MC Study of Target Temperatures and Dimensional Changes after 2. 10^{21} POT

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Outline:

- Introduction
- T2K Target Cooling System
- Energy Deposition
- Temperature Distribution
- Radiation Effects
- Summary and Outlook

Introduction

Study triggered by A. Fiorentini's talk at Beam MC meeting (5/9/2017)

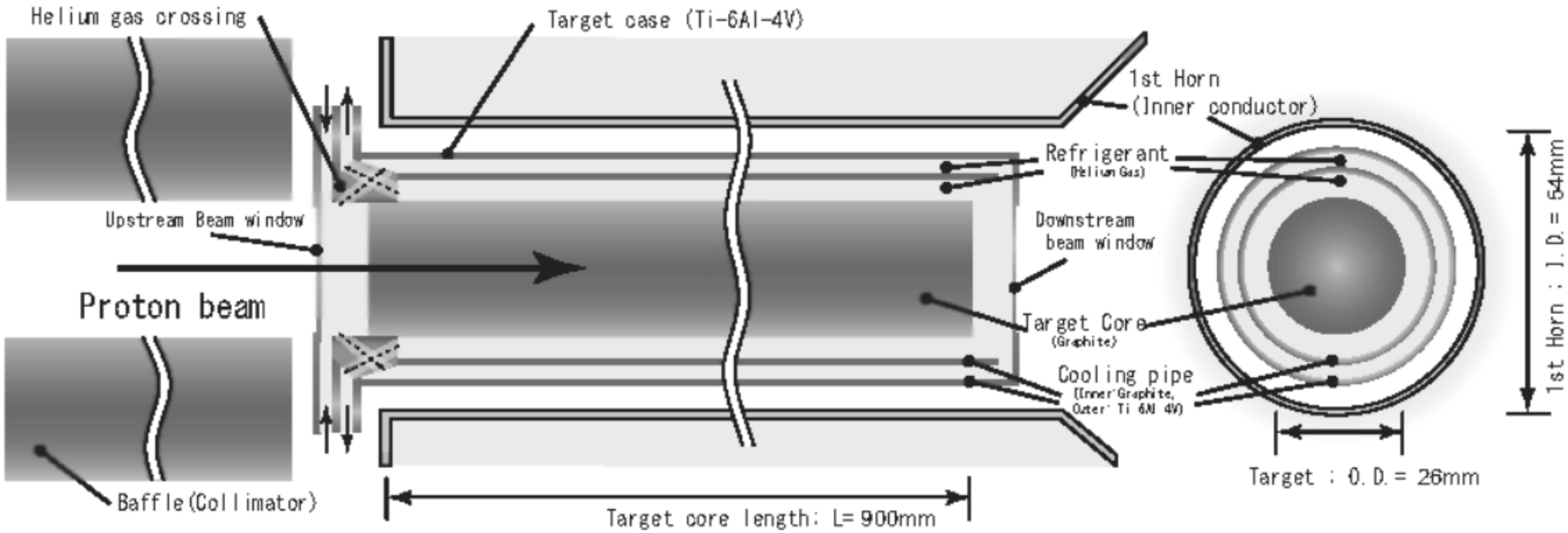
- **Fit is better with Target Density reduced by ~9 %**
- **But Thermal Volume Expansion of Graphite expected to be 1.2 % at highest temperature T = 700 ^{O}C**
  (at nominal beam power P = 750 kW)
- **Looks intriguing... Also interested by very high temperature (700 ^{O}C) reached in Target Core.**

⇨ **Check this using**
- GEANT4 simulation for Energy Deposition
- simple Heat Transfer simulation
(with vital help of G. Daubard, mechanical engineer at LPNHE)

⇨ **Investigate effects of Radiation on Graphite**

T2K Target Cooling System

- **1.9 Int. Length (L = 91.4 cm, D = 2.6 cm) Graphite Cylinder, d = 1.831 g/cm^3**
- **Nuclear Graded Isotropic Graphite IG-430 produced by Toyo Tanso**
  → high density & strength, high thermal conductivity (140 W/m/K)
  → high stability with temperature (thermal expansion coeff = 4.8 10^{-6} K^{-1})
  → high stability and resistance to radiation, planned for use in HTGR



- **Cooling pipe: 2 mm thick Graphite tube inside 0.3 mm thick Titanium case**
- **Cooling system: He flow rate 32 g/s, Outlet Pressure 0.2 MPa, ~ speed 250 m/s**
  T_{in} = 30 ^{O}C, T_{out} = 200 ^{O}C
- **T_{max} = 700 ^{O}C** at the center of the Target for P = 750 kW assuming that
  "radiation damage.. reduced.. thermal conductivity.. by a factor of four"

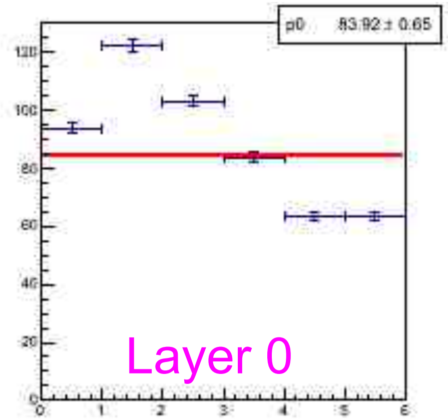
"T2K experiment" NIM paper & "T2K target", T.Nakadaira et al., AIP Conference (NuFact 07) Proceedings 981, 290 (2008)

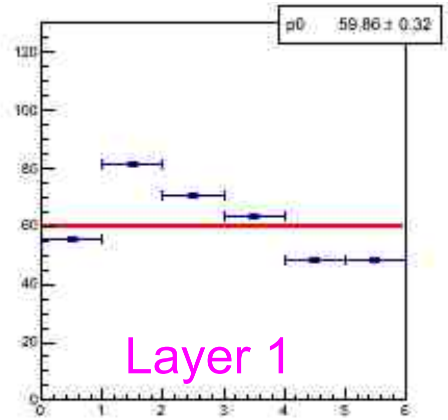
Target Temperatures Study - Energy Deposition

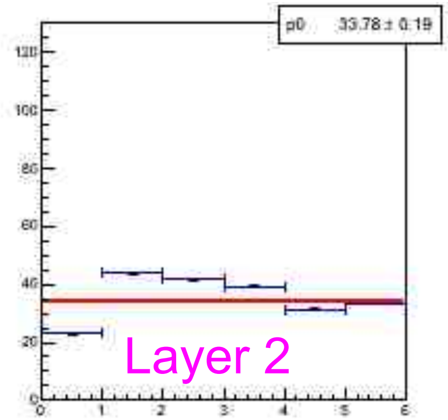
- **What is the spatial distribution of Energy Deposition in Target during beamtime?**
  → Setup a simple GEANT4 MC simulation of 30 GeV protons impinging on T2K Target.

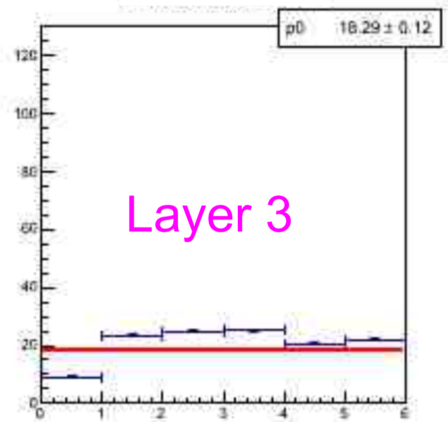
- Target divided in 6 segments along beam axis and 5 layers radially = 30 cells.
  In each cell, $P \times \langle E_{dep} \rangle$ / 30 GeV = beam power deposited as heat.
  Dividing by cell volume gives deposited power density (in W/cm^3).

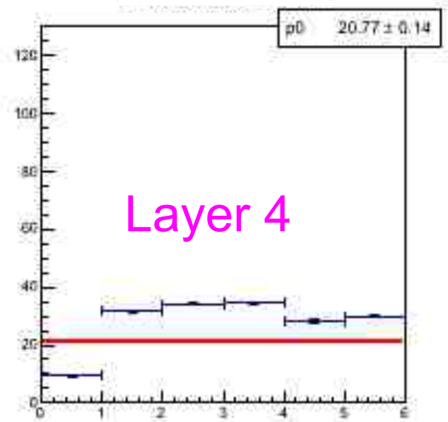
- Results: overall mean deposited power in Target = 16.5 kW for P=750 kW
  (to be compared with 20 kW in "T2K Target" report → to be investigated)











Mean power density vs Z for all layers, from ~80 (inner) to ~20 (outer) W/cm^3.

Target Temperatures Study - Heat Transfer

- **What is the temperature distribution in Target during beamtime?**

  → Setup a simple simulation of Heat Transfer between T2K Target and Cooling System, using power density distribution in Target found with GEANT4 as heat source

  → Basically all work done by G. Daubard (mechanical engineer at LPNHE).

- 1) estimate Heat Transfer coefficient **H** at surface between **He** flow and Target given the geometry and other cooling system characteristics

  → Done on **thermal-wizard.com**

  → Very crude approximation, as e.g. geometry of flow between two tubes is not available (Geometry of a flow inside a tube was used instead, then a correction factor was applied)

  → Result: **400 < H < 700 W/m²/K**

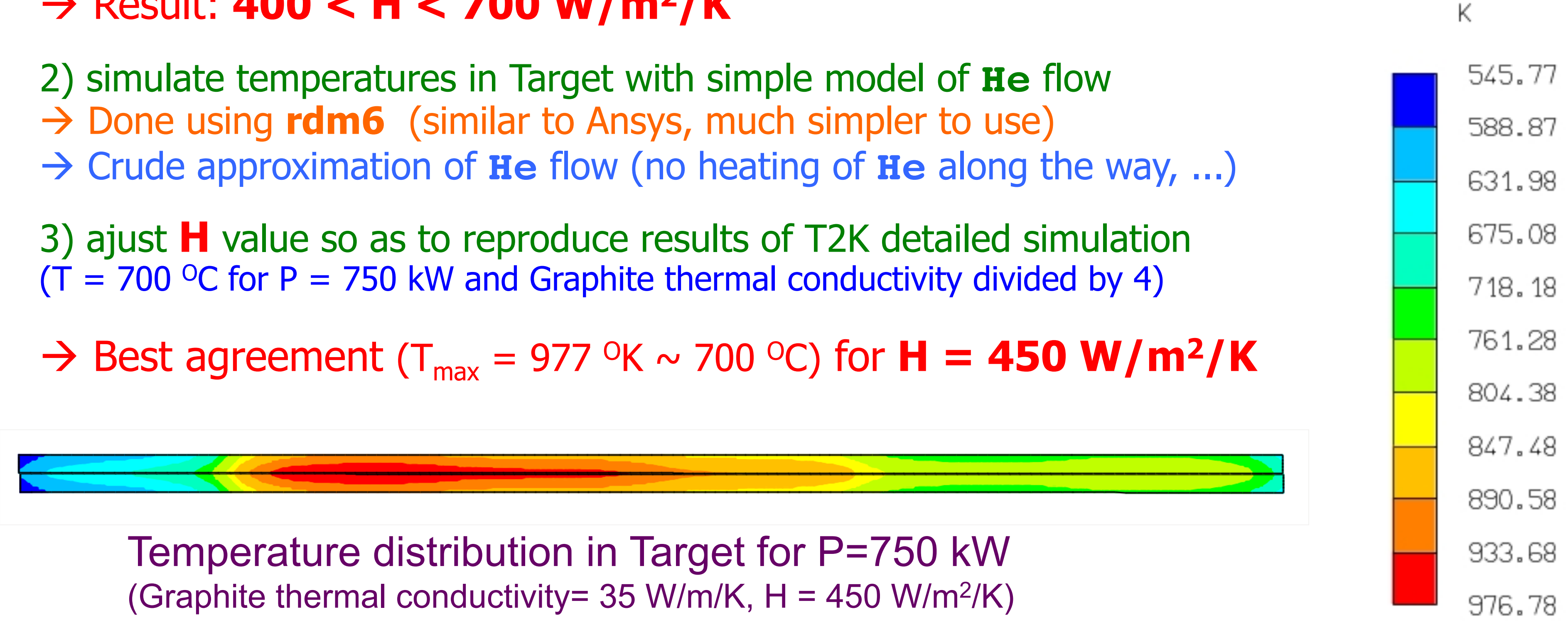
- 2) simulate temperatures in Target with simple model of **He** flow

  → Done using **rdm6** (similar to Ansys, much simpler to use)

  → Crude approximation of **He** flow (no heating of **He** along the way, ...)

- 3) ajust **H** value so as to reproduce results of T2K detailed simulation (T = 700 ^{O}C for P = 750 kW and Graphite thermal conductivity divided by 4)

  → Best agreement (T_{max} = 977 ^{O}K ~ 700 ^{O}C) for **H = 450 W/m²/K**



Temperature distribution in Target for P=750 kW
(Graphite thermal conductivity= 35 W/m/K, H = 450 W/m²/K)

Mechanical Effects of Radiation and Temperature on Graphite

Graphite is a favorite material for nuclear industry.

- Many studies of irradiation effects on thermo-mechanical properties of Graphite performed since at least 60 years.

  e.g. A. de Combarieu, Journal de Physique 1967, 28 (11-12), "Conductibilité thermique de graphite quasi mono cristallin et effets d'irradiation aux neutrons – I: mesures"

  → Degradation of thermal conductivity $K_{\perp}$ by a factor 10 after 5. 10^{16} n/cm^2 at low T

- Degradation of thermal conductivity with increasing T also observed.

- In the following, I summarize a selection of articles/reports most relevant to our problem.

- **Caveat:** I'm not a specialist of this matter (understatement).

  → Please correct (and forgive) me if I say something wrong.

Effects of Radiation on Graphite - Basics

The radiation damage event is defined as the transfer of energy from an incident projectile to the solid and the resulting distribution of target atoms after completion of the event. This event is composed of several distinct processes:

1. The interaction of an energetic incident particle with a lattice atom
2. The transfer of kinetic energy to the lattice atom giving birth to a primary knock-on atom (PKA)
3. The displacement of the atom from its lattice site
4. The passage of the displaced atom through the lattice and the accompanying creation of additional knock-on atoms
5. The production of a displacement cascade (collection of point defects created by the PKA)
6. The termination of the PKA as an interstitial

The result of a radiation damage event is, if the energy given to a lattice atom is above the threshold displacement energy, the creation of a collection of point defects (vacancies and interstitials) and clusters of these defects in the crystal lattice.

The essence of the quantification of radiation damage in solids is the number of displacements per unit volume per unit time R :

$$R = N \int_{E_{min}}^{E_{max}} \int_{T_{min}}^{T_{max}} \phi(E_i)\, \sigma(E_i, T)\, v(T)\, dT\, dE_i .$$

where N is the atom number density, E_{max} and E_{min} are the maximum and minimum energies of the incoming particle, $\phi(E_i)$ is the energy dependent particle flux, T_{max} and T_{min} are the maximum and minimum energies transferred in a collision of a particle of energy E_i and a lattice atom, $\sigma(E_i, T)$ is the cross section for the collision of a particle of energy E_i that results in a transfer of energy T to the struck atom, $v(T)$ is the number of displacements per primary knock-on atom.

The two key variables in this equation are $\sigma(E_i, T)$ and $v(T)$. The term $\sigma(E_i, T)$ describes the transfer of energy from the incoming particle to the first atom it encounters in the target, the primary knock-on atom (PKA); The second quantity $v(T)$ is the total number of displacements that the PKA goes on to make in the solid; Taken together, they describe the total number of displacements caused by an incoming particle of energy E_i, and the above equation accounts for the energy distribution of the incoming particles. The result is the total number of displacements in the target from a flux of particles with a known energy distribution.

In radiation material Science the displacement damage in the alloy ($[dpa]$ = **displacements per atom in the solid**) is a better representation of the effect of irradiation on materials properties than the fluence (neutron fluence, $[MeV]$).

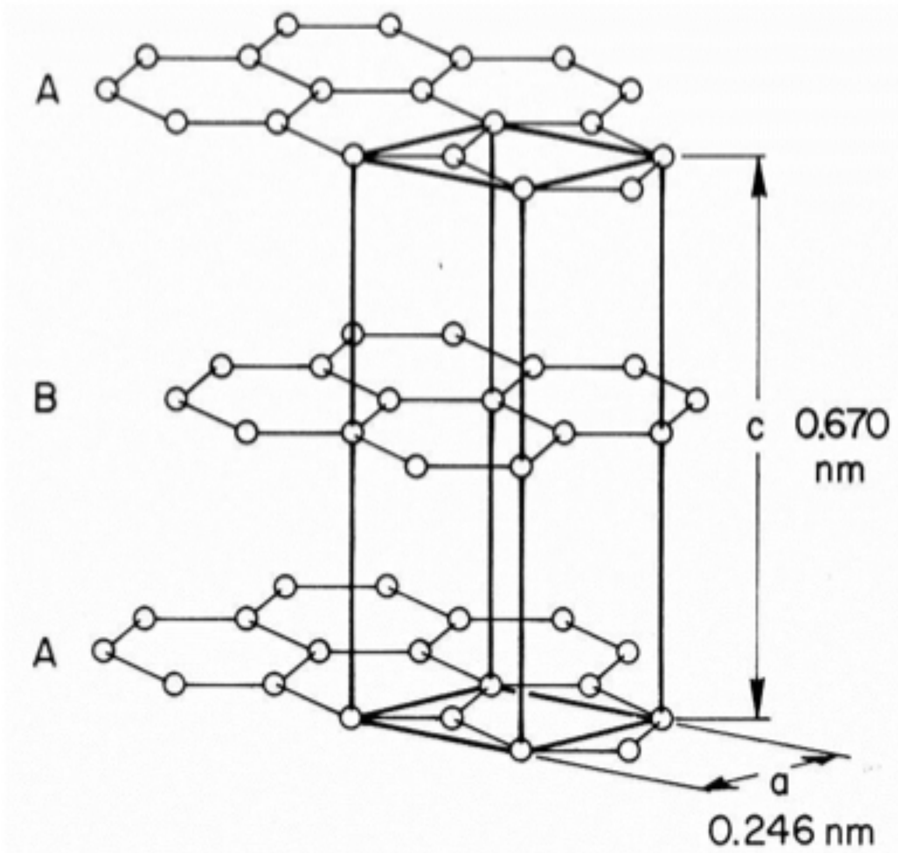
"Radiation material science" wikipedia

Neutron Irradiation Damage

- Neutron irradiation causes carbon atom displacement
- Dimensional and physical property changes result
- Damage mechanism well understood
- Key physical properties are:

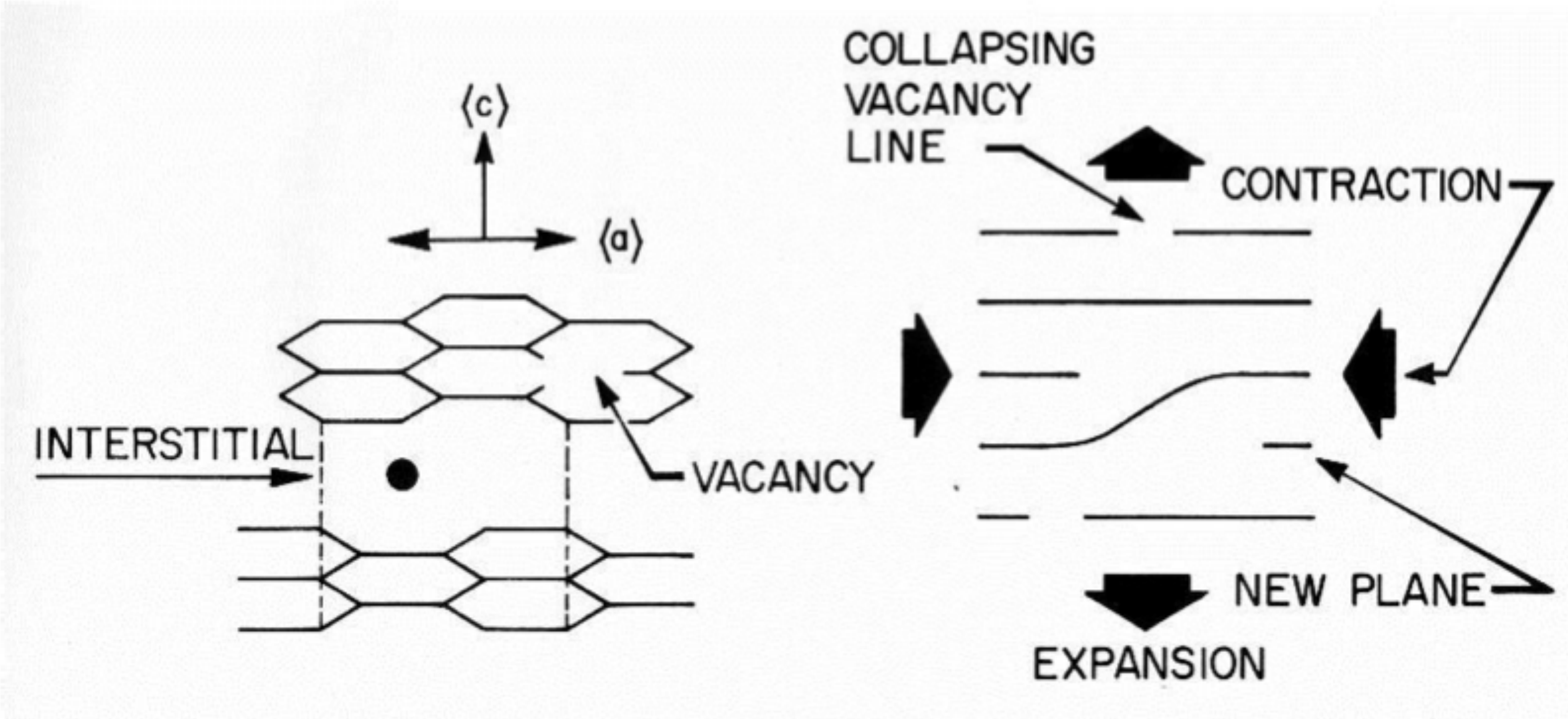
irradiation dimensional stability, strength, elastic moduli, thermal expansion coefficient, thermal conductivity, radiation creep behavior, fracture behavior, oxidation behavior

GRAPHITE CRYSTAL STRUCTURE



T. D. Burchell, talk at Technical Meeting on High-T Qualification of High-T Gas Cooled Materials (2014) "Irradiation Damage in Graphite – from the Nano- to the Millimetric Scale"

The Radiation Damage Mechanism In Graphite



CARBON ATOM BINDING ENERGY IN GRAPHITE LATTICE IS 7 eV

DISPLACEMENT ENERGY FOR CARBON ATOM IS APPROX. 30 eV

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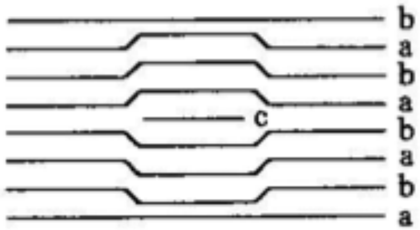
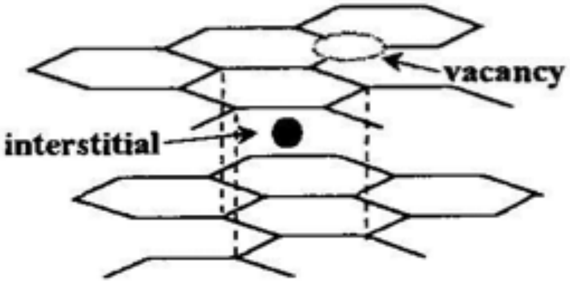
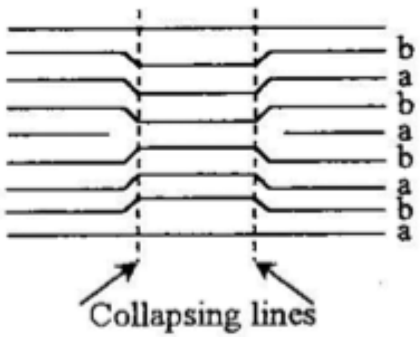
Radiation Damage In Graphite Is Temperature Dependent







INTERSTITIALS

Mobile at room temperature.
Above ~200°C form into clusters of 2 to 4 interstitials.
Above 300°C form new basal planes which continue to grow at temperatures up to 1400°C.

VACANCIES

Immobile below 300°C.
300-400°C formation of clusters of 2-4 vacancies which diffuse in the basal planes and can be annihilated at crystallite boundaries (function of lattice strain and crystal perfection).
Above 650°C formation of vacancy loops.
Above 900°C loops induce collapsing vacancy lines.

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Effects of Radiation on Graphite - Measurements (1)

- IG-110U Graphite (also produced by Toyo Tanso, similar to IG-430) submitted to neutron (E > 1 MeV) doses of 1.4 10^{19} n/cm^2 (~0.02 dpa) and 1.9 10^{20} n/cm^2 (~0.25 dpa) at 200 ^{O}C

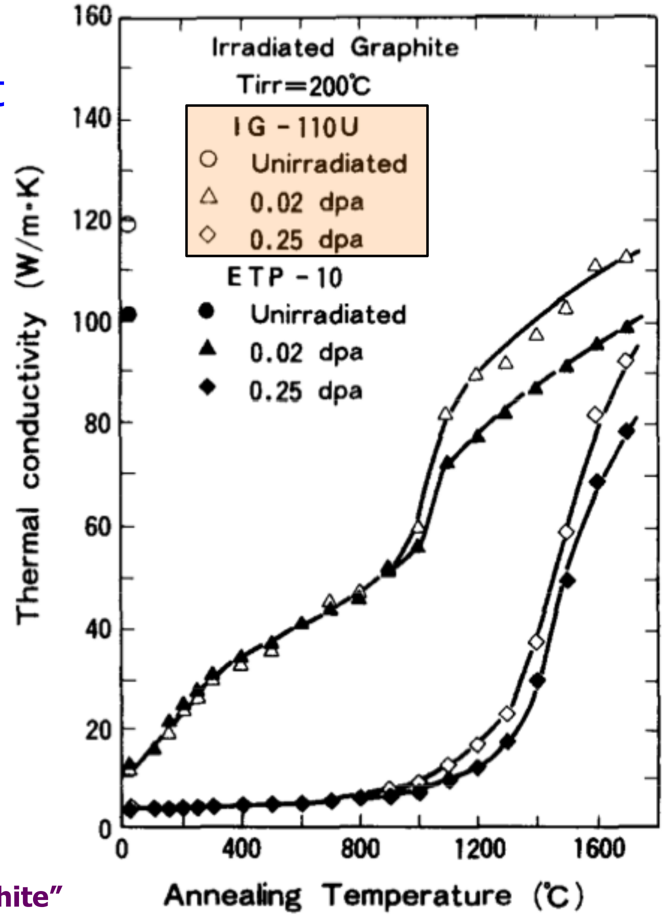
Irradiation	Thermal conductivity (W/(m K))			Dimensional change (%)		
	IG-110U	ETP-10	GC-30	IG-110U	ETP-10	GC-30
Unirradiated	119	101	16	–	–	–
0.02 dpa, 200°C	10.9	11.8	3.7	0.04	0.10	−0.14
0.25 dpa, 200°C	2.6	3.4	1.9	0.14	0.24	−0.68

→ With a dose of 0.25 dpa, thermal conductivity drops by a factor ~50! - from 119 to 2.6, a value almost equivalent to that of normal Carbon (1.7 W/m/K).

→ Recovery of thermal conductivity with annealing possible, but needs much higher temperatures and is almost absent up to 900^0 C for high irradiation doses.

→ Dimensional change effects of irradiation at constant T are limited (O(0.1%)), can even induce negative expansion coefficients (shrinkage) with increasing T.

Irradiation	Dimensional change (%)	
	CX-2002U	IG-110U
Unirradiated	–	–
0.01 dpa, 20°C	0.03	0.12
0.13 dpa, 300°C	−0.02	−0.01
0.82 dpa, 4300°(	−0.27	−0.25



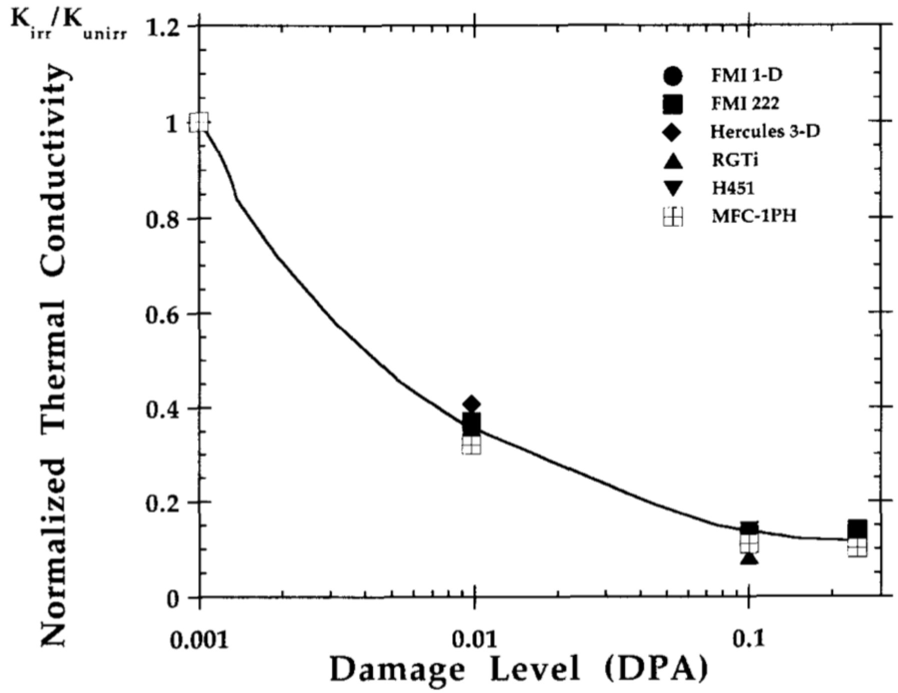
T. Maruyama, M. Harayama, Journal of Nuclear Materials 195 (1992) 44-50
"Neutron Irradiation Effect on the Thermal Conductivity and Dimensional Changes of Graphite"

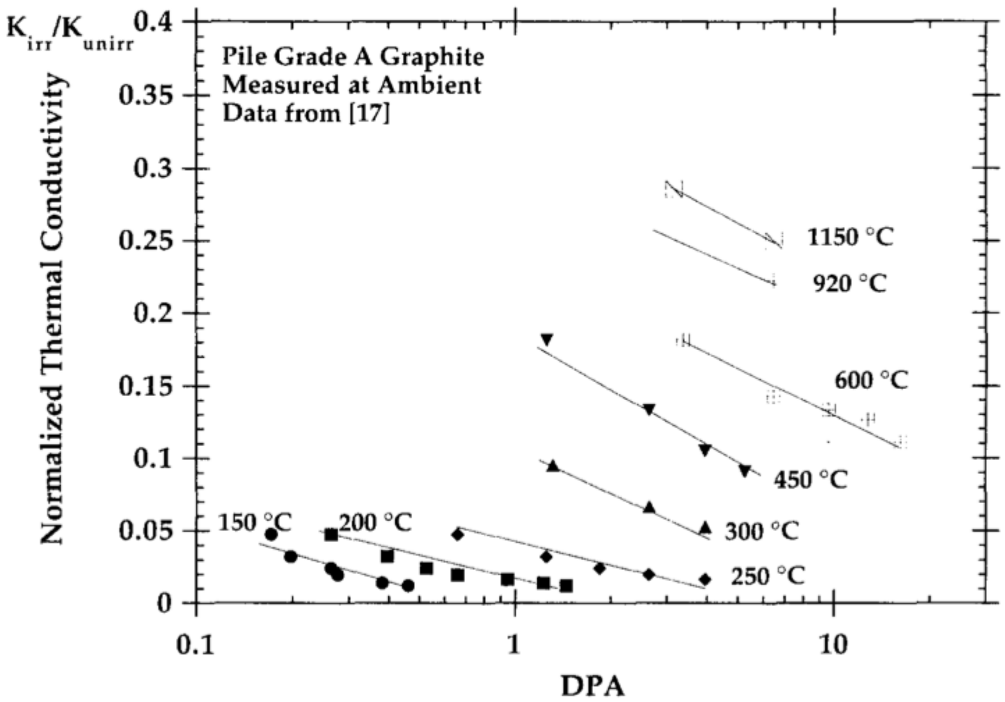
Effects of Radiation on Graphite - Measurements (2)

- Different Graphites with varying thermal conductivity (from 114 to 670 W/mK) irradiated with fission neutrons (E > 0.1 MeV) near 150 ^{O}C at fluences up to 3.2 10^{20} n/cm^2 (~0.24 dpa).

→ All materials show similar rates of degradation of thermal conductivity to approximately 10 to 14% of original values after irradiation.

→ Again recovery of thermal conductivity with annealing possible, less efficient and needs higher temperatures for higher irradiation doses.





→ Degradation in thermal conductivity higher at lower temperature (huge effect).

→ For another Graphite* after irradiation at 150°C, thermal conductivity reaches asymptotic value of ~ 1% of original.

*Pile Grade A nuclear graphite, medium grained, extruded, anisotropic material with thermal conductivity 172 W/m/K

L. L. Snead, T. D. Burchell, Journal of Nuclear Materials 224 (1995) 222-228
"Thermal conductivity degradation of graphites due to neutron irradiation at low temperature"

Effects of Radiation on Graphite - Measurements (3)

- Several Graphites (including IG-430) irradiated at BNL with 117 or 200 MeV, 90 μA p beam.

- 2 phases of Irradiation:
  - 0.02 dpa followed by annealing
  - peak fluence of ~0.5×10^{21} p/cm^2

- No effect of irradiation on thermal expansion coefficient for IG-430

- "the carbon composites and the IG-43 graphite all suffer structural degradation at fluence > 0.5×10^{21} p/cm^2."

- "The IG-430 did not quite reach the threshold fluence but it showed no degradation signs. Its resistance to high fluence needs to be further explored."

while carbon composites at moderate doses exhibited interesting behavior of damage reversal through thermal annealing, at higher dose levels of peak proton fluences >5×10^{20} protons/cm^2 they exhibited serious structural degradation. Also, the experimental study showed that graphite suffered similar structural damage when subjected to the same proton fluence. The latter was a surprise given that reactor experience on graphite indicates that graphite has exhibited survivability under high neutron fluence and to estimated radiation damage of several dpa. It appears that the effects of neutrons and protons on the structure of the material are very different and therefore attention needs to be paid in establishing the right correlation so the wealth of data from reactor, operations can be utilized in the accelerator field.

N. Simos, H. Kirk, K. Mc Donald, Research Gate 228528681 (2008)
"Experimental study of radiation damage in Carbon composites and graphite considered as targets in the Neutrino Super Beam"

Target Temperatures Study - Effect of Reduced Conductivity

- A simple simulation of Energy Deposition (GEANT4) and Cooling System (rdm6) reproduces maximum temperature in Target for nominal beam power, assuming thermal conductivity divided by 4.

- **Now what if thermal conductivity is reduced, as measurements seem to indicate, by a factor 10? or even 50?**

  → Repeat simulation for present (P = 450 kW) and nominal (P = 750 kW) beam power with thermal conductivity reduced by a factor 4, 10 or 50 (keeping **H = 450 W/m²/K**).

  → **Results for T_{min} and T_{max}**

T_{max} / T_{min}	K = 140	K = 35	K = 14	K = 3
P = 450 kW	387 °C / 198 °C	425 °C / 174 °C	498 °C / 154 °C	1019 °C / 109 °C
P = 750 kW	632 °C / 314 °C	704 °C / 272 °C	818 °C / 240 °C	1527 °C / 164 °C

Max/Min Temperatures in Target vs beam power P and graphite thermal conductivity K (in W/m/K)

- **Comments**

  → T_{max} increases with P and when K decreases, as expected.

  → **Dramatic effect of K= 3! T_{max} above 900 °C even for P = 450 kW.**

  → T_{min} increases with P, but decreases with decreasing K! Heat trapped in Target Core.

Neutron Irradiation Induced Dimensional Change

- Graphite dimensional changes are a result of crystallite dimensional change and graphite texture.
- Swelling in c-direction is initially accommodated by aligned microcracks that form on cooling during manufacture.
- Therefore, the a-axis shrinkage initially dominates and the bulk graphite exhibits net volume shrinkage.
- With further irradiation, incompatibilities in crystallite strains causes the generation of new porosity and the volume shrinkage rate falls eventually reaching zero.

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"Irradiation Damage in Graphite – from the Nano- to the Millimetric Scale"

Neutron Irradiation Induced Dimensional Change (continued)

- The graphite begins to swell at an increasing rate with increasing damage dose due to c-axis growth and new pore generation.
- The graphite thus exhibits volume “turnaround” behavior from initial shrinkage to growth.
- Eventually loss of mechanical integrity occurs due to excessive pore/crack generation.

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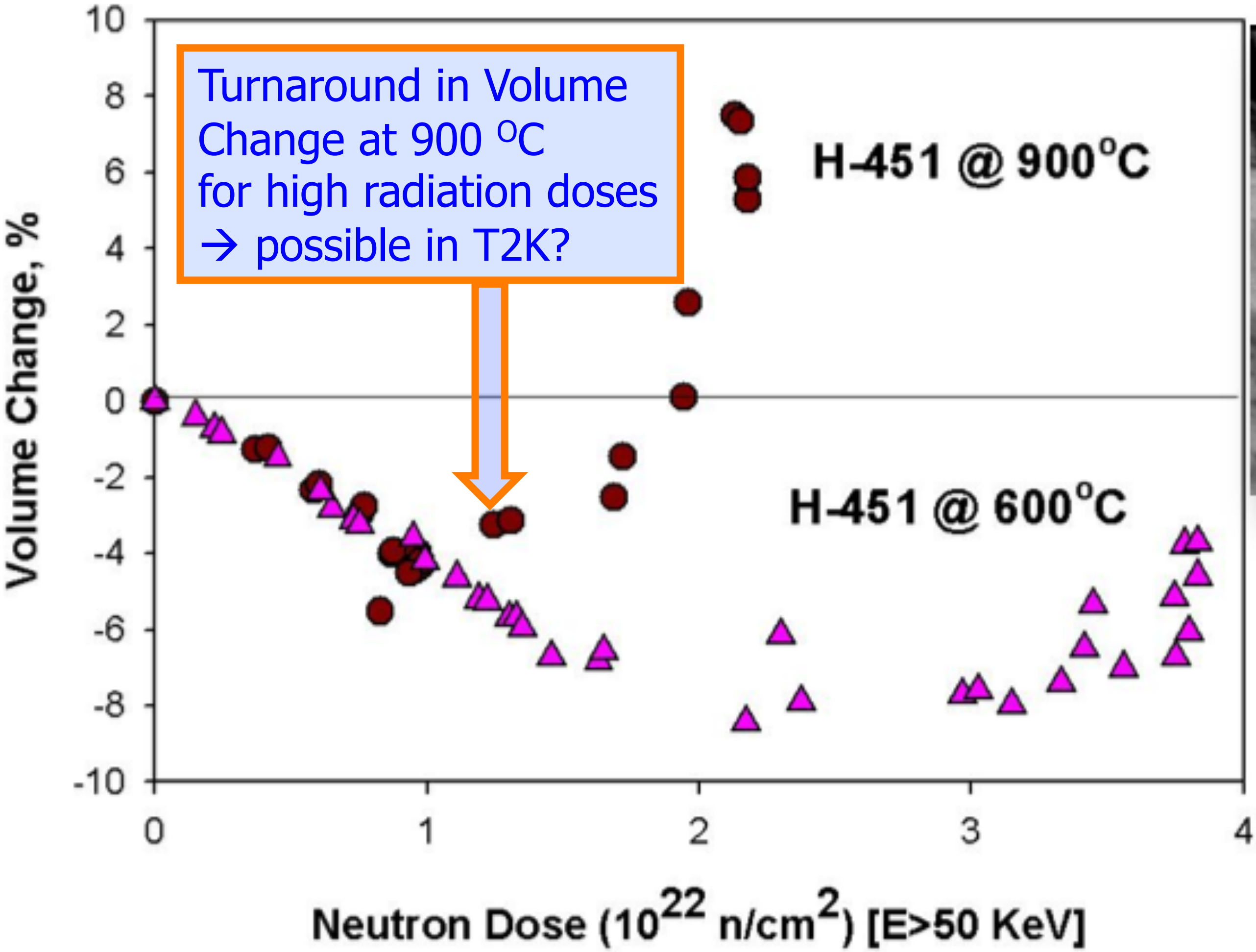
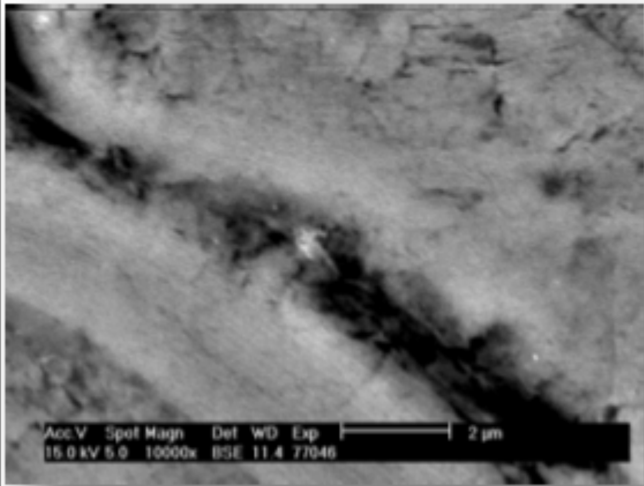
Radiation Induced Volume Changes in H-451 (Effect of Temperature)





Interplaner cracks and porosity accommodate thermal expansion and c-axis irradiation induced swelling

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Summary

Very preliminary study: no affirmation, but interesting questions!

- Simple simulations of Energy Deposition and Heat Transfer used to reproduce expected temperatures in Target at P = 750 kW with thermal conductivity reduced by a factor of 4.
- However published results show possible degradation of thermal conductivity by factors up to 100.
- Simple simulations show possible maximum temperatures in Target above 1000 ^{O}C, even for P = 450 kW, if thermal conductivity of Graphite is indeed reduced by a factor ~50.
- The combination of very high neutron doses and high temperature (>900 ^{O}C) has been shown to induce Volume Changes of up to 10%. → could such an event occur in T2K?
- At this stage, nothing can be affirmed for sure, but at least the question seems legitimate and needs further investigation.

Outlook

Short term

- Cross-check Geant simulations.
- Estimate the flux of low energy neutrons for more relevant comparisons with Nuclear science results.

Mid term (if needed)

- Discuss with Nuclear Physicists / Graphite specialists to get a more precise idea of the evolution of thermal conductivity as a function of proton irradiation doses and temperature of irradiation.
- Set up a more realistic Heat Transfer simulation.

⇒ Eventually could a direct examination of the Target and measurements of its thermo-mechanical properties be needed to assert the effects of irradiation?