Conceptual Design of a High Power Target for the Jefferson Lab Positron Source

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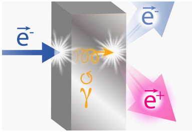
Outline

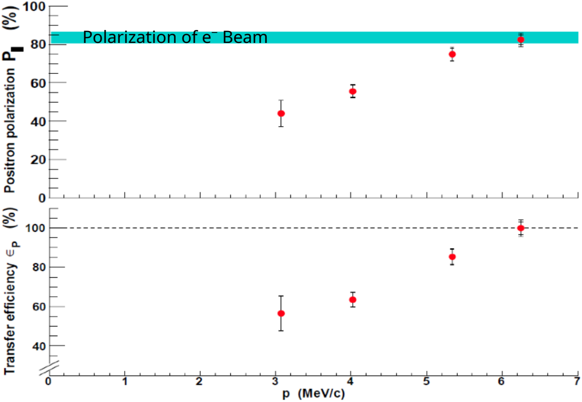
- Efficiency of polarization transfer from polarized electrons to positrons
- CEBAF polarized e^+ source
- Optimized polarized positron production
- Energy deposited in target by beam
- Water cooled spinning target
- Temperature and thermal stress
- Radiation damage
- Summary

Using Polarized e^- for Production of Polarized e^+

Polarized **E**lectrons for **P**olarized **Po**sitrons (PEPPo) 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 (tungsten with thickness of 1 mm).



e^+ Polarization and Efficiency of Polarization Transfer

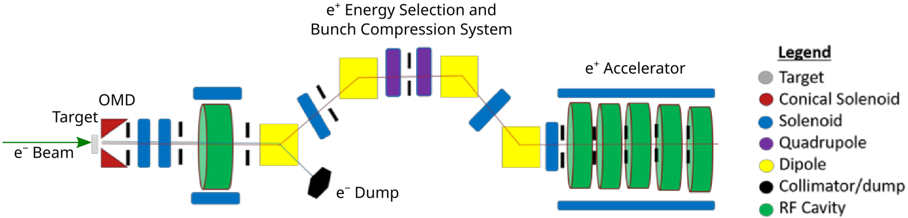


D. Abbott et al. (PEPPo Collaboration), *Phys. Rev. Lett.* **116**, 214801 (2016)

Scheme and Parameters of JLab Positron Source

The Physics program is asking for e^+ beams with polarization of $>$60% and current of $>$100 nA

Scheme of Positron Source

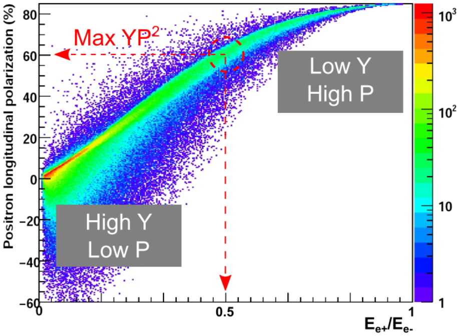


J. Grames, J-Future Workshop, JLab/Messina, March 28-30, 2022

- Energy of primary e^- beam: **120 MeV**
- e^- beam current: **1 mA cw**

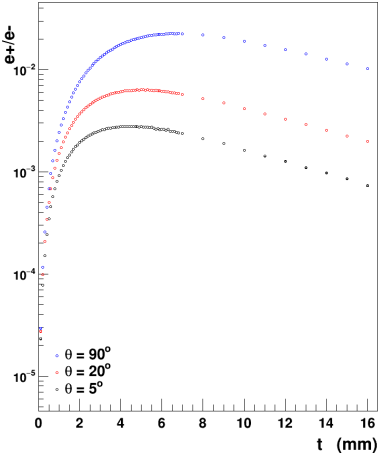
Selection of Optimal Positron Energy after the Target and Optimal Target Thickness

Selection of Optimal e^+ Energy



J. Dumas, PhD Thesis, Université de Grenoble (2011)

Yield vs Target Thickness
for $\Delta p/p = 10$ %

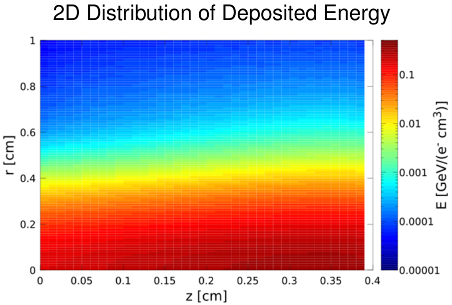


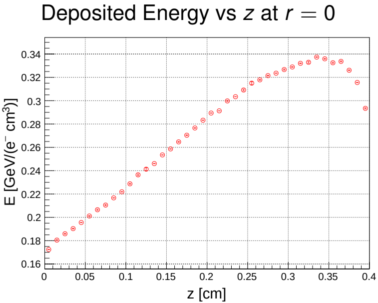
S. Habet, UPS/IJCLab/JLab (2020)

Optimal e^+ energy after the target is $\simeq$50% of e^- beam energy

Optimal thickness of tungsten target for 120 MeV e^- is **4 mm**

Deposited Energy by Beam with 1.5 mm RMS Size


2D Distribution of Deposited Energy

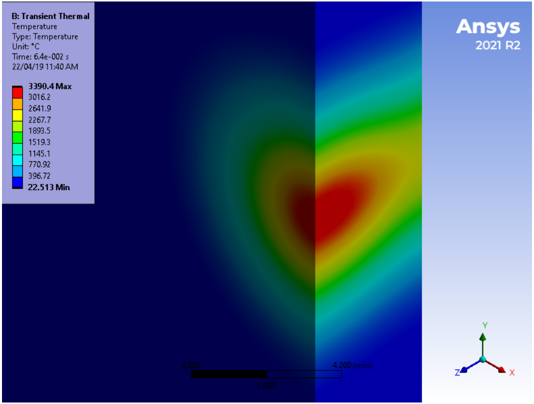

Deposited Energy vs z at $r = 0$

120 kW e^- beam (1 mA @ 120 MeV) deposits in average 17 kW (14%) in Tungsten with 4 mm thickness

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

In case target rotated with 4 m/s: 0.34 GeV/(e^-cm^3) $\Rightarrow$ 17.6 J/g

Stationary Target Heated by 1 mA cw e^- Beam

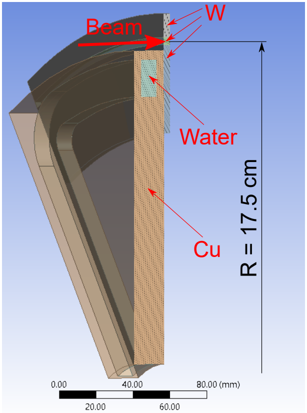


1 mA @ 120 MeV cw electron beam with 1.5 mm rms size
melts the **stationary** 4 mm thick tungsten target in 64 ms

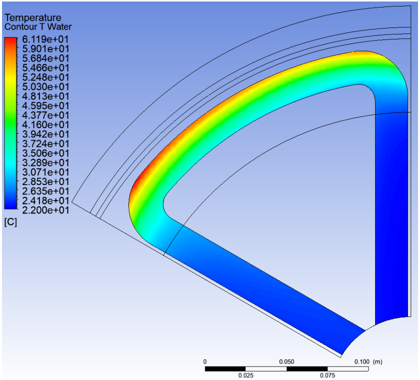
- Target has to be moved/rotated to distribute heat over bigger volume
- Efficient target cooling is needed

Water Cooled Rotating 17 kW Tungsten Target

Cross-section of Target



Temperature of Water



$T_{\max}$ = 61 °C

e^- beam passes rotated target at R = 17.5 cm

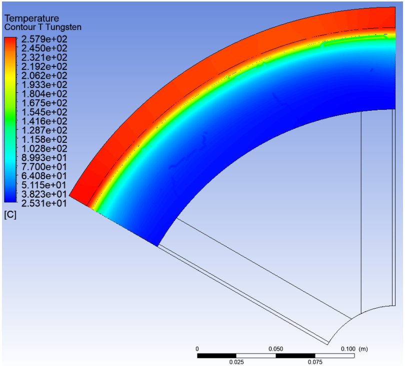
Cross-section of water channel is 10 mm x 20 mm

Speed of turbulent water flow is 2 m/s

Temperature of water at inlet is 22 °C

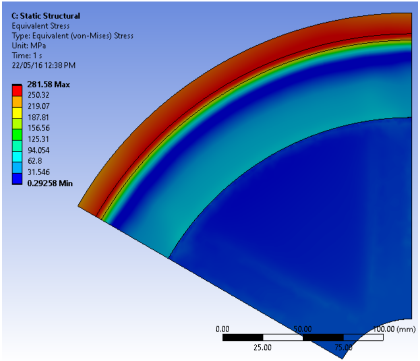
Average Temperature and Thermal Stress

Average Temperature of Tungsten



$T_{\max} = 258$ °C

Equivalent von-Mises Stress

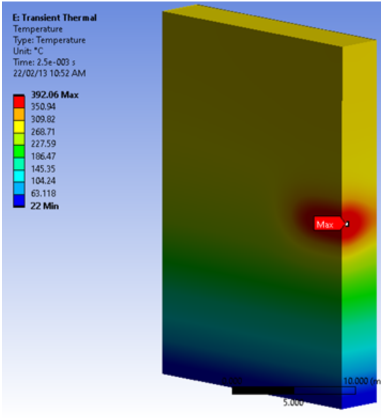


Max $\sigma_{vM} = 282$ MPa

Thermal Cycling of a Spinning Target

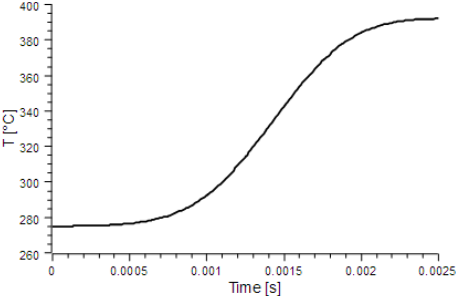
RMS beam size = 1.5 mm. Target rot. speed = 4 m/s

Snapshot of T after 2.5 ms



Temperature vs time

during heating by beam

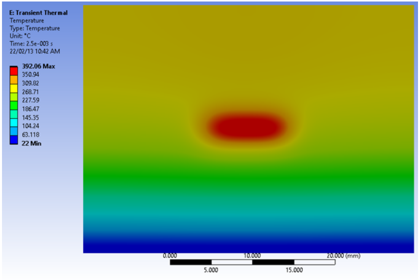


$$\Delta T_{max} = 120\ ^\circ\mathrm{C}$$

Thermal Stress at the ”End of Pulse”

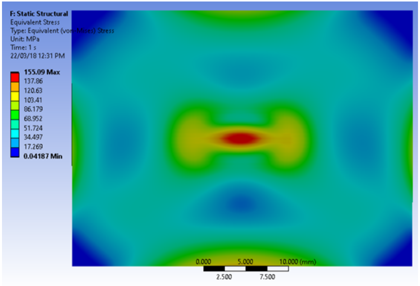
Temperature after 2.5 ms

10 mm beam path on target (4 m/s)



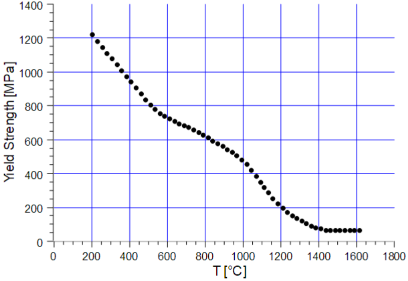
$$\Delta T_{max} = 120\ ^\circ\mathrm{C}$$

Equivalent von-Mises Stress after 2.5 ms

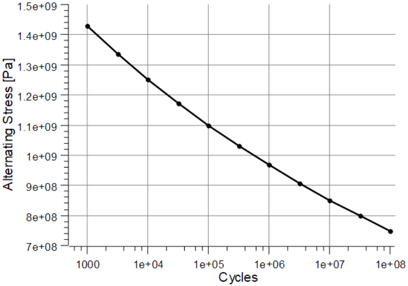


$$\text{Max } \sigma_{vM} = 155\ \text{MPa}$$

Yield and Fatigue Strength of Tungsten



Yield Strength $\sigma_{0.2}$ vs Temperature



Fatigue Strength vs Number of Cycles at Room Temperature

$\sigma_{0.2}$ (22°C) = 1500 MPa

$\sigma_{0.2}$ (380°C) = 977 MPa

5000 h of source operation with 0.275 s cycles $\Rightarrow 6.5 \cdot 10^7$ cycles

Fatigue Strength (22°C; $6.5 \cdot 10^7$ cycles): 774 MPa

Fatigue Strength (380°C; $6.5 \cdot 10^7$ cycles) = **504 MPa**

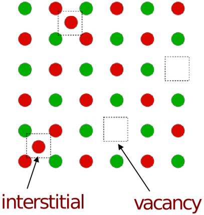
Max von-Mises stress estimated for JLab rotated W target:
280 MPa ($T_{ave} \backsimeq 260$°C) + 155 MPa ($\Delta T = 120$°C) = **435 MPa**

Test of tungsten targets at the Mainz Microtron is planned

Introduction to Radiation Induced Damage

0.5 dpa means every second atom in the material has been displaced in average from its site within the lattice of the material.

$$\mathrm{DPA} = \frac{A}{N_A\,\rho} N_d$$



A is the mass number, N_A is the Avogadro number, ρ is the density, N_d is the number of defects (Frenkel pairs)

Simplest Kinchin-Pease model:

$$N_d = 0, \quad \text{for} \quad T_d < E_d$$

$$N_d = 1, \quad \text{for} \quad E_d < T_d < 2E_d/0.8$$

$$N_d = \frac{0.8T_d}{2E_d}, \quad \text{for} \quad 2E_d/0.8 < T_d < \infty$$

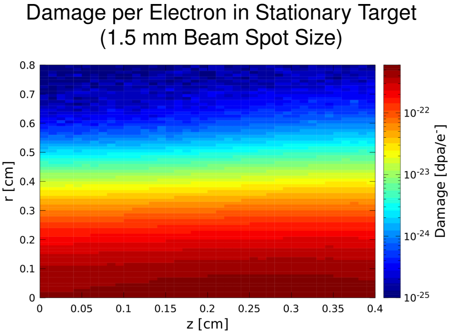
T_d is the damage (kinetic) energy,

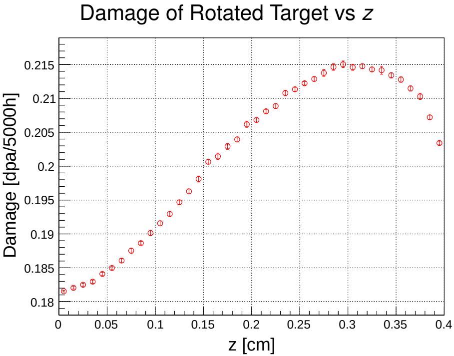
E_d is the displacement damage threshold.

E_d for tungsten is 90 eV [R.E. MacFarlane and A.C. Kahler, *Nuclear Data Sheets*, **111**(12), 2739 (2010)].

Radiation Damage

Stationary Target and Rotated Target with Diameter of 35 cm





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

Max Damage per Year = 0.215 dpa/5000h

0.5 dpa is typical limit of radiation damage for different materials

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. $\mathrm{dpa}_{5000\mathrm{h}} \sim 1/r_{\mathrm{target}}$

Proposed Size of Rotated W Target

Deposited Power	kW	17			
Thickness of W	mm	4			
Beam Width	mm	4			
Target Radius	mm	**150**	**175**	**200**	**250**
Volume	mm^3	15080	17593	20106	25133
Power Density	W/mm^3	1.13	0.97	0.85	0.68
Average T_{max} of W	°C	306.1	**257.9**	229.5	198.4
T_{max} of Water	°C	70.8	**61.2**	56.7	52
Eq. Stress_{max} in W	MPa	347.7	**281.6**	243.2	221.2
Max Rad. Damage	dpa/5000h	0.250	**0.214**	0.188	0.150

Summary

- Average power of 17 kW is deposited in 4 mm thick tungsten target by 1 mA @ 120 MeV electron beam
- Average, peak temperatures and thermal stress in target were calculated
- Radiation damage of tungsten has been estimated
- Conceptual design of rotated tungsten target cooled by water is developed
- For proposed 35 cm in diameter W target spinning with 4 m/s, cooled by water (2 m/s flow) and 1.5 mm rms beam spot size on target:
  - Max. average T $\simeq$ 260 °C and max. peak T $\simeq$ 380 °C
  - Max. von-Mises stress $\lesssim$ 435 MPa
  - Max. radiation damage $\simeq$ 0.215 dpa/5000h