Laser stripping of H^- beam

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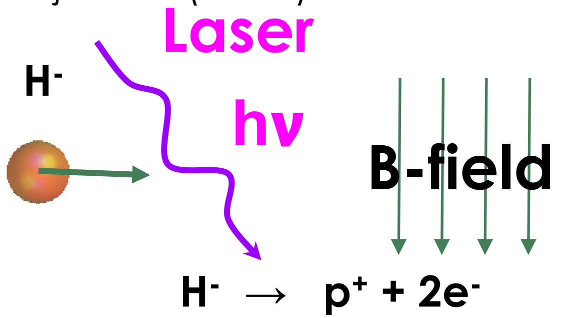
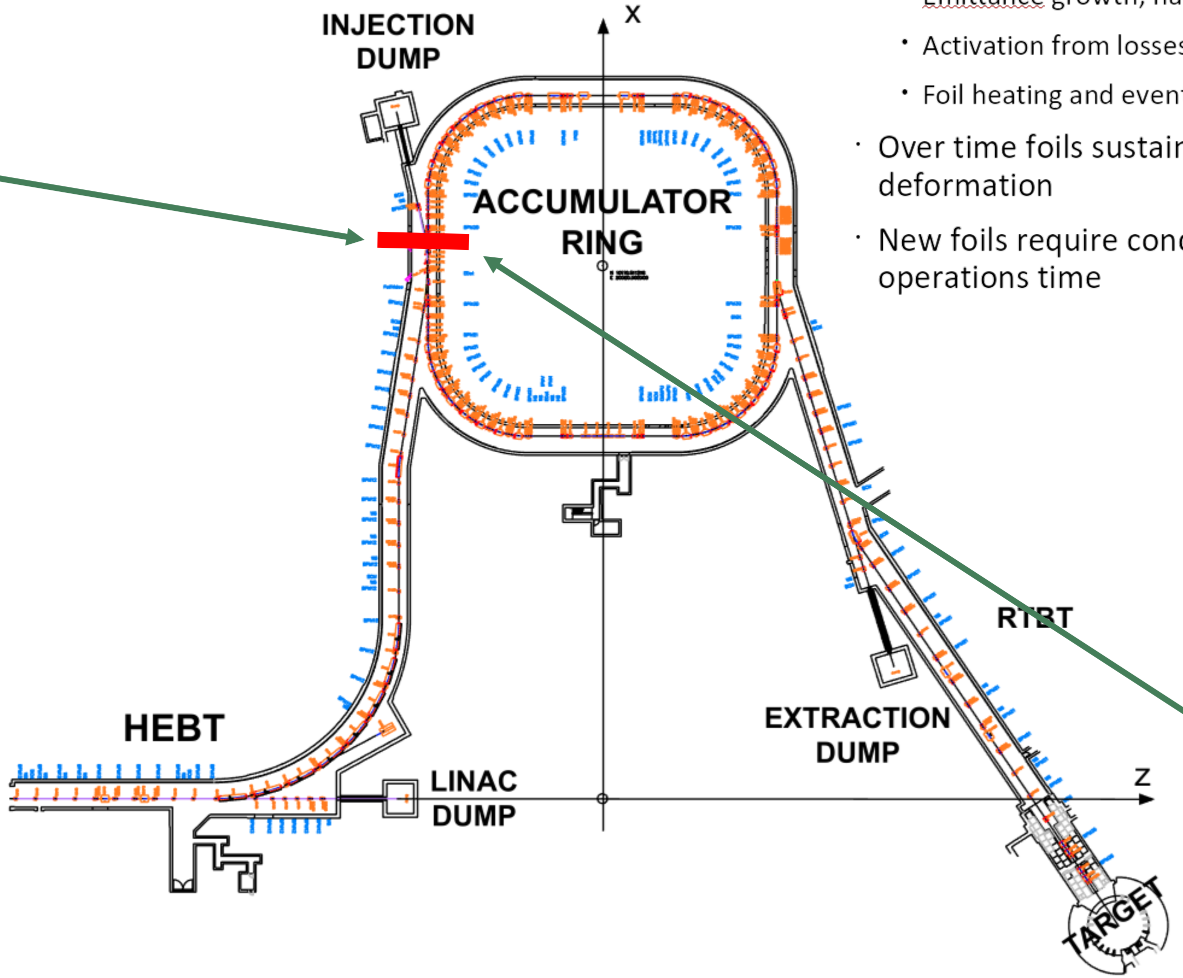
Charge exchange beam injection of H^- beam into the Ring.

Thin carbon stripping foil. Foil Injection.

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

Laser assisted charge exchange injection (LACE)



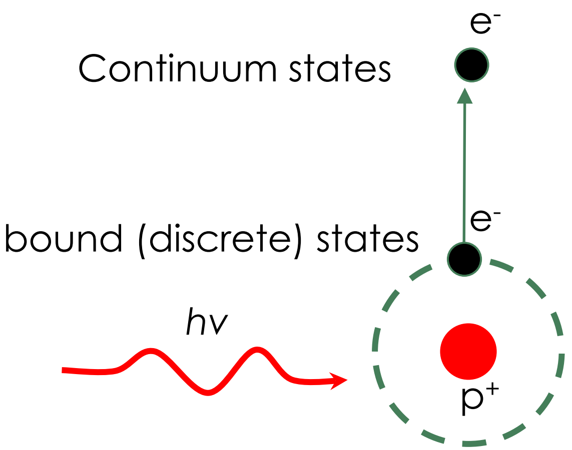


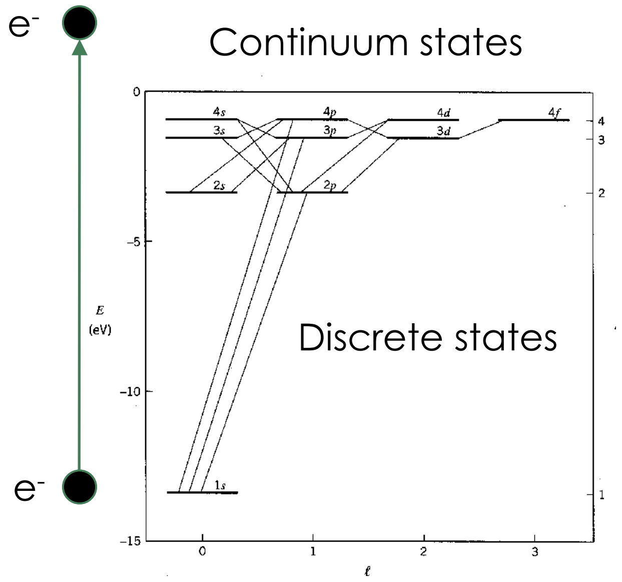
1.3 GeV H^- beam
2MW beam power

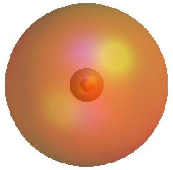
Issues with Foils (courtesy of N. Evans)

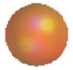
- Interaction of beam with foil causes:
  - Emittance growth, halo formation
  - Activation from losses (injection ~10x hotter than rest of SNS)
  - Foil heating and eventual sublimation
- Over time foils sustain damage causing deformation
- New foils require conditioning which eats into operations time

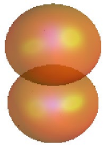
Photoionization of H^- and H^0.

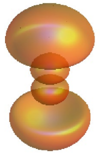




σ_{H-} = 4.0×10^{-21} m^2 for 800 nm  H^-

σ_{1s} = 6.3×10^{-22} m^2 for 91 nm  H_{1s}

σ_{2p} = 1.7×10^{-21} m^2 for 364 nm  H_{2p}

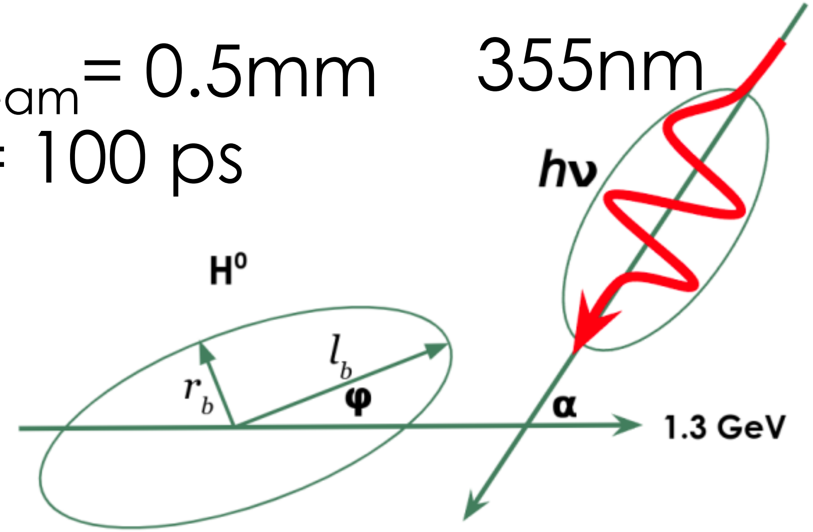
σ_{3p} = 3.3×10^{-21} m^2 for 820 nm  H_{3p}

Gaussian laser-beam interaction

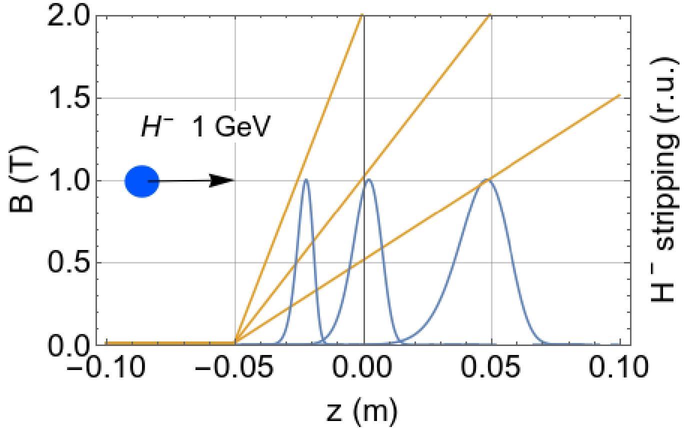
Energy=35mJ for 99% stripping (requires ~500 times more laser power than existing laser)

r_{beam}= 0.5mm 355nm

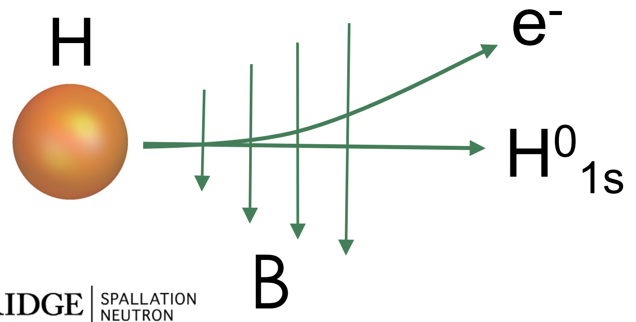
l_b= 100 ps



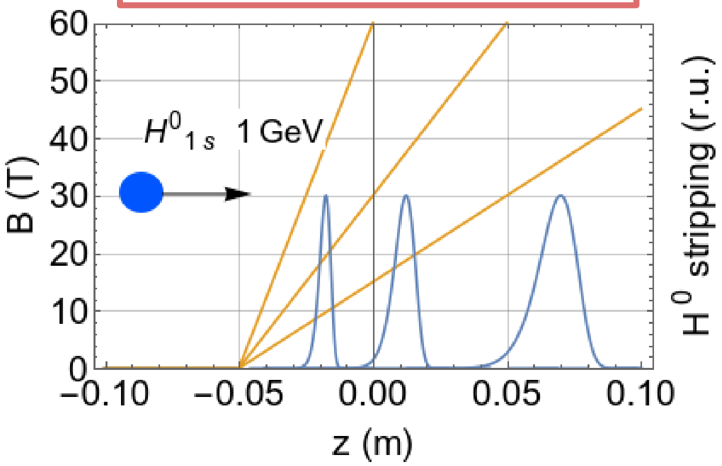
Lorentz stripping of hadron beams. 1GeV H^0, H^- beams



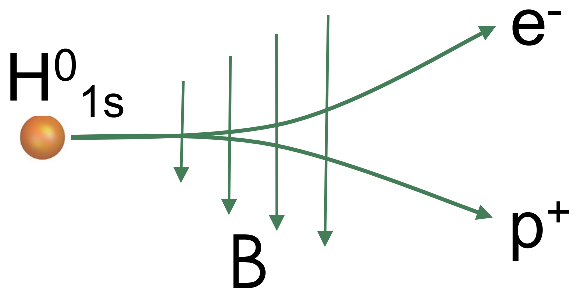
$H^- \rightarrow H^0 + e^-$

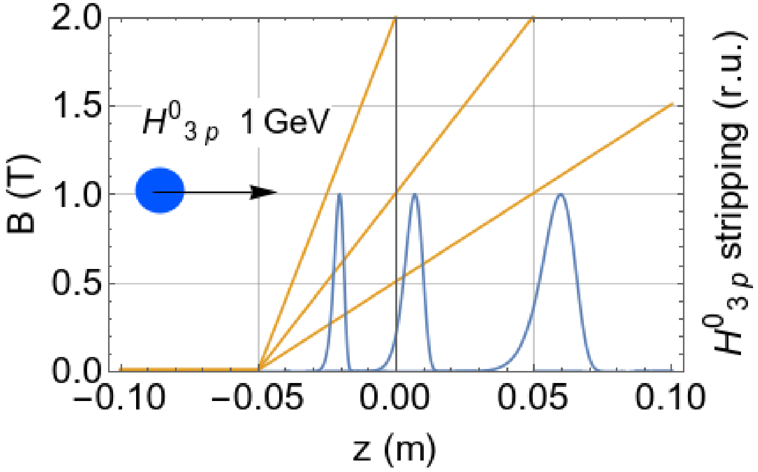


40 Tesla magnet !

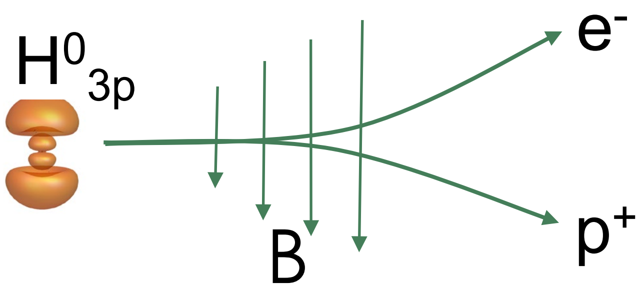


$H^0_{1s} \rightarrow p^+ + e^-$

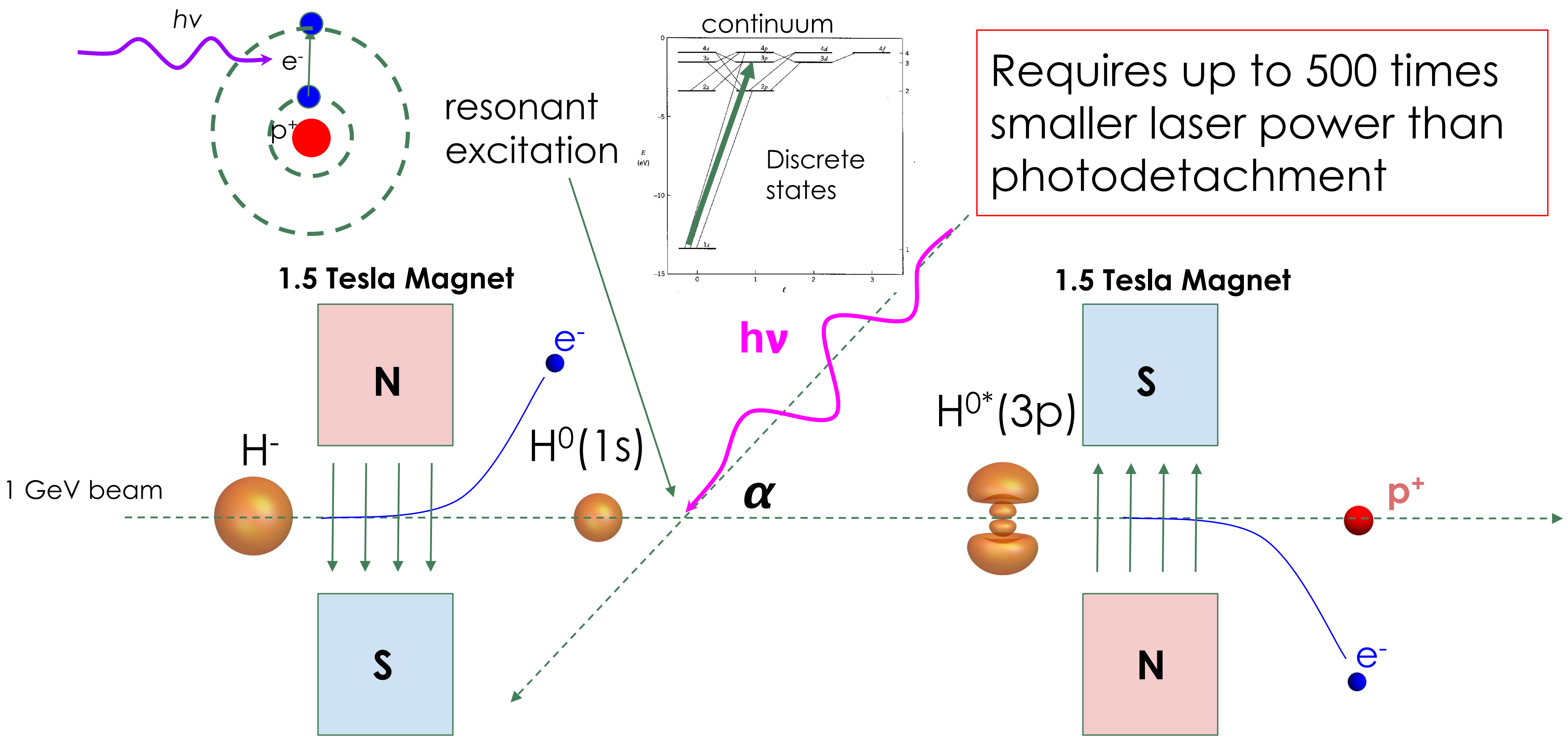




$H^0_{3p} \rightarrow p^+ + e^-$



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

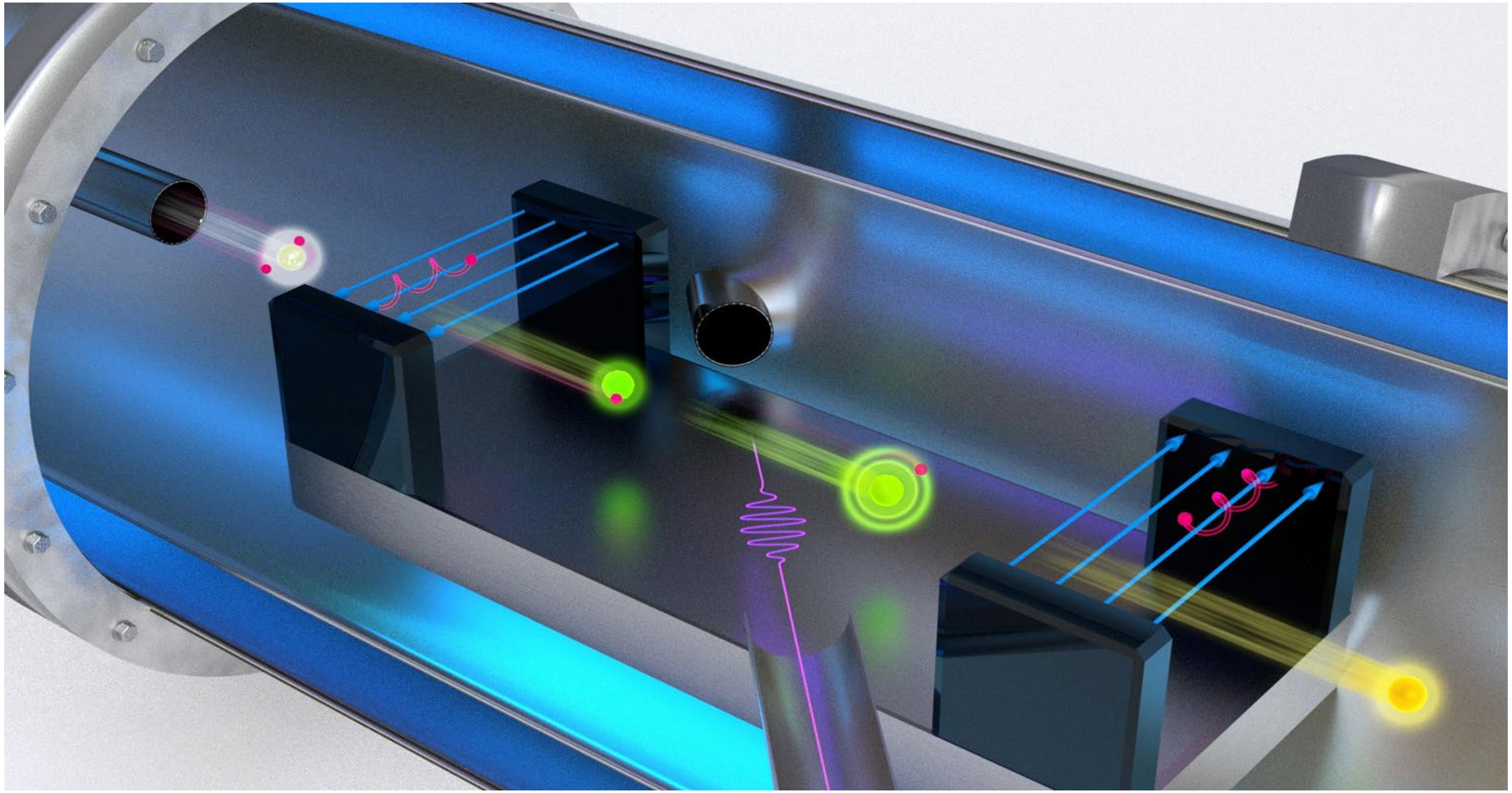


1st step:
Lorentz stripping
$H^- \rightarrow H^0 + e^-$

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

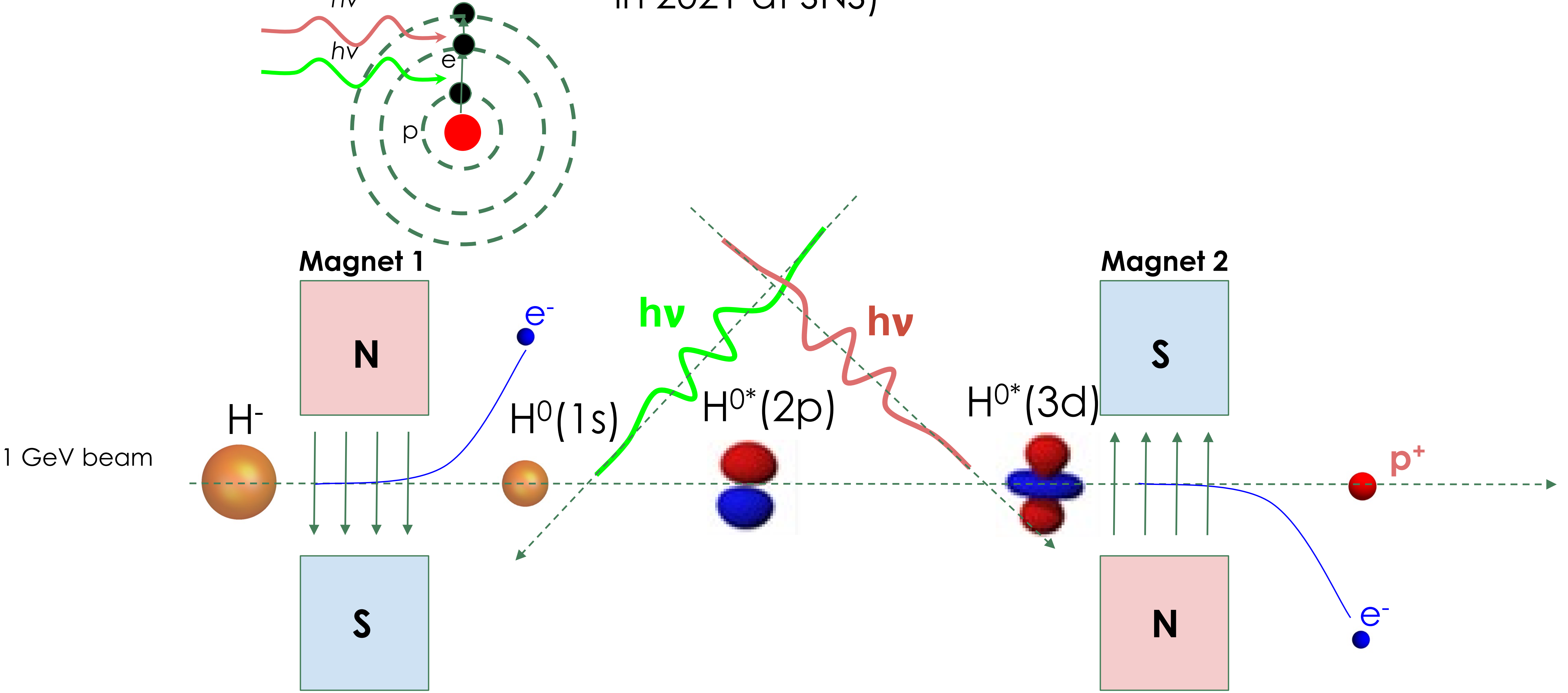
3rd step:
Lorentz stripping
$H^{0*} \rightarrow p^+ + e^-$

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

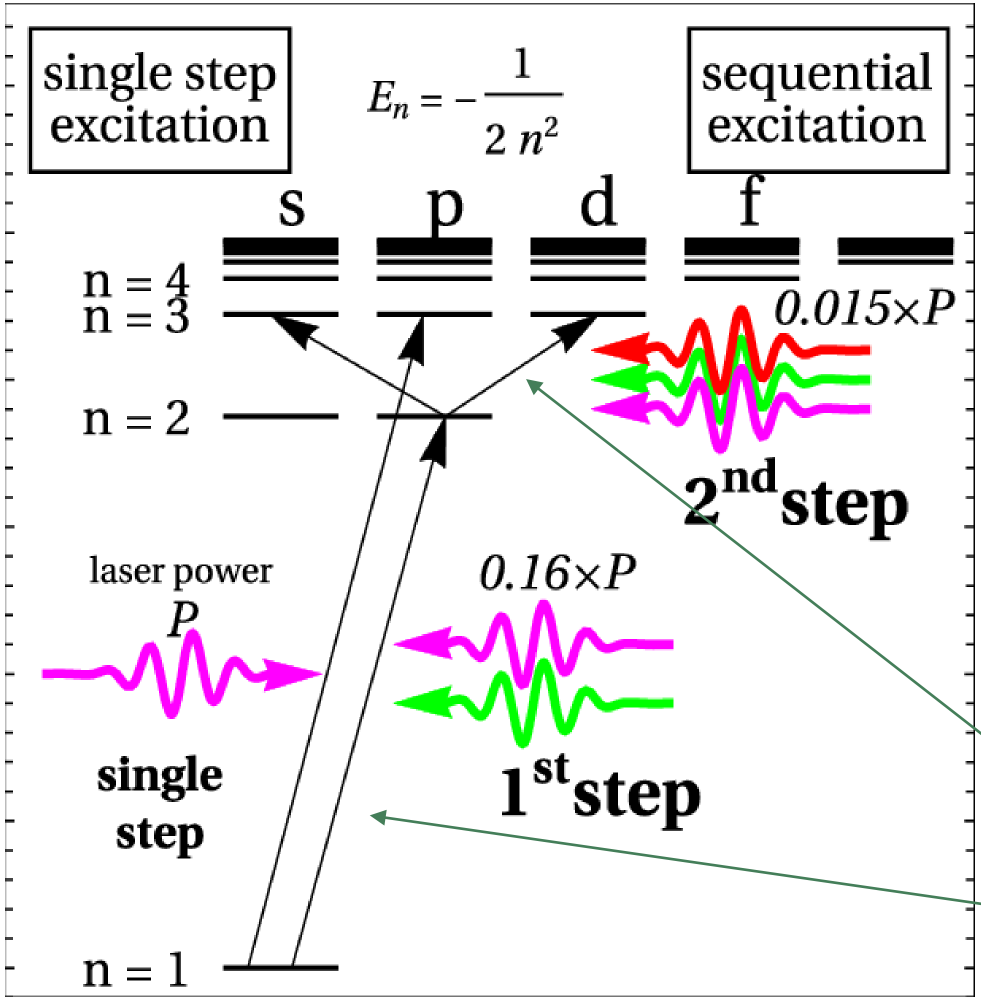
2nd step:
laser resonant excitation
$H^0 + h\nu \rightarrow H^{0*}$

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:

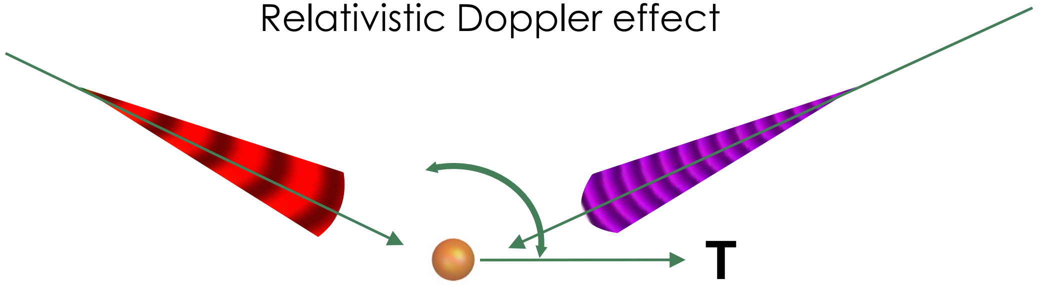
Hydrogen atom structure and different excitation mechanisms by different lasers for 1.3GeV H^0 beam



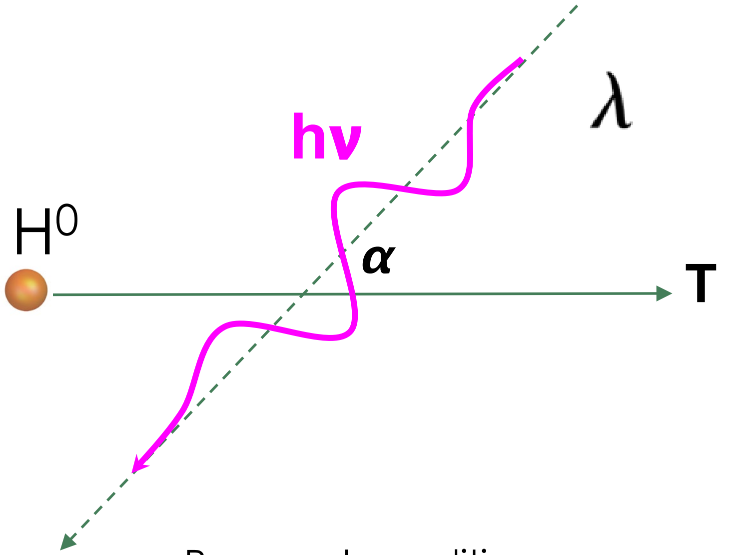
The smaller step requires less laser power and considered to be more effective

Resonant excitation of stochastic beam with energy-angular spread.

Relativistic Doppler effect



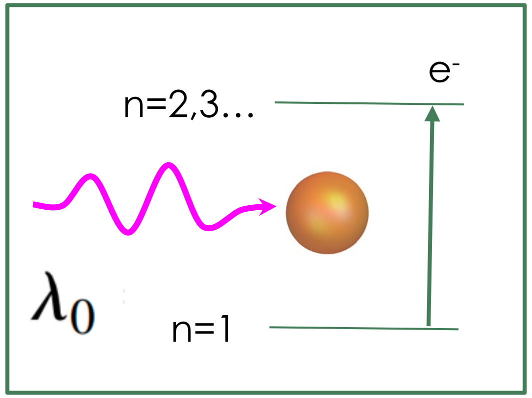
Relativistic Doppler effect for single particle



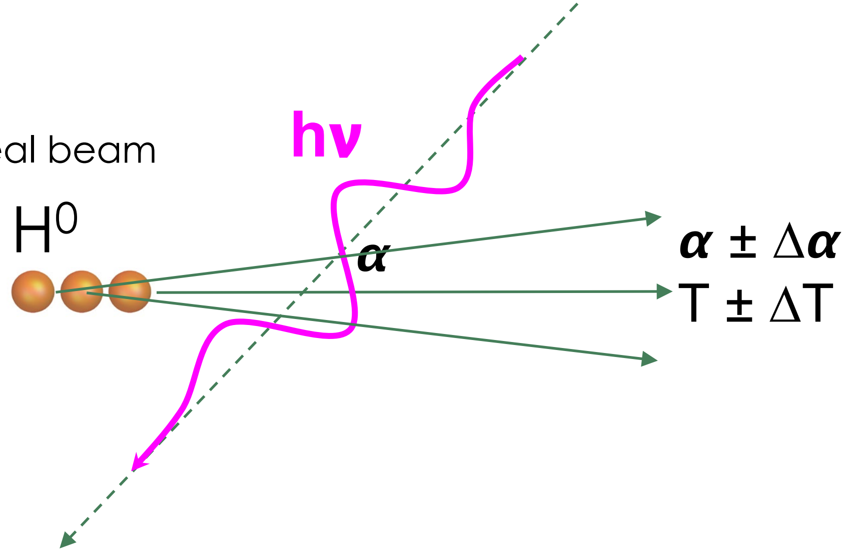
Resonant condition:

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

Particles rest frame



Real stochastic beam with angular-energy spread



Most of the beam is not in resonant conditions

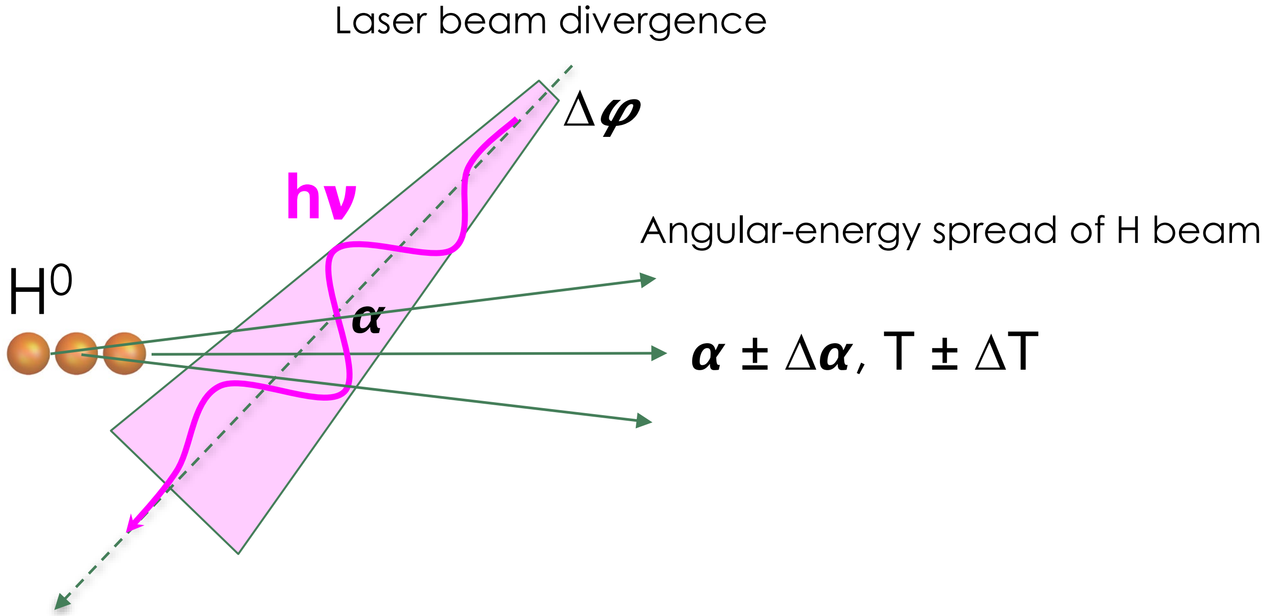
$$\lambda_0 \neq \frac{\lambda}{\gamma(1 + \beta \cos\alpha)}$$

Methods of excitation of realistic beams

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

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

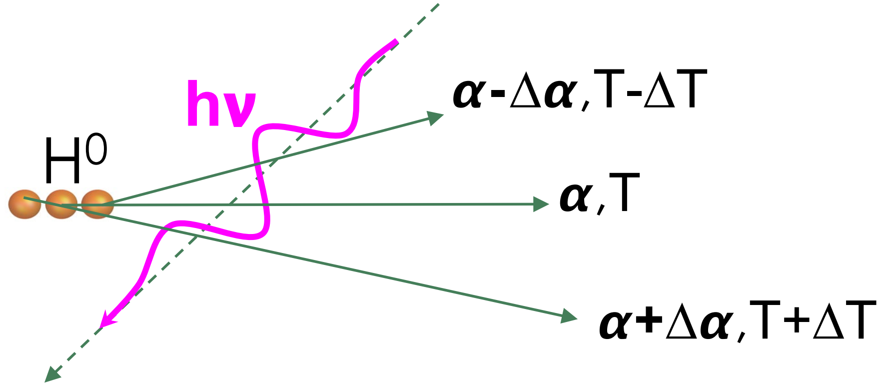
laser angular spread



Methods of excitation of realistic beams

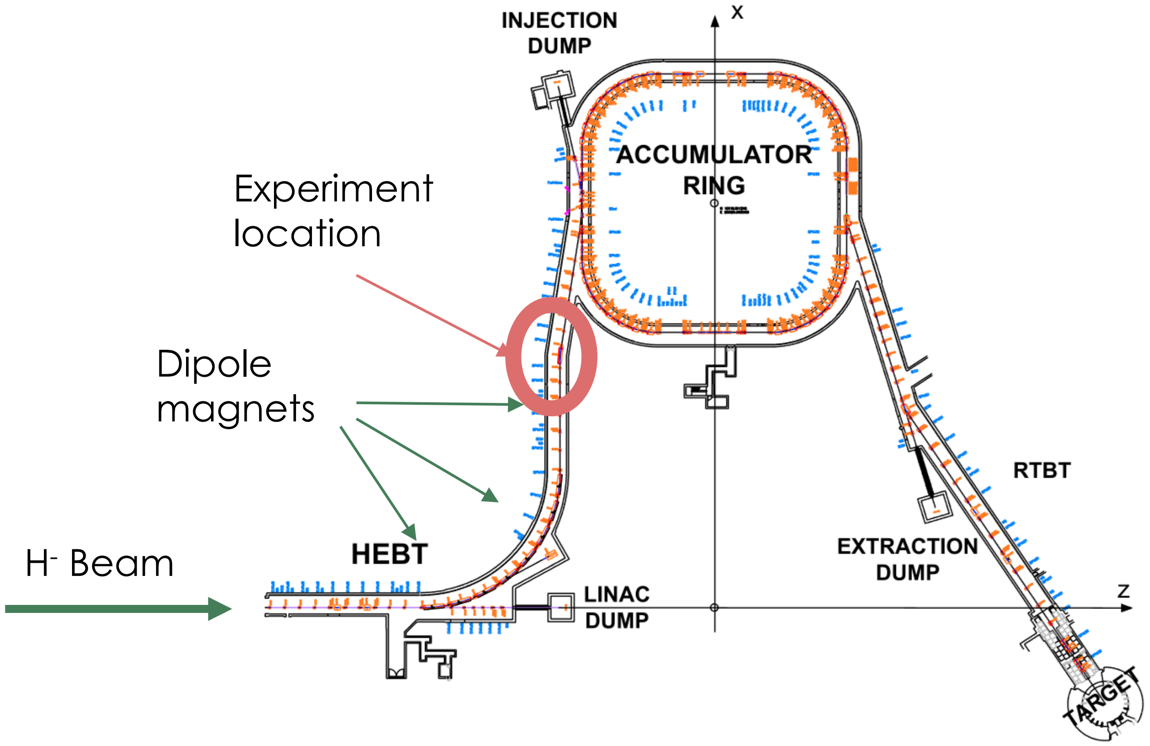
2. Beam tailoring. Correlation between T and $\boldsymbol{\alpha}$.

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



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

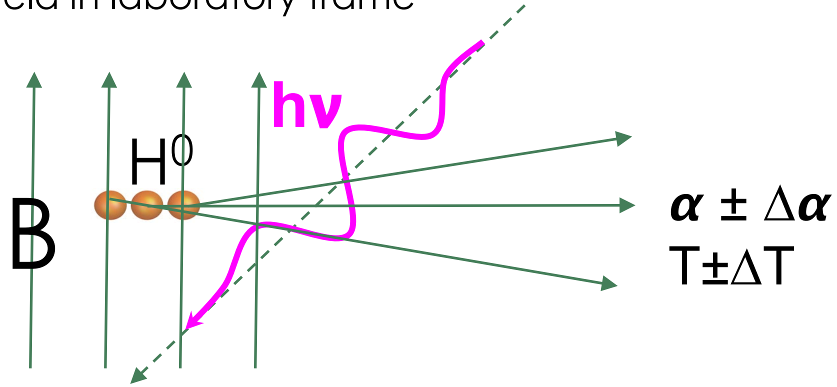
$\boldsymbol{\alpha} \leftrightarrow$ T correlation

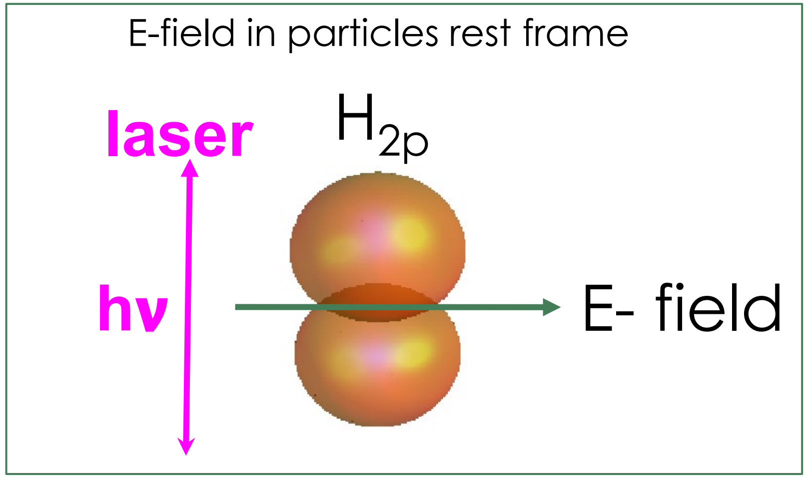


Methods of excitation of realistic beams

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

B-field in laboratory frame



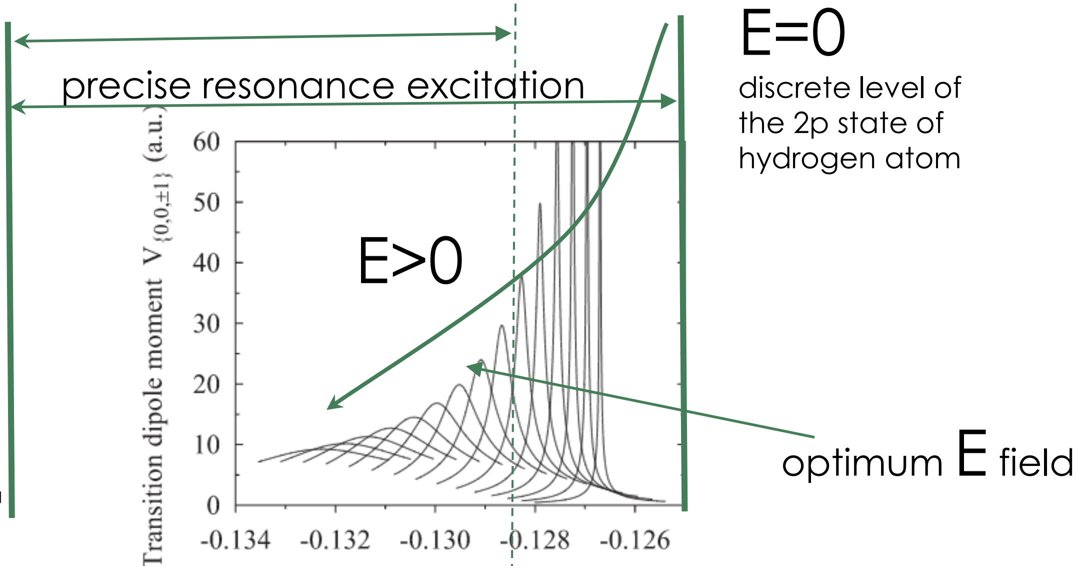


$$\lambda_0 = \frac{\lambda}{\gamma(1+\beta\cos\alpha)}$$

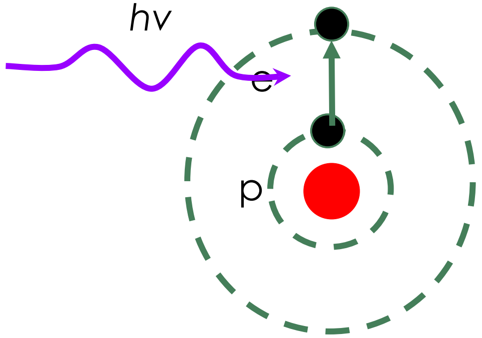
widening

wide resonance excitation

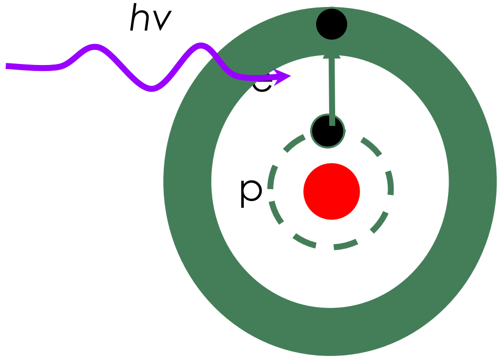
discrete level of the 1s state of hydrogen atom



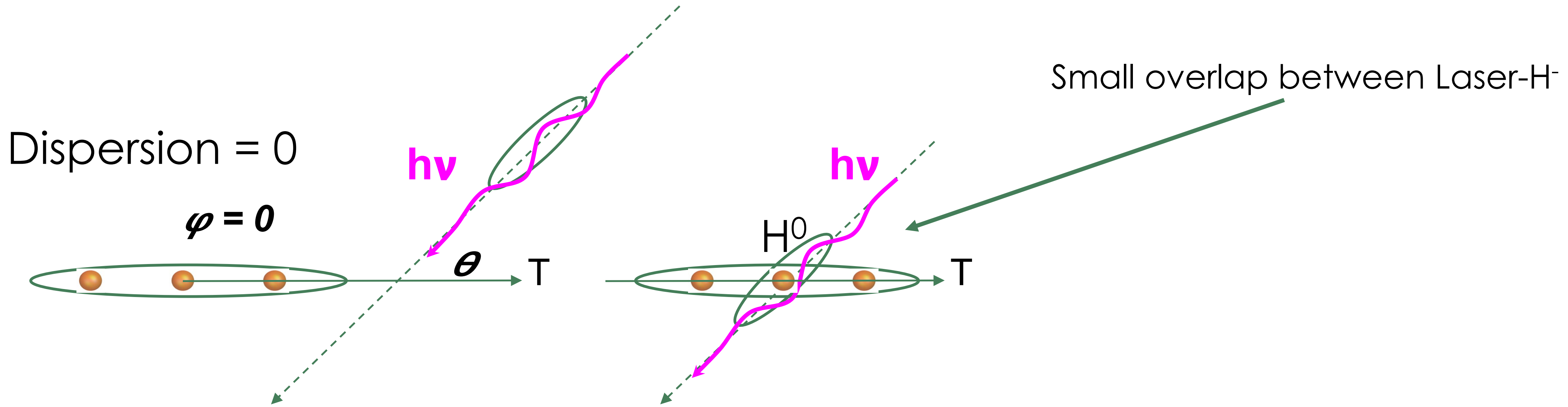
Narrow resonance, E=0



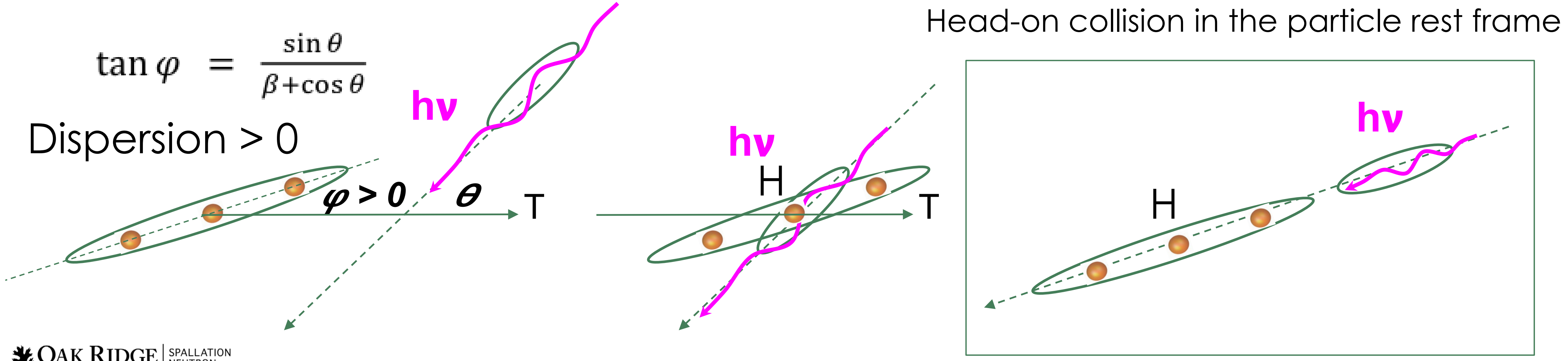
Broad resonance, E>0



Crab-crossing LACE scheme (A. Aleksandrov)



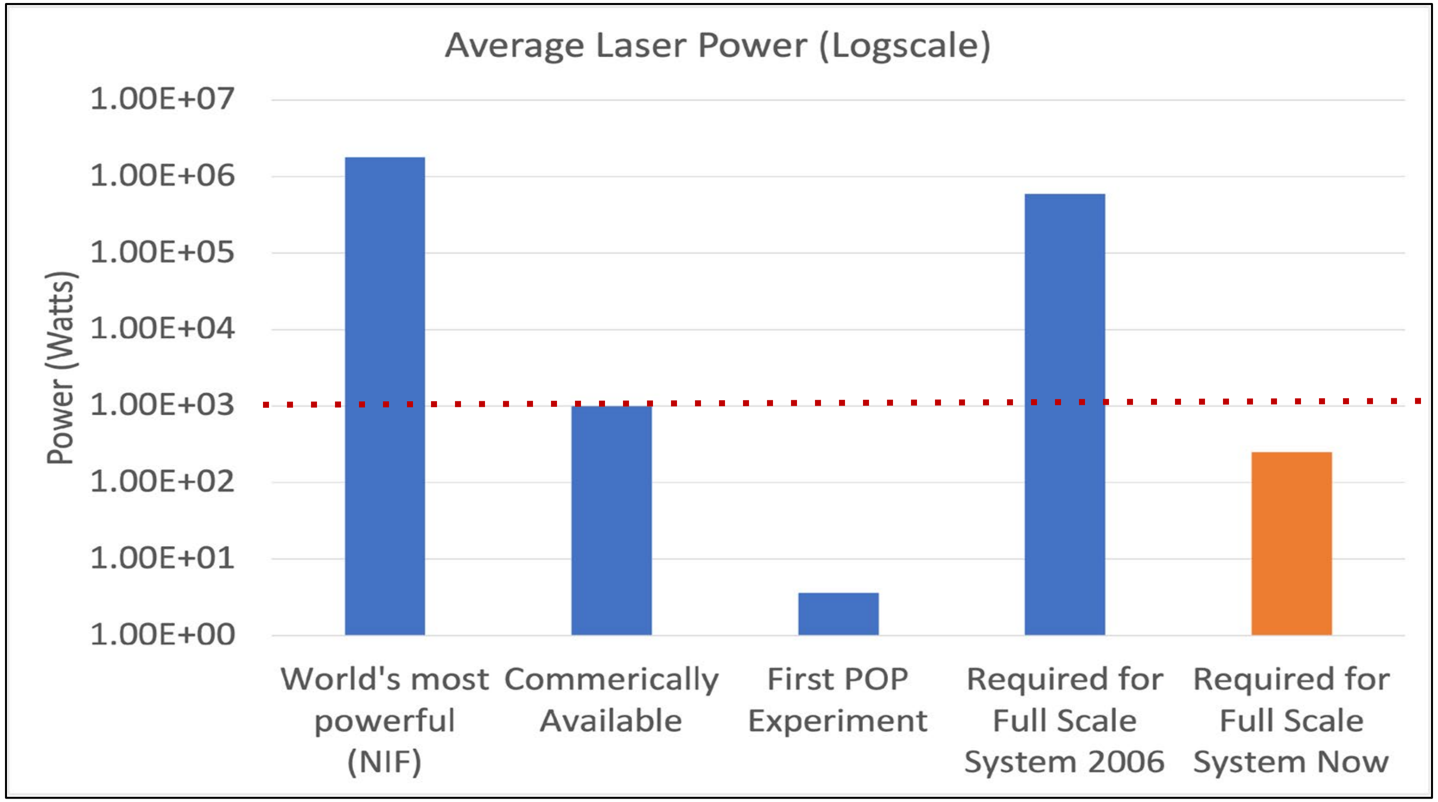
$$\tan\varphi = \frac{\sin\theta}{\beta + \cos\theta}$$



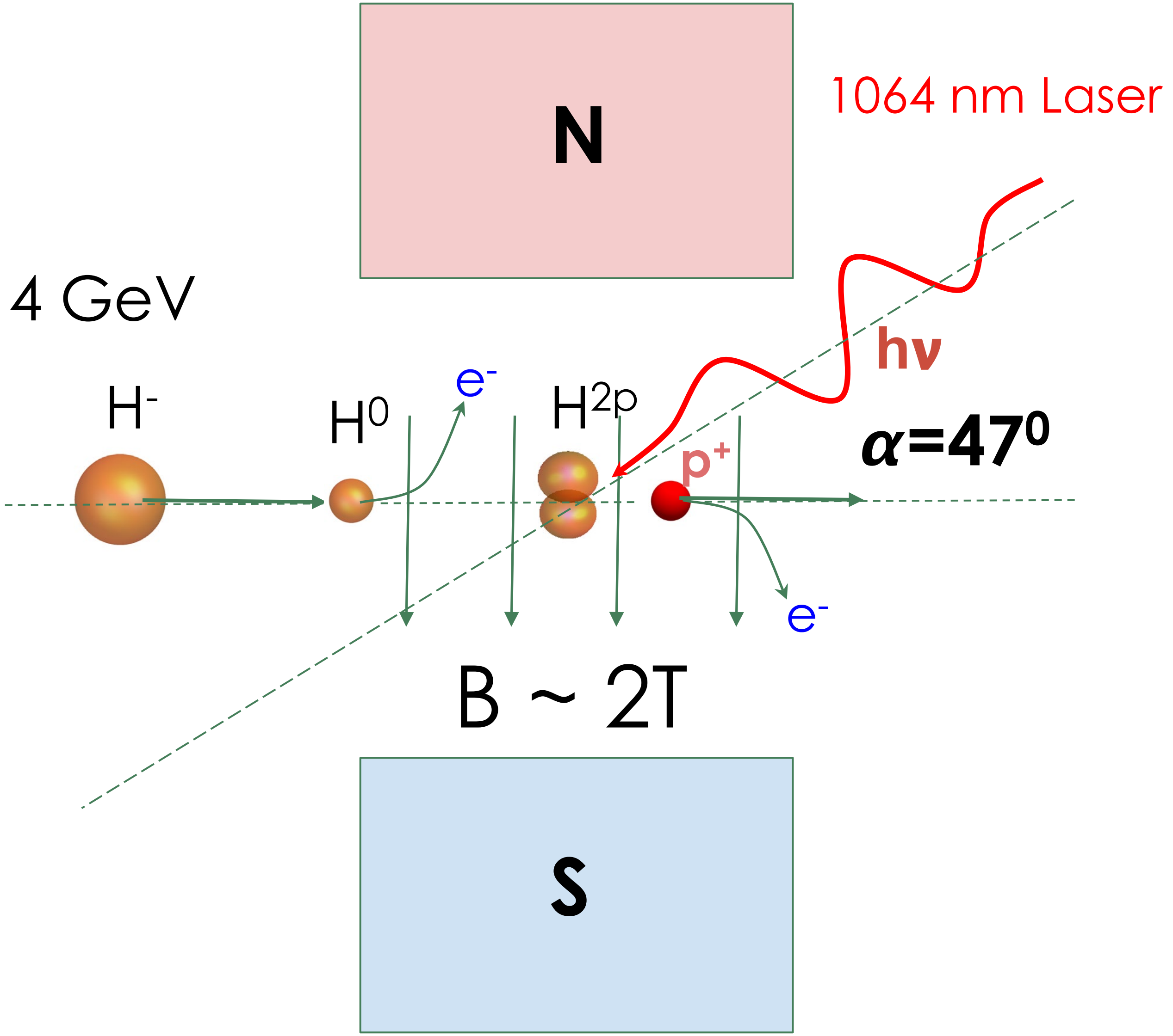
Laser power challenges has been overcome

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**



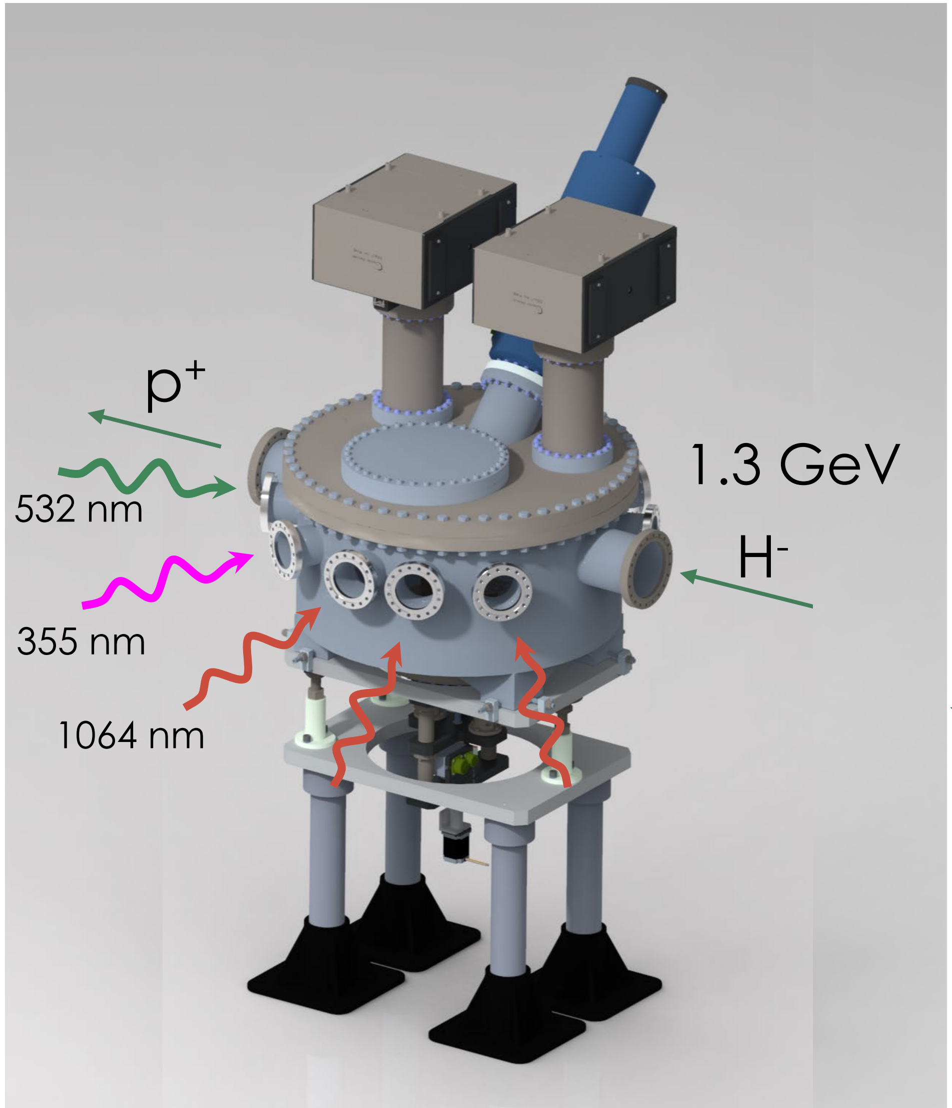
Most optimal laser stripping scheme for 4GeV H^- beam.



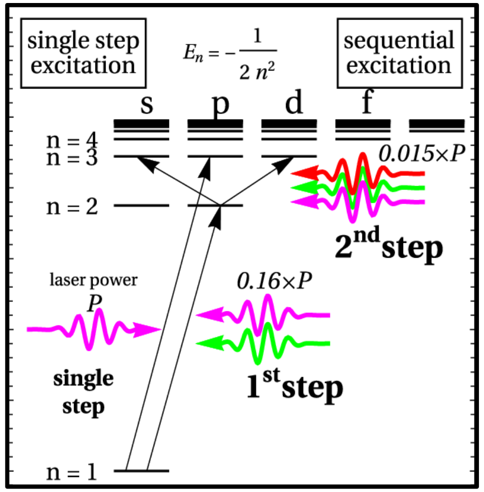
Benefits of LACE for 4GeV energy

- 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: γ+1s→2p
- No decay loss: 2p→1s+γ

Next LACE experiments at the SNS for 1.3 GeV



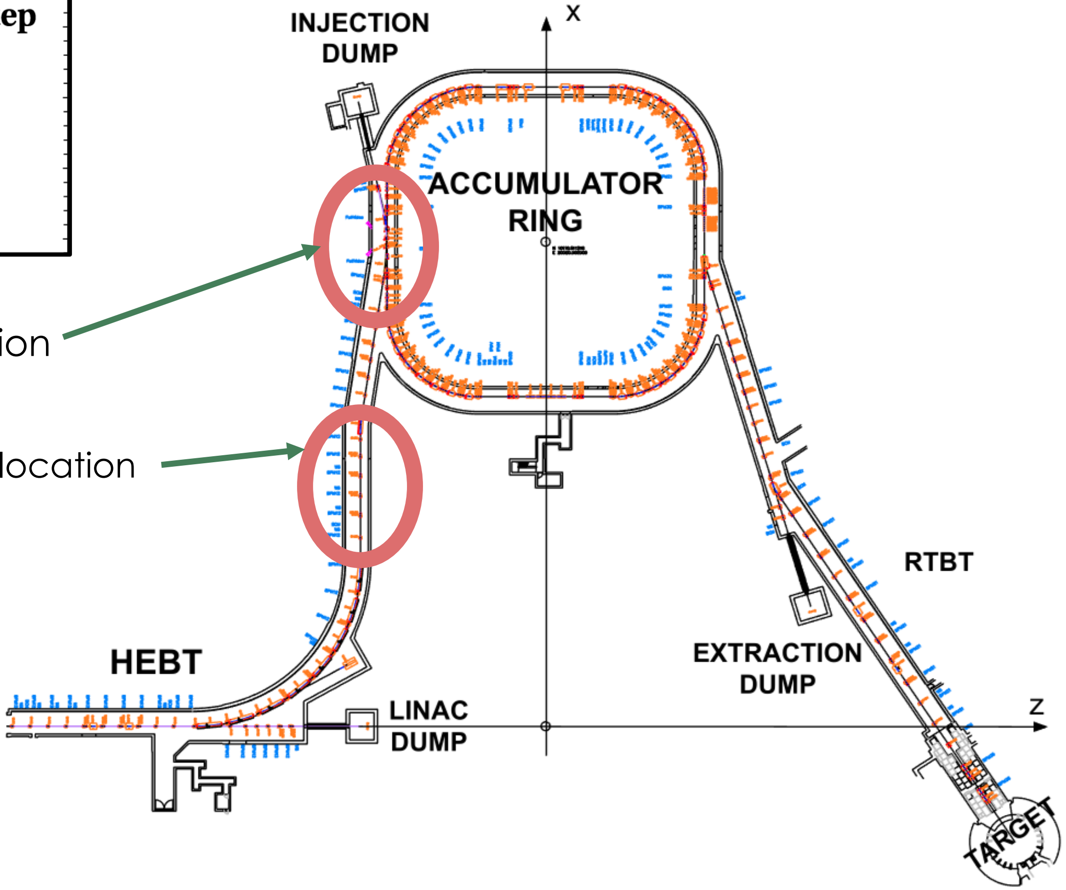
Schematics of hydrogen atom structure and mechanisms of different excitation schemes



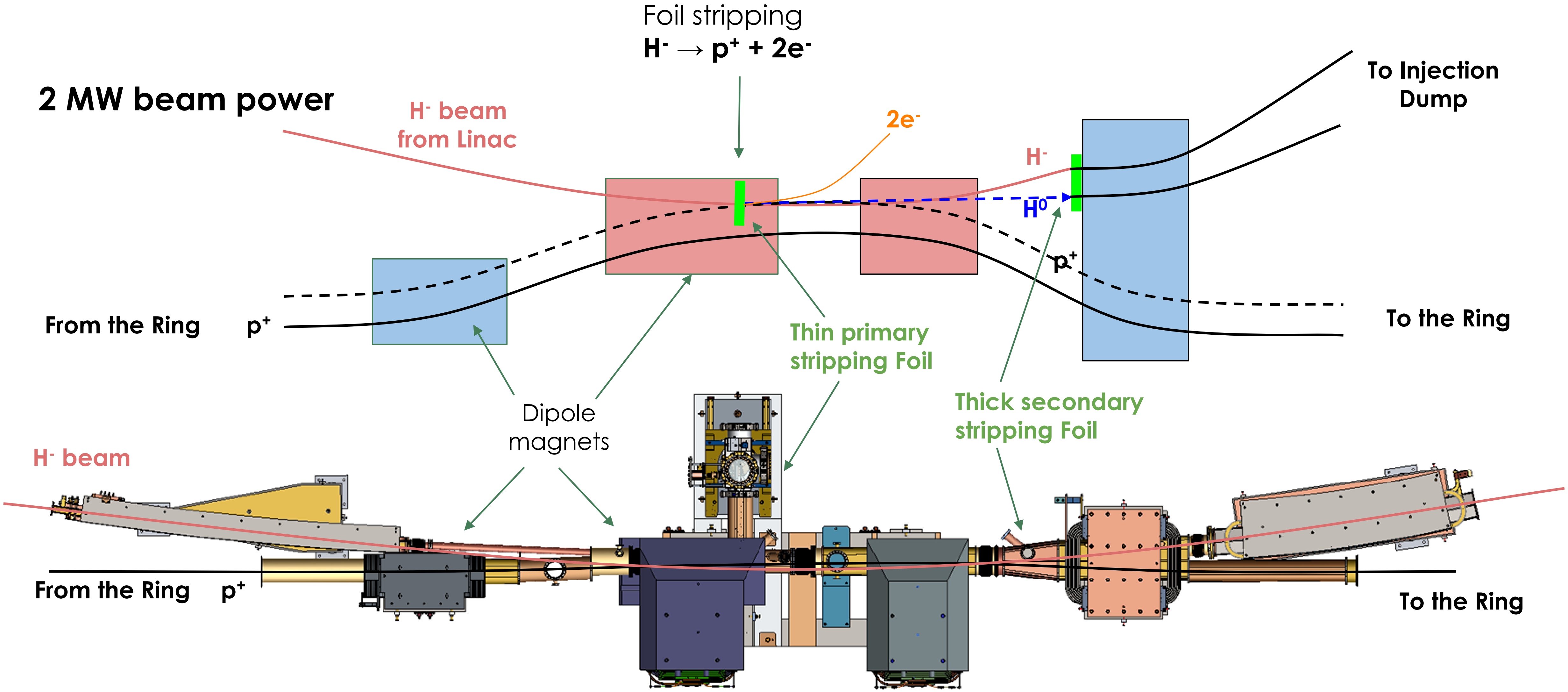
Real injection

Experiment location

1.3 GeV

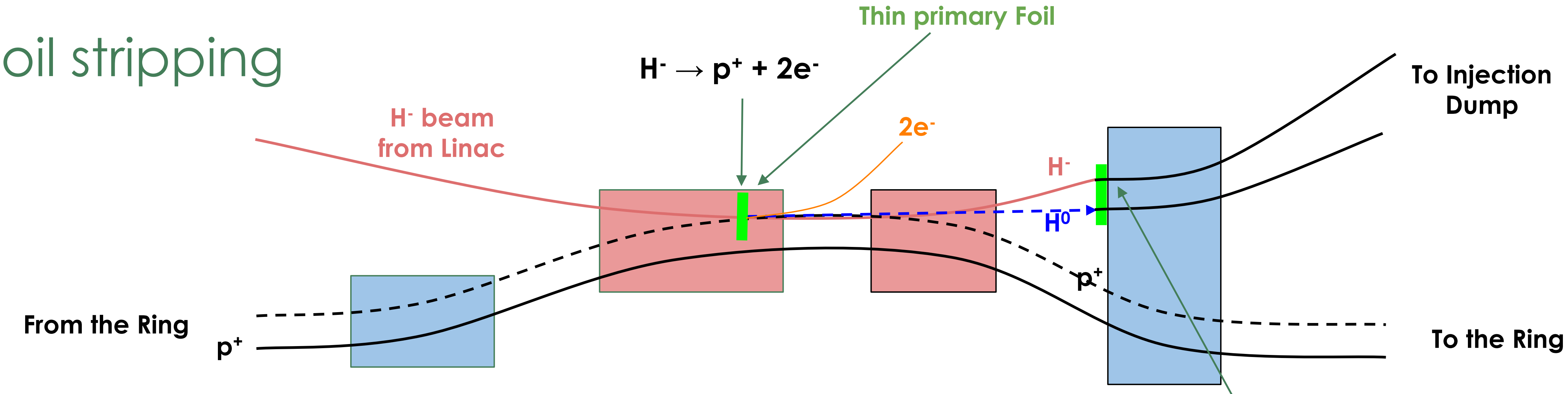


Foil assisted beam injection design for 1.3 GeV at the SNS. Future project.

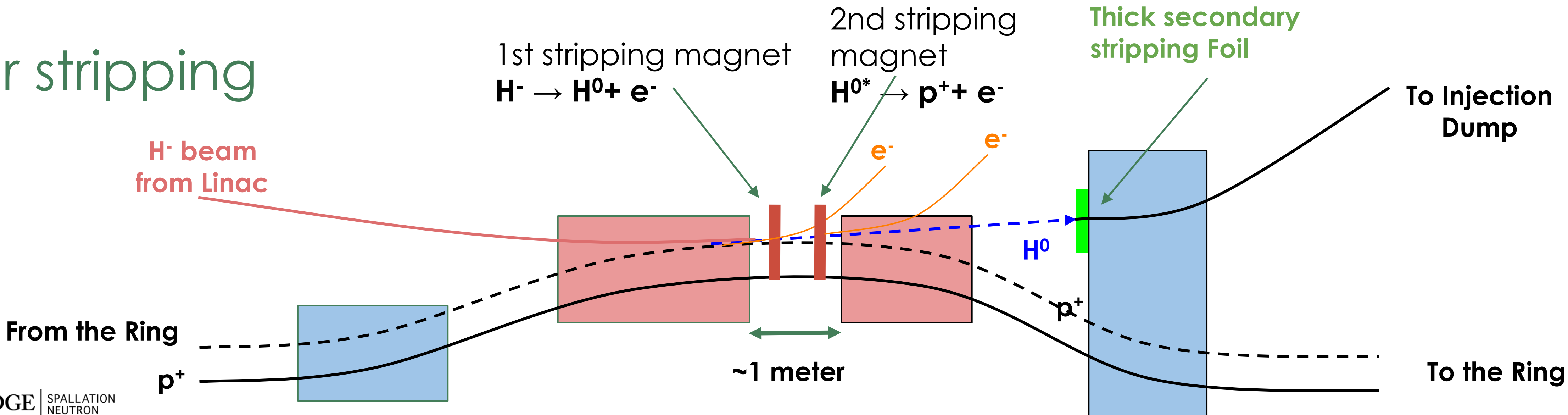


Foil injection vs LACE injection at the SNS

Foil stripping



Laser stripping



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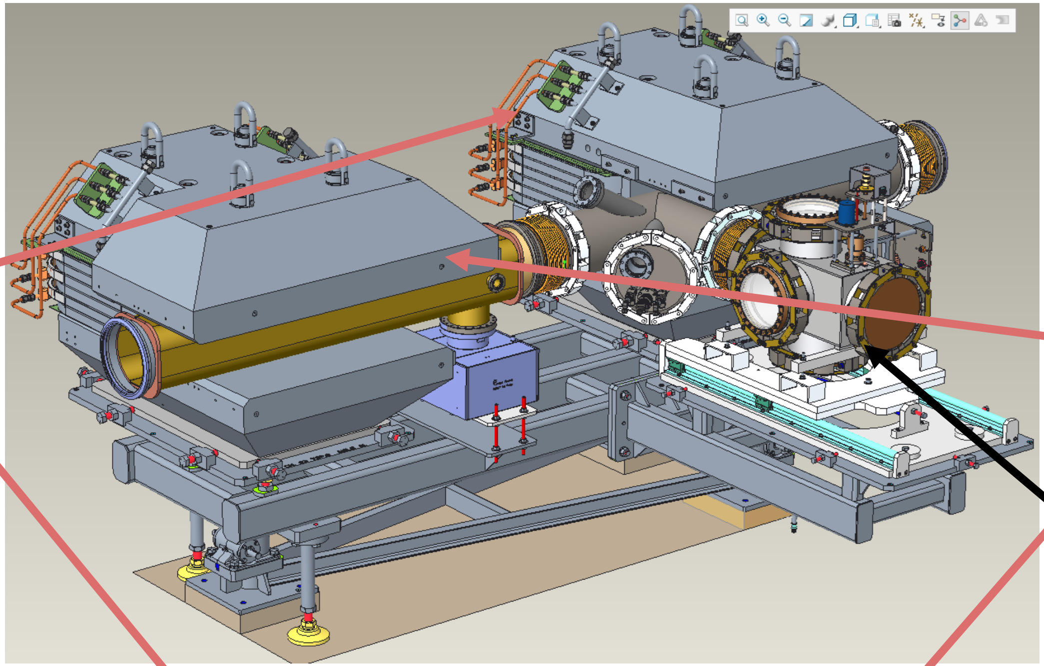
Laser strippng implementation into injection area of the Ring PPU power upgrade

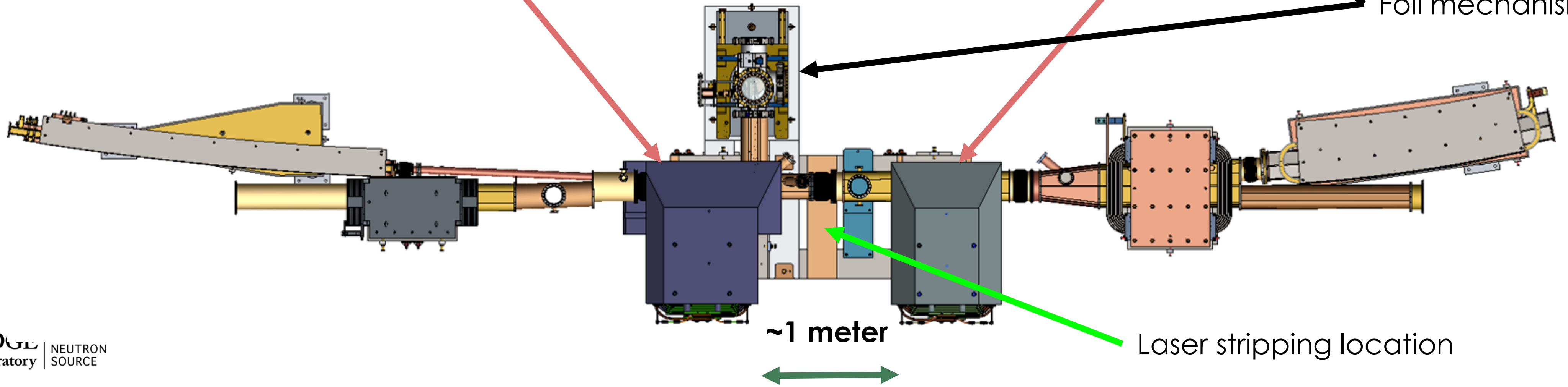


Drawings of the Injection area of the Ring.
Courtesy of A. Menshov

Dipole magnet (Chicane 02)

Dipole magnet (Chicane 03)

Foil mechanism

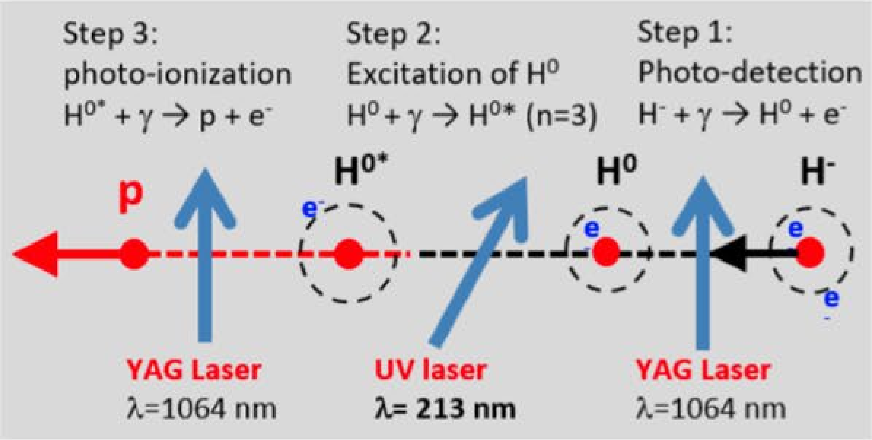


Laser stripping location

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

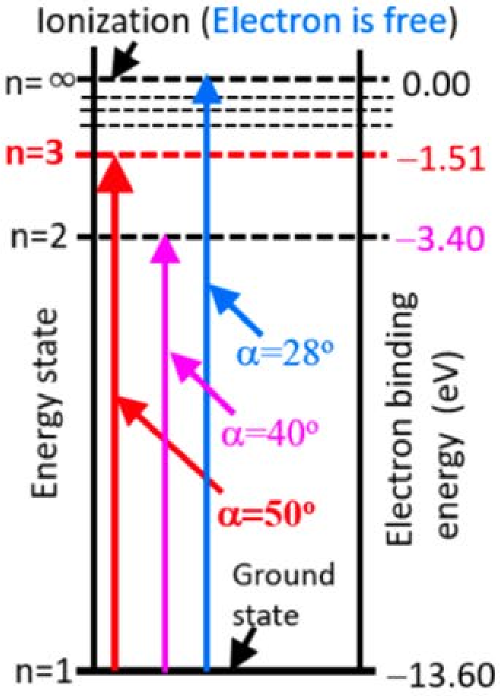
- ◆ Beam energy 0.4 GeV. → Needs much higher magnetic fields
- ◆ Angular spread due to a fringe field striiping is also concerned.

→ **Consider using only lasers.**



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.