Study on the International Linear Collider Beam Dump by plasma-wakefield deceleration

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1st Nov. 2016
Academia meets industry forum
IEEE-NSS/MIC
Strasbour, France

1. Abstract

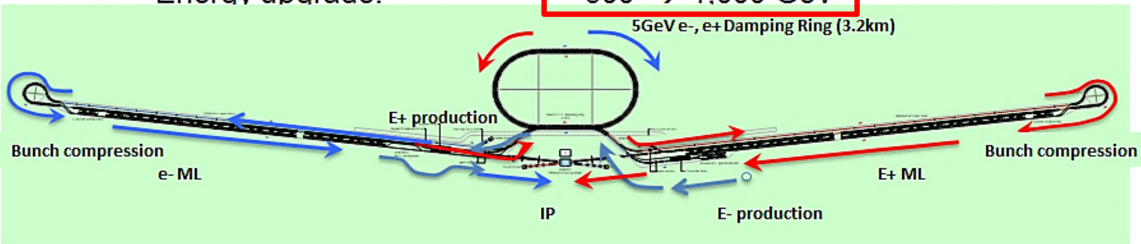
As the scale of accelerator projects and their power consumptions increase, improving the power efficiency and the power recovery of accelerator systems become immediate and important requirement and goal. Moreover, the radiation level in the accelerators should be kept to a minimum extent to cope with environmental consideration. In the design of the next future largest accelerator, the International Linear Collider (ILC), the power consumption is estimated to be 161 MW. Important efforts are being undertaken to reduce the electricity consumption and to lower the radiation level in the current study of its implementation plans. Consequently, we proposed a new system of beam dump which is based on the wakefield deceleration of beams in plasma, where the radiation level is far less than in the conventional designs and where the beam power might be recovered. We started the study in early 2015 and first focused on simulation where the ILC electron beams at 250 GeV is dumped into a gas chamber of an appropriate pressure and size so as to create a plasma and therefore to achieve efficient deceleration. We will also consider energy recovery from the created plasma in the gas chamber. The resulting radioactive products are expected to be reduced drastically when compared to the conventional designs. The article presents the current status of these studies.

Contents

Beam dump from a view point of Green-ILC

Requirements from Physics Exp.

- Basic requirements :
  - Luminosity : $\int Ldt$ = 500 fb^{-1} in 4 years
  - E_{cm} : 200 – 500 GeV and the ability to scan
  - E stability and precision: < 0.1%
  - Electron polarization: > 80%
- Extension capability :
  - Energy upgrade: 500 → 1,000 GeV



1. Less radioactivity is more Green for the environment.
2. If energy can be recovered, it is further Green.

ILC in design phase

	loss rate
Infrastructure : 50 MW	**50 % : 25 MW**
RF System : 70 MW	**50 % : 35 MW**
Cryogenics : 70 MW	**90 % : 60 MW**
Beam Dump : 10 MW	**100 % : 10 MW**
200 MW	**～ 130 MW**

Improve efficiency

This talk

Increase recovery

2. Water beam dump design in Technical Design Report (TDR) of ILC

four dumps

10 bar water vessels

30cm diameter, 1mm thick Ti window

Water serves as both The coolant and the stopping medium

vortex flow

8.8 Beam dumps and Collimators

8.8.1 Main Dumps

The beam-delivery system contains two tune-up dumps and two main beam dumps. These four dumps are all designed for a peak beam power at nominal parameters of 18 MW at 500 GeV per beam, which is also adequate for the 14 MW beam power of the 1 TeV upgrade. The dumps consist of 1.8 m-diameter cylindrical stainless-steel high-pressure (10 bar) water vessels with a 30 cm diameter, 1 mm-thick Ti window and also include their shielding and associated water systems (Fig. 8.15). The design [188] is based on the SLAC 2.2 MW water dump [189, 190].

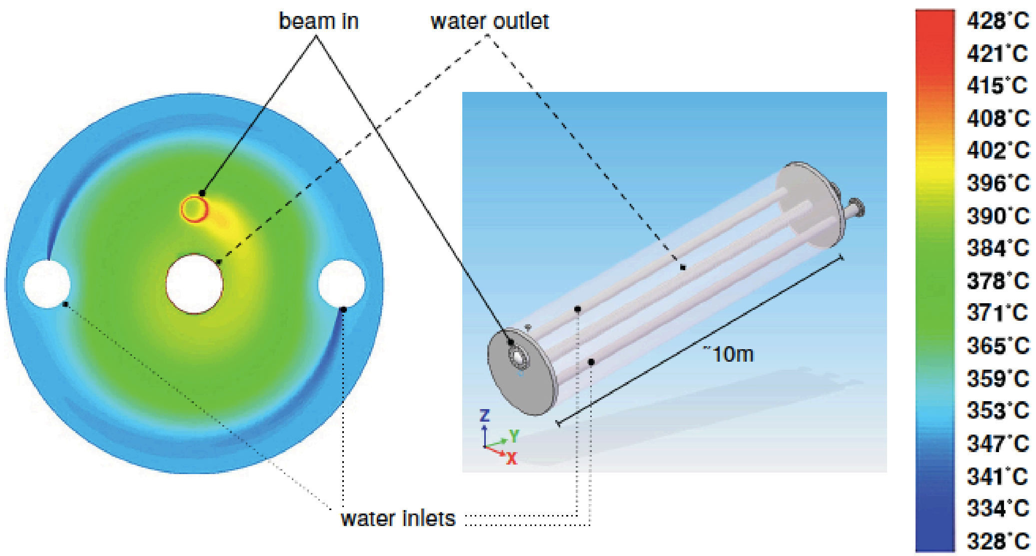
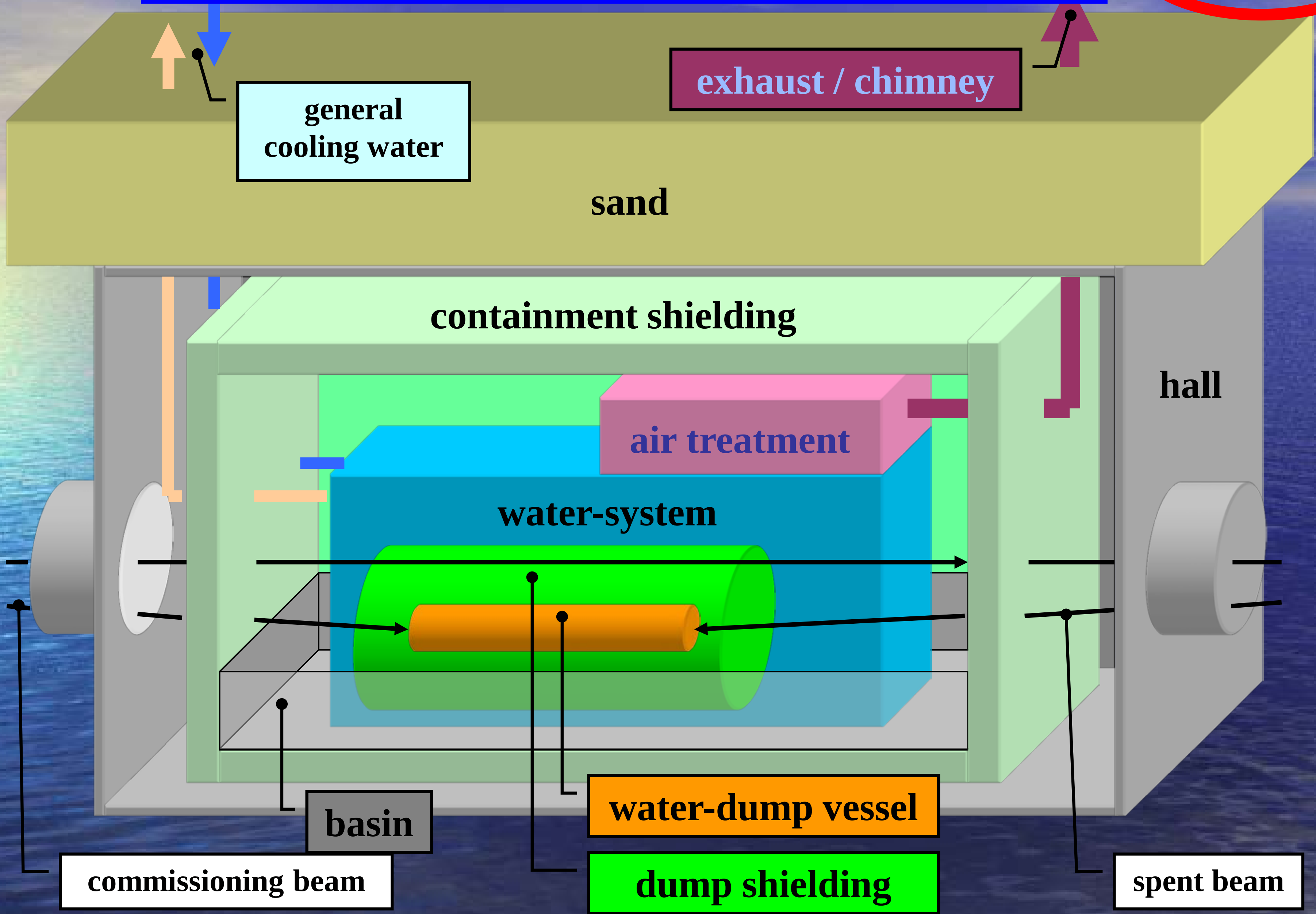


Figure 8.15 Temperature distribution at the shower maximum of the beam in the main 18 MW dump just after passage of the beam train (left). (The geometry of the dump is also shown on the right.) The colour bar shows temperature in kelvin; the maximum temperature is 155 °C [191].

A.3 Schematic Layout of Water Beam Dump



Water beam dump design

- The water dump system in TDR/ILC is well studied and a lot of simulation have been carried out.
- It, however, has issues to further study points;

  (1) Dump window with 10 bar,

  (2) Treatment of Hydrogen gas production,

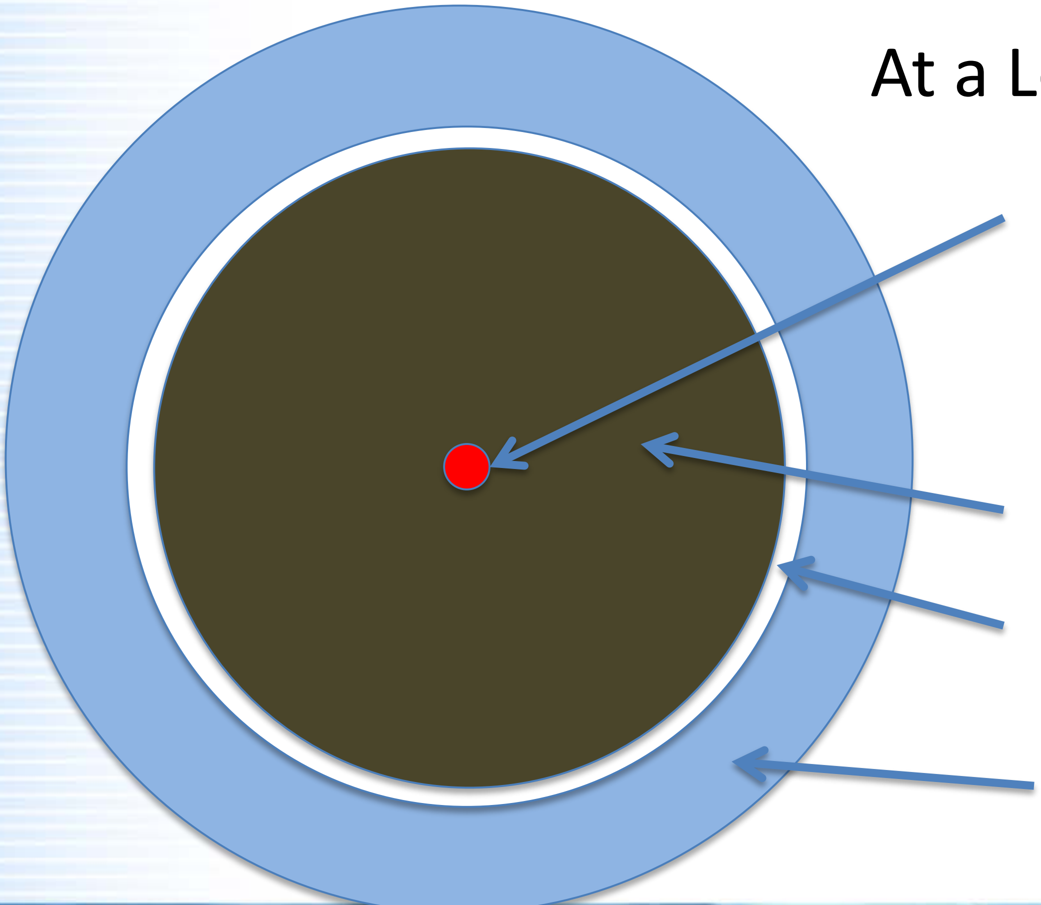
  (3) Mitigation of water-activation products,

  (4) 155^{o}C hot-water can be obtained

3. Alternative discussed design: noble gas dump

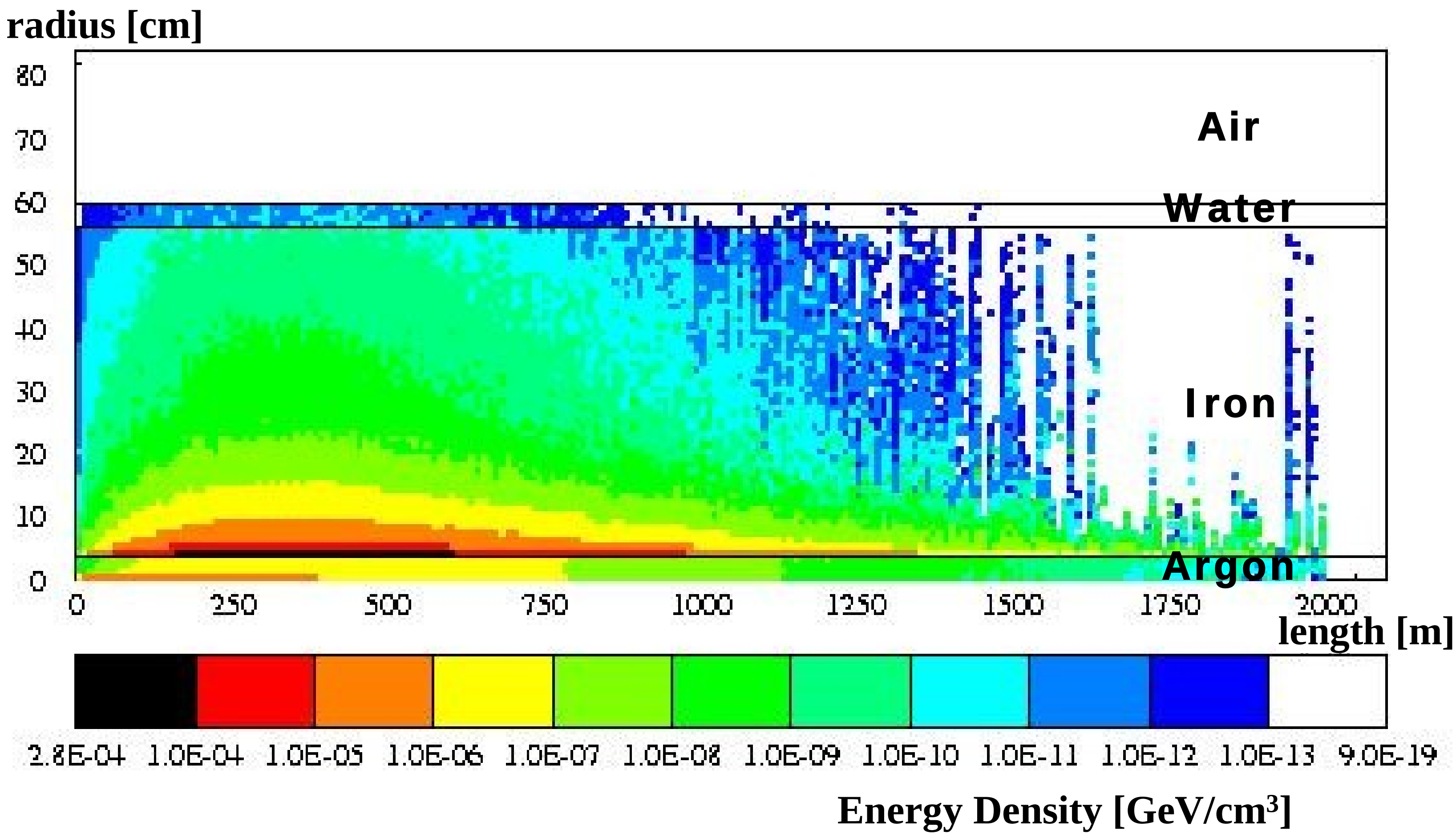
Based on "Another idea of a LC dump"
by Albrecht Leuschner 16/09/2003

Cross section of a tunnel



Albrecht Leuschner

Energy deposition with 400 GeV electron



Gas beam dump design

(1) No dump window problem because of 1 bar

(2) No hydrogen bubble production problem

(3) Less iron-activation

(4) Too long facility/tunnel (1000 m)

(5) Not been built before

4. Collective deceleration for compact beam dump

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **13**, 101303 (2010)

Collective deceleration: Toward a compact beam dump

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(Received 10 December 2009; published 5 October 2010)

Bethe-Bloch formula for stopping power in material

$$-(dE/dx)_I = (F/\beta^2)[\ln(2m_e\gamma^2 v^2/I) - \beta^2], \quad (1)$$

where E is the electron kinetic energy, $F = 4\pi e^4 n_{e,m}/m_e c^2 = e^2 k_{pe,m}^2$, $n_{e,m}$ is the electron density in the stopping material, $k_{pe,m} = \omega_{pe,m}/c$ is the plasma wave number, and $\beta = v/c$ is the normalized electron velocity.

The collective stopping power for plasma wakefield deceleration of the electron bunch is large;

$$-(dE/dx)_{\text{coll-wave break}} = m_e c \omega_{pe}(n_b/n_e). \qquad (5)$$

Equation (5) is exact for the resonant excitation of a wake-field with bunch length $\sigma_L/\lambda_{pe} \approx 0.5$, transverse size $\sigma_T/\lambda_{pe} \geq 0.3$, and modest density ratio $n_b/n_e < 10$

where λ_{pe} is the plasma wavelength of the background plasma with density n_e, n_b is the bunch density.

For a long beam $\sigma_L/\lambda_{pe} \gg 1$, the stopping power decreases exponentially with the factor $k_{pe}\sigma_L \times \exp(-k_{pe}^2\sigma_L^2/2)$. For a narrow beam $\sigma_T/\lambda_{pe} \ll 1$, the stopping power decreases with the factor $k_{pe}^2\sigma_T^2$.

Original idea was to apply the collective deceleration beam dump to a LPWA beam with high beam density. The required dump length ~ 1mm. We now consider it for ILC with a much more dilute beam. The dump becomes longer.

From $\sigma_L/\lambda_{pe} = ½$, then $\sigma_L = \pi\ c/\omega_{pe}$ and $n_b = N_b/(\sigma_L \sigma_T{}^2)$,

$-(dE/dx)_{coll\text{-}wave\ break}$ [GeV/cm] = 5.74 × N_b/σ_T^2 [cm]

means

L_{dump}[m] = 1.7 × 10^{13} $\sigma_T^2/N_b\, E_0$[GeV], $\sigma_T > 0.6\ \sigma_L$

In the case of ILC, N_b=2 × 10^{10}, E_0=500 GeV,

L_{dump}[m] = 4.3 × 10^5 σ_T^2[cm]
= 130 m w/ σ_L= 300 μ m, σ_T= 0.6 × σ_L= 180 μ m
= 10 m w/ σ_T= 50 μ m, σ_L= σ_T/0.6 = 83 μ m

- Collective deceleration dump
  (1) No dump window problem
  (2) No hydrogen gas production problem
  (3) Less radioactivation
  (4) Compact facility
  (5) Energy might be extracted as electric energies
- From the view point of Green-ILC, it is worth to study the possibilities to apply collective deceleration dump system.
- It should be checked that it works for the ILC long beam condition.
- If introducing the bunch compression after the collision point, it is possible to shorten the length of the beam dump facility.
- Efficiency of recovering energy is important from the view point of Green-ILC

5. Study Group of the Green ILC Beam Dump

We successfully obtained the budget (~40,000 dollars for 3 years, 2015 - 2017) from the Japan Society for the Promotion of Science (JSPS) to study the Green Beam Dump by plasma wakefield deceleration.

The University of California at Irvine
Plasma Wakefield calculation / simulation

KEK
ILC design
Organization of the group
ILC design / Providing Computer facility (KEKCC computer cluster, dedicated Linux workstation computer) for simulation

Future experiments for the plasma wakefield deceleration

ELI-NP
Plasma wakefield calculation

SLAC
ILC design / Plasma wakefield calculation

LAPP/IN2P3
ILC design / Plasma wakefield calculation

6. Preliminary result of beam deceleration simulation

beam :

$\sigma_x = 300\mu m; \sigma_r = 50\mu m;$

$E = 250G\,\mathrm{eV}(\gamma_0 = 5\times 10^5)$

$\mathrm{dE/\,E} = 0.1\%$

$\mathrm{N}_b = 2\times 10^{10}\left(3.2nC\right)$

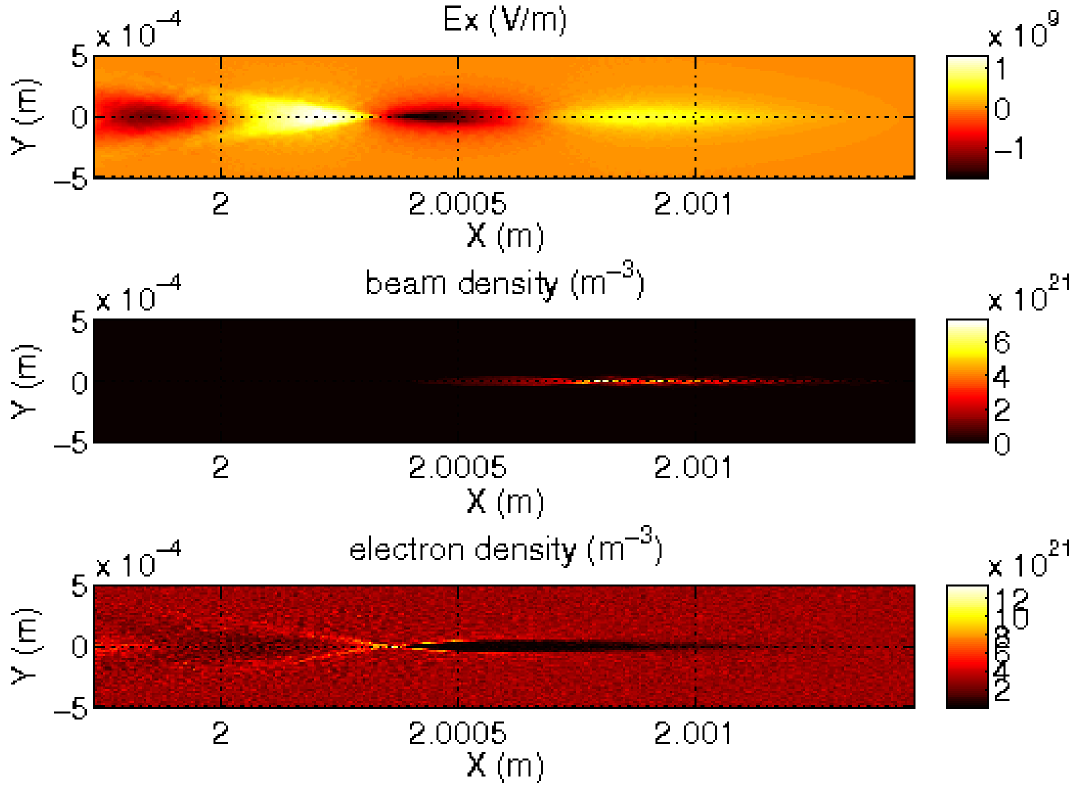
$n_b = \dfrac{N_b}{(2\pi)^{3/2}\left(\sigma_x\sigma_r\sigma_r\right)} = 1.7\times 10^{21}\,/\,m^3$

plasma :

$n_p = 3\times 10^{21}\,/\,m^3$

$\lambda_p \sim$ 600 μm

$\sigma_x \sim \lambda_p\,/\,2$

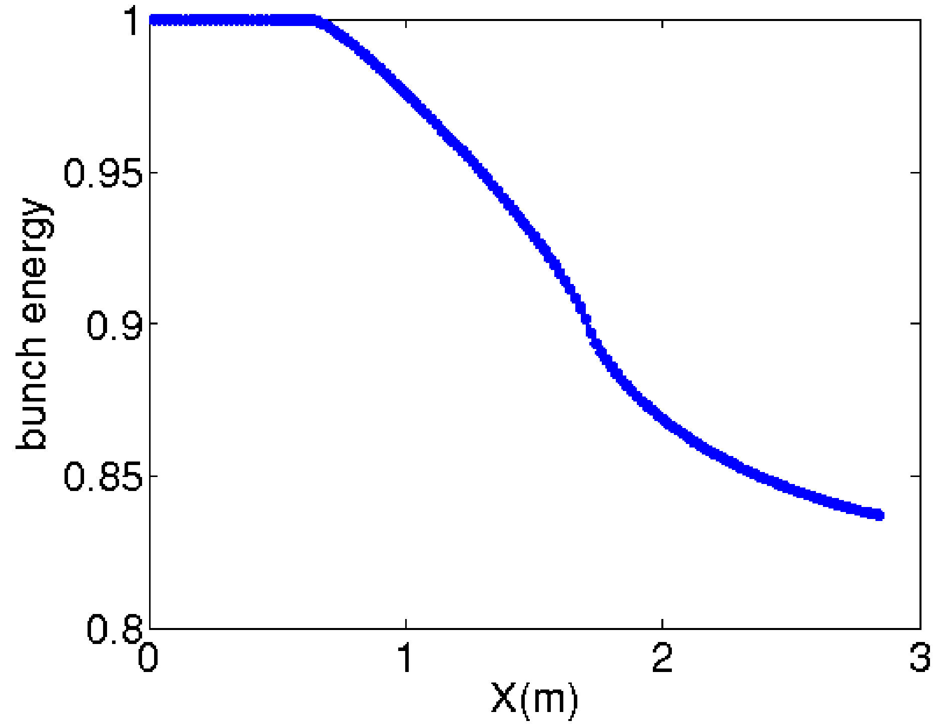


Simulation code: EPOCH **Dr. X. Zhang (UCI)**

Preliminary result of beam deceleration simulation

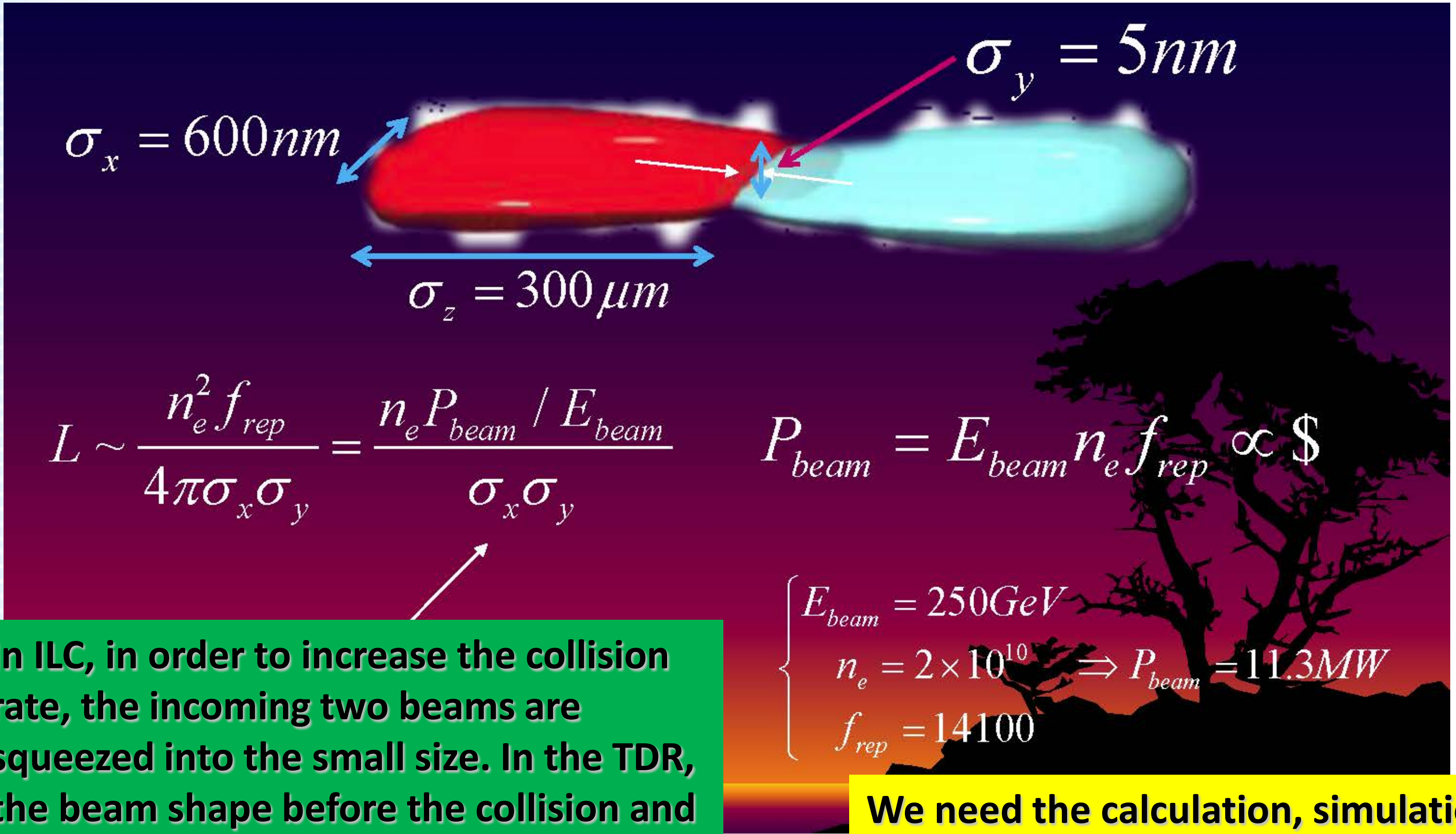
Dr. X. Zhang (UCI)

More than 15% energy loss after 3m



First result of simulation is encouraging. Working is continuing with priority.

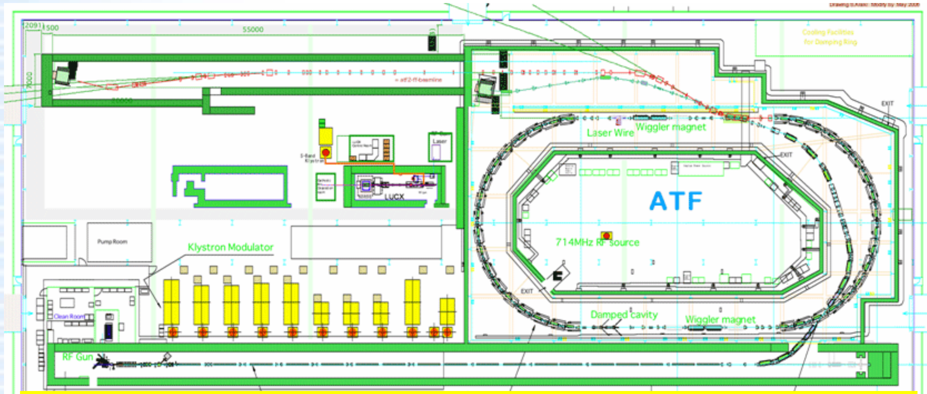
ILC beam after collision



In ILC, in order to increase the collision rate, the incoming two beams are squeezed into the small size. In the TDR, the beam shape before the collision and collision rate is estimated and simulated, but the beam shape after the collision has not been estimated and simulated.

We need the calculation, simulation, and design of optics for the collided beam to be made into the ideal shape for the collective deceleration. Present preliminary result used the undisrupted beam parameters.

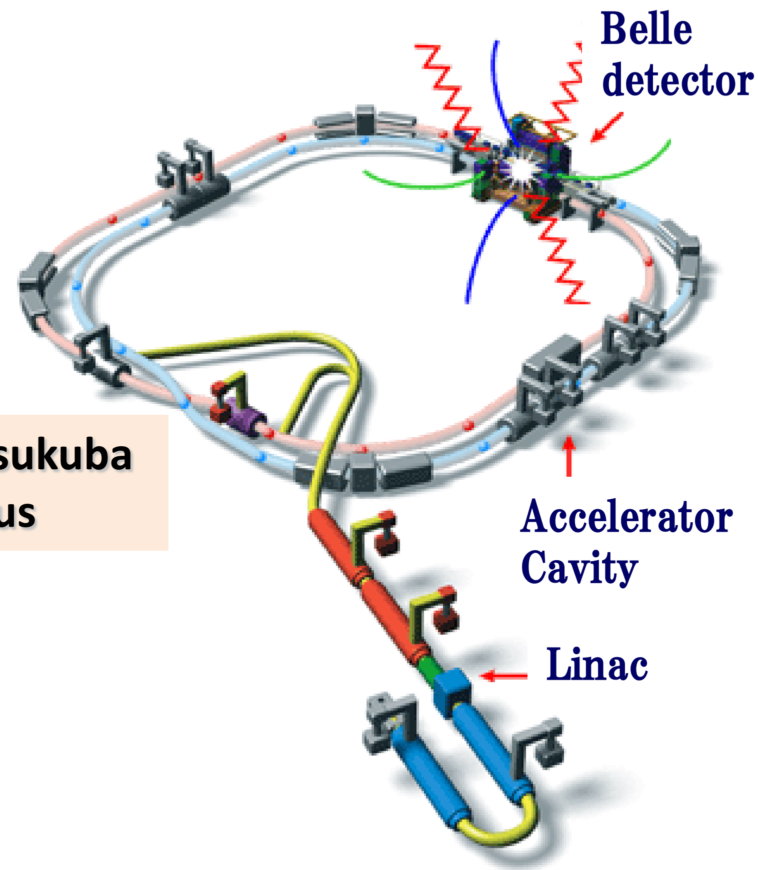
Possibility of proof-of-principle experiment at KEK. Three possible testbeds.



Accelerator Test Facility (ILC test facility)

KEK Tsukuba campus

Superconducting RF Accelerator Test Facility in 100-m tunnel (ILC test facility)



Linac of KEKB accelerator

If simulation results look good, we will propose the plan of proof-of-principle experiment at KEK to use existing accelerator beams. Funding to be secured.

Energy recovery from plasma wakefield

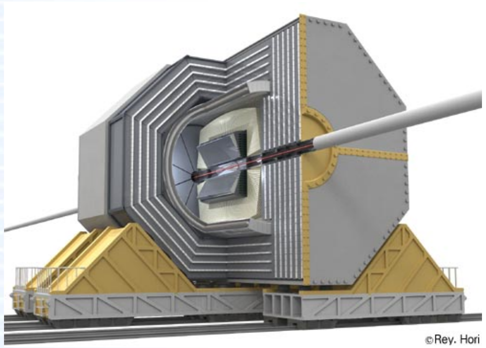
- The paper claimed that at least in the linear wake regime, "in principle, the energies from the decelerated beams deposited in the form of organized plasma wakefield may be recovered into electricity."
- Any electric circuit such as a metallic loop in the plasma picks up coherent electric currents caused by the plasma collective oscillations. Then, external circuit extract electric energies rather than heat.
- "Because the energy of the plasma electrons is much less than that of the beam electrons, the collisions do not give rise to excessive radioactivation."

7. Summary and outlook

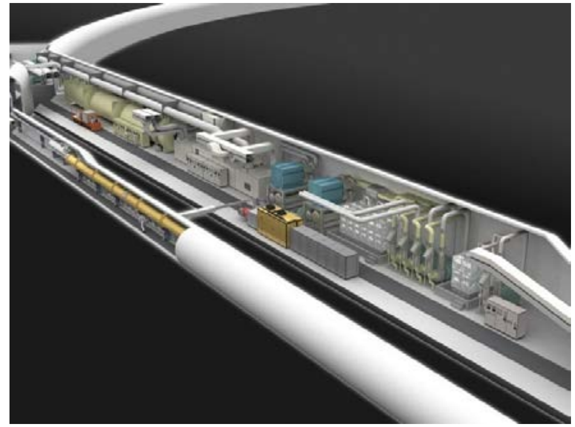
- The conventional design of ILC beam dump (water dump system) in TDR is well studied, but it has several difficulties. Alternative design (gas dump system) is very long (~1000 m).
- Collective deceleration dump (Green beam-dump) has several advantages: no pressure problem, no hydrogen problem, less radio-activation, compact facility, and potential energy recovery.
- First preliminary result of collective deceleration dump of 250 GeV electron beam shows that 15% of energy loss in first 3 m of beam dump.
- To realize the green beam dump in ILC, the beam shape after collision should be optimized to the collective deceleration.
- If simulation results look good, we will propose proof-of-principle experiment at KEK.

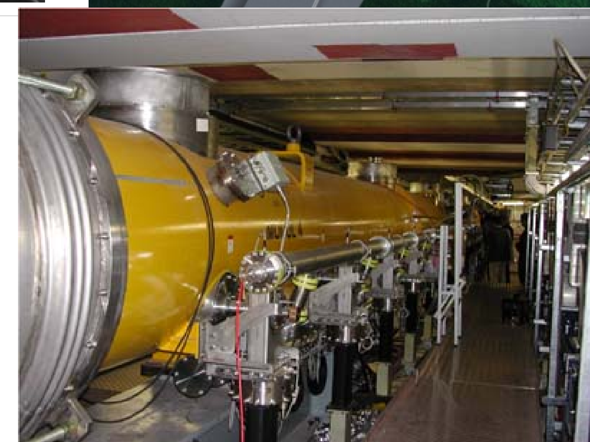
Backup slides

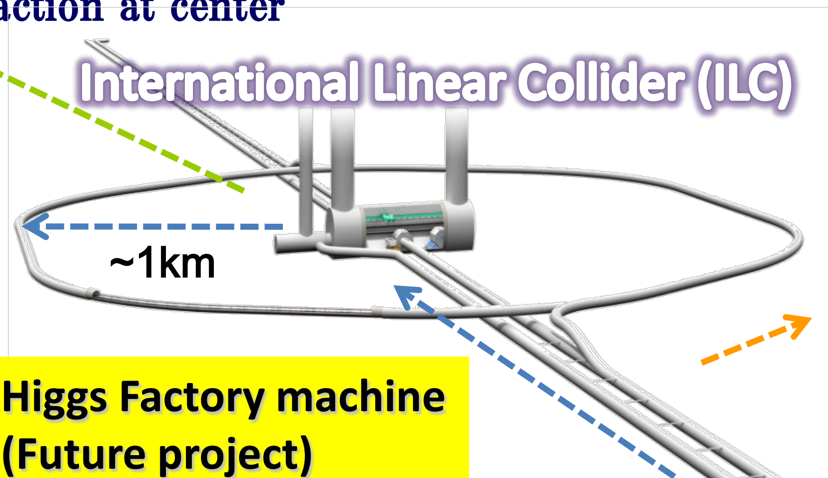
2. Introduction



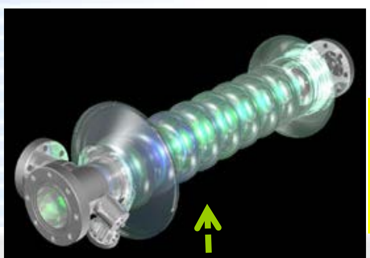
Detector for particle reaction at center







# of Superconducting Accelerator Cavities~15000



Higgs Factory machine (Future project)

Pros/cons

	Water dump	Gas dump
length	10 m	1000 m
Window pressure	10 bar static, 0.5 bar dyn.	1 bar static, 0.01 bar dyn
Window diameter	30 cm	8 cm
Hydrogen gas producing	Several liter/sec @ 20 MW	no
Tritium production	300 TBq	30 TBq (in Iron)
Component Activity	1.2 mSv/h	~ 1 … 10 mSv/h

The dumps absorb the energy of the electromagnetic shower cascade in 11 m ($30\,X_0$) of water. Each dump incorporates a beam-sweeping magnet system to move the charged beam spot in a circular arc of 6 cm radius during the passage of the 1 ms-long bunch train. Each dump operates at 10 bar pressure and also incorporates a vortex-flow system to keep the water moving across the beam. In normal operation with 500 GeV beam energy, the combination of the water velocity and the beam sweepers limits the water temperature rise during a bunch train to 155 °C [191]. The pressurisation raises the boiling temperature of the dump water; in the event of a failure of the sweeper, the dump can absorb up to 250 bunches without boiling the dump water.

8.8.1.2 Mitigation of water-activation products

Activation products are primarily the result of photo-spallation on ^{16}O, primarily ^{15}O, ^{13}N, ^{11}C, ^{7}Be and ^{3}H (tritium). The first three radionuclides have short half lives and decay after ~ 3 hours. The ^{7}Be is removed from the system by filtering it out in a mixed-bed ion-exchange column located in the dump-support cavern. Tritium, a ~ 20 keV β emitter with a half life of 12.3 years, builds up in the water to some equilibrium level; the tritium is contained by the integrity of the dump system and the backup measures described in the preceding section.

8.8.1.4 Shielding and protection of site ground water

Assuming a dry rock site, as in the baseline configuration, 50 cm of iron and 150 cm of concrete shielding are needed between the dump and other areas of the tunnel enclosure to protect equipment from radiation damage. If the chosen site is not dry, the area surrounding the dump must be enveloped by an additional 2 m-thick envelope of concrete to prevent tritium production in the ground water.

Scheme of the water system for the water beam dump

TESLA

DESY, February 2001, TESLA Report 2001-04

Concept of the High Power e$^{\pm}$ Beam Dumps for TESLA

W. Bialowons, M. Maslov, M. Schmitz, V. Sytchev

- 70^{o}C hot water can be obtained.

  - Energy recovery

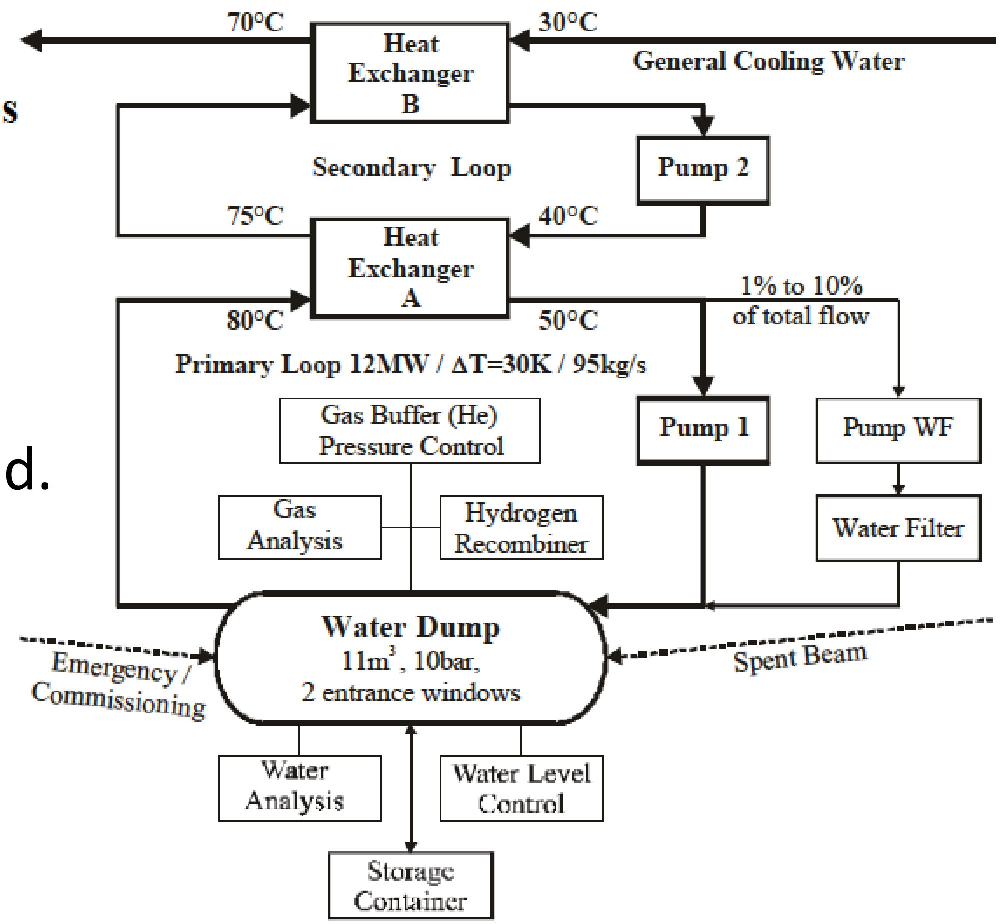


Figure 6: Scheme of the water system for the water based beam dump

ILC parameters

IP and General Parameters			TF = Traveling Focus						E_{cm} Upgrade	
								L Upgrade	A1	B1b
Centre-of-mass energy	E_{cm}	GeV	**200**	**230**	**250**	**350**	**500**	**500**	**1000**	**1000**
Beam energy	E_{beam}	GeV	100	115	125	175	250	500	500	500
Collision rate	f_{rep}	Hz	5	5	5	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	10	10	10	5	5	5	4	4
Number of bunches	n_b		1312	1312	1312	1312	1312	2625	2450	2450
Electron bunch population	N_-	$\times 10^{10}$	2.0	2.0	2.0	2.0	2.0	2.0	1.74	1.74
Positron bunch population	N_+	$\times 10^{10}$	2.0	2.0	2.0	2.0	2.0	2.0	1.74	1.74
Bunch separation	Δt_b	ns	554	554	554	554	554	366	366	366
Bunch separation $\times f_{RF}$	$\Delta t_b\, f_{RF}$		720	720	720	720	720	476	476	476
Pulse current	I_{beam}	mA	5.8	5.8	5.8	5.8	5.79	8.75	7.6	7.6
RMS bunch length	σ_z	mm	0.3	0.3	0.3	0.3	0.3	0.3	0.250	0.225
Electron RMS energy spread	$\Delta p/p$	%	0.206	0.194	0.190	0.158	0.125	0.125	0.083	0.085
Positron RMS energy spread	$\Delta p/p$	%	0.187	0.163	0.150	0.100	0.070	0.070	0.043	0.047
Electron polarisation	P_-	%	80	80	80	80	80	80	80	80
Positron polarisation	P_+	%	31	31	30	30	30	30	20	20
Horizontal emittance	$\gamma\varepsilon_x$	μm	10	10	10	10	10	10	10	10
Vertical emittance	$\gamma\varepsilon_y$	nm	35	35	35	35	35	35	30	30
IP horizontal beta function	$\beta_x{}^*$	mm	16.0	14.0	13.0	16.0	11.0	11.0	22.6	11.0
IP vertical beta function (no TF)	$\beta_y{}^*$	mm	0.34	0.38	0.41	0.34	0.48	0.48	0.25	0.23
IP RMS horizontal beam size	$\sigma_x{}^*$	nm	904	789	729	684	474	474	481	335
IP RMS veritcal beam size (no TF)	$\sigma_y{}^*$	nm	7.8	7.7	7.7	5.9	5.9	5.9	2.8	2.7
analytical estimates										
Horizontal distruption parameter	D_x		0.2	0.2	0.3	0.2	0.3	0.3	0.1	0.2
Vertical disruption parameter	D_y		24.3	24.5	24.5	24.3	24.6	24.6	18.7	25.1
Horizontal enhancement factor	H_{Dx}		1.0	1.1	1.1	1.0	1.1	1.1	1.0	1.0
Vertical enhancement factor	H_{Dy}		4.5	5.0	5.4	4.5	6.1	6.1	3.5	4.1
Total enhancement factor	H_D		1.7	1.8	1.8	1.7	2.0	2.0	1.5	1.6
Geometric luminosity	L_{geom}	$\times 10^{34}$ cm^{-2}s^{-1}	0.30	0.34	0.37	0.52	0.75	1.50	1.77	2.64
Luminosity	L	$\times 10^{34}$ cm^{-2}s^{-1}	**0.50**	**0.61**	**0.68**	**0.88**	**1.47**	**2.94**	**2.71**	**4.32**
Average beamstrahlung parameter	Υ_{av}		0.013	0.017	0.020	0.030	0.062	0.062	0.127	0.203
Maximum beamstrahlung parameter	Υ_{max}		0.031	0.041	0.048	0.072	0.146	0.146	0.305	0.483
Average number of photons / particle	n_γ		0.95	1.08	1.16	1.23	1.72	1.72	1.43	1.97
Average energy loss	δE_{BS}	%	0.51	0.75	0.93	1.42	3.65	3.65	5.33	10.20
simulation										
Luminosity	L	$\times 10^{34}$ cm^{-2}s^{-1}	0.498	0.607	0.681	0.878	1.50	3.00	3.23	4.31
Coherent waist shift	ΔW_y	μm	250	250	250	250	250	250	190	190
Luminosity (inc. waist shift)	L	$\times 10^{34}$ cm^{-2}s^{-1}	**0.56**	**0.67**	**0.75**	**1.0**	**1.8**	**3.6**	**3.6**	**4.9**
Fraction of luminosity in top 1%	$L_{0.01}/L$		91.3%	88.6%	87.1%	77.4%	58.3%	58.3%	59.2%	44.5%
Average energy loss	δE_{BS}		0.65%	0.83%	0.97%	1.9%	4.5%	4.5%	5.6%	10.5%
Number of pairs per bunch crossing	N_{pairs}	$\times 10^3$	44.7	55.6	62.4	93.6	139.0	139.0	200.5	382.6
Total pair energy per bunch crossing	E_{pairs}	TeV	25.5	37.5	46.5	115.0	344.1	344.1	1338.0	3441.0

ILC parameters

基本的ビームパラメータ（baseline, 5Hz）

- 繰り返周波数 5Hz
- パルスあたりバンチ数 1312
- バンチあたり粒子数 2x10^10
- バンチ間隔 554 ns
- バンチ長 0.3 mm

- 水平エミッタンス 10 μm
- 垂直エミッタンス 35 nm
- 衝突点水平ビームサイズ 474nm
- 衝突点垂直ビームサイズ 5.9nm