ILC beam dump issues

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Contents of talk

- Review of the context of beam dumps at the ILC
- The possible beam dump choices
  - Solid C/Cu design with water cooling
  - Water-based beam dump (as used in SLC at 2MW)
  - Noble gas (Ar) based beam dump (water cooled)
- Very briefly, the 4GLS beam dump
- Dump issues – where the problems lie
- On-going studies (SLAC/KEK)
- Opportunities and possible collaborations
- Summary conclusion.

This talk is not exhaustive, and is a starting point for discussion
In 1996, SLAC installed two primary, industry built, 2 MW beam dumps. Designed using water as the primary absorbing medium (Walz et al). Very successful, but only run at around 800kW of power operation.
A generic beam dump layout

bunch train with \( N_t \) particles

e- or e+ with \( E_0 \)

repitition time \( 1/v_{\text{rep}} \)

Distribution of Beam on Absorber
- intra bunch train (fast sweep)
- average power (slow sweep)

Separation of beam vacuum and absorber

The beam to be dumped, with some bunch structure, total power and particle distribution
# General parameters

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Number of bunches: 2820  
Repetition rate: 5 Hz

*For reference and discussion*: The typical dump vessel diameter is around 1.5m. The window is typically 30cm in diameter, 1mm thick and made of Cu (the size is set by the disrupted beam)
Common e+/e- and g dump for 20mrad and a separate g dump for 2mrad. Note optics can be adjusted to allow beam growth.
The available kinds of beam dump

- **Solid dump (Graphite based)**: Limited by heat extraction, not an option.
- **Liquid dump (Water based)**: Most viable, but not without its problems.
- **Gas dump (Ar based)**: Maybe okay, and worth study, (never been built).
Snowmass ‘05 beam dump summary (BCD/ACD)

- BDS Baseline:
  - Main beam dumps based on water vortex scheme rated for 18MW beam.
  - Common e⁺/e⁻ and g dump for 20mrad
  - Separate g dump for 2mrad
  - Separate beam dumps rated for full power for all beam lines (total six beam dumps).
  - Undisrupted beam size increased by distance.

- Baseline R&D:
  - Prototype and tests of beam dump window?

- Option and Option R&D:
  - Elliptical wide window
  - Gas beam dump (1km of Ar in Fe)
  - Beam sweeping and/or graphite rod to increase undisrupted beam size.
The solid dump: C embedded in Cu

- Capture shower longitudinally
- Heat of order 100kW/cm
- Extracted by transverse heat conduction

Discussion:
Is a huge and heavy absorber, with insufficient heat removal for the ILC…not an option
The water based dump

- Design originated in SLAC – increase the cooling rate by having the dump material the same as the cooling material.
- Each pulse strikes a longitudinal column of water and heats it. The hotter water is then swept away and cooled.
- Developed at SLAC, and many studies done for TESLA at DESY, including involvement by industrial companies:
  - Framatone, Erlangen (Nuclear power plant constructors)
  - Fichtnerm, Stuttgart (technical engineering)
  - TUV-Nord, Hamburg (pressure dynamics calculations)
- XFEL work takes DESY staff focus at present time, but they are willing to be involved in ILC work. This may be in some kind of supervisory role – they have lots of good experience on the TESLA beam dump studies.
water-system

air treatment

sand

closure

hall

normal cooling water

exhaust / chimney?

basin

emergency/comm. beam tilted ≈15mrad

spent beam, tilted ≈15mrad

water-dump vessel

dump shielding
Water Dump: External Water System

Generals
- two loop system with \( p_B > p_A \)
- main piping DN 350mm

Primary Loop
- fully He gas-tight system
- 140kg/s between 50°C / 80°C
- 10bar static \( \Rightarrow T_{\text{boil}}=180°C \)
- ≈30m³ water content
- water filtering
- hydrogen recombination

Scheme of Water System
General water dump parameters

- Volume of water around $18\text{m}^3$
- Length of dump around 10m (sufficient multiple of $X_0$)
- Diameter of dump about 1.5m
- Pressure of water 10bar, at which water boils at 180°C
- Water flow rate around 1-1.5 ms$^{-1}$
- Window made of Cu, 1mm thick and 30cm diameter. The shape is always talked about as hemispherical.
- Dump tilted at 15mrad, to point muon flux downwards

All of these are representative, and depend on who you talk to and which studies you believe!
How the water dump may look
Heat removal and water flow

Goal is to keep $T_{eq}$ below the boiling point of the water, pressurised to 10bar.

Vapour column shifts shower max down, to expose solid dump at end to excess power.

Remove heat through water flow e.g. vortex (Fichtner scheme)
The gas dump

One atomic noble gas core (Ar, Xe) is surrounded by solid material (Fe)

gas core acts as scattering target (only small amount of energy deposition) and distributes energy longitudinally over ~ 1km into surrounding material. See Ilya’s talk at this meeting
The water dump issues (well, some of them)

- The water dump has been studied at both SLAC and DESY – some of these studies are now being restarted
- The main issues for this kind of design are:
  - The beam on the dump window, both from a stress perspective and from a delta-T perspective
  - The temperature rise of the water system
  - The formation of pressure waves
  - Radiation handling, for water, concrete and the window
  - Radiolysis, but this should be okay

The following slides will touch on some of these…
Issues (1.1): stress and temperature rise of the window

- The beam window is a very contentious issue...to some it matters and to others it’s a simpler affair.
- The window provides the passage from the vacuum to the water system, and needs to be thin enough to avoid becoming a dump itself! 1mm of Cu or C seems favourable. It needs to be thin compared to a radiation length.
- The size is set by disrupted beam, Ø=30cm is favoured.
- Need to be careful of
  - Peak temperature rise of the window
  - Mechanical stresses on the window – radiation leak in case of breakage. Need to compute displacements per atom (DPA) with ANSYS or some other code.
Issues (1.2): stress and temperature rise of the window

- TESLA TDR studies at DESY indicate that extreme stresses are avoided with a sandwich design.
- Furthermore, DESY team has computed that if the beam size is large enough to limit the temperature rise in the water to 40K during one pulse, then the window is safe in terms of cyclic stress. The safety margin is an order of magnitude.
- Note that the maximum allowable water temperature jump over one pulse is higher (computed using FLUKA, see later in this talk), but the window will break due to cyclic stress.
- ANSYS studies at SLAC are just beginning, to compute the stress levels (the displacements per atom) in the window.
**Issues (2): water temperature and volumetric boiling**

- FLUKA studies of energy deposition tell us about the temperature rises in the water volume.
- For 10 bar of pressure, water boils at \(~180^\circ\text{C}\).
- Vapour column pushes shower maximum towards solid end-cap, exposing it to high energy.
- Different studies are hard to compare, but nominal beam sizes of around 1-3 cm should be okay.

**Lower delta-T:**
- Optical beam blow-up
- Beam rastering
- Pressure/flow rate increase
- Metallic vapours
Issues (3): pressure waves

- Form when train hits dump
- Modelled at DESY using CFD

\[ \Delta p(r) @ z=2.5m, 0 \leq t \leq 800 \mu s \]
\[ \Delta p(r) @ z=2.5m, 0.8 \leq t \leq 1.6ms \]

in water:
\[ \Delta p_{\text{max}} \approx 3.7\text{bar} \text{ near } z\text{-axis @ 100 } \mu \text{s} \]
\[ \Delta p_{\text{min}} \approx -1.6\text{bar} \text{ near } z\text{-axis @ 950 } \mu \text{s} \]

→ reduces boiling point & solubility of gases!

Pressure drop may push local temperature to boiling point!
Issues (4): radiolysis (although this should be okay)

- What happens:
  - The H$_2$O molecule is “cracked” by the particle beam
  - Production rate profile similar to dE/dx profile
- Solution is through catalytic recombination – well studied
- Dangerous because of two factors:
  - Local H$_2$ gas bubble leads to pressure drop – similar to the formation of local pressure waves
  - Pocket accumulation of H2 and danger of explosion (this has happened in industry – we wouldn’t want this!)
- Recombiner uses “Helicat” catalyst and should be readily achieved through established technology
Issues (5): radiation handling

- Primary direct radiation:
  - Neutrons. Isotropic distribution. Shielding to surface
  - Muons. Protected by 15mrad tilt and sand.
- Activation of primary circuit. 18m$^3$ of water. $\sim$300TBq:
  - $^3$H, $\beta$ emitter. A danger if released
  - $^8$Be, $\gamma$ emitter. Local shielding and remote handling
- Issue: what if the window breaks? (DPA). Catastrophe!
- Activation of air system – necessary for total enclosure
- Activation of the window. This is studied through the thermal and mechanical stress studies, and necessitates a remote window handling/replacement operation.
- Have not discussed dismantling or subsequent storage, but this is highly non-trivial and costly.
The 4GLS beam dump

- The 4\textsuperscript{th} generation light source proposal needs to dump a beam of 100mA, with particles around 10 MeV and a total beam power of 1.3MW (including ~30\% safety factor)
- Lower energy means \(\frac{dE}{dx}\) is higher – much shorter shower distance for 4GLS than for the ILC
  - (400 GeV e stops in 5m Cu, 10 MeV e stops in 8mm Cu)
- Need to spread beam transversely – wide, flat dump.
- Water dump is not feasible, as the window would need to be very thin and very large – not possible.
- Cornell made a detailed study, and concluded that a solid Cu or Al dump is the most promising
- Proposal is around 80 Cu or Al bars, with cooling channels
Figure 2. Temperature (K, top) and Von-Mises stress (MPa, bottom) distribution in the central extrusion of the Glidcop tube dump.

Figure 3. Temperature (K, top) and Von-Mises stress (MPa, bottom) distribution in the central extrusion of an aluminum tube dump.
Some on-going studies

- Recently, interest has been reignited on dump studies (which is a needed thing!).
- There is nothing active as DESY (as far as I know), due to XFEL commitment (BUT lots has been done for TESLA).
- At SLAC, Vincke has started FLUKA calculations of energy disposition into water, for new ILC parameters at both 500 GeV and 1000 GeV CoM energy. These were first presented at Snowmass by Dieter.
- At KEK, Ban et al studied the GLC dump in some detail (together with some industrial partners). Sugahara reviewed these studies at Snowmass and plans to start some ILC-based studies in the near future.
- Next few slides show results from this on-going work.
Energy deposition

500 GeV electrons, $\sigma_x = 3.83$ mm, $\sigma_y = 0.44$ mm, bin size in $r = 2$ cm
Energy deposition in water

500 GeV electrons - $\sigma_x = 3.83 \text{ mm}, \sigma_y = 0.44 \text{ mm}$
energy deposition vs. radius

500 GeV electrons - $\sigma_x = 3.83 \text{ mm}$, $\sigma_y = 0.44 \text{ mm}$
Discussion of the SLAC FLUKA results

- Transverse input beam size that was found to be acceptable for long term safe window operation ($\sigma_x=3.83\text{mm}$, $\sigma_y=0.44\text{mm}$, $500\text{GeV CM}$) is too small to prevent volume boiling in region of maximum volumetric energy deposition in water, even more so for $1000\text{ GeV CM}$
- Minimum input beam size $\sigma_x=\sigma_y=8.47\text{mm}$ (for circular beam cross section) or $\sigma_x\sim25\text{mm}$, $\sigma_y\sim2.87\text{mm}$, when scaled from May 2005 $\sigma_x=0.87$, $\sigma_y=0.1\text{mm}$, will result in temperature rise per bunch train of $\sim170\text{°C}$ ($1000\text{GeV CM}$, $36.1\ \mu\text{A}$). This is $\sim$boiling point of water at $8\text{atm}$
- An independent check using the EGS4 code by Lewis Keller for $\sigma_x=\sigma_y=10\text{mm}$ gave $dT\sim158\text{°C}$
- Raising the flow rate by $15\%$ to $2650\text{gpm} = 10,200\ \text{l/min}$ will raise required supply pressure to $\sim10.5\text{atm}$ with commensurate increase in boiling point in water
- Raising flow rate will increase the velocity transverse to the beam direction to $\sim2.65\ \text{m/s}$
GLC KEK-based studies

To estimate radioactivity in the water:

- Be-7: 60 TBq
- C-11: 96 TBq
- N-13: 72 TBq
- O-15: 280 TBq

Amount of Radioactivity in the water

Cross Section Calculation Code PICA3/GEM

(Need to update for ILC parameters)
Summary of dump beam size computations

- SLAC FLUKA results of temperature rise in dump allow computation of minimum beam dimensions:
  - Shown that beam size needs to be blown up to 1cm avoid volume boiling (or increase flow rate or increase water pressure)
  - Achieved through combination optics and rastering.
  - TESLA TDR stated 1-3cm sweeping required (FLUKA) (although the beam parameters were different)
- Beam rastering non-trivial and essential for nominal beam. The TESLA TDR used 10m kickers in both planes.
- It is not yet clear what beam size and kick radius we need, but this may prove to be a tricky problem for us
- Note that the dT is also constrained by window stress
Summary of computational studies

- KEK radiation studies (PICA3/GEM) compute the radiation content of the sealed water systems. These have been done for the GLC (much lower power) and are going to be updated for the ILC parameter sets.
- DESY CFD codes compute pressure wave formation in the water dump. These were done for the TESLA parameters. There is interest in SLAC to study the formation of pressure waves and their localised boiling implications.
- SLAC studies using ANSYS of the thermal and mechanical stresses on the beam window. The evaluation of the DPA is a critical study, to assess the window durability. However, the DESY studies (dT limited to 40K) need consideration.
Summary of beam dump issues

- There is much I have not touched upon e.g. beam dump layout, the Beamstrahlung dump etc.
- The ILC BCD uses a water-based dump. The issues are
  - The thermal and mechanical stress of the window. The severity of this problem is under debate and study.
  - The formation of pressure waves in the water flow, and the subsequent risk of localised boiling.
  - Radiation handling and protection issues of the water, the concrete and the beam window.
- Other issues e.g. radiolysis are understood to a greater degree, but are still design factors.
- And, finally, we must consider the cost of these things!
Possible studies and collaborations on the water dump

- Work is starting in SLAC and KEK on various aspects of the water dump. DESY may be involved in a supervisory role.
- Dieter Walz is keen to collaborate with us, on both the water dump and the gas dump.
- Possible water dump studies for us are the beam window, and the evaluation of thermal and mechanical stress. Some work has started on ANSYS, but the window is a key area for the water dump success. We should also consider a window prototype study, perhaps based at RAL.
- Pressure wave studies (CFD) and FLUKA water-heating studies are also required, in collaboration with SLAC. We can quickly get involved in this.
- Radiation issues could also be explored (with KEK?)
- Prototypes: water dump window and a (mini) gas dump.
Conclusions

- The beam dumps are a crucial and difficult part of the ILC design. Some work is starting, but much more is needed.
- The main issues are the window design, and some dynamics of the water e.g. pressure wave formation
- We are well placed to take a role in the physics-based studies needed, and good collaborations are possible.
- The gas dump is a very interesting topic – I’ve not discussed much of it, but we should get involved as there is much to do. A prototype is would probably be needed to elevate it from the ACD to the BCD. See Ilya’s talk for more details and the possible physics studies. My view is that a gas dump study should form a big chunk of our work.