Design Principles for High Power Targets

4th HPTW in Malmö

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Peter Sievers-Retired from CERN
Peter.Sievers@cern.ch

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Contents

1. Temperatures and Thermal Stresses.

- Temperatures and Thermal Stress $\frac{dQ}{dV}$
- From Beam Pulse, Codes, like FLUKA: $T(r) = \frac{dQ}{\rho \times c \times dV}$ $\quad T(r) = T_0(1 - \frac{r^2}{R^2})$
- Edge cooled Granular Targets:
  - Cylinder $T(0) = \frac{dW}{dV} \times \frac{R^2}{4\lambda}$
  - Spheres $T(0) = \frac{dW}{dV} \times \frac{R^2}{6\lambda}$
- Small R gives small T(o)!
- Thermal Stress due t_0 edge cooling: at R:
  - Cylinder $\sigma = \frac{E\alpha T(0)}{2(1-\nu)}$
  - Spheres $\sigma = \frac{2 \times E\alpha T(0)}{5(1-\nu)}$
  - Disk $\sigma = \frac{E\alpha T(0)}{2}$
- Stress Sphere/Cylinder at the same dW/dV and R about ½.

1. Temperatures and Thermal Stresses.

What not to do!

1. Temperatures and Thermal Stresses.

- Initial, bell shaped temperature profile created by the beam inside a cylinder (or sphere) will become uniform by internal, thermal diffusion.

- Time constant $\tau_d = \dfrac{R^2}{8\lambda / c\rho}$

- For Cu and W with R=0.5 cm this becomes 30 ms and 50 ms respectively.

1. Temperatures and Thermal Stresses.

- Pulsed Beams: at pulse durations of ms no cooling occurs: adiabatic heating by ΔT. Cooling only after the pulse over time t_1 between pulses.
- T_p is peak temperature above the temperature of the cooling fluid.
- Choose small R!

$$T(t) = T_p \times e^{-\frac{t}{\tau}}$$

$$Tp = \frac{\Delta T}{1 - e^{-\frac{t_1}{\tau}}}$$

$$\tau = \frac{mc}{\gamma F}$$ Cooling time constant

$$\tau = \frac{\rho c R}{3\gamma}$$ For spheres

$$\tau = \frac{\rho c R}{2\gamma}$$ For cylinders

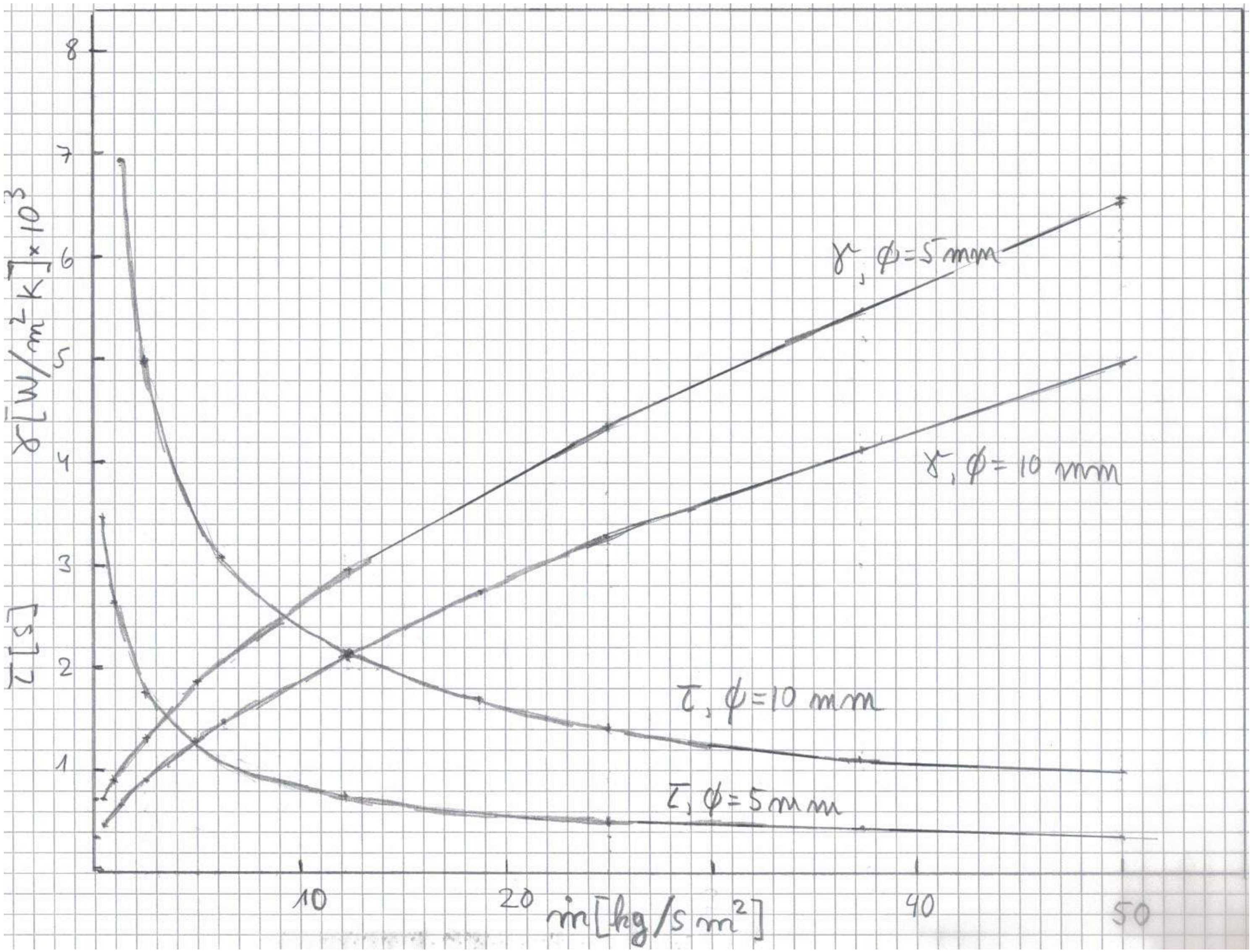
m: masse of sphere
c: specific heat of sphere
γ: convection coefficient
F: surface of sphere

The following parameters are relevant for He cooled spheres (and cylinders):

- Diameter of the spheres.
- He mass flow per free unit cross section between the spheres $\dot{m}$ ($kg.s^{-1}.m^{-2}$).
- Forced cooling convection coefficient γ($W.m^{-2}.K^{-1}$).
- Cooling time constant τ(s).
- Example: He pressure 2 bar; velocity between spheres 40 m/s;diameter of sphere 0.01 m; He mass flow 14.4 $kg.s^{-1}.m^{-2}$:
  - ☛ γ = 2400 $W.m^{-2}.K^{-1}$; τ = 2 s (longer than internal diffusion time!).

- Applicable for a wheel rotating at 30 rpm for ESS.

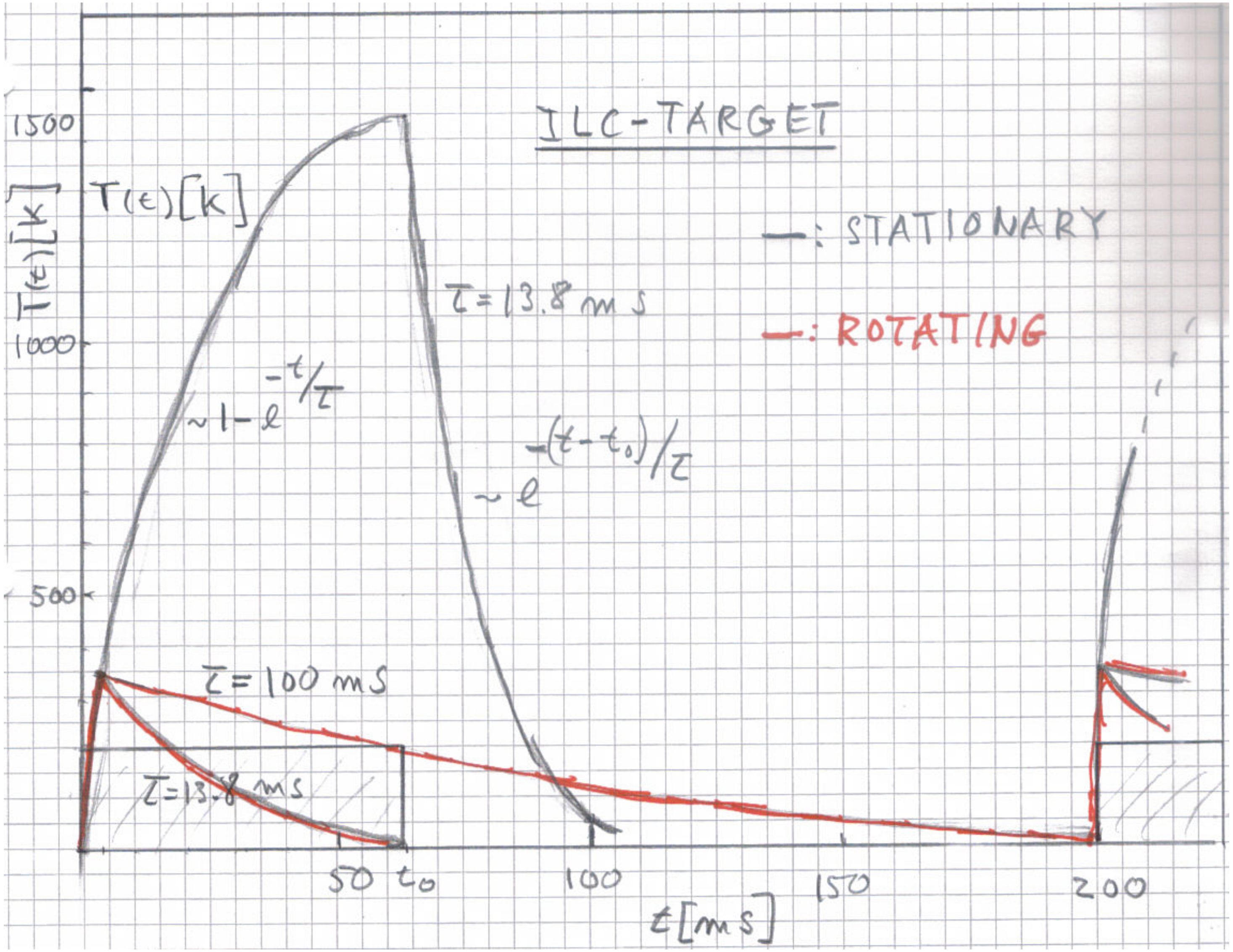
1. Temperatures and Thermal Stresses.



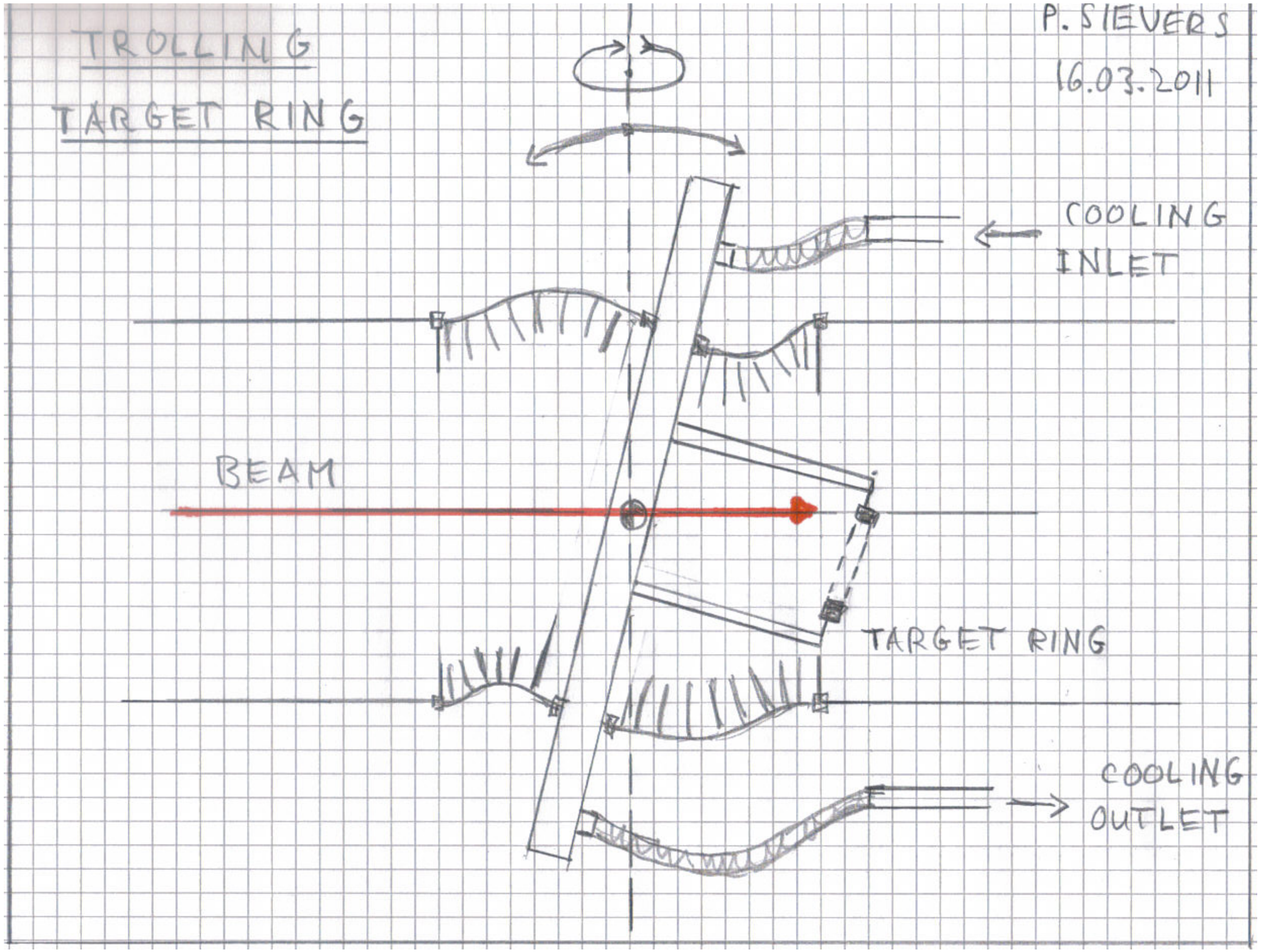
He Cooled Granular Target for the International Linear Collider-ILC

- Positrons could be produced in a He-cooled granular W-target, irradiated by an electron beam.
- Maximum energy deposition density: 10 kJ/kg per pulse !!!! (Ref: Robert Chehab). At 5 Hz (t_1 = 200 ms), average power density 50 kW/Kg. Adiabatic temperature rise 7000 K per pulse. Pulse duration t_0 = 63 ms.
- Push He cooling to the extreme: spheres ϕ=1mm; He pressure 20 bars; inside velocity 80 m/s: ϒ = 3.3 x 10^4 $W.m^{-2}.K^{-1}$; cooling time constant
- τ = 13.8 ms.
- Temperature cycling T(t) (above that of He) can be expressed in a closed form as a function of τ, t_0 and t_1(see Annex 1).
- Cooling takes place allready during the pulse. T(t_0) = 1500 K. Better than 7000 K, but still high.
- Rotate Target: Want t_0 gain a dilution by a factor of 20. Need a wheel with a diameter of 8 cm, rotating at 1000 r.p.m.
- The temperature rise in the He during its passage through the target has still to be added. This depends on the He mass flow as well as on the direction it traverses the target: vertically, horizontally or axially.
- Results are shown in Fig.2, ignoring the temperature rise in the He stream.

Temperature cycles in the stationary and rotating ILC-target



Trolling ILC-target



- The energy loss per proton passing thin windows (not much absorption and cascading of secondaries) is in good approximation for all elements:

$$\frac{dE}{d\zeta} = (1-2)\frac{MeV}{g \cdot cm^{-2}}$$

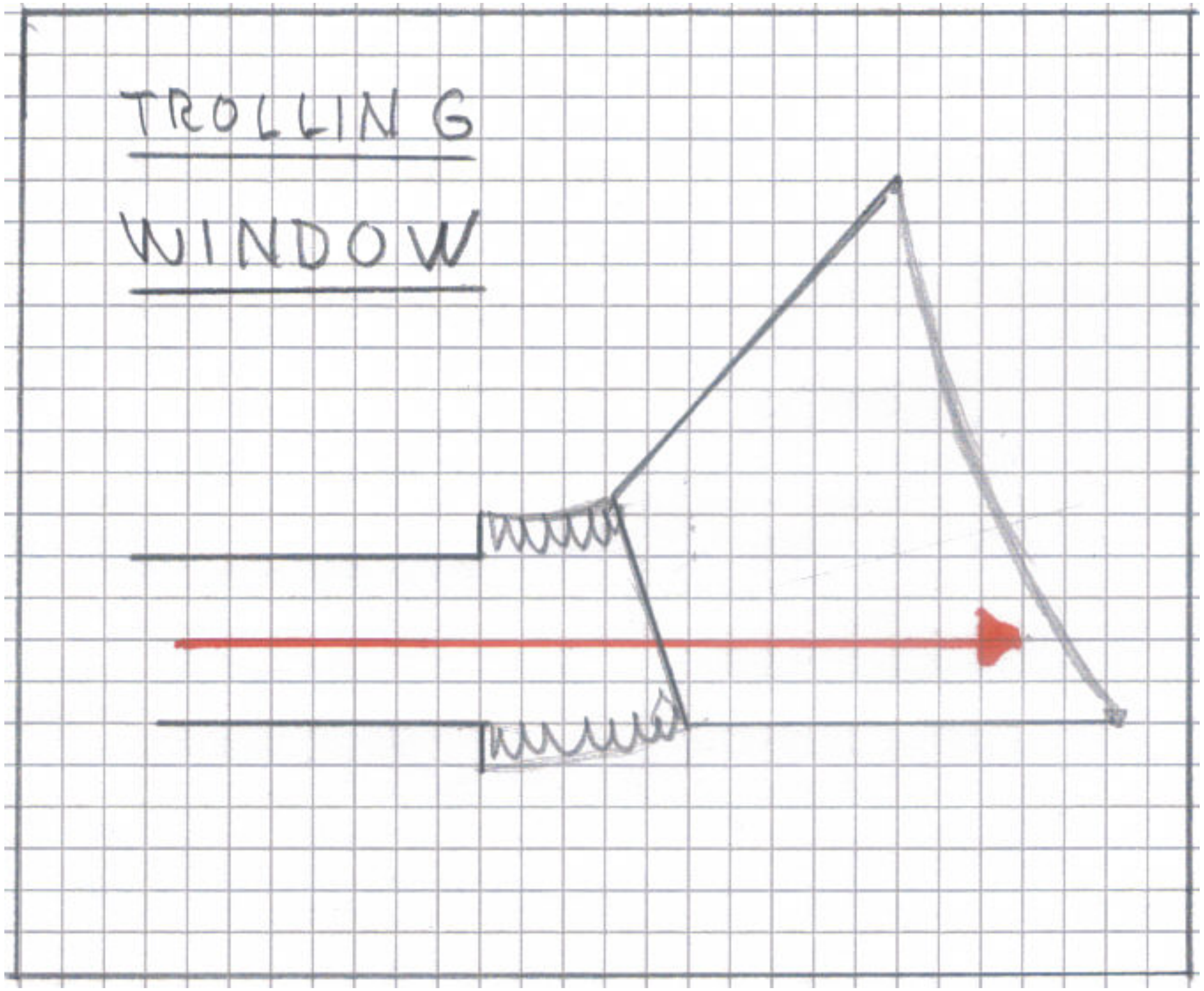
$$\frac{dE}{d\zeta} = (1.6-3.2)\times 10^{-14}\frac{J}{kg \cdot m^{-2}}$$

- Thus the adiabatic temperature rise ΔT is: $\Delta T = \frac{dN}{df} \times \frac{dE}{d\xi} \times \frac{1}{c}$
- Depends only on specific heat c.
  - For the ESS beam with σ_x=5 cm and σ_y=1.5 cm the proton density in the beam center with $\frac{1}{2\pi \times \sigma_x \sigma_y}$

$$\frac{dN}{df} = 1.324 \times 10^{17} \text{ protons.m}^{-2}$$

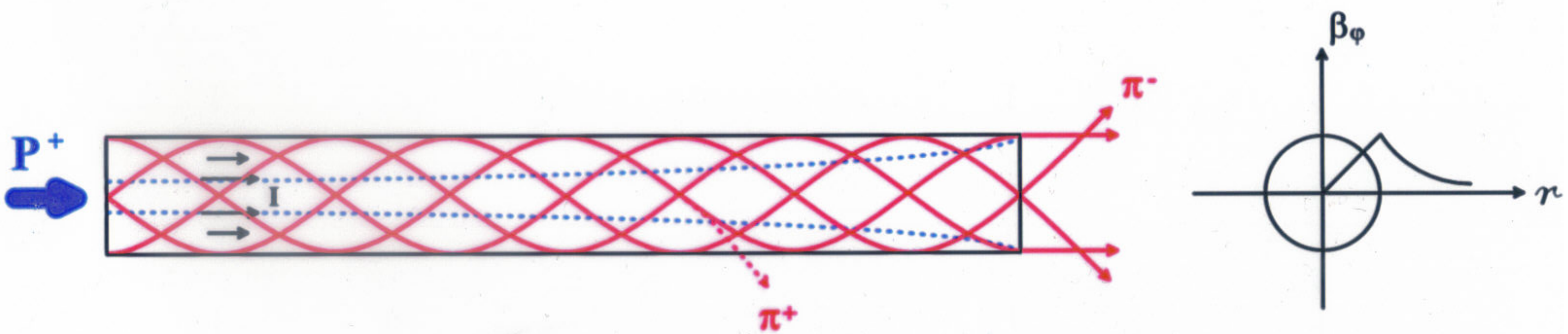
- Adiabatic max. temperature rises per pulse in Ti and St.Steel are (3.3-6.6) K and (4.2-8.4) K respectively.
- Thermal stresses in the centre are
- $\sigma_{th}=-E\alpha\Delta T/2$,compressive at the centre and decay with $1/r^2$ outside the heated zone. They are low, but fatigue will be important!
- Cooling is easy: the cooling time constant for a 0.2 mm thick st.st. window, cooled from only one side with He is about 80 ms, of the same order as the time space between pulses of 50 ms. Thus, temperatures of about 2 x ΔT may be expected. However, for a thicknes of 1 mm things get worst.
- How to fight fatigue and radiation damage: Wobbling Window?

- Better ideas are most welcome.



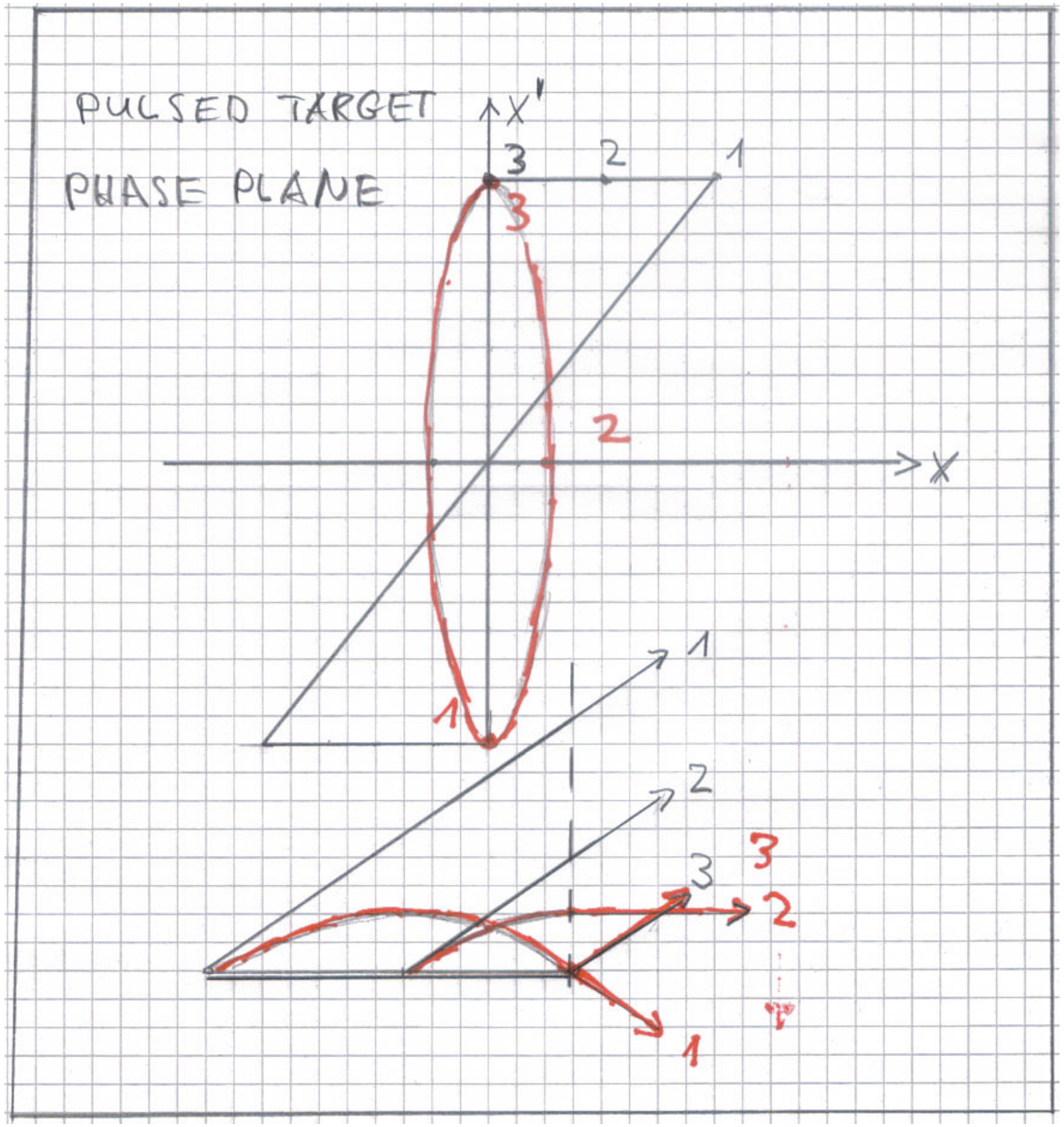
- A strong cirular magnetic field inside the target focuses the secondaries inside and along the target. This allows to increase the phase space density (normally forbidden by Lioville’s Theorem).

Li - TARGET - LENS

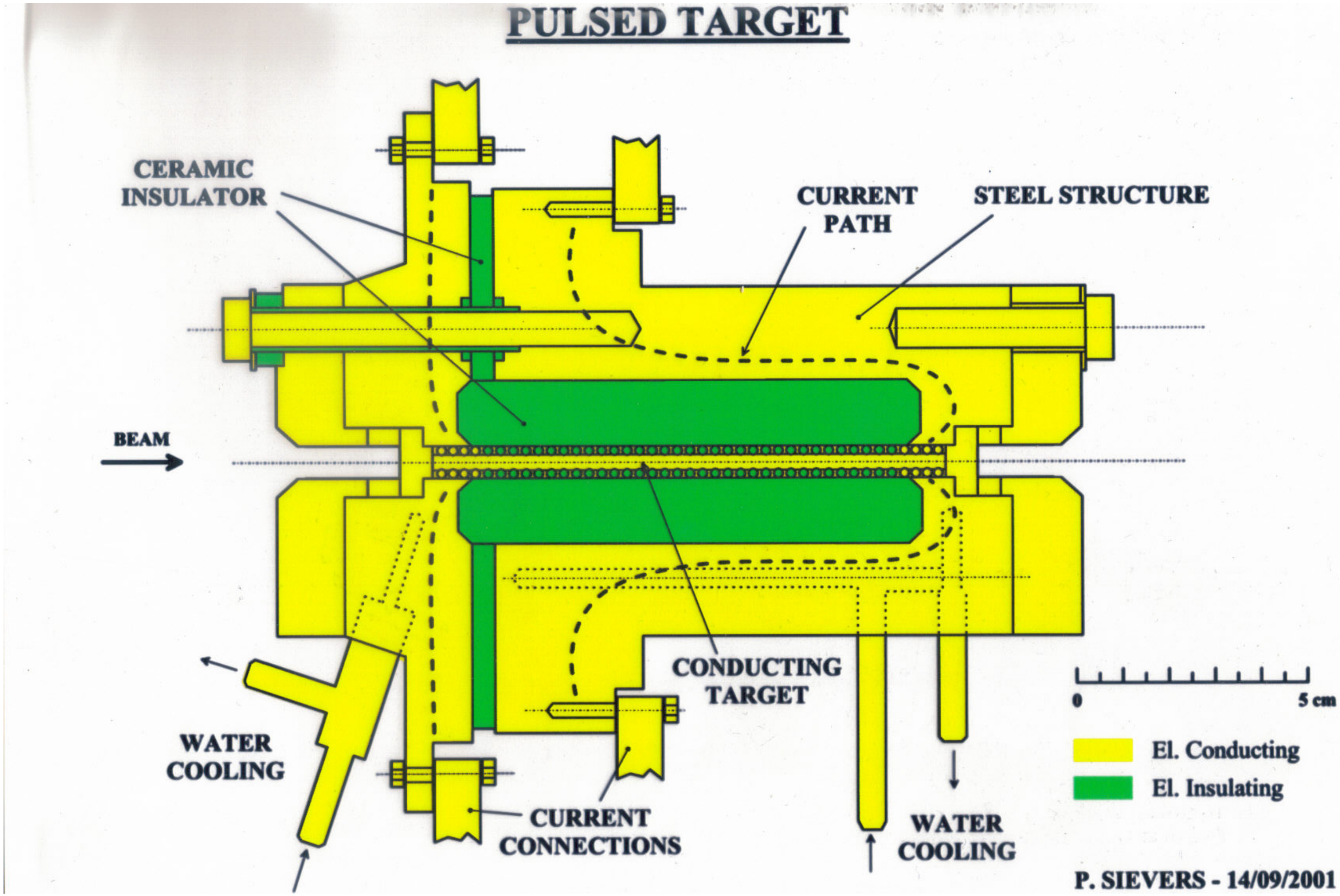


P. SIEVERS 23/05/2000

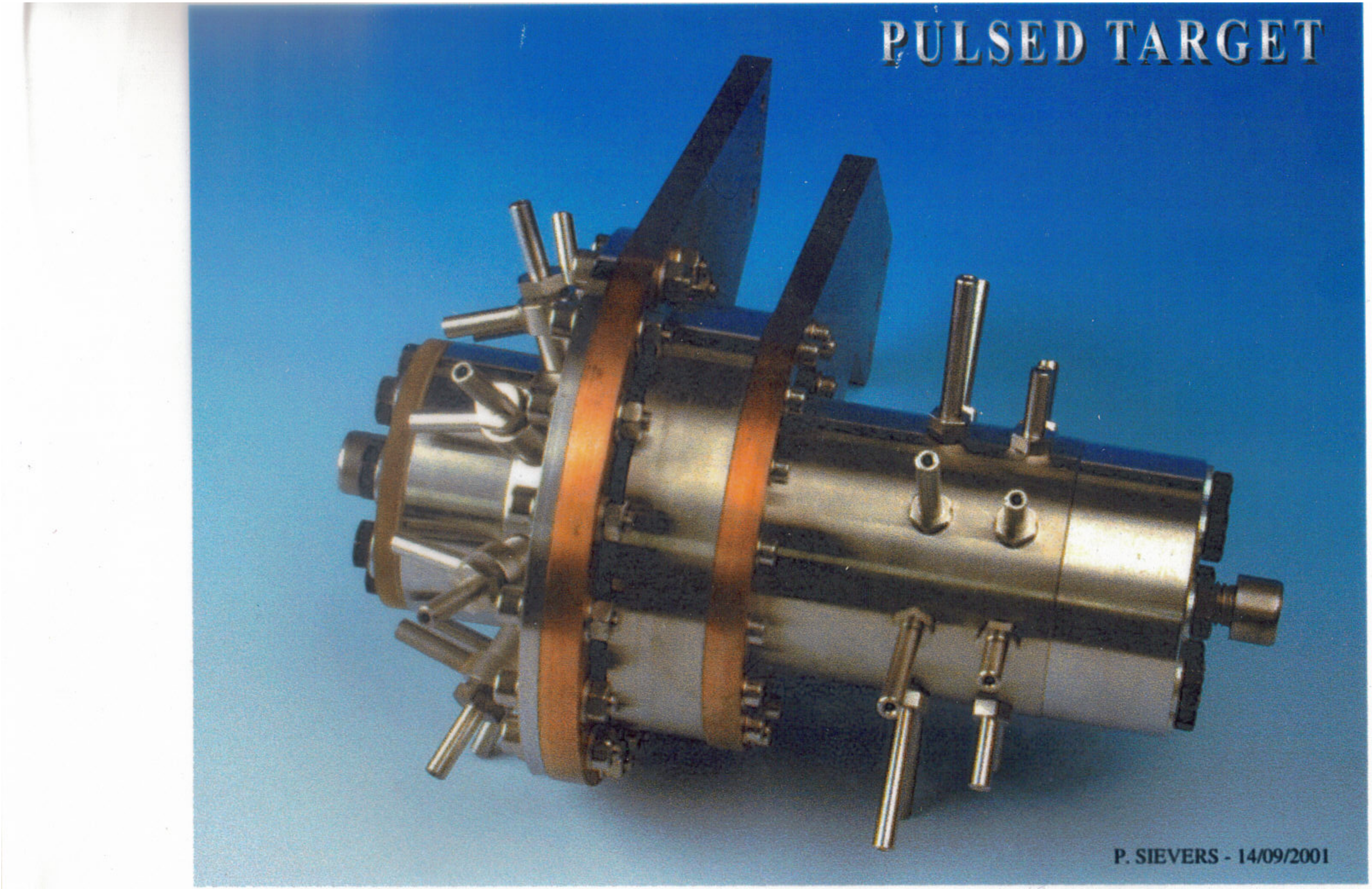
Pulsed Target



Pulsed Target



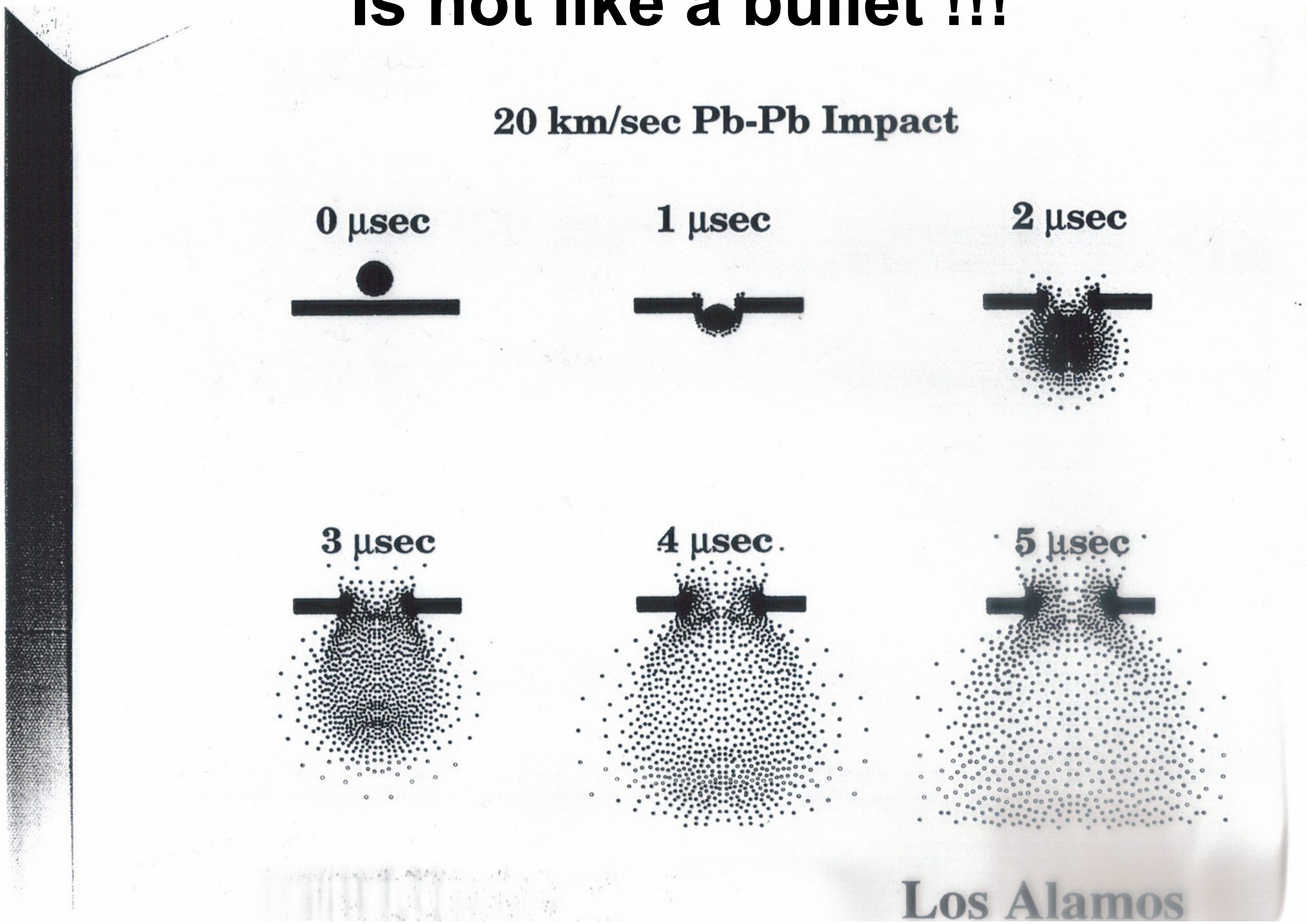
Pulsed Target



Pulsed Target

- Problems:
- In addition to beam heating: Joule heating!
- For Pi-minus or Anti-Proton production the incident proton beam is defocused. Its momentum is usually much higher than that of the secondaries?!
- The secondaries are forced to travel along the inside of the target: Re-absorption!
- One must have very good reasons to use pulsed targets. « Only » solution: liquid metal target.

Is not like a bullet !!!



- Instant heating does not move material at time zero, due to its mass inertia! It changes only the equilibrium position of the material: At time zero a bar is too short and it is under stress or pressure.
- The evolution in time thereafter is governed by the wave equation, taking into account the initial conditions and the boundary conditions: at time zero there is uniform stress along the bar, but at both ends of the free bar the stresses remain allways zero.

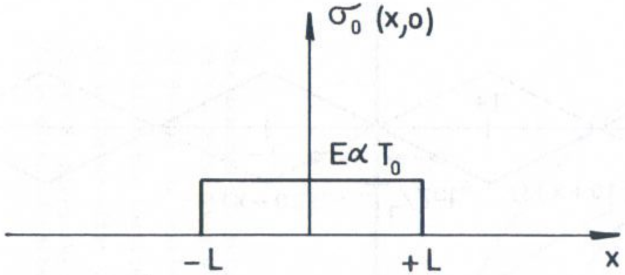


Fig. 1 Initial axial stress distribution in an instantaneously heated rod.

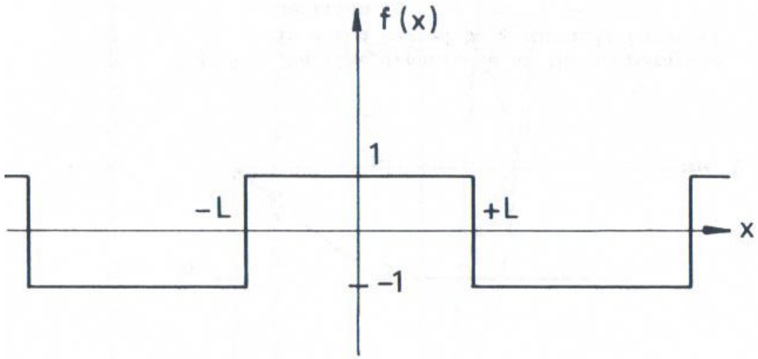
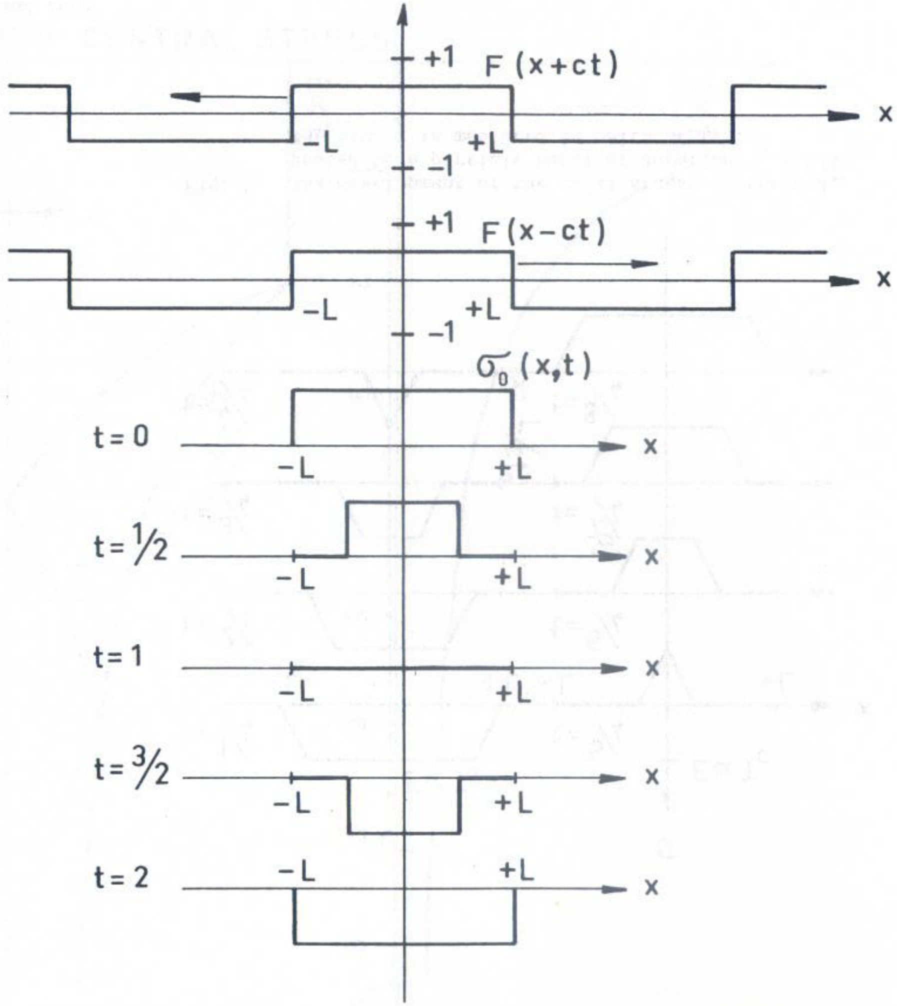


Fig. 2 The square wave describing the initial axial stress distribution in the rod $-L \le x \le +L$.



Thermal Shock

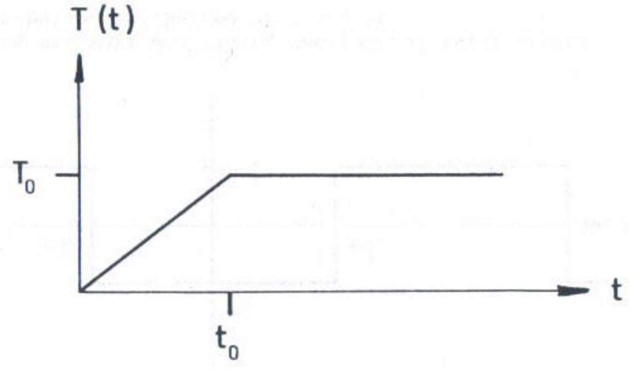


Fig. 4 The time dependence of the temperature in a rod heated by a particle burst of duration t_0.

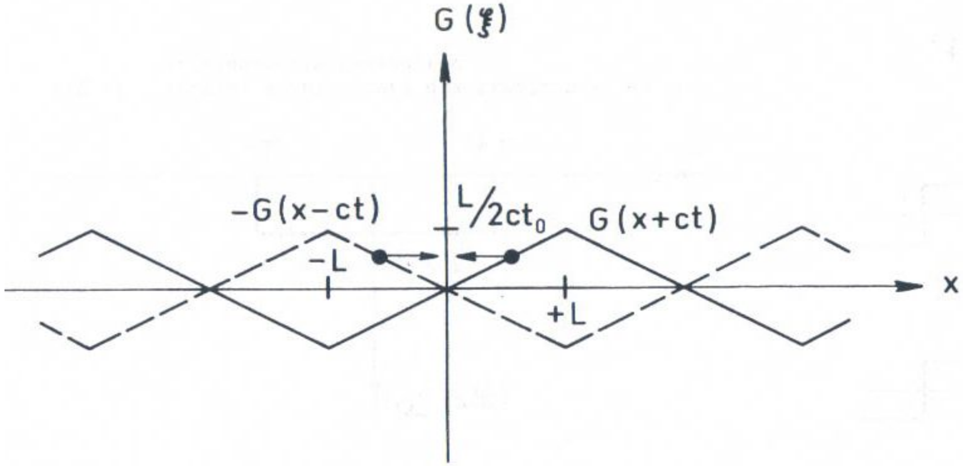


Fig. 5 The saw-tooth functions travelling in opposite directions and constituting the stresses in a rod, heated by a particle burst of duration t_0.

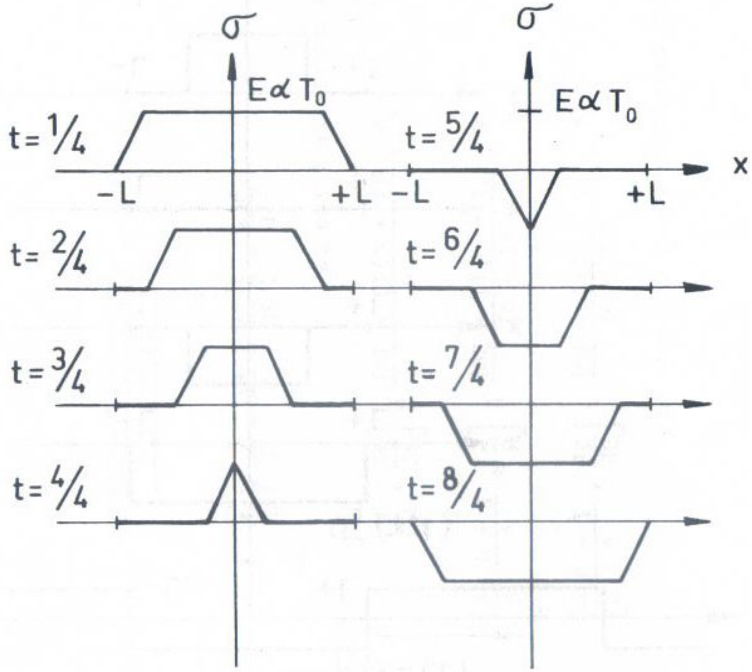


Fig. 6 The development of the axial stress in the rod, heated by a particle burst of duration $t_0 = L/4c$. The time t is measured in units of L/c.

Thermal Shock

- For « slower » heating over τ the stress becomes

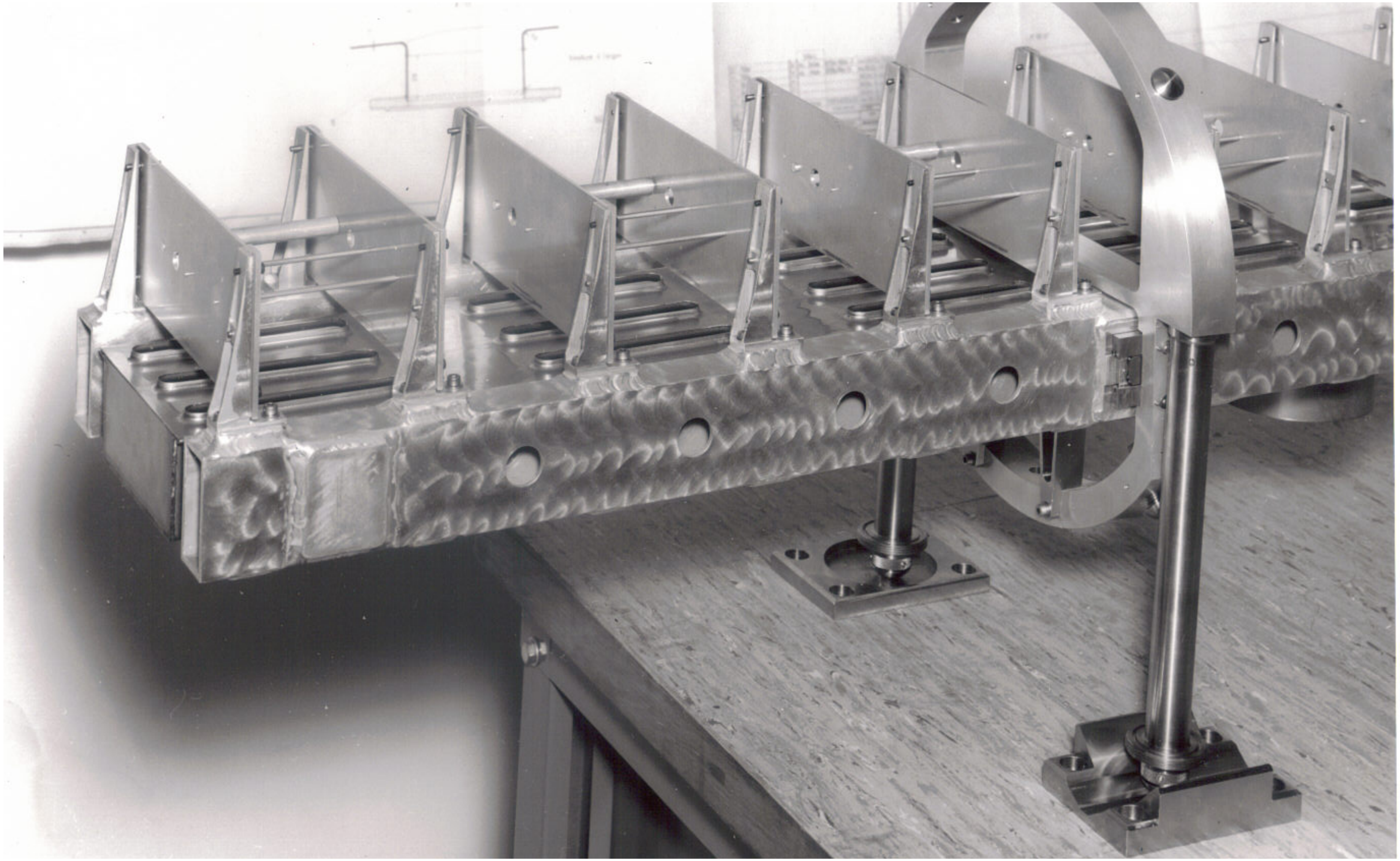
$$\sigma = \frac{\sigma_0 \tau_0}{\tau} = E\alpha\Delta T \times \frac{\tau_0}{\tau}$$

- τ_o: Time for sound to traverse half of the target length L/c or the radius of a sphere R/c. c: velocity of sound.
- τ: Pulse duration.
- For CLIC τ = 156 ns; R = 1 mm: some shock reduction may be expected???
- Maximum material velocity v can be expressed as a Mach No. :

$$\mathrm{m} = \frac{\mathrm{v}}{c} = \alpha\Delta\mathrm{T}$$

- Only when m approaches 1, one may speak about thermal shock!

Some history



Some history

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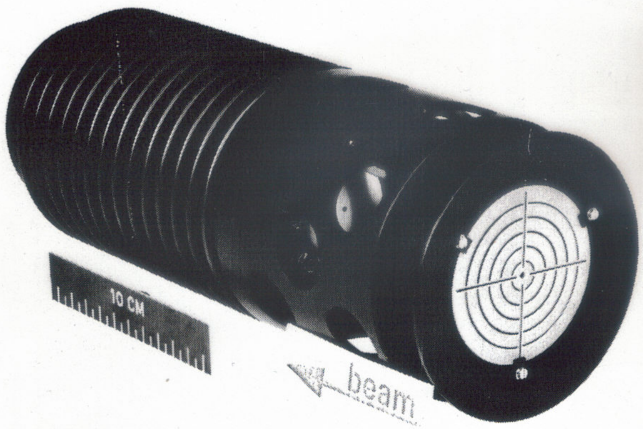


Fig. 5 – Overall view of the target assembly. The aluminium container is anodised black to aid cooling via radiation. The hole in the upstream luminescent screen avoids premature aging and radiation damage of the latter.

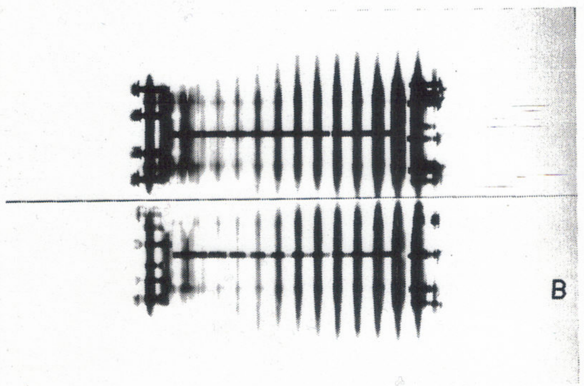
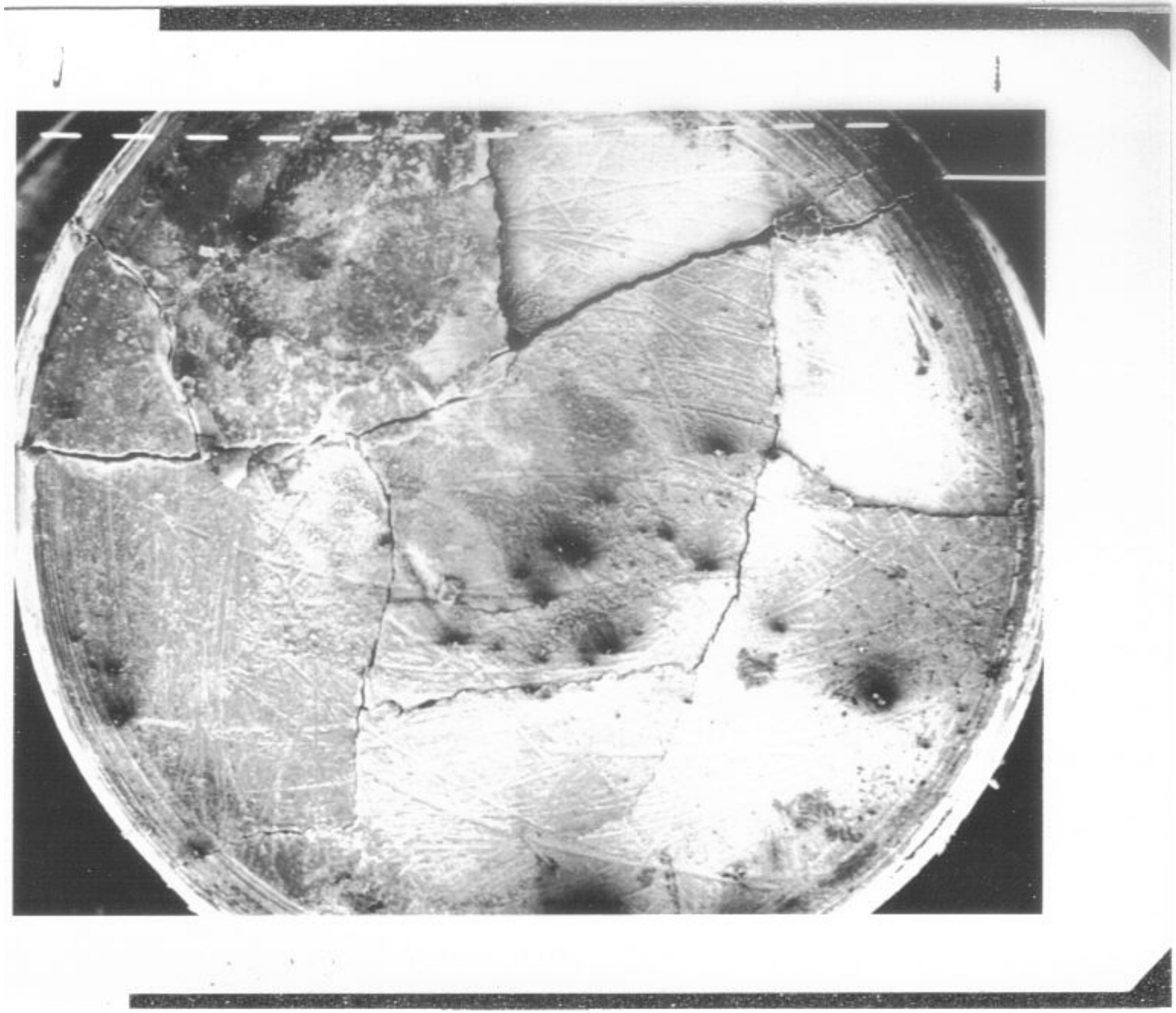
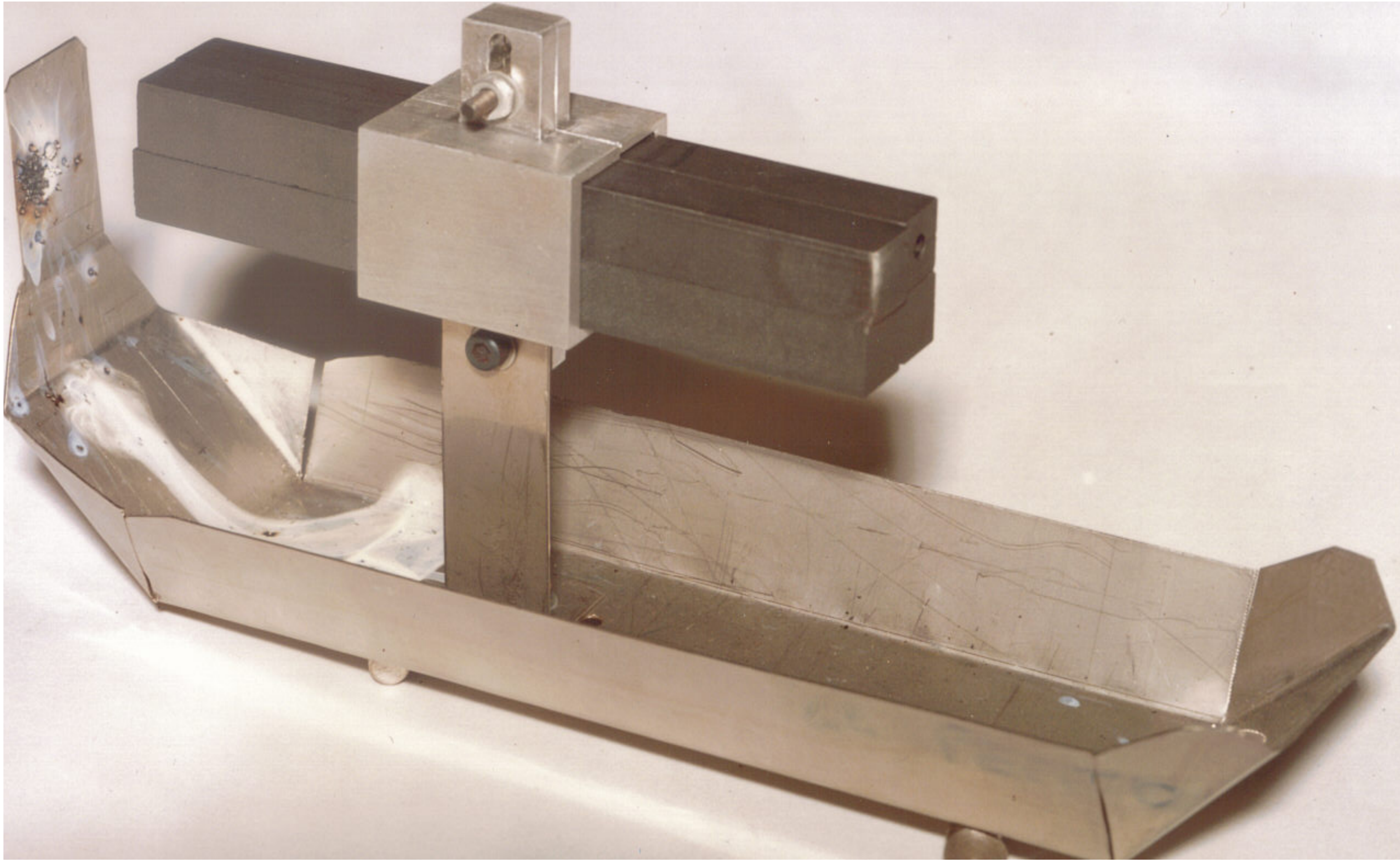


Fig. 6 – X-ray photo of the target ensemble after irradiation.

Some history



Some prescribed crimes !!!



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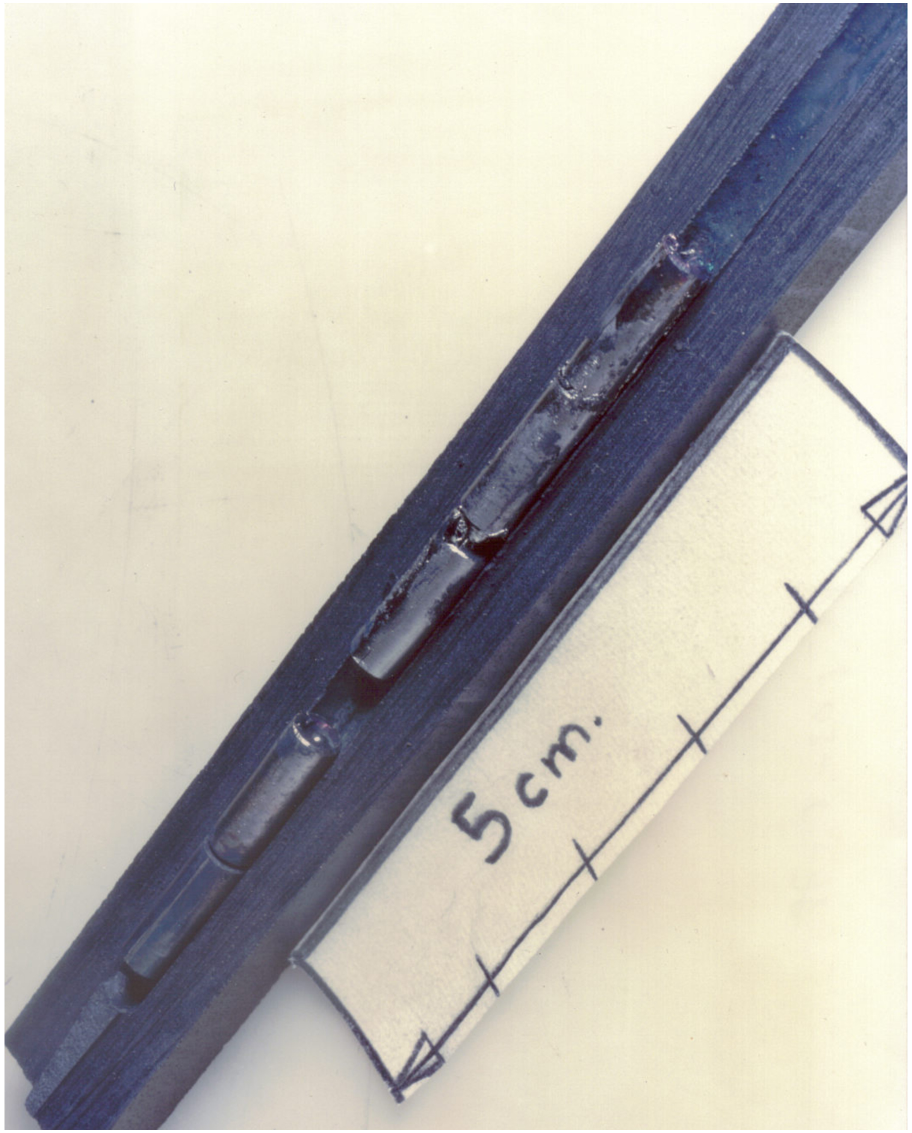


That's all Folks!

Temperature cycling with pulsed beams:

- Duration of pulses t_0.
- Repetition time of pulses t_1.
- Cooling constant τ.
- Adiabatic temperature rise without cooling during one pulse ΔT.

For $0 < t < t_0$:

$$T_i(t) = \frac{\Delta T \times \tau}{t_0} \times \left(1 - \frac{\left(e^{-\frac{t}{\tau}} / e^{-\frac{t_0}{\tau}} \right) \times \left(e^{-\frac{t_0}{\tau}} - e^{-\frac{t_1}{\tau}} \right)}{1 - e^{-\frac{t_1}{\tau}}} \right)$$

- For $t_0 < t < t_1$

$$T_e(t) = \frac{\Delta T \tau}{t_0} \times \left(\frac{e^{-\frac{t}{\tau}}}{e^{-\frac{t_0}{\tau}}} \right) \times \frac{1 - e^{-\frac{t_0}{\tau}}}{1 - e^{-\frac{t_1}{\tau}}}$$

  - The peak temperature is reached at $t = t_0$:

$$T(t_0) = \frac{\Delta T \tau}{t_0} \times \frac{1 - e^{-\frac{t_0}{\tau}}}{1 - e^{-\frac{t_1}{\tau}}}$$

- For short pulses with little cooling during the pulse with $t_0 \ll \tau$:

$$T(t_0) = \frac{\Delta T}{1 - e^{-\frac{t_1}{\tau}}}$$

$$T(t_1) = \Delta T \times \frac{e^{-\frac{t_1}{\tau}}}{1 - e^{-\frac{t_1}{\tau}}}$$