Injection and extraction - stripper foils

USPAS

by
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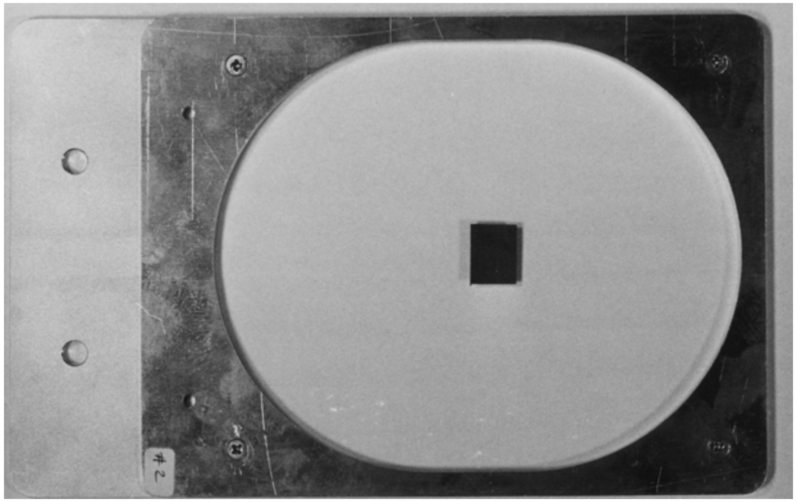
The ideal stripper foil

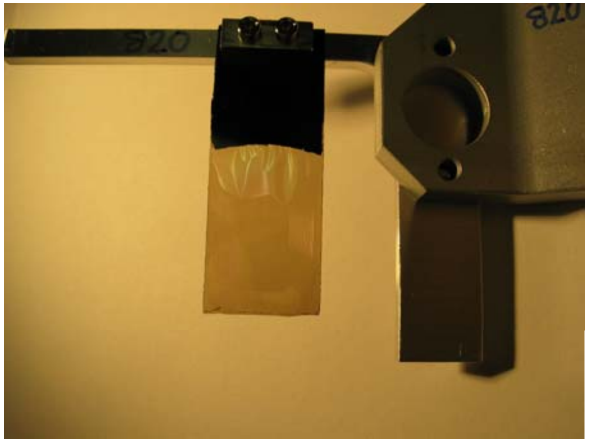
- The ideal stripper foil
  - Minimizes beam scattering
  - Fully strips the incoming beam (e.g. H^- to H^+)
  - Has no pinholes
  - Does not wrinkle or change its shape
  - Has infinite lifetime
  - Can be supported from one edge
- Unfortunately this foil doesn't exist
- Laser stripping could be the perfect stripper, but this technology is still being developed. (Prototype work is underway at SNS.)

Some example stripper foils

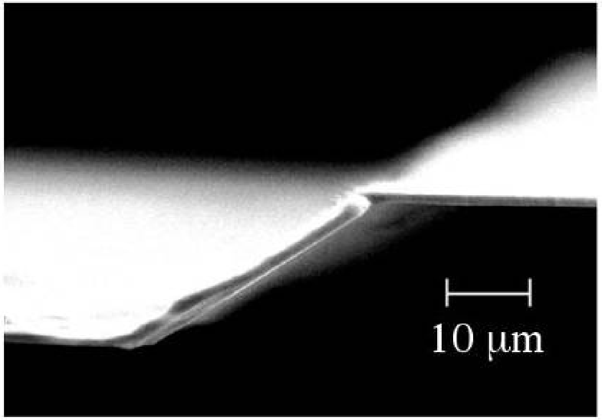


Old style PSR foil completely supported by carbon fibers

New style PSR foil

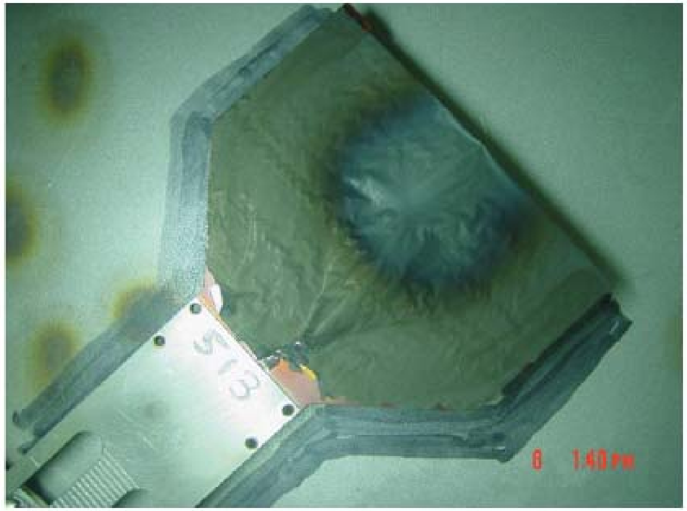


SNS diamond foil



Close up showing SNS diamond foil corrugation

Stripper foil examples (cont.)



FNAL booster, from Chou, NIM A590

ISIS stripper foil, 0.25 μm (~50 ug/cm^2) thick aluminum oxide

Foil thickness

- As the stripping foil thickness increases, the fraction of the beam that is fully stripped increases (**good thing**)
- BUT, the scattering of the injected and circulating beam also increases (**bad thing**)
- ALSO the energy deposited in the foil increases, which can overheat and damage the foil (**bad thing**)
- Specifying the optimum foil thickness is a balancing act between the stripping efficiency, the scattering, and foil heating

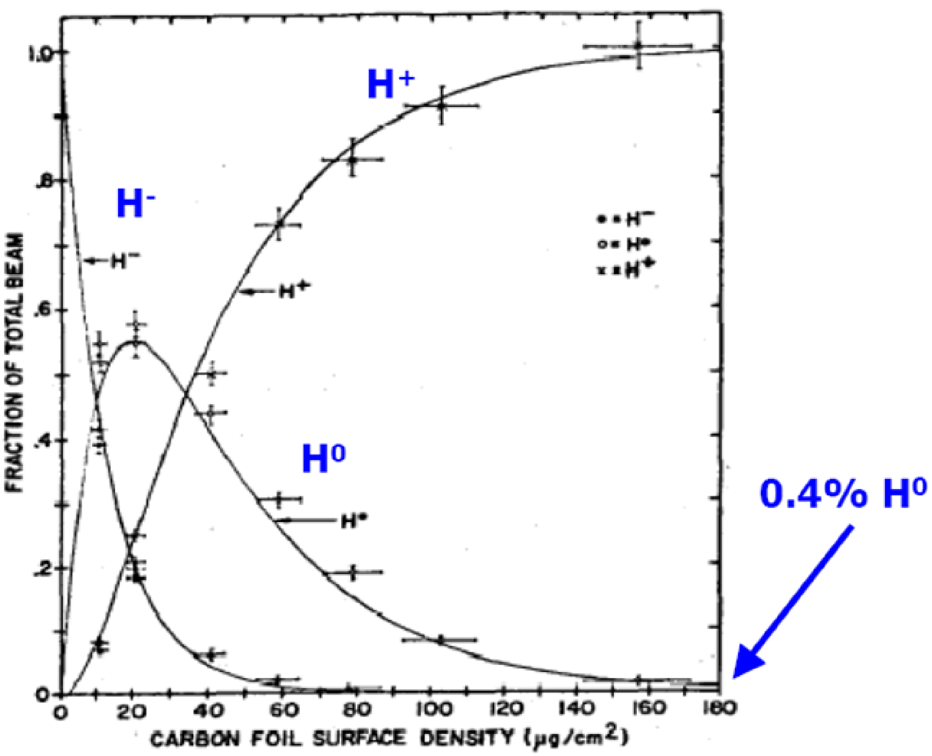
Stripping efficiency

- Stripping efficiency is a function of foil material, foil thickness, foil density, beam species, and beam energy
- As the beam energy increases, a thicker foil is needed to get the same stripping efficiency
- Examples:
  - ISIS injection energy is 50 MeV, foil is ~50 ug/cm^2
  - SNS injection energy is 1000 MeV, foil is ~300 ug/cm^2

Stripping efficiencies for carbon

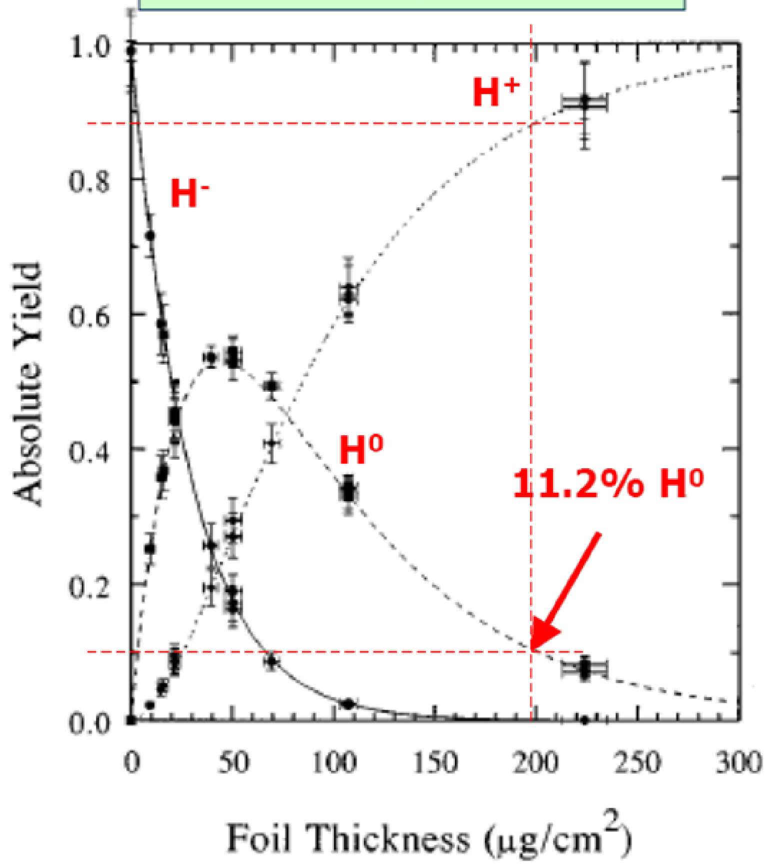
Webber & Hojvat, 1979

Fermilab linac, 200 MeV



Gulley et al., 1996

LANL linac, 800 MeV



(W. Chou, H^- inj. wkshp, FNAL 2004)

Stripping efficiency for carbon

d = graphite density = 5×10^{16} atoms /μg, t = foil thickness in $\mu g/cm^2$, β = relativistic factor Cross section scaling

$$a = 0.676 \times (0.84181 / \beta)^2 \times 10^{-18}\ \mathrm{cm}^2$$

$$b = 0.012 \times (0.84181 / \beta)^2 \times 10^{-18}\ \mathrm{cm}^2$$

$$c = 0.264 \times (0.84181 / \beta)^2 \times 10^{-18}\ \mathrm{cm}^2$$

Fractional yield is:

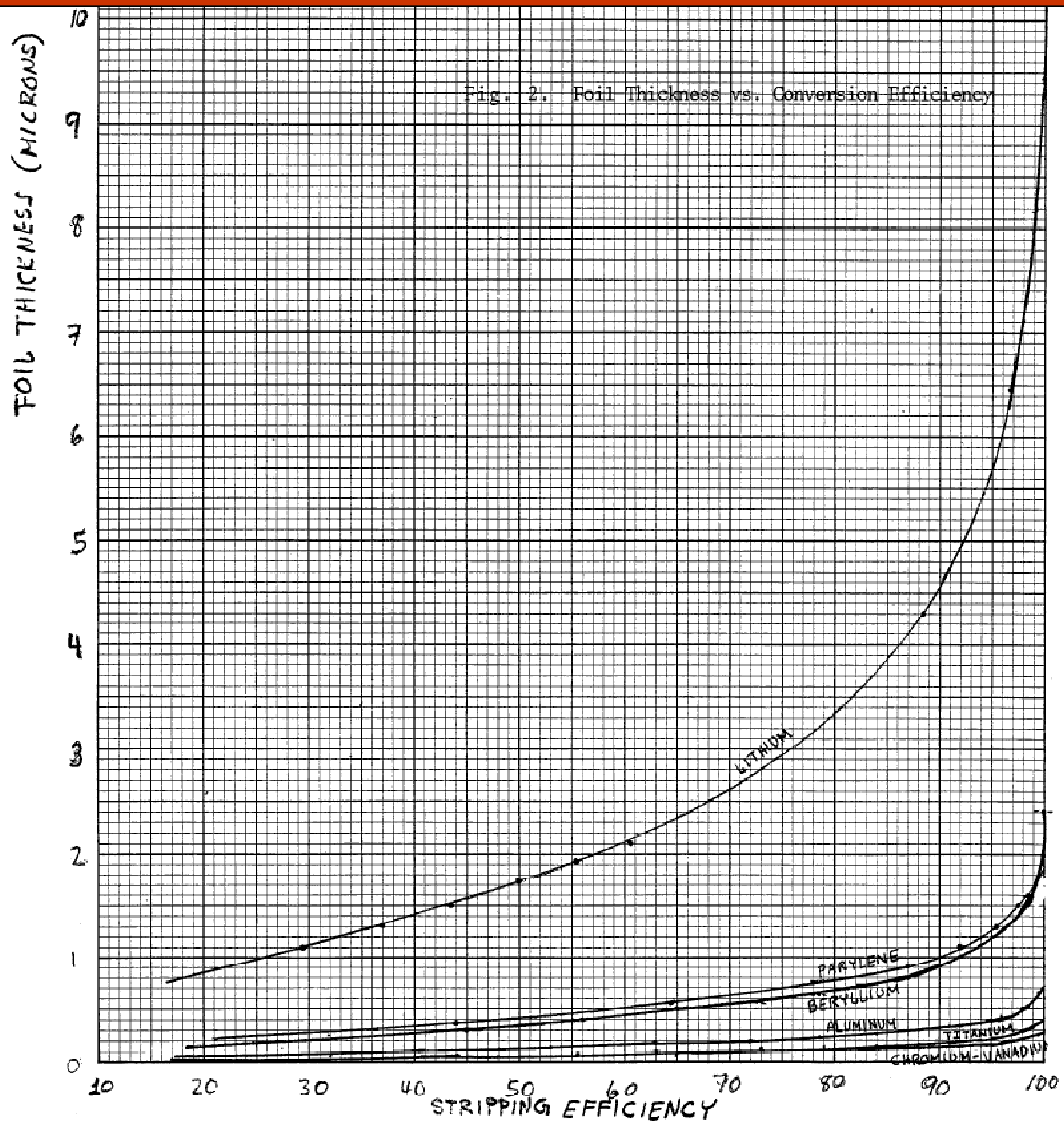
$$\mathrm{H}^- = \exp[-(a+b)\times d \times t]$$

$$\mathrm{H}^0 = \left(\frac{a}{a+b-c}\right)\left(\exp(-c\times d\times t) - \exp[-(a+b)\times d\times t]\right)$$

$$\mathrm{H}^+ = 1 - \mathrm{H}^- - \mathrm{H}^0$$

(W. Chou, e.g. NIM A590)

Stripping efficiencies for various materials



200 MeV H^- beam

Element	Density (g/cm^3)
Li	0.54
Be	1.8
Al	2.7

M. Joy, FNAL TM-0699

Foil scattering

- Foil scattering is an important (often dominant) cause of beam loss in a ring
- Just like stripping efficiency, foil scattering depends on foil material, thickness, density, and beam species
- Huge amounts of money and resources are spent to minimize scattering of the circulating beam
  - Injection painting
  - Foils supported by just one edge or by fibers
  - Laser stripping
- There are three main types of scattering:
  - Small angle, multiple Coulomb scattering [Gradual emittance incr.]
  - Large angle, single Coulomb scattering (Rutherford) [At foil]
  - Nuclear scattering [At foil]

Multiple Coulomb scattering

$$\theta_0 = \frac{13.6\,\mathrm{MeV}}{\beta \mathrm{cp}} z\sqrt{x/X_0}\left[1+0.038\ln(x/X_0)\right]$$

$$X_0 = \frac{716.4\,\mathrm{g\,cm^{-2}}\ \ A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

Scattering angle roughly scales with square root of foil thickness

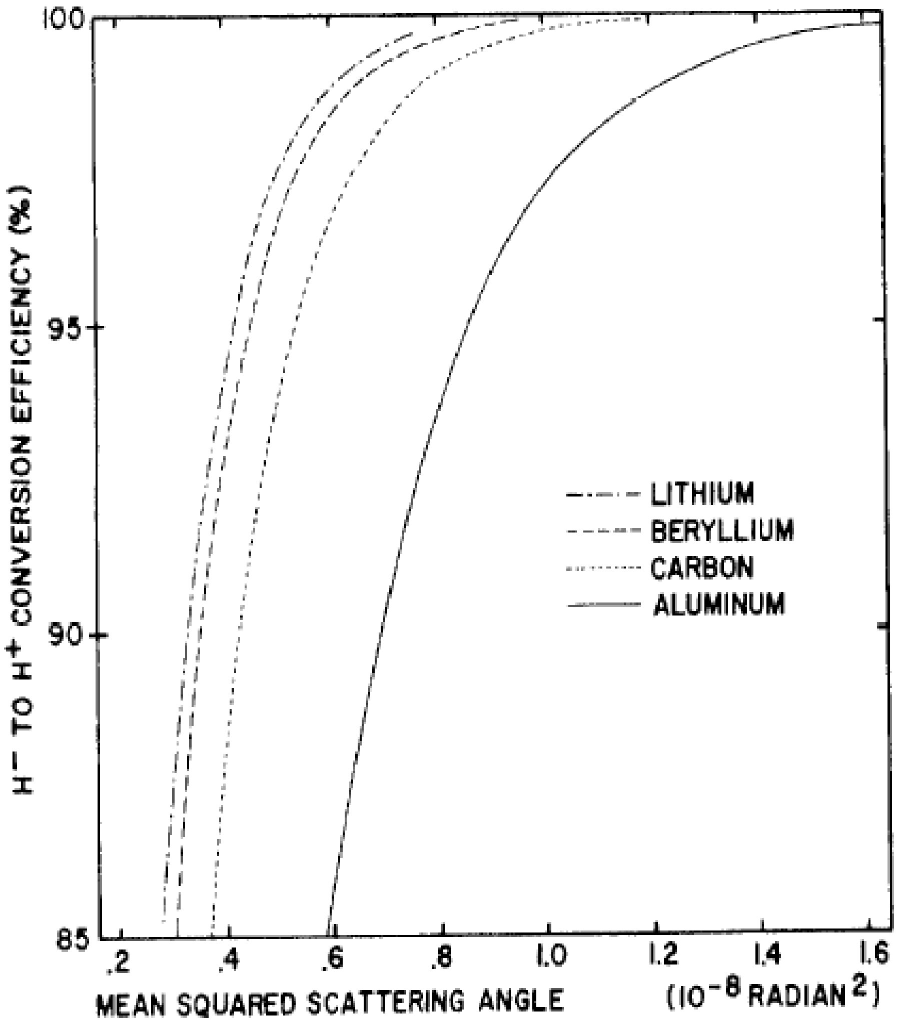
p, *βc*, and *z* are the momentum, velocity, and charge number of the incident particle,

x/X_0 is the thickness of the scattering medium in radiation lengths

A = atomic mass of foil (=12 for carbon)

Z = atomic number of the foil (=6 for carbon)

Multiple Coulomb scattering



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STRIPPING FOILS FOR MULTITURN CHARGE EXCHANGE INJECTION INTO THE FERMILAB BOOSTER

C. Hojvat, M. Joy , R. C. Webber*†

- Low-Z materials are best
- Lithium and beryllium are hazardous materials
- Carbon is often the best practical choice

Foil scattering – large angle Coulomb

- Large angle Coulomb scattering (Rutherford Scattering) – number of particles scattered outside of angles θ_{xl} and θ_{yl} :

$$P = \left(\frac{2Zm_e r_e}{\gamma M \beta^2}\right)^2 N_0 \left(\frac{\rho t}{A}\right)\left[\frac{1}{\theta_{xl}\theta_{yl}} + \frac{1}{\theta_{xl}^2}\tan^{-1}\left(\frac{\theta_{yl}}{\theta_{xl}}\right) + \frac{1}{\theta_{yl}^2}\tan^{-1}\left(\frac{\theta_{xl}}{\theta_{yl}}\right)\right]$$

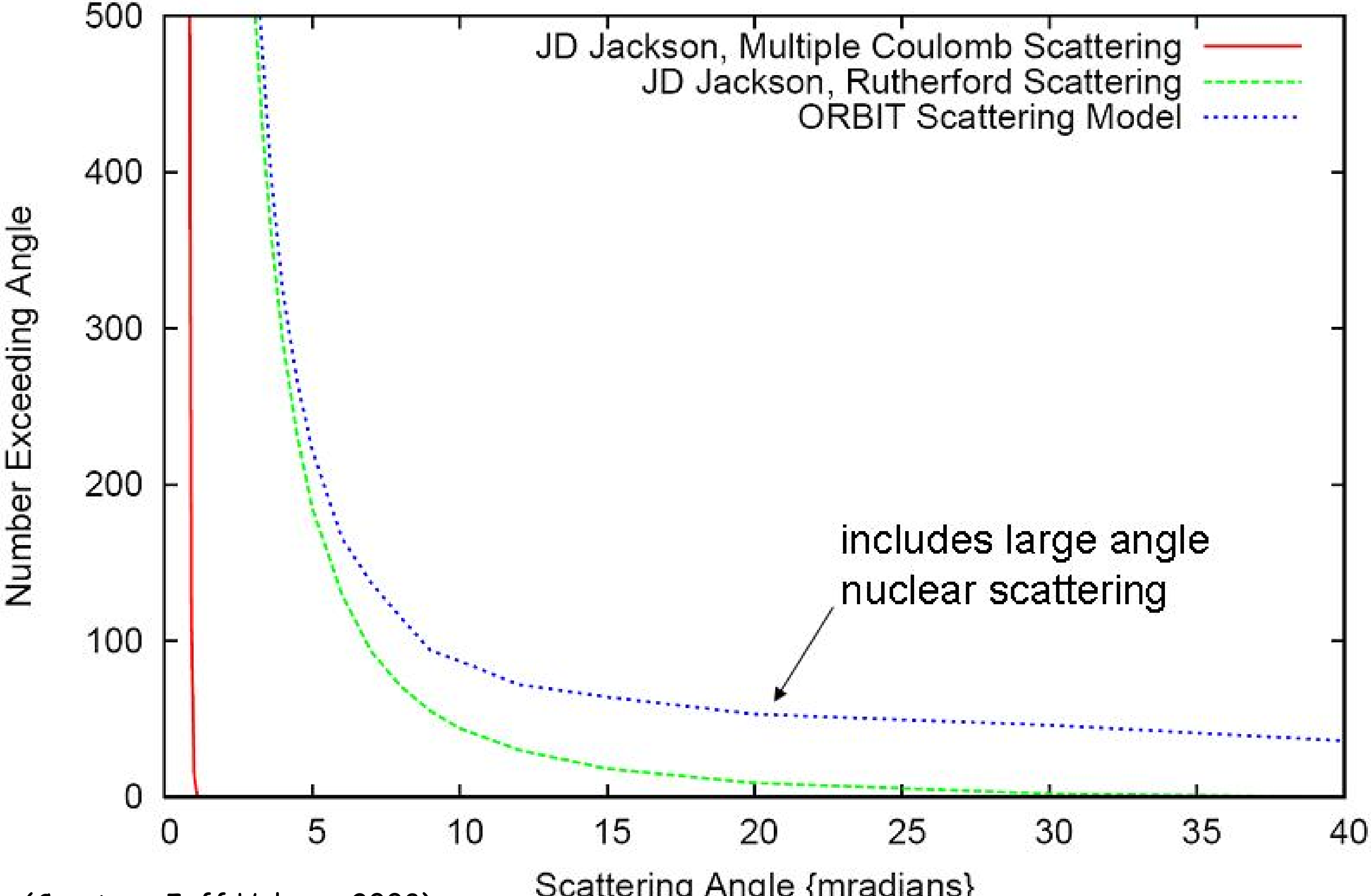
(R. Macek, 2004)

target; angles

- For a given thickness (ρt) the scattering is proportional to Z^2/A. For low-Z materials, Z≈A, so scattering is proportional to Z.
- The lowest-Z practical material is carbon
- Carbon is also good because it has a high melting point, a low partial pressure at high temperatures, is rigid, easy to work with, and non-hazardous

The scattering contributors

100,000 particles launched, scattering in 18 mg/cm² carbon



(Courtesy Jeff Holmes, 2008)

Foil heating

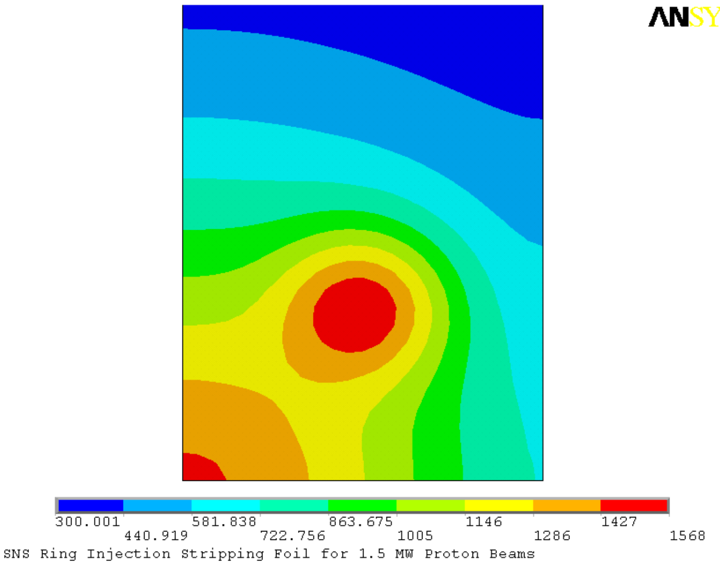
Foil heating assuming no cooling via conduction or convection

$$\rho V c \frac{dT}{dt} = \frac{dE}{d(\rho x)}(\rho x)\frac{dN_{hits}}{dt} - 2A\varepsilon\sigma(T^4 - T_0^4)$$

Temperature change

Energy deposited in foil

Temperature decrease due to radiation cooling



Example of SNS foil temperature model calculation, courtesy of Y. Zhang, SNS

Foil heating (cont.)

$$\rho V c \frac{dT}{dt} = \frac{dE}{d(\rho x)} (\rho x) \frac{dN_{hits}}{dt} - 2A\varepsilon\sigma(T^4 - T_0^4)$$

$$\frac{dT}{dt} = \frac{dE}{d(\rho x)} \frac{dN_{hits}}{dt} \frac{1}{Ac} - \frac{2\varepsilon\sigma(T^4 - T_{amb}^4)}{\rho x c}$$

$\frac{dT}{dt}$ = change in temperature with time

N_{hits} = hits per unit area

c = specific heat

ε = emissivity

A = area, ρ = density, V = volume, x = thickness

$\frac{dE}{d(\rho x)}$ = stopping power, constant for a given material and beam energy

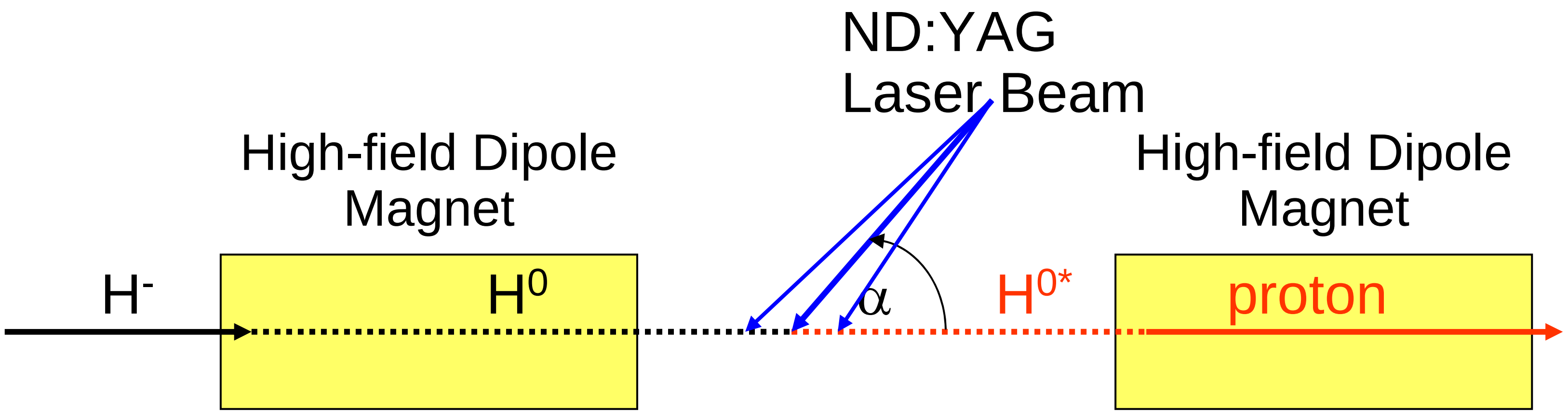
- Thicker materials don't cool as well since heating is proportional to volume and radiative cooling is proportional to area
- dE/d(ρx) doesn't change much from one material to the next
- Heat capacity, density, and emissivity can vary a lot from one material to the next

Foil summary

- Prefer non-hazardous self-supporting foils that can be easily handled
- Prefer low-Z foils to minimize scattering
  - Carbon is in widespread use
- For high intensity machines prefer foils that can withstand high temperatures
  - Again, carbon is a good choice

Laser stripping

90% stripping efficiency demonstrated at SNS in October 2006, for ~900 MeV, ~10 ns, H^- beam. Now working to extend method to longer pulse lengths.



Step 1: Lorentz Stripping

Step 2: Laser Excitation

Step 3: Lorentz Stripping

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

$H^0\ (n=1) + \gamma \rightarrow H^{0*}\ (n=3)$

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

(Danilov, SNS, 2007)

Laser stripping

- Fun fact:
  - At the Fermilab proton injector project (Project X), which calls for an 8 GeV H^- beam, room-temperature blackbody radiation strips the H^- beam!
  - Current plans call for cooling the beam pipe to liquid nitrogen temperatures (78 deg. K)!

Recap

- Best to keep stripper foils as thin as possible
  - Thick foils get hotter and increase beam loss
- Three types of scattering – large angle Coulomb, nuclear, and small angle multiple scattering
- H^0 excited states are an important component of beam loss
  - Thicker foils are better in this regard
  - Can be controlled with magnetic fields
- Foil temperatures vary widely for different materials
- Laser stripping is a promising new development
  - Not yet practical, but it will be as technology improves

- backup slides