# ILC MAIN BEAM DUMPS
# CONCEPT OF A WATER DUMP

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# Historical Perspective

- 1966
  - SLAC installed two primary beam dumps
  - SLAC Design (D. R. Walz etal), Industry-built
  - 2.2 MW average beam power capacity
  - Principal power absorption medium is water
- 1996
  - Based on NLC parameters for 10 MW average power
    D. Walz proposed design concept based on original 1966 SLAC water dump
  - NLC ZDR, Ch. 11A
  - http:www.slac.stanford.edu/cgi-wrap/getdoc/slac-r-474-Ch11.pdf

# Issues in 1996 Proposal

- Water velocity ~ 1 m/s so that for NLC case water volume exposed to the 192 bunch train moves at least 2σ transverse to the momentum vector of the beam during the 8.3 ms interbunch period
- Temperature rise in this volume sufficiently low to avoid volume boiling
- Longitudinal and transverse size of power absorption medium adequate to contain and absorb cascade shower to a level where adjacent structures are not compromised.
- Window
  - — Hemispherical in shape, large enough in diameter to accept any transverse beam excursion
  - — Thin enough to result in acceptable temperature rises due to thermal conductivity
  - — Thermal heat fluxes into the water that can be conservatively managed by forced convection with the window cooling system

## Issues in 1996 Proposal (Cont'd)

- Dynamic cyclic thermal stresses due to beam heating when superimposed onto static stresses due to hydrostatic pressure at or below the endurance limit of the window material
- Radioactive cooling water system to be a closed system to contain radioactive isotopes generated primarily by photospallation on $^{16}O$, but communicating with the atmosphere via small diameter tubing from gas space on top of surge tank (to avoid nuclear pressure vessel issues)
- Radiolytically evolved gases ($H_2$, $O_2$) to be contained and recombined into water by catalytic $H_2$-$O_2$ recombiner.

## Summary of General Parameters in 1996 Concept

- R=30cm where momentum vector traverses dump vessel
- Water velocity across beam = 1-1.5 m/s
- Hydrostatic pressure ~8 atm to guarantee required water velocity and raise boiling temperature of water to $T_b$ ~160°C
- Dump vessel diameter ~1.5 m
- Overall dump length ~40$X_o$ of which ~18 $X_o$ are water (~6.5 m) and ~22$X_o$ (~ 1 m) of medium to high-Z material to attenuate and dissipate that part of cascade shower which remains after water section
- 30 cm diameter 1mm thick Cu window

## ILC Beam Conditions* at 20 mrad Dumps

| CM Energy | Average Current | Power/Beam | Beamstrahlung | Undisrupted $\sigma_x$ | $\sigma_y$ |
|---|---|---|---|---|---|
| GeV | μA | MW | MW | mm | mm |
| 500 Nominal | 45.1 | 11.3 | 0.3 | 0.87 | 0.1 |
| 500 High | 45.1 | 11.3 | 0.8 | 1.25 | 0.12 |
| 1000 Nominal | 36.1 | 18.0 | 0.9 | 0.51 | 0.35 |
| 1000 High | 36.1 | 18.0 | 3.2 | 0.39 | 0.35 |
| Recommend σ values | | | | | |
| 500 Nominal | 45.1 | 11.3 | 0.3 | 3.83 | 0.44 |

*May 2005 values

# ILC Main Beam Dump Window

- Worst Case $E_0$ = 250 GeV; $I_{av}$ = 45.1 μA ; $P_{av}$ = 11.3 MW
  - Beam has 2820 bunches in bunch train
  - Each bunch contains 2 x $10^{10}$ e
  - Bunch train contains 5640 x $10^{12}$ e, or 50X NLC ZDR
  - Each bunch train is 1 ms long
  - There are 5 bunch trains per second (5 Hz)

- Window Geometry
  - Could be circular (hemisphere) if large enough diameter
  - Could be rectangular (hemi-cylinder)
  - Window membrane to be attached to flange to allow non-destructive replacement
  - Let's choose rectangular window with 1 mm wall thickness
  - Let's choose a good austenitic stainless steel like Type 316L Results will be applicable to stronger materials like Invocel, etc.
  - Maximum stresses are meridian and with safety factor 2 Window could be ~ 35 cm tall, a 35 cm diameter hemi cylinder

- Beam/Window Issues

  — Total power deposition in window $P_{av}$ ~ 52 W for 45.1 μA
  
  — Let's fold in a double-convoluted Gaussian and we find the effective power deposition in a control volume bounded by $\sigma_x$ = 0.87 mm, $\sigma_y$ = 0.1 mm $p_{w,\ \sigma x\ \sigma y}$ ~20 W
  
  — Assuming for the moment uniformly distributed heat sources (neglecting the peak at r = o and averaging over $\sigma_x$ $\sigma_y$) the source term becomes S ~ 74 x $10^3$ W/$cm^3$
  
  — Temperature rise for one bunch train in control volume is $\Delta T_b$ ~ 3900° C
  
  — Heat diffusion is millisecond to second type process
  
  — Temperature rise is ≤ $10^{-15}$ second type process and will not save the day
  
    - Most window materials will melt in one bunch train
    - Must increase beam spot size to a level where expected temperature spikes are well below the melting point of the window material and where the expected cyclic thermal stresses are at or below the endurance limit of the material

Beam/Window Issues (Cont'd)

- From experience and material properties we know that $\Delta T_w \sim 200°$ C/bunch train will not exceed endurance properties of the material; can adjust later for specific material
- Consequential cyclic thermal stress spikes in a fully restrained body are of the order of $\sigma_{th} \sim 75 \times 10^3$ psi, a bit high, but ok for now since window is unrestrained in beam direction

- What beam size would it take to produce $\Delta T_w \sim 200°$**?**

  - Working backwards and expanding both $\sigma_x$ and $\sigma_y$ by the same ratio we find $\sigma_x \sim 3.83$ mm and $\sigma_y \sim 0.44$ mm
    We have expanded the effective spot size by ~ factor 20
    ($\sigma_x \sigma_y \pi$ went from $0.0273\ cm^2$ to $0.531\ cm^2$)

Beam/Window Issues (Cont'd)

- Next let's examine the temperature rise in the cooling water right adjacent to the window, neglecting window cooling transverse velocity as well as the small increase in shower multiplicity and transverse beam size increase due to single and multiple scattering in the window
  - Power deposition is $P'_{H2O}$ ~ 90 W/cm
  - Power into control volume bounded by $\sigma_x\ \sigma_y$ $P'_{H20}$, $\sigma_x\ \sigma_x$ ~ 35 W/cm
  - Heat source term becomes $S_{H20}$, $\sigma_x\ \sigma_y$ ~ 660 W/cm$^3$
    Temperature rise in control volume $\Delta T_{H20}$ ~ 30°C/bunch train which is ok
  - Power rejected by the window into this control volume of water is superimposed and might raise the water temperature to $\Delta T_{H20}$ ~ 50°C/bunch train which is acceptable

## Beam/Window Issues (Cont'd)

- Temperature rise across the window
  - In zeroth order approach, neglecting lateral conduction for the moment, we find a heat flux to the water interface from the $\sigma_x \sigma_y$ control volume of q" ~ 20/0.053 ~ 380 W/cm$^2$
  - For uniformly distributed heat sources the temperature rise is $\Delta T$ = q" t/2k = 380 x 0.1/2x0.165 ~ 115° C
  - Temperature rise across window with lateral conduction is of the order of 20° C if the wings of the Gaussian are neglected. If all the power (52W) under the Gaussian is deposited in the $\sigma_x\sigma_y$ volume (3.83 mm x 0.44 mm x 1 mm), the maximum temperature rise would be ~ 50° C. The real value is between 20 & 50° C, very modest
- Other suitable window materials

  (1) Titanium, such as alloy Ti-6Al-4V
  - Has lower thermal conductivity which is more than offset by higher strength, particularly at elevated temperatures
  - Has lower Z resulting in lower power deposition

Beam/Window Issues (Cont'd)

— Using same approach as above we find
$P_w$ ~ 32W ; $P_{w,\, \sigma x \sigma y}$ ~ 12.5 W ; S ~ 235W/cm$^3$
$\Delta T$ ~ 20° C/bunch train and $\sigma_{th}$ ~ 2,800 psi

— All these values are very modest; can probably reduce window thickness on account of its high strength

— Window must be attached (by e-beam welding) to titanium window flange

— Heat flux to the water interface for same approach as above
q" ~ 235 W/cm$^2$ $\Delta T$ ~ 170° C

Very modest for this material

(2) Inconel

- Alloys like A601 has superior corrosion resistance and mechanical properties at elevated temperature
- 718 has superior resistance, high strength, outstanding weldability and resistance to post weld cracking, excellent creep-rupture strength
- X750 good corrosion resistance, high tensile and creep rupture properties

- Any of these and other alloys have similar Z and dE/dx values as the austenitic stainless steel examined above, but they are much stronger at elevated temperature, possibly allowing reduction in window thickness
- These alloys have been extensively used in nuclear reactors

## Window Cooling Water System Issues

- Window to be cooled by forced convection
  - Separate cooling loop from main dump, but supplied by same pump
  - Several individual water jets impinge in the region where the beam passes through the window
  - Heat flux of q” ~ 380 W/cm$^2$ presents no problem, even when superimposed onto heat load from beam interaction with water near window surface
  - Heat flux is in range of forced convection and, with good subcooling, there exists much headroom before nucleate boiling and two-phase flow conditions are reached.
  - In this type of geometry heat fluxes of 2 kW/cm$^2$ can be supported indefinitely, provided that the surface can handle the cavitation exposure from the collapsed water vapor bubbles near the window surface

## Main Dump Cooling Issues

- A “vortex-like” flow configuration analogous to the original 1966 SLAC beam dumps is suggested, although other flow patterns will work too
- An inlet manifold located on the inside of the dump next to the shell will supply the flow and its initial direction;
  - A series of equally spaced holes injecting water approximately tangentially into the vessel over the full length of the water section will initiate the vortex-like flow
  - This is an economical way to dissipate large amounts of beam power
- In the region of beam impingement at R ~ 30 cm the flow behaves approximately like Vxr – constant (potential flow theory)
- The outlet manifold or “sink” is located in the center of the dump.
  - It provides a stabilizing influence on the flow, although its absence and provision of a sink in the center at the downbeam end of the water section will work too. The flow pattern is then approximately a 3-dimensional vortex

## Main Dump Cooling Issues (Cont'd)

- It is essential that the volume of water exposed to the core of the beam be moved transverse to the momentum vector of the beam to prevent "volume boiling." A water vapor column along the beam trajectory would shift shower maximum downbeam and perhaps expose the solid material section at the end of the dump to excessive power
- How much would a control volume of water move azimuthally in the vortex-like flow if the water velocity across the beam trajectory was 1 to 1.5 m/s?
  - During the length of one bunch train (1 ms) we find 1 mm and 1.5 mm for velocities of 1 and 1.5 m/s, respectively
  - By the time the next bunch train arrives for 5 Hz (≡ 200 ms) the control volume of water will have moved ~ 200 mm ≡ 8 inch
- How many of the 2820 bunches at 2 x $10^{10}$e/bunch will get deposited in a 2 $\sigma_y$ volume?
  Near the window, before the radial shower develops, 2 $\sigma_y$ ~ 0.2 mm and we find 564 bunches for 1 m/s and 375 bunches for 1.5 m/s, respectively. These values are for the original $\sigma_y$ = 0.1 mm. For the $\sigma_y$ = 0.44 mm we find most of the bunches in the train (2480) for 1m/s and 1650 for 1.5 m/s

## Main Dump Cooling Issues (Cont'd)

Consequently, the temperature rise in the control volume bounded by 2 $\sigma_y$ will be < 5° C, even allowing for the contribution from the wings of the assumed Gaussian distribution

- What about conditions at $T_{max}$, the maximum of the cascade shower?

$T_{max,\ 250\ GeV} \sim 7.2\ X_0$ ; $T_{max,\ 500\ GeV} \sim 7.9\ X_0$; $T_{max,\ 750\ GeV} \sim 8.3\ X_0$

Shower multiplicity by $\Pi^{(e)}_{max,}$ at $T_{max}$ is

$\Pi^{(e)}_{max,\ 250\ GeV} \sim 382$; $\Pi^{(e)}_{max,\ 500\ GeV} \sim 732$; $\Pi^{(e)}_{max,\ 750\ GeVv} \sim 1072$

Power deposition per unit length at $T_{max\ is\ then}$

250 GeV: $P'_{max} = (-\rho dE/dx)\ I_{av}\ \Pi^{(E)}_{max} = 2.03 \times 10^6 \times 46.1 \times 10^{-6} \times 382 \sim 35.7 \times 10^3$ W/cm
500 GeV: $\sim 53.6 \times 10^3$ W/cm
750 GeV: $\sim 78.6 \times 10^3$ W/cm

## Main Dump Cooling Issues (Cont'd)

- Total flow rate required to dissipate 18 MW of beam power allowing for a conservative bulk temperature rise of 30° C is ~ 2300 gpm ≡ 8850 l/min

  — For same flow rate and 11.3 MW we find $T_{bulk}$ ~ 19° C

  — Or for same 30° C rise could perhaps run pumps slower and deliver only ~ 1430 gpm ≡ 5600 l/min, subject to adequate flow velocity near the window and in region of maximum volumetric heating

# Window Exchange Issues

- Radiation damage to the window, i.e. formation of highly immobile multiple vacancies and interstices
  - Much data exists, but specifics for beam windows are scarce
  - It might be prudent to replace window on a regular schedule driven by integrated specific dose in region of nominal beam impingement
- Window Activation
  - Window will be highly activated, probably to a level where window exchange will have to be done semi-remotely, regardless of window material
- Water Activation
  - Activation products are primarily the result of photo-spallation on $^{16}O$: we find $^{15}O$, $^{13}N$, $^{11}C$, $^{7}Be$ and $^{3}H$
  - The first 3 have short half lives, will have decayed after ~ 3 hours

    $^{7}Be$ will be removed, filtered out in mixed bed ion exchange column which is not next to window

## Window Exchange Issues (Cont'd)

- — Tritium ($^3H$) will build up to some equilibrium level; half life is 12.3 years; is $B^-$ emitter with low energy, ~ 20 KeV. Can install temporary shielding
- Dump Shell Activation
  - — The stainless steel shell will be activated
- Concrete Housing Activation
  - — The "cave" will be activated with higher or lower activity depending on components in concrete
- A semi-remote window removal mechanism was designed for the original SLAC A-beam dump
  - — Mechanism was built and had a dry run before dump was activated
  - — 15 cm ≡ 6 inch diameter window was captured between two massive flanges with seal ridge; two large diameter bolts were tightened/loosened simultaneously by impact wrench tool
- Device has not been used in real activated application since window never failed and activity levels are low enough that people can perform the task

## Window Exchange Issues (Cont'd)

- For ILC dump need to adopt flange design that can be made up with 2 or maximally 3 bolts
  - This probably forces a circular cross section design
- A hemispherical window could be made thinner than a hemi-cylindrical window

## Radiolysis and $H_2$ – Evolution in ILC Beam Dumps (of the SLAC A-Dump/Beam Dump East Variety)

$P_{av}$ = 18 MW

$H_20 \rightarrow H_2\uparrow + H_20_2$

$H_20_2 \rightarrow 0_2\uparrow + H_20$

— Rate of evolution of $H_2$ is 0.3 l/MWs

Thus 18 MW x 0.3 l/MWs ~ 5.4 l $H_2$/s

- The lower explosive limit (LEL) of hydrogen in air is ~ 4%
- Maximum concentrations allowed in industry and acceptable to underwriters is 50% LEL or 2% $H_2$ in air
- At SLAC we adopted a maximum value of 25% LEL or 1% $H_2$ in air
- The 5.4 l $H_2$/s is an upper limit, since a fraction of the beam power is absorbed and dissipated in solid materials in the downbeam end of the dump

  Using 5.4 l/s adds some conservatism

  — This is 8.3 X the amount of $H_2$ to be processed compared to the original SLAC dumps

Radiolysis and $H_2$ – Evolution (Cont'd)

- SLAC developed hydrogen-oxygen catalytic recombiners
  - Extensive tests demonstrated that a catalyst consisting of a high-nickel stainless steel ribbon coated with platinum and palladium, in form of mats that look like a coarse steel wool, will sufficiently reduce the H2 concentration in one pass if the thickness is ~ 2.5 inch ≡ 6.4 cm
  - The diameter of the SLAC catalyst mats is 5-3/4 inch and their thickness is 1-1/4 inch. We stuck two of these mats on top of each other. Thus, the gas flow intake surface area is ~ 26 inch$^2$ ≡ 170 cm$^2$ and the volume is 65 inch$^3$ ≡ 1065 cm$^3$.
- For the ILC we would need ~ 10X as much catalyst or ≤ 260 in$^2$ ≡ 1700 cm$^2$ inlet cross section and ≤ 650 inch$^3$ ≡ 10,650 cm$^3$ of catalyst volume
  - This could be accomplished with an ~ 18 inch diameter mat in an 18 inch diameter pipe, 2-1/2 inch deep

## Radiolysis and $H_2$ – Evolution (Cont'd)

- Starting in 1974 the catalyst manufacturer offered a second type catalyst, using same platinum/palladium active surface. The substrate shape is a small coil ('helicat material'). This allows 5X the capacity of catalyst per unit volume than the earlier version. The 2-1/2 inch depth dimension could thus be reduced to 1 inch ≡ 2.5 cm. The coils are small and can be "poured" into any shape container. The bulk density of this material is 40#/ft$^3$ ≡ 0.65 g/cm$^3$ (there are ~ $10^6$ coils per ft$^3$)
  - The coils are mechanically strong and thermal shock resistant
  - Some of the catalyst at SLAC is of this variety
  - None of the catalysts at SLAC had to ever be replaced because they wore out
- The catalyst bed is in a recombiner housing
  - The gases are "pumped" through the catalyst by means of an ejector pump type setup. A nozzle below the catalyst supplied by water form the main pump discharge provides the motive power, creating a negative pressure below the catalyst bed. The water droplets from the water jet also condense and cool the water vapor after recombination

## Radiolysis and $H_2$ – Evolution (Cont’d)

- The gases from the surge tank are preheated to ~150° F before entering the catalyst bed for greater recombination efficiency
- An ILC catalyst bed would require ~ 6# ≡ < 3 Kg of catalyst of the “Heli Cat” variety

# Conclusions

- Beam dump dissipating up to 18 MW of average power is feasible with the primary power absorption medium being water
- The dump window material can be materials like stainless steel 316L, Titanium, both alloy and pure, or several of the Inconel alloys, perhaps others
- Design challenges remain how to replace the window when it, the dump shell, the cooling water, and the concrete of the dump cave are activated
- A dump that consists of 6.5 m (18$X_0$) water followed by 1 m (22 $X_0$ of water cooled plates (like Cu) with a 1.5 m diameter will adequately attenuate the electromagnetic cascade shower
- The radiolytically evolved hydrogen and oxygen can readily be recombined by a catalytic $H_2$-$O_2$ recombiner of modest size, using existing technology
- Questions remain about radiation damage to the window material for long-term exposure to ILC expected beam currents
- Rastering the beam would allow distribution of accumulated dose over a much larger volume, thereby extending life expectancy