ANTIMATTER SOURCES ENGINEERING

MORE……"SECONDARY" PARTICLE GENERATION

- Produce unstable daughter particles of interest:
  - Positrons, neutrons, radio-isotopes, pions, kaons, muons, neutrinos, …

- Examples:
  - $p+A \longrightarrow p$, p-bar, $\pi^{\pm}$, $K^{\pm}$ — secondary beams
  - $p+A \longrightarrow \pi^{\pm}$, $(K^{\pm}) \longrightarrow \mu^{\pm}, \nu$ — neutrino (super)beams
  - $p+A \longrightarrow \pi^{\pm} \longrightarrow \mu^{\pm} \longrightarrow \nu_e, \nu_\mu$ — μ-collider
  - p(or ion) +A $\longrightarrow$ ions(A,Z) — fragmented ions or RIB

- with highest flux possible

  achieve high statistics and/or background suppression
  - Collider luminosity: $L \to N^2 f / A$

ANTIMATTER SOURCES ENGINEERING -> TARGETS

- Primary beams -> Energy losses
- Target Heating - melting and vaporization
- Target Thermomechanical stress (PEDD)
- Target Shock waves

} Reliability

- Radiation damage -> change of material properties (Lifetime dose against radiation damage (dislocations, cracking...) of most solids materials is 10^{22} protons/cm^2)
- Target Activation

EFFECT OF ENERGY LOSSES IN MATERIALS

- Ionization -> **Heating**, no single event atomic damage , statistical temperature effect at the melting point
- Elastic events -> Transfer of energy via atomic recoil, The Nucleus loses energy by

1) **Ionization/excitation** -> Heating
2) **Nuclear reactions** -> Cascades (displacement cascade) -> Production of vacancies, interstitials, modification of the material structure (damages) and change of the mechanical and physical properties

- Inelastic events -> nuclei transmutation

-> Activation, impurities that effect the thermal conductivity, production of H and He and so change of the material properties.

-> Nucleus recoil (see above)

ENERGY LOSSES

- $K = 4\pi N_A r_e^2 m_e c^2$ N_A= Avogadro's Number
- ze = charge of the incident particle
- Z,A = Atomic number and mass of the target material
- β, γ = relativistic factors
- m_e = electron mass
- c = light velocity
- I = mean excitation energy in eV
- T = kinetic energy
- T_{max} = max kinetic energy transferred to an electron in a single collision
- $\delta(\beta\gamma)$ = density effect for ionization losses
- M = incident particle mass

$$T_{\max} = \frac{2m_e c^2\,\beta^2\gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}\,.$$

ENERGY LOSS

- Mailnly ionization losses. Heavy particles: Rutheford differential cross section

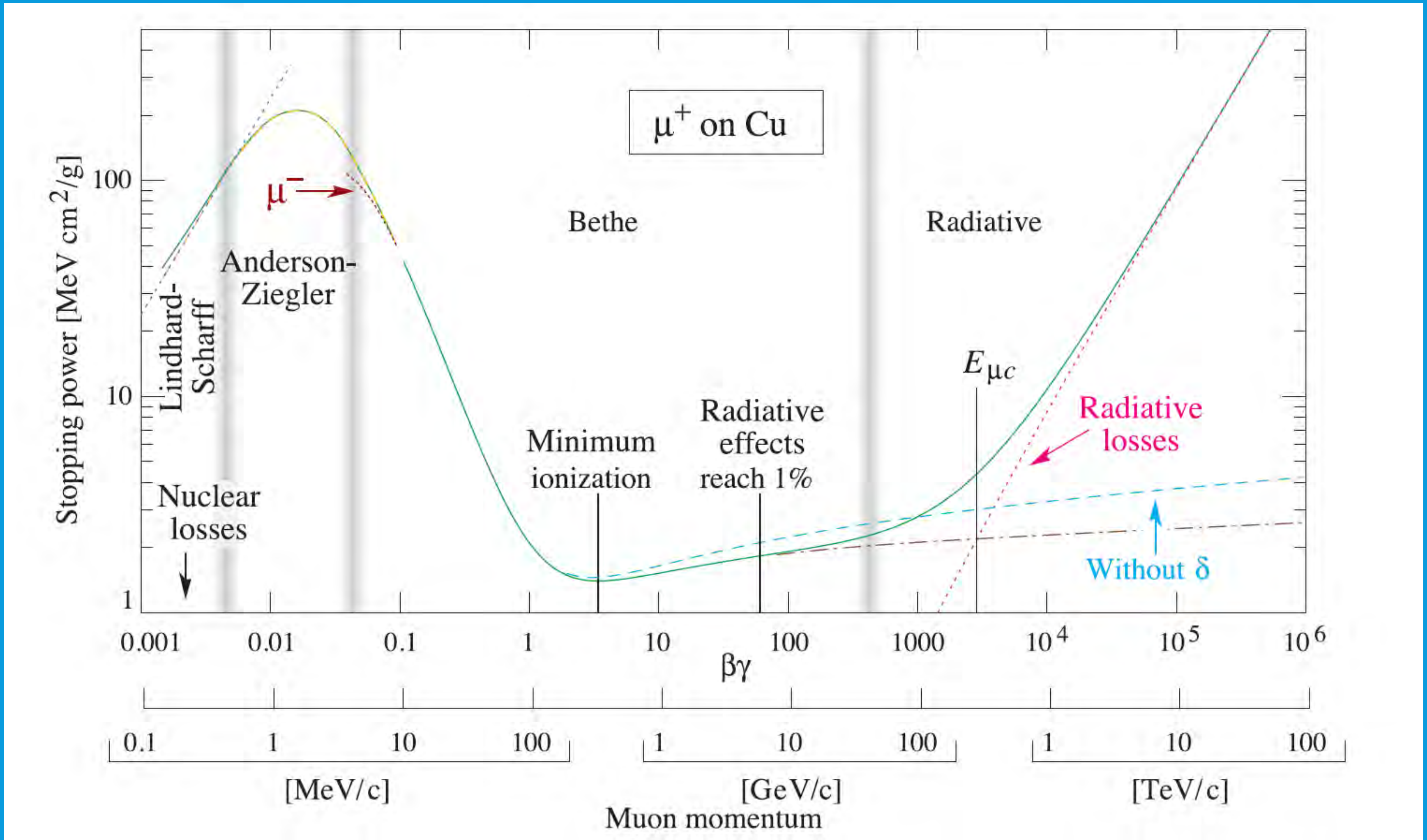
$$\frac{d\sigma_R(E;\beta)}{dE} = \frac{2\pi r_e^2 m_e c^2 z^2}{\beta^2} \frac{(1-\beta^2 E/T_{\max})}{E^2} ,$$

- From this it is possible to obtain the Stopping Power, in the range $0.1 \lesssim \beta\gamma \lesssim 1000$:

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] .$$

- BETHE equation

HEAVY PARTICLES - MUONS



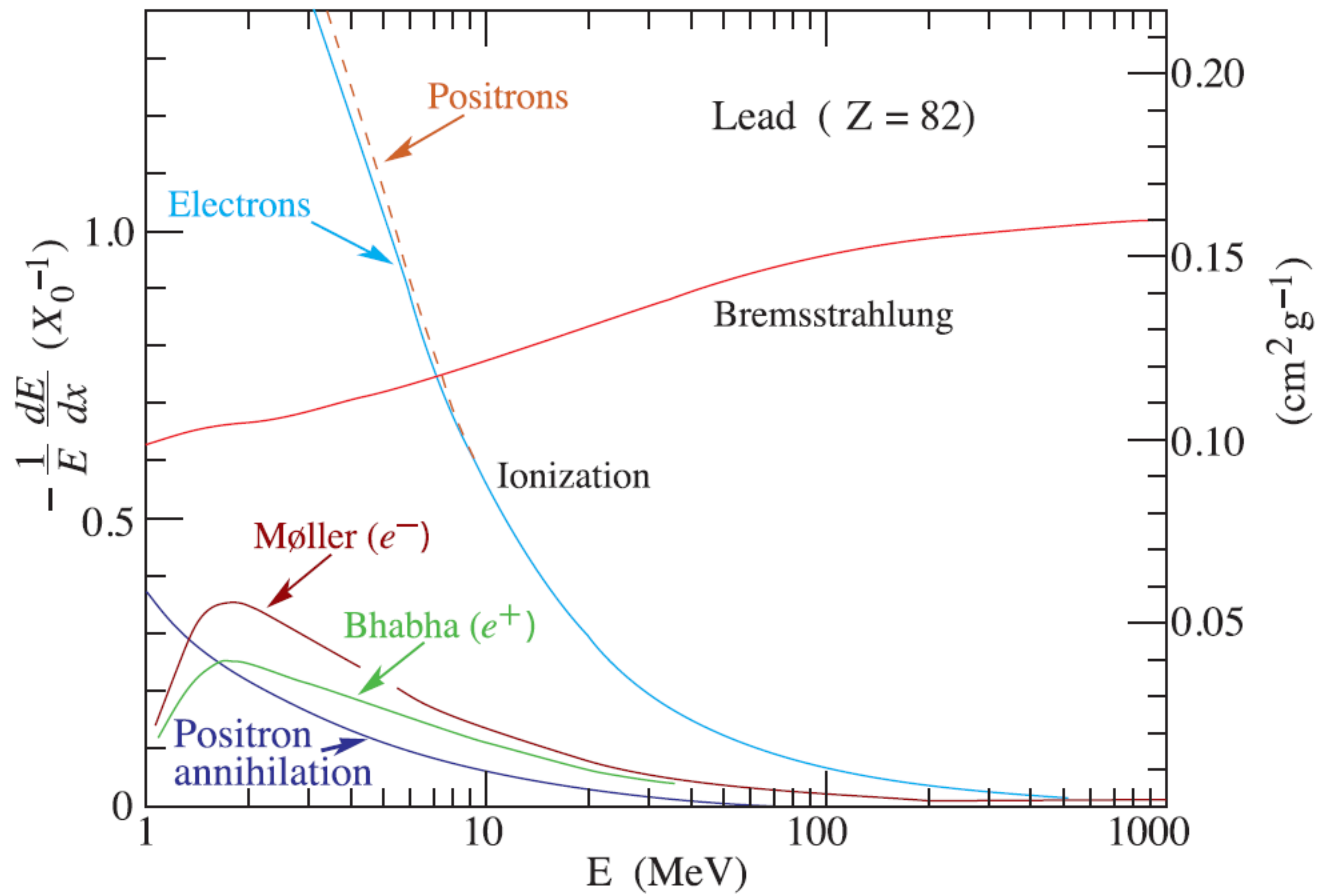
LIGHT PARTICLES - ELECTRONS

- Main energy losses in bremsstrahlung for electrons and pair creation for photons
- Radiation Length (amount of matter traversed) in g cm^{-2}
- Mean Distance for an electron to loose 1/e of its energy by bremsstrahlung or Mean Free Path for a photon to produce one pair

$$\frac{1}{X_0} = 4\alpha r_e^2 \frac{N_A}{A} \left\{ Z^2 [L_{\rm rad} - f(Z)] + Z\, L'_{\rm rad} \right\} .$$

- L, Lrad and f(z) available in literature for different materials
- Critical energy -> ionization and brem rate are equal

FRACTIONAL ENERGY LOSS (UNIT RADIATION LENGTH) - ELECTRONS



MULTIPLE SCATTERING

$$\theta_0 = \theta_{\rm plane}^{\rm rms} = \frac{1}{\sqrt{2}}\theta_{\rm space}^{\rm rms} ,$$

$$\begin{aligned}\theta_0 &= \frac{13.6 \text{ MeV}}{\beta c p}\, z \sqrt{\frac{x}{X_0}}\left[1 + 0.088 \log_{10}\left(\frac{x\, z^2}{X_0 \beta^2}\right)\right] \\ &= \frac{13.6 \text{ MeV}}{\beta c p}\, z \sqrt{\frac{x}{X_0}}\left[1 + 0.038 \ln\left(\frac{x\, z^2}{X_0 \beta^2}\right)\right]\end{aligned}$$

HEATING

AVERAGE T

Density (g/cm^3)
Elastic Modulus (GPa)
Tensile Strength (MPa)
Yield Strength (MPa)
Endurance Limit (MPa)
Specific Heat (J/g-K)
Thermal Expansion $(10^{-6}/°)$
Thermal Conductivity (W/cm-K)

- AVERAGE
- $Q = Mc_p\Delta T$,

M = target mass, $c_p(T)$ = specific heat -> $C_T = Mc_p(T)$ = Thermal capacity

Q = Energy given to the target $$\Delta E = \frac{\partial E}{\partial z}\rho\Delta z,$$ [eV cm²/g][g/cm³][cm]

T_{max} must be lower of Melting Point (but before plastic deformation)

MORE PRECISELY T(X,Y,Z,T)

But in an accelerator the energy deposition follows the TEMPORAL beam structure:

1) Bunches (ps, ns)
2) Macro bunches (trains of m10^n bunches)
3) CW

Energy will also be deposited following the bunch shaping -> T(x,y), usually Gaussian like

Temporal evolution phases ->

1) Instantaneous rise (respect to the Temperature characteristic time constants)
2) Diffusion and cooling starts
3) Equilibirum

T_{MAX} << of Melting point

BEAM INSTANTANEOUS HEATING

- Consider the energy deposition in the target $$\frac{dE}{dm} = \int_{T_{in}}^{T_{in}+\Delta T_{bc}} c_p(T)\, dT\,,$$ T_{in} = initial T, ΔT_{bc} = final T

If c_p ~const in the T range-> $$\Delta T_{bc}(x,y,z) = \frac{1}{c_p}\frac{dE}{dm}(x,y,z)$$

To calculate the density let's assume thin targets (dE/dz ~const) so taking only the average in z, assuming d the target thickness

$$\Delta \bar{T}_{bc}(x,y) = \frac{1}{c_p}\left(\frac{1}{d}\int_0^d \frac{dE}{dm}(x,y,z)\, dz\right).$$

Assuming a Gaussian beam $$\Sigma = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{xy} & \sigma_{yy} \end{pmatrix} \equiv \begin{pmatrix} < x^2 > & < xy > \\ < xy > & < y^2 > \end{pmatrix}$$

$$\Delta \bar{T}_{bc} = \frac{N_e}{2\pi\rho c_p a_{rms}}\left(\frac{1}{d}\int_0^d \frac{dE}{dz}(\tau)\, d\tau\right)\exp\left(-\frac{1}{2}\Sigma^{-1}\begin{pmatrix} x \\ y \end{pmatrix}\cdot\begin{pmatrix} x \\ y \end{pmatrix}\right)$$

Where N_e is the number of particles n the beam, dE/dz is the energy deposition per unit length per electron, a_{rms} SQRT(det Σ) is the rms beam spot size

Taking into account N bunches (N_{bc}) in the train and considering the Gaussian peak

$$\Delta \bar{T}_{tr} = N_{bc}\cdot\Delta \bar{T}_{bc} = \frac{N_e \cdot N_{bc}}{2\pi\rho c_p a_{rms}}\cdot\left(\frac{1}{d}\int_0^d \frac{dE}{dz}(\tau)\, d\tau\right)$$

COOLING

- Emission - $\varepsilon\sigma(T-T_{env})^4$ -> ε = surface emissivity and σ= Stefan Boltzmann constant
- Convection - hT -> h = convection heat transfer coefficent
- Diffusion + target boundary conditions $\bar{T}\big|_{x^2+y^2=R^2} = T_{fl}$ $\bar{T}(x,y,0) = T_{in}$

- To evaluate the Temporal final equilibrium the heat diffusion equation has to be taken into account $$\rho\, c_p \frac{\partial T}{\partial t} = \nabla\,(\lambda \nabla T) + Q(x,\, y,\, z,\, t)$$ where Q represent the internal heating

sources and $$-\lambda \frac{\partial T}{\partial z}\bigg|_{z=d} = h\,(T|_{z=d} - T_{air}) + \varepsilon\,\sigma\,\left(T^4\big|_{z=d} - T^4_{air}\right)$$ at each surfaces in z direction

EQUILIBRIUM EQUATION

$$\bar{T}\Big|_{x^2+y^2=R^2} = T_{fl}$$

$$\bar{T}(x, y, 0) = T_{in}$$

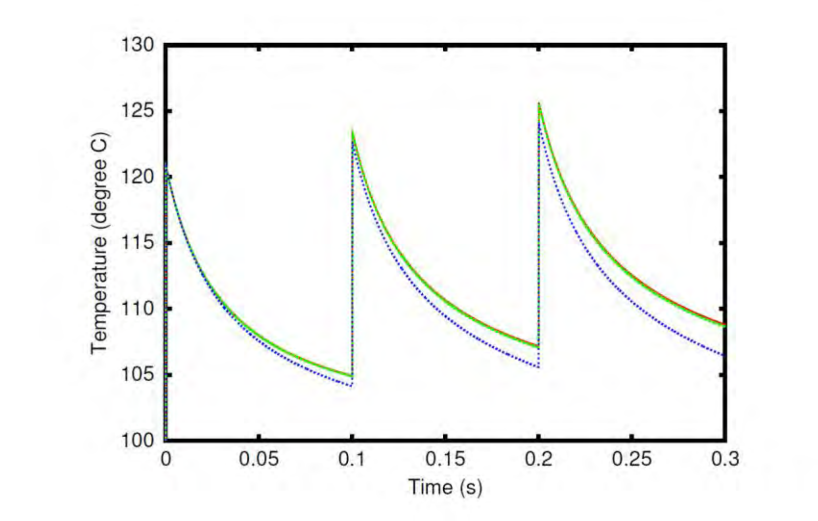
$$\frac{\partial T(x,y,t)}{\partial t} = \frac{1}{c_p \rho}\left[\frac{\partial E}{\partial z}\frac{N_e(t)\rho}{2\pi\sigma_x\sigma_y}e^{-\left(\frac{x^2}{2\sigma_x^2}+\frac{x^2}{2\sigma_y^2}\right)} + \lambda\nabla_t^2 T(x,y,t) - \frac{h}{\Delta z}(T - T_{conv}) - \frac{2\epsilon\sigma}{\Delta z}(T^4 - T_{env}^4)\right]$$

Heating source

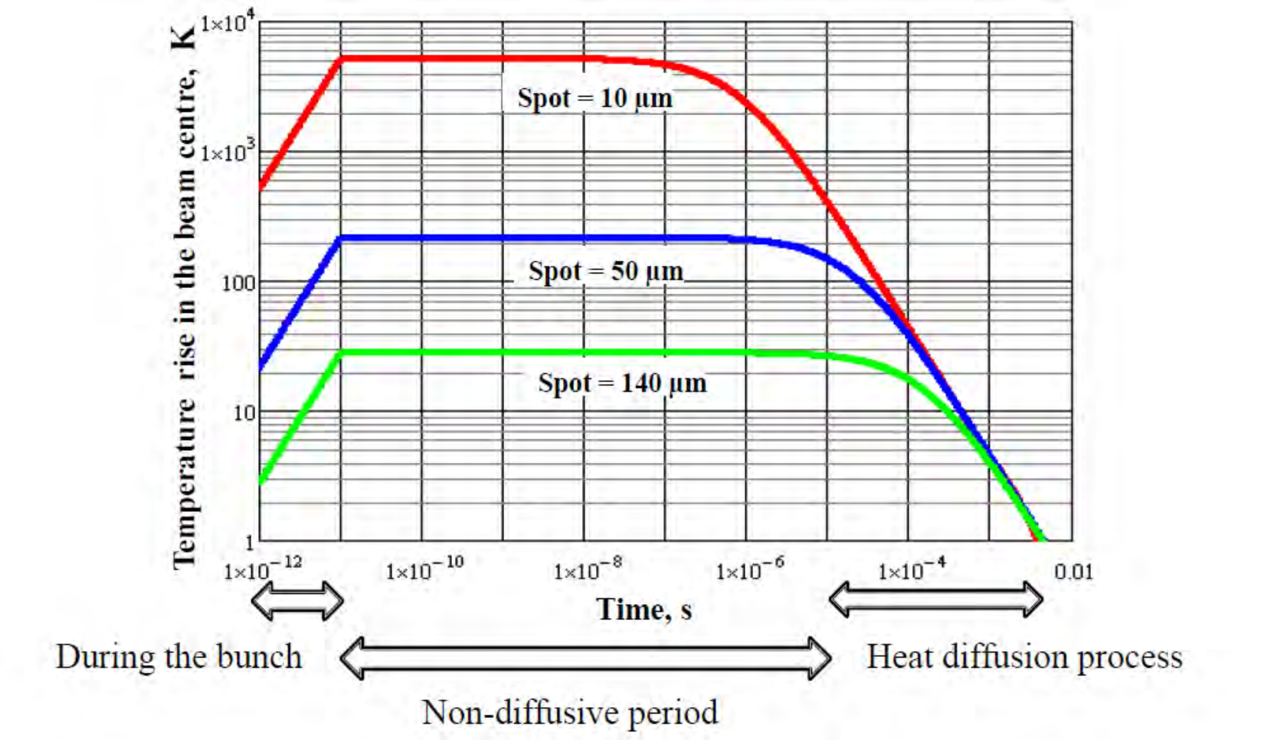
Diffusion

Convection cooling

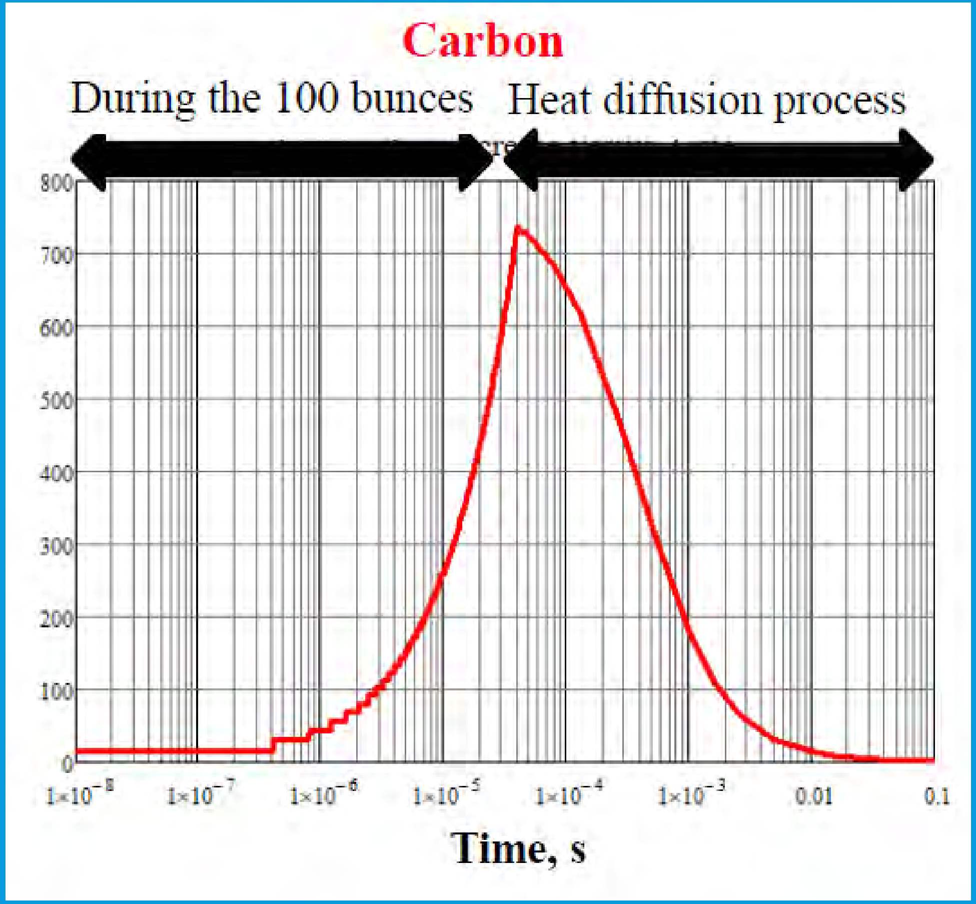
Radiative cooling



HEATING AND DIFFUSION

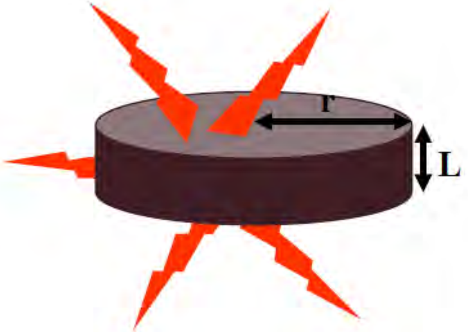


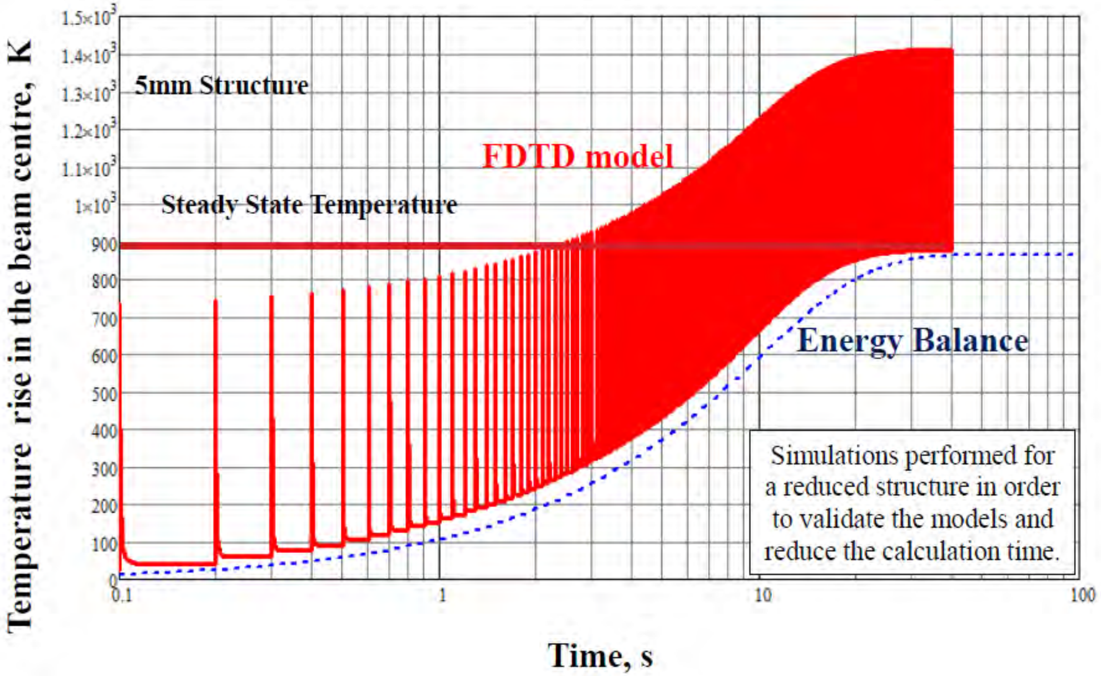
multibunches

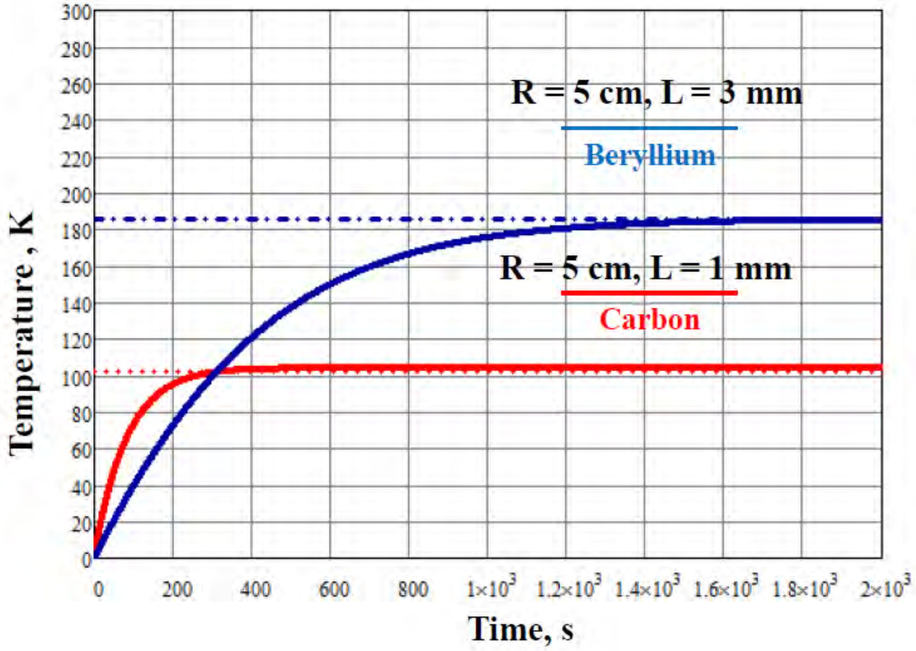


TARGET WITH NO CONVECTION -> STEADY STATE TEMPERATURE)

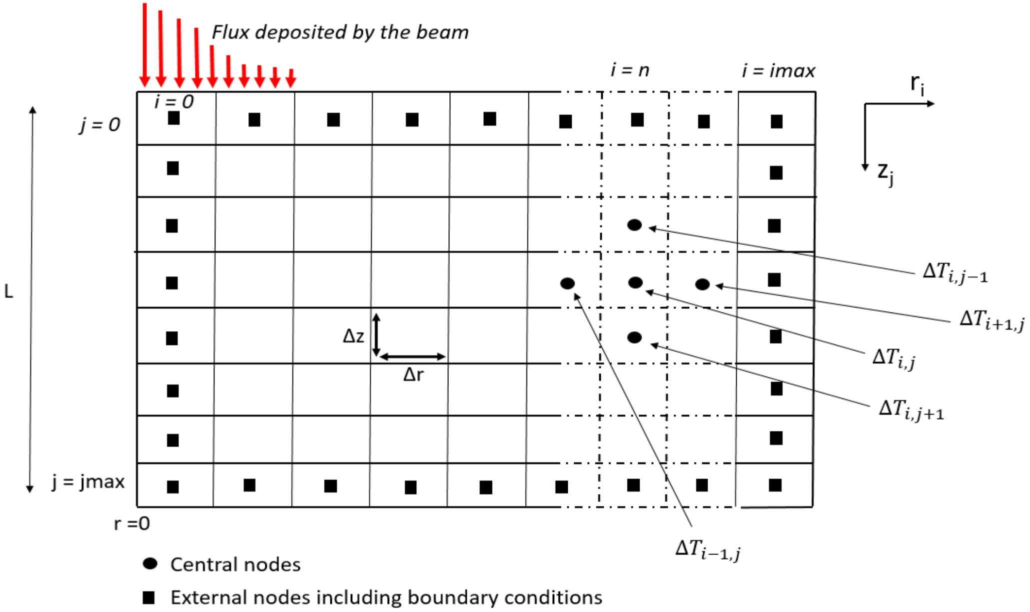
$$\Delta T = \sqrt[4]{T_{amb}^4 + \left(\frac{a^2 \cdot L}{r^2 + r \cdot L}\right)\frac{C_{\max,a} \cdot N_{part} \cdot N_{pulses}}{\varepsilon \cdot \sigma_B \cdot T_{rep}}} - T_{amb}$$

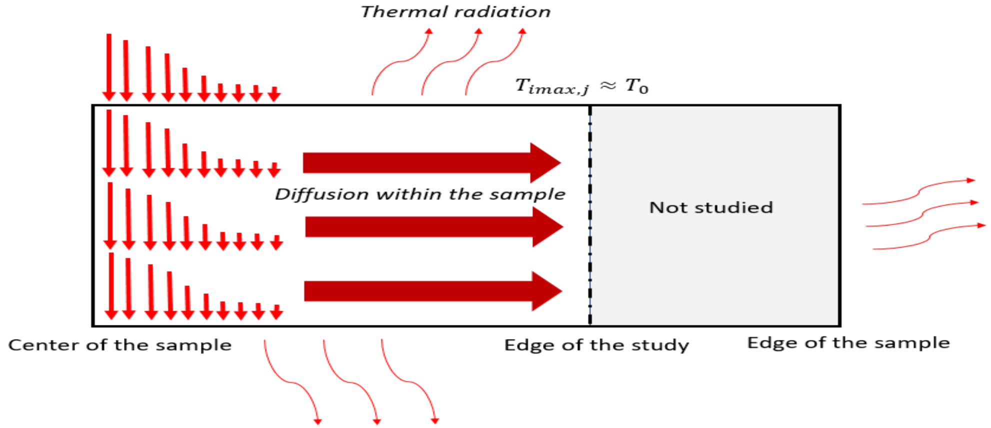






NUMERICAL SOLUTIONS-FINITE ELEMENTS





Basic model equation

$$\Delta T'_{i,j} = \Delta T_{i,j} + \left(\frac{W_{i,j} + \Phi_{net}}{V_{i,j}}\right)\frac{\Delta t}{\rho c_p}$$

i scan on r, j scan on z

$\Delta T_{i,j}'$ temperature at time t', $\Delta T_{i,j}$ at time t
$W_{i,j}$ power deposited in element i,j
Φ_{net} heat flow exchanged by the element i,j in the time unit
Δt time lapse
V element volume i,j
ρ density
C_p specific heat
D thermal diffusivity

Convergence condition
(Fourier number $F_0 = Dt/L^2 \leq \frac{1}{2}$):

$$\Delta t < \frac{min(\Delta r^2, \Delta z^2)}{4D_{max}}$$

THERMOMECHANICAL STRESSES

PEAK ENERGY DENSITY DEPOSITION

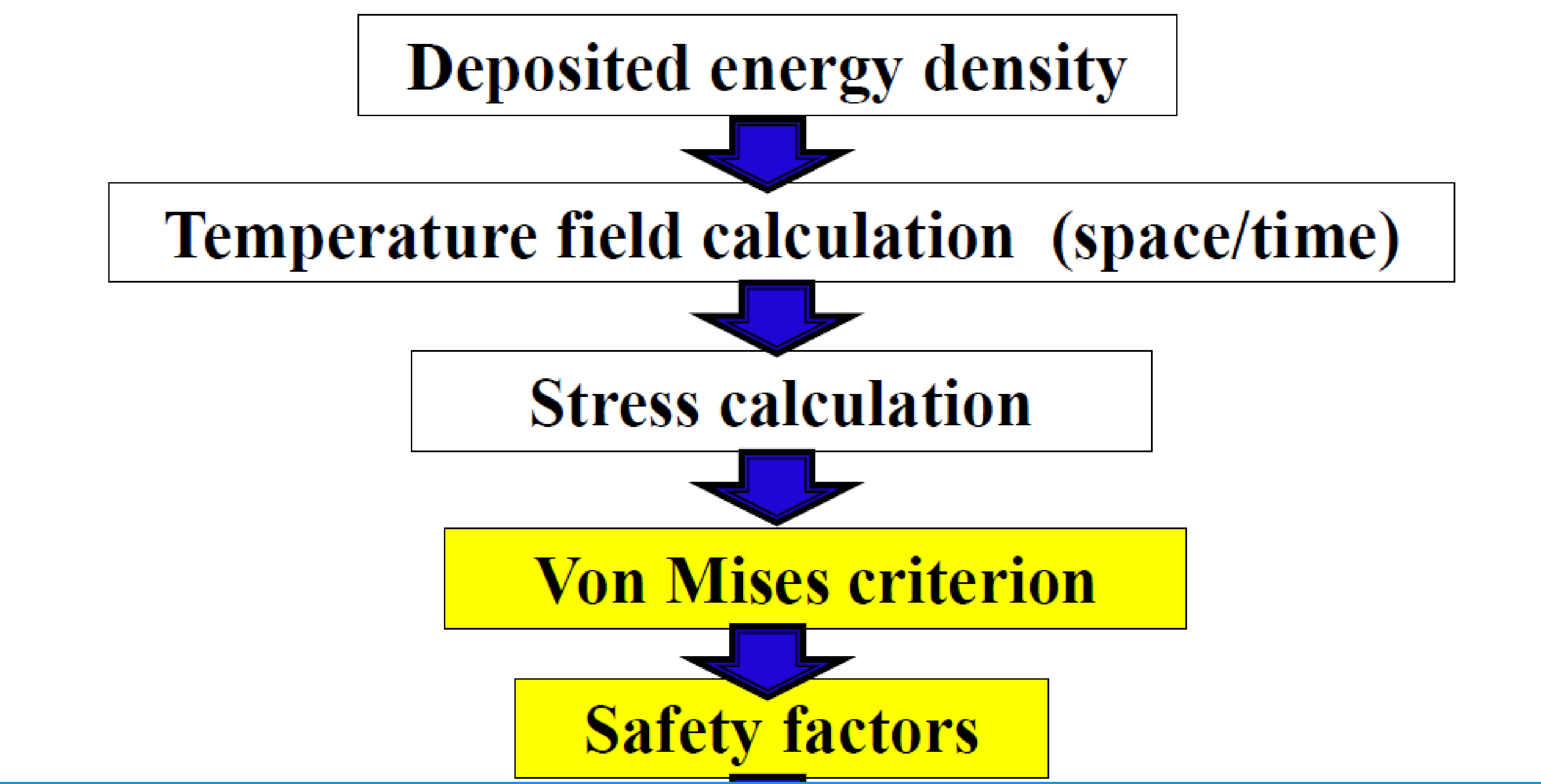
The local and almost instantaneous energy deposition in a target (for instance during a pulse duration) may be very critical for the target survival.

Thermal gradients causing mechanical stresses lead to target destruction as by shock waves.

After the SLC target destruction, analyses showed that a maximum value of 35J/g (in tungsten) must not be exceeded.

The PEDD is strongly depending on the incident beam intensity and on its transverse dimensions.

'STATIC' PEDD


Deposited energy density
Temperature field calculation (space/time)
Stress calculation
Von Mises criterion
Safety factors

Radial Stress

$$\sigma_{rr} = \frac{E(r)}{1-\nu}\left[\frac{1}{R^2}\int_0^R \alpha T(r,t) r dr - \frac{1}{r^2}\int_0^r \alpha T(r,t) r dr\right]$$

Hoop (azimuthal) Stress

$$\sigma_{\theta\theta} = \frac{E(r)}{1-\nu}\left[\frac{1}{R^2}\int_0^R \alpha T(r,t) r dr + \frac{1}{r^2}\int_0^r \alpha T(r,t) r dr - \alpha T(r,t)\right]$$

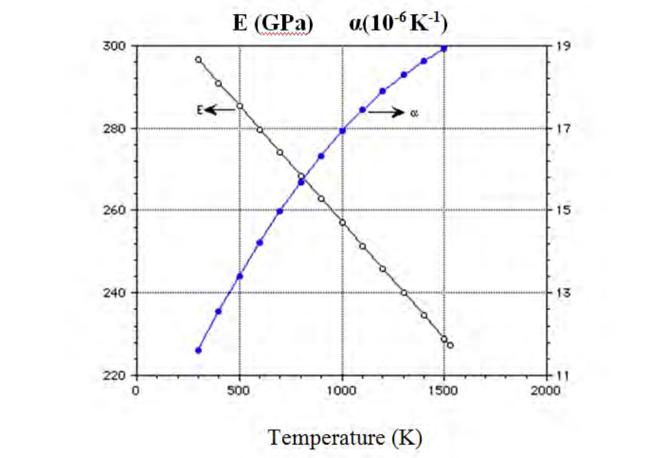
Axial Stress

$$\sigma_{zz} = \frac{E(r)}{1-\nu}\left[\frac{2}{R^2}\int_0^R \alpha T(r,t) r dr - \alpha T(r,t)\right]$$

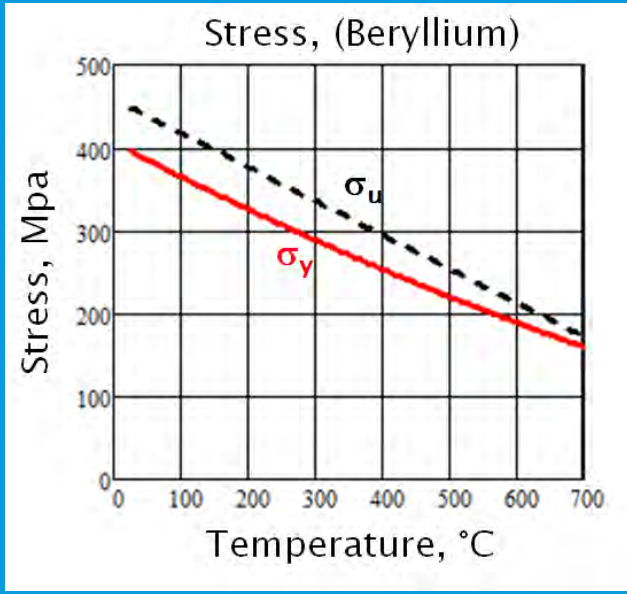
α= coefficient of thermal expansion (linear)
ν= Poisson ratio ($d\sigma_{trans}/d\sigma_{axial}$)

ELASTIC MODULUS (T)

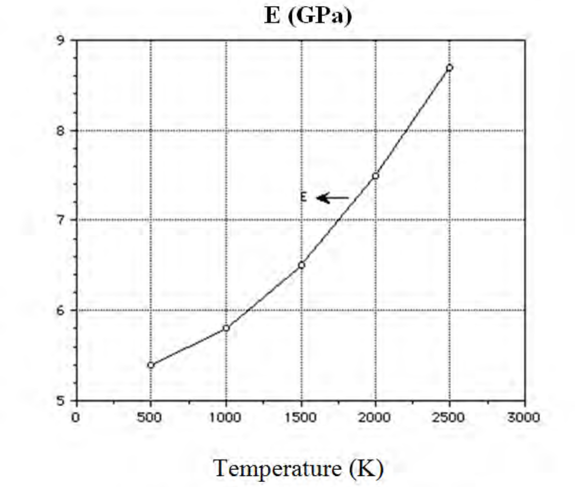
Beryllium



Elastic modulus and coefficient of thermal expansion for beryllium.



Graphite



Elastic modulus of pyrolytic graphite

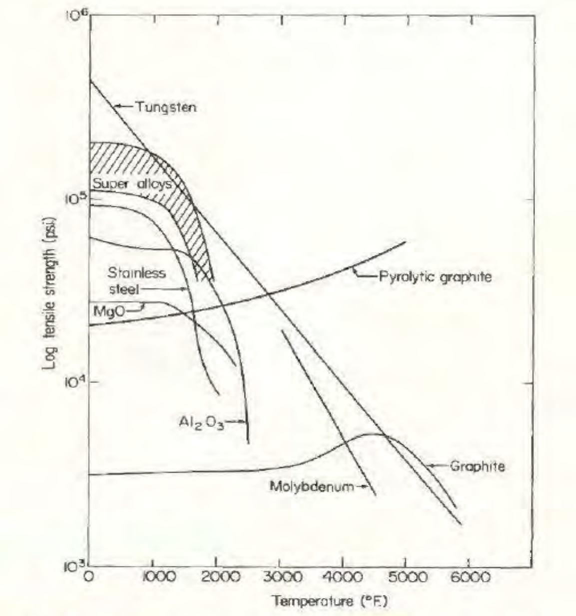
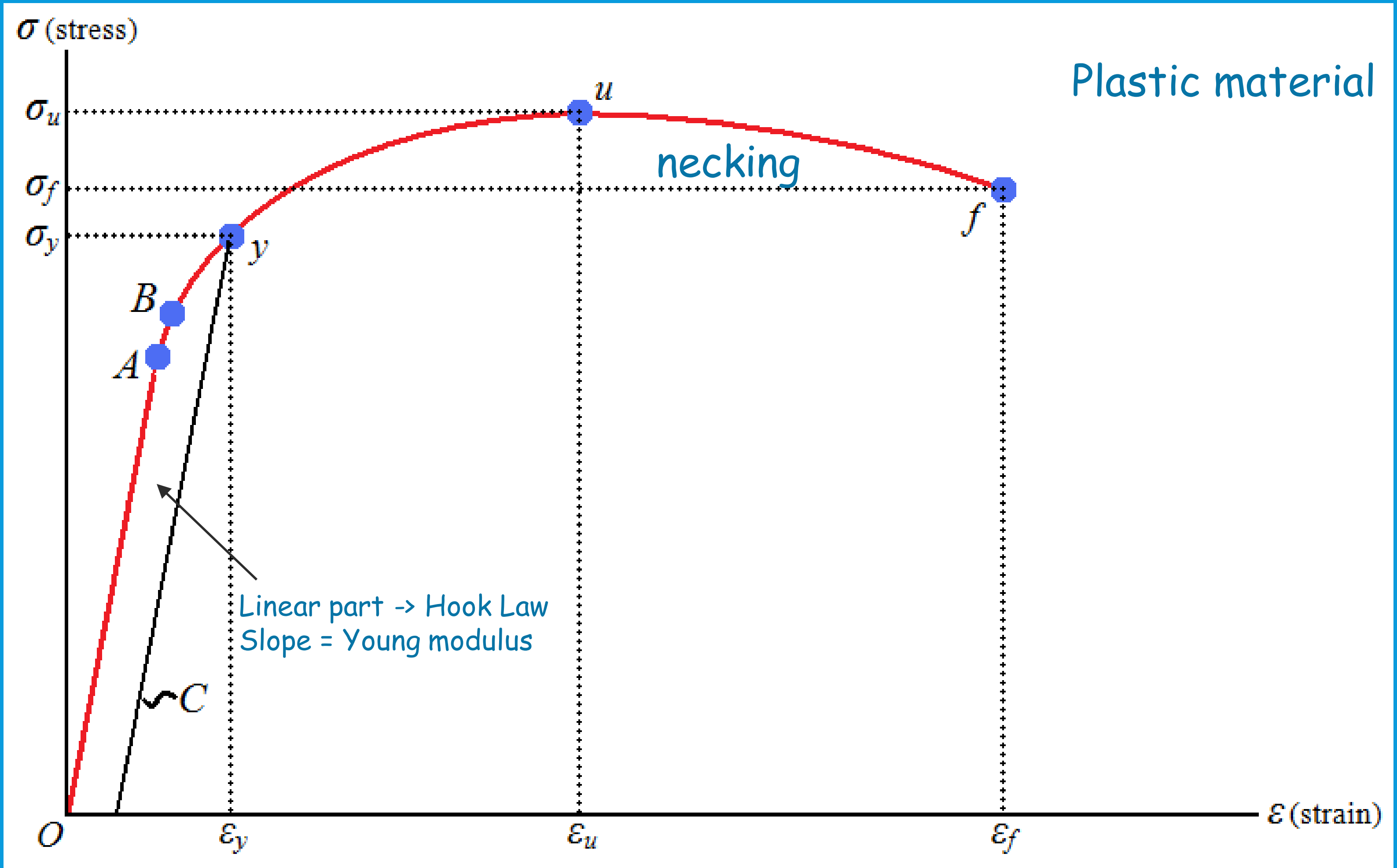


Fig. 8. Ultimate tensile strength of pyrolytic graphite parallel to basal planes in comparison with other high-temperature materials.

STRESS-STRAIN DIAGRAM



*

σ_{uts} = Ultimate

σ_f = Fracture

Brittle materials (Beryllium, Carbon):

$\sigma_{uts} = \sigma_f$

VON MISES STRESSES AND SAFETY FACTORS

Von Mises Equivalent Stress

$$\sigma_e = \sqrt{\frac{(\sigma_{rr} - \sigma_{\theta\theta})^2 + (\sigma_{rr} - \sigma_{zz})^2 + (\sigma_{\theta\theta} - \sigma_{zz})^2}{2}}$$

$$\frac{\sigma_y}{\sigma_e} > 1$$

Safety factor to be introduced

$$\frac{\sigma_{uts}}{\sigma_e} > 2$$

Safety factor to be introduced

DYNAMICS -> SHOCK WAVE (P, T)

- Thermomechanical stresses travel with the sound velocity in the material. Must take into account the P, T behaviour. Usually solving unchoerenet phonons propagation in metals.
- HYDRODYNAMICAL MODEL ->$T = T(x_{123},t), P(x_{123},t)$ *(Mikhailichenko)*

- Hydrodynamical model
  - Heat equation: $\nabla(k\nabla T) + \dot{Q} = \rho c_V \dot{T}$ $\rightarrow$ time scale $\mathcal{O}(1\ \mathrm{s})$
  - Pressure: $\ddot{P} - \nabla(c_0^2 \nabla P) = \Gamma / V_0 \dot{Q}$ c_0: speed of sound; $\Gamma = \Gamma(V) = V/c_V(\partial P/\partial T)_V$

    $\rightarrow$ time scale $\mathcal{O}(10^{-10}\ \mathrm{s})$ for $\dot{Q}$

    and $\mathcal{O}(10^{-7}\ \mathrm{s})$ for pressure wave (c_0)

rapid energy deposition, $v_s T_p \leq \left(\sigma_{in}^2 + \sigma_S^2\right)^{\frac{1}{2}}$

PHYSICAL REVIEW ACCELERATORS AND BEAMS 19, 073402 (2016)

CERN antiproton target: Hydrocode analysis of its core material dynamic response under proton beam impact

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SOLUTIONS

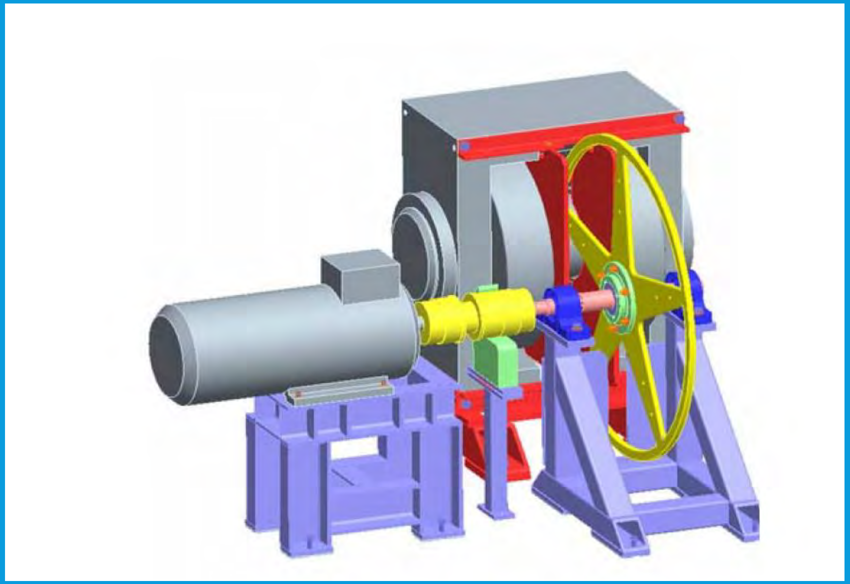
- 1) ELECTRONS/PHOTONS -> primary beam. Multiple scattering and radiation losses. The thermal budget and the secondary beam production has to be managed in thin targets and careful optimization of the target material Z.
- 2) PROTONS -> primary beam -> Higher power but thicker target. Average thermal aspects and thermomechanical stresses determinant.

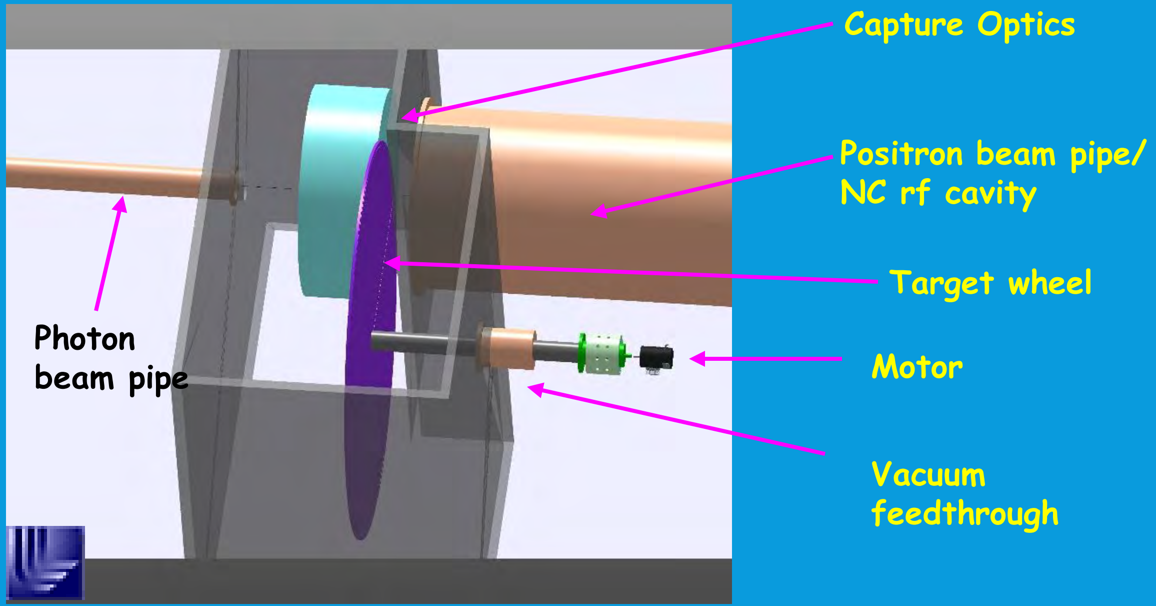
- Mixed considerations are surely possible depending on the final required performance

1 - ELECTRONS

ILC ROTATING TARGET (ILC)

Target wheel diameter	2	m
Target thickness	1.4	cm
Wheel RPM	1000	rpm
Wheel perimeter velocity	100	m/s
Stress in wheel due to rotation	$3x10^7$ (4)	Pa (ksi)
Maximum Ti temperature increase	411	K
Peak stress due to beam energy deposition	$4x10^8$ (58)	Pa (ksi)
Expected lifetime of target wheel at ILC	2	years

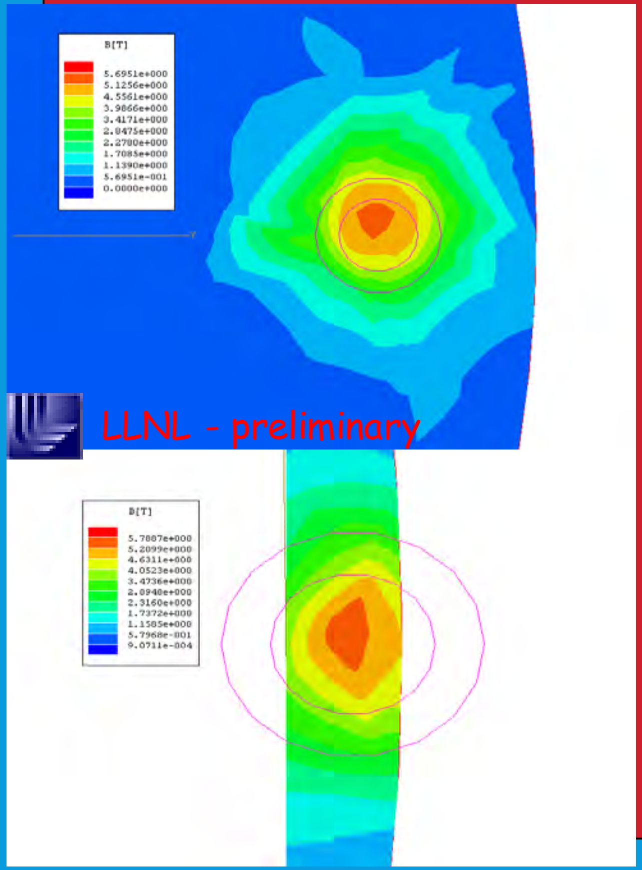




I.Bailey

EDDY CURRENTS…

Eddy Current Simulations



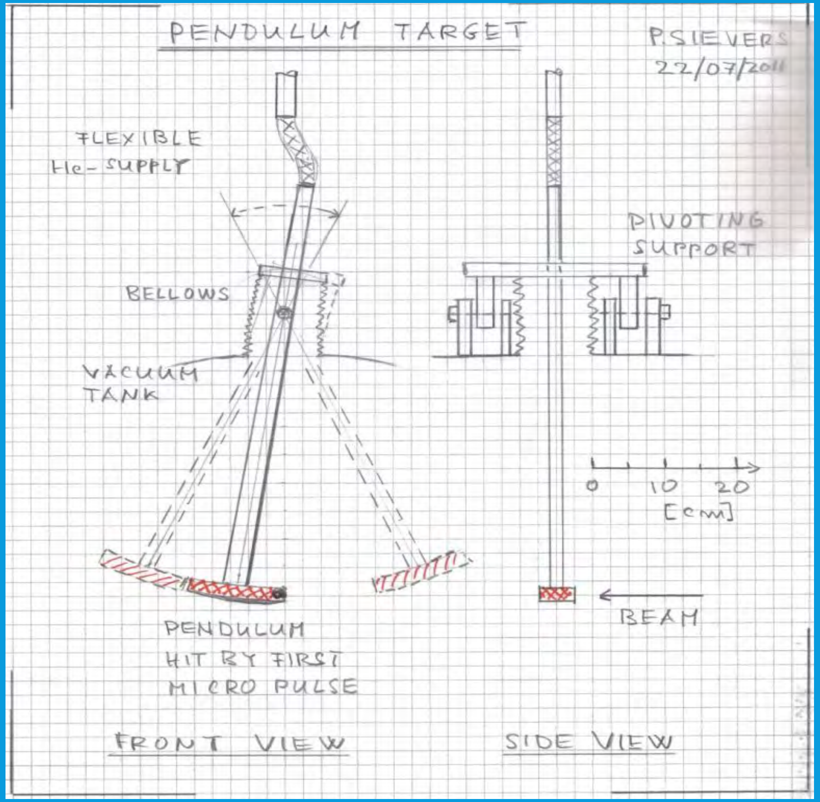
Initial "Maxwell 3D" simulations by W. Stein and D. Mayhall at LLNL indicate:

- ~2MW eddy current power loss for 1m radius solid Ti disc in 6T field of AMD.
- <20kW power loss for current 1m radius Ti rim design.
- However - Simulations do not yet agree with SLAC rotating disc experiment.
  - 8" diameter Cu disc rotating in field of permanent magnet.
- Possibility of OPERA-3D simulations at RAL.

I.Bailey

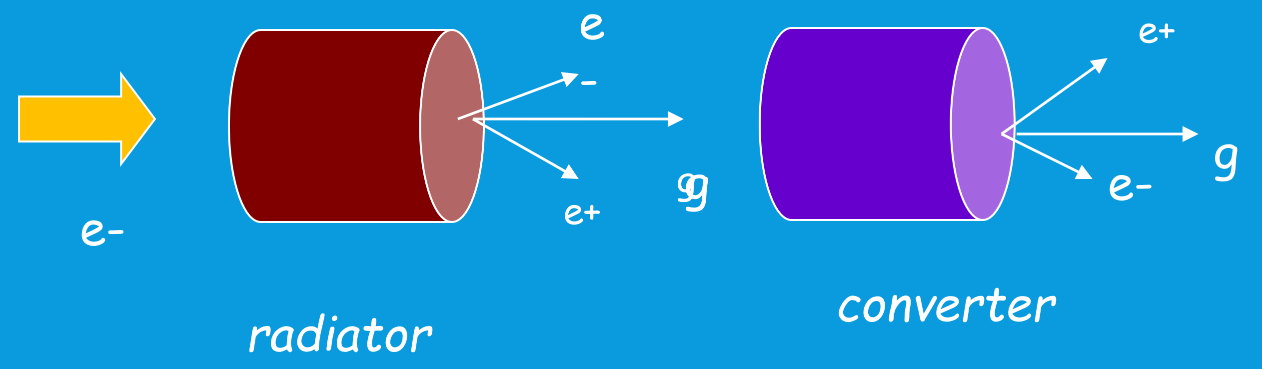
A GRANULAR CONVERSION TARGET FOR THE HYBRID POSITRON SOURCE

P.Sievers



- **AN ALTERNATIVE SOLUTION TO THE WHEEL: THE PENDULUM**
- -To avoid rotating seals, wobbling or trolling targets have been devised where the displacement of the target structure from the outside into the vacuum is made via flexible, vacuum tight bellows. The injection of the cooling fluid can thus be ensured through a rigid, non rotating structure. "Pendulum Target", where the required displacement and velocity is provided by the sinusoidal oscillation of the target.
- ILC CASE: The width of the target is 13 cm, providing space for 13 micro pulses with a diameter of 1 cm each and being displaced, when the beam is hitting the target, at a velocity of about 3 m/s over +/- 7.5 degrees. The total swing is +/- 23 degrees, allowing for comfortable inversion of the direction of the movement during the "off beam" time of 160 ms. The same range in angle must be sustained by the bellows oscillating at 2.5 Hz.

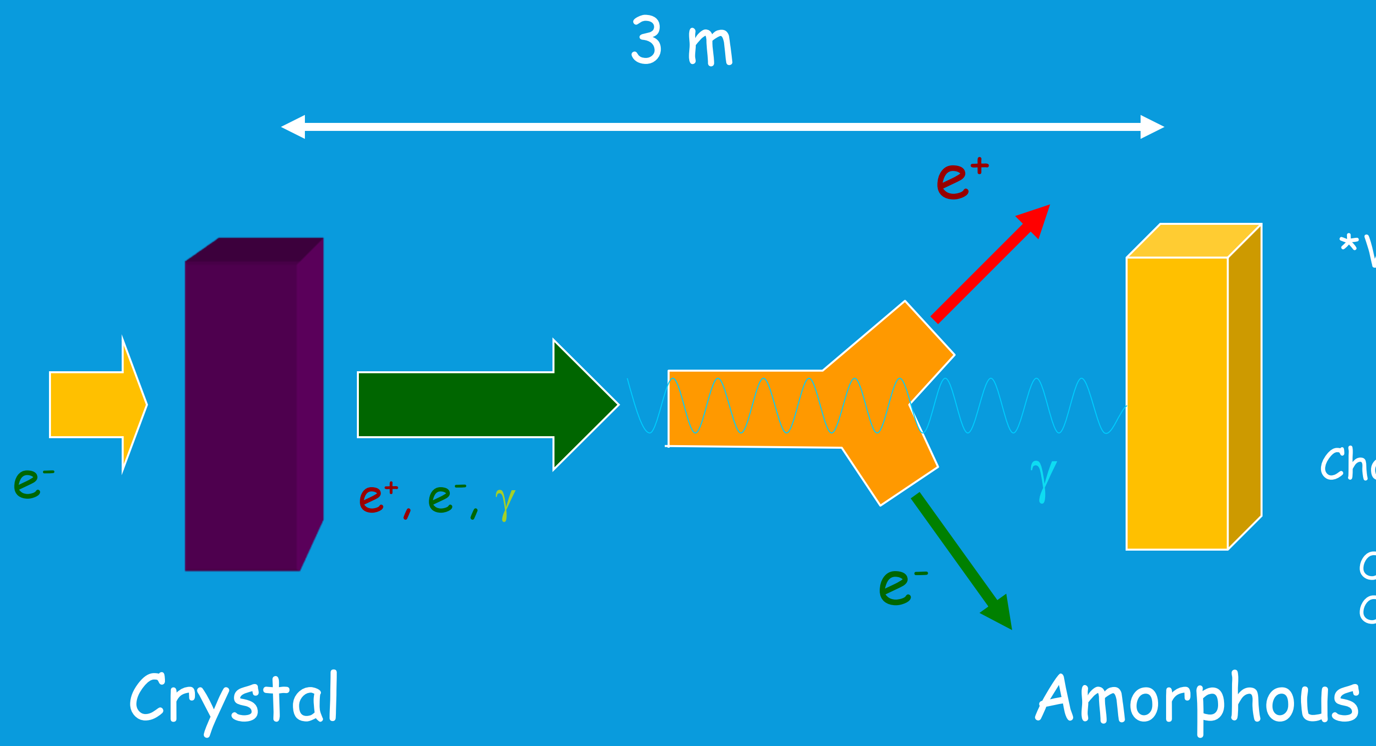
SEPARATED TARGET



Two targets are used: a *radiator* to produce the photons and a *converter* for the materialization of the photons in e+e- pairs
The radiator may be a source of photons as a magnetic undulator, a Compton backscattering device, a monocrystal providing channeling radiation,…The Converter is a piece of amorphous material (W, for example).

MOTIVATIONS FOR SEPARATE TARGETS
Obtaining polarized positrons using polarized photons produced in helical undulators or in Compton process
Avoid target destruction using a powerful g source (undulator, Compton) associated to a thin converter
Avoid excessive thermal heating using a crystal in channeling conditions delivering an intense photon beam associated to a thin converter
Improve significantly the positron yield using coherent pair production in oriented monocrystals with a photon beam at glancing incidence from the crystal rows; in that case, the converter is a crystal

APPLICATION -> HYBRID TARGET (CLIC BASELINE)



*crystal; 1.4 mm thick

*W,amorphous: 8mm thick

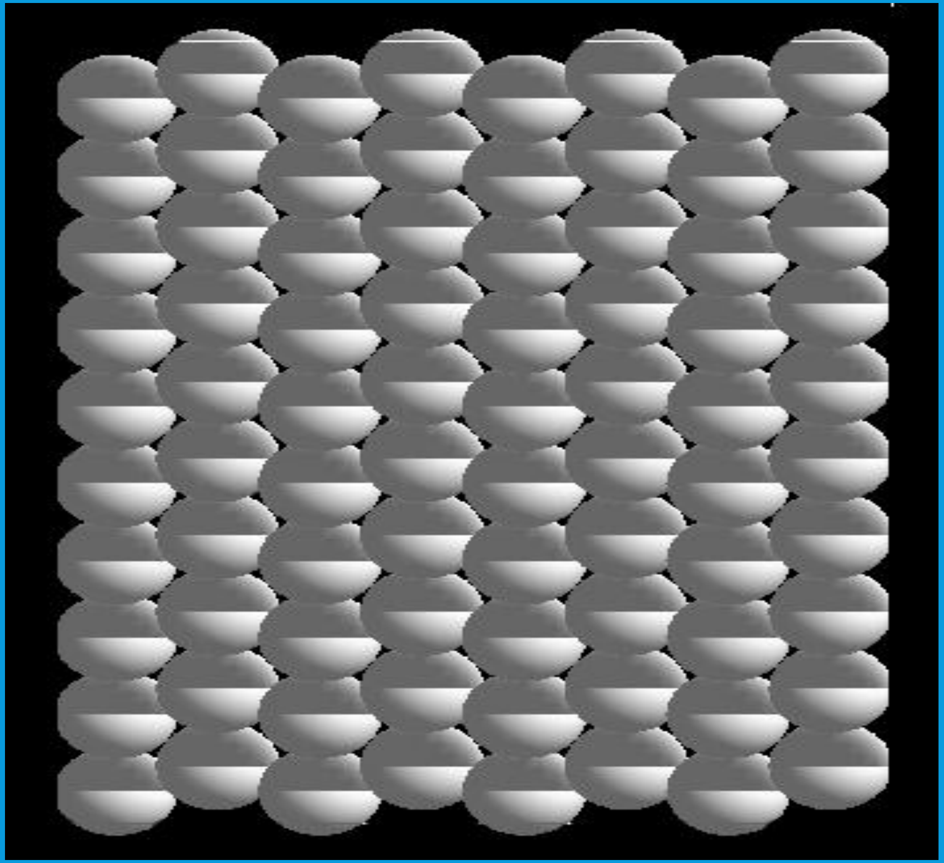
e- beam: 5 GeV

Charged particles, swept off

Only γ with E_γ > 2 MeV
On amorphous target

GRANULAR CONVERSION TARGET

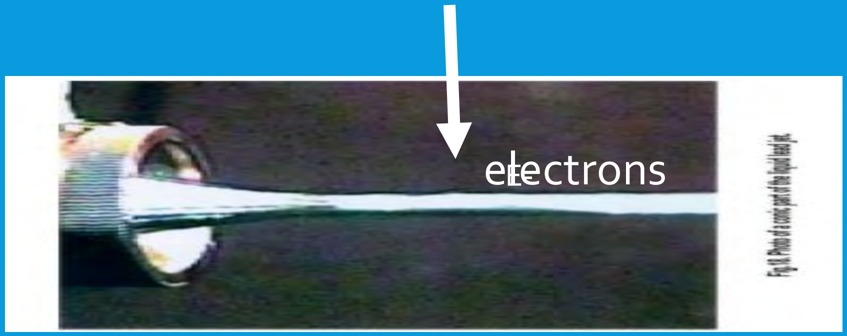
- 3-THE GRANULAR AMORPHOUS CONVERTER
- A granular converter made of small spheres of ~ mm radius offers the advantages of presenting a relatively high [surface/volume] ratio which is interesting for the power dissipation. Staggered rows of spheres have been considered, which leads to an effective density of about 72 % of pure W. The densest possible packing would be 85 % with special arrangement.



P.Sievers

THE LIQUID TARGET

- G.Silvestrov from Budker Institute.
- A free plain jet of liquid metal [gallium-indium alloy and lead] flowing out of a narrow nozzle is one of the proposed solutions. Mercury (Hg) has also been proposed previously. The main advantages of this kind of target are:
- # Heat removal
- # Avoid target destruction with high energy densities
- # Reduction of beam energy deposition due to side exit of the secondaries

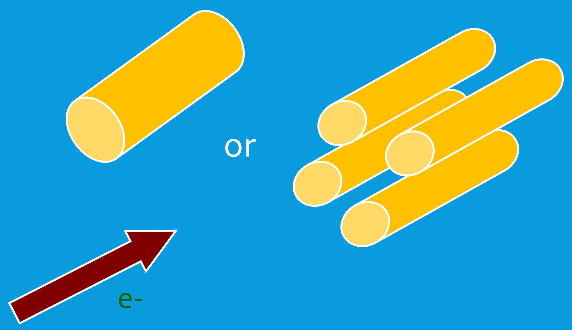


- Other possibilities consist in: concave liquid metal flow, mercury in aluminum containers,…

WIRE TARGET

positrons to leave the target without being absorbed before the downstream edge of the target, wire targets have been proposed (R.Miller et al, 1990). In these targets, positrons are allowed to emerge from the sides. For SLC beam (33 Gev incident) one mm diameter and 10 Xo long W wires showed promising results (3 x yield) [calculations by R.Miller et al]

- Similar conclusions were derived from a recent study (N.Shul'ga, 2006)



Appropriate focusing device is foreseen. The better collection is due to lower transverse momenta.

2 - PROTONS

- HIGH POWER!!!!!

WHAT ABOUT TARGET FAILURE

- Going to the MW range is not trivial!
- Increasing proton beam power without paying attention leads to uncontrolled energy deposition
- Causes excessive heating, Structural failure
- Above 20 % of the primary beam power are deposited in the target! 0.8 MW for a 4 MW beam (in the neutrino factory)

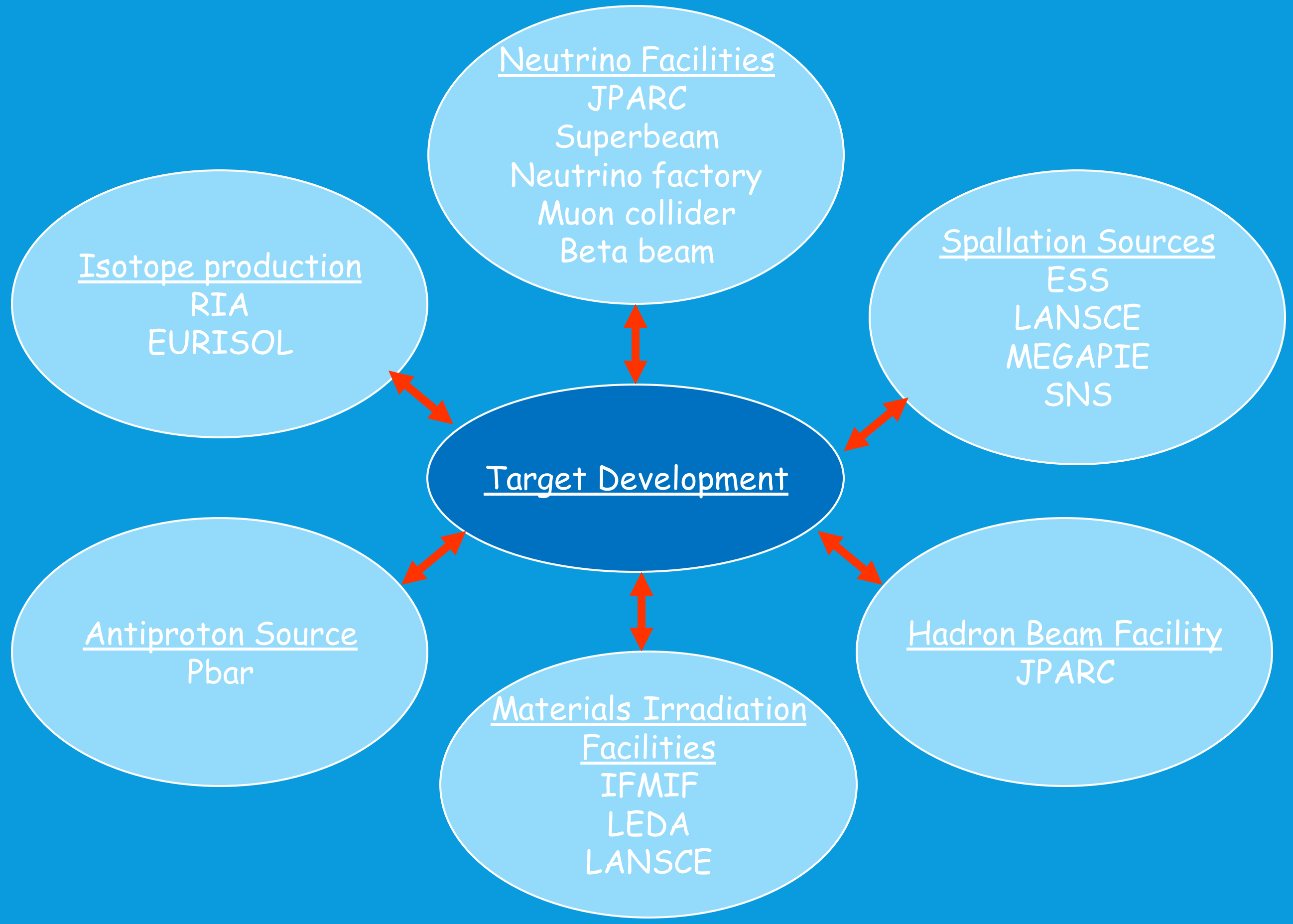
No quotation on purpose

FUTURE TARGET STATIONS

HIGH POWER TARGETRY
At present 300-400 kW

Future challenges: Pulsed DC (or CW) beams, Pulsed beams

Materials –
Solid Targets / Liquid Targets / Hybrid : fluidized powder target



TOWARDS 1 MW ON TARGET

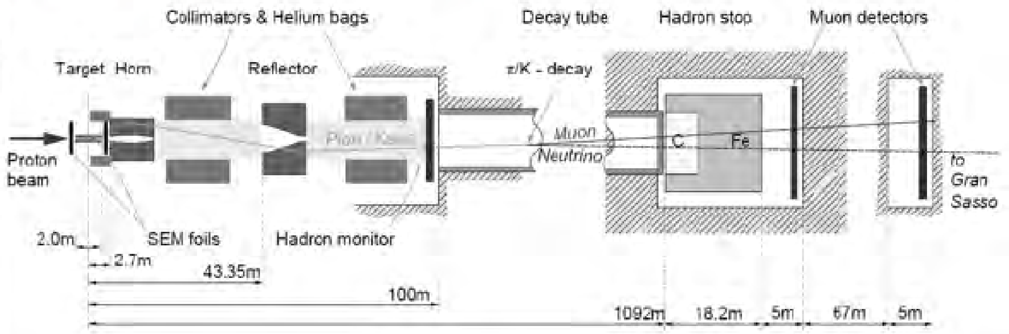
- CNGS: CERN neutrinos to Gran Sasso, start 2006
- 750 km neutrino beam line
- 0.75 MW proton beam power

- Target: graphite
  - high pion production
  - small α
  - good tensile strength
- 10x rods
  - l=10 cm, d=5 mm
  - Helium cooled

CNGS graphite target assembly (2005, D.Grenier et al.)

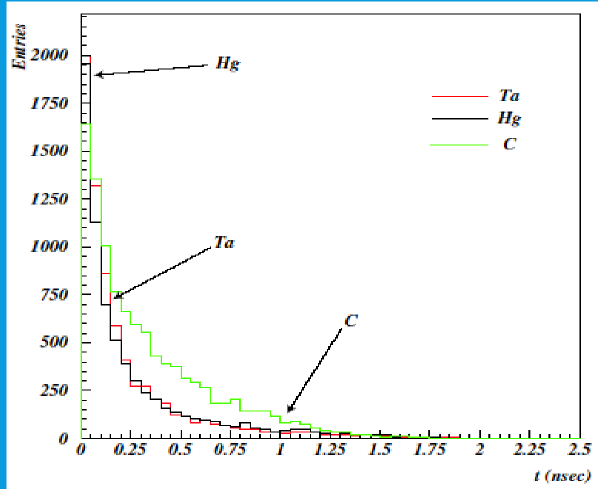
- **CNGS is a sub-MW class facility**
  - 350kW operation, target design up to 750kW)

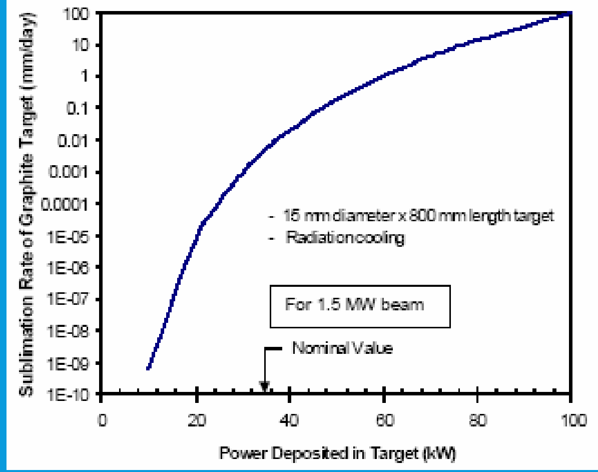
Proton beam parameters	
Energy	400 GeV/c
Cycle length	• 6 seconds • 2 extractions/cycle, 50ms apart
Extraction	• 2.4×10^{13} protons • 10.5 μs long pulse
Beam power	• 500 kW



CARBON A CANDIDATE FOR MULTIMW?

Pion time spread





Very good material properties like thermal expansion, but …

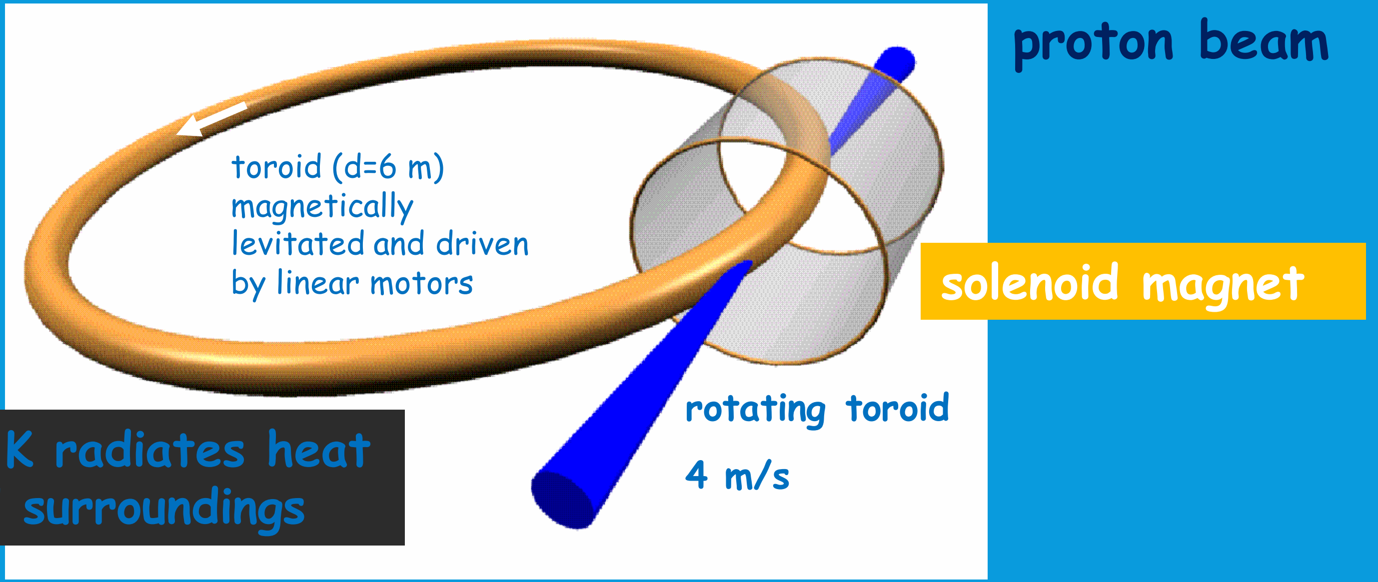
- For Carbon 2 λ_I = 80 cm → target not point-like
  - difficult to find an efficient horn design
  - cost of the solenoid capture

- Pion time spread large , Carbon would add > 0.5 nsec

- A Carbon target in vacuum sublimates away in one day at 4MW.
- Radiation damage limits lifetime to about 12 weeks

ROTATING TOROIDAL TARGET

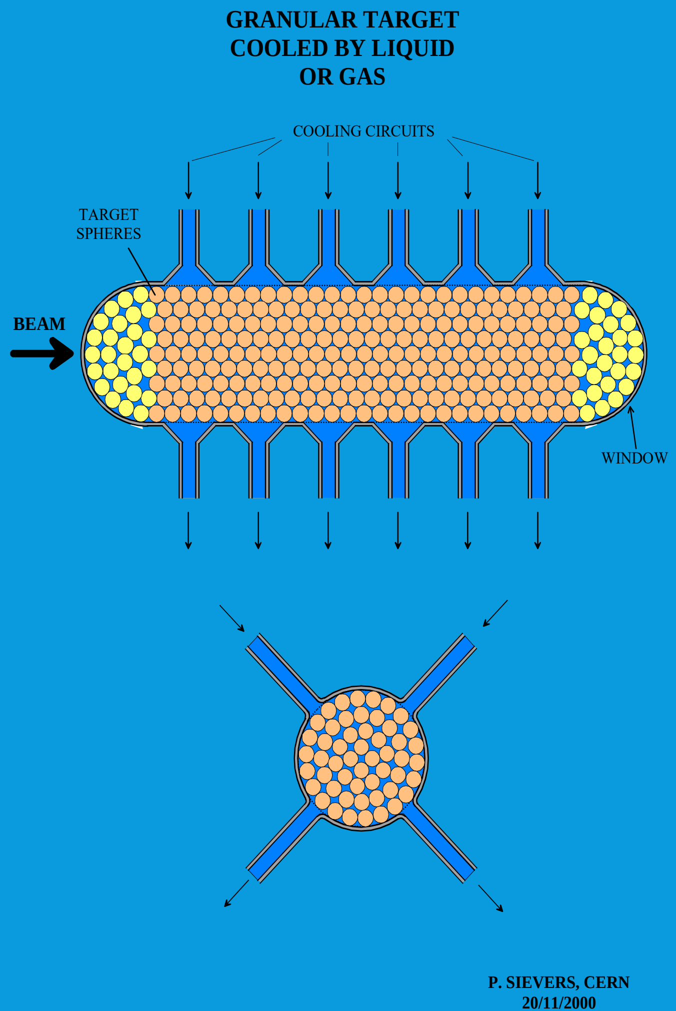
- Distribute the energy deposition over a larger volume
  - Similar a rotating anode of a X-ray tube



Toroid at 2300 K radiates heat to water-cooled surroundings

- Tensile strength of many metals is reached with stresses induced by the equivalent of a 1.5 MW proton beam → structural failure

GRANULAR TARGETS



Tantalum Spheres: ∅ = 2 mm, $\rho = 0.6 \times 16.8 \approx 10$ g / cm^3

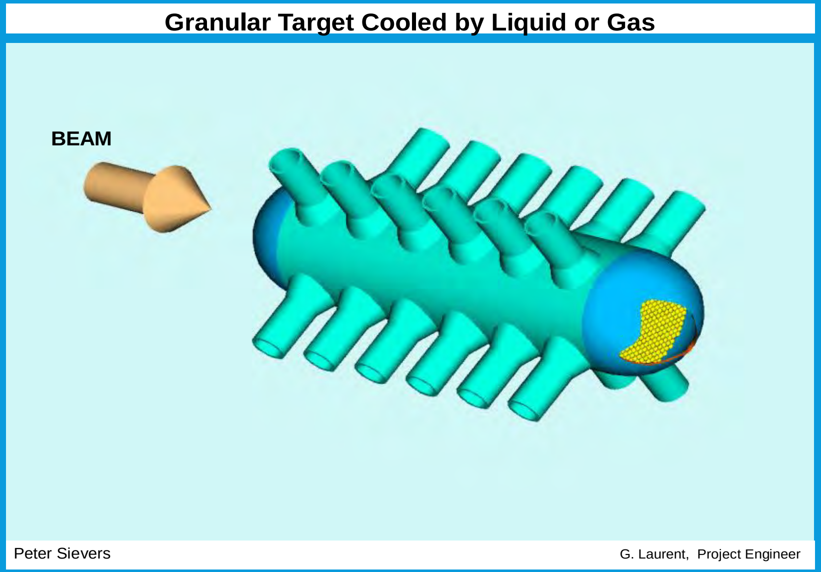
Small static thermal stress: Each sphere heated uniformly.

Small thermal shock waves: Resonance period of a sphere is small relative to the heating time

Large Surface / Volume: Heat removed where deposited.

Radiation/structural : damage of spheres, container and windows: Lifetime of Target

- Volume of Tantalum beads, d~2mm
- Cooled by liquid or gas



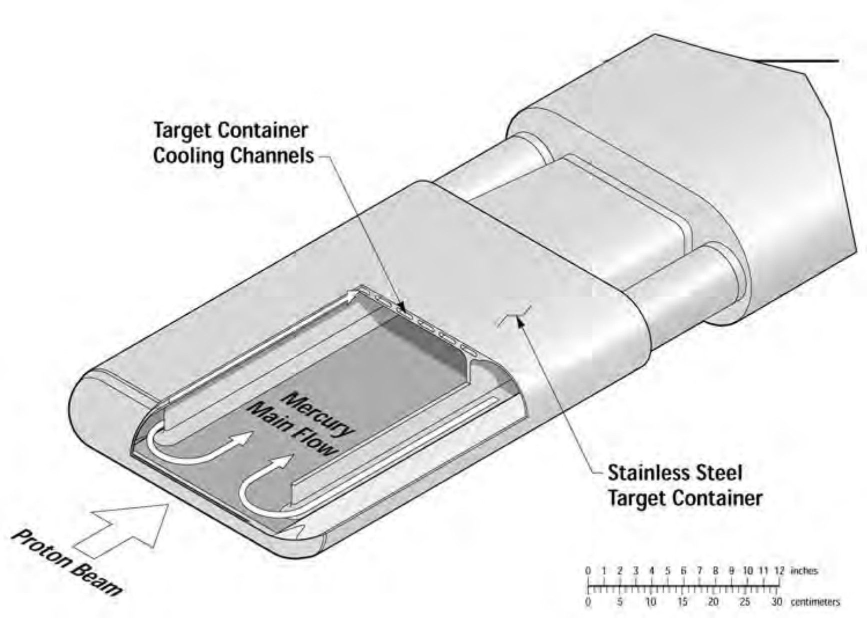
CONTAINED LIQUID TARGET

- SNS, ESS: high power spallation neutron sources
- 1m/s mercury flow
- Liquid immune to stresses
- passive heat removal
- No water cooling

- Not an option for charged particles…losses

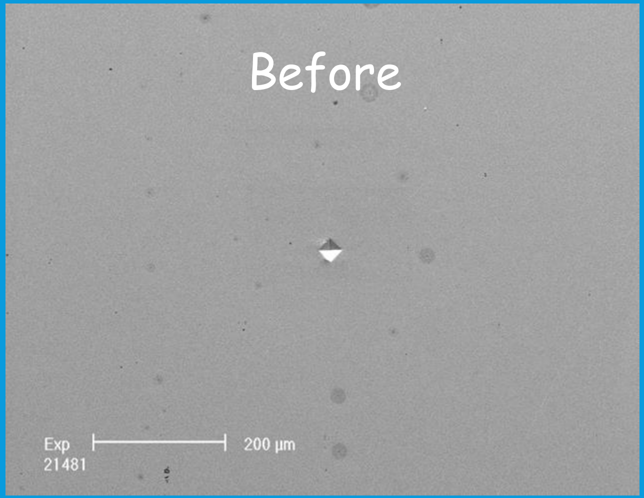
!!! Beam window:

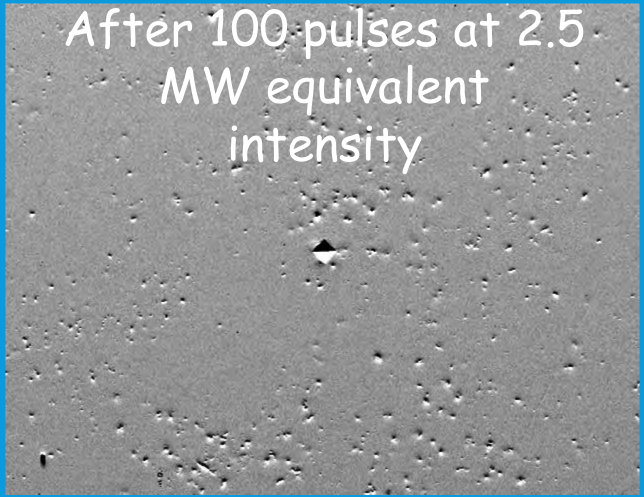
- Beam induced stresses
- Cavitation induced erosion (pitting)



- MERCURY
- Advantages
  - High Z
  - Liquid at ambient temperature
    - Highly convenient for R&D
  - Easily available
- Disadvantages
  - Toxic
  - "only" compatible with very few materials
    - Stainless steel, Titanium, EPDM, …
  - High thermal expansion coefficient

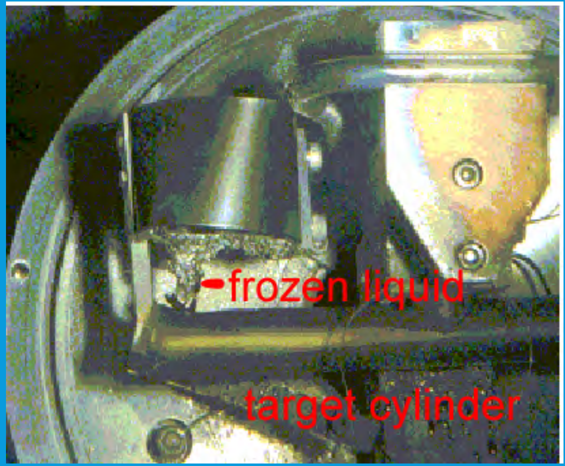
CAVITATION INDUCED EROSION (PITTING)





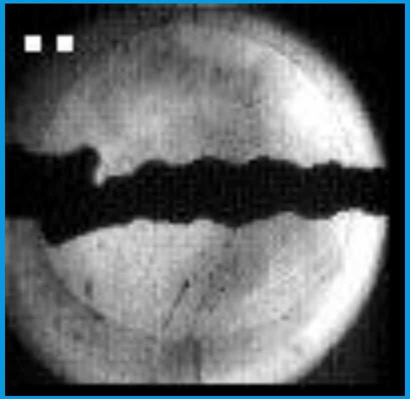
"solved by":

- surface treatment
- Bubble injection



Containment failure

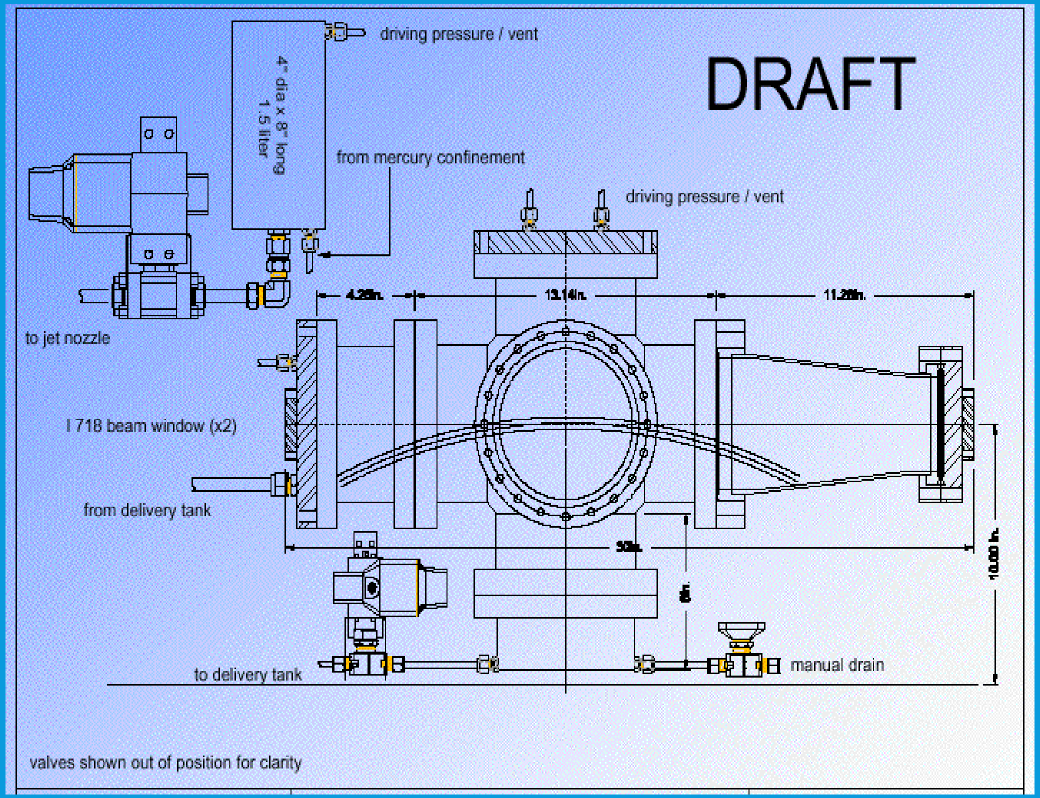
HG JET TEST A BNL E-951



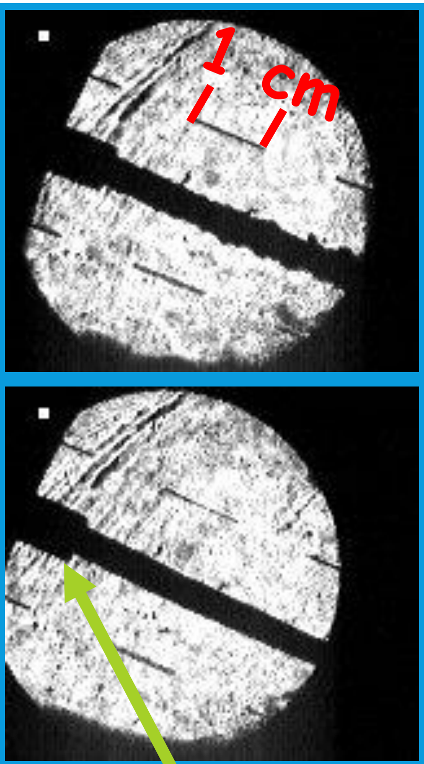
Protons

P-bunch: 2.7×10^{12} ppb
100 ns
t_0 = ~ 0.45 ms

Hg- jet : diameter 1.2 cm
jet-velocity 2.5 m/s
perp. velocity ~ 5 m/s



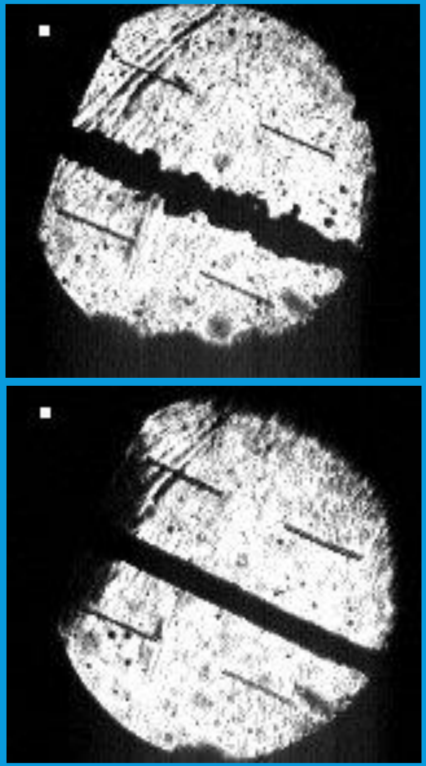
EXPERIMENTAL RESULTS

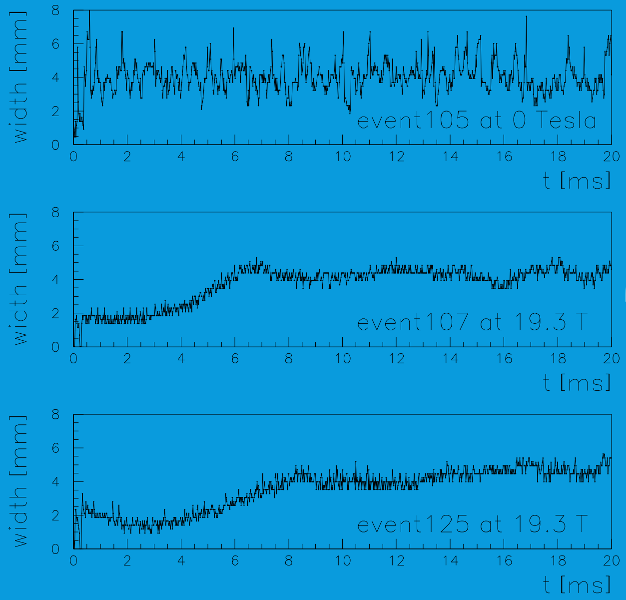


0 Tesla

20Tesla

nozzle



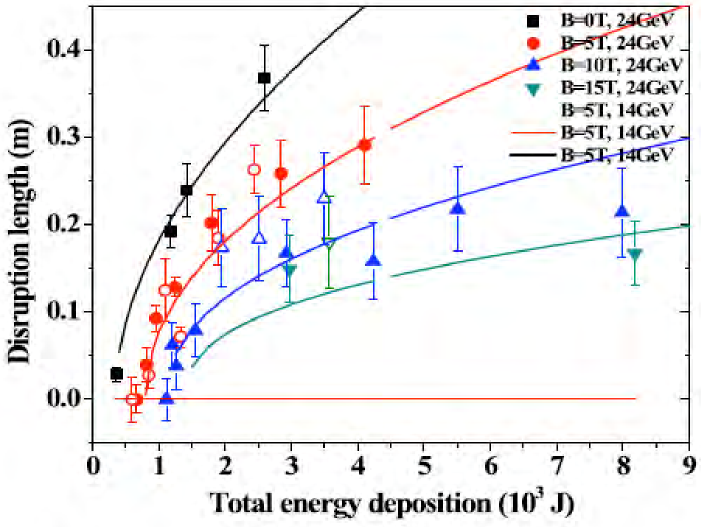


B=0 T

B=19.3 T

15 m/s mercury jet injected into 20 T field.

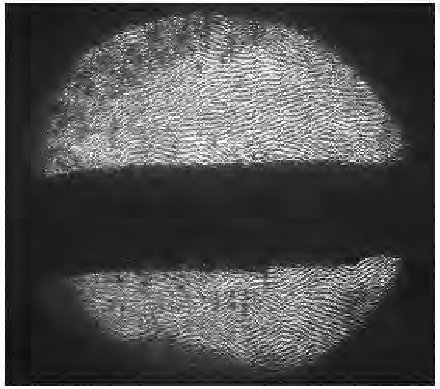
MERIT EXPERIMENT CERN



Key results #1

- Hg-jet disruption mitigated by magnetic field
- 20 m/s jet operation allows up to **70Hz** operation with beam

Hg-jet – beam impact
4×10^{12} protons, 10T field

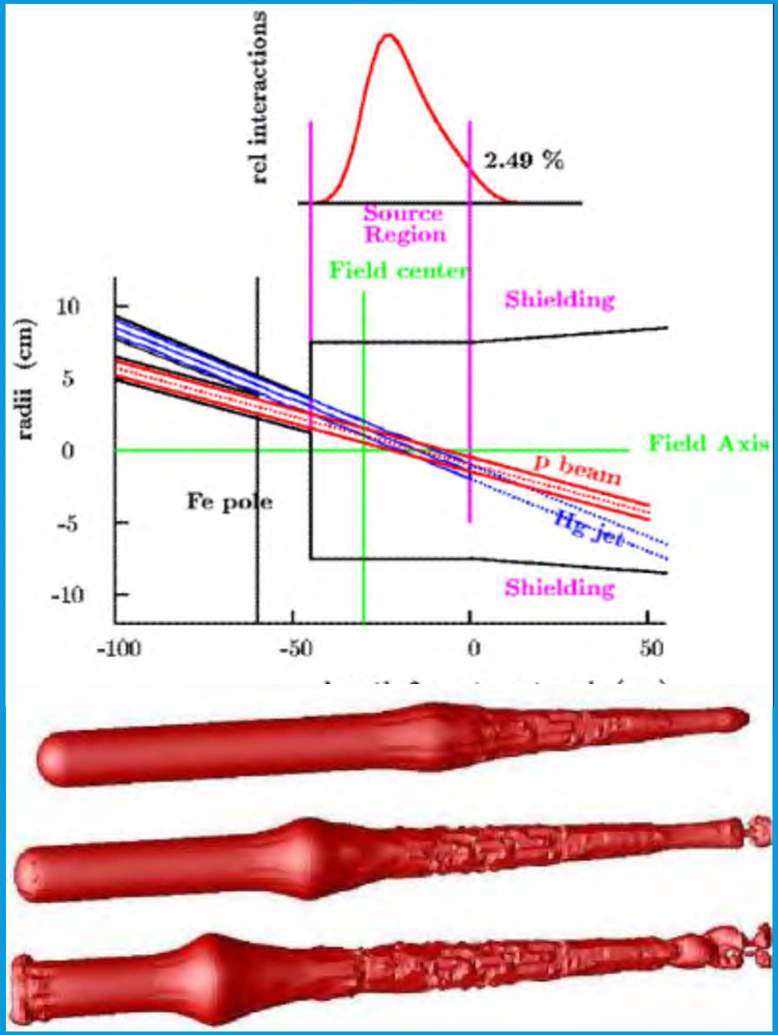


Key results #2

- Disruption threshold: **>4×10^{12} protons@14 GeV, 10T field**
  - **115kJ** pulse containment demonstrated
  - **8 MW** capability demonstrated

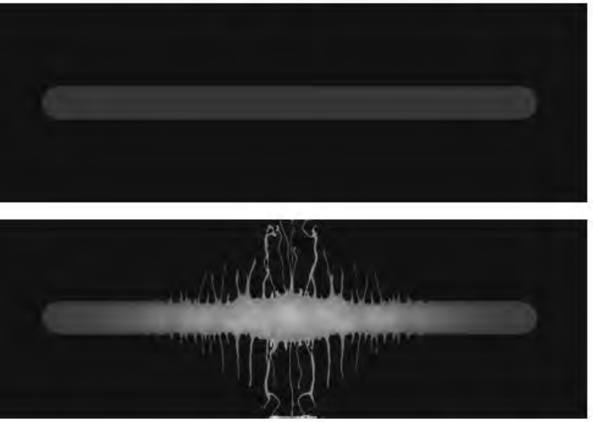
MAGNETO-HYDRO-DYNAMICS CODES

- 20-T solenoid DC-field for sec. particle capture
- Moving mercury target sees dB/dt
- Farady's law → eddy currents induced
- Magnetic field acts back on current and mercury jet
- Forces: repulsive, deflecting, quadrupole deformation, …

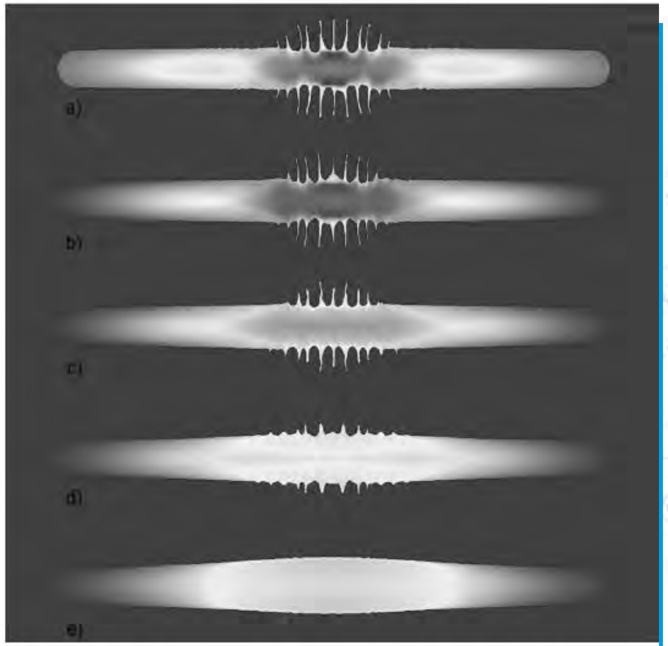


SIMULATION: SHOCKS

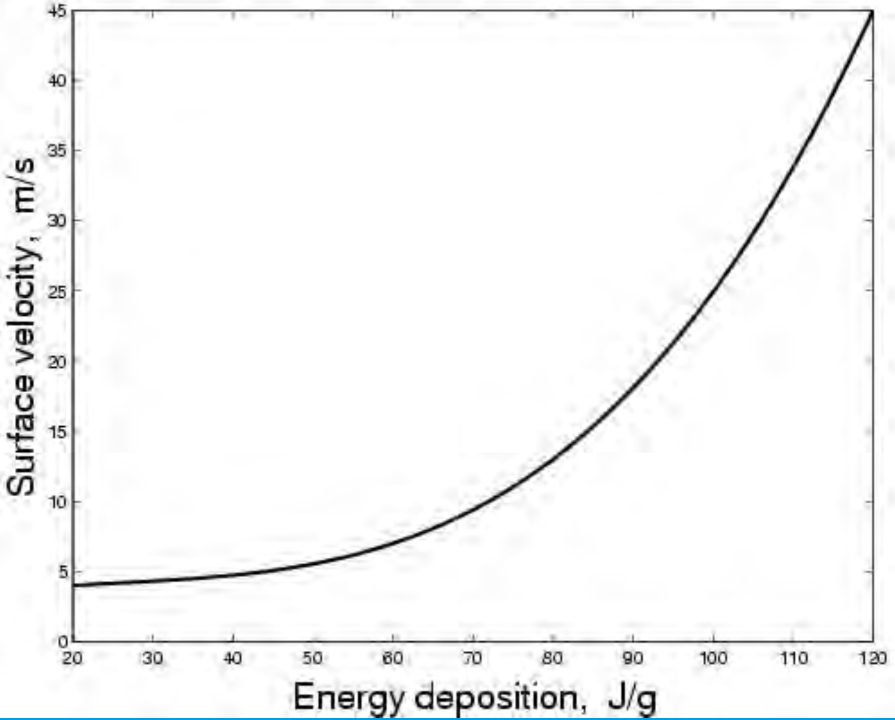
Frontier code, R.Samulyak et al.



- Simulation of the mercury jet – proton pulse interaction during 100 microseconds, B = 0
- damping of the explosion induced by the proton beam

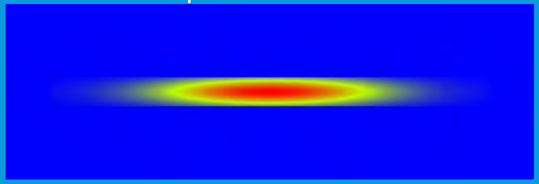


a) B = 0 b) B = 2T c) B = 4T
d) B = 6T e) B = 10T

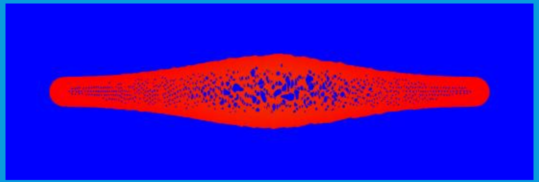


Initial density

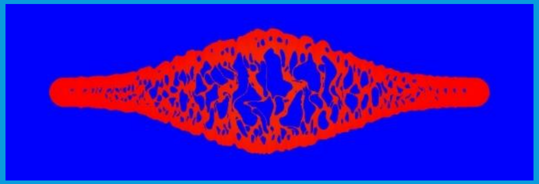
Initial pressure is 16 Kbar



Density at 20 microseconds



400 microseconds



RADIATION AND NEUTRONS

WHY?

- Disposal of nuclear waste

-Nuclide inventory needed before disposal

- Future installations – facilities

- Estimation of the accumulated waste after operation
- Dose rates for shielding dimensioning

- Dismantling

- Dose rates are mandatory for the interventions

In all estimations cross validations with measurements are needed…..

RADIOACTIVITY - WHEN A MATERIAL IN CONSIDERED AS RADIOACTIVE?

- Radioactive-> All emitting material that needs to be managed in the regulation (IAEA) to avoid adverse effect on health and environment.
- ACTIVITY : decay/sec, unit Bq → condition: $\sum_i \frac{A_i}{R_i} > 1$

with A_i : specific activity [Bq/g], R_i: exemption limit provided in the RADIOPROTECTION REGULATION

OR

- EQUIVALENT DOSE RATE D: biological factor x absorbed energy/kg [Sv/h] : takes into account the biological damage

ITALY - no radiologic relevance 10 μS/y, D> 0,1 μS/h roughly , free access zone

OR

- SURFACE CONTAMINATION:

>1 Bq/cm^2 for unidentified β and γ emitters

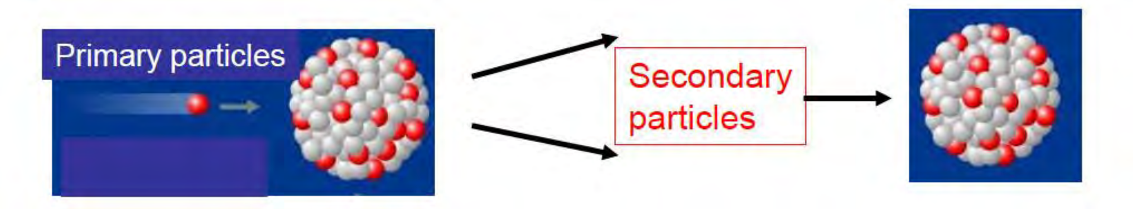
>0.1Bq/cm^2 for unidentified α emitters

>CS-value (provided in radioprotection regulation) for a specific isotope

ACTIVATION

- INTERACTION OF A BEAM WITH THE MATERIAL NUCLEUS

Nuclear reactions-> Variation in the proton or / and neutron number -> Transmutation into other isotopes, often the new isotope is radioactive



Production rate (Isotope/s):

$$P_Y = N_A n_x \int \frac{d\phi_x(E)}{dE} \cdot \sigma_{xA \to Y}(E) \cdot dE$$

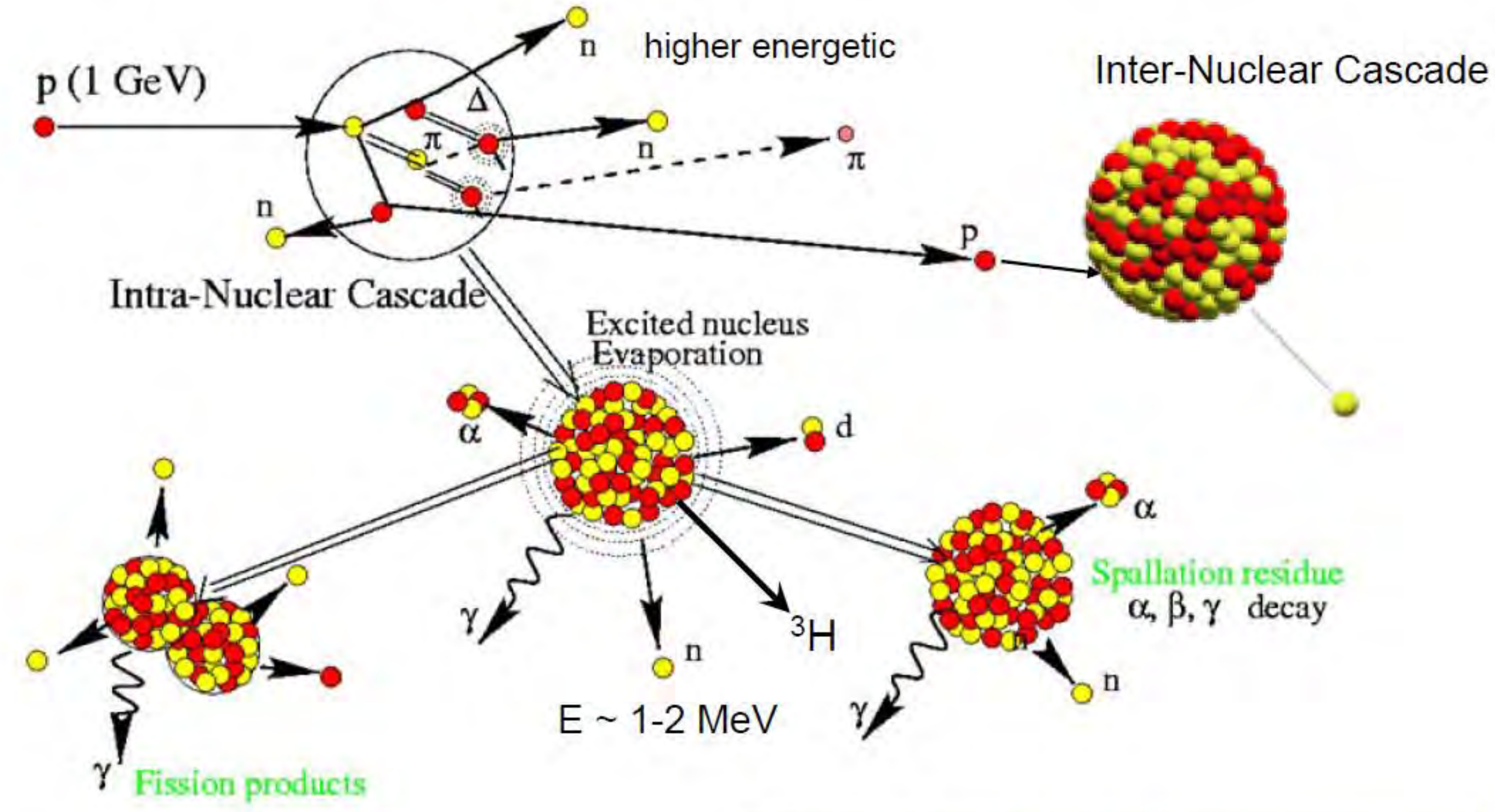
with $\sigma_{xA \to Y}$ = cross section for the process+ secondaries,

fluence ϕ : energy distribution per unit area [cm^{-2}]

N_A : Nuclei Number

n_x : beam particles impinging per second (with energy roughly above the MeV threshold, average binding energy per nucleon)

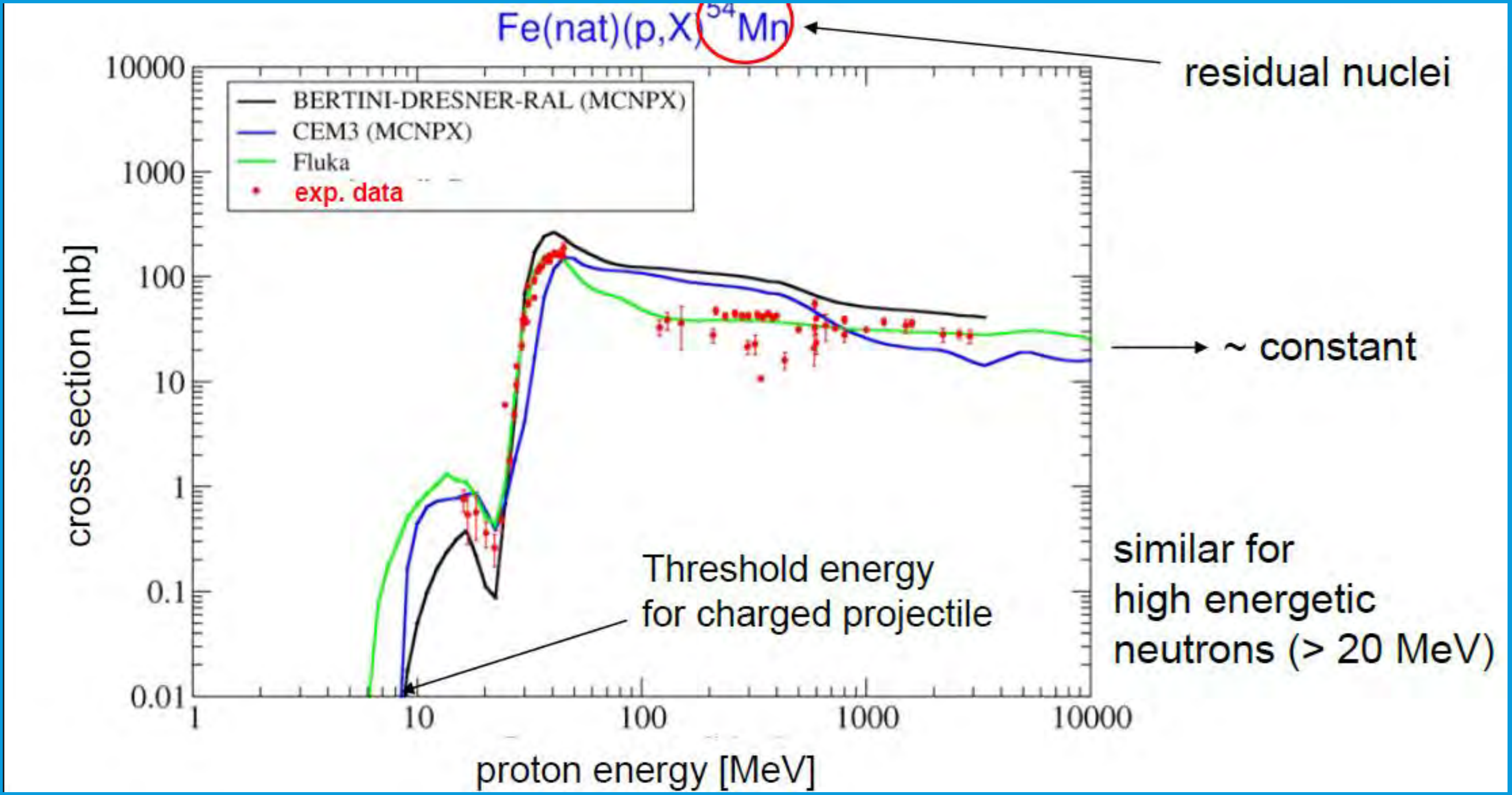
EXAMPLE



Example:
Pb-Target: ~ 20 n/p,

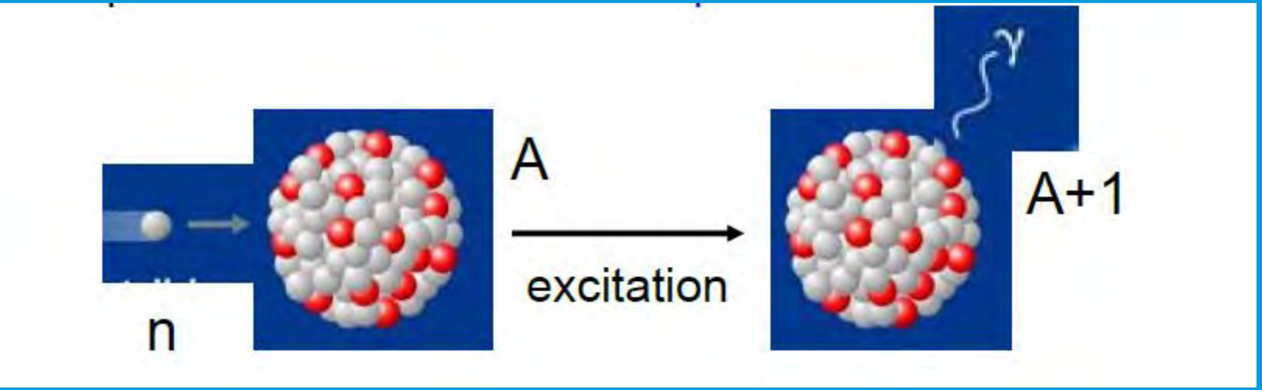
complicated coupled processes
→ Monte Carlo Simulation (MCNPX)

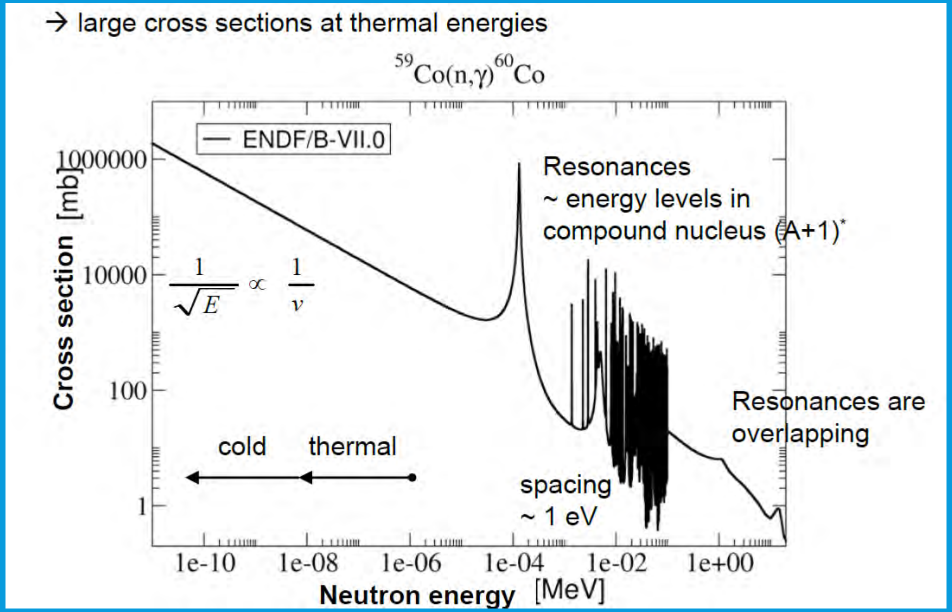
CROSS SECTION



REACTION IN THE ENVIRONMENT

- Mainly secondaries
- Charged particles slow down and are absorbed, it remains neutrons -> moderate and thermalize mainly with collision with light nuclei.
- Then another important reaction : Neutron capture





ACTIVITY

- Number of activation per second per cubic centimetre in a material is called ACTIVATION RATE -> R
- $R = N\,\sigma\Phi = \Sigma\Phi$

with

- N = number of nuclei per cm3 (taking ρ= density, A_m= Atomic mass and the Loschmidt constant NL= 6,025 $10^{23}mol^{-1}$)$\longrightarrow N = \frac{\rho N_L}{A_m}$,

-σ =cross section (barn – 10^{-24} cm^2) -> $\Sigma=\sigma\Phi$ -> macroscopic cross section (mean free path in the material before activation)

- Φ= Fluence [act. particles/cm^2]

- K = number of existing activated nuclei and

- A = activity -> number of decay per second (proportional to K)= -dK/dt =λK

– λ is the decay constant = $\ln 2/T_{1/2}$ $T_{1/2}$ = half life

ACTIVITY

DECAY1 ISOTOPE (simplest case) only activation, $A(t) = -\frac{dK(t)}{dt} = \lambda \mathrm{K(t)} = -\frac{dK_0 e^{-\lambda t}}{dt} = \lambda K_0 e^{-\lambda t}$

Adding the production phase

$$\frac{dK(t)}{dt} = \Sigma\Phi - \lambda K(t) \; with \; K(0) = 0 \rightarrow K(t) = \frac{\Sigma\Phi}{\lambda}\left(1 - e^{-\lambda t}\right) \rightarrow \mathrm{A(t)} = \Sigma\Phi\left(1 - e^{-\lambda t}\right)$$

In bracket lim-> 1 , so it exists a Saturation Activity (A(∞)) -> $A_{sat} = \Sigma\Phi$ (for $K(t) < K_0$ daughter<<parents)

Let's evaluate K_0 after irradiation for a time 0-t_{irr}-> $K_0 = K(t_{irr}) = \frac{\Sigma\Phi}{\lambda}\left(1 - e^{-\lambda t_{irr}}\right)$

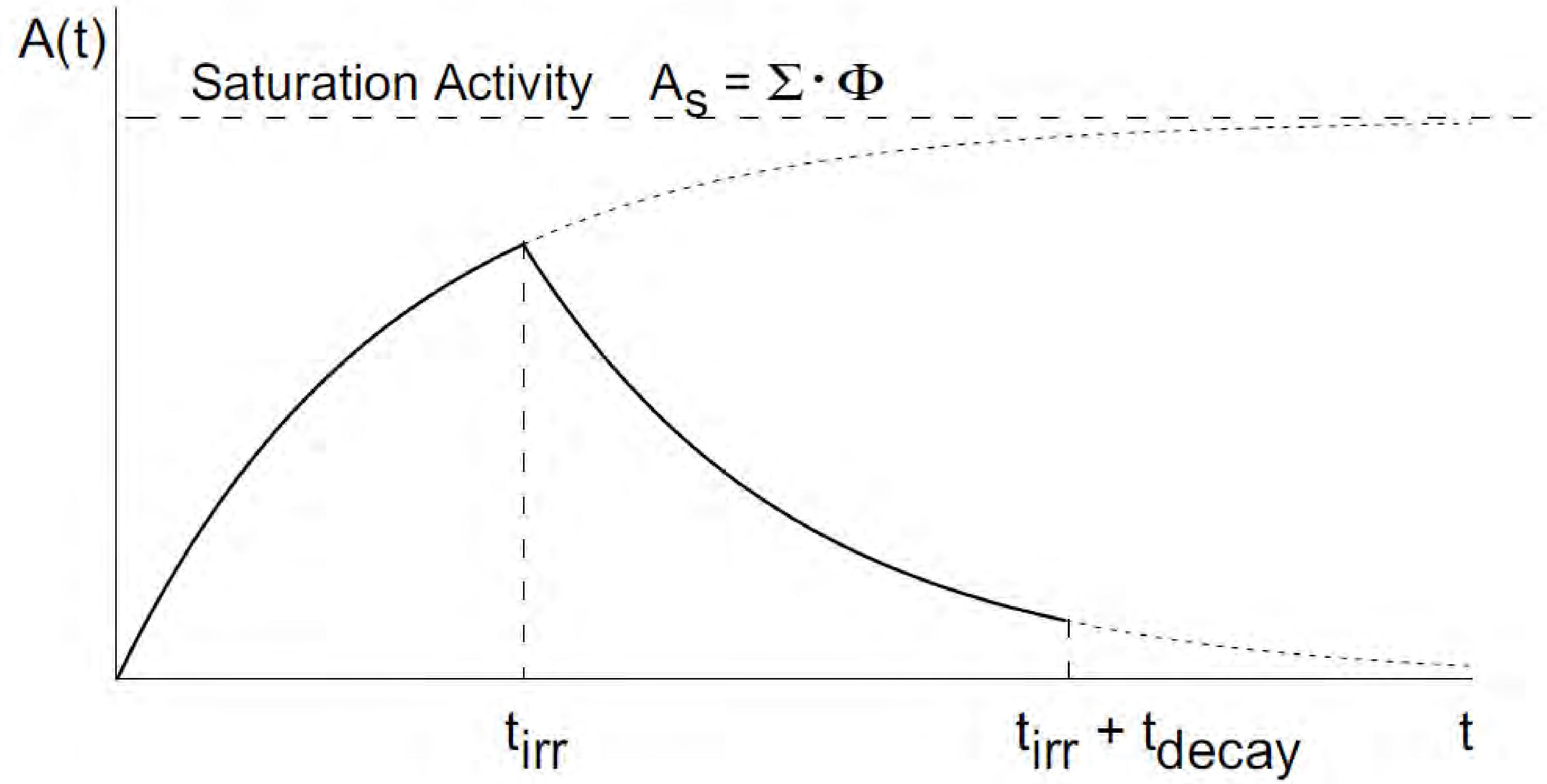
So the number of active nuclei after tirr will be $K\left(t_{decay}\right) = \frac{\Sigma\Phi}{\lambda}\left(1 - e^{-\lambda t_{irr}}\right)e^{-\lambda t_{decay}}$

Giving the decay (cooling) activity $A\left(t_{decay}\right) = \Sigma\Phi\left(1 - e^{-\lambda t_{irr}}\right)e^{-\lambda t_{decay}}$

For many isotopes we have to evaluate the contribution via the following formula

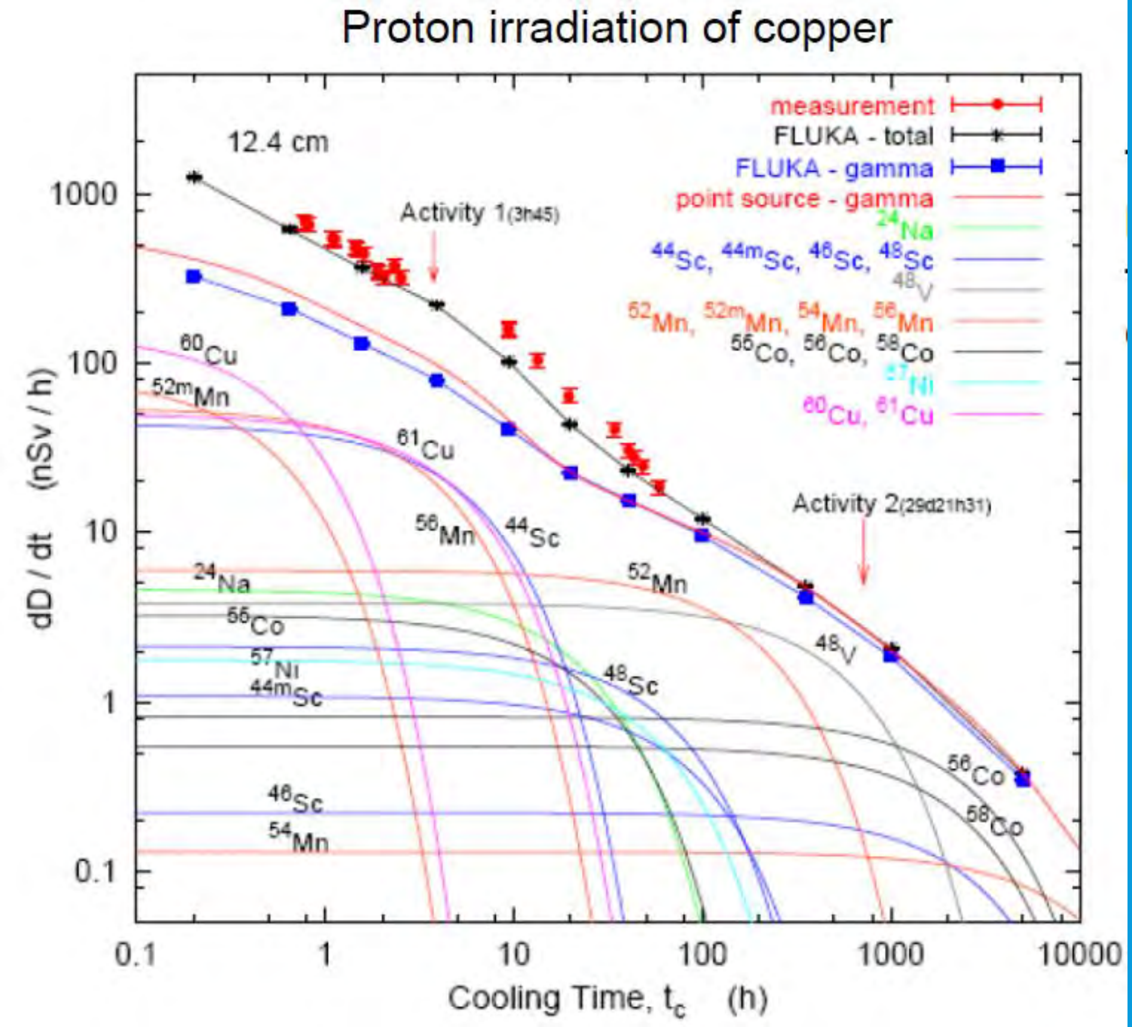
$$\frac{dK_m(t)}{dt} = \sum_{k \neq m} K_m(t)\, \Phi\sigma_{k \rightarrow m} - K(t)\left(\lambda_m + \Phi\sigma_m^{abs}\right)$$

The first term takes into account the production
The second the losses due to decay and absorption



A(t)
Saturation Activity $A_S = \Sigma \cdot \Phi$
t_{irr}
$t_{irr} + t_{decay}$
t

IN TOTAL : CU FOR EXAMPLE



EXAMPLE, PSI WASTE EVALUATION

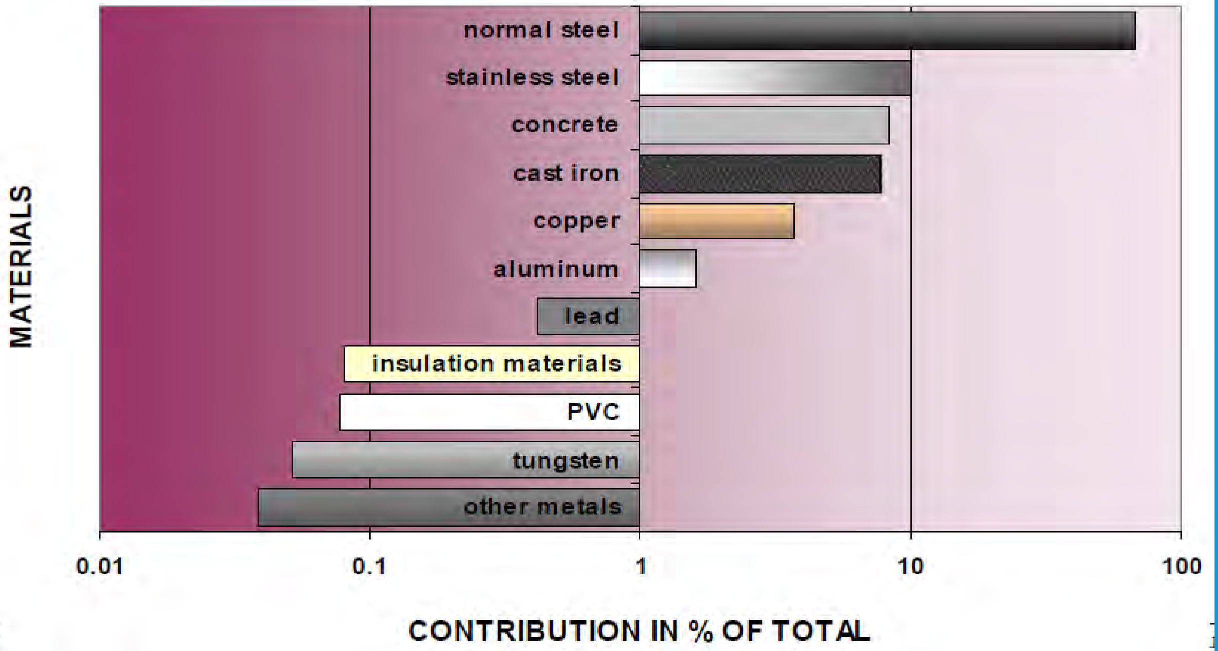
mainly low level waste: $1 < \sum_i \frac{A_i}{R_i} < 1000$

For final disposal:

- filled into concrete containers or steel drums
- components fixed with concrete (conditioning)

  Accelerator waste at PSI:

  activity per container: 10^{10} – 10^{12} Bq (4.5 t of waste)



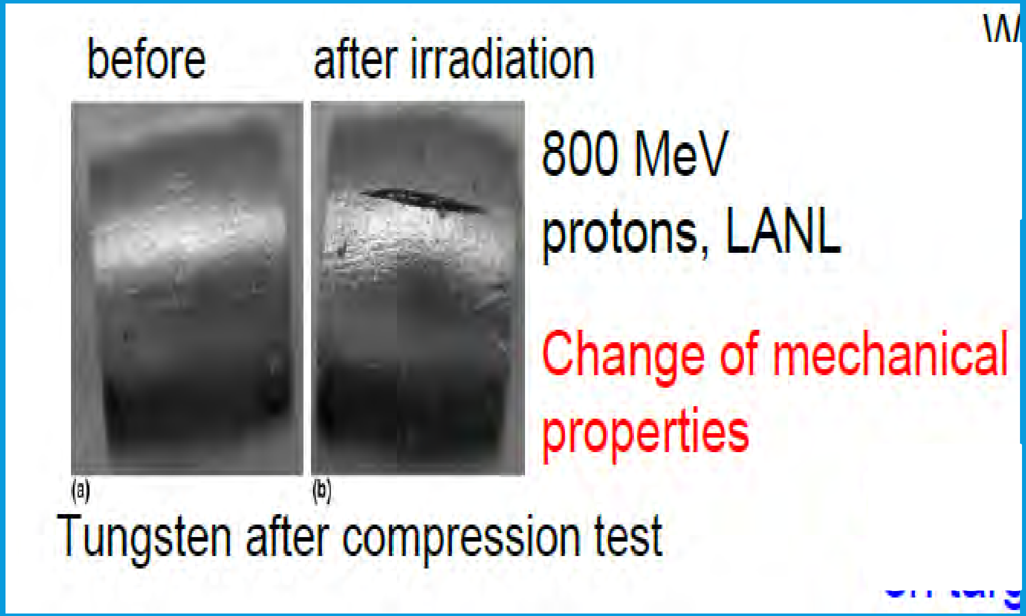
PSI,

RADIATION DAMAGE

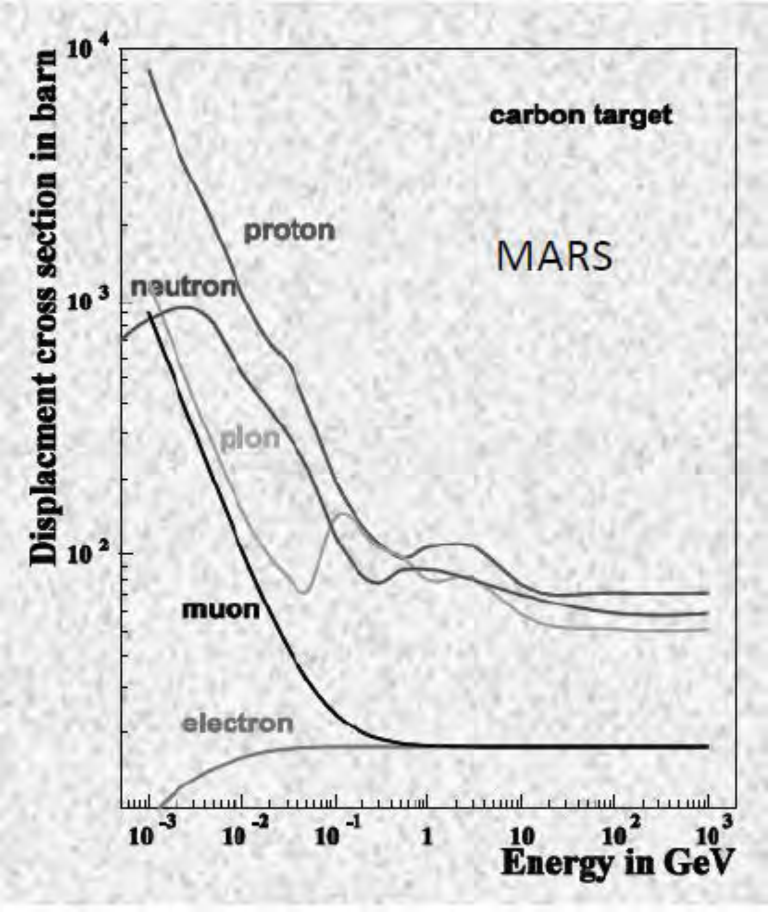
RADIATION DAMAGE - MACROSCOPIC EFFECTS

Effect on Material
Degradation of mechanical properties
1) Hardening (tensile strength variation) – ductility
2) Embrittlement -> cracks and creeps
3) Growth and swelling (bubbles)
4) Segregation of alloy elements

Physical properties
1) Thermal conductivity – Electrical resistivity
2) Thermal expansion
3) Thermoelectric voltage



- Radiation damage (change of the crystalline structure of materials, deterioration of the physical properties) is analysed as a function of displacement per atom (DPA)
- DPA = f(particles type, beam parameters, material, environment (T,P))
- Typical murders -> low energy neutrons Z2 dependence of slow particles, He gas production for high energy target
- DPA not 'micro'measurable – a lot of data for irradiation, difficult to extrapolate to small beam sizes.



EXAMPLES

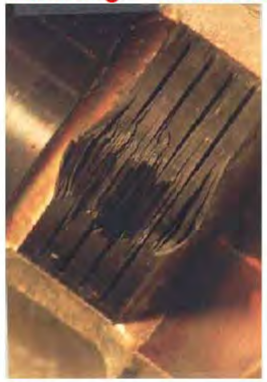
Mechanical

NSCL, MSU

crack

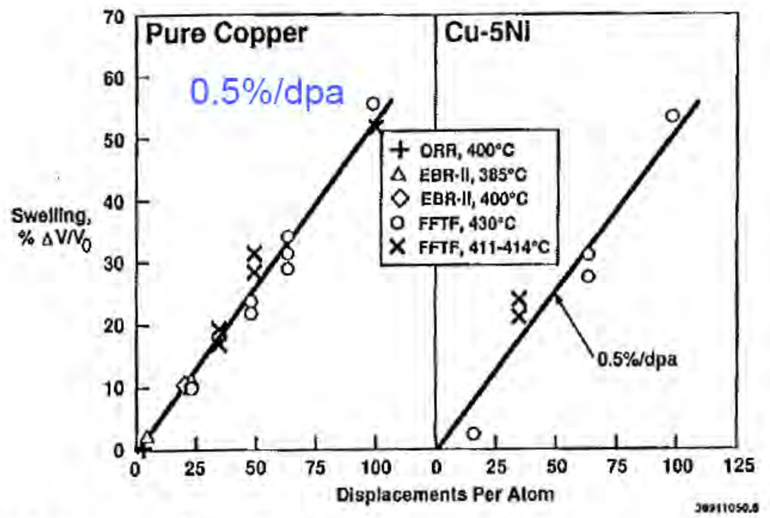
Tungsten target 580 mg/cm2 (0.03 cm) $^{76}Ge^{30+}$ at 130 MeV/nucleon (5.77 x 10^{16})

swelling + deformation



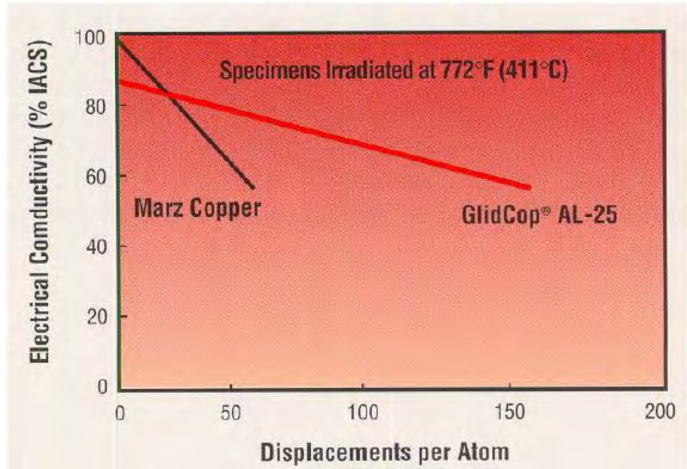
500 MeV protons

Water-cooled/Edge-cooled graphite target at TRIUMF

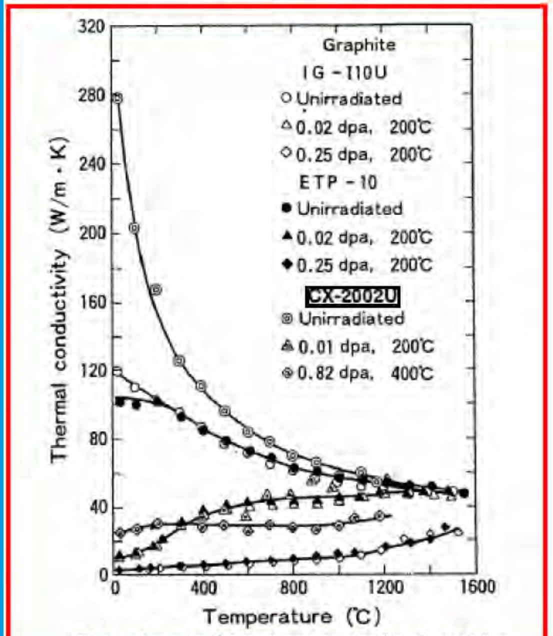


Physical

Copper + Glidcop

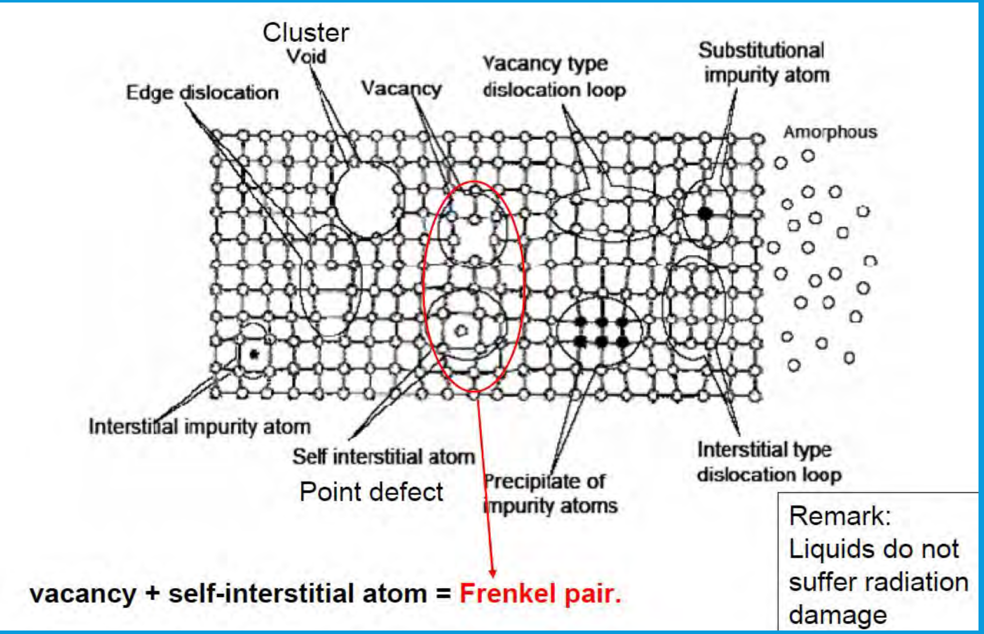


Graphite



Thermal conductivity of neutron-irradiated graphites.

MICROSCOPIC AND SUBMICROSCOPIC EFFECTS



- DPA in cascade - Mechanism:
- 1) p/n interaction -> nucleus recoil

The recoiled nucleus loses energy by ionization – heating

The available energy for nuclear reaction (damages) is $E_{dam} = En_{recoil} - En_{ioniz}$

To displace an ATOM it is necessary to overcome a threshold (Displacement energy E_D) to break the bond. This is ~ twice the sublimation

Typical Energies . Cu 30eV, Fe, Ni, Co 40eV

It is possible to identify two regimes:

1) $E_D < En_{recoi} < 2{,}5E_D$ -> 1 Atom is displaced -> creation of a lattice vacancy

2) $En_{recoi} > 2{,}5E_D$ -> Local cascade of collision -> displacement spike

(few nm diameter after 1ps for En_{recoi} =10kEv)

DISPLACEMENT PER ATOM (DPA)

$$\sigma_{dis}(E) = \int_{E_D}^{E_{max}} \frac{d\sigma_{Dam}(E, E_{Recoil})}{dE_{Recoil}} f_D(E_{Recoil}) dE_{Recoil}$$

With

$\sigma_{Dam}(E, E_{Recoil}) = damage\ cross\ section\ \rightarrow \frac{\delta(E_{Recoil})}{T\ \rho},$

$\delta(E_{Recoil}) = recoil\ spectrum, T = tagret\ thickness, \rho = Atomic\ density$

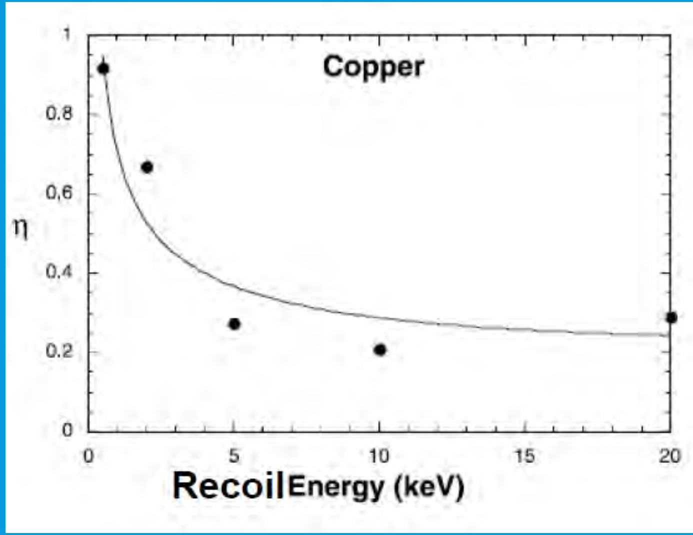
$f_D(E_{Recoil}) = \frac{0{,}8\ E_{dam}(E_{Recoil})}{2E_D} = damage\ function$

ED is subject of errors , 0,8 is a calculated coefficient….

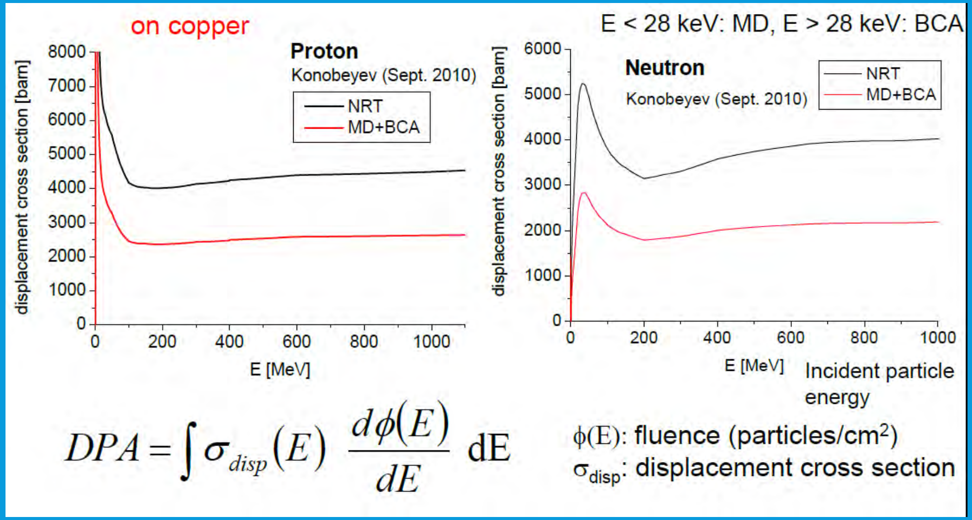
So, DPA - displacement per Atom, number of displacement in the irradiation

$$DPA = \int \sigma_{dis}(E) \frac{d\Phi(E)}{dE} dE$$

$\Phi(E)$= Fluence [particles/cm^2]



DEFECT PRODUCTION EFFICIENCY



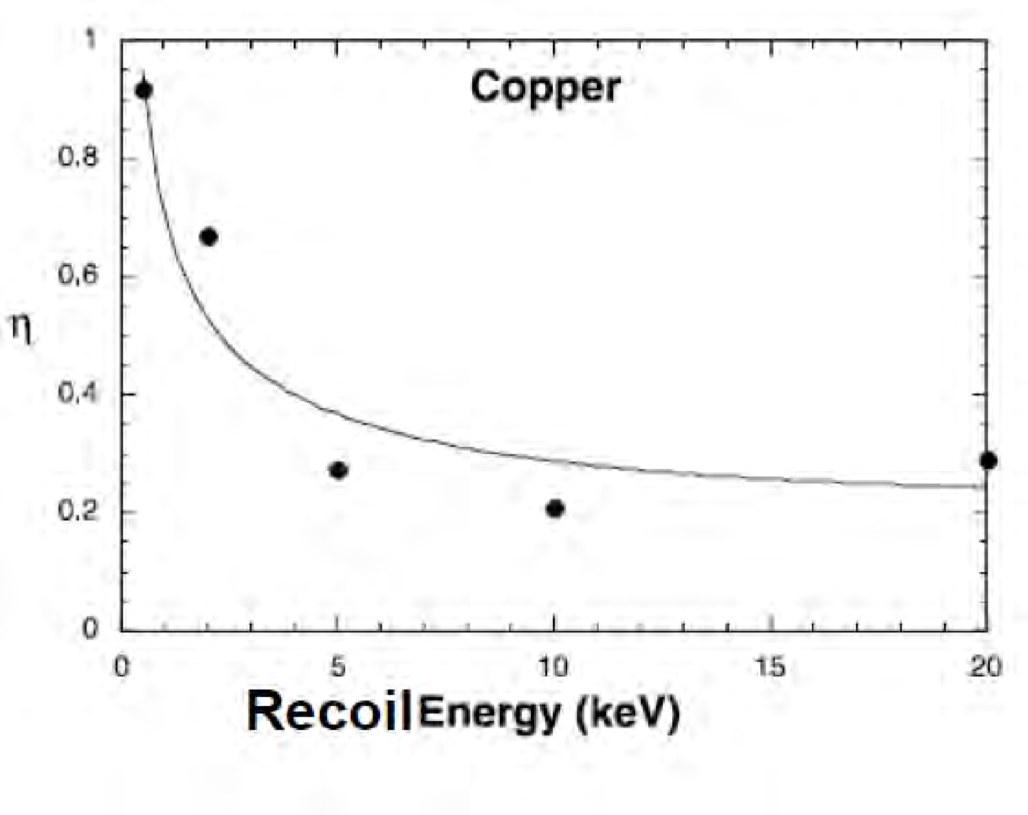
DPA is quantitative but it cannot be measured, since only a fraction leads to permanent (measurable) defects
So the Defect Production Efficiency is introduced

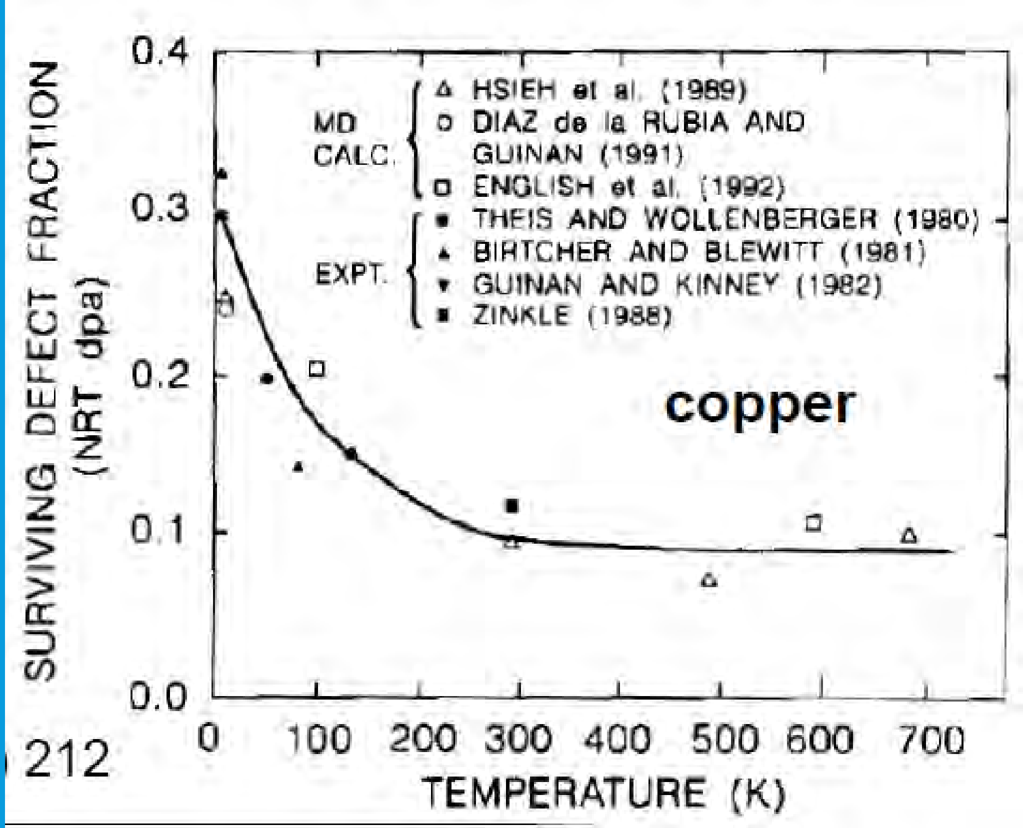
$$\eta = \frac{N\ permanent\ defects}{N\ Displacement \rightarrow\ (DPAx\ NAtoms)}$$

Varying the damage function accordingly

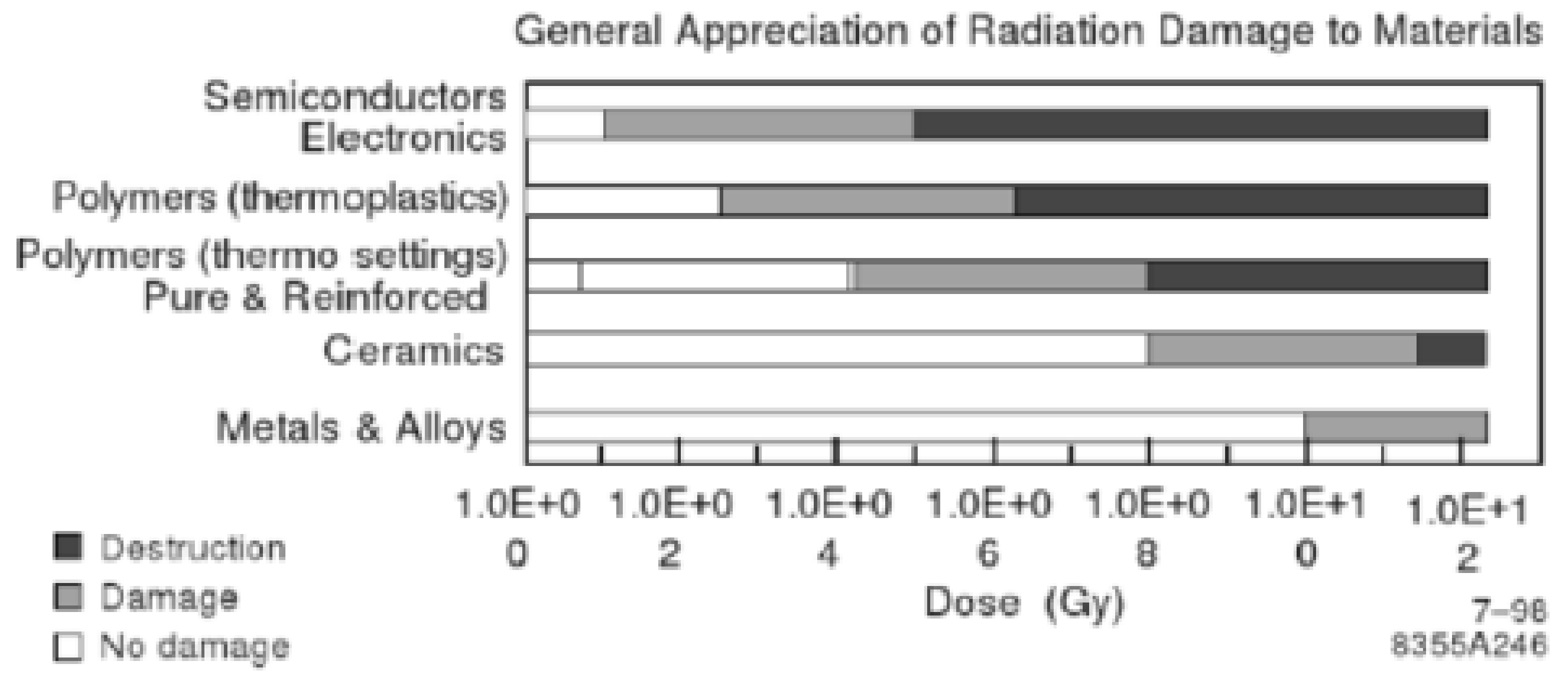
$$f_D(E_{Recoil}) = \eta \frac{0{,}8\ E_{dam}(E_{Recoil})}{2E_D}$$

It is possible to quantify the permanent (measurable) DPA's-> Surviving Defect Fraction


Copper
η
0
0.2
0.4
0.6
0.8
1
0
5
10
15
20
Recoil Energy (keV)


SURVIVING DEFECT FRACTION (NRT dpa)
0.0
0.1
0.2
0.3
0.4
0
100
200
300
400
500
600
700
TEMPERATURE (K)
MD CALC.
HSIEH et al. (1989)
DIAZ de la RUBIA AND GUINAN (1991)
ENGLISH et al. (1992)
EXPT.
THEIS AND WOLLENBERGER (1980)
BIRTCHER AND BLEWITT (1981)
GUINAN AND KINNEY (1982)
ZINKLE (1988)
copper
212

HOW TO ESTIMATE THE DAMAGE?



- The final effect on the material properties is difficult to predict
- Function of :
- 1) Temperature (defects are mobile)
- 2) Impurities (produced but also present)
- 3) Grains structures sizes
- 4) Irradiation rate and kind of particle

- SPECIFIC TESTS ARE NEEDED

- So DPA is a very good parameter for define the degree of damages, not to precisely evaluate the consequences.

EVALUATION FOR CRYSTAL

- crystal targets where the elastic Coulomb collisions of the incident electrons on the aligned nuclei may dislodge the nucleus from the lattice.
- This dislodgement may occur if the recoil energy is above some threshold (E_d ~25 eV, for W). For a recoil energy larger than $2E_d$ the primary nucleus may initiate a cascade of displacements among the neighbouring atoms.
- An evaluation [See X.Artru et al. NIMA 344 (1994)443] showed that for W, a maximum fluence – accumulated number of incident particles per unit area- of 10^{20}e-/cm^2 is tolerable. An experimental test has been operated at SLAC (see below); this test was probably the first using electrons to test the radiation resistance of a crystal. Tests made with protons on Si showed no damages for the same fluence.
- It must be pointed out that annealing can occur during beam operation and as a consequence, the maximum fluence considered may be pessimistic.

- END MODULE 4