1. Temperatures and Thermal Stresses.

2. Cooling. Use of He Gas as Cooling Fluid.


4. Thermal « Shock ».
1. Temperatures and Thermal Stresses.

- Temperatures and Thermal Stress

- From Beam Pulse, Codes, like FLUKA:

\[ T(r) = \frac{dQ}{\rho \times c \times dV} \]

\[ T(r) = T_0 \left(1 - \frac{r^2}{R^2}\right) \]

- 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(0)!

- Thermal Stress due to 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.
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 $\tau_d = \frac{R^2}{8\lambda/c\rho}$

- 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 $\Delta T$. 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!

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

$$T_p = \frac{\Delta T}{1 - e^{-\frac{t}{\tau}}}$$

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

For spheres

$$\tau = \frac{\rho cR}{3\gamma}$$

For cylinders

$$\tau = \frac{\rho cR}{2\gamma}$$

$m$: masse of sphere
$c$: specific heat of sphere
$\gamma$: 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 $\gamma$ (W.m$^{-2}$.K$^{-1}$).
- Cooling time constant $\tau$ (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$^{-2}$:
  - $\gamma = 2400$ W.m$^{-2}$.K$^{-1}$; $\tau = 2$ s (longer than internal diffusion time!).

- Applicable for a wheel rotating at 30 rpm for ESS.
1. Temperatures and Thermal Stresses.
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 $\phi=1$mm; He pressure 20 bars; inside velocity 80 m/s: $Y = 3.3 \times 10^4$ W.m$^{-2}$K$^{-1}$; cooling time constant $\tau = 13.8$ ms.
- Temperature cycling $T(t)$ (above that of He) can be expressed in a closed form as a function of $\tau, t_0$ and $t_1$ (see Annex 1).
- Cooling takes place already 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

![Graph showing temperature cycles](image)

- **Stationary**: $T(t) = 13.8\, \text{ms}$
- **Rotating**: $T(t) = 100\, \text{ms}$

Parameters:
- $T_0 = 13.8\, \text{ms}$
- $t_0 = 2\, \text{ms}$
- $T(t) = 13.8\, \text{ms}$
- $T(t) = 100\, \text{ms}$

Legend:
- Red: Rotating
- Black: Stationary

4th HPTW - Malmö – 02-06/05/2011 P. Sievers
Trolling ILC-target

P. Sievers
16.03.2011

TROLLING
TARGET RING

BEAM

COOLING INLET

TARGET RING

COOLING OUTLET
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 $\Delta T$ 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 $\sigma_x = 5\, \text{cm}$ and $\sigma_y = 1.5\, \text{cm}$ the proton density in the beam center with

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

Adiabatic max. temperature rises per pulse in Ti and St.Steel are $(3.3-6.6)\, \text{K}$ and $(4.2-8.4)\, \text{K}$ respectively.

Thermal stresses in the centre are

$$\sigma_{\text{th}} = -E\alpha\Delta T/2,$$

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 $0.2\, \text{mm}$ thick st.st. window, cooled from only one side with He is about $80\, \text{ms}$, of the same order as the time space between pulses of $50\, \text{ms}$. Thus, temperatures of about $2 \times \Delta T$ may be expected. However, for a thickness of $1\, \text{mm}$ things get worst.

How to fight fatigue and radiation damage: Wobbling Window?
Better ideas are most welcome.
A strong circular magnetic field inside the target focuses the secondaries inside and along the target. This allows to increase the phase space density (normally forbidden by Liouville’s Theorem).
Pulsed Target

Pulsed Target

Phase Plane

1 2 3

x' y

P. Sievers
Pulsed Target

PULSED TARGET

- Ceramic Insulator
- Current Path
- Steel Structure
- Beam
- Conducting Target
- Current Connections
- Water Cooling

P. Sievers - 14/09/2001
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.
Thermal Shock

Is not like a bullet !!!

20 km/sec Pb-Pb Impact

0 μsec

1 μsec

2 μsec

3 μsec

4 μsec

5 μsec

Los Alamos
• 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 always zero.
Thermal Shock

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 $-L \leq x \leq +L$. 
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 $t_0 = t/L/c$. The time $t$ is measured in units of $L/c$. 

For « slower » heating over $\tau$ the stress becomes

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

$\tau_0$: Time for sound to traverse half of the target length $L/c$ or the radius of a sphere $R/c$. $c$: velocity of sound.

$\tau$: Pulse duration.

For CLIC $\tau = 156$ ns; $R = 1$ mm: some shock reduction may be expected???

Maximum material velocity $v$ can be expressed as a Mach No.:

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

Only when $m$ approaches 1, one may speak about thermal shock!
Some history
Some history
Some history

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 assembly after irradiation.
Some history
Some prescribed crimes !!!
Some prescribed crimes !!!
That's all Folks!
Temperature cycling with pulsed beams:

- Duration of pulses $t_0$.
- Repetition time of pulses $t_1$.
- Cooling constant $\tau$.
- Adiabatic temperature rise without cooling during one pulse $\Delta T$.

For $0 < t < t_0$:

$$T_i(t) = \frac{\Delta T \times \tau}{t_0} \times \left(1 - \frac{\frac{t}{\tau} / \frac{t_0}{\tau}}{1 - e^{-\frac{t}{\tau}}} \times \frac{\frac{t_0}{\tau} - \frac{t_1}{\tau}}{1 - e^{-\frac{t_1}{\tau}}}ight)$$
The peak temperature is reached at $t = t_0$:

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

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

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

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