Laser Notcher for PIP2IT and Mu2eII

Monica Tecchio,
Myron Campbell, Yongyi Wu

University of Michigan

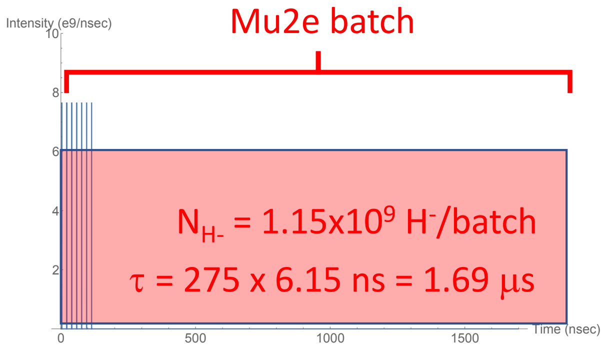
Mu2e II Workshop at Northwestern University
Aug. 29, 2018

PIP2IT and Mu2e-II Beam parameters

(based on Paul Derwent’s talk at last Mu2Ie Collaboration Meeting of Mar. 2, 2018)

- PIP-II can generate pulsed 800 MeV H^- beam for Mu2e-II, with extinction requirement of 10^{-11}
- PIP-II Injector Test (PIP2IT) generates 25 MeV H- beam after Warm Front End (where bunch-by-bunch selection at 2MeV happens) -> can be used to measure intrinsic extinction of chopping system.

- <u>Mu2eII beam time-structure</u>
    - 6.15385 nsec bunch
    - populate 1 every 3 bunches for 100 ns: 1.15×10^9 H-
    - add 259 empty bunches for a total 275 bunches (or 1.69 μs)
    - batch frequency: 591 kHz



Mu2e batch

$N_{H-} = 1.15 \times 10^9$ H^-/batch

$\tau = 275 \times 6.15$ ns $= 1.69$ μs

”Continuous” beam of 1.15×10^9 H^-/batch at 591 kHz $\Longrightarrow$ rate $R_{H-} = 6.8 \times 10^{14}$ H^-/s

To measure an extinction requirement of 10^{-11}

we want to be sensitive to $n^{ext} = R_{H-} \times 10^{-11} = 6.8 \times 10^{3}$ H^-/s = 4.4×10^{-5} H^-/bunch

<u>Assuming we can observe the single H^- in a bunch at a rate of once per batch</u>

- 591 kHz batches x 4.4×10^{-5} H^-/bunch = 26 H^-/s $\Longrightarrow$ 15600 H^-/600 s

  $\Longrightarrow$ 0.8% extinction rate measurement in 10' assuming 100% efficiency for single observation

- if we aim at for 5% measurement in 10' $\Longrightarrow$ 400 H^-/10' $\Longrightarrow$ 0.11×10^{-5} H^-/bunch

  $\Longrightarrow$ 2.5% single observation efficiency

Photo-ionization of H- beam

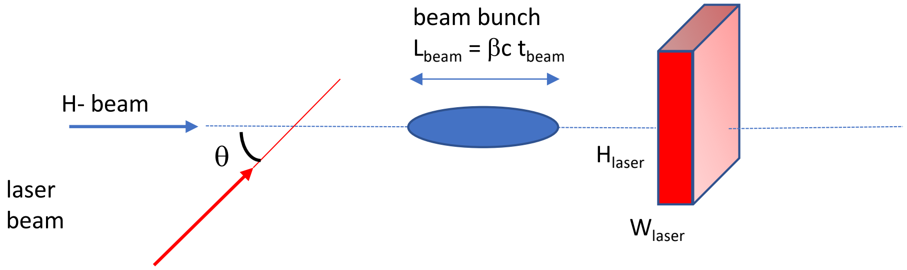
H- is H atom plus second electrons, ie bound state of p+ and two e- with no excited states. Binding energy of second electron is 0.756 eV [1]. Binding energy of the first 1s electron is 13.6 eV.

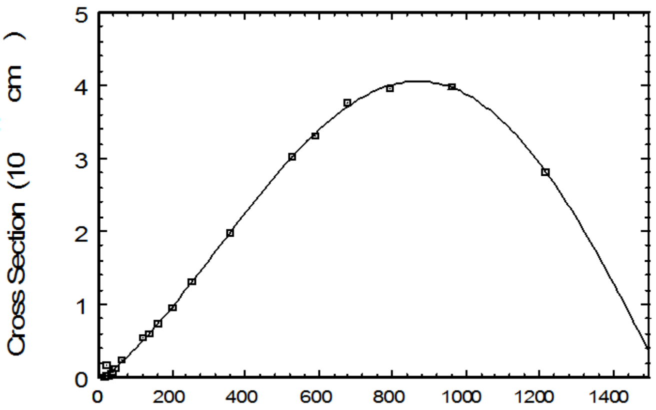
H- can be neutralized by:
- interaction with residual gas in beam pipe (gas stripping cross-section ≈ $3\text{x}10^{-18}$ cm^2/atom)
- photo-ionization induced by photon of energy above 0.756 eV, ie $\lambda<1640$nm

Photo-ionization cross-section vs photon λ, as found in [2], is reported below. It peaks at about $4\text{x}10^{-17}$ cm^2 for a λ=820 nm, or eV=1.51 eV.

Q-switched laser discharges in few ns and is able to provide instantaneous power of order 10 MW (ie 100 mJ pulse energy in 10 ns). Laser based on solid Nd:YAG or ytterbium doped fibers produce light at 1064 nm, for which photo-ionization $\sigma(\lambda) = 3.66\text{x}10^{-17}$ cm^2.

Laser-beam geometry





Neutralization fraction f_{neut}

The probability that an H- passing through a laser beam will be neutralized is[4]:

$$f_{neut} = \left(1 - e^{-\Phi_{CM}\sigma(\lambda)\tau}\right)$$

where, using the symbols introduced in the previous page:

- $\sigma(\lambda)$ is the photo-electron cross-section
- τ is the transit time of an ion through the laser beam, or $W_{laser} / \beta c$
  (if $W_{laser} = 1$ *mm(*)*, E=800/25/0.75 MeV beam has τ = 4/14.7/83.5 ps)
- Φ_{CM} is the flux of photons at the interaction in the H^- rest frame

The flux of photons in the H- rest frame is equal to:

$$\Phi_{CM} = M \left(\frac{E_{laser}\lambda_{lab}}{hc\,\tau_{laser}}\right)\left(\frac{1}{A_{laser}}\right)$$

where: E_{laser} is the laser energy

τ_{laser} is the laser pulse duration

A_{laser} is the laser cross-section, ie $W_{laser}\,x\,H_{laser}$

M is the number of crossings between the H- beam and the laser

Mnemonics

For a given E_{laser}, f_{neut} increases (i.e. line moves to the left) for anything that make the exponent increase:

- longer τ, higher $\sigma(\lambda)$
- longer λ_{lab}
- shorter τ_{laser}
- smaller Al_{aser}

Neutralization rate for higher beam energy

Following calculation done by D. Johnson in [3] for his laser-notcher realization, for H- beams of of 750 KeV vs 25 MeV vs 800 MeV

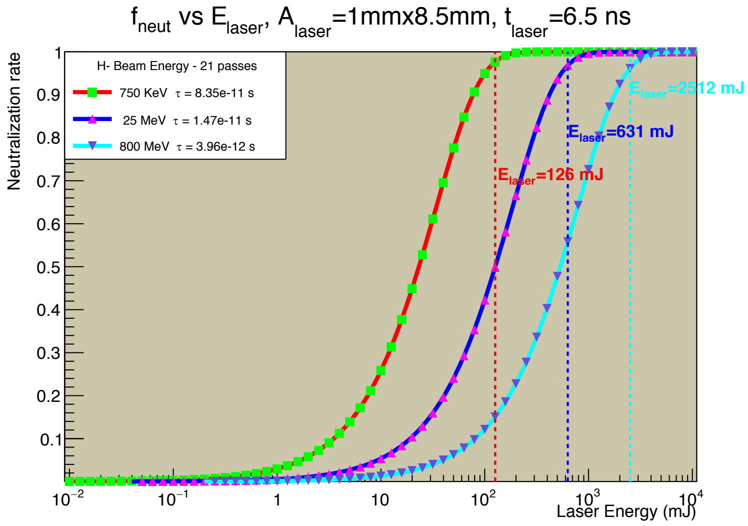
keeping constant

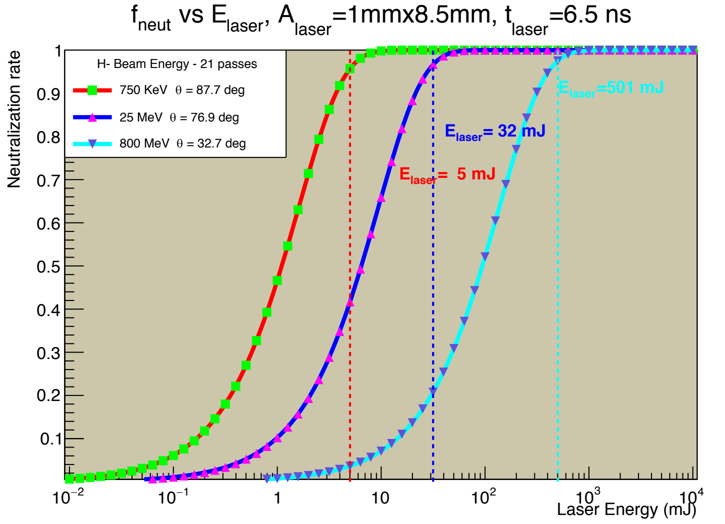
A_{laser} = 1mm x 8.5 mm

τ_{laser} = 6.5 ns

I get the neutralization fraction vs E_{laser} shown in the top plot. The dashed line shows the 95% rate.

Adding a cavity with M=21, brings down the laser energy requirement to what shown in the lower plot. The dashed lines show the 95% neutralization rate.





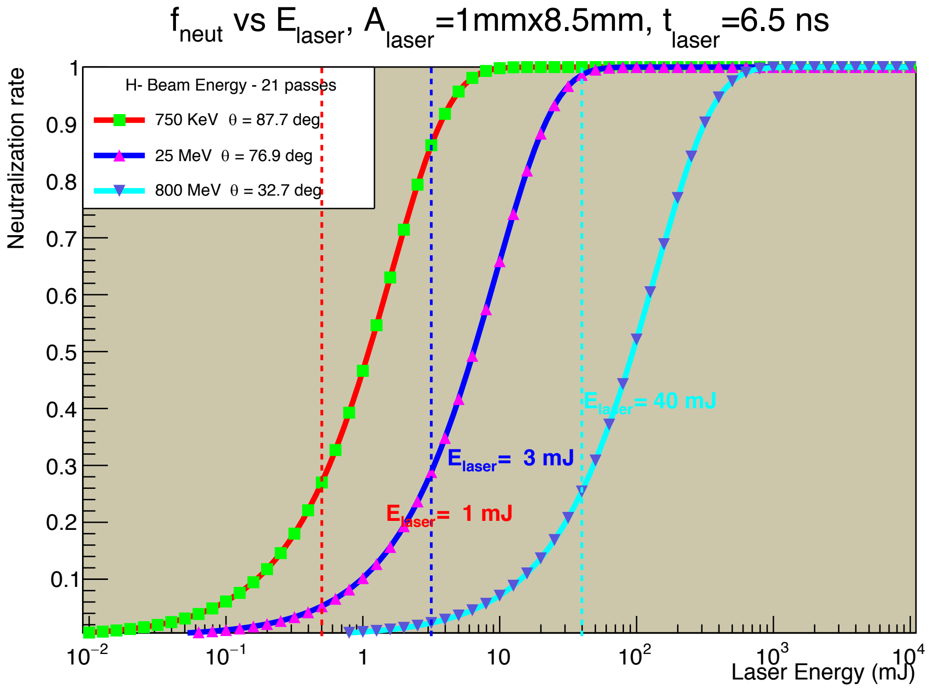
Beam Power

To get a 2.5% single H^- observation, let's assume 25% electron knock-off probability and 10% single electron identification efficiency.

For 25 MeV beam 25% neutralization rate with a laser pulse of 25 ns is obtained with a 3mJ laser energy, corresponding to 461kW.

The repetition rate is 590 kHz.

For 800 MeV, the laser power requirement increases to 6.1MW.



Bibliography

1) *R.Connolly et al* 2012 JINST 7 P02001
2) *R.Connolly at al.* NIM A312 (1992) 415-419
3) *D. Johnson et at*, Fermilab-Conf-16-388-AD