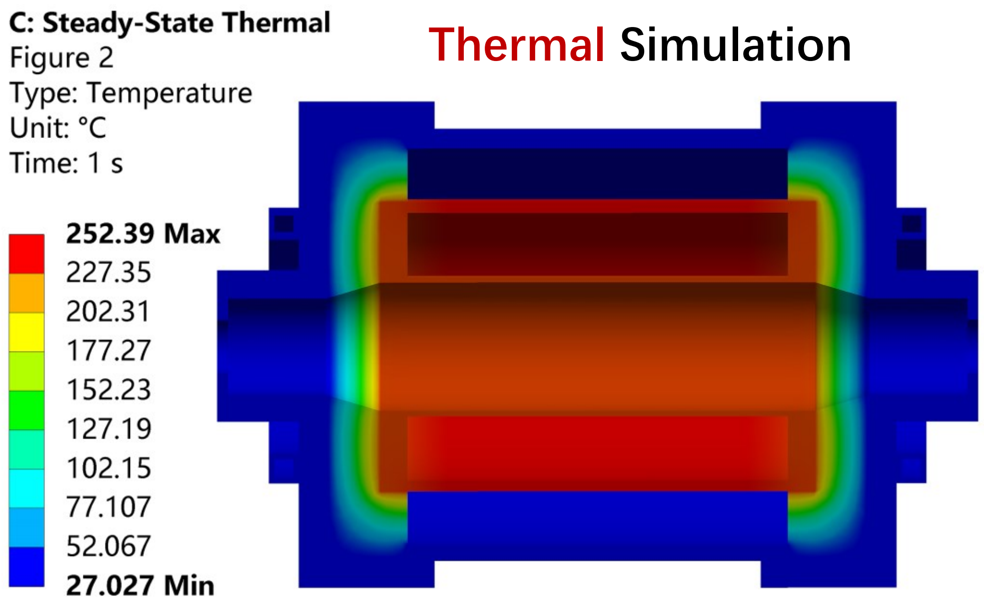
- Align spin direction with beam axis
- Decelerate ions from 20 to 2 keV
- Inevitable space charge effect

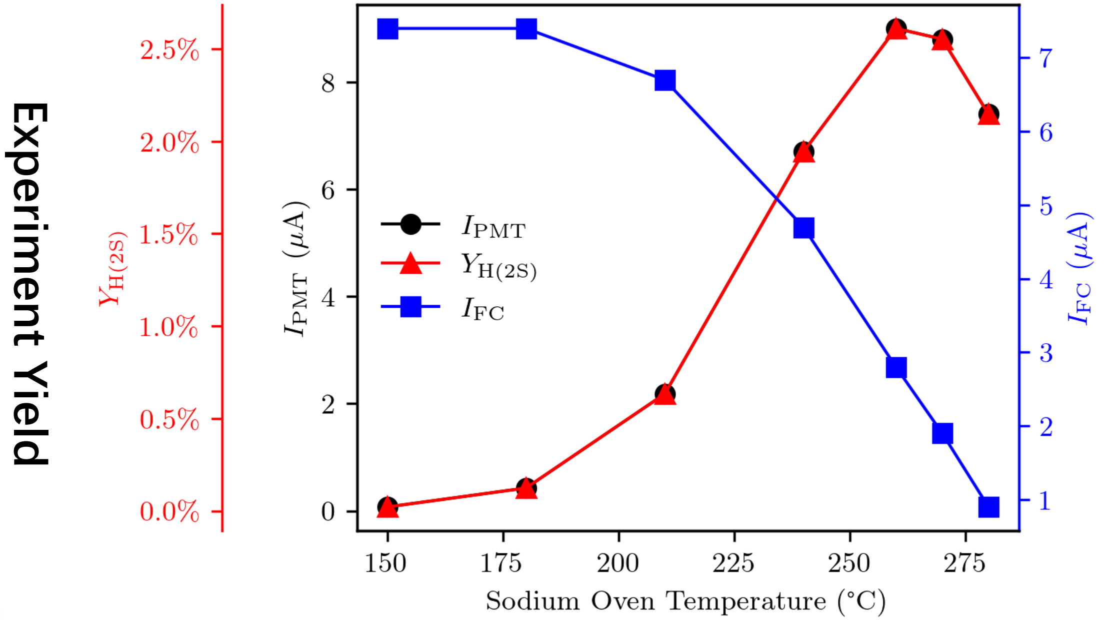
Status of SPIS at IMP

Lamb Shift Polarimeter – Sodium Oven

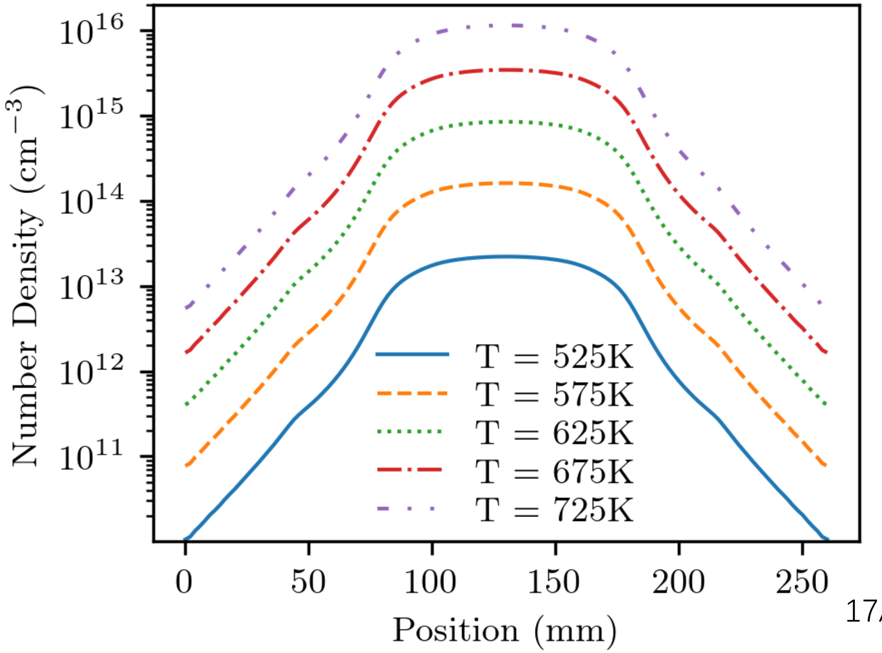
- Yields of the metastable atom is sensitive to thickness of sodium atoms (2 x 10^{14} cm^2)
- Low temperature inlet and outlet restrict excessive diffusion of sodium atoms

Thermal Simulation



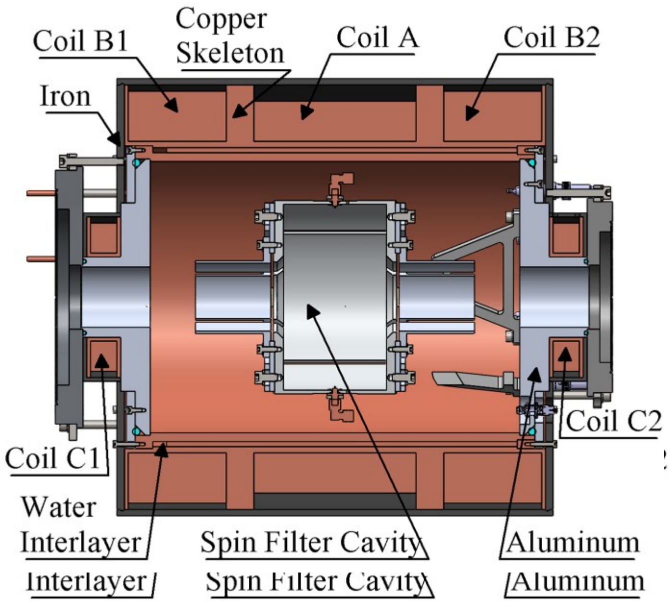


Evaporation Simulation

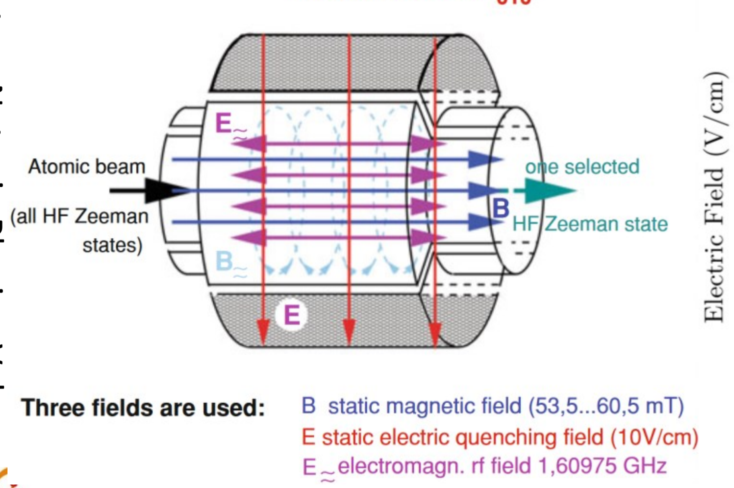


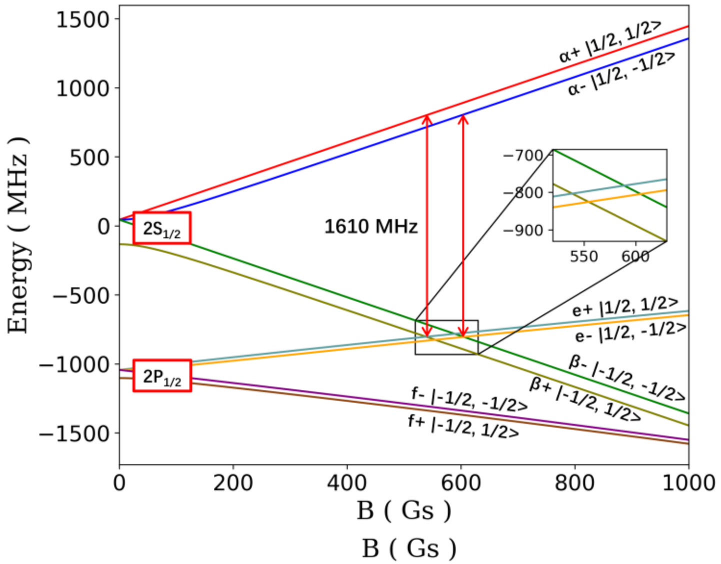
Status of SPIS at IMP

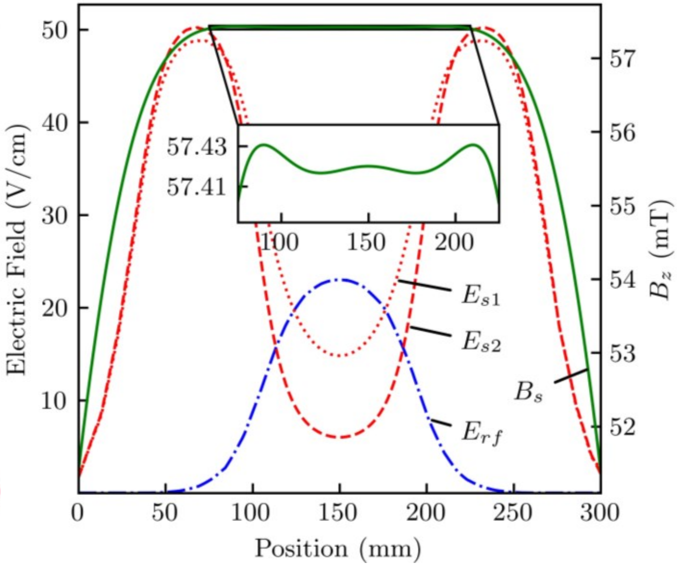
Lamb Shift Polarimeter – Spin Filter – Principle

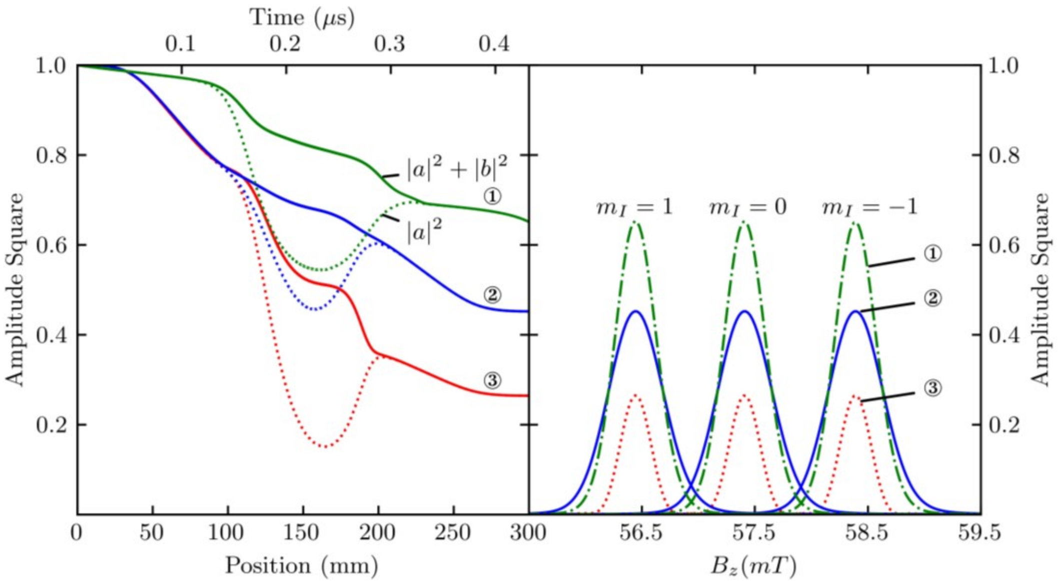


Lecture Notes in Physics, Volume 842, Spring, 2012





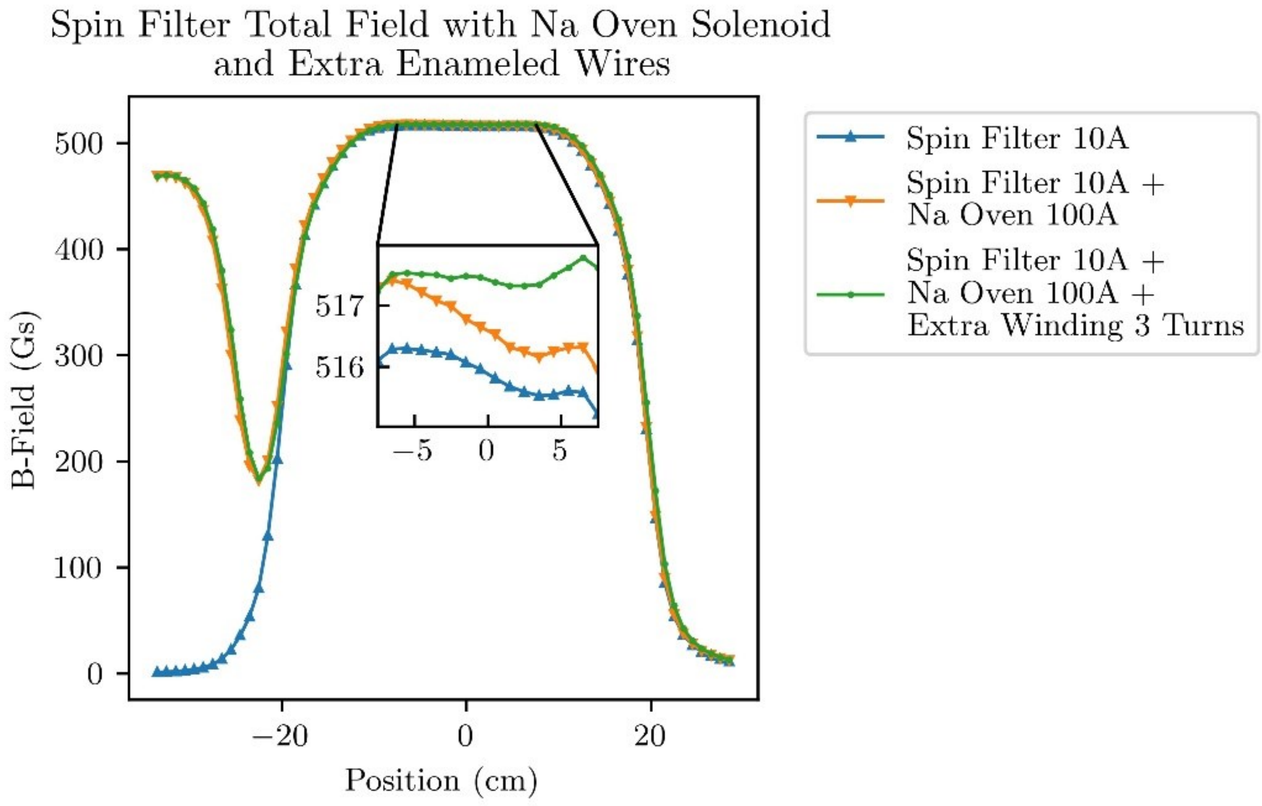


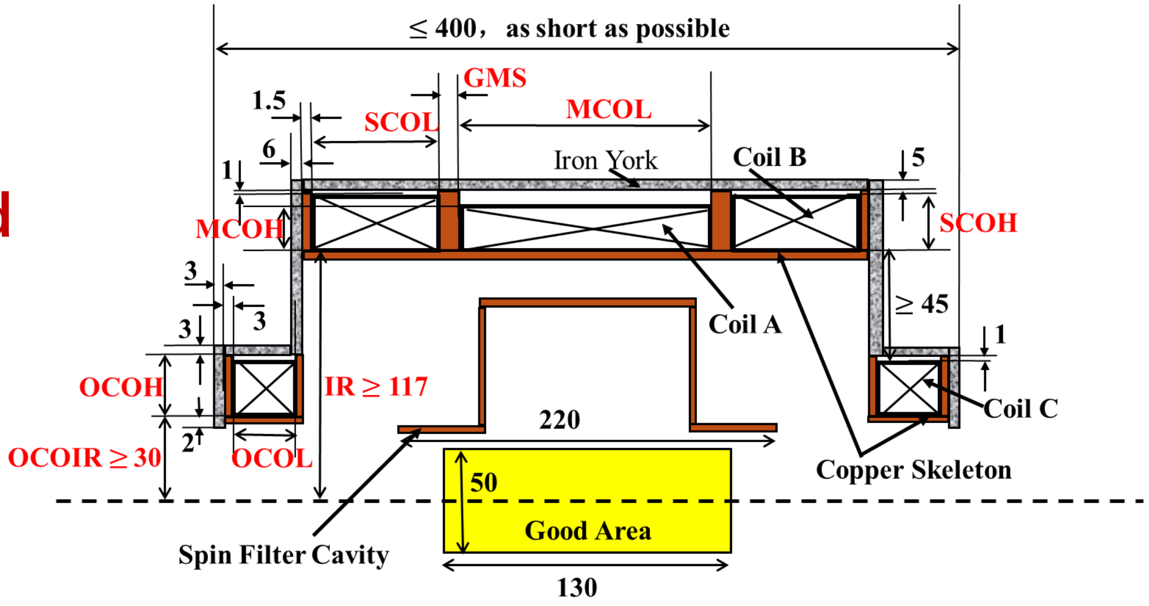


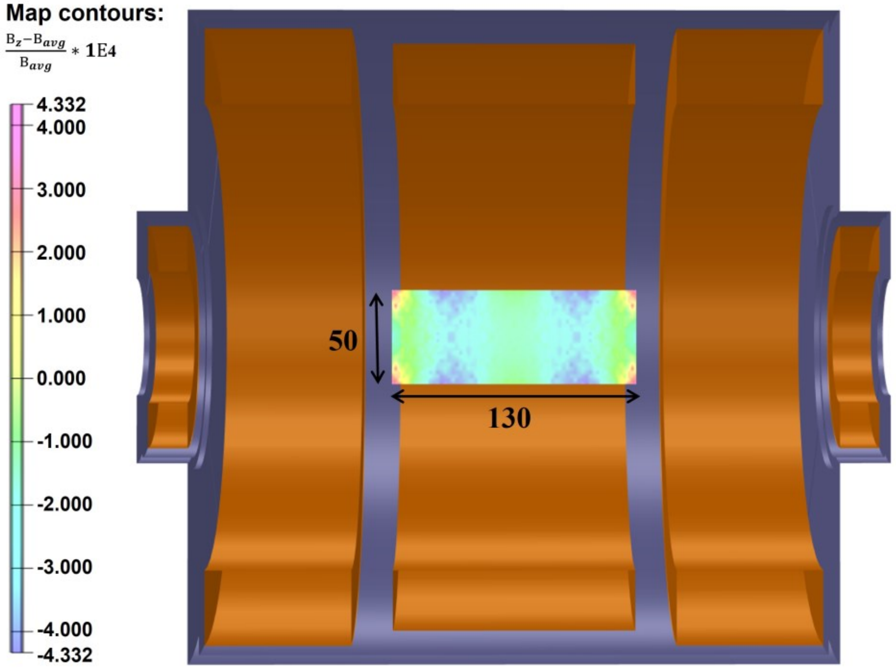
- Quenching of all H/D(2S) atoms via α-e and β-e resonance
- Preservation of H/D(2S) atoms with specified m_I via α-β-e three-level resonance

Status of SPIS at IMP

Lamb Shift Polarimeter – Spin Filter – Solenoid







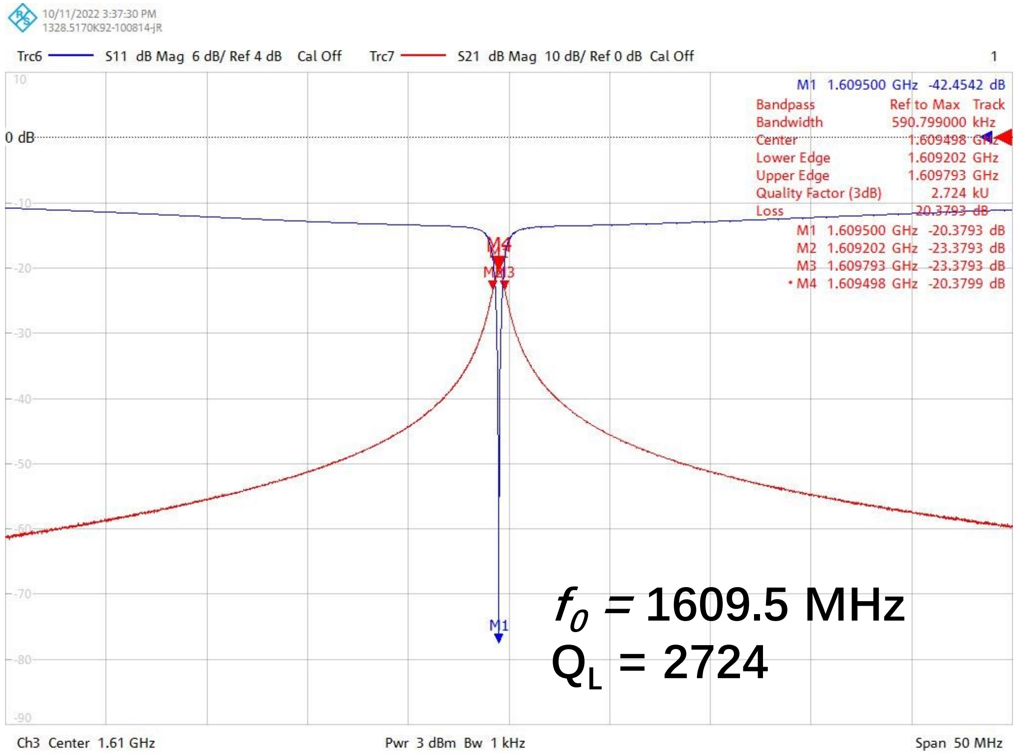
- Additional compensation windings based on measured B-Field
- B-Field Fluctuation of Spin Filter: < 1 Gs within ±6.5 cm

Status of SPIS at IMP

Lamb Shift Polarimeter – Spin Filter - Cavity

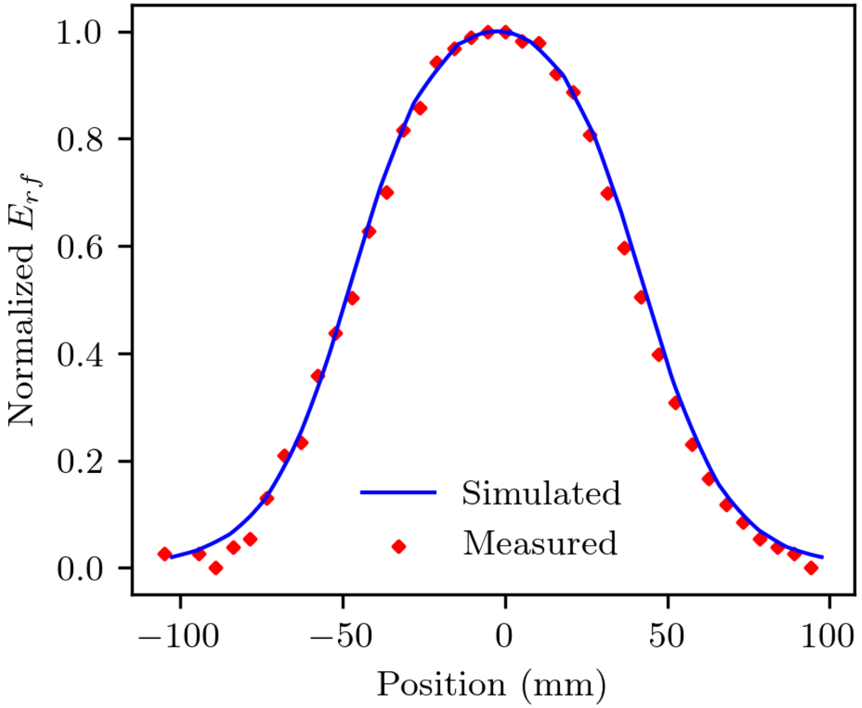
Assembly

f_0 and Q measurement with Vector Network Analyzer



f_0 = 1609.5 MHz
Q_L = 2724

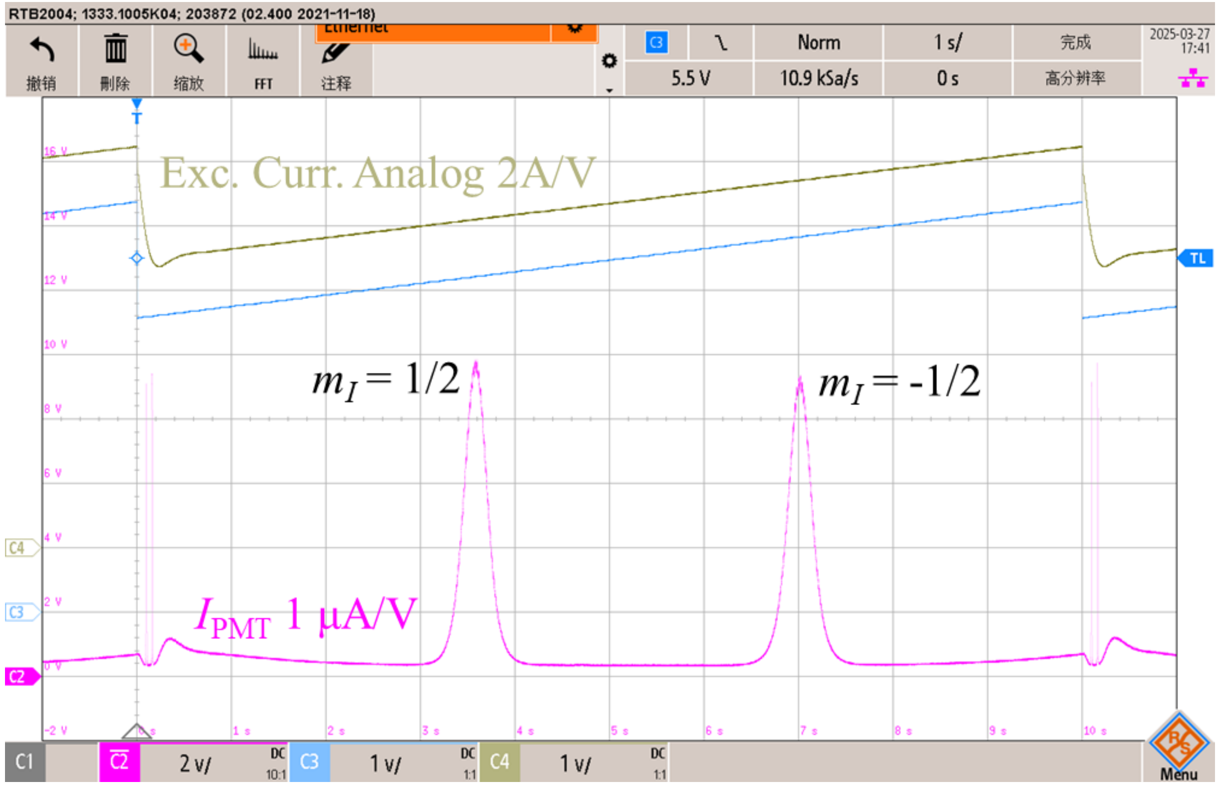
Measured E_{RF} field distribution with a perturbed ball

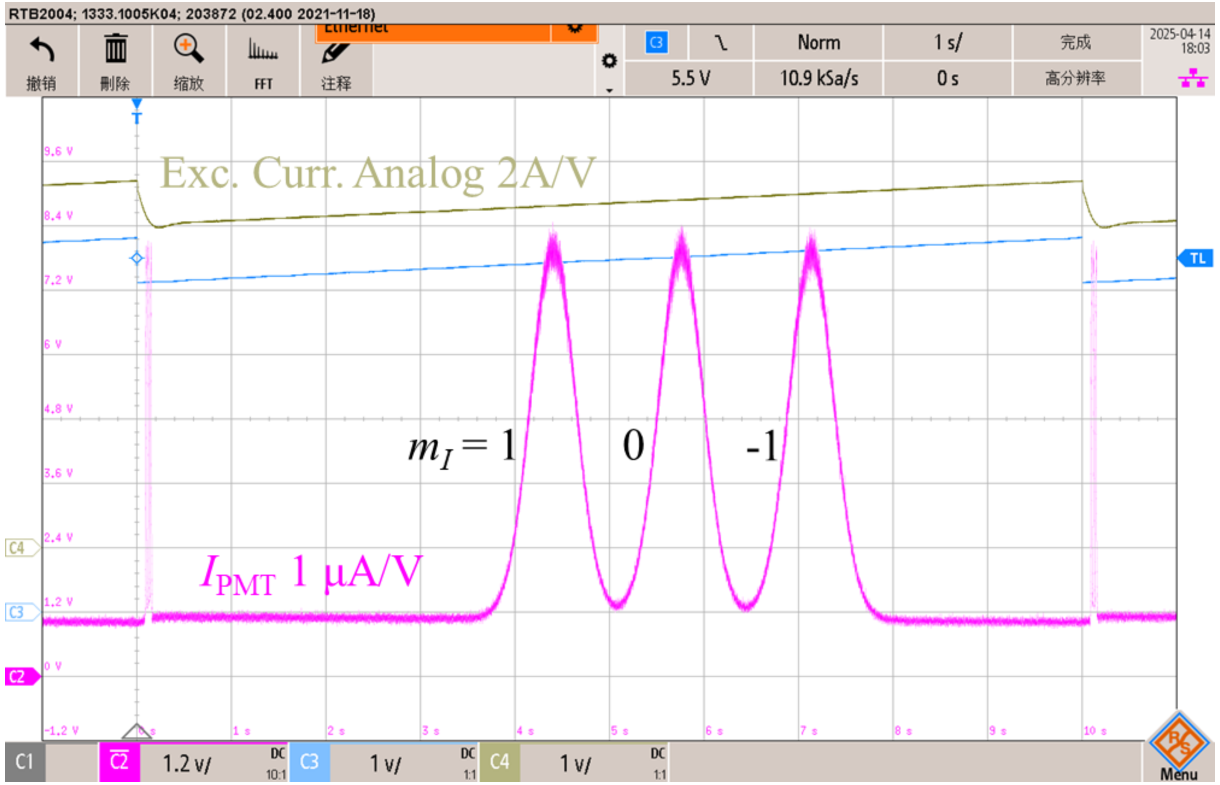


Status of SPIS at IMP

Lamb Shift Polarimeter – Pretest

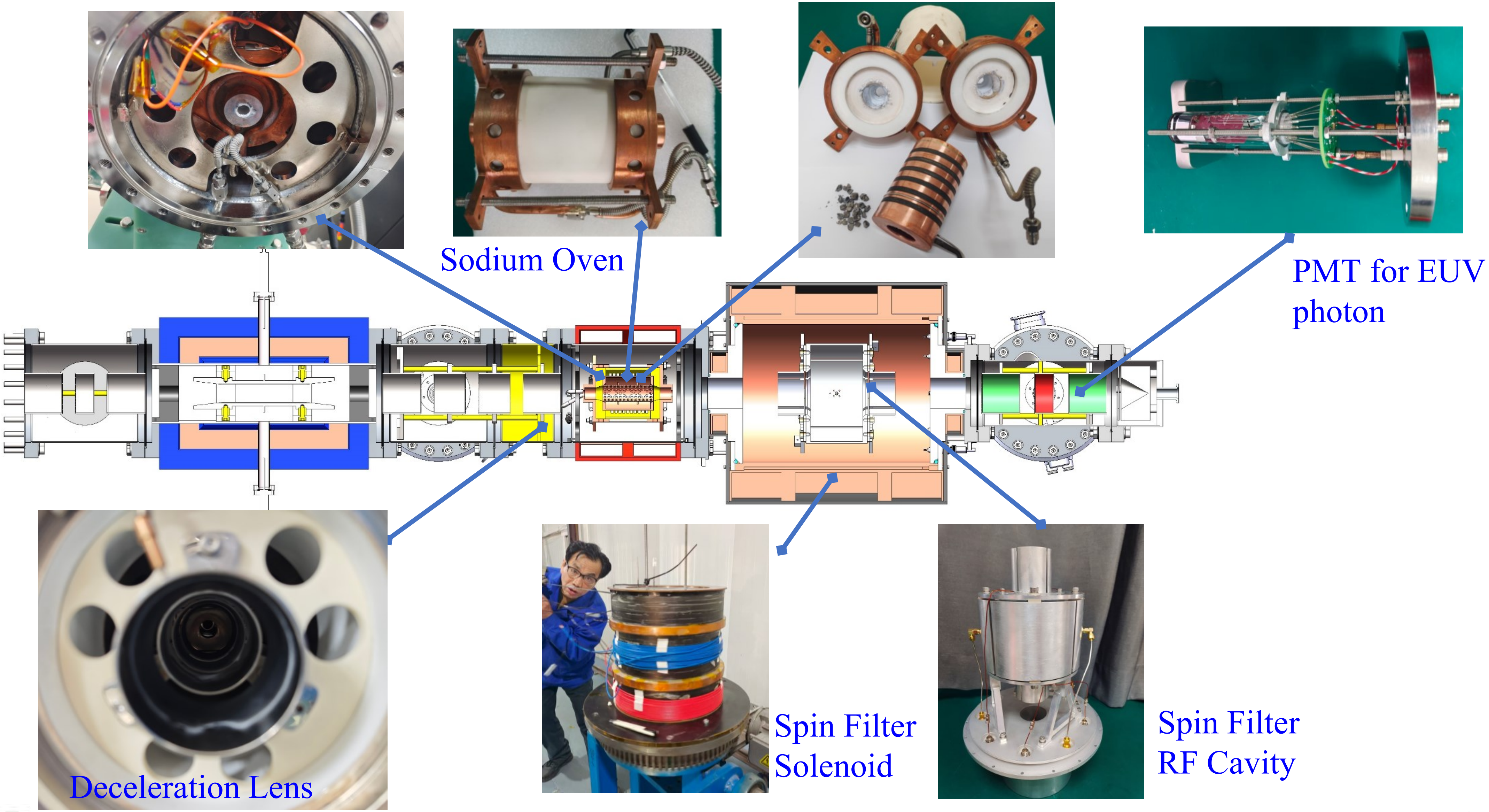
- Lyman spectrums measured with unpolarized H^+/D^+ beams (DC)





Status of SPIS at IMP

Lamb Shift Polarimeter – Photos



Status of SPIS at IMP

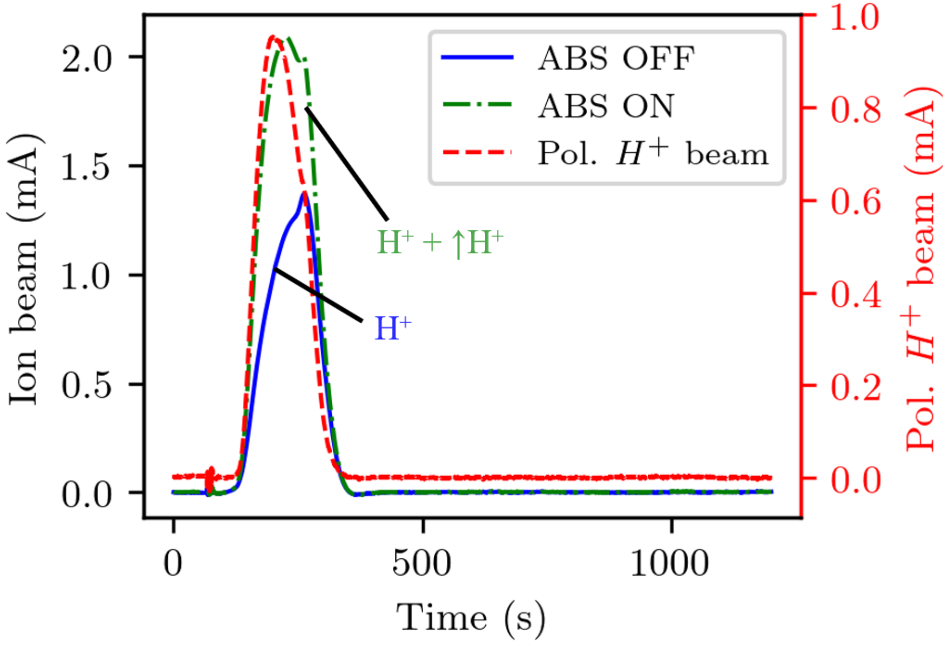
Beam test – Intensity

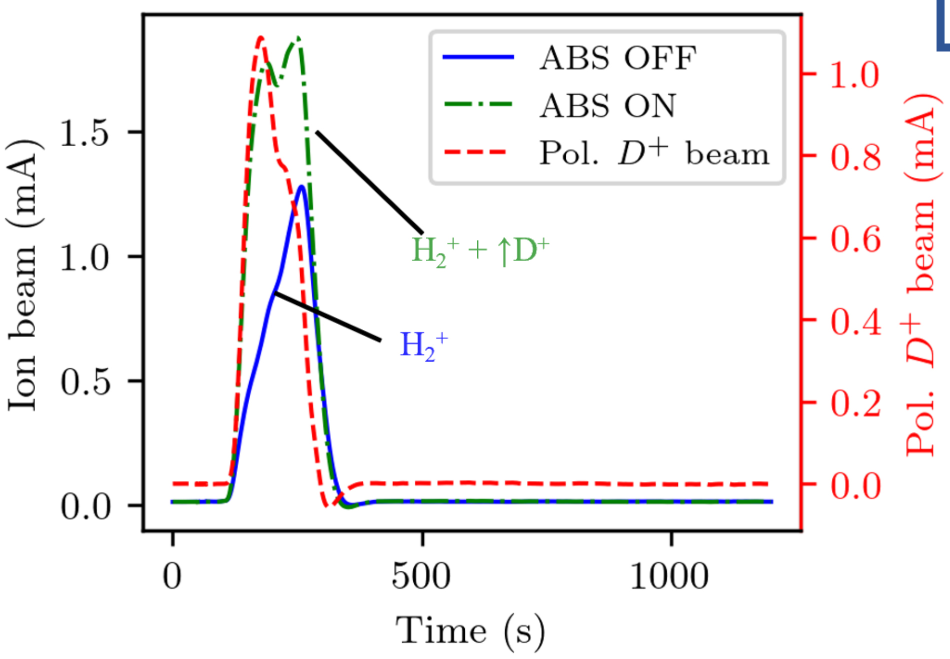
	Polarized proton operation			Polarized deuteron operation		
Operation mode	$\vec{H}^+$ mA	H^+ mA	D^+ mA	$\vec{D}^+$ mA	H_2^+ mA	H^+ mA
Free atomic beam	0.3	1.5	140	0.3	9.0	160
With storage cell	1.0	1.3	70	1.0	1.3	100

Intensity of $\vec{H}^+$ and $\vec{D}^+$ up to 1 mA (6 x 10^{11} ppp)

Flux of $\vec{H}^0$ and $\vec{D}^0$ is about 3 x 10^{16} /s

Ionization efficiency 20%

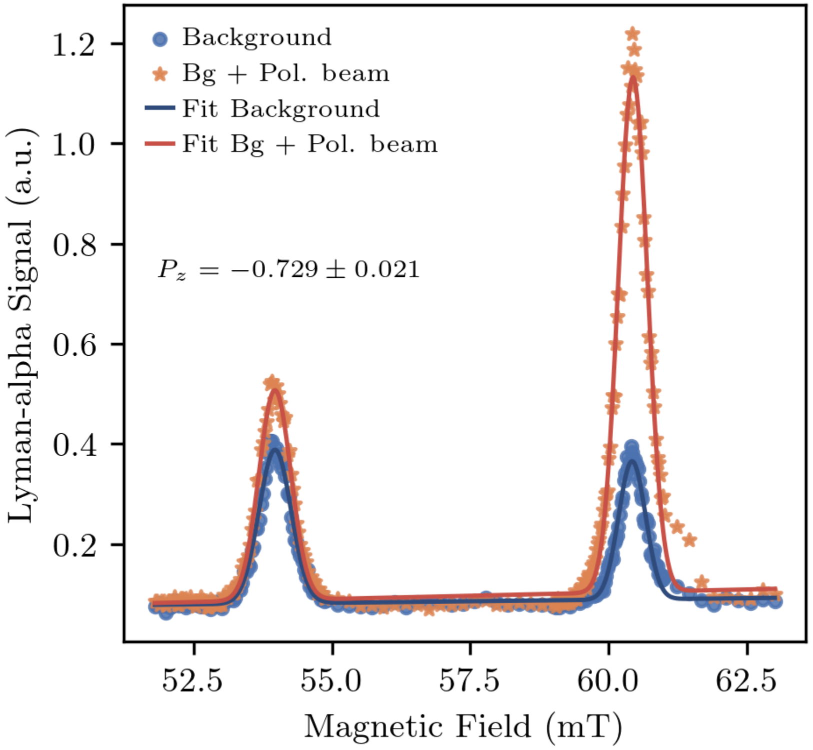




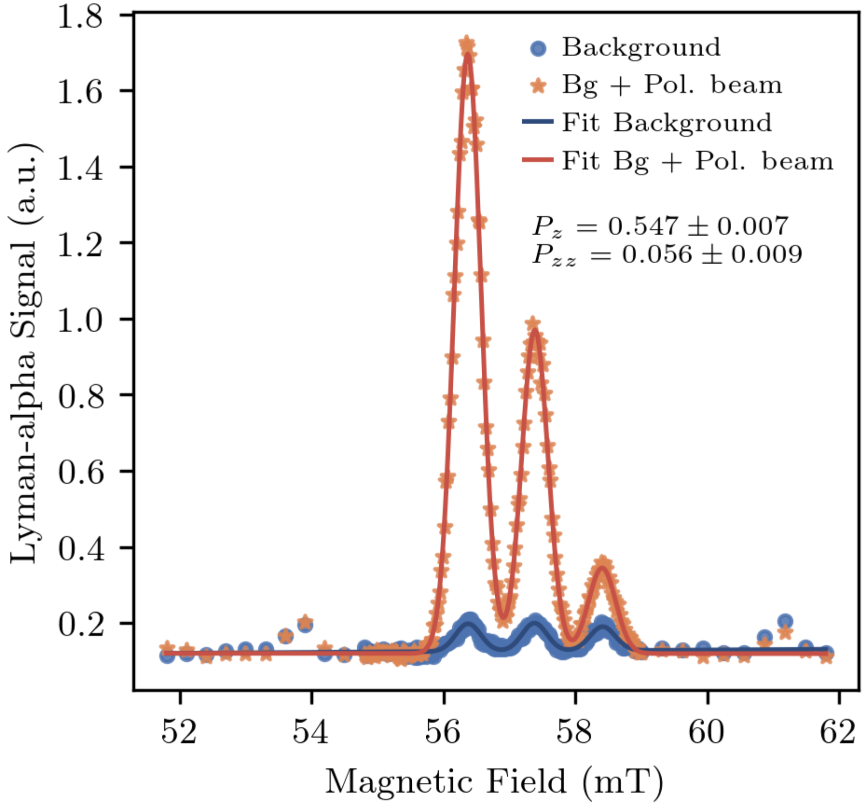
Sixfold increase in atom flux and ion beam intensity within 1-2 years

Status of SPIS at IMP

Beam test – Polarization



- $\vec{H}^0$ beam polarization 73%
- Contamination of background H^+
- Overall $\vec{H}^+$ beam polarization 38%
- Sixfold in $\vec{H}^0$ and $\vec{H}^+$ flux --> overall polarization 63%

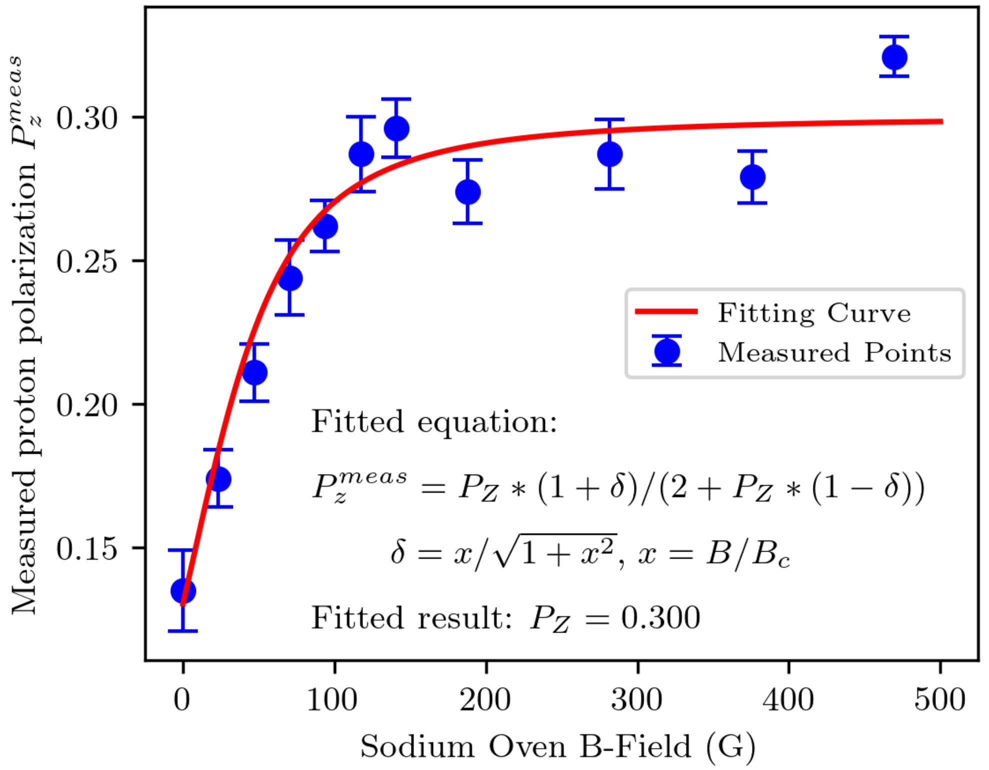


- Vector polarized $\vec{D}^+$ beam polarization 82%
- Mixed H_2^+ has no effect on polarization measurement of $\vec{D}^+$ beam
- Mixed H_2^+ can be swept out before injection to synchrotron

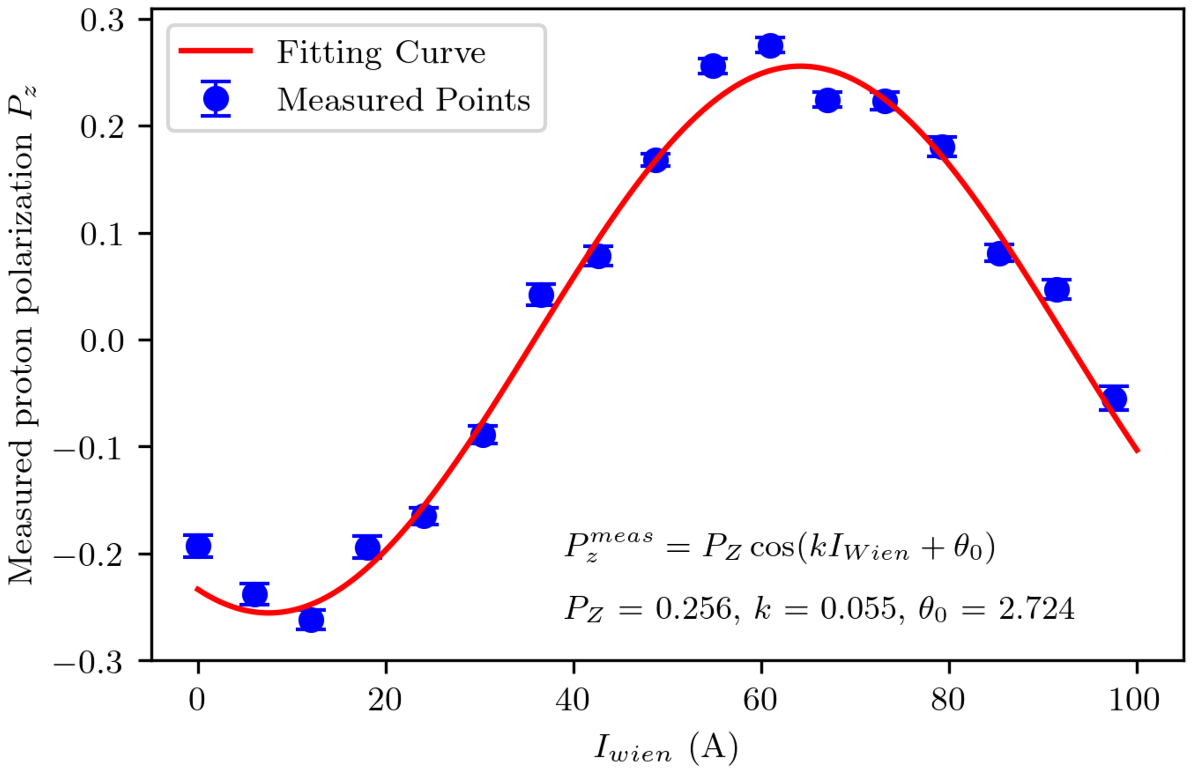
Status of SPIS at IMP

Beam test – Polarization

Measured Polarization V. S. B-Field of Sodium Oven



Measured Polarization V. S. B-Field of Wien Filter

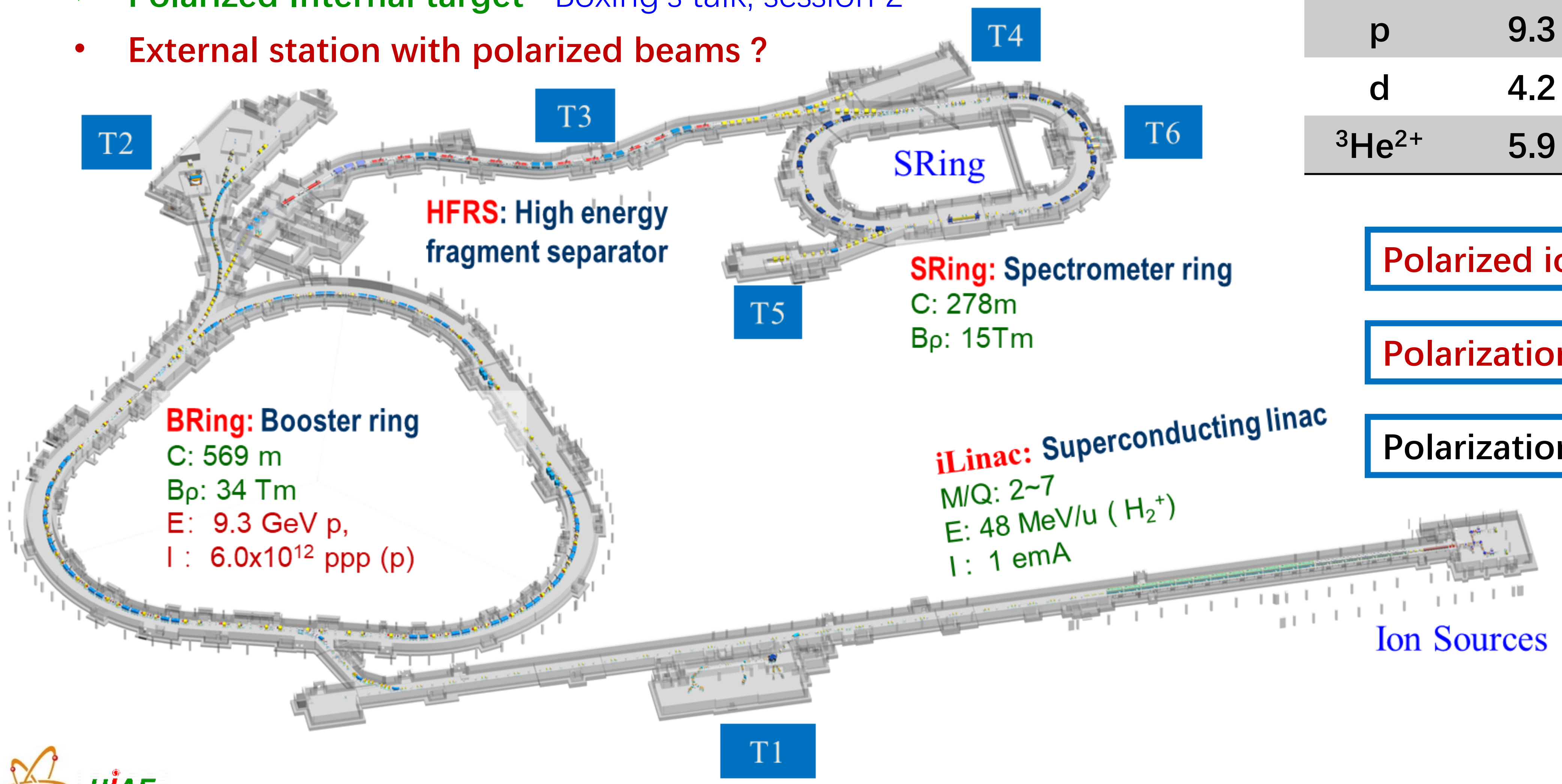


Lamb Shift Polarimeter: stable and reliable

Acceleration of polarized ions with HIAF

- **Spin-polarized experiments at HIAF**
  - ✓ **Polarized Internal target** Boxing's talk, session 2
  - **External station with polarized beams ?**

Ion species	Energy (GeV/u)	Intensity (ppp)
p	9.3	1 x 10^{13}
d	4.2	~2 x 10^{12}
$^3He^{2+}$	5.9	



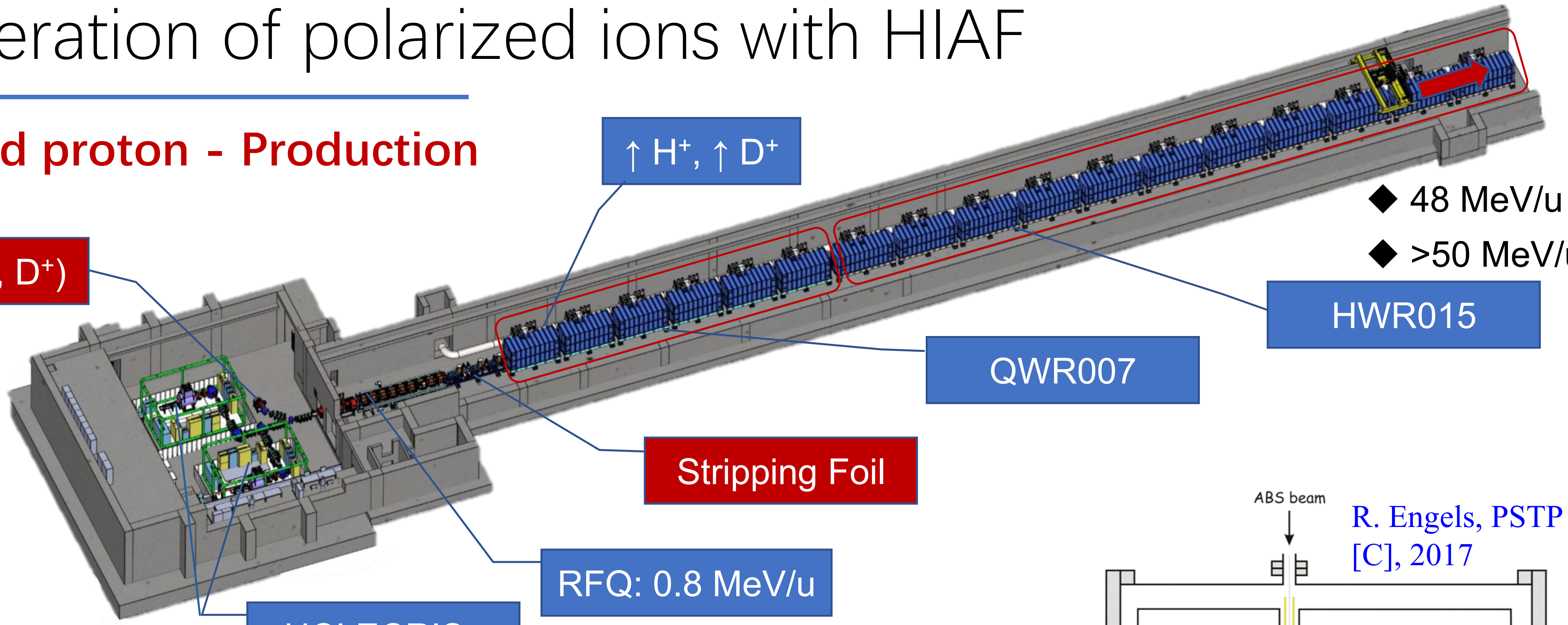
Polarized ion production

Polarization preservation

Polarization measurement

Acceleration of polarized ions with HIAF

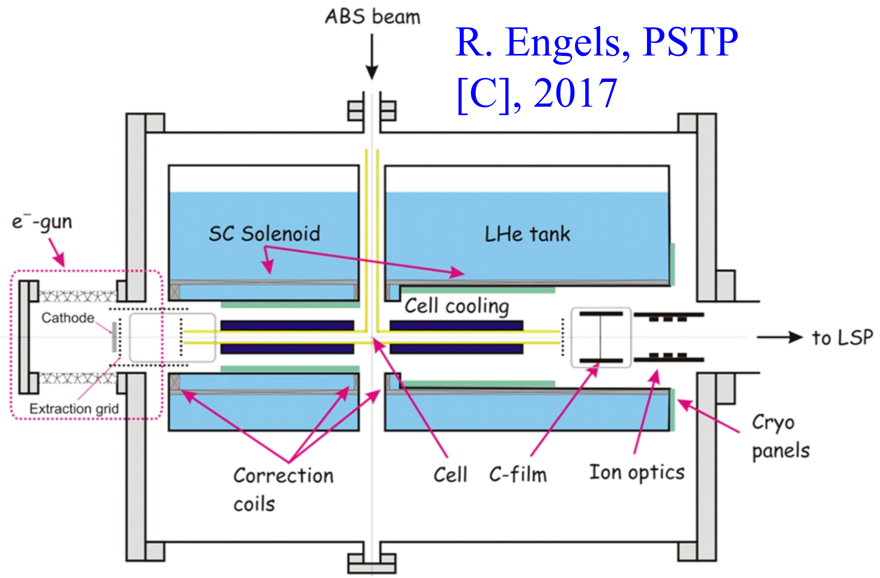
Polarized proton - Production



- ◆ 48 MeV/u ↑D^+
- ◆ >50 MeV/u ↑H^+

Current RFQ only accelerates particles with m/q = 2~7

➢ Polarized H_2^+ source & Stripper maybe feasible



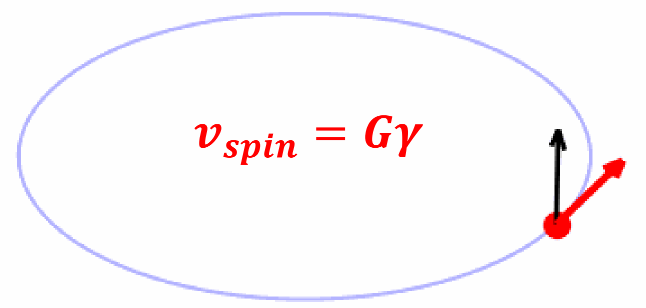
R. Engels, PSTP [C], 2017

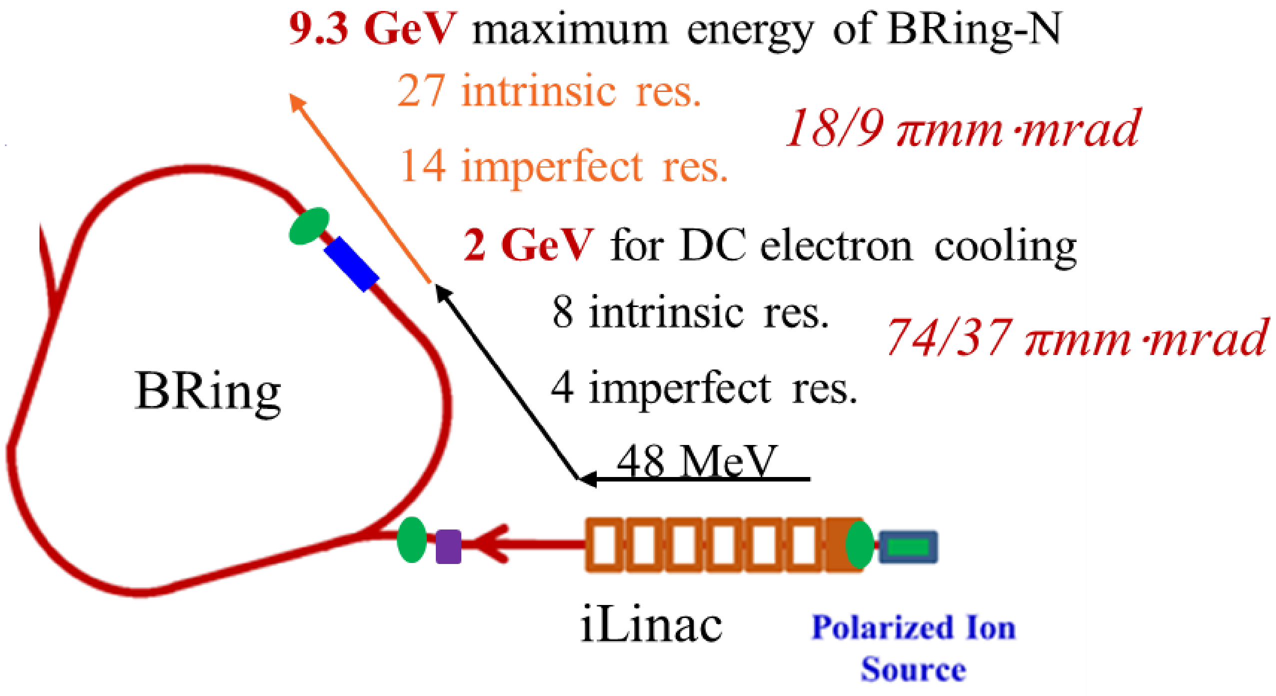
Challenge!!!
No existing polarized H_2^+ ion source
Serious depolarization even with low energy

Acceleration of polarized ions with HIAF

Polarized proton - Preservation

G = 1.79





- **Imperfection resonance**

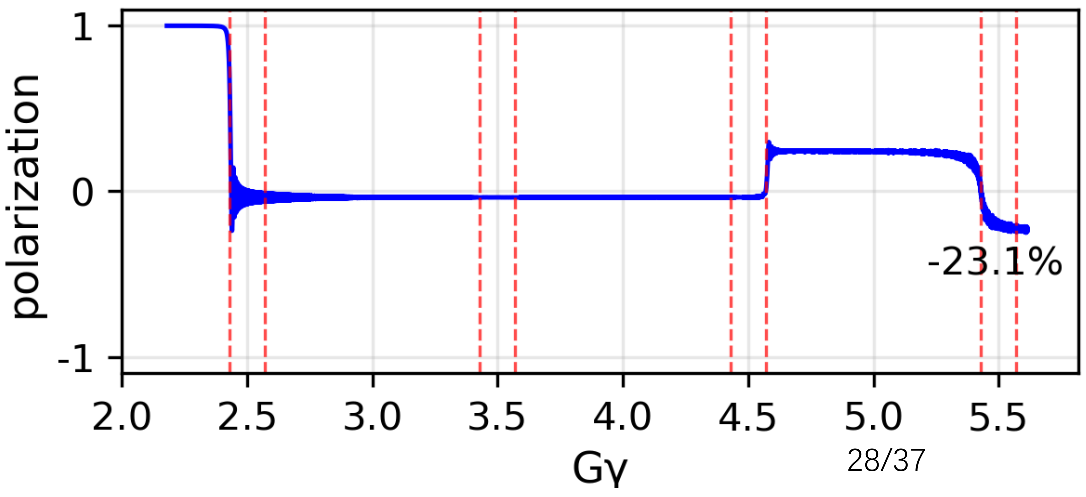
$$\nu_{spin} = n \text{ (integer)}$$

driven by magnet errors and misalignments

- **Intrinsic Resonance**

$$\nu_{spin} = nP \pm \nu_y$$

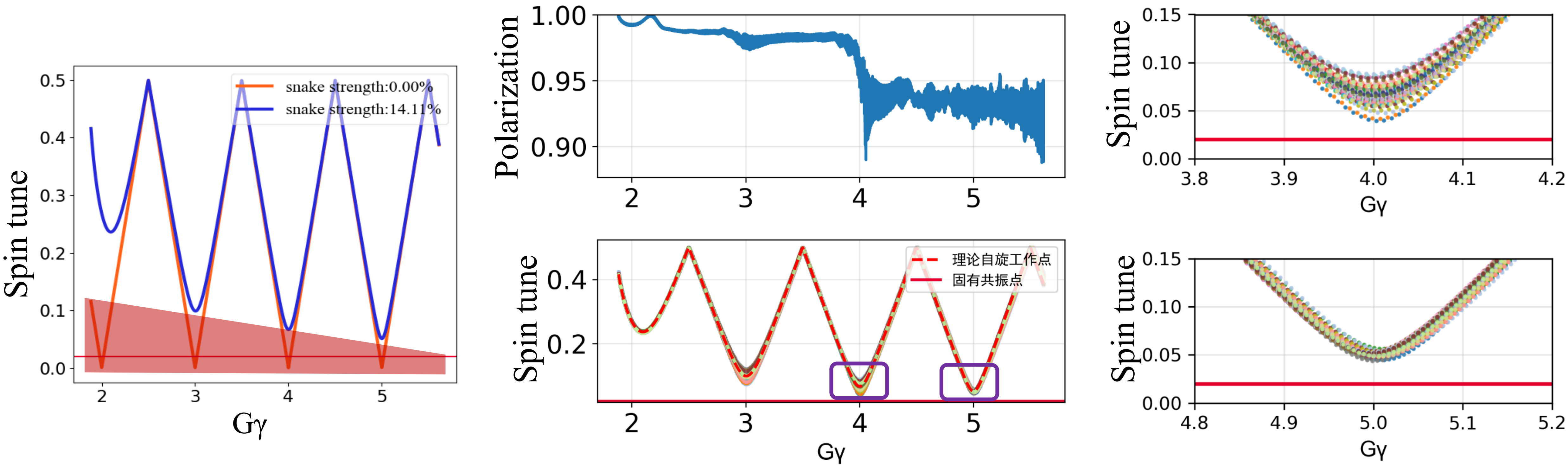
driven by focusing fields, P = 3, ν_y= 9.43 for BRing



Acceleration of polarized ions with HIAF

Polarized proton – Preservation (0.2 – 2.0 GeV)

- **A constant field solenoid snake makes enough spin tune gap for avoiding depolarization resonance** [M.X. Li, NIMA, 2022]

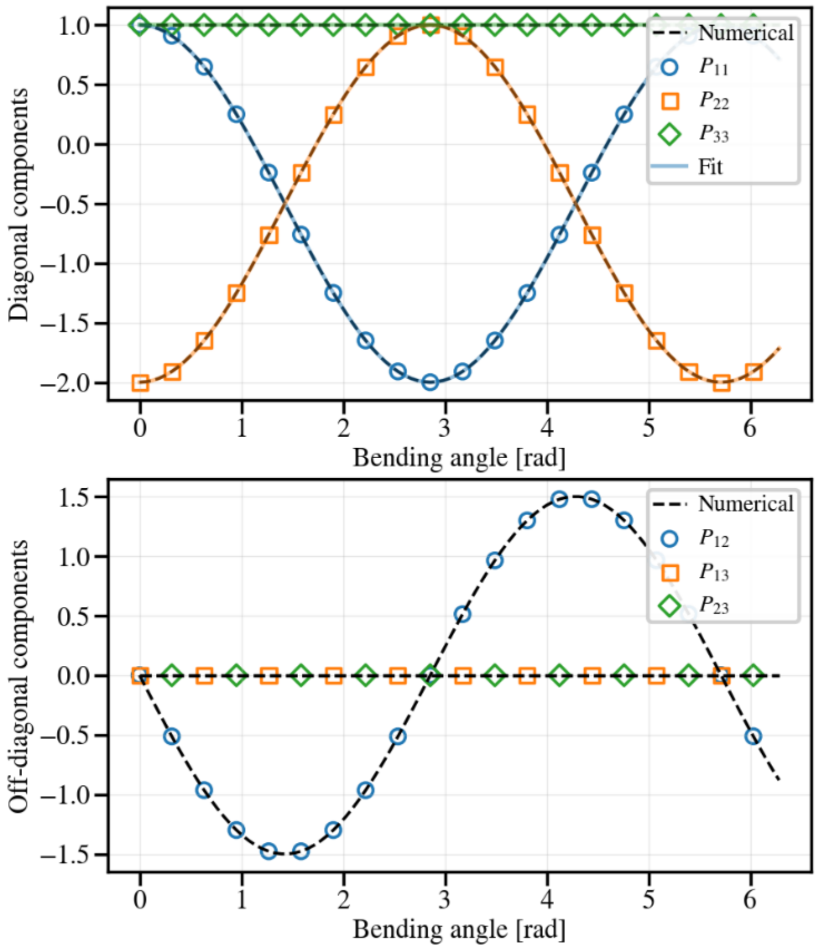


- **To higher energy (9.23 GeV), a helical snake (strength 30%) is a feasible option.**

Acceleration of polarized ions with HIAF

Polarized deuteron – Preservation

- **Development of tensor-polarized transport matrices**



PHYSICAL REVIEW ACCELERATORS AND BEAMS **28,** 094002 (2025)

[M.X. Li, PRAB, 2025]

Acceleration and spin direction control of tensor-polarized deuteron beams in a synchrotron

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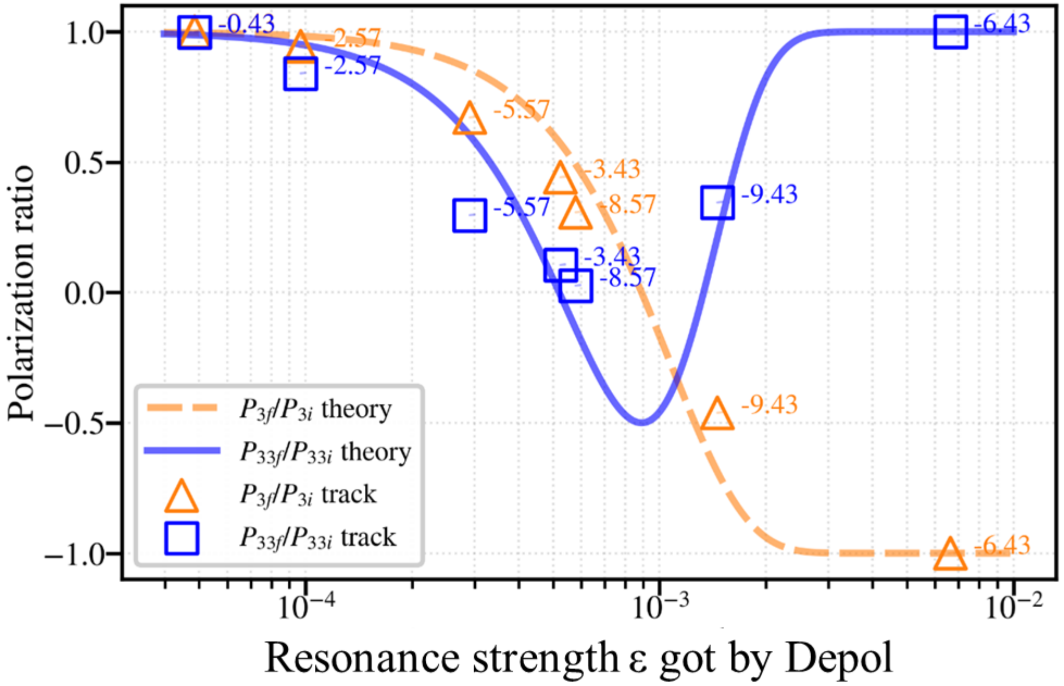
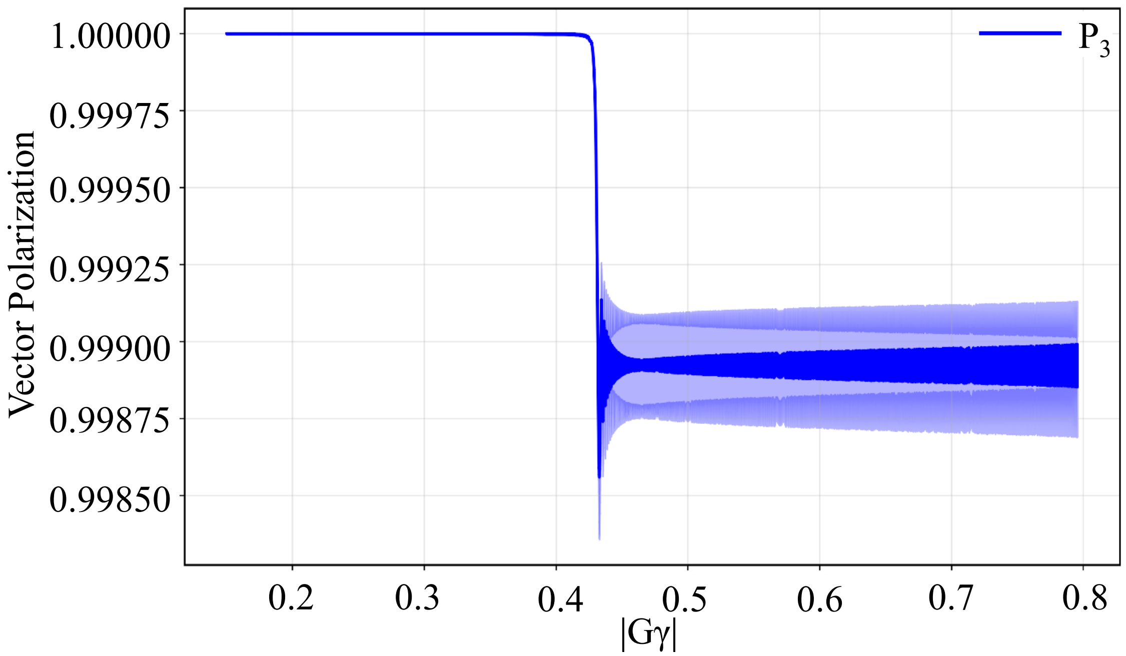
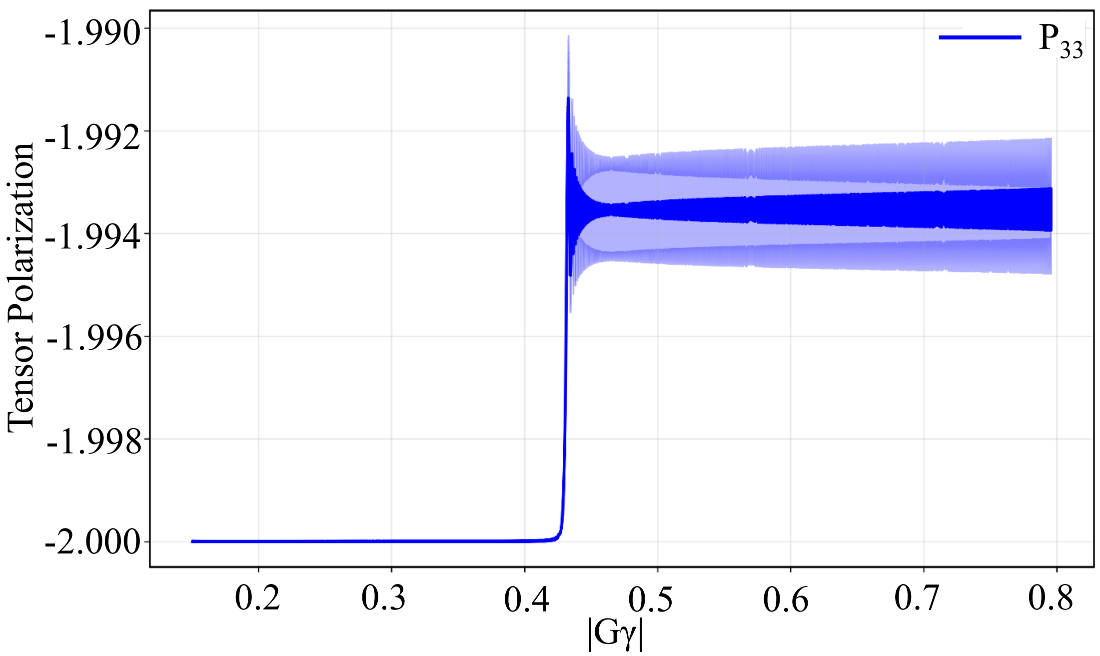


Acceleration of polarized ions with HIAF

Polarized deuteron – Preservation **G = -0.14, 4.21 GeV/u**

Within the HIAF energy range, the losses of vector and tensor polarizations of deuteron beams are negligible.

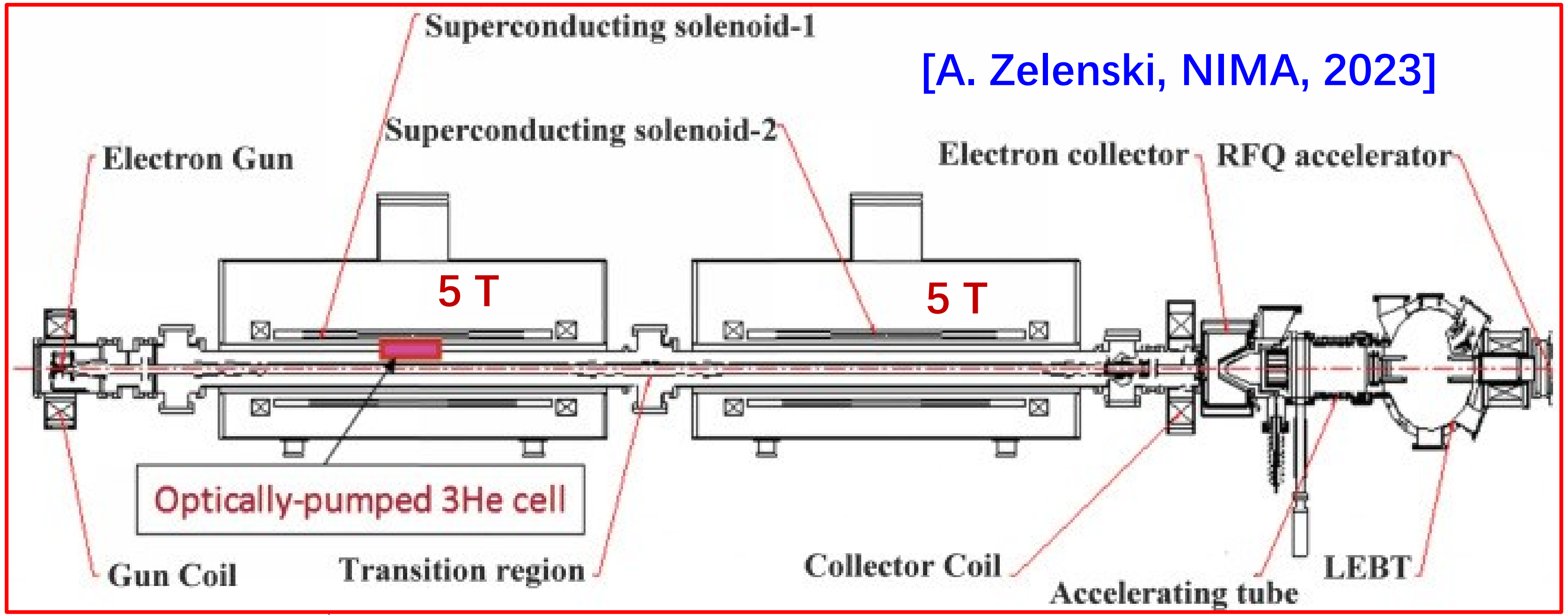




Acceleration of polarized ions with HIAF

Polarized $^3He^{++}$ - Production

No existing intense polarized $^3He^{++}$ ion source



High-field MEOP Prof. Li's Talk (Session 6)

$$e + {}^3He \rightarrow {}^3He^+ + 2e$$

$$e + {}^3He^+ \rightarrow {}^3He^{++} + 2e$$

B_c for $^3He^+$: 0.31 T

- **B-Field of ionizer >> B_c**
- **Polarize ^3He in-situ**

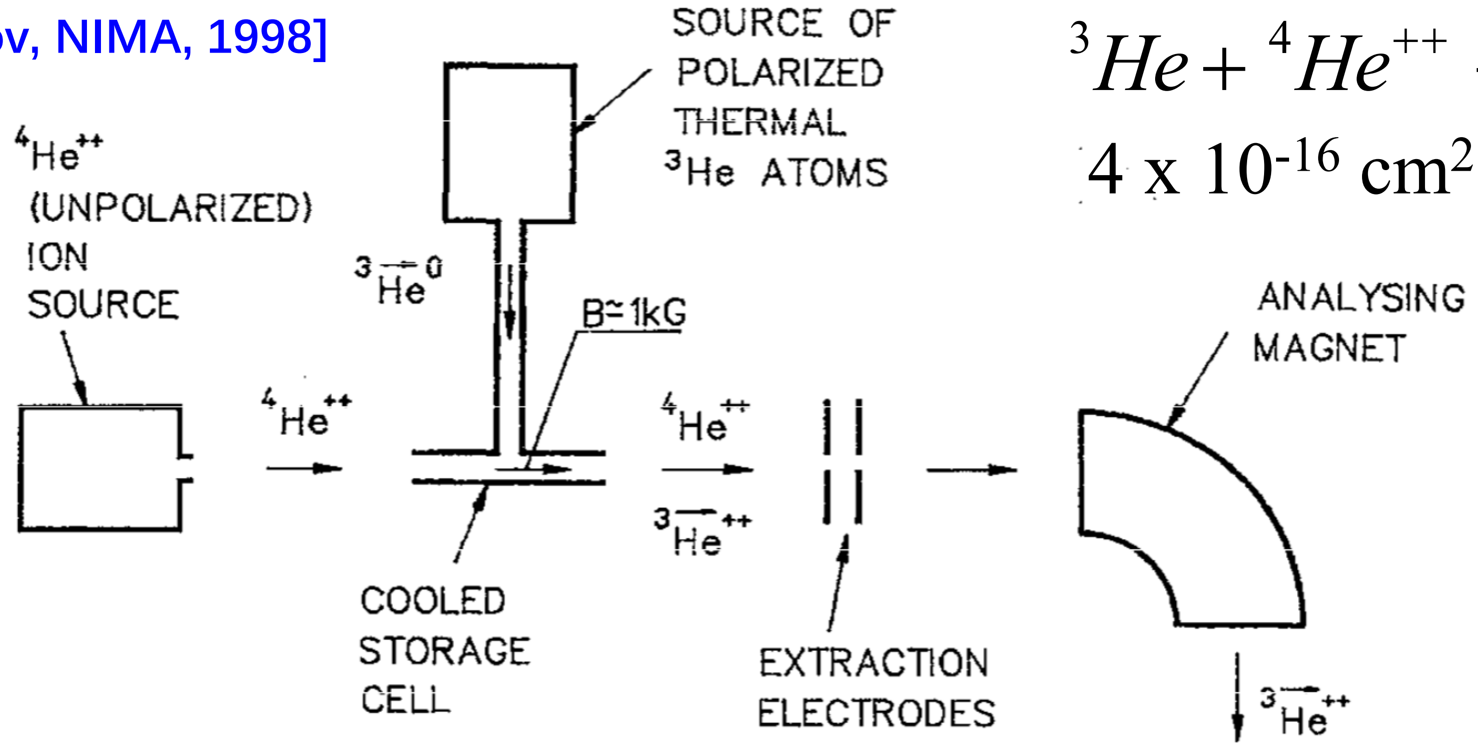
Polarized $^3He^{++}$ source based on extend EBIS is under development at BNL

Acceleration of polarized ions with HIAF

Polarized $^3He^{++}$ - Production

Other possible solution: resonant charge exchange

[A.S. Belov, NIMA, 1998]



$$^3He + {^4He^{++}} \rightarrow {^3He^{++}} + {^4He}$$

4×10^{-16} cm^2 @ 50 eV

- No occurrence of $^3He^+$, no requirement for a strong B-Field
- Intense $^4He^{++}$ with low energy (~50 eV) (Challenging)

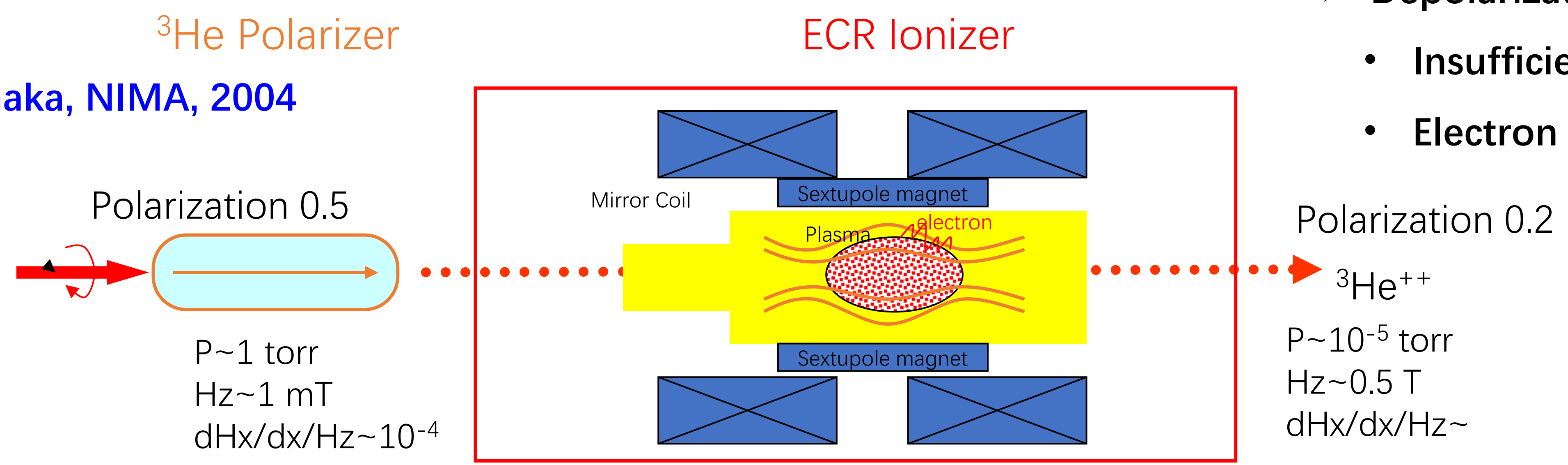
Acceleration of polarized ions with HIAF

Polarized $^3He^{++}$ - Production

Other possible solution: ECR ionizer

- Depolarization
  - Insufficient B-field
  - Electron spin reverse

M. Tanaka, NIMA, 2004

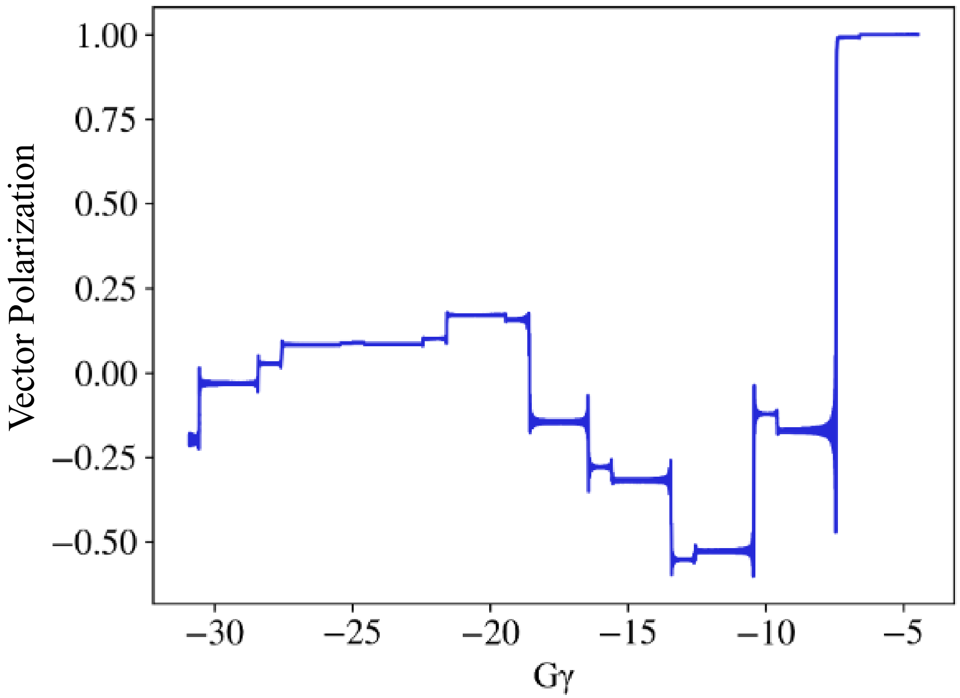


- Development of ECR ionizer and ^3He optical pumping in these years
- Polarized $^3He^{++}$ source based on ECR ionizer is worth considering

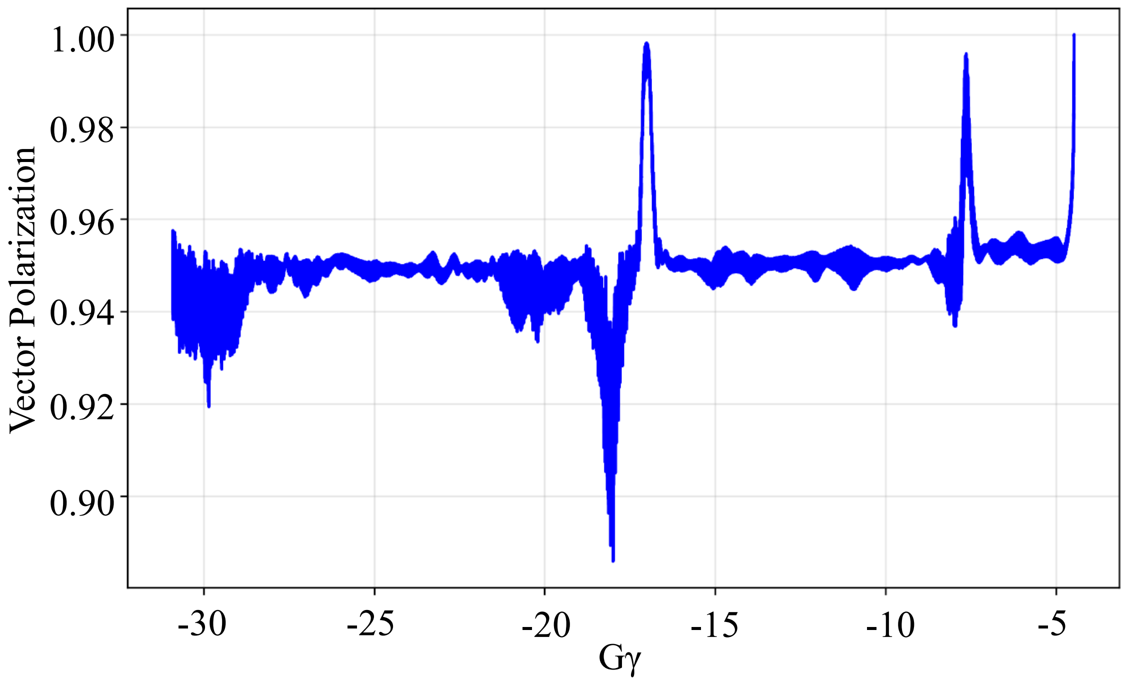
Acceleration of polarized ions with HIAF

Polarized $^3He^{++}$ - Preservation　　　G = -4.18, 5.89 GeV/u

- The G-factor of $^3He^{++}$ is greater than that of the proton
- Depolarization is more severe



- With a helical Siberian snake (strength 40%)



Summary

Status of SPIS at IMP

- ✓ Vector (and tensor) polarized proton (deuteron) beams
- ✓ Intensity 1 mA (6E11 ppp)
- ✓ Polarization 80%
- ✓ Repetition 2-5 Hz
- ☐ Future, Sixfold increase in beam intensity by optimizing the polarized atom-beam flux

Polarized ion acceleration with HAIF

- ➢ Polarized proton, 9.23 GeV, 6 x 10^{12} ppp
  - ☐ Existing RFQ cannot acc. H^+
  - ☐ A polarized H_2^+ ion source or another RFQ
  - ☐ Helical Siberian snake (strength-30%) for polarization preservation
- ➢ Polarized deuteron, 4.21 GeV/u, ~2 x 10^{12} ppp
  - ✓ Feed HIAF-BRing with polarized deuteron from SPIS
  - ✓ No depolarization within the HIAF energy range
- ➢ Polarized $^3He^{++}$, 5.89 GeV/u, ~2 x 10^{12} ppp
  - ☐ Intense polarized $^3He^{++}$ is being discussed
  - ☐ Helical Siberian snake (strength-40%)

Outlook

Polarized ion acceleration with HAIF

- Polarized deuteron acceleration ▲

  basic requirements have been met

- Polarized proton acceleration ▲▲

  a new RFQ (easy) OR a polarized H_2^+ source (challenging) & a Siberian snake (moderate)

- Polarized $^3He^{++}$ acceleration ▲▲▲

  a new RFQ (easy) & a polarized $^3He^{++}$ source (challenging) & a Siberian snake (moderate)

What is most important is the physics that can support all these developments for HIAF. We need good physics.

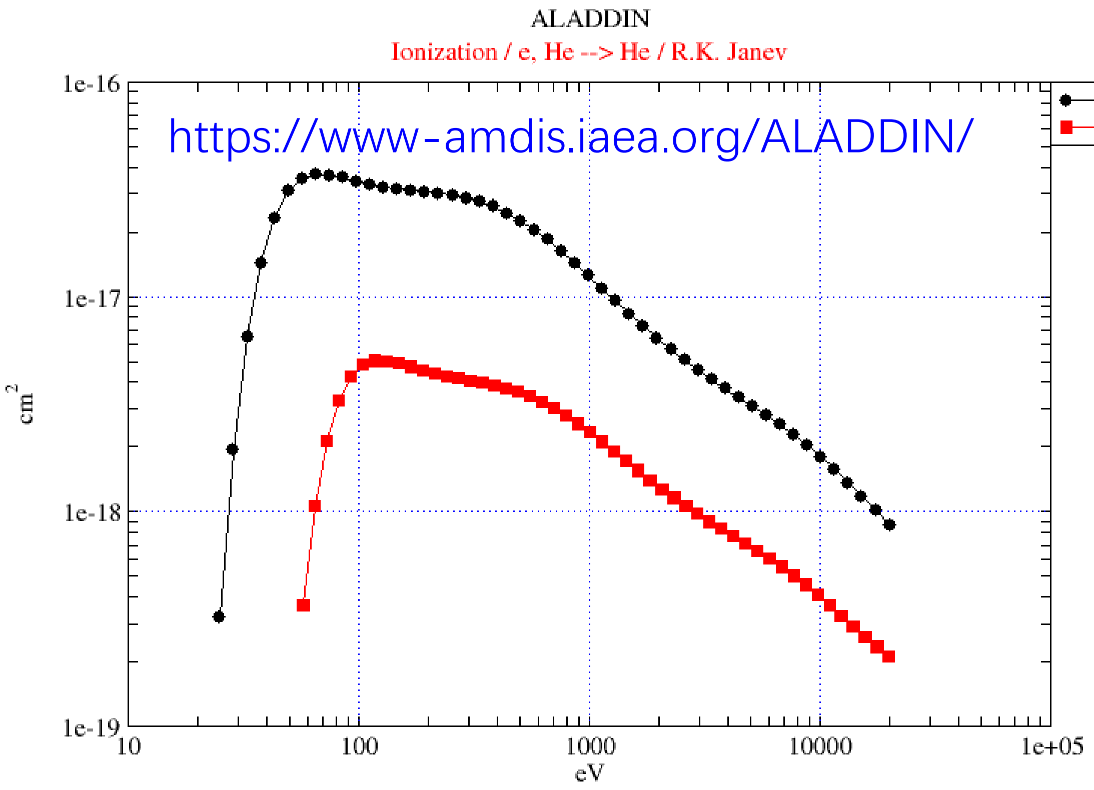
Thanks for your attention!!

如何电离极化 3He 原子

➢ 电子碰撞逐步电离

$$e + {}^3He \rightarrow {}^3He^+ + 2e, \quad e + {}^3He^+ \rightarrow {}^3He^{++} + 2e$$

- 中间产物 $^3He^+$ 的临界磁场为 0.31 T，为避免电离过程中的解极化，电离区磁场须达到 2 T

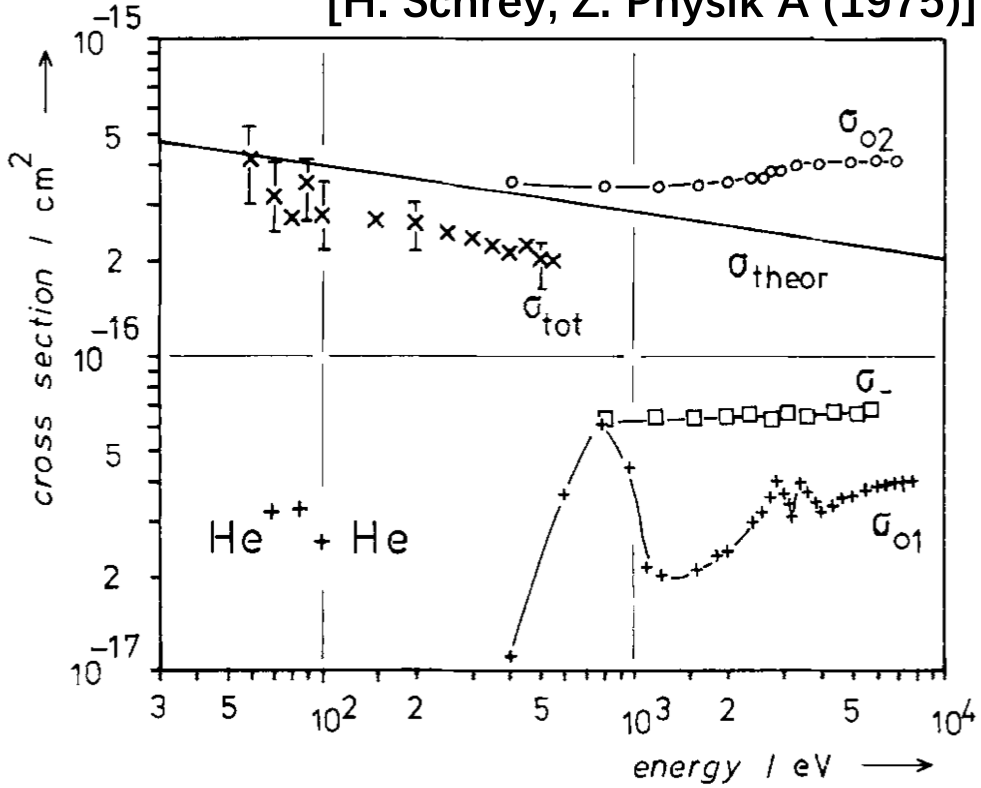


➢ 电荷交换

$$^3He + {}^4He^{++} \rightarrow {}^3He^{++} + {}^4He$$

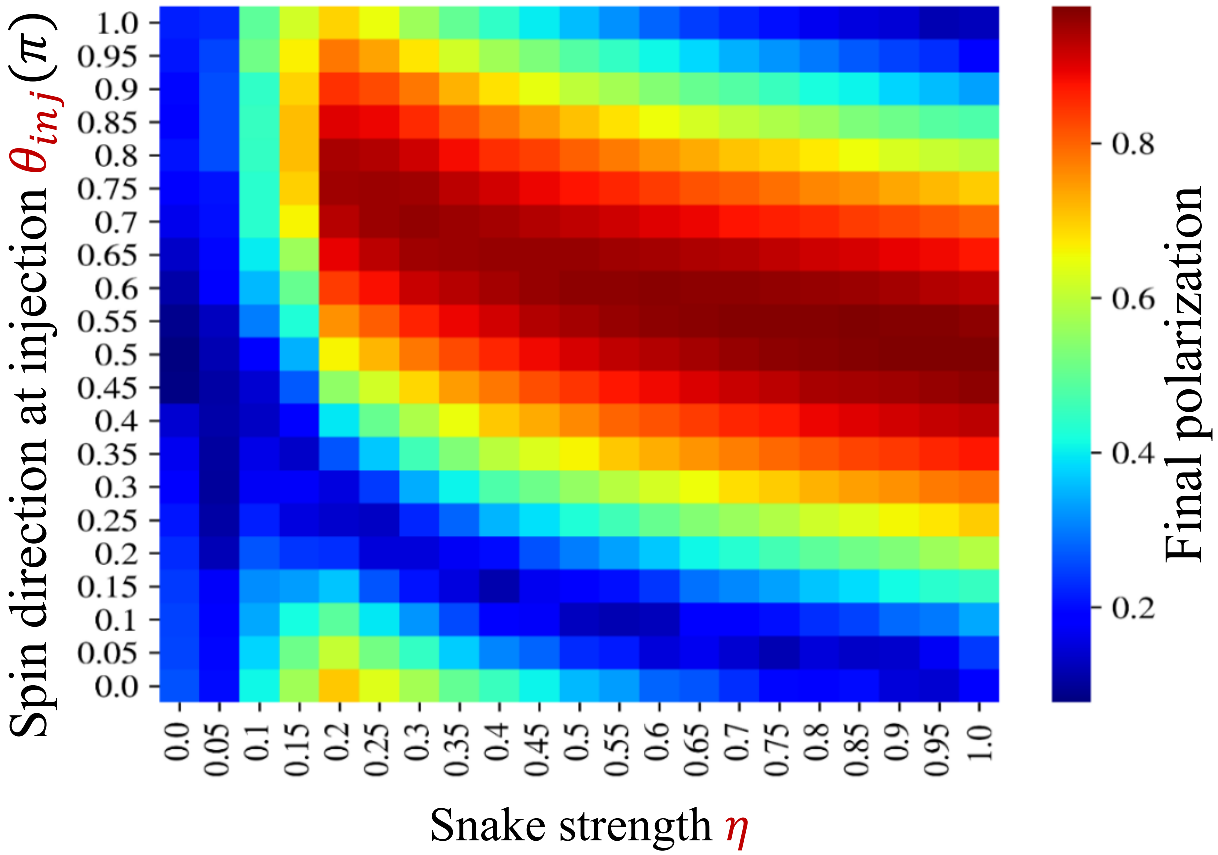
- 没有中间产物，无需强磁场避免解极化，只需提供磁场束缚离子

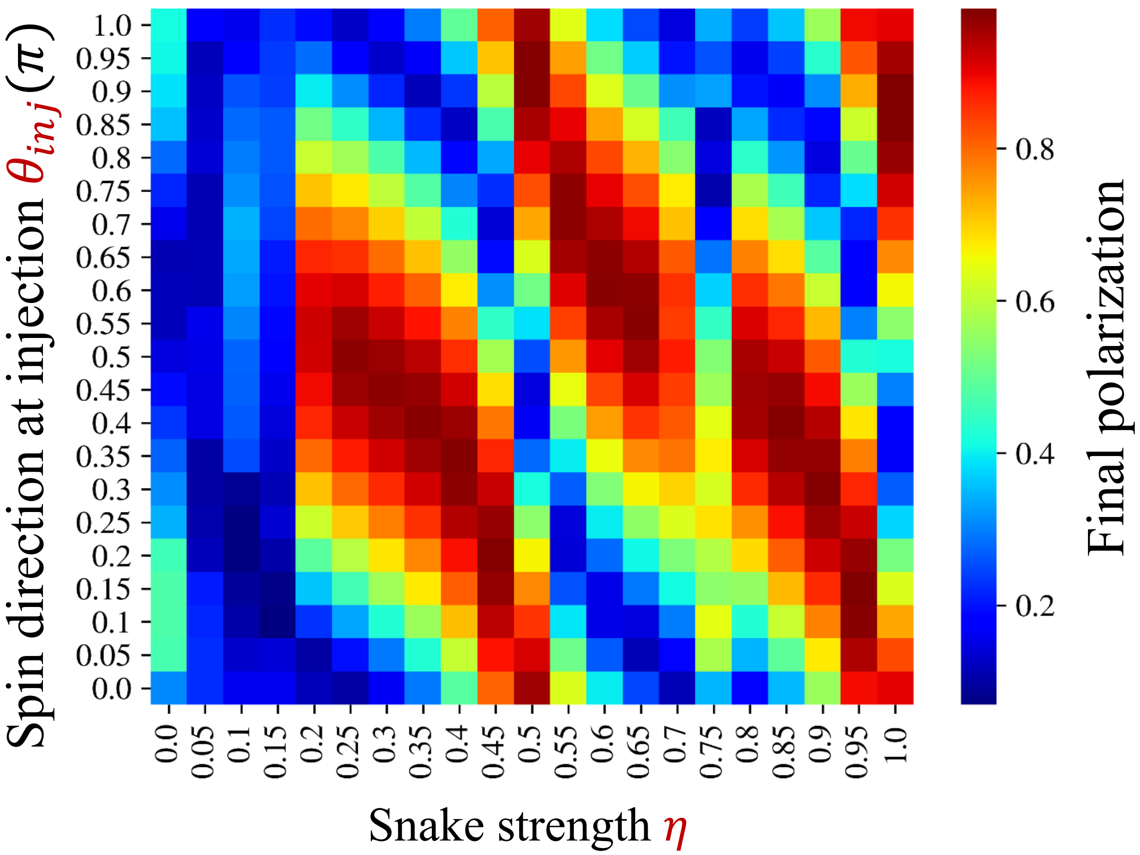
[H. Schrey, Z. Physik A (1975)]



Acceleration of polarized ions with HIAF

Polarized proton – Preservation (0.2 – 2.0 GeV)





- Both constant strength and constant field solenoidal snakes can control the depolarization less than 10%
- HIAF-BRing works with a fast-ramping rate → Constant-strength snake: field ramping rate 29 T/s

To realize polarized ion beams acceleration with HIAF

Polarized ion beam team