Considerations of Material Stress under Cyclic Load:
KEKB Experiment for Damage of Ti Extraction Window

A. Ushakov, G. Moortgat-Pick (*University of Hamburg*),
F. Dietrich, S. Riemann (*DESY*),
P. Sievers (*CERN*)

Asian Linear Collider Workshop (ALCW2015)

24 April 2015

KEK Tsukuba, Japan

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

LINEAR COLLIDER COLLABORATION

DESY

What are the Limits for Ti-alloy?

What we know about Ti6Al4V:

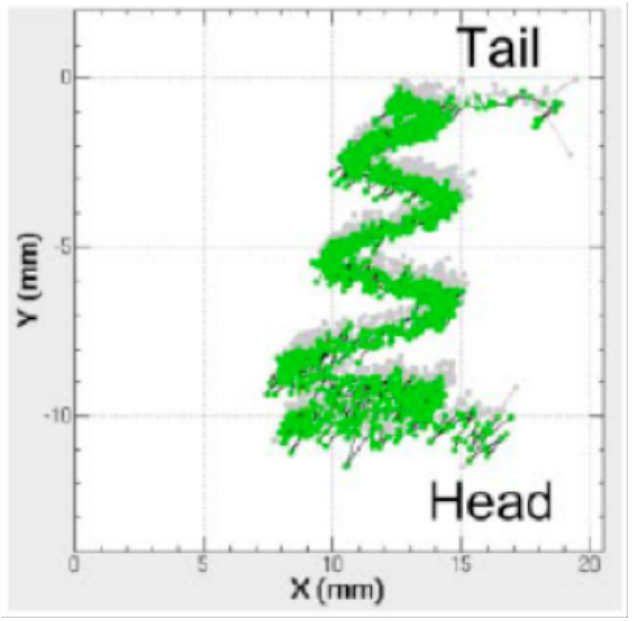
- Fatigue strength at 10M cycles: 510 MPa (unnotched)
- Tensile yield strength: 880 MPa
- Compressive yield strength: 970 MPa
- Elongation at break: 14%

What we need to know/check:

- Max. thermal stress induced by a beam pulse or few pulses at that corresponds to ***elasticity limit***
  - We profit from an experiment done for the KEKB beam exit window [T. Mimashi, IPAC2014, MOPRO024]
  - Mimachi et al. estimate energy deposition and average temperature rise at which the Ti window is damaged
  - Calculate thermal stress to understand the results of KEKB experiment and to use it as benchmark (topic of this talk)
- ***Fatigue strength*** for Ti-alloy after long irradiation time ← experiment *is planned* (more details at end of the talk)

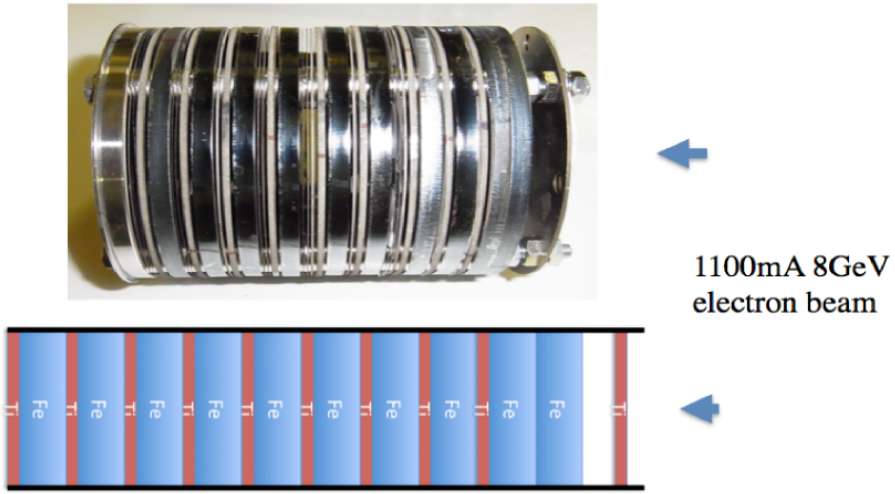
KEKB Beam

- e^- beam energy: 8 GeV
- Beam size on window: $\sigma_x = 700\mu$m, $\sigma_y = 10\mu$m
- Beam pulse: 1584 bunches
- Bunch charge: 7.2 nC ($4.5 \cdot 10^{10} e^-$/bunch)
- Beam is moved in x and y directions during the pulse by kicker magnets
- For simulations: sweeping is described by vertical (y) shift of every next bunch by 6μm (see also M. Kikuchi talk at POSIPOL2014)



KEKB Target

Idea: create an electromagnetic shower to reach high load in Ti probes placed in the shower



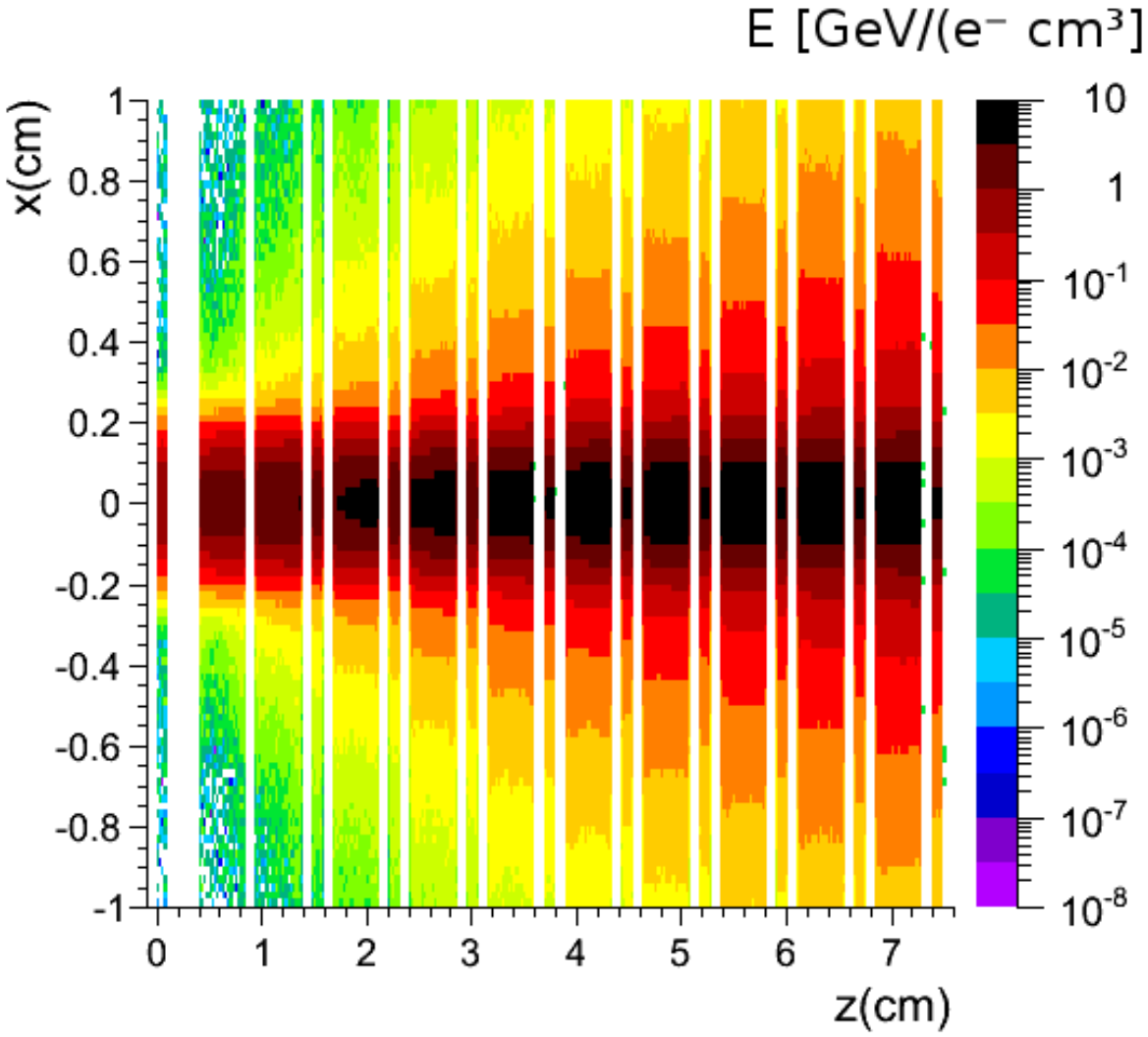
- Target consists of 10 Ti and 10 iron plates
- Ti plate numbering ("-1" or "window" is 1st Ti, "0" is 2nd, "1" is 3rd and so on)
- 100% Ti and Fe disks ($r = 1cm$) have been used for calculations of energy deposition (FLUKA)
- Thickness of Ti disk = 1 mm and thickness of Fe disk = 4.4 mm (total iron thickness is 2.5 X_0)

Results of KEKB Experiment

# Ti Plate	Radiation Length(Fe)	Energy Deposit	δX	Relative Charge Density	Ti Alloy (1mm)	Ti (1mm)
	0	4.9	1.17	0.5	○	○
0	0.5	11.4	1.17	1.3	○	○
1	0.75	18.7	1.17	2.1	○	○
2	1.0	28.6	1.17	3.3	○	○
3	1.25	41.2	1.17	4.8	○	△
4	1.5	56.5	1.17	6.5	△	×
5	1.75	74.5	1.17	8.4	△	×
6	2.0	95.2	1.17	10.9	△	×
7	2.25	118.5	1.17	21.2	△	×
8	2.5	144.6	1.17	25.8	△	×

Surface color change or damage (bulging) has been observed for Ti plates #4−#8

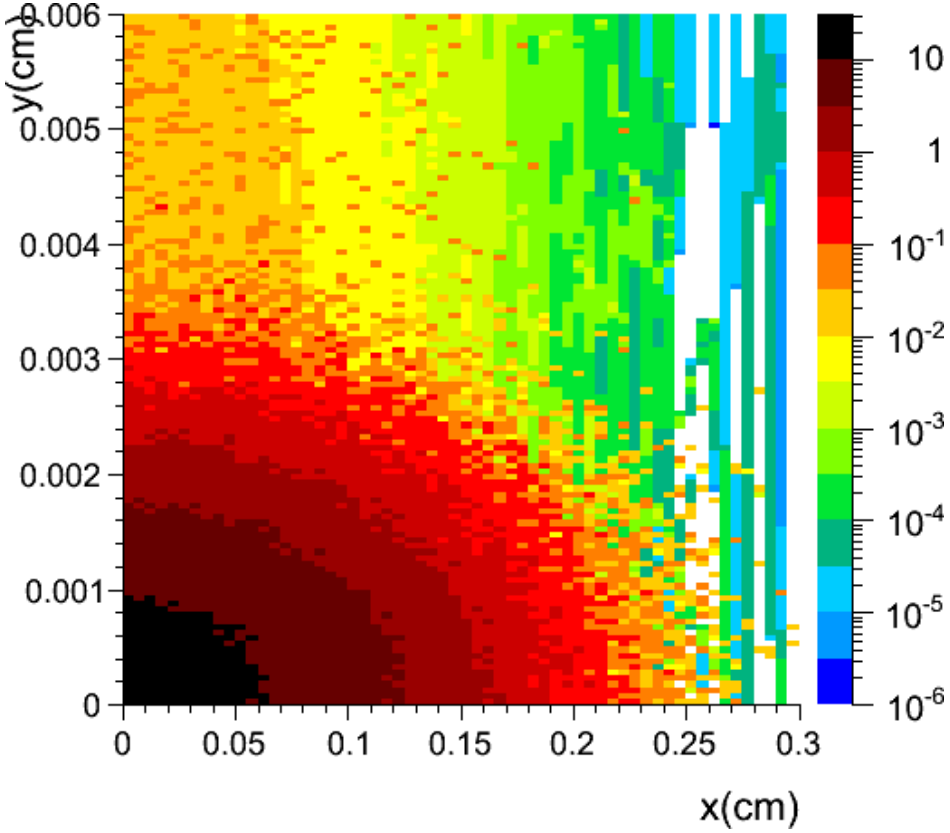
E_{dep} in whole Exit Window Test System*



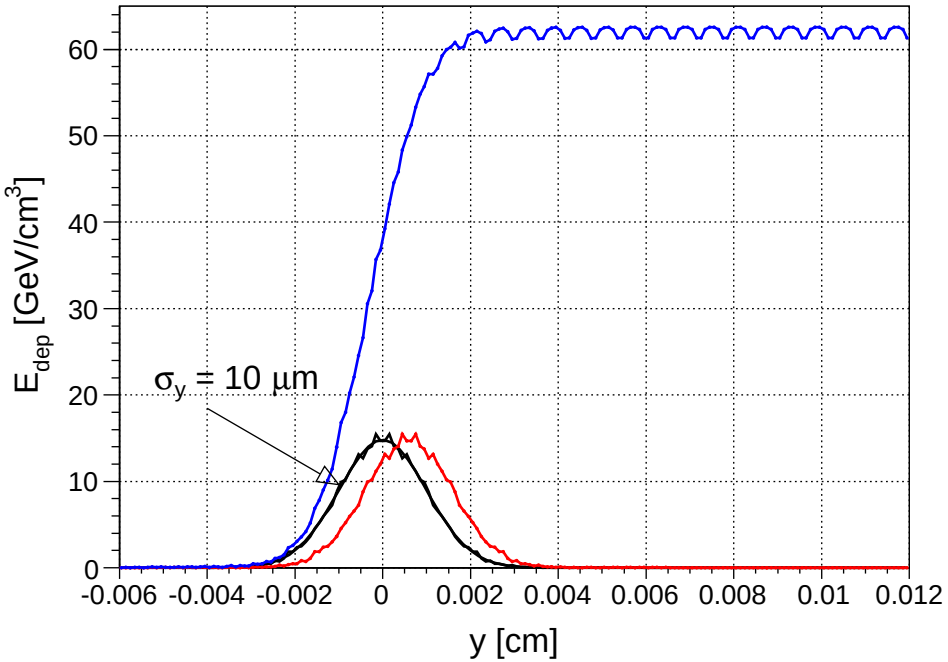
*Note: The plot is shown for presentation of FLUKA target geometry only.

Energy Deposition in Ti Window (#−1)

Energy Deposited by Bunch [GeV/(e$^-$ cm^3)] in XY Plane

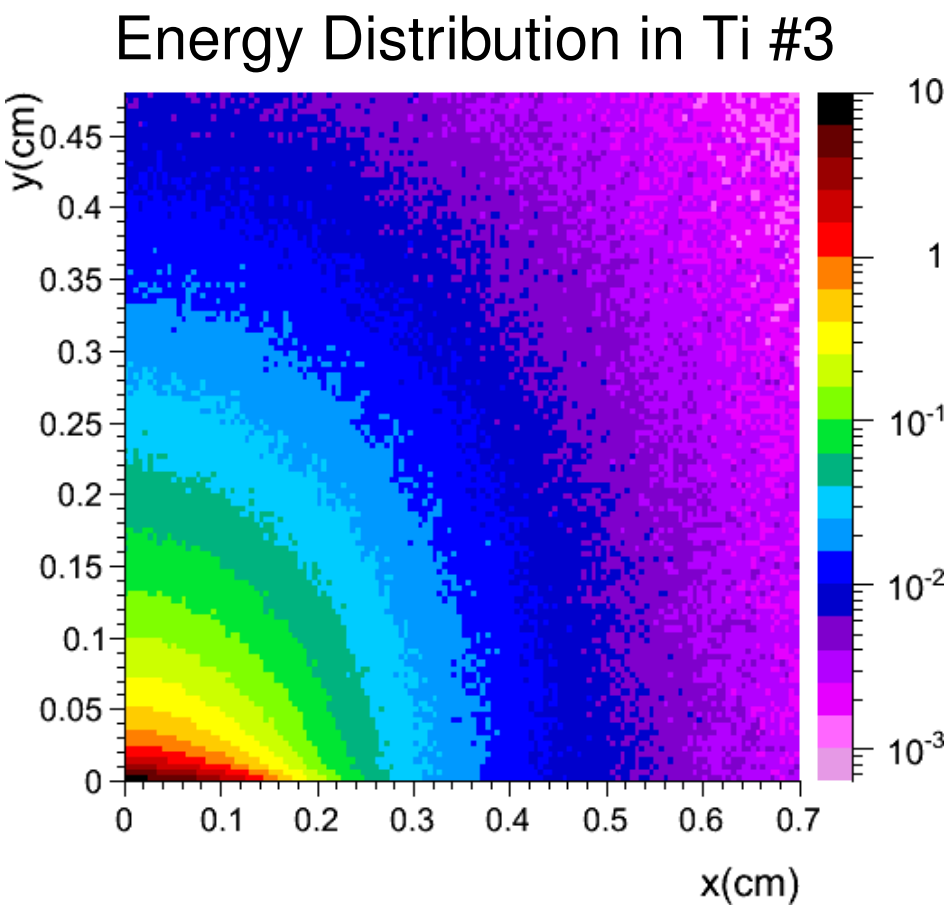


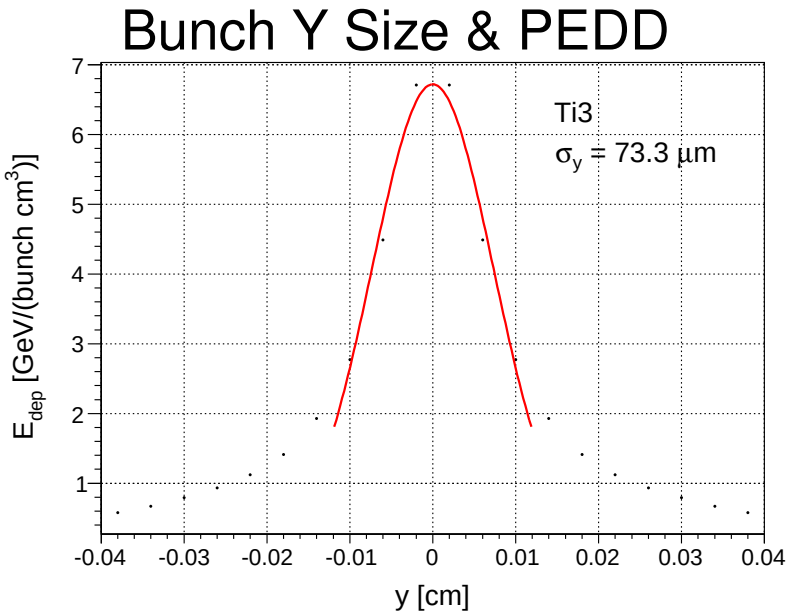
PEDD per Bunch and Pulse

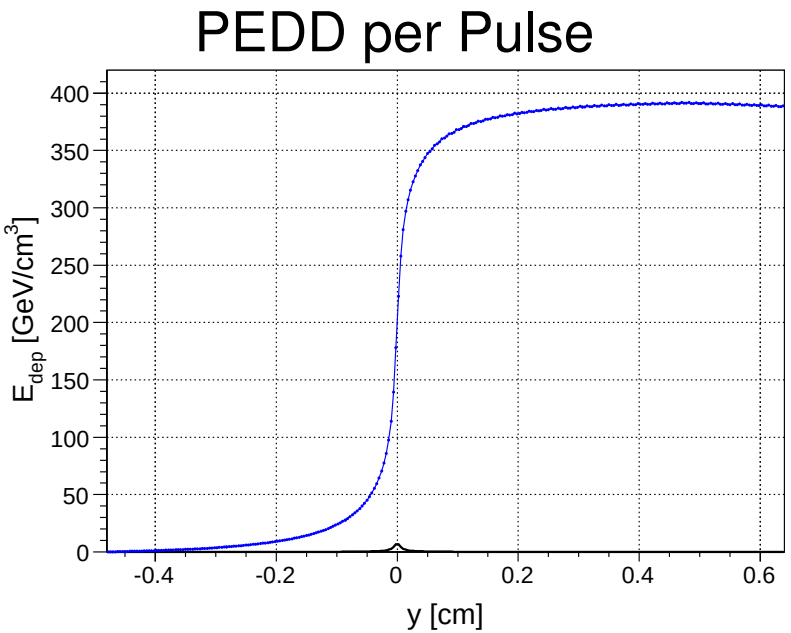


Black curve – 1st bunch,
red – 2nd bunch,
blue – 1584 bunches (pulse)

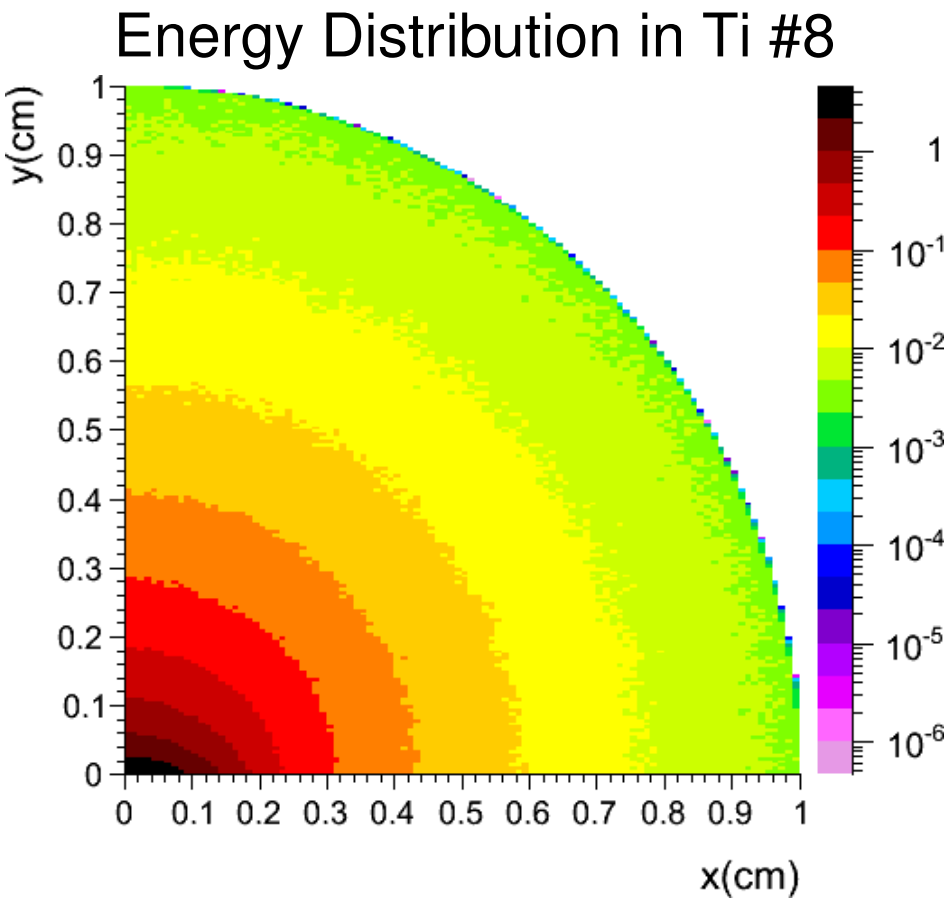
Ti Plate #3: E_{dep} per Bunch and Pulse

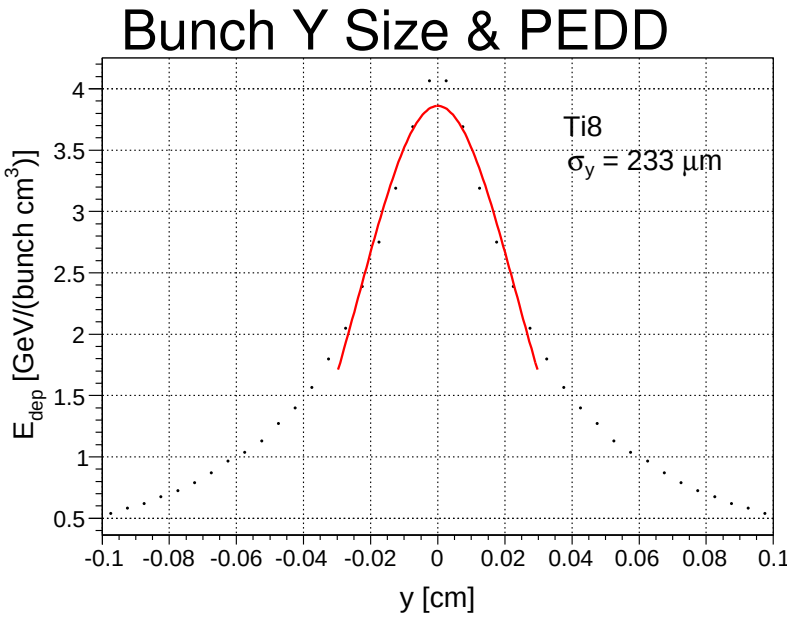


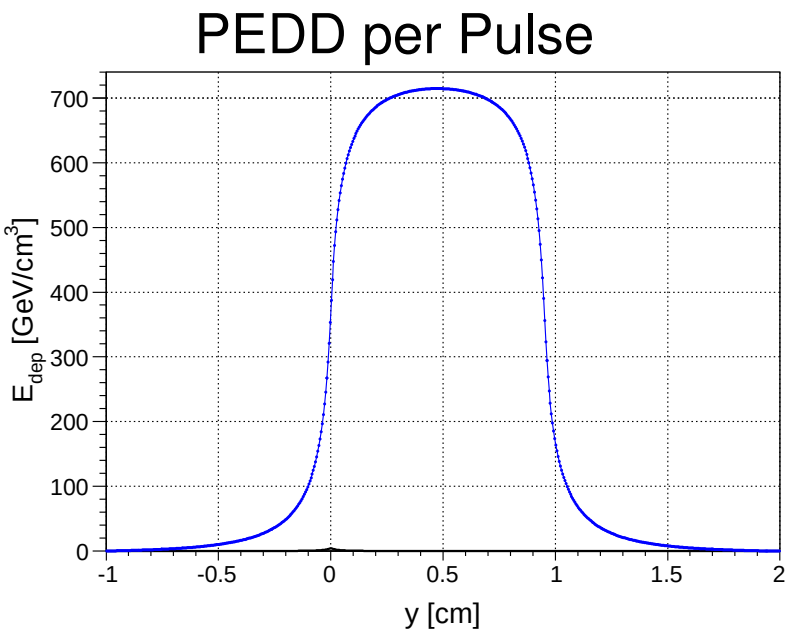




Ti Plate #8: E_{dep} per Bunch and Pulse

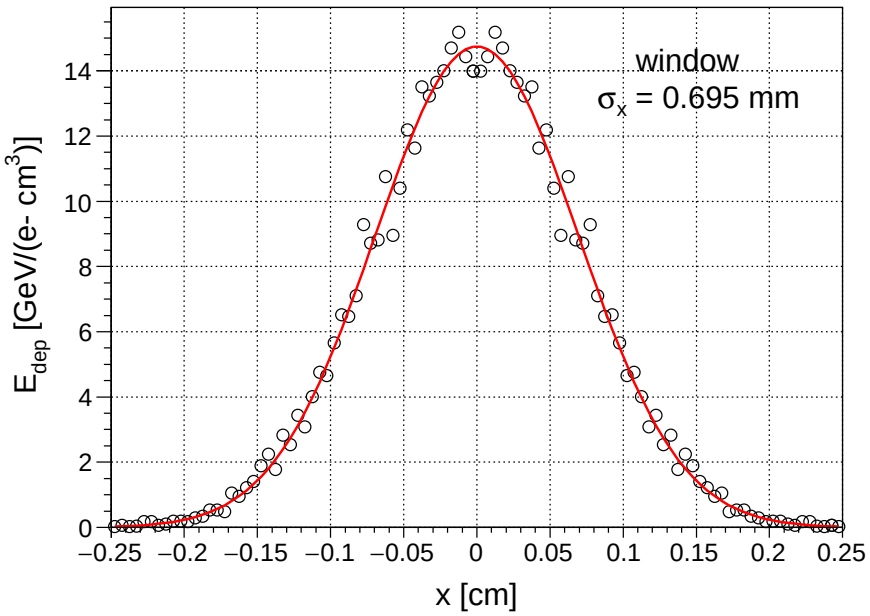




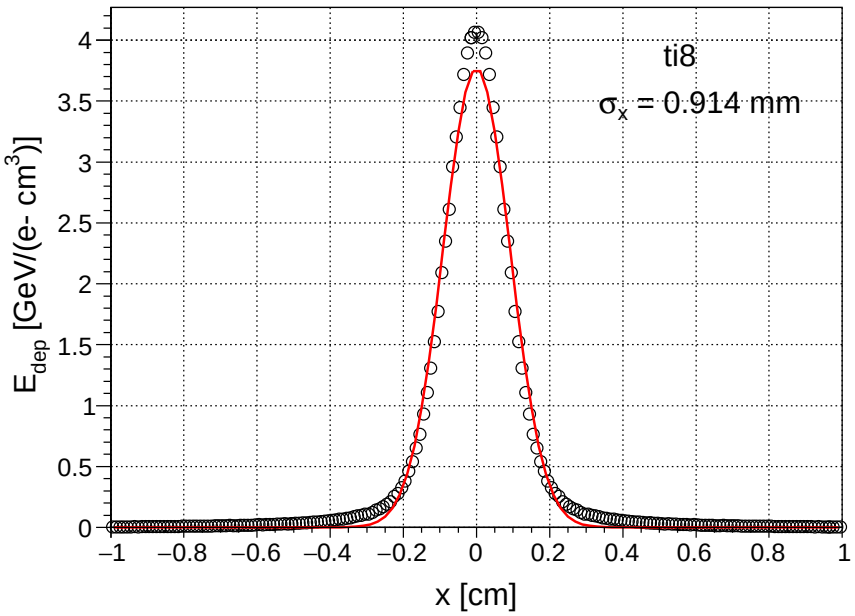


Change of Beam X-Size

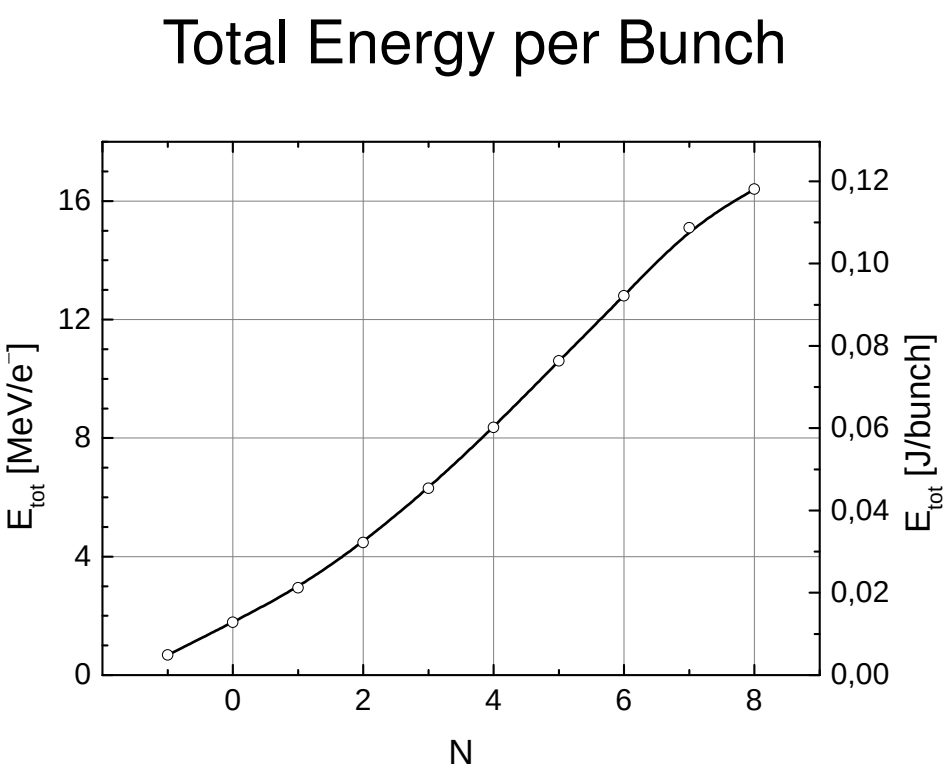
E_{dep} vs X for Ti #-1 (window)

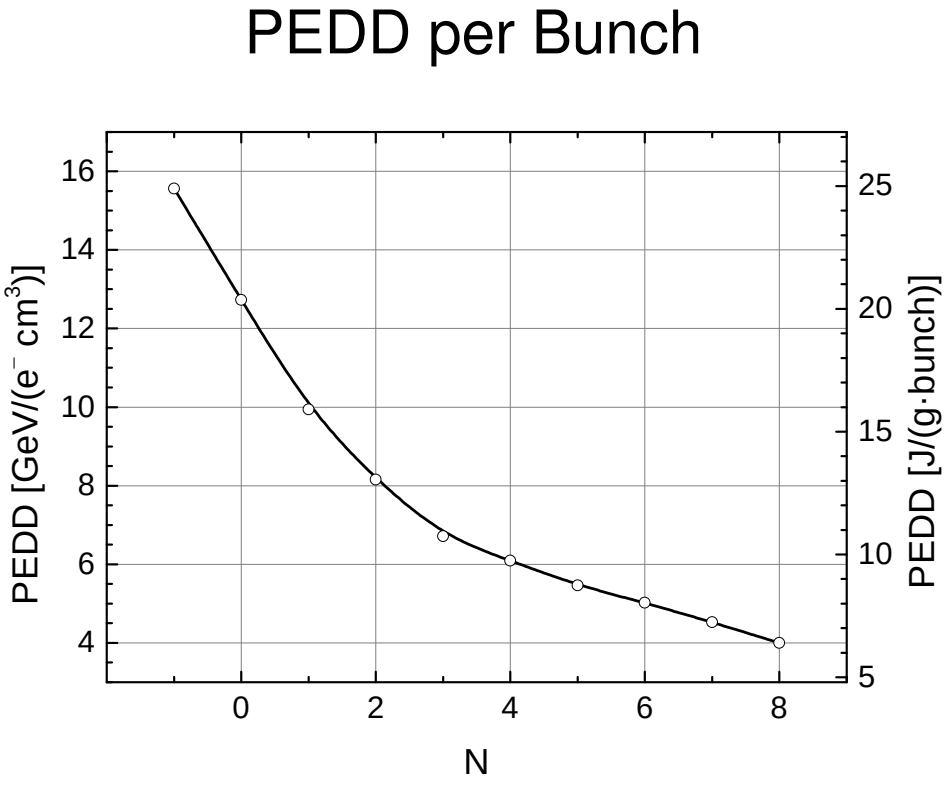


E_{dep} vs X for Ti #8



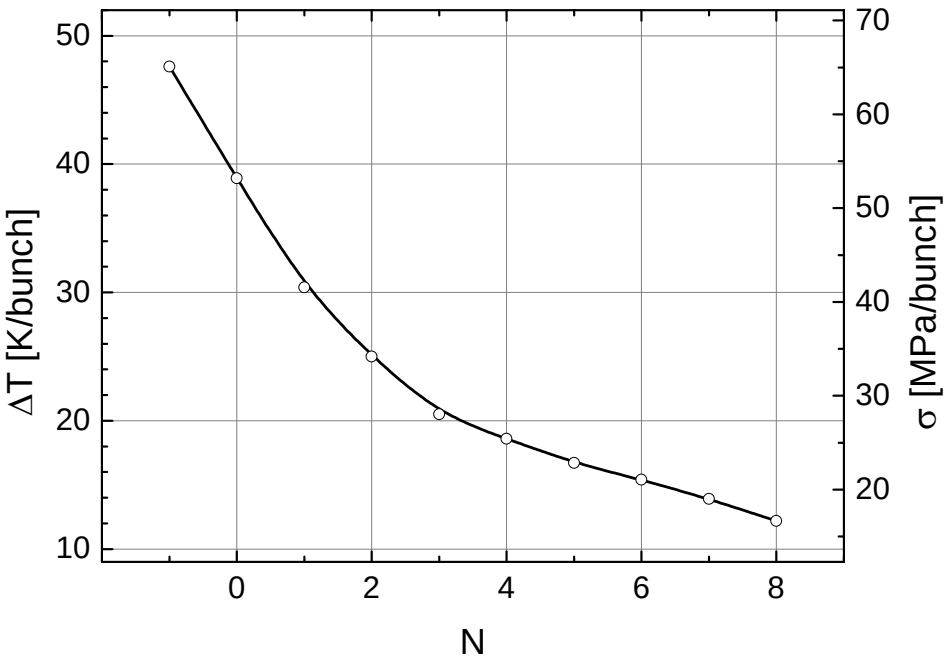
Energy Deposition per Bunch





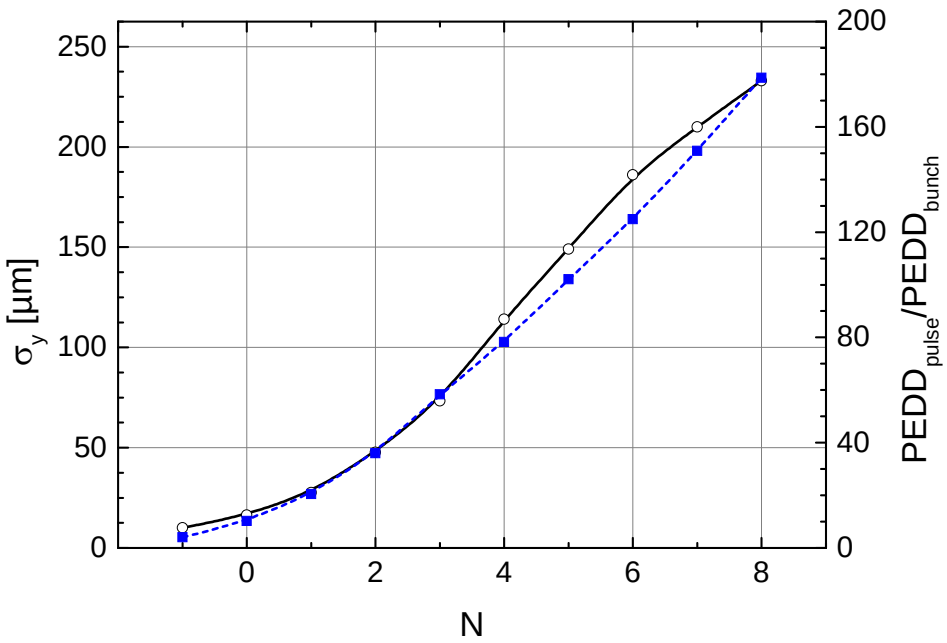
ΔT and Max. Stress per Bunch, Bunch Size and Bunch Overlapping

Temperature Rise and Thermal Stress per Bunch



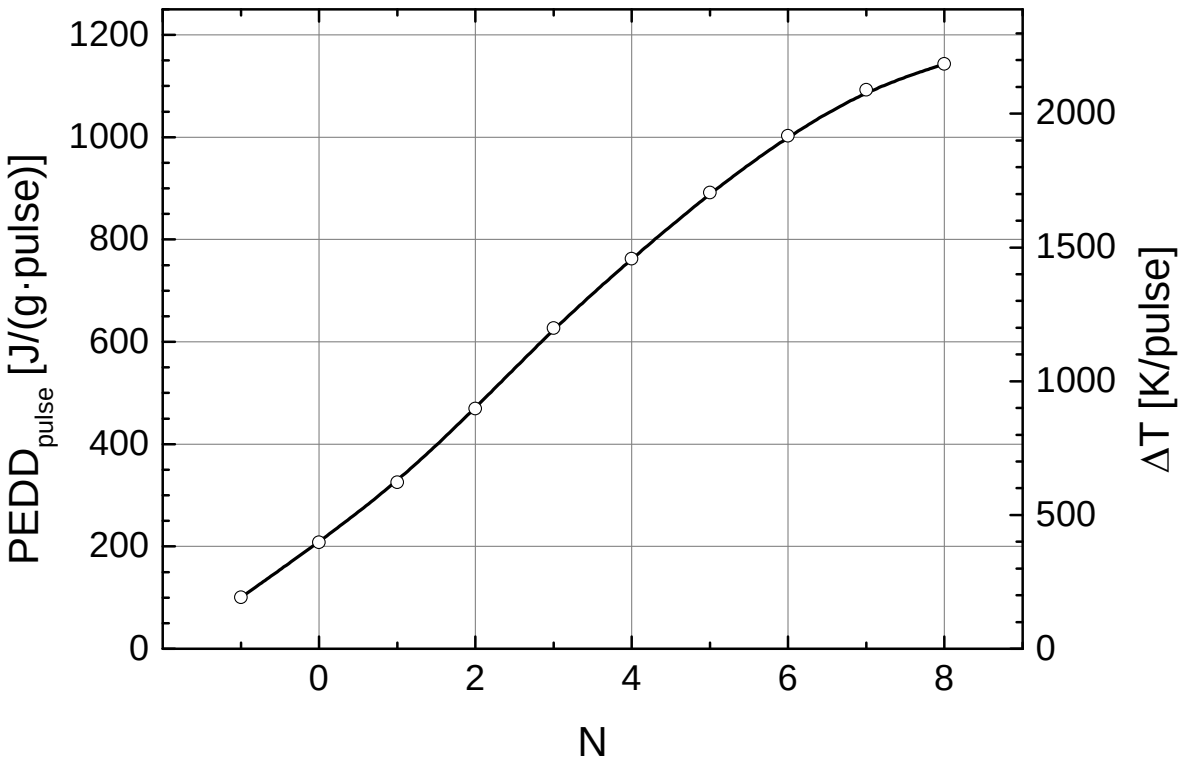
$$\sigma = \frac{\alpha E \Delta T}{1 - \sigma}$$

Bunch Y Size and Bunch Overlapping Factor



σ_y is the black solid curve, $\mathrm{PEDD_{pulse}}/\mathrm{PEDD_{bunch}}$ is the blue dash curve

PEDD and Temperature Rise per Pulse



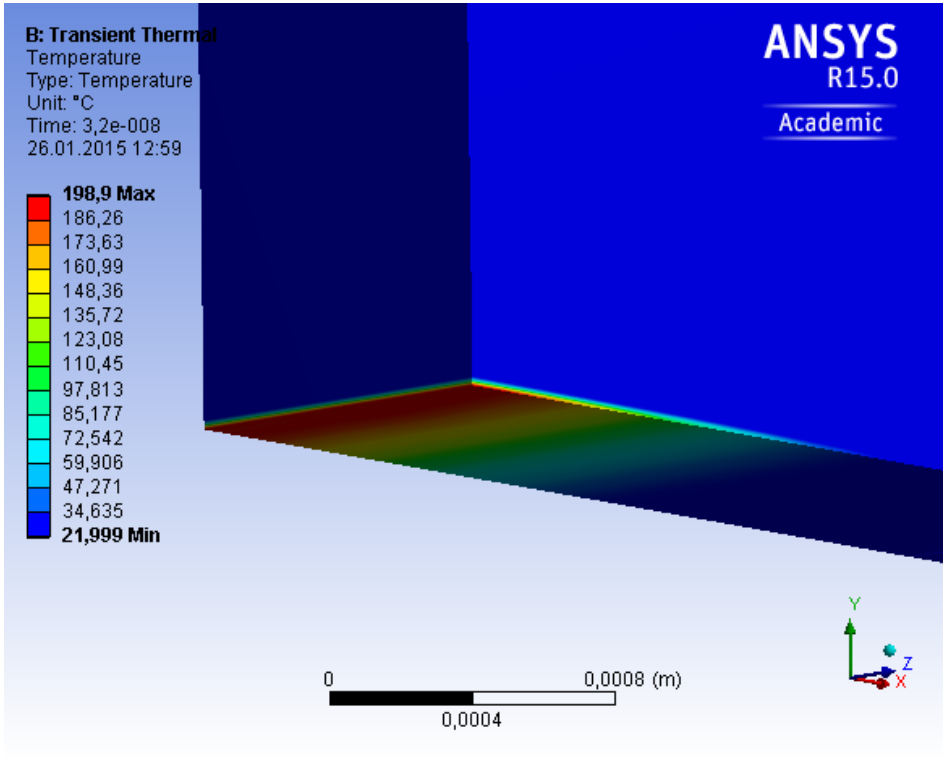
Ti-Alloy Properties (ANSYS)

Properties of Outline Row 3: Titanium Alloy

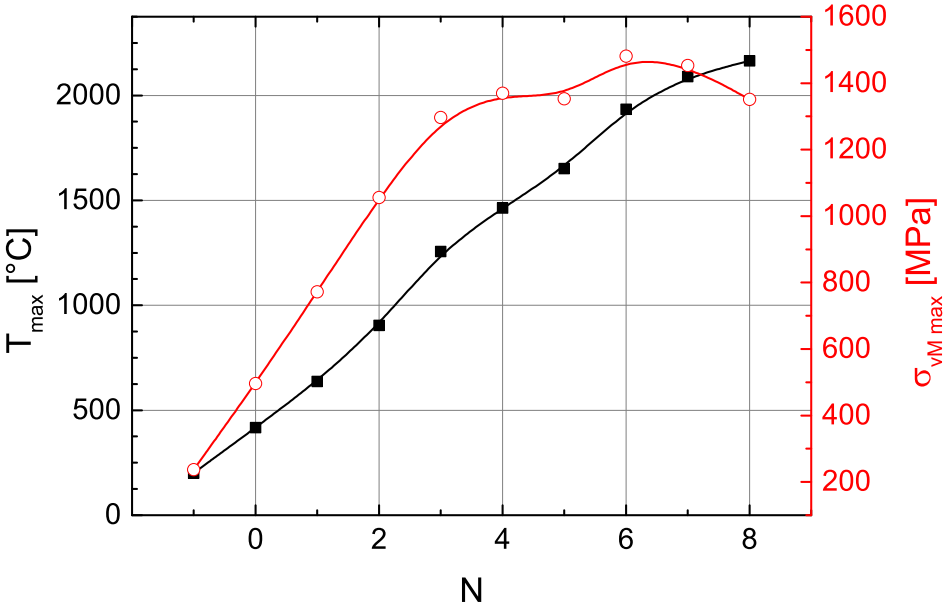
	A	B	C	D	E
1	Property	Value	Unit		
2	Density	4620	kg m^-3		
3	Isotropic Secant Coefficient of Thermal Expansion				
4	Coefficient of Thermal Expansion	9,4E-06	C^-1		
5	Reference Temperature	22	C		
6	Isotropic Elasticity				
7	Derive from	Young's Mod...			
8	Young's Modulus	9,6E+10	Pa		
9	Poisson's Ratio	0,36			
10	Bulk Modulus	1,1429E+11	Pa		
11	Shear Modulus	3,5294E+10	Pa		
12	Tensile Yield Strength	9,3E+08	Pa		
13	Compressive Yield Strength	9,3E+08	Pa		
14	Tensile Ultimate Strength	1,07E+09	Pa		
15	Compressive Ultimate Strength	0	Pa		
16	Isotropic Thermal Conductivity	21,9	W m^-1 C^-1		
17	Specific Heat	522	J kg^-1 C^-1		
18	Isotropic Relative Permeability	1			
19	Isotropic Resistivity	1,7E-06	ohm m		

T_{max} and max. Thermal Stress (static, von Mises)

Temperature Distribution (Window)

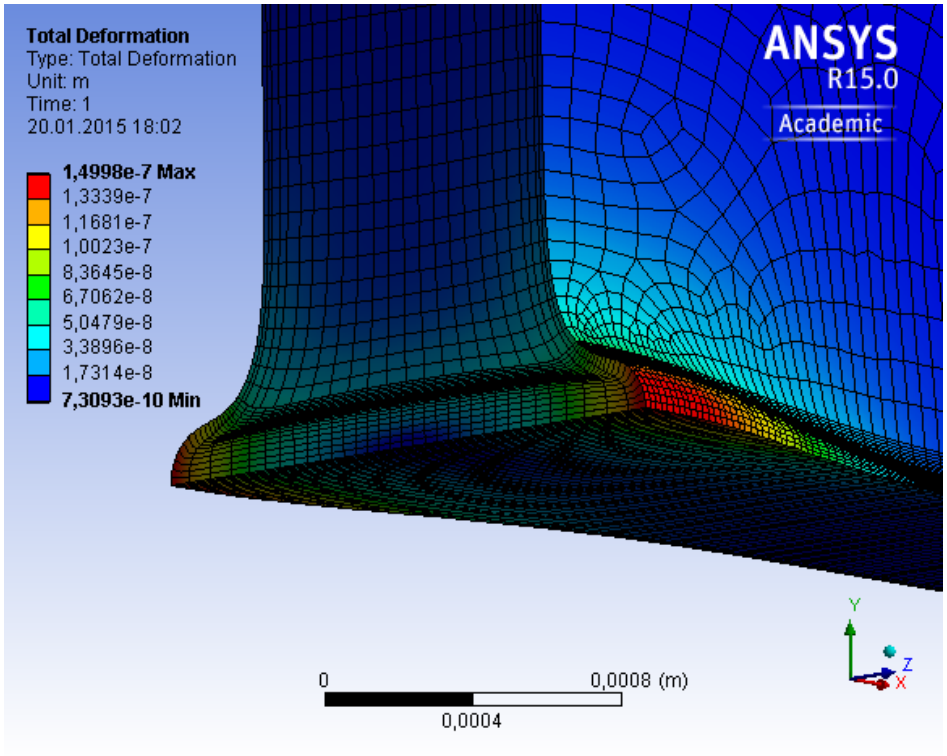


T_{max} and max. Static von Mises Stress

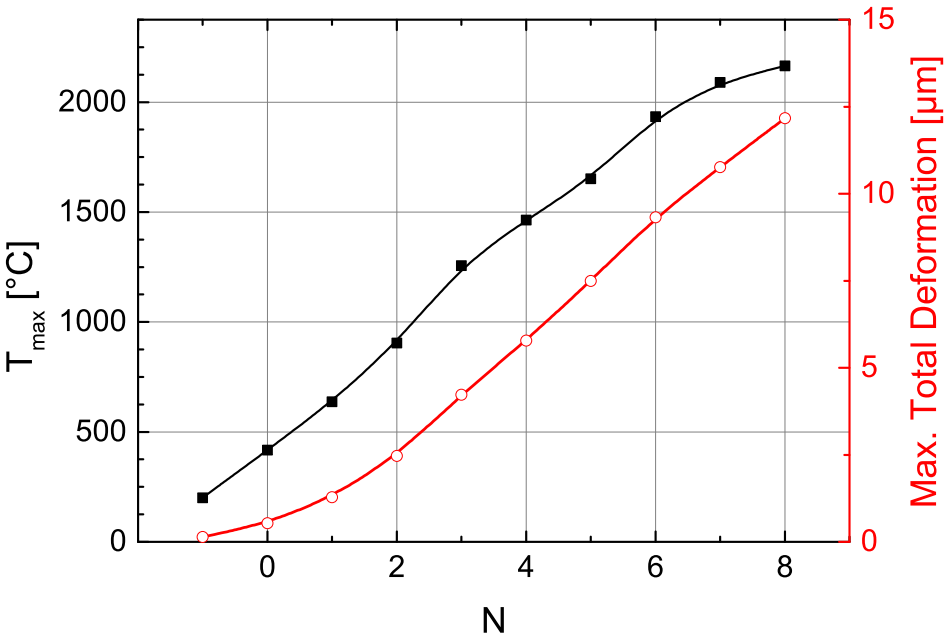


Max. Deformation (ANSYS, Static Structural)

Total Deformation of Window



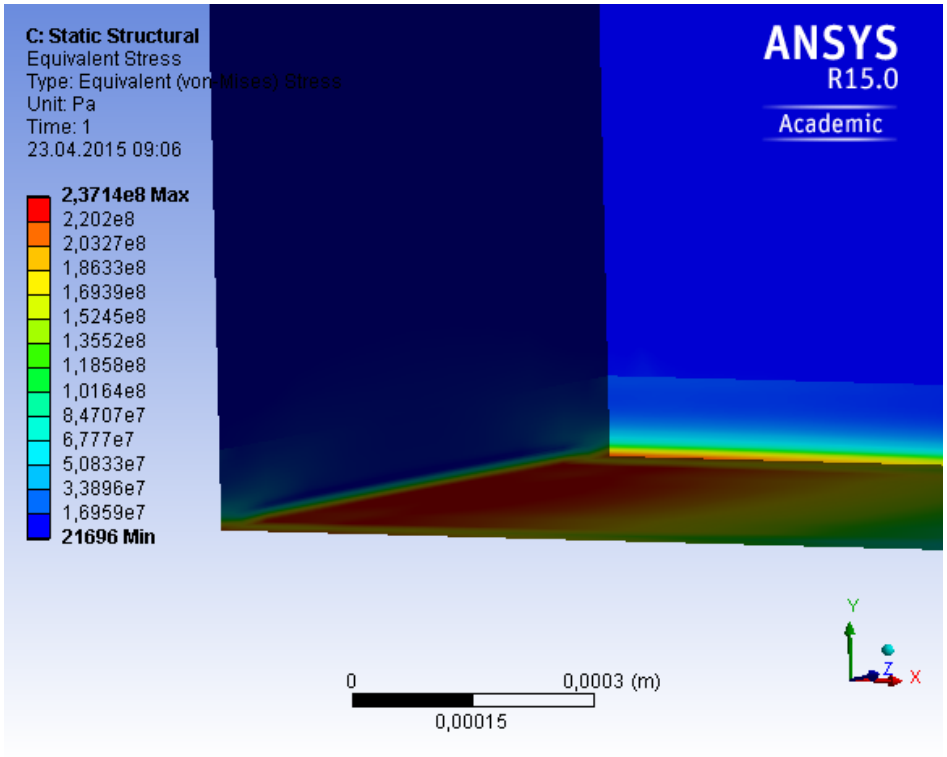
T_{max} and max. Total Deformation



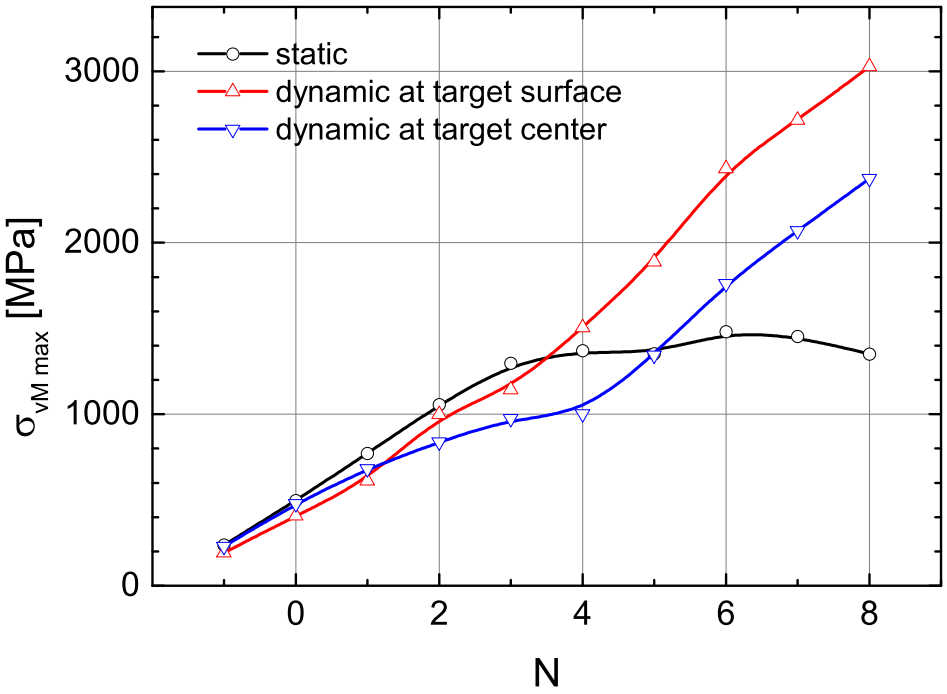
Max. Dynamic von Mises and Normal Stress

ANSYS, Explicit Analysis

vM Stress Distribution in Window

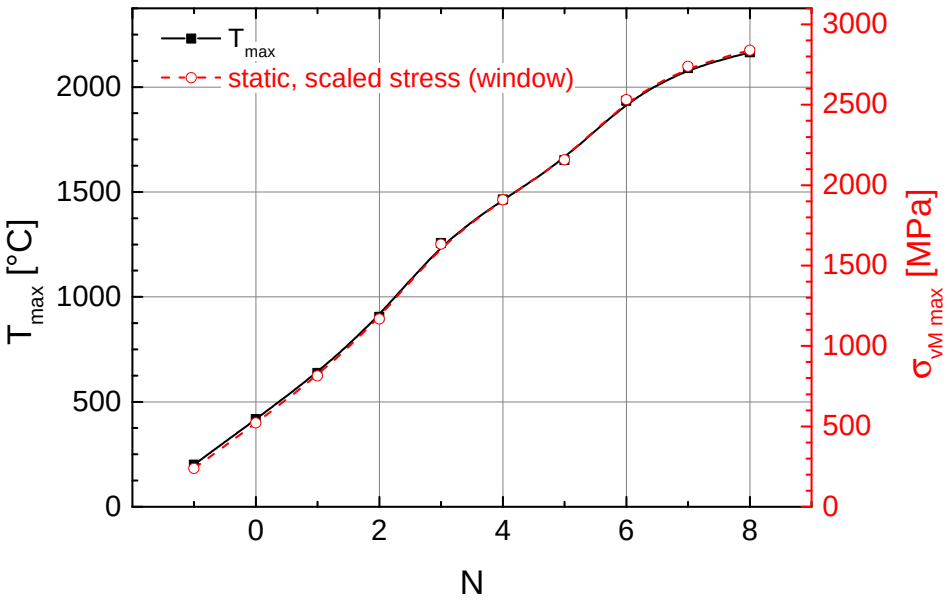


Max. Equivalent von Mises Stress

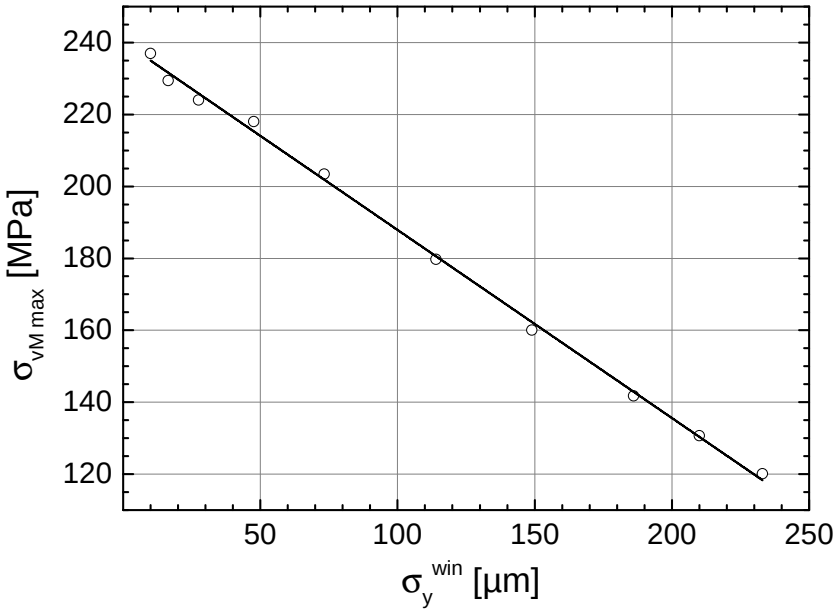


Impact of Beam Size on Stress

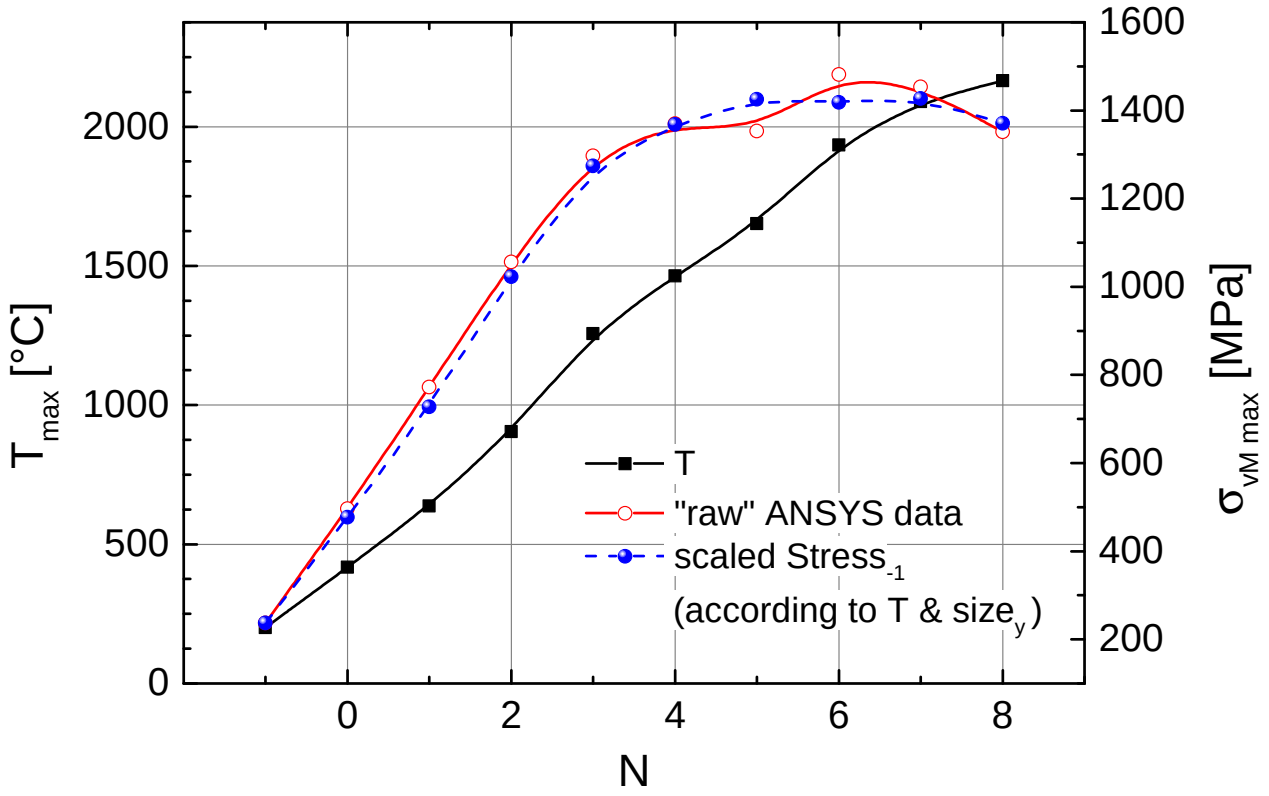
von Mises Stress in Window for E_{dep}
scaled according to PEDD
$\sigma_y = const$, $PEDD \neq const$



von Mises Stress in Window for E_{dep}
scaled according to σ_y
$\sigma_y \neq const$, $PEDD = const$



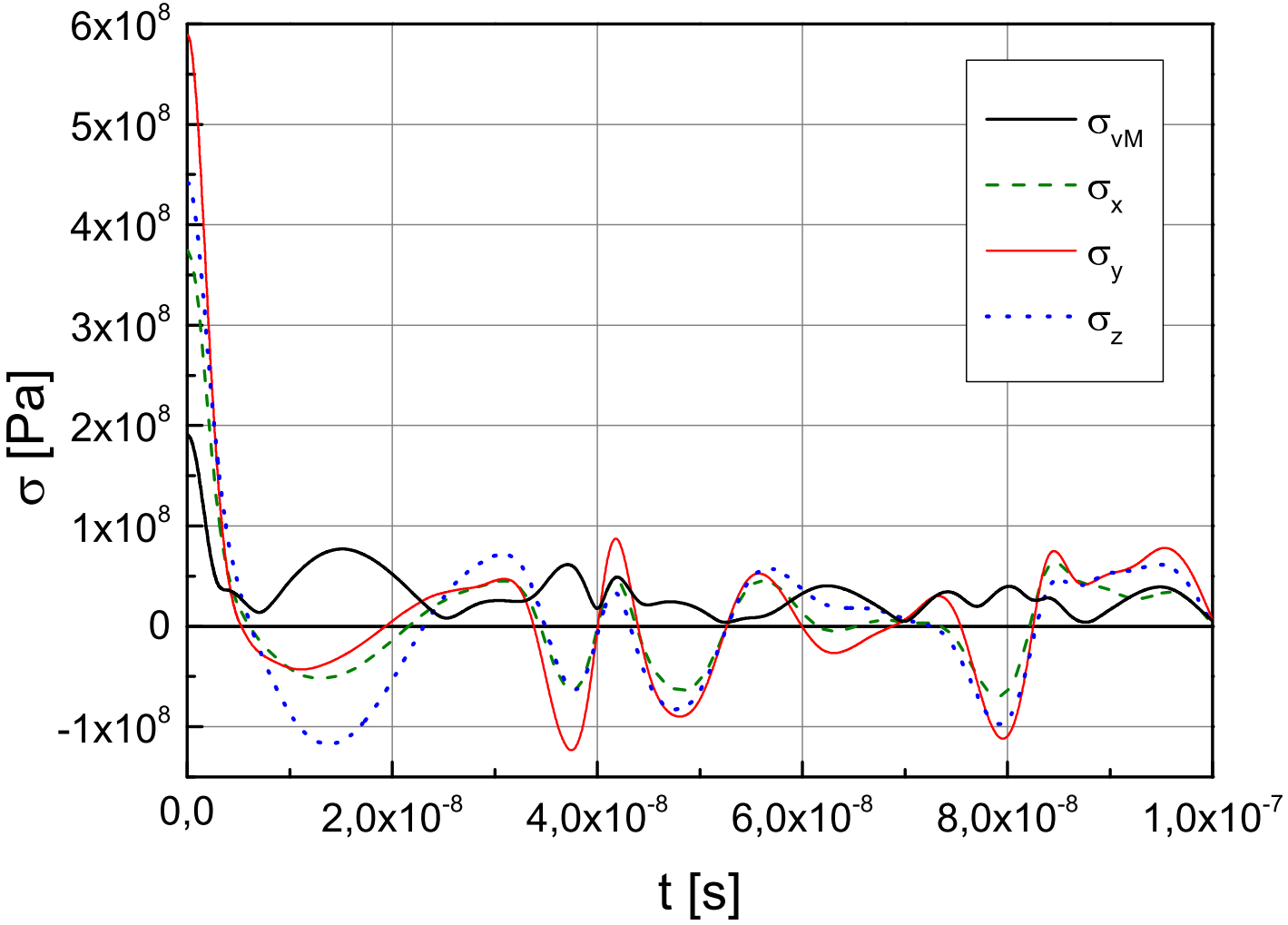
Stress Saturation?



Stress "saturation" at downstream half of target system is connected with increasing beam size

Dynamic Stress

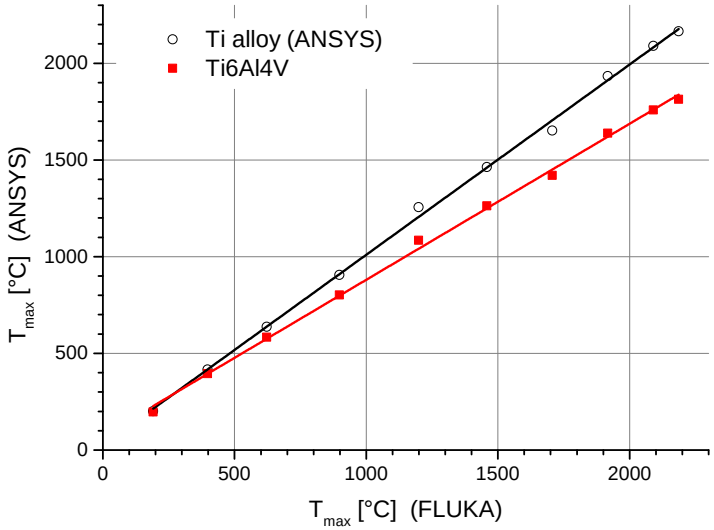
von Mises and Normal Stress Components at Window



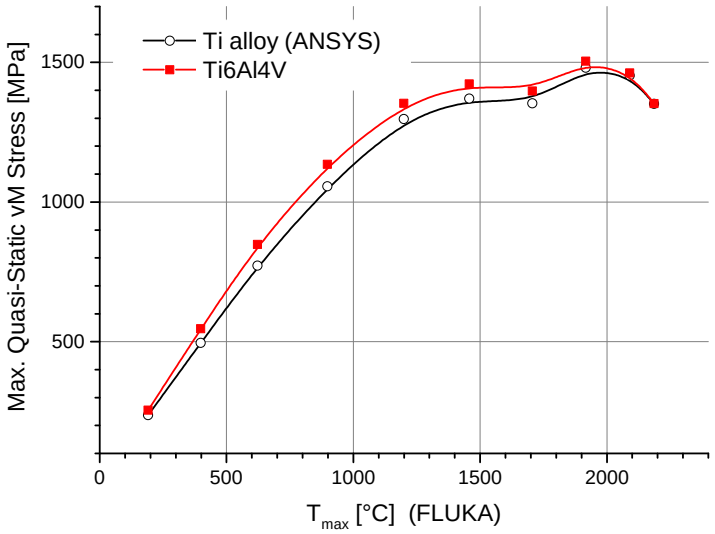
Target with Temperature Dependent Ti6Al4V Properties

Density, thermal conductivity, specific heat, coefficient of thermal expansion and *Young's modulus* were defined in range between 22 °C and 1650 °C for Ti6Al4V

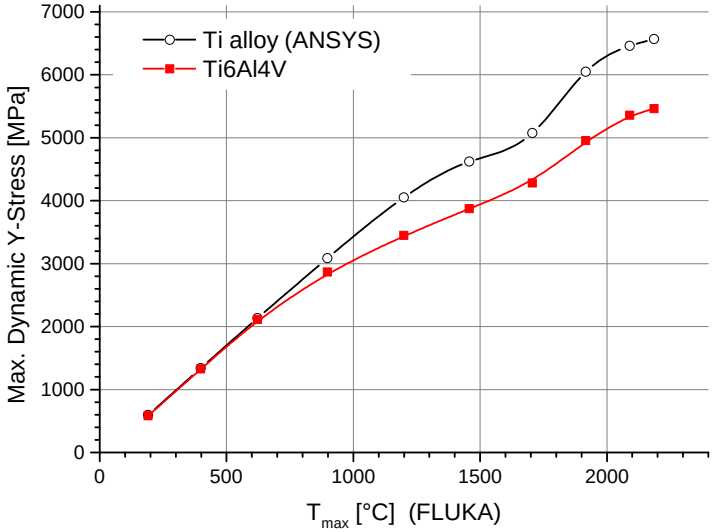
Maximal Temperature



Quasi-Static vM Stress



Dynamic Y-Component of Stress



Summary

- Simulation performed to estimate the PEDD, peak temperature rise and thermal stress in Ti-alloy targets induced by 8 GeV KEKB e^- beam
- 1 mm thick Ti-alloy target can survive a "single" beam pulse that increases temperature up to $T_{max} \approx 1200\ ^\circ$C,
  quasi-static von Mises $\sigma_{vM\,max} \approx 1300$ MPa and
  dynamic normal stress up to $\sigma_{max} \approx 3400$ MPa,
  if Ti-alloy is Ti6Al4V and bunch shift is 6 μm

Results have not yet been discussed with Mimashi et al.

Results are relevant for ILC e^+ target, however:

- Test for material thickness $>$ 1 mm has to be done to extrapolate results to ILC Ti-alloy target
  ($\leq$ 1 mm Ti target can be considered as "thin" or 2D)
- Cyclic load has to be included

Outlook

- We applied for a grant from the German ministry of science (BMBF) to perform an experiment on long term irradiation of Ti alloy and other materials at MAMI/MESA (Mainz). Partners are University of Hamburg, DESY, University of Mainz and Technical University Darmstadt.
- Goals:
  - Behavior of Ti alloy and other materials under cyclic stress
  - Fatigue stress limits based on cyclic irradiation (instead of cyclic mechanical load)
- Official decision on project approval is expected in June 2015
- Project duration planned for 3 years