Fermilab

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NTO2 Graphite Fin Swelling Analysis

Sujit Bidhar

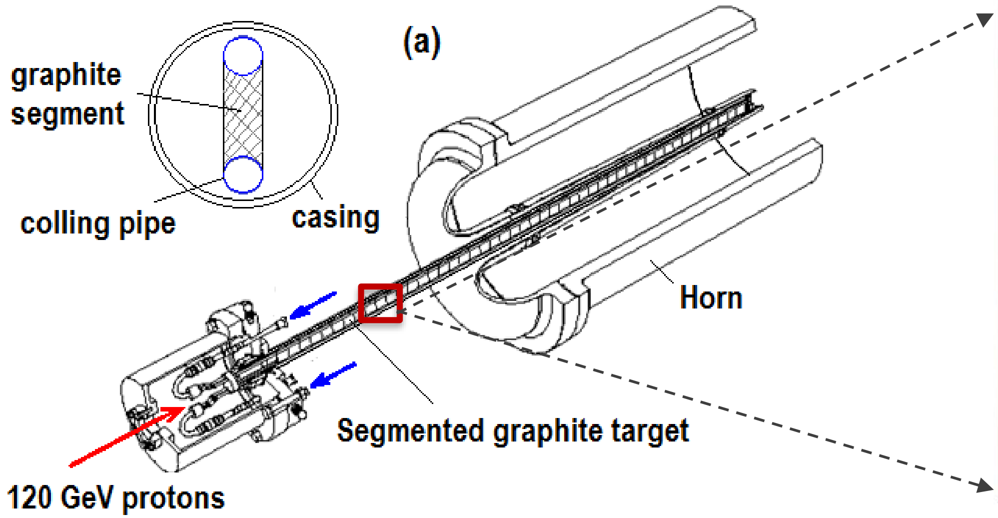
TSD Topical Meeting

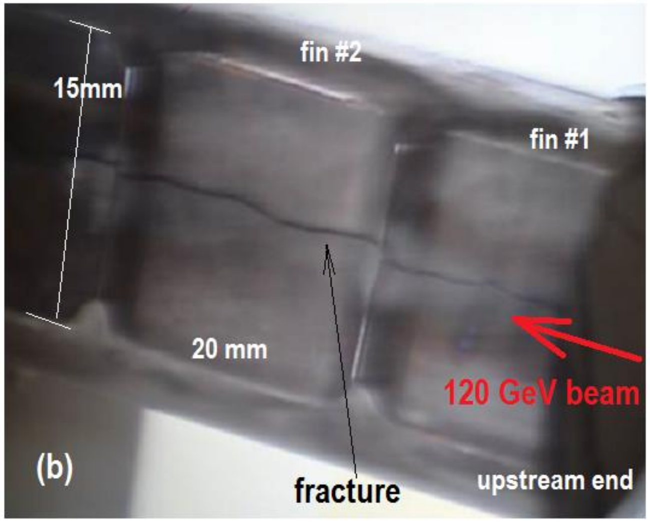
April 18, 2019

Outline

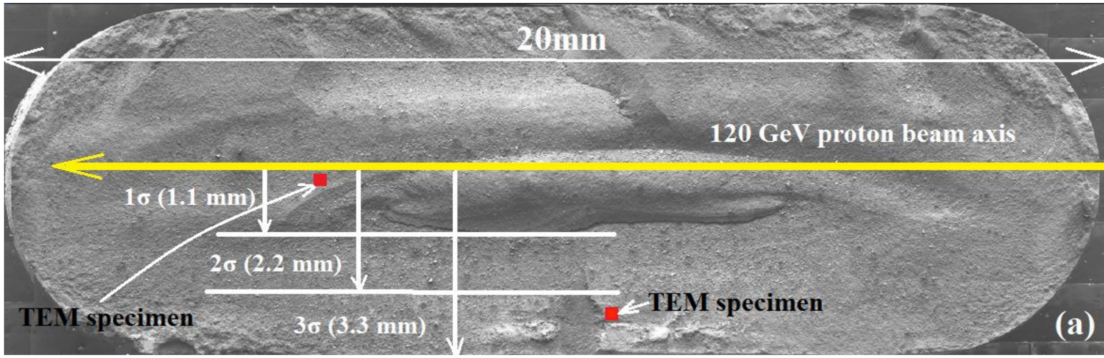
- Background NTO2 fin
- Empirical modeling of swelling
- Finite element implementation
- Thermal-structural dynamic analysis
  - Failure investigation

Neutrino (NuMI) target





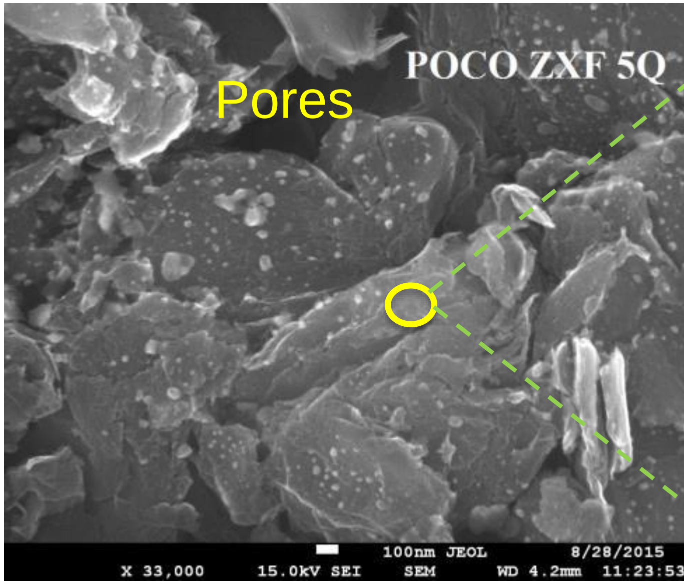
Fractured surface

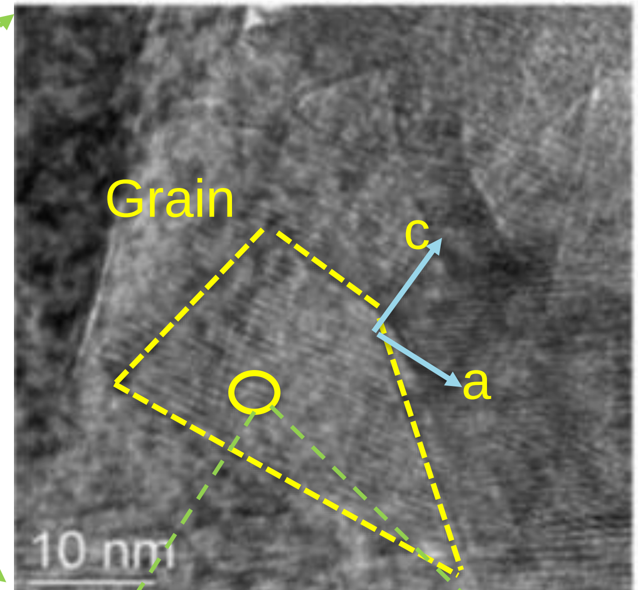


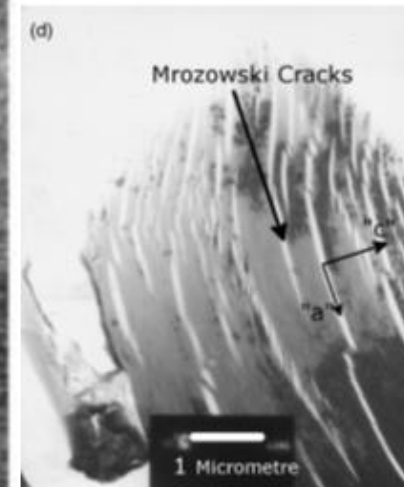
Bulk swelling ~2%
Fractured fins at upstream

Beam Power:350 kW, 120GeV
Beam Sigma: 1.1 mm

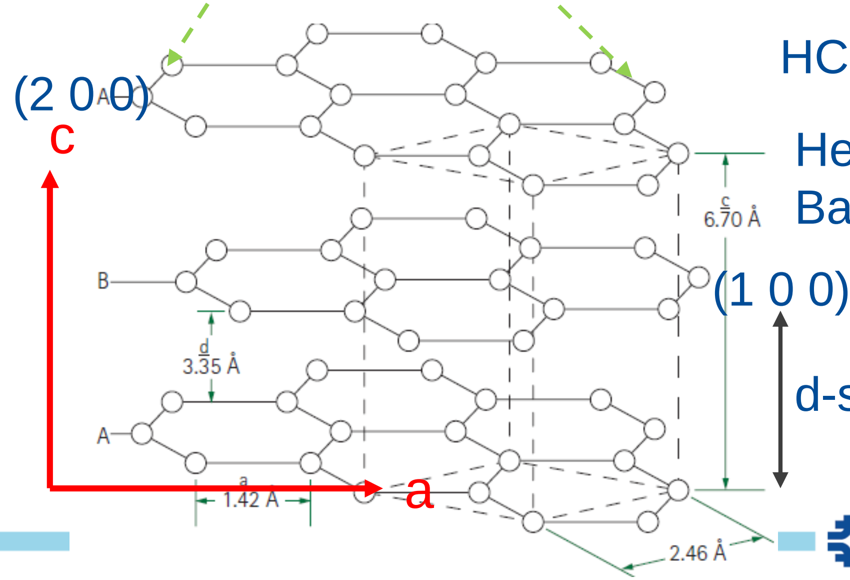
POCO ZXF 5Q Graphite microstructure





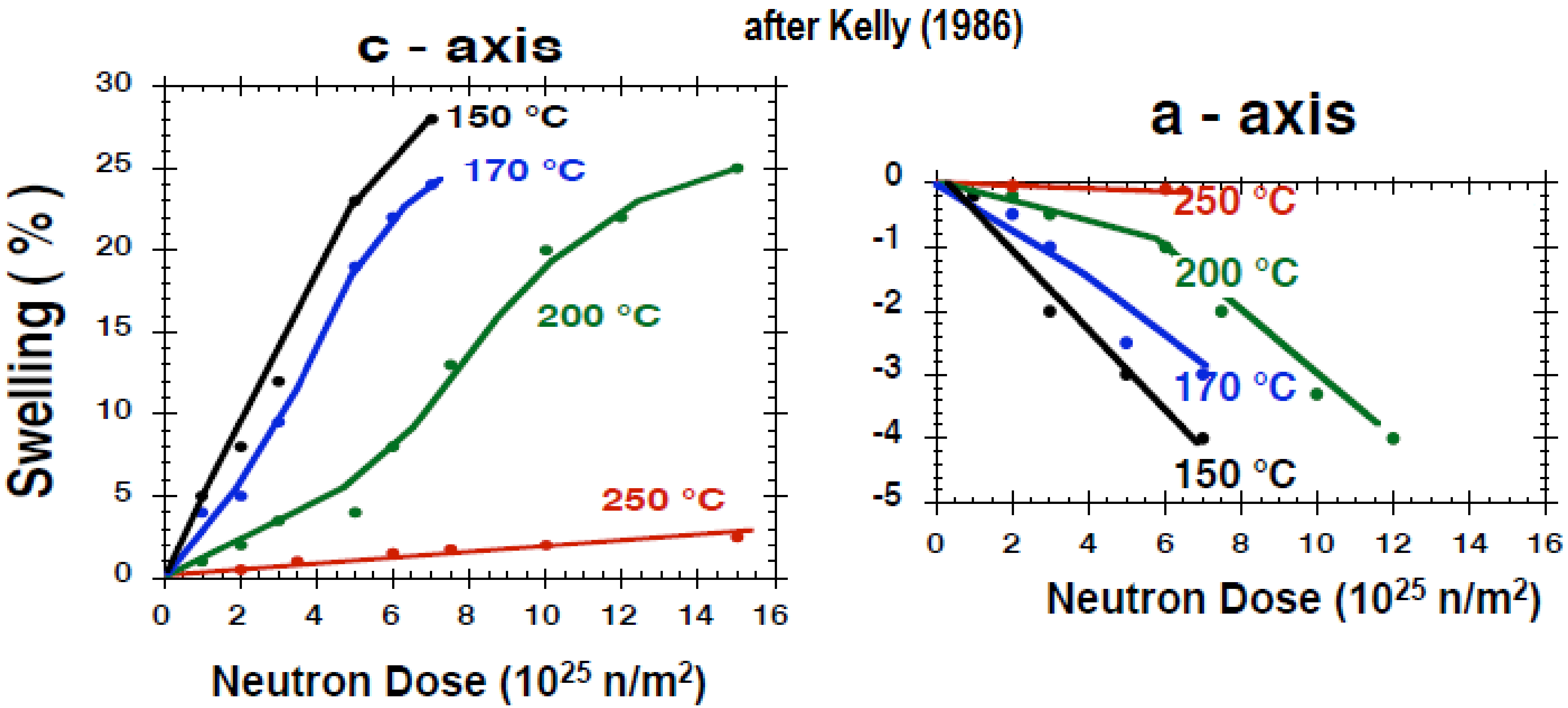


- Less Mrozowski cracks
- Randomly oriented grains
  - isotropic
- Fine grains (~30nm)
- Porosity ~ 20%



Carbon 1971. Vol. 9, pp. 697444.

XRD – Pyrolytic carbon



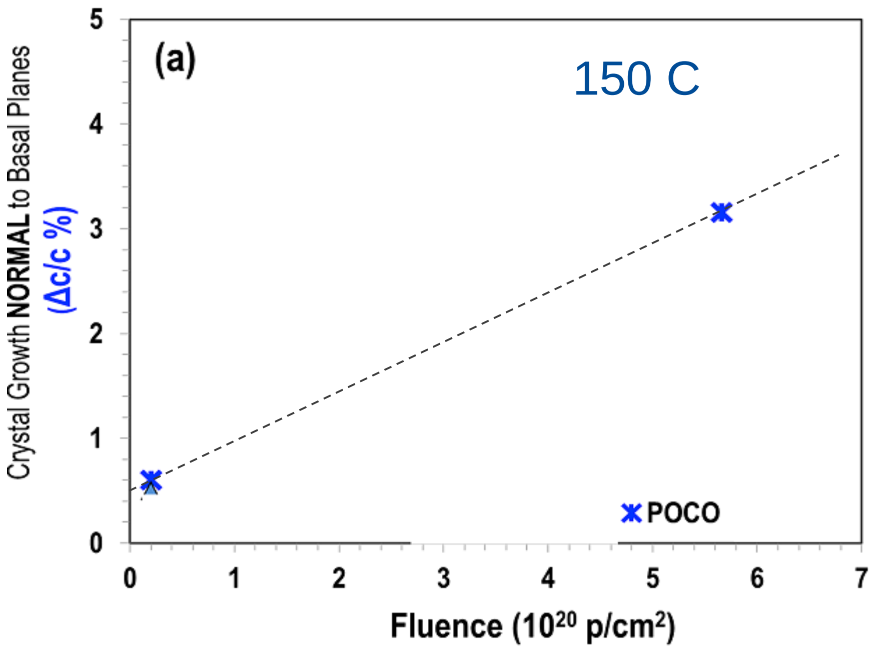
C-axis expansion is more than a-axis contraction

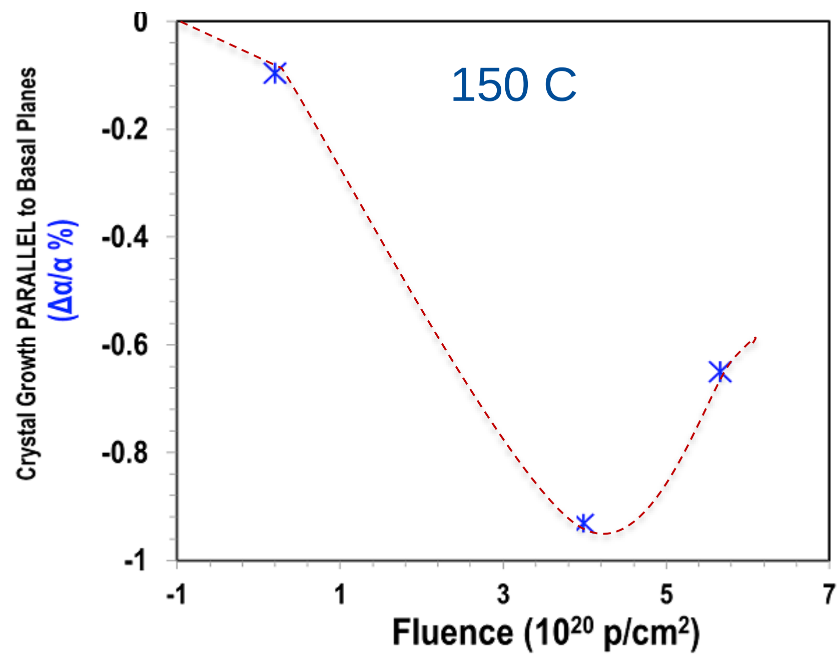
Swelling →f(fluence, temperature)

- More pronounced at lower temperature

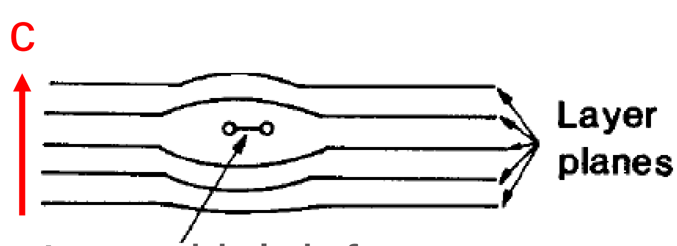
Kelly, J. Vac. Sci. Technol. A 4 (3), 1986

XRD- POCO ZXF5Q

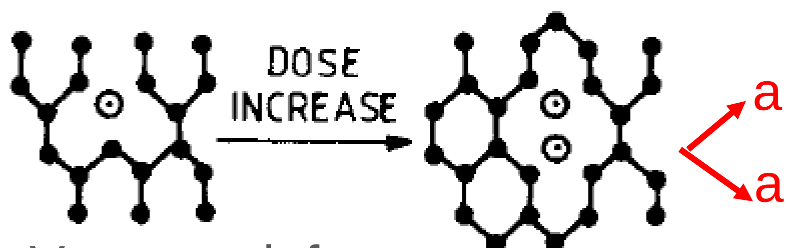




C-axis expansion is more than a-axis contraction

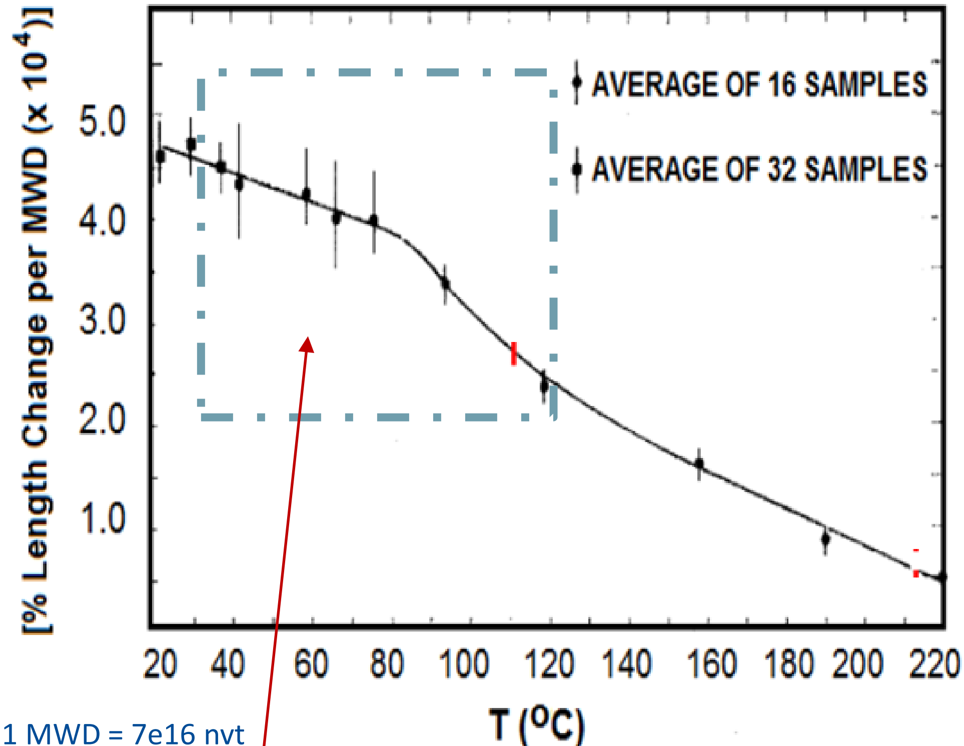


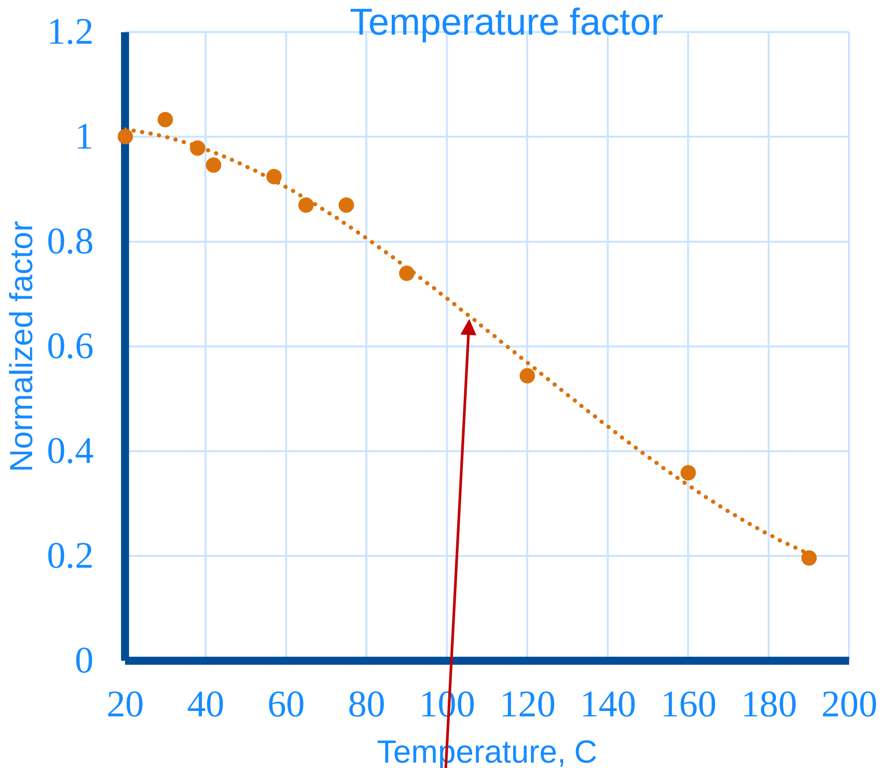
Interstitial defects



Vacancy defects

Swelling →Temperature factor





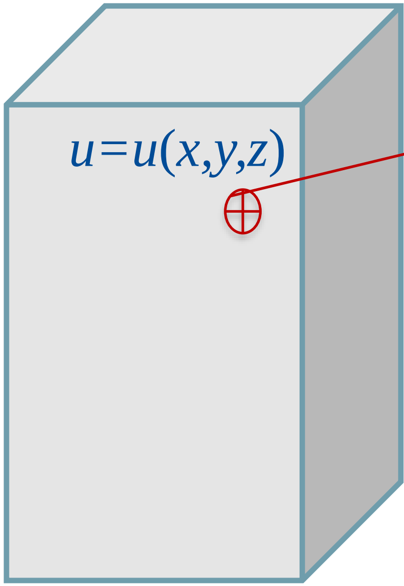
1 MWD = 7e16 nvt

NTO2 steady state operating temperature range

$g(T)=2\text{x}10^{-7}\,T^3 - 7\text{x}10^{-5}\,T^2 + 1.5\text{x}10^{-3}\,T+1.0083$

D. Schweitzer, Physical Review, Vol 128 (2), 1962, pp .556-559

Swelling factor function



Local Swelling factor
=f(fluence)*g(temperature)
sw(Ø,*T*)= f(Ø).g(*T*)

Fluence is Gaussian distribution with location

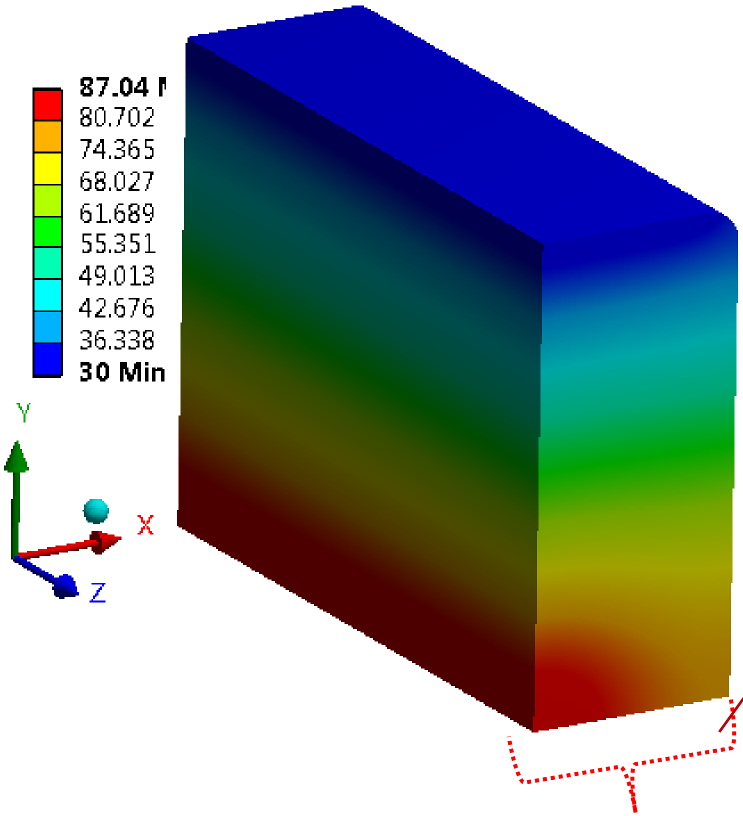
$$f(Ø)=\exp\{-b(u/\sigma)^2\}$$

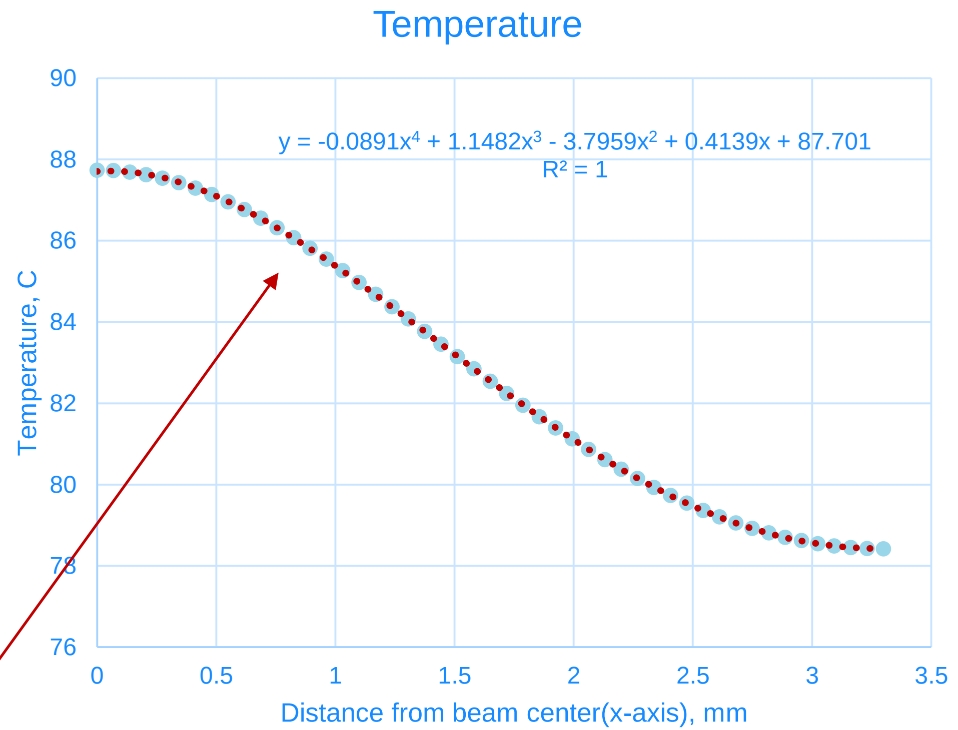
$$\partial(sw)= g(T).\ \partial f(Ø) + f(Ø).\{\partial g(T)/\partial T\}.\ \{\partial T/\partial u\}$$

At constant fluence swelling factor follows a polynomial function with temperature

Steady state thermal analysis

Steady state thermal analysis

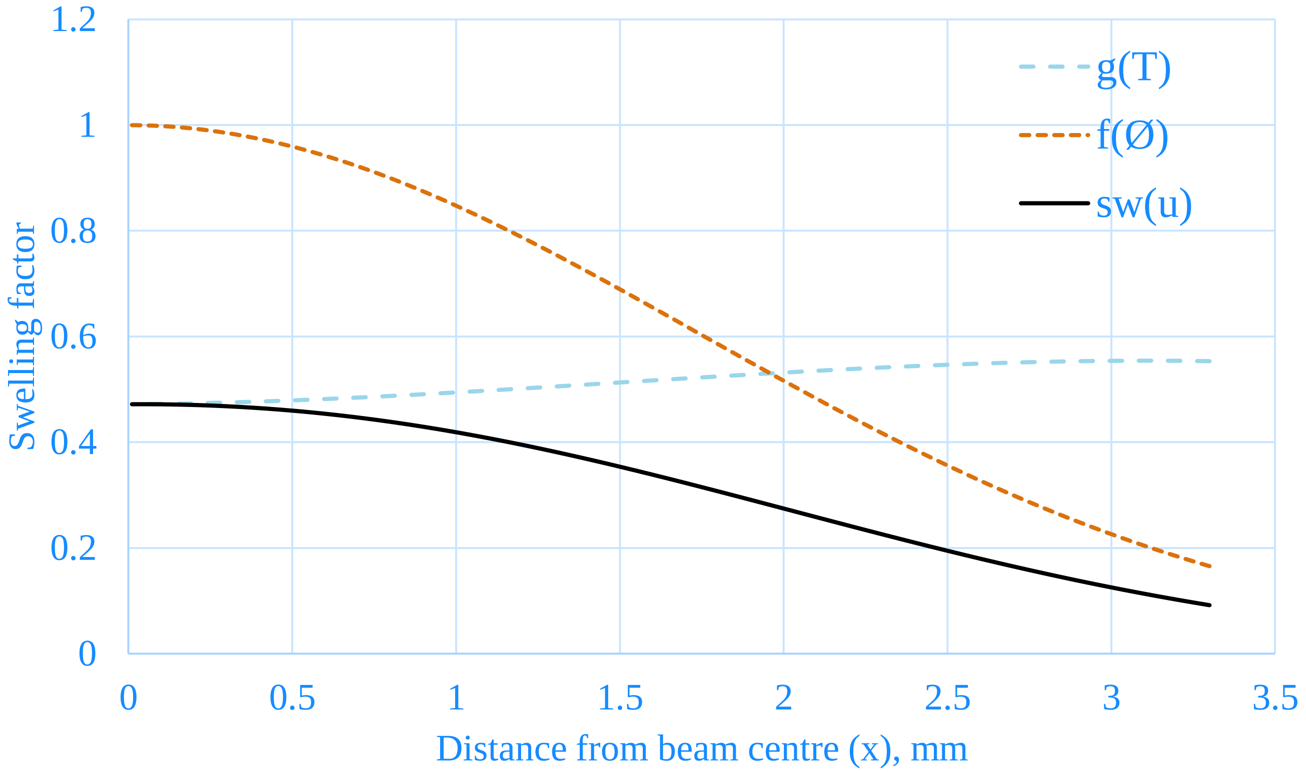




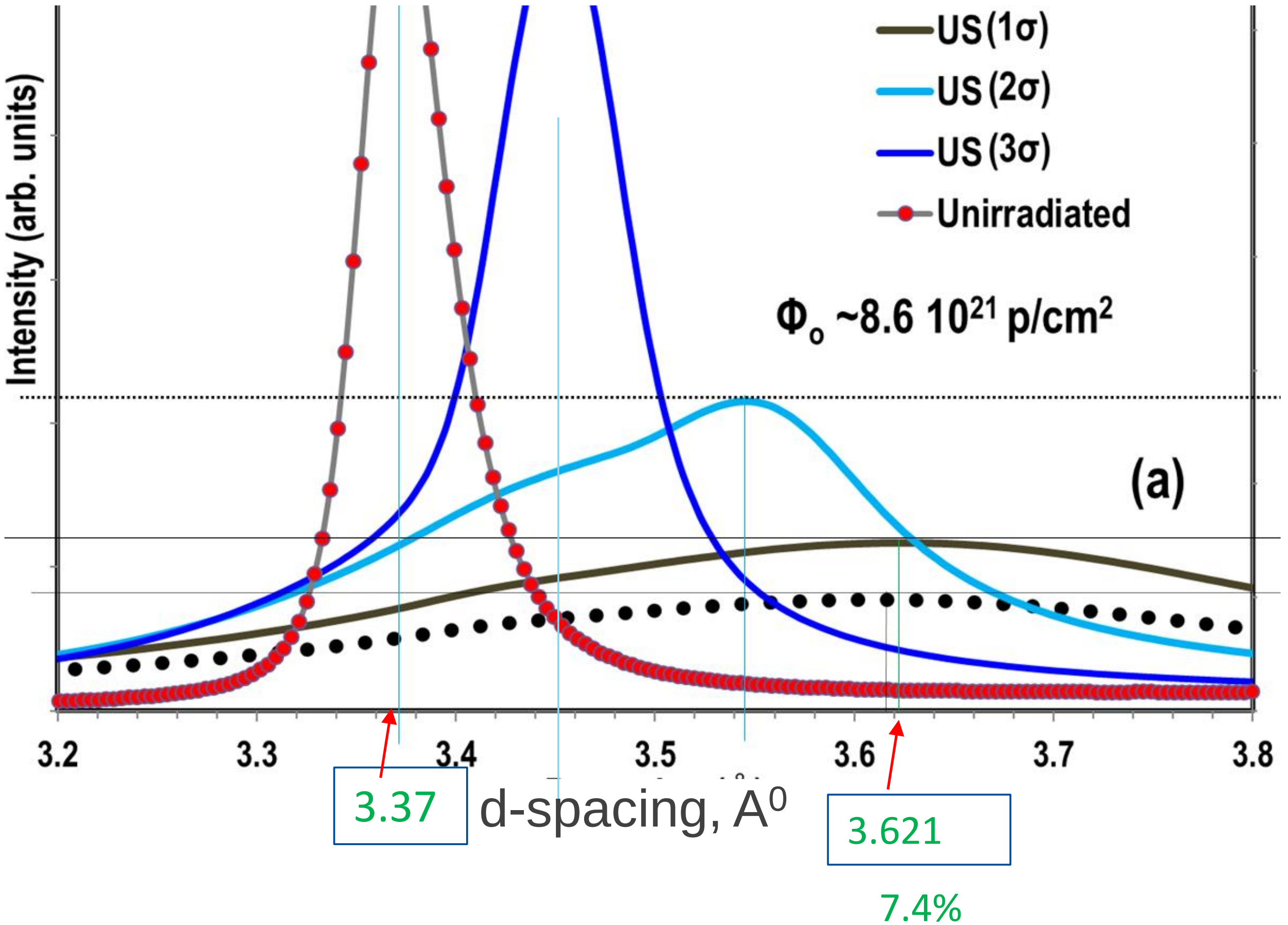
Swelling factor →combined function of fluence and temperature

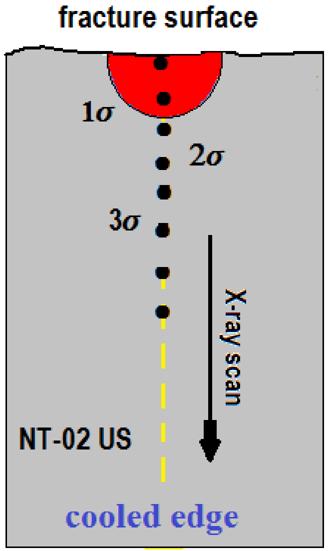
sw(*u*,*T*)

$$=C.\exp\{-b\left(\frac{u}{\sigma}\right)^2\}.\{2x10^{-7}\,T^3-7x10^{-5}\,T^2+1.5x10^{-3}\,T+1.0083\}$$



XRD data NTO2





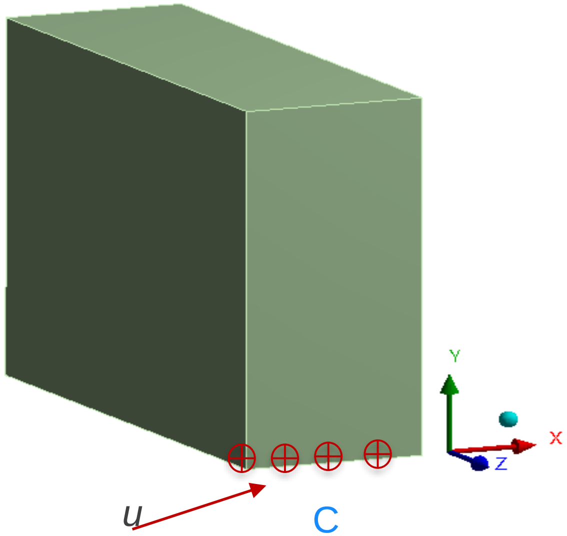
Assumption
Experimental swelling = ∂d/d0

At BNL

Determining Swelling Coefficient

U (mm)	Temperature	sw	d-spacing	∂d/d0	C
0	88	0.779	3.621	0.074481	0.095604
1.1	84	0.686	3.618	0.073591	0.107303
2.2	81	0.442	3.542	0.051039	0.115405
3.3	78	0.210	3.45	0.023739	0.112924

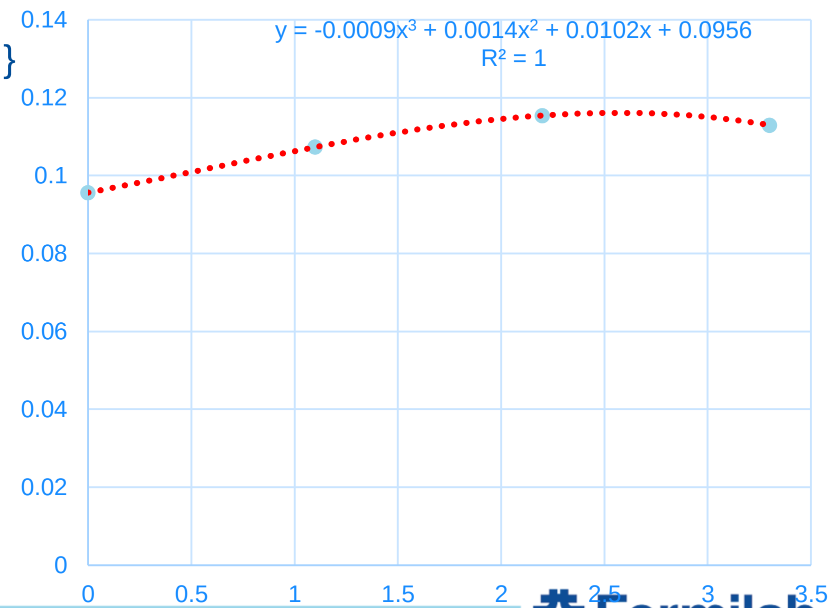
XRD



sw(*u*,*T*)

$$=C.\exp\{-b\left(\frac{u}{\sigma}\right)^2\}.\{2x10^{-7}T^3 - 7x10^{-5}T^2 + 1.5x10^{-3}T + 1.0083\}$$

Equating sw(u,T) to ∂d/d0 ➔ **C**



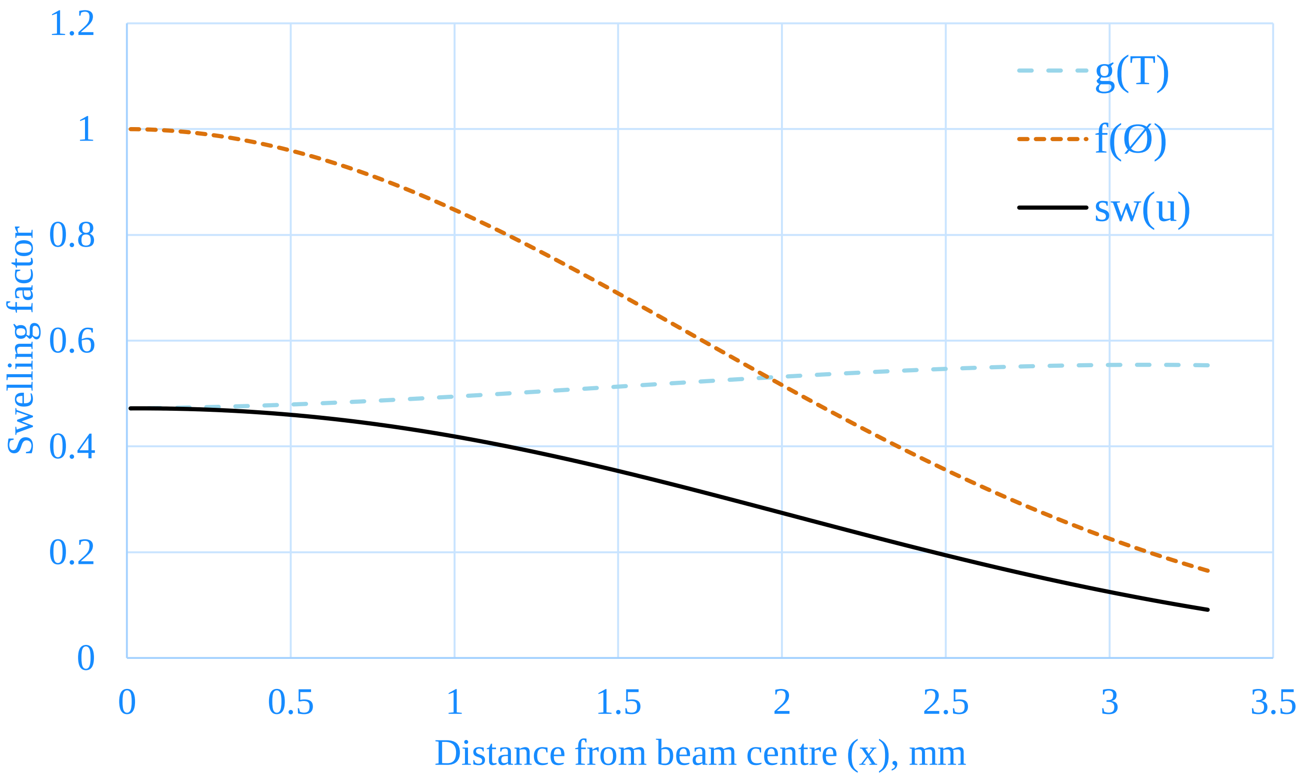
Multi-variable regression analysis:

Varying "*b*" and "*σ*"to get C curve as flat as possible

→ ***b*= 0.155, C = 0.107, σ =1.11**

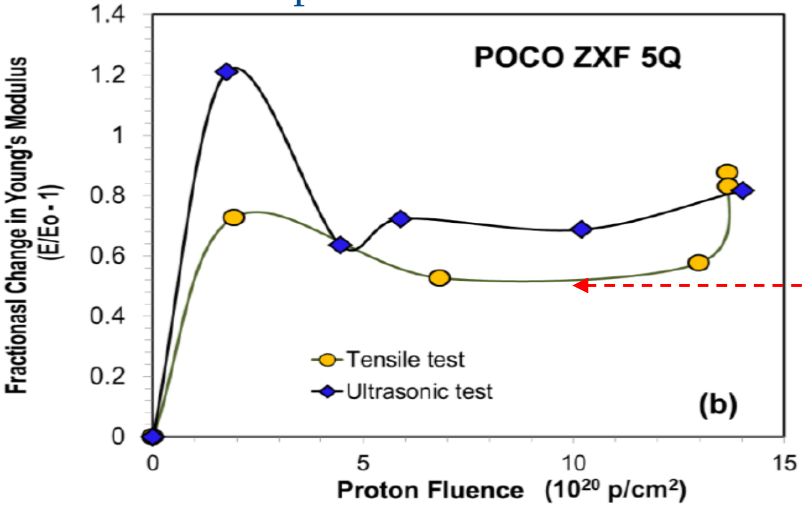
Swelling factor → combined function of fluence and temperature

$$\mathrm{sw}(u,T) = 0.107.\exp\{-0.155\left(\frac{u}{1.11}\right)^2\}.\{2\mathrm{x}10^{-7}\,T^3 - 7\mathrm{x}10^{-5}\,T^2 + 1.5\mathrm{x}10^{-3}\,T + 1.0083\}$$

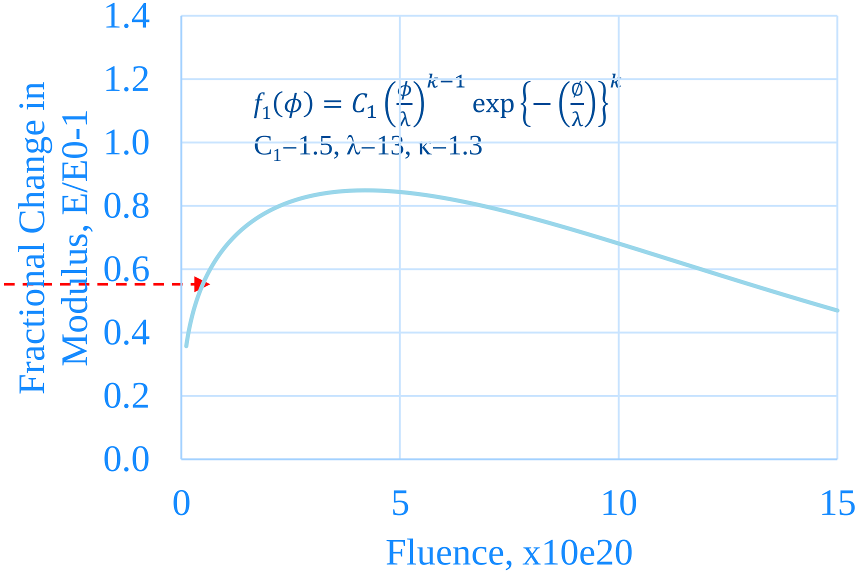


Young's Modulus variation with Fluence Ø

Experimental observation



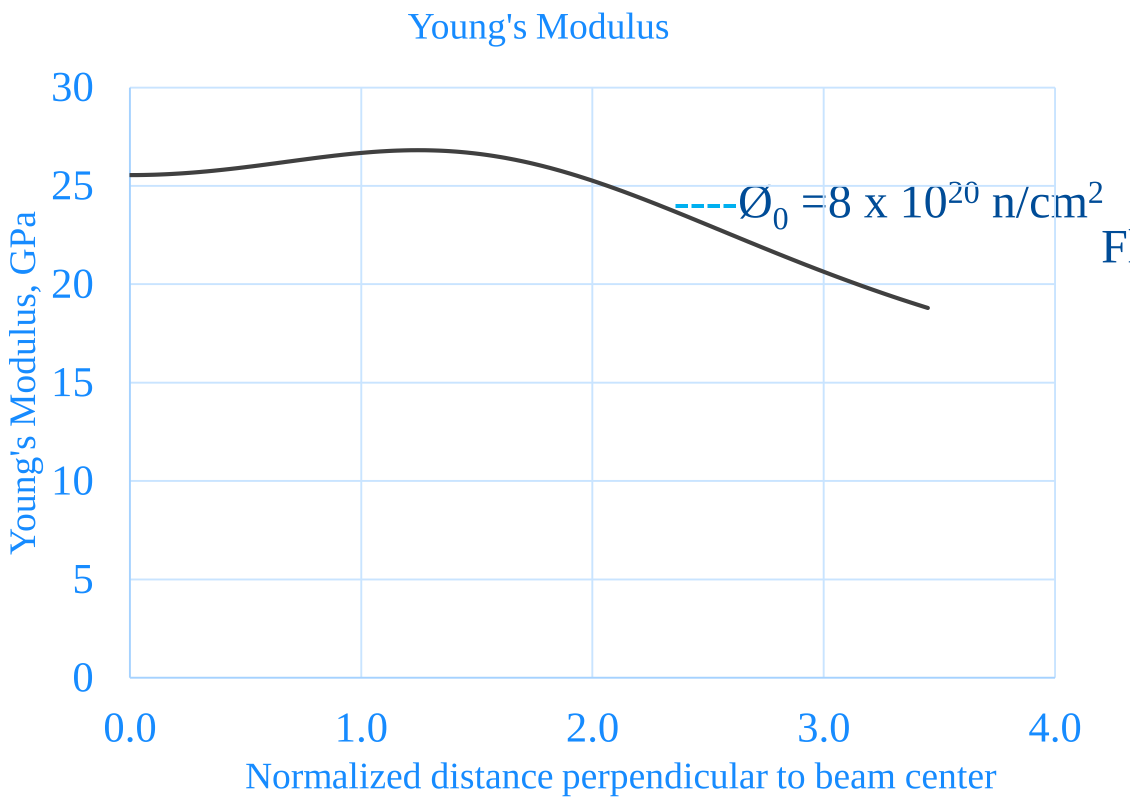
Analytical function fit (Weibull)



"E" varies with Ø
Ø varies with location.

This two relationship is used to map "E" as a function of location

Young’s Modulus variation with location



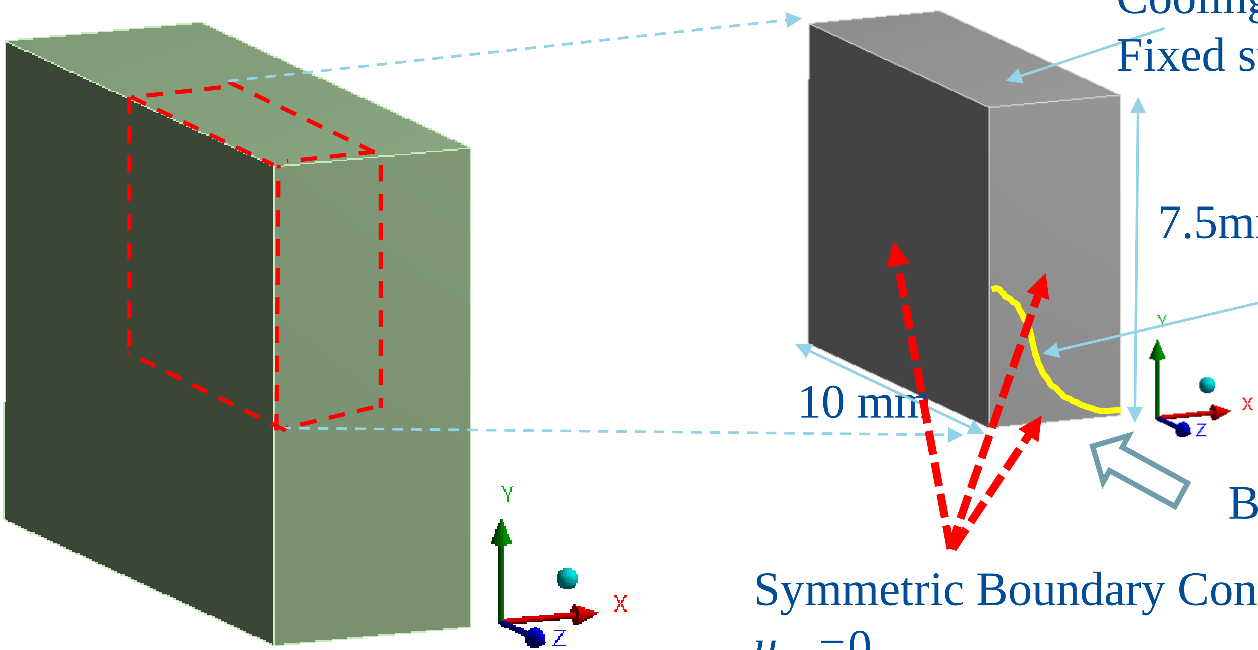
$E = E0[1+f_1(\varnothing)\,]$

Fluence

$\varnothing = \varnothing_0\, exp\{-0.5(u/\sigma)^2\}$

location

Model- Geometry



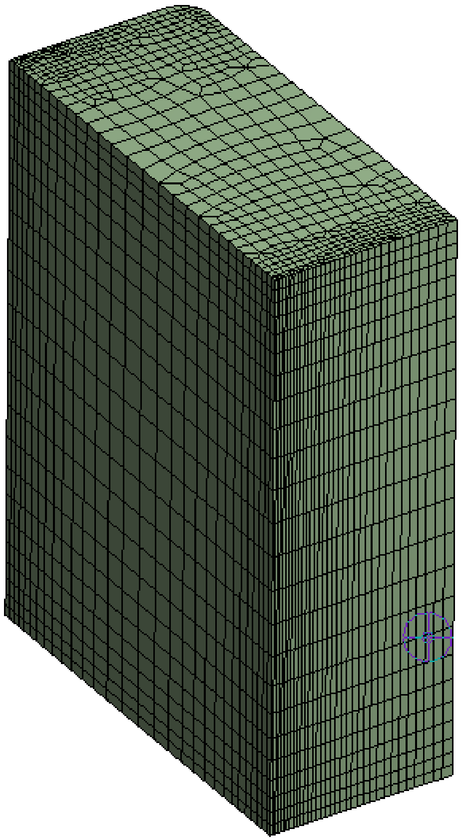
Symmetric Boundary Condition on x, y and z plane

$u_{i,i} = 0$

$\theta_{i,j} = 0 \quad i \neq j$

$\quad = free \quad i = j$

FE Model

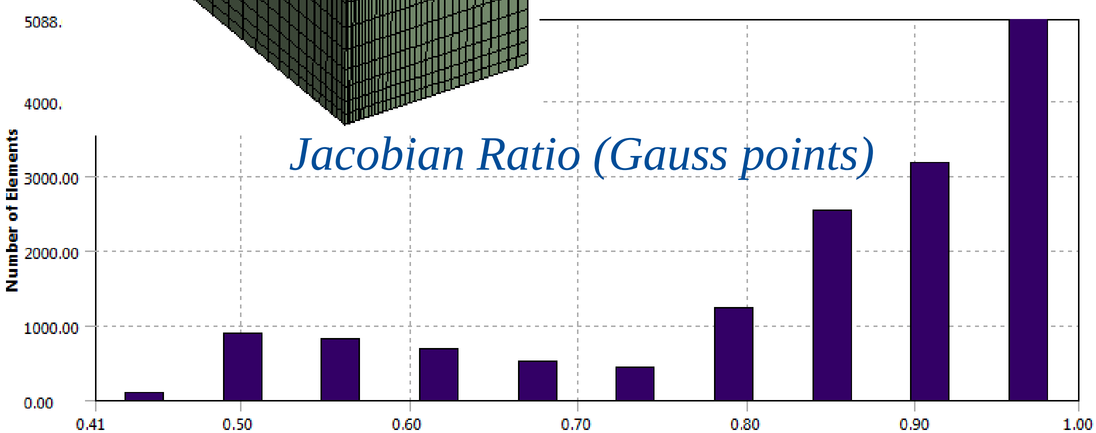


Larger temperature gradient within beam center

Adaptive mesh (Optimization)
- Finer elements at the beam center
- Progressively larger elements
- 30 elements within 1-σ of beam
- Minimum distorted elements
- Curvature and proximity refinement.

15000 elements 68,0000 nodes

Check element quality
High Jacobian ratio → spurious stress values



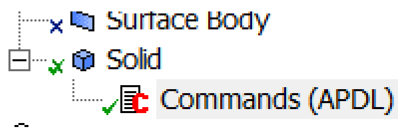
Jacobian Ratio (Gauss points)

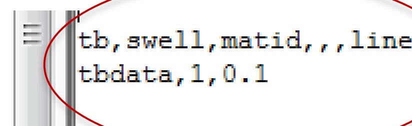
FEM Implementation of Empirical Formula

Total Strain $\varepsilon = \dot{\varepsilon}_{el} + \dot{\varepsilon}_{pl} + \dot{\varepsilon}_{cr} + \dot{\varepsilon}_{th} + \dot{\varepsilon}_{sw}$

Linear swelling model $\dot{\varepsilon}_{sw} = C\dot{\Phi}_t$

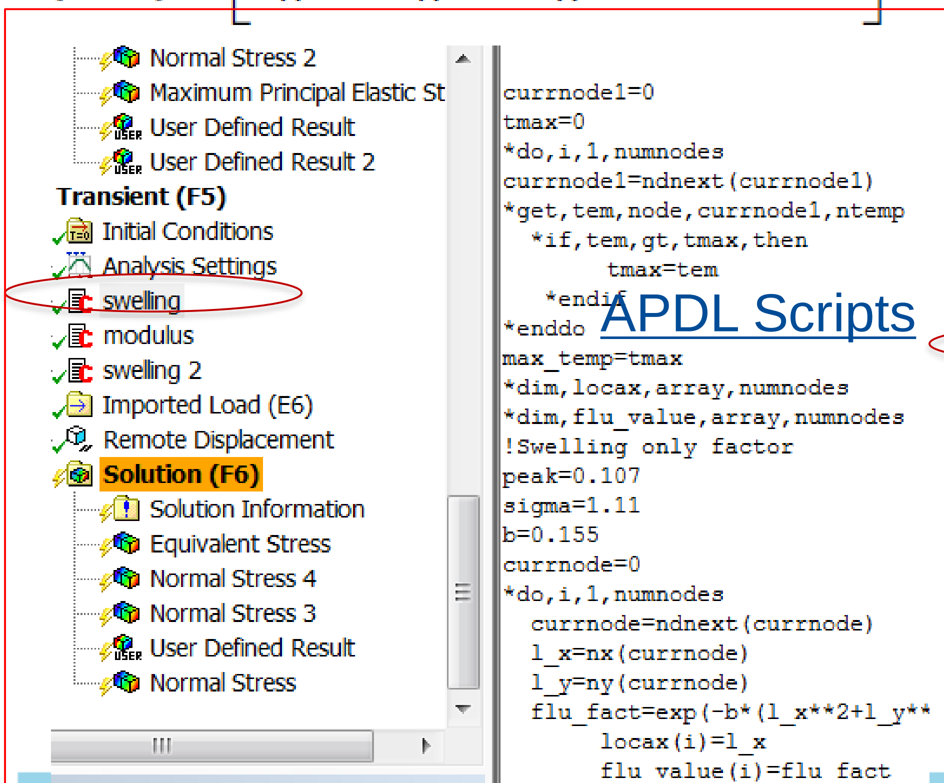
Swelling Strain $\dot{\varepsilon}_{sw} = \varepsilon_{sw}(t, T, \Phi_t, \sigma)$

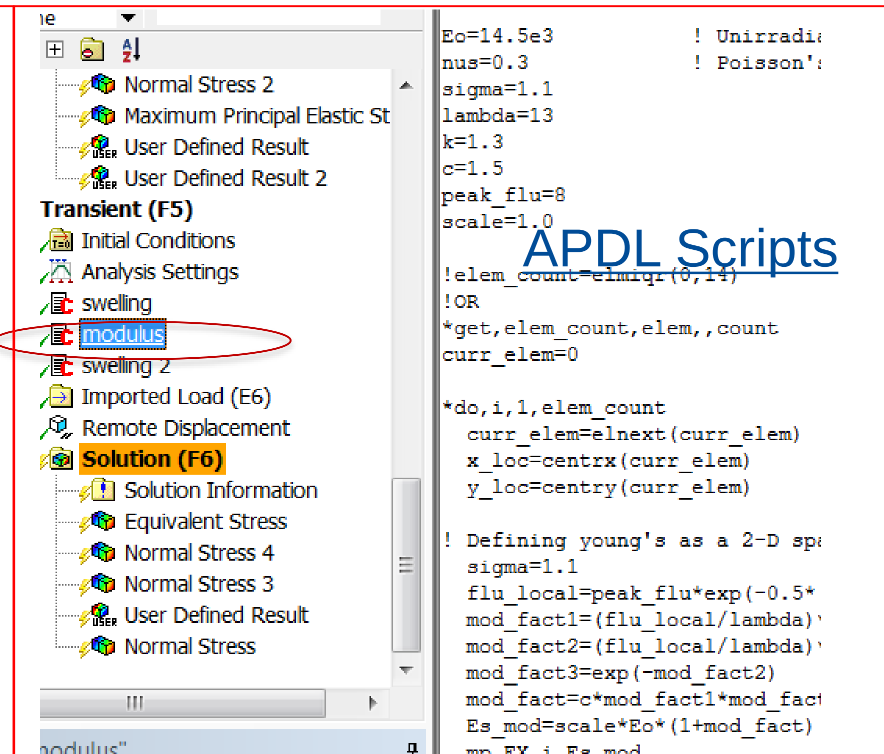




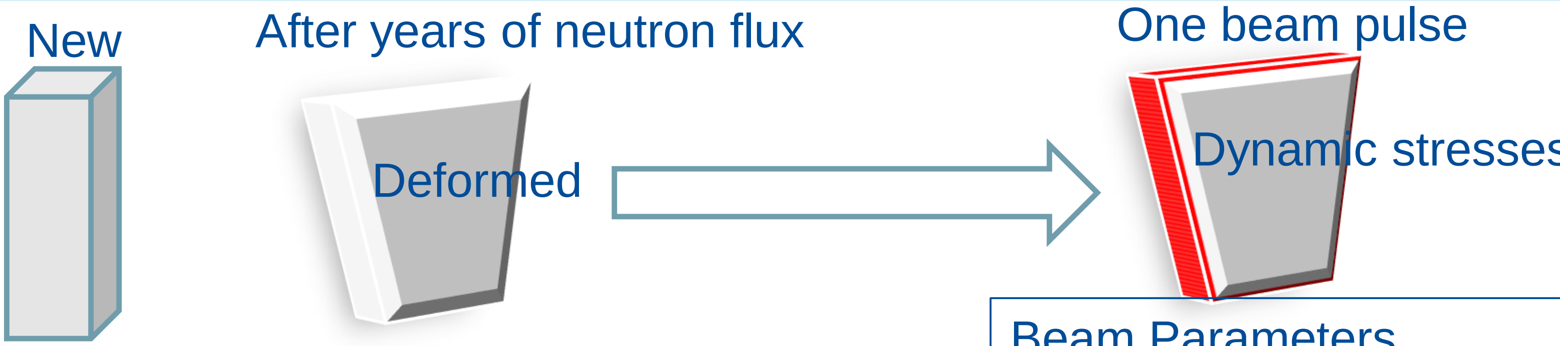
$$\{\varepsilon^{SW}\} = \begin{bmatrix} \varepsilon_n^{SW} & \varepsilon_n^{SW} & \varepsilon_n^{SW} & 0 & 0 & 0 \end{bmatrix}^T$$

⇨ No shear, only volume change





Simulation Flow



Beam Parameters

Number of protons pulse: $4x10^{13}$
Pulse duration : 10µsec
Beam σ : 1.1 mm
Energy deposited/ pulse : 480 J/cm^3

Steady State Thermal Analysis

Static structural analysis

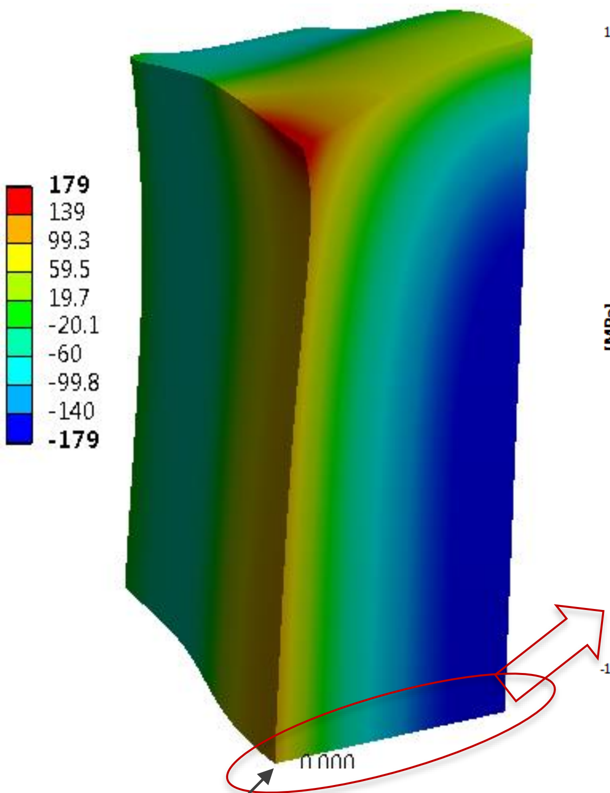
- swelling factor as function of fluence,temperature sw(Ø,*T*)
- Variable Young's modulus
- Solve stress, strain , deformation states

Transient Thermal-Dynamic analysis

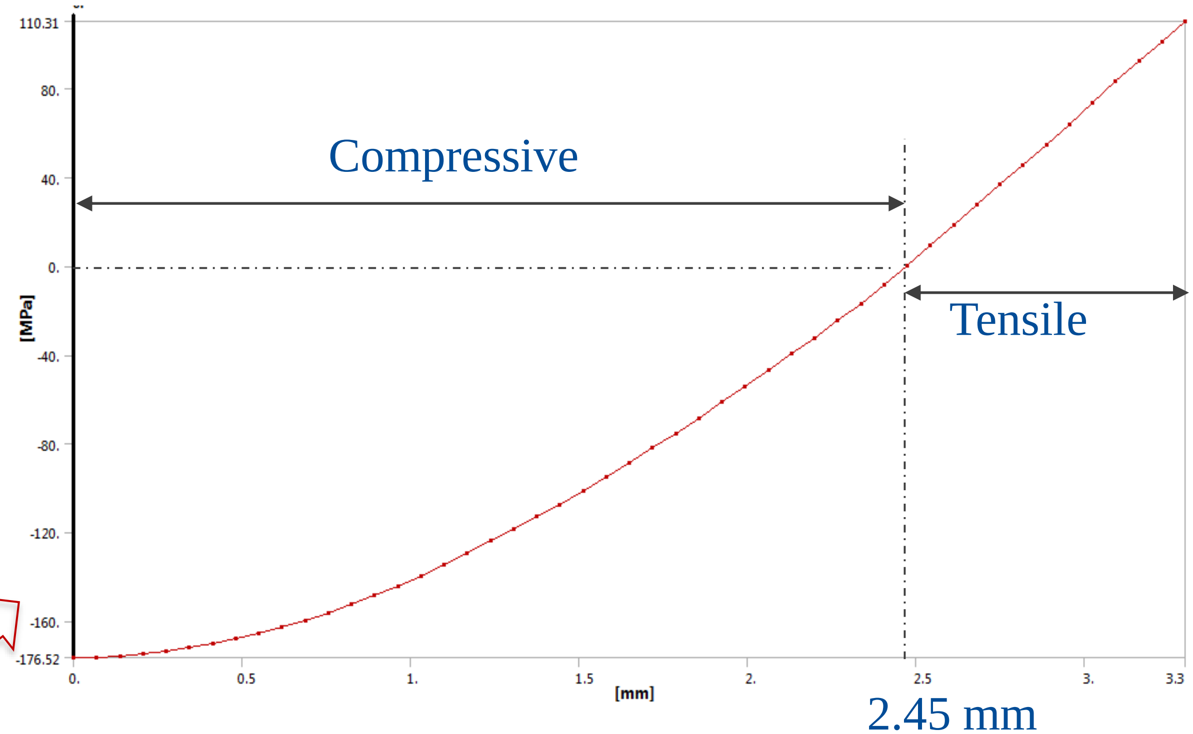
- Initialize domain with σ,ε, *u* from static structural
- No swelling during transient thermal
- Variable Young's modulus

Static Structural analysis

Syy



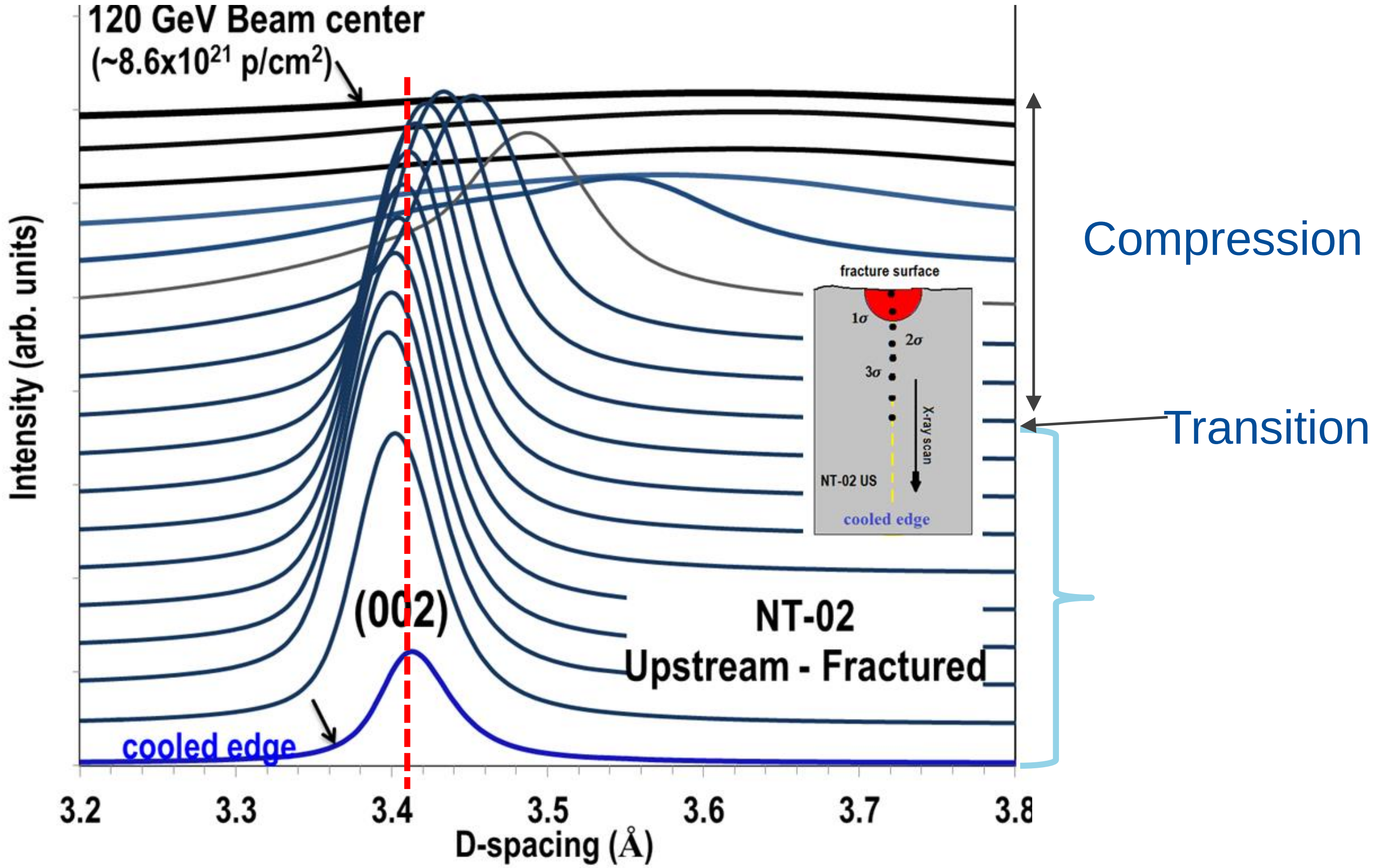
Syy along X-axis



State just before beam pulse after number of years of exposure to neutrons

X-Coordinate of outer node=3.3293, Original position=3.3
→ swelling=0.8% Observed swelling ~2%

XRD Scan NTO2



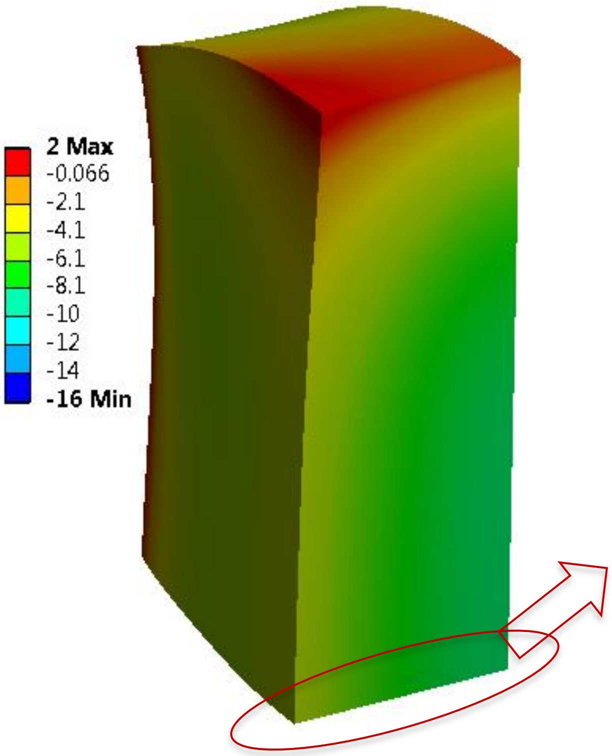
ɔn of the (**002**) crystallographic plane of the top half of the upstream (US) t

@ BNL

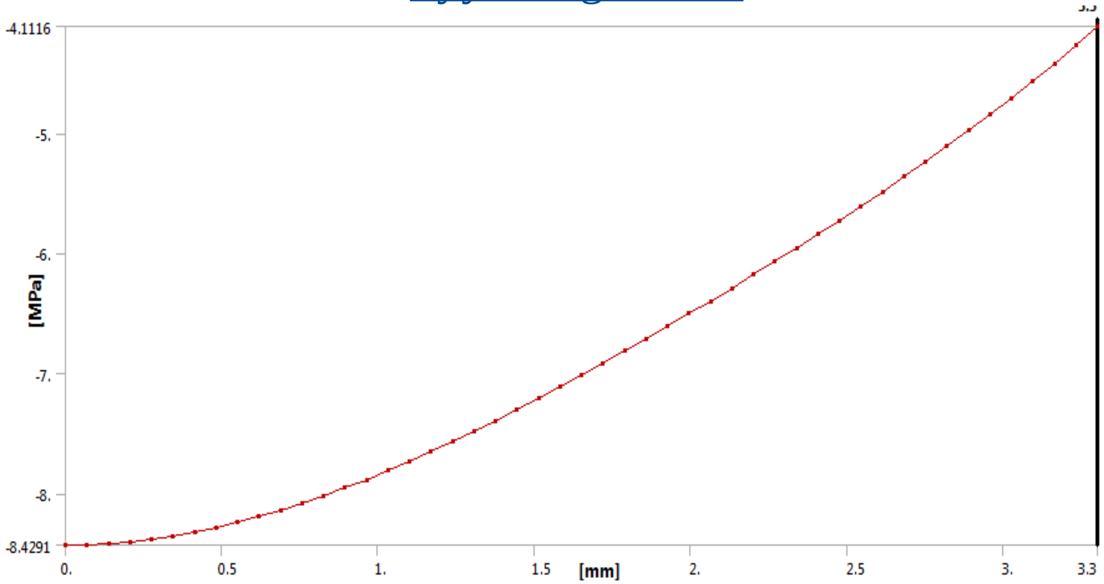
Fermilab

Static Structural analysis without swelling formula

Syy

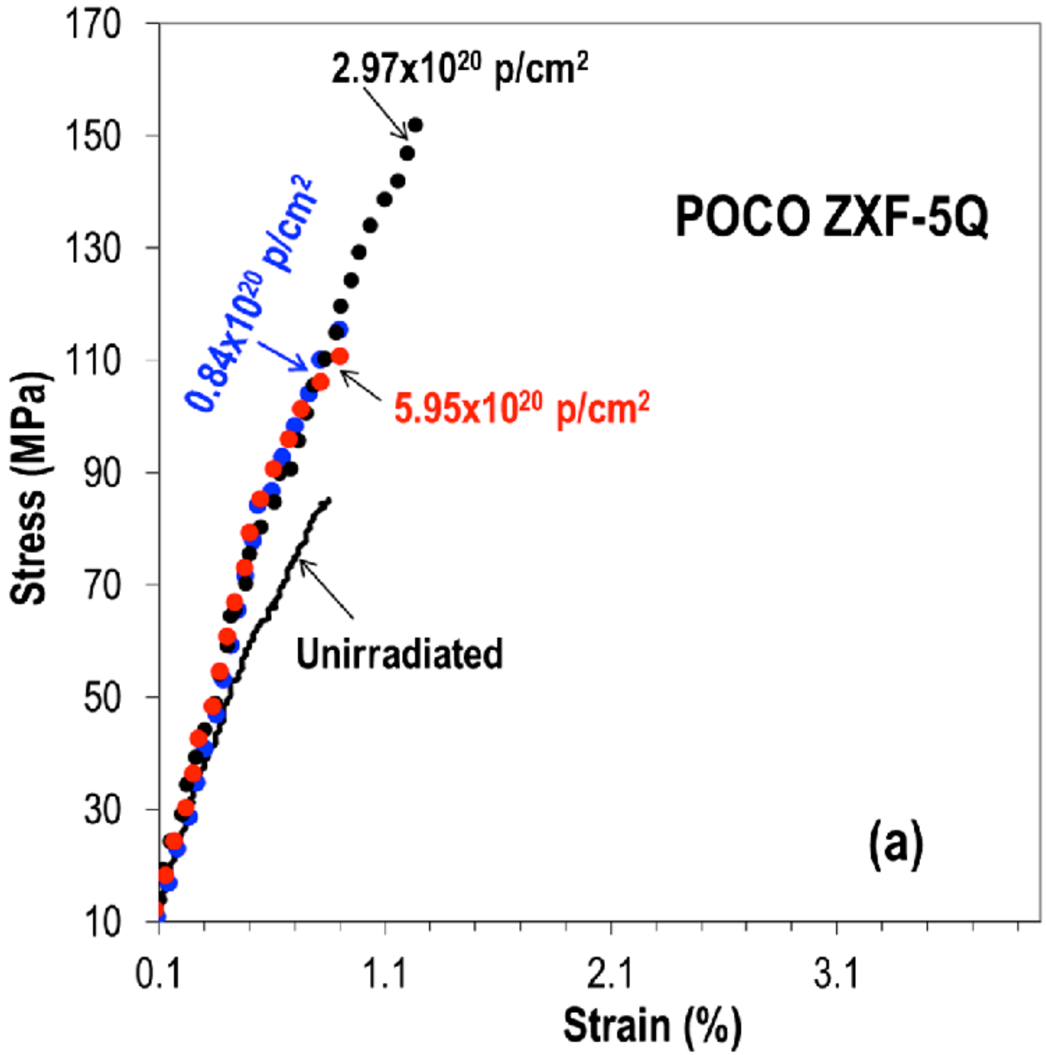


Syy along X-axis



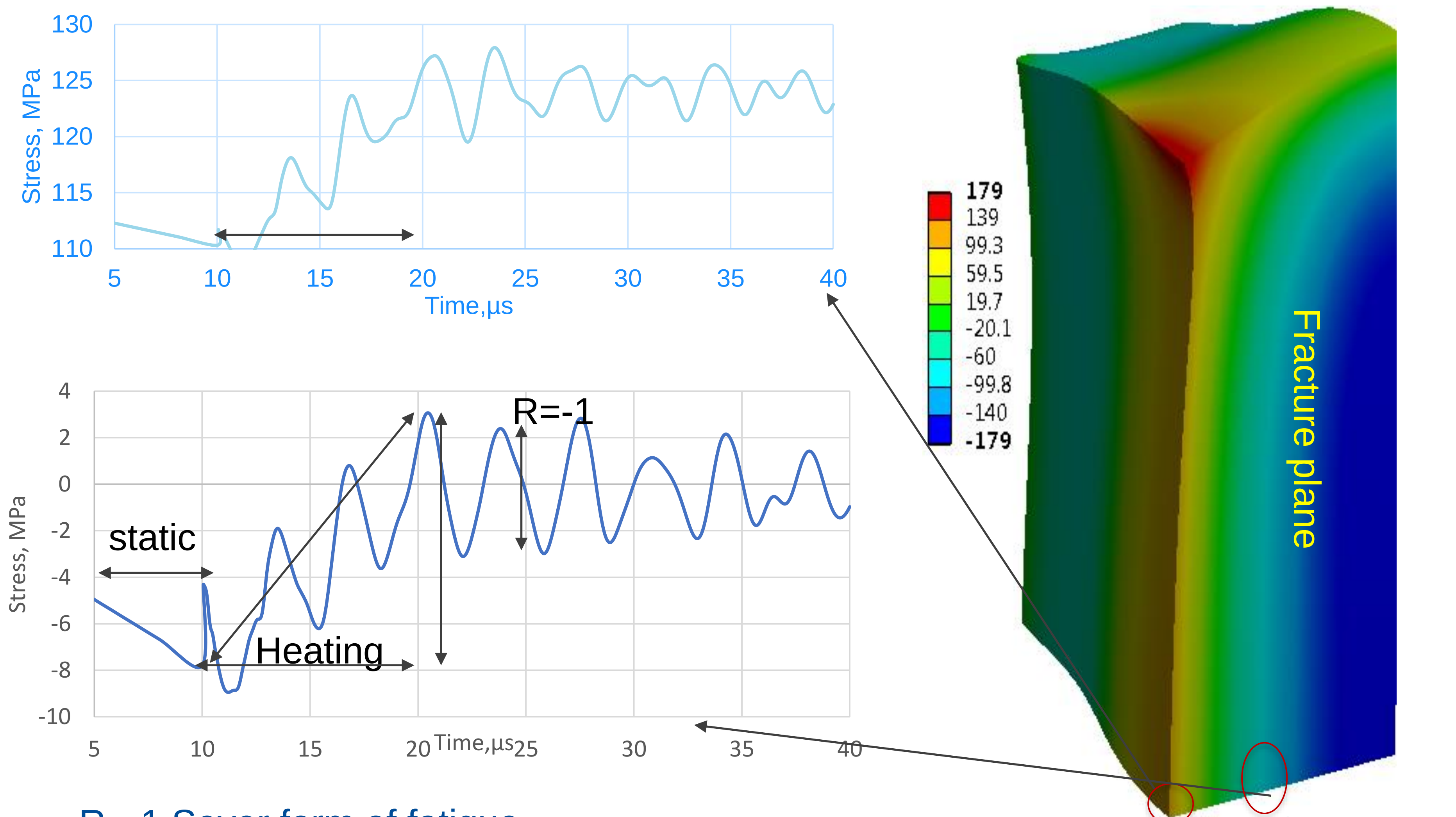
Small thermal stresses
All Compressive
Doesn’t support XRD data

Stress-strain Proton Irradiate POCO ZXF 5Q



PRAB, 20, 071002 (2017)

Dynamic stresses- Syy

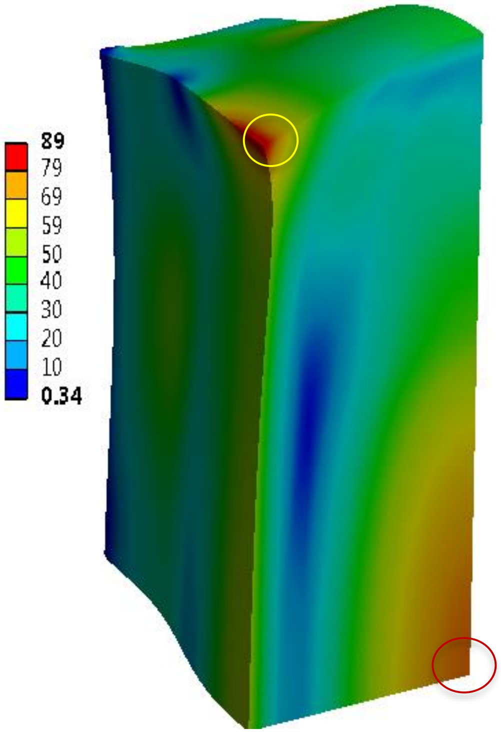


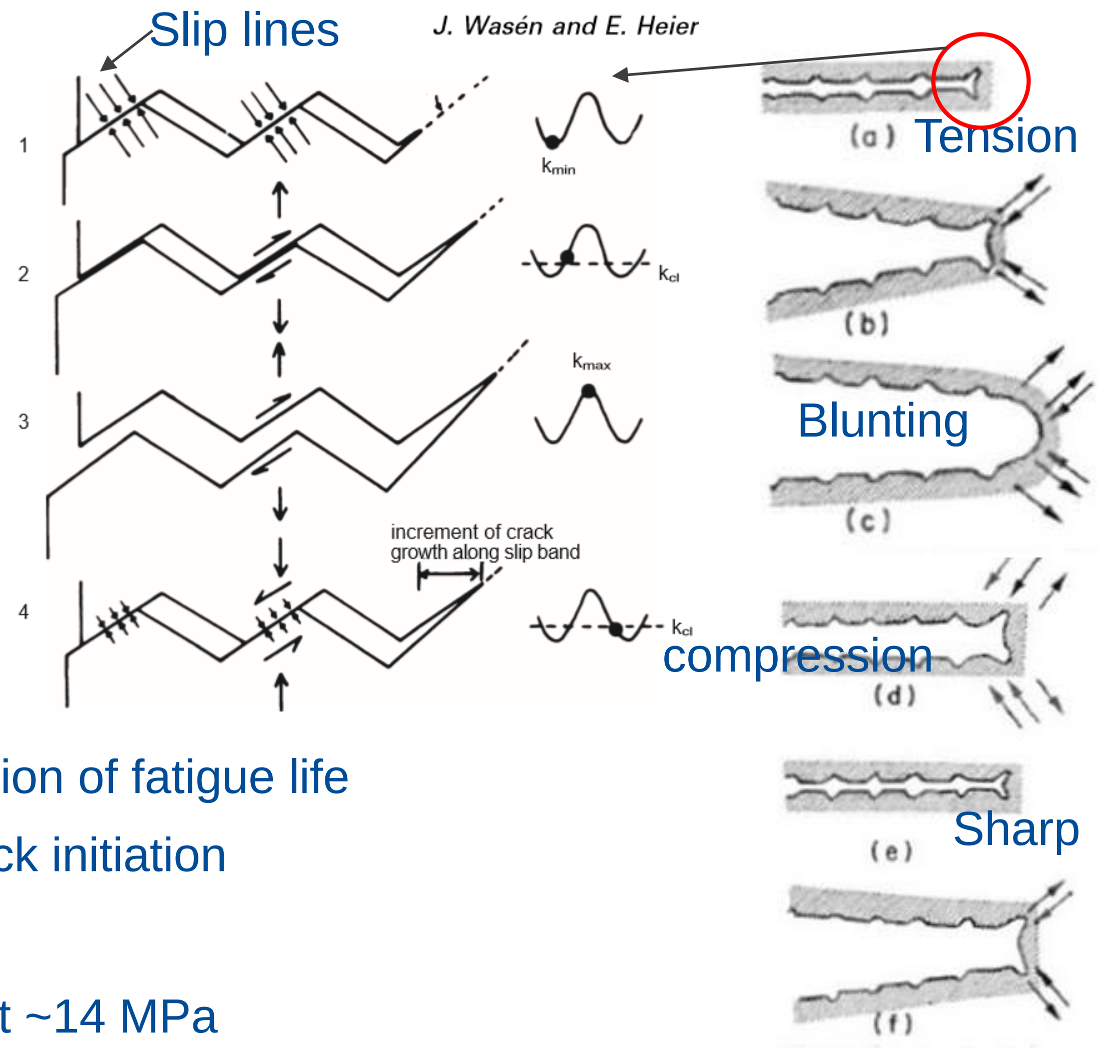
R=-1 Sever form of fatigue

Two fatigue loading 1) 10MPa with 1.87sec 2) 5MPa with 4µsec

Graphite has low endurance limit ~14 MPa

Maximum Shear stress distribution





Crack initiation→ significant portion of fatigue life

High shear stress→ Fatigue crack initiation

σ_{yy} fracture driving force

Graphite has low endurance limit ~14 MPa

Int. J. Fatigue Vol. 20, No. 10, pp. 737–742, 1998

Summary

- Crack seems to initiated near beam and propagated outward
  - Smooth crack surface→ brittle fracture

- Swelling raises the stresses close to failure strength
- Beam induced dynamic stresses may lead to fatigue failure
  - High amplitude low frequency (~50 million over 3 years!)
  - Low amplitude high frequency
- Predicted susceptible area
  - Near beam center →High Max. shear stress probable crack initiation
  - 2.4mm away from beam→ R<-1 severe form of fatigue

Further work

- Model radiation damage through user-subroutine
  - Knowledge of dislocations distribution
  - Multiscale modelling