GEANT4 SIMULATIONS ON FARADAY CUP DESIGN FOR PIP-II LASER WIRE SCANNER SYSTEM

S.A.K. Wijethunga, R. M. Thurman-Keup, V. E. Scarpine

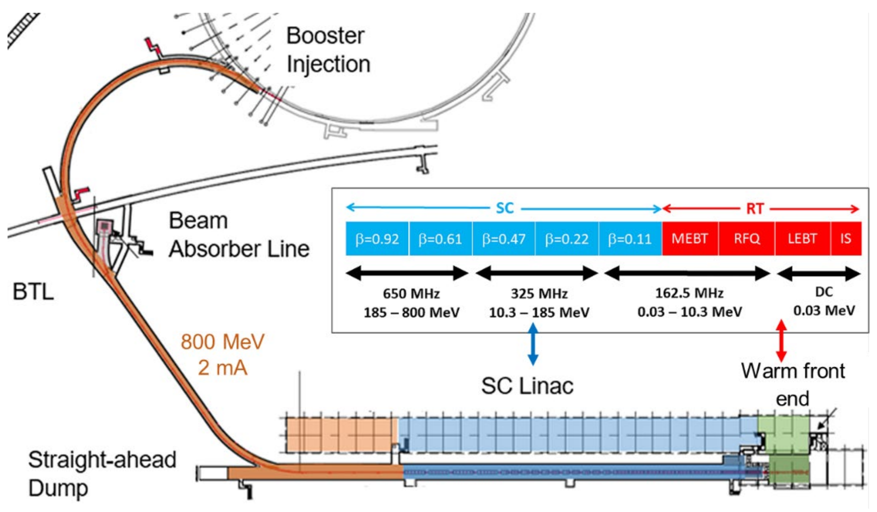
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

ABSTRACT

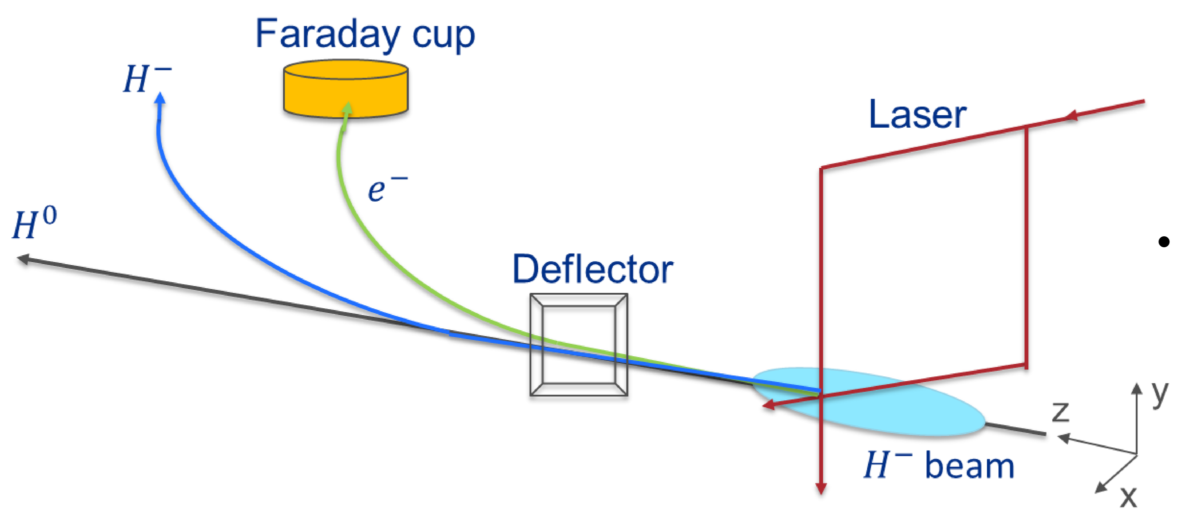
The PIP-II accelerator upgrade at Fermilab represents a groundbreaking leap forward in high-energy physics research. This ambitious initiative involves enhancing Fermilab's accelerator complex by replacing the current linear accelerator with a warm front end (WFE) capable of accelerating H^- beams up to 2.1 MeV. Subsequently, a superconducting linac further accelerates these beams up to 800 MeV. To precisely measure the transverse beam profile, a combination of traditional wire scanners at the WFE section and Laser wire scanners along the superconducting linac are planned for implementation. This investigation centers on refining the Faraday cup design for the PIP-II Laser wire scanners by utilizing GEANT4, a Monte Carlo simulation toolkit. Leveraging this method enables a comprehensive analysis of particle trajectories, energy deposition, secondary electron emission, backscattering, etc., facilitating optimization through adjustments to cup geometries, materials, and placement to maximize its efficacy in beam diagnostics.

INTRODUCTION

- The Warm Front End (WFE) of the Proton Improvement Plan - II (PIP-II) beamline accelerates H^- beams to 2.1 MeV, with the superconducting (SC) linac further boosting them to 800 MeV.
- Traditional invasive methods for beam profile measurement are unsuitable for the SC linac due to particle contamination, vacuum degradation, and beam loss, which leads to heating and quenching.
- The PIP-II beamline uses a laser-based profile monitor (laserwires) system to acquire non-invasive transverse and longitudinal beam profiles, avoiding the above disruptions.
- This technique involves photoionization.



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



- The stripping electrons are deflected using a magnetic field and collected in a Faraday cup.
- There are 13 laserwire stations along the 200m long SC linac, with 1st at 2.1 MeV and the last at 800 MeV.

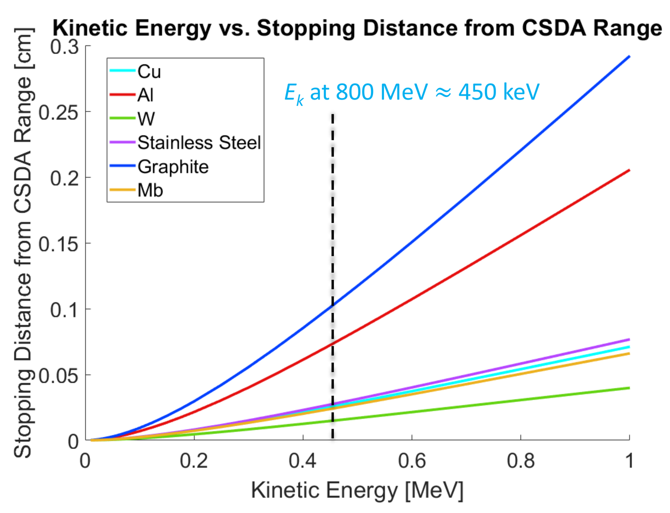
DESIGN CONCEPT

- H^- energy at 1st laser wire scanner ~ 2.1 MeV
- H^- energy at last laser wire scanner ~ 800 MeV

E_k of electrons ≈ 1 keV

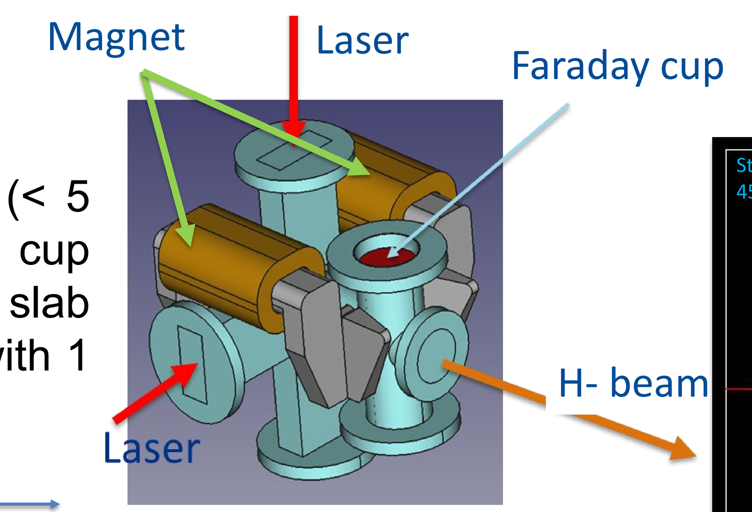
E_k of electrons ≈ 450 keV

- At E_k = 450 keV, the electron stopping distance for Cu and stainless steel is ~ 0.25 mm.
- Thus, a cup width of a few cm is enough to collect the stripping electrons.



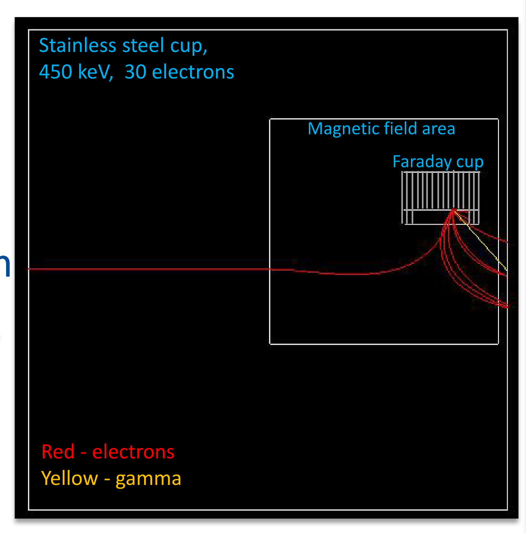
Magnet design

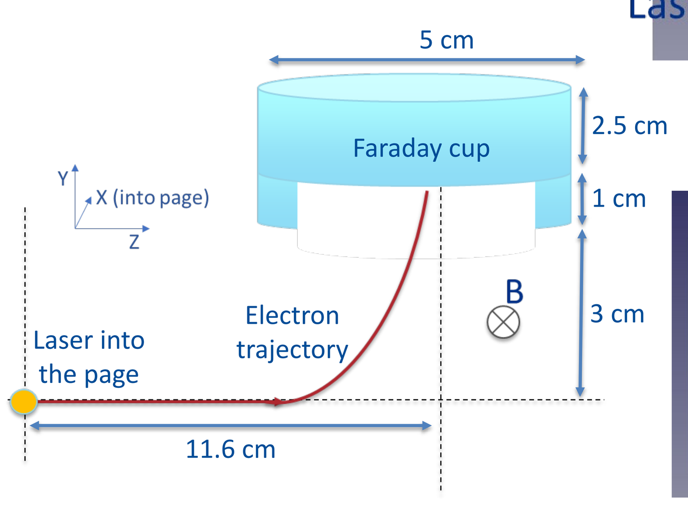
- Deflecting magnet was modeled using CST.
- Angled pole pieces intended to produce a quadrupole field to keep electrons from spreading transversely.



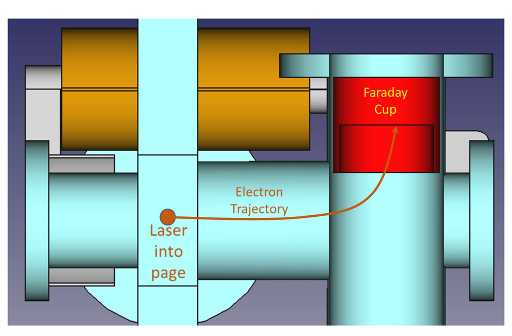
Faraday cup design

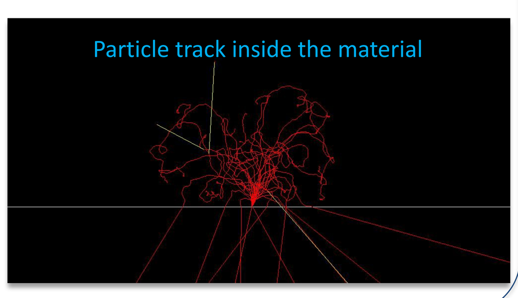
- With the limited space (< 5 cm) the design of the cup was selected to be a slab with 2.5 cm thickness with 1 cm height outer ring





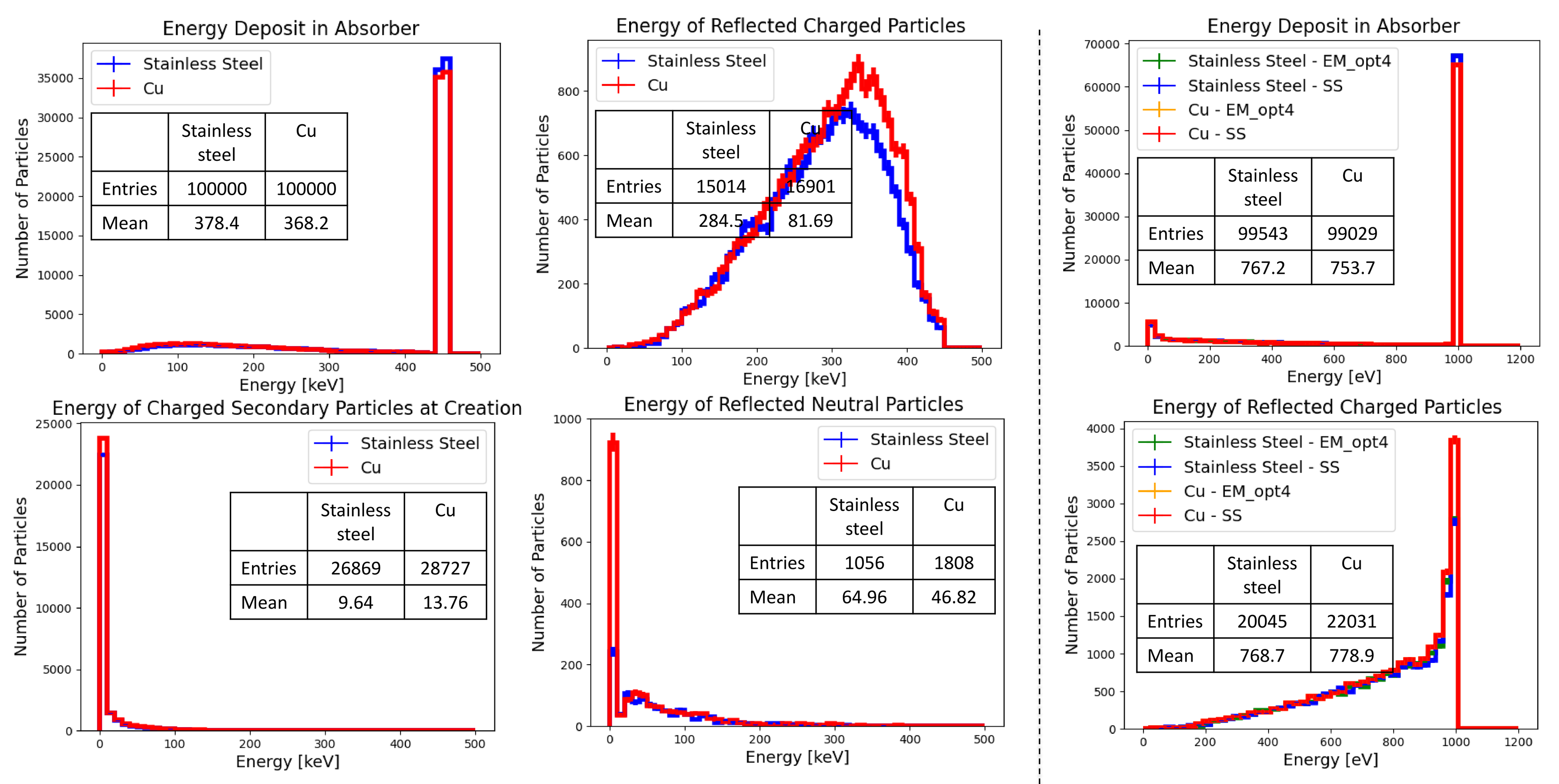
Cross section





GEANT4 SIMULATIONS

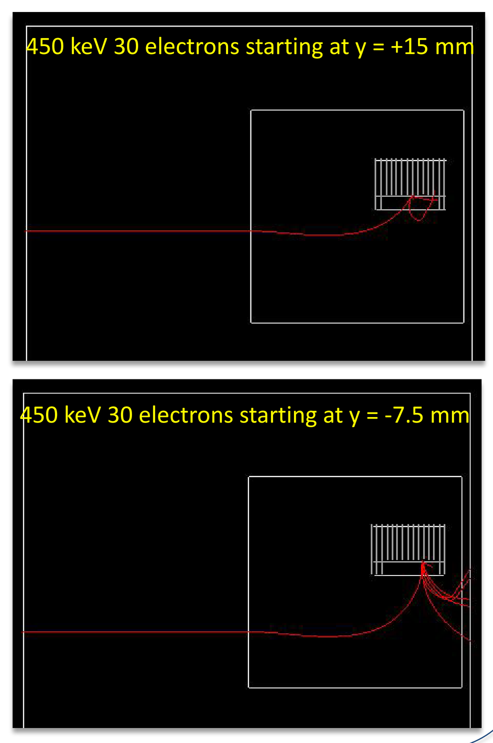
- **Purpose of Geant4:** Geant4 is a Monte Carlo-based software toolkit designed for simulating the transport and interaction of elementary particles through matter.
- **Key physics processes:** The main physics processes of interest are bremsstrahlung, pair production, Compton scattering, and ionization.
- **Physics constructors used:** The G4EmStandardPhysics_option4 (multiple scattering) was used for 450 keV simulations. For 1 keV simulations, both G4EmStandardPhysics_option4 and G4EmStandardPhysicsSS (single scattering) were used to compare the accuracy of modeling electromagnetic interactions at these lower energy levels.



450 keV	1 keV
Both stainless steel and Cu give similar results	Both G4EmStandardPhysics_option4 and G4EmStandardPhysicsSS give similar results
All the particles got impacted	Almost all the particles got impacted for both materials
Backscattering coefficient for Stainless steel ~15% Backscattering coefficient for Cu ~17%	Backscattering coefficient for Stainless steel ~20%, Backscattering coefficient for Cu ~22%,
4.2% charged secondaries created 4.1% neutral secondaries created	No secondary particles created
0.8% neutral particles got reflected	No neutral particles got reflected
All the reflected particles are primary particles	
No particles transmitted through the cup	

Electron collection efficiency across the Faraday cup

Electron beam position [mm]	450 keV		1 keV	
	Impacted [%]	Reflected [%]	Impacted [%]	Reflected [%]
-7.5	100	15.58±2.53	99.49	21.08±2.18
-5	100	14.98±2.58	99.48	20.47±2.21
-2.5	100	14.98±2.58	99.47	19.86±2.24
0	100	14.88±2.59	99.46	19.47±2.27
+2.5	100	14.63±2.61	99.58	19.10±2.28
+5	100	14.76±2.60	99.65	19.39±2.27
+7.5	100	14.58±2.62	99.65	18.78±2.31
+10	100	14.61±2.62	99.56	17.96±2.36
+12.5	100	14.72±2.63	99.66	17.88±2.36
+15	100	14.77±2.60	99.58	16.74±2.44



SUMMARY AND OUTLOOK

- Geant4 provides a good understanding of backscattered particles and secondary electrons, which are crucial for accurate measurements.
- Stainless steel and Cu yielded similar results in simulations, but stainless steel was chosen for its suitability in vacuum environments.
- With nearly 100% collection efficiency across the cup, the current Faraday cup design is suitable for accurate profile measurements.
- With no reflection of secondary electrons and an almost steady reflection coefficient along the cup surface, the measurement remains consistent regardless of the point of interaction, leading to more reliable data collection.
- The simulations will continue for different energies along the SC linac to refine the measurement process and optimize the setup.

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