Laser stripping of H^- beam

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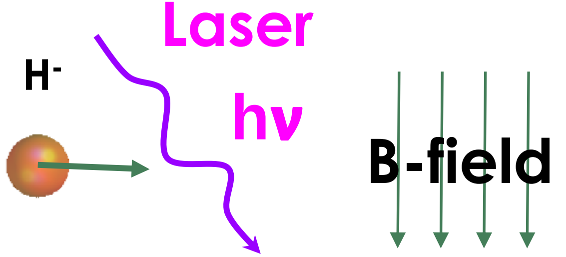
Charge exchange beam injection of H^- beam into the Ring.

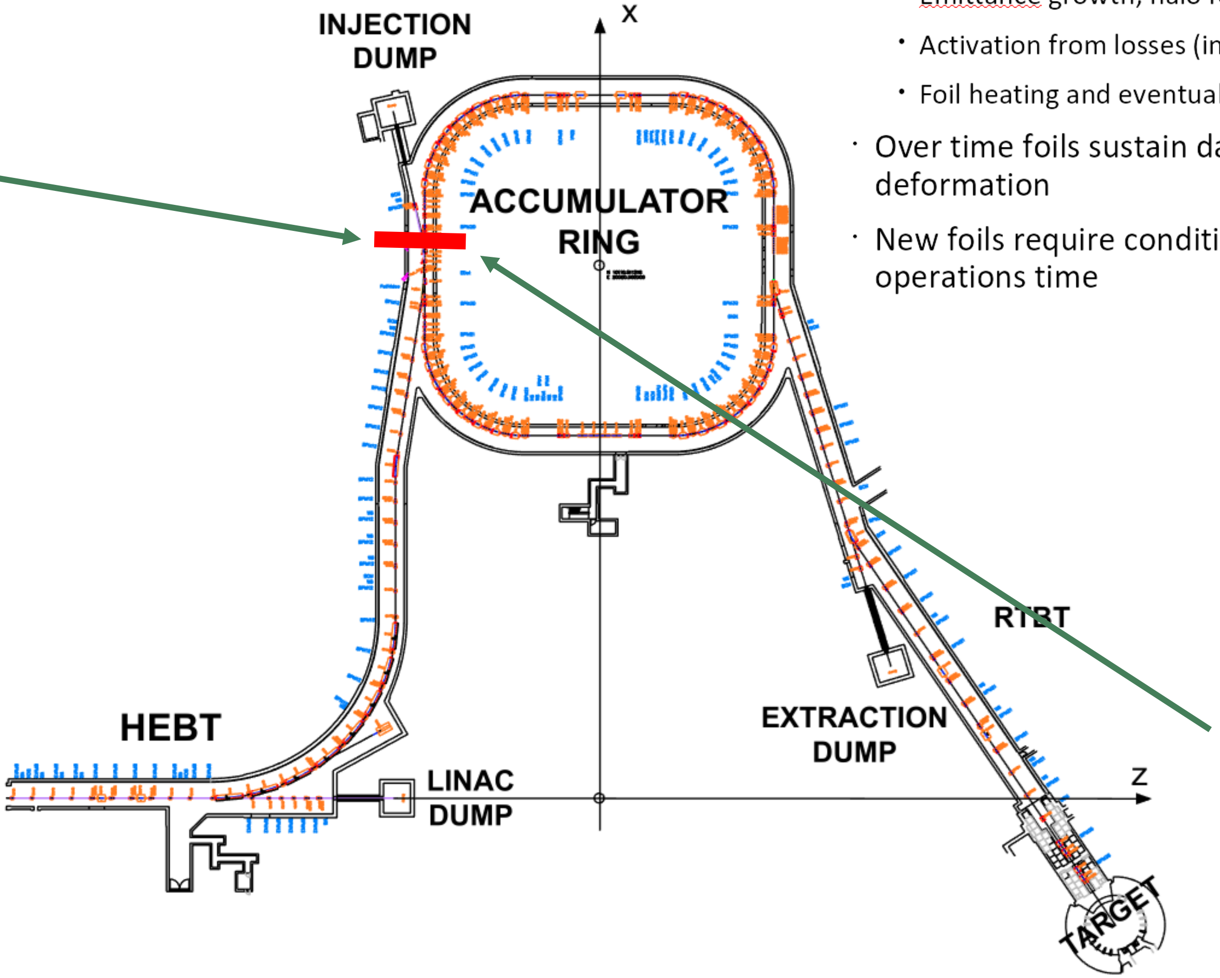
Thin carbon stripping foil. Foil Injection.

$H^- \rightarrow | \; p^+ + 2e^-$

Laser assisted charge exchange injection (LACE)



$H^- \rightarrow \; p^+ + 2e^-$

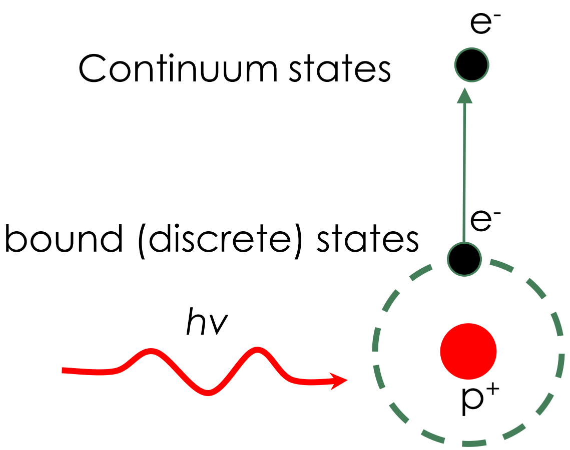


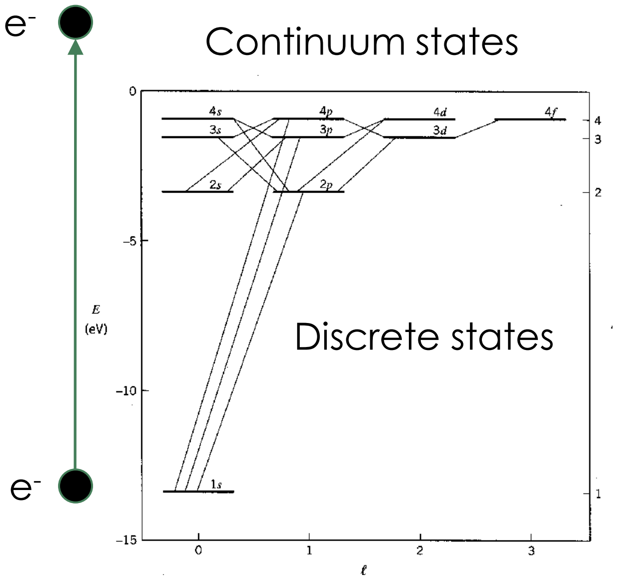
1.3 GeV H^- beam
2MW beam power

Issues with Foils (courtesy of N. Evans)

- Interaction of beam with foil causes:
  - Emittance growth, halo formation
  - Activation from losses (injection ~10x hotter than rest of SNS)
  - Foil heating and eventual sublimation
- Over time foils sustain damage causing deformation
- New foils require conditioning which eats into operations time

Photoionization of H^- and H^0.

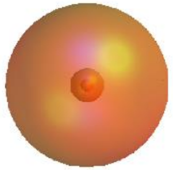




Gaussian laser-beam interaction

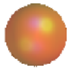
Energy=35mJ for 99% stripping (requires ~500 times more laser power than existing laser)

$\sigma_{H-} = 4.0\times10^{-21}$ m^2 for 800 nm



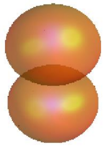
H^-

$\sigma_{1s} = 6.3\times10^{-22}$ m^2 for 91 nm



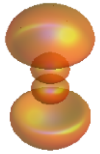
H_{1s}

$\sigma_{2p} = 1.7\times10^{-21}$ m^2 for 364 nm



H_{2p}

$\sigma_{3p} = 3.3\times10^{-21}$ m^2 for 820 nm

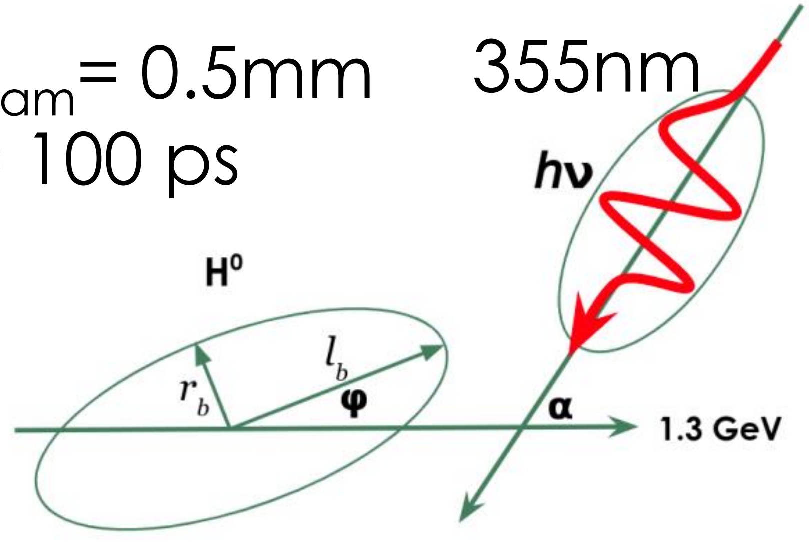


H_{3p}

r_{beam}= 0.5mm

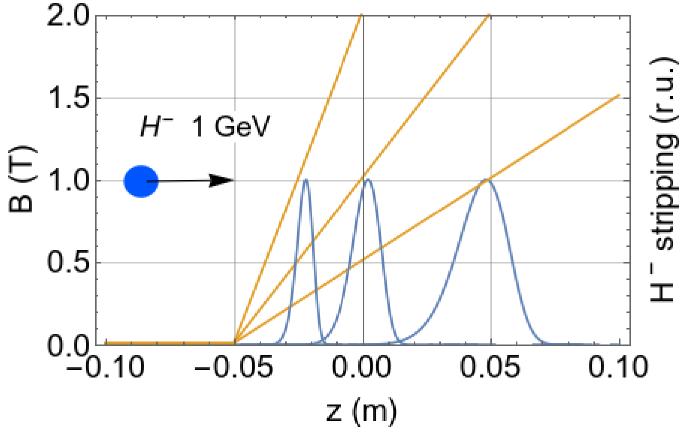
355nm

l_b= 100 ps

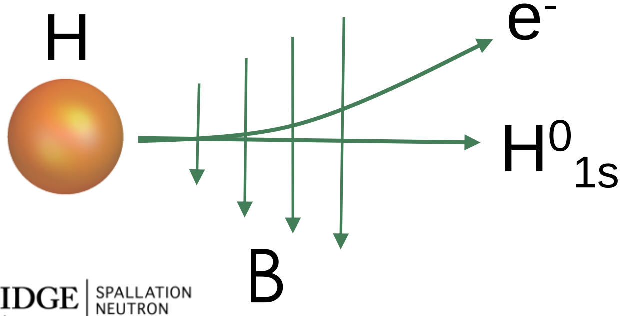


Lorentz stripping of hadron beams. 1GeV H^0, H^- beams

✓

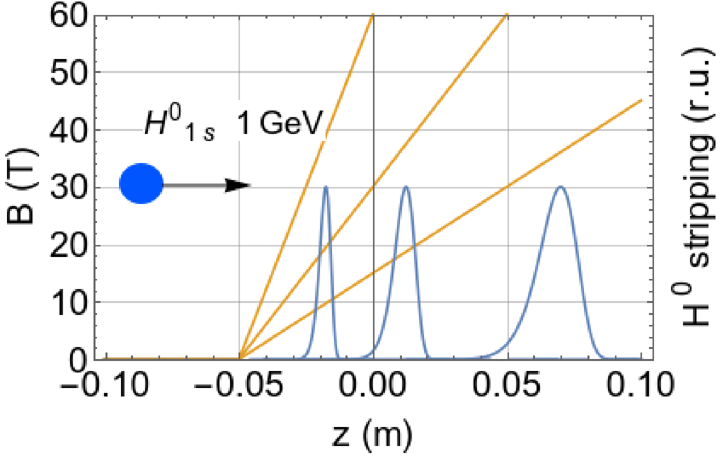


$$H^- \rightarrow H^0 + e^-$$

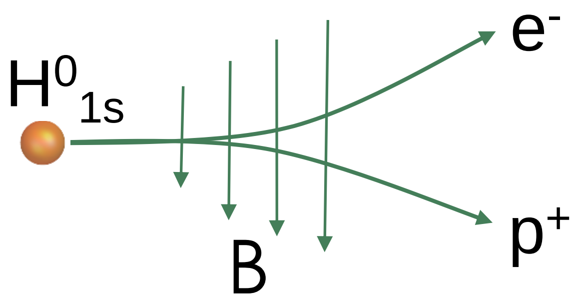


✗

40 Tesla magnet !



$$H^0_{1s} \rightarrow p^+ + e^-$$



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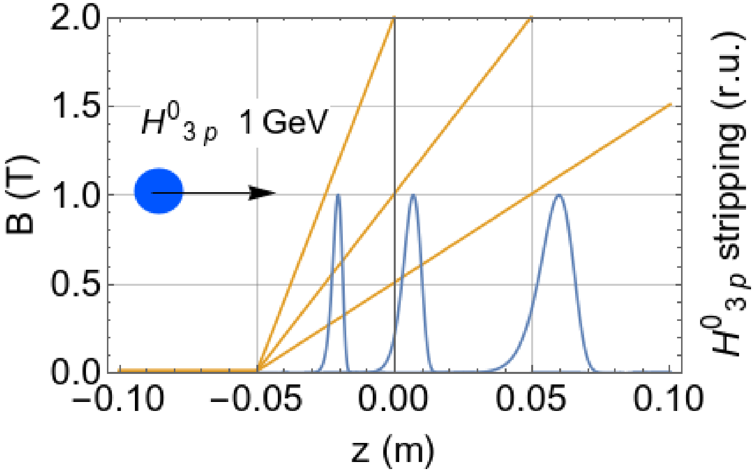
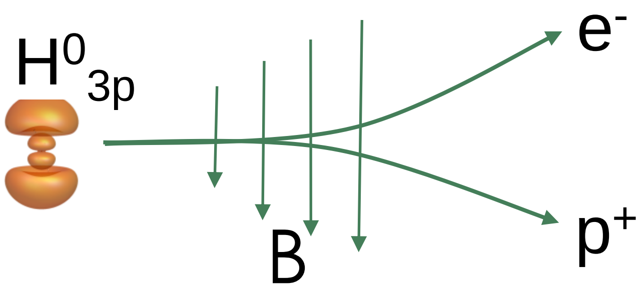
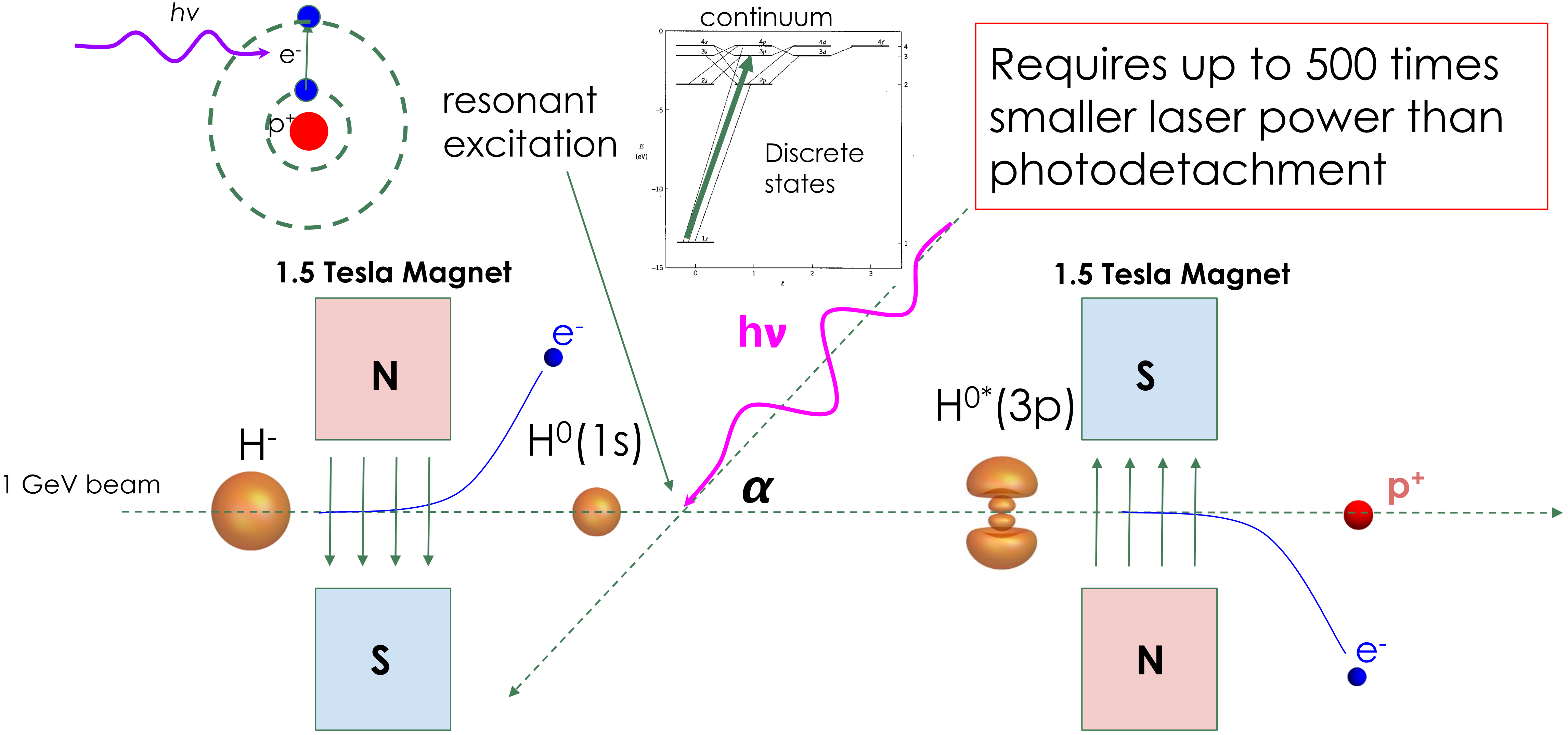


$$H^0_{3p} \rightarrow p^+ + e^-$$



Practical scheme of laser stripping (I. Yamane 1998, V. Danilov, 2003)



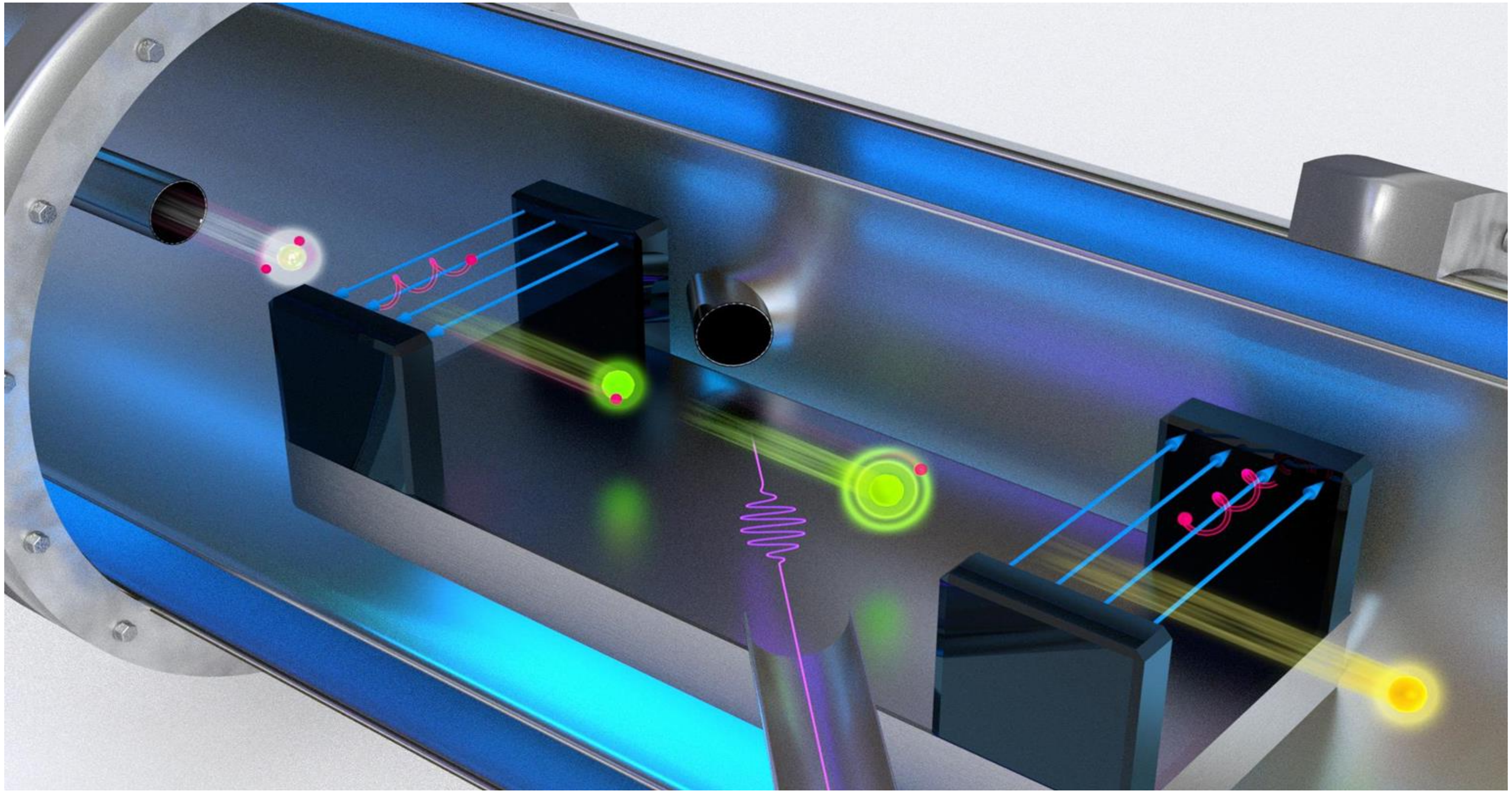
Requires up to 500 times smaller laser power than photodetachment

1st step:
Lorentz stripping
$H^- \rightarrow H^0 + e^-$

2nd step:
laser resonant excitation
$H^0 + h\nu \rightarrow H^{0*}$

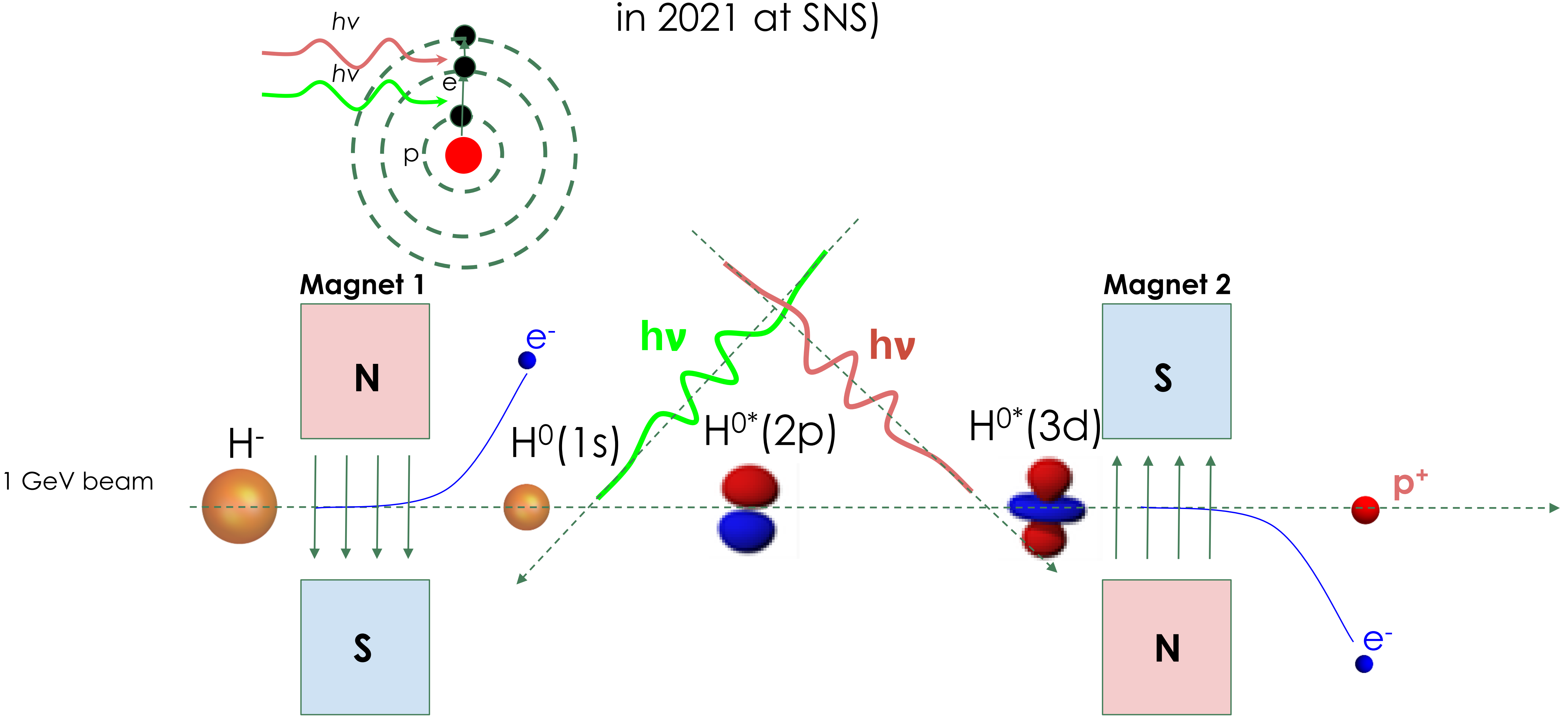
3rd step:
Lorentz stripping
$H^{0*} \rightarrow p^+ + e^-$

LACE experiments at SNS



- Proof of principle laser stripping experiment (2006). 90% efficiency, ~ 6 ns pulse
- Stripping of microsecond duration H^- beams (2016). 90% efficiency, ~ 10 us pulse

4 step/sequential laser assisted charge exchange injection scheme (demonstrated in 2021 at SNS)



1st step:
magnetic stripping
$H^- \rightarrow H^0 + e^-$

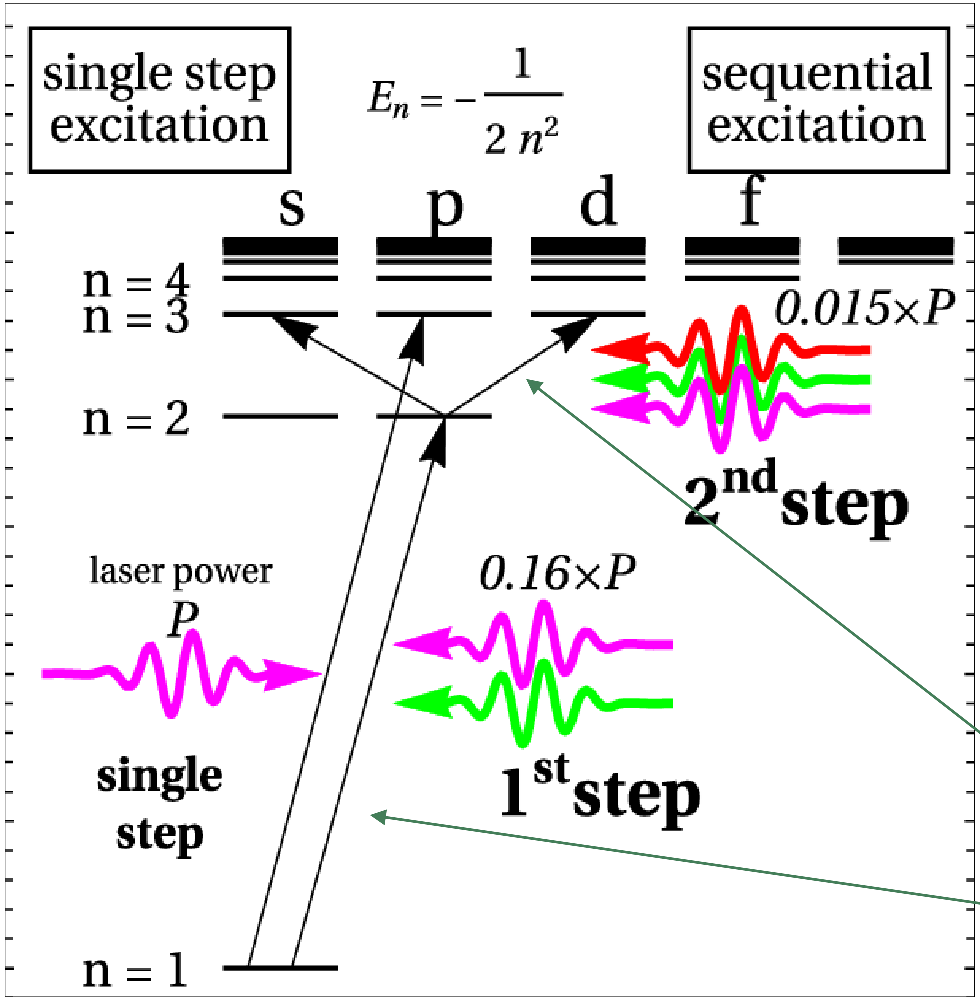
2nd step:
laser resonant excitation
$H^0 + h\nu \rightarrow H^{0*}$

3rd step:
laser resonant excitation
$H^{0*} + h\nu \rightarrow H^{0*}$

4th step:
magnetic stripping
$H^{0*} \rightarrow p^+ + e^-$

Different schemes of H^0 excitation:

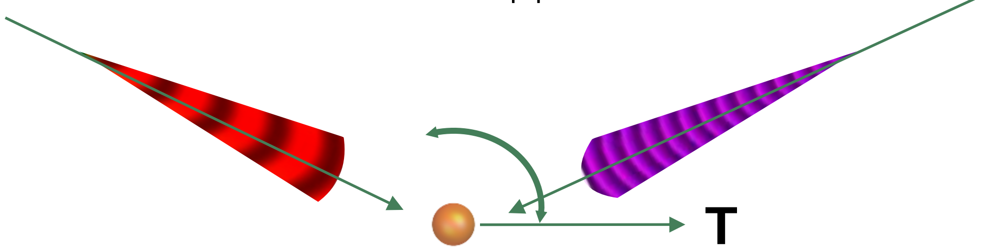
Hydrogen atom structure and different excitation mechanisms by different lasers for 1.3GeV H^0 beam



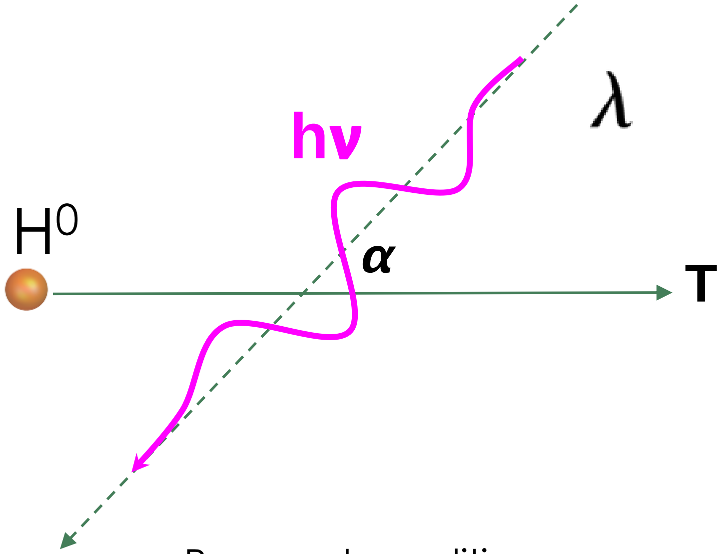
The smaller step requires less laser power and considered to be more effective

Resonant excitation of stochastic beam with energy-angular spread.

Relativistic Doppler effect



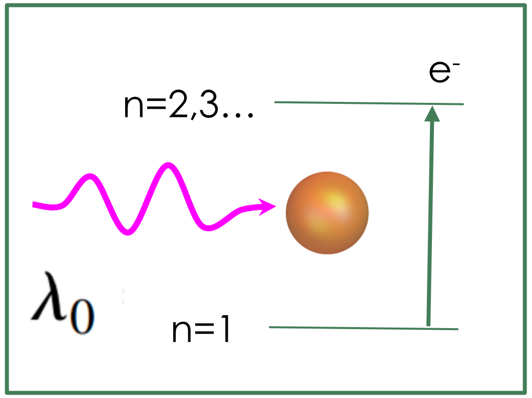
Relativistic Doppler effect for single particle



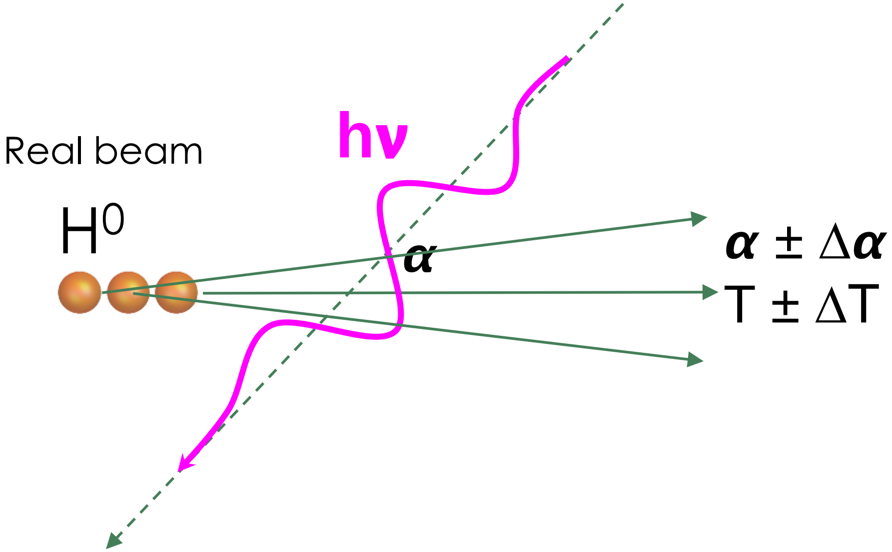
Resonant condition:

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

Particles rest frame



Real stochastic beam with angular-energy spread



Most of the beam is not in resonant conditions

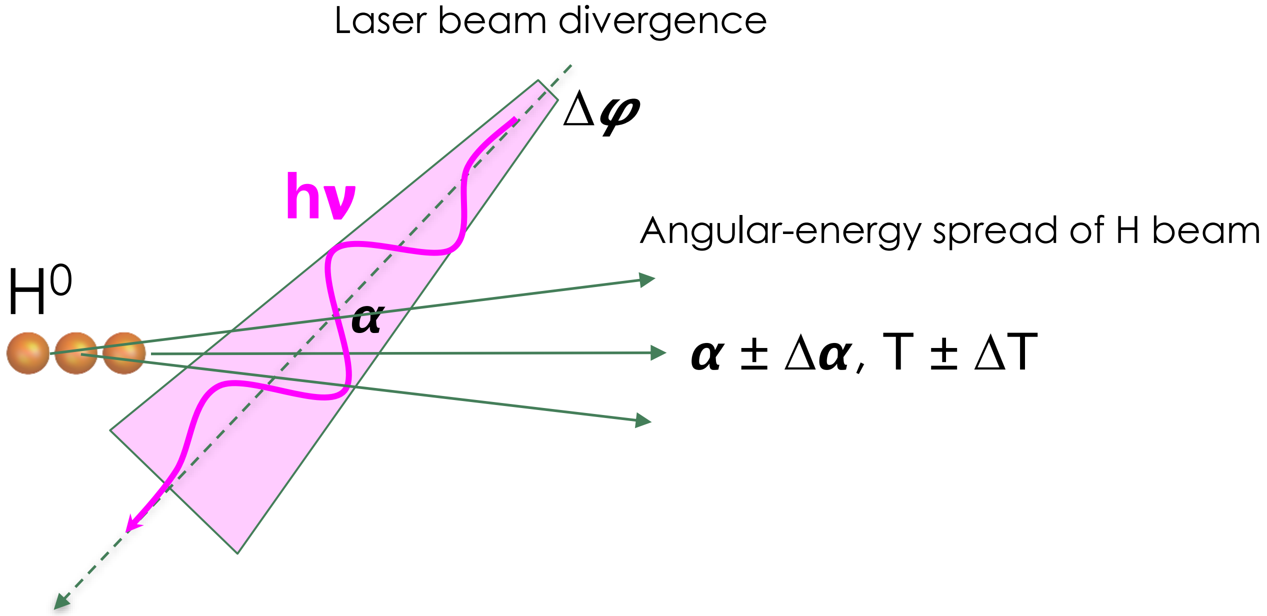
$$\lambda_0 \neq \frac{\lambda}{\gamma(1 + \beta \cos\alpha)}$$

Methods of excitation of realistic beams

1. Apply laser beam divergence to compensate angular-energy spread of H beam $\Delta\boldsymbol{\varphi} \sim \Delta\boldsymbol{\alpha}$

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

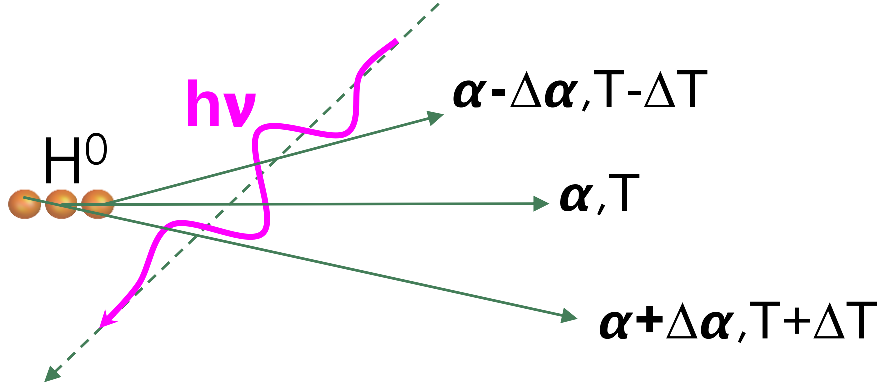
laser angular spread



Methods of excitation of realistic beams

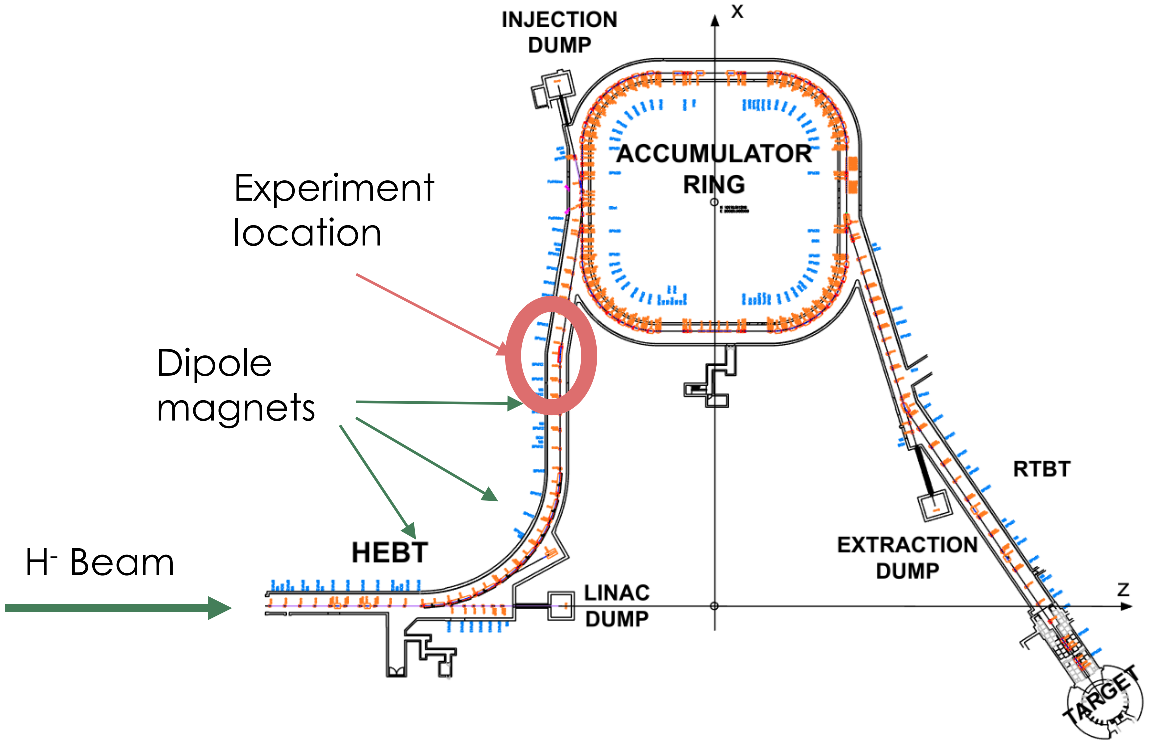
2. Beam tailoring. Correlation between T and *α*.

Dispersion function of the beam D is needed.
Strong dipole magnets are needed to control dispersion function.



$$\lambda_0 = \frac{\lambda}{\gamma_T(1+\beta_T\cos\alpha)}$$

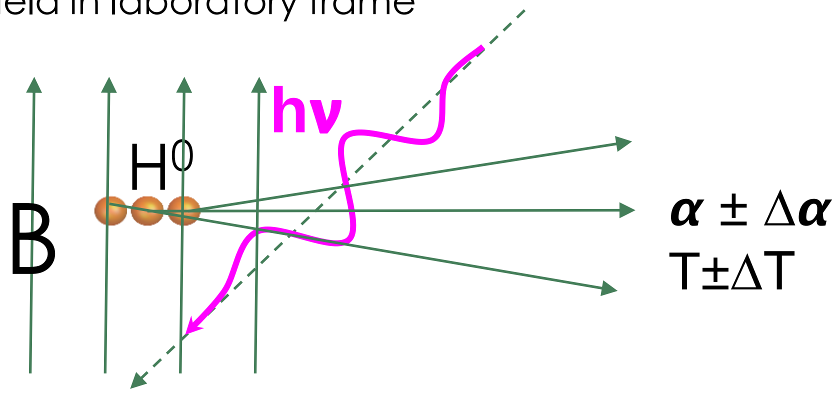
α ↔ T correlation



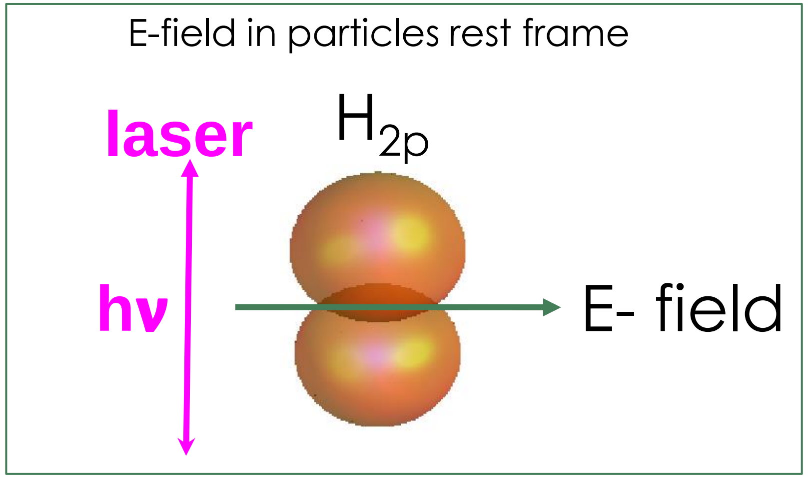
Methods of excitation of realistic beams

3. Resonance broadening of hydrogen atom in a strong electric field (I. Yamane 2002, T. Gorlov 2010)

B-field in laboratory frame

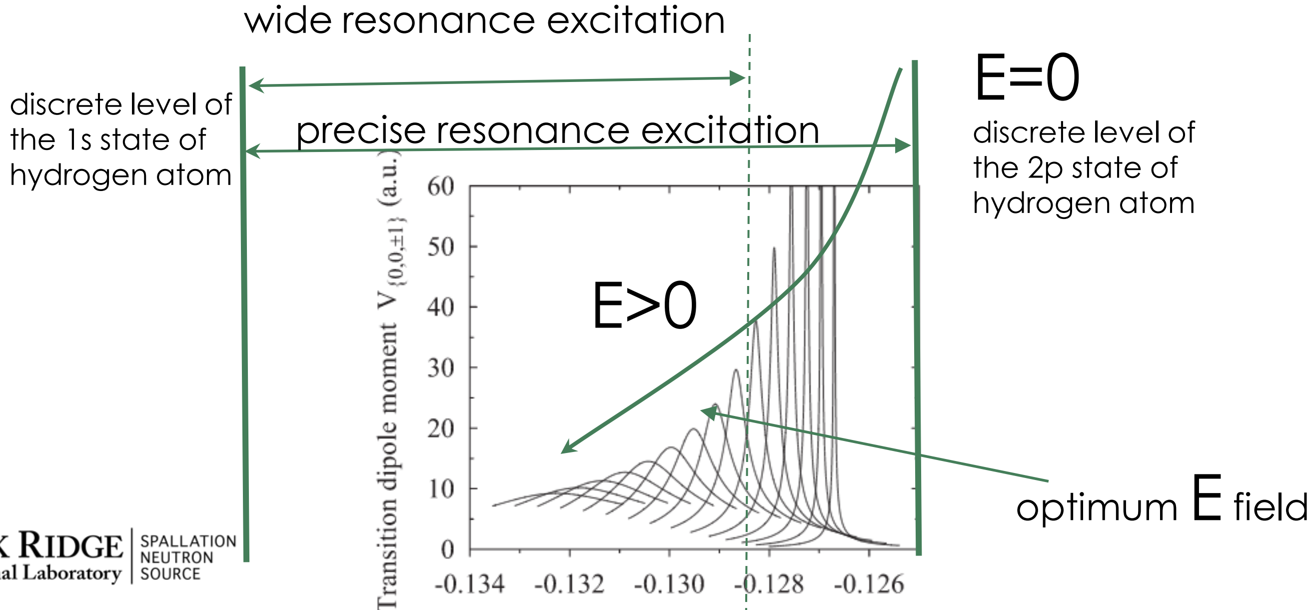


E-field in particles rest frame



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

widening



wide resonance excitation

precise resonance excitation

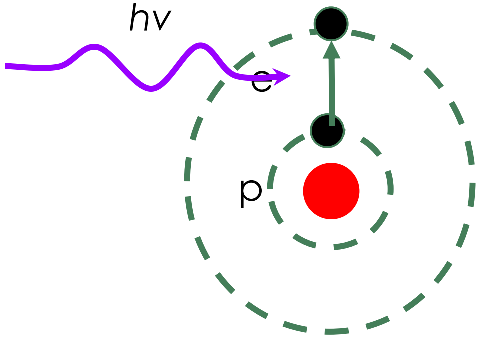
discrete level of the 1s state of hydrogen atom

E=0

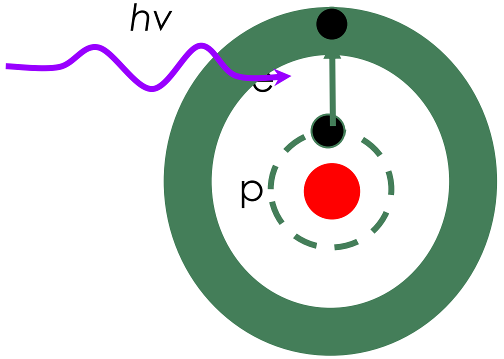
discrete level of the 2p state of hydrogen atom

optimum E field

Narrow resonance, E=0



Broad resonance, E>0

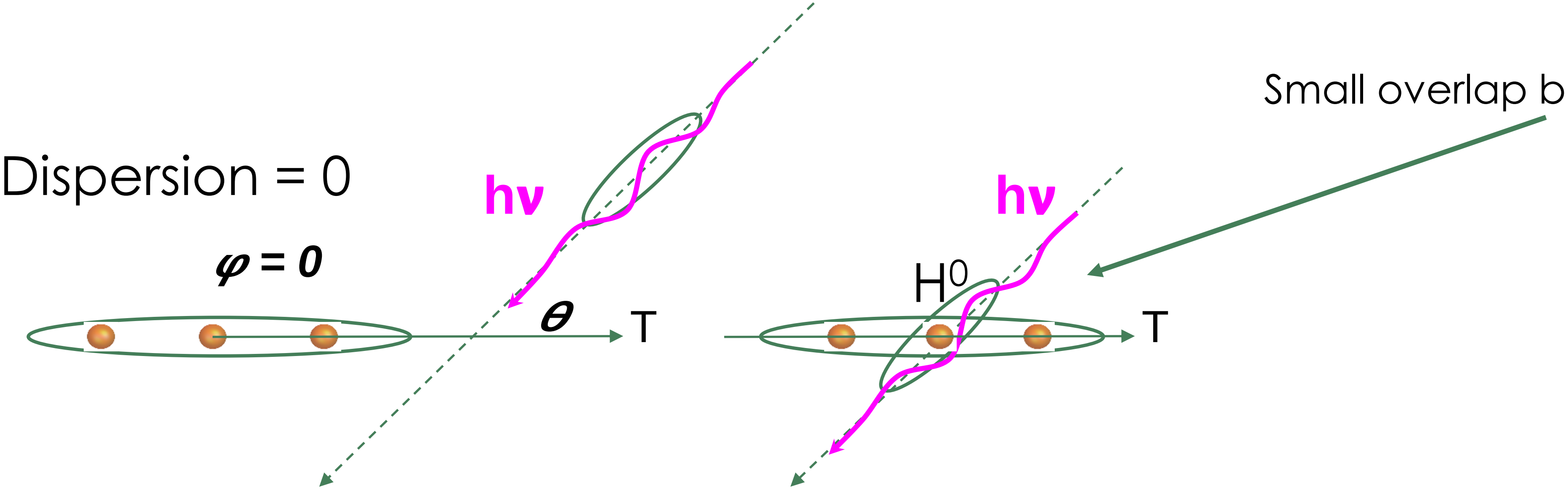


Crab-crossing LACE scheme (A. Aleksandrov)

Dispersion = 0

$\varphi = 0$

Small overlap between Laser-H^-

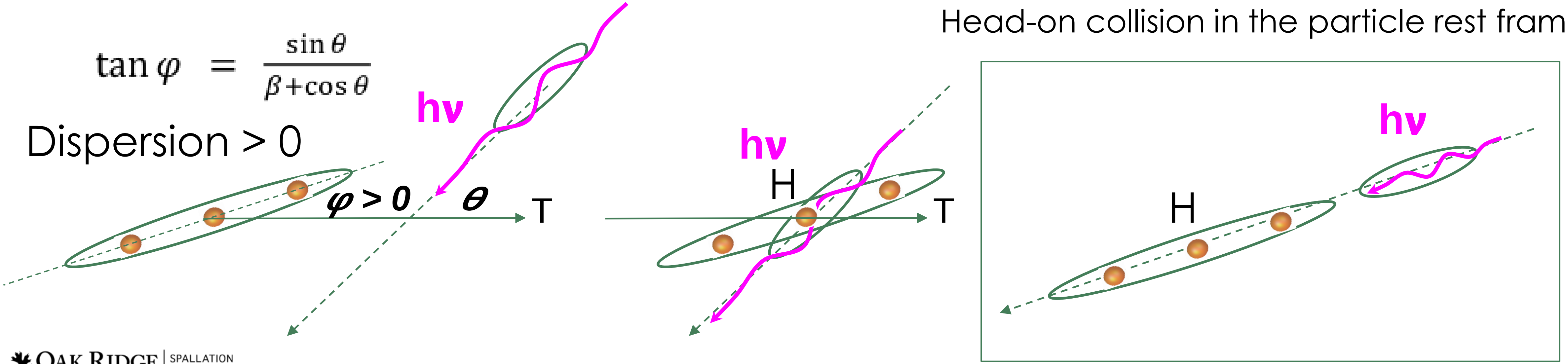


$$\tan\varphi = \frac{\sin\theta}{\beta+\cos\theta}$$

Dispersion > 0

$\varphi > 0$

Head-on collision in the particle rest frame



Laser power challenges has been overcome

Beam gymnastics, temporal matching

Sequential Resonance

Crab crossing

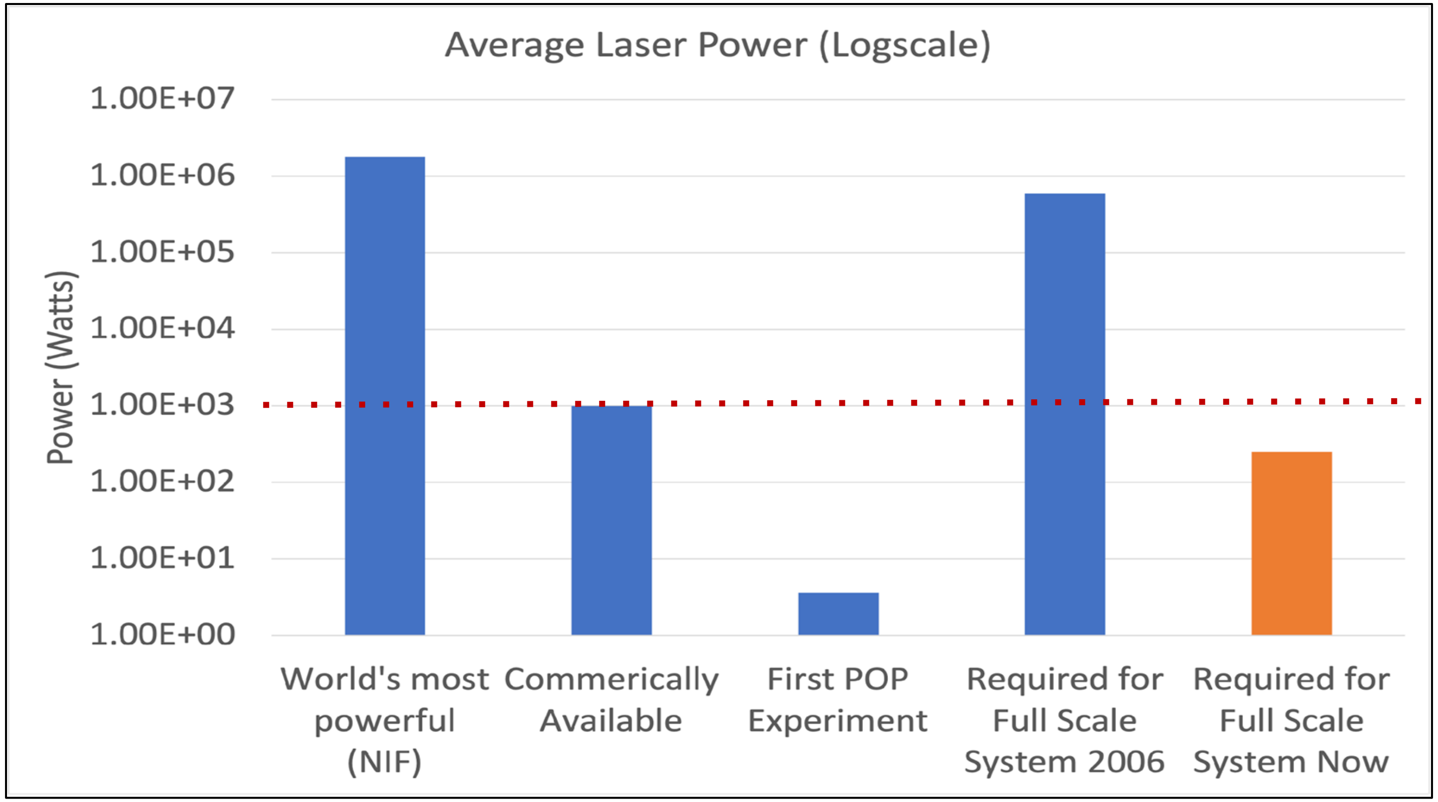
Required initial IR laser P_{ave}

600kW
2006

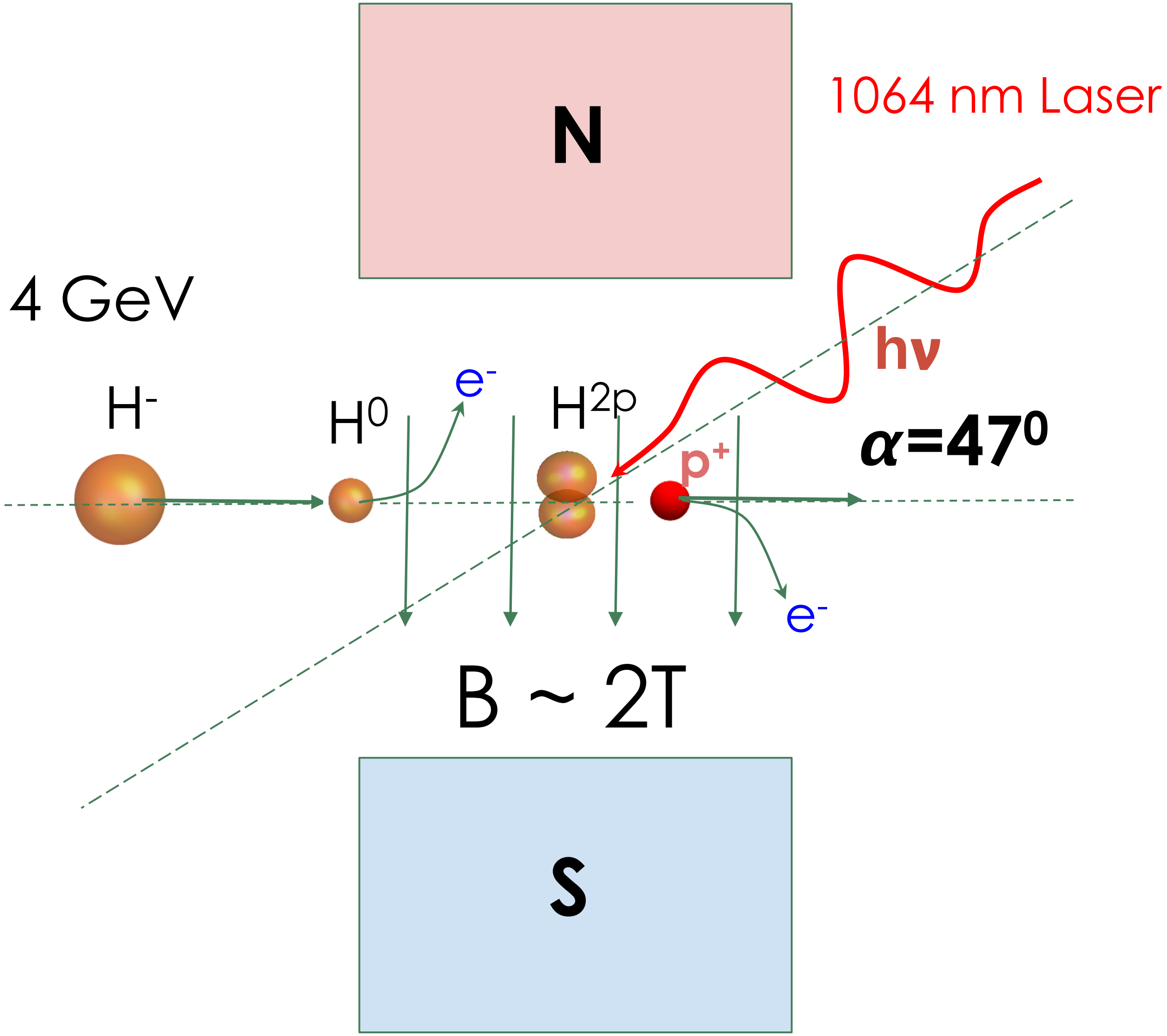
8 kW
2015

1 kW
2022

50 W
2023



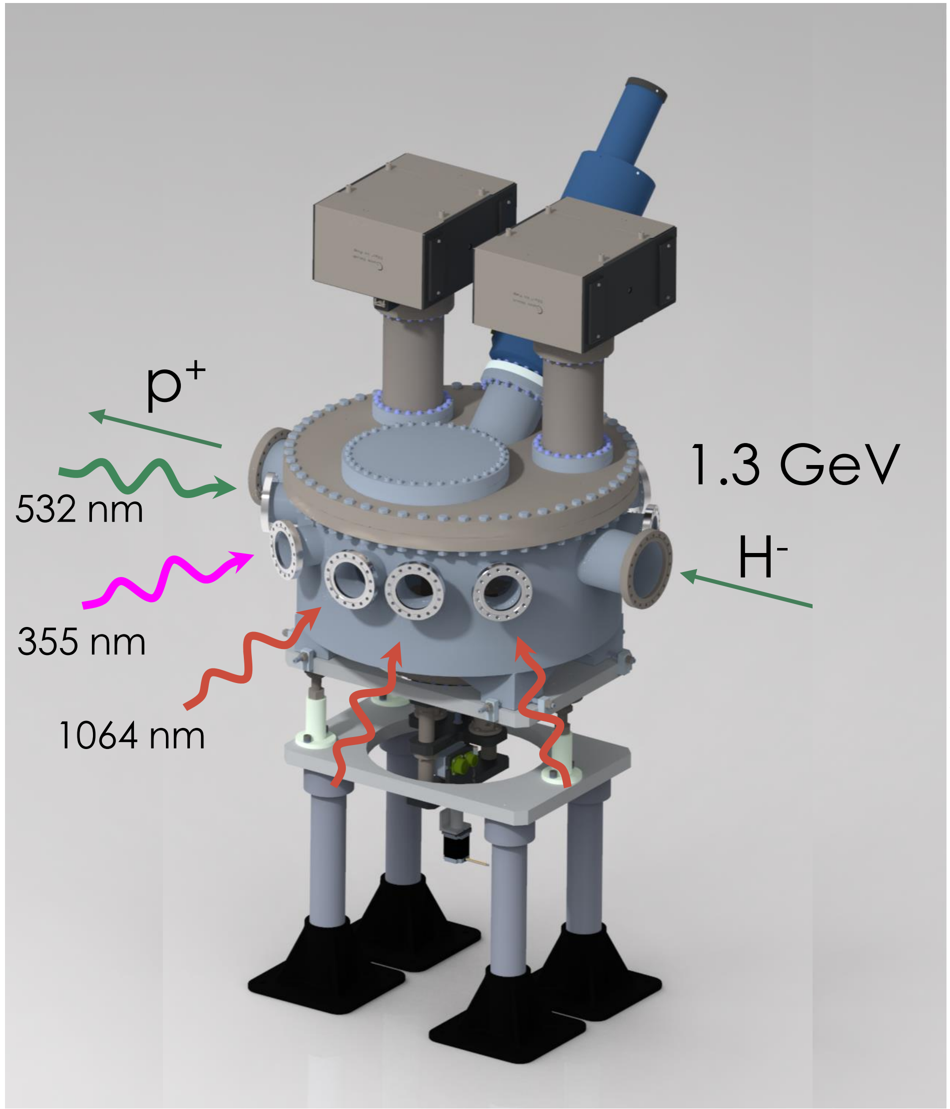
Most optimal laser stripping scheme for 4GeV H^- beam.



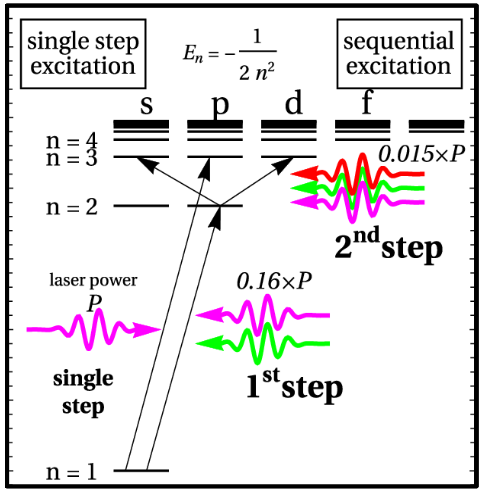
Benefits of LACE for 4GeV energy

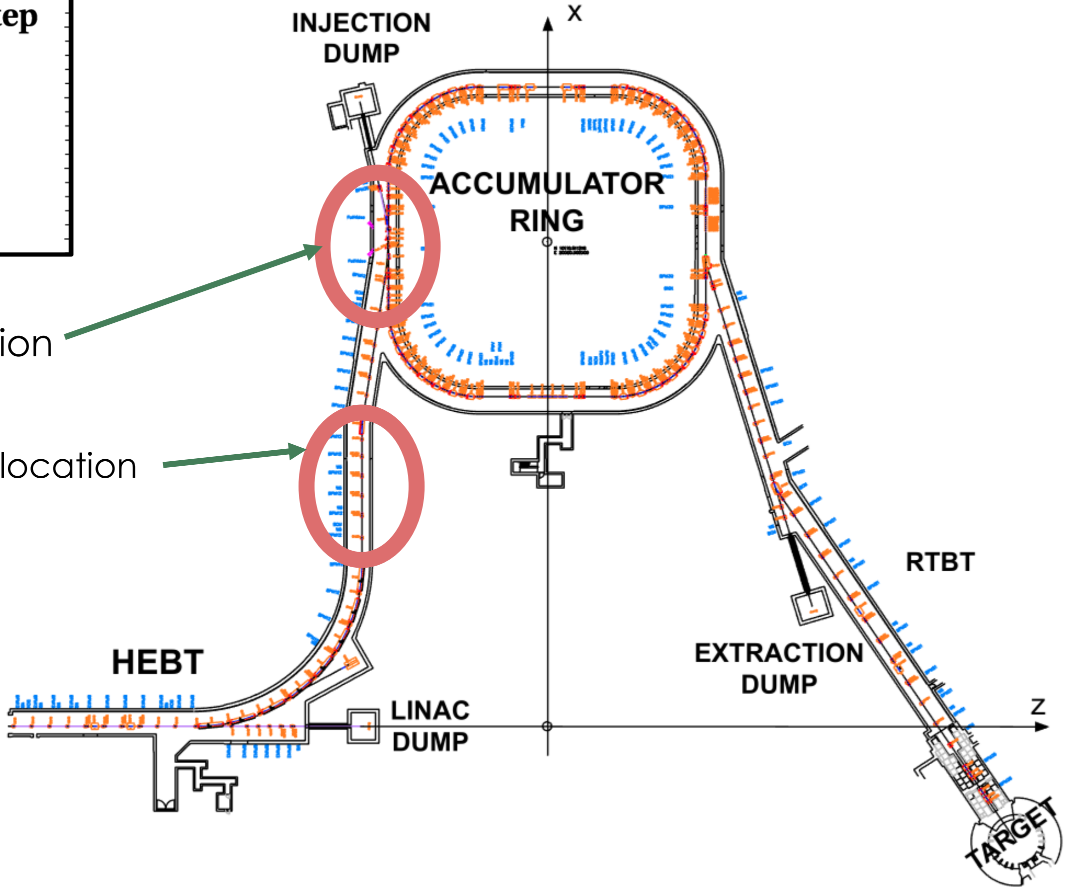
- Using only one magnet that makes LACE very compact.
- Using powerful 1064 nm narrow band laser.
- Resonant excitation of the most effective 1s→2p atomic transition in magnetic field without Stark effect.
- Using 2p state broadening due to the strong magnetic/electric field and simplification of resonant excitation: $\gamma+1s\rightarrow 2p$
- No decay loss: $2p\rightarrow 1s+\gamma$

Next LACE experiments at the SNS for 1.3 GeV



Schematics of hydrogen atom structure and mechanisms of different excitation schemes





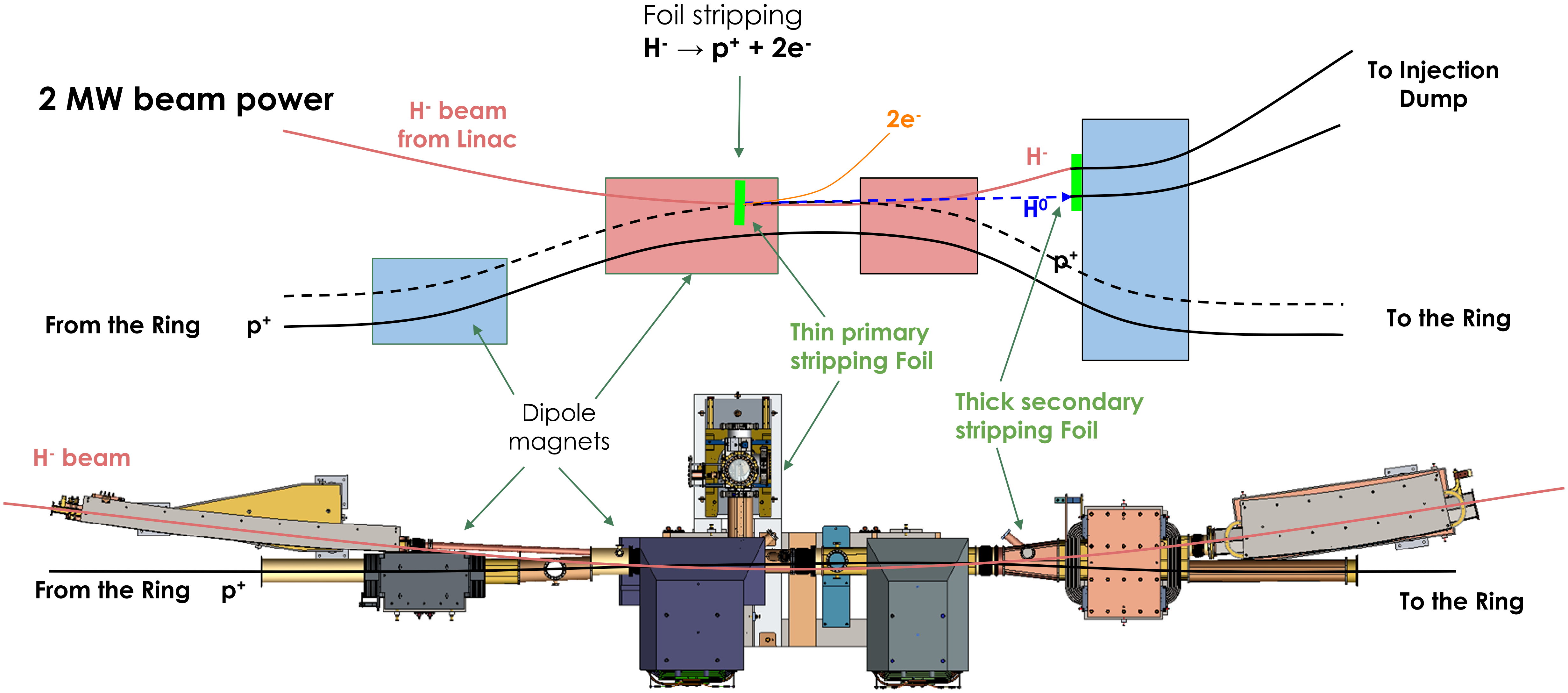
Real injection

Experiment location

1.3 GeV

Foil assisted beam injection design for 1.3 GeV at the SNS. Future project.

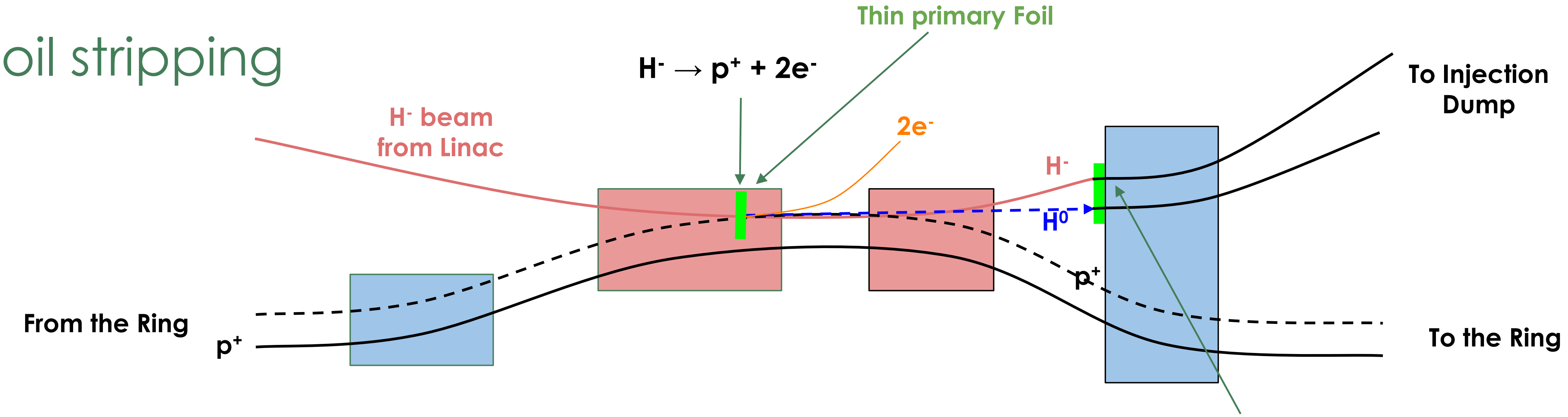
2 MW beam power



Foil stripping
$H^- \rightarrow p^+ + 2e^-$

Foil injection vs LACE injection at the SNS

Foil stripping



Thin primary Foil

$H^- \rightarrow p^+ + 2e^-$

H^- beam from Linac

$2e^-$

H^-

H^0

p^+

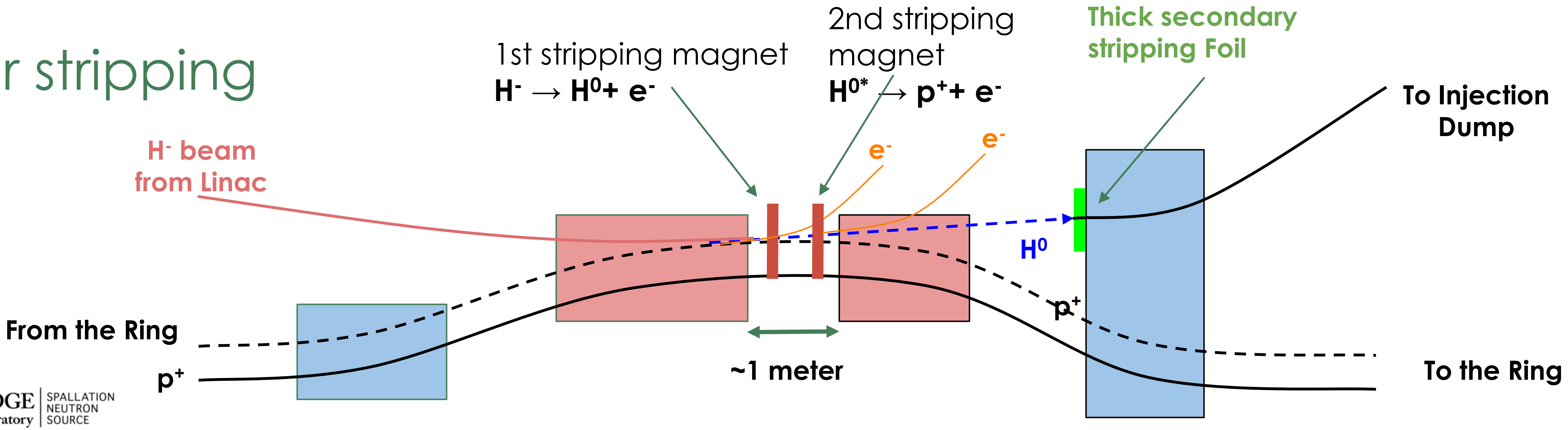
To Injection Dump

From the Ring

p^+

To the Ring

Laser stripping



1st stripping magnet
$H^- \rightarrow H^0 + e^-$

2nd stripping magnet
$H^{0*} \rightarrow p^+ + e^-$

Thick secondary stripping Foil

H^- beam from Linac

e^-

e^-

H^0

p^+

To Injection Dump

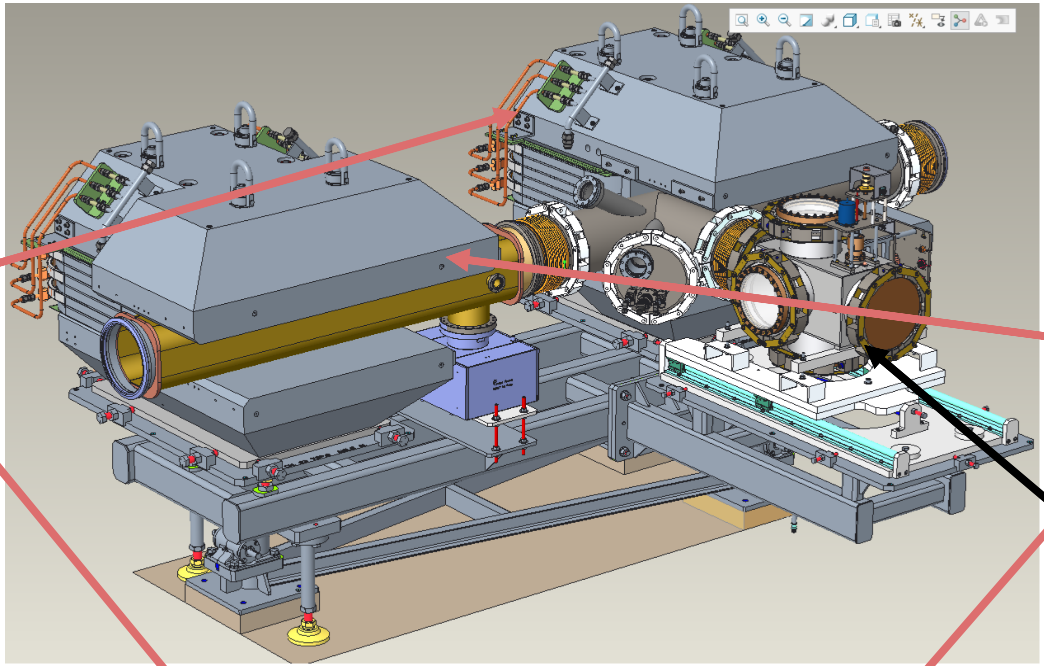
From the Ring

p^+

~1 meter

To the Ring

Laser strippng implementation into injection area of the Ring PPU power upgrade

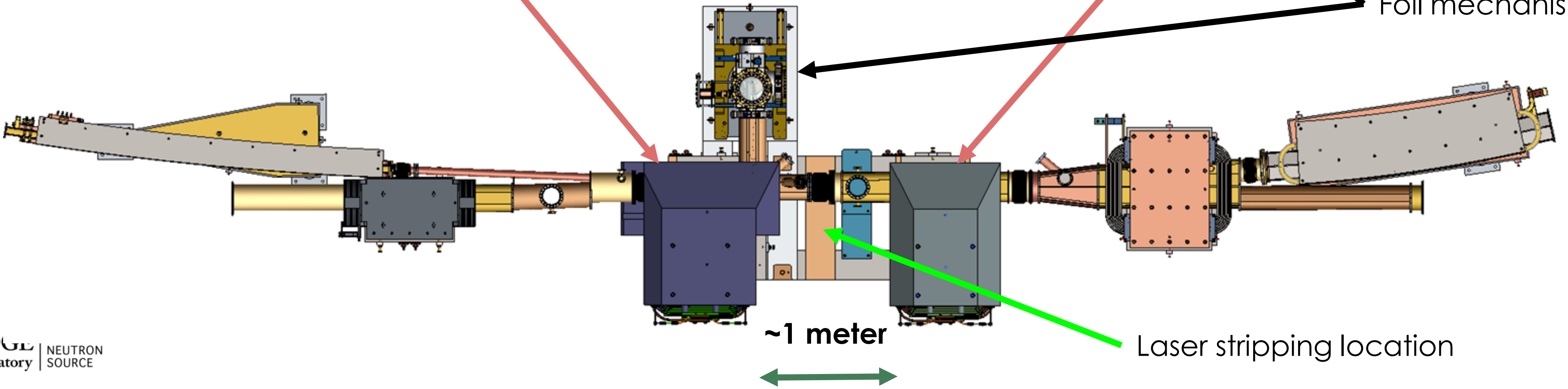


Drawings of the Injection
area of the Ring.
Courtesy of A. Menshov

Dipole magnet (Chicane 02)

Dipole magnet (Chicane 03)

Foil mechanism



~1 meter

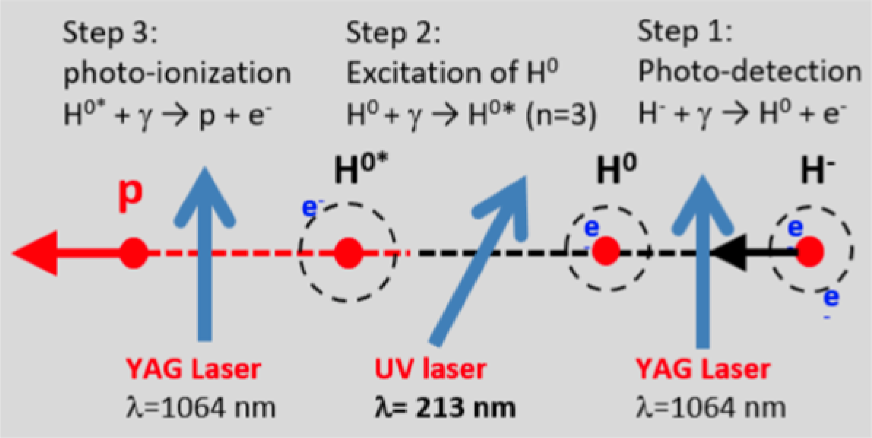
Laser stripping location

LACE for low energy beam. 400 MeV beam for J-PARC.

◆ Beam energy 0.4 GeV. → Needs much higher magnetic fields

◆ Angular spread due to a fringe field striiping is also concerned.

→ Consider using only lasers.



Step 3:
photo-ionization
$H^{0*} + \gamma \rightarrow p + e^-$

Step 2:
Excitation of H^0
$H^0 + \gamma \rightarrow H^{0*}$ (n=3)

Step 1:
Photo-detection
$H^- + \gamma \rightarrow H^0 + e^-$

YAG Laser
λ=1064 nm

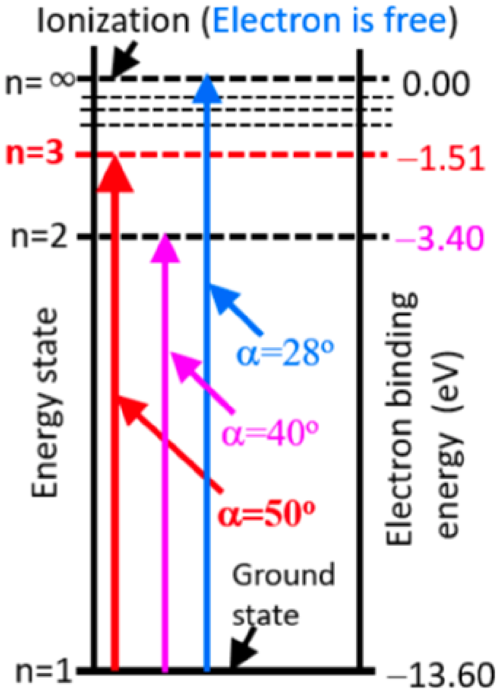
UV laser
λ= 213 nm

YAG Laser
λ=1064 nm

A POP demonstration at 400 MeV is under preparation.
Experimental studies will be started in 2024.

◆ A prototype YAG laser system and a multi-reflection cavity system to sufficiently reduce the seed laser energy have been developed.

◆ The R&D of the UV laser just started.



A relatively bigger vacuum chamber is installed. UV laser angle can be changed for different excitation state.