Beam Interaction with Thin Materials

HEAT DEPOSITION, COOLING PHENOMENA AND DAMAGE LIMITS

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Disclaimer

Subject is wide but the presentation is biased because author worked with highly relativistic hadron beams

(protons and Pb^{82+} on LHC and SPS).

The experience is based on wire scanners with carbon fibers.

- no SEM wire grids, OTR screens will be discussed
- only a little about scrapper foils

Contents

Contents

- Beam energy deposition
- Damage mechanisms
- Cooling processes
- Sublimation
- Secondary particles
- Radiation damage
- CERN experiments
- SLAC wire scanners
- Scrapper foils

educative

Beam energy deposition

- For heavy particles: energy loss dominated by electronic dE/dx - almost 100 years of theoretical development (still ongoing!)
- Can be described as a series of individual collisions.
- Collision cross section: Rutheford model – free electron, Bethe-Fano model – free atom, PAI model
- for Si, C: 2-5 collisions/μm
- Thin target: large variation of dE/dx
- Ion beam: z^2

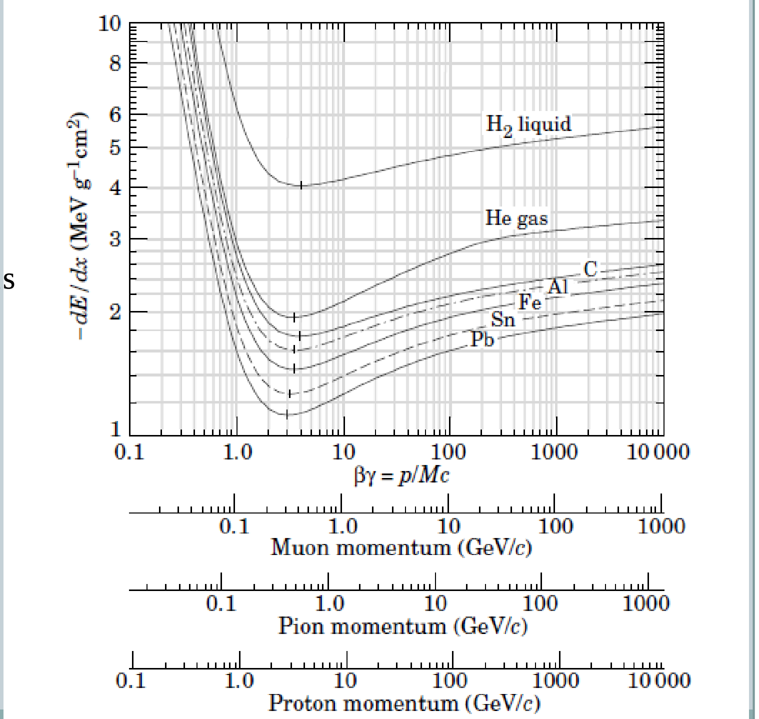
+ higher-order terms

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A}\frac{1}{\beta^2}[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}]$$

$$K = \frac{4\pi e^4 N_A}{m_e c^2} \quad \text{(CGS)}$$

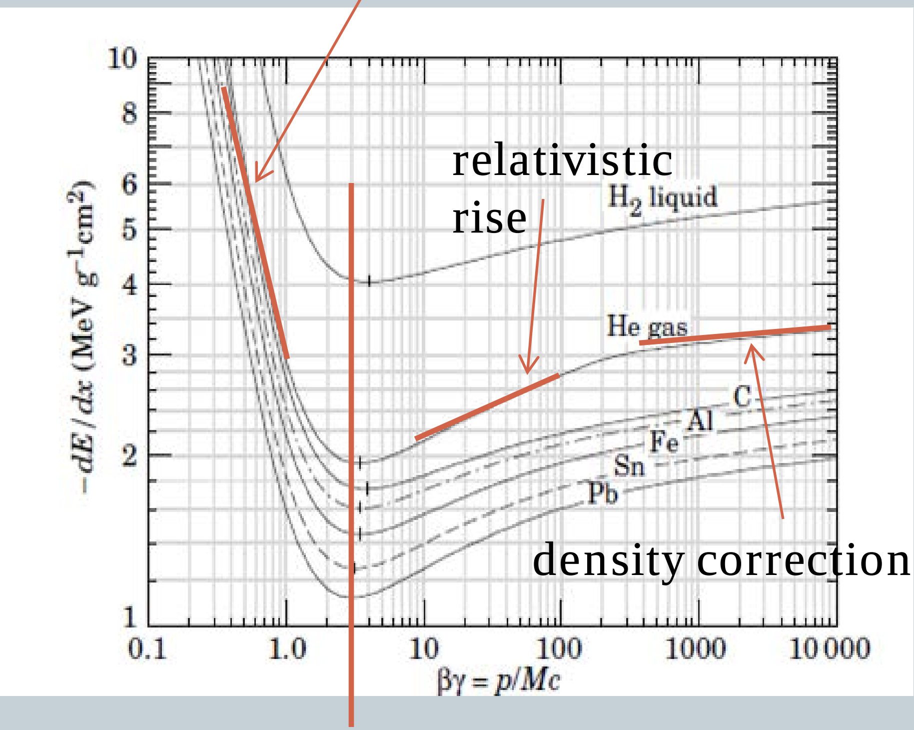
valid:
0.05<βγ<500

I – mean excitation energy (material)
ρ – material density



Understanding Bethe-Bloch

dE/dx ~ β^{-2} (precisely $\beta^{-5/3}$)



Minimum Ionizing Particle: $\beta\gamma$ = 3-4

- Below MIP: $\beta^{-5/3}$ behaviour because slower particles have more time to interact

$$\Delta p_\perp = \int F_\perp dt = \int F_\perp \frac{dx}{v}$$

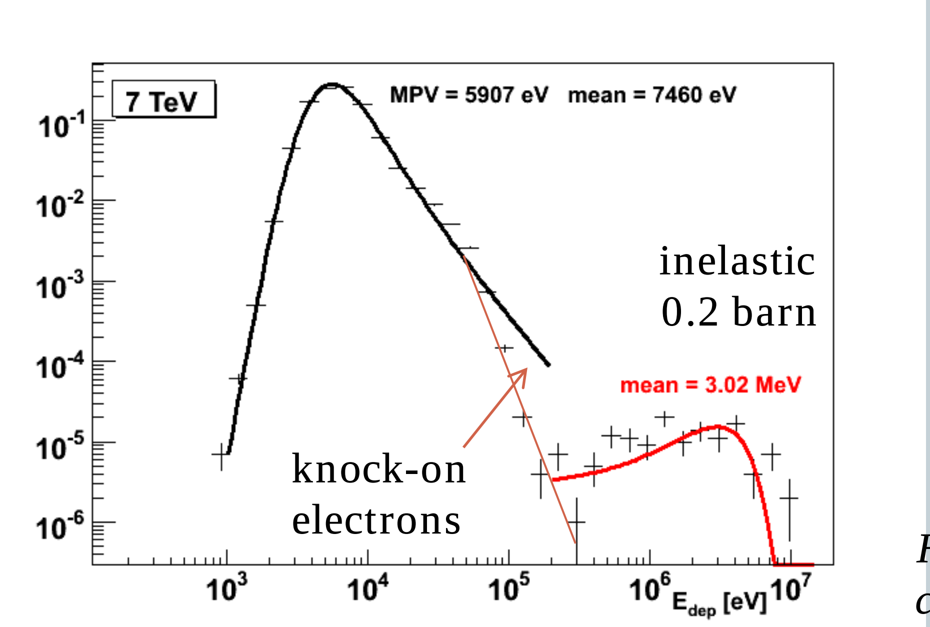
- Relativistic rise due to Lorentz transformation of transverse electric field:

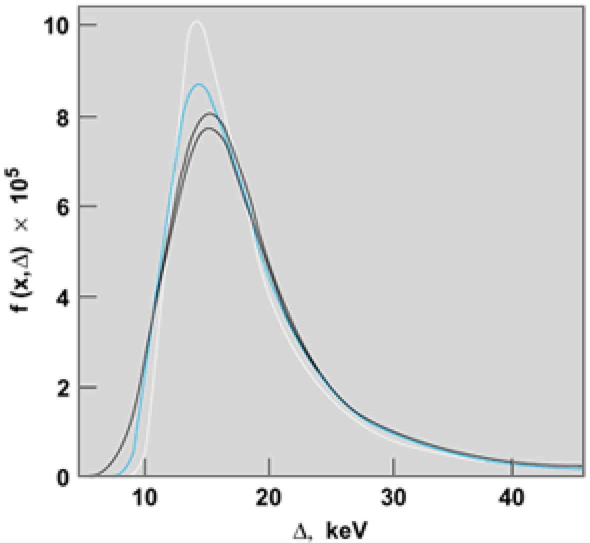
  $E_T` = \gamma E_T$

- Saturation due to density effect (δ) – polarization shielding the effective range of interaction

Beam energy deposition

- Straggling function (Bichsel): for thin targets different than Landau
- But for 30 microns difference is already very small (~1%)
- Beam heating is volumetric effect
- Geant4 simulations





20 MeV protons on 3 μm
Aluminium – various calculations

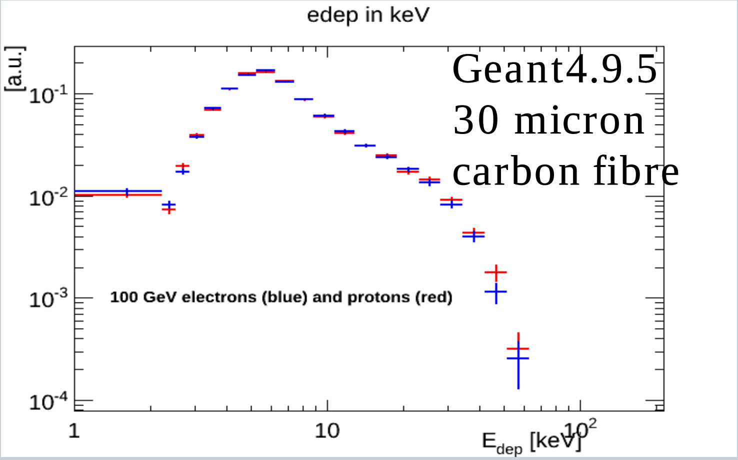
H. Bichsel and R. Saxon, Comparison of calculational methods for straggling in thin absorbers, Phys. Rev., A11:1286–1296, 1975

Beam energy deposition - electrons

- For ions the nuclear dE/dx, bremsstrahlung are small
- Ionization loss for high-energy electrons is different, because:
  - Electrons are much smaller than heavy particles
  - They are identical to the electrons in material
- Bethe-Bloch formula for electrons valid until E<50 MeV (critical energy):

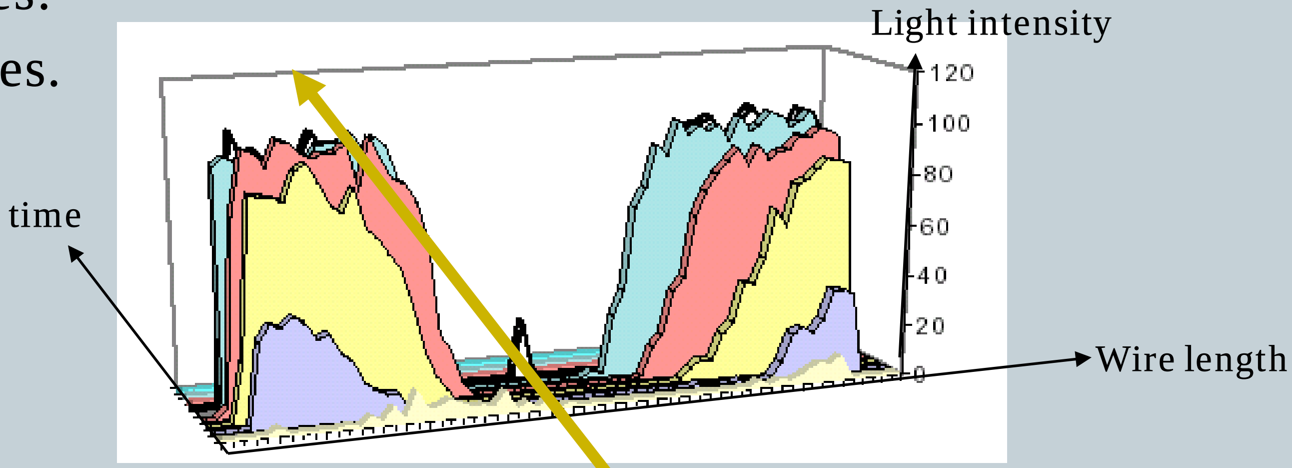
$$-\frac{dE}{dx} = K\frac{Z}{A}\frac{1}{\beta^2}[\ln\frac{m_e c^2 \beta^2 \gamma\sqrt{\gamma-1}}{\sqrt{2}I^2} + \frac{1}{2}(1-\beta^2) - \frac{2\gamma-1}{2\gamma^2}\ln 2 + \frac{1}{16}(\frac{\gamma-1}{\gamma})^2 - \frac{\delta}{2}]$$

- The formula is different for positrons
- Above 50 MeV bremsstrahlung
- But for thin target similar result (small cross section of radiative loss, produced photon escaping target)



RF heating

- But direct beam heating is not everything
- Accelerator is like microwave owen (but don't cook on it!)
- In LEP in 90's wire breakage has been observed WITHOUT scanning the beam
- Observation of temperature profile with CCD camera revealed temperature profiles:
- Use of resistive wires.



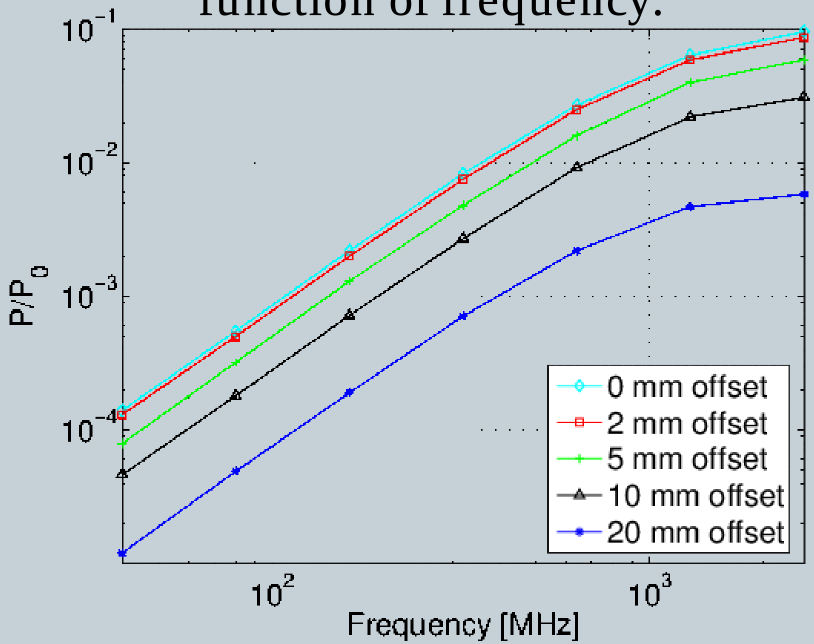
C. Fischer et al., *Quartz wires versus carbon fibres for improved beam handling capacity of the LEP wire scanners*, BIW 1996

In SPS with LHC beam: CERN-AB-2003-067-BI

RF heating

- Heating due to RF coupling affects also LHC beams (CERN-AB-2003-067-BI)
- The effect can be calculated using Ansoft HFSS.

Total relative loss as a function of frequency.



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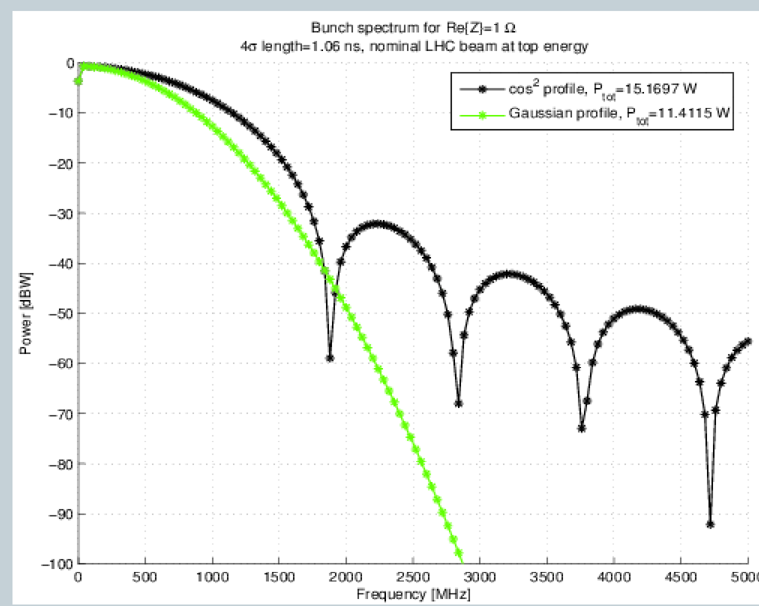
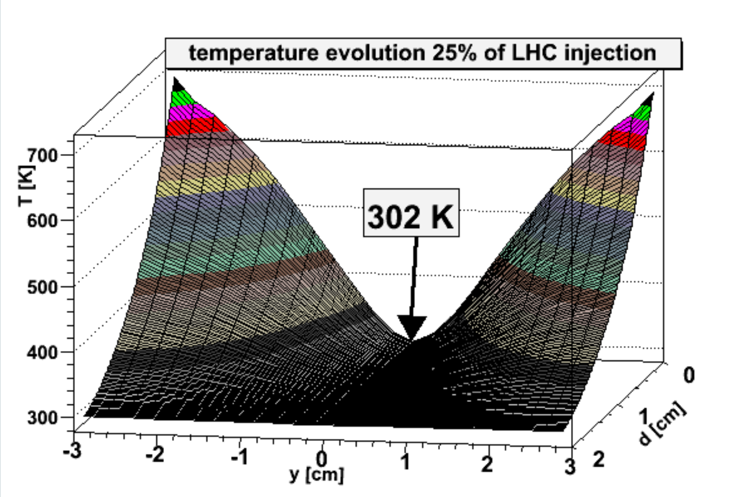
Power distribution



M. S., T. Kroyer, “Operational limits of wire scanners on LHC beam”, BIW2008

RF heating in LHC

- Temperature evolution during scan of 25% of nominal LHC beam at injection:



- Scanner tank redesigned to limit wakefield creation.
- Ferrites installed to dump RF frequencies.

Damage mechanisms

We know how the wire is heated, but why it breaks?

- Brittle failure
- Plastic failure (deformation)
- Thermo-mechanical fatigue
- Thermal shock (graphite – resistant!)
- Electrical discharges (SLAC, tungsten)
- Radiation damage
- Melting/Sublimation

Momentum transfer from the beam to the wire has been estimated to be negligible, so brittle/plastic failure could be only due to acceleration during scan, and they happen after other damage mechanism weakens the wire.

Damage mechanisms

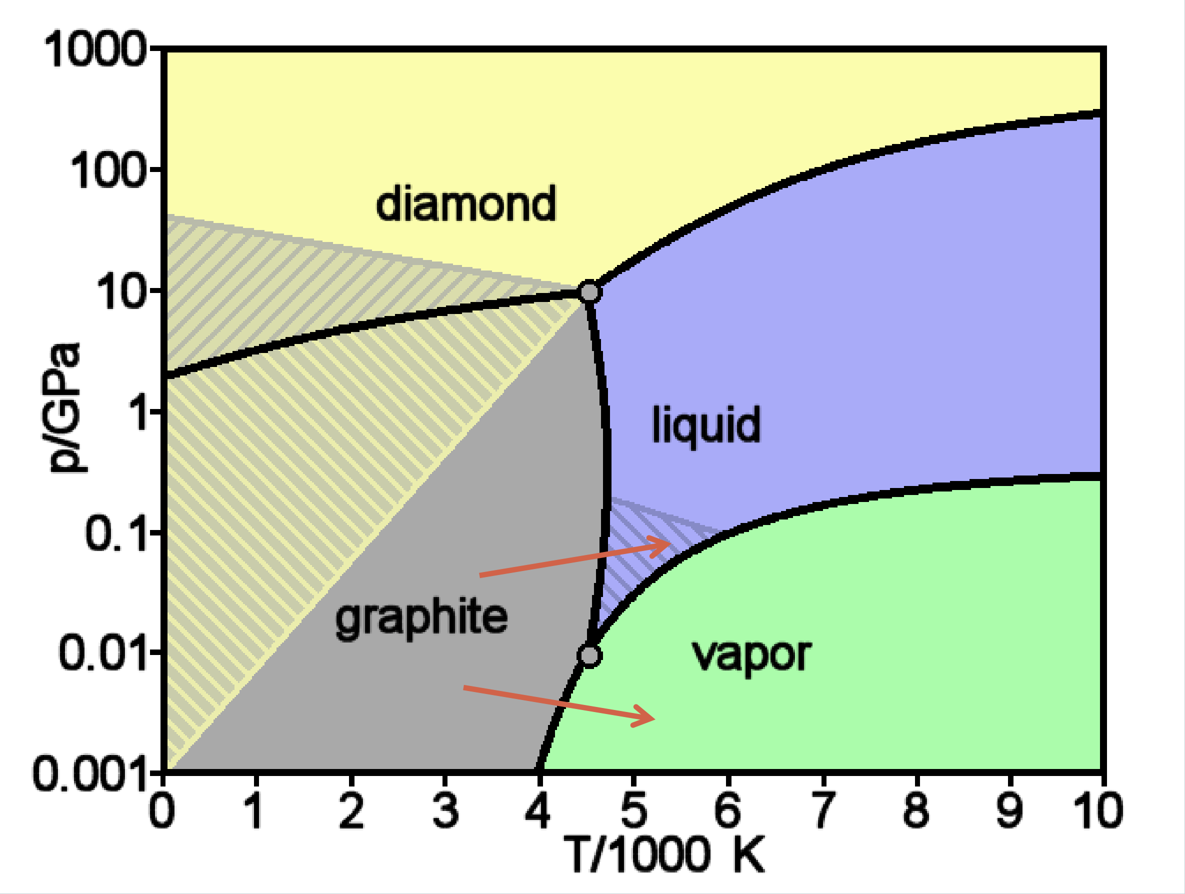
We know how the wire is heated, but why it breaks?

- Brittle failure
- Plastic failure (deformation) — secondary
- Thermo-mechanical fatigue — long-term - future investigations?
- Thermal shock (graphite – resistant!) — a bulk of material needed ?
- Electrical discharges (SLAC, tungsten) — design
- Radiation damage — long-term
- Melting/Sublimation — actual beam intensity limit?

Momentum transfer from the beam to the wire has been estimated to be negligible, so brittle/plastic failure could be only due to acceleration during scan, and they happen after other damage mechanism weakens the wire.

Phase diagram

- Will our material melt? Sublimate? Convert to jewelry?



Temperature evolution in time

Numerical model describing a fragment of wire

beam

heat capacity

radiative cooling

conductive cooling

$$
\begin{aligned}
E_{dep}\frac{\Delta N_{hits}}{\Delta t} &= \rho_C V c_p(T)\frac{\Delta T}{\Delta t} \\
&- A_{rad}\epsilon\sigma(T^4 - T^4_{amb}) - \lambda(T)A_d\frac{\Delta T}{\Delta y} \\
&- A_{rad}(\phi + \frac{2k_B T}{q_e})J_{th}(y) + C(y)\Delta R J^2_{th-tot} \\
&- H_{sub}\frac{\Delta n}{\Delta t}
\end{aligned}
$$

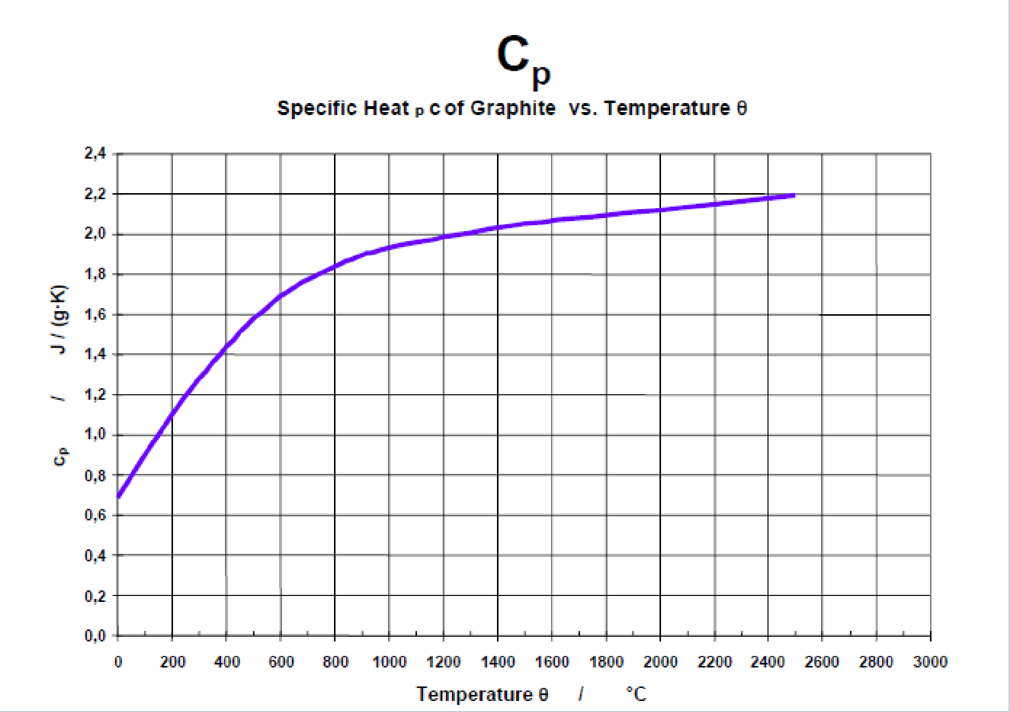
thermionic cooling

reheating from compensation current

sublimation cooling

Heat capacity

- Specific heat increases with temperature – nice!
- Beryllium has 2x heat capacity, melts at 1560 K
- Tungsten has 3x heat capacity, melts at 3500 K and is good conductor!
- Quartz 4x heat capactiy,
  melts at 1500 K



- Conclusion:
  a few materials
  to choose, specific heat
  is an important criterium

Cooling processes

radiative cooling

conductive cooling

thermionic cooling

$$
\begin{aligned}
E_{dep}\frac{\Delta N_{hits}}{\Delta t} &= \rho_C V c_p(T)\frac{\Delta T}{\Delta t} \\
&- A_{rad}\epsilon\sigma(T^4 - T^4_{amb}) - \lambda(T)A_d\frac{\Delta T}{\Delta y} \\
&- A_{rad}(\phi + \frac{2k_B T}{q_e})J_{th}(y) + C(y)\Delta R J^2_{th-tot} \\
&- H_{sub}\frac{\Delta n}{\Delta t}
\end{aligned}
$$

sublimation cooling

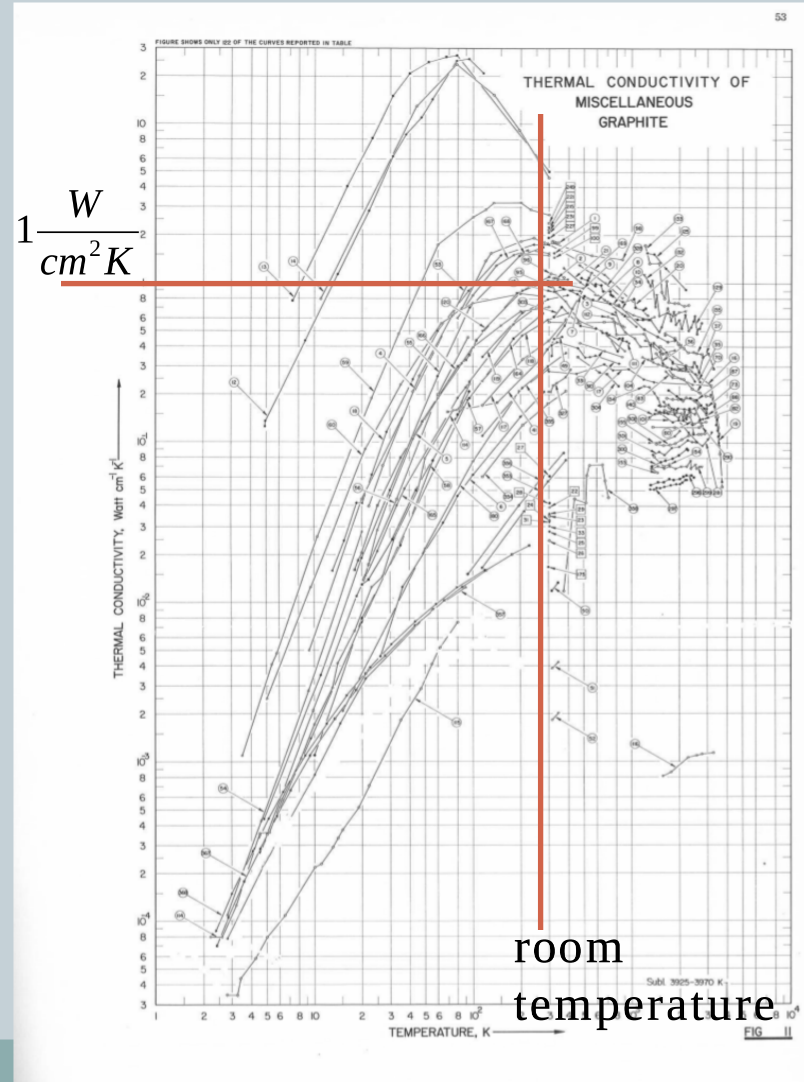
Conductive cooling

- Bulk section effect (A_d)
- Fourier law, for 1D geometry:

$$P = -\lambda(T) A_d \frac{dT}{dx}$$

- A_d is very small (thin material)
- There are material with particularly high thermal conductivity

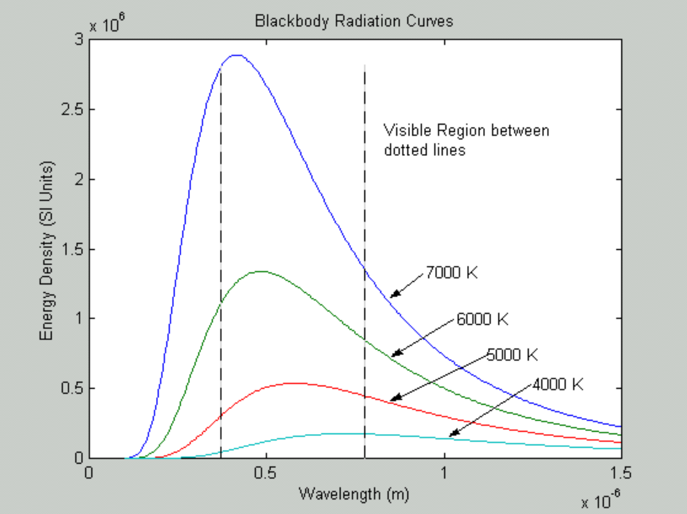
(e.g. nanotubes, reported up to 370 W/cm^{2}K)



Radiative cooling

- Surface effect (A_{rad})
- Stefan-Boltzmann law: $P = A_{rad}\, \varepsilon\, \sigma\, (T^4 - T_{env}^4)$
- thinner wire = better A/V
- Emissivity: $0<\varepsilon<1$, similar plot as for heat conductivity
- carbon fiber ε=0.7-0.8
- Stefan-Boltzmann constant: $\sigma = 5.6\ 10^{-8}\ W/m^2K^4$
- Cooling constant:

$$\tau = \frac{m}{A\varepsilon\sigma} \int_{T/2}^{T} \frac{c(T)dT}{(T^4 - T_{env}^4)}$$

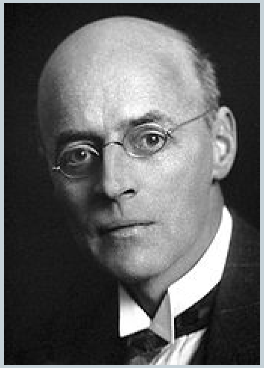


- e.g. 40 ms for T=3300 K

Thermionic emission

- Surface effect, as for radiative cooling
- Thermionic current density, Richardson-Dushman equation:

$$j_{th} = A_R T^2 \exp(-\frac{\phi}{k_B T})(1-R)$$



Nobel 1928

- A_R=120.173 [A cm^{-2}K^{-2}] – Richardson constant
- Work function: φ
- R-reflection coefficient – small for carbon fiber

$$P = A_{rad}(\phi + \frac{2k_B T}{q}) j_{th}$$

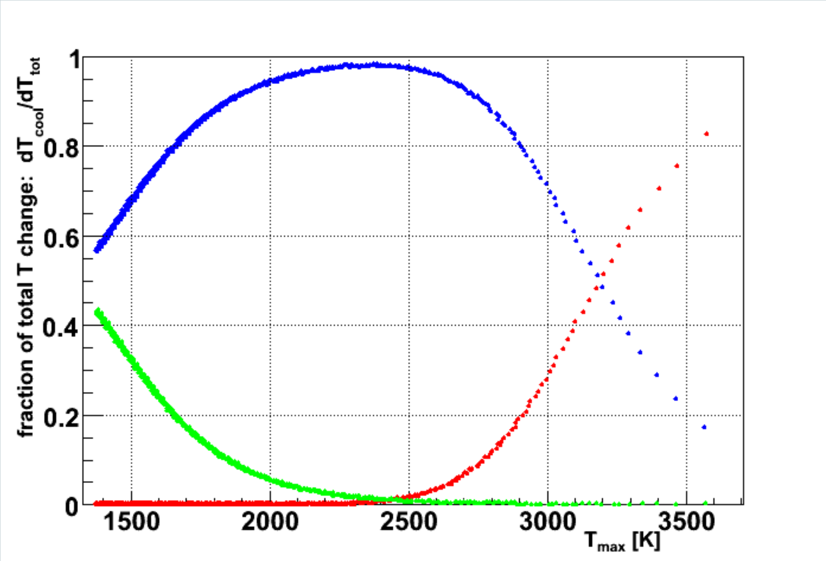
Thermionic emission

- Removed electrons are replaced – current – reheating
- Work function – smaller, better cooling!
- Carbon: φ=4-5 eV
- External electric field decreases the work function and could improve cooling:

$$\Delta\phi = \sqrt{\frac{eE}{4\pi\varepsilon_o}}$$

Comparison of cooling processes

- Thermionic cooling the most important for high temperatures.
- Typical scan is 1 ms, total cooling time constant is about 10-15 ms, so cooling during measurement gives small contribution.



Sublimation

- Simple model, assuming a thin layer around wire where carbon vapour pressure in equilibrum with wire material. Conservative assumption – can overestimate sublimation. No re-sublimation taken into account:

$$d_{sub} = \frac{1}{2} u_{vap}(T) \rho_{vap}(T) \rho_{fiber} \Delta t$$

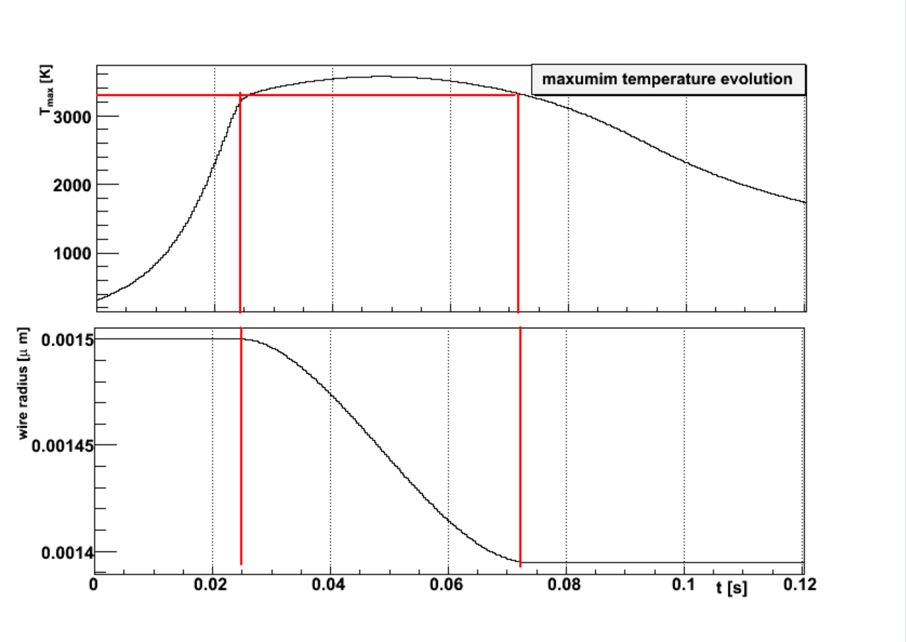
$$u_{vap} = \frac{1}{2}\sqrt{\frac{8k_B T}{m\pi}}$$ ideal gas theory

W. Thieberger, *Upper limits for sublimation losses from hot carbon targets*, MUC-0186

- Other possibility:

$$\log W[\frac{g}{cm^2 s}] = 12{,}04 - 0.5\log T - \frac{4 \bullet 10^4}{T}$$

S. Dushman, *Scientific foundations of vacuum technique*, 1966



Sublimation/melting is cooling as well

- For various useful materials (data often difficult to find!)

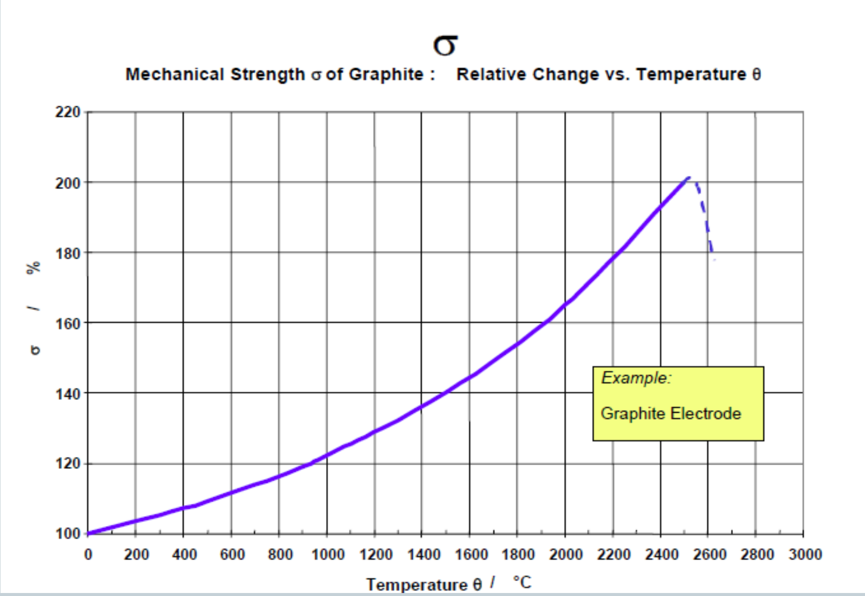
material	Melting temp [K]	heat of fusion [kJ/mole]	Vaporization temp [K]	Vaporization heat [kJ/mole]
Carbon	-	-	3915	356
Beryllium	1560	12.2	2740	297
Tungsten	3695	35.3	5828	807
Quartz	~1900	13.8	~2500	?

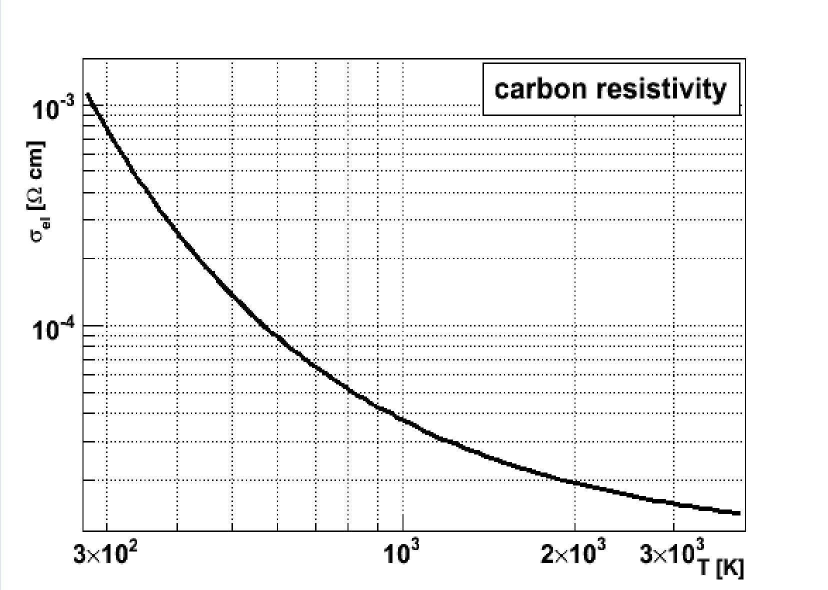
- Vaporization heat is much larger than fusion, but most materials first melt (even at very low pressure) and this is enough to damage.

Other effects

Typically other properties of materials must be taken into account:

- Thermal expansion – low for graphite
- Mechanical strength change – increase with temperature!
- Decrease of electrical resistivity



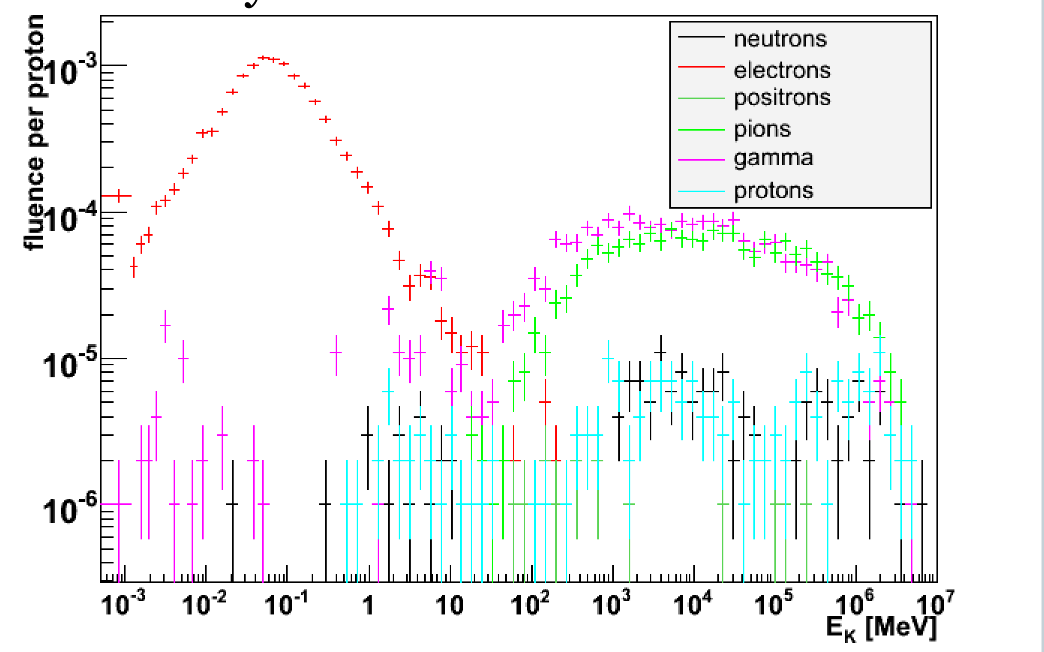


Secondary particles

- Secondary particles come from inelastic interactions (reading beam profile)
- Inelastic cross-section ~0.2-0.25 barn
- Probability of inelastic interaction: about $5 \cdot 10^{-5}$
- During 1 scan of LHC beam $3 \cdot 10^{14}$ protons: $5 \cdot 10^{9}$ in about 1 ms, i.e. $5 \cdot 10^{12}$ Hz, for comparison luminosity $6 \cdot 10^{8}$ Hz
- Number of secondaries:

$$n_s = 7.6 s^{0.125} - 7.4$$

Typically 10-20/interaction

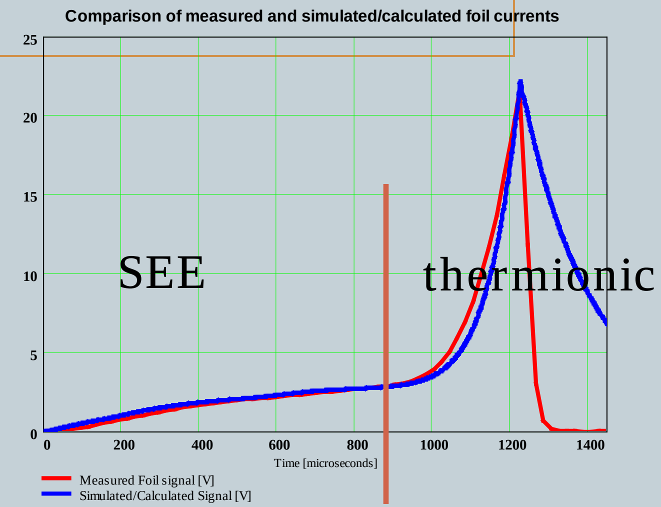


Making clear electron case

There are 3 types of electrons emitted from target!

	process	current	cooling
Knock-on	Ionization(*)	no	Yes
Secondary emission	Ionization	Yes	No
Thermionic	Temperature	Yes	Yes

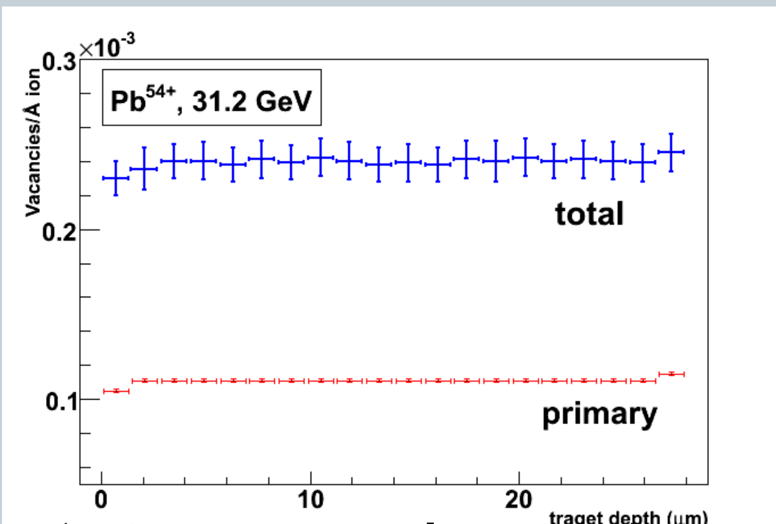
(*) there is also contribution from inelastic interactions



T.Spickermann, ICFA-HB2004

Radiation damage

- We have not really observed radiation damage
- But we used SRIM code to investigate DPA anyway
- 10^4 scans provoke 0.004 DPA



(M.S., M.Meyer et al., HB2010)

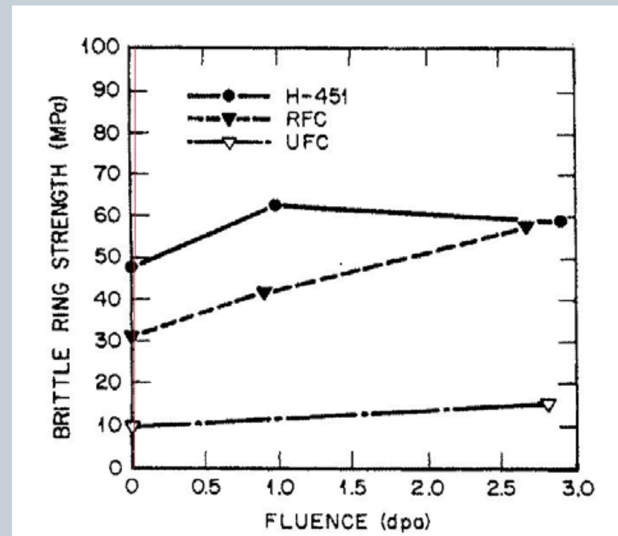


Fig. 11. The influence of neutron irradiation on the brittle ring strength of H-451 graphite, and carbon-carbon composites UFC and RFC irradiated at 600 °C.

- This comfortable situation probably changes for OTR and scrapper foils…

Emittance growth

- Impact on the beam

$$\theta_{rms} = \frac{13.6\,MeV}{\beta cp}\sqrt{\frac{d}{L_{rad}}}\left[1 + 0.038\,ln\left(\frac{d}{L_{rad}}\right)\right]$$

See:

- B. Rossi, High Energy Particles, Prentice-Hall (1961)
- V.L. Highland, Nucl.Instr. And Meth. 129 (1975)
- G.R. Lynch, O.I.Dahl, Nucl.Instr. And Meth. B58 (1991)
- F. Roncarolo, “Accuracy of the Transverse Emittance Measurements of the CERN LHC”, EPFL PhD Lausanne 2005

Wire scanners at CERN

- Wire origin (Lyn Evans mail, 2011) 34 microns:

I believe that the carbon fiber you are using is the one I got from Los Alamos in about 1979, with which I built the very first wire scanner.

It was given to me by a real pueblo Indian, who was a technician at the lab.

Wire scanners at CERN

I am surprised that you have not found anything better!

1988 experiment

- Wire broken in SPS under following conditions:

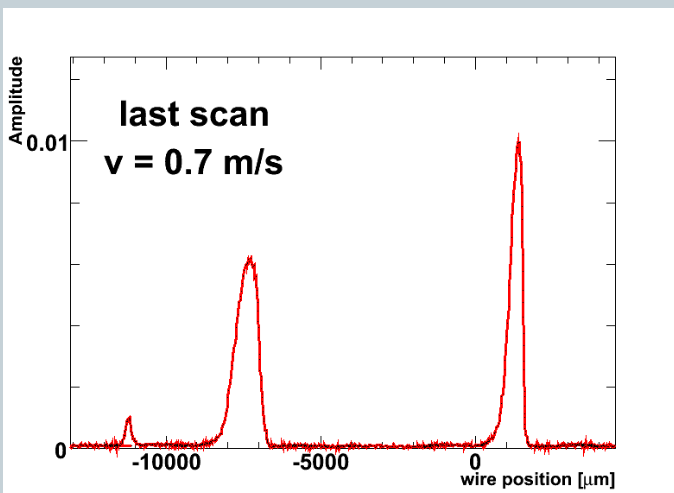
N_{ch}	σ_l	σ_t	E_{beam}	v_{wire}
	[mm]	[mm]	[GeV]	[cm/s]
$2 \cdot 10^{13}$	1.63	0.65	400	10

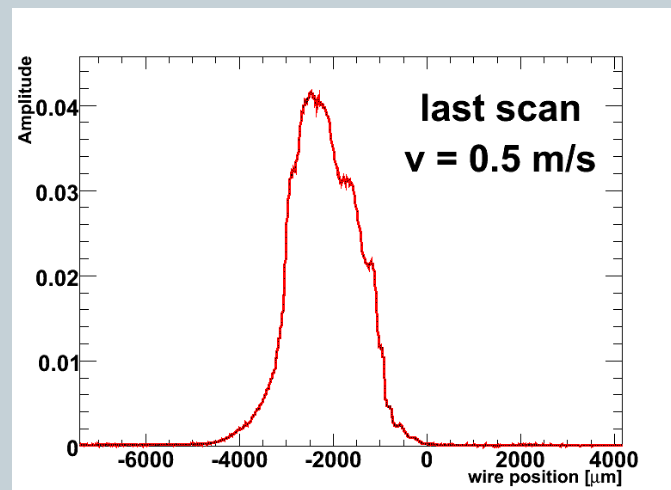
- Beam parameters uncertain.
- Damaged wire not found.

2008 experiment

- October 23rd, 2008, SPS beam
- Special long cycle, coasting beam (reduce RF effect)
- 2 fibers broken

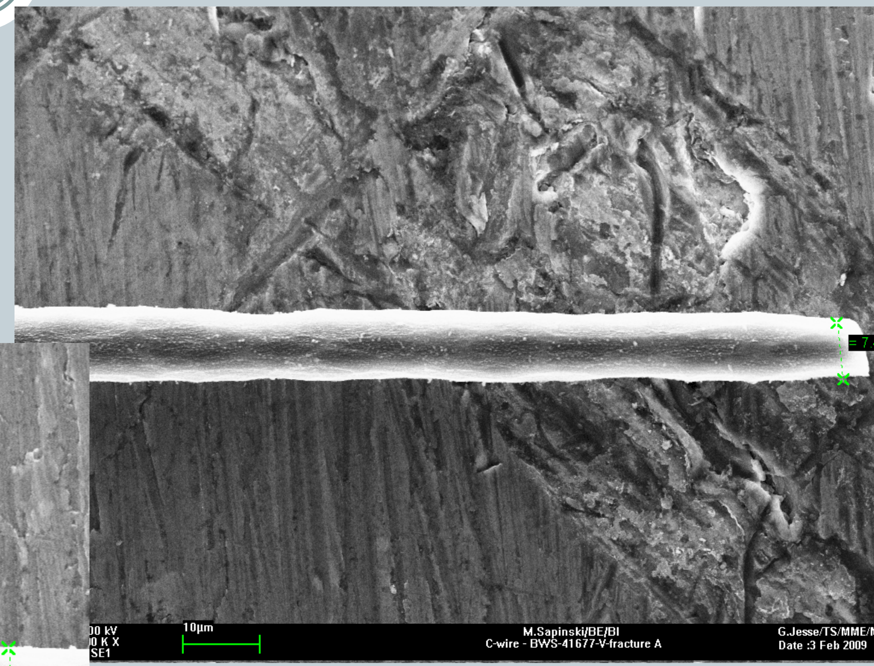
N_{ch}	σ_l	σ_t	E_{beam}	v_{wire}
	[mm]	[mm]	[GeV]	[cm/s]
$2.4 \cdot 10^{13}$	0.57	0.73	400	50
$2.2 \cdot 10^{13}$	0.73	0.57	400	70

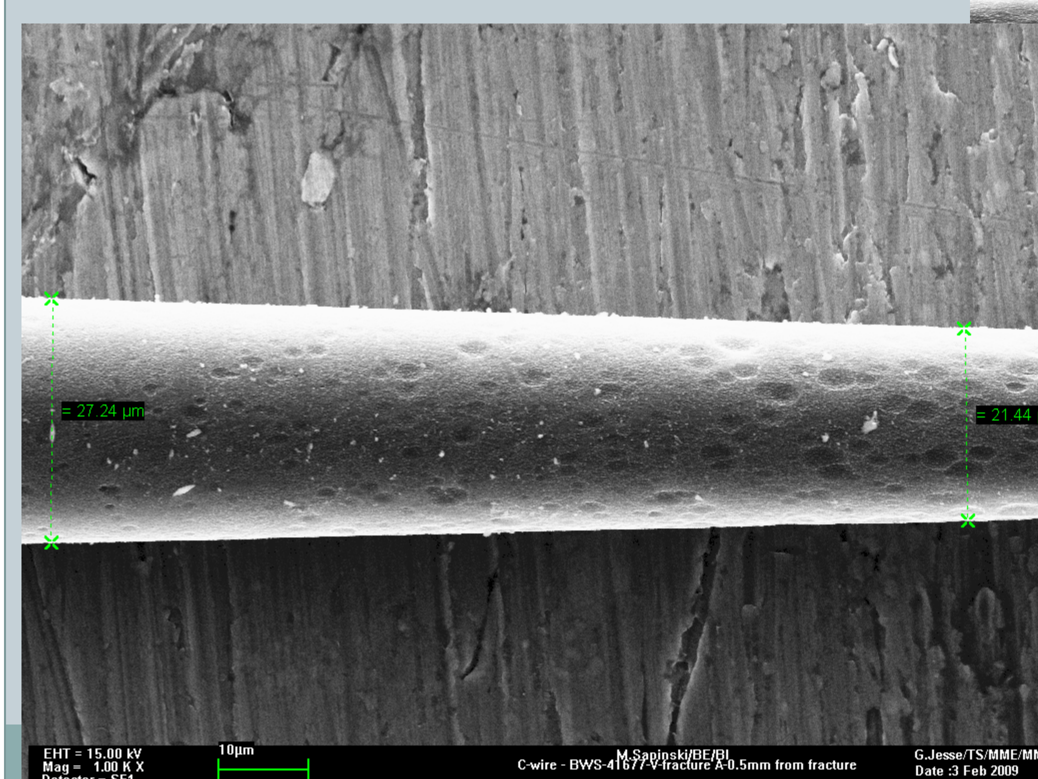




2008 experiment

Electron microscope images.
Wire damaged by sublimation.

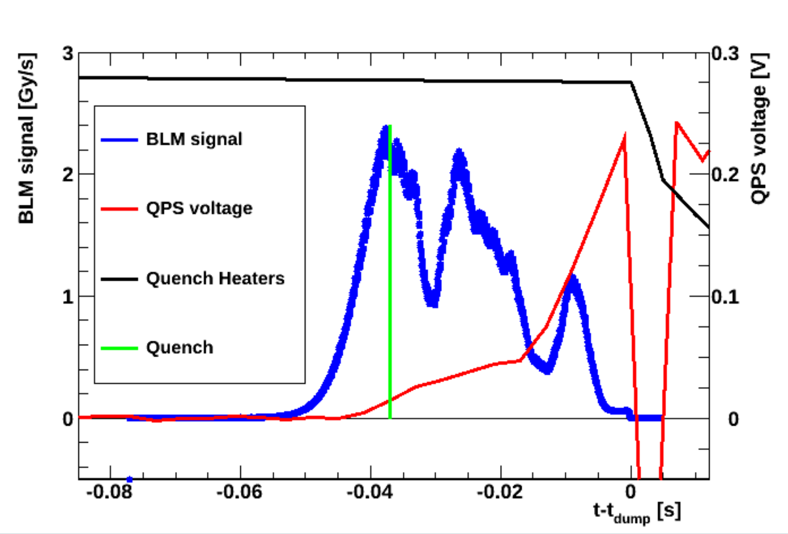




2010 experiment

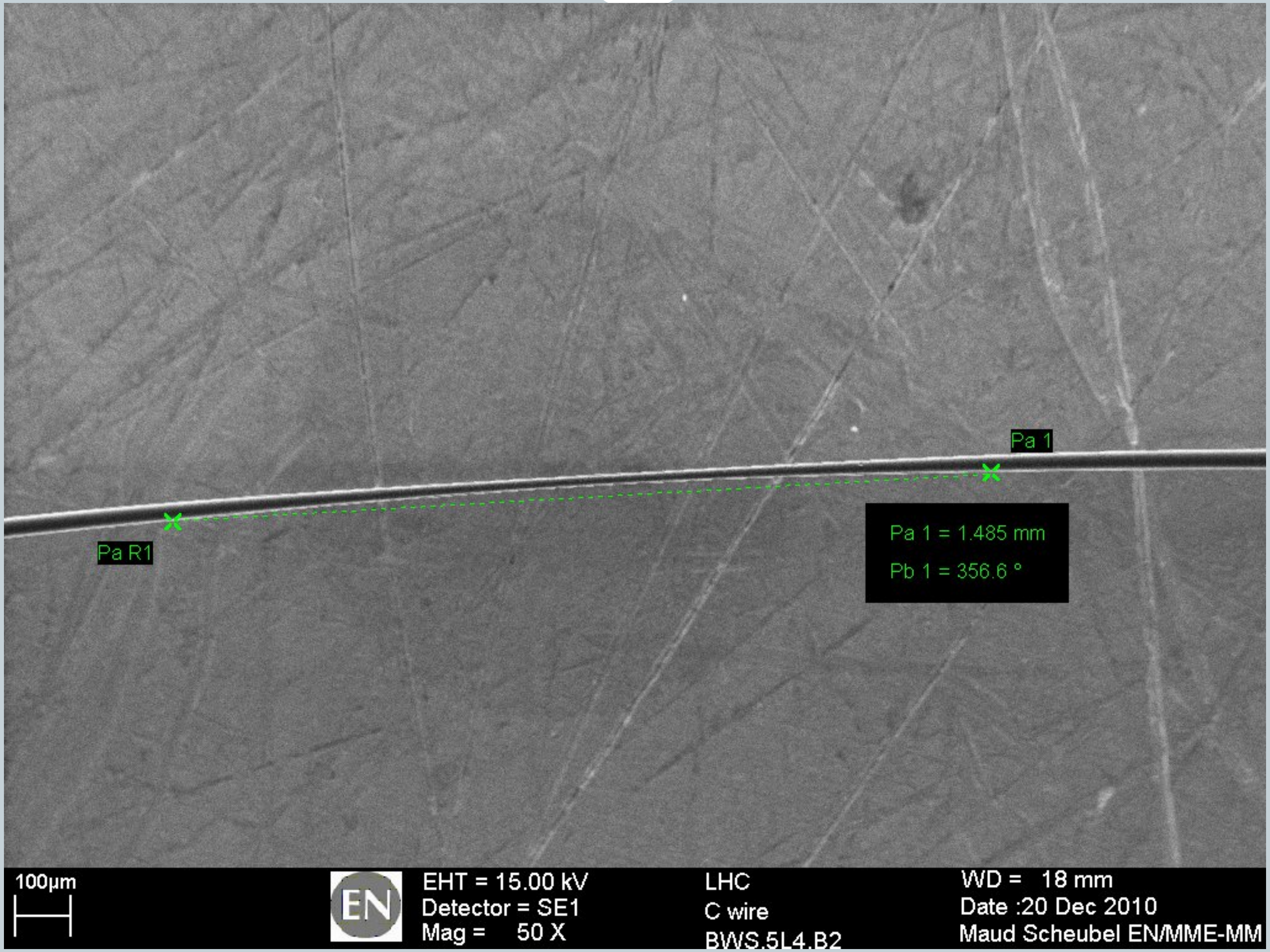
- November 1st, 2010, LHC beam at 3.5 TeV
- Testing quench levels in ms timescale (for UFO losses)

N_{ch}	σ_l	σ_t	E_{beam}	v_{wire}
	[mm]	[mm]	[GeV]	[cm/s]
$1.53 \cdot 10^{13}$	0.28	0.53	3500	5



Wire scanner acquisition was not working, but we have BLM post-mortem buffer.

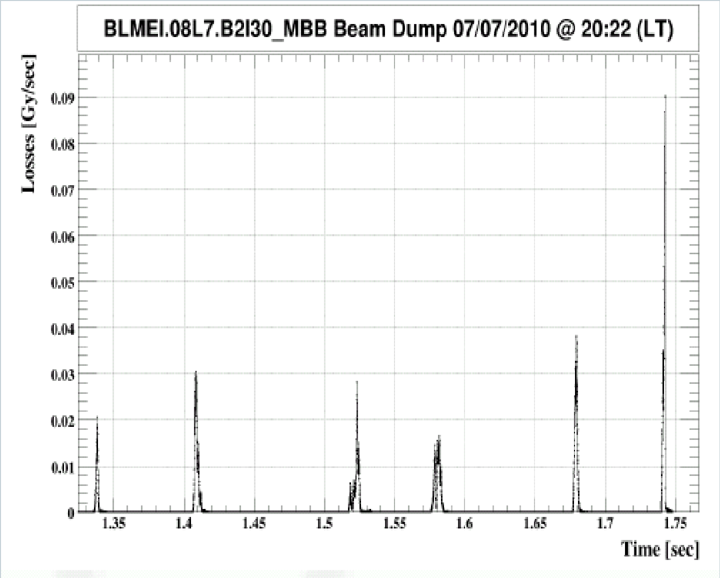
2010 experiment



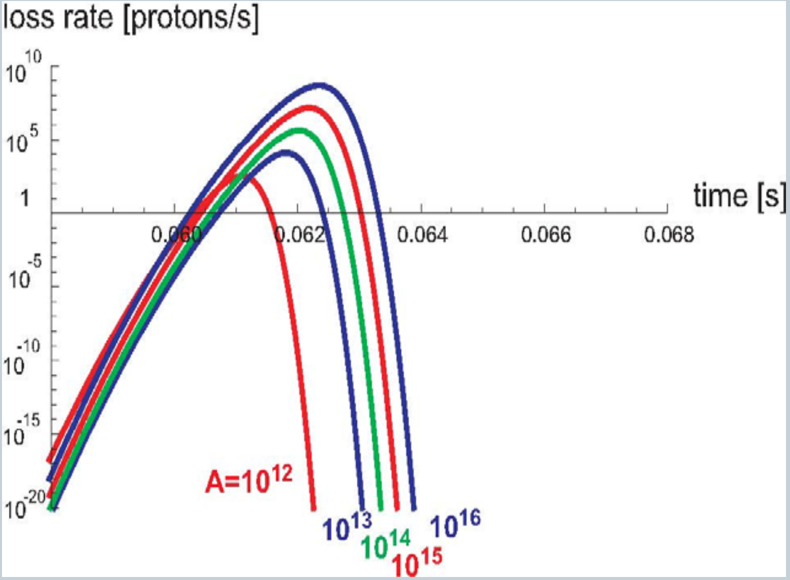
LHC UFOs

- Multiple crossings – beam forces

F. Zimmermann et al.,CERN-ATS-2011-093



first UFO observed



dynamic simulation of macroparticle movement

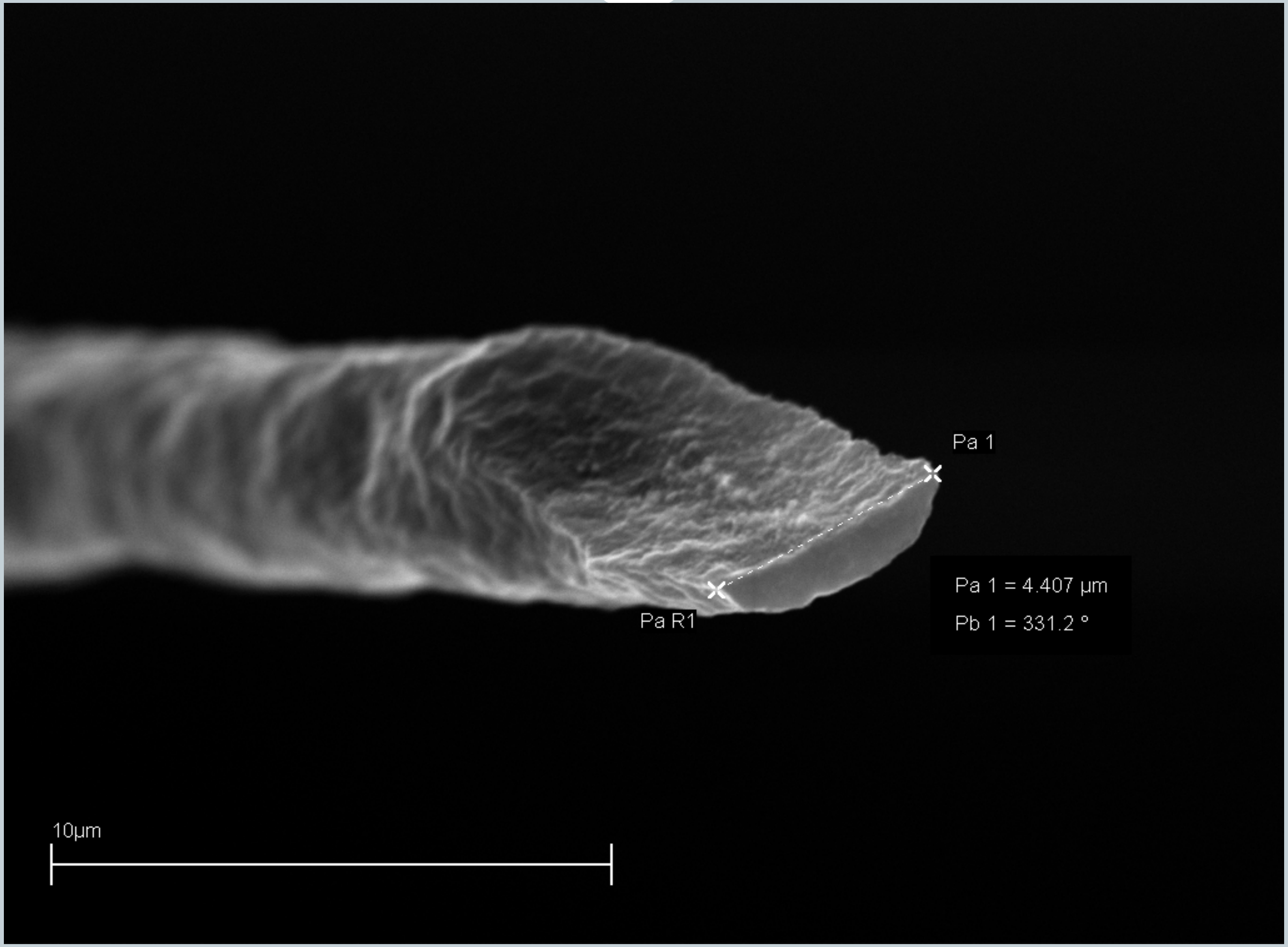
- BTW forget about measuring emittance with a “wire” shot into the beam – forces are too strong for light object, its movement is heavily affected.

2011 experiment - ions

- December 1st, 2011, SPS ion beam
- Fiber not detected to be broken!
- Horizontal scanner chosen (vertical beam size as for protons)

N_{ch}	σ_l	σ_t	E_{beam}	v_{wire}
	[mm]	[mm]	[ZGeV]	[cm/s]
$2.6 \cdot 10^{11}$	0.8	0.6	450	2

2011 experiment - ions



Experiments: summary

- Quantity describing the conditions to which the wire center was exposed (charges/mm):

$$n_{ch} = \frac{N_{ch} d_w}{v_{wire} t_{revol} \sigma_t}$$

No	N_{ch}	v_{wire} [mm/s]	t_{revol}	σ_t [mm]	N_{ch} [10^{13}/mm]	remarks
1	$2 \cdot 10^{13}$	100	SPS	0.7	37.3	rot WS
2	$2.4 \cdot 10^{13}$	500	SPS	0.73	8.6	rot WS
3	$2.2 \cdot 10^{13}$	700	SPS	0.57	7.2	rot WS
4	$1.5 \cdot 10^{13}$	50	LHC	0.53	19.1	lin WS, not broken
5	$2.6 \cdot 10^{11}$	20	SPS	0.6	2.8	ions, lin WS, not broken

SLC experience

- SLAC – breakage with electron beams

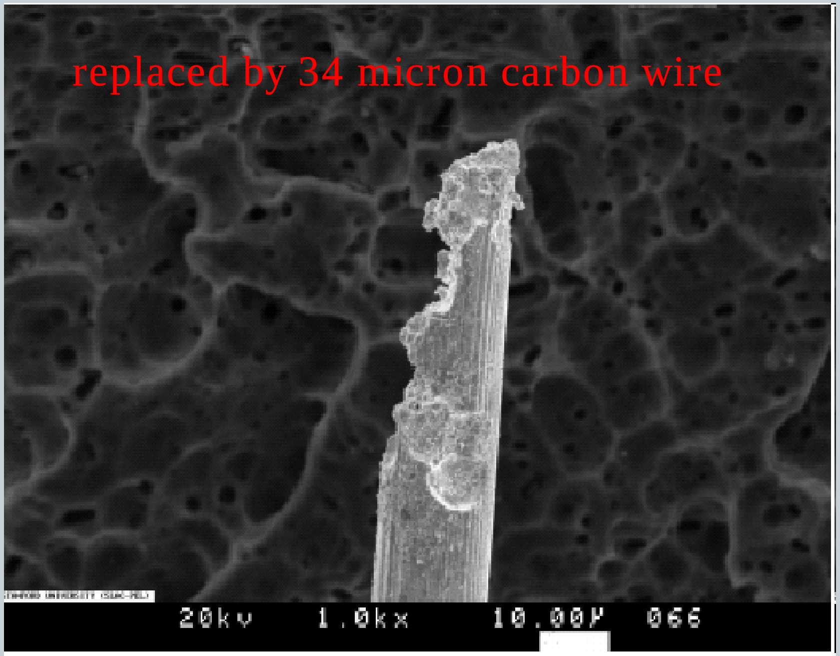
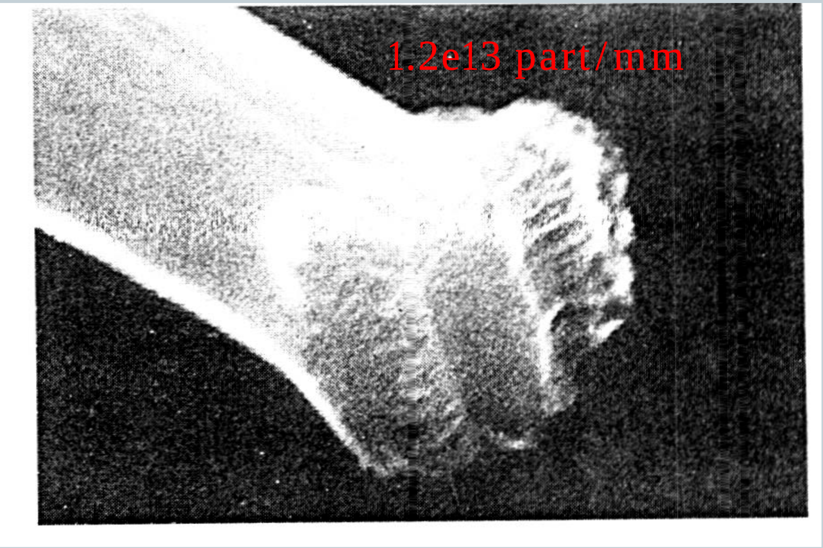


FIGURE 3. Failed 15 µm diameter tungsten wire showing the rough surface resulting from many discharges.

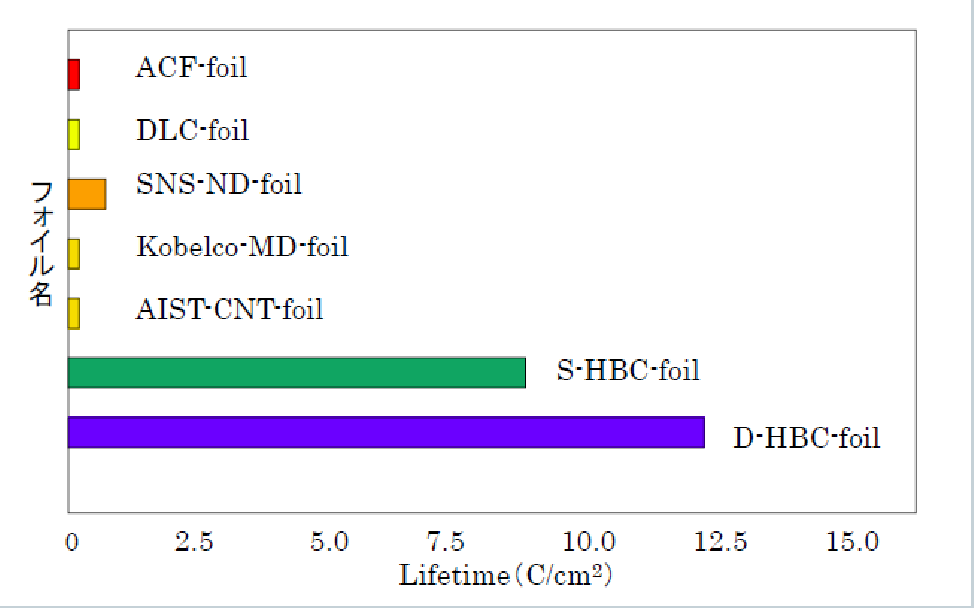


4 micron carbon wire
traces of single pulses seen
damage mechanism more violent than sublimation – thermal shock?

SLAC-PUB-7832 (1998), 8th BIW

Scrapper foils

- Very interesting story of perfect material research.
- Many studies by T. Spickermann (Los Alamos PSR) and colleagues from KEK, also studied in SNS…
- PSR – operational temperatures about 2000 K
- Single and double-layer HBC (Hybride Boron mixed Carbon) foils found to have the longest lifetimes.



Summary and conclusions

- Choose carefully material to your application.
- There is still room for development: new materials, enhanced cooling..
- There is still room to study the thermal phenomena– almost every aspect of the process.
- Your material can be affected by RF or HV sparking.
- Damage mechanisms can vary, often complex.
- Thin materials will remain crucial for interceptive beam diagnostics (wire scanners but OTR screens as well, as you've heard yesterday)
- Modern high-intensity systems us H^- accelerators in early stage – stripper foils are crucial part of them.

Thank you for your attention!