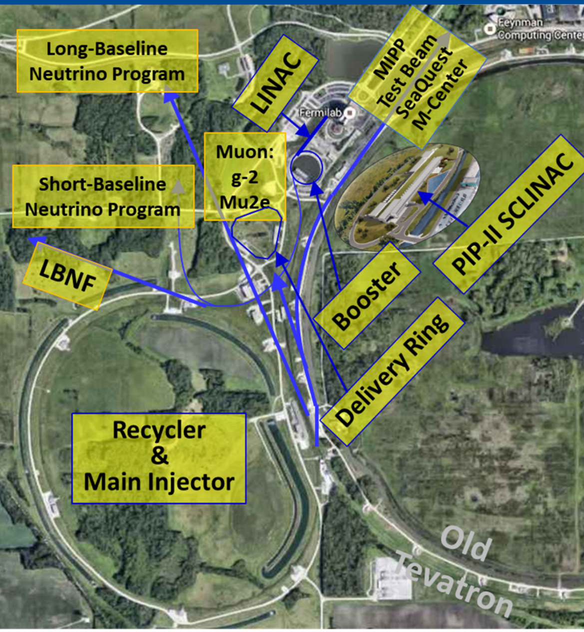

WEYBB3

Foil Scattering Model for Fermilab Booster

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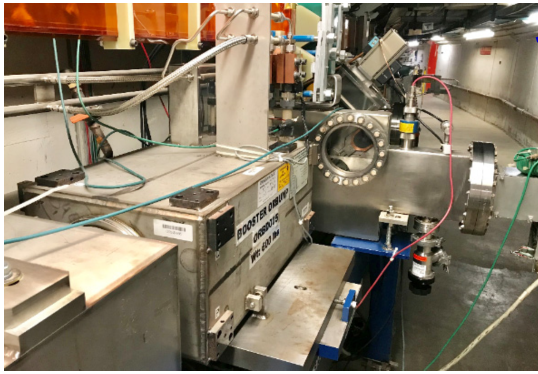
NAPAC2019, Lansing, Michigan, USA

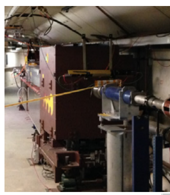
September 4, 2019

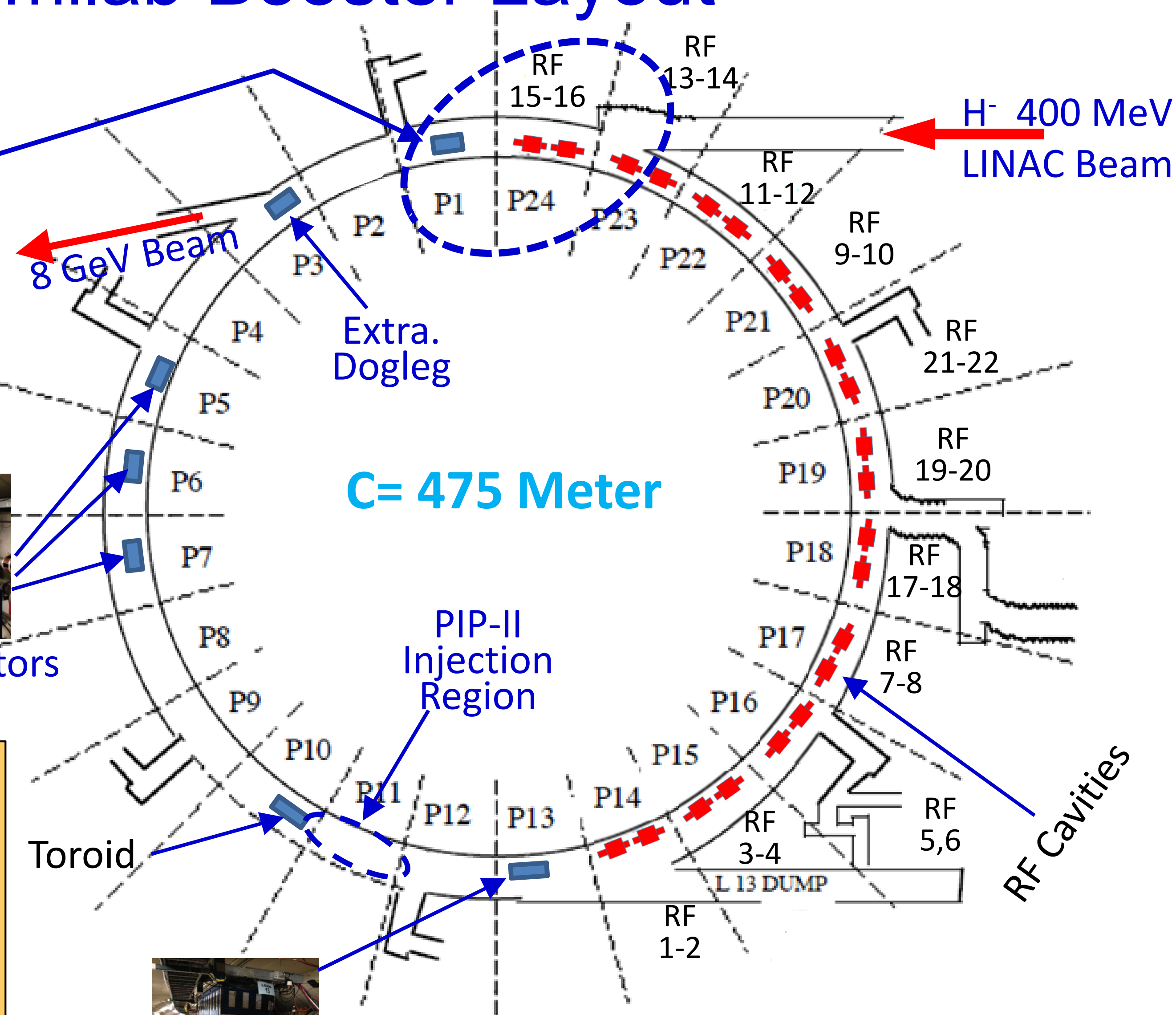
Special Thanks to
- ❑ K. Triplett
- ❑ D. Johnson

Fermilab Booster Layout

Injection Region







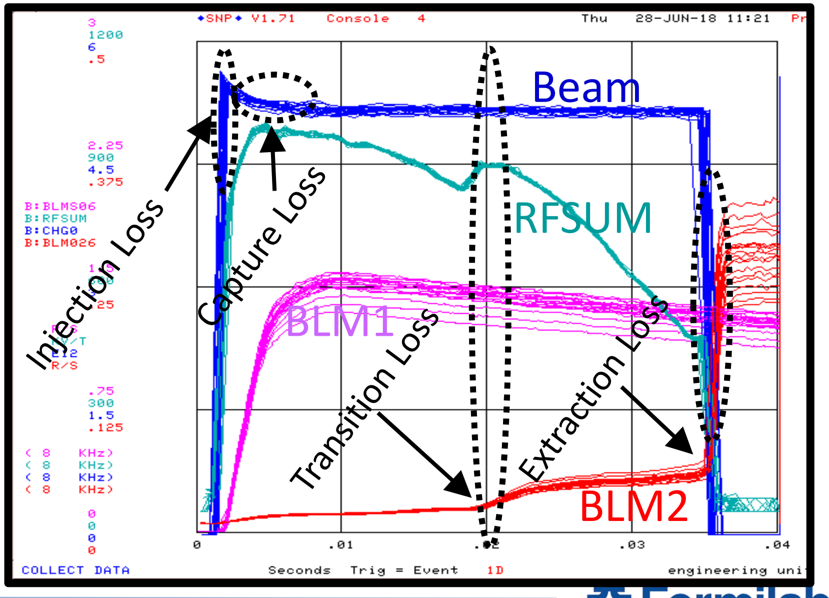
96 Combined Function Dipole magnets
& 22 RF cavities
swing freq.: 37.8 MHz-52.8 MHz
h=84

Goal of the Foil Scattering Measurements

- With Proton Improvement Plan (PIP) Fermilab is providing world record beam power >700 kW on NOvA neutrino target with
  - Booster output beam intensity ~4.6E12 ppBc
- In the future, PIP-II added to the complex the proton beam power will be increased to ~1.2 MW on the LBNF/DUNE neutrino target
  - Booster output beam intensity will increase by ~50%

So, it is extremely important to understand the loss mechanism and minimize beam loss in the Booster (and other accelerators in the complex, i.e., RR/MI).

- The beam losses in the Booster
- So, there is an on-going campaign to study & mitigate each one of the loss modes ← **Important to the current operation, PIP-II and in-between**
- Early this year S. Nagaitsev initiated "Foil Scattering Measurements in the Booster" as the first step.



Measurement Plan

- Find a highly sensitive fast detector to measure the beam loss as close to the stripping foil as possible.

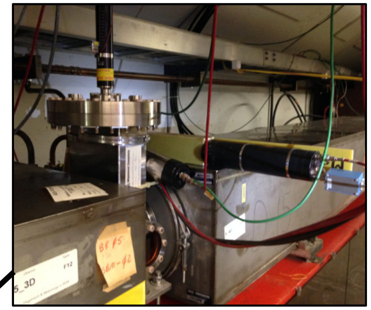
  Note that standard ion chamber loss monitors used in the Booster ring are not fast enough

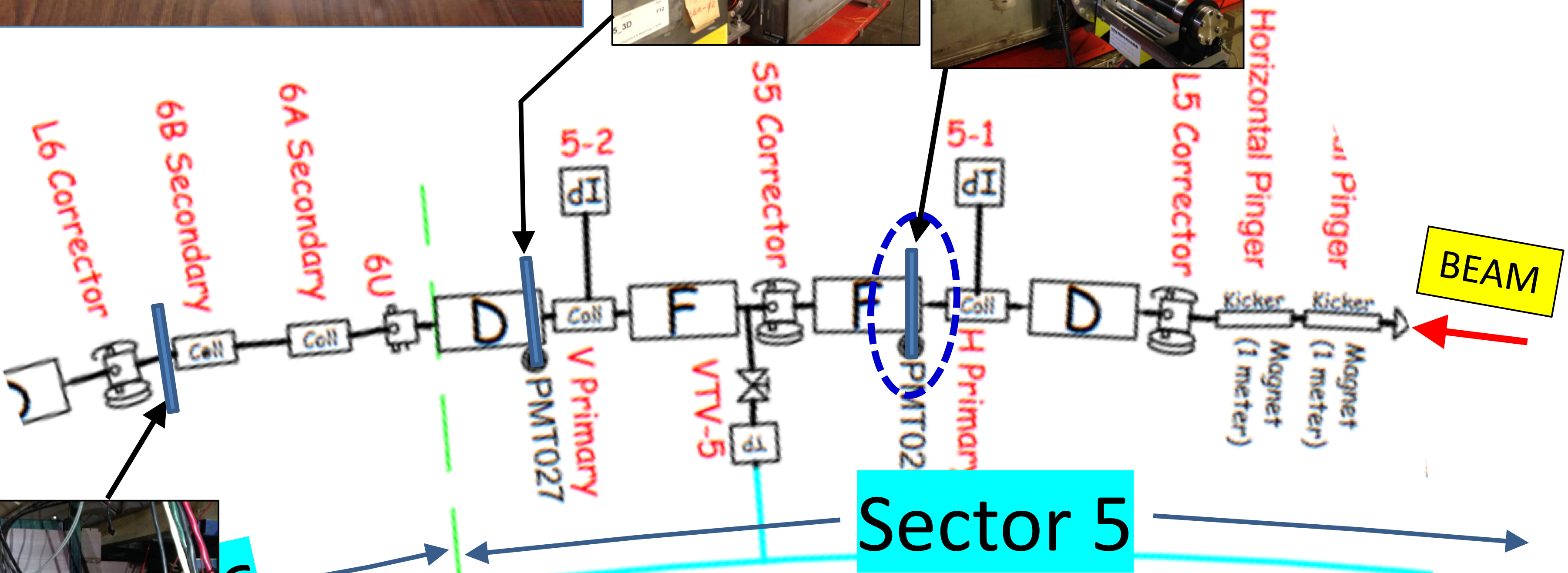
- Variables in Measurements
  - LINAC Beam Energy 400 MeV (fixed).
  - LINAC Beam Intensity
    - 25 mA, 20 mA, 10 mA and 2mA
  - LINAC beam Pulse length
    - 22μs (*10 BT*) and 31 μs *(14 BT)*
  - Vary the duration of the beam on the foil
    - Duration of ORBUMP: $BT \times T_0$+40 μs (nominal) to $BT \times T_0$+70 μs

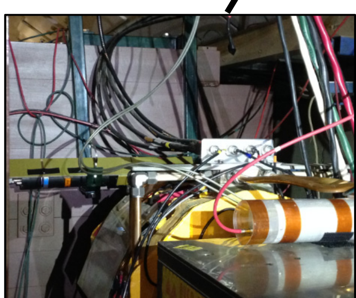
      ← This varies number of beam hits on the foil

Scattering Measurements

Placement of Tesarek's PMTs in Booster Ring





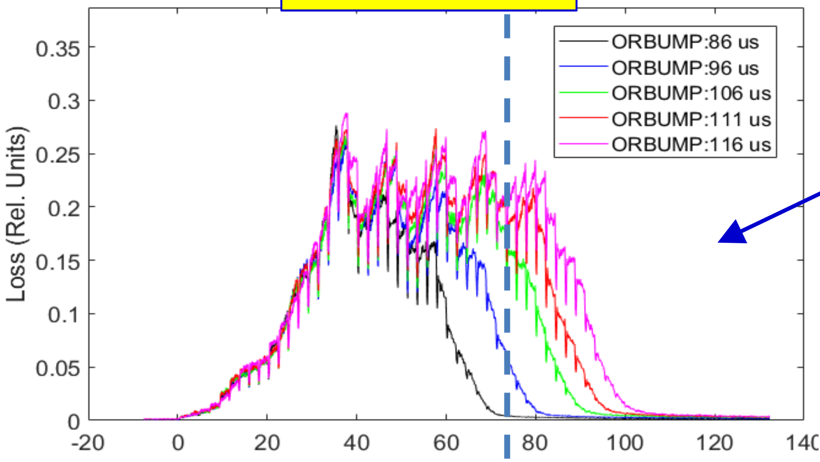


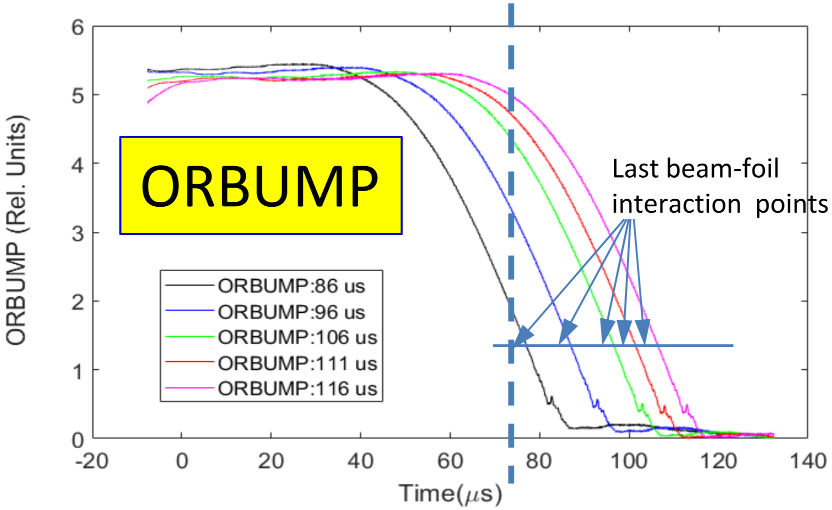
Original goal of installing these PMTs were to Investigate collimator performance

Loss data using PMT and Toroid

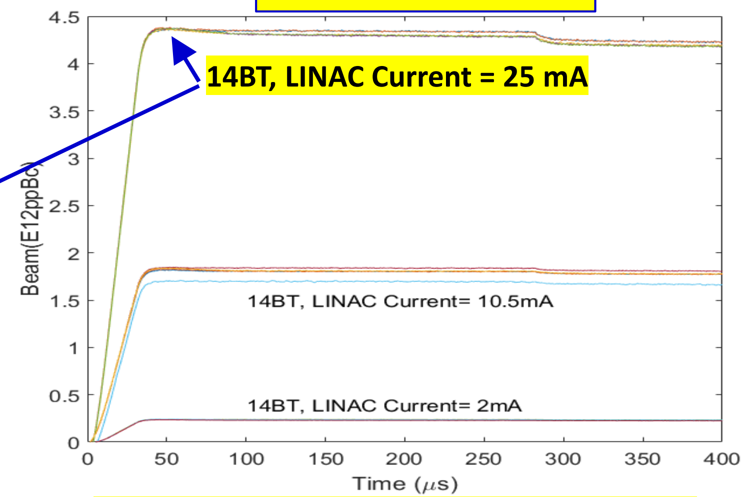
Preliminary Results

PMT Data

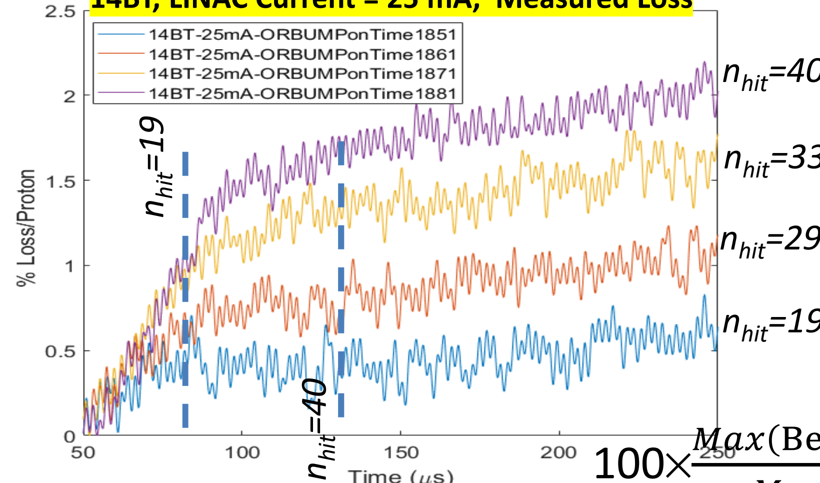




Toroid Data



14BT, LINAC Current = 25 mA, Measured Loss



$$100\times\frac{Max(\text{Beam})-\text{Beam}}{Max(\text{Beam})}$$

Total beam loss is estimated using the Toroid data

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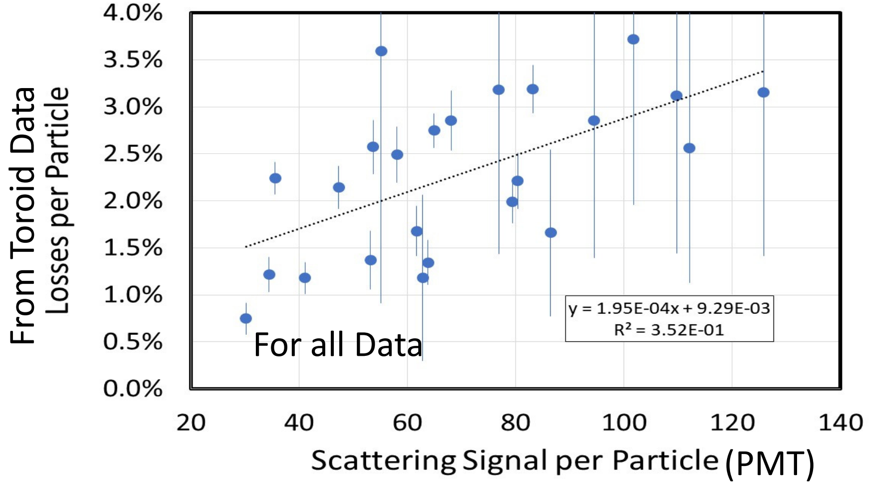
Foil-Scattering Loss Estimate

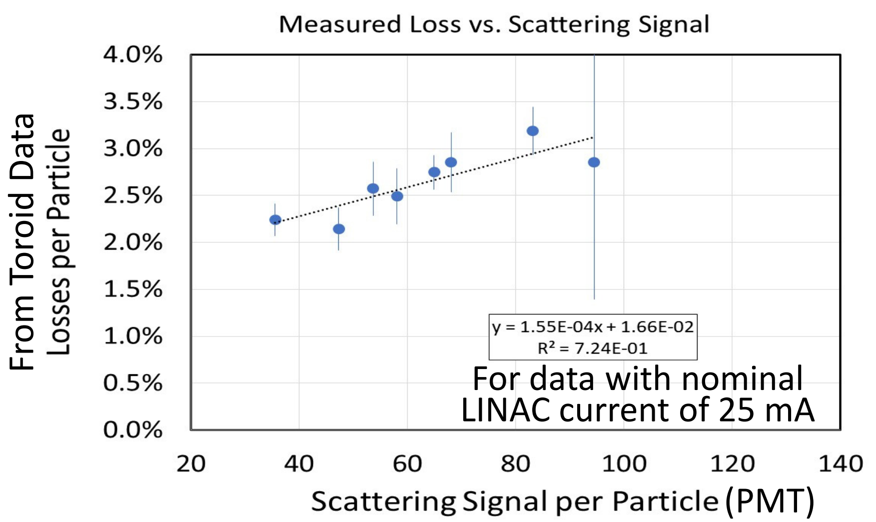
Correlation between Toroid & PMT Measured Loss



Preliminary Results

We see clear **correlations** between Toroid and PMT measured data. But, it is very early to make any conclusions from PMT alone.

- Not enough statistics
- Still to investigate any systematics
- lattice effect should be imbeded



From Toroid data the foil scattering loss is in the range of 0.5% - 1.7%.

Foil-Scattering Loss Model

- Interaction of 400 MeV and 800 MeV H^- with a Carbon foil
  - $H^- \rightarrow H^-$
  - $H^- \rightarrow H^0$ and H^0 with n=1,2,3
  - $H^- \rightarrow H^+$

Gulley-Model
PRA53, (1996) p 3201

$$y_-(x) = Ae^{-\rho\sigma_- x}; \quad y_{1,2}(x) = AC\left(e^{-\sigma_{12}\rho x} - e^{-\sigma_-\rho x}\right)$$

$$A = 1 \qquad C = \sigma_{-12}/(\sigma_- - \sigma_{12})$$

$$y_n(x) = A_1 e^{-\rho\sigma_- x} + A_2 e^{-\rho\sigma_{12} x} + A_3 e^{-\rho\sigma_n x}$$

$$A_1 = \frac{A(\sigma_{-n} - C\sigma_{12n})}{\sigma_n - \sigma_-} \quad A_2 = \frac{AC\sigma_{12n}}{\sigma_n - \sigma_{12}} \quad A_3 = -(A_1 + A_2)$$

- Beam loss due to Nuclear scattering during multi-turn injection
  - The first turn undergoes more number of hits than the last turn.

$$P_{loss}(\text{Nucl. Scat.}) = \frac{1}{BT}\left\{BT - e^{(n_{hit}+1)\frac{x}{\lambda}}\left[\frac{1 - e^{BT\frac{x}{\lambda}}}{1 - e^{\frac{x}{\lambda}}}\right]\right\} \text{ with}$$

Nucl. Int. Length $\lambda = 35 * A^{\frac{1}{3}}\ g/cm^2$, $\approx$ 80 g/cm2 or 38 cm

BT= # of multi−turn, n_{hit}= # additional hits

- Emittance growth due to multiple Coulomb scattering
- Beam loss due to large angle Coulomb scattering taking into the effect of multi-turn injection

Probability/proton is $P = \Upsilon x\left\{n_{hit} + \frac{BT+1}{2}\right\}$, BT= # of multi-turn, n_{hit} = # additional hits

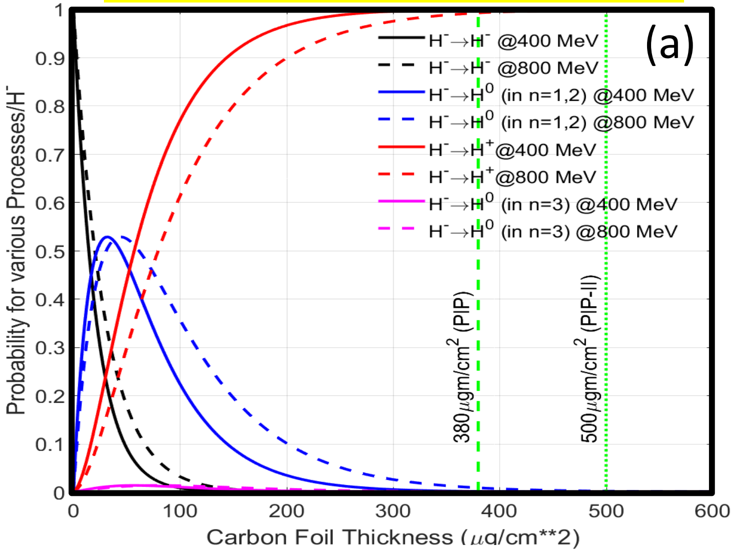
$$\Upsilon = \rho\left(\frac{2Zm_e r_e}{\gamma m_p \beta^2}\right)^2\left[\frac{1}{\theta_{xl}\theta_{yl}} + \frac{1}{\theta_{xl}^2}\operatorname{atan}\frac{\theta_{yl}}{\theta_{xl}} + \frac{1}{\theta_{yl}^2}\operatorname{atan}\left(\frac{\theta_{xl}}{\theta_{yl}}\right)\right]$$

Improved upon R.J. Macek, HB'14

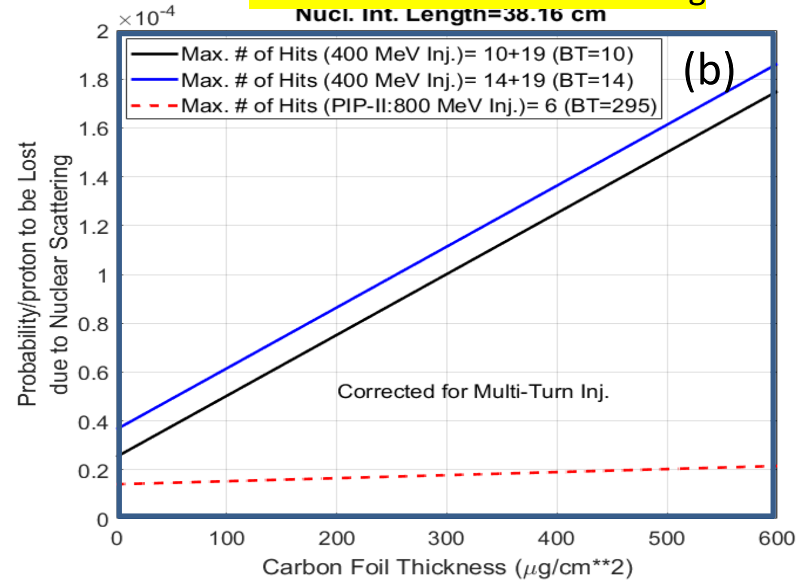
$$\theta_{xl} = \theta_{xlim} = \sqrt{\frac{X_A^2}{\beta_{fx}\beta_{xA}}} = 4\text{ mrad}, \ \theta_{yl} = \theta_{ylim} = \sqrt{\frac{Y_A^2}{\beta_{fy}\beta_{yA}}} = 2\text{ mrad}$$

Foil-Scattering Loss Model

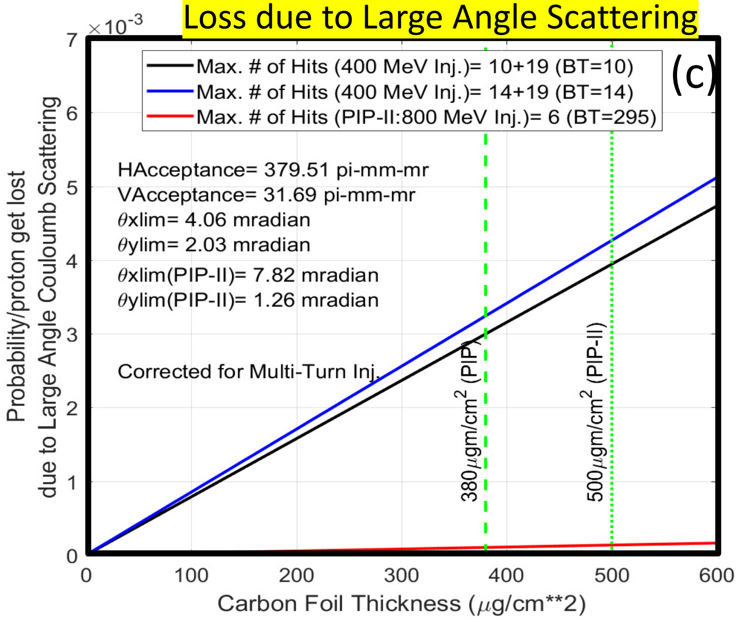
H- Stripping Probability on Carbon Foil



Loss due to Nuclear Scattering



Loss due to Large Angle Scattering



- Predictions:
  - Stripping efficiency ≈99.9% for carbon foil of ~380μg/cm²
  - Loss due to multiple nuclear scattering ~0.02%
  - $\Delta\varepsilon_T$ due to multiple Coulomb scattering ~3 π-mm-mr out of beam ε_T (95%)≈6π-mm-mr, <Acceptance
  - Loss due to Large Angle Coulomb Scattering ~0.3%

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Summary & Future Plans

- Within the next decade the beam power on the neutrino targets will be increased from 700 kW to >1.2 MW at Fermilab.
  - Loss mitigation in the Booster is one of our prime goals
- Recently, we have been looking at data from foil scattering experiment to understand loss mechanism during injection time by varying
  - LINAC Beam Current
  - Number of turns in the multi-turn injected beam and
  - Beam exposed to the stripping foil

  Data is being analyzed. Correlation between PMT measured data and Toroid measured data is seen. Toroid measured data give 0.5 - 1.7%/proton in the first 130 μs of the beam cycle.
- "Foil scattering model" shows the loss from the foil (380μg/cm^2 C) is about ~0.3%.
- Additional PMTs to be added to make better measurements.