Approaches to a High Power BEAM DUMP for an (TESLA 800 - like) ILC

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ILC-BDIR Workshop, Royal Holloway, London, 22nd June 2005

A. Introduction

B. Solid Dump (Graphite based)

heat extraction limit

C. Liquid Dump (Water)

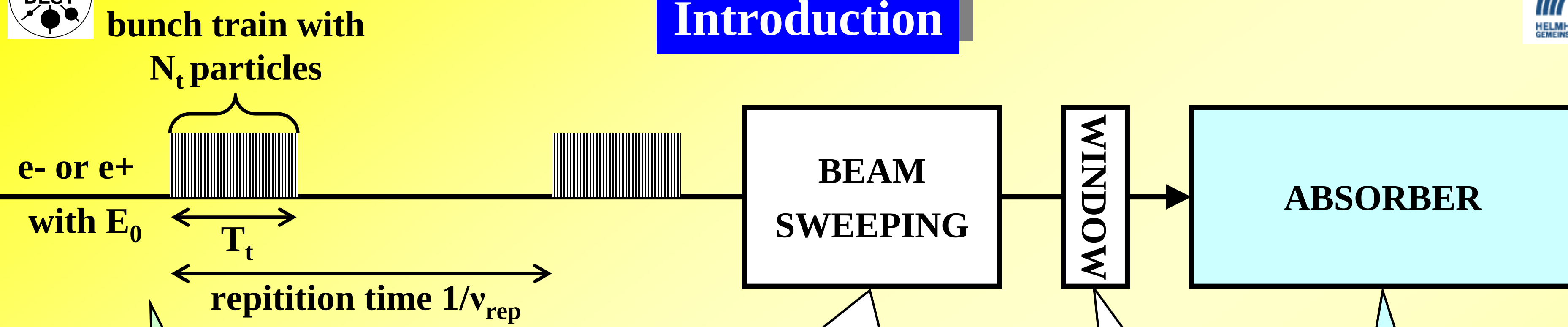
Focus of this Talk

D. Gas Dump (Argon)

new crazy idea ?

E. Comparative Summary

Introduction



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

Separation of beam vacuum and absorber

Beam to be dumped (TESLA 800 parameters)

E_0=400GeV, N_t=6.84·10^{13}e-, T_t≈1ms, ν_{rep}=4Hz

⇒ pulsed power source with
W_t=4.4MJ per train
P_{ave}=17.5MW in average

Thermal and Mechanical Issues
- heating and heat extraction
- stresses and pressure

Radiochemical Aspects
- radiolysis, dissociation

Radiological Issues
- handling of induced radioactivity
- shielding of direct radiation

Solid Dump: Heat Extraction

C-based absorber embedded in Cu

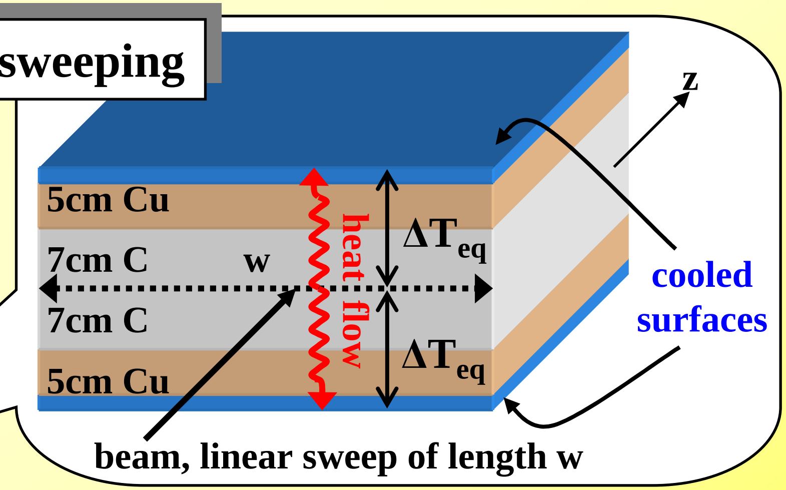
- capture 400 GeV shower ⇒ longitudinal: ≈5m, transversal: $1R_m(C)+3R_m(Cu)=7cm+5cm$
- E_0=400GeV, P_{ave}=17.5MW ⇔ I_{ave}=44μA ⇒ $(dP/dz)_{max} \approx$ 75kW/cm ! How to get rid of ?

Heat extraction by transverse heat conduction and sweeping

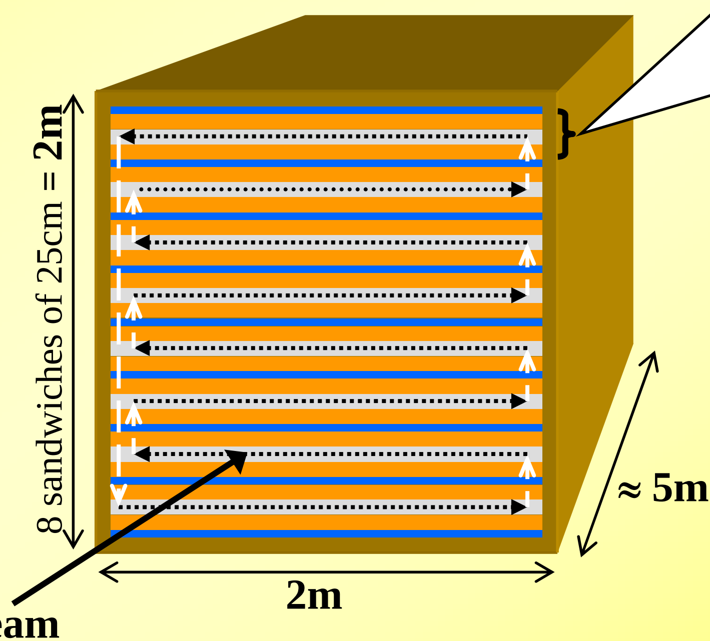
$\alpha_{tot} \approx 0.12W/(cm^2 \cdot K)$ and $(dP/dz)_{max} = \alpha_{tot} \cdot w \cdot (\Delta T_{eq})_{max}$

allow $(\Delta T_{eq})_{max} \leq$ 400K (prevent oxidation of C)

⇒ $w \approx 20cm / (kW/cm) \cdot (dP/dz)_{max}$



75kW/cm
⇒ 15m !
slow sweep



Discussion

- huge and heavy absorber
- huge vacuum system
- complicated slow beam sweeping

⇒ C-Cu Approach not suitable

only reasonable for

$(dP/dz)_{max} \approx$ kW/cm ⇔ $P_{ave} \approx$ 100kW level

Water Dump: Introduction

Motivation

heat extraction in solid absorbers limited by heat conductivity
$\Rightarrow$ improve heat extraction by flow of a liquid absorber material $\rightarrow$ water

Own Investigations supported by 3 Companies

Feasibility study of water dump

1.) Framatome (Erlangen): branch of Siemens / KWU, construction of nuclear power plants

2.) Fichtner (Stuttgart): worldwide operating engineering office, technical consulting,

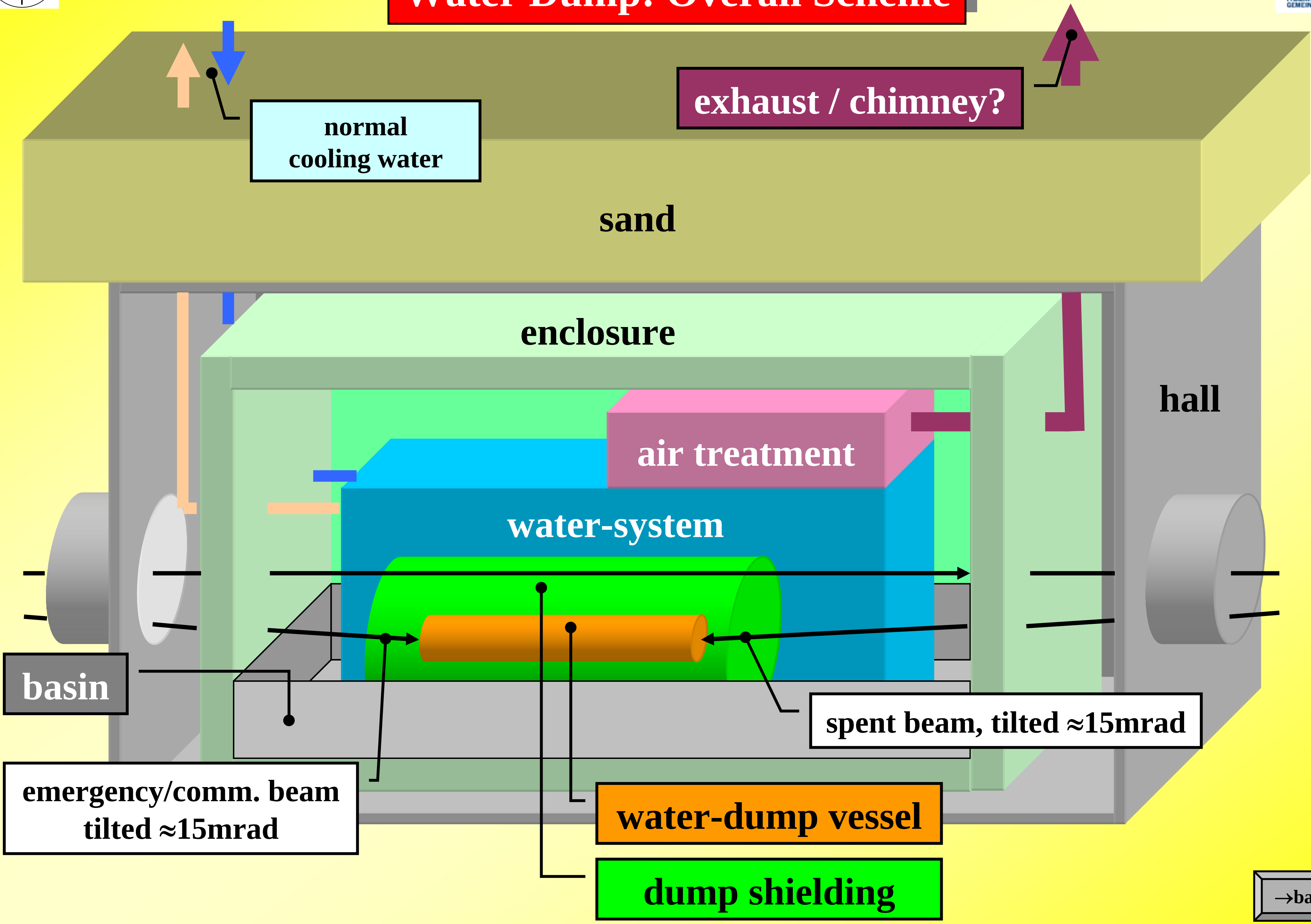
Calculations on transient pressure dynamics in the water dump

3.) TÜV-Nord (Hamburg): technical consulting, supervision of technical facilities and cars

Assumptions for the Water Dump Studies

- beam: 400GeV, $6.84 \cdot 10^{13}$ e-, 4Hz, 4.4MJ per train resp. 17.5MW in average
  $\sigma_x = \sigma_y = 0.55$mm <u>and</u> fast (within train) circular sweep with $R_{fast} = 8$cm
- water dump: cylindrical H_2O volume ($\approx 18m^3$)
  L=10m (shower capture), Ø=1.5m (shower capture + off axis tilted beam from both ends)
  10bar=10^6Pa $\Rightarrow$ $T_{boil} = 180°C$
- not considered here: window, beam sweeping, beamstrahlungsdump

Water Dump: Overall Scheme



→back

Water Dump: External Water System

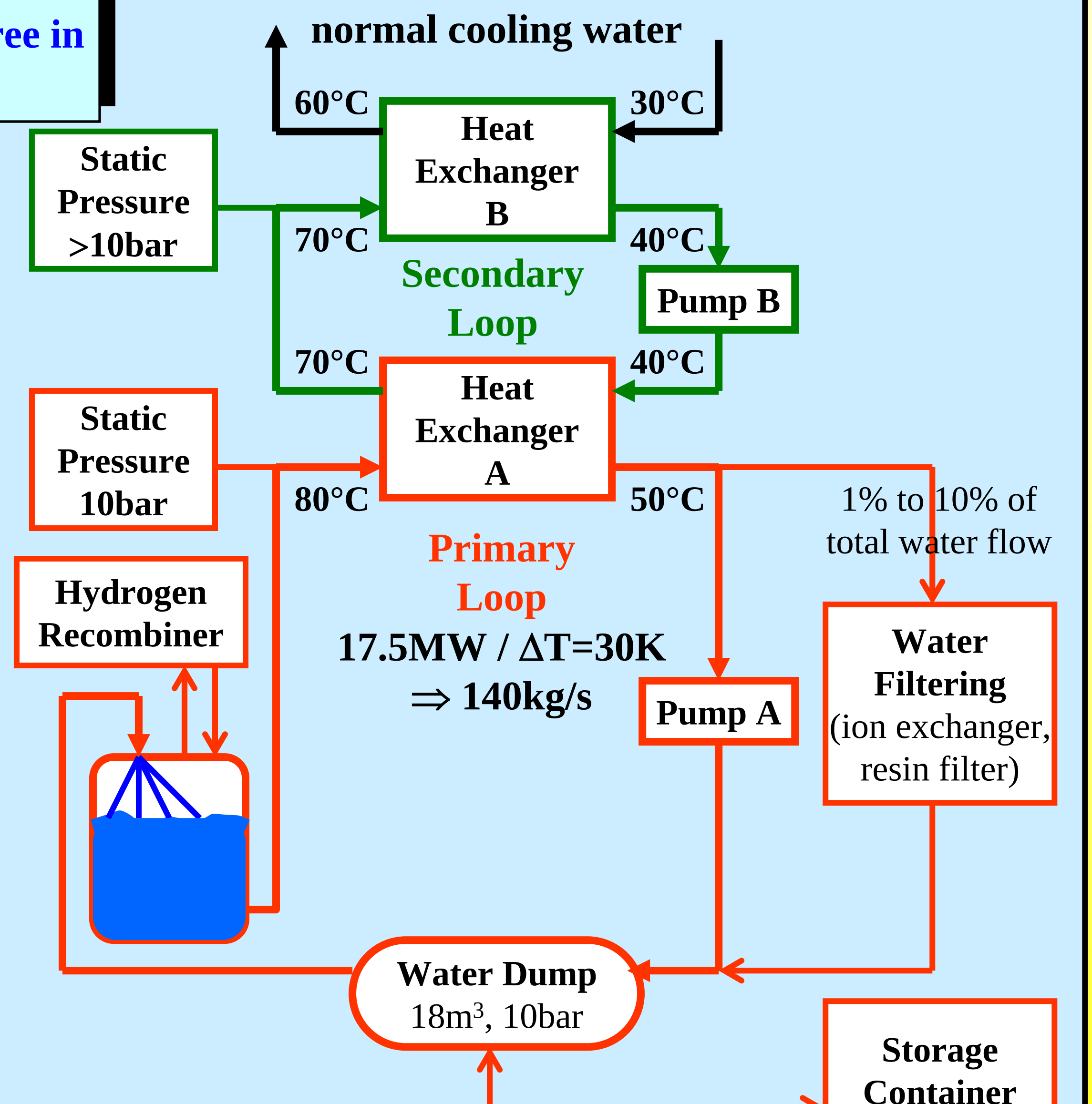
Fichtner and Framatome mainly agree in layout of external water system

Generals

- two loop system with $p_B > p_A$
- main piping DN 350mm

Primary Loop

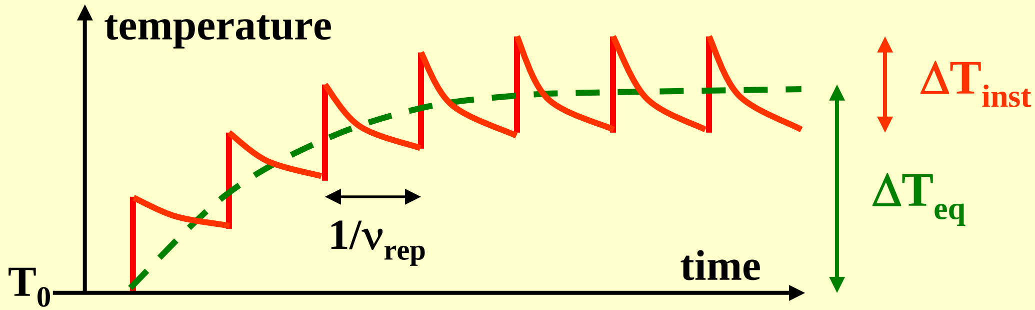
- fully He gas-tight system
- 140kg/s between 50°C / 80°C
- 10bar static ⇒ T_{boil}=180°C
- ≈30m^3 water content
- water filtering
- hydrogen recombination



Scheme of Water System

Water Dump: Internal Heat Extraction – introduction

Heating Process



ΔT_{inst} : instantaneous temp. rise caused by energy deposition of 1 bunch train,
$dE/dV(r,z) = c \cdot \rho \cdot \Delta T_{inst}(r,z)$, thermal diffusion within 1ms only 10µm in water

ΔT_{eq} : temperature rise assuming a time independent heat source S, with average power
and spatial distribution given by subsequent bunch trains, $S(r,z) = 4Hz \cdot dE/dV(r,z)$

⇒ conservative estimation for the temperature at a given position $\hat{s}=(r,z,\phi)$:

$$T(\hat{s}) \leq T_0 + \Delta T_{eq}(\hat{s}) + \Delta T_{inst}(\hat{s})$$; where T_0 = water inlet temp. (50°C)

Task

under the given external water mass flow of 140kg/s,
create a suitable water velocity field inside the dump vessel, in order to:

keep $T(\hat{s})$ well below boiling point (180°C) at any position, i.e minimize $\Delta T_{eq}(\hat{s})$

Water Dump: Internal Heat Extraction – the heat source

$\Delta T_{inst}(r,z) = 1/(c\cdot \rho) \cdot dE/dV(r,z)$

$\Rightarrow (\Delta T_{inst})_{max} = 40K$ @ r = 8cm, z ≈ 200cm

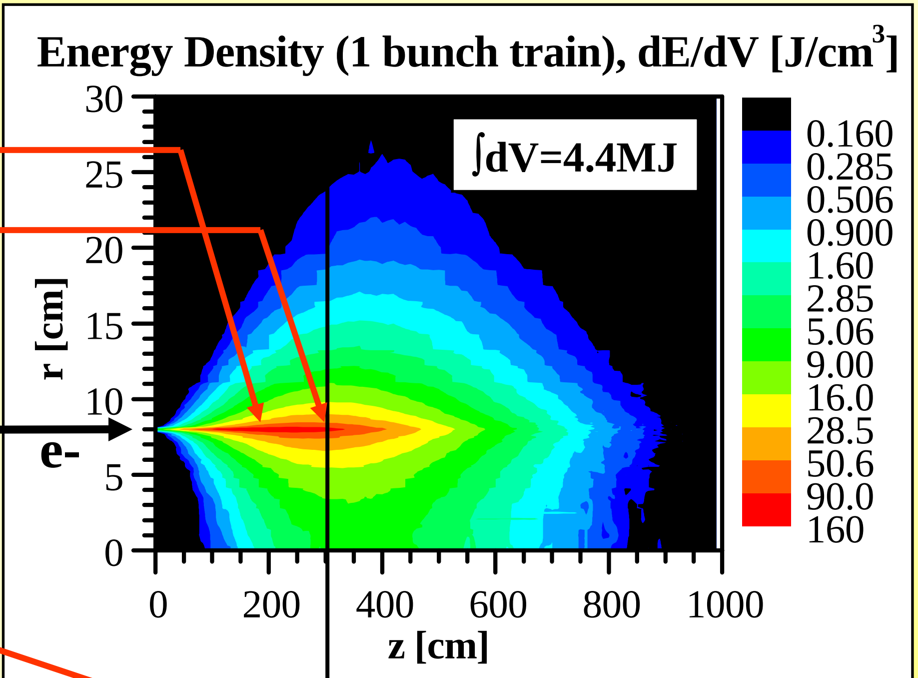
$\Rightarrow \Delta T_{inst} = 28K$ @ r = 8cm, z ≈ 300cm

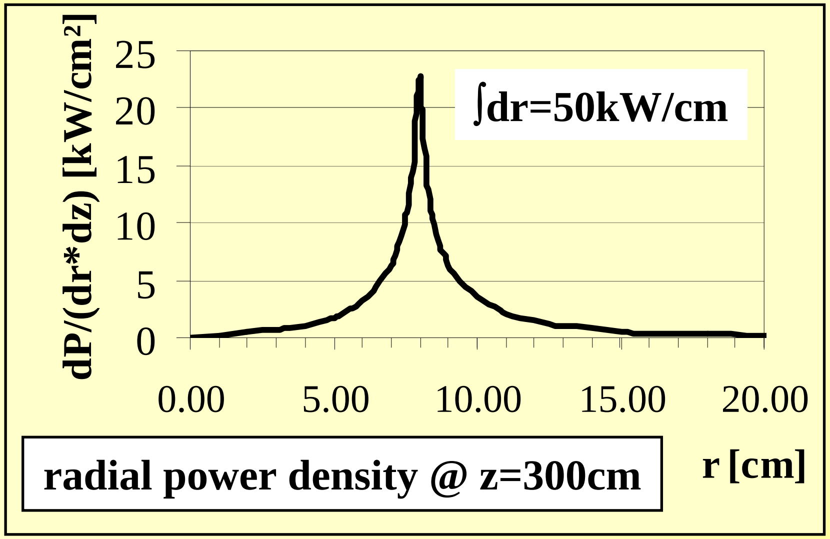
1 bunch train in water, $6.84\cdot 10^{13}$ e- @ 400GeV

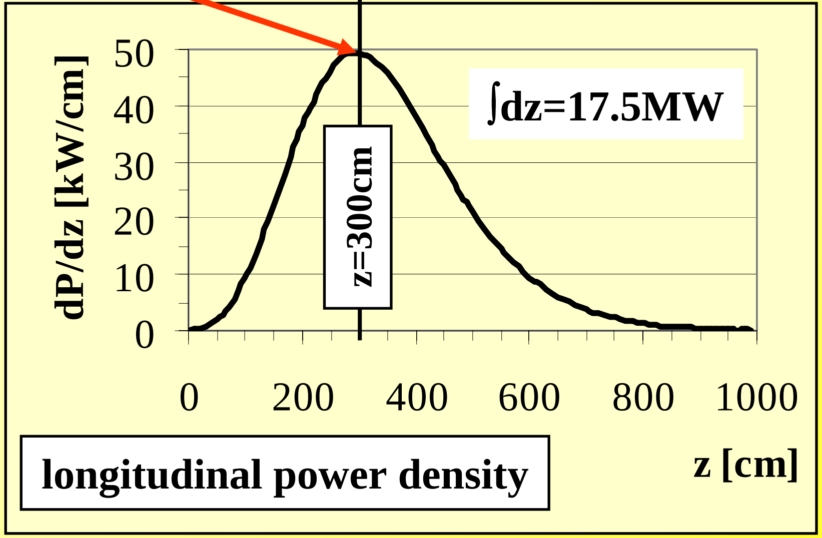
$\sigma_x = \sigma_y = 0.55mm$ and fast sweep $R_{fast} = 8cm$

4Hz bunch train repetition:

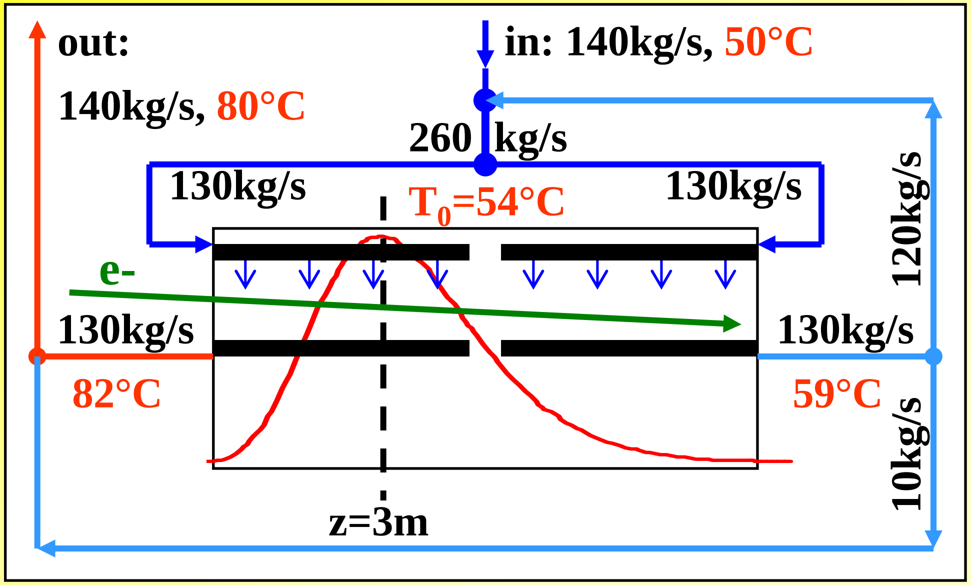
$\Rightarrow (dP/dz)_{max} \approx 50kW/cm$ @ z ≈ 300cm

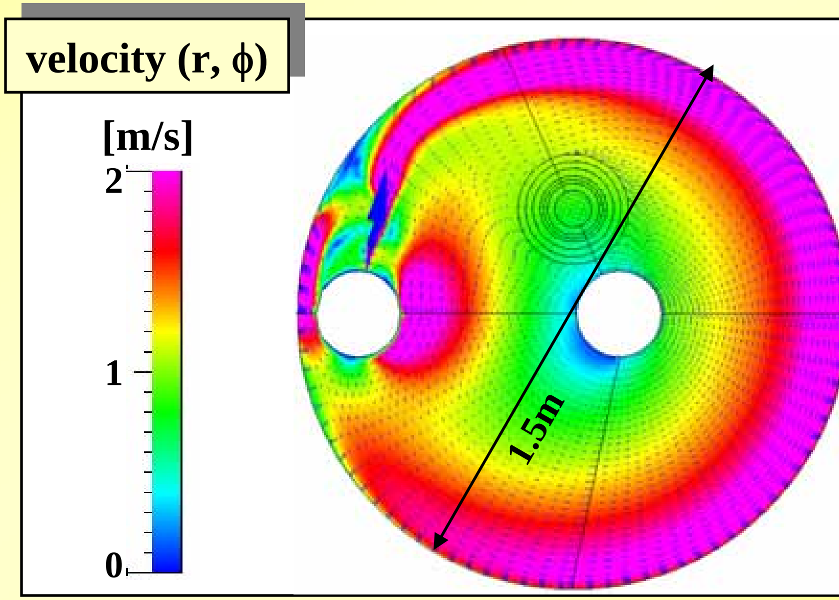






Water Dump: Internal Heat Extraction – Fichtner scheme





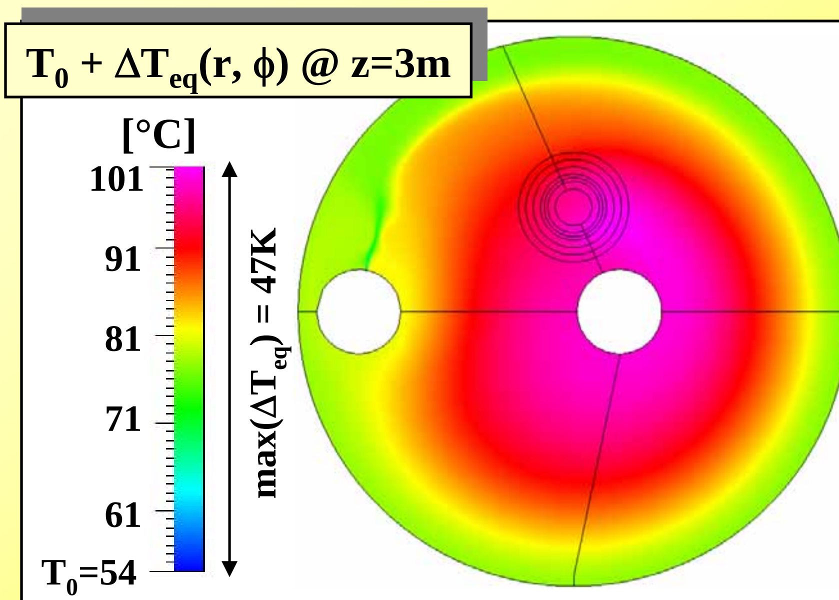
- vortex-like flow, velocity ≠ f(z), CFD code
- front / rear part split and water mixing

  ⇒ internal flow 140 to 280 kg/s, here 260 kg/s
- water velocity at inlet nozzle ≈ 30 m/s !

  Δp (in-out) ≈ 5 bar ⇔ 130 kW pump power !
- 2d (r, ϕ) stationary simulation at z=3m :

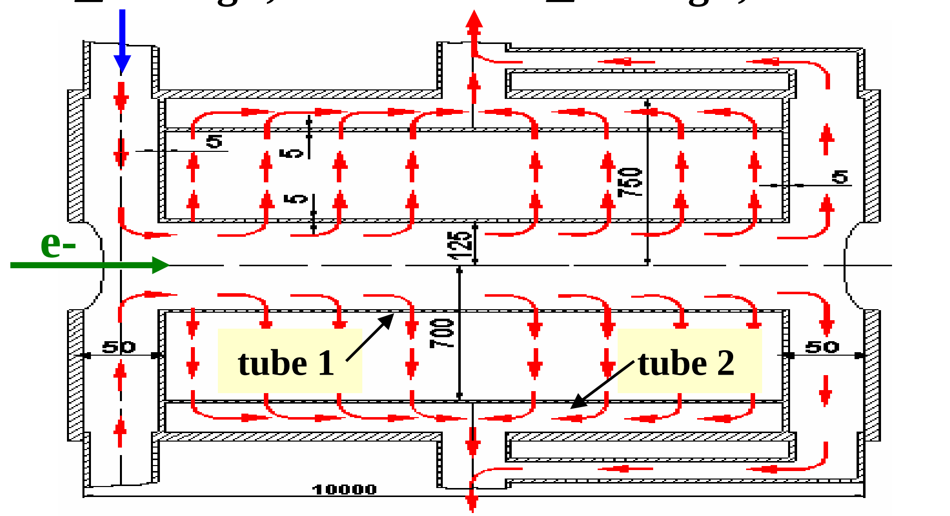
  $T_0+\max(\Delta T_{eq}+\Delta T_{inst})$ = 54°C+47K+28K = 125°C

  well below 180°C boiling point

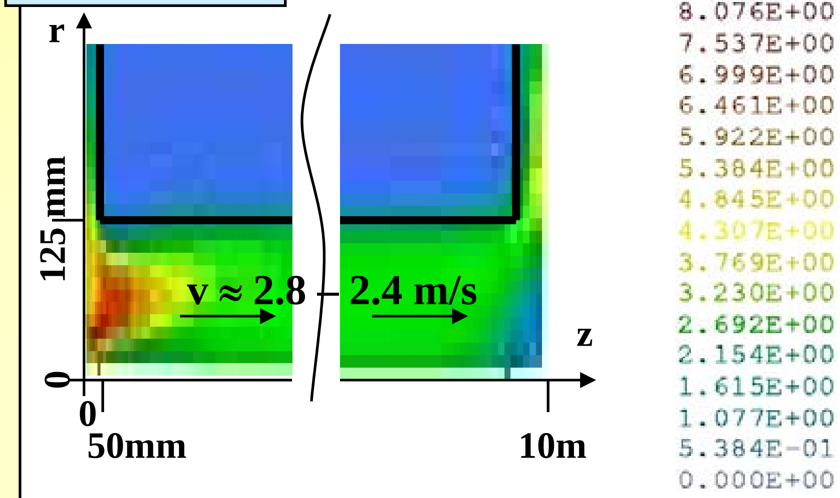


Water Dump: Internal Heat Extraction – Framatome scheme

in: Σ=140kg/s, 50°C out: Σ=140kg/s, 80°C



velocity (r, z)

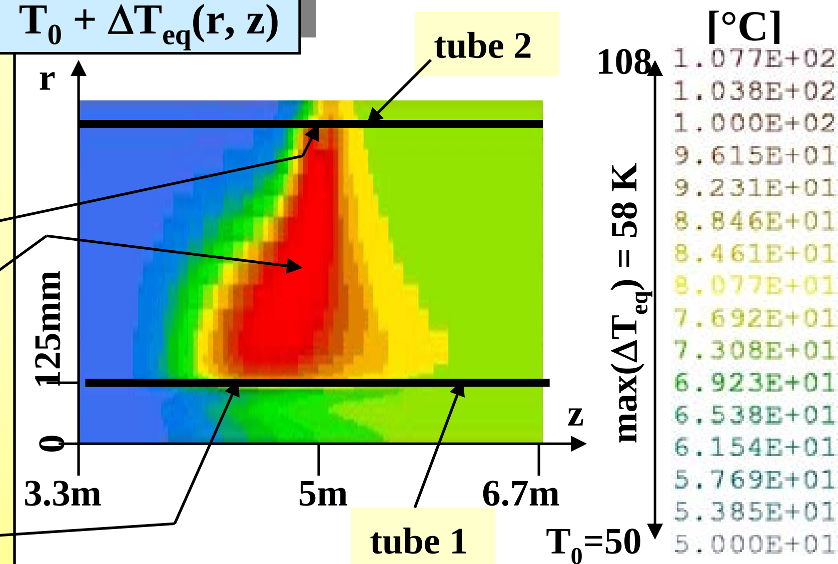


- long. + radial flow, 3d-sim., PHOENIX code
- internal flow = external flow = 140kg/s
- tube 1/2: 0.1/0.02% porosity → 15% radial flow
- max. tube 2 temp., 50°C+45K+0K = 95°C
- max. water temp. between tube 1 & 2

  $T_0+\max(\Delta T_{eq}+\Delta T_{inst})$ = 50°C+58K+0K = 108°C
- max. tube 1 temp. is at z ≈ 4m, r=130mm

  $T_0+\max(\Delta T_{eq}+\Delta T_{inst})$ = 50°C+34K+7K = 101°C

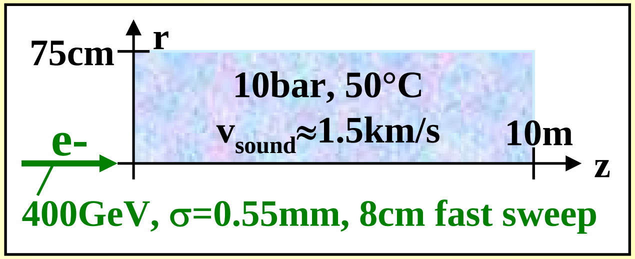
$T_0 + \Delta T_{eq}(r, z)$



Water Dump: Pressure Waves (TÜV-Nord)

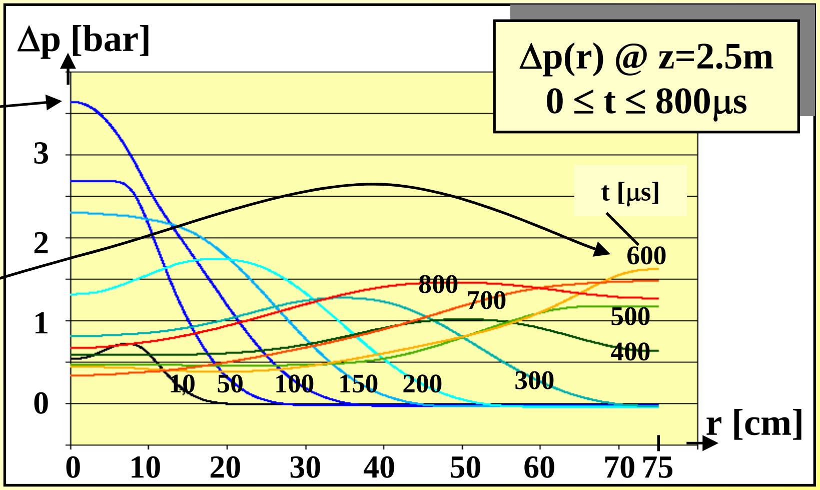
Assumptions

- **consider 1 bunch train 860µs long as dc-beam**
  source: S = 1/860µs · dE/dV for 0 ≤ t ≤ 860µs and S = 0 otherwise
- **CFD code, no handling of phase transition: fluid → vapour**



Results

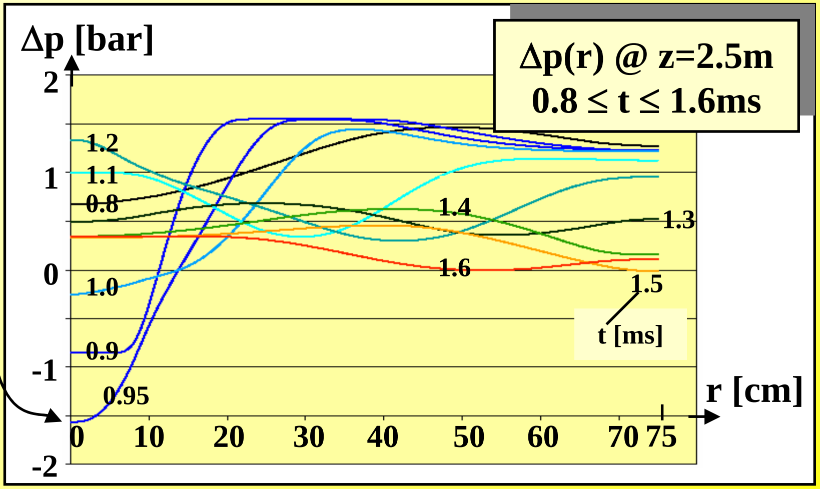
- **in water:** Δp_{max} ≈ 3.7bar near z-axis @ 100 µs
  Δp_{min} ≈ -1.6bar near z-axis @ 950 µs
  → reduces boiling point & solubility of gases !
- **at vessel cylinder:** Δp_{max} ≈ 1.8bar @ 650 µs
- **at front/rear face (windows):** Δp_{max} ≤ 0.5bar
- **pressure wave decay to 0 after ≈ 3ms**



<u>if heating gets near boiling temperature</u>

(simulated σ ≈ 6mm, no sweep, stop beam after 325µs)

- **in water:** Δp_{max} ≈ 9bar, Δp_{min} ≈ -6bar !
- **at vessel cylinder:** Δp_{max} ≈ 2.7bar
- **at front/rear face (windows):** Δp_{max} ≈ 0.5bar
- **pressure wave decay to 0 after ≈ 20ms**



Water Dump: Radiolysis

Fundamentals

- **H_2O cracked by shower of high energy primary electron**
- **net production rate at 20°C / 1 atm (n.c.): 0.3 l/MJ H_2 and 0.15 l/MJ O_2 ⇔ 0.27 g/MJ H_2O**
  spatial distribution according to dE/dV profile
- **solubility in 60°C water: H_2: 16 ml/l and O_2: 19.4 ml/l**

Our Case

- **at 20 MW: 4.82 g/s H_2O ⇒ whole primary water (30m³) would be radiolysed in 72 days !**
  thus recombination: 6 l/s (n.c.) H_2 + 3 l/s (n.c.) O_2 → 4.82 g/s H_2O + 58 kW (0.3% · P_{beam})
- **solubility limit during 1 bunch train at 10 bar**
  $dE/dV \leq 530\ J/cm^3$ for H_2 & $dE/dV \leq 1300\ J/cm^3$ for O_2 ; our case $(dE/dV)_{max} = 160 J/cm^3$

So far it looks almost good, BUT H_2 control is critical:

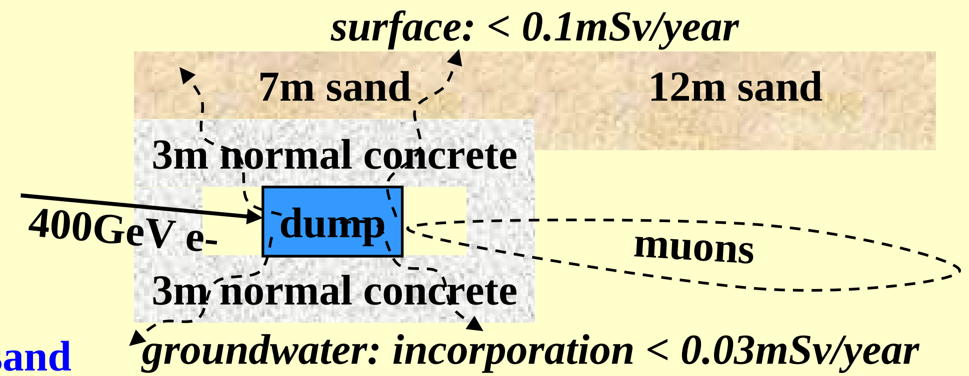
- **solubility during bunch train passage can be exceeded locally**
  due to local pressure drops (negative Δp), rise of ΔT_{inst} and amount of solved $H_2 \neq 0$
  → danger of H_2 gas bubbles and induced pressure waves comparable to local boiling
- **if not all H_2 is recombined, H_2 can accumulate at prominent locations (local pockets)**
  → danger of explosion (e.g. nuclear power plant Brunsbüttel)
  ⇒ need 100% recombination, i.e. out gassing at low pressure + recombiners in return pipe

→scheme

Water Dump: Radiation Handling (1)

Shielding of direct radiation

- neutrons: ~ isotropic distribution
  shielding to protect surface, soil, groundwater & air
- muons: range in soil ≈ 700m
  surface protected by 15mrad tilt + 12m sand



Activation of primary circuit, 18MW, 30m³ water

$A(t)=p\cdot(1-e^{-\lambda\cdot t})$	$p \equiv$ production rate $= A_{sat}$ $\lambda \equiv \ln 2/t_{1/2}$

- in water besides short lived isotopes also ^{7}Be , ^{3}H=T, ...

^{3}H: 20keV β^-, $t_{1/2}$=12a, A_{sat} =280TBq (0.76g, 2.8l T_2 or 5g HTO), A(5000h)=9TBq, A(10a)=120TBq

- no outside dose rate, but incorporation risk if released due to accident or maintenance !

^{7}Be: 478keV γ, $t_{1/2}$=54d, A_{sat}=120TBq, main contributor to dose rate

- equal distribution in primary loop → 300mSv/h ! at surface of components
- accumulation in resin filters, but also adsorption on circuit surfaces (esp. heat exchanger)

→ local shielding, remote handling procedures

Legal limit of draining ^{3}H & ^{7}Be: ≈5MBq/m³<<TBq/m³ → dilution is not the solution to pollution

- 20mm thick stainless steel dump vessel gives ≈ 400mSv/h on its axis (5000h op., 1month wait)

→ regular inspection of vessel (welds, ...) seems to be problematic

DESY →scheme

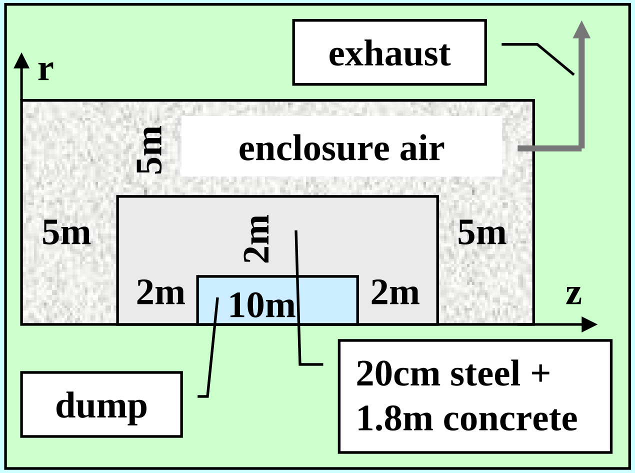
Water Dump: Radiation Handling (2)

HELMHOLTZ GEMEINSCHAFT

Activation of air in enclosure, 18MW, ≈ 3000m^3 air

- necessity of enclosure, „closed“ ⇔ keep under lower pressure by continuous exchange rate of ≈ 1/h and controlled exhaust

	A_{sat}	A(5000h)	specific A @ saturation [Bq/m^3]		
			w/o air exchange	with ex-change 1/h	legal limit
^{3}H	1.4GBq	43MBq	470k	3	1k
^{7}Be	390MBq	370MBq	120k	70	6k



⇒ O.k., except for: a) short lived need „delay line“ of ≈ 1h, b) opening of primary circuit

Scheduled opening of primary circuit, 30m^3, 100TBq of ^{3}H after 10years

- flush water in storage tank, ≈ 100l remain (0.1mm on 1000m^2), vent system with dry gas via 95% efficiency condenser ⇒ 5l ≈ 10GBq tritium have to be released to outside air
- meet the limit of 1kBq/m^3 needs dilution in 10^7m^3 and takes 1000h=42days! with 10^4 m^3/h

⇒ extrememly strong recommendation to use a chimney ≥ 20m

Dismantling of activated system after final shut down, 20 years 200TBq of ^{3}H

- primary water solidifying as concrete ⇒ 5000 barrels (200l, 40GBq)
- steel components (150t, ≤10^6Bq/g) & concrete shielding (1500t, ≤200Bq/g)

} Σ ≥ 50M€

Water Dump: Discussion

Compared to the solid C-Cu dump,
the water dump looked quite attractive at first sight, BUT ...
... Except for the answer to the heat extraction issue
other critical aspects showed up at a closer look:

- **Radiolysis and Hydrogen Gas**
- **Transient Pressure**
- **Window**

additionally quite similar (not calc.) to C-Cu approach:

- **handling of highly activated (cooling) system, esp. High Tritium Content in cooling water requires huge effort in radiation protection**
  → even scheduled opening for maintenance reasons is complicated
  → enclosure and 20m high chimney
- **dismantling costs not negligible**

Inherent Potential of Destruction / Explosion of a Highly Activated Water System

Difficult to get permission and
antis of the LC-project will find here "good" arguments

⇒ Motivation for a new idea

Gas Dump: First Thoughts

Basic Idea

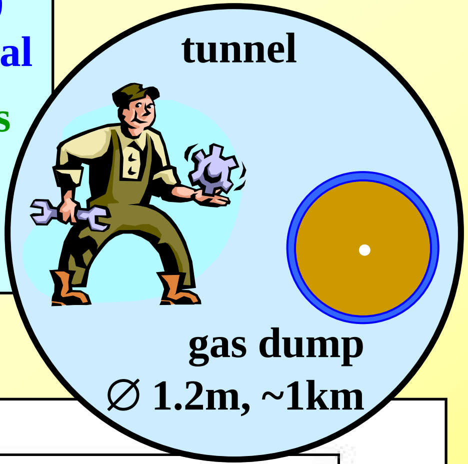
One atomic noble gas core (Ar, Xe) is surrounded by solid material (Fe)

- gas core acts as scattering target (only small amount of energy deposition) and distributes energy longitudinally over ~ 1km into surrounding material

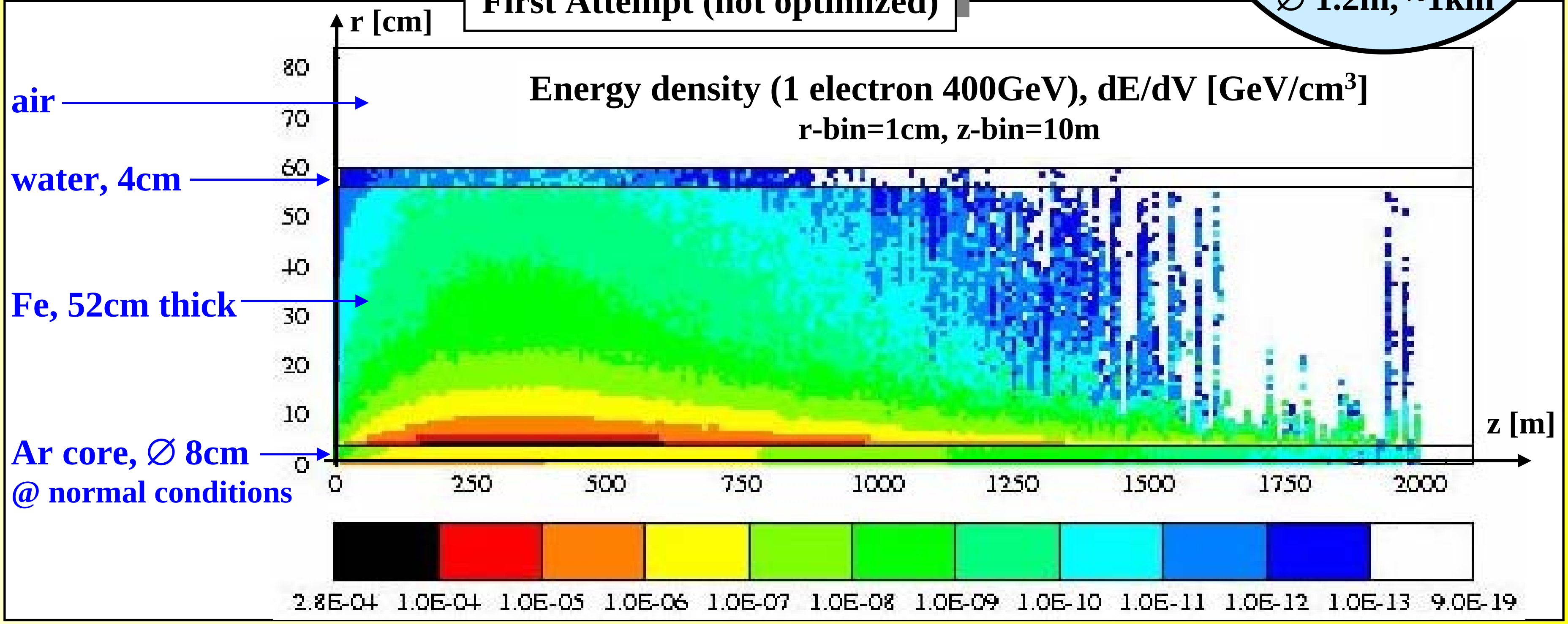
  → low energy densities, no sweeping, small spot size possible, no radiolysis

- surrounding material takes main part of energy

  Z > 20 → reduced tritium production



First Attempt (not optimized)



Gas Dump: Rough Results 1km long dump, *(compared to water dump)*

Thermal & Mechanical Issues

- **Argon:** 5000l@n.c. ⇔ 8kg, takes only 0.5% primary energy, i.e. 22kJ per train resp. 90kW
  22kJ → ΔT_{inst} ≈10K (total volume) → Δp ≤ 0.03bar, i.e. low transient pressure on window *(0.5bar)*
- **Iron:** m=8000tons, takes "all" primary energy, $(dE/dm)_{max}$ per train=3J/g → ΔT_{inst} ≤ 1K *(40K)*
  18MW over 400m → $(dP/dz)_{max}$ ≈50kW/m *(50kW/cm)*
  ΔT_{eq} (heat conduction in iron) ≈ 420K and ΔT_{eq} (heat transfer iron/water) ≈ 30K
  ⇒ Argon core and inner iron area will reach temperatures of about 500°C
  ⇒ Argon pressure will go up to 2-3 bar

Radiological Aspects, 18MW, (no extra shielding around iron assumed)

- neutron dose at surface: 10m sand shielding gives ≤ 0.1mSv/year *(3m concrete + 7m sand)*
- muon dose at surface: dump longer than muon range,
  50cm iron of the dump itself is equivalent to 2m sand shield → depth of dump tunnel relaxed
- tritium inventory @ sat.: 30 TBq in Fe (solid), 0.7 TBq in Ar, 0.02 TBq in cooling water *(300TBq)*
- tunnel air activation (tritium content @ sat.): 8.4GBq in 20000m^3 = 420kBq/m^3 *(470kBq/m^3)*
- dose levels at the dump and in tunnel: few mSv/h *(1mSv/h at shielding, but 100mSv/h at components)*

Gas Dump: Rough Results cont'd, *(compared to water dump)*

Maintenance

- **Water System: lower activated** *(10^{-4} of water dump)*, **no hydrogen**
- **Opening of Argon core: 5000l, 0.3TBq of ^3H after 10years** *(120TBq in water)*
  activated gas is rinsed out and pressed into a vessel (5000l @ n.c.)
  how much is released to air during this process ? ≤ 0.1% → 0.3GBq *(10GBq)*

Discussion, Open Questions

- **1000m of tunnel is activated to dose rate levels of few mSv/h**
  → optimization of dump & additional shielding to reach ≤ 0.1mSv/h
  → an adapted or extra tunnel design is desirable (crossing angle preferred)
- **high gas and iron temperature → flatten dP/dz profile via Ar pressure by sectioning the dump**
- **spot size limit of this dump? → need no fast sweep, applicable as dump for γ/γ-collider**
- **study thermal effects in Ar core: convection, change in density profile**
- **is the (angular) beam stability compatible with the long axis of the dump ? (4cm/1km=40μrad)**
- **make it suitable to dump beamstrahlung as well. Consequences? (e.g. wider gas core, ..)**

The gas dump approach seems to be an attractive alternative,
it should be considered in an early design stage of the ILC.

Comparative Summary

Graphite-Copper Dump	Water Dump	Noble Gas Dump
2m x 2m, 5m long	∅1.5m, 10m long	∅1.2m, 1km long (extra? tunnel)
heat conductivity & immense slow sweep	adequate water flow no slow sweep	heat conductivity no slow sweep
radiation degradation of heat conductivity of graphite ?	explosive radiolysis gases in a highly activated system	no dissociation of one atomic gas
cyclic stress in C tolerable	transient pressure in water	gas buffers transient expansion
window ∅2m unless not put upstream of sweeping	vac./water window ∅20cm challenging design	vacuum/gas window ∅8cm design ~exists
need increased spot size (fast sweep) to limit energy density		applicable for smaller spot sizes and therefore as γ/γ-dump
total tritium inventory ≈300TBq ≈30% in water, rest in C-Cu	all in water	tritium inventory factor 10 less and 98% bound in a solid
maintenance complicated		easier maintenance
high activated components, dismantling costs not negligible		activation of 1km tunnel
Technically not practicable for high power applications	Principally feasible, but inherent risks will make it difficult to „sell“ it as reliable, safe and robust.	Attractive new idea, which should be investigated in more detail