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?

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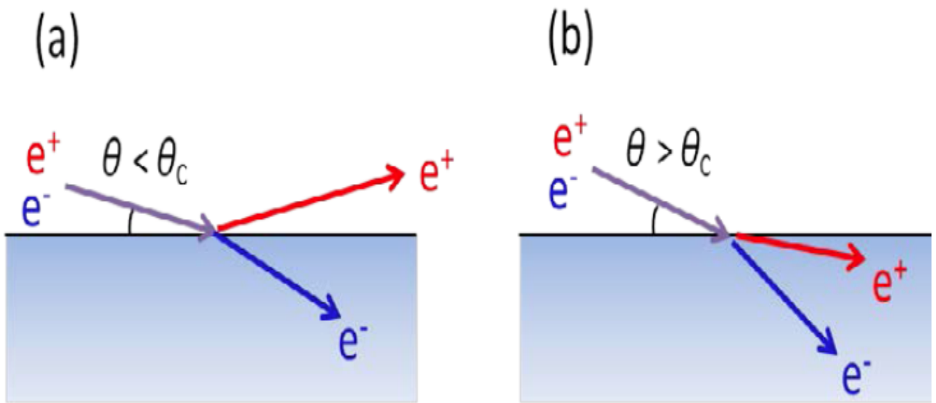
Computational Center for Fundamental and Applied Science and Education at NCCU

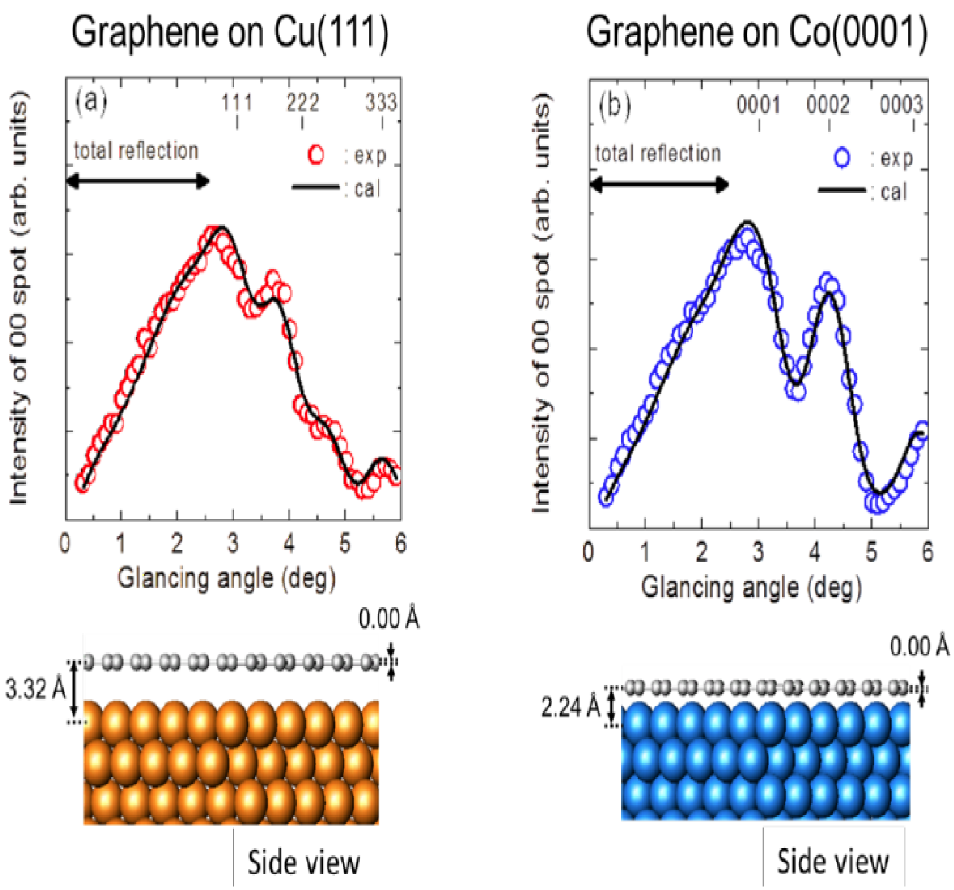
- e^+ diffraction limit is shorter than that of relevant energy photons --> atomic resolution
- e^+ interaction cross-section is greater than that for X-rays --> stay near the surface
- e^- attracts into while e^+ repels from the material -> big advantage over TEM/AFM, for early stage material degradation 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

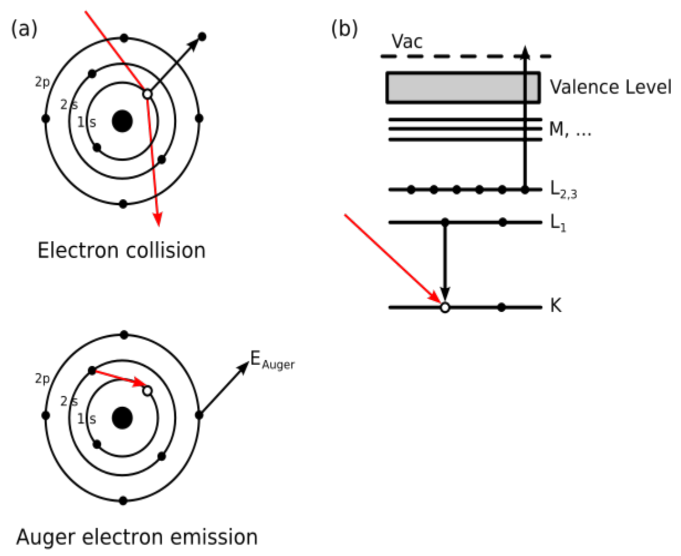
  Ps in material --> unaffected by Coulomb interaction (neutral !!), very sensitive to internal vibrations, has negative work function and tends to enter micro-cavities, probes free volume type defects and porosity (mechanical stability !!) of dielectric materials, including biological materials (e.g., living tissue), biopolymers, etc.

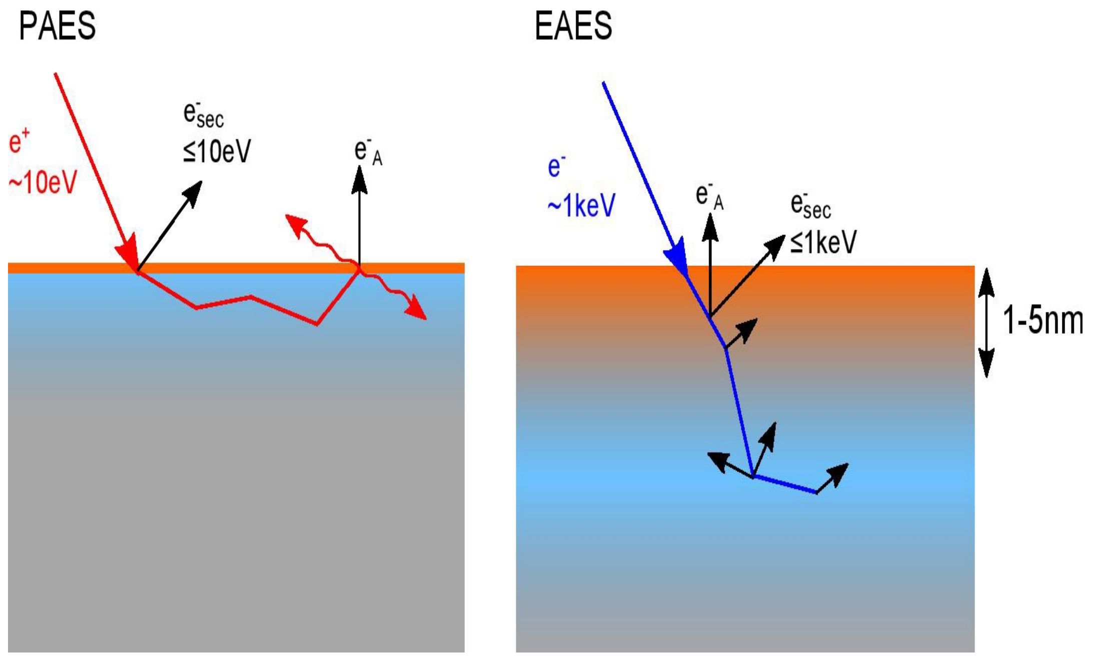
Difference between electron and positron refraction and reflect



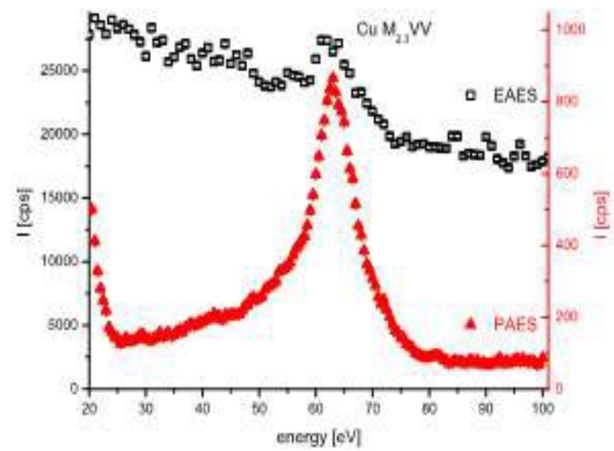


Difference Between Electron and Positron Auger Spectroscopy





Method	EAES	PAES
Current	$I_{e^-} > \mu A$	$I_{e^+} < pA$
Setup	simple	elaborate
Beam energy	$\approx$ keV	$\approx$ 20 eV
e^- background	high	"zero"
Information depth	several at. layers	topmost at. layer
Auger yield (relative to EAES)	1	>100
SNR (relative to EAES)	1	>20



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

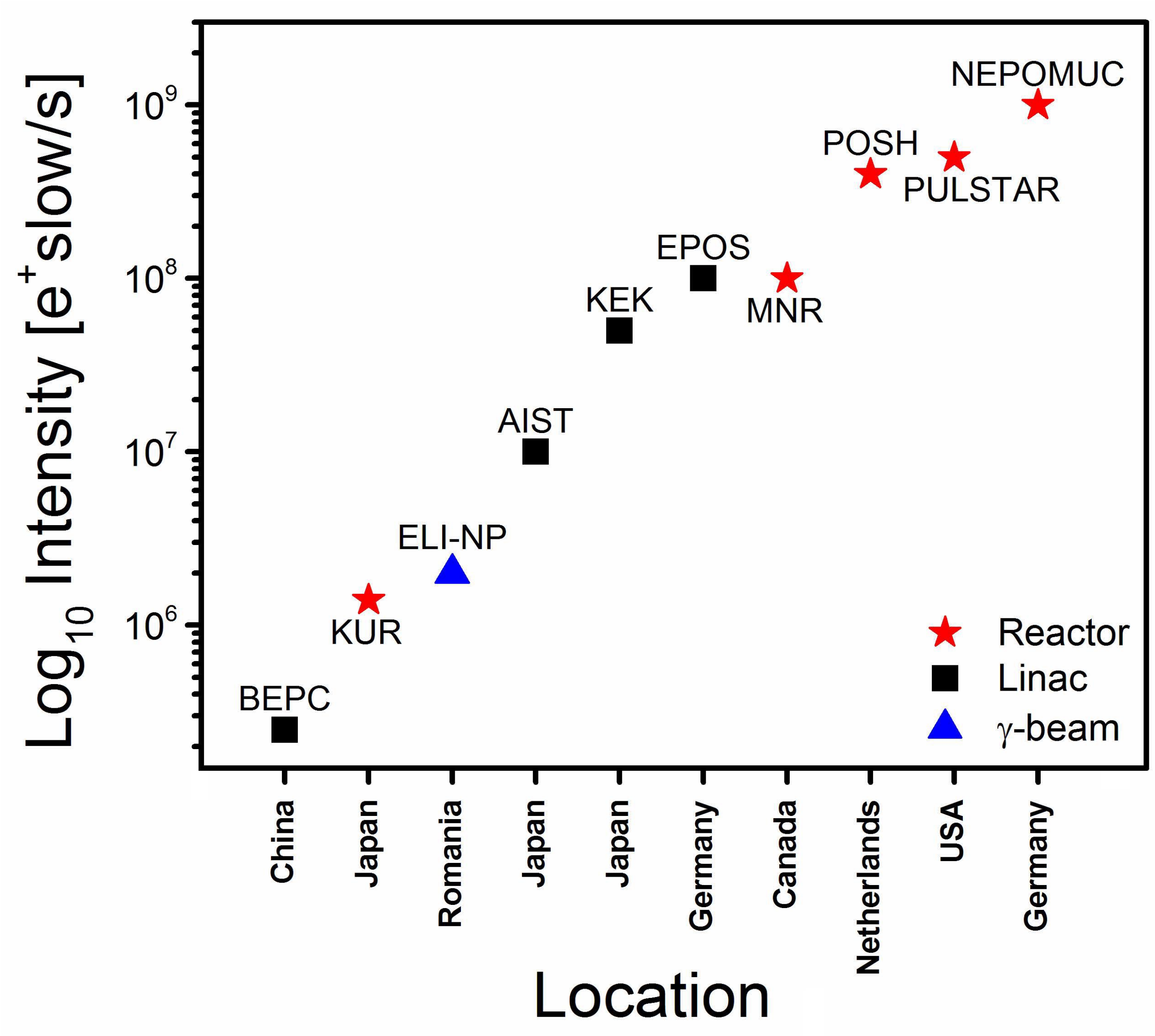
B) Reactor-based slow positron facilities:

- 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 ~ 5×10^8 slow e^+/s)
- Munich Reactor Positron Source (Achieved : ~9×10^8 slow e^+/s)

C) Electron linac-based slow positron facilities:

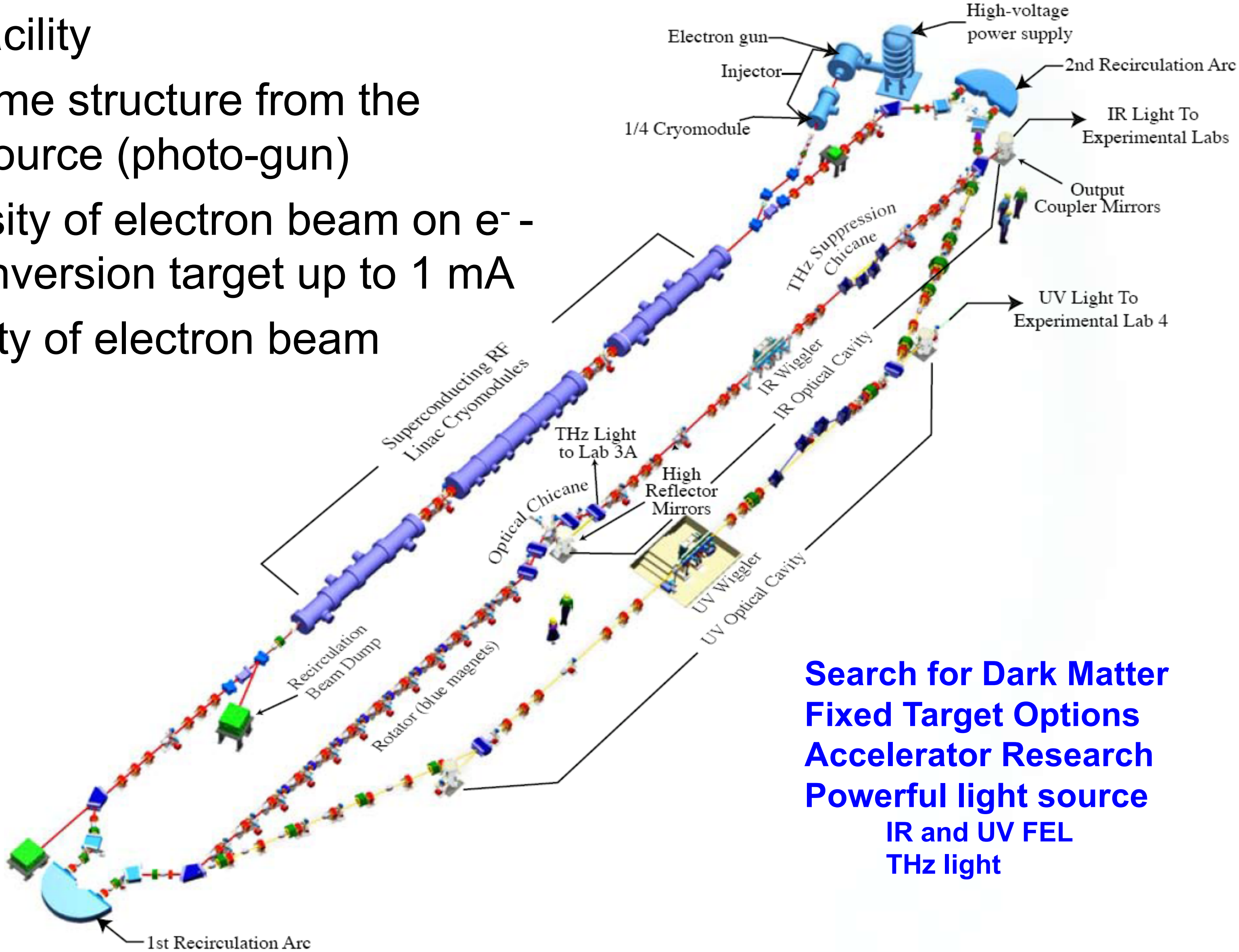
- Positrons are produced via pair production from bremsstrahlung photons
- *Advantages*: e^+ intensity is proportional to intensity of incident electron beam, adjustable time structure.
- *Disadvantages*: Radiation concerns, high initial cost of infrastructure
- *Operational*: Elbe Positron Source (EPOS) 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



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



Search for Dark Matter
Fixed Target Options
Accelerator Research
Powerful light source
IR and UV FEL
THz light

Production stages of slow positrons at accelerators

Linac

↓ High energy e^- beam

Converter — i.e. W, Ta

↓ $e^+ \sim < 5$ MeV

Moderator — i.e. W, Pt foils, or solid rare gas

↓ $e^+ \sim$ 1-30 keV

Electrostatic extraction, remoderation, and focusing

↓ $e^+ \sim$ 3-4 eV

Sample

1[st] efficiency

$\eta_+ = e^+/$ incident e^-

2[nd] efficiency

$\eta_{++} =$ slow $e^+/$ fast e^+

$$\text{Brightness} = \frac{\text{Intensity}}{\Theta^2 d^2 E_l}$$

$$\Theta = \sqrt{E_t/El}$$

E_t and E_l are transverse and longitudinal components of the positron energy

d is positron beam diameter

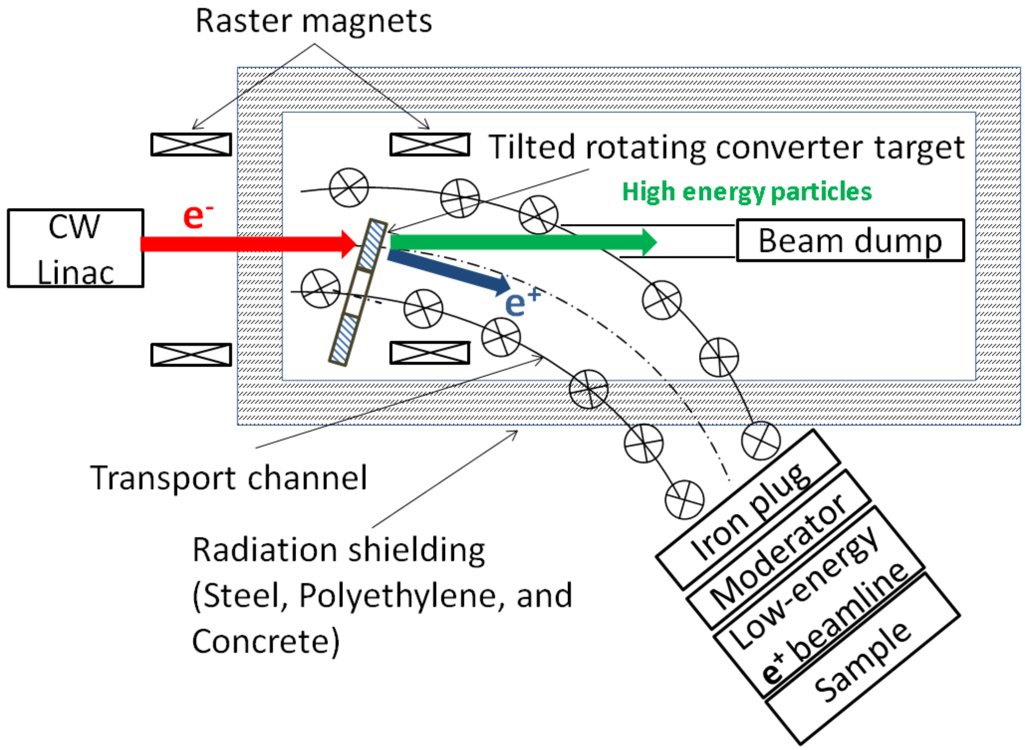
Monoenergetic beam with a spot size Ø < 0.1 mm.

Conceptual design of the positron source at the LERF

Concept: The concept in our design relies on transport of positrons (T_+ 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

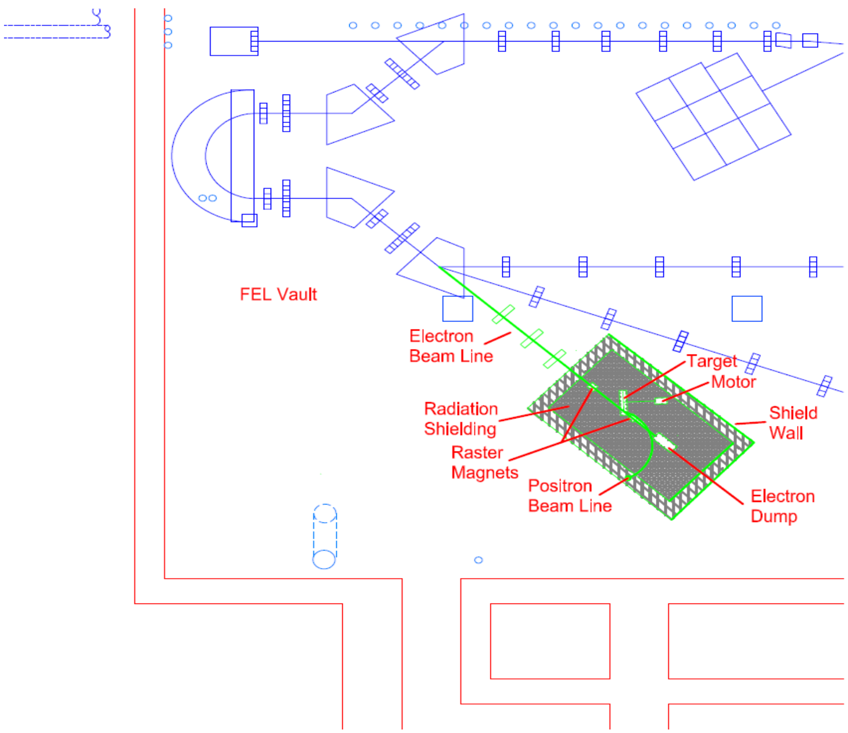


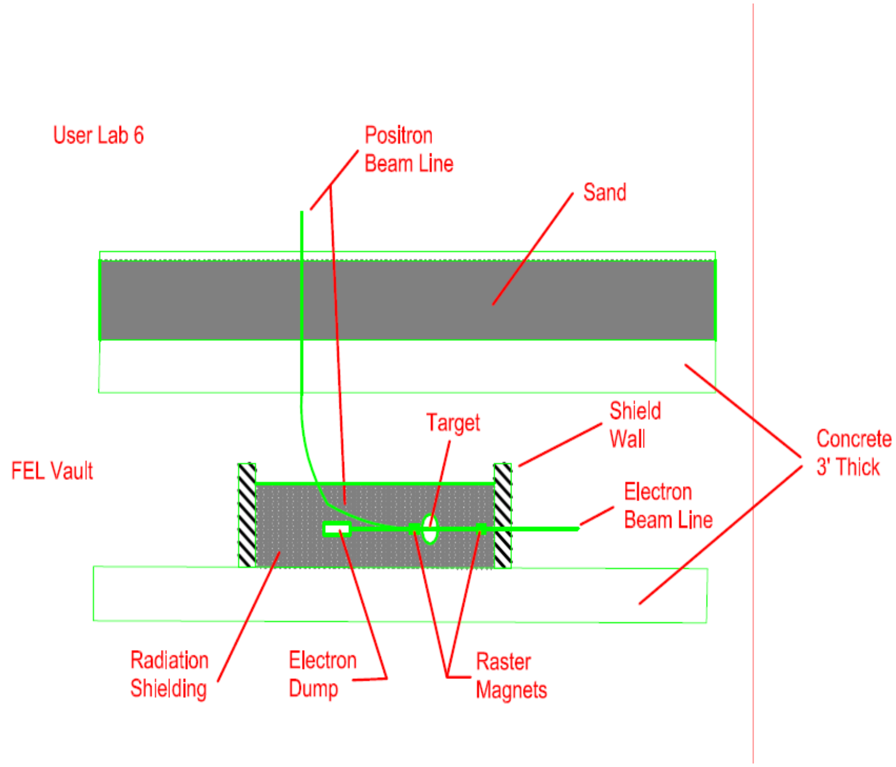
*The illustration is not to scale.

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.





Proposed Solenoid End Cap

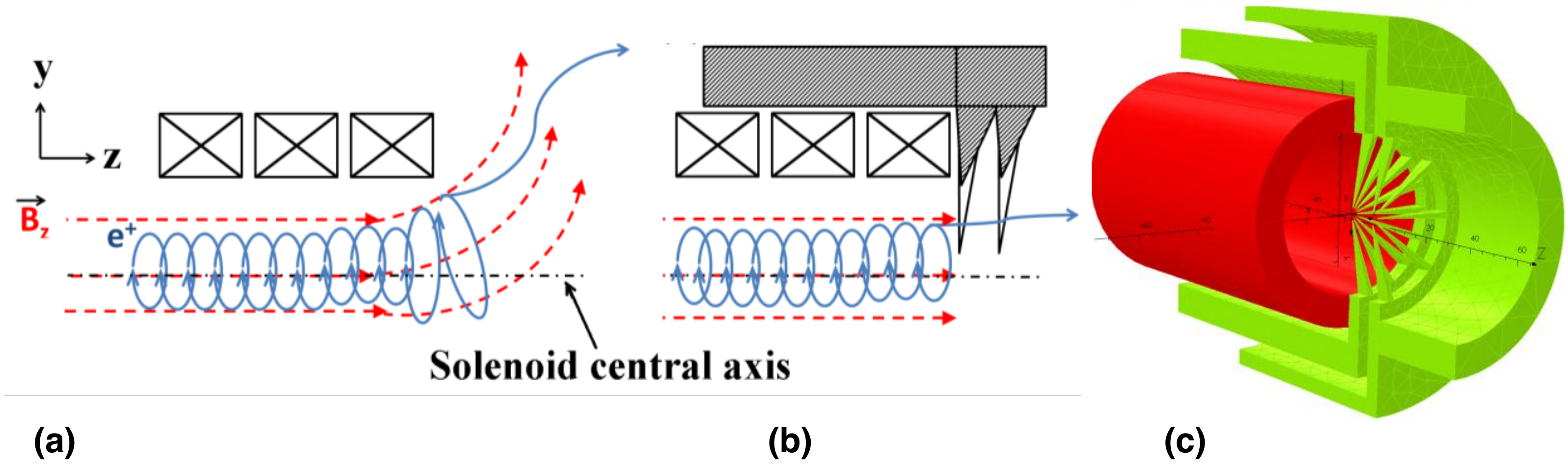


FIG. 5: Concept of transport through the solenoid channel (a) without and (b) with the magnetic steel plug. Solid blue lines show e^+ track. Dashed red lines are magnetic field lines. Only the upper half of solenoid is shown. (c) OPERA 3D Model of the magnetic plug is shown.

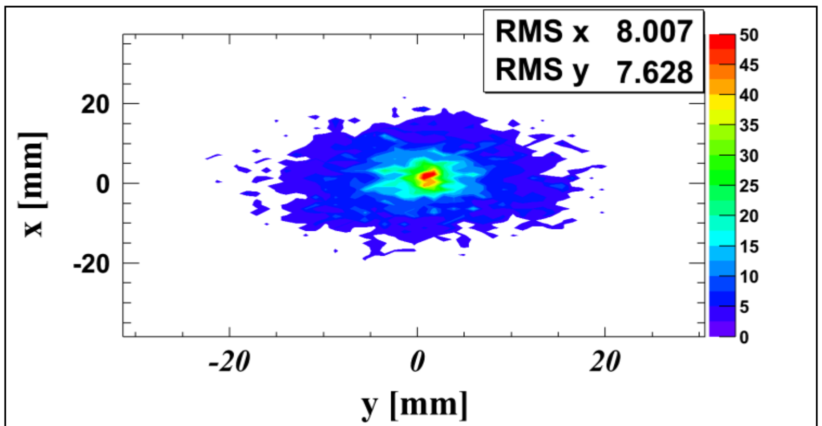


FIG. 8: The transverse spot profile of the positron beam on the moderator. Here we present positrons with energies below 600 keV.

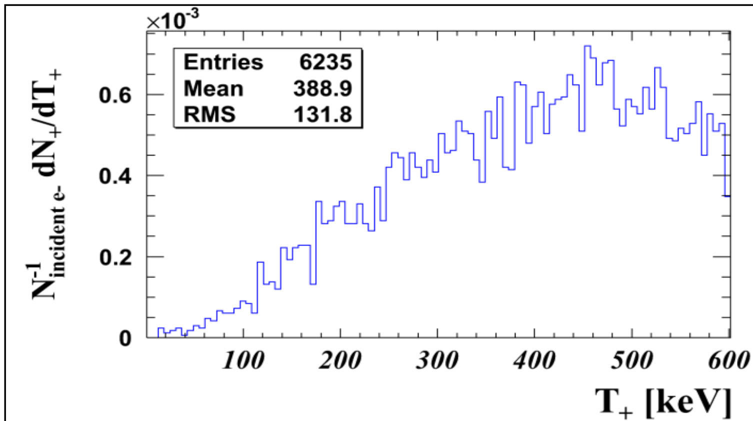


FIG. 7: Kinetic energy of the positrons after the iron plug. Positrons shown here have a cut in energy with $T_+ < 600$ keV.

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

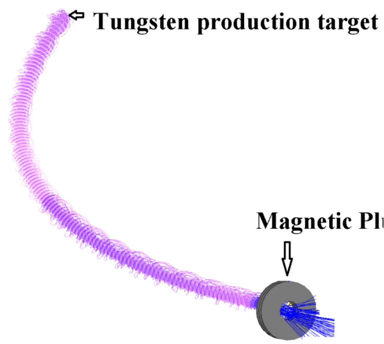
- The LERF will be used to test LCLSII cryo-modules for the next 18 months. During that time it will be limited to about 50 MeV. After that it will be restored to its previous state.
- To carry out an experiment in the LERF one needs:
  - Funding sufficient to cover operating expenses on a full cost-recovered 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.

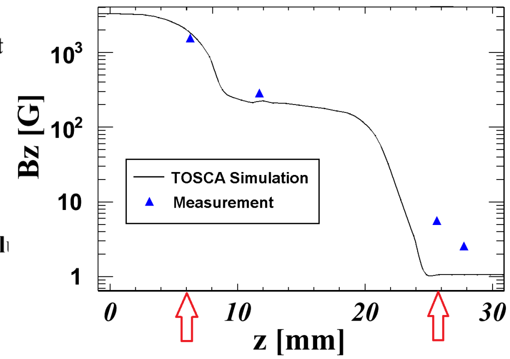
So How Do We Get There?

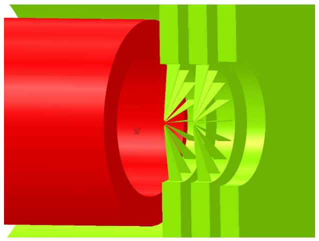
- Form a consortium board
  - monthly meetings
- Conference at JLab
  - potential users
  - physics program
- Colloquium/Seminars by prominent experts
- Committee for experiments and beam time integrated with FEL PAC operation
- Involve industry/NASA/NAVY and local government
- Provision of expansion,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

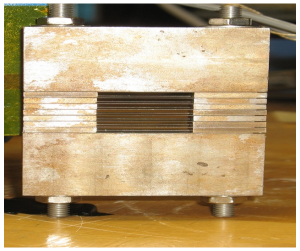
What is done

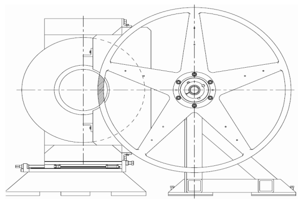
- Production and transport simulations
- Prototype plug, test of magnetic field termination completed with TOSCA and OPERA-3D magnetic field calculation
- Calculated parameters for a rotating converter target
- Power deposition in the elements
- Radiation shielding estimate calculation by Serkan Golge 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

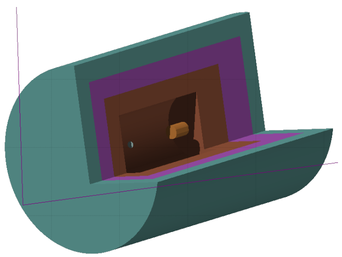


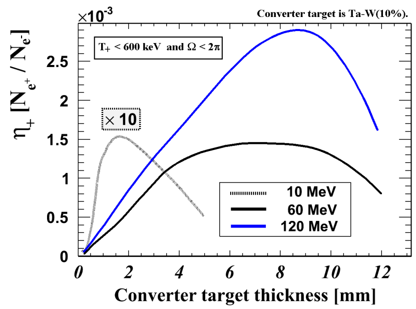


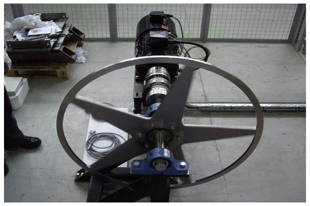


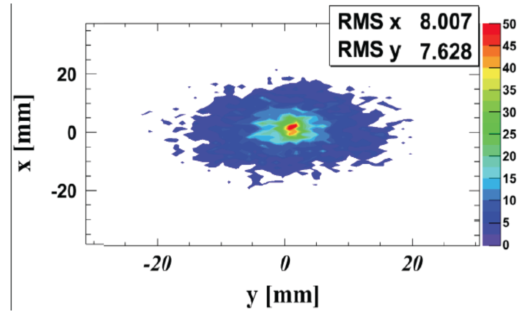












Construction of beamline

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Positron Beam Test Costs Installation & Checkout	Need	Available	Missing	K$/each	Material Cost, $K	MTech Heavy	MTech Align	MTech Vac	Mag Test	MTech FEL	Mech Design	Mech Eng	Elec Tech DC	Elec Tech	Elec Design	Elec Eng	Skilled Trade	Scientist	Senior Staff	Labor Cost, $K
						Labor - Hrs														
					$/Hr	41	41	41	41	41	46	67	42	42	51	67	34	66	107	
Layout & Assembly Dwg											160	40						20		11.4
Build Shed on Roof, Move SF6 Bag, & Plumb	1	0	1	20.0	20.0	120					40	20		40	20					10.8
Design & Fab Stands & Girders (16)	16	0	16	5.0	80.0						120	30								7.5
Install Stands & Griders						80	40			80										8.2
Design & Fab Vacuum Chamber for MGX2F10	1	0	1	15.0	15.0						40	20								3.2
Install Vacuum Chamber for MGX2F10						32	16	16		16										3.3
Procure & Install Valves for New Beam Line	4	0	4	4.0	16.0			24				16								2.1
Design & Fab Electron Beam Pipe (5)	5	0	5	1.0	5.0						40	8					40			3.7
Install Electron Beam Pipe								16		16										1.3
Procure Raster Magnets, Install, & Test	2	1	1	5.0	5.0					16		4		16		8				2.1
Procure Raster Function Gen. & Power Amps	3	0	3	3.0	9.0															0.0
Procure DQ di-pole Magnets	3	3	0	30.0	0.0															0.0
Procure Box Power Supply for DQ Magnets	1	1	0	70.0	0.0															
Design & Fab DX Pole Tips (12)	12	0	12	1.0	12.0						40	20					40			4.5
Install Cabling for DX, Quads & Trims (7000')	7000	0	7000	0.0021	14.7					40				40		8				3.9
Install & Test Quadrupole Magnets (10-QH)	10	10	0	4.0	0.0					8		8		8		8				1.7
Quad P. S. (Trim Card)	10	10	0	2.1	0.0									4						0.2
Install & Test Corrector Magnet Sets (3)	3	0	3	3.0	9.0					10				10		10				1.5
Corrector P. S. (Trim Card)	3	0	3	2.1	6.3									4						0.2
Design & Fab Converter Rotating Target	1	0	1	60.0	60.0						750	750		10	200	280	40			115.5
Design & Fab Target Chamber	1	0	1	30.0	30.0						1000	1000					20			113.7
Assemble Target, Chamber, Shaft, Motor, etc.										24		16		8		8				2.9
Design & Test Software for Target														30		20				2.6
Fiducialize Target & Chamber							16							8						1.0
Install & Test Target on Beam Line								8		8				8		8				1.5
Design & Fab Iron Spider	1	0	1	2.0	2.0						200	120					60			19.3
Design & Fab Spider Chamber	1	0	1	7.0	7.0						200	120								17.2
Design & Fab 1st Solenoid Pipe Segment	1	0	1	20.0	20.0						120	60								9.5
Design & Fab Solenoid Pipe Segments (7)	7	0	7	1.5	10.5						120	60								9.5
Wrap Magnet Wire on Beam Pipe Segments	8	0	8	3.0	24.0															0.0
Install Spider & Chamber to Last Segment										20		20								2.2
Weld Segments & Install Curved Solenoid								48		48							16			4.5
Design & Fab Gap Cover Solenoids (8)	8	0	8	2.0	16.0						80	20					32			6.1
Design & Fab Small Bending Dipoles (20)	20	0	20	3.0	60.0						40	10					40			3.9
Install Di-poles & Gap Cover Solenoids										60				60		8				5.5
Drill Hole & Connect Vault to Tel. Room					10.0		20													0.8
Move Equipment Racks in Tel. Room					10.0															
Install Solenoid Beam Pipe						20		20		20	20	20								4.7
Procure Box Power Supply for Solenoid	1	1	0	70.0	0.0															0.0
Wire P.S. & Test Curved Solenoid Line (1400')	1400	0	1400	0.0400	56.0					32				32		32				4.8
Design Dump Water System											160	80								12.7
Fab & Install Dump Water System	1	0	1	40.0	40.0	80						20								4.6
Procure & Install Ion Pumps & P. S.	10	0	10	20.0	200.0			40		40	10	10		40		10				6.8
Procure & Install & Test Viewers & Cameras	10	0	10	16.0	160.0					80	30	15		16				16		7.4
MPS Mods	1	0	1	3.0	3.0									20		10				1.5
PSS Mods	1	0	1	3.0	3.0									20		10				1.5
Interlock Mods - Crate & H/W	1	0	1	12.0	12.0									40		10				2.4
Align Positron Beam Line							40					15								2.6
Align Electron Beam Line & Dump							40					15								2.6
Procure Blocks for Concrete Wall Around Equip.	1	0	1	12.0	12.0	40				40										3.3
Design & Fab Shielding for Target & Dump	1	0	1	40.0	40.0						160	160					300	40		30.9
Install Shielding Around Target & Dump						320				160							120			23.8
Replace & Reconnect 10 Quads, 2 Box P.S., etc.										60				60		16				6.1

Raw Costs, $K	Raw Material Cost, $K		967.5	Raw Labor Cost, $K		497.0
G & A Rate	G & A	48%	464.4	G & A	48%	238.6
Burdened Costs, $K	Burdened Material Costs, $K		1431.9	Burdened Labor Costs, $K		735.6

Total Cost Installed		Installation, $K		2167.5
Machine Setup Hours (Includes G&A)	80		3.4	272.0
Machine Run Experiment (Includes G&A)	240		3.2	768.0
Total Cost		Total Cost, $K		3207.5

1/29/2013 - R. Walker

Conclusions

- Modifying JLAB FEL the most intense $4x10^{10}$ e^{+}/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

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Computational Center for Fundamental and Applied Science and Education at NCCU

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° 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.

TIMELINE		2013	2014				2015				2016				2017		
	Leader	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3
Design of the beamline	G. Neil																
Procurement and testing	B. Vlahovic																
Manufacturing of the components	G. Neil																
Positron transport channel	G. Neil																
Radiation shielding	S. Golge																
Installation of beam diagnostics	S. Ozkorucuklu																
Installation of detectors	G. Neil																
Commissioning of fast e^+ beamline	W. Kossler																
Design of moderator	B. Vlahovic																
Construction of moderator	B. Vlahovic																
Slow e^+ transport beamline	A. Weiss																
Commisioning of the slow e^+ beamline	W. Kossler																
Slow e^+ detection	D. Van Horn																
Design of micro-beamline	A. Bansil																
Installation of micro-beamline	B. Barbiellini																
Design of sample holding chamber	D. Van Horn																
Installation of sample holding chamber	D. Van Horn																
Installation of high-resolution detectors	W. Kossler																
Commissioning	B. Vlahovic																