Opportunities and Challenges of a Low-energy Positron Source in the LERF

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Outline

• Motivation
• The Jefferson Lab Low Energy Research Facility
• Accelerator source in the LERF
• Target design
• Issues to consider.
• Summary (future work)
Why Positrons?

• $e^+$ diffraction limit is shorter than that of relevant energy photons --> atomic resolution
• $e^+$ interaction cross-section is greater than that for X-rays --> stay near the surface
• $e^-$ attracts into while $e^+$ repels from the material --> big advantage over TEM/AFM, for early stage material degradation monitoring, for single molecule detection, etc.
• $e^+$ can be traced inside the material while $e^-$ is getting lost inside the “electron sea”
• $e^+$ directly probes the electronic structure of metals and metallic compounds, positron annihilation (PA) with outer-shell electrons provides a direct image of the Fermi surface
• $e^+$ interacts with collective excitations --> molecular resonances in gases, vibrations in liquids and solids, delocalized and/or localized electronic states, defects in materials
• $e^+$ can probe surfaces and interfaces --> depth-profiling studies, 3D imaging of defects
• $e^+$ can form Ps in insulator materials, or in ($e^+ - e^-$) scattering reactions:
  Ps in vacuum --> a unique tool for advanced QED models testing
  Ps in material --> unaffected by Coulomb interaction (neutral !!), very sensitive to internal vibrations, has negative work function and tends to enter micro-cavities, probes free volume type defects and porosity (mechanical stability !!) of dielectric materials, including biological materials (e.g., living tissue), biopolymers, etc.
Difference between electron and positron refraction and reflect.
Difference Between Electron and Positron Auger Spectroscopy

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<thead>
<tr>
<th>Method</th>
<th>EAES</th>
<th>PAES</th>
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<tbody>
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<td>Current</td>
<td>$I_{e^-} &gt; \mu A$</td>
<td>$I_{e^+} &lt; pA$</td>
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<td>Setup</td>
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<td>SNR (relative to EAES)</td>
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Comparison of e+ Beams

• Over the years, it has been recognized by experts of positron community the necessity to have a slow positron source exceeding at least $10^9$ e+/s.

• At present, the NEutron induced POsitron source at MUniCh (NEPOMUC) provides the world’s highest intensity of $\sim 9 \cdot 10^8$ slow e+/s.

• The proposed e+ beam at the FEL will have:
  a) 10-40 times higher positron intensity ($>10^{10}$ slow e+/s)
  b) brightness would be at least 1000 times higher than available brightness at the best existing facility.
Existing slow positron facilities (T+ < 30 keV)

A) Radioisotope-based slow positron facilities:

- Positron emitting isotopes are used, i.e. $^{22}$Na ($t_{1/2}=2.6$ yr), $^{58}$Co ($t_{1/2}=71$ d), $^{18}$F ($t_{1/2}=109$ min)
- Advantages: Commercially available, low infrastructure costs, modest radiation shielding
- Disadvantages: Low-intensity (<10^6 slow e^+/s)
- Operational: There are many small-sized research and medical labs in the world

B) Reactor-based slow positron facilities:

- Positrons are produced via pair-production from the emission of high energy prompt γ-rays after thermal neutron capture i.e. $^{113}$Cd (n, γ) $^{114}$Cd
- Advantages: e^+ intensity is proportional to the reactor core power
- Disadvantages: Radiation concerns, high initial cost of infrastructure, large source size
- Operational: North Carolina State University Positron Source (Projected ~ 5x10^8 slow e^+/s)
  - Munich Reactor Positron Source (Achieved: ~9x10^8 slow e^+/s)

C) Electron linac-based slow positron facilities:

- Positrons are produced via pair production from bremsstrahlung photons
- Advantages: e^+ intensity is proportional to intensity of incident electron beam, adjustable time structure.
- Disadvantages: Radiation concerns, high initial cost of infrastructure
- Operational: Elbe Positron Source (EPOS) in Germany. Projected ~10^8 slow e^+/s
  - Advanced Industrial Science and Technology (AIST) in Japan. Achieved ~10^7 slow e^+/s
Most intense positron sources

![Graph showing the intensity of positron sources from various locations. The y-axis represents the logarithm of the positron intensity in units of $e^+$/s, and the x-axis represents the location. The graph includes points for China, Japan, Romania, Japan (another location), Japan (another location), Germany, Canada, Netherlands, USA, and Germany. The sources are represented by different symbols: Linacs by squares, reactors by stars, and $\gamma$-beams by triangles.]

JPos17, Sept. 12-15, 2017
JLAB ERL: Low Energy Research Facility (LERF)

- Existing facility
- Variable time structure from the electron source (photo-gun)
- The intensity of electron beam on $e^-$ - $e^+$ pair conversion target up to 1 mA
- High quality of electron beam
Production stages of slow positrons at accelerators

- **Linac**
  - High energy e\(^-\) beam

- **Converter**
  - \(e^+ \sim < 5 \text{ MeV}\)
  - \(\eta_+ = e^+ / \text{incident } e^-\)

- **Moderator**
  - \(e^+ \sim 1-30 \text{ keV}\)
  - \(\eta_{++} = \text{slow } e^+ / \text{fast } e^+\)

- **Electrostatic extraction, remoderation, and focusing**
  - \(e^+ \sim 3-4 \text{ eV}\)

- **Sample**
  - Monoenergetic beam with a spot size \(\Theta < 0.1 \text{ mm}\).
Concept: The concept in our design relies on transport of positrons ($T_e$ below 600 keV) from the converter to a low-radiation area for moderation in a high-efficiency cryogenic rare gas moderator.

Key features:
- Incident $e^-$ beam: 120 MeV – 0.25 mA (30 kW)
- Rotating electron-positron converter
- Synchronized raster magnets
- Solenoid transport channel
- Beam-dump (~ 8 kW)
- Radiation shielding of the converter area
- Extraction to a magnetic field-free area
- High-efficiency solid-Ne moderator
- Micro-beam formation via remoderation

*The illustration is not to scale.*
Proposed location in the FEL vault

(Left) A new (3rd) port next to the IR-UV beamline that will enable $e^-$ beam to be sent to the positron converter target.

(Right) Collected $e^+$ will be transported vertically to the User Lab-6 (~ 20 x 30 ft$^2$) for moderation and physics experiments.
FIG. 5: Concept of transport through the solenoid channel (a) without and (b) with the magnetic steel plug. Solid blue lines show e\(^+\) track. Dashed red lines are magnetic field lines. Only the upper half of solenoid is shown. (c) OPERA 3D Model of the magnetic plug is shown.

FIG. 7: Kinetic energy of the positrons after the iron plug. Positrons shown here have a cut in energy with T\(_+\) < 600 keV.

FIG. 8: The transverse spot profile of the positron beam on the moderator. Here we present positrons with energies below 600 keV.
Potential Applications

13:00  Positron annihilation induced Auger electron spectroscopy (PAES) to investigate the Auger relaxation of deep valence holes in single layer graphene

13:25  Electronic structure probed with positronium: Theoretical viewpoint

other  Low-Energy Positron Diffraction (LEPD) and (Total) Reflection High-Energy Positron Diffraction ((T)RHEPD) - for surface structure determination studies of the topmost atomic layer, determination of the atom positions of (reconstructed) surfaces with outstanding accuracy, all kinds of surfaces, 1D and 2D structural, buckling of 2D systems such as graphene and silicene, phase transitions of overlayers and self-assembled organic molecules at surfaces to understand extraordinary electronic structure
LERF Availability

• The LERF will be used to test LCLSII cryo-modules for the next 18 months. During that time it will be limited to about 50 MeV. After that it will be restored to its previous state.

• To carry out an experiment in the LERF one needs:
  – Funding sufficient to cover operating expenses on a full cost-recovered basis (~$3000/hour)
  – Safety and technical reviews of the installation
  – All safety documentation complete and approved.
  – Scheduling committee approval (this is easier after LCLSII work).

• Linac operation is very low risk for the required beam. The beam dump is moderately challenging, but much of the design is done.
So How Do We Get There?

- Form a consortium board
  - monthly meetings
- Conference at JLab
  - potential users
  - physics program
- Colloquium/Seminars by prominent experts
- Committee for experiments and beam time integrated with FEL PAC operation
- Involve industry/NASA/NAVY and local government
- Provision of expansion, e.g. a larger lab building
What is done

- Production and transport simulations
- Prototype plug, test of magnetic field termination completed with TOSCA and OPERA-3D magnetic field calculation
- Calculated parameters for a rotating converter target
- Power deposition in the elements
- Radiation shielding estimate calculation by Serkan Golge using GEANT4 and RadCon performed with FLUKA simulation for the same geometry and verified results by two different parametric codes
- Design of new beamline layout in the FEL and total budget by Richard Walker
- Evaluation of the project by JLab Director’s Review Panel
## Construction of Beamline

### Table: Position Beam Test Costs

<table>
<thead>
<tr>
<th>Position</th>
<th>Material</th>
<th>Beam Test Cost</th>
<th>Installation &amp; Checkout</th>
<th>Material</th>
<th>Beam Test Cost</th>
<th>Installation &amp; Checkout</th>
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### Details:

- **Layout & Assembly Casing:**
  - **Beam Test Cost:** 100, 40
  - **Installation & Checkout:** 40, 20

- **Design & Fabrication of Beamline:**
  - **Beam Test Cost:** 120, 20
  - **Installation & Checkout:** 40, 20

- **Install Dampeners & Grinders:**
  - **Beam Test Cost:** 30
  - **Installation & Checkout:** 10

- **Design & Fab Vacuum Chamber for MSG21:**
  - **Beam Test Cost:** 60
  - **Installation & Checkout:** 10

- **Install Vacuum Chamber for MSG21:**
  - **Beam Test Cost:** 40
  - **Installation & Checkout:** 10

- **Pressure & Install Vacuum for New Beam Line:**
  - **Beam Test Cost:** 20
  - **Installation & Checkout:** 10

- **Design & Fab Electron Beam Pump (5):**
  - **Beam Test Cost:** 10
  - **Installation & Checkout:** 10

- **Pressure Test Casing, Installs, & Test:**
  - **Beam Test Cost:** 0
  - **Installation & Checkout:** 10

- **Pressure Test Inaccessible & Power Amps:**
  - **Beam Test Cost:** 0
  - **Installation & Checkout:** 10

- **Pressure Test Single & Power Mosaic:**
  - **Beam Test Cost:** 0
  - **Installation & Checkout:** 10

- **Procure Box Power Supply for DOC Magnet:**
  - **Beam Test Cost:** 60
  - **Installation & Checkout:** 20

- **Design & Fab Damping Tube:**
  - **Beam Test Cost:** 0
  - **Installation & Checkout:** 10

- **Install Cellid for DC, Guides & Meters:**
  - **Beam Test Cost:** 60
  - **Installation & Checkout:** 10

- **Inst & Test Quadrupole Magnet:**
  - **Beam Test Cost:** 0
  - **Installation & Checkout:** 10

- **Quad P.S. (Main Cost):**
  - **Beam Test Cost:** 0
  - **Installation & Checkout:** 10

- **Install & Test Corrector Magnet Set (3):**
  - **Beam Test Cost:** 0
  - **Installation & Checkout:** 10

- **Converter L. (Quad Cost):**
  - **Beam Test Cost:** 0
  - **Installation & Checkout:** 10

- **Design & Fab Convex-Convex Target:**
  - **Beam Test Cost:** 0
  - **Installation & Checkout:** 10

- **Design & Fab Target Chamber:**
  - **Beam Test Cost:** 0
  - **Installation & Checkout:** 10

- **Assemble Target, Chamber, Shaft, Motor, etc.:**
  - **Beam Test Cost:** 0
  - **Installation & Checkout:** 10

- **Design & Test Software for Ringer:**
  - **Beam Test Cost:** 0
  - **Installation & Checkout:** 10

- **Install Convex & Convex Vane:**
  - **Beam Test Cost:** 0
  - **Installation & Checkout:** 10

- **Drive Motors & Connect Vane to Tal. Room:**
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- **Move Equipment Reset to Tal. Room:**
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  - **Installation & Checkout:** 10

- **Procure Box Power Supply for Solenoid:**
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  - **Installation & Checkout:** 10

- **Wise P.S. & Test Bored Solenoid Line (1000):**
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  - **Installation & Checkout:** 10

- **Design Damp Water System:**
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  - **Installation & Checkout:** 10

- **Fab & Install Damp Water System:**
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- **Procure & Install Pen & P.S.:**
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- **Procure & Test Viewers & Cameras:**
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- **MPS Mods:**
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- **PSS Mods:**
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  - **Installation & Checkout:** 10

- **Interlock Mods - Cwt & V/W:**
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  - **Installation & Checkout:** 10

- **Align Positions Beam Line:**
  - **Beam Test Cost:** 0
  - **Installation & Checkout:** 10

- **Align Electron Beam Line & Damp:**
  - **Beam Test Cost:** 0
  - **Installation & Checkout:** 10

- **Procure tools for Coolant Well Around Ringer:**
  - **Beam Test Cost:** 0
  - **Installation & Checkout:** 10

- **Design & Fab Sheet Cooling for Target & Damp:**
  - **Beam Test Cost:** 0
  - **Installation & Checkout:** 10

- **Replace & Realignment (Op Quants, 2 Line P.S., etc.):**
  - **Beam Test Cost:** 0
  - **Installation & Checkout:** 10

### Additional Information:

- **Raw Cost, SK:**
  - **Raw Material Cost:** 567.5
  - **G & A:** 0.4

- **Burdened Costs, SK:**
  - **Burdened Material Costs:** 1431.9

- **Total Cost Installed:**
  - **Installation, SK:** 2187.8
  - **Machine Run Experiment (includes G & A):** 240
  - **Total Cost:** 3207.5
Conclusions

• Modifying JLAB FEL the most intense $4 \times 10^{10} \text{ e}^+/\text{s}$ and the highest brightness 1,000 times more than elsewhere positron beam could be produced

• Unique research laboratories and programs could be created and JLAB could be the world center for material science

• There is strong interest in academia and industry, both willing to support program

• The project is in alignment with existing FEL research

• Significant work is already completed and there is no any technical difficulty to realize the program

• The cost is modest and could be easily achieved
Backups
Budget and support from other institutions

Need $4M for positron beam (stage 1 of the project) and about $3M for laboratory infrastructure (if only existing space will be used, no new building)

- After NSF approval, additional funding from the NCCU existing grants up to $300K could be used
- Probable support from NCCU NASA-URC program up to 1M for this project
- All participating universities will contribute toward building laboratory experimental infrastructure
- Funding up to $4M through MRI is possible
- DOE Material Science Division (likely support, according to Prof. Bansil, who is a former program manager of Theoretical Condensed Matter Physics division at DOE)
- Industry support, listed are just a few that submitted letters of support: IBM, Boeing, Northrop Grumman, Lockheed Martin Corporation, Intel
Other Applications

Near surface or depth and/or laterally resolved lattice defect analysis, vacancy-like defects and their chemical surrounding - single vacancy concentrations as low as $10^{-7}$ vacancies per atom

- **Positron Annihilation Lifetime Spectroscopy (PALS)** – determines electron density at the annihilation site - depth dependent characterization of free volume in thin polymers or to identify the species of vacancies in thin films

- **Doppler-Broadening Spectroscopy (DBS)** - of the positron electron annihilation line - imaging defect distributions, distribution open-volume defects

- **Coincidence DBS (CDBS)** – measuring energy of both gamma quanta - determines longitudinal momentum of the electron - chemical surrounding of open volume defects or the presence of precipitates in thin layers or near the surface - element selective analysis of metallic cluster, structure and defects in the near surface region, thin films, multi-layers, and interfaces few nm to mm

- **Angular Correlation of Annihilation Radiation (ACAR)**, the angular deviation of the $180^\circ$ collinearity of the two annihilation gamma quanta – to derive the transversal momenta of the electrons to study the electronic structure of matter, valence electrons

- **Depth-Dependent ACAR and 2D-ACAR** - to analyze the electronic structure in thin layers and to observe the evolution of the Fermi surface from the bulk to the surface

- **Age-Momentum Correlation (AMOC, 2D-AMOC, 4D-AMOC)**, positron lifetime and the Doppler-shift are detected simultaneously for each annihilation event, determines longitudinal electron momenta and the defect types with its respective concentrations, detects the defect type and the chemical vicinity of the annihilation site
Table II: Estimated timeline and team leader of each objective is provided.

<table>
<thead>
<tr>
<th>TIMELINE</th>
<th>Leader</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
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