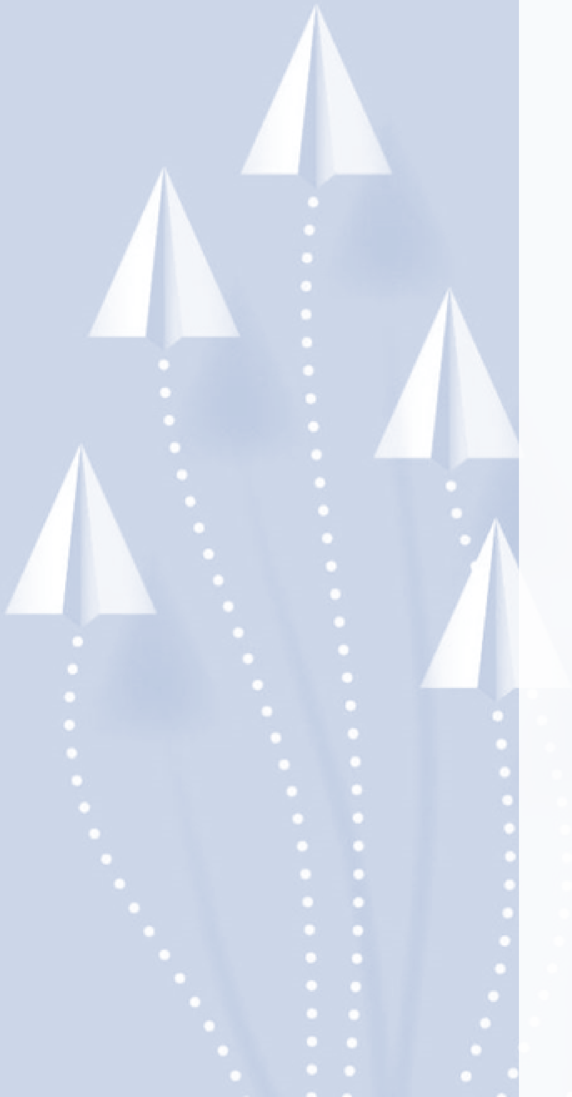
Stripping Extraction and Lorentz Dissociation

Hui Wen Koay

TRIUMF



Outlines

1. Introduction
2. Lorentz Dissociation
   - H^-
   - H_2^+
   - H_3^+
3. Conclusion and prospects

Introduction

Electrostatic extraction	Stripping extraction
H^+	$\mathrm{H}^-, \mathrm{H}_2^+, \mathrm{H}_3^+$ etc.
1. No magnetic field or energy limit from Lorentz dissociation 2. A large final turn separation and small beam size is needed 3. Activation from beam loss	1. Turn separation is not necessary 2. A limited magnetic field and maximum energy (to prevent a large Lorentz loss) 3. Regular replacement of extraction foil
1. PSI, iThemba, RIKEN etc. 2. Commercial cyclotrons: IBA-C235	1. TRIUMF, Deaδalus(plan) 2. Commercial cyclotrons: TR30, IBA-Cyclone 30 etc.

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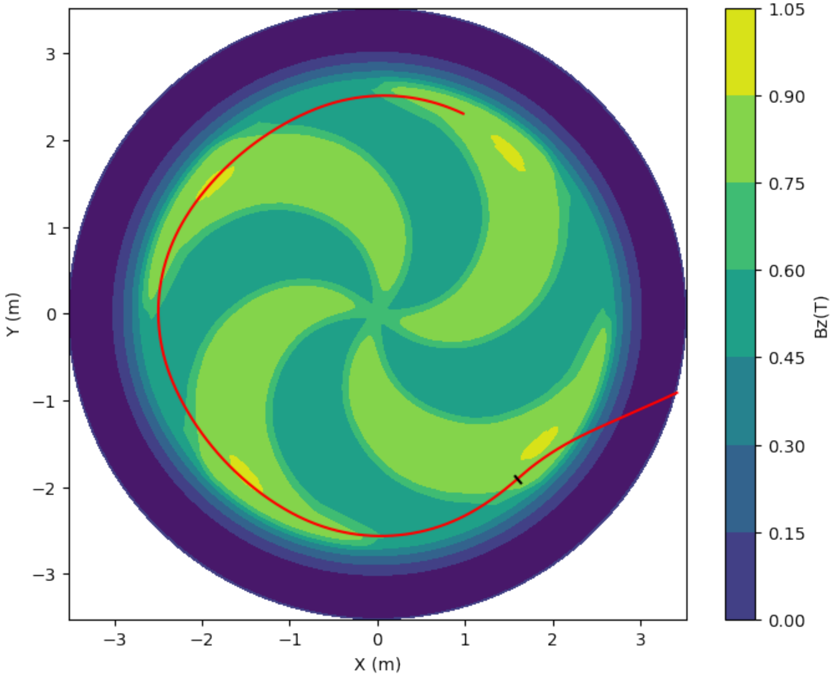
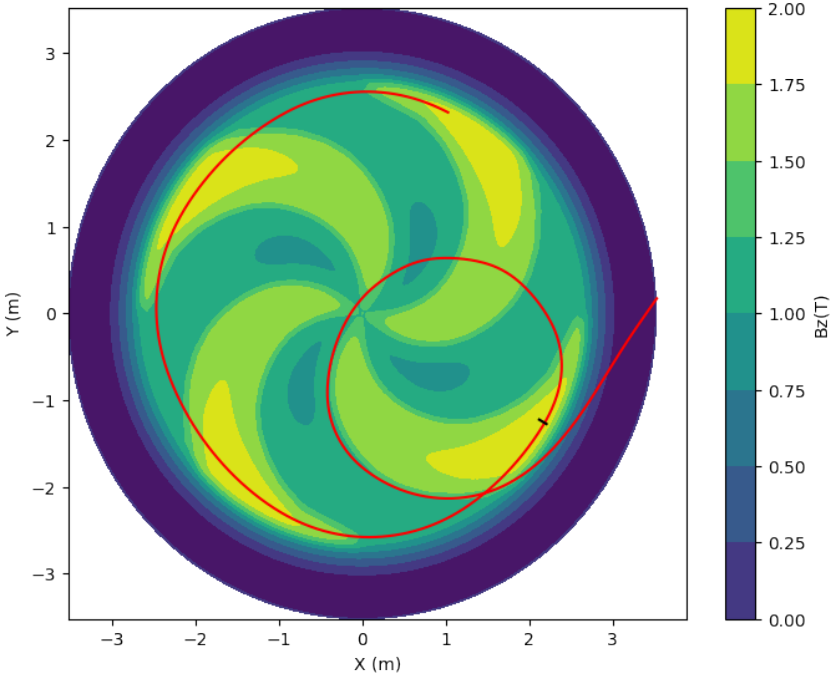
Stripping Extraction

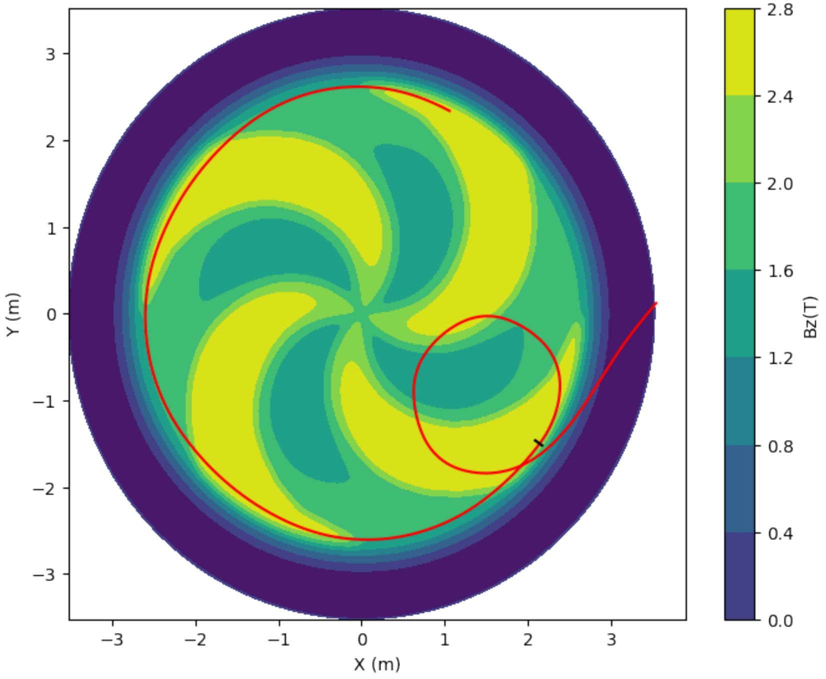
$$B\rho = m_0 c\gamma\beta \cong A\gamma\beta(3.1\ \mathrm{Tm})$$



H^-



H_2^+



H_3^+

What is Lorentz dissociation??

Equivalent Electric Field

$$\mathcal{E}_{\parallel} = E_{\parallel}$$

$$\mathcal{E}_{\perp} = \frac{(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})_{\perp}}{\sqrt{1-\beta^2}}$$

$$\boxed{\therefore \mathcal{E} = \gamma\beta c B_z \cong (3\mathrm{MV/cm})\gamma\beta(B_z/\mathrm{T})}$$

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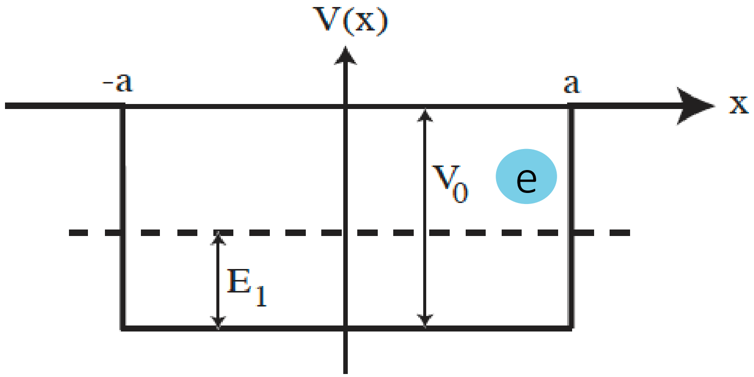
Lorentz dissociation is the dissociation of hydrogen ions due to the existence of equivalent electric field during acceleration

WKB Approximation



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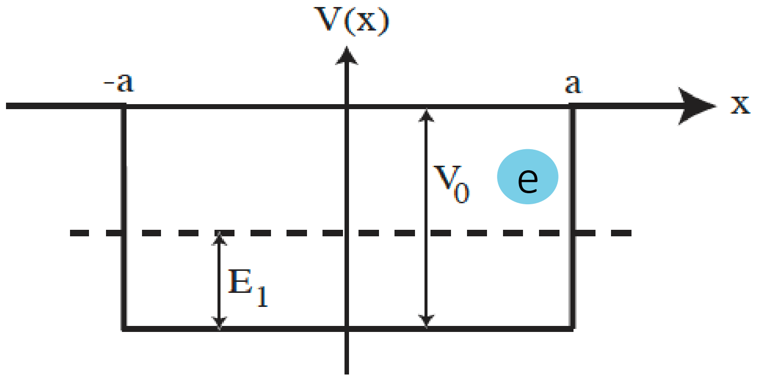

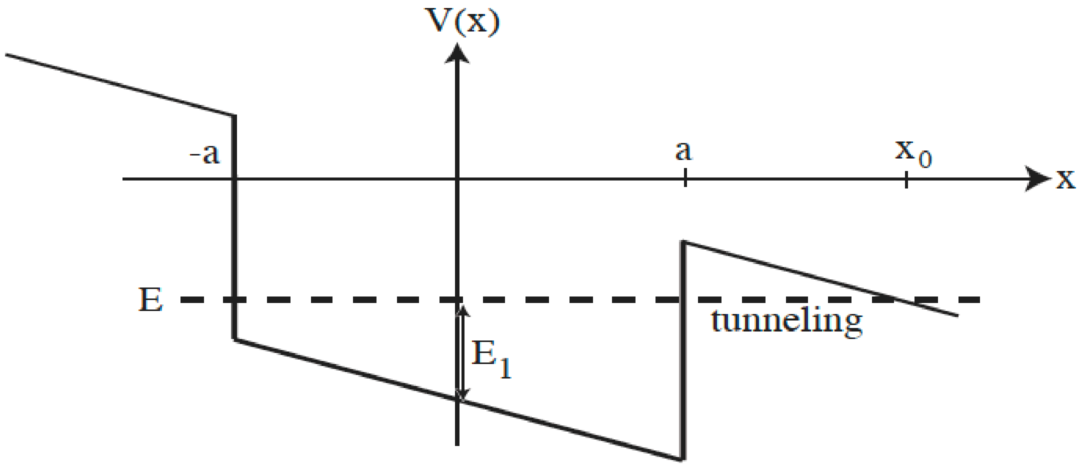

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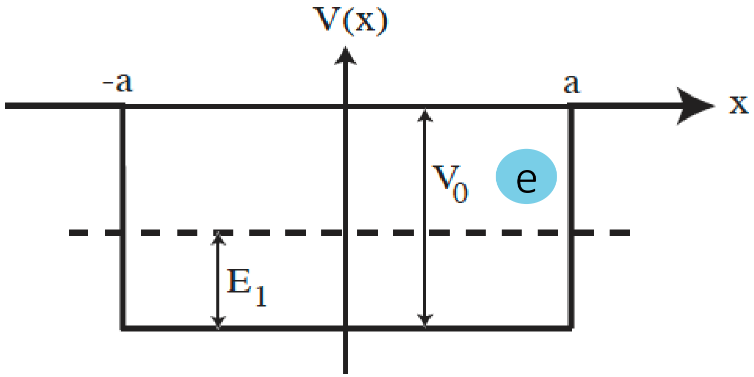

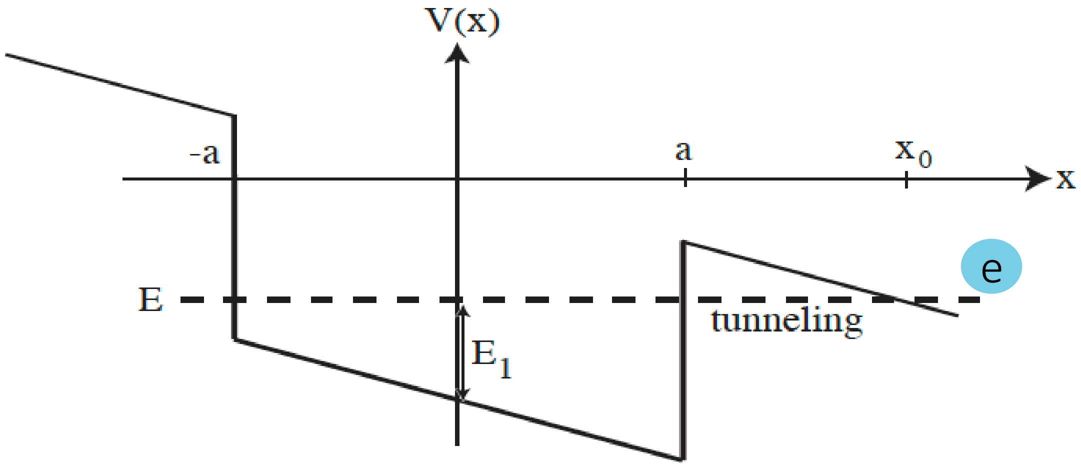

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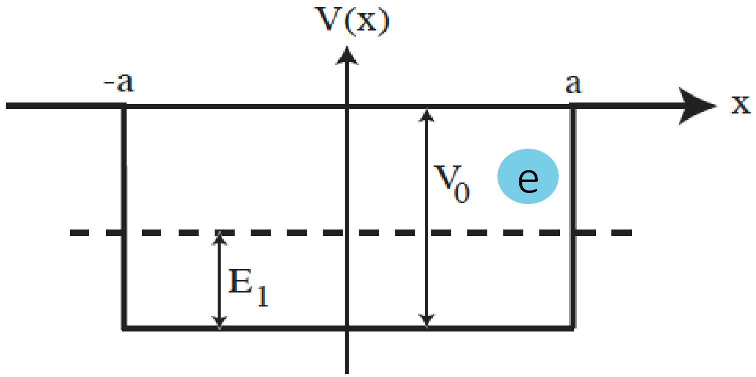
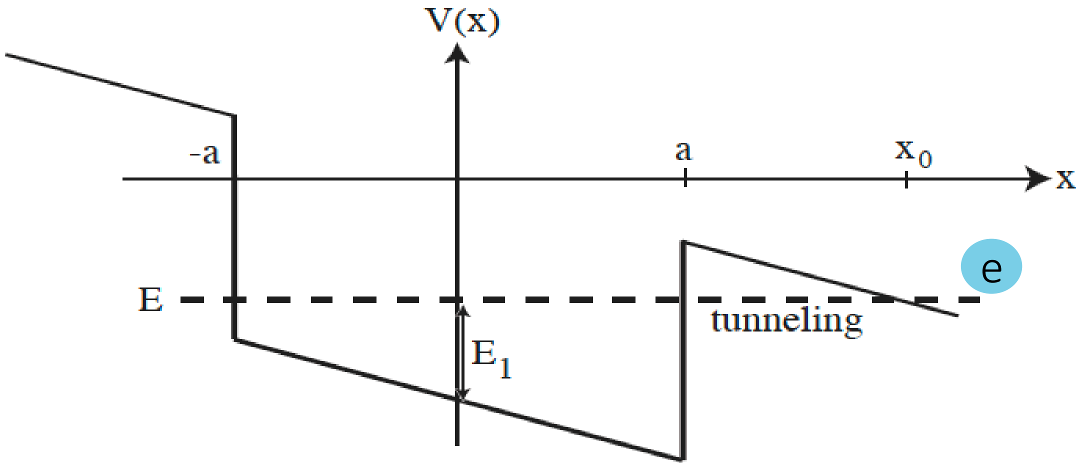




$$\frac{\hbar}{2m}\frac{d^2\Psi(x)}{dx^2} = [V(x,\mathcal{E}) - E]\Psi(x)$$

$$p(x,\mathcal{E}) = \sqrt{2m\,[V(x,\mathcal{E}) - E]}$$

$$\therefore \tau \propto e^{\int_a^{x_0} |p(x,\mathcal{E})|\, dx}$$

Lifetime of H$^-$

- Experimental lifetime of H$^-$, τ

$$\tau = \frac{A_1}{\mathcal{E}} \exp \frac{A_2}{\mathcal{E}}$$

$A_1 = 3.07 \times 10^{-6}$ Vs/m ;

$A_2 = 4.414 \times 10^{9}$ V/m (Keating et. al.)

- Integrating it throughout acceleration, the survival fraction f per distance (s) becomes:

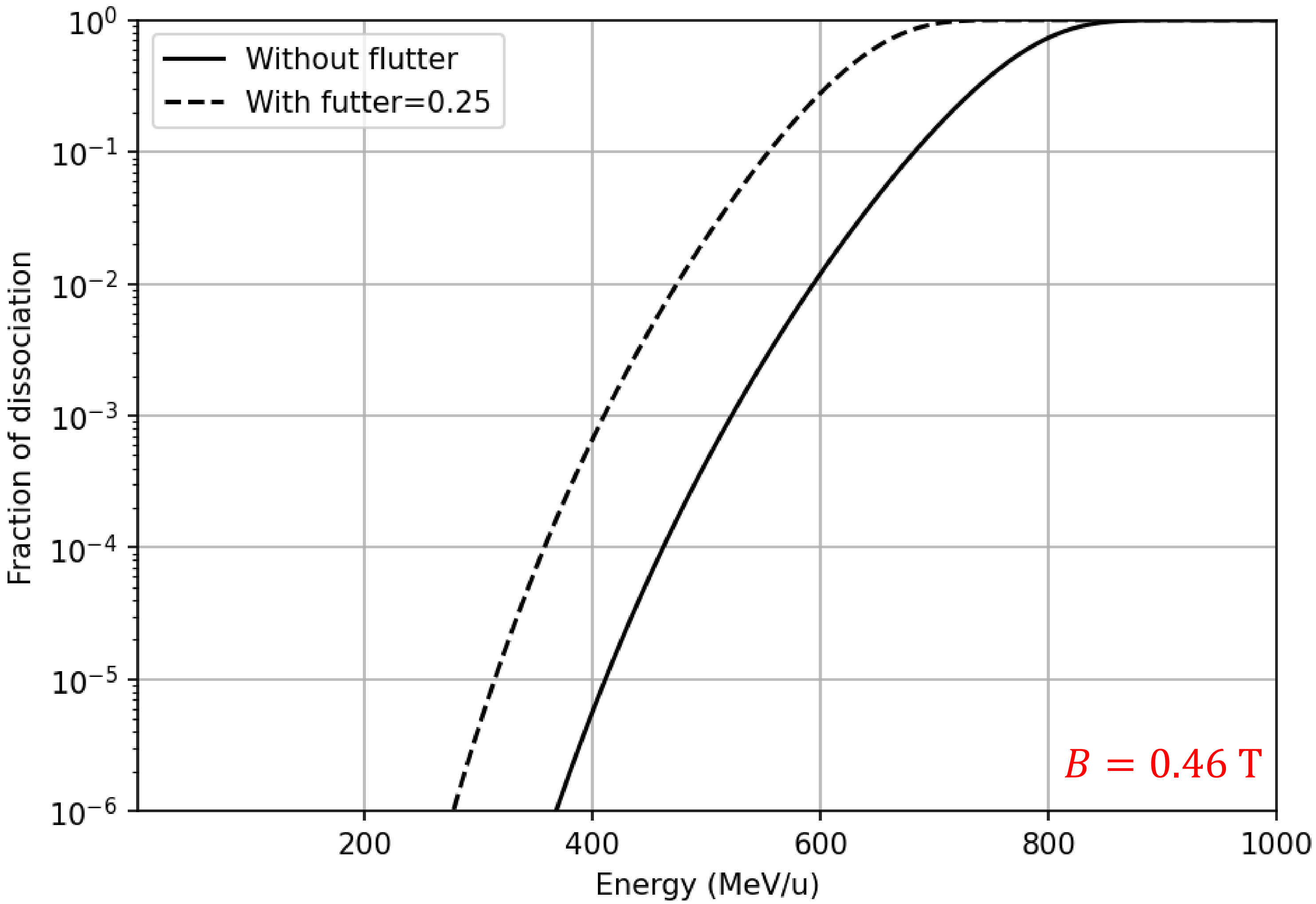
$$\frac{df}{ds} = -\frac{f}{\gamma\beta c\tau}$$

$$f = f_0 \exp -\frac{\Delta s}{\gamma\beta c\tau}$$

- The integrated fractional loss F throughout acceleration is

$$\therefore F = 1 - f$$

Example: Lorentz Dissociation of H$^-$



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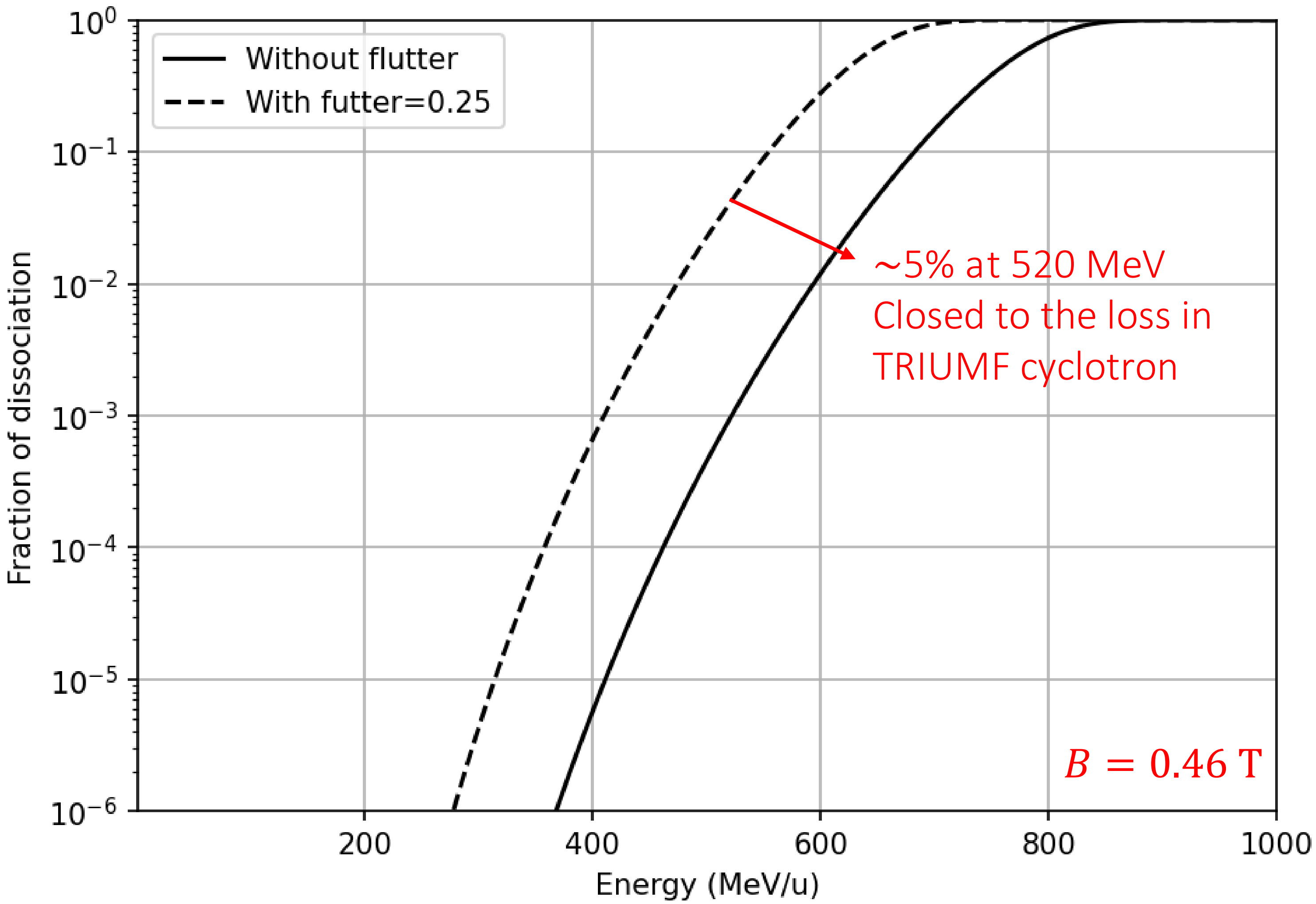


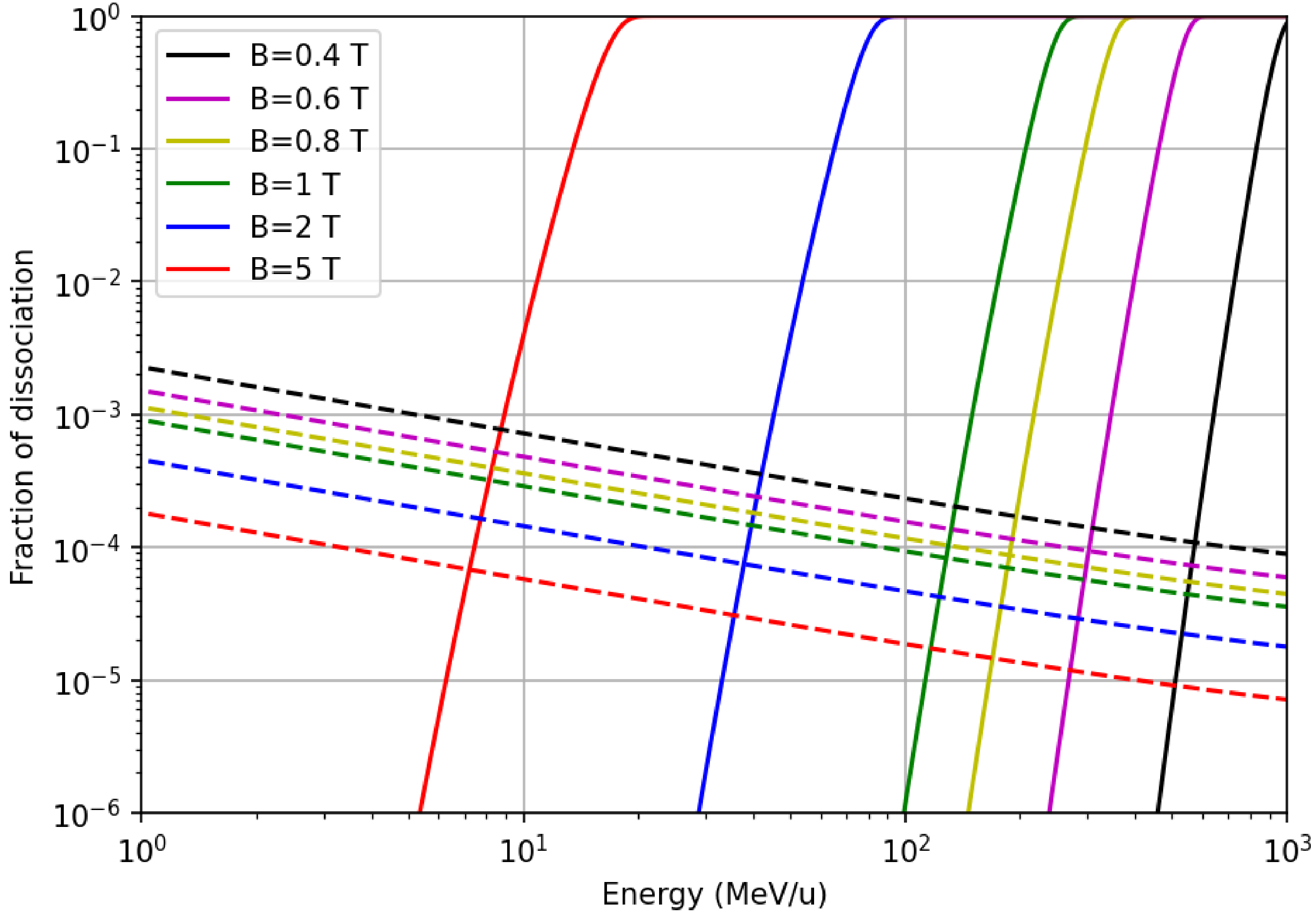
~5% at 520 MeV
Closed to the loss in TRIUMF cyclotron

$B = 0.46\ \mathrm{T}$

Power Loss Limit

- Power loss limit of a proton beam $\mathrm{P_m} \approx 1$ W/m for hands-on maintenance
- Losses are usually spread along the inside surface of the outer wall of the vacuum chamber.
- Taking the circumference of the vacuum wall to be $2\pi\hat{R}$, where the radius is the radius at the highest energy $\hat{R} = \frac{\hat{p}}{eB}$

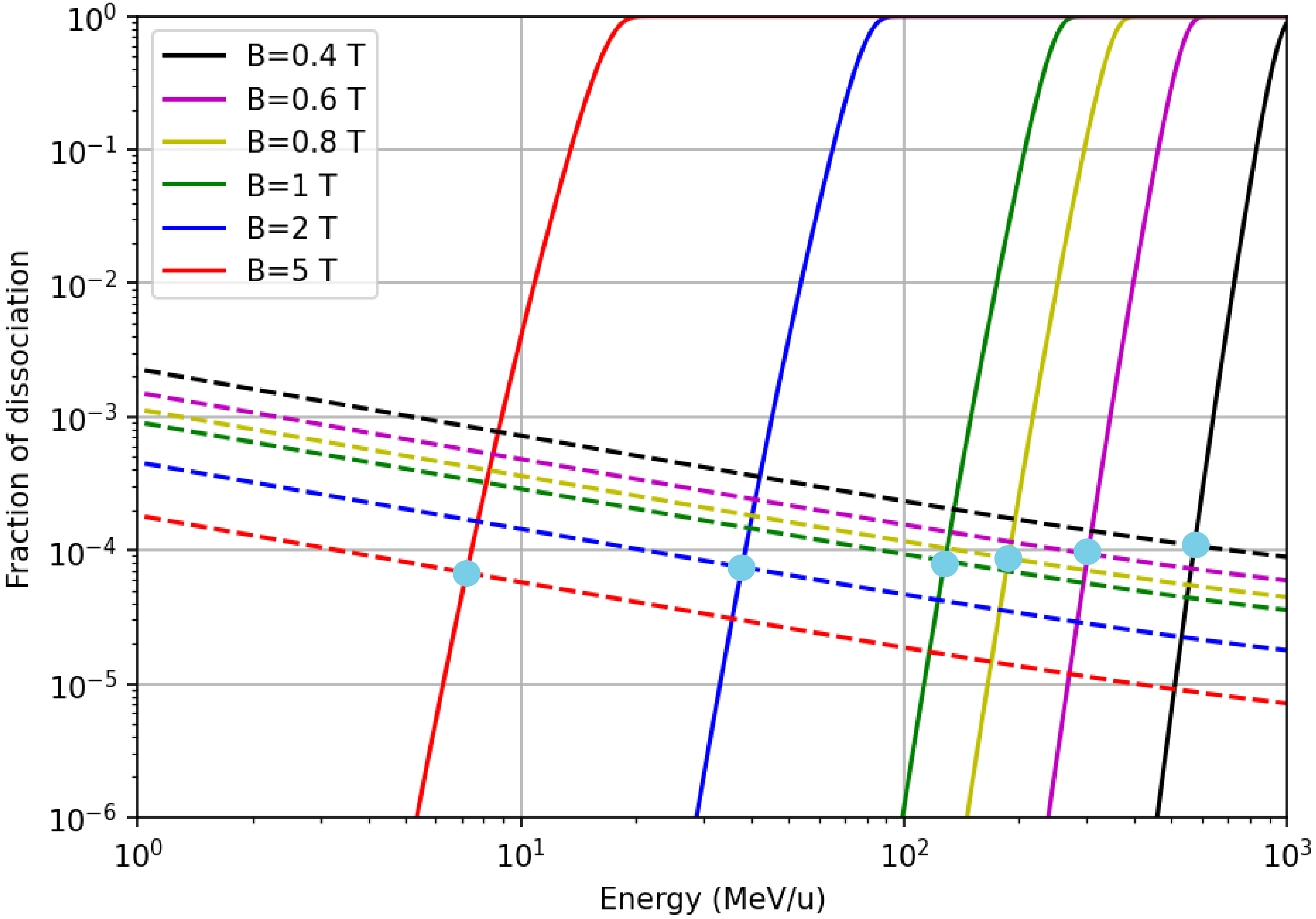
Lorentz Dissociation of H^-



Solid line: Lorentz dissociation at respective B

Dashed lines: Power loss limit at 1 mA

Lorentz Dissociation of H^-



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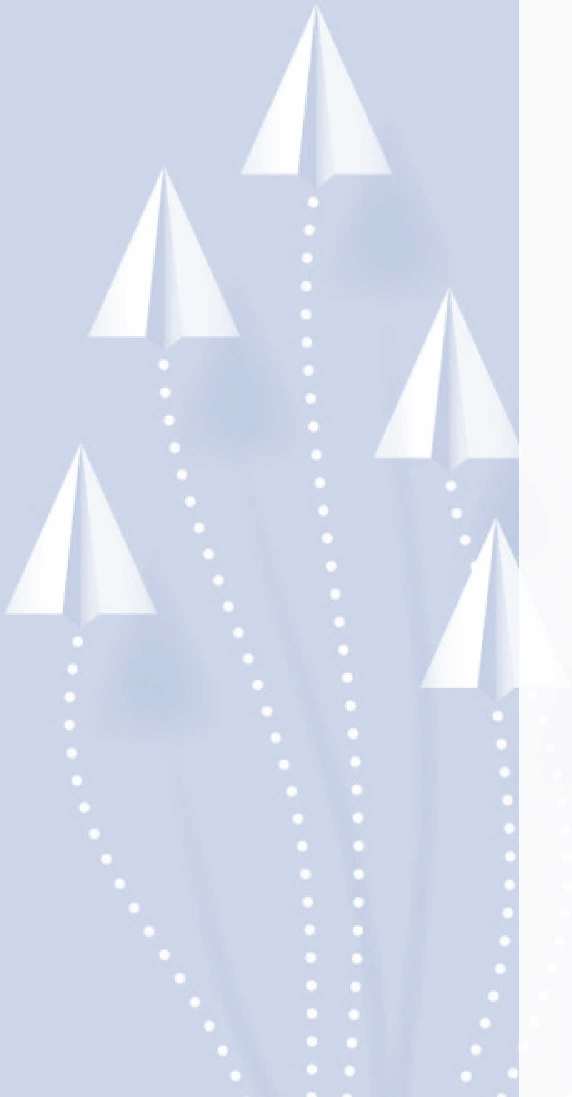
Blue dots: Max allowed energy for hands-on maintanence



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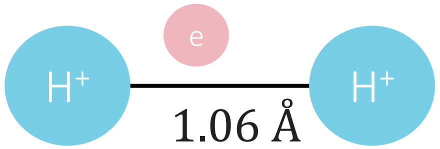
General Introduction of H_2^+

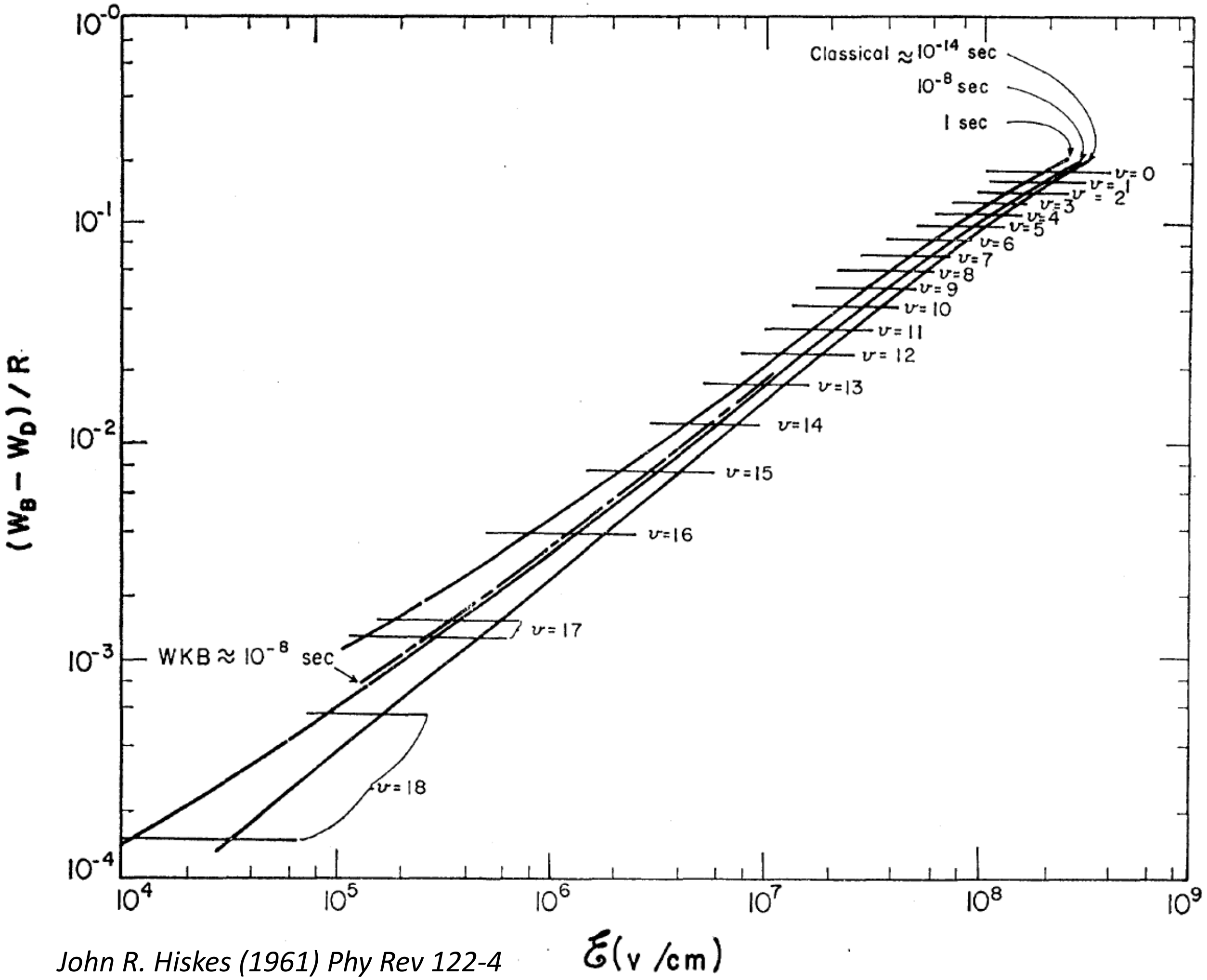
- Binding energy ~ 2.7 eV
- Internuclear distance ~ 1.06 Å
- Mainly pre-dissociate through

$$H_2^+ \rightarrow H^+ + H$$

- Lack of experimental verification of Lorentz loss of H_2^+



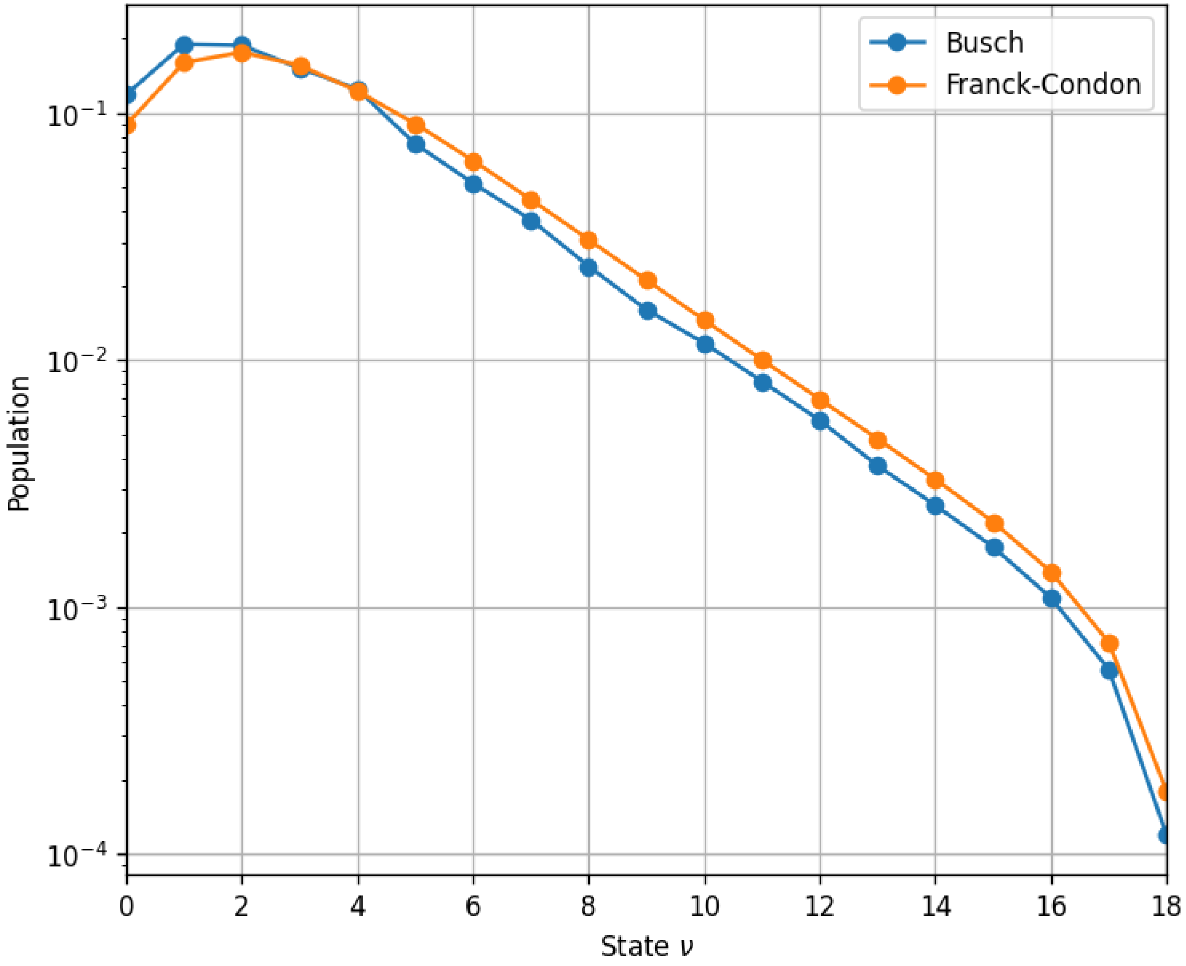
Theoretical lifetime of H_2^+



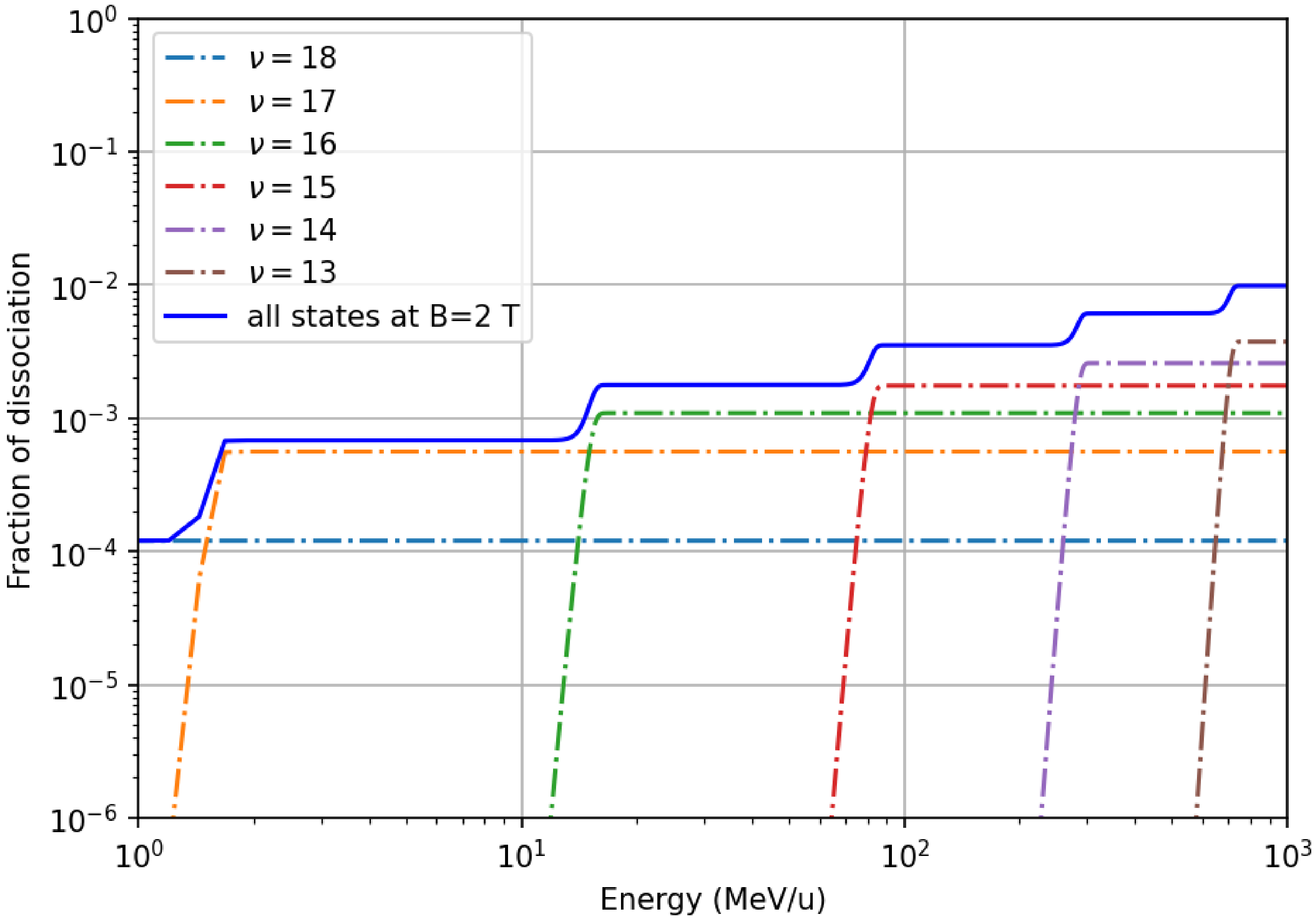
John R. Hiskes (1961) Phy Rev 122-4

*Only J=m=0 state is considered (no rotation)

State Population of H_2^+



Lorentz Dissociation of H_2^+



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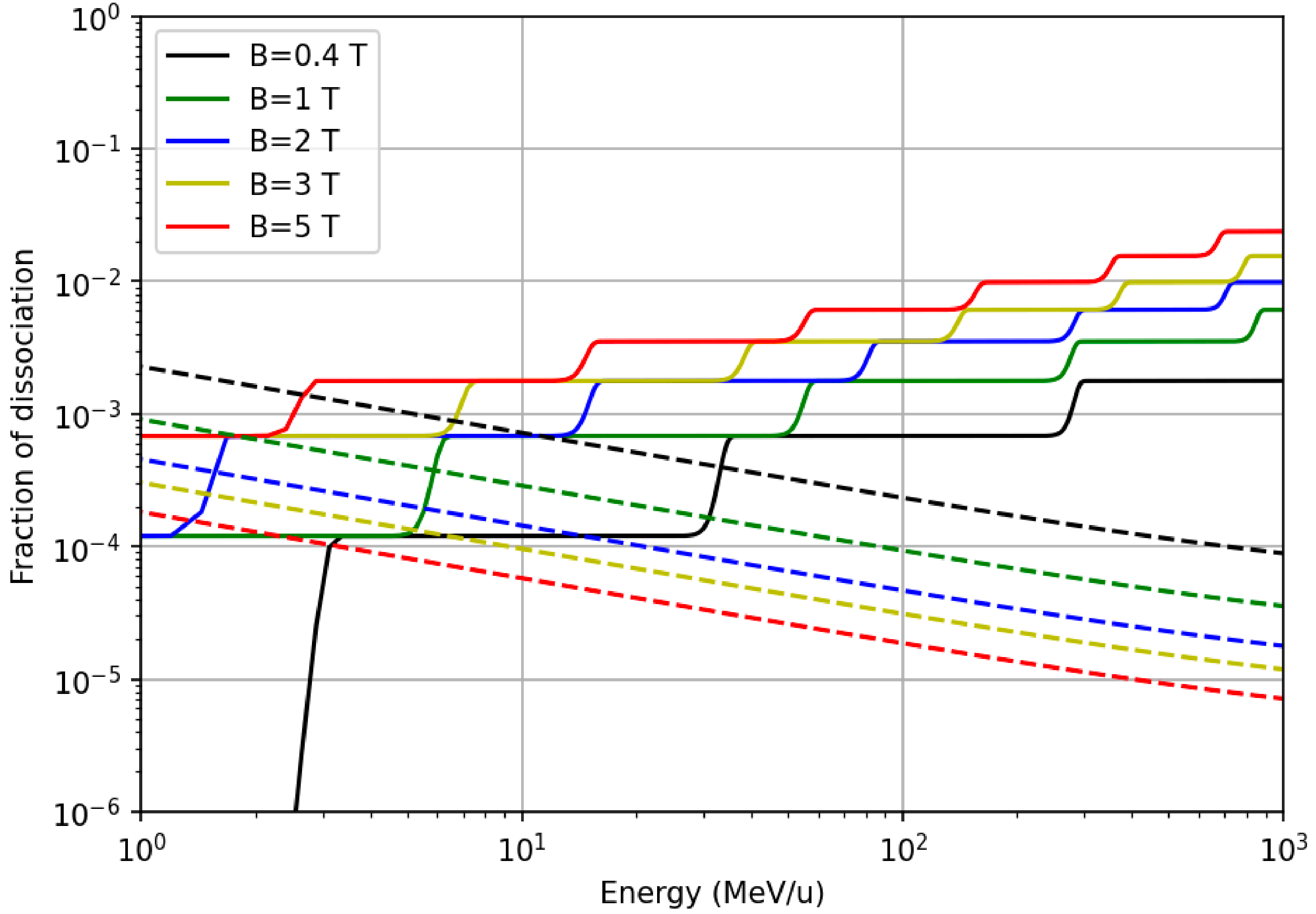

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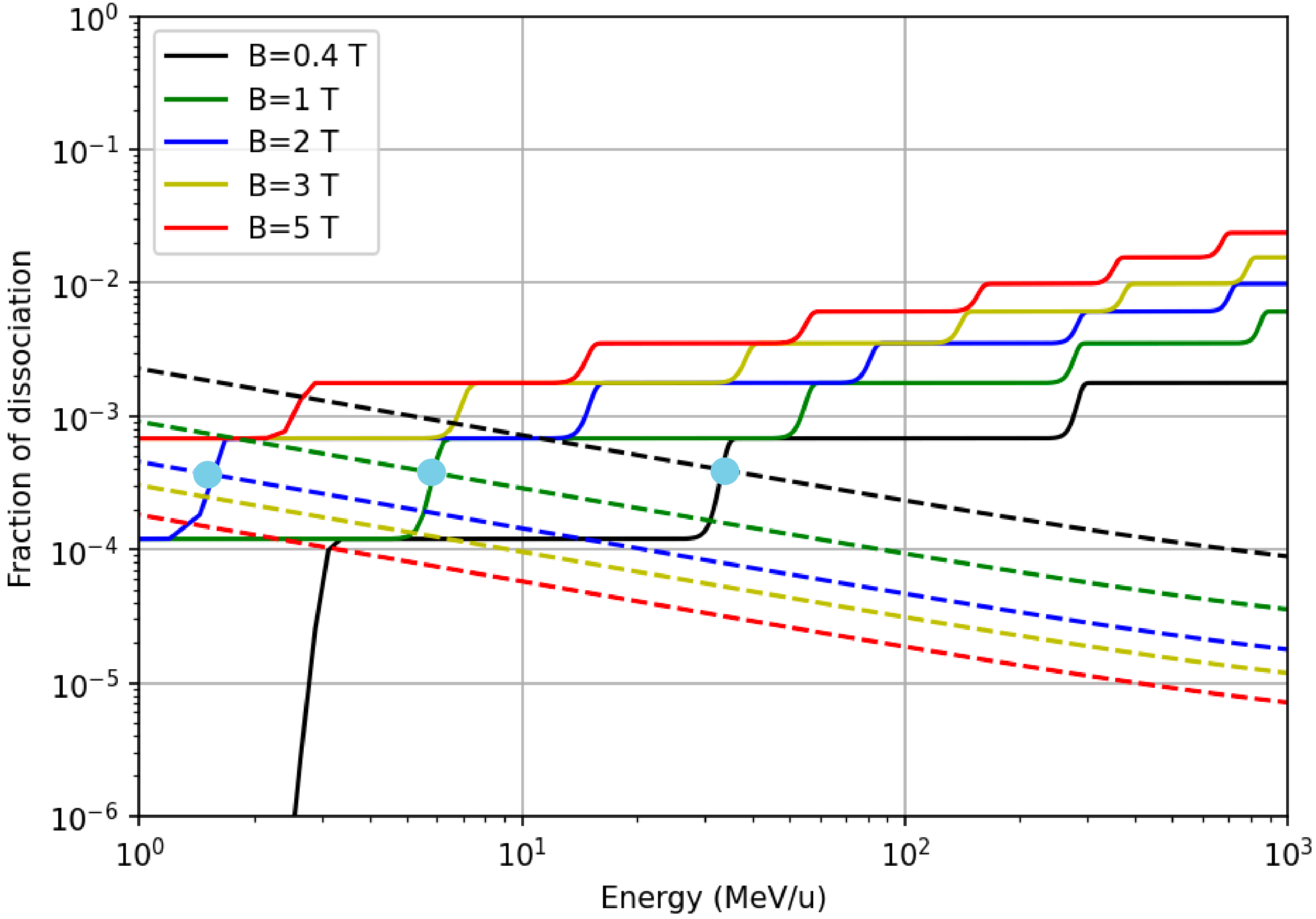
Lorentz Dissociation of H_2^+



Solid line: Lorentz dissociation at respective B

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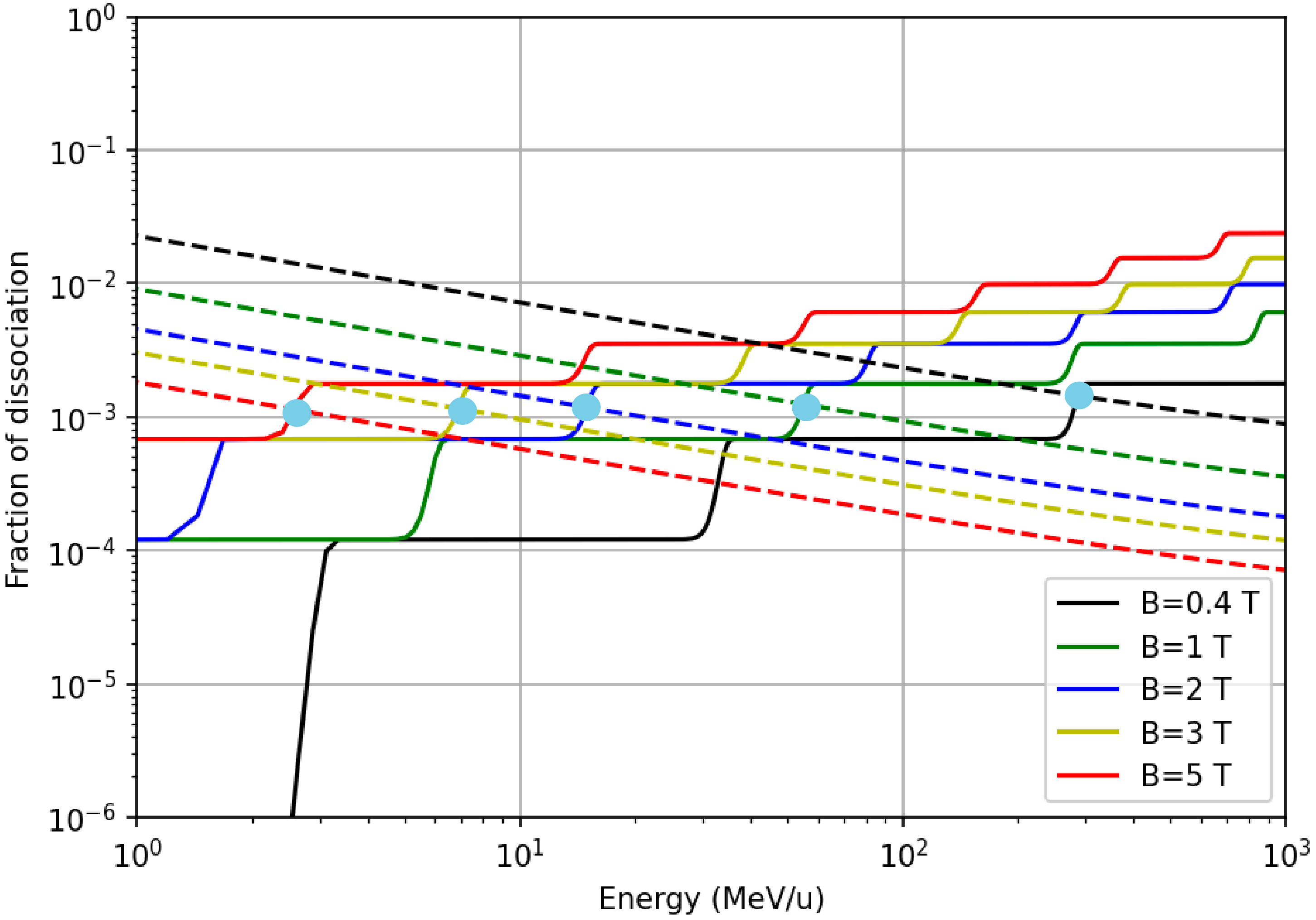
Blue dots: Max allowed energy for hands-on maintanence

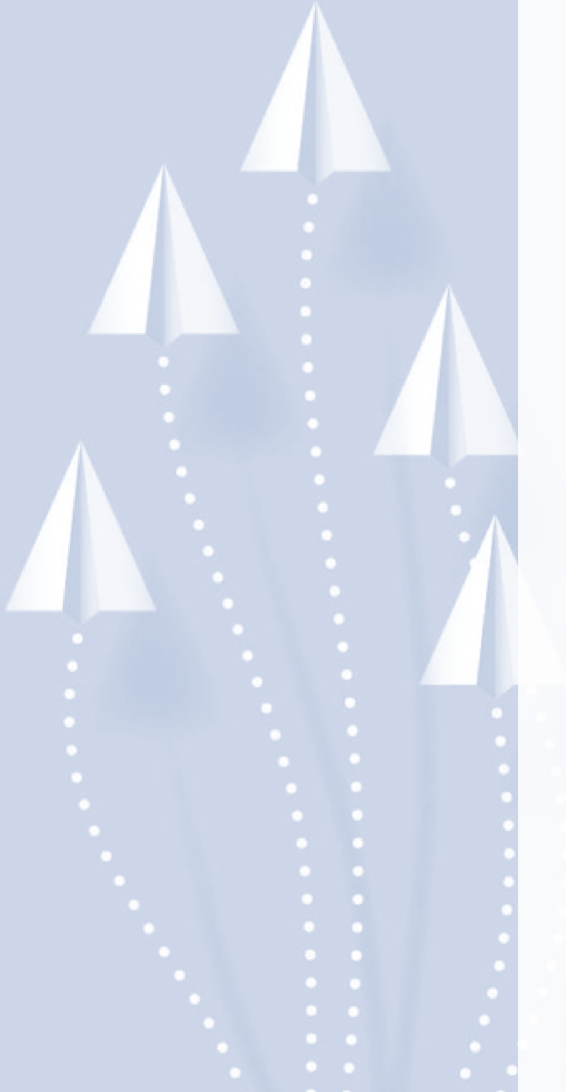
Lorentz Dissociation of H_2^+



Solid line: Lorentz dissociation at respective B

Dashed lines: Power loss limit at **100 µA**

Blue dots: Max allowed energy for hands-on maintanence



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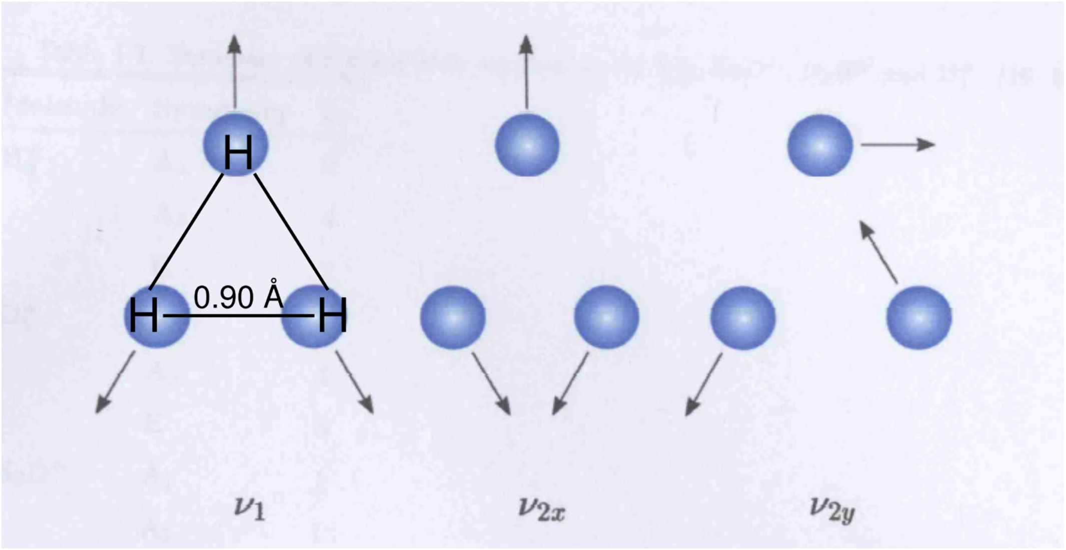
General Introduction of H_3^+

- First detected in 1911 by J. J. Thomson
- Binding energy ~ 4.5 eV (7 times of H^-)
- Internuclear distance ~ 0.90 Å
- Main structure is an equilateral triangle
- No permanent dipole moment
- Formed from the exothermic reaction

$$H_2^+ + H_2 \rightarrow H_3^+ + H\ (\text{exo} \sim 1.7\ \text{eV})$$

2 Vibrational modes



(1) Breathing (symmetry) mode (A_1, A_2)

(2) Bending mode - Doubly degenerate (E)

Evidence: Lorentz Dissociation of H_3^+ at DCX-1

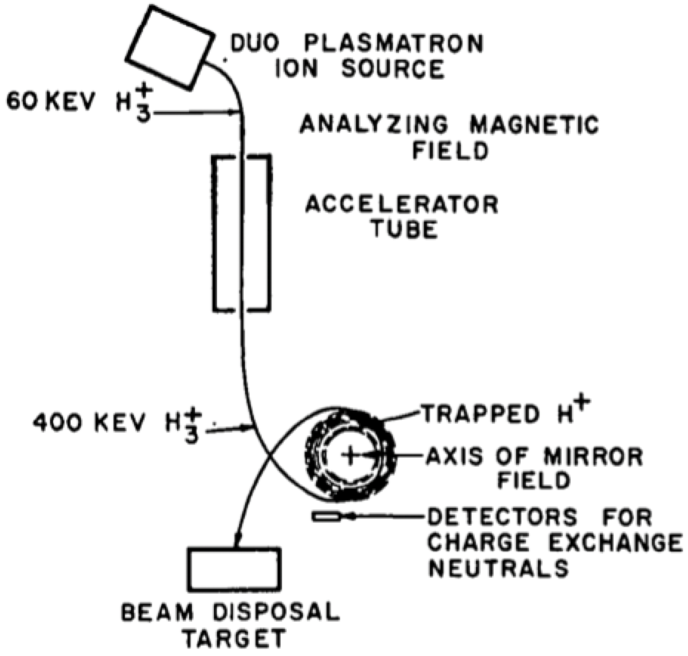
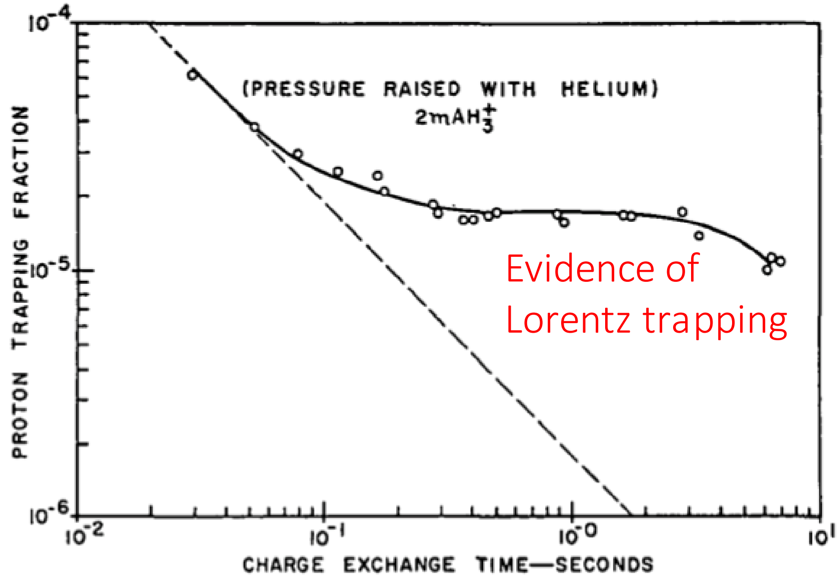


Figure 1 Injection system for Lorentz dissociation of H_3^+.

G.R. Haste *et al* 1965 *Nucl. Fusion* **5** 164

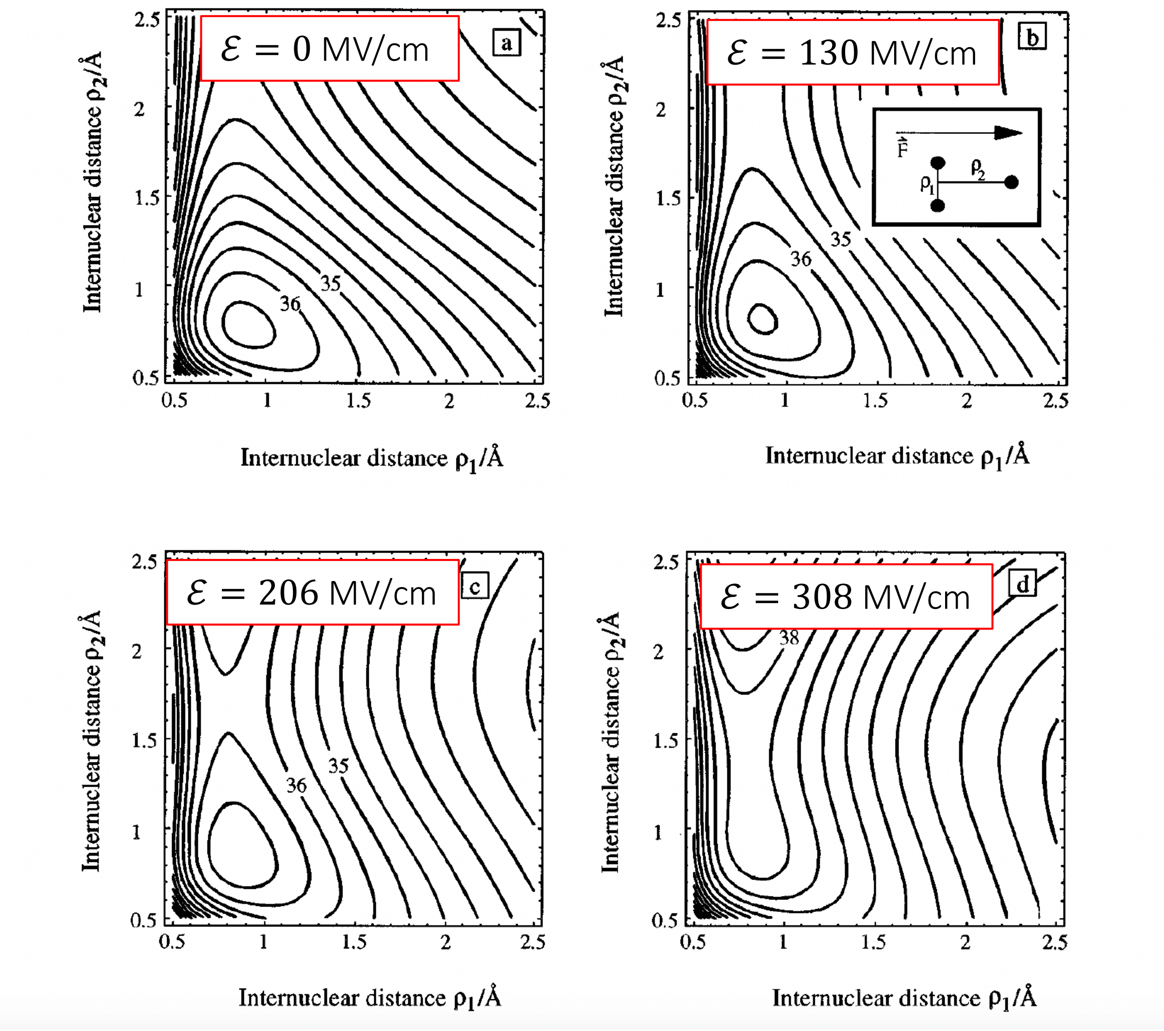


Evidence of Lorentz trapping

Figure 2 Proton trapping fraction for H_3^+ injection vs charge exchange time.

Equivalent electric field within the plasma region was 33 to 48 kV/cm

Potential Energy Surface



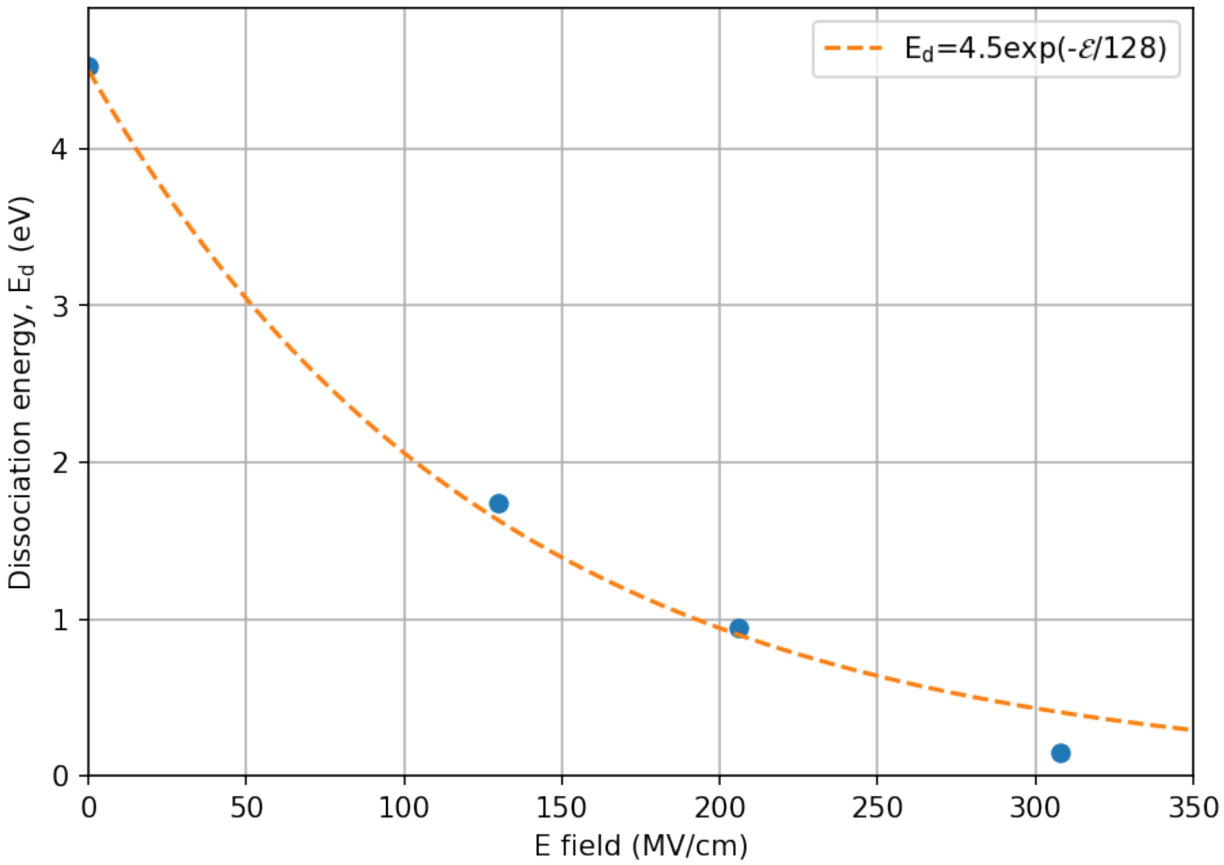
Reckzügel et. Al. (1995) J. Chem. Phys., Vol. 102, No. 19

Dissociation Energy of H_3^+

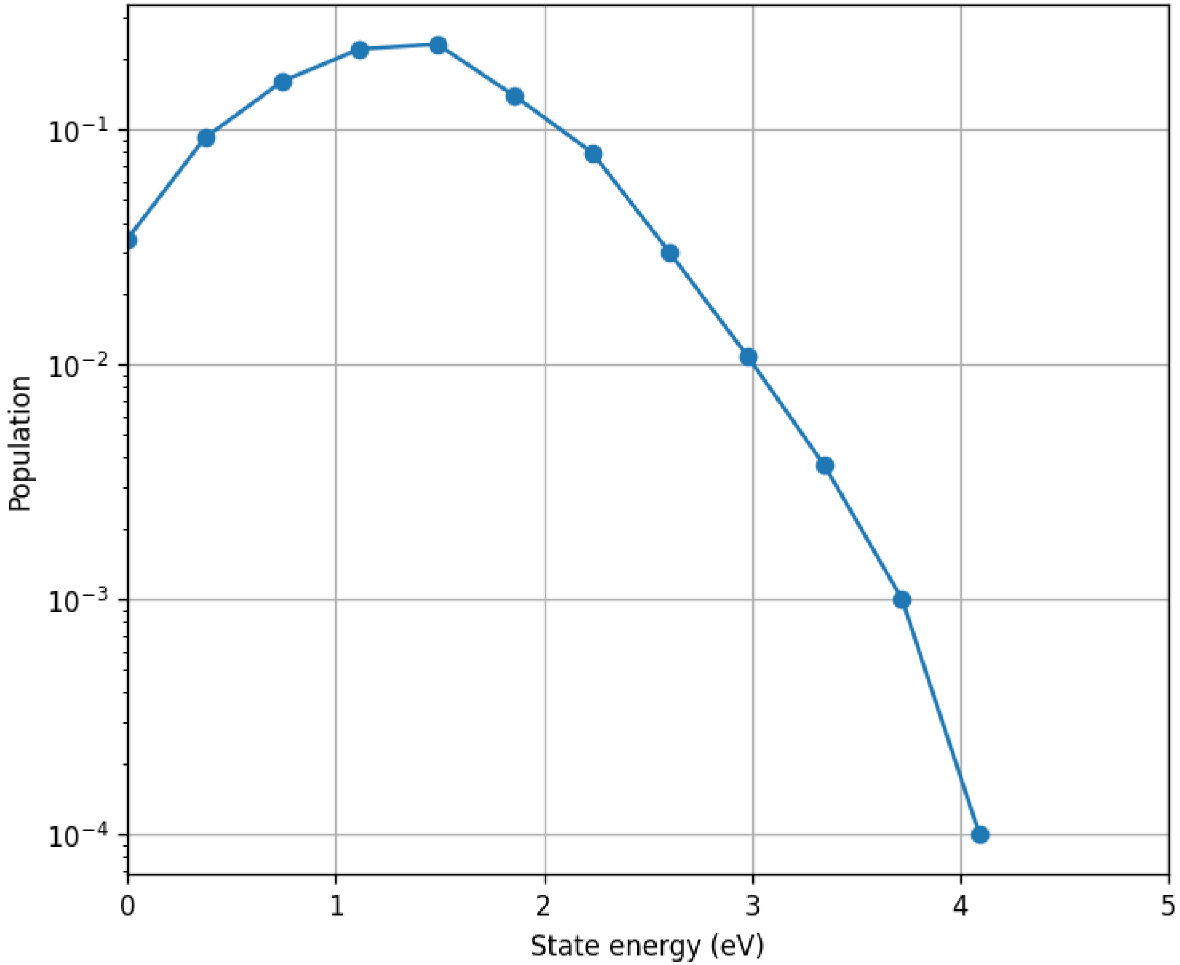
- Fitting the dissociation energy from previous graph:

$$E_d = 4.5 \exp - \frac{\mathcal{E}}{128}$$

- Example: At 1 GeV/u in a 3 T field, $\mathcal{E} \sim 16.3$ MV/cm, $E_d \sim 4.0$ eV. Any excited state with energy greater than 4 eV will dissociate



State population of H_3^+



V.G. Anicich et. al. International Journal of Mass Spectrometry and Ion Processes, 55(2):189–215, 1984

Estimated Lorentz Dissociation of H_3^+

Assume the Hamiltonian is similar to that of the heteronuclear molecules by Hiskes et. al:

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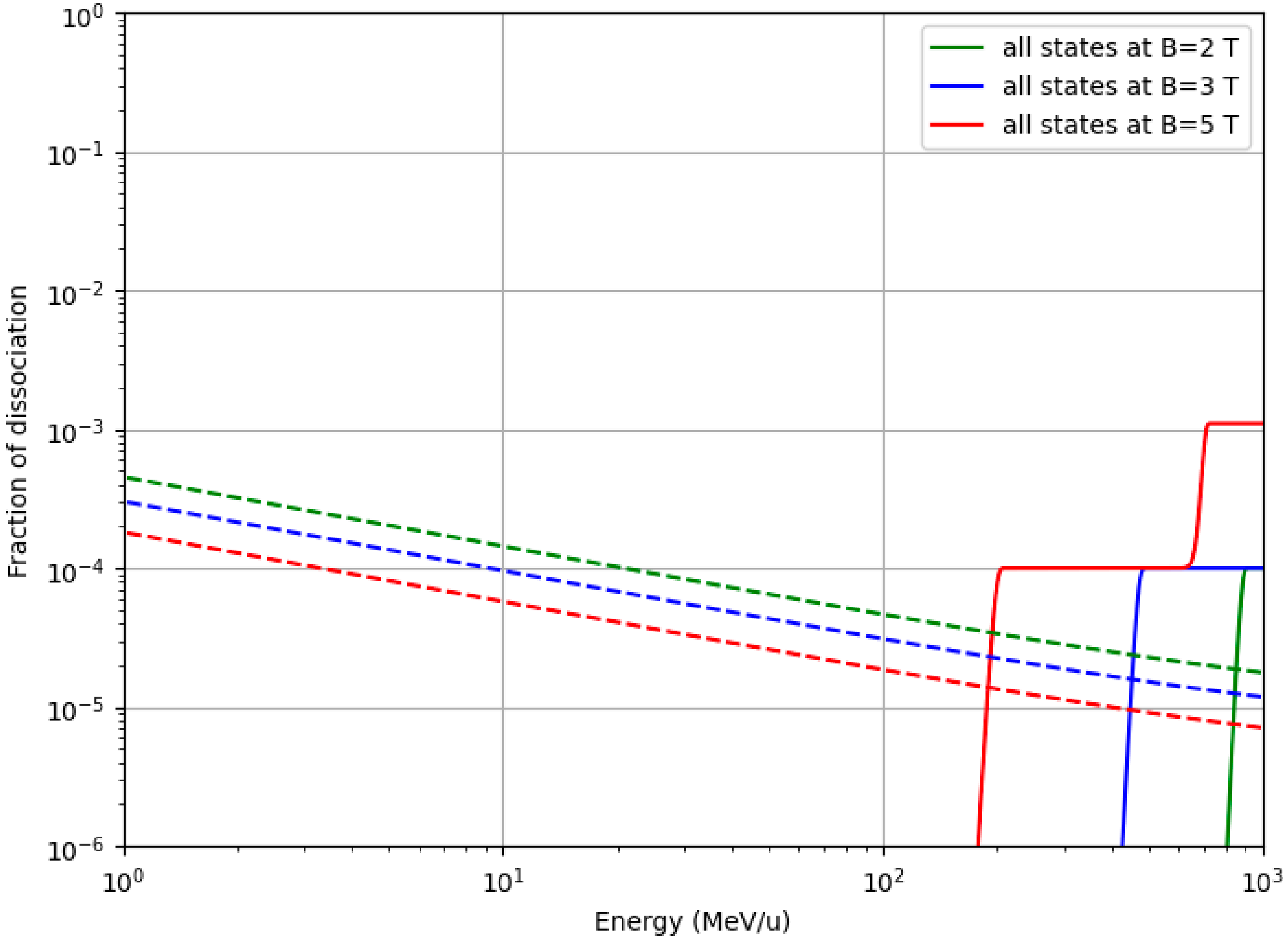

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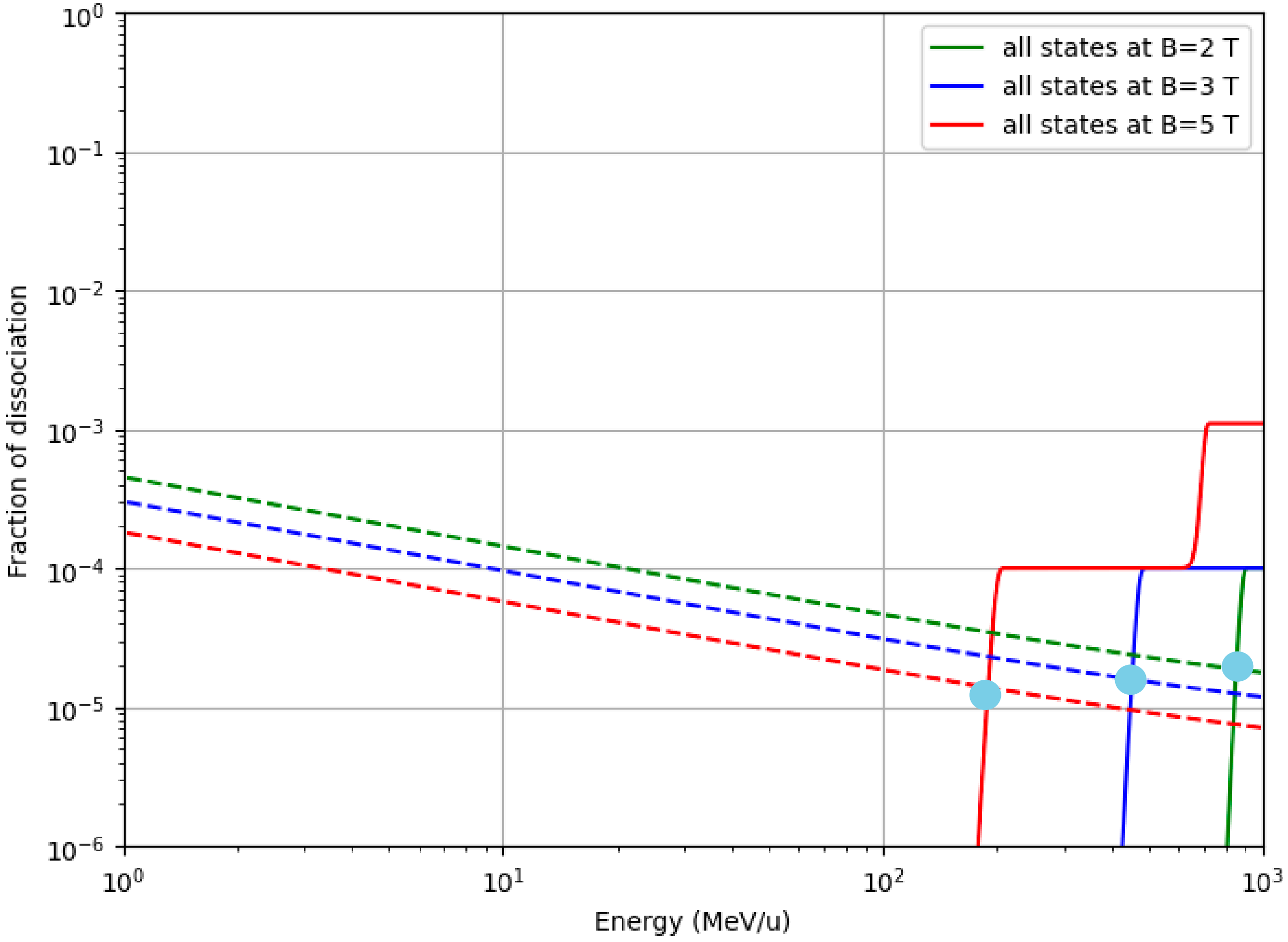

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Conclusions

- Overall, the order of stability goes from $H_3^+ > H_2^+ > H^-$ at energy greater than 100 MeV/u.
- At low energy < 100 MeV/u, H- is the most cost efficient; while H3+ is the most stable at energy higher than 100 MeV/u.
- In general, a larger machine is more conducive for stripping extraction at a high power due to a lower Lorentz dissociation at a lower B and a larger power loss permissible for hands-on maintenance.
- Initial state distribution from the ion source is the game-changer: important to be able to tune it accordingly.

Prospects

Experimental verification is NECESSARY, especially for H_2^+ and H_3^+, as many practical factors have been omitted.

Thank you!