

Ce⁺BAF : Positron Beams at Jefferson Lab

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Nuclear physics experiments requiring spin polarized positron beams are being proposed at the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Laboratory. This workshop proceedings describes the framework for implementing polarized positron beams at CEBAF and highlights some of the main technical challenges. Specifically, a new polarized positron injector is needed, where the positron beam polarization is created from the bremsstrahlung of an intense continuous-wave (CW) spin polarized electron beam.

*19th Workshop on Polarized Sources, Targets and Polarimetry (PSTP2022),
26-30 September, 2022
Mainz, Germany*

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1. Motivation

Positron beams, both polarized and unpolarized, are identified as essential ingredients for the experimental programs at the next generation of lepton accelerators. In the context of the hadronic physics program at JLab, positron beams are complementary tools for a precise understanding of the electromagnetic structure of nucleons and nuclei, in both the elastic and deep-inelastic regimes. Furthermore, positron beams offer the possibility of alternative tests of the Standard Model of particle physics through the search of a dark photon, the precise measurement of electroweak couplings, and the investigation of charged lepton flavor violation. Perspectives on an experimental program with high duty-cycle positron beams at JLab may be found in [1, 2].

1.1 Framework

A relatively new technique referred to as PEPPo (Polarized Electrons for Polarized Positrons) [3] has been adopted for polarized positron beam generation at JLab. Here the spin polarization of a high energy electron beam is transferred to positrons in the two step process of polarized bremsstrahlung and polarized pair creation, both within the same high-Z target [4, 5]. This technique was tested

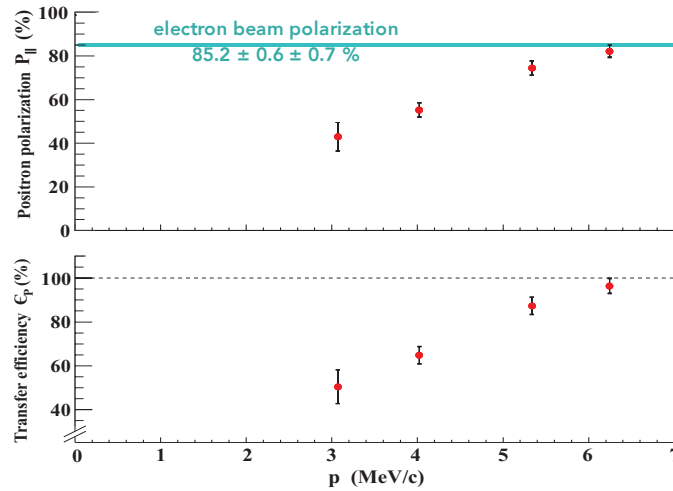


Figure 1: Positron polarization and polarization fraction reported in [3].

with an 8.2 MeV/c polarized electron beam at CEBAF, demonstrating positrons with polarization significantly above 50% (Fig. 1) and a maximum limited only by the electron beam polarization. Notably, the measured polarization transfer efficiency is expected to behave similarly for *any* electron beam energy, while the yield of positrons is proportional with the beam energy. For example, the yield of positrons at 4.2 MeV was measured to be about 10^{-5} but at 4.2 GeV the yield is nearly 1%. Importantly, in the PEPPo approach the figure of merit ($FoM = Yield \times Polarization^2$) maximum occurs at half of the electron beam energy. Consequently, one may choose the electron beam energy and electron beam current to achieve a desired polarized positron beam current.

1.2 Implementation at Jefferson Lab

The present baseline of Ce⁺BAF is optimized to provide users with spin polarization >60% at intensities >100 nA, and with higher intensities when polarization is not needed. To accomplish this

two existing accelerators will be modified. First, the Jefferson Lab Low Energy Recirculator Facility (LERF) building (see Fig. 2) will be repurposed to take advantage of existing electrical, cryogenic,

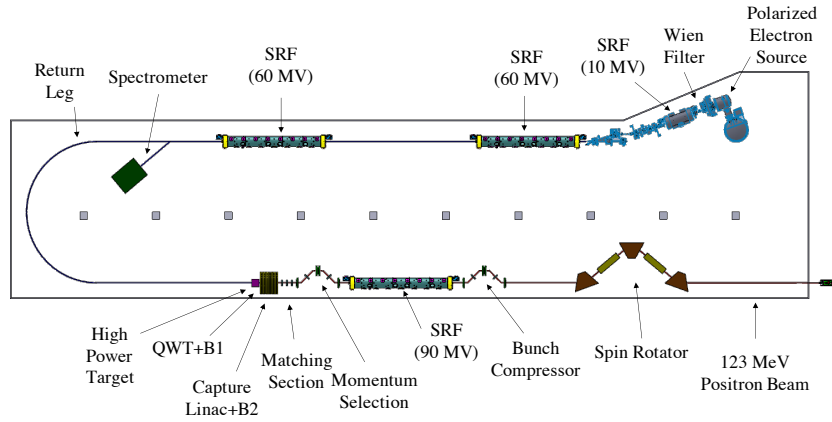


Figure 2: LERF layout of polarized e^- and e^+ injectors.

and shielding facilities. A high current >1 mA spin polarized CW electron beam is produced, accelerated to an energy of 120 MeV and transported to the high-power target to generate the spin polarized positrons. Afterwards, the positrons are collected to maximize intensity or polarization, bunched and re-accelerated to 123 MeV. Finally their spin direction may adjusted in a novel spin rotator. Once the positron beam exits the LERF it is transported from ground level through a new beam line (see Fig. 3) to the CEBAF accelerator tunnel underground. There the positron beam

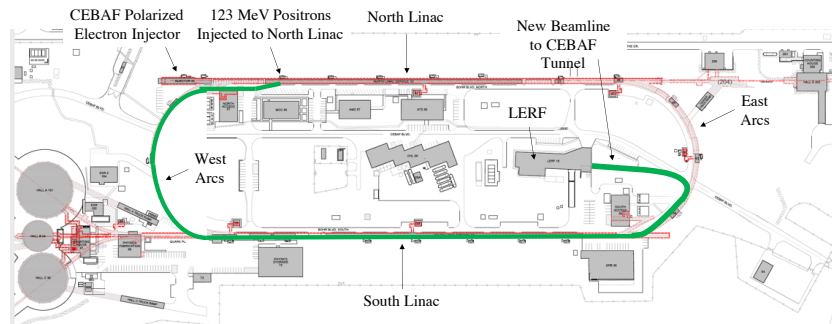


Figure 3: CEBAF and LERF accelerators. Green line shows the new 123 MeV transport beam line connecting LERF to CEBAF for high energy acceleration of positron beams.

is transported half-way around the accelerator and injected as a usual electron beam would from the existing CEBAF electron injector. The positrons are then accelerated to 12 GeV and may be extracted at any pass (intermediate energies) to any of the four halls.

2. Technical Challenges

2.1 Polarized electron source

Because the LERF electron injector is anticipated to operate with an energy of 100-200 MeV, the expected conversion efficiency from electrons to highly polarized positrons will be relatively

low, in the range of 10^{-4} to 10^{-3} . To compensate for the low efficiency the LERF polarized electron source (PES) should provide at least 1 mA of electron beam current to the conversion target for extended periods of time. The problem is that the quantum efficiency (QE) of GaAs is delicate. The electron beam leaving the photogun ionizes residual gases in its path and these ions then bombard the photocathode, reducing QE and therefore limiting the useful operating lifetime of the PES [6]. It is typical to describe the “charge lifetime” performance, describing the amount of charge extracted from the photocathode before QE falls to $1/e$ of the initial value. Assuming there is enough laser power, a typical photogun can continue to deliver beam to $1/10^{\text{th}}$ of the initial value, corresponding to $2.3 \times$ “charge lifetime”.

In units of charge, operating at 1 mA means the PES should provide 605 C/week, or about 2.4 kC/month. Consequently the LERF PES should operate with a charge lifetime >1000 C to provide the required beam currents for the proposed positron-based nuclear physics experiments. However, this is a demanding specification, especially when considering the charge lifetime of the CEBAF PES is 200 C [7]. Even achieving this performance resulted from many years of developments; improving the gun vacuum; eliminating stray electron emission with an activation mask; diluting and minimizing the areal damage of bombarding ions at the photocathode location where electron emission occurs. Consequently, reaching and exceeding a charge lifetime greater than 1 kC requires further improvement(s), especially when considering the LERF PES would operate with more demanding conditions of heating and potential for beam loss near the photogun.

In this context, three avenues of improvement are being explored. Firstly, the application of a small positive bias voltage to the photogun anode limits ions from entering the photogun, and thereby eliminates the highest energy ions from reaching the photocathode. This technique has been implemented at CEBAF resulting in improved charge lifetimes >400 C, an increase by about two when compared to an unbiased anode configuration [8]. Secondly, increasing the size of the drive laser at the photocathode distributes the number of bombarding ions over a larger area resulting in a slower rate of QE decay at the sites of photoemission. This technique had been implemented at CEBAF many years ago and achieved a four-fold increase when the laser diameter was doubled from 0.5 to 1 mm [6]. Most recently, tests performed at CEBAF demonstrated that increasing the laser area to 5 mm^2 further demonstrated an increase in charge lifetime to >400 C while operating with much higher current more than 1 mA and without anode biasing [9]. These results suggest further improvements should be possible, albeit likely requiring larger cathode and anode electrodes than exist at CEBAF to manage all of the electron beam without aberration or beam losses. Finally, a further reduction of the vacuum pressure in the vicinity of photogun would have a direct and proportional reduction in the rate of ion bombardment of the photocathode. This might be achieved by choosing different material of the vacuum chamber and cathode materials which have reduced outgassing gas rates. We intend to fabricate a new photogun chamber from low-carbon steel, which exhibits 1000 times lower H_2 outgassing. Recent measurements [10], including those made at JLab, show low-carbon steel possess H_2 outgassing rate in the 10^{-16} Torr L/s cm^2 range following relatively low temperature bakeout, this compared to 10^{-13} Torr L/s cm^2 of conventional 304 or 316 stainless steel baked at 400 C. Since the pressure inside a leak-free UHV/XHV vacuum chamber is directly proportional to the hydrogen outgassing rate, we expect significantly improved vacuum inside the new photogun.

2.2 High power e⁺ target

Three important metrics of the positron conversion target are the total Yield (number of useful positrons per incident beam electron), the average longitudinal polarization of the beam P_z and the statistical polarized Figure of Merit. The total yield of the e⁺/e⁻ pairs depends on both the electron beam energy and the thickness of the target; the target should be thick enough to generate a healthy electromagnetic shower, yet not behave as an absorber (see Fig. 4) shows that a tungsten converter of 3–5 mm is optimal when the electron beam energy is 120 MeV, yielding approximately 1 e⁺ for

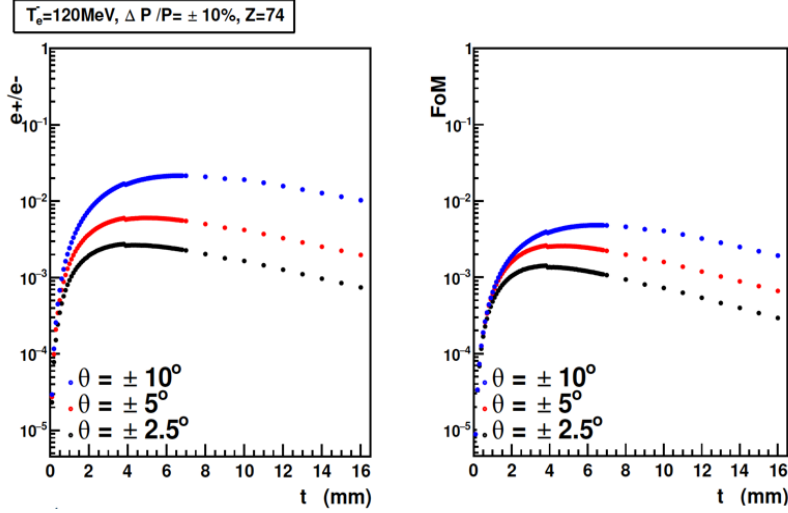


Figure 4: Positron yield and polarized FoM are computed as a function of tungsten target thickness for a beam energy of 120 MeV.

every 1000 incident e⁻. Assuming approximately 1% of the positrons are collected into the positron bunch for acceleration, an electron beam current of 1 mA is needed (i.e. 123 kW) for the production of a 10–100 nA polarized e⁺ beam. If a single conversion target is used as both the e⁻ radiator and e⁺ generator, it must have the ability to dissipate 15–20 kW of beam power and be closely integrated with the positron collection. This requires a sophisticated vacuum volume which includes the target, a vacuum beam line, some form of a powerful solenoid magnetic matching device, and shielding for the surrounding area. Both spinning solid and liquid jet targets composed of high Z atoms are considered for the target material. Consequently, significant conceptual development activities are anticipated for the high power e⁺ target and collection system.

2.3 Reversing CEBAF magnets for positron beams

The CEBAF magnetic transport system contains over 2100 magnets whose polarity must be configured separately for either electron or positron operation. Fortunately, more than 90% (>1900) are steering and quadrupole magnets with existing bipolar power supplies. These can be used for electron or positron beams without hardware modifications.

All the recirculation dipole magnets are powered by unipolar power supplies without polarity reversal capacity, namely 21 recirculation and dogleg units, and 18 power supplies in the extraction and beam dump lines. All 39 units and their respective shunt modules to distribute current to

magnets require an engineered solution for reversing the current and a firmware upgrade of the controls. The four experimental halls have a small number of mixed bipolar and unipolar power supplies for their beamline magnets that would similarly need to be addressed.

The magnets must provide reliable magnetic fields for both polarities. Existing bipolar magnet field maps have been examined for polarity invariance as an internal self-consistency validation. In some low-field magnets the earth's field is apparent, but only as a measurement offset. Generally, observations are consistent with no change in magnetic field performance with bipolar operation.

The unipolar recirculation dipoles have not yet been tested for polarity inversion. The relative size of effects associated with remnant fields (10–15 Gauss), sudden power supply trips which introduce uncontrolled flux as the dipole field collapses, and occasional adjustment or correction of hardware during the life span of the magnets suggest the magnet iron is magnetically “soft” enough such that no persistent calibration shifts after field reversal are anticipated. In order to test this, typical magnets operated at CEBAF require testing, for reliability after polarity inversion to quantify any systematic effects.

2.4 Acceptance of CEBAF 12 GeV

The injection chicane properties (aperture and dispersion) control the CEBAF beam acceptance. These are normally configured for low emittance and low momentum spread beams, but the configuration has considerable flexibility. For instance, the chicane dispersion can be configured to accept up to 2% momentum dispersion and for the low currents anticipated for positron operation, the acceptable RMS beam radius may be as high as several millimeters matching a normalized emittance acceptance of 40 mm-mrad for a beam energy of 120 MeV. Because this principal limiting aperture is very localized, it can be readily modified to increase its acceptance. After injection, the beam momentum is increased by a factor of 9 in the first linac (the north linac). The result of this strong adiabatic damping is that the momentum acceptance of the accelerator is dominated by the injection chicane. The transverse emittance is similarly strongly damped, and the injection chicane again provides a principal limitation.

Two main regimes are affecting the beam properties: the acceleration damping within the CEBAF accelerating sections, and the synchrotron radiation in the recirculating arcs. As can be seen from (see Fig. 5) the dynamics of the momentum spread of electron beams is dominated by synchrotron radiation. On the other hand, positron beams essentially benefit from acceleration damping which results in the same momentum spread than electron beams, despite a much larger initial momentum spread. The large positron beam emittance at the injector entrance is also strongly reduced by acceleration effects which result in a final emittance 4–5 times larger than the electron beams, resulting in beam sizes only about twice as large.

3. Outlook

The Ce⁺BAF working group developed a scheme to provide users with high energy polarized positron beams. Early calculations suggest achieving spin polarization >60% at intensities >100 nA, and with higher intensities when polarization is not needed. The focus in coming months is to further develop the design, and complete supporting simulations for LERF and CEBAF beamlines.

electron beam				positron beam			
Area	$\delta p/p$ [$\times 10^{-3}$]	ϵ_x [nm]	ϵ_y [nm]	Area	$\delta p/p$ [$\times 10^{-3}$]	ϵ_x [nm]	ϵ_y [nm]
Chicane	0.5	4.00	4.00	Chicane	10	500	500
Arc 1	0.05	0.41	0.41	Arc 1	1	50	50
Arc 2	0.03	0.26	0.23	Arc 2	0.53	26.8	26.6
Arc 3	0.035	0.22	0.21	Arc 3	0.36	19	18.6
Arc 4	0.044	0.21	0.24	Arc 4	0.27	14.5	13.8
Arc 5	0.060	0.33	0.25	Arc 5	0.22	12	11.2
Arc 6	0.090	0.58	0.31	Arc 6	0.19	10	9.5
Arc 7	0.104	0.79	0.44	Arc 7	0.17	8.9	8.35
Arc 8	0.133	1.21	0.57	Arc 8	0.16	8.36	7.38
Arc 9	0.167	2.09	0.64	Arc 9	0.16	8.4	6.8
Arc 10	0.194	2.97	0.95	MYAAT01	0.18	9.13	6.19
Hall D	0.18	2.70	1.03				

Figure 5: Synchrotron radiation effects typically begin degrading the CEBAF electron beam after Arc 4 (4 GeV), however, the larger positron beam 6d phase space generally benefits from SR until Arc 9 (10 GeV).

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