Development of a polarized H/D gas target at IMP

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on behalf of the HIAF spin team

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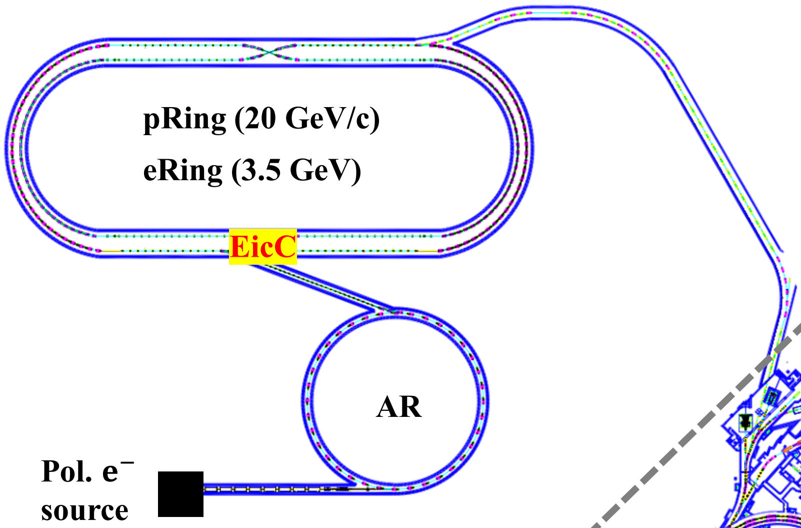
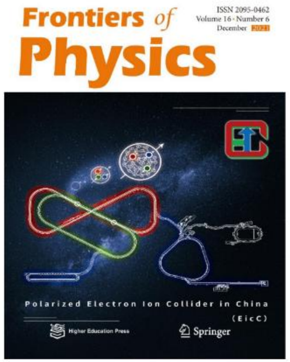




Electron ion collider in China (EicC)

- **currently being proposed**

High Intensity Heavy-ion Accelerator Facility (HIAF)

✓ **to be commissioned in 2025**

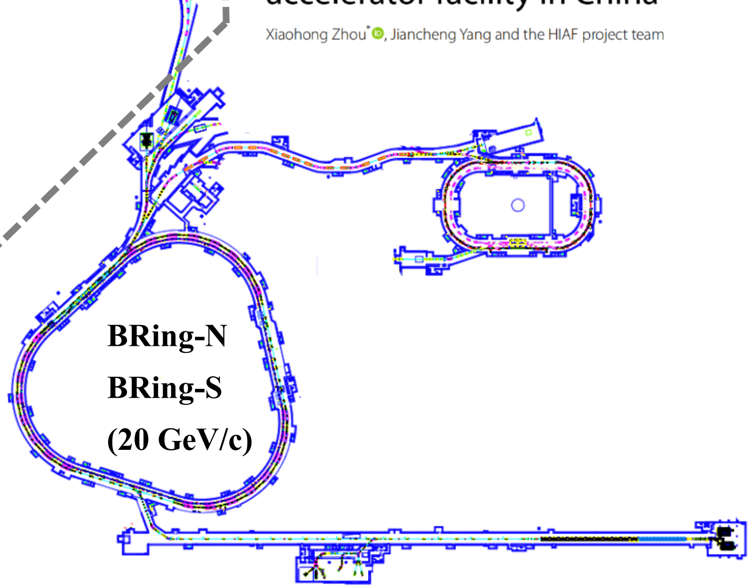
Zhou *et al. AAPPS Bulletin* (2022) 32:35
https://doi.org/10.1007/s43673-022-00064-1

AAPPS Bulletin

REVIEW ARTICLE — Open Access

Status of the high-intensity heavy-ion accelerator facility in China

Xiaohong Zhou*, Jiancheng Yang and the HIAF project team



Motivation

1. A key device for HIAF and EicC (beam polarimetry).
2. Spin-polarized experiments at HIAF (see Boxing' talk).

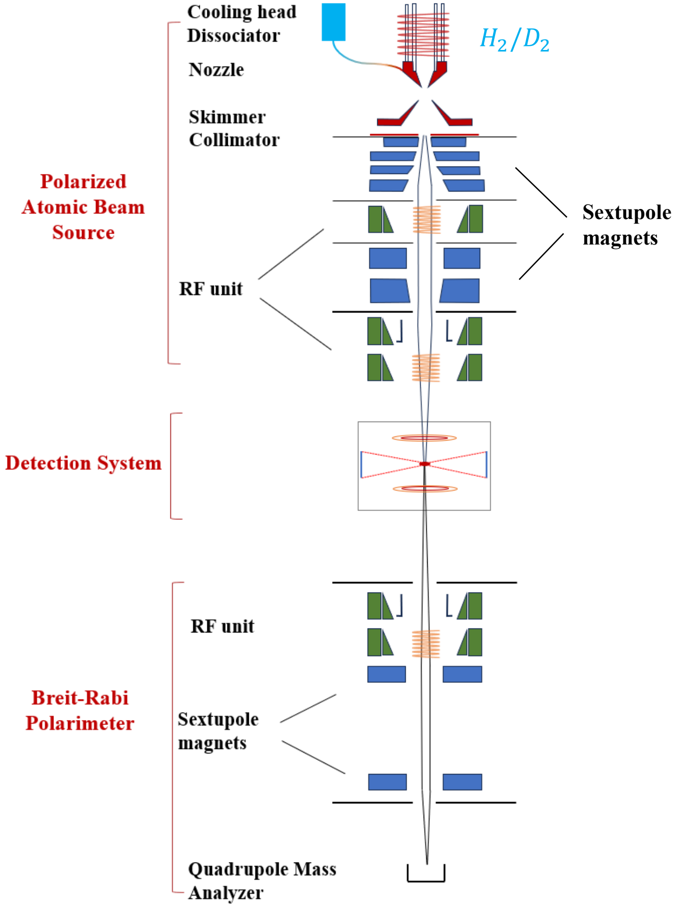
Aim

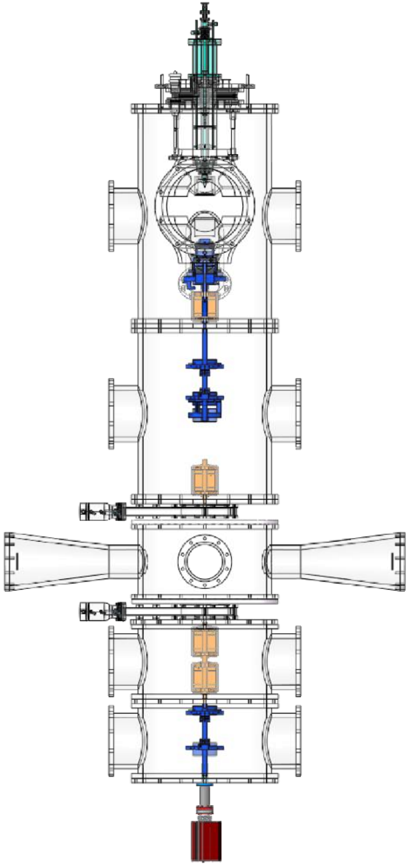
Build a high-performance polarized H/D gas target.

1. Degree of polarization ——— $> 90\%$
2. Target thickness/beam intensity ——— 1×10^{17} Atom/s

Content

Polarized H/D gas target





- Based on polarized Atomic Beam Source(ABS) and Breit-Rabi Polarimeter(BRP).
- The preliminary engineering design has been completed.

Content

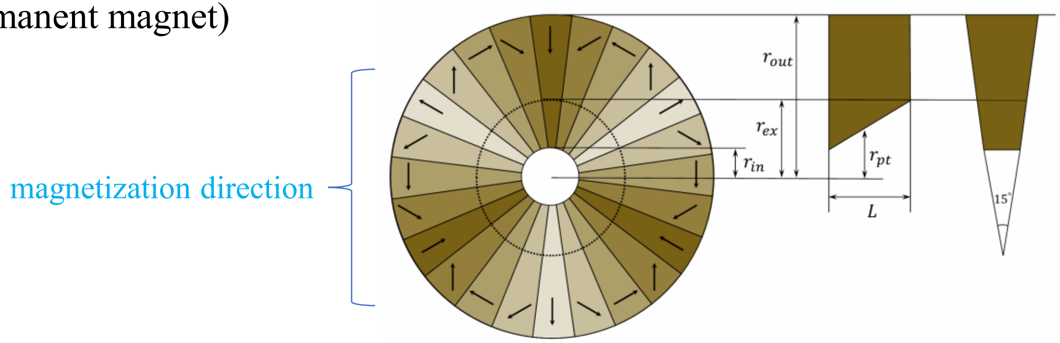
- Motivation
- Polarized H/D gas target
- Design of atomic beam source
  - Atomic beam tracking in sextupole magnets
  - Calculation for radio-frequency transition
- Breit-Rabi polarimeter
- Summary

Spin separation in sextupole magnets

- Halbach sextupole magnet of 24-segment(permanent magnet)

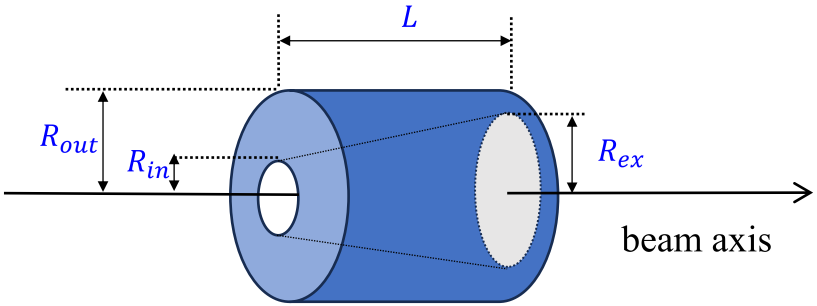
$$B_{tip} = \frac{3}{2} \cdot B_{rem} \cdot [1 - \left(\frac{r_{pt}}{r_{out}}\right)^2] \cdot 0.95$$

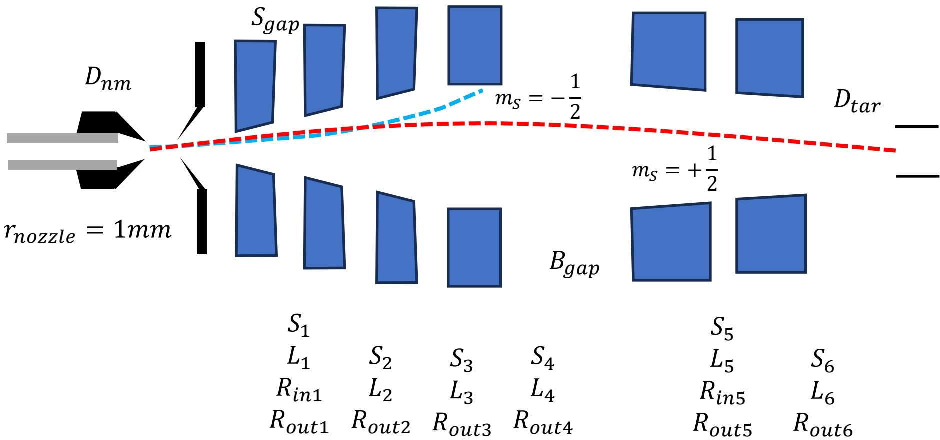
$$B(r) = B_{tip} \cdot \left(\frac{r}{r_{pt}}\right)^2$$



- Parameters of magnet system

24 parameters





Tracking in sextupole magnets system

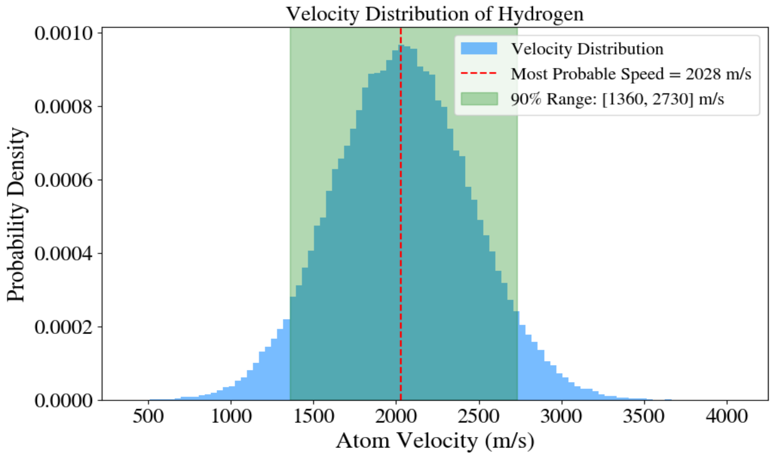
- The velocity of atoms (Maxwell distribution)

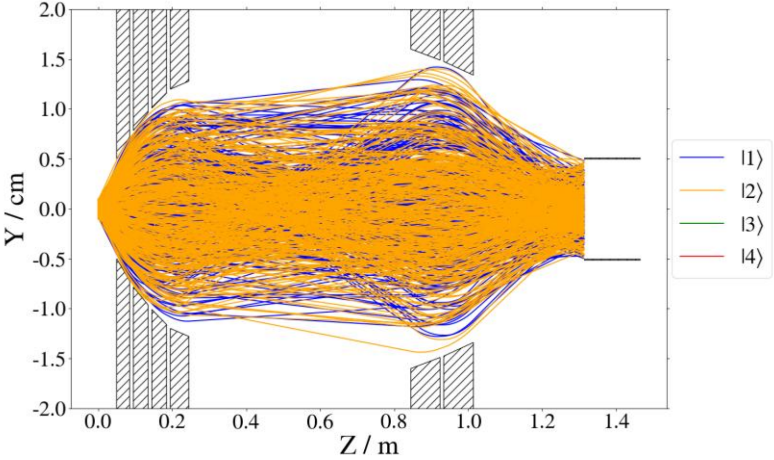
$$f(v;T_b,v_d)=v^2\cdot e^{-\frac{m}{2kT_b}(v-v_d)^2}$$

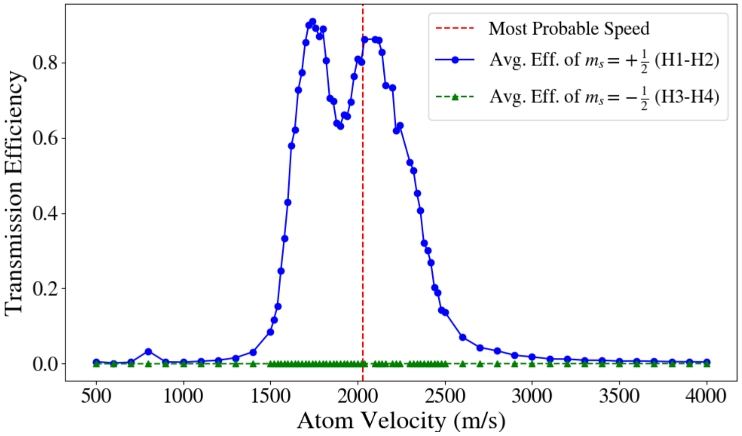
- The dominant radial force to an atom in state |n⟩ in an inhomogeneous magnetic field ($x=\frac{|\vec{B}|}{B_c}$)

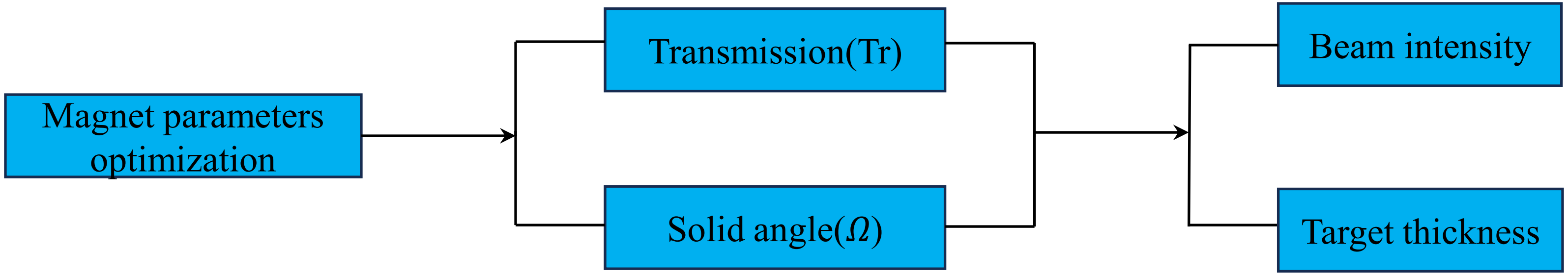
$$\vec{F}_n=-\nabla E_n=-\frac{dE_n}{dx}\frac{1}{B_c}\cdot\frac{\partial\left|\vec{B}\right|}{\partial r}\frac{\vec{r}}{r}$$

- The trajectories and transmission efficiency of hydrogen atom









- Tool

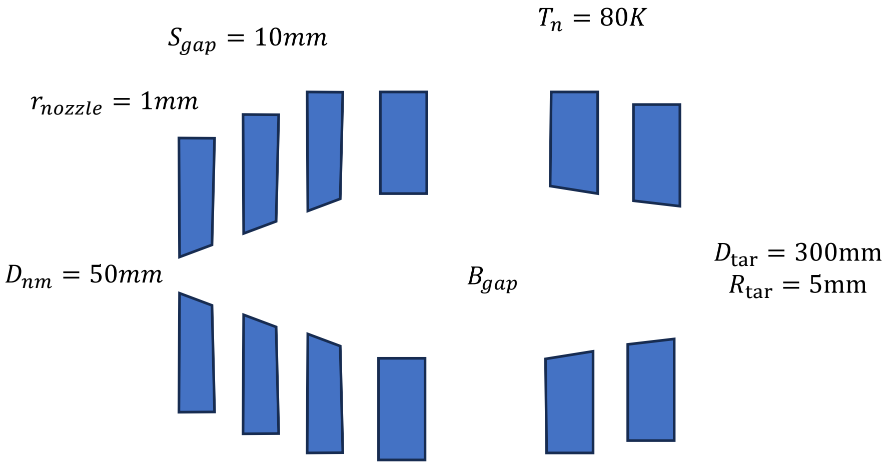
  - Tree-structured Parzen Estimator(TPE). *Bergstra J, et al., Advances in neural information processing systems, 2011, 24.*

  - Based on a Bayesian optimization algorithm:

    1. Applicable to high-dimensional or mixed-type parameter spaces.
    2. Efficient for hyperparameter optimization.

    } Fit for optimizing magnet hyperparameters

- Obtain an optimal set from 10^5 parameter systems by TPE algorithm



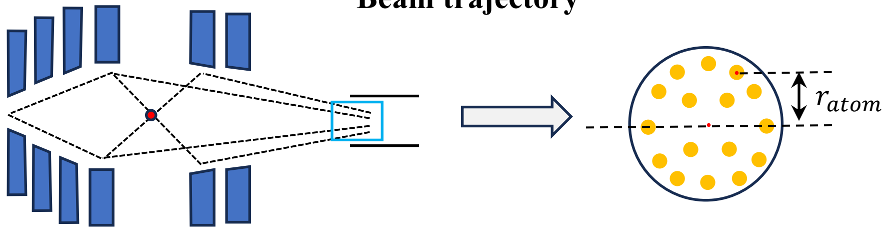
R_{in}(mm)	5.0	7.8	10.1	12.0	16.0	14.8
$R_{ex}(mm)$	7.2	9.6	11.6	12.8	14.9	14.3
$L(mm)$	35	40	40	50	79	80
$R_{out}(mm)$	24.9	39.6	37.9	45.0	58.0	60.0

Material	Neodymium iron boron(NdFeB)
Remanence	$B_r = 1.5$ T
Pole tip field	1.8-1.9 T
Expected results	
Transmission	48.35%
Intensity	$\sim 9.46 \times 10^{16}$ atom/s

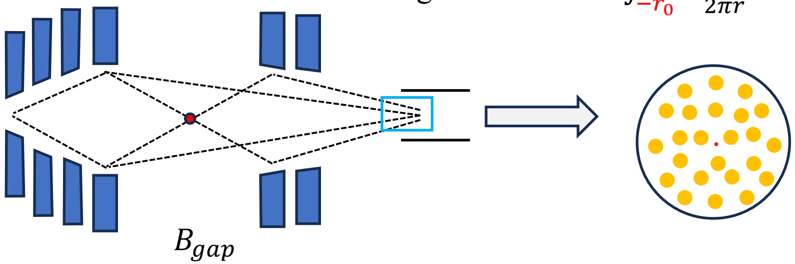
- Assuming a dissociation and attenuation factor of 0.8, expected beam intensity is 9.46×10^{16} atoms/s.

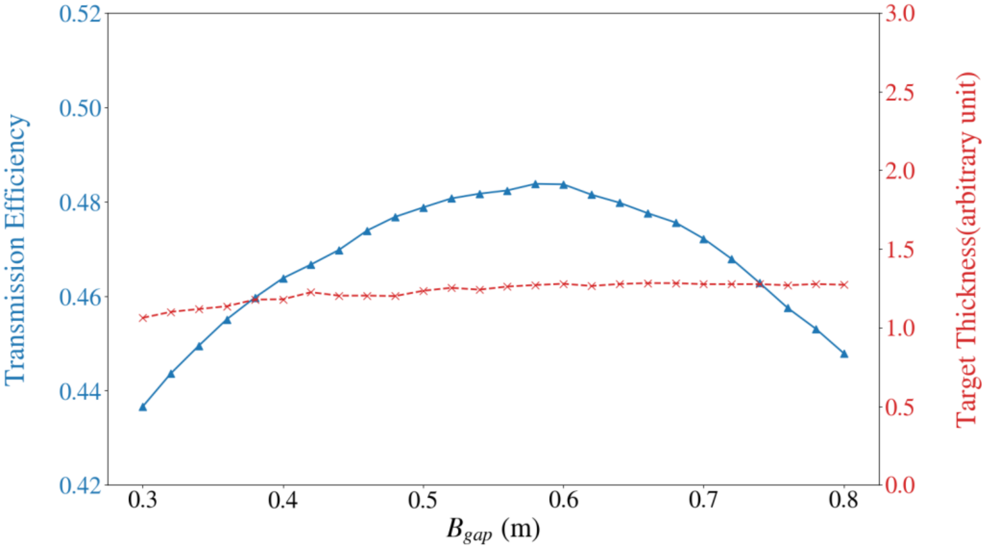
- Look for an optimal B_{gap} value for target thickness

Beam trajectory

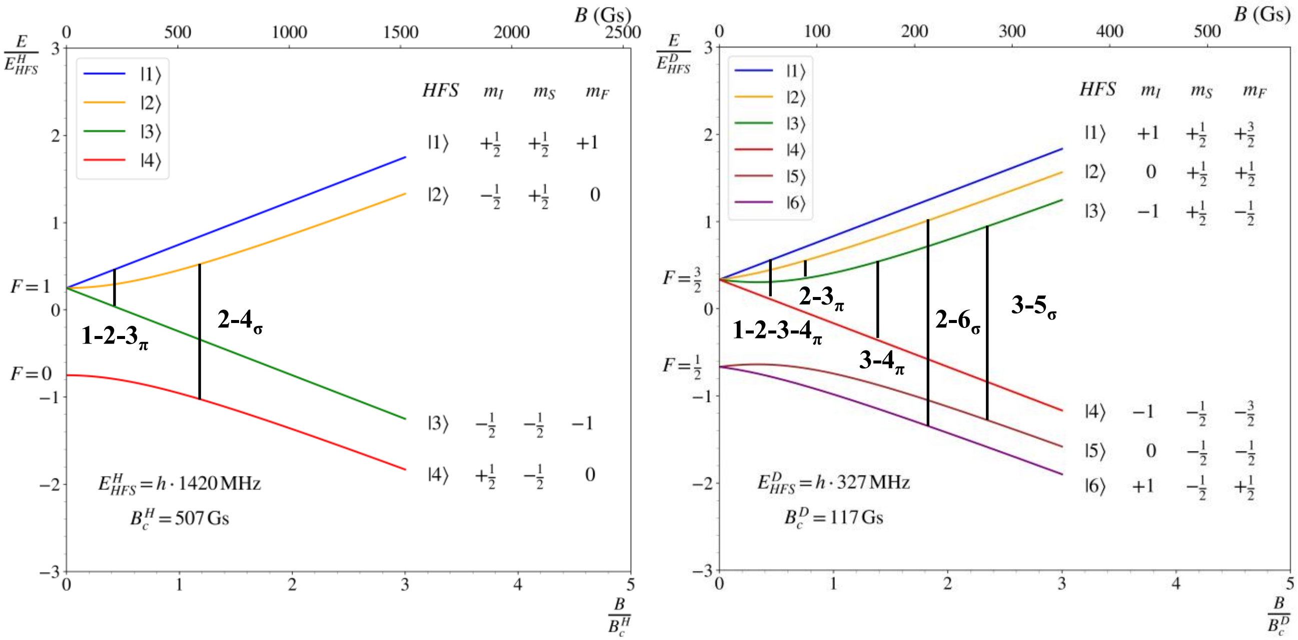


Target thickness $\propto \int_{-r_0}^{+r_0} \frac{n(r)dr}{2\pi r}$





- Long drift length(B_{gap}) is benefit to increase target thickness
- Long drift length may increase intra beam scattering



B orientation	π/σ transition	$\lvert\Delta m_F\rvert$
$B_{rf} \parallel B_{sta}$	σ	0
$B_{rf} \perp B_{sta}$	π	1

- Quantum-mechanical treatment

The main Hamiltonian H_0 in a static field

$$H_0 = A_{H,D}\boldsymbol{S}\cdot\boldsymbol{I} + \left(\frac{g_s\mu_B}{\hbar}\boldsymbol{S} - \frac{g_I\mu_N}{\hbar}\boldsymbol{I}\right)\cdot\boldsymbol{B}_{sta}$$

The interaction Hamiltonian H_{int} in a perturbed radio-frequency field

$$H_{int}(t) = (g_s\mu_B\boldsymbol{S} - g_I\mu_N\boldsymbol{I})\cdot\boldsymbol{B}_{rf}(t)$$

The vary of state population obtained by solving the time-dependent Schrodinger equations

$$i\hbar\frac{\mathrm{d}\Psi(t)}{\mathrm{d}t} = [H_0 + H_{int}(t)]\Psi(t)$$

$$i\hbar\dot{c}_k(t) = \sum_{j=1}^{(2S+1)(2I+1)} c_j(t)e^{-i\omega_{kj}t}\langle k|H_{int}(t)|j\rangle$$

Transition matrix element

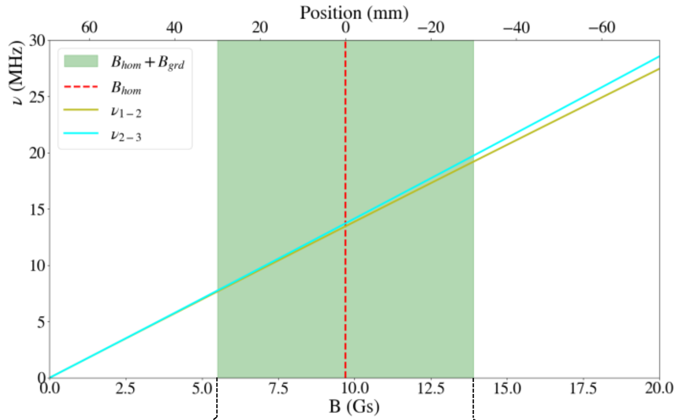
$\lvert\Delta m_F\rvert \,!= 2$ (forbidden)

Radio-Frequency Transition

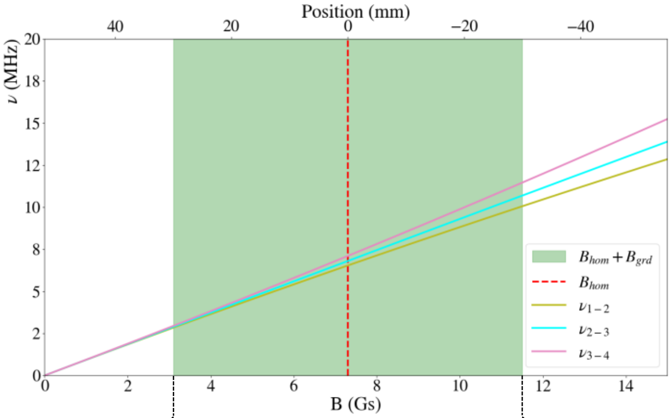
Operation model	1	2	3	4	5	6	7	8
Atom	H	H	H	H	D	D	D	D
Initial states	1+2+3+4				1+2+3+4+5+6			
Sextupole	1+2				1+2+3			
MFT	off				3⇋4		1⇋4	
	1+2				1+2+4		2+3+4	
Sextupole	1+2				1+2		2+3	
SFT	2⇋4	off	off	2⇋4	2⇋6	off	2⇋6	3⇋5
	1+4	1+2	1+2	1+4	1+6	1+2	3+6	2+5
WFT	off	1⇋3	off	1⇋3	off	1⇋4, 2⇋3	off	off
	1+4	2+3	1+2	3+4	1+6	3+4	3+6	2+5
P_z	+1	-1	0	0	+1	-1	0	0
P_{zz}	-				+1	+1	+1	+2
P_e	0	0	+1	-1	0			

Vector polarization : $P_z = n_\uparrow - n_\downarrow$ Tensor polarization: $P_{zz} = 1 - 3n_0$

Multi-quantum transition

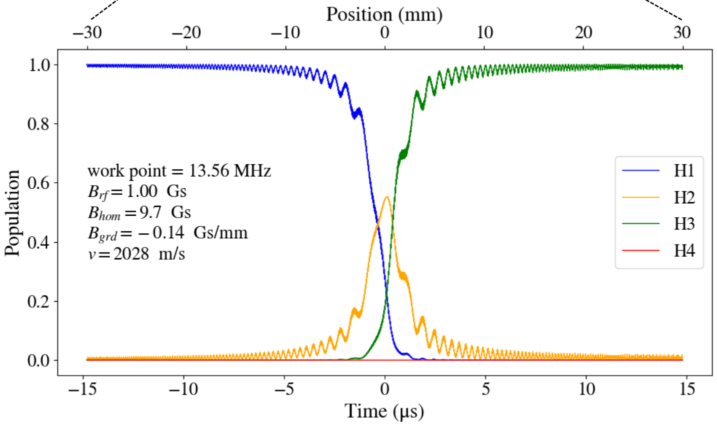


Hydrogen

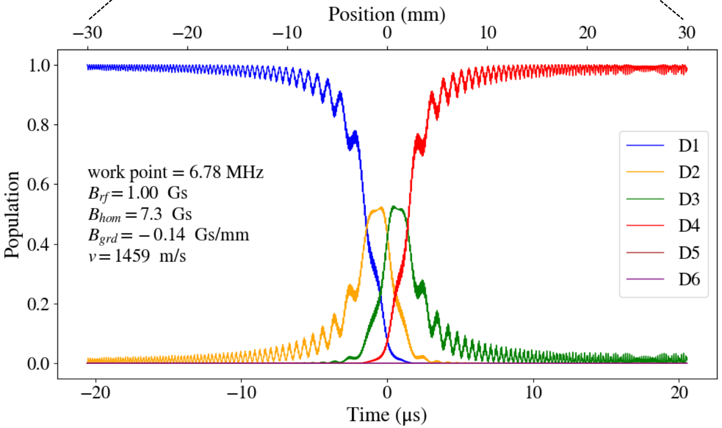


Deuterium

H_{1-3}

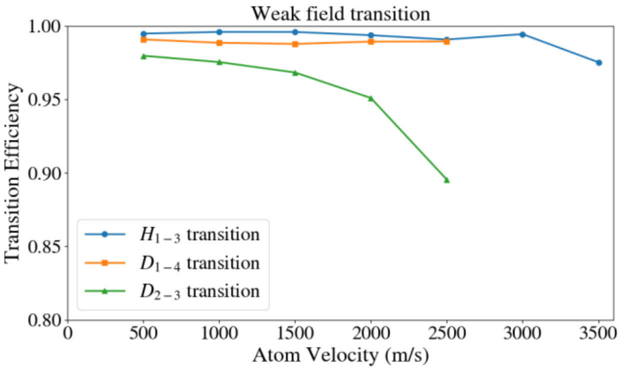


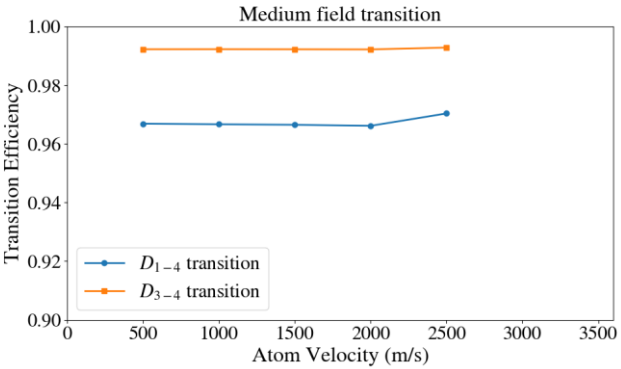
D_{1-4}

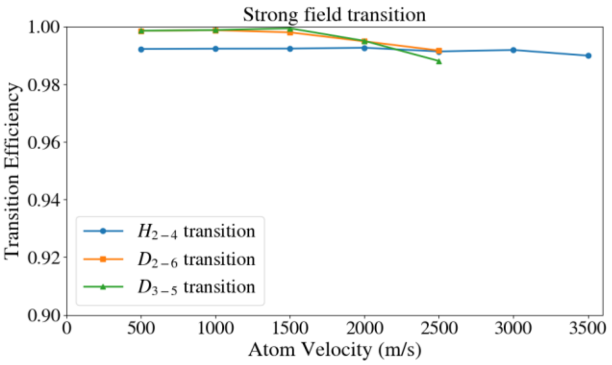


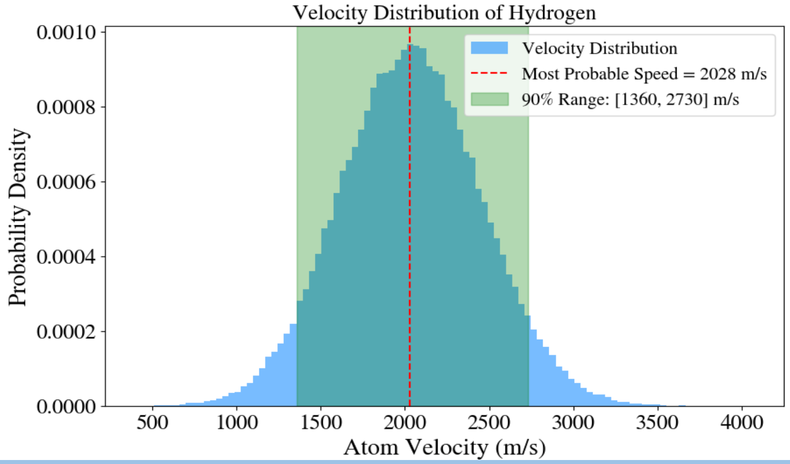
RF transition efficiencies

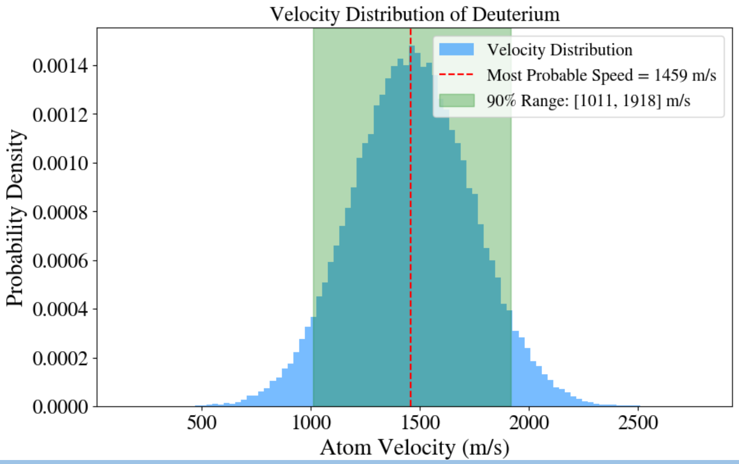
- Numerically solved transition efficiency at different velocity points











RF unit parameters

Weak field transition	H_{1-3}	D_{1-4}	D_{2-3}
Radio frequency	13.56 MHz	6.78 MHz	
Radio-frequency field	1 Gs	1 Gs	
Homogeneous field	9.7 Gs	7.3 Gs	
Gradient field	-0.14 Gs/mm	-0.14 Gs/mm	

Medium field transition	D_{1-4}	D_{3-4}
Radio frequency	25.4 MHz	50 MHz
Radio-frequency field	1 Gs	1 Gs
Homogeneous field	28 Gs	42.5 Gs
Gradient field	-0.14 Gs/mm	-0.14 Gs/mm

Stong field transition	H_{2-4}	D_{2-6}	D_{3-5}
Radio frequency	1430 MHz	433 MHz	
Radio-frequency field	0.5 Gs	1 Gs	
Homogeneous field	60 Gs	69.5 Gs	148 Gs
Gradient field	+0.3 Gs/mm	+0.2 Gs/mm	

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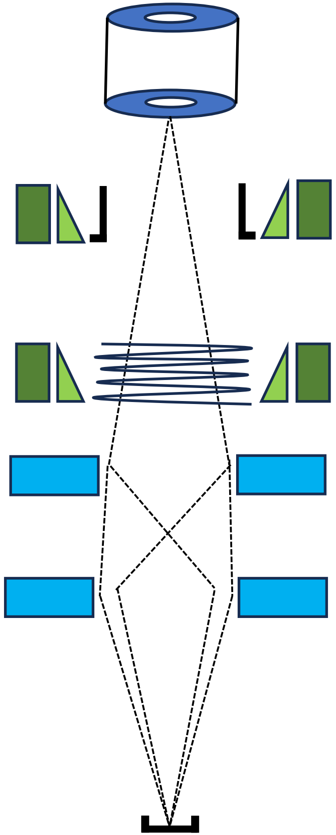

Some BRP signals of hydrogen:

BRP mode	signal name	SFT-RF	SFT-B	MFT-RF	MFT-B
RF-OFF	rfoff	OFF	ON	OFF	ON
SFT 1-4	s14	ON	1-4	OFF	ON
SFT 2-4	s24	ON	2-4	OFF	ON
MFT 1-3	m13c14	OFF	1-4	ON	1-3
MFT 2-3	m23cl4	OFF	1-4	ON	2-3
MFT 1-3	m13c24	OFF	2-4	ON	1-3
MFT 2-3	m23c24	OFF	2-4	ON	2-3
SFT 1-4 + MFT 1-3	m13s14	ON	1-4	ON	1-3
SFT 1-4 + MFT 2-3	m23s14	ON	1-4	ON	2-3
SFT 2-4 + MFT 1-3	m13s24	ON	2-4	ON	1-3
SFT 2-4 + MFT 2-3	m23s24	ON	2-4	ON	2-3

C. Barschel, Calibration of the Breit-Rabi Polarimeter for the PAX Experiment, Diploma Thesis, RWTH Aachen (2010), Chap. 3.

$$S_i = \sum_i M_{ia}\, I_a \quad , \qquad M_{ia} = \sum_b \sigma_b \prod_j T_{ba}^{j}$$

$$I_a = \sum_i (M_{ia})^{-1} S_i$$

$$\mathbf{M_p^H} = \begin{pmatrix} 1 & \cos 2\theta & 1 & -\cos 2\theta \\ 1 & -\cos 2\theta & -1 & \cos 2\theta \end{pmatrix}$$

$$(P_e, P_z)^T \quad = \quad \mathbf{M_p^H}(n_1, n_2, n_3, n_4)^T$$

- By using the signal matrix and combining it with the measurement matrix of the BRP system, the occupancy of atomic hyperfine state can be determined.

Content

Summary

- ✓ Development of a polarized H/D gas target for spin physics at HIAF.
- ✓ Parameter optimization of the sextupole magnets have been essentially finished.
- ✓ The transition efficiencies of radio-frequency unit have been calculated and provides specific parameters.
- ✓ Mechanical design of target and calculation related with BRP are ongoing.

Thank you for your attention!

Backup

➢ Parameter

- Transmission efficiency $\frac{Tr|1\rangle + Tr|2\rangle}{2}$
- Intensity $I(Q, T_{\mathrm{noz}}) = \frac{1}{n}\sum_i^n Tr|i\rangle \cdot Q \cdot \left(\frac{\Omega}{2\pi}\right) 2 \cdot 2 \cdot 1.15 \cdot A(Q, T_n) \cdot \alpha(Q, T_n)$
- Target thickness $\text{Target thickness} \propto Q\Omega A(Q, T_{\mathrm{noz}})\alpha(Q, T_{\mathrm{noz}}) t^*(Q, T_{\mathrm{noz}})$

$$t^* = \frac{\sum_{atoms}\frac{1}{rv}}{\sum atoms}$$

T. Wise, et al., Nucl. Instr. and Meth. A , 556(1):1–12, 2006.

➢ Nozzle temperature

For hydrogen

$$v_d[m/s] = 1351 + 6.1 \cdot T_n[K]$$

$$T_b = 0.29 \cdot T_n$$

For deuterium

$$v_d[m/s] = 1070 + 3.45 \cdot T_n[K]$$

$$T_b = 0.25 \cdot T_n$$

B. Lorentz, Diploma Thesis, Ruprecht-Karls-Universität Heidelberg, 1993.

- RF transition(D_{2-3})