

Laboratory Directed Research and Development Proposal
Title: jleic polarized positron injector

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| **Proposal Term:** | **From:** 10/2016**Through:** 10/2019**If continuation, indicate year (2nd/3rd)**:  |

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| --- | --- |
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Abstract

This proposal aims to generate polarized positron beams and perform critical tests to demonstrate the feasibility of a full scale positron beam injector for JLEIC, providing luminosity >1033 cm-2s-1 and positron polarization >40%. Simulations and corresponding measurements of the production, accumulation and conversion of polarized electrons to polarized positrons are planned. Three key areas of research include the polarized electron source/injector, the electron accumulator ring, and the polarized positron conversion source.

# Summary of Proposal

## Description of Project

Complementary to the proposed JLEIC electron-ion collider there is also physics motivation for positron-ion collisions, provided a luminosity >1033 cm-2s-1 and with positron polarization >40% is achievable.

*Lepton beam polarization asymmetry in neutral current deep inelastic scattering (NC DIS)*

The difference of the NC cross sections for leptons with different helicity states, predicted in the Standard Model, arises from the chiral structure of the neutral electroweak exchange. The lepton charge asymmetry of the NC cross sections can be used to measure the structure function xF3 using a combination of the unpolarized cross sections.

The charge-dependent longitudinal polarization asymmetries of the NC cross sections are defined as



The HERA results for polarization asymmetries are shown in Fig. 1. A variation of the lepton beam charge allows the structure function xF3 to be measured using the unpolarized data. The structure function xF3 can be obtained from the cross section difference between electron and positron data.



The dominant contribution to xF3 arises from the γZ interference, which allows xF3γZ to be extracted according to xF3γZ ≃ −xF3 /kae by neglecting the pure Z exchange contribution. The xF3γZ measurement is directly sensitive to the valence quark distributions [YF1].



Fig. 1. Measurements of the polarization asymmetry in the e+ p and e− p NC interactions at HERA.

*Charged current deep inelastic scattering (CC)*

The cross section for charged current (CC) deep inelastic scattering (DIS) depends linearly on the longitudinal polarization of the lepton beam [YF2]. Since the Standard Model does not predict right-handed charged currents, the cross section for electron(positron)-proton charged current DIS is predicted to be zero at polarization +1(-1). Measuring the total cross section as a function of polarization allows the Standard Model to be tested through searches for right-handed charged currents and setting a limits on the right-handed W-boson exchange. The linear dependence of the CC cross sections on Pe is shown in Fig. 2.

 

Fig. 2. Dependence of the e±p CC cross sections on the longitudinal lepton beam polarization Pe (left). Feynman diagrams for Charm production in (e+p) CC DIS (right).

*Charm production in Charged Current DIS*

Charm production in charged current (CC) deep inelastic scattering (DIS) is the best way to obtain information on the strange sea density [YF3]. Fig. 2 (right) shows Feynman diagrams contributing to charm production in charged current reactions up to O(αs) a) Born level, b) boson-gluon fusion. With the Standard Model, the Charm production in positron-proton (e+p) CC DIS is charge asymmetric, namely only the charm and no anti-charm quark is produced in the hard process.

*Beyond the Standard Model*

Longitudinally polarized positron beam offer extra sensitivity for some searches for physics beyond the Standard Model since chiral couplings are often involved in the production of new particles [YF4]. For example excited leptons require chiral couplings between ordinary left(right)-handed and excited right(left)-handed (anti)leptons. In addition, for squark production in R-parity violating SUSY models only left(right)-handed electrons (positrons) contribute, so polarized electron(positron) beams will give increase of sensitivity in these searches. Conversely for leptoquarks, where chiral states with coupling to left or right handed leptons are possible, a different lepton beam polarizations will allow a selective increase in sensitivity for different leptoquark-types.

Similar to the electron bunch train proposed for JLEIC [-1], a train of polarized positron bunches has been suggested (Fig. 1), based on a primary estimation of the luminosity for a full acceptance detector (Table 0) [0]. Considering the polarization design with two polarization states coexisting in the electron/positron collider, two long, oppositely polarized positron bunch trains are injected in to the collider. The time interval of 20 ms between the two bunch trains allows the injected beam to damp to the closed orbit and should be long enough for the source to change the laser helicity and flip the polarization.

In the JLEIC baseline design, the PEP-II 476 MHz RF system is reused in the electron/positron collider ring. Note that, 7/22 of the CEBAF linac frequency of 1497 MHz is 476.3 MHz. This frequency is well within the operational range of the PEP-II cavities and klystrons. Unlike the 476 MHz collision frequency for electron beams, the collision frequency for positron beams is chosen to be 159 (=476/3) MHz. By doing this, one can lower the stored positron beam current in the collider to reduce the injection time, but still reach the required luminosity. To synchronize the two bunch trains between the CEBAF and the collider ring, the polarized positron source operates at 22.7 MHz repetition rate (1/21 of the collider ring and 1/66 of the CEBAF SRF frequencies). Then the similar injection scheme for electron beams [-1] can be applied to positron beams, except that positron beams only occupy 1/3 of the RF buckets in the collider ring.

Table 0. Primary estimation of the luminosity for a full acceptance detector.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| CM energy | GeV | **33.5** | **40** | **52.9** |
|  |  | *p* | *e+* | *p* | *e+* | *p* | *e+* |
| Beam energy | GeV | 70 | 4 | 100 | 4 | 100 | 7 |
| Collision frequency | MHz | **476/3=159** | **476/3=159** | **476/3=159** |
| Particles per bunch | 1010 | 1.8 | **0.59** | 1.8 | **0.59** | 2.0 | **0.59** |
| Beam current | A |  0.46 | **0.15** | 0.46 | **0.15** | 0.5 | **0.15** |
| Polarization | % | >70% | **~40%** | >70% | **~40%** | >70% | **~40%** |
| Bunch length, RMS | cm | 2 | 1.2 | 2 | 1.2 | 2 | 1.2 |
| Norm. emitt., vert./horz. | μm  | 0.5/0.25 | 36/18 | 0.5/0.25 | 36/18 | 0.5/0.25 | 190/95 |
| Horizontal & vertical *β\** | cm | 4/2 | 5.8/2.9 | 2/4 | 4.1/2.0 | 7.1/3.55 | 2.4/1.2 |
| Vert. beam-beam |  | 0.002 | 0.15 | 0.002 | 0.15 | 0.002 | 0.03 |
| Laslett tune-shift |  | 0.056 | small | 0.028 | small | 0.03 | small |
| Det. space, up/down | m | 3.6/7  | 3/3.2 | 3.6/7 | 3/3.2  | 3.6/7 | 3/3.2 |
| Hour-glass reduction |  | 0.89  | 0.87 | 0.82 |
| Lumi./IP, w/HG, 1033 | cm-2s-1 |  **0.9** | **1.2** | **0.7** |



Fig. 1. Possible scheme for polarized positron injector bunch structure for JLEIC.

However, the creation of polarized positrons and with sufficient intensity is particularly challenging. Radioactive sources can be used for low energy positrons [1], but the flux is restricted. Storage or damping rings can be used at high energy, taking advantage of the self-polarizing Sokolov-Ternov effect [2], however, this approach is generally not suitable for continuous wave injection facilities. In the context of the International Linear Collider project, recent schemes for polarized positron production rely on the polarization transfer in the e+e−-pair creation process from circularly polarized photons [3, 4], 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 [5], and the synchrotron radiation of a multi-GeV unpolarized electron beam travelling within a helical undulator [6]. 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 the use and management of high-energy electron beams and challenging technologies.

A new approach, referred to as the Polarized Electrons for Polarized Positrons (PEPPo) concept [7, 8], has been investigated at the Continuous Electron Beam Accelerator Facility (CEBAF) of the Thomas Jefferson National Accelerator Facility (JLab). Taking advantage of advances in high polarization, high intensity electron sources [9] it exploits the polarized photons generated by the bremsstrahlung radiation of low energy longitudinally polarized electrons within a high-Z target to produce polarized e+e−-pairs. It is expected that the PEPPo concept can be developed efficiently with a low energy (10-100 MeV/c) and high polarization (>80%) electron beam driver, opening access to polarized positron beams to a wide community. Results submitted for publication in [10] demonstration positron polarization up to 82% have been measured for an initial electron beam momentum of 8.19 MeV/c, limited only by the electron beam polarization. These data show large positron polarization (P> 40%) for positron momenta >3 MeV/c. The bremsstrahlung of longitudinally polarized electrons is therefore demonstrated as an efficient process to generate longitudinally polarized positrons.

The pair creation and collection efficiencies are of critical concern for this proposal. Pair-creation scales approximately with beam power; so for example, at the Stanford Linear Accelerator Center a 35 GeV electron beam was used to produce and collect the 220 MeV positrons, with an e+/e- efficiency >1 [11]. But at, the APosS system at Argonne National Laboratory electrons are accelerated first 12-20 MeV, but with high pulse charge ~1000 nC in order to compensate for low efficiency ~10-7 [12].

The strategy we propose to compensate for the low positron efficiency is to accumulate charge. However, rather than accumulating “hot” positrons after conversion we propose to accumulate “cold” electrons before conversion. A high-level diagram of a possible positron injection scheme is shown in Fig. 2.



Fig. 2. A 10 MeV polarized electron injector provides bunches that are phase painted into an accumulate ring for 100-1000 turns before being extracted and directed to a positron conversion target, where polarized positrons are created and collected to a beam of about 5 MeV.

Accumulation of polarized positrons in the JLEIC electron collider ring requires an average polarized positron current of about 10 nA. Assuming polarized positron production and collection efficiency of about 10-5 demonstrated by PEPPo with a 10 MeV polarized electron beam, the required polarized electron current is about 1 mA. The positron production efficiency improves with increase in the electron energy. However, 10 MeV electrons have the advantage of being below the neutron production threshold and produce no activation. 1 mA average current is within the reach of a polarized electron gun. However, injection into the electron collider ring in a CW fashion is not possible because injected bunches need on the order of 20 ms to damp near the cores of the stored bunches. Therefore, injection requires very low-duty, relatively high-current macro bunch structure with low average current. Thus, the key of polarized positron injection is accumulation of low-current CW beam from the positron source into high-current, low duty-factor macro pulses.

Our proposed scheme for positron beam formation is illustrated in Fig. 2. Lowering of the duty factor is done in two steps. First, the frequency of the electron gun is lowered as much as practically possible. This is why experimental investigation of the electron gun performances at different repetition rates and bunch charges is one of the goals of our proposal. The second step is collection of the beam coming out of the source in an accumulator ring.

There are a number of techniques that are conceivable for beam accumulation. One may consider using damping rings for accumulation of a few GeV electrons or positrons. However, such damping rings are usually large complicated devices. At low energies of a few MeV, one cannot rely on synchrotron radiation for cooling. Another cooling technique, ionization cooling, even if feasible, results in large equilibrium emittances, which make the beam difficult to accelerate. Thus, we are left with the phase-space painting as, perhaps, the only applicable accumulation technique. The phase-space painting does not increase the local phase-space density but accumulates the beam at the expense of increasing its 6D emittance. For this reason, trying to accumulate polarized positrons with a low phase-space density would probably not be efficient. On the other hand, electron bunches can be generated at the photo cathode with very low emittances and can be efficiently stacked in the accumulator ring.

Finally, we optimize the positron production target region. Its design is a balance of the production and collection efficiencies. In fact, similar work has been done in the context of radiator region design for isotope production [Amy Sy reference]. The methodology is briefly described below. The target region design is one of the key components for production of a CW polarized positron beam. That is why, after completion of the electron gun experimental tests, we will focus on optimization and experimental testing of the positron collection system.

It is meaningful to note that besides JLEIC the motivation for positron beams at Jefferson Lab has broad interest (see Table 1 and Refs. [1-8]), as evidenced by User Group members for positrons at CEBAF, inclusion of positron beam parameters in Electron Ion Collider documents, and recent proposals for a Dark Matter Search and Slow Positron Facility at the LERF. A summary of possible physics interests [13] and required average positron intensity is provide in Table 1 with references.

Table 1. Physics interest using positrons at JLab in recent years.

|  |  |
| --- | --- |
| **Physics interest** | **positron intensity** |
| Two Photon Exchange [14] | 10 – 50 nA |
| Positron Proton Elastic Scattering [15] | 20 – 40 pA |
| GPD’s and DVCS with Positrons [16] | 8 – 40 nA |
| Inclusive Structure Functions [17] | 100 – 250 nA |
| U-Boson Dark Matter Search [18] | 20 nA |
| Slow Positron Facility [19] | 10 – 100 pA |

## Expected Results

* Polarized Electron Injector
	+ Experience operating polarized electron source at voltage >300 kV, bunch charge >1 pC, repetition rate <100 MHz, and current > 1mA,
	+ Multivariate optimization of 10 MeV injector configuration and application for test bed at JLab, e.g. at UITF, LERF, CEBAF
* Accumulator Ring
	+ Result…
* Polarized Positron Source
	+ Simulate and optimize positron distribution from possible pair-creation targets and collection with various magnetic geometries,
	+ Construct source and diagnostic line to characterize beam properties such as yield, energy spread, emittance and polarization,

# Proposal Narrative

## Purpose/Goals

The goal of this LDRD is to simulate, test and measure the production of polarized positrons for JLEIC. This is accomplished within the context of accumulating a high bunch charge of polarized electron necessary for producing the required polarized positron macro-pulse structure suitable for acceleration and injection into the ion collider. These simulations and measurements will provide insights on ways to optimize the JLEIC polarized positron injector, and help us design the appropriate electron source, accumulator ring, pair-production and positron collection method.

## Approach/Methods

|  |  |  |
| --- | --- | --- |
| Year/Quarter | Calc/Simulation | Design/Experiment |
| OCT-DEC, 2016 |  |  |
| JAN-MAR, 2017 |  |  |
| APR-JUN, 2017 |  |  |
| JUL-SEP, 2017 |  |  |
| OCT-DEC, 2017 |  |  |
| JAN-MAR, 2018 |  |  |
| APR-JUN, 2018 |  |  |
| JUL-SEP, 2018 |  |  |
| OCT-DEC, 2018 |  |  |
| JAN-MAR, 2019 |  |  |
| APR-JUN, 2019 |  |  |
| JUL-SEP, 2019 |  |  |

Below we describe the individual component of the polarized positron production system.

* Polarized Electron Injector

[Brief description of the polarized gun – Joe]



Fig. X. Time structure of the polarized electron beam injection at 6 GeV with the PEP-II 476.3 MHz RF system.

The preliminary scheme shown in Fig. 2 assumes that the gun operates at 22.7 MHz necessary for injection into the 476 MHz electron collider ring with an average current of 1 mA. This is to be demonstrated and optimized experimentally.

* Accumulator Ring

Synchronization of the accumulator ring with the electron source requires that the ring circumference is an integer number of bunch spacings at the source. The scheme shown in Fig. 2 assumes the ring circumference of two bunch spacings or, in other words, a ring harmonic number of 2 at 22.7 MHz. This gives a ring circumference of about 26.5 m. Increasing the ring circumference helps lower the duty factor but, of course, incurs a higher cost.

To preserve the polarization of the injected beam, the ring is shaped as figure 8. In a racetrack, the polarization of the circulating beam would undergo a rotation on each turn misaligning it with the injected beam’s polarization. If needed spin stabilization can be provided by a small solenoid. If considering solenoidal focusing of the circulating beam, which seems to be a good option for the optics design of such a ring, one has to compensate the spin effect of the focusing solenoids, for example, by using them in opposite-field pairs.

[High-level description of the accumulator ring requirements – Vasiliy]

* Polarized Positron Source

[Description of the target region design – Vasiliy]

Risk mitigation

[Brief description of the alternative design – Vasiliy]

## Specific Location of Work

The work will be performed at Jefferson Lab. For the purpose of the proposal we imagine to stage experiment tests at the Upgrade Injector Test Facility (UITF), however, these can be recast, for example, at LERF if practical. While tests will be performed at one lab area, we intend to offer a pre-conceptual design that may be staged at CEBAF, LERF or green-field.

We anticipate collaboration with Niowave Inc., to consider the integration of a high power radiation they are developing as a suitable pair-creation target. We intend to consider their target in simulation, and may consider an integrated beam test at Jefferson Lab. This outcome would possibly require a trip to Niowave to plan and coordinate the activity.

## Anticipated Outcomes/Results

The ultimate deliverable of this proposal is a pre-conceptual design of a polarized positron injector for JLEIC. Three critical areas are addressed, a) 10 MeV low-frequency, high-charge polarized e- injector, b) polarized electron accumulator/extraction figure-8 ring, and c) polarized pair-creation source with efficient collection of cw-MeV polarized positron beam.

Primarily, the design effort will address the efficient conversion of polarized electron beam power to a quality positron beam that may be accelerated to higher energy and for JLEIC injection. The design goal specifications will be motivated by a physics case for a positron-ion collisions at JLEIC, but consideration will also be given to [polarized] positron beams, for example, at CEBAF for the 12 GeV Nuclear Physics Program or LERF for a Slow Positron Program.

Explicit tests to benchmark capabilities for each of these sub-systems are presented with the aim to experimentally test some or all of these as the funding profile allows. Specifically, the following are meant:

* Polarized electron source (P>80%) operating at high voltage (>300 kV) with low repetition rate (<100 MHz), high bunch charge (>1 pC) with good operating lifetime (>200C) at high average current (>1 mA)
* Optimized parameters for acceleration of bunch train to ~10 MeV
* Electron accumulation ring with high gain (>100), preservation of polarization in figure-8 constructions (P>80%), and suitable injection/extraction (<100 ns)
* PEPPo pair-creation target with collection optimized for final yield, polarization, emittance, momentum spread, and bunch length, and bunch train structure

Those tests that are not performed within this project, can be proposed subsequent to, and guided by, this LDRD. The report will conclude with recommendations on how one may proceed toward a Conceptual Design Report to the DOE, particularly highlighting the engineering, development and risks associated with the effort. As stated earlier, we believe 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*.

# VITA (Lead Scientist)

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1. **Education**

B.S., Physics, Stevens Institute of Technology, Hoboken, NJ, May 1992

M.S., Physics, University of Illinois, Urbana-Champaign, IL, May 1994

Ph.D., Physics, University of Illinois, Urbana-Champaign, IL, Dec 1999

1. **Position**

1999-present: Staff Scientist and Deputy Group Leader, Center for Injectors and Sources

1. **Recent Journal Publications**
2. M. BastaniNejad, A. A. Elmustafa, E. Forman, J. Clark, S. Covert, J. Grames, J. Hansknecht, C. Hernandez-Garcia, M. Poelker, R. Suleiman, "Improving the Performance of Stainless-Steel DC High Voltage Photoelectron Gun Cathode Electrodes via Gas Conditioning with Helium or Krypton", Nuclear Instruments and Methods in Physics Research A 762 135 (2014).
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6. **Professional Activities**
7. Member - American Physical Society and Division of Beams
8. Referee - Phys. Rev. Accelerators and Beams and IEEE
9. **Committees**
10. Convener, Intense Electron Beam Workshop at Cornell U., Ithaca NY (2015)
11. Organizer, Int’l Workshop on Positrons at Jefferson Lab, Newport News, VA (2009)
12. Organizer, Workshop on Polarized Electrons Sources, Newport News VA (2008)

# Budget Explanation

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Attachments

*Include here (if desired), starting on a new page for each, additional information in the form of attachments.*