ILC Polarized Positron Source at Center-of-Mass Energies of 250 GeV and 1 TeV

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EUCARD workshop "Spin Optimization at Lepton Accelerators"

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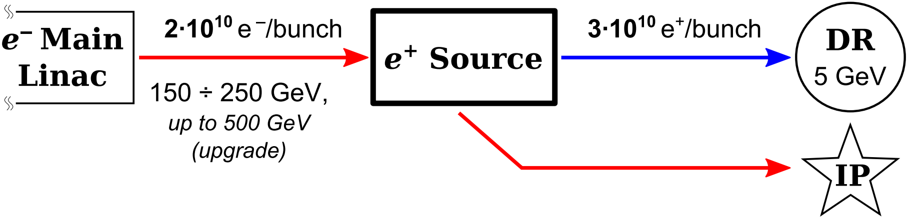
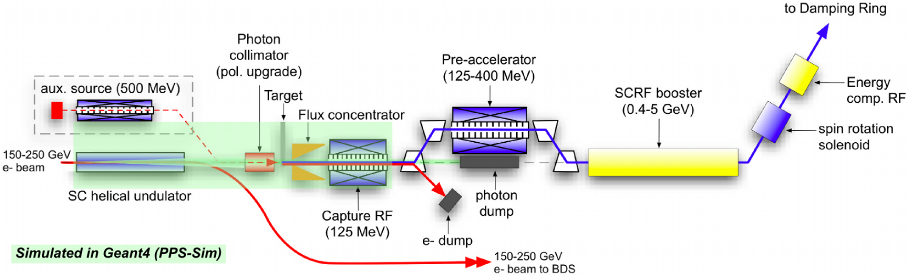
ILC e^+ Source Requirements



- Wide range of drive e^- energy: 120 GeV (lowest?), 250 GeV (design), 500 GeV (upgrade)
- **e^+ yield**: 1.5 e^+/e^- (50% safety margin)
- DR acceptance:
  - Transverse emittance: $\epsilon_{nx} + \epsilon_{ny} \leq 70$ mm rad
  - Max. energy spread: ± 37.5 MeV
  - Longitudinal bunch size: ≤ 34 mm
- **e^+ polarization**: $\sim$ 30% (up to 60%, upgrade)

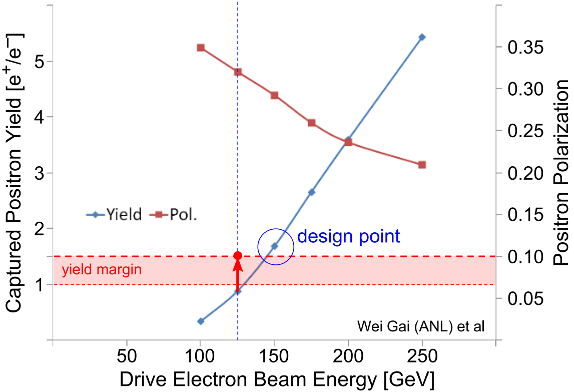
Schematic Layout of e^+ Source



- SC Helical Undulator: 231 m length, 11.5 mm period, $K \leq 0.92$ ($B \leq 0.86$ T)
- Photon Collimator: details in Friedrich's talk (today)
- Target: $0.4X_0$ thickness, Ti6Al4V rim rotated with 100 m/s tangential speed
- Flux Concentrator: 12 cm length, $B_{\text{max}} = 3.2$ T, $B_{\text{end}} = 0.5$ T
- NC Capture RF: 1.3 GHz, $\approx$10 m length, 14.5 MeV/m and 8.5 MeV/m

Yield and Polarization vs e^- Energy

e^+ Yield vs e^- Energy **147 m** Undulator with $K = 0.92$



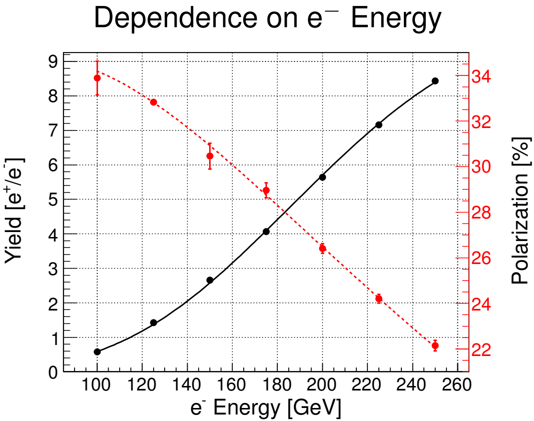
To get 1.5 e^+/e^- at $E_{e^-} < 150$ GeV:

⇒ Increase undulator length (ILC TDR: 231 m is reserved)

To get 30% e^+ polarization at $E_{e^-} > 150$ GeV:

⇒ Reduce undulator *B*-field

Yield and Polarization vs e^- Energy (231 m Undulator)



Geant4 simulations for

- **231 m** undulator, $K = 0.92$
- 0.4 X_0 Ti6Al4V target
- FC: 3.2 T to 0.5 T in 12 cm and R_{ini} = **6 mm**
- ≈10 m 1.3 GHz RF structure

Yield at 120 GeV e^-:

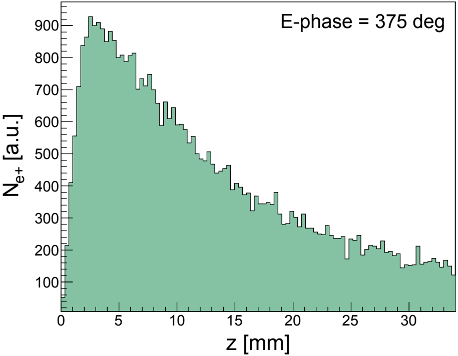
⇒ Required undulator length is about 250 meters

⇒ Optimization of source with 231 m undulator is needed

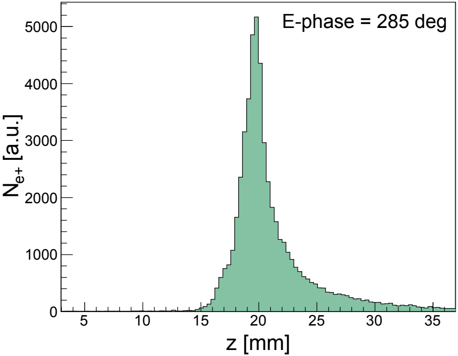
Bunch Compression by Decelerating Field of Capture RF

$$E_z = E_0 \cos(kz + \omega t + \varphi_0)$$

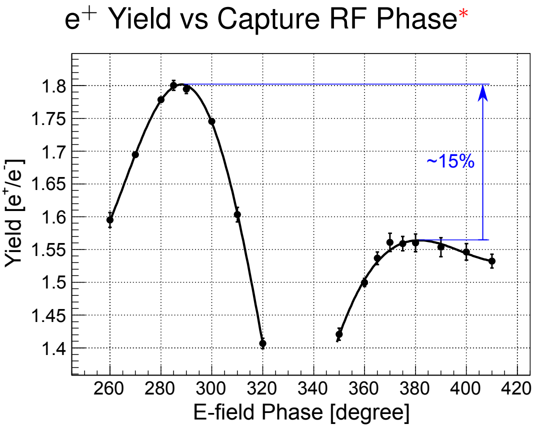
Longitudinal Bunch Profile
for Optimal "Acceleration" Phase



Longitudinal Bunch Profile
for Optimal "Deceleration" Phase



Yield vs E-Field Phase of Capture RF



Proper choice of capture RF phase (only!) allows to use e^{+} source down to **120 GeV** e^{-} (*without any additional modifications*)

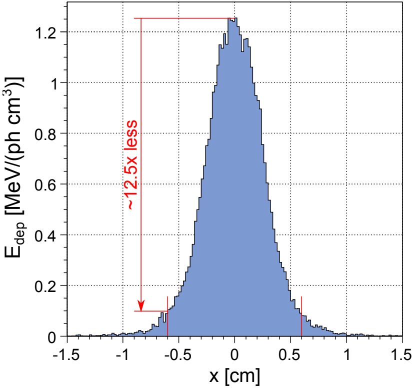
$$P_{e^+}(\varphi_0 = 375\,\text{deg}) = 33.0\% \quad \Rightarrow \quad P_{e^+}(\varphi_0 = 285\,\text{deg}) = \mathbf{29.6\%}$$

*Note: the smallest aperture size of FC was increased from 12 mm to 17 mm

Aperture Size of FC

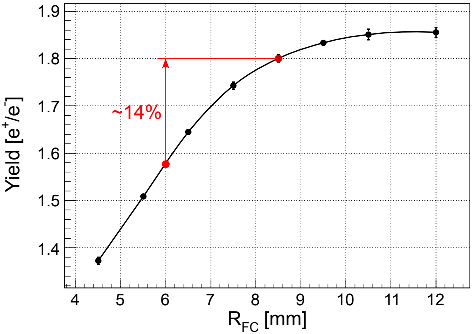
Lower E_{e^-} + Longer Lndulator $\Rightarrow$ Bigger Beam Spot Size

Transverse Profile of Deposited Energy in Target



$\sigma_x \simeq 2.5$ mm

Yield vs Aperture Radius of FC



$R_{FC}\uparrow \;\Rightarrow\; Y\uparrow + E_{dep}\downarrow$

Energy Deposited in Target at 120 GeV e^-

Source Parameters:

- 120 GeV e^- beam
- Undulator $K = 0.92$
- **Optimal phase of capture RF**
- **8.5 mm aperture radius of FC**
- 192.5 m undulator active length
- 266.5 m undulator lattice length
- 412 m between undulator and target

Photons on Target:

- $E_{1\,\mathrm{ph}} = 6.4$ MeV
- $\langle E_{ph} \rangle = 6.8$ MeV
- $\langle P_{ph} \rangle = 54.1$ kW

Energy Deposited in Target:

$$\langle E_{dep} \rangle = 9.2\%\ (5\ \mathrm{kW})$$

- Target rotated with 100 m/s tangential speed
- 554 ns bunch spacing

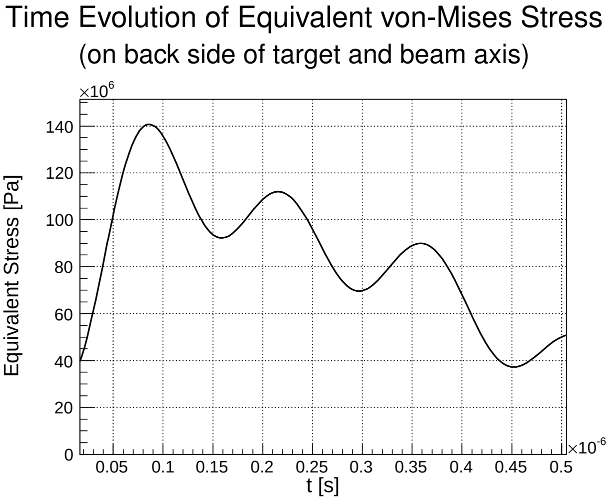
Peak Energy Deposition Density

PEDD $\simeq$ 44 J/g

Temperature Rise

$\Delta T \simeq 84$ K per pulse

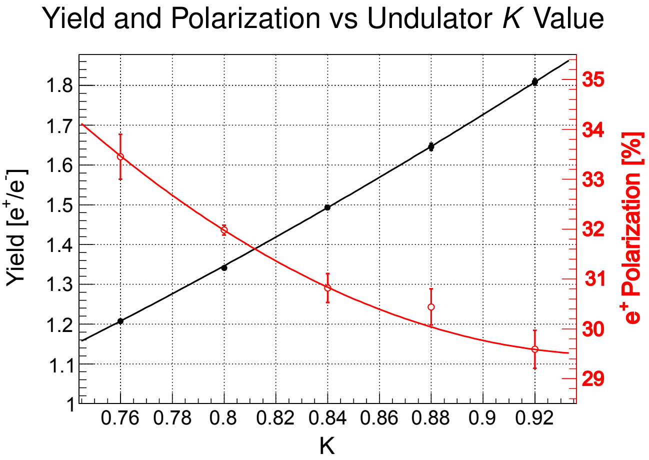
Thermal Stress in Target at 120 GeV e^- (ANSYS)



Max. Equivalent Stress: $\simeq$ 140 MPa (**27.5%** of Fatigue Strength)

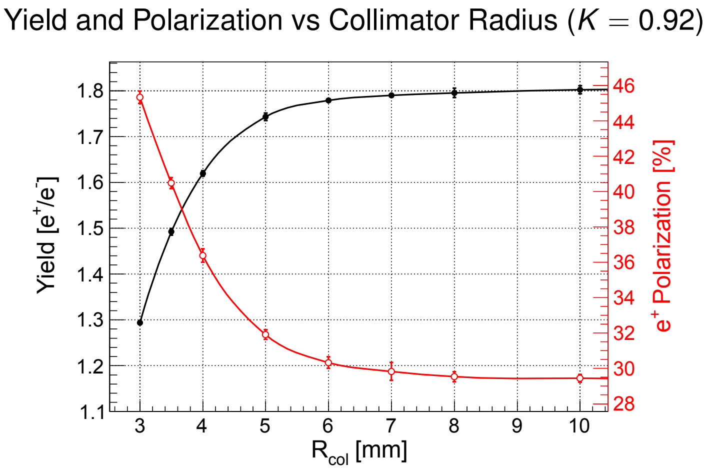
Ti6Al4, Fatigue Strength (Unnotched 10M Cycles): 510 MPa

e^+ Polarization at 120 GeV wo Photon Collimator



$P_{e^+\,\text{max}} \simeq$ **31%** at $K = 0.84$

e^+ Polarization at 120 GeV with Photon Collimator



$P_{e^+ \, \mathrm{max}} \simeq$ **40%** for $R_{\mathrm{col}} = 3.5$ mm

Summary 1: e^+ Source at 120 GeV

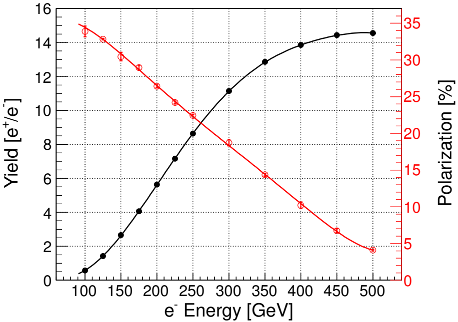
- Baseline positron source operated at $E_{e^-} =$ **120 GeV** and **231 m** active undulator length **can provide 1.5 e^+/e^-**
- Polarization of positrons is 31% for source without photon collimator and undulator $K = 0.84$
- 40% polarization can be achieved with photon collimator having 3.5 mm aperture radius
- At 120 GeV the maximal thermal stress in target induced by pulse is $\approx$ 27.5% of fatigue strength
- *Heat load and thermal stress in FC has to be checked*

Base-Line Undulator at High Energies

Increase of e^- beam energy results in

1. Higher energy of photons ($\sim E^2$)
   - Bigger e^+ yield
   - Bigger energy spread
   - More difficult to capture
2. Smaller angle of photons ($\sim E^{-1}$)
   - Higher photon density
   - Higher PEDD per bunch
3. Smaller e^+ polarization

Yield and Polarization vs e^- Energy
$K = 0.92$, $\lambda_u = 11.5$ mm

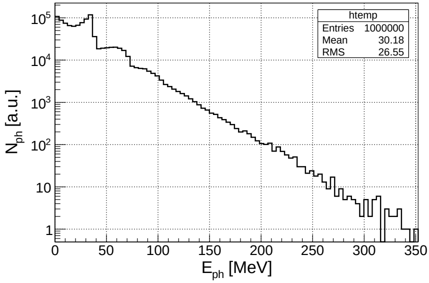


Suggestion for ILC 1 TeV upgrade:

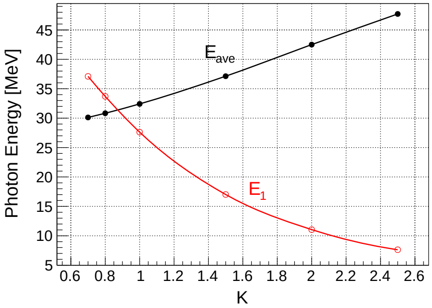
Use **another SC helical undulator with bigger period** ($\lambda_u = 4.3$ cm, same NbTi technology), that will keep energy of photons "small" ($E_{ph} \sim \lambda_u^{-2}$)

Photon Energy vs K Value. $\lambda_u = 4.3$ cm

Energy Distribution for K = 0.7

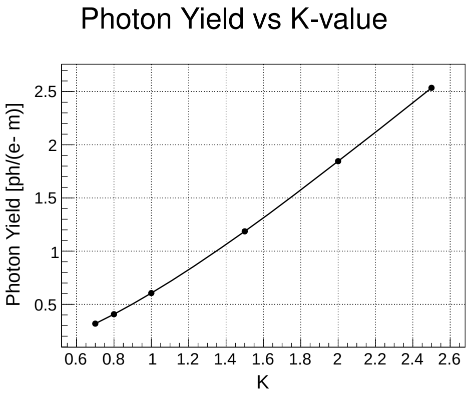


Photon Energy vs K-value



Contribution of higher harmonics is more significant for high K undulators

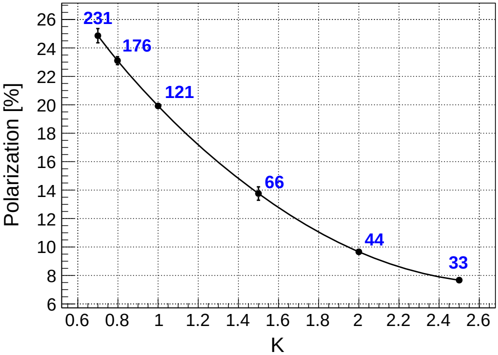
Photon Yield vs K-value



High *K* undulators
generate
more photons

e^+ Polarization vs K for Source wo Photon Collimator

Yield $\approx$ 1.5 e^+/e^-



K	# Modules	e+ Yield [e+/e-]
0.7	21	1.564
0.8	16	1.500
1.0	11	1.521
1.5	6	1.586
2.0	4	1.655
2.5	3	1.688

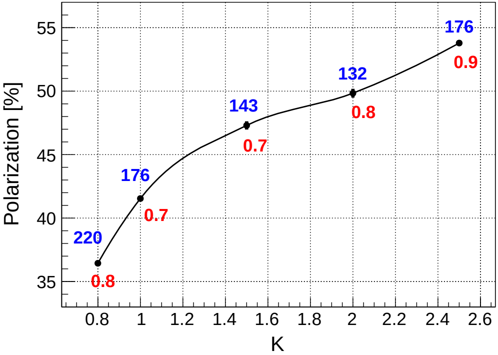
Length of undulator module is 11 m

blue numbers – required active undulator length [m]

Max. polarization without collimator is about 25% for $K = 0.7$

Polarization vs K for Source with Photon Collimator

Yield $\approx$ 1.5



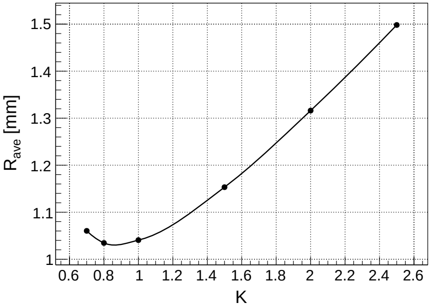
K	# Modules	e+ Yield [e+/e-]
0.8	20	1.556
1.0	16	1.507
1.5	13	1.523
2.0	12	1.499
2.5	16	1.511

blue numbers – required active undulator length [m]
red numbers – aperture radius of collimator [mm]

54% e^+ polarization can be achieved for source with $K = 2.5$ and $r_{coll} = 0.9$ mm

Photon Beam Radius vs K wo Collimator

Mean Photon Beam Radius vs K



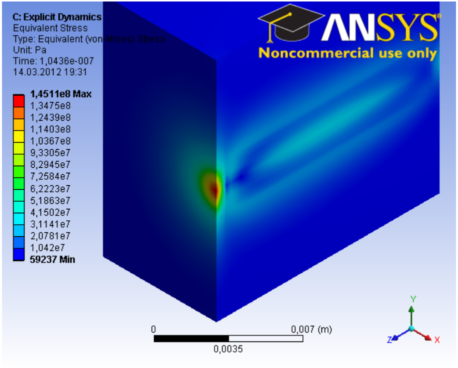
Higher K results in bigger spot size on target

Increase of the spot size for $K < 0.8$ is connected with significant increase of undulator length (longer distance from source of photons to target)

Maximal Thermal Stress

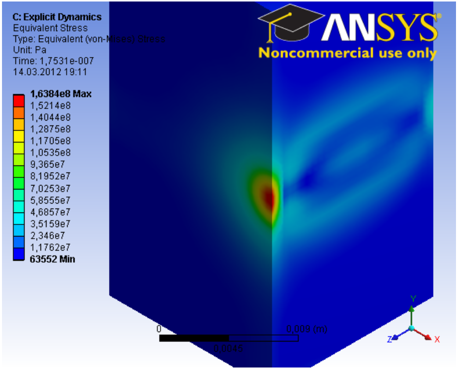
at $\sim$ 100 ns after pulse end

500 GeV e^-, $K = 2.0$, $\lambda = 4.3$ cm,
$R_{col} = 0.8$ mm



$\sigma_{max} = 145$ MPa

150 GeV e^-, $K = 0.92$, $\lambda = 1.15$ cm,
$R_{col} = 2$ mm



$\sigma_{max} = 164$ MPa

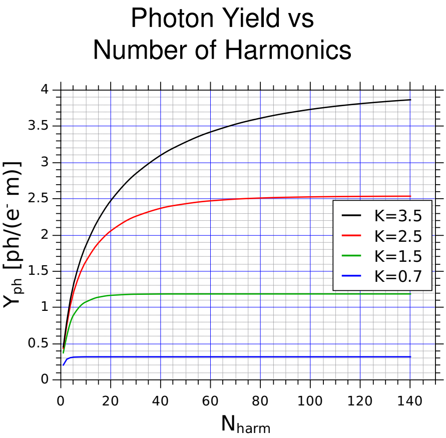
Dynamic thermal stress in target is at acceptable level

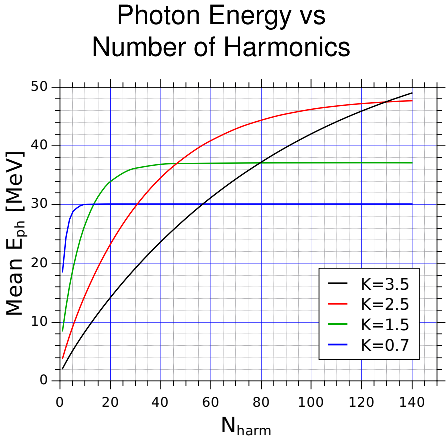
Summary 2: e^+ Source for ILC 1 TeV Upgrade

- Source for ILC 1 TeV upgrade is a topic of current/future R&D
- Max. e^+ polarization of source with SC helical undulator (NbTi, 231 m long) having 4.3 cm period at 500 GeV e^-:
  - 25% for $K = 0.7$, without collimator;
  - 54% for $K = 2.5$, with collimator ($R_{col} = 0.9$ mm)
- Relatively small photon spot size on target does not result in target damage
  - Peak thermal stress in target for $K = 2$ and photon collimator with $R_{col} = 0.8$ mm is about 150 MPa

Backup Slides

Yield and Energy of Undulator Photons vs Number of Harmonics



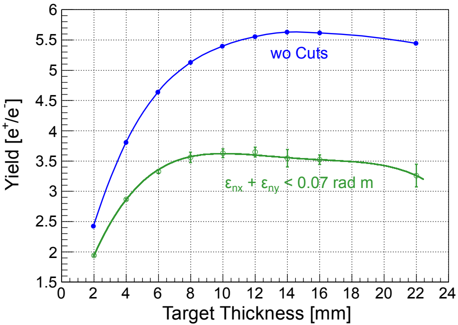


Highest K value for 140 harmonics is about 2.5

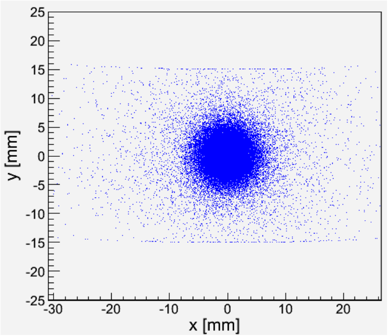
Positron Production

120 GeV e^-, 231 m undulator with $K = 0.92$, 412 m space to target

e^+ Yield after Target



Positron Distribution after Target

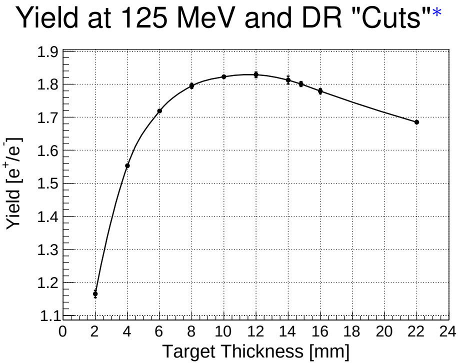


Ti6Al4V, 0.4 X_0

$\epsilon_{nx} = 24.5$ mm rad

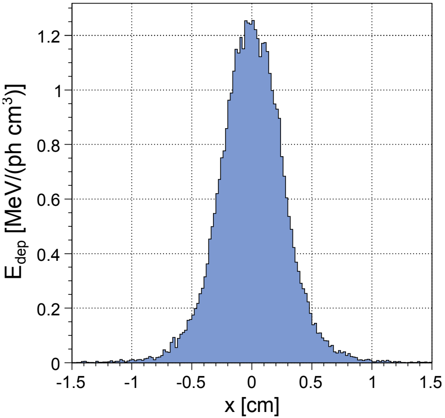
$\epsilon_{ny} = 20.4$ mm rad

Captured Yield vs Target Thickness

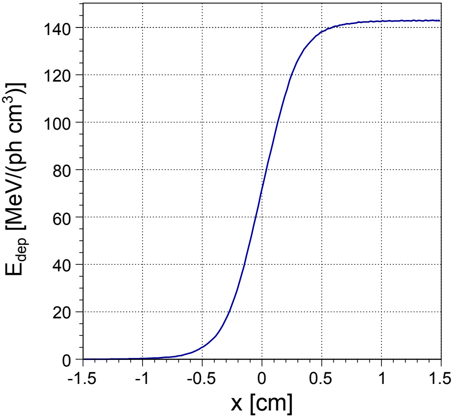


Deposited Energy in Target

Deposited Energy by **Bunch**



Deposited Energy by **Bunch Train**



$\sigma_x \simeq 2.5$ mm; Bunch Shift = 55.4 μm

Bunch Overlapping Factor = **114**

Simplified ANSYS Model

- "Instantaneous" spacial distribution of $E_{MeV/ph}(x, y, z)$
  max $E_{MeV/ph} = 1.2$ MeV/(ph·cm^3)
- Bunch Overlaping Factor (BOF): 114 bunches/train

- $N_{ph/\text{"train"}} = N_{e^-/bunch} \cdot Y_{ph/(e^- m)} \cdot L_u \cdot BOF = 8.5 \cdot 10^{14}$
- PEDD = max $E_{MeV/ph} \cdot N_{ph/\text{"train"}} \simeq 44$ J/g
  $\Delta T_{max} \simeq 84$ K
- $\Delta t_{\text{"train"}} = 554$ ns * BOF = 63.2 μs
- Heat Rate $\dot{Q}(x, y, z) = E_{MeV/ph}(x, y, z) \cdot N_{ph/\text{"train"}} / \Delta t_{\text{"train"}}$
  $\dot{Q}_{max} = 3.1 \cdot 10^{12}$ W/m^3

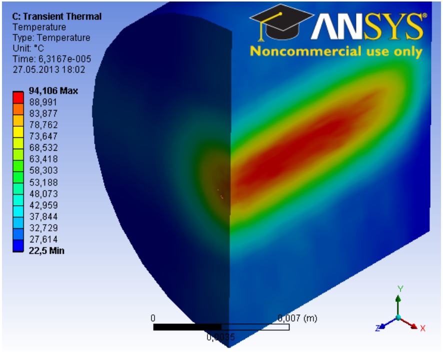
ANSYS Heat Source:

$\dot{Q}(x, y, z)$, for $t \leq \Delta t_{\text{"train"}}$
0, for $t > \Delta t_{\text{"train"}}$

Task: to find max. stress shortly after the end of bunch train

ANSYS Results

Temperature after Bunch Train



Maximal Equivalent Stress