Simulations of Polarized Positron Source at Jefferson Lab

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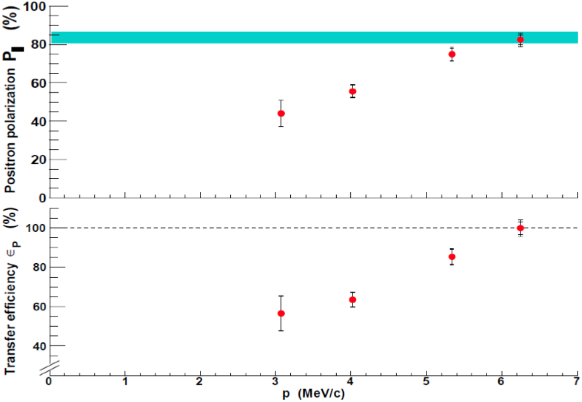
PEPPo Production of Positron Beam

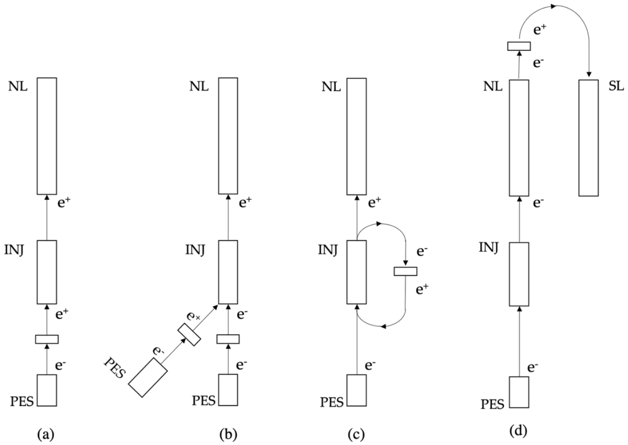
Polarized Electrons for Polarized Positrons PEPPo experiments have demonstrated a high polarization transfer from 8.19 MeV polarized electrons ($P_{e^-} = 85\%$) to positrons via bremsstrahlung radiation and pair production in the same high Z conversion target (1 mm W).

PEPPo measurements of the positron polarization and efficiency of polarization transfer



D. Abbott et al. (PEPPo Collaboration), *Phys. Rev. Lett.* **116**, 214801 (2016)

Considered e$^+$ Production Schemes (Joe Grames)



PES – polarized electron source

INJ – injector linac

NL – north CEBAF linac

SL – south CEBAF linac

(a): low energy option ($E_{e^-} \simeq 10$ MeV)

(b): high energy option ($E_{e^-} \simeq 123$ MeV)

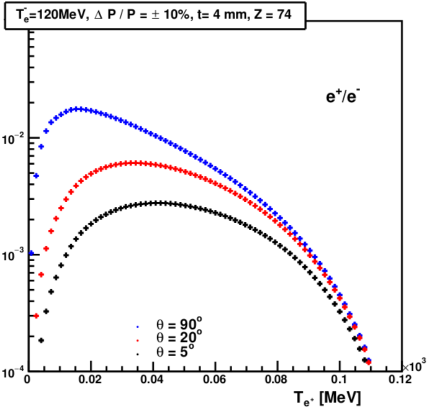
(c): high energy recycler option ($E_{e^-} \simeq 123$ MeV)

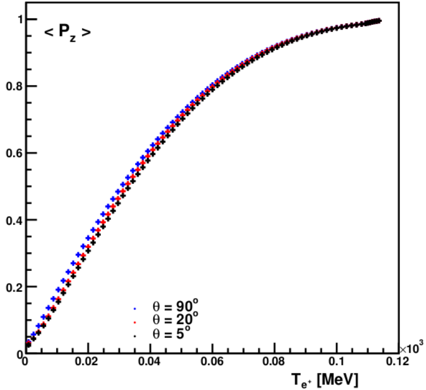
(d): very-high energy option ($E_{e^-} \simeq 1090$ MeV)

Correlation between Positron Polarization and Energy (Sami Habet)

FoM = Yield * Polarisation^2

FoM (left) and Polarization (right) vs Positron Energy after W Target

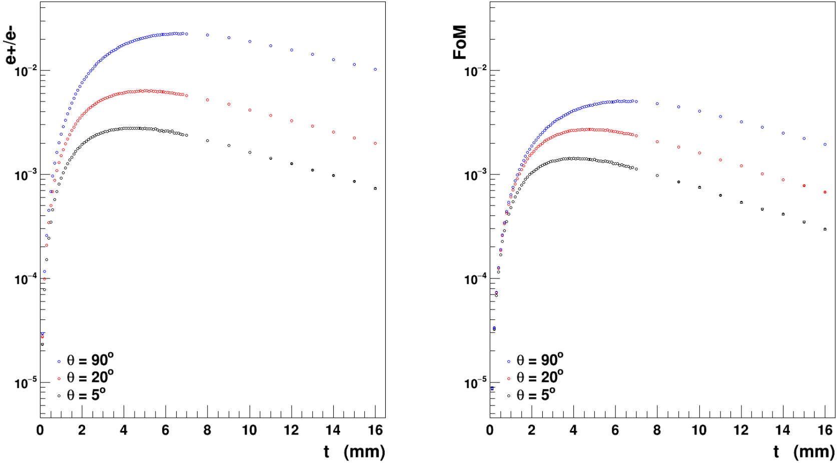




Optimal Thickness at 120 MeV e^- (Sami Habet)

For finding the best target thickness the optimal energy for max FoM ($\sim$ 45 MeV) and $\pm$10% energy spread have been used

Yield (left) and FoM (right) vs Target Thickness



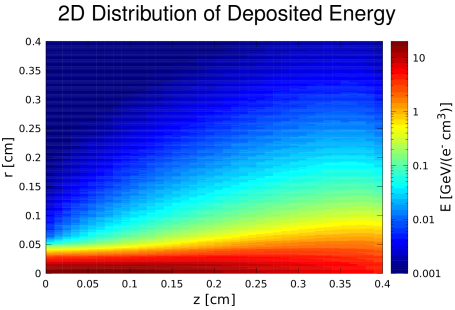
Main Questions to Target

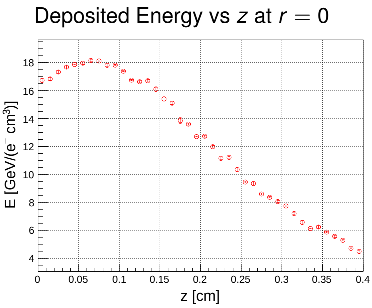
- CEBAF can provide 1 mA cw electron beam (RF frequency = 1.497 GHz) with energy of $\simeq$120 MeV
- 120 MeV electrons deposit in 4 mm thick tungsten target in average $\simeq$14% of energy
- Average deposited in target power is $\simeq$17 kW

Tasks:

1. Estimate the Peak Energy Deposited Density (PEDD):
   How quickly the target has to be moved/rotated?
2. Estimate the average temperature:
   How target has to be cooled?
3. Estimate the radiation damage:
   What is life time of the target? What target radius has to be?

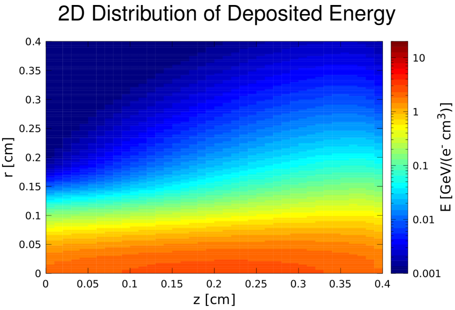
Deposited Energy by Beam with 150 μm RMS Size

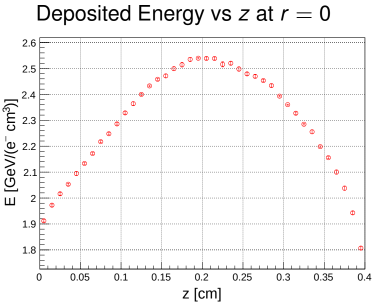




PEDD = 18 GeV/(e^{-}cm^{3})

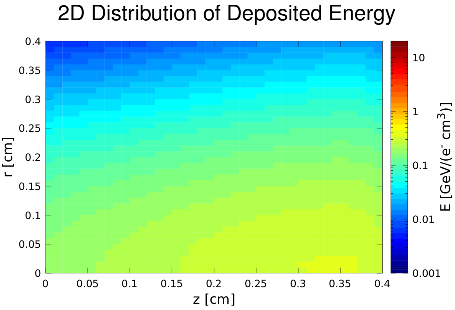
Deposited Energy by Beam with 450 μm RMS Size

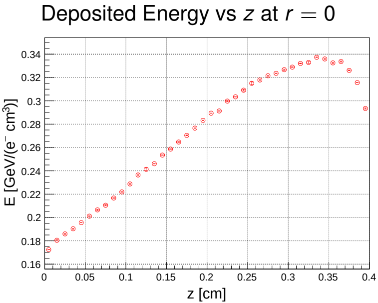




PEDD = 2.5 GeV/(e^- cm^3)

Deposited Energy by Beam with 1.5 mm RMS Size





PEDD = 0.34 GeV/(e^- cm^3)

PEDD and Temperature Rise in Stationary Target

$$\text{PEDD} = E_{\max}[\text{GeV}/(\text{e}^{-}\text{cm}^3)]$$

If energy deposited instantaneously:

$$(dT/dt)_{\max} = \text{PEDD} \cdot k_{\text{J/GeV}} \cdot dN_{\text{e}^-}/dt\,[\text{e}^-/\text{s}]\,/\rho\,[\text{g/cm}^3]\,/c_p\,[\text{J}/(\text{g K})]$$

I = 1 mA

$dN_{\text{e}^-}/dt = 6.24 \cdot 10^{15}$ e$^-$/s

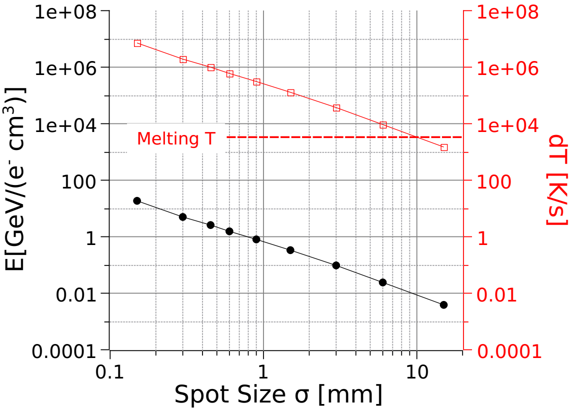
ρ (W) = 19.3 g/cm^3,

c_p (W) = 0.134 J/(g K) at 20 °C

$T_{melting}$ (W) = 3370 °C

Tungsten properties were taken from www.matweb.com

PEDD and Max dT/dt



Maximal Tolerable PEDD

$$PEDD = \Delta T_{\text{max}}\, c_p,$$

ΔT_{max} is the maximal tolerable (instantaneous) temperature rise,
c_p = 0.134 J/(g K) for tungsten at 20 °C.

$$\Delta T_{\text{max}} = \frac{(1-\nu)\,\sigma_{\text{u}}}{\alpha\, E},$$

where Poisson number $\nu = 0.28$,
σ_{u} is the endurance strength,
coefficient of thermal expansion $\alpha = 4.4 \cdot 10^{-6}$ m/(m K) at 20 °C,
modulus of elasticity $E = 4 \cdot 10^{11}$ Pa at 20 °C.

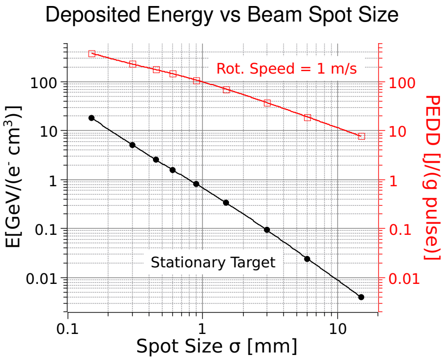
$$\sigma_{\text{u}} = 0.4\, \sigma_{0.2},$$

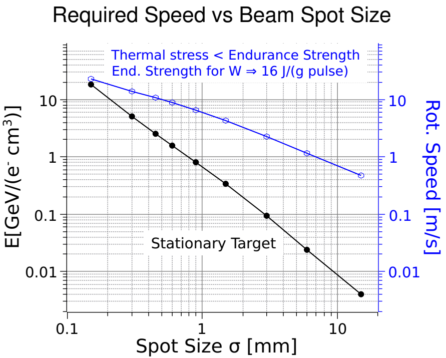
tensile yield strength $\sigma_{0.2} = 750$ MPa (www.matweb.com).

Yield strength is the plasticity limit at which a non elastic elongation of 0.2% remains after removing load.

At 20 °C max tolerable PEDD = 16.45 J/g

PEDD in Rotated Target and Required Rot. Speed





23 m/s is required for 0.15 mm rms beam spot size on target

4.3 m/s is required for 1.5 mm rms beam spot size on target

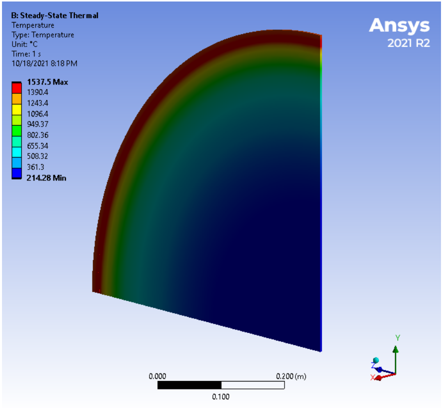
ANSYS Estimation of Average T in Rotated Target

17 kW distributed equally in volume $V = \pi(r_{out}^2 - r_{in}^2) \cdot thickness$, where $r_{out} = 50.2$ cm, $r_{in} = 49.8$ cm and *thickness* = 4 mm

Target is cooled by radiation; *emissivity* = 0.5

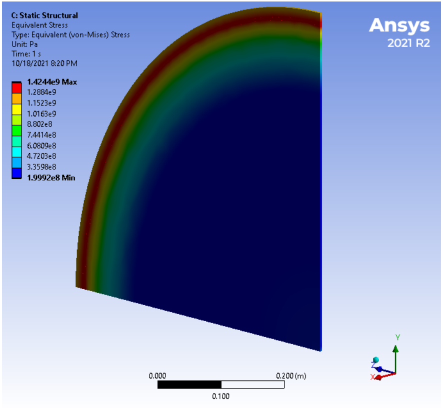
Temperature dependent W properties were taken from ANSYS Granta material database

Average Temperature



$T_{max} \simeq 1530$ °C

Equivalent von-Mises Stress

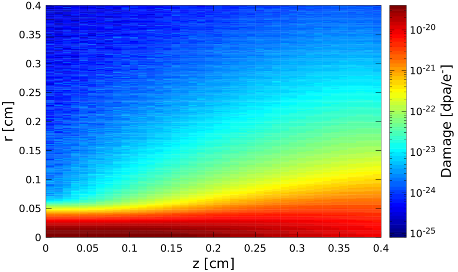


Max $\sigma_{vM} \simeq 1420$ MPa

2D Distributions of Radiation Damage per Electron

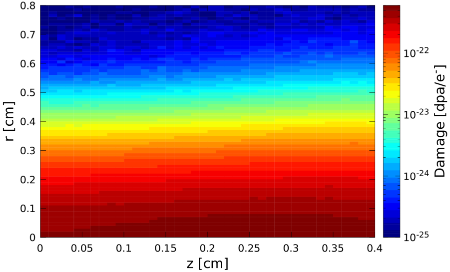
Stationary Target

Damage by 0.15 mm Beam Spot Size



Max Damage = $4.7 \cdot 10^{-20}$ dpa/e$^-$

Damage by 1.5 mm Beam Spot Size

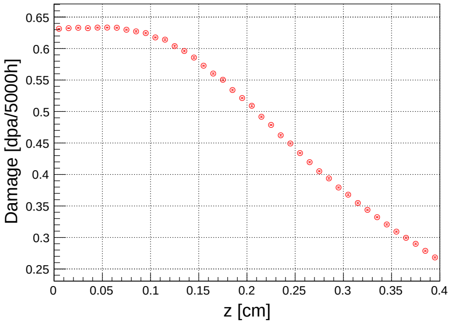


Max Damage = $5.7 \cdot 10^{-22}$ dpa/e$^-$

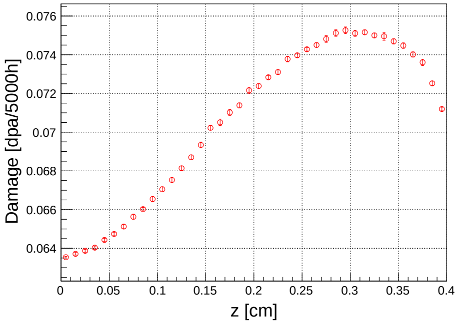
Damage Profiles

Rotated Target. Diameter = 1 m

Damage vs z for 0.15 mm Beam Spot Size



Damage vs z for 1.5 mm Beam Spot Size



max dpa = 0.63 dpa/5000h

Diameter has to increased to 1.26 m in order to keep damage below 0.5 dpa/5000h

max dpa = 0.075 dpa/5000h

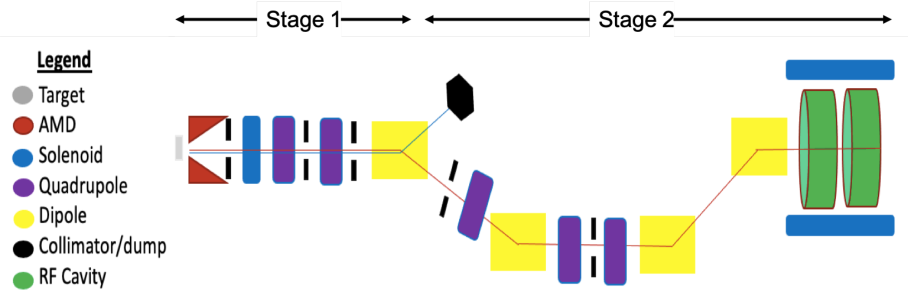
Life time of 1 m diameter target is 6.67 "years" or target diameter can be reduced to 15 cm

Note: Higher rotation speed of target reduces dpa per turn and increases number revolutions per hour. Therefore, the annual value of dpa does not depend on target speed. $\mathrm{dpa}_{5000\mathrm{h}} \sim 1/r_{\mathrm{target}}$

Scheme of Positron Beam Line (Mark Stefani)

Mark is working on positron tracking simulations using General Particle Tracer (GPT) code

Several schemes are considered now. One of them is shown below:

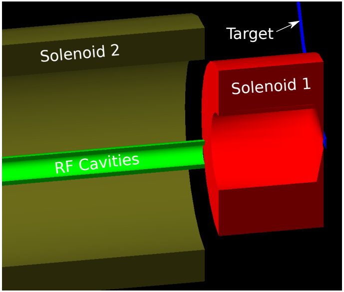


Geant4 Model of Positron Source with QWT

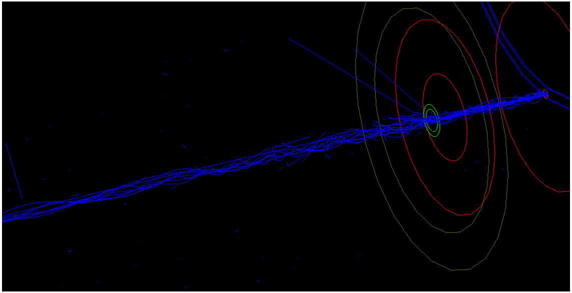
Quarter Wave Transformer QWT consists from 2 solenoids: 2 T short (length of 30 cm) solenoid 1 and 0.5 T very long solenoid 2

QWT helps to select/capture positrons in desired energy range (positrons with high polarization)

Geant4 Geometry



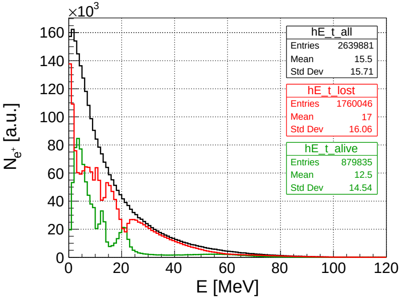
Positron Trajectories



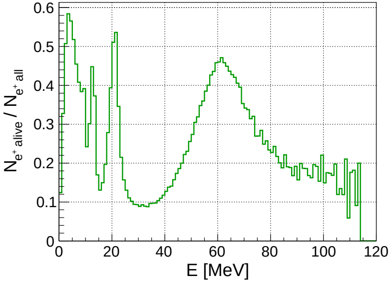
Positron Energy Distribution after Target

Number of primary electrons was 10^7

Energy Distribution after Target



Ratio of Positron Number after 15 m Accelerator to All Positrons after the Target



black curve: all positrons at the exit side of target,

red curve: positrons lost between the target and the end of 15 m accelerator,

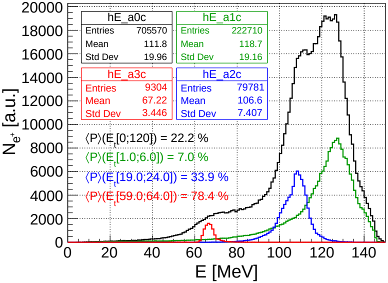
green curve: (alive) positrons that achieve the end of accelerator.

Positron Energy Distribution after 15 m Accelerator

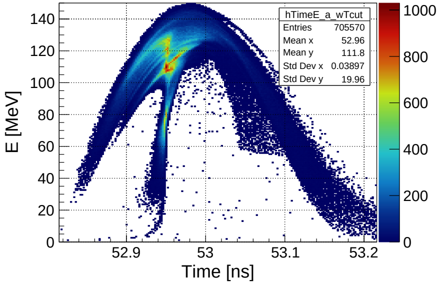
Number of primary electrons was 10^7

Electric field phase was selected to get the highest positron yield at the end of accelerator

Energy Distribution after Accelerator



Positrons in Time-Energy Space



black curve: all positrons in the main bunch at the end of accelerator,

green curve: positrons having after target energy between 1 MeV and 6 MeV,

blue curve: positrons having after target energy between 19 MeV and 24 MeV,

red curve: positrons having after target energy between 59 MeV and 64 MeV

Summary

- Tolerable PEDD of 16.45 J/g was estimated for pure W at room temperature and simplified (instantaneous) heat load
- Based on approach of instantaneous energy deposition, it was found that for 150 μm rms beam spot size on target:
  - Required rotation speed is 23 m/s
  - Radiation damage of target with 1 m diameter is 0.63 dpa/5000h
- For the 1.5 mm rms beam spot size:
  - Required rotation speed is 4.3 m/s
  - Radiation damage of target with 1 m diameter is 0.075 dpa/5000h
- 1 mA @ 120 MeV e^- beam deposits 17 kW in 4 mm W target
- First rough ANSYS estimations of average T and equivalent von Mises stress in radiation cooled target of 1 m in diameter show that the thermal stress is too high. More simulations and better design of target cooling are needed.
- Beam dynamics simulations are ongoing.