PROPOSAL FOR FY2021 LABORATORY DIRECTED RESEARCH AND DEVELOPMENT FUNDS

TITLE: A POSITRON SOURCE FOR OUR FUTURE

TOPIC: NEW RESEARCH DIRECTIONS USING EXISTING JLAB FACILITIES

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Mentor (if needed)	n/a
Proposal Term:	**From:** 10/2020 **Through:** 09/2022 **If continuation, indicate year (2nd/3rd)**:

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Abstract

The Program Advisory Committee of PAC46 (2018) agreed the development of positron beams (both polarized and unpolarized) would provide important new research opportunities for the 12 GeV CEBAF nuclear physics program. The 2018 Jefferson Lab Accelerator Advisory Committee (JLAAC) recommended further investigation of this capability at CEBAF. This LDRD proposal addresses the most challenging component - the positron source – providing a comprehensive evaluation of the technical aspects of the source (energy, target, collection) and defining a follow-on PEPPo-II prototype experiment.

Description of Project

CEBAF Users want beams of polarized and unpolarized positrons, with qualities and modes of operation similar to those of 12 GeV CEBAF electron beams. In 2018 the Jefferson Lab Positron Working Group (https://wiki.jlab.org/pwg) submitted a Letter of Intent to PAC 46 titled "*Physics with Positron Beams at Jefferson Lab 12 GeV*" [Gra18]. The PAC46 committee agreed the development of positron beams would provide important new research capabilities for CEBAF and the 12 GeV nuclear physics program, and stated specifically that:

> *"These measurements all have significant physics interest. The proposers should carefully evaluate feasibility and present the best case possible in a future proposal."*

The subsequent 2018 Jefferson Laboratory Accelerator Advisory Committee (JLAAC) reviewed the status of positron beams at Jefferson Lab issuing two recommendations:

- *"R26: Make an initial overall layout of what a full positron complex would look like at CEBAF including injectors, targets, capture regions, electron dumps, diagnostics, and new halls to see if an important design item has been missed."*
- *"R27: It would be a good time to re-verify if the following possibility is not better: Making polarized positrons from a 1.5 GeV polarized electron beam (i.e. a single pass in the North Linac) and sending this beam into a target or through a helical undulator to make polarized gammas."*

This LDRD proposal addresses the most critical aspect of these recommendations, the positron source. The production of antimatter in materials produces an extremely large phase space of resulting particles. For colliders, damping rings are employed to improve positron beam characteristics. But for CEBAF, the machine parameters are fixed, and no one expects to build a damping ring. Consequently, the positron distribution must be managed at the source. Specifically, the choice of the incident electron beam energy, the design of the conversion target limited by thermal and mechanical stresses, the integration of a magnetic matching device, and of RF cavities to capture and accelerate the positrons are the critical parameters to minimize transverse emittance and energy spread and maximize yield.

The positron source we propose includes spin polarization, which is VERY noteworthy. The scheme relies on the transfer of polarization from the electron beam to the positron beam. A PhD thesis [Dum11] produced the design of an experiment to evaluate this capability. In 2012, the Polarized Electrons for Polarized Positrons (PEPPo) experiment was performed at the CEBAF injector, using a simple target and modest electron beam energy ~8 MeV. The experiment demonstrated that polarization transfer can be highly efficient, with some positrons carrying the full electron beam polarization. The results were published in *Physical Review Letters* [Abb16] and the American Physical Society recognized the potential for broad impact in a Focus Article "Low Cost Polarized Positrons" [Sch16] published on their web-site.

News of the successful PEPPo experiment spread rapidly to users and positron source groups with diverse interests, from eV to GeV scale physics. A Jefferson Lab Positron Working Group with over 120 members from 39 institutions, of which more than 90% are Jefferson Lab Users, now promotes a program of physics experiments at CEBAF. The International Linear Collider project is considering a PEPPo-style source, to restore "polarization" to the baseline project [Cra19]. There is an international community of scientists that use positrons for materials studies who are very interested in the PEPPo technique, which could provide positron beam intensities that far exceed the capability beta-decay sources used today. Most recently, there has been discussion about positron beams at the Electron Ion Collider (EIC). These diverse physics interests are documented by many contributions to workshops and conferences, POSIPOL 2009 [Vou09], JPos 2009 [Elo09], EIC 2016 [Vou16] SPIN 2016 [Gra16], JPos17 [Gra17], NSTAR 2017 [Gra17a], ICPA 2018 [Gra18a], Linear Collider Workshops LCWS 2018 [Gra18b] and LCWS 2019 [Gra18c], and future invited talks, for example, 2020 CFNS Workshop on Beam Polarization and Polarimetry at EIC.

For CEBAF, various schemes for positron beams have been discussed. A PhD thesis [Gol10] explored the possibility of building an entirely separate 123 MeV electron accelerator to produce unpolarized positron beams. Another scheme [Car17] suggests producing and recirculating positrons through the existing 123 MeV injector, while a third suggested by the author is to build a small but intense 10 MeV positron source, leveraging JLab's capability to produce milliampere polarized electron beams, to minimize both cost and footprint. Schemes employing higher energy electron beams have been suggested as well, for example, an electron beam exiting the North Linac at 1.1 GeV, striking a conversion target, generating positrons that are transported to the South

Linac for acceleration, as referenced by the 2018 Jefferson Laboratory Accelerator Advisory Committee.

The proposed work will consider a number of realistic options, with electron beam energies of 10, 123 and 1100 MeV, and suggest the best approach for CEBAF (Figure 1 shows these schemes in broad context). The optimization will be based on polarization, and achievable positron beam current compatible with 12 GeV machine acceptance, as well as the overall cost, radiological impact and physical footprint. After this 2-year LDRD program, we can begin engineering and building the positron source.

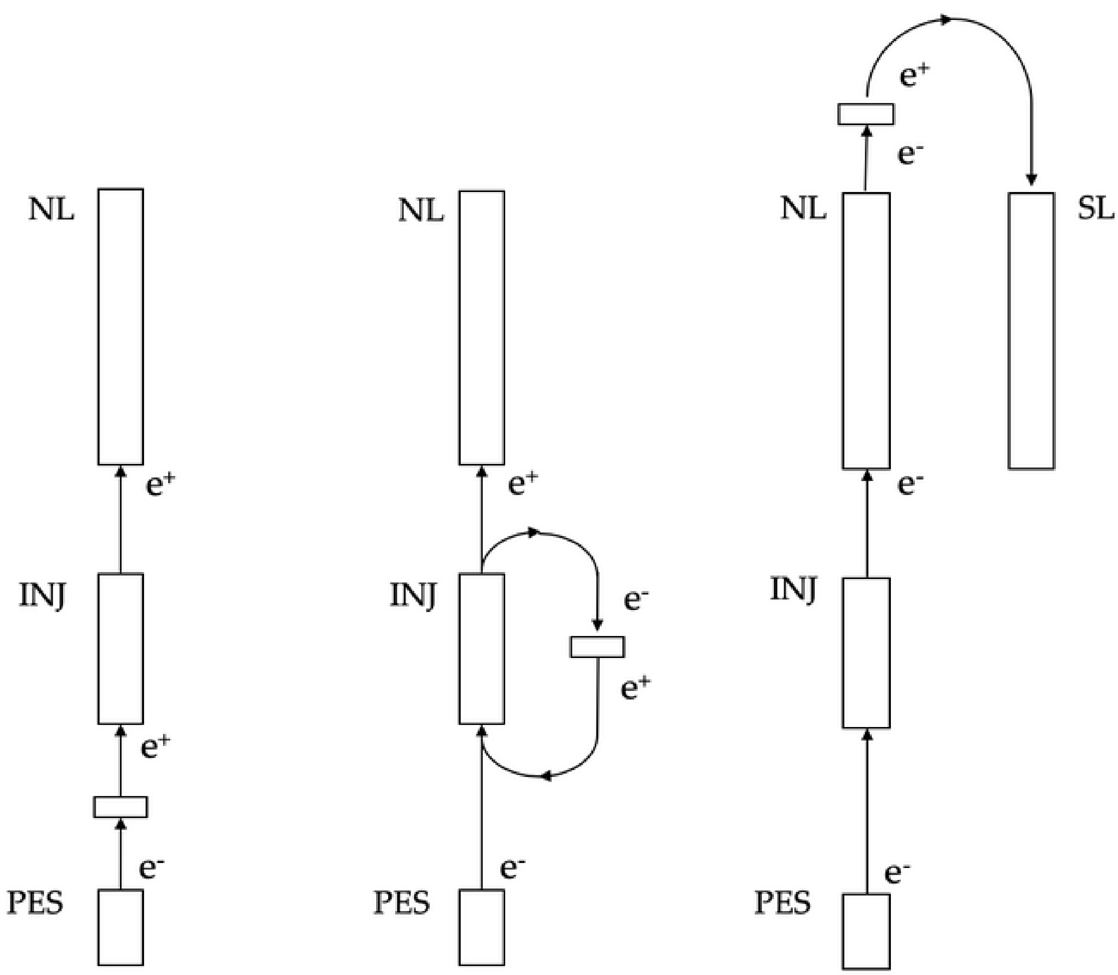

Figure 1. Three possible locations for the polarized positron source at CEBAF, from left to right with electron beam energies 10, 123 and 1100 MeV.

Expected Results

The three deliverables of this 2 year LDRD proposal are:

1) a technical evaluation of critical design parameters of a polarized positron source suitable for CEBAF, i.e., a positron source providing transverse and longitudinal emittance compatible with existing CEBAF linac structures (electron beam energy, pair-production target, positron collection)
2) a multi-object genetic algorithm optimization of a source concept that offers tunability between high intensity and high polarization, and
3) a conceptual layout of a proof-of-principle "PEPPo-II" experiment to test yield and polarization performance of a positron source.

This proposal is well aligned to the Jefferson Lab Strategic Plan and highly compatible with LDRD funding criteria, by exploring a new avenue for future Nuclear Physics at Jefferson Lab. Additionally, this technical evaluation will yield dividends in developing Jefferson Lab's competency in positron beams which may benefit a number of substantial science projects including the Electron Ion Collider [Doe20], the International Linear Collider [Hir19], CLIC [Bur18], the FCC-ee project [Cha19], or considered for a positron User facility such as needed for Quantum Information Science (QIS).

Proposal Narrative

Purpose/Goals

Polarized electrons have been key to some of the highest impact results of the JLab/CEBAF science program, including: measurements of the strangeness distribution in the nucleon (HAPPEX [Ani06] and G0 [Arm05]); precision tests of the Standard Model (Q_{Weak} [And13]); a measurement of the neutron radius of ^{208}Pb (PREx [Hor01]); and the accurate determination of the ratio G_E/G_M for the proton [Puc17] using the polarization transfer technique. During the life of the "6 GeV Program", the quality and intensity of polarized beams has evolved remarkably. Between the first experiment in 1995 and the shutdown in May of 2012 for the start of the 12 GeV Upgrade the Figure of Merit (P^2I) improved by a factor of 42 (from 30 μA beams with 35% polarization to 200 μA beams with 89% polarization) [Wei16].

Positron beams would provide a new tool for pushing the precision of electron scattering experiments further. The comparison of e^- results with the same data taken with e^+ beams tests our understanding of two photon effects in electron scattering, which currently define the limit of precision of these experiments. Furthermore, if the positron beams are polarized, two additional possibilities present themselves. First, one could expand the nature and sensitivity of the two-photon-effect experiments by allowing direct measurements of two photon effects in the polarization transfer experiments (such as G_E/G_M for the proton). Second, they would provide an essential tool for unraveling nucleon structure through the measurement of the charge-sensitive Generalized Parton Distributions (GPDs). There is also great interest in polarized and unpolarized positron beams for condensed matter physics.

Unfortunately, the creation of polarized positron beams is difficult. Radioactive sources can be used for low energy positrons [Zit79], but the flux is very small. Storage or damping rings can be used at high energy, taking advantage of the self-polarizing Sokolov-Ternov effect [Sok64]; however, this approach is generally not suitable for external target experiments performed at continuous wave facilities like CEBAF. Recent schemes for polarized positron production at proposed collider facilities like the ILC rely on polarization transfer in the e+/e- pair creation process from circularly polarized photons [Ols59,Kur10] but use different methods to produce the polarized photons. Two techniques have been investigated successfully: the Compton backscattering of polarized laser light from a GeV unpolarized electron beam [Omo06], and the synchrotron radiation of a multi-GeV unpolarized electron beam traveling within a helical undulator [Ale08]. Both demonstration experiments reported high positron polarization, confirming the efficiency of the pair production process for producing a polarized positron beam. However, these techniques require high energy electron beams (i.e., expensive linacs) and challenging technologies that limit their range of application.

The Polarized Electrons for Polarized Positrons (PEPPo) experiment [Abb16] demonstrated a new approach to the efficient production of polarized positrons. It used the highly polarized electron beam available at CEBAF and generated polarized positrons through a two-step process: bremsstrahlung followed by pair production, with both reactions taking place (in series) in the same physical target. Results of PEPPo, for an incident polarized electron beam of 8.2 MeV/*c* and 85.2% polarization are shown in Fig. 2. The transfer of the initial electron beam polarization to the extracted positron beam can be very efficient, approaching 100% as the positron beam momentum approaches the initial electron beam momentum.

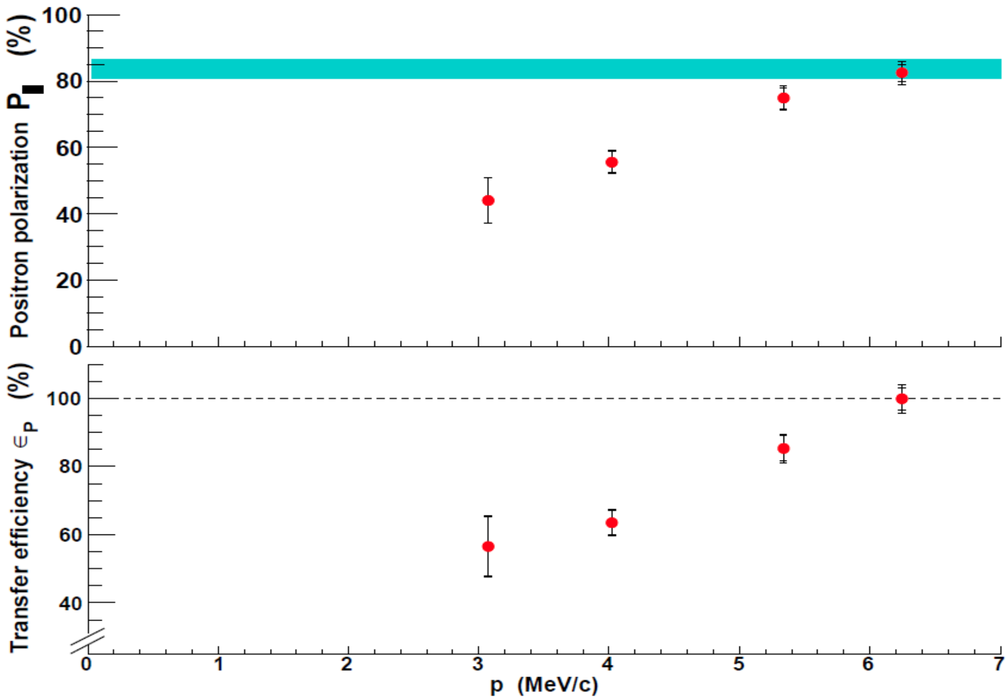

Figure 2. PEPPo measurements of the positron polarization (top) and polarization transfer efficiency (bottom); statistics and systematics are reported for each point. The shaded area indicates the electron beam polarization.

The PEPPo experiment only intended to demonstrate efficient polarization transfer, a very important first step towards the construction of a polarized positron source. This proposal represents the equally important second step, namely, it evaluates the pros and cons of performing PEPPo at various CEBAF electron beam energies, predicting the achievable positron yields and polarizations, the corresponding positron distributions in space and time, and it quantifies the requirements of collection devices that must be constructed to deliver acceptable positrons beams to existing CEBAF linac structures.

In plain spoken language, making positrons within a solid target is “messy”. This proposal evaluates this complex “positron mess” originating from a target located at various possible CEBAF electron beam energies. The optimum solution depends on competing factors. For example, a high energy electron beam (~ 1 GeV) provides greater yield, but polarization tunability becomes very complicated because of the large disparity between collection energies: 10’s of MeV for unpolarized positrons versus > 500 MeV for polarized positrons, and the source and surrounding area would become highly radioactive. Conversely, a lower energy electron beam (10 MeV) places a greater burden on the electron source (higher current), but offers a compact design more easily integrated into existing CEBAF and with much less activation. In both cases, the beam power will be high and the target geometry challenging. No less challenging, will be describing the optimum collection that satisfies collection losses and meeting the CEBAF transverse and longitudinal acceptance requirements.

Approach/Methods

To date, prospective positron Users at CEBAF have requested 1 μA CW unpolarized positron beams with typical CEBAF beam time structure, and 100 nA CW polarized positron beams with polarization > 60%. These are modest currents compared to normal e-beam CEBAF operations, but unfortunately only a small fraction of the generated positrons can be "captured" and accelerated to the halls, and an even a smaller fraction if the goal includes polarization.

Perhaps this biggest practical concern relates to tune up and real-time non-invasive beam monitoring of relatively low current positron beams during production running. Operations requires "Tune Mode" beam, with peak current high enough to be detected by beam position monitors, but with power low enough to avoid damaging the beamline when beam is mis-steered. "Tune Mode" at CEBAF describes beam with 8 μA peak current within a 250 μsec macropulse (plus the 4 μsec trailing macropulse). Producing this beam with only highly polarized positrons is VERY challenging and likely not possible working with CEBAF constraints. It is likely Operations can thread beam to the end stations with much less than 8 μA peak current, and this beam can be unpolarized. One scheme to consider is a positron source capable of collecting positrons beams of differing momenta, using the same target but with different collection settings. One mode collects a broad range of positron momenta for un-polarized tune up, and the other mode collects a narrow positron momentum spread, providing less current but high polarization.

Once a good orbit has been established, low current beam (≈100 nA) must be monitored and corrected for drifts. Many CEBAF diagnostics, in particular the receivers for beam position and beam current monitors, have been improved such that these devices function with far less current today [J. Musson, private communication]. Table 1 describes the capabilities of today's BPMs and BCMs. Clearly, it will be much easier to monitor the magnitude and position of positron beams at higher current, but CEBAF has successfully operated over day- and week- long periods with electrons beams of intensity less than 100 nA, and should do so similarly with positron beams. Alternatively, modulating the positron beam intensity at audio frequencies and employing lock-in amplifier detection techniques may be considered to improve diagnostic capability at low current.

Table 1. Summary of expected Jefferson Lab Beam Current Monitor (BCM) and Beam Position Monitor Stripline/M15 BPM performance (courtesy J. Musson).

Intensity	BCM	σ BCM, 1Hz	BPM	σ BPM, 1 Hz
10 nA	-80 dBm	<= 500 pA	-120 dBm	30 μm
100 nA	-60 dBm	<= 500 pA	-100 dBm	3 μm
1μA	-40 dBm	<= 500 pA	-80 dBm	0.3 μm
10 μA	-20 dBm	<= 500 pA	-60 dBm	0.03 μm
100 μA	0 dBm	<= 500 pA	-40 dBm	0.003 μm

A generalized list of positron source design goals is provided in Table 2, for positron beams generated *somewhere* at the CEBAF injector and accelerated up to 123 MeV for injection into the North Linac. The positron beam characteristics are based on the work of Golge [Gol11] who envisioned a completely separate and new 123 MeV electron/positron injector to produce unpolarized positron beams transported to the North Linac, with acceptable properties for acceleration and recirculation. An important goal of this LDRD proposal is to predict and optimize the positron beam specifications, for each candidate electron beam energy, to create positrons with acceptable quality for acceleration in existing CEBAF linac-structures.

Table 2. Broad design goals for the positron source, with positrons injected into the north linac at 123 MeV, based on Golge Ph.D. thesis [Gol11].

Parameter	Value
Tune Mode current	>5 uA within macropulse
Unpolarized e+ current	1 uA CW
Polarized e+ current	100 nA CW
Polarization	> 60%
Geometric Emittance	< 20 mm-mrad
Energy spread	< 2%
Temporal spread	< 5 ps

The basic components of a conventional positron source are depicted in Fig. 3 (beam moving left to right, [Che75]). Each of these components will be modeled as part of this proposal. The incoming electron beam arrives via a linac (S) with suitable downstream matching optics (FQ) to transport electrons to the positron conversion target (C). The target collection system must be capable of dealing with 10’s of kW of beam power and be integrated with a matching device (MD). The matching device is comprised of powerful solenoid magnets, with shaped aperture to focus positron distributions with large angles. Then a subsequent RF section, immersed in a solenoid magnetic field (S +

Sol), longitudinally captures and accelerates the positrons within a useful bunched positron beam. Finally, the beam is matched from solenoid focusing by a skew quadrupole transformation (TRQ) into the subsequent linear accelerator with normal quadrupole focusing (S + FODO).

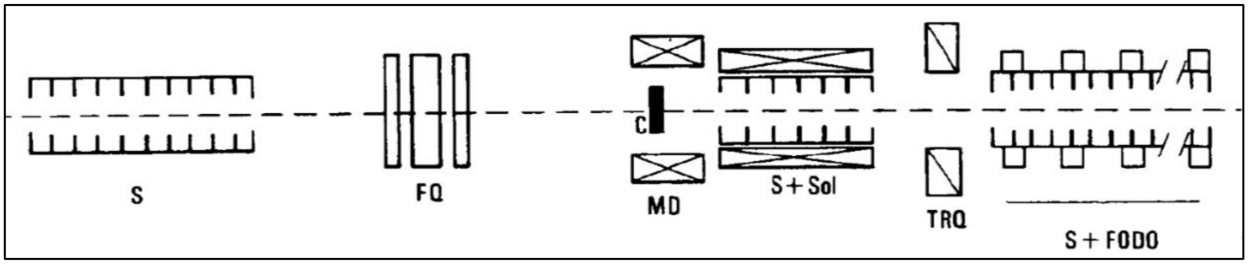

Figure 3. Conventional linac-based positron source (from [Che75]).

A positron source design is usually optimized to maximize yield and emittance. Our approach is different in two ways. First, we are constrained by the existing CEBAF 12 GeV machine and second, the design will be optimized not only for luminosity, but also for degree of spin polarization. Fig. 4 shows a sample positron distribution resulting from 10 MeV/c polarized electron beam, similar to conditions of the PEPPo experiment. Most positrons are produced with 2 MeV/c momentum but these positrons possess less than 20% polarization. These figures demonstrate the "cost" of producing polarized positron beams: most of the positrons (low energy) carry little (or opposing) polarization.

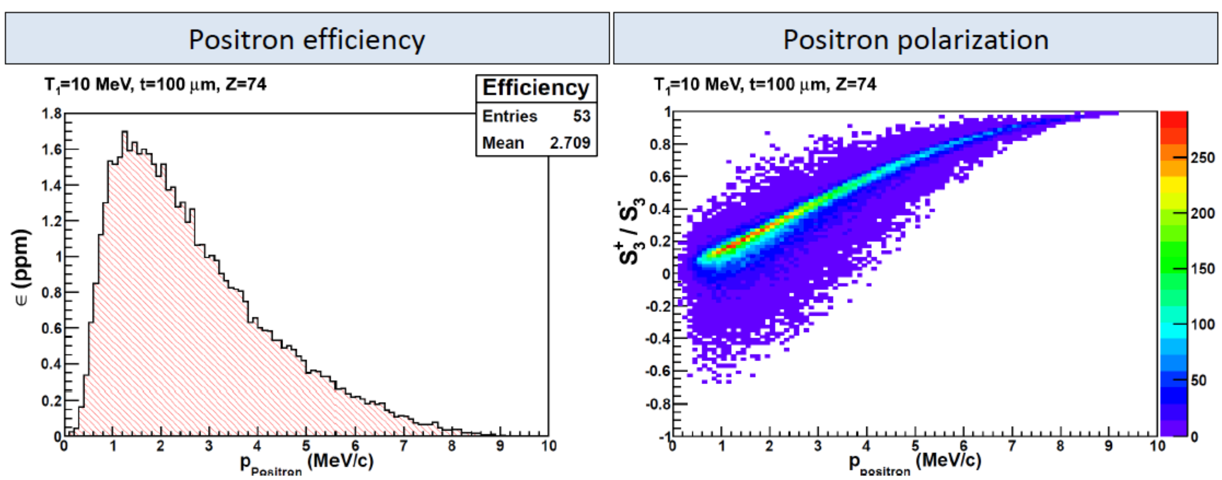

Figure 4. Example positron distribution (ε = Ne+/Ne-) and polarization (S^{+}_{3}/S^{-}_{3}) of a 10 MeV polarized electron beam striking a 0.1 mm thick tungsten foil.

In addition to re-evaluating the ≈10 MeV case explored for the PEPPo experiment and shown in Fig. 4, we will simulate positron production using higher energy electron beams. Fundamentally, the positron yield from an electro-magnetic shower depends critically on converting the electron beam power into bremsstrahlung photons with sufficient energy. Higher energy and/or higher electron beam current both serve to generate more positrons. But real-world targets melt, so increasing these quantities is not something that can be done without limitation. Further, there is an ideal target thickness to optimize the yield as a function of electron beam energy; and notably this optimum thickness changes when spin polarization is included since the positron polarization depends strongly on positron momentum.

At the highest level, our approach is to build a model that accurately includes polarized positron production and the components of a conventional positron source; then simulations can be performed to evaluate the critical parameters, mainly the beam energy and target thickness, which through simulations will characterize the yields (polarized and unpolarized), including spatial and temporal distributions that constrain CEBAF operations. Once our model and simulation is developed, we will use an advanced optimization technique to explore the large number of parameter dependencies. At the end of this work (about the time of the annual LDRD reporting) a review will be organized with invited experts to critique the prototype layout. Results will be summarized in a technical report and for publication. The remainder of this section describes technical details of the Topics that are to be addressed.

Topic 1 – Accurate Polarized Electro-Magnetic Cross-Sections

A model will be created to predict the spatial and temporal distributions of electrons, photons and polarized positrons emerging from the production target, as well as the energy deposited within the target. The model will be developed within the framework of Geant4, a software toolkit for the simulation of particles through matter [Ago03]. The two essential electromagnetic processes needed for the target simulations are bremsstrahlung and pair creation, both of which are available in Geant4. However, while the unpolarized cross-sections have been experimentally verified (see e.g. reviews by [Koc59,Tsa74]) the polarized cross-sections as determined in 1959 by Olsen and Maximon [Ols59] were performed in the ultra-relativistic limit (>100 MeV). For CEBAF injector energies (10 - 123 MeV), issues related to electron screening and energy conservation not treated by Olsen and Maximon lead to unphysical results (see Fig. 5). Navigating these "pot-holes" proved to be the bane of early PEPPo modeling and required developing an "in-house" version of Geant4 named G4PEPPo that includes hard-coded approximates necessary to accurately predict the polarization transfer from electrons to photons and from photons to positrons.

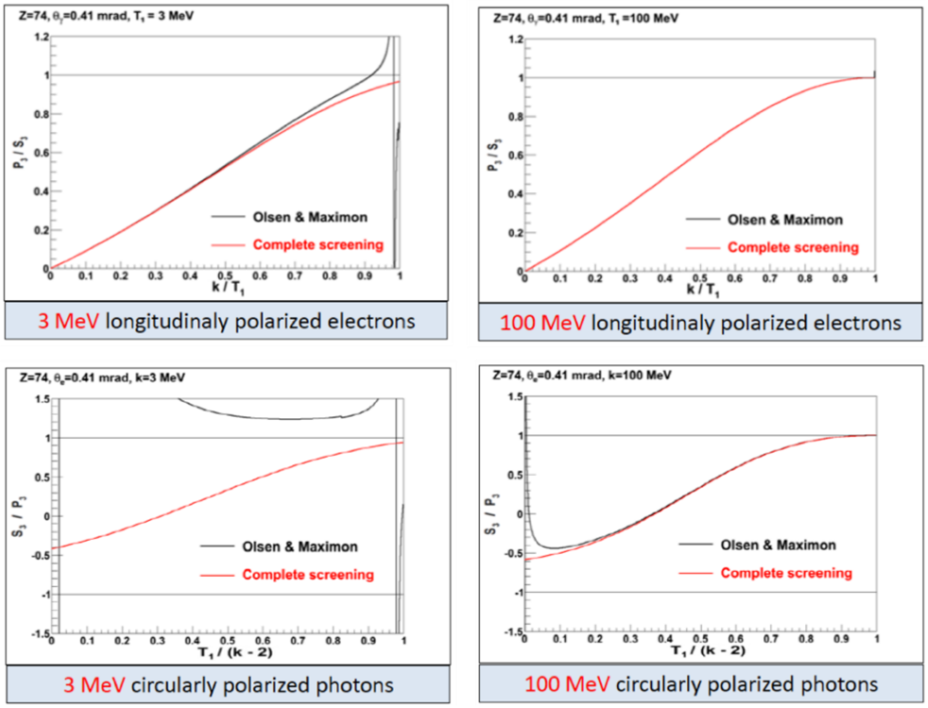

Figure 5. For CEBAF injector energies <123 MeV polarized bremsstrahlung (upper plots) and polarized pair-creation (lower plots) as calculated by Olsen and Maximon (**black**) lead to increasingly inaccurate or unphysical behavior (transfer > 100%) when compared with approximate, yet improved, calculations (**red**).

Since publishing the results of PEPPo, new theoretical calculations have been published [Kur10] (see Fig. 6) which accurately address polarized bremsstrahlung and pair-production and are globally valid at both low and ultra-relativistic energies, suitable for 10, 123 and 1100 MeV.

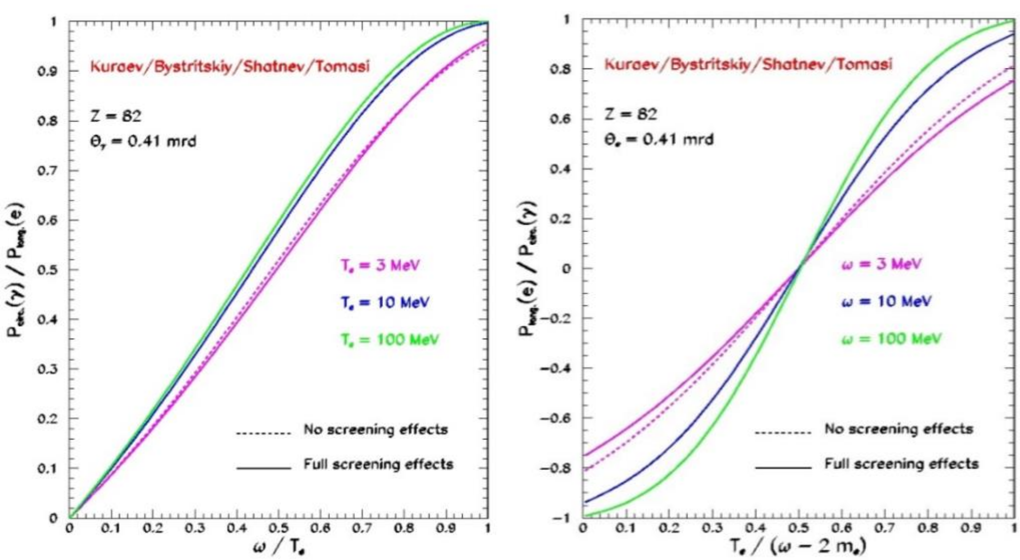

Figure 6. Modern calculations [Kur10] of the polarized cross-sections for bremsstrahlung (left) and pair creation (right) accurately account for screening and lepton masses at low energies and agree with the Olsen and Maximon calculations in the ultra-relativistic limit.

A first step will be to update and benchmark our "in-house" version of G4PEPPo with the new polarized cross-sections from [Kur10], which will provide continuity of the simulations across all the electron beam energies studied. A secondary benefit of this work will be providing the CERN Geant4 software group with a benchmarked update for future release.

Topic 2 – Modeling the Positron Collection System with Polarization

Positron beam intensity and emittance are strongly related to the methods of production and collection. Collecting large distributions of positrons from a production target is technically very challenging. Large emission angles-and large energy spreads must be transformed by a beam collection system into small angles and small energy spreads. These distributions are most sensitive to beam energy and target thickness, which are critical parameters for yield and polarization. Figure 7 once again presents the 10 MeV PEPPo condition, with the graph on the right showing the spatial distribution and energy spread of the (mostly) 1 MeV positron "beam" leaving a 1 mm thick tungsten target. To provide context, the CEBAF electron beam at 1 MeV has diameter 0.5 mm and energy spread <10 keV, considerably smaller than those of the positron beam.

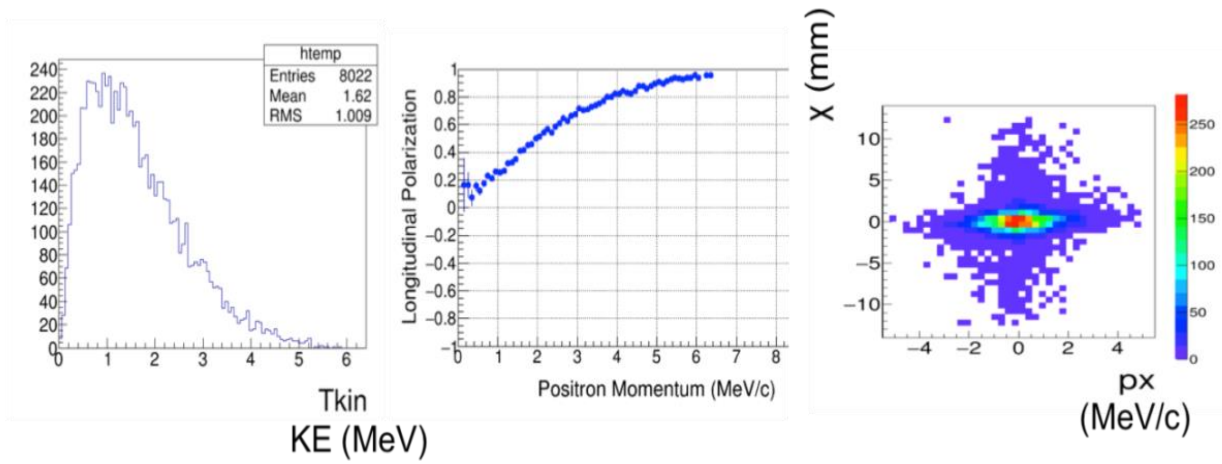

Figure 7: A Geant4 simulation exemplifies the relative energy, polarization and spatial/angular distribution resulting from a 100% polarized 7 MeV electron beam incident on a 1 mm thick tungsten foil.

The majority of the proposed work involves evaluating the positron yield and polarization for various target materials and thicknesses for a range of electron beam energies (10 to 1100 MeV). For photon and positron production in a single thick target, the total positron yield grows rapidly from the electro-magnetic shower until there is no longer sufficient energy for pair-creation. The target must be thick enough to let the shower propagate however thin enough so that positrons may still escape. When polarization is considered, *Yield x Polarization*^{2} is the target-specific quantity to optimize.

Multiple-scattering of the positrons grows in thicker targets and leads to dilution of the longitudinal polarization, however, thicker targets will absorb the lower energy positrons that contribute the least to polarization.

Notably, unlike any prior conventional positron source design, optimized only by yield and 6D-emittance, the CEBAF positron source must provide; a) high spin polarization, b) survive continuous-wave operation, and c) be compatible with the existing CEBAF energy footprint, nominally utilizing either the 10-123 MeV electron injector or one of the 1.1 GeV recirculating linacs. Key work will occur in this phase studying the (a) transverse and (b) longitudinal collection options:

Transverse positron collection is performed with a solenoid magnet "matching device" and the approach depends upon the expected positron yield and the allowed energy dispersion. The Quarter-Wave Transformer (QWT) is more conventional with a stepped solenoid magnetic field and small energy aperture, and the Adiabatic Matching Device (AMD) employs a tapered solenoid magnetic field with larger energy acceptance. We will evaluate both approaches in a "new" fresh manner in the sense that we have uniquely new criteria associated with polarization tunability and short pulse bunching of CW beams.

Longitudinal positron collection is achieved using a short warm-rf linac capture section immersed in a solenoid magnetic field to minimize losses. The main purpose of the linac is to provide the correct energy-phase correlation for matching into the downstream FODO-linac. An important aspect of the linac capture is to match the longitudinal phase of the positron distribution of positrons with different velocities passing through the magnetic collection system.

For initial studies, a generic conventional model of the target and collection system will be created or adapted from an existing layout. Simulations will be performed using the beam dynamics codes General Particle Tracer (GPT) and Astra. The CEBAF injector is already completely modeled in GPT, and additional existing magnetic or cavity field maps are readily available for CEBAF. Alternatively, model fields may be created with commercial codes CST Microwave Studio and Tosca or alternatively with free codes Poisson and Superfish. It is also likely that field models of existing QWT and AMD matching devices can be made readily available and shared from positron source groups at CERN, Italy, France or Japan.

Polarized positron collection requires simultaneous integration of the classical time-dependent spin equation of motion [Jac99] of the positrons through the electro-magnetic fields of the positron source beamline components. A beta version of GPT which includes spin tracking has recently been developed for Jefferson Lab and is being evaluated using the CEBAF polarized electron photo-injector beamline. We anticipate using this version of GPT with spin-tracking for this LDRD project, especially for optimizing the figure of merit *Yield x Polarization*^{2}. Modest additional development efforts to improve GPT are anticipated and budgeted for (a one week visit by the author to JLab) in order to develop an interface with the G4PEPPo event generator and to deploy an MPI (Message Passing Interface) instance of the code for parallel-processing on the Jefferson Lab scientific computing farm.

Topic 3 - Multi-Object Genetic Algorithm (MOGA)

We intend to apply a sophisticated optimization strategy to systematically evaluate the positron source model we develop. The Multi-Object Genetic Algorithm (MOGA) is a powerful method that implements principles employed in biological evolution to optimize multi-dimensioned non-linear problems. Introduced into accelerator physics relatively recently (1992) the Multi-Object Genetic Algorithm has been increasingly employed, first for optimizing the design of magnets and RF cavities, and later for increasingly sophisticated problems, such as determining the operating parameters to achieve the highest brightness high-current electron photo-injector ever [Baz05a], to optimize luminosity of the International Linear Collider design [Baz05b] and to optimize the design and operating costs for an SRF linac [Baz05c]. The proposed work would be synergistic with existing expertise at Jefferson Lab in applying the Genetic Algorithm to problems in accelerator physics [Hof13]. Specifically, the infrastructure for applying MOGA using simulation codes useful for the proposed work (Astra, G4Beamline and Elegant) exists at Jefferson Lab.

The MOGA optimization will be used to study and optimize the complicated phase-space relationships in regard to the spatial, temporal, momentum, and/or polarization optimization with respect to radiator configuration. While not all candidate solutions may practically be explored this way, the MOGA approach is a powerful utility for the conceptual design to proceed pragmatically and would be used when relevant to distill optimal specifications, from a clearly broad set of "parent" parameters. The strength of this technique with respect to the proposed work is the capability to globally judge desirable or dominant traits such as positron Yield, brightness (Yield/Emittance), figure of merit (Yield x Polarization^2), and so on. While some parameters readily optimize (e.g. one may always benefit from an electron drive beam with highest polarization), it is possible with a large parameter base for design-bias or local optimization (meaning, a subset of parameters in the system) to mislead.

Topic 4 – Managing High Beam Power at Conversion Target

As positron yield scales roughly with beam power, it is estimated that for all proposed scenarios roughly 50-100 kW of beam power will be required, assuming an efficiency of collecting 1 useful positron for every 100-1000 beam electrons. Collisional (2 MeV/g/cm^2) and radiative losses of the electro-magnetic shower as well as multiply-scattered primary electrons in the target (or separated beam dump) will need to be managed. The prompt mechanical stresses and long term radiative thermal stresses will need careful consideration related to material selection, cooling and long-term maintenance. In addition to these considerations, the real- and virtual- photo-neutron reactions that lead to radioactivity must be considered, which depend on threshold energies and scale with total beam power.

A single stage source, combining the positron capture with the higher power absorber capable of dissipating 100 kW represents a challenging design that limits collection efficiency. For example, a single stage requires a sophisticated vacuum volume including the target and magnetic matching device, and shielding for the surrounding area adds practical and environmental overhead. As an alternative, we will study a two-stage source design with separated radiator and positron production target. It could be easier to design a radiator that dissipates the majority of the electron beam power, and a separated positron production target that must function with only a few percent of the total power. It will provide more comfortable heat and radiation conditions for the e+ capture hardware. The design choices for a two-stage target may include magnetic field removal of the spent electron beam, or may utilize electron scattering and narrow collimation to absorb the bulk of energy inside the shielding. Another solution would keep some positrons produced forward in the radiator - but it will increase also the flux and power of forward-going electrons significantly, so it should be optimized and checked for the figures-of merit.

Topic 5 – Design of a PEPPo-II Prototype

A main deliverable of the LDRD is a "PEPPo-II" prototype that can be experimentally evaluated. Once designed and built this apparatus would be tested (either at the CEBAF injector or at LERF) to measure the polarized and unpolarized positron yields within the acceptance specifications of CEBAF. We note that if the apparatus is built carefully, and the calculations are accurate, it should be straightforward to use it at CEBAF.

A diagram of a possible experimental setup to test positron production and efficient CW collection is illustrated in Fig. 8.

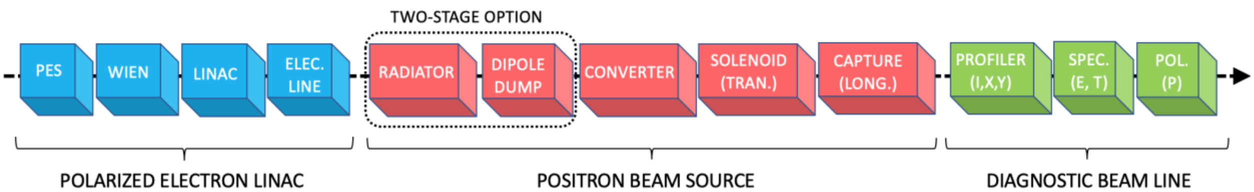

Figure 8. The main parts of the PEPPo-II proto-type experiment are the polarized electron linac the positron beam source with target and collection components, and a diagnostic beam line to measure the beam distributions (intensity, emittance, energy, time, polarization).

The experiment includes three main parts,

1. ***Polarized electron linac*** – A dc high voltage photo-gun provides polarized electron beams with characteristics similar to those at CEBAF. A bulk GaAs photocathode conveniently provides high intensity beams with ≈35% polarization; later a superlattice GaAs/GaAsP photocathode with ≈90% polarization will be tested. A Wien filter is helpful for systematic calibrations, but is not essential as the polarized source already provides the necessary longitudinal polarization. The beam energy and current determined by the LDRD are the main factors in selecting the linac to use. A short electron beam line manages the beam position and size at the positron production target, and includes necessary diagnostics (beam current (BCM), position (BPM) and profile (HARP) monitors).

2. ***Positron beam source*** – Elements of the positron beam source are the focus of this LDRD and have been described in detail. The eventual engineering design of the positron beam source requires as additional main components shielding from radiation produced within the target, a cooling system to 'dump' beam power lost to the target or apertures, and power supplies for the solenoid and RF capture elements. The prototype may have the capability to test both the single-stage and two-stage targets concepts.

3. ***Diagnostics beam line*** – A diagnostic beam line characterizes the beam distributions from the positron source. The diagnostic beam line will be capable of operating with both positrons and electrons to exploit a technique used for PEPPo by first "tuning" the beam line and calibrating diagnostics with an electron beam or energy-degraded electrons from a thin target before switching polarity for positron beams. The positron beam intensity and position are measured with a combination of silicon detectors, annihilation counters, and conventional diagnostics used at CEBAF to monitor electron beams (Faraday Cup, wire scanner, BPM and BCM). The positron beam energy and energy spread are measured with

a magnetic spectrometer and profile diagnostic. The temporal spread of the positron bunches are determined from measurements of their beam size in the spectrometer after imparting an energy-time correlation on the positrons within the RF capture section. A Compton transmission polarimeter will be used to measure the positron beam polarization, after first being calibrated with a well-known electron beam polarization.

Goals for FY21

- Q1
    - Identify graduate student and new hire post-doc for Q2 start date
    - Develop a GPT interface to Geant4 and test spin tracking of positrons
    - Review of past positron source, literature, discussions with experts
    - Develop framework for simulations using analytic calculations
- Q2
    - Implement new polarized electro-magnetic cross-sections to Geant4
    - Implement Geant4 interface and parallel processing to spin version of GPT
    - Review and summarize solenoid magnet and RF cavity options
- Q3
    - Use Geant4 to evaluate polarized distributions (e+/e-/photon) and deposited power in target as a function of beam energy, target material and thickness
    - Evaluate and define CEBAF acceptance using Elegant and/or beam studies
    - Build a GPT model of a positron source with AMD/QWT and RF capture
- Q4
    - Evaluate multi-momentum collection from single target using test bunch distribution
    - Evaluate single- and double-stage target distributions using Geant4
    - Complete evaluation of the target distribution parameter space

Goals for FY22

- Q1
    - Guided by the parameter evaluation, define and evaluate start-to-end layouts in GPT (e.g. dedicated positron injector, a recycled injector or a north linac injector)
    - Concurrently, develop a framework for evaluating the integration and footprint of each source design, e.g. requirements of polarized electron source, electron linac, available space, estimate of required shielding
- Q2
    - A lengthy job, complete the MOGA optimizations of candidate layouts, evaluate and weigh the results, to select the best candidate

  - Begin defining the PEPPo-II layout and parameter space
- Q3
  - Finalize the layout and develop physical design requirements for the prototype source
  - Define specifications for the positron diagnostics and model the beam line
  - Hold a technical review of the proposed prototype layout and parameters
- Q4
  - Write-up and publish results of the LDRD
  - Give a seminar at JLab and at a workshop or conference summarizing the results
  - Write a proposal to build and test the follow-on PEPPo-II prototype

Required Resources

We expect to need the following resources from Jefferson Lab:

- desk space for a post-doc and graduate student
- scientific computing farm to run Geant4 and GPT MPI simulations
- disk space for storing simulation; note CUE area /group/positron already exists
- because post-doc contract will not begin until start of FY1Q2, may seek division level support for 3-6 months after the LDRD ends

Anticipated Outcomes/Results

At the end of the project we will have evaluated critical design parameters of a linac based polarized positron source for CEBAF. In doing so, we will have developed a new core competency, improved the Geant4 modeling software, developed a GPT model of a positron source and the framework for multi-object optimization. A key end result will be a layout of a prototype source design with optimized parameter set and diagnostics to characterize the yield, polarization and 6D beam quality.

- **Year 1** will be developing the tools for the positron source design including improving Geant4, implementing a spin-tracking MPI version of GPT on the scientific computing farm, building a positron beam model in GPT, and initial evaluation of parameter space by simulation.
- **Year 2** will be defining and optimizing a prototype layout in GPT, considering practical parameters of beam power, the integration to CEBAF, radiological footprint, defining a follow-on PEPPo-II prototype experiment, and most importantly recommending where to build the positron source for CEBAF.

Budget Explanation

Computers:

- If they don't have them, (2) computers for post-doc and grad-student

Personnel:

Year 1

- Joe Grames (20%) – co-PI, supervise daily work and collection studies
- Matt Poelker (20%) – co-PI, supervise progress and target evaluation
- Grad student (75%) – Leads Geant4, single- vs. two-stage target eval.
- Post-doc (75%) – Leads GPT MPI, multi-energy collection eval.
- Alicia Hofler (1 week) – Expert advisor on GPT & MOGA
- Pavel Degtiarenko (1 week) – Expert advisor on Geant & FLUKA
- Scientst/Engineer I (1 week) – Magnetic and RF cavity model support

Year 2

- Grames (20%) – co-PI, supervise daily work and source optimization
- Poelker (20%) – co-PI, supervise progress and PEPPo-II layout
- Grad student (100%) – Leads MOGA optimization and layout
- Post-doc (100%) – Leads CEBAF integration and PEPPo-II prototype
- Alicia Hofler (1 week) – Expert advisor on GPT & MOGA
- Pavel Degtiarenko (1 week) – Expert advisor on Geant & FLUKA
- Scientist/Engineer I (1 week) – Thermal and stress target model support

Travel:

Year 1

- Grad student – domestic trip to United State Particle Accelerator School
- Post doc – travel and/or relocation expenses (up to $3k)

Year 2

- Grad student – One trip to workshop a permitted workshop/conference
- Post doc – One trip to a permitted workshop/conference
- Review meeting – Two domestic trips to JLab + overnight (room/per diem)

Collaborators:

Year 1

- **Dr. Eric Voutier** (PEPPo co-PI) – Support room, per diem and rental car (no airfare) for two week visit to implement Geant 4 polarized cross-cross sections
- **Dr. Sebastiaan van der Geer** (author of GPT) – Support international airfare and on-site housing for a one week visit to Jefferson Lab to develop and

implement Geant4 interface and platform for parallel processing on the Scientific Computing cluster.

Year 2

- **Dr. Eric Voutier** – Support housing, per diem and rental car (no airfare) for a two week visit to Jefferson Lab to integrate diagnostics of the positron source prototype.

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Attachments

Please find attached four letters of support from the following individuals,

- **Dr. Marco Battaglieri**, Hall B Leader, Jefferson Lab
- **Dr. Lawrence Cardman**, (retired) Assoc. Director, Physics Division, Jefferson Lab
- **Dr. Farida Selim**, Dept. of Physics and Astronomy, Bowling Green State Univ.
- **Dr. Achille Stocchi**, Director of IJCLab and **Dr. Marie-Hélène Schune**, Head of the High Energy Physics Pole of IJCLab

Jefferson Science Associates

Thomas Jefferson National Accelerator Facility

May 28 2020

Subject: Letter of support for the LDRD proposal 'A Positron Source for our Future'

Dear LDRD Committee Member,

I'm writing to support the LDRD proposal 'A Positron Source for our Future' (PIs: J.Grames and M.Poelker).

Running a positron beam (unpolarized and polarized) using CEBAF provides an incredible opportunity to extend the physics program of Jefferson Lab in unexplored territories. Positrons will allow for testing fundamental symmetries of Nature, probe physics beyond the Standard Model and disentangle QED effects usually neglected but relevant for the ultimate assessment of the electromagnetic structure of the nucleon. The capability of running a high quality, high energy (up to 10 GeV) and intensity (up to 1 uA), highly polarized positron beam, in parallel to the standard CEBAF operations represents a unique feature not available elsewhere in the World. Elastic form factors, GPD functions, charged current physics as well as novel tests of the SM via electroweak interaction represent some of the physics topics among the reach program possible with a new positron beam at Jefferson Lab.

In these years, a significant progress has been made to solve the technical issues related to produce and accelerate a polarized positron beam to obtain a similar quality of the exceptional CEBAF electron beam. Proponents are engaged by many years in this program that dating back to the early PEPPo experiment, demonstrated the possibility of transferring efficiently the polarization from low energy electrons to positrons ready to be accelerated to multi-GeV energy. With this proposal they are addressing one of the most critical issues still remaining: produce a positron source with the highly demanding requested characteristic. If they will succeed, providing a technical evaluation of the future positron source suitable for CEBAF and a conceptual layout of a proof of principle of a generation-two PEPPo experiment, another step forward to bring a positron beam at Jefferson Lab and extend its already reach physics program will be done.

For all aforementioned reasons I'd strongly support the LDRD proposal 'A Positron Source for our Future'.

With my best regards,

Dr. Marco Battaglieri

Experimental Physics Hall B Leader

MBattaglieri

Jefferson Lab
Thomas Jefferson National Accelerator Facility
Exploring the Nature of Matter

Lawrence S. Cardman
Senior Scientist Emeritus

May 22, 2020

Drs. Joseph Grames and Matthew Poelker
Thomas Jefferson National Accelerator Facility
12000 Jefferson Avenue
Newport News, VA 23606

Dear Joe and Matt:

I was delighted to learn that you continue to pursue the goal of developing a world-class polarized positron source for CEBAF and am writing to support your application for LDRD funding for the project.

Positron beams would provide important new capabilities for nuclear physics at Jefferson Lab. A comparison of unpolarized electron and positron scattering permits the quantitative, experimental determination of the ultimate precision of electron scattering experiments. This precision is a key motivation for the lab's very existence. If, in addition, the positron beams can be polarized one could expand the precision determination to polarization transfer experiments, such as the measurement of G_E/G_M for the proton, a key result from the Jefferson Lab program. In addition, polarized positron beams would provide an important new tool for unraveling nucleon structure through the measurement of the charge-sensitive Generalized Parton Distributions (GPDs). The technology developed for the production of polarized and unpolarized positron beams is also of great interest for both high energy and condensed matter physics, and for the program planned for the Electron Ion Collider.

I regret that my current circumstances make it impossible for me to join your effort directly (my health has rendered commitments of this sort difficult to support), but I hope to follow your work and provide suggestions as my experience and expertise permit and look forward to the result of the work with great interest.

Sincerely yours,

Lawrence S. Cardman

Lawrence S. Cardman

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BGSU®
BOWLING GREEN STATE UNIVERSITY
Department of Physics and Astronomy

May 5, 2020

Dear Dr. Grames

On behalf of the positron community in the USA, I enthusiastically endorse your proposal to develop a positron beam source at Jefferson Laboratory. In the last International Conference on Positron Annihilation (ICPA-18) hosted in Orlando, Florida in August 2018, the positron community came together and discussed the absence of an intense positron source user facility in the USA, and recognize there exists an urgent need.

Positrons provide a unique and transformative probe in a wide range of fundamental and applied science, from positronium BEC and gamma laser to the study of engineered devices at the forefront of Quantum Information Science (QIS).

My group is now completing a state-of-the-art beam lines, one at Bowling Green State University and the second at Los Alamos National Laboratory, in order to moderate MeV energy positrons for the development of low energy beams. These beam lines can be readily reconstructed at Jefferson Lab whenever needed.

We recognize that your proposal, if funded and successful, would lead to an intense positron source with remarkable spin polarization properties like those illustrated by the proof-of-principle Polarized Electrons for Polarized Positrons (PEPPo) experiment. Such a capability that appears possible by this approach *is not available anywhere in the world*. We believe a positron source as you intend to pursue will enable fundamental research of significance importance in physics from the MeV to eV energy range, including transformative research in QIS.

Finally we would be glad to discuss future opportunities to collaborate and possibilities on developing a positron source at Jefferson Lab. Please do not hesitate to contact me if you need further support or have any questions at 419-372-9956 or faselim@bgsu.edu.

Sincerely

Farida Seli

Farida Selim
Associate Professor of Physics
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Achille STOCCHI
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& **Marie-Hélène SCHUNE**
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To Whom It May Concern

Orsay, May, 28th 2020

Subject: Support Letter for LDRD proposal "*A Positron Source for our Future*"

Over the last decade important research programs have existed within the international landscape to study and develop positron sources, each critically linked to the expected machine performance of a major research program (e.g. the ILC, CLIC, SuperKEKB, or FCC-ee projects).

Today, new and important physics experiments are envisioned for a future program of measurements at Jefferson Laboratory's 12 GeV CEBAF accelerator using both polarized and unpolarized positron beams. In comparison with electron beam measurements, positron beams offer a new set of experimental observables of importance to the study of the structure and dynamics of nucleons and nuclei via elastic and deep inelastic scatterings. They further provide new paths to test the Standard Model predictions with dark matter searches and charge conjugation violation experiments. In general, polarized and unpolarized positron beams at CEBAF support a large program of high impact measurements.

Critical to this endeavor is a careful optimization of the expected positron source design, to a) provide the beam intensity and polarization required for a successful program at CEBAF, while b) satisfying the existing requirements of the existing machine performance at CEBAF.

The Principal Investigators of the LDRD proposal entitled "*A Positron Source for our Future*" plan to address these issues, while also taking a highly innovative approach, which exploits the success of the Polarized Electrons for Polarized Positrons (PEPPo) concept. Within this framework each step of the positron production, capture and transport of a "conventional" linac-driven positron source will be evaluated not only for expected luminosity performance, but also for the degree of spin polarization.

This opportunity to explore a new route for positron beams offers not only a novel approach for retro-fitting CEBAF for polarized and unpolarized positrons beams, but also bodes to offer meaningful insight for both existing and future facilities as well.

In these regards, we highly endorse supporting this research activity and look forward to learn of its successes.

Sincerely,

Achille STOCCHI   Marie-Hélène SCHUNE

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