"Positrons for Our Future" LDRD Final Project Report

Project ID: 2021-LDRD-LD2104

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Project Description

JLab Users want beams of polarized (and unpolarized) positrons, with beam qualities and modes of operation similar to those provided in the electron beams at CEBAF today [Gra19]. The creation of positrons with a high degree of spin polarization is however very challenging – limited to beta decay, self-polarization in rings, or via e+/e- pair-production, a process requiring a source of polarized gamma rays.

At JLab we have a unique source of polarized gamma rays – the bremsstrahlung radiation produced when the spin polarized electron beams of CEBAF interacts with matter – called Polarized Electrons for Polarized Positrons (or PEPPo) [Abb04].

This project sought to extend the PEPPo concept by exploring a possible layout and parameter space for a polarized positron injector at CEBAF based on this approach.

Choosing a toy model

Any polarized electron beam (E > 1.022 MeV) will produce a shower of polarized positrons when impinging a target – with an intensity roughly proportional to the beam power – electron beams with higher energy yield more positrons per incident electron. We however needed to make use of the existing beam energies available from the CEBAF "footprint".

Brain-storming led us to four possible schemes (see Fig. 1) – each defined by a decade of beam energy between them (10, 123, 1090 MeV). The 10 MeV scheme produces least radioactivity, but also has the smallest yield. The 1090 MeV scheme provides highest yield but most complicated integration. The 123 MeV option was selected as the best choice to explore first –we make use of the existing electron injector (or build a small compact injector) to produce a sufficient yield of positrons.

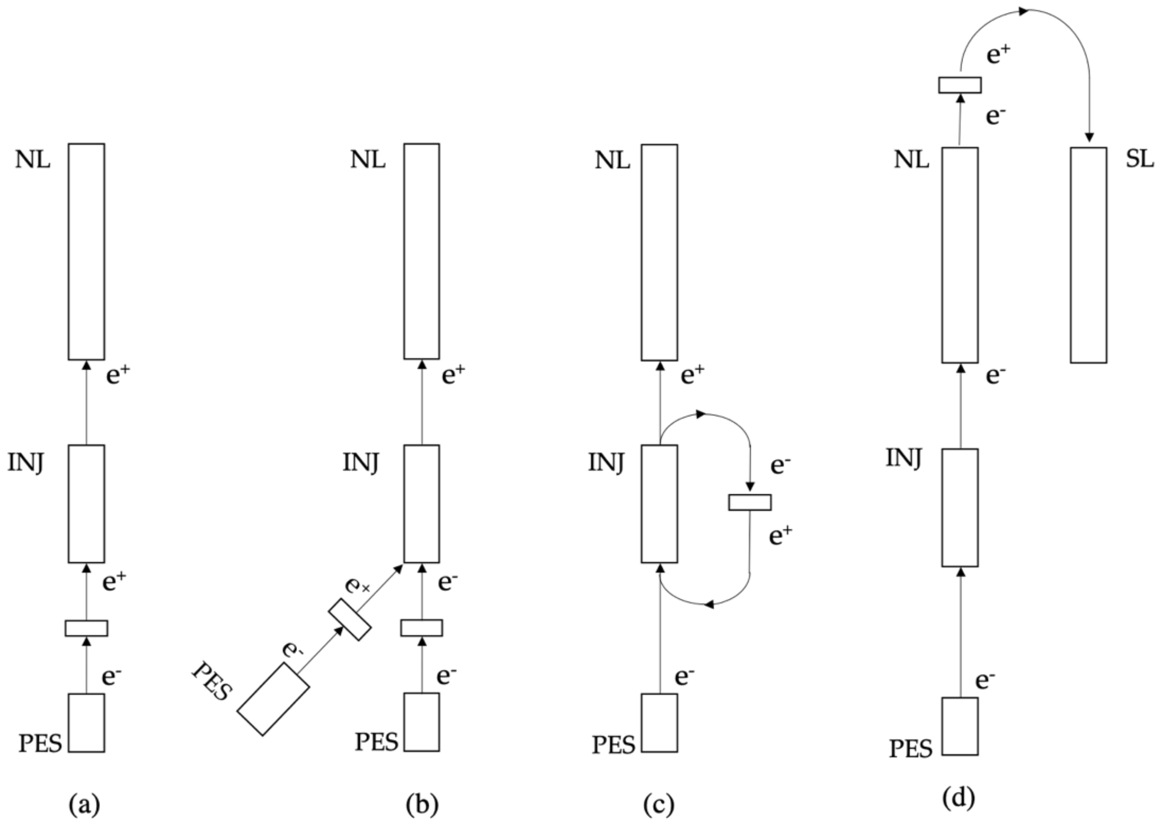

Figure 1. Four potential schemes considered: (a) low-E 10 MeV option, (b) high-E 123 MeV option, (c) high-E 123 MeV recycler option, and (d) very-high-E 1090 MeV option.

Choosing the target material & thickness

A target with a heavy nucleus produces the best stopping potential for generating bremsstrahlung radiation. Tungsten or alloyed compounds is recommended – having high atomic number (74), melting point (3422 C) and tensile strength (1700 MPa). Most likely the target would spin to evenly distribute a head load, so it must also have strength.

Next, the target should be thick enough to generate a healthy electromagnetic shower, yet not behave as an absorber. Two metrics are essential – the number of positrons produced per incident electron (Yield) and a figure-of-merit (Yield x Polarization^2) for polarized scattering experiments. Simulations were performed using the Geant4 tool-kit to find a target of 3 to 5 mm thick (see Fig. 2) is most appropriate – resulting in approximately 1 e+ for every 1000 e-. Assuming ~1% of the positrons are collected to a useful beam means 1 mA of polarized electrons is required (i.e. 123 kW).

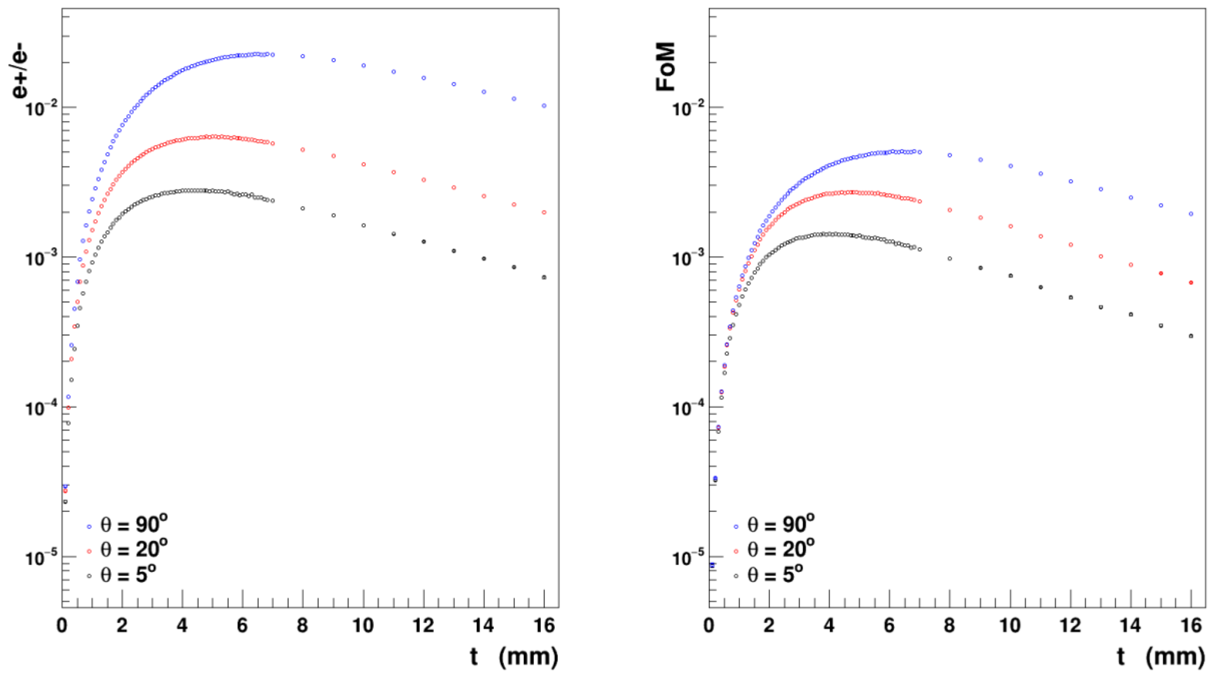

Figure 2. Simulated positron Yield (left) and FoM (right) versus target thickness.

New JLab software tracks positron spin

Positrons exiting the target have an extreme energy distribution – albeit with correlated yield, polarization and angular divergence (see Fig. 3). Collecting positrons to a beam must address converting an initial sizeable emission angle and energy spread of the positron distribution to a small angle and energy spread that is suitable for CEBAF.

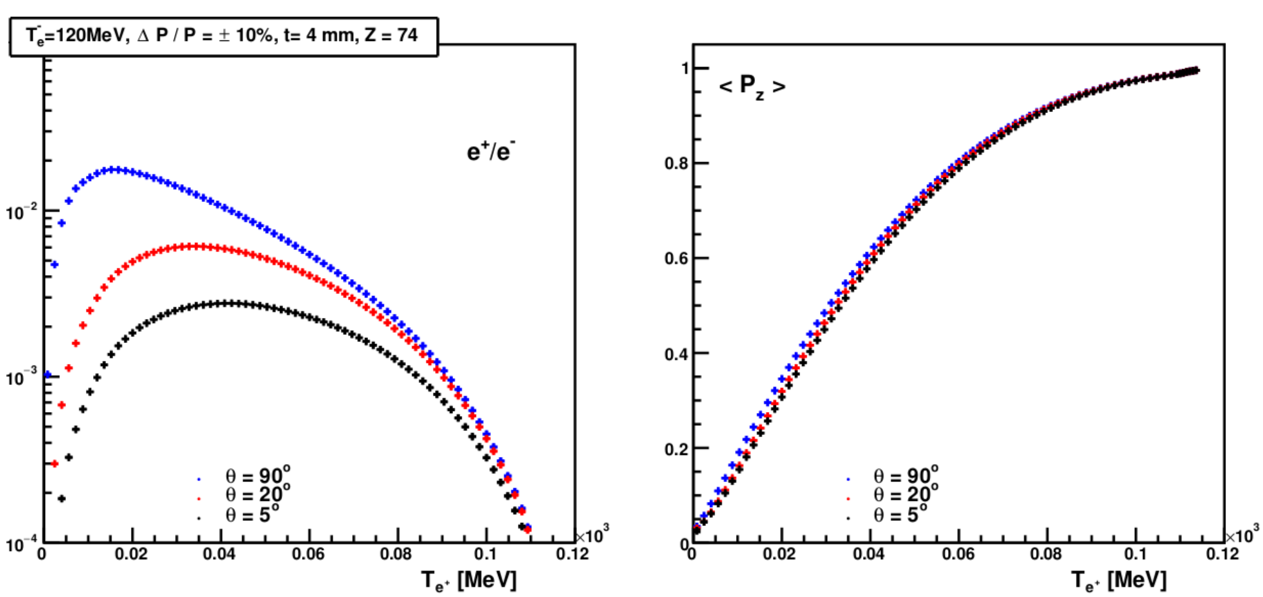

Figure 3. Positrons produced from 120 MeV e- impinging a 4 mm tungset target.

The model the magnetic and time-dependent electric fields (rf cavities) required to collect positrons the commercial software General Particle Tracer (GPT) is used, a natural choice as it is used extensively at JLab already to model the CEBAF, UITF and GTS beam lines. But, with one exception – GPT did not previously account for the particle's spin.

A significant accomplishment of this project is developing a GPT-Spin extension, cable to track particle spin coordinates in GPT using the generalized Thomas-BMT equation [Jac99]. When spin-tracking is enabled, the following differential equation is solved for the i^{th} particle

$$\frac{d\mathbf{s}_i}{dt} = \mathbf{\Omega}_i \times \mathbf{s}_i$$

where

$$\mathbf{\Omega}_i = -\frac{q_i}{m_i}\left[\left(a_i + \frac{1}{\gamma_i}\right)\mathbf{B}_i - \frac{a_i\,(\gamma_i \boldsymbol{\beta}_i \cdot \mathbf{B}_i)}{\gamma_i + 1}\boldsymbol{\beta}_i - \left(a_i + \frac{1}{\gamma_i + 1}\right)\frac{\boldsymbol{\beta}_i \times \mathbf{E}_i}{c}\right]$$

With $\mathbf{s}$ the particle spin coordinate, and $a_i = g/2 - 1$ where g is the particle's magnetic moment, generalized to any particle (electron, positron, proton, etc.). The software is now available in both the Windows and Linux OS – the latter is deployed to the JLab Scientific Computing platform ("the farm").

Optimizing a polarized positron injector

Within GPT candidate beamlines were simulated and optimized utilizing a built-in Multi-objective Global Optimization (GMO) Genetic Algorithm. The benefit of the GMO is that no assumptions fare made upon how beam property objectives relate to the beamline variables. Moreover, it avoids local maximal or minimal solution – in order to seek the globally best conditions regardless of complexity between the objective beam properties and beamline variables [Gee21].

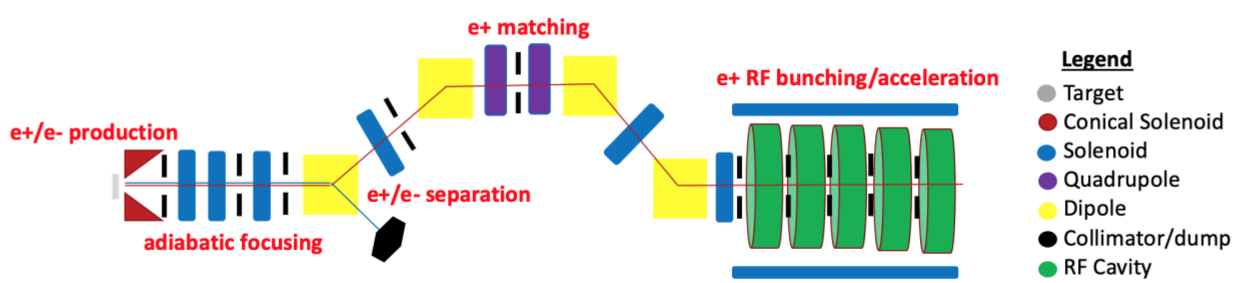

Figure 4. Toy model of a polarized positron injector for CEBAF.

Three positron injection schemes were studied, each illuminating a 3.5 mm W target with 1 mA of polarized electrons and energy 123 MeV. An optimum configuration was down-selected (see Fig. 4). Collection begins with a high-field 2.3 Tesla tapered solenoidal magnet – known as an Adiabatic Matching Device (AMD) – with large momentum acceptance in order to maximize the number of positrons which may be focused into quadrupoles and collimators which define the transverse acceptance [Gol10]. Next, a dipole separates electrons from positrons while also defining the momentum spread of the positrons across a dispersive aperture. A chicane compresses the bunch before passing through a warm-rf linac. The linac is immersed in a focusing solenoidal magnetic field to manage the beam size prior to injection at 123 MeV into the first linac of CEBAF (see Table 1).

Table 1. Properties of a polarized beam for injection in CEBAF.

Parameter	Polarized e^+ Captured	Polarized e^+ at Injection	CEBAF Acceptance
Efficiency	2×10^{-4}	4×10^{-5}	>5 x 10^{-5}
Mean Energy	63 MeV	123 MeV	123 MeV
$\frac{\Delta P}{P}$	15%	1%	2%
ϵ_n	90 mm-mrad	43 mm-mrad	<40 mm-mrad
Bunch Length	15 ps	3 ps	<4 ps
Transverse rms	4 mm	2 mm	<3 mm
Polarization	$\sim$ 66%	$\sim$ 66%	>60%

Summary

This LDRD provided the support necessary to hire a post-doctoral scientist and allow CIS, OPS and CASA scientists to work on this timely topic. A possible layout of a conventional injector for delivering polarized positrons at 123 MeV to the North Linac was optimized and the parameter space summarized. New spin tracking was developed within the commercial software General Particle Tracer – providing an important enhancement to the world-wide community using this software.

The LDRD is only a first step. Based on growing desire for positron beams at CEBAF and of interest by other institutions to collaborate future work will be supported by NP-Ops R&D beginning in FY22.

Conferences

M. Stefani and S.B. van der Geer, 24th International Spin Symposium, Japan (2021)

References

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