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Progress of the Laser-assisted H^- stripping injection in the CSNS-II

Ming-Yang Huang

Institute of High Energy Physics, Chinese Academy of Sciences

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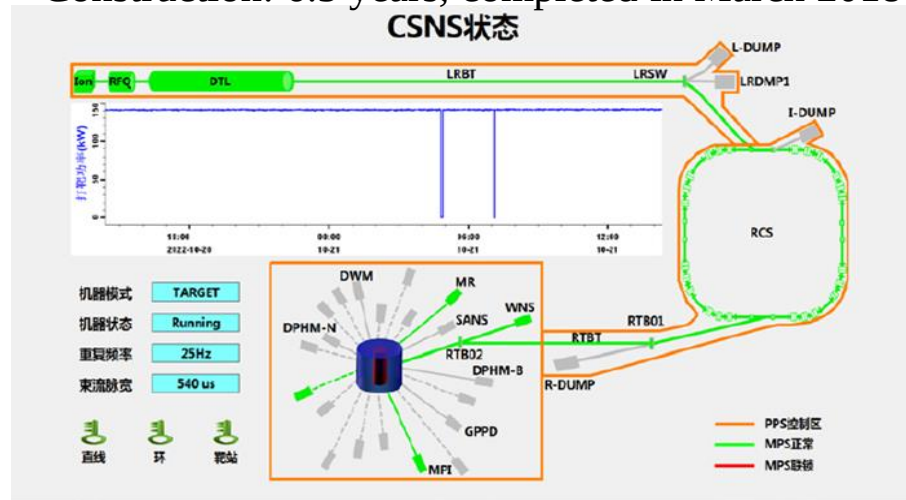
- Introduction
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- Summary

I. Introduction

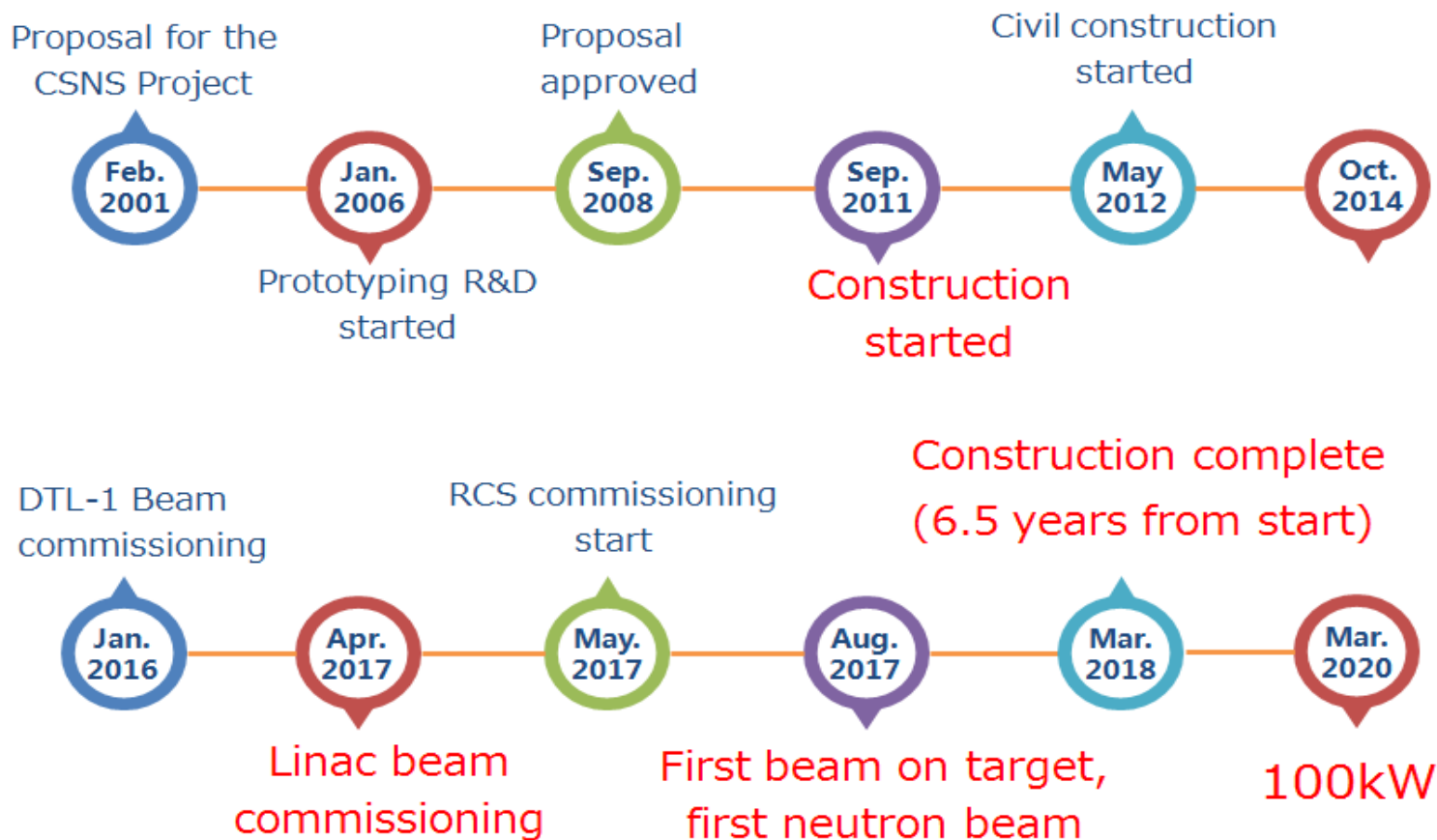


- 80 MeV Linac
- 1.6 GeV RCS
- Target station
- Three neutron spectrometers

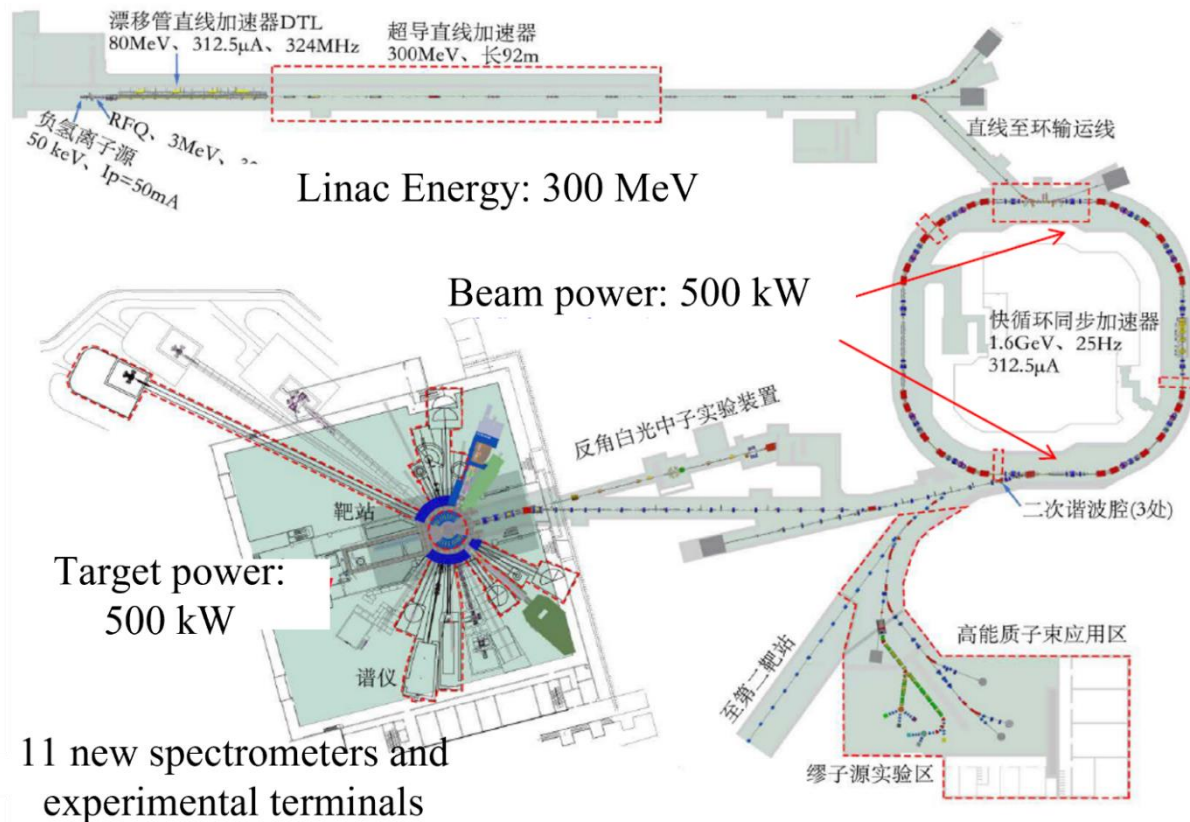
- Budget: ¥ 1.86632 billion
- Location: Dalang Town, Dongguan, Guangdong
- Commencement Date: September 2011
- Construction: 6.5 years, completed in March 2018



CSNS brief history



Upgrade of the China Spallation Neutron Source

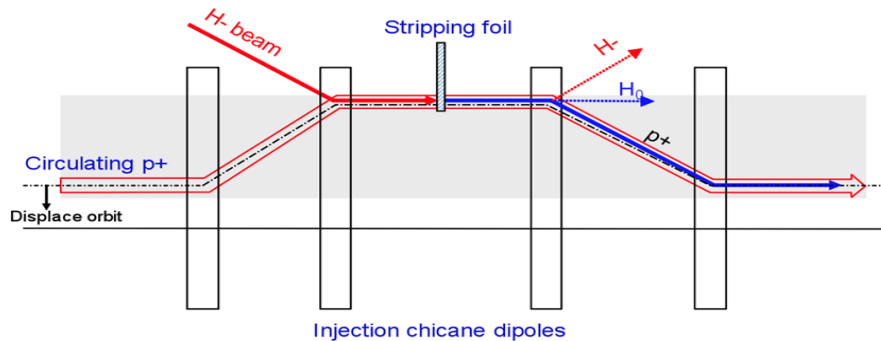


Parameter	CSNS	CSNS-II
Beam power (kW)	100	500
Repetition rate (Hz)	25	25
Target number	1	1
Ave. beam current (uA)	62.5	312
Extraction beam energy (GeV)	1.6	1.6
Injection beam energy (MeV)	80	300
Spectrometer number	3	11+9

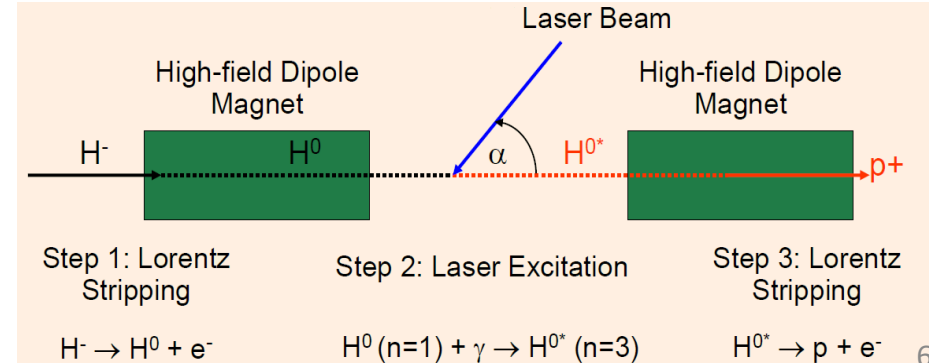
H⁻ stripping

- **H⁻ Stripping:** The Linac accelerates the H⁻ beam. During the preparation for injecting into the RCS, the H⁻ particles are stripped into protons, which then enters the ring through a multi-turn injection method.
- **Two methods:** foil stripping injection, laser-stripping injection.

Foil stripping injection

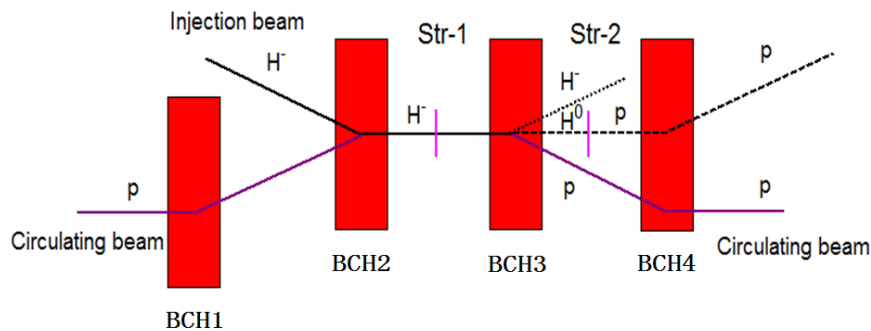


Laser-stripping injection



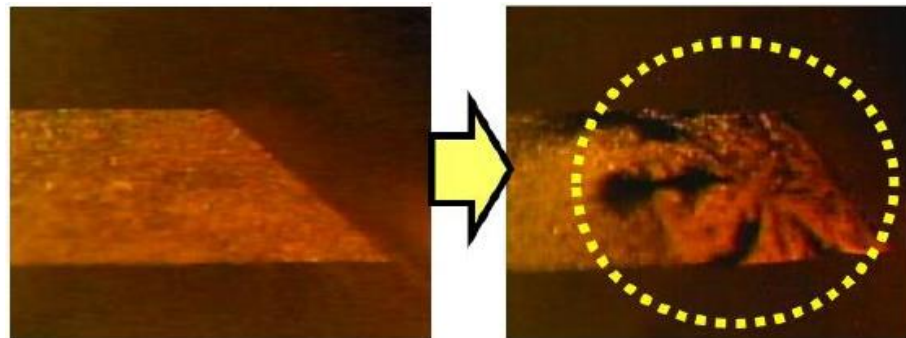
H⁻ stripping for the CSNS-II

- **H⁻ stripping scheme:** foil stripping
- **Stripping foils:** a primary foil and an secondary foil



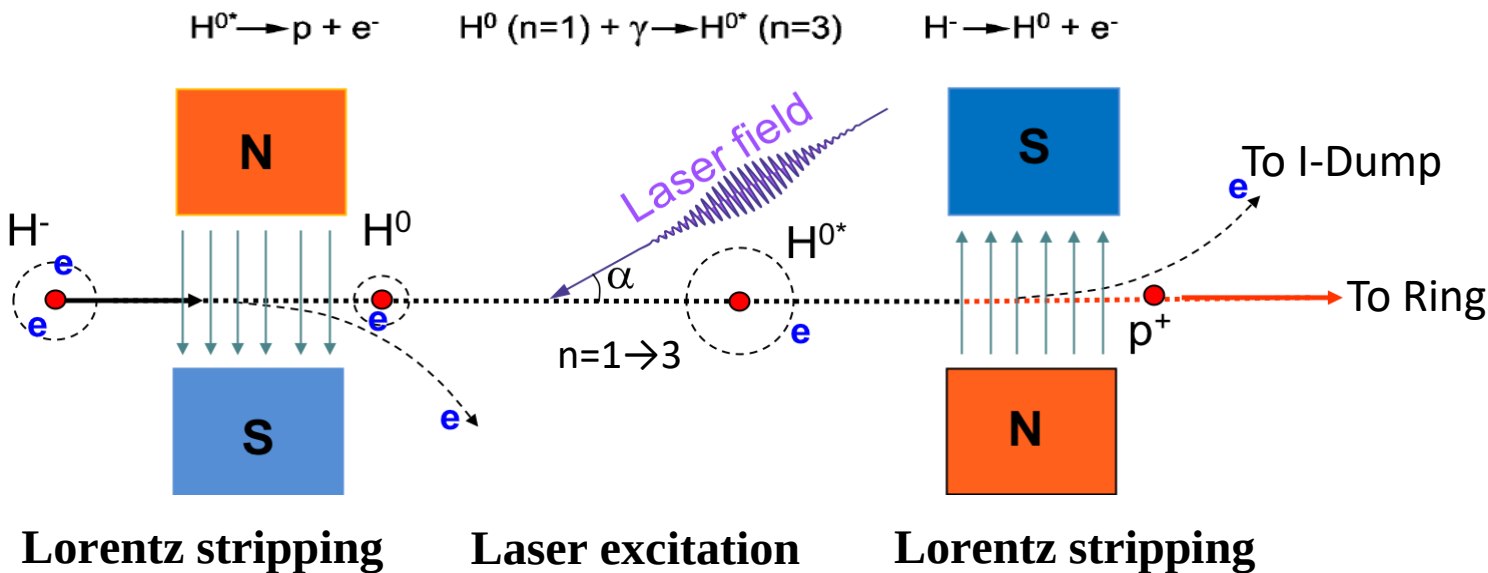
	Material	Structure	Thickness	Stripping efficiency
Primary foil	HBC	Double-layer	260 ug/cm ²	99.7%
Secondary foil	HBC	Double-layer	450 ug/cm ²	100%

- **Disadvantages of foil stripping:** short lifetime, failure at high temperatures (limiting beam power and density), large beam loss and radiation dose.
- Laser-assisted H⁻ stripping injection method can solve the defects of the foil stripping.



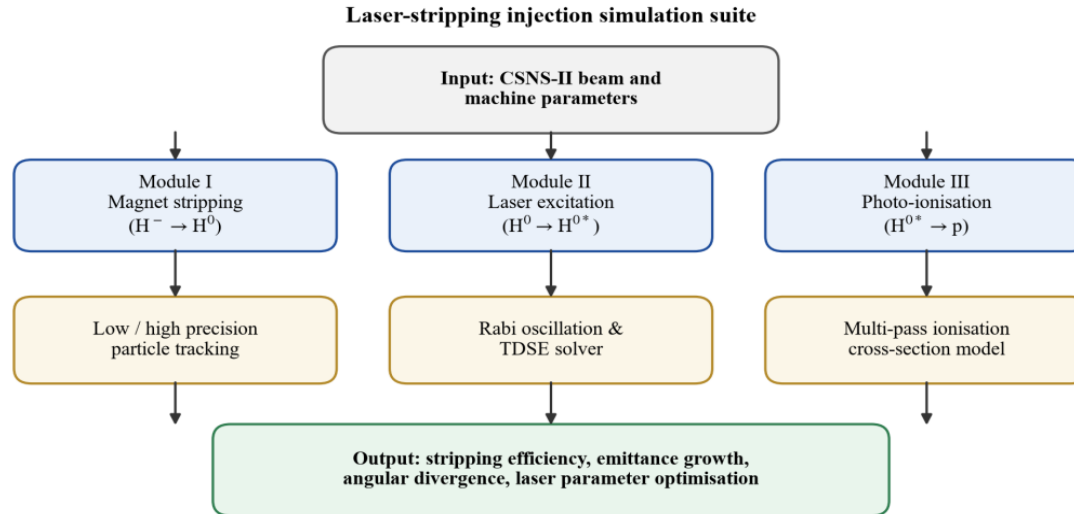
II. Laser stripping injection for the CSNS-II

- The integration of the laser and dipole magnet can be used to replace the traditional foil stripping injection method.



2.1 Simulation codes

- A simulation code covering magnetic stripping, laser excitation, and photoionization was developed in hybrid Python/MATLAB. All modules share beam-parameter and magnetic-field data interfaces and can run standalone or in combined iterations.



Verification of the magnet stripping simulation code

- For a trapezoidal magnetic field, there exists an analytical solution for the stripping efficiency, which is used as the verification standard.

Table. Parameters of trapezoidal magnetic field (Values in bold are analytical results)

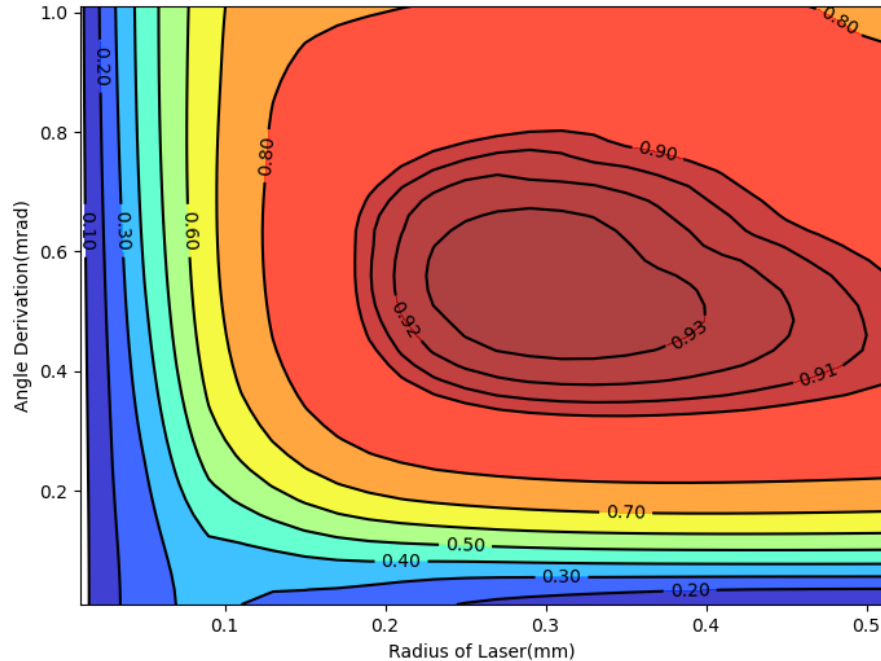
gradient	Field length	Stripping efficiency	Average angle spread	RMS angle spread
T/m	mm	%	mrاد	mrاد
10	200	99.99593/ 99.99593	38.31099	7.21655
20	100	99.36204/ 99.36204	21.11151	4.14564
30	70	99.57821/ 99.57921	15.33314	3.06230
40	60	99.99993/ 99.99993	12.19231	2.50208

$$p = 1 - \exp\left(-\frac{G}{2A_1}\left(L\left(L - \frac{A_2}{\gamma\beta cG}\right) \cdot \exp\left(-\frac{A_2}{\gamma\beta cGL}\right) - \left(\frac{A_2}{\gamma\beta cG}\right)^2 \cdot Ei\left(-\frac{A_2}{\gamma\beta cGL}\right)\right)\right)$$

- The results calculated by the code show no different from the theoretical results in the first four significant figures, verifying the correctness of the code.

Verification of the laser excitation code

- The laser parameters (radius and angular divergence) are changed to optimize the excitation efficiency



	parameter	Unit	value
beam	energy	GeV	0.982
	X-beta	m	1
	X-emittance	mm.mrad	0.09
	Y-beta	m	1
	Y-emittance	mm.mrad	0.09
	D	m	0
	D'	rad	-2.7
laser	power	MW	2
	length	nm	355
	Waist radius	mm	0.7
	radius	mm	0.25
	angular divergence	mrad	0.43
	RMS pulse	ps	35

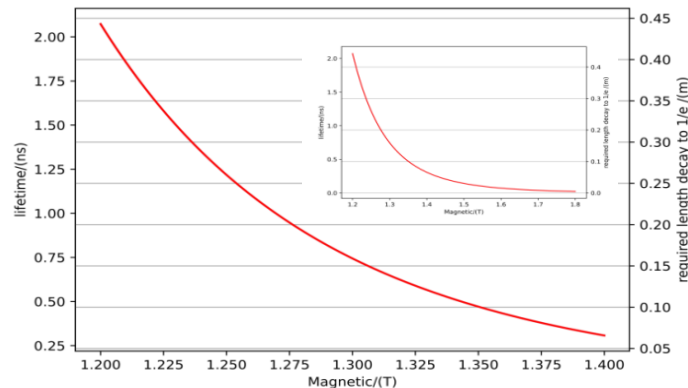
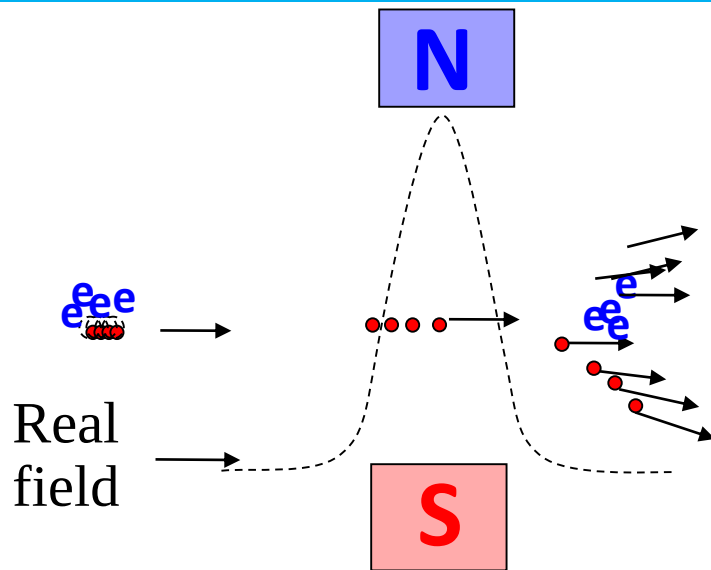
- By using the SNS parameters and results, the laser excitation code has been verified

2.2 Laser stripping injection for the CSNS

	CSNS	CSNS-II
Injection beam energy (GeV)	0.08	0.3-0.4
Average beam current (uA)	62.5	312.5
Particle per pulse	1.56×10^{13}	7.8×10^{13}
Repetition rate(Hz)	25	25
Beam width(us)	390	500
Injection beam size (1σ) (mm)	1.0	1.5
Ion source type	Penning	RF Volume

- The injection beam energy of the CSNS-II is approximately increased by 4 times, and the injection beam power is approximately increased by 20 times.

2.2.1 Lorentz stripping



- RMS angular dispersion caused by beam separation at different positions :

$$\sigma_{\theta} = \sqrt{\int_0^L \frac{ds}{\beta c \tau_1(s)} \exp\left(-\int_0^s \frac{ds'}{\beta c \tau_1(s')}\right) \left(\int_0^s \frac{ds'}{\rho(s')} - \bar{\theta}\right)^2}$$

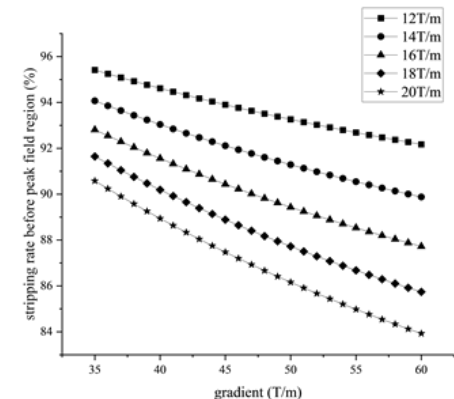
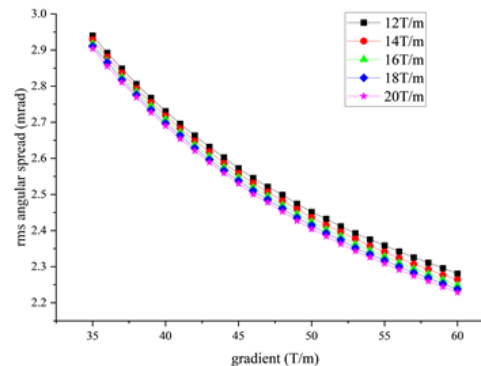
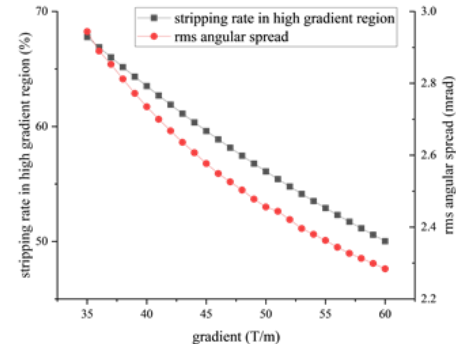
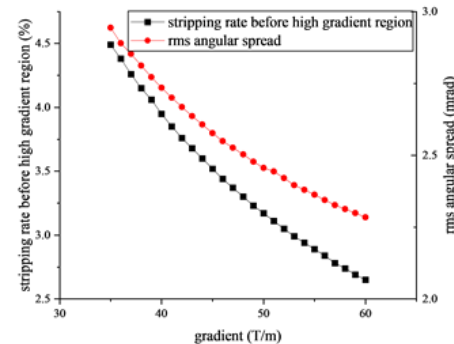
- RMS emittance growth: $\frac{\varepsilon'}{\varepsilon} = \sqrt{1 + \frac{\sigma_{\phi}^2}{\sigma_{22}(1-r^2)}}$

Design requirements for the stripping magnet

➤ Constraints for the new dipole magnet:

- ✓ The magnetic field stripping rate in the region below 1.4T is about 7% or less; its effect on increasing the gradient is limited.
- ✓ The fringe field stripping rate exceeds 90%.
- ✓ The main optimization is the gradient of the magnetic field between 1.4T and 1.8T.

Range	gradient
Lower than 1.4 T	$\geq 80\text{T/m}$
1.4 T-1.8 T	$\geq 60\text{T/m}$
Upper than 1.8 T	$\geq 20\text{T/m}$

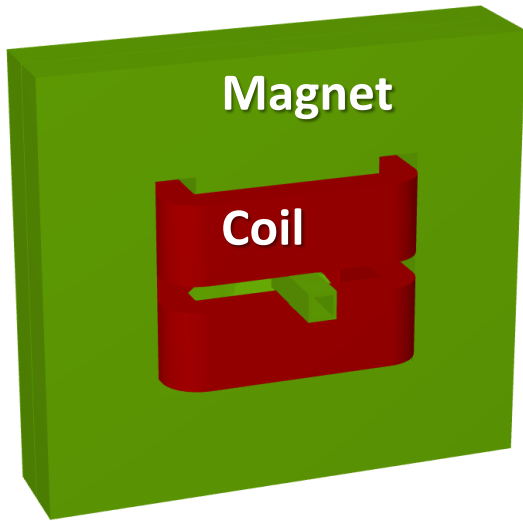


Design goals of the stripping magnet

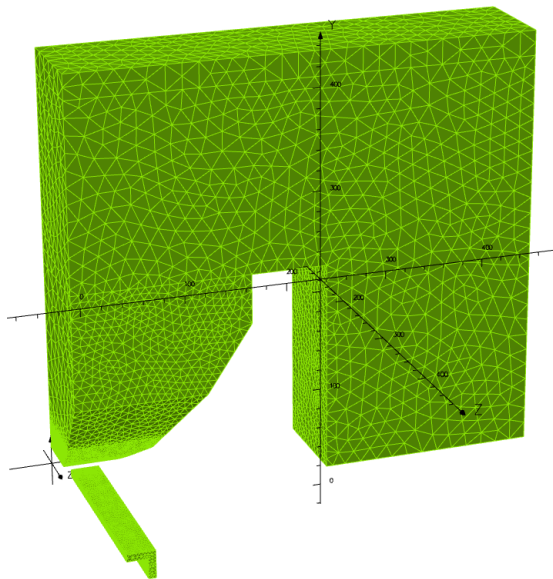
- The design indicators in the two stages : RMS angular divergence of 3.10 mrad and 1.91 mrad respectively.
- The main magnetic field region: between 1.4 T and 1.8 T.
- The magnet design should focus on increasing the magnetic field gradient in this region.
- When the RMS angular divergence is set to 1.91 mrad, the magnetic field gradients in the main region (1.4 – 1.8 T) must be strictly controlled.

(1) Electromagnet

➤ Optimization goal: improve the fringe field gradient



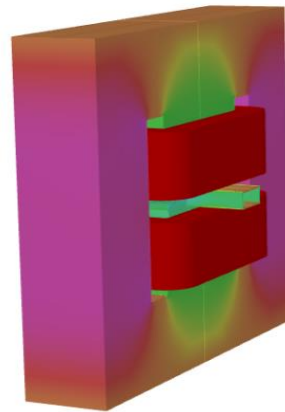
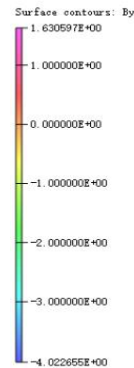
Full Magnet Geometric Model



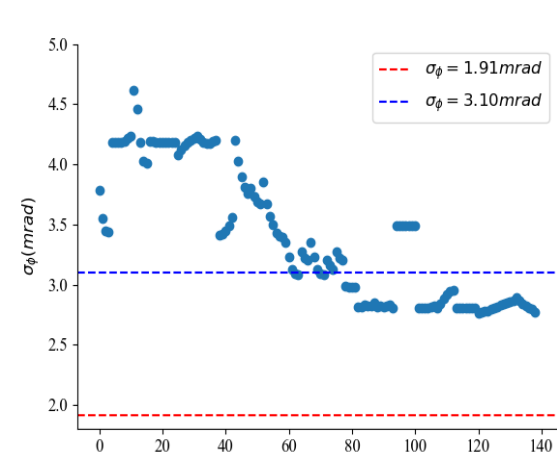
1/8 Magnet Geometric Model

➤ Methods to improve the fringe field gradient:

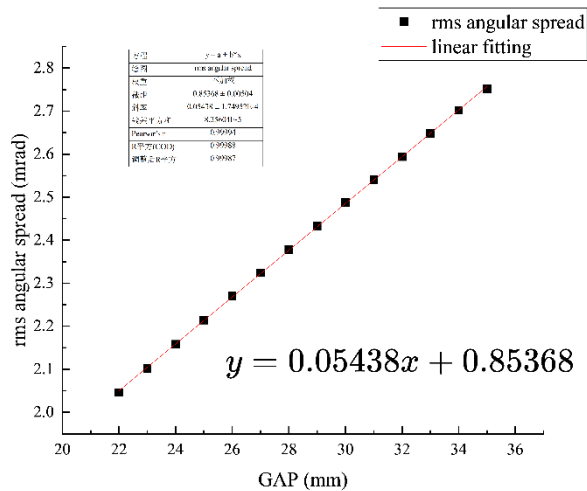
- ✓ Add shielding bodies
- ✓ Adopt unilateral shimming
- ✓ Similar to quadrupole chamfering



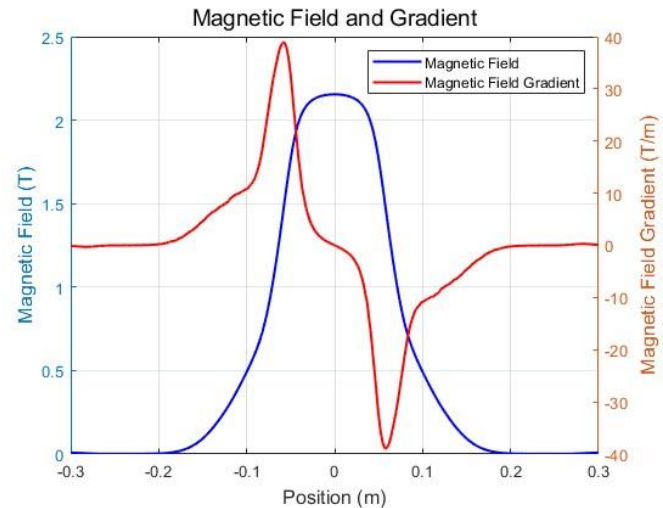
Design of the stripping electromagnet



RMS angular divergence during the magnet iteration process



RMS angular divergence V.S. magnet aperture

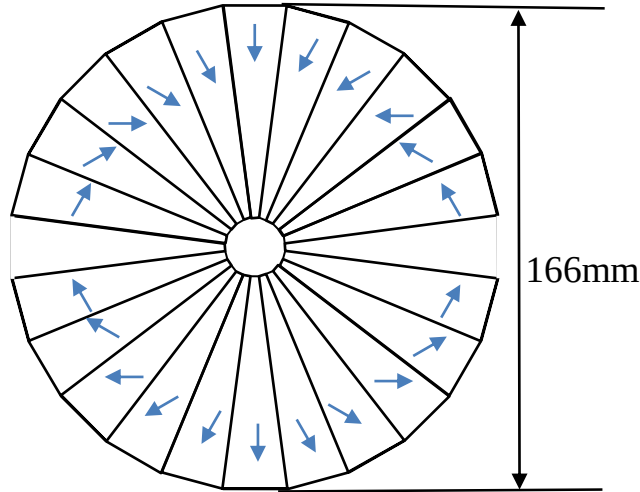
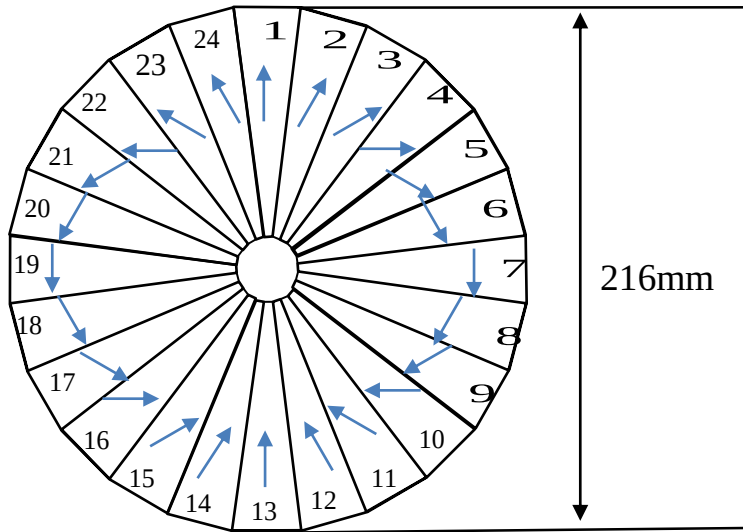


Magnetic field distribution

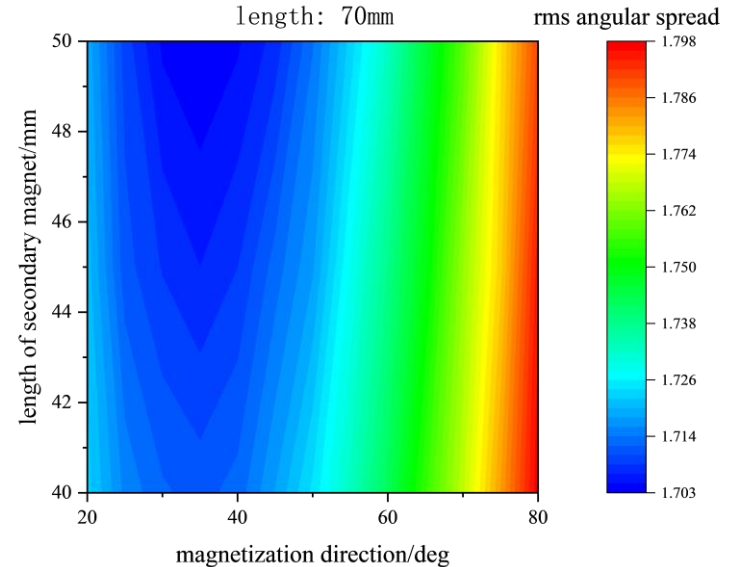
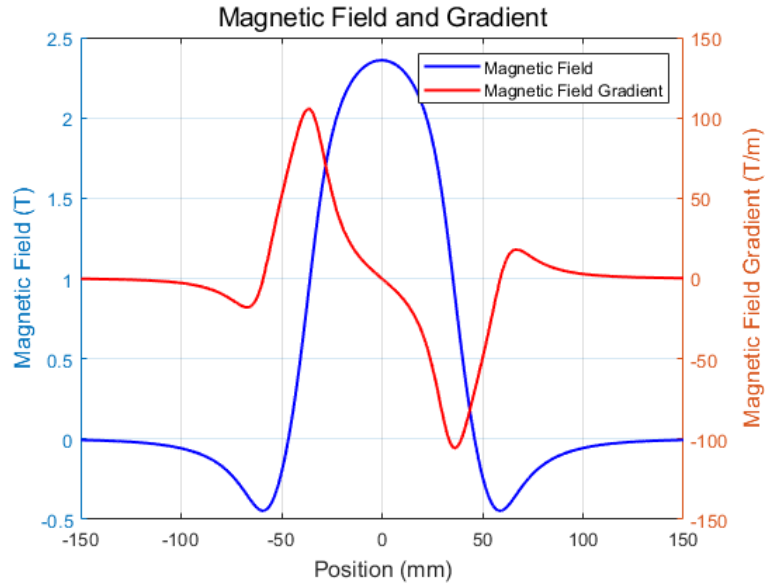
- When the aperture of the electromagnet is 26 mm, the peak magnetic field gradient does not exceed 40 T/m, which fails to meet the second-stage design requirement of the RMS angular divergence (1.91 mrad). Therefore, a new design of permanent magnets need to be studied.

(2) Permanent magnet

- Considering the beam aperture and magnet size, a Halbach-type dipole magnet was selected as the main stripping magnet
- The peak field at the aperture center is jointly determined by the remanence of the magnet material, the number of array elements, and the ratio of outer to inner radii. It can be tuned by adjusting this ratio

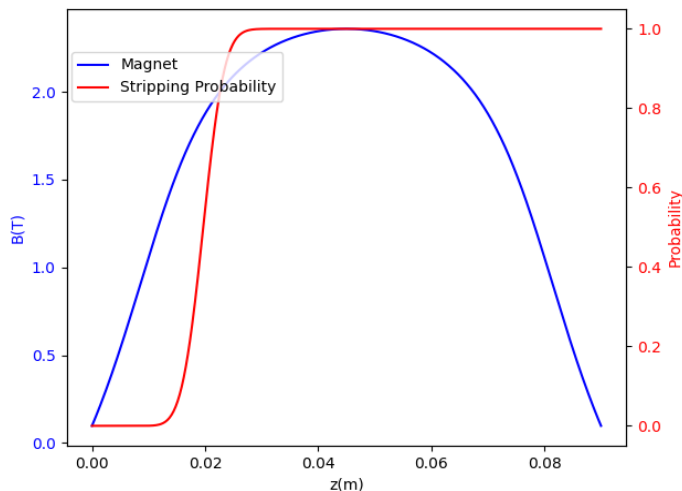


Stripping permanent magnet scheme

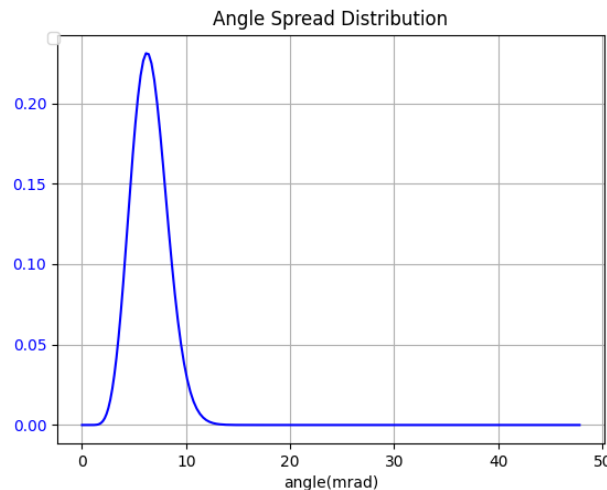


- The peak magnetic field strength of the laser stripping permanent magnet reaches 2.358 T, and the magnetic field gradient in the main stripping region is 61.80 T/m.
- The selection of magnetization direction is determined by the stripping results. The optimal range $30^\circ \sim 40^\circ$ for reducing the growth of RMS angular divergence is chosen.

Stripping permanent magnet analysis



Magnetic strength V.S. stripped probability



Stripped angular distribution

- The H^- particles complete the stripping process in the high-gradient region which is before the peak magnetic field region. All H^- particles are converted into H^0 particles, which no longer deflect, thereby reducing the emittance growth.
- By designing a high-gradient magnetic field, the angular divergence distribution achieves the expected Gaussian distribution.

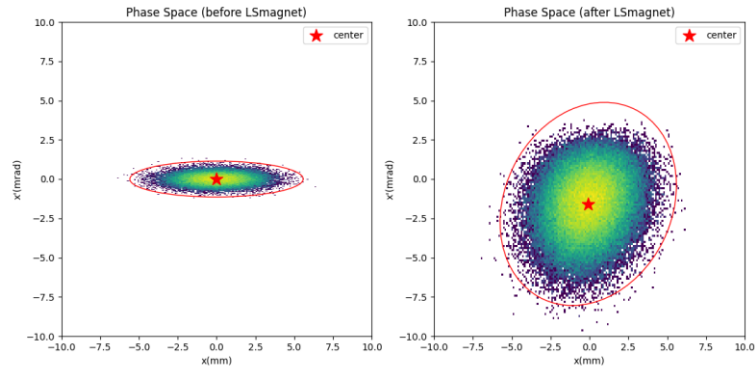
Stripping permanent magnet parameters

Parameter	Value
Peak field strength	2.35852 T
Peak field gradient	104.589 T/m
Field gradient at 1.8 T	61.8022 T/m
Field gradient at 1.4 T	92.2427 T/m
Integrated field	0.12571 T.m
Maximum field error	0.04883 T

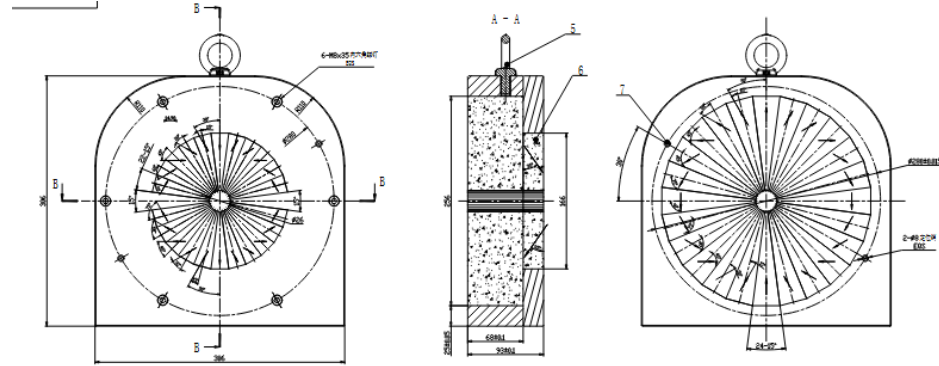
Parameter	Value
Stripped efficiency	99.9999%
RMS angular divergence	1.693($\pm 2\%$) mrad
Average angular deflection	2.180($\pm 7\%$) mrad
RMS emittance ratio	5.615($\pm 1.95\%$)

Permanent magnet prototype

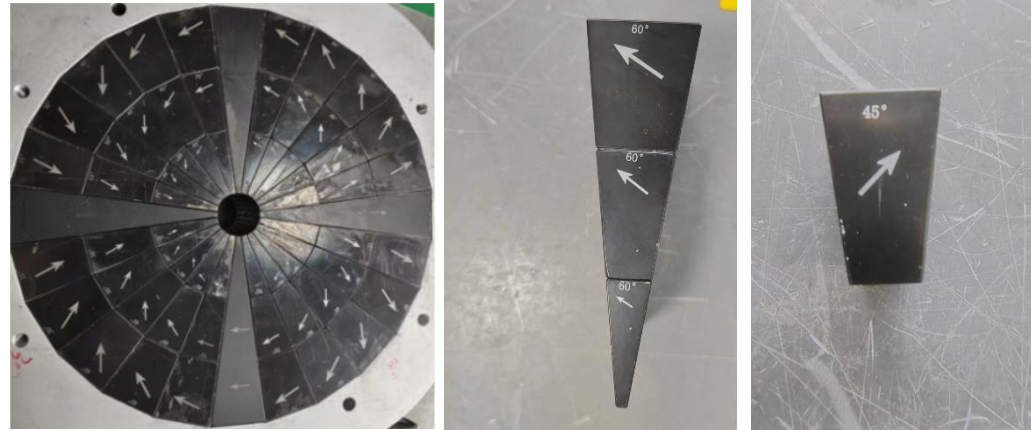
Difference in the phase space



- RMS emittance ratio is 5.615

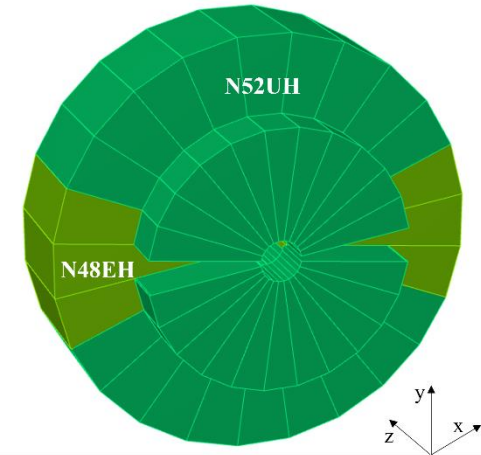
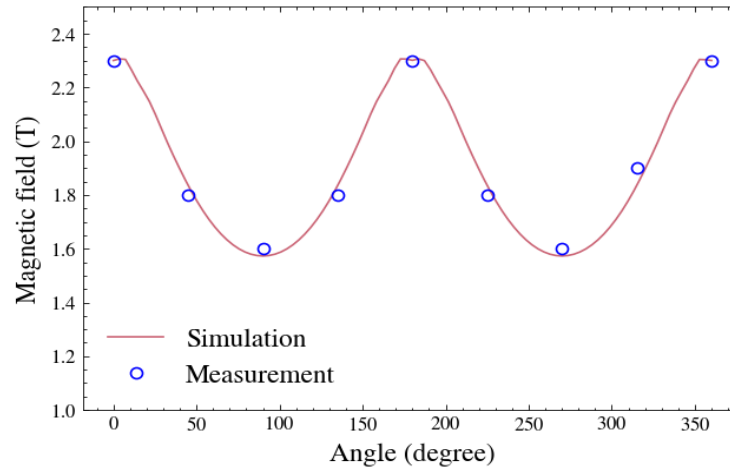
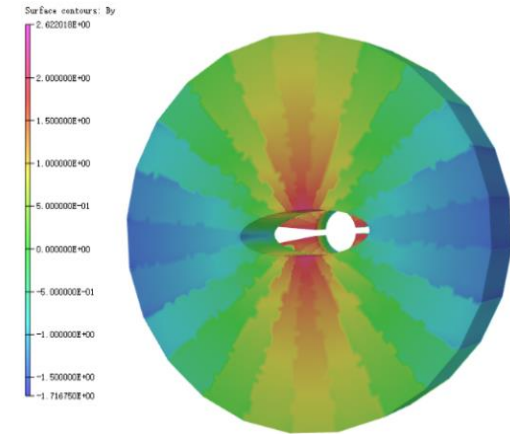


Schematic drawing of the magnet

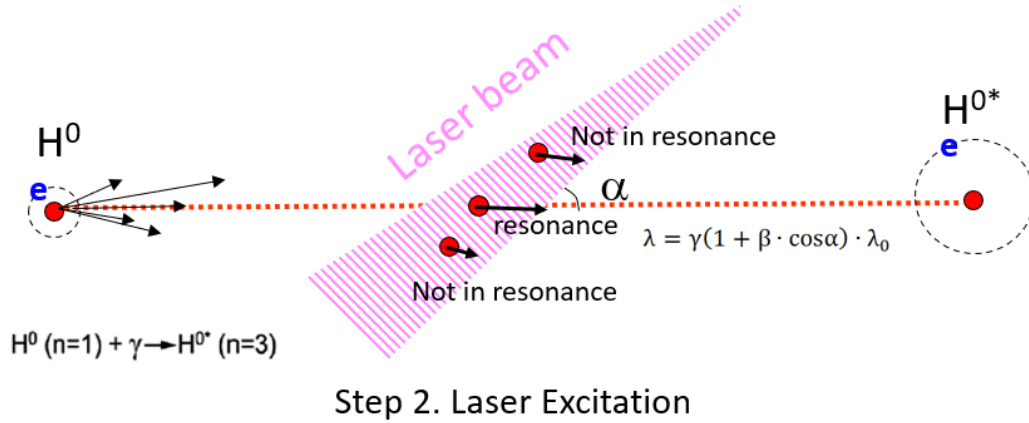


Demagnetization Issue

- After the prototype magnet was built, demagnetization was observed at the mid-plane
- A demagnetization model was established; simulations agree with measurements, and the magnet design was optimized accordingly



2.2.2 Laser excitation

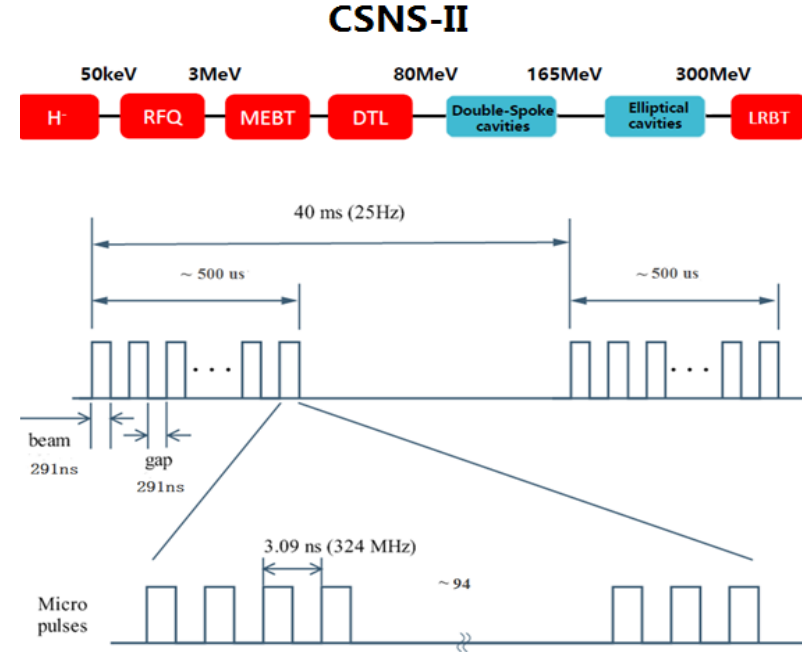


- **Peak power of the laser:**

$$P_{\text{peak}} = \frac{\ln(1/\delta) \cdot \hbar^2 \cdot \epsilon_0 \cdot c^2 \cdot \kappa \cdot \omega_0 \cdot \sin\alpha \cdot h}{2\mu_{1n}^2 \cdot \gamma \cdot (1 + \beta \cdot \cos\alpha)^2}$$

- **Proportion of hydrogen atoms in the ground state:**

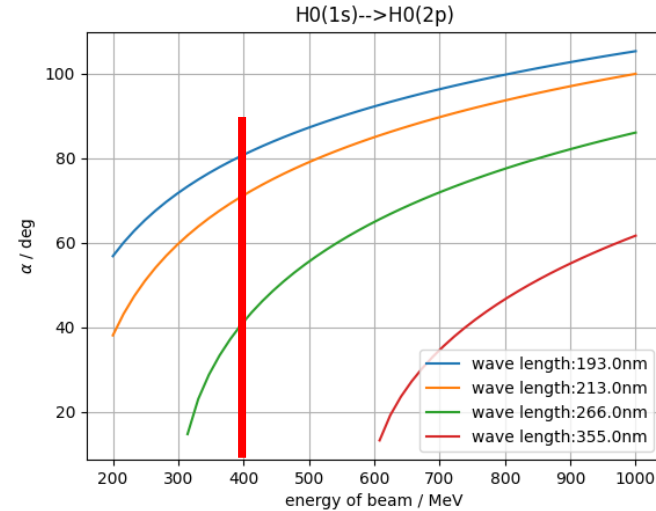
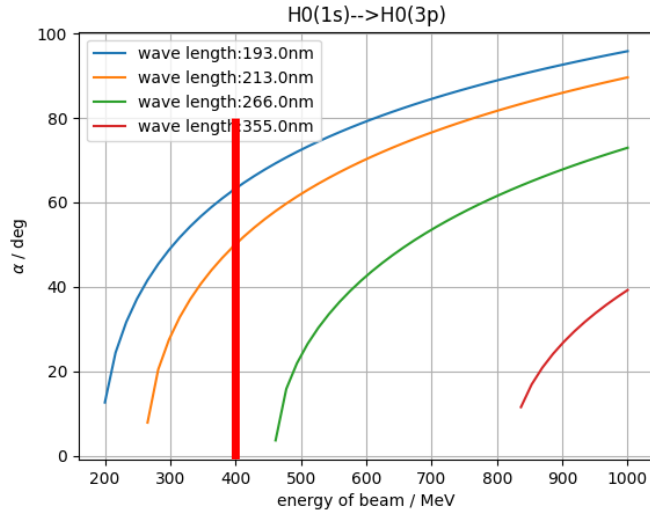
$$\delta = \exp\left[-\frac{P_{\text{peak}} \cdot 2\mu_{1n}^2 \cdot \gamma \cdot (1 + \beta \cdot \cos\alpha)^2}{\hbar^2 \cdot \epsilon_0 \cdot c^2 \cdot \kappa \cdot \omega_0 \cdot \sin\alpha \cdot h}\right]$$



- **Average power of the laser:**

$$P_{\text{ave}} = P_{\text{peak}} f_{\text{rf}} \tau_{\text{micro}} d$$

Laser excitation process



$$E_n = -\frac{1}{2n^2} \frac{\hbar^2}{m_e a_0^2}$$

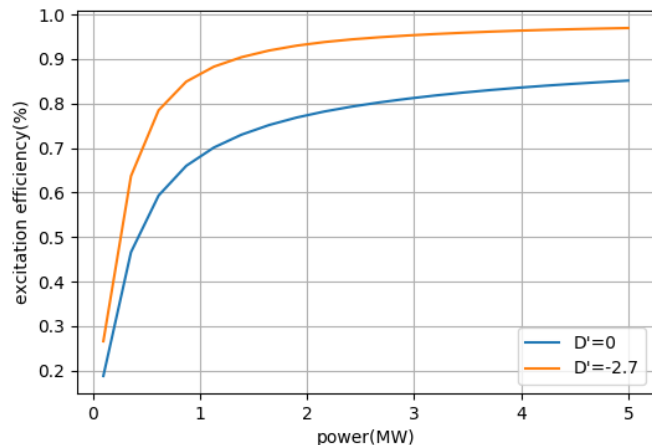
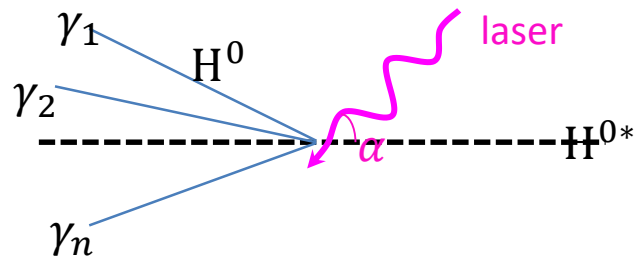
$$\lambda = \lambda_0 \gamma (1 + \beta \cos \alpha)$$

- For the H^- beam, if one chooses direct excitation to the $n=3$ state in a single step, a minimum of 213 nm laser wavelength is required. If a stepwise excitation approach is selected, first exciting the hydrogen atoms to the $n=2$ state, the required laser wavelength can be extended to 266 nm.

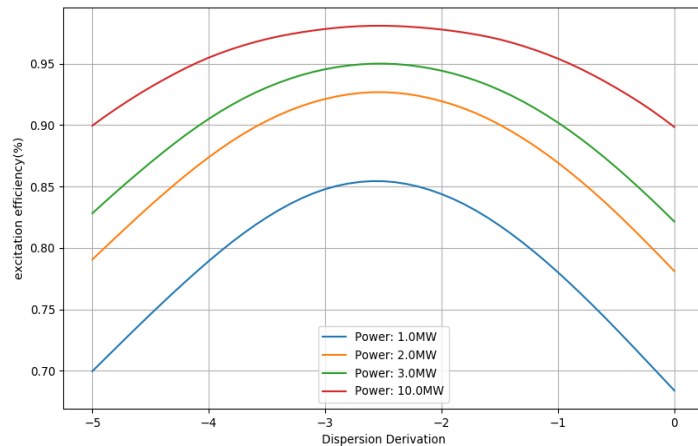
Dispersion derivative

- For handling the off-energy particles, the dispersion derivative must be adjusted to make them satisfy a specific incident angle with the laser.

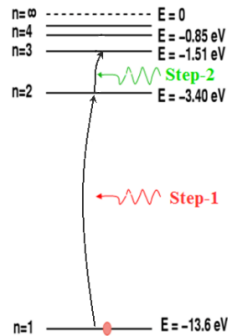
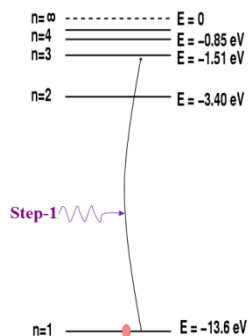
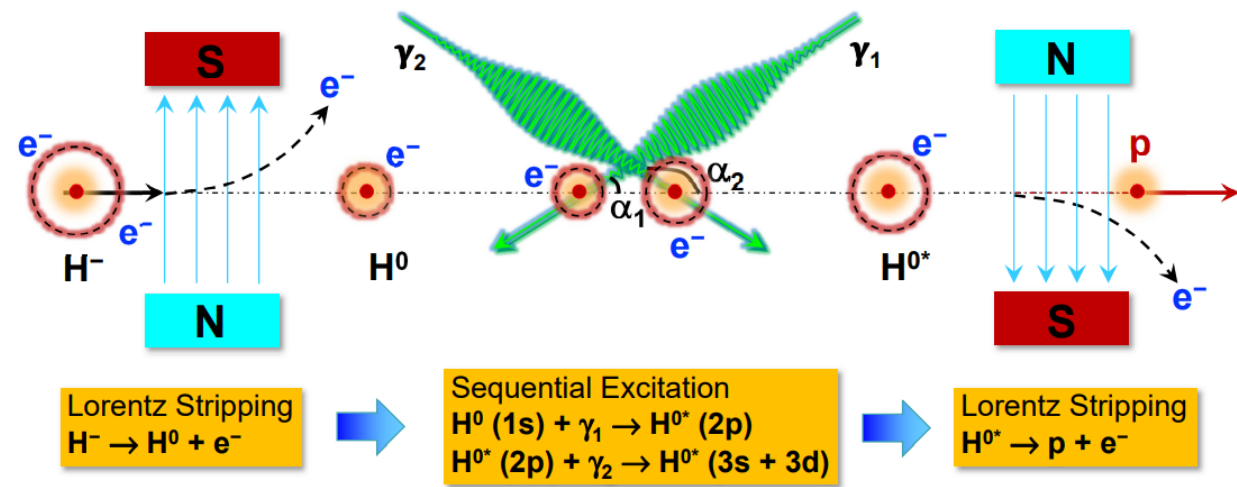
$$D' = -\frac{\beta + \cos\alpha}{\sin\alpha}$$



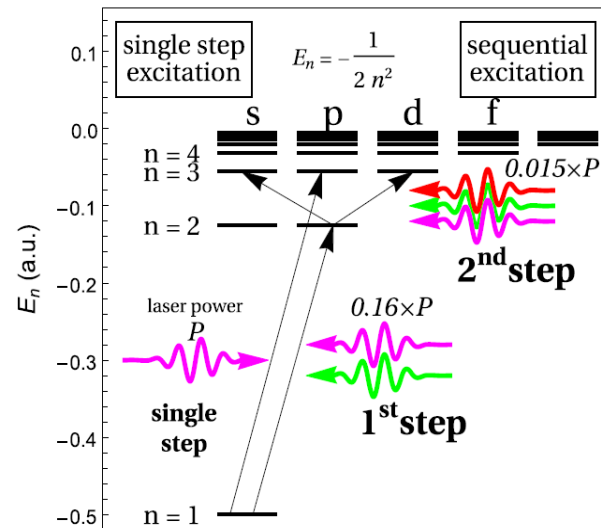
Impact of D' on excitation efficiency



Laser scheme with sequential excitation



Refer to SNS



$$\frac{p_{1s \rightarrow 3p}}{p_{1s \rightarrow 2p}} = \frac{\mu_{12}^2}{\mu_{13}^2} \approx 6.236$$

➤ Advantages of the sequential resonance scheme:

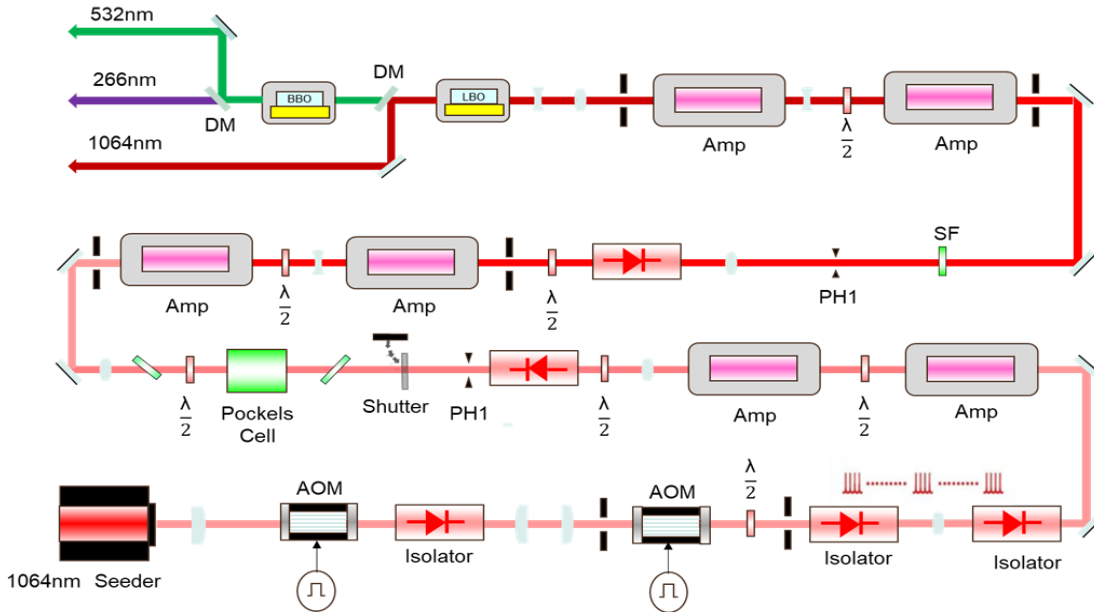
- ✓ Lower power required for each excitation
- ✓ Increase the flexibility in laser wavelength selection

Single vs. sequential excitation for CSNS-II

Parameter	Single excitation	Sequential excitation	
	1s→3p	1s→2p	2p→3d
Transition energy ΔE	12.09eV	10.20eV	1.89eV
Transition wavelength	102.6 nm	121.5 nm	656.1 nm
Laser wavelength λ	213 nm	266 nm	532 nm
Laser incident angle α	50.11 ⁰	41.31 ⁰	127.24 ⁰
Peak power (Stripping efficiency 99%)	2.97 MW	311.10 kW	70.13 kW
Micro-pulse energy (Stripping efficiency 99%)	24.06 uJ	2.52 uJ	0.57 uJ
Meso-pulse energy (Stripping efficiency 99%)	9.18 mJ	0.96 mJ	0.22 mJ
Macro-pulse energy (Stripping efficiency 99%)	864.27 mJ	90.53 mJ	20.41 mJ

Design of the Laser Excitation Beam Line

- The laser system adopts a master oscillator power amplifier (MOPA) scheme
- It not only produces laser with the same time structure as the H⁻ beam, but also meets the laser power requirement for efficiently stripping the H⁻ beam



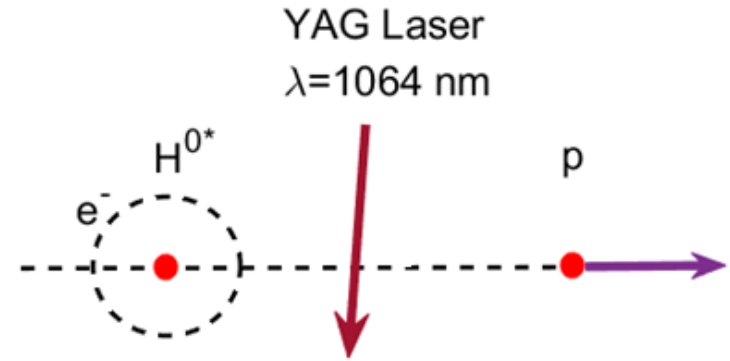
- ✓ The beam time structure comprises macro-pulses, intermediate pulses, and micro-pulses
- ✓ The required wavelength can be obtained by fourth harmonic generation of a common high-power pulsed Nd:YAG laser

2.2.3 Third stage stripping process

➤ Difficulties by using magnet stripping for the third stage stripping:

- ✓ The inner diameter of the magnet in the third stage stripping needs to be extremely large, and the stripping magnet will also affect the circulating beam.
- ✓ The protons stripped at the initial stage are highly susceptible to magnetic fields, resulting in a significant increase in angular dispersion.

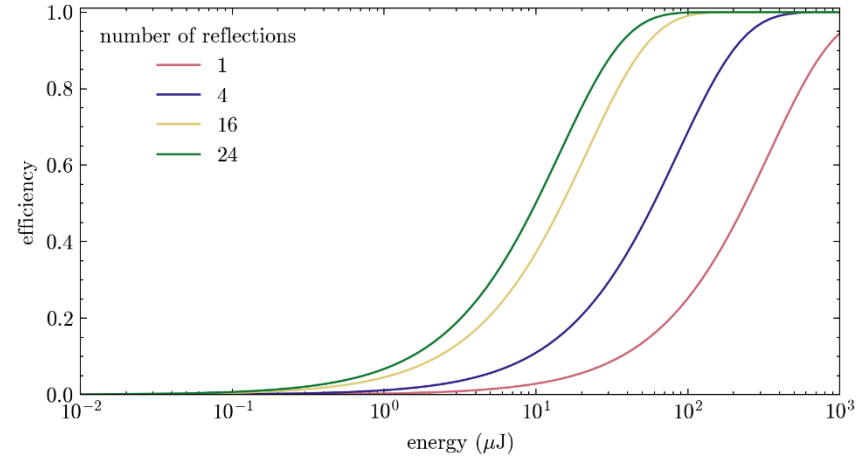
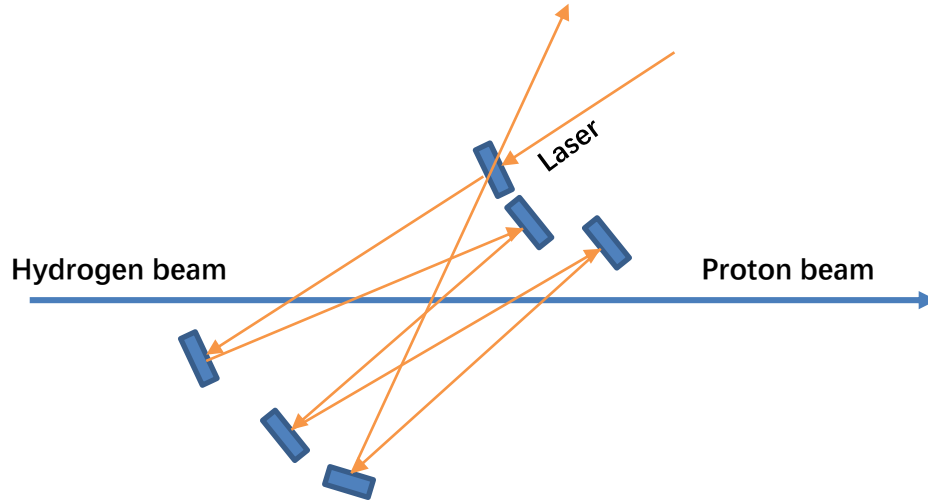
➤ YAG laser stripping is considered for the third stage stripping.



$$\sigma_{nlm} = \pi a_0^2 \frac{m}{2l+1} \frac{P_1 P_2}{P_3 P_4^{7/2+l}}$$

$$P = \frac{\pi \beta \ln(1/\text{loss}) hc^2 \sin \alpha H}{2N \lambda \sigma (1 + \beta \cos \alpha)}$$

Third stage stripping: multiple reflections



The role of multiple reflections in reducing laser pulse energy

➤ Establishing a suitable mirror system:

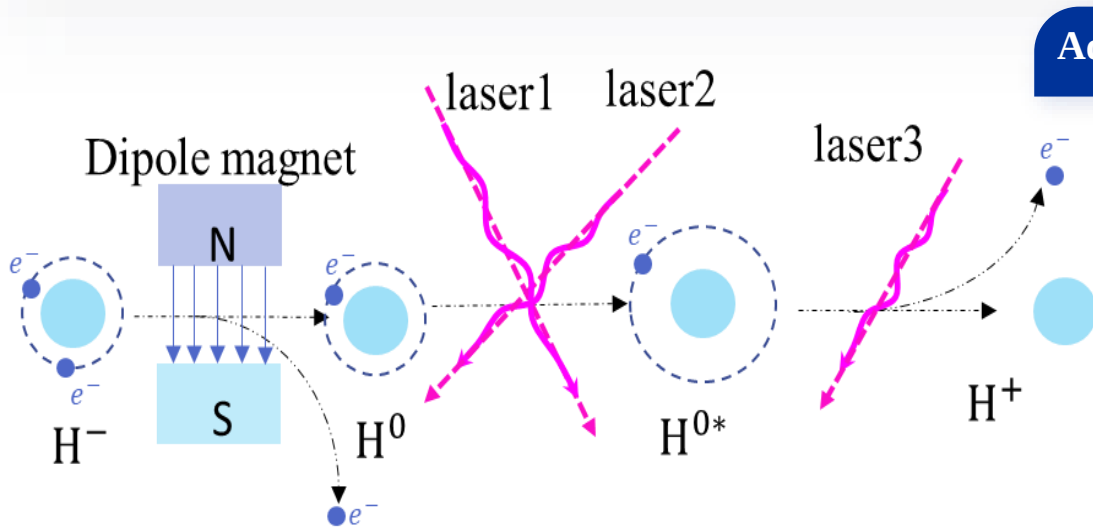
- ✓ Improving the utilization efficiency of laser energy.
- ✓ Reducing the requirement for laser pulse power.

Third stage laser stripping parameters

Parameter	value
Interaction cross-section	$3.3 \times 10^{-17} \text{ cm}^2$
Micro pulse width of H ⁻ beam	8.1 ps
Interaction time	15 ps
Laser pulse width	23.1 ps
Laser cross-sectional radius	1.6 mm
Laser wavelength	1064 nm
Incident angle	97.25°
Laser power (reflection 24)	1.25 MW

2.3 Design scheme of the laser-stripping for the CSNS-II

- Considering the new injection system layout and beam parameters, a new laser stripping injection scheme is proposed
- **Three-stage stripping: H^- ions are converted to neutral H atoms by a magnet, excited to the second excited state via two-step sequential excitation, and ionized to protons by an infrared laser**



Advantages

- Reduced the laser power
- Improved safety
- Good engineering feasibility
- Good installation compatibility

III、 Summary

- A brief introduction was provided to the CSNS H^- charge exchange injection method.
- Based on in-depth research and detailed simulations, a design scheme of the laser stripping injection for the CSNS-II has been proposed.
- The stripping magnet prototype has been fabricated, and demagnetization was observed in some regions. A redesigned magnet was developed to resolve the demagnetization issue.

Thank you for your attention!