Positron Sources, Applications and the PEPPo Experiment

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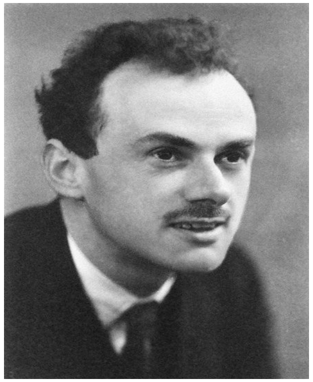
I would like to acknowledge those whose work and inspirations are incorporated to this talk: D. Cassidy, S. Chemerisov, J. Dumas, A. Freyberger, W. Gai, S. Golge, C. Hyde, J. Jonah, R. McKeown, A. Mikhailichenko, A. Mills, Y. Saquin, E. Voutier

CAS Seminar
Old Dominion University
April 2, 2015

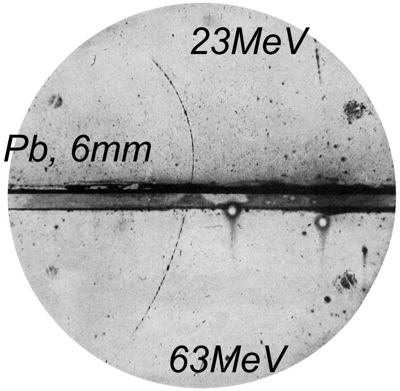
A Distinguished Field



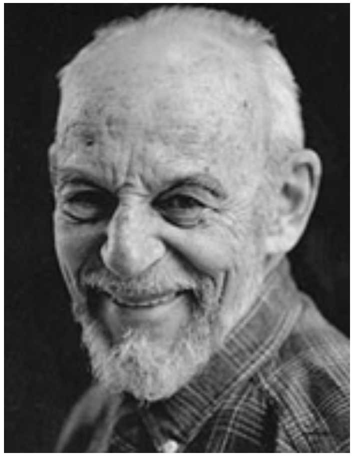
P.A.M. Dirac (1902 – 1984) shared 1933 Nobel prize (with Erwin Schrodinger) for the relativistic wave equation of massive spin-1/2 particles. The theory predicts negative energy “holes” with properties identical to the electron yet having a positive charge!

$$\left[\frac{W^2}{c^2} - p_r^2 - m^2c^2\right]\psi = 0$$

Carl Anderson (1905 – 1991) shared 1936 Nobel prize (with Victor Hess) for detecting the positron (March 15, 1933, PRL, V. 43, The Positive Electron). The term positron was given by the *Physical Review* editor! He also co-discovered the muon!

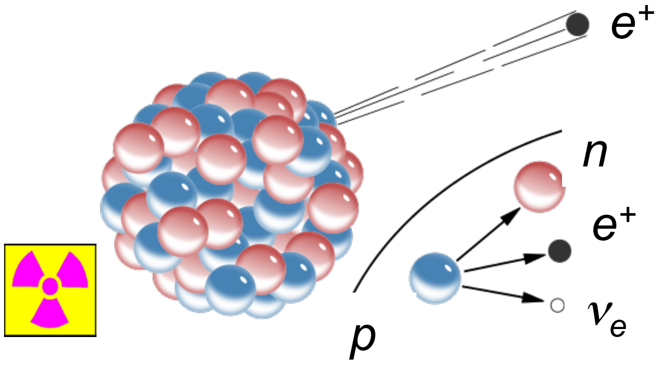


Martin Deutsch (1917 – 2002) awarded 1956 Nobel prize for discovery of bound positrons given the name Positronium (Ps), which also had been predicted by Anderson.



30,000 foot (9144 meter) view

β^+ emission by radioactive decay



Extended Radioactive Decay

- Nuclear reactors
- Accelerators/Cyclotrons

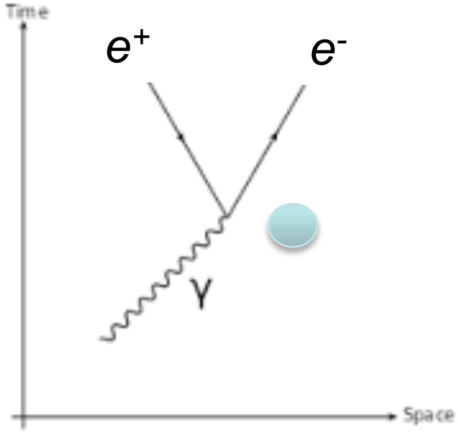
Lower energy

- Emission <MeV
- Random emission
- Half-life ~months-years

Lower Intensity

- 10^6 - 10^8 e^+/s

Pair Conversion by energetic photon



Prompt Pair Creation (>1.022 MeV)

- Bremsstrahlung
- Synchrotron/Undulator
- Inverse Compton scattering

Higher Energy

- LINAC acceleration >MeV
- Synchronous emission

Higher Intensity

- 10^{10} - 10^{12} e^+/s

Talk Outline

Applications

- Diverse activities and energy requirements

Radioactive β^+ decay

- Sources and applications

Pair production by gamma rays

- Accelerator based sources
- Technical challenges

Polarized Positrons

- Methods
- Polarized Electrons for Polarized Positrons (PEPPo)

Outlook

- Positrons at Jefferson Lab (CEBAF, LERF, UITF)
- R&D Opportunities

How are positrons used ?

Applications from 1 eV to 1 TeV

- Medical Diagnosis
- Materials Characterization
- Positronium Creation
- Anti-Gravity Test
- Nuclear Physics Probe
- Precision Standard Model Test

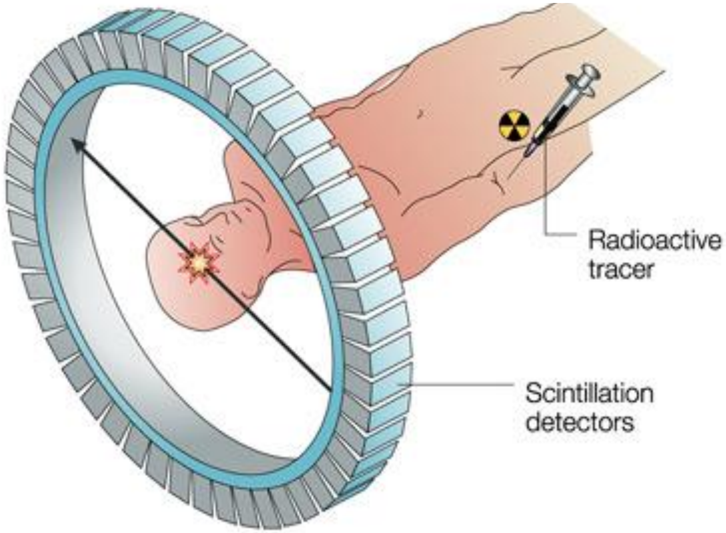
Medicine: Positron Emission Tomography

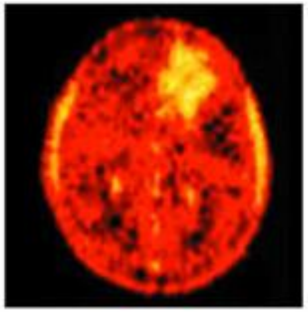
- A short-lived (10's of minutes) radioactive tracer is incorporated to a biologically active molecule, e.g. fluorodeoxyglucose (^{18}F)

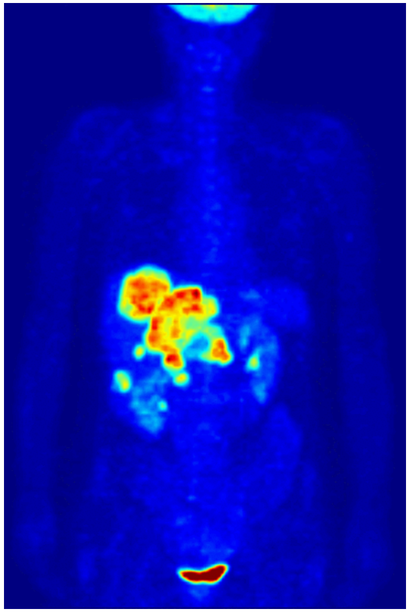
- Injected into the blood tissue becomes concentrated with the tracer after a short waiting period

- After travelling up to a few millimeters the thermalized positron annihilates into a pair of oppositely moving gammas

- Technique depends upon high energy resolution of photons which arrive in pairs.

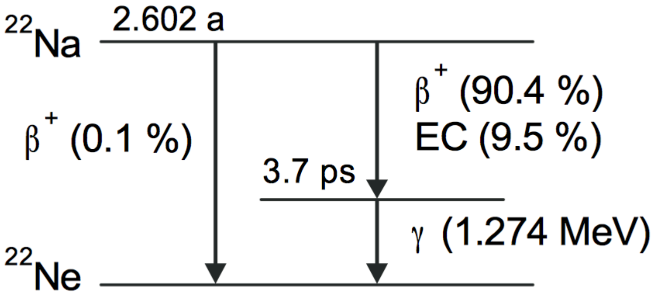


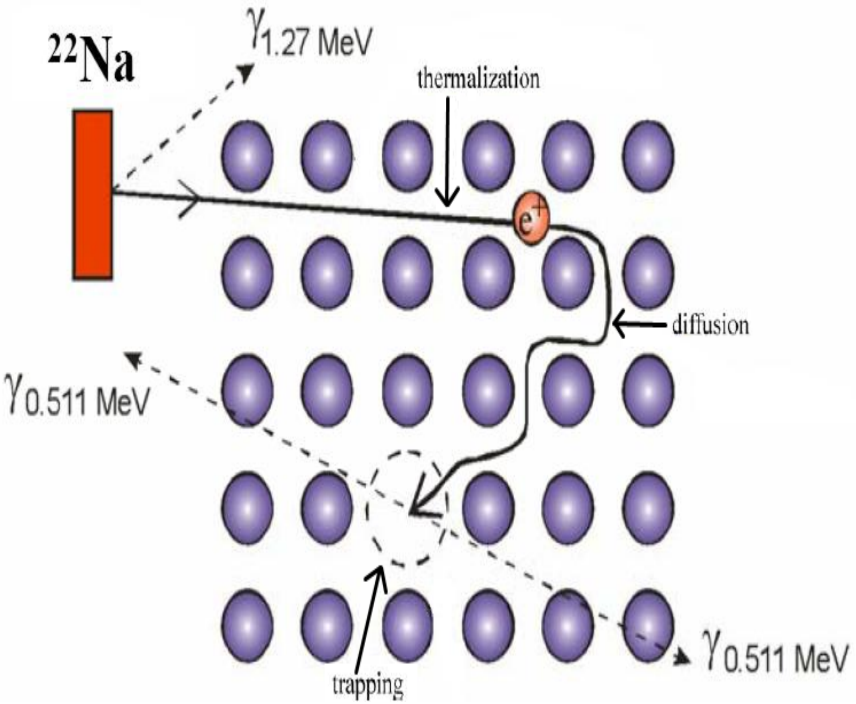




Materials Science: Positron Annihilation Spectroscopy

- Probe for semiconductors, electronic structure of metals and alloys, radiation damage, surfaces and interfaces





e^+ annihilation rate $\propto$ e^- density

PAS Techniques and Observables

Positron Lifetime (PALS)

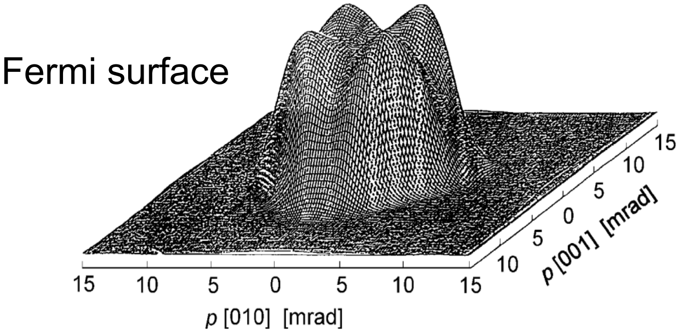
Time between trigger and annihilation photon depends on void size and defect density

- Silicon (bulk): 218 ps
- Defect (dopant): 260-330 ps

Angular Correlation (ACAR)

Angular deflection between annihilation photons due to transverse momentum of electrons

$\theta \propto p_{x,y}/m_{e-}$

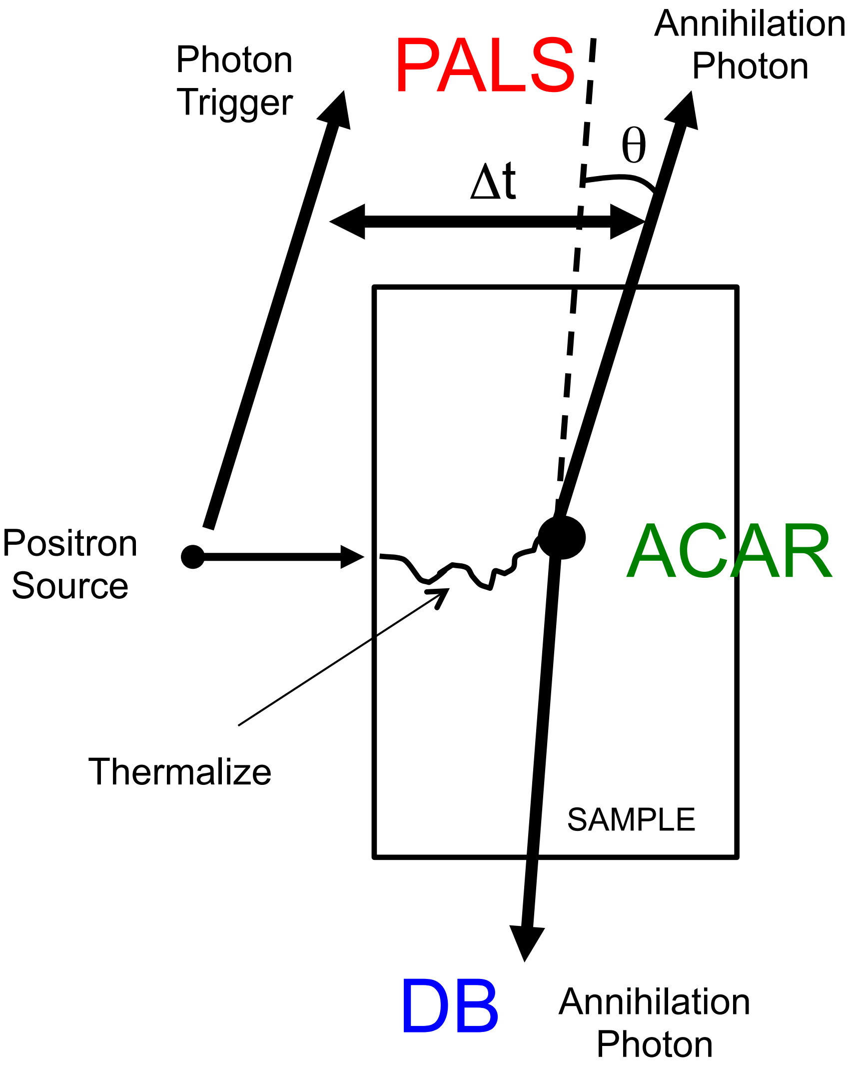


(Tanigawa et al., 1995)

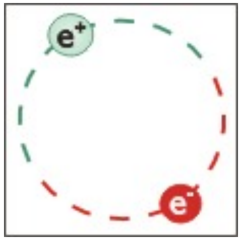
Doppler Broadening (DB)

Annihilation photon energy shift due to the longitudinal momentum of electrons

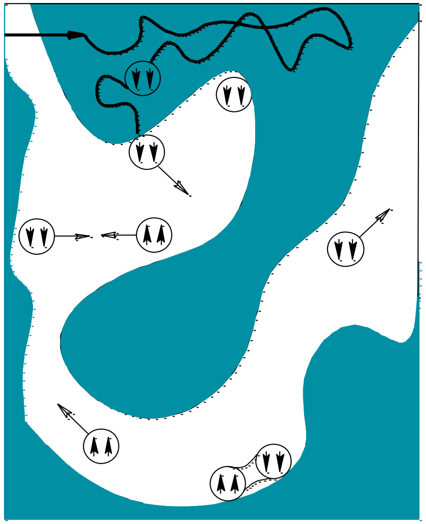
E_γ=0.511 MeV ± ΔE ($\Delta E \propto p_z/2$)



Positronium (Ps) Formation



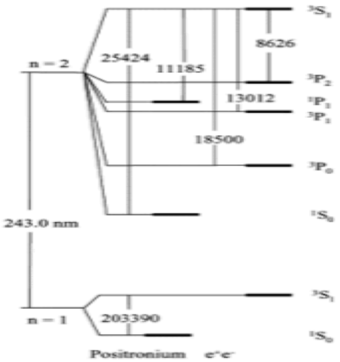
- Although an electron/positron pair are doomed to annihilate they can briefly exist in a bound state described as a hydrogen atom with corresponding reduced mass of e^+/e^-
  - Positrons directed into porous silica can **pick up an electron to form Ps** in the bulk and then diffuse to the surface or remain in internal voids
  - Ps can also be become trapped on the surface to **form Ps_2 molecules**
  - **Ps behaves like atom**: provide tool for atomic (QED) or condensed matter physics, or production of anti-matter



Spin **Lifetime** **Hydrogen Like Energy Levels**

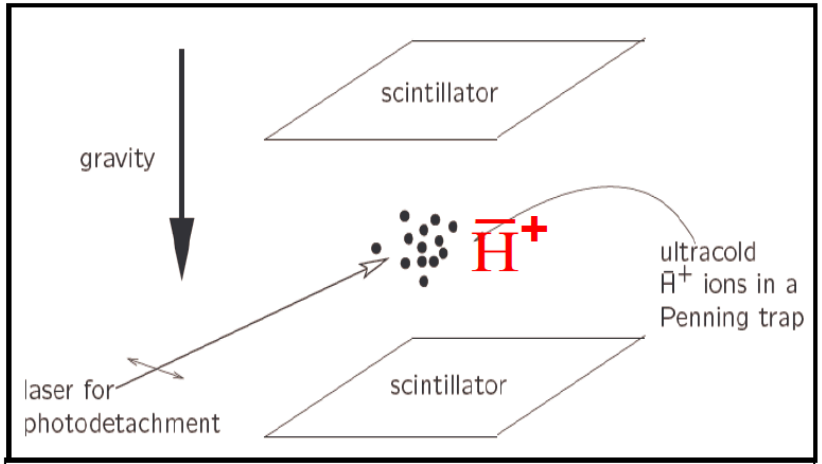
$$\left.|0,0\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)\right\}\ \text{para-Ps (s=0)} \sim 125\ \text{ps}$$

$$\left.\begin{aligned} |1,0\rangle &= \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right) \\ |1,1\rangle &= |\uparrow\uparrow\rangle \\ |1,-1\rangle &= |\downarrow\downarrow\rangle \end{aligned}\right\}\ \text{ortho-Ps (s=1)} \sim 142{,}000\ \text{ps}$$



Gravitational Force on Anti-Hydrogen

Measure "free-fall" of $\bar{\mathrm{H}}^+$ cooled to a few μK



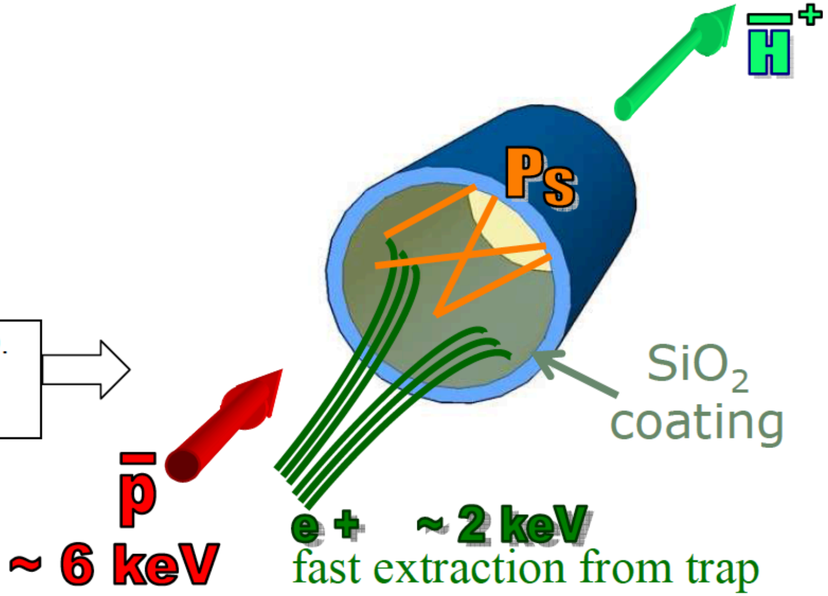
J.Walz & T. Hänsch,
General Relativity and Gravitation, **36** (2004) 561.

$\bar{\mathrm{H}}^+$ formation

$$\bar{p} + \mathrm{Ps} \rightarrow \bar{\mathrm{H}} + e^-$$

$$\bar{\mathrm{H}} + \mathrm{Ps} \rightarrow \bar{\mathrm{H}}^+ + e^-$$

P.Pérez and A. Rosowsky, Nucl. Inst. Meth. A 545 (2005) 20-30.
P. Pérez et al., CERN-SPSC-2007-038, December 2007.
P. Perez, SLOPOS-11 communication



Needs high intensity
slow positron beam!

Nuclear Physics

Jefferson Lab's CEBAF Accelerator
CW electron beam to 3 halls
Electron Polarization ~90%
Max Energy: 11 GeV(ABC) / 12GeV(D)
Max Current: 200 uA

Nuclear physics benefits using a polarized positrons beam:

- ☐ Parton Imaging (Nuclear Momentum)
- ☐ Deeply Virtual Compton Scattering
- ☐ Two Photon Exchange

Other efforts may also benefit:

- ☐ Electron Ion Collider
- ☐ Materials Science Collaborations

The **charge** and **polarization** of the probe beam provide ***degrees of freedom*** which constrain physical observables.

INTERNATIONAL WORKSHOP ON
POSITRONS
AT JEFFERSON LAB

March 25-27, 2009
JEFFERSON LAB

TOPICS:

- Positron-proton elastic scattering
- Deeply virtual Compton scattering
- New 12 GeV experiments with positrons
- Technology of positron sources
- Polarized positrons
- Electron/photon drivers
- Positron & electron polarimetry
- Applied physics with positrons

International Advisory Committee:

- X. Artru (IPN Lyon)
- L. Cardman (JLab)
- P. Cole (Idaho State U.)
- A. Freyberger (JLab)
- P. Guichon (CEA Saclay)
- R. Holt (ANL)
- A. Hunt (Idaho Accelerator Center)
- C. Hyde (LPC Clermont Ferrand)
- M. Klein (U. Liverpool)
- K. Kumar (U. Massachusetts)
- M. Poelker (JLab)
- J. Sheppard (SLAC)
- A. Variola (LAL Orsay)

Local organizing committee:

- L. Elouadrhiri (JLab)
- T. Forest (Idaho State U.)
- J. Grames (JLab)
- W. Melnitchouk (JLab)
- E. Voutier (LPSC, Grenoble)

email: jpos09_admin@jlab.org
conferences.jlab.org/JPOS09

Experimental Observables

M.P. Rekalo, E. Tomasi Gustafsson, NPA 742 (2004) 322 C. Carlson, M. Vanderhaeghen, ARNPS 57 (2007) 171

- **Unpolarized e$^\pm$** elastic scattering and **polarization transfert observables** off the nucleon involve up to **5 unknown** quantities.

Cross Section

$$\sigma_R = G_M^2 + \frac{\varepsilon}{\tau} G_E^2 \pm 2 G_M \Re\left[f_0\left(\delta\tilde{G}_M, \delta\tilde{F}_3\right)\right] \pm 2 \frac{\varepsilon}{\tau} G_E \Re\left[f_1\left(\delta\tilde{G}_E, \delta\tilde{F}_3\right)\right]$$

Polarization Transfer

$$\sigma_R P_t = -\sqrt{\frac{2\varepsilon(1-\varepsilon)}{\tau}} \left(G_E G_M \pm G_E \Re\left[\delta\tilde{G}_M\right] \pm G_M \Re\left[f_1\left(\delta\tilde{G}_E, \delta\tilde{F}_3\right)\right]\right)$$

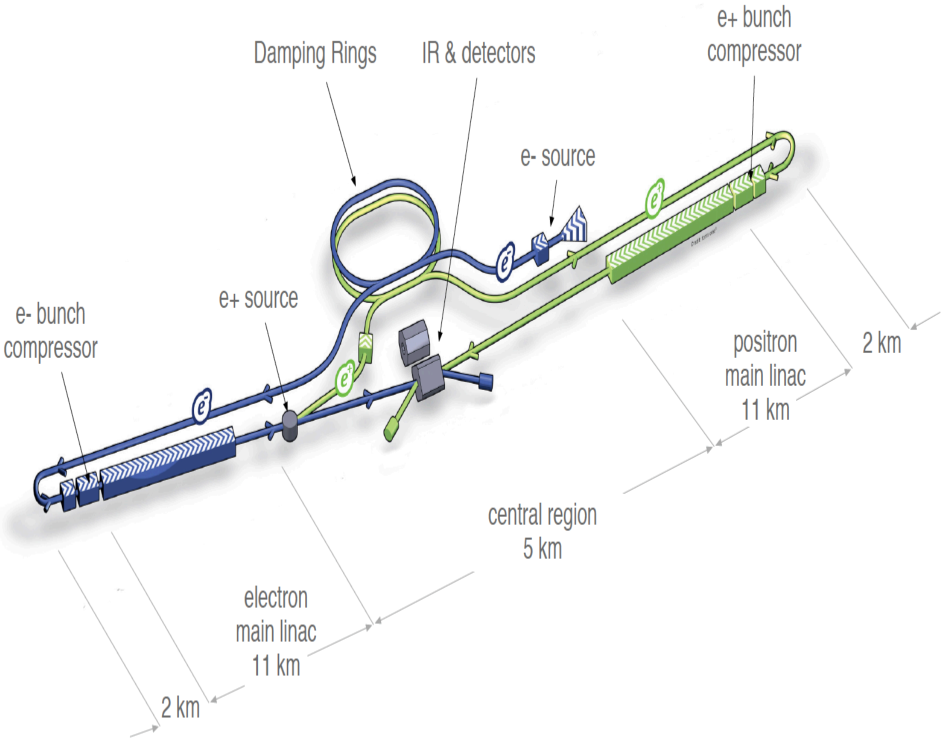
$$\sigma_R P_l = \sqrt{1-\varepsilon^2} \left(G_M^2 \pm 2 G_M \Re\left[f_2\left(\delta\tilde{G}_M, \delta\tilde{F}_3\right)\right]\right)$$

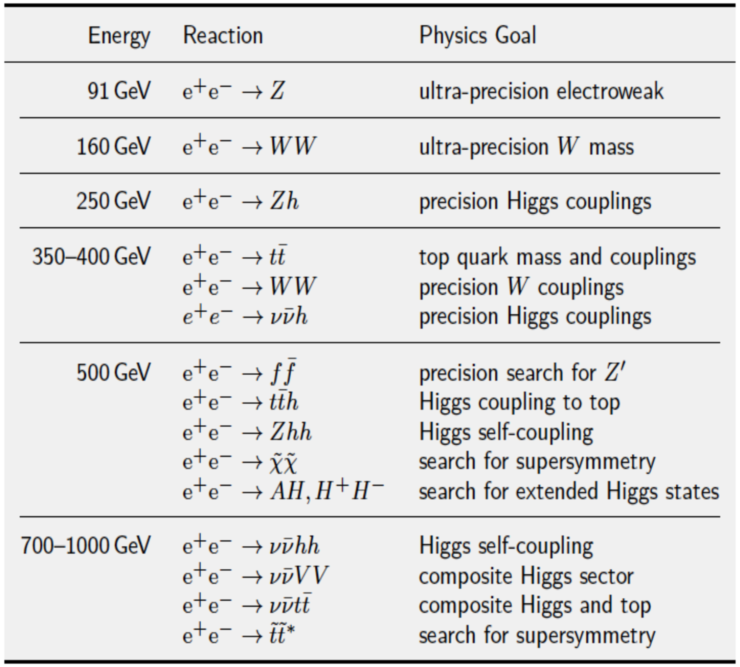
5 unknown contributions for 6 independent observables

Combining **Polarized electrons and positrons** allows a **model independent separation** of the electromagnetic form factors of the nucleon.

Energy Frontier Tests of the Standard Model (1 TeV)

International Linear Collider design relies on the collision of *polarized electrons* and *polarized positrons* resulting in center-of-mass-energies up to 1 TeV





Energy	Reaction	Physics Goal
91 GeV	$e^+e^- \to Z$	ultra-precision electroweak
160 GeV	$e^+e^- \to WW$	ultra-precision W mass
250 GeV	$e^+e^- \to Zh$	precision Higgs couplings
350–400 GeV	$e^+e^- \to t\bar{t}$ $e^+e^- \to WW$ $e^+e^- \to \nu\bar{\nu}h$	top quark mass and couplings precision W couplings precision Higgs couplings
500 GeV	$e^+e^- \to f\bar{f}$ $e^+e^- \to t\bar{t}h$ $e^+e^- \to Zhh$ $e^+e^- \to \tilde{\chi}\tilde{\chi}$ $e^+e^- \to AH, H^+H^-$	precision search for Z' Higgs coupling to top Higgs self-coupling search for supersymmetry search for extended Higgs states
700–1000 GeV	$e^+e^- \to \nu\bar{\nu}hh$ $e^+e^- \to \nu\bar{\nu}VV$ $e^+e^- \to \nu\bar{\nu}t\bar{t}$ $e^+e^- \to \tilde{t}\tilde{t}^*$	Higgs self-coupling composite Higgs sector composite Higgs and top search for supersymmetry

- Thrust is to provide precision tests of Standard Model that benefit from model independent reactions that **do not depend on the additional "stuff" which results from colliding massive particles**, e.g. like that at the LHC.

- The polarization of the e+ and e- further isolate spin-dependent channels

Producing Positron Beams

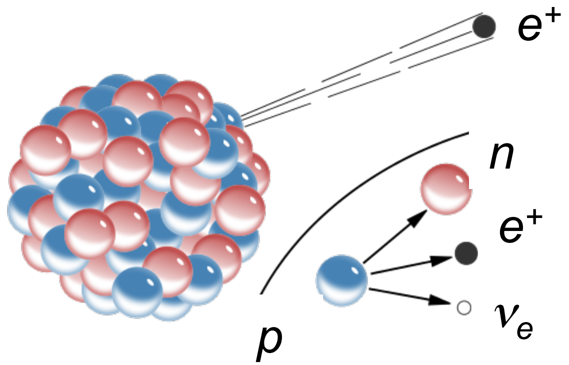
- **Application Driven**
  - energy
  - intensity
  - polarization
- **Source**
  - yield
  - collection
  - (de)acceleration
- **Beam Quality**
  - transverse/longitudinal emittance
  - time structure
- **Technical Challenges**
  - managing beam power
  - thermal loads
  - radioactivity

Positron Generation by β Decay

Beta-plus (β^+) decay occurs when a proton inside a nucleus becomes a neutron via emitting W^+ (or absorbing W^-) via the weak interaction.

$$\underbrace{{}^{23}_{12}\mathrm{Mg} \rightarrow {}^{23}_{11}\mathrm{Na}} + e^+ + \nu_e$$

The daughter nuclide retains the mass number (A) but the atomic number (Z) decreases by 1 unit.



$$Q = \left[m\left({}^A_Z\mathrm{X}\right) - m\left({}^{A}_{Z-1}\mathrm{X}'\right) - 2m_e\right]c^2$$

Q > 0 implies

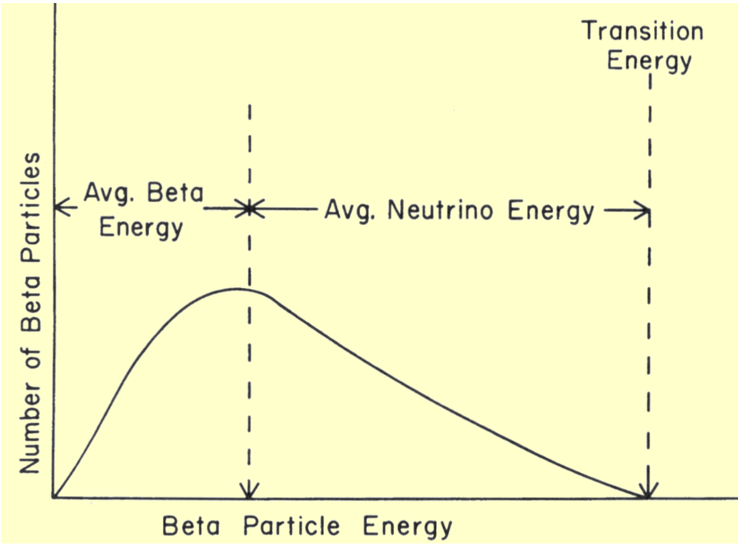
- mass of parent nuclei must exceed mass of daughter by twice m_e
- isolated proton cannot decay into a (heavier) neutron

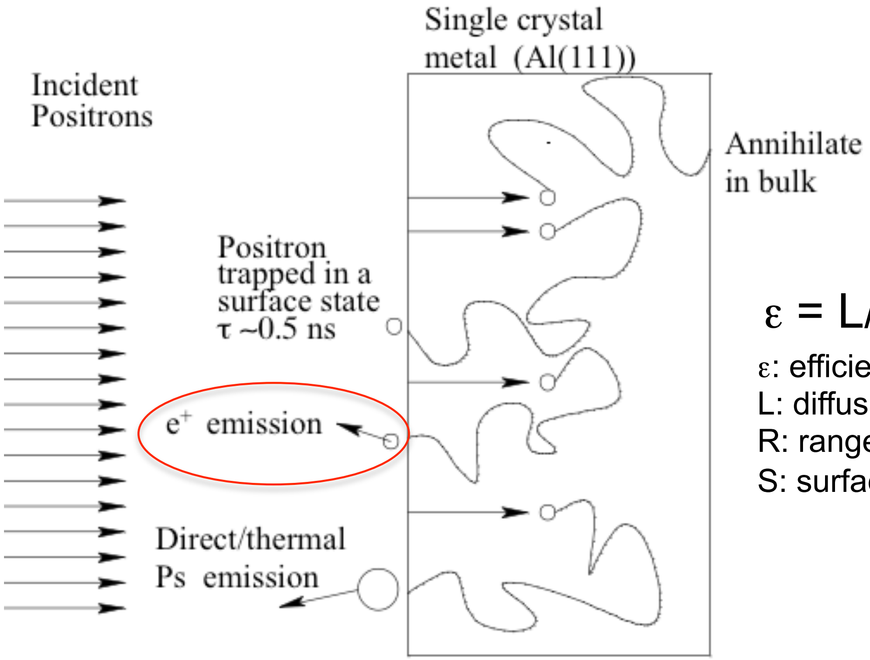
Positron Energy

- typically 10-100 keV but can be as high as ~10 MeV
- Q is partitioned to β^+ and ν_e

Moderating Radioactive β^+ Sources

Na^{22}, mean 178keV, endpoint 545keV





ε = L/R * S

ε: efficiency for e+ emission
L: diffusion length ~100 nm
R: range ~15,000 nm
S: surface prob ~ 35%

Use of moderators

Thermalize Positrons (~1 ps)

- inelastic collisions w/ core electrons
- plasmons (optical) ~ 10 V
- phonons (acoustic) ~ 1 V

Their fate is varied

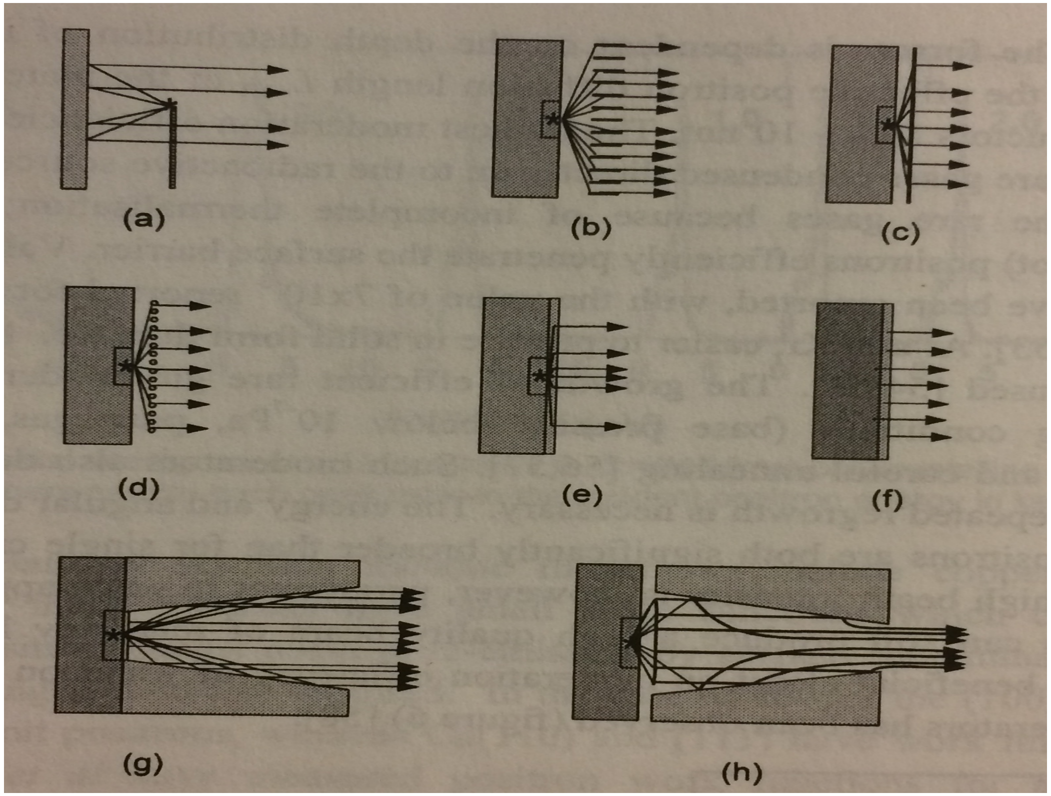
- Most annihilate in bulk
- Some capture at surface and annihilate
- Some pick up e- and leave as Ps
- And some remit !!!!

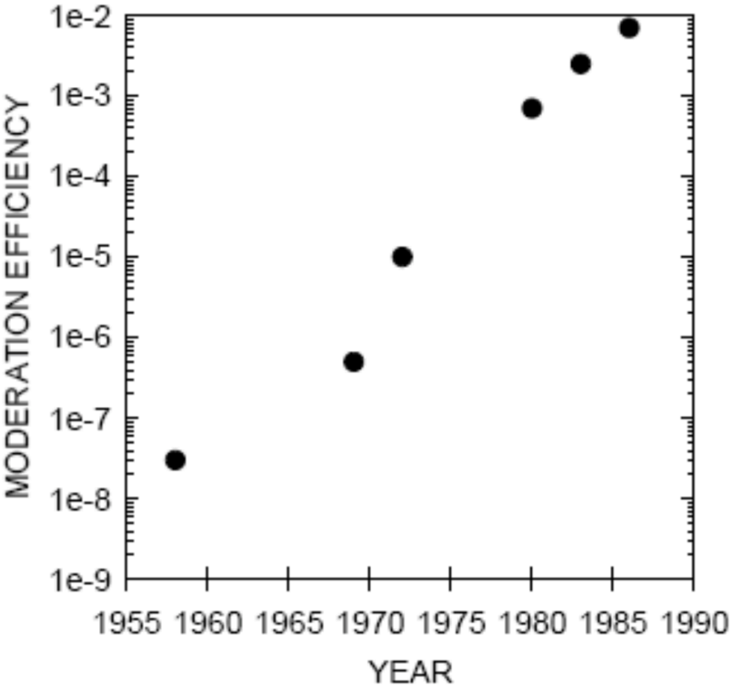
Types of Moderators and Configurations

- Moderators based on a negative work-function for positrons.

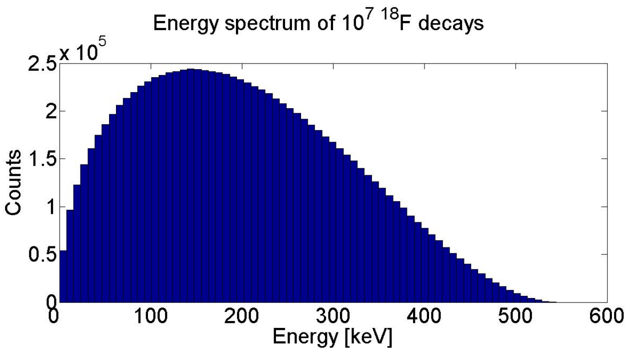
- Thermalized positrons exit with work-function energy e.g. 2-3 V from W(110)/W(100)

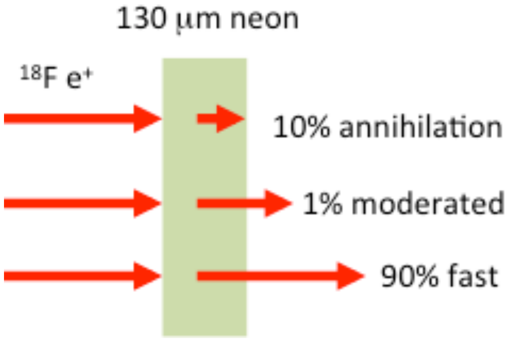
- Rare gas moderators (e.g Ne, Kr, Ar) limit thermalization so “hot positrons” w/ ~tens of Volts have a greater diffusion length and thus higher escape probability ~1%





β^+ beam based on ^{18}F (30eV - 30keV)


Energy spectrum of 10^7 ^{18}F decays

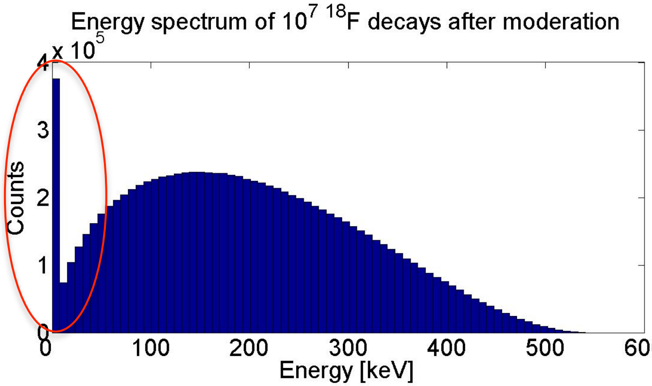

130 μm neon

^{18}F e^+

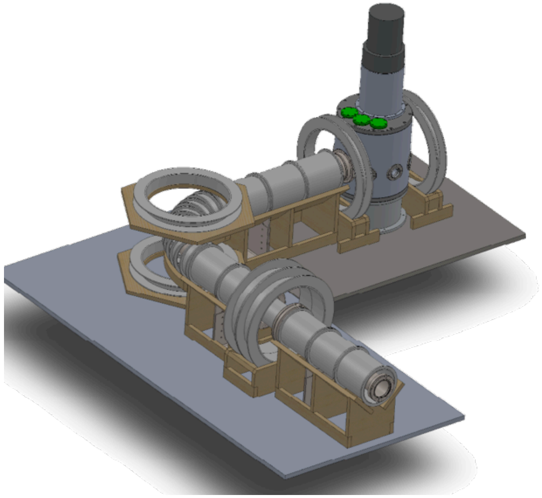
10% annihilation

1% moderated

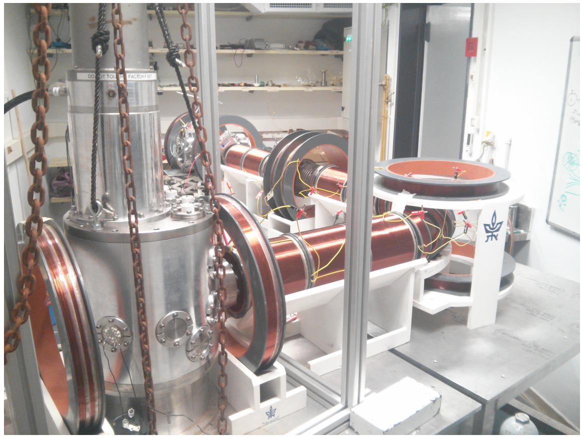
90% fast


Energy spectrum of 10^7 ^{18}F decays after moderation

- A radioactive source (^{18}F) is moderated with frozen neon to 2 eV +/- 1 eV
- Positrons DC accelerated to 30eV-30keV energy selected produce intense (10^6 e^+/s) mono-energetic beam



Slow POsitron faciliTy (SPOT)
(J. Dumas)
Hebrew University of Jerusalem
Racah Institute of Physics



This study is supported by the KAMIN program of the Chief Scientist of the Ministry of Economy, Trade, and Labor

β^+ beam based on ^{22}Na (0.5 - 6.5 MV Pelletron)

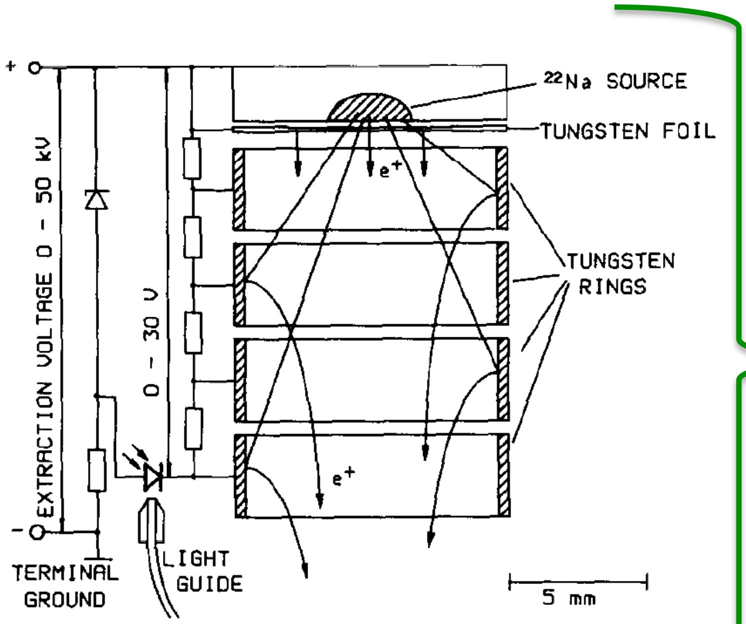


Fig. 1. Schematic of the slow-positron source with tungsten moderators.

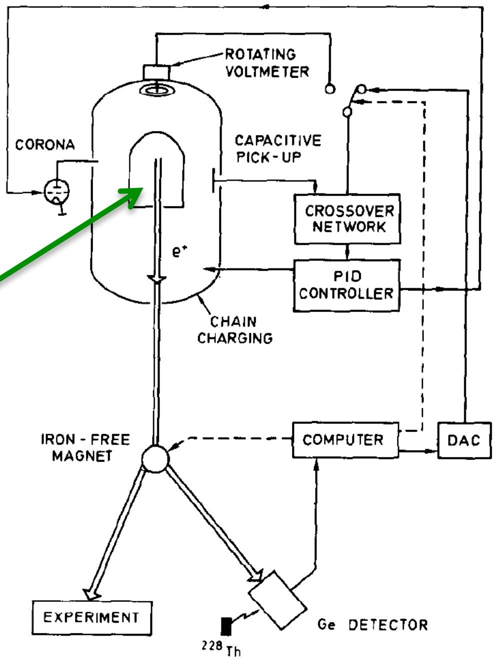


Fig. 3. Block diagram of the circuit used for the stabilization and calibration of the positron energy. The positron beam is periodically switched onto a windowless Ge detector for absolute energy measurement.

Nuclear Instruments and Methods in Physics Research B50 (1990) 300–306

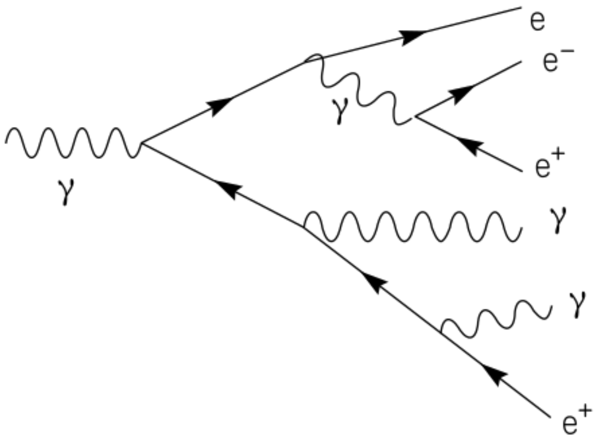
^{22}Na source (6 x l0^{8} Bq) moderated by tungsten foil (thickness 3-6 micron) and tungsten rings (height X diameter = 3.3 mm X 10 mm) in a combined transmission-reflection geometry

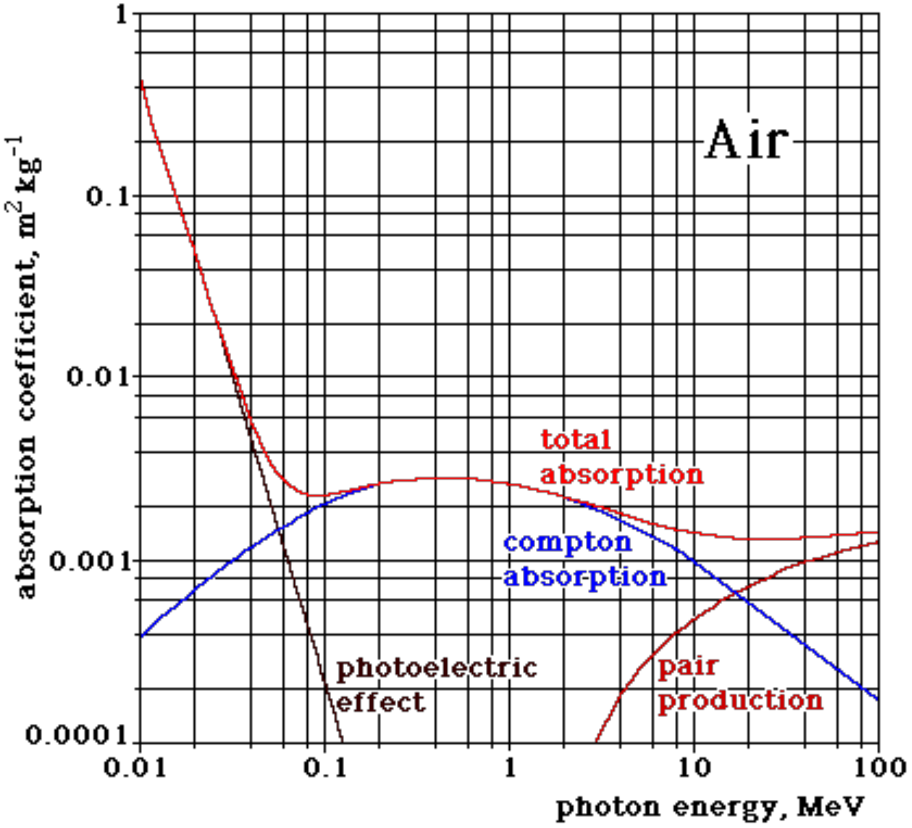
- ***Intensity 6 x l0^{4} e+/s at target***
- ***Pelletron DC acceleration 0.5 - 6.5 MeV***
- ***Energy stability $\Delta E/E < 10^{-4}$***

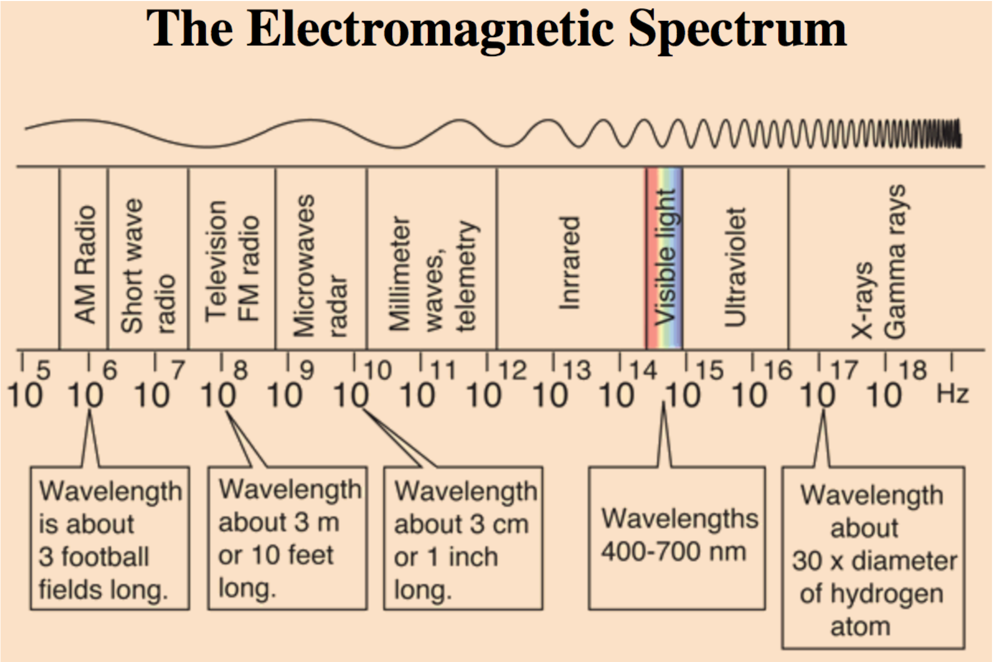
Positron Production by Electromagnetic Showers

An ***electromagnetic shower*** is generated by high energy electrons, positrons or photons in matter

- e+ and e- primarily emit photons (bremsstrahlung)
- Photons > ~few MeV dominate pair production



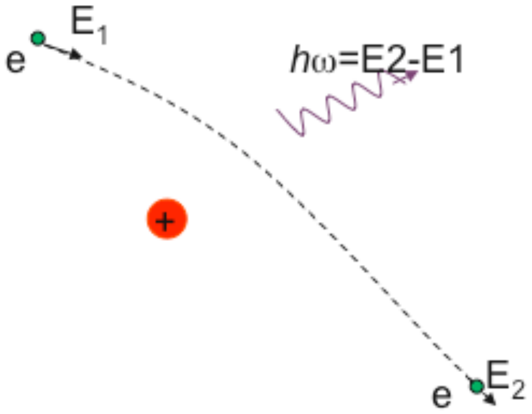




Using **Electrons** to Generate Gamma Shower

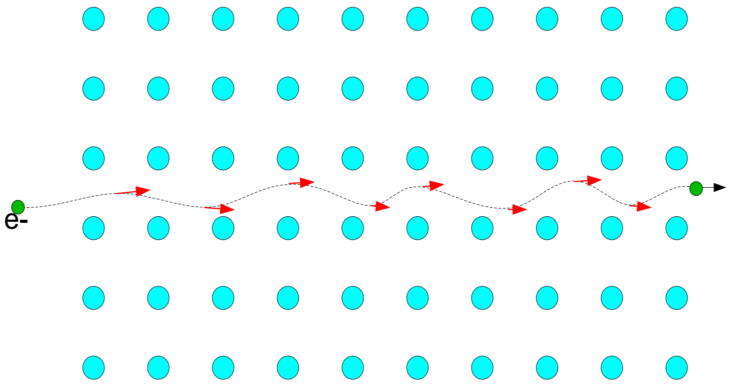
Bremsstrahlung

($E_\gamma < E_{beam}$)



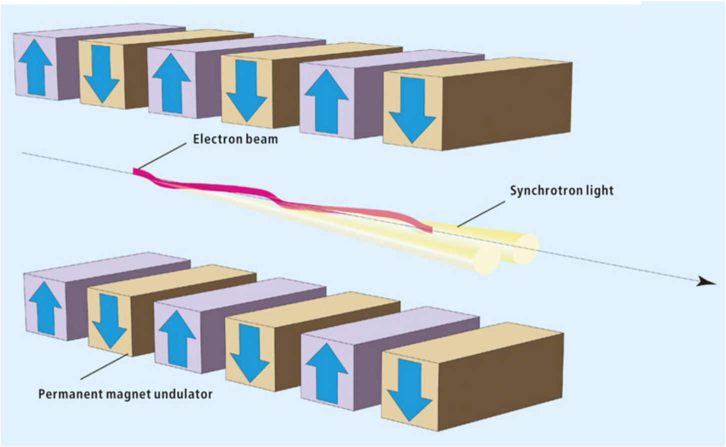
Coherent Bremsstrahlung

(Yield ~ 20-40 greater)



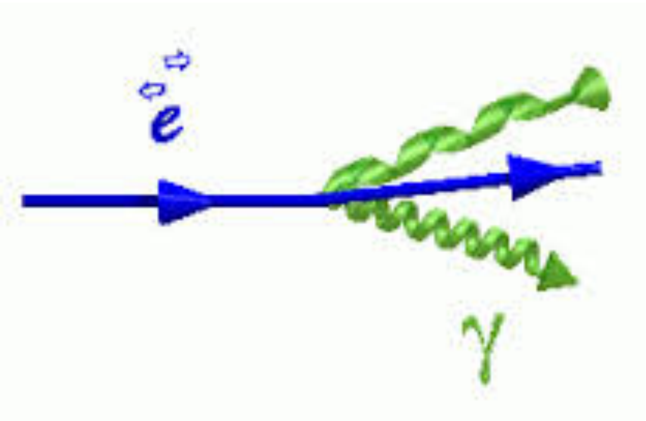
Undulator

$$E_\gamma \cong 23.7\,\mathrm{MeV}\frac{(E_e/50\,\mathrm{GeV})^2}{(\lambda_u/1\,\mathrm{mm})(1+K^2)}$$



Inverse Compton Scattering

($E_\gamma \sim E^2_{beam} * \nu$)

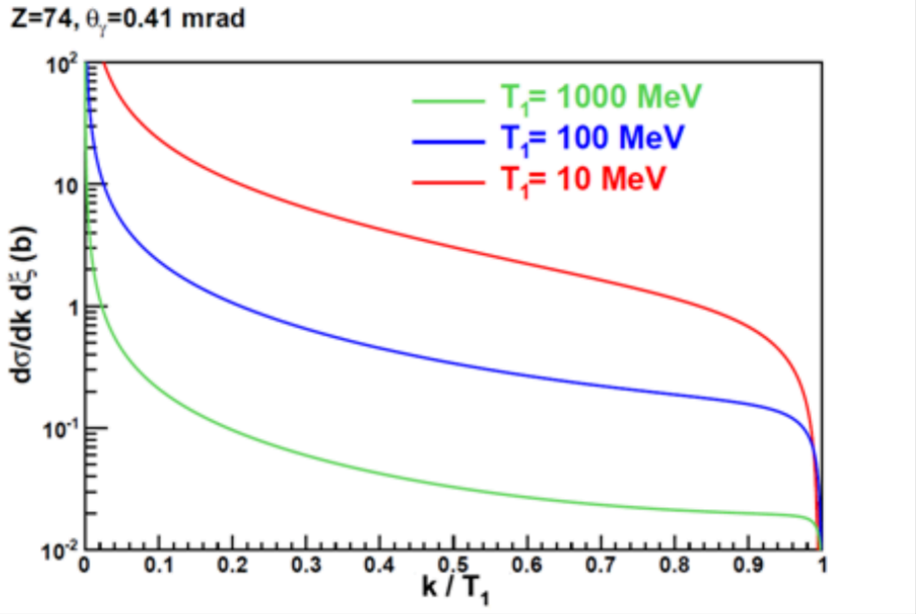


Electromagnetic Shower Cross Sections

Bremsstrahlung

- Photon energy **k** up to electron energy **T1**
- Cross section decreases as 1/k

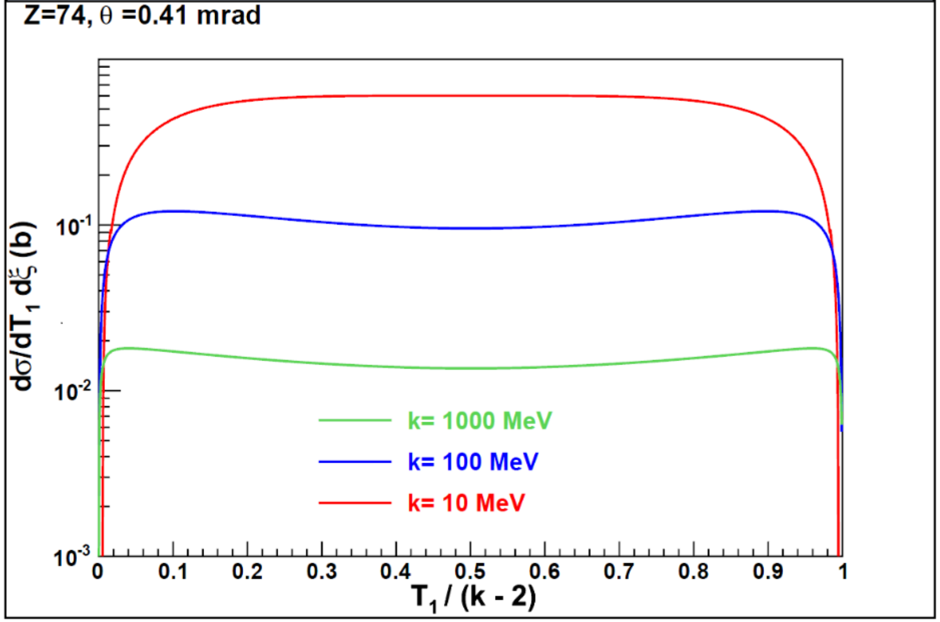
Cross section



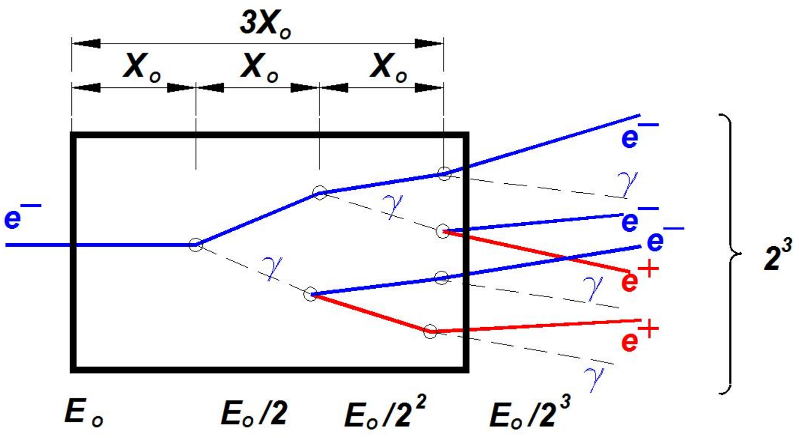
Pair Production

- Positron energy **T1** to photon energy **k**-2mc^2
- Cross section essentially energy independent

Cross section



Yield from an Electromagnetic Shower



Positron yield depends on…

- Incident power (energy x intensity)
- Target material (radiation length)

$$X_0^{-1} \cong 4 r_0^2 \alpha \frac{N_A}{A} Z(Z+1)\ln\left(\frac{183}{Z^{1/3}}\right)[cm^2/g]$$

Radiation length

- Mean electron energy loss (1/e)
- 7/9 mean path for pair production

Element	C	Al	Ti	Fe	Cu	W
Z	**6**	**13**	**22**	**26**	**29**	**74**
A	12	27	47.9	55.8	63.5	183.8
E_c (MeV)	84.2	42.8	26.2	22.4	20.2	8.1
X_0 (g/cm^2)	**43.3**	**24.3**	**16.1**	**13.84**	**13**	**6.8**
L (cm)	**19.2**	**9**	**3.58**	**1.75**	**1.45**	**0.35**

Accelerator Positron Sources

Previous

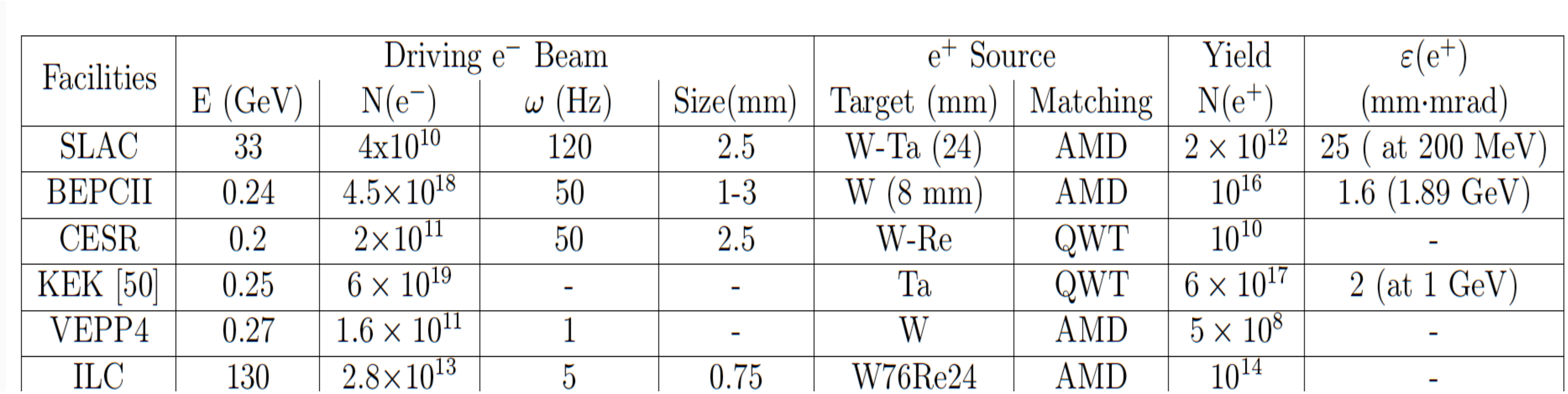
- SLAC – Stanford Linear Accelerator Center (US)
- HERA – Hadron Electron Ring Accelerator (Germany)
- CESR – Cornell Electron Storage Ring (US)

Present

- BELLE/KEK – National Laboratory for High Energy Physics (Japan)
- VEPP – Budker Institute of Nuclear Physics (Russia)
- BEPCII – Beijing Electron Positron Collider (China)

Proposed

- ILC - International Linear Collider



Facilities	Driving e^- Beam				e^+ Source		Yield	$\varepsilon(e^+)$
	E (GeV)	$N(e^-)$	ω (Hz)	Size(mm)	Target (mm)	Matching	$N(e^+)$	(mm·mrad)
SLAC	33	$4 \text{x} 10^{10}$	120	2.5	W-Ta (24)	AMD	2×10^{12}	25 (at 200 MeV)
BEPCII	0.24	4.5×10^{18}	50	1-3	W (8 mm)	AMD	10^{16}	1.6 (1.89 GeV)
CESR	0.2	2×10^{11}	50	2.5	W-Re	QWT	10^{10}	-
KEK [50]	0.25	6×10^{19}	-	-	Ta	QWT	6×10^{17}	2 (at 1 GeV)
VEPP4	0.27	1.6×10^{11}	1	-	W	AMD	5×10^{8}	-
ILC	130	2.8×10^{13}	5	0.75	W76Re24	AMD	10^{14}	-

Managing Beam Power

High power deposition in **conversion target** and surrounding materials

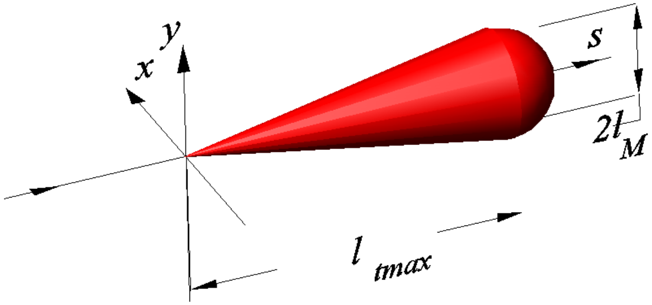
Details depends upon

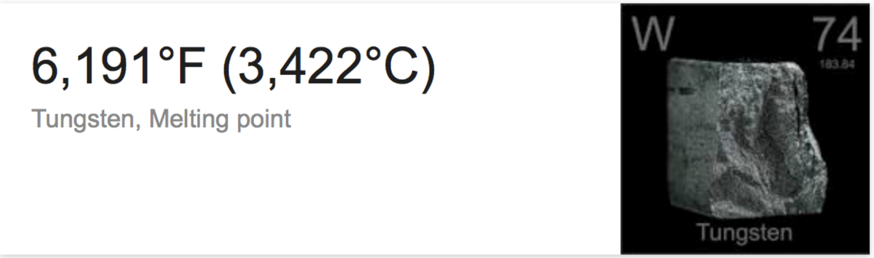
- Conversion efficiency (number of positrons per incident electron or photon)
- Ultimate positron intensity required
- Target material
- Time structure

It's not uncommon to require **100's of kW** of beam power.

Consider 20 kW deposited in $1X_0$ of tungsten (W) :

$$\Delta T \cong \frac{E_{tot}}{mC_p} \cong \frac{E_{tot}}{\rho \frac{\pi}{3} l_{t_{\max}} l_M^2 C_p} \cong 3000\,\deg C$$




6,191°F (3,422°C)

Tungsten, Melting point

W 74

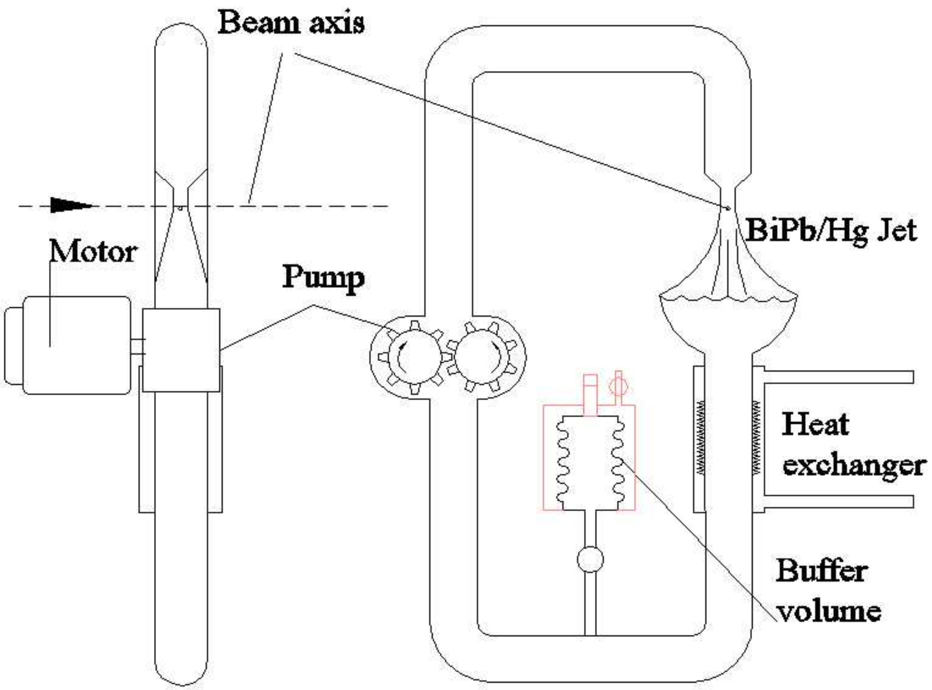
183.84

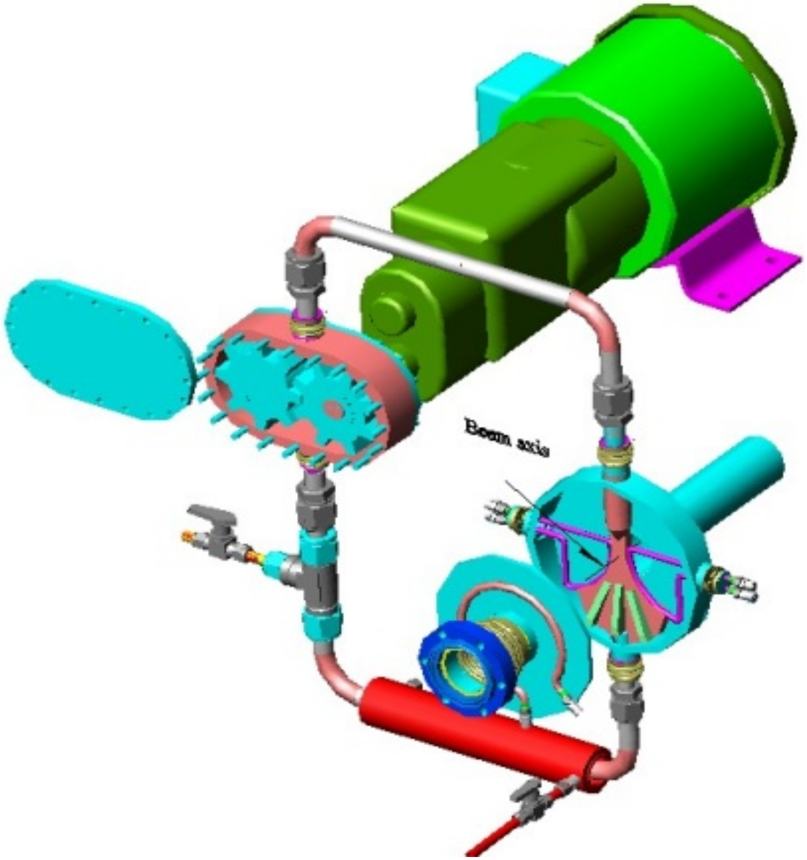
Tungsten

High Power Alternative: High-Z Liquid Jet Target

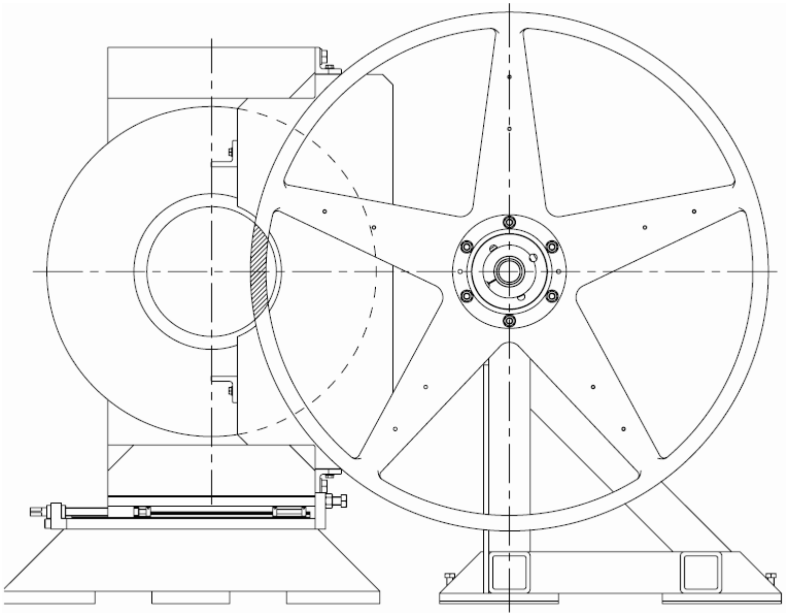
Jet or stream for rapid mass transfer

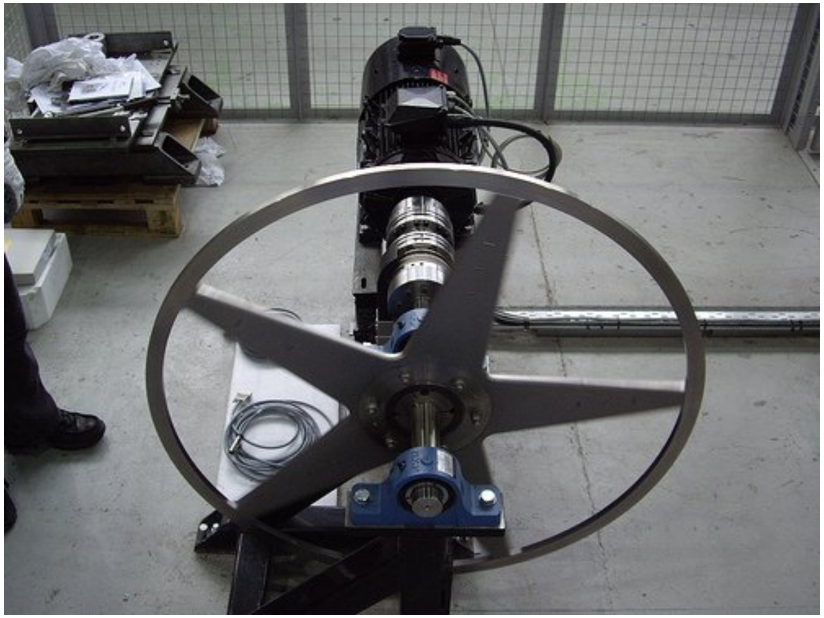
- Heat exchangers
- High boiling point metals
  - Bismuth-Lead (BiPb) ~ 1670 °C
  - Mercury (Hg) ~ 356 °C





High Power Alternative: Rapidly Rotating Cooled Target





ILC target design schematic and prototype

- 1 m diameter Ti-alloy wheel rotating at 2000 rpm
- Target is immersed in magnet field (positron collection)
- **Strong eddy-currents are a challenge**
- 10 kW power deposition @ 130 kW photons

Manage Radioactivity

R.Montalbetti, L.Katz, J. Goldemberg, "*Photoneutron Cross Sections*", Phys.Rev. **91**, 659 (1953).

Elements →	C	W	Cu	Al	Fe	Pb	U
$E_{\gamma th}\,(\gamma,n)\quad MeV$	18.72[1]	**6.19**	9.91	13.03	11.21	6.73	6.04

[1] Natural Graphite contains 1.1% of C^{18} which has a threshold of 4.9 *MeV*

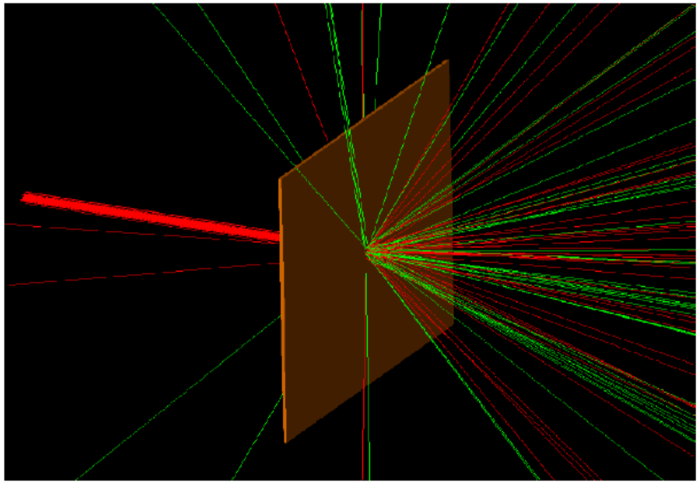
Neutron dose for electron beam carrying power $P[kW]$ at distance $R[m]$

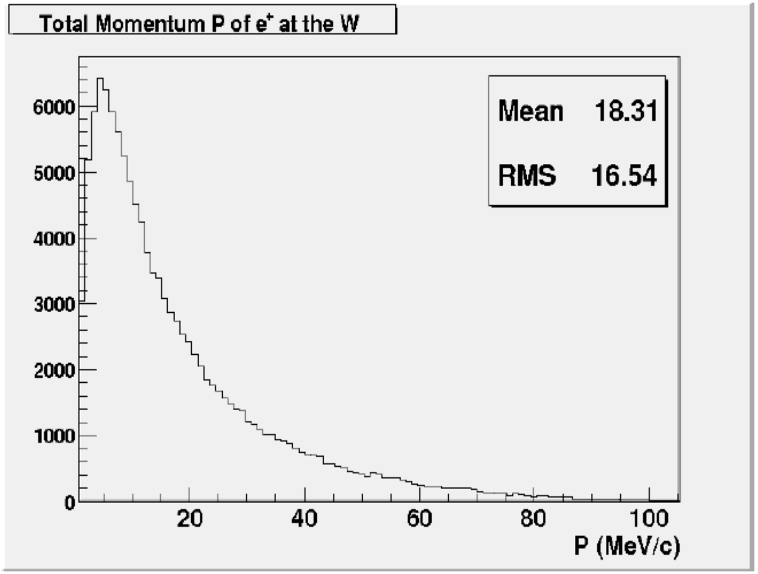
$$\dot{D}(rem/hour) \cong 93\cdot Z^{0.73}\,\frac{P[kW]}{R[m]^2}$$

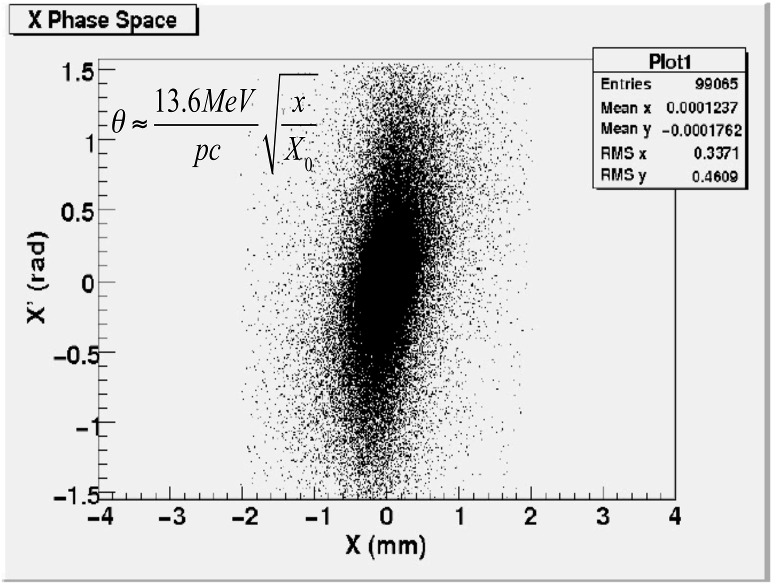
W.P.Swanson, "*Calculation of Neutron Yields Released by Electrons Incident on Selected Materials*", Health Physics, Vol.35, pp.353-367, 1978.

Neutron shielding and radiological design is integral to overall design

Manage Large Angular & Momentum Distribution







Incident e- Beam Properties on a 3mm W:

Power = 120MeV×10mA = 1.2 MW

$\varepsilon = 10^{-8}$ m•rad

Emerging e+ Properties:

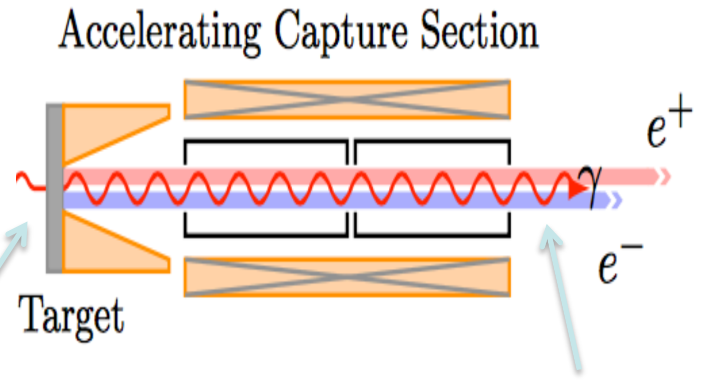
$\varepsilon = 0.3$ mm x 460 mrad ~ 14000×10^{-8} m•rad

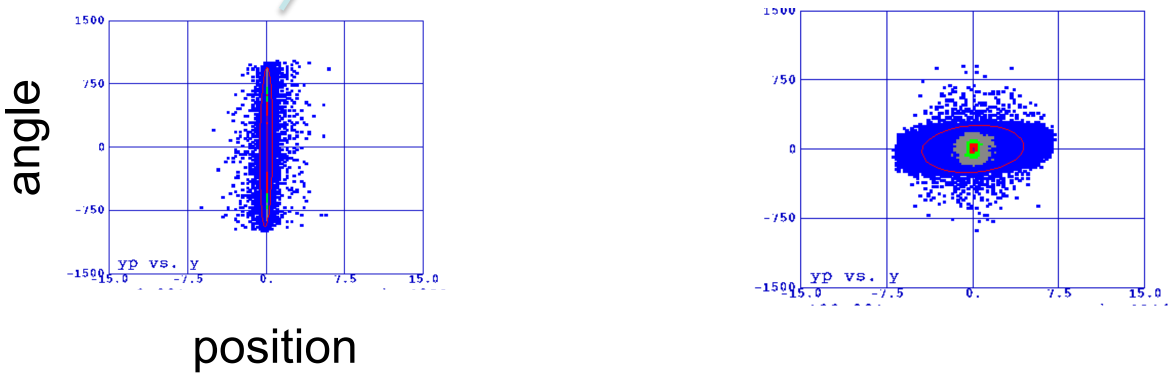
Yield : 0.12 e^+ per e^-

Taming the Positrons

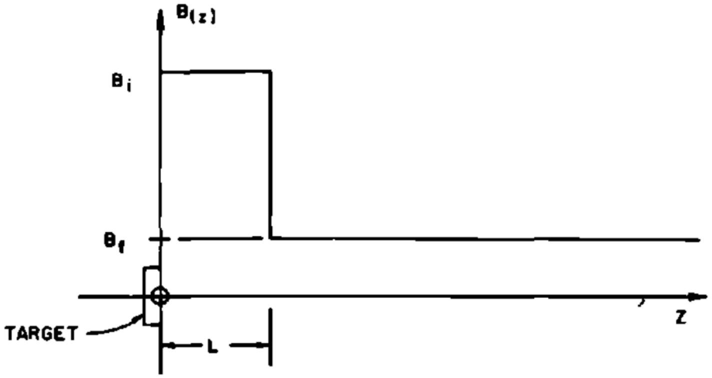
High field solenoid transforms large divergence small radius at radiator to smaller divergence and larger radius

Low field solenoid maintains beam envelope through nearby acceleration sections

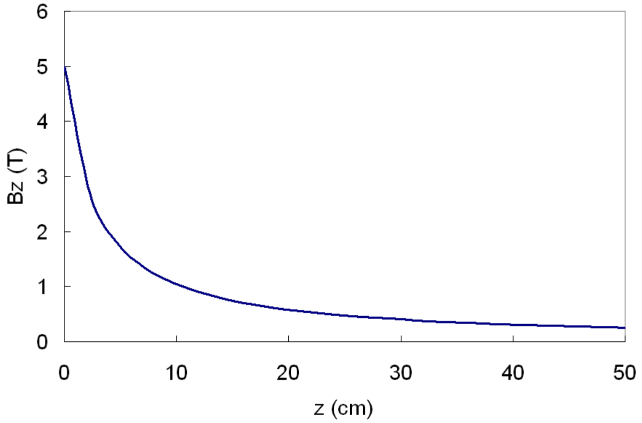




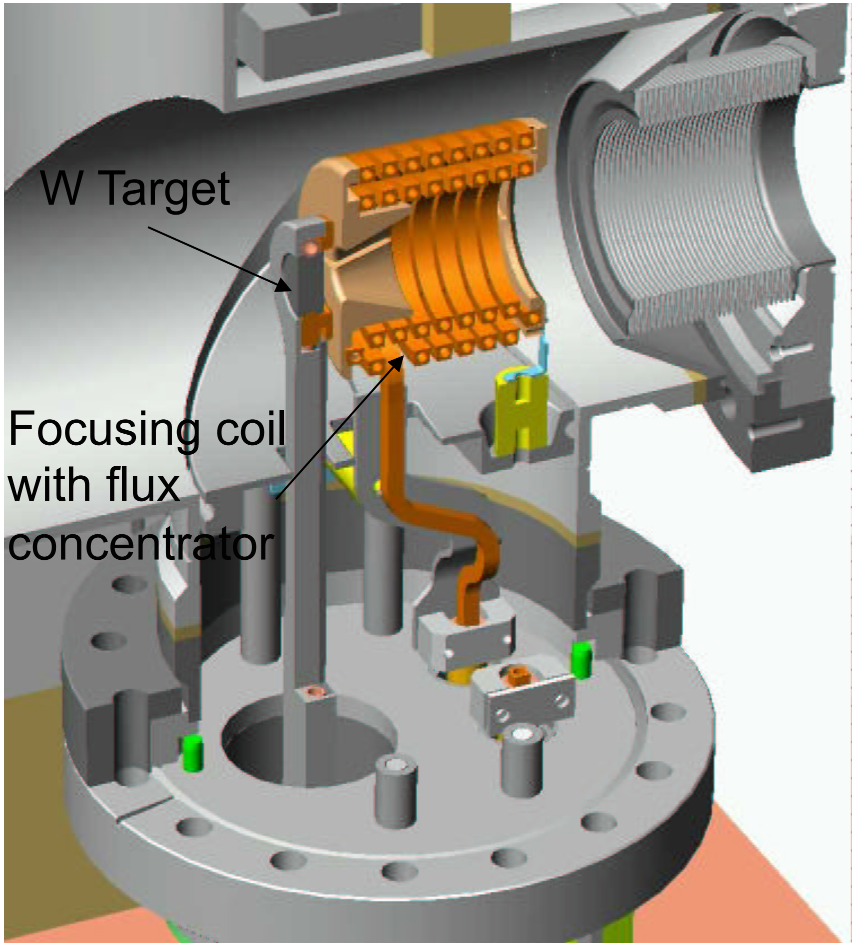
Quarter Wave Transformer (QWT)

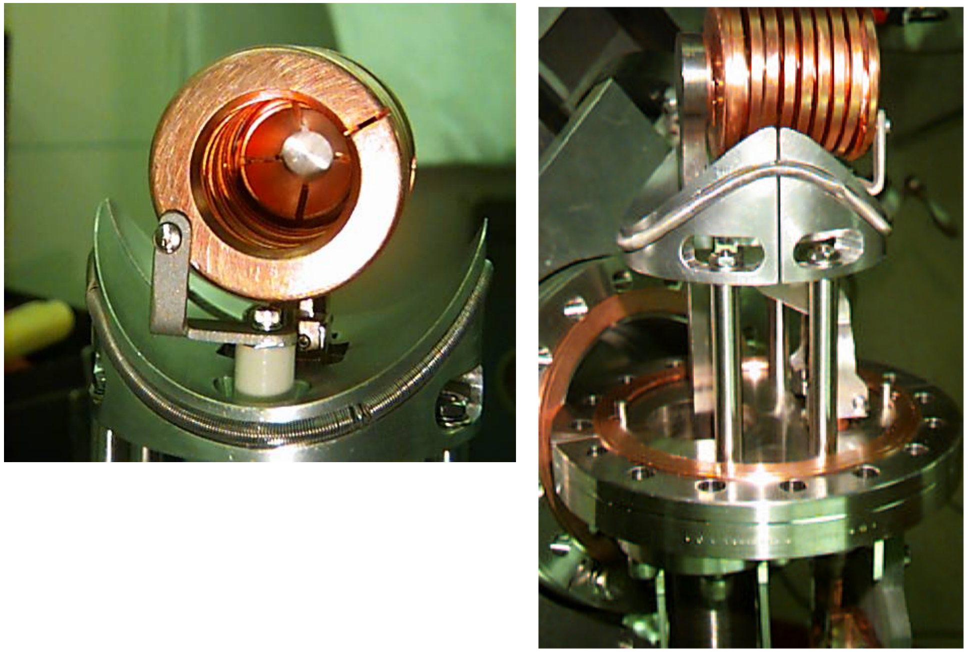


Adiabatic Matching Device (AMD)



Example: Cornell Positron Source (QWT)





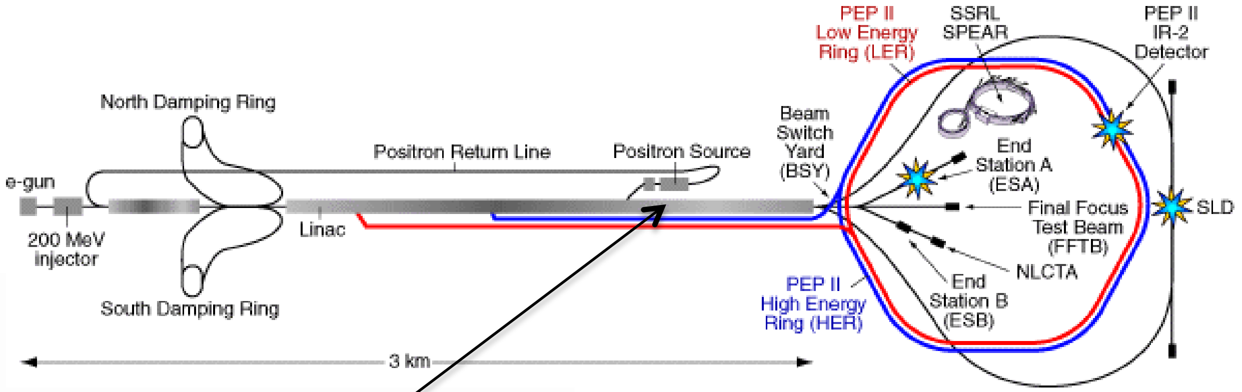
This short-focusing lens followed by RF structure immersed in solenoid

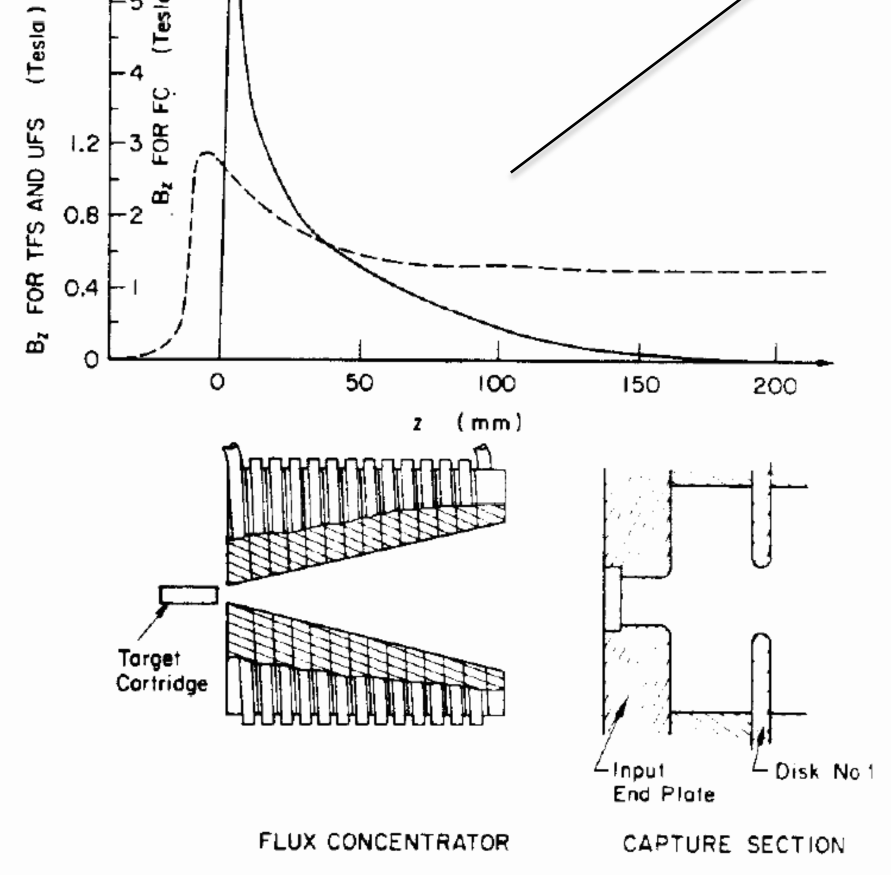
Positron rate ~10^{11} /sec at 50 Hz operation at ~200 MeV

Conversion efficiency~2.5%, DC power consumption ~2.5 kW

J. Barley, V. Medjidzade, A. Mikhailichenko, "New Positron Source for CESR", CBN-01-19, Oct 2001. 16pp.

Example: Stanford Linear Accelerator Center (AMD)





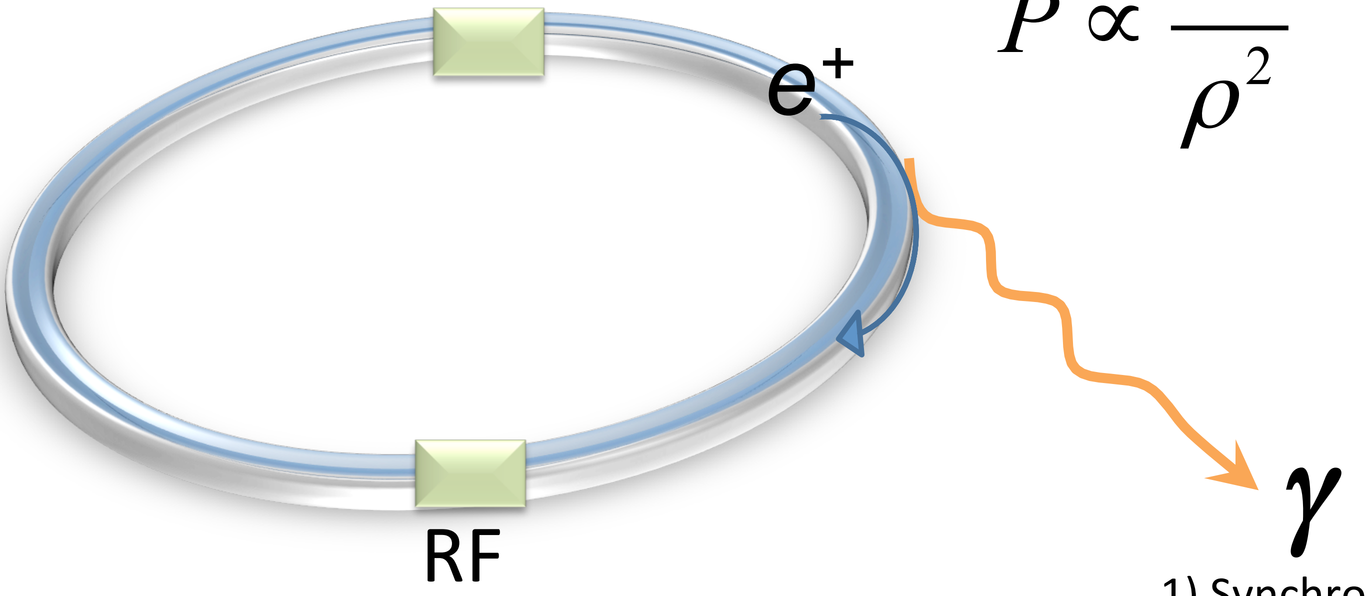
Driving electron beam	
Energy (GeV)	33.0
Spot Size 1σ (mm)	0.6
Intensity	5×10^{10} / pulse
Pulse Energy (Joule/pulse)	264.0
Pulse Rate (Hz)	120-180
Beam Power (kW)	47.0
Target	
Material	90% Ta - 10% W and WRe
Length (mm)	20 (or 6 rad. length)
Deposited Energy (Joule/pulse)	53.0
Deposited Power (kW)	9.0
Positron beam	
Capture Energy (MeV)	5 - 20
Spot Size (mm) 1σ	2.0
Normalized Emittance (m·rad)	10^{-2} at 200 MeV
Yield (e^+/e^-)	2.5

More Taming: Damping Ring to Reduce Emittance

$$\varepsilon(t) = \varepsilon_{\text{inj}} e^{-2t/\tau} + \varepsilon_{\text{equ}}\left(1\text{-}e^{-2t/\tau}\right)$$

$$P \propto \frac{E^4}{\rho^2}$$

P :Radiated power
E: Energy of the particle
ρ : Bending radius



2) RF cavities **restore energy** to off-momentum particles undergoing synchrotron oscillations

1) Synchrotron radiation "steals" momentum from **all** components

SLAC e^+ (1.2 GeV, ρ=5.6m) damping time ~ 12 milliseconds

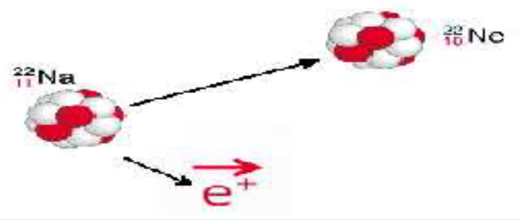
Lower energy increases damping time to seconds!

"long" damping times are not suited for CW operation

What about Polarization ?

Polarized β^+ Decay

L.A. Page & M. Heinberg. Phys. Rev. 106(6):1220-1224 (1957)

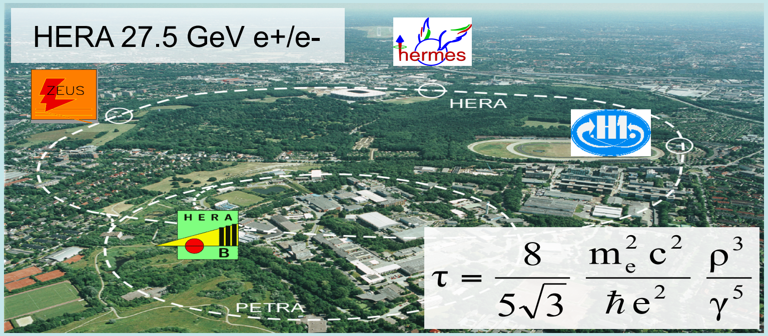


Polarized due to parity non-conservation in the weak interaction

$P(e^+) \sim 40$ %

Sokolov-Ternov Effect

D. Barber , AIP Conf. Proc. 588, 338 (2001)

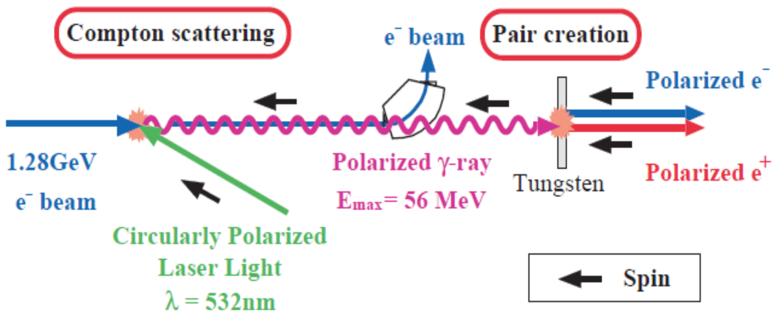


$$\tau = \frac{8}{5\sqrt{3}} \frac{m_e^2 c^2}{\hbar e^2} \frac{\rho^3}{\gamma^5}$$

$P(e^+) \sim 70$ %

Inverse Compton Backscattering (KEK)

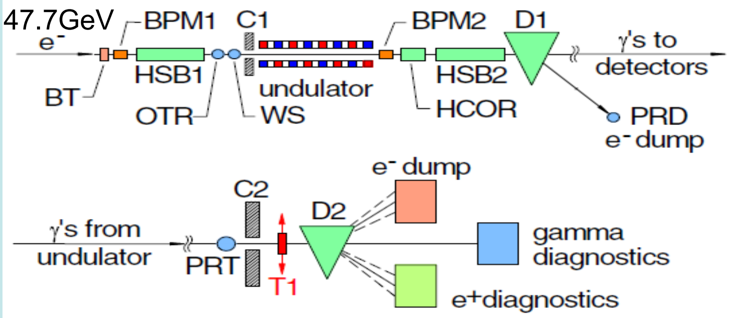
T. Omori et al, PRL 96 (2006) 114801



$P(e^+) = 73 \pm 15_{(stat)} \pm 19_{(syst)}$ %

Helical Undulator (SLAC E166)

G. Alexander et al, PRL 100 (2008) 210801



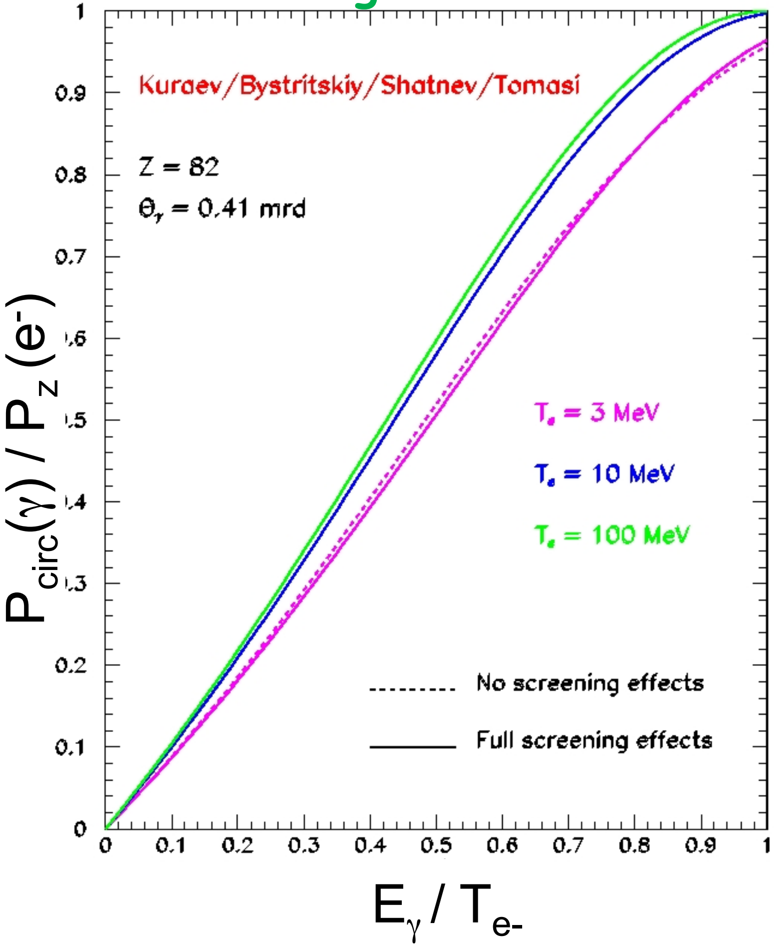
$P(e^+) = 80 \pm 7_{(stat)} \pm 9_{(syst)}$ %

New Method : Uses Spin Polarized Electron Beam

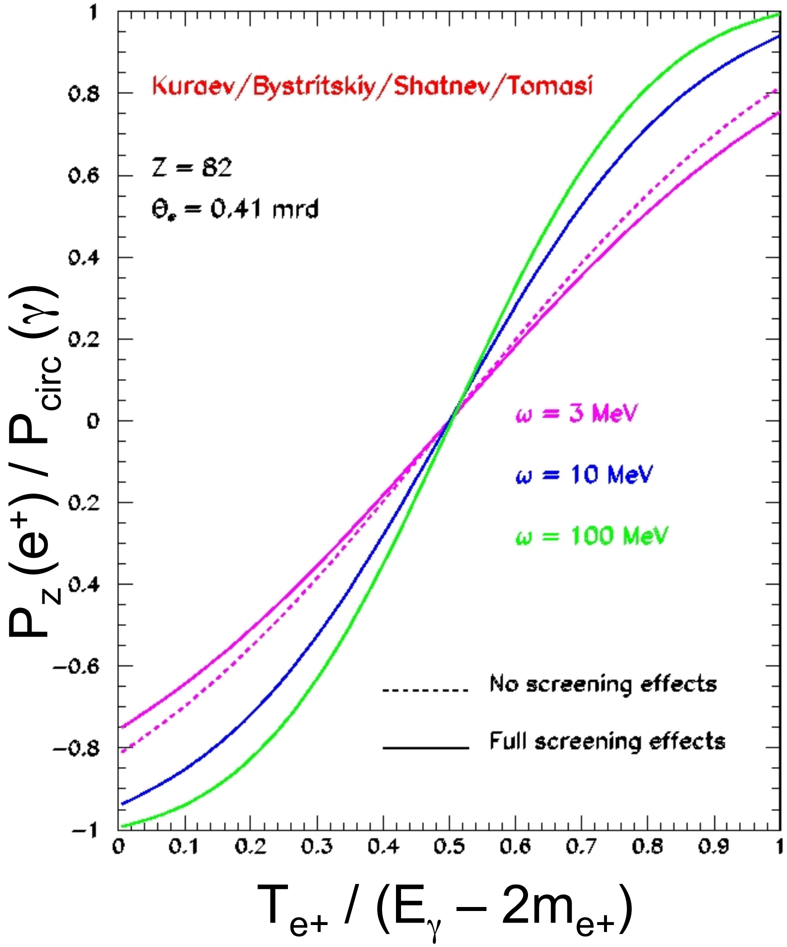
E.G. Bessonov, A.A. Mikhailichenko, EPAC (1996)   A.P. Potylitsin, NIM A398 (1997) 395

$$\vec{e}^{\,-} \rightarrow \overset{\circlearrowright}{\gamma} \rightarrow \vec{e}^{\,+}\ (+\ \vec{e}^{\,-})$$

Bremsstrahlung



Pair Creation



E.A. Kuraev, Y.M. Bystritskiy, M. Shatnev, E.Tomasi-Gustafsson, PRC 81 (2010) 055208

Polarized Electrons for Polarized Positrons

A Proof-of-Principle Experiment

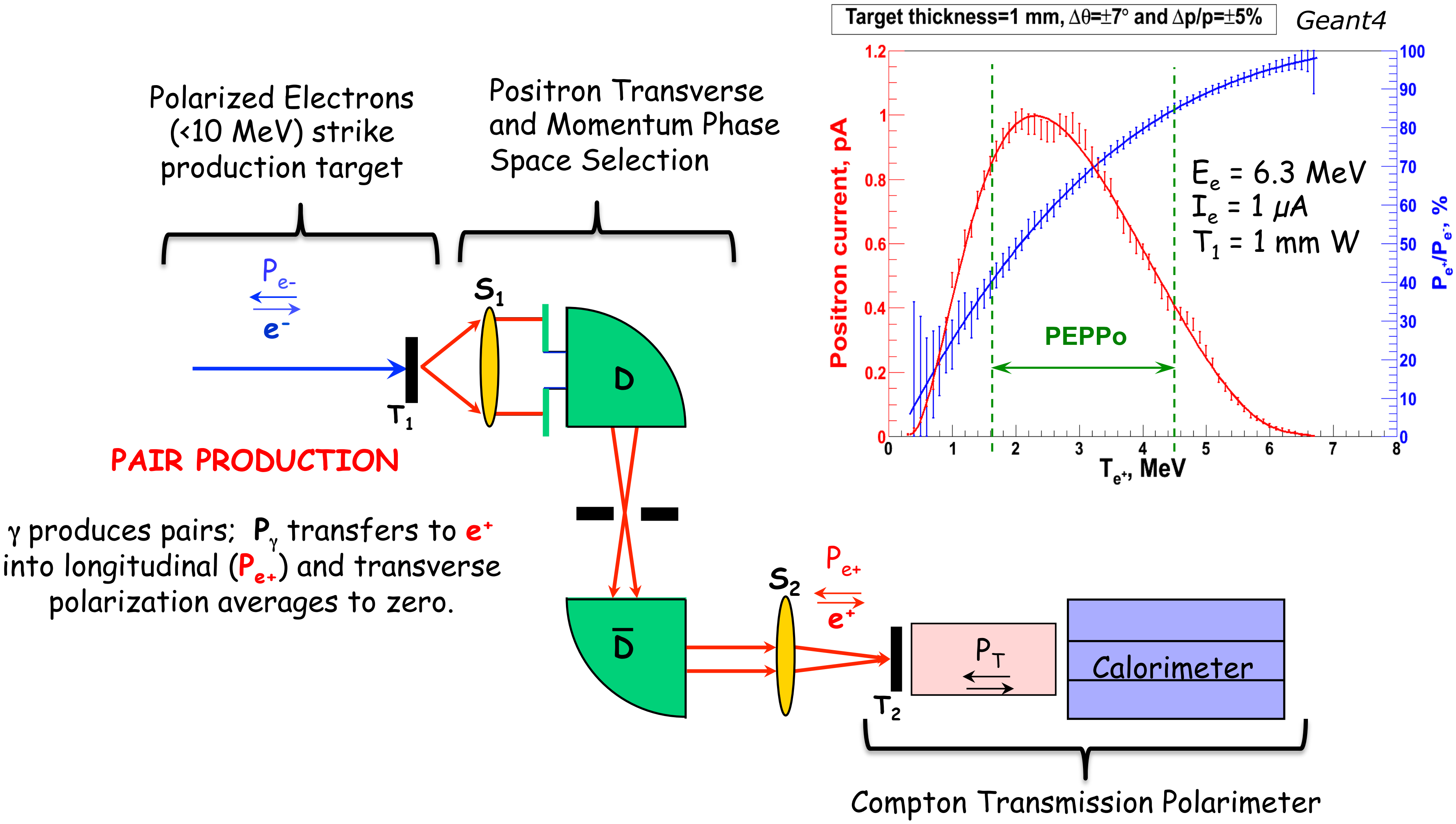
P. Aderley[1], A. Adeyemi[4], P. Aguilera[1], M. Ali, H. Areti[1], M. Baylac[2], J. Benesch[1], G. Bosson[2], B. Cade[1], A. Camsonne[1], L. Cardman[1], J. Clark[1], P. Cole[5], S. Covert[1], C. Cuevas[1], O. Dadoun[3], D. Dale[5], J. Dumas[1,2], E. Fanchini[2], T. Forest[5], E. Forman[1], A. Freyberger[1], E. Froidefond[2], S. Golge[6], J. Grames[1], P. Guèye[4], J. Hansknecht[1], P. Harrell[1], J. Hoskins[8], C. Hyde[7], R. Kazimi[1], Y. Kim[1,5], D. Machie[1], K. Mahoney[1], R. Mammei[1], M. Marton[2], J. McCarter[9], M. McCaughan[1], M. McHugh[10], D. McNulty[5], T. Michaelides[1], R. Michaels[1], C. Muñoz Camacho[11], J.-F. Muraz[2], K. Myers[12], A. Opper[10], M. Poelker[1], J.-S. Réal[2], L. Richardson[1], S. Setiniyazi[5], M. Stutzman[1], R. Suleiman[1], C. Tennant[1], C.-Y. Tsai[13], D. Turner[1], A. Variola[3], E. Voutier[2], Y. Wang[1], Y. Zhang[12]

[1] Jefferson Lab, Newport News, VA, US [2] LPSC, Grenoble, France [3] LAL, Orsay, France
[4] Hampton University, Hampton, VA, USA [5] Idaho State University & IAC, Pocatello, ID, USA
[6] North Carolina Central University, Durham, NC, USA [7] Old Dominion University, Norfolk, VA, US
[8] The College of William & Mary, Williamsburg, VA, USA [9] University of Virginia, Charlottesville, VA, USA
[10] George Washington University, Washington, DC, USA [11] IPN, Orsay, France
[12] Rutgers University, Piscataway, NJ, USA [13] Virginia Tech, Blacksburg, VA, USA

SLAC E-166 Collaboration
International Linear Collider Project
Jefferson Science Association Initiatives Award

PEPPo Concept

J. Dumas, Ph.D. Dissertation, University Joseph Fourier, Grenoble (2010)



Polarized Electrons (<10 MeV) strike production target

Positron Transverse and Momentum Phase Space Selection

PAIR PRODUCTION

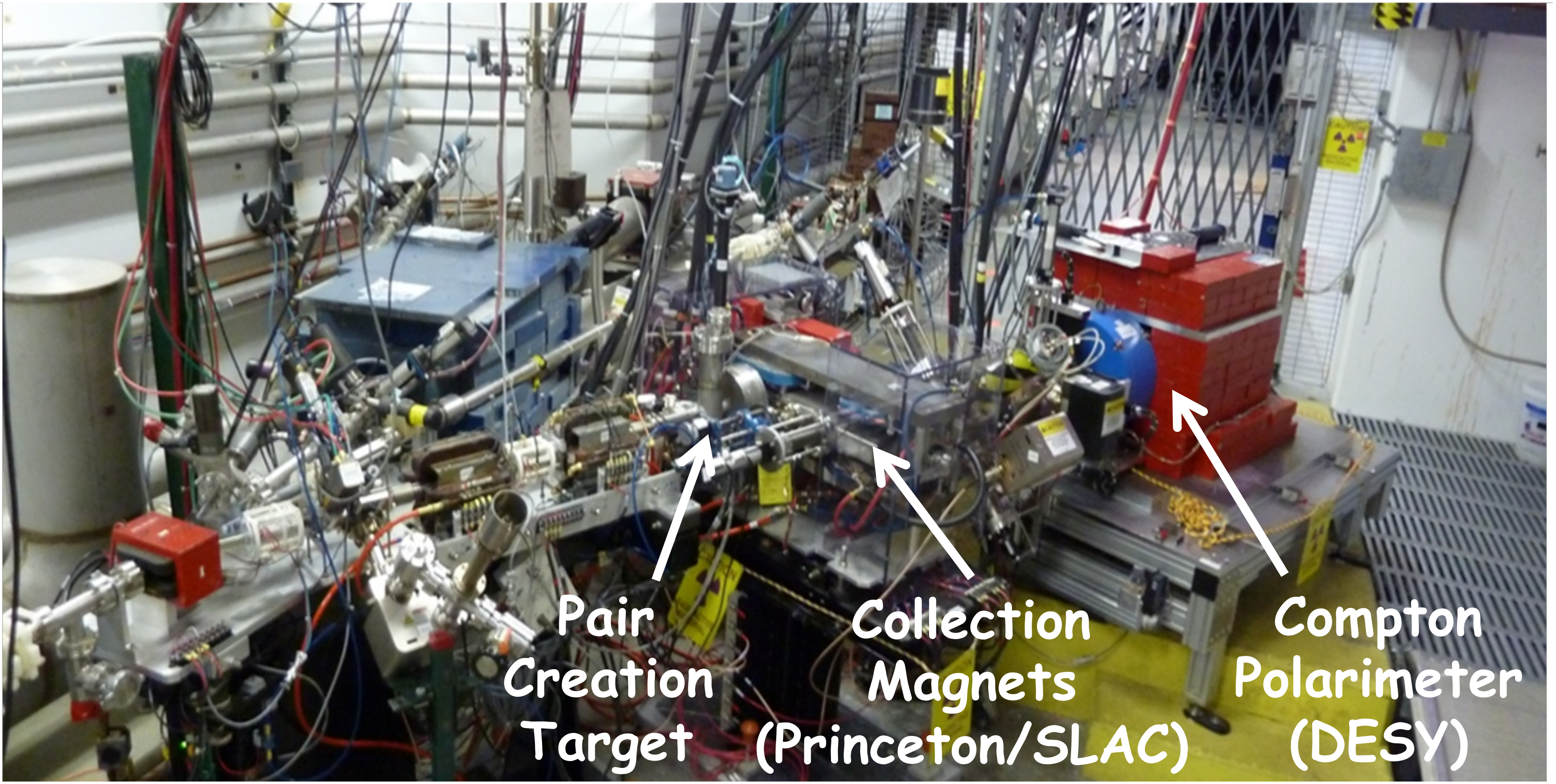
γ produces pairs; P_γ transfers to e^+ into longitudinal (P_{e+}) and transverse polarization averages to zero.

Compton Transmission Polarimeter

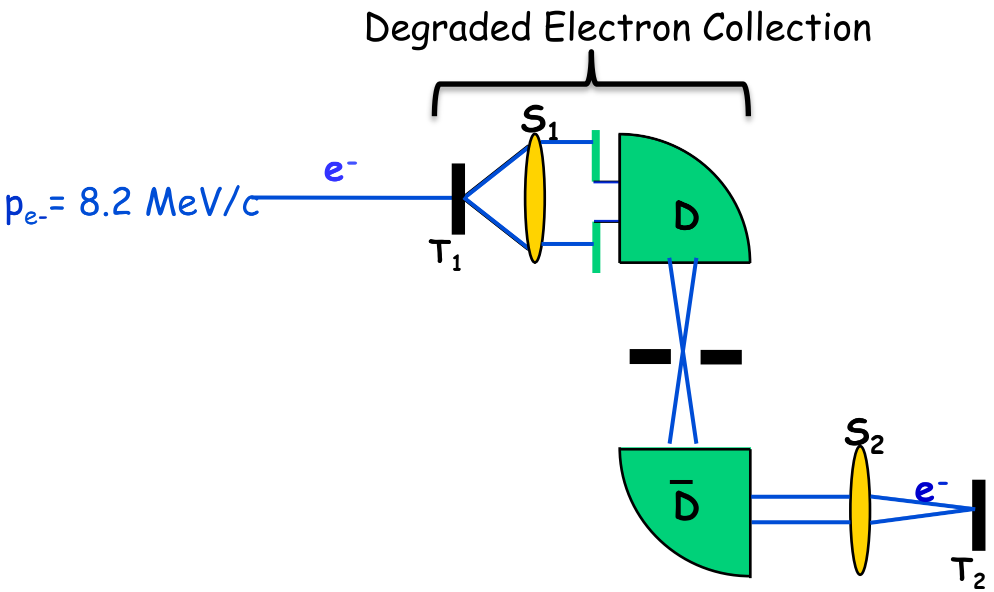
PEPPo at the CEBAF Injector

PEPPo measured the **polarization transfer** from **8.2 MeV/c longitudinal electrons** to longitudinal positrons in the **3.1-6.2 MeV/c momentum range**.

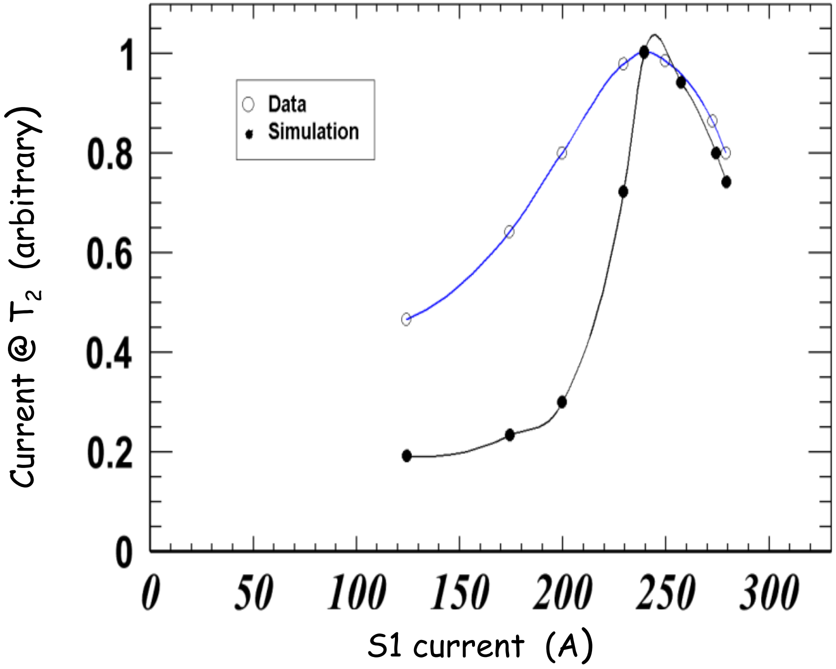
Final Installation June 2012

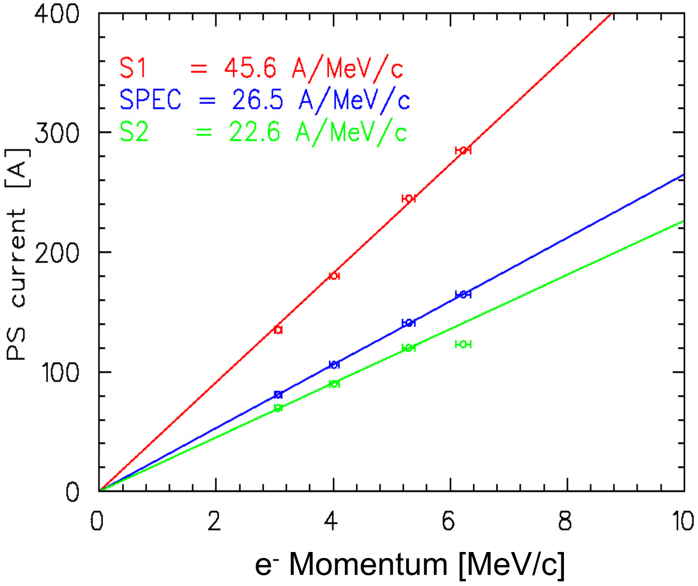


Using Degraded Electrons to Optimize Positron Collection



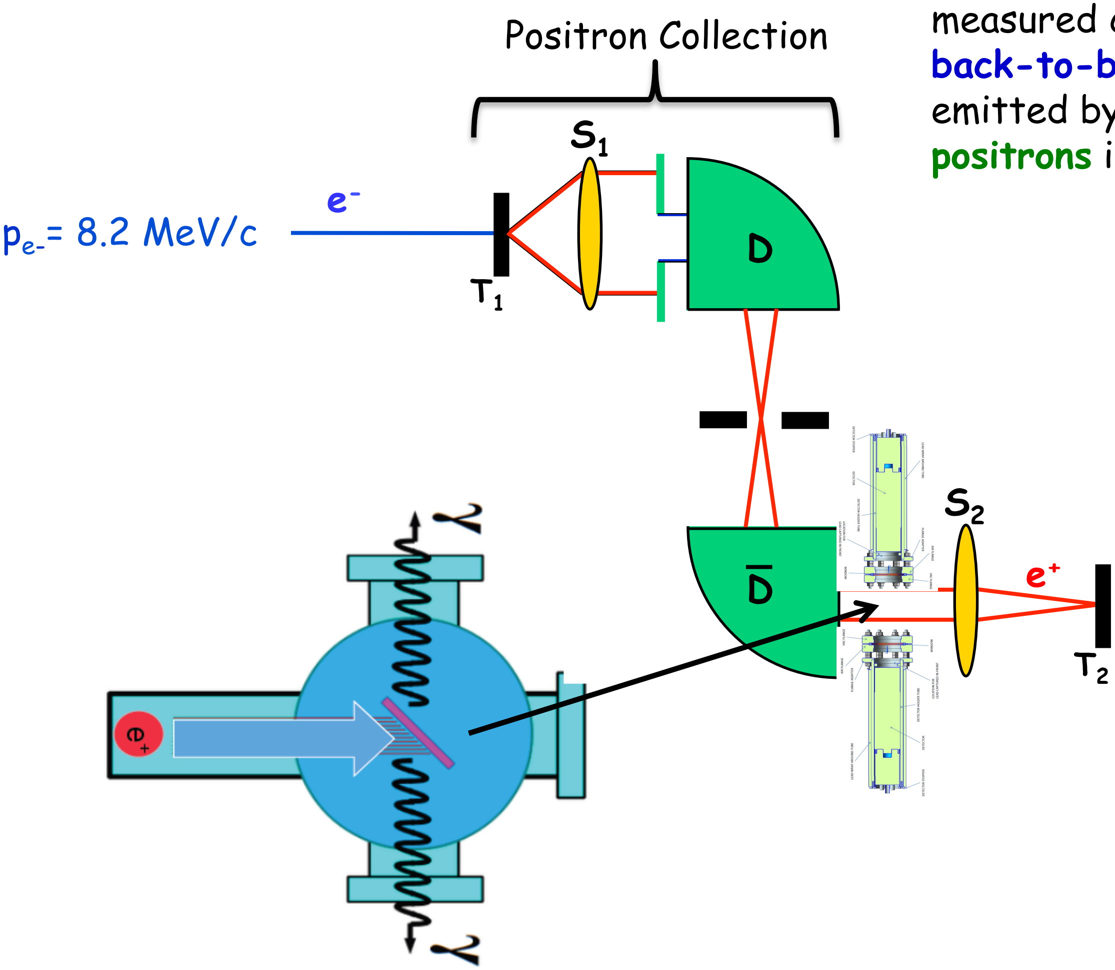
S_1 current optimization at 5.5 MeV/c



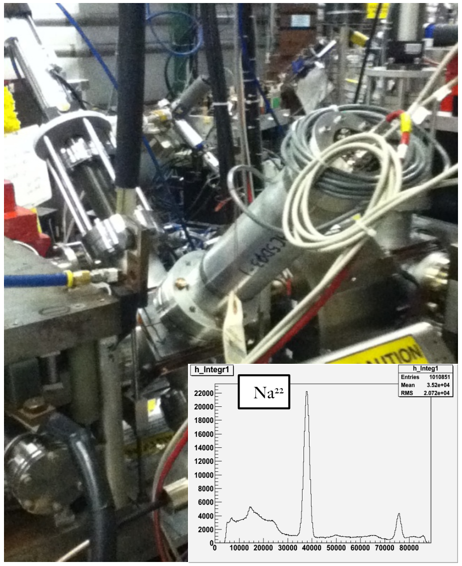


- "Low Power" exp't generated pA's of e+
- Degraded electrons allowed optimizing magnets with measurable currents ~10's nA

Positron Detection by Annihilation Coincidence

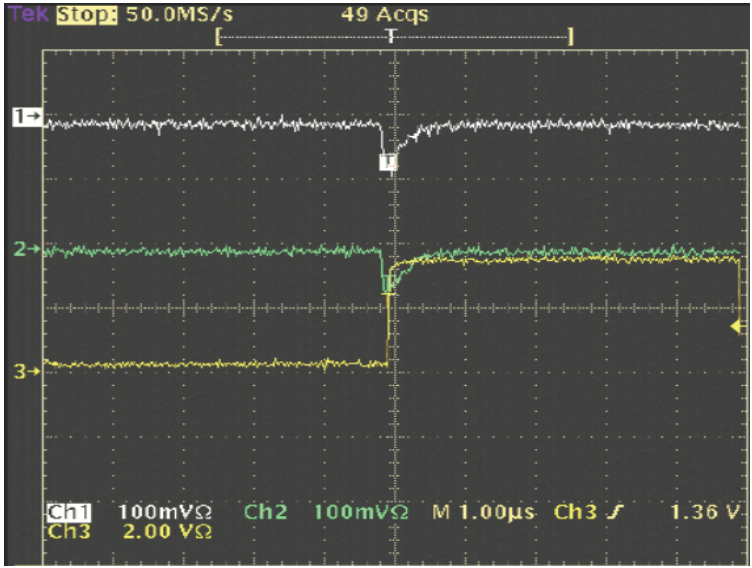


Two **NaI** detectors measured coincidence of **back-to-back photons** emitted by **annihilation** of **positrons** in a viewscreen.

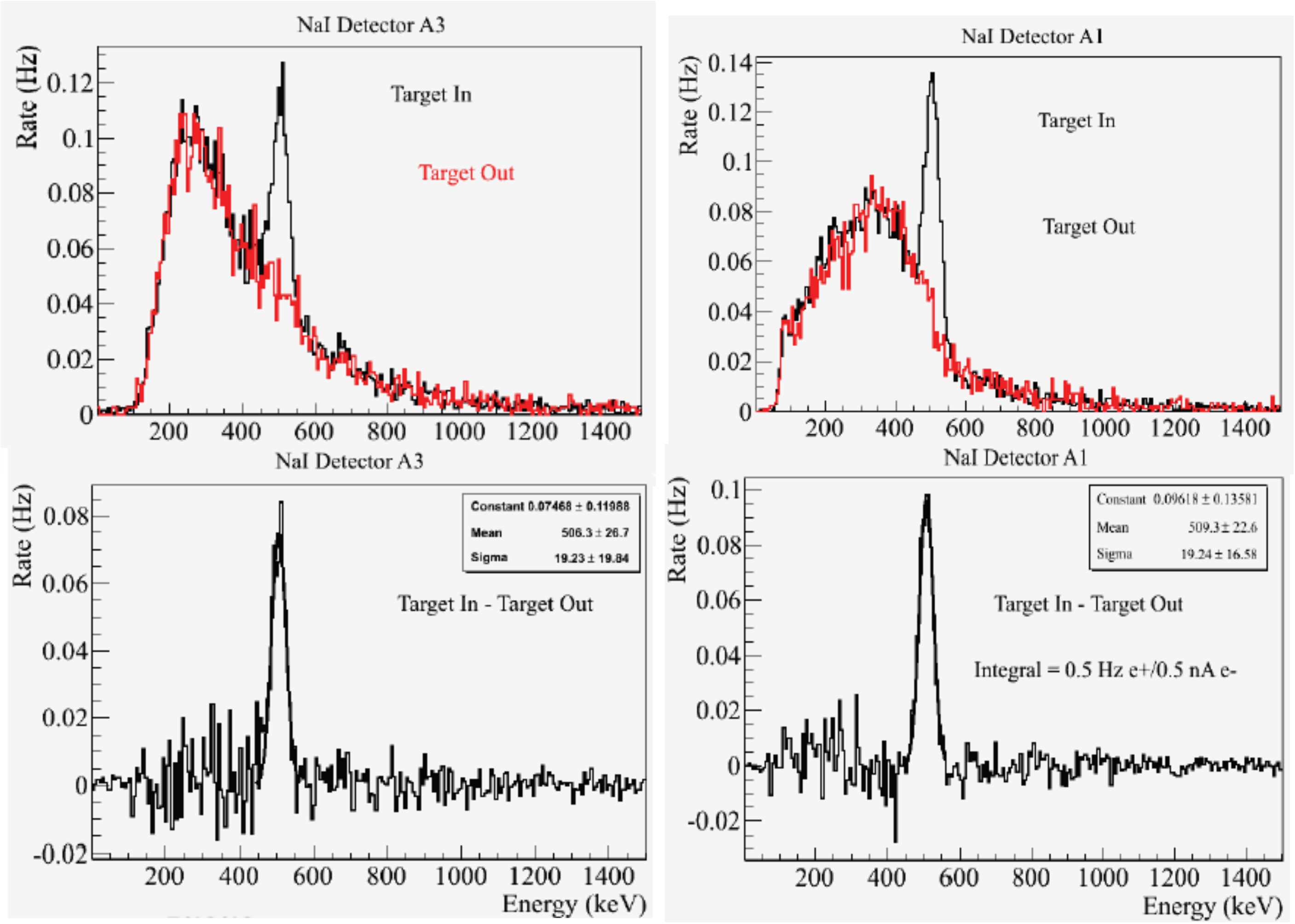


Viewscreen

- 0.011 thick @ 45 deg to beam line
- 99.5% aluminum oxide Al_2O_3
- 0.5% chromium doped $Al_2O_3/Al_2O_3Cr_2O_3$



Measuring Positron Yield



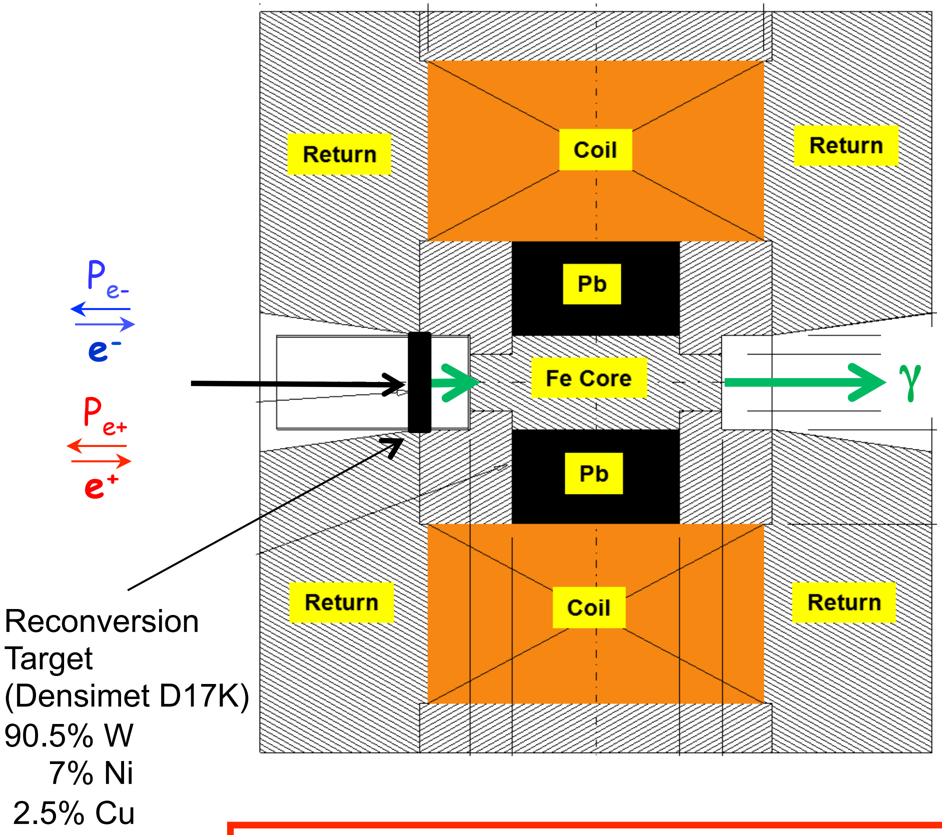
Detected e+ rate (1 e^+ per 10^{10} e^-)
Solid Angle (0.1 sr)
GEANT annihilation probability (1/400)
Coincidence detector efficiency (0.49 @ 511keV)

1 e^+ per 10^6 e^-
(consistent with proposal)

Measuring Positron Polarization: Compton Transmission Polarimeter

Electrons or Positrons radiate polarized photons by Bremmstrahlung in reconversion target

Energy dependent Compton scattering of photons transmitted through polarized target correspond to polarization of incoming Electrons or Positrons (aligned or anti-aligned).



Reconversion Target (Densimet D17K)
90.5% W
7% Ni
2.5% Cu

$$A_T = \frac{N^+ - N^-}{N^+ + N^-} = \tanh(-P_3\, P_T\, \mu_1 L)$$

$\mu 1$ - Compton absorption coefficient
L - target length
P_3 - photon polarization (long.)

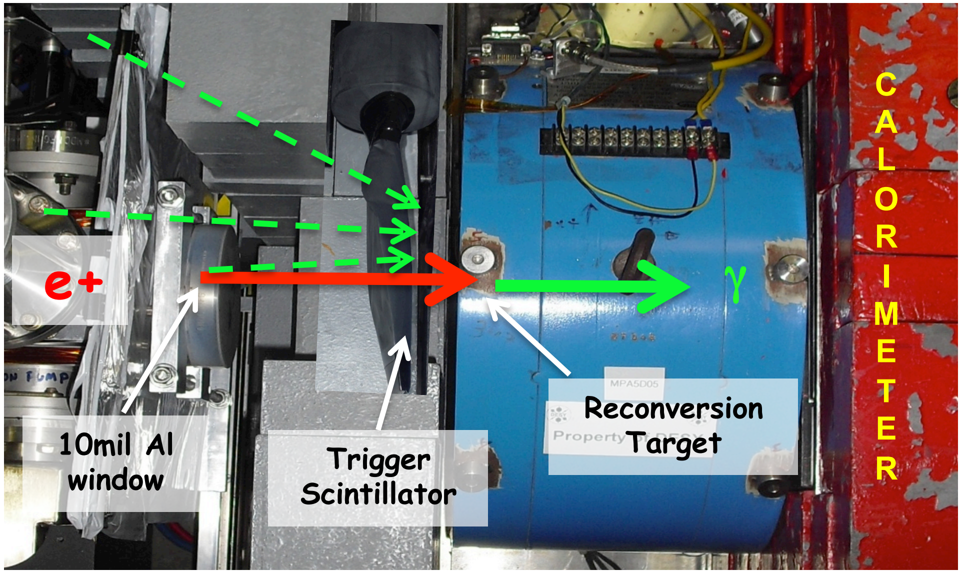
$$A_T = P_e P_T A_e$$

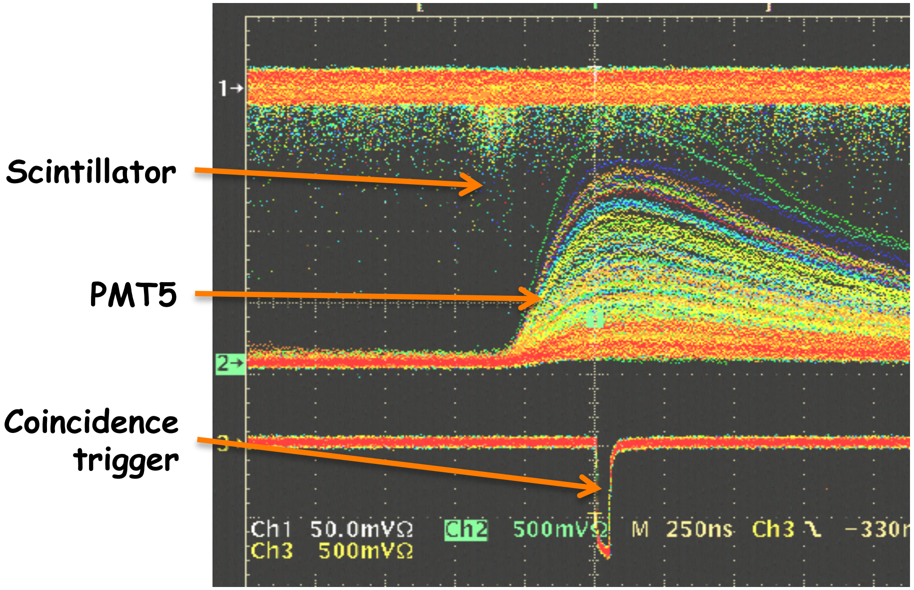
P_e - electron/positron polarization
P_T - target polarization
A_e - analyzing power

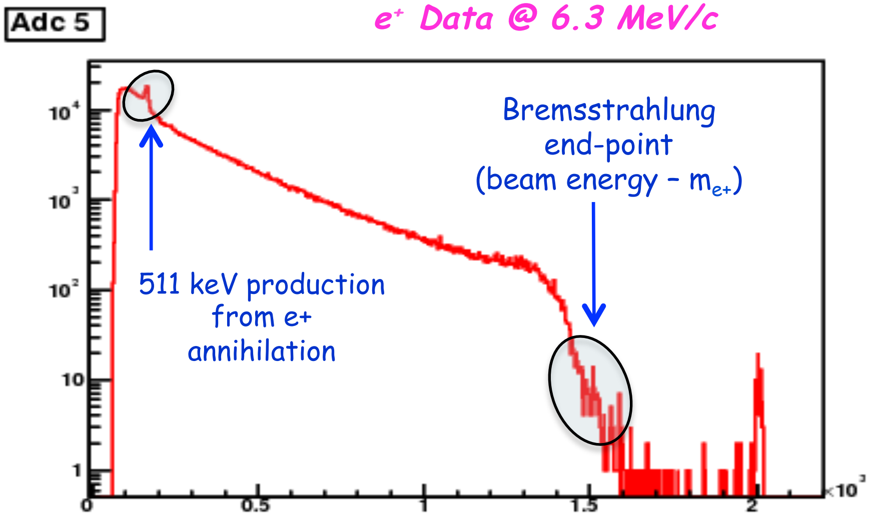
Bremmstrahlung photon spectrum requires energy-dependent analyses
- Energy binning
- Energy integration

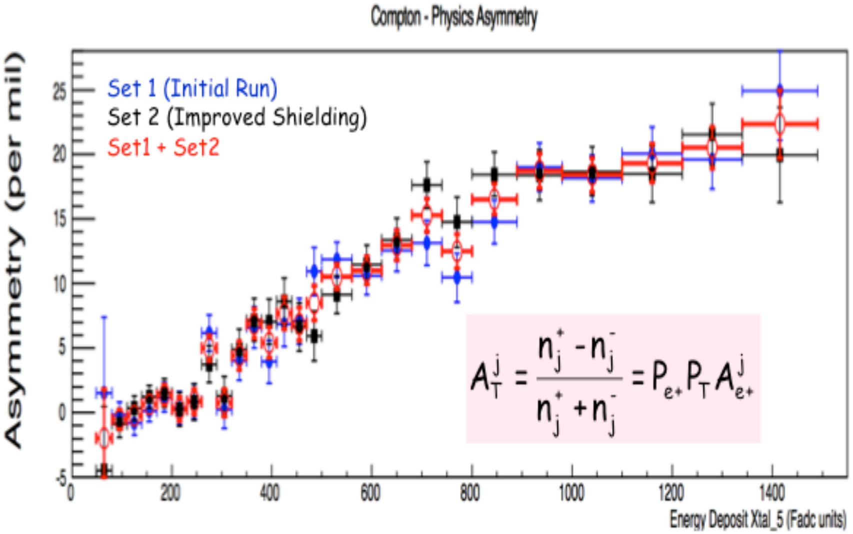
Positron Polarimetry

Positrons are detected in **coincidence** between a thin **trigger scintillator** placed prior to the reconversion target and the **central crystal** (PMT5) and **tagged by e- helicity**.





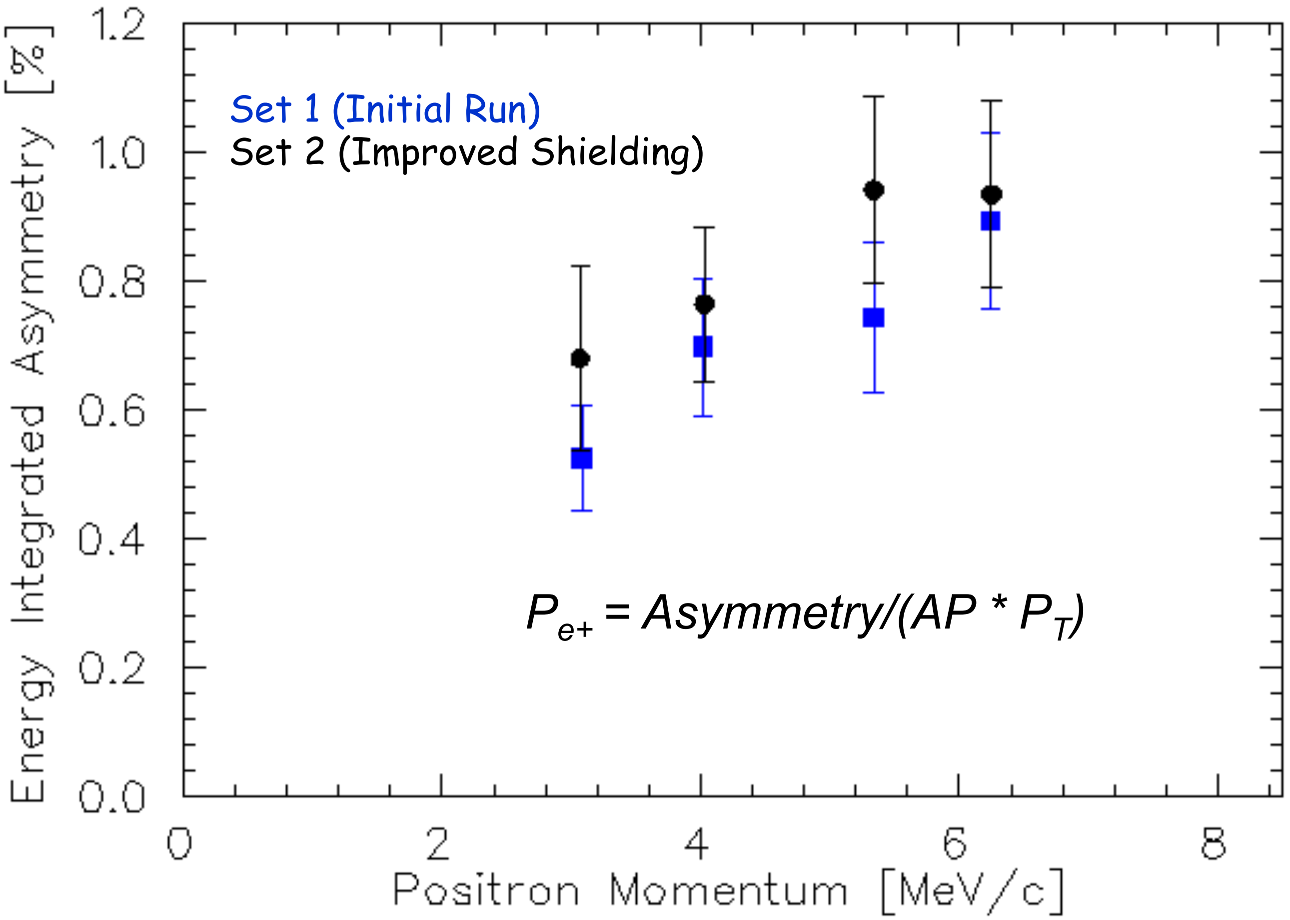




$$A_T^j = \frac{n_j^+ - n_j^-}{n_j^+ + n_j^-} = P_{e+} P_T A_{e+}^j$$

Preliminary Positron Results

Positron asymmetry **significantly non-zero**, **increases with momentum** and **reduction of background** (which may have analyzing power itself).



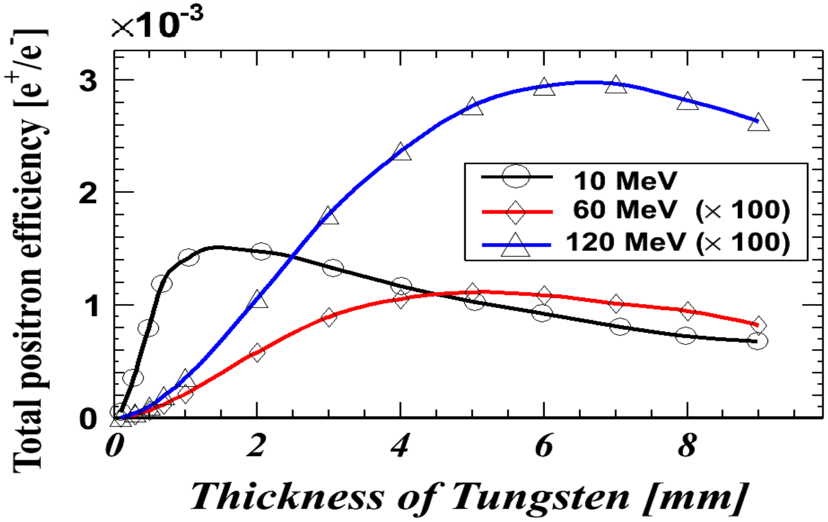
We are in final stages of analysis and will unveil results Spring 2014.

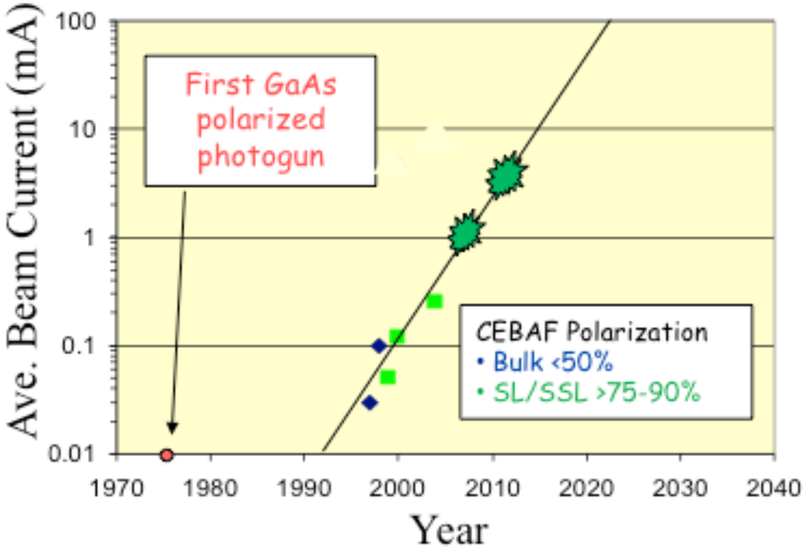
What about positrons at Jefferson Lab ?

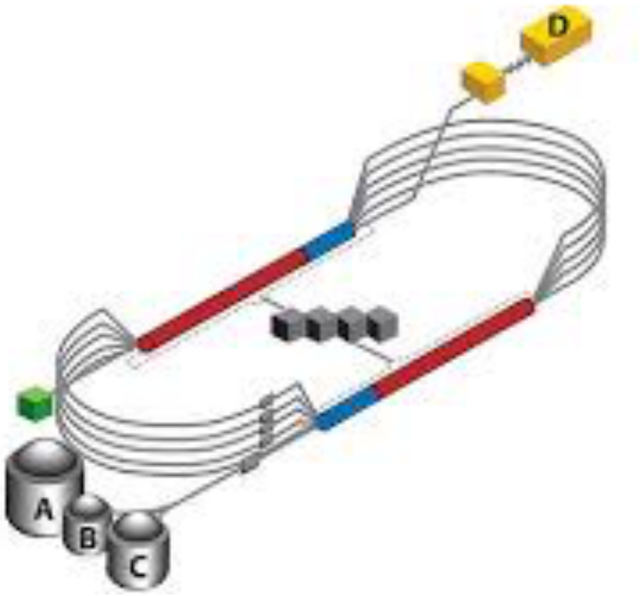
Positrons for JLAB Nuclear Physics
100 nA – 10 μA (CW)
Polarized

What about injecting positrons into CEBAF ?

Energy ***X*** ***Current***



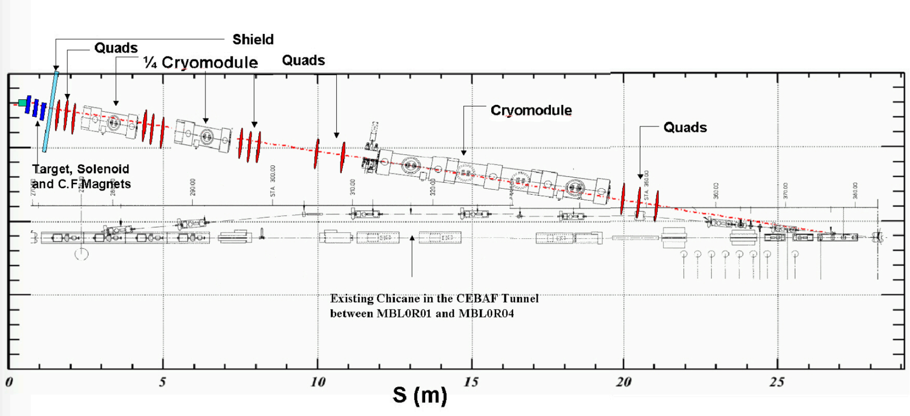


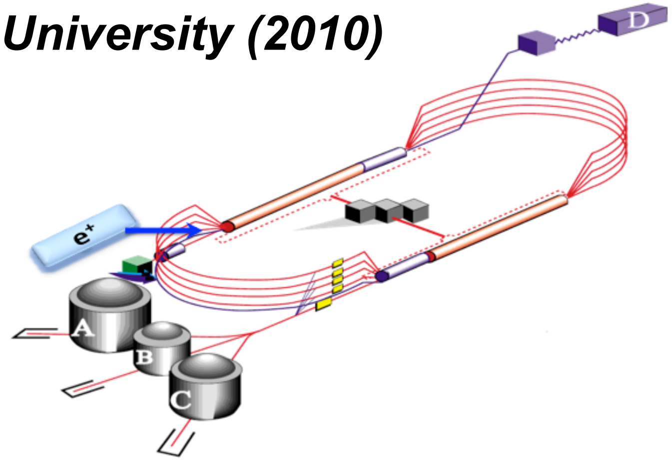


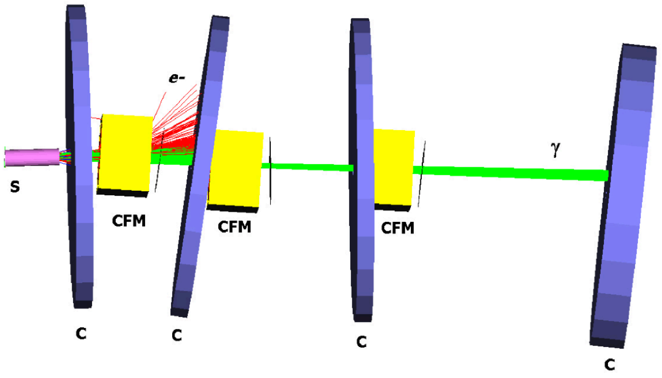
- ✓ Low enegy (GeV) injector requires **milli-Amps**
- ✓ **High power** (100’s kW) target & compoents
- ✓ Arc dipole **power supplies are unipolar**
- ✓ **Low beam intensity** challenges diagnostics
- ✓ Quasi-simultaneous **electron/positron delivery**

CW Positron Source at CEBAF

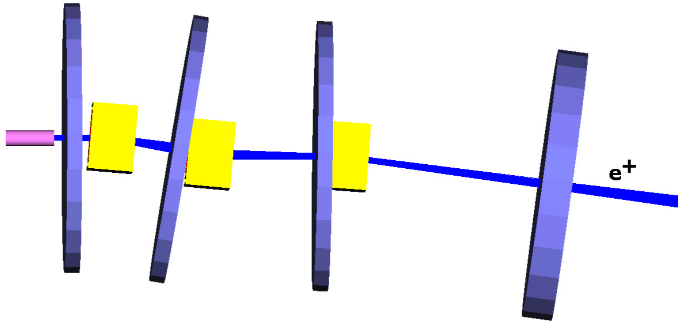
S. Golge, Ph.D. Dissertation, Old Dominion University (2010)







(a)



Combined Function Magnet Solution

- p (e-) = 126 MeV/c
- p (e^+) = 126 ± 1.0 MeV/c
- σ_t = 1.8 ps (to maintain dp/p < 10^{-3})
- $\varepsilon_{x/}\varepsilon_y$ = 1.6/1.7 mm.mrad (<5 mm-mrad)

Efficiency is ~ 2.9×10^{-4}

- 0.1 – 10 uA => 0.35 – 35 mA
- **100kW to 1MW !**

126 MeV/10 mA	Power Source		Deposited Power	
	(e$^-$ and γ)	e$^+$	(%)	(kW)
Target	✓	✓	4.5	55
Solenoid	✓	✓	21.0	250
Collimators	✓	✓	10.0	120
Capture Area Magnets	✓	✓	17.0	200
1/4 Cryomodule-1		✓	2.0×10^{-3}	0.025
1/4 Cryomodule-2		✓	9.0×10^{-4}	0.01
Full Cryomodule		✓	1.2×10^{-3}	0.015

Positron Opportunities at Jefferson Lab ?

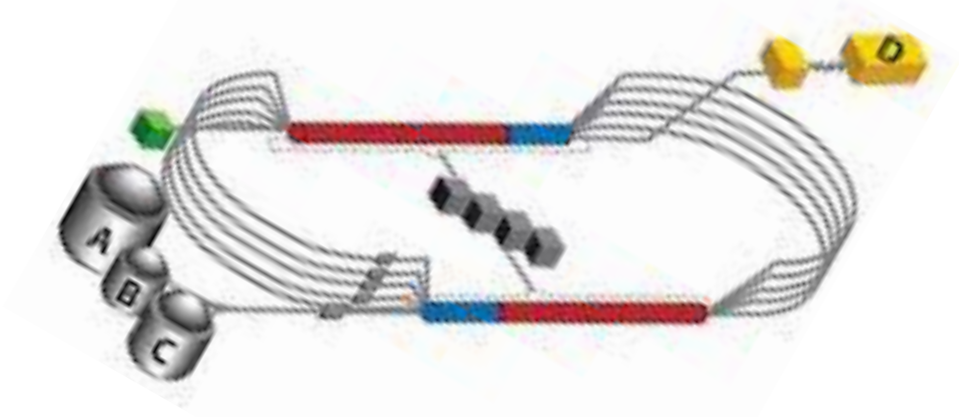
CEBAF

Improve conversion efficiency

- **~100uA / 11 GeV**
- **~1 uA / 12 GeV (Hall D)**

Manage high power

- Shielded Radiator
- Accessible conversion target



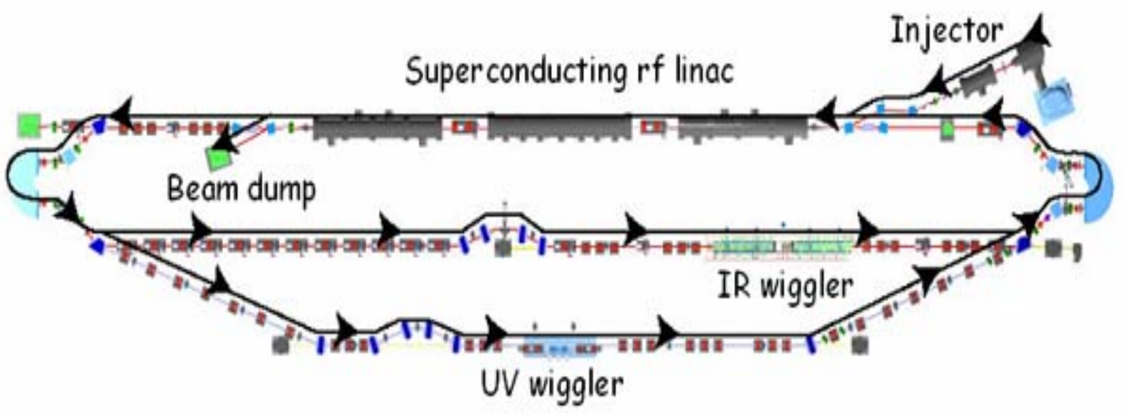
LERF

High current : 10 mA @ 200 MeV

- Test bed for CW concept

ERL dump : 10 mA @ 10 MeV

- Low intensity source

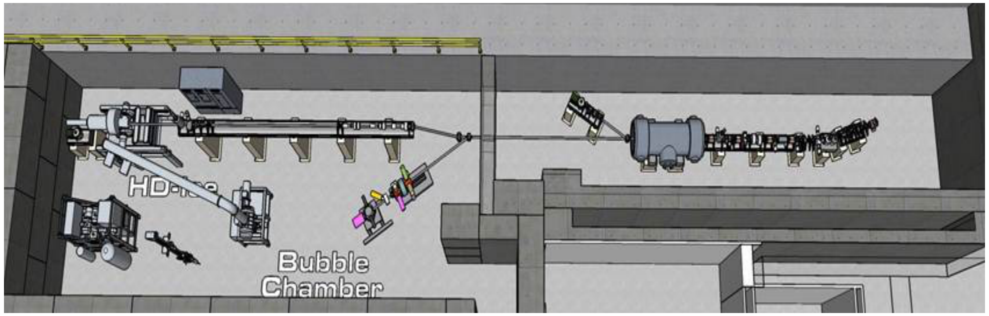


UITF

10 MeV/1 nA facility to test HDIce

Compatible with <1 nA e+ source

- Keep energy / photo-neutron yield small
- Add local shielding



Outlook & Opportunities

Compelling Motivation

- International Workshop on Positrons at Jefferson Lab (2009)
- High Energy Nuclear Physics at CEBAF
- Dark matter searches
- Low Energy Materials Science

Accelerator R&D Track Record

- J. Dumas, PhD, **PEPPo Conceptual Design** (2010)
- S. Golge, PhD, **CW Positron Source Design** (2010)
- PEPPo, **PAC A Rated E11-105** (2012)
- L. Adeyemi, PhD, **PEPPo Proof-of-Principle** (expected 2015)

INTERNATIONAL WORKSHOP ON
POSITRONS
AT JEFFERSON LAB

March 25-27, 2009
JEFFERSON LAB

TOPICS:
- **Positron-proton elastic scattering**
- **Deeply virtual Compton scattering**
- **New 12 GeV experiments with positrons**
- **Technology of positron sources**
- **Polarized positrons**
- **Electron/photon drivers**
- **Positron & electron polarimetry**
- **Applied physics with positrons**

International Advisory Committee:
- X. Artru (IPN Lyon)
- L. Cardman (JLab)
- P. Cole (Idaho State U.)
- A. Freyberger (JLab)
- P. Guichon (CEA Saclay)
- R. Holt (ANL)
- A. Hunt (Idaho Accelerator Center)
- C. Hyde (LPC Clermont Ferrand)
- M. Klein (U. Liverpool)
- K. Kumar (U. Massachusetts)
- M. Poelker (JLab)
- J. Sheppard (SLAC)
- A. Variola (LAL Orsay)

Local organizing committee:
- L. Elouadrhiri (JLab)
- T. Forest (Idaho State U.)
- J. Grames (JLab)
- W. Melnitchouk (JLab)
- E. Voutier (LPSC, Grenoble)

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conferences.jlab.org/JPOS09

Future Directions ?

- P. Degtiarenko, J. Grames, E. Voutier, Integrated Conceptual Design (Unfunded 2013 LDRD)
- Consideration being given for low energy positron program at LERF
- Exploit accelerator expertise & facilities to develop integrated design and address challenges

Some R&D Opportunities…

- ***High Current Electron or Photon "Driver"***
- ***High Power Conversion Target***
- ***Collection Optimization – Split Radiator : Conversion Target***
- ***Simultaneously managing electrons and positrons***