Science & Technology Facilities Council

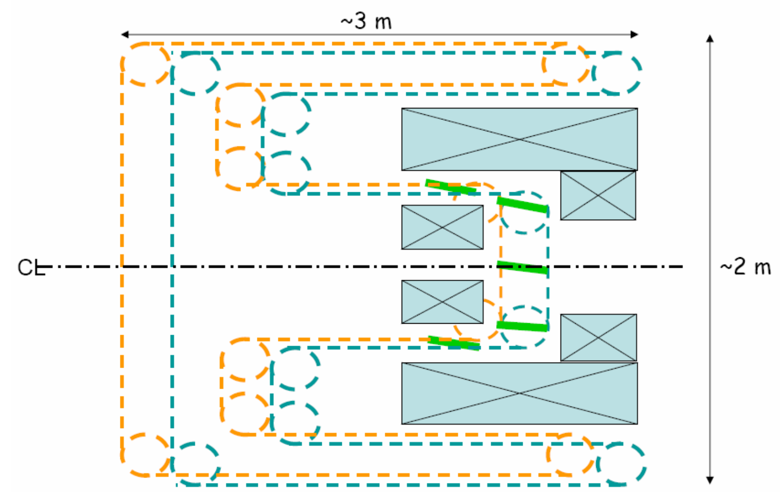
Solid Target Engineering

Peter Loveridge
P.Loveridge@rl.ac.uk
STFC Rutherford Appleton Laboratory

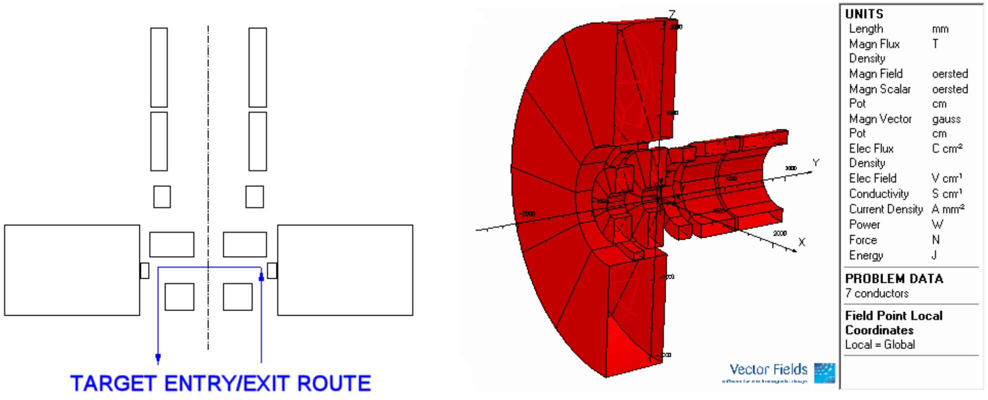
UKNF meeting, April 2008

Background

- Solid target solution being pursued as an alternative to the liquid-mercury baseline
- “Bicycle Chain” system proposed by Roger Bennett
  - Many individual solid tungsten target rods interact sequentially with each beam pulse
  - System operates in phase (at 50 Hz) with incoming beam pulses
  - Targets supported and driven by transmission chain
  - Target cooling occurs during recirculation
  - Target spacing = 100 mm
  - Chain Speed = 5 m/s
- “study-2” solenoid magnet geometry not compatible with solid target conveyor system
  - Alternative magnet layout proposed by Roger Bennett and developed by Jim Rochford



Solid Target Schematic Diagram [RJB]



Compatible Solenoid Magnets [RJB, JHR]

Some Engineering Issues

- Cooling
  - ~1 MW average power dissipated in target
  - How to cool the targets?
  - What is the required operating temperature?
- High temperature strength of target materials
  - Being addressed by thin wire shock studies at RAL
- High Radiation Environment
  - Material damage issues
- Lubrication and Wear
  - Temperature and radiation constraints infer that we cannot follow normal design rules
- Reliability
  - Minimum operating lifetime of several months under continuous operation
  - No service or repair
- Cost
  - Closely linked to overall target station dimensions

Target Cooling

- Beam Parameters:
  - Average proton beam power = 4 MW
  - Proton kinetic energy = 10 ± 5 GeV
  - Pulse repetition frequency = 50 Hz

- Target Heating:
  - Average power (heating) dissipated in target = 1 MW
  - Energy deposited in each target bar = 20 kJ
  - Temperature rise per beam hit = 124 K

- Cooling Options Considered:
  - Radiation cooling
  - Forced convection water cooling

Assume:

- 1 MW (mean) power dissipated in the target
- Beam pulsed at 50 Hz
- Each consecutive target bar interacts with a single beam pulse

Energy deposited in each target bar: $E = \frac{1\times10^6}{50} = 20\text{ KJ}$

Temperature rise in a Tungsten Target Bar:

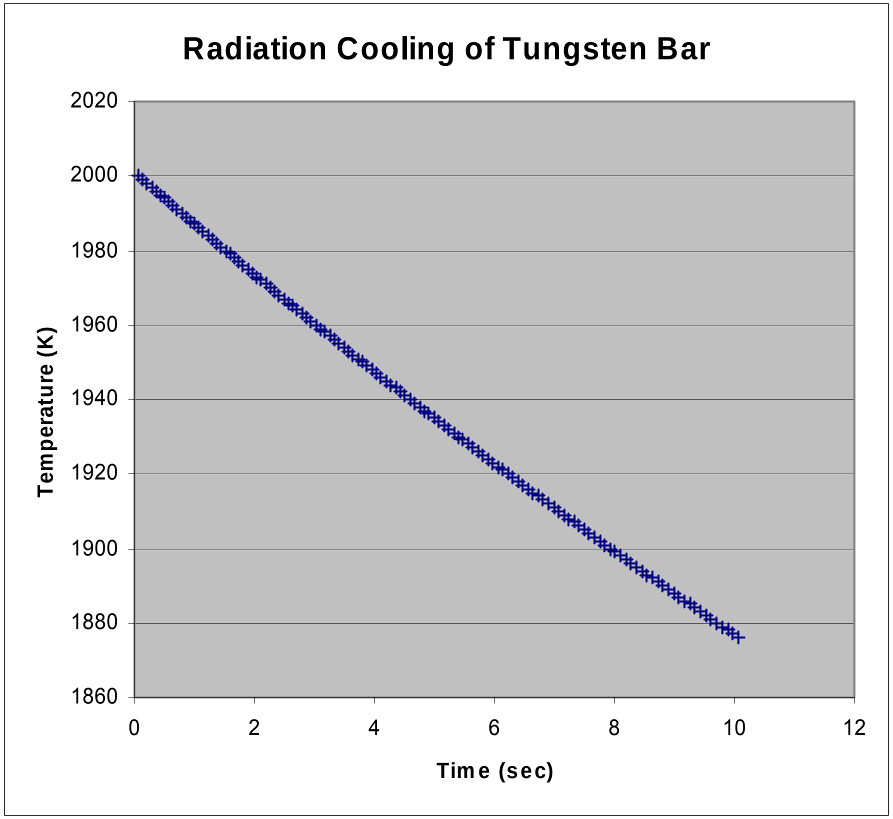
m = 1.21 kg

$C_p = 133\ \text{J.kg}^{-1}.\text{k}^{-1}$

$$\Delta T = \frac{E}{m.C_p} = \frac{20\times10^3}{1.21\times133} = 124\text{ K}$$

Radiation Cooling Option

- Assumed method of cooling in shock study test programme at RAL
- Need both a very high temperature and a very long cooling time
  - Tungsten upper use temperature ~1700 ˚C
  - Cooling time to remove heat dissipated by a single beam pulse ~10 sec (right)
- Chain Length:
  - 10 sec x 5 m/s = 50 m
- Number of Targets:
  - 10 sec x 50 Hz = 500 targets (!)
- Worth investigating surface treatments that could potentially enhance the Emissivity (ε) of the target bar?

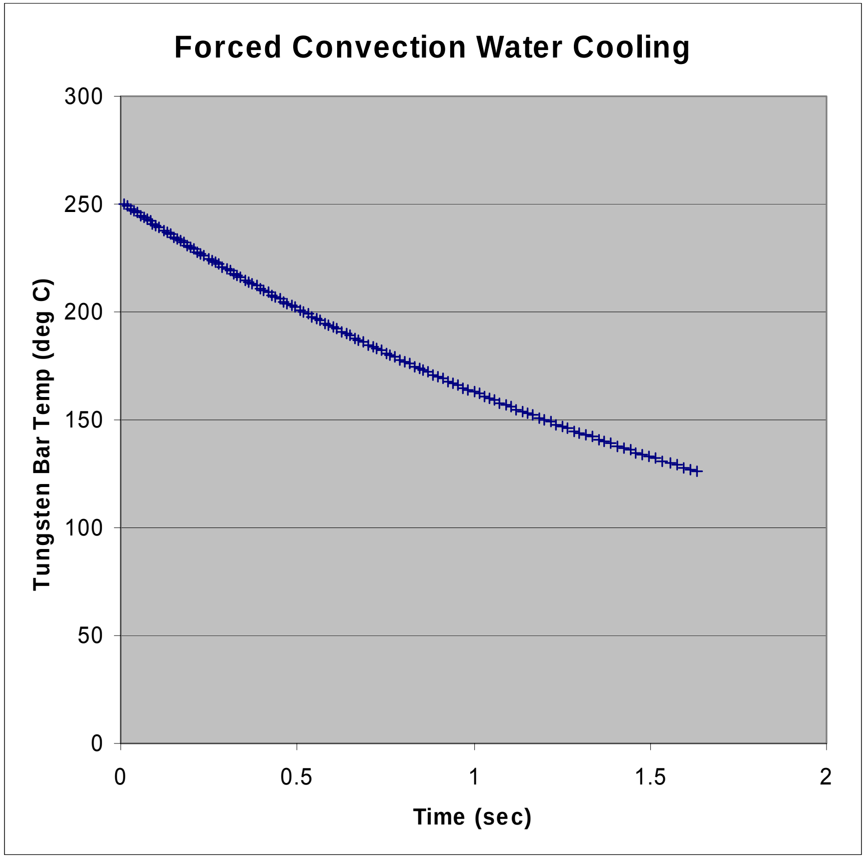


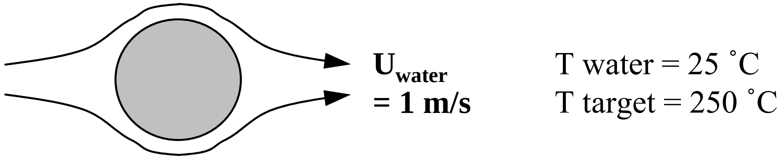
$$Q = A\varepsilon\sigma\,(T^4 - T_0^4)$$

$T = 2000$ K, $T_0 = 323$ K, $\sigma = 5.670$ e-8,
Rod: Length = 0.2 m, Diameter = 0.02 m
Tungsten: $\rho = 19{,}300$ kg/m^3, Cp = 133 J/kg.K, $\varepsilon = 0.2$

Forced Convection Water Cooling Option

- Could we achieve higher cooling rates at a lower operating temperature using direct water cooling?
  - Initial calculations assuming a continuous cross-flow of water look promising (right)
- Could we achieve a similar rate of heat transfer using water-spray cooling?
  - Used in magnetic horns...
  - Used in steel industry...
  - Further research required
- Need to avoid boiling the cooling water
  - A critical heat transfer rate exists, (~1 MW/m²), at which surface boiling occurs
  - Even below this limit there is enough cooling power to remove heat dissipated by a single beam pulse in ~2 seconds

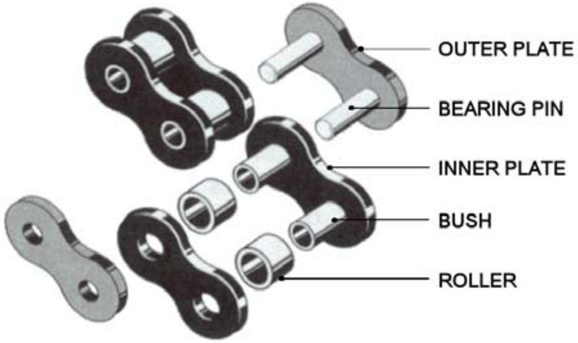




Heat transfer coefficient ~6000 W/m².K

Lubrication / Wear

- Normal design rules dictate lubrication regime based on chain speed and power requirements
  - Neutrino factory constraints:
    - High radiation environment
    - High operating temperature
    - Cannot use mineral oils!



Roller Chain Construction

- Alternative lubricants?
  - No commercially available lubricant rated for the required radiation levels, or at high enough temperatures for radiation cooling
  - Research on powder lubricants required. Talc? Graphite?
- Chain wear
  - Wear occurs at the pin/bush bearing surfaces
  - Bearing pressure is proportional to the tensile force carried by the chain
  - Chain wear realised as a pitch elongation
  - Limits for precision running ~1 % elongation
    - Chain/sprocket compatibility issue
  - Wear rates for unlubricated (degreased) chains not quoted!

Target System Loads

- Tensile chain forces arise from a number of sources:
  - Power transmission
    - Under steady state operation the chain needs only to transmit enough power to overcome frictional losses. Tensile forces are low.
  - Inertial load at start-up
    - From $f = m.a$
    - Can reduce the start-up acceleration to a level where it does not dominate the chain loads. Allow a few seconds to reach operating speed (5 m/s)
  - Centripetal loads
    - The main reason for speed limitations in chain drives
    - The limiting factor in this design
    - Centripetal load acting on a target engaged on a sprocket is proportional to 1/R
    - Select large sprocket sizes?
  - Sag
    - Allowance needs to be made for the small difference in position of the chain between zero and maximum load
    - Tensile forces low, and balanced within the chain

Design Philosophy

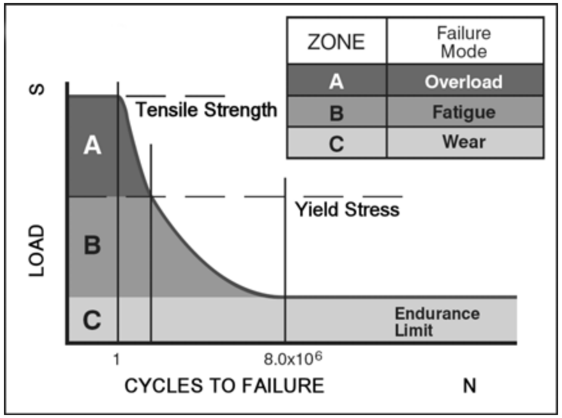
- Since proper lubrication seems impossible we must take other steps to control chain wear rates

- Propose to reduce pin/bush bearing pressure by "over-specifying" the chain

- Manufacturer suggestions:
  - 20 MPa "low" bearing pressure
  - 8 MPa "very low" bearing pressure

- Preliminary calculations indicate that it should be possible to operate in the "very low" bearing pressure regime

- Other implications:
  - Stress in chain links will be well below endurance limit
  - Fatigue failure can be discounted



Typical Steel Chain S-N Curve

Summary: Radiation Cooled Scheme

- System Characteristics:
  - Maximum possible steady-state target temperature, ~1700 ˚C for tungsten
  - ~500 targets, 50 m long chain, 10 seconds cooling time

Advantages	Problems
Remote cooling. No corrosion / erosion effects.	Need both a very high temperature and a very long cooling time.
Possibility to have target station in a vacuum. This would remove need for beam windows at entry and exit of target station.	Leads to a requirement for very long target chain, many 100's of separate targets, and large target station volume.
	Large target station volume leads to high shielding costs.
	Cannot use commercially available chain, -research required.
	Thermal expansion chain/sprocket compatibility issues.
	Need to design for moving parts to run at high temperature.
	Loss of mechanical properties at high temperature.

- R&D Needed:
  - A significant research programme is needed to develop a "very high temperature" chain
  - Candidate materials include tungsten, ceramics, carbon-carbon composite

Summary: Water Cooled Scheme

- System Characteristics:
  - Target temperature limited to ~250 ˚C
  - ~100 targets, 10 m long chain, 2 seconds cooling time
  - Can use standard commercially available stainless-steel chain

Advantages	Problems
Heat can be removed at a low temperature.	Cooling water in contact with target material. Possible corrosion / erosion issues.
Potential for short cooling time.	Activation of cooling water.
Can use commercially available chain.	Risk of boiling the cooling water.
Temperature range does not exclude the use of standard materials and parts.	Unknown chain wear life, - research required.
Targets better able to withstand beam induced shocks at low temperature (greater fatigue strength).	Target station pressurised to atmosphere. Requirement for beam windows at entry and exit from target station.

- R&D Needed:
  - Verify heat-transfer rates achievable with water spray
  - Investigate corrosion / erosion issues
  - Measure wear rates of unlubricated stainless-steel chain
  - Could water provide some lubrication?