

SIMULATION OF WAKEFIELD EFFECT IN ILC IR CHAMBER*

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Abstract

To achieve super high luminosity, high current beams with very short bunch length are needed, which carry high intensity EM fields. For ILC, two bunch trains with bunch length of 300 μ m and bunch charge of 3.2nC are needed to collide at the IR to achieve the ILC luminosity goals. When the 300 μ m bunches pass through the IR chamber, wakefields will be excited, which will cause HOM power flowing through the IR chamber beam pipe to the final doublets due to the high frequency characteristic of the induced wakefields. Since superconducting technology is adopted for the final doublets of ILC BDS, whose operation stability might be affected by the HOM power produced at the IR chamber, quench might happen. In this paper, we did some analytical estimation and numerical simulation on the wakefield effects in ILC IR chamber.

INTRODUCTION

In order to answer what the universe is made of and provide new insights into its working principle, energy regimes beyond the reach of today's accelerators need to be investigated. The International Linear Collider (ILC) is a new cosmic doorway to realize this. The two main linacs of ILC accelerate very short (\sim 300 μ m) and high peak current (3.2nC/bunch) bunches into the Beam Delivery System (BDS) on the way to the interaction point [1]. The ILC BDS is responsible for transporting the e^+/e^- beams from the exit of the high energy linacs, focusing them to the sizes required to meet the ILC luminosity goals [1][2] ($\sigma_x^*=639$ nm, $\sigma_y^*=5.7$ nm for nominal), bringing them into collision, and transporting the spent beams to the main beam dumps. In order to realize this, superconducting final doublet is adopted and placed on each beam line just before the IR chamber.

When charged particle beams traverse through non-smooth or resistive beam pipe walls, wakefield will be excited. If the wakefield frequency is below the beam pipe's cut-off frequency, it will be trapped, otherwise it will propagate out and cause HOM heating of the surrounding components. For ILC IR chamber, one choice of the geometry is shown in Fig. 1 (here we simplify it to 2D to facilitate the analysis) [3]. The radius of the ingoing and outgoing beam pipe is very small (\sim 10mm), whose cut-off frequency is about 18GHz for TE modes and 12GHz for TM modes, so part of the wakefield will stay in the chamber after the beam's passage. On the other hand, due to the very short bunch length of ILC, the induced field spectrum will go to higher frequency (far beyond beam pipe cut-off frequency), so most of the wakefield will propagate

out of the chamber, which may cause quench of the SC final doublets. We evaluated the geometric wakefield effects in IR chamber analytically and numerically, but it is limited to 2-D analysis based on the capability of simulation tools. The numerical analysis was done with simulation codes ABCI[4] and MAFIA[5].

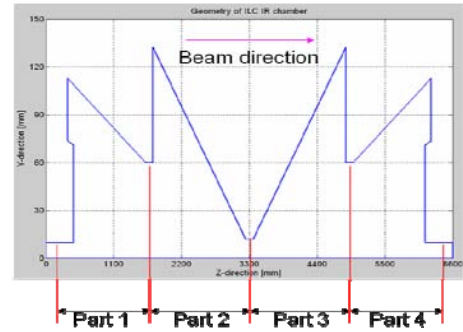


Figure 1: Geometry of ILC IR chamber (Geo-1).

ANALYTICAL ESTIMATION

To do the analytical estimation, we split the whole IR chamber into 4 regions, shown in Fig. 1. Every part can be looked as one shallow cavity, the impedance of which can be roughly estimated by

$$Z_0^{\parallel} = \frac{Z_0}{\pi} \ln \frac{r_{out}}{r_{in}} \quad (r_{out} > r_{in}) \quad (1)$$

$$Z_0^{\perp} = \frac{Z_0}{2\pi k} \left(\frac{1}{r_{in}^2} - \frac{1}{r_{out}^2} \right) \quad (r_{out} > r_{in}) \quad (2)$$

or

$$Z_0^{\parallel} \approx 0 \quad (r_{out} < r_{in}) \quad (3)$$

$$Z_0^{\perp} = \frac{Z_0}{2\pi k} \left(\frac{1}{r_{out}^2} - \frac{1}{r_{in}^2} \right) \quad (r_{out} < r_{in}) \quad (4)$$

Where Z_0 is the free space impedance (\sim 377 Ω in MKS units), $k=\omega/c$. Here our focus is the longitudinal impedance, i.e., HOM heating effect, while for integrity we still list the transverse impedance. The impedance of Part 1 and Part 3 can be estimated with Eqs. (1)-(2), while that of Part 2 and Part 4 can be estimated with Eqs. (3)-(4). It is worth to note that for the other kinds of geometry, the formulae used might be different, for example, the alternative geometries of IR chamber shown in the later part of this paper.

Substitute the geometry parameters into Eqs (1) and (3), we obtain the total longitudinal impedance for the geometry shown in Fig.1,

$$Z_{Total} = \frac{Z_0}{\pi} \ln 30 \quad (5)$$

Correspondingly, the total loss factor is

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$$k_{Total} = \frac{Z_0 c}{2\pi^{3/2} \sigma_z} \ln 30 \quad (6)$$

For $\sigma_z=0.6\text{mm}$, 0.5mm , 0.4mm , 0.3mm , 0.2mm and 0.1mm , the loss factor will be 57.57V/pC , 69.08V/pC , 86.35V/pC , 115.13V/pC , 172.71V/pC , 345.41V/pC .

NUMERICAL SIMULATION

Due to the very short bunch length we concerned and the big structure, very dense mesh need to be used in the numerical simulation (usually the mesh size ddz should be at least 10 times smaller than σ_z), otherwise dispersion effect will cause big error. Fig. 2 shows the ABCI simulation results for 0.3mm bunch with different ddz , only when $\sigma_z/ddz > 15$ the unphysical bump at the bunch head can be ignored. For even shorter bunch, σ_z/ddz should be further increased to obtain the correct result, which might exceed the current computer capability.

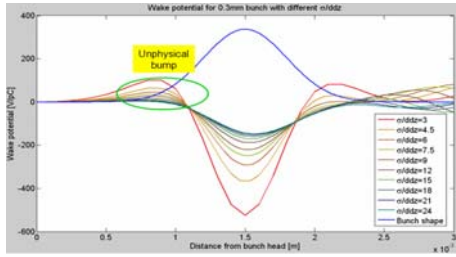


Figure 2: ABCI simulation results for 0.3mm bunch.

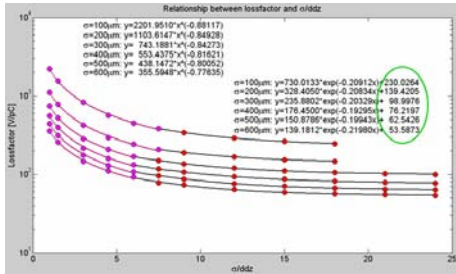


Figure 3: Simulation for different σ_z with different σ_z/ddz .

In our simulation, we use extrapolation method to eliminate the dispersion effect; Fig. 3 shows the simulation result. The loss factors with different mesh size are calculated first, then they are fitted to one exponential decay curve with constant offset, the constant offset is the correct loss factor. We can see the fitted curve agrees well with the simulation.

MAFIA 2D is used to confirm ABCI simulation result; Fig. 4 shows the simulation result of MAFIA for different bunch length. MAFIA agrees well with ABCI except the large dispersion effect at bunch tail for very short bunch length, however, this doesn't result in large loss factor deviation. Fig. 5 shows the relation between loss factor and bunch length.

Fig. 6 shows the long range wakefield, frequency spectrum for 0.3mm bunch. After calculating the TE and TM modes' cutoff frequency in the incoming and

outgoing beam pipes, we can see that most of the power will go out of the chamber.

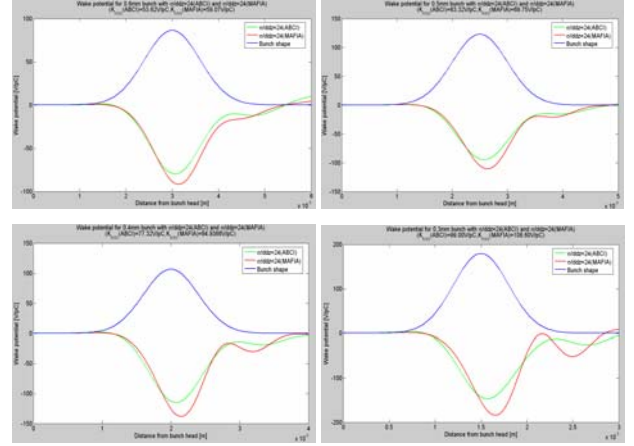


Figure 4: Comparison of MAFIA 2D and ABCI.

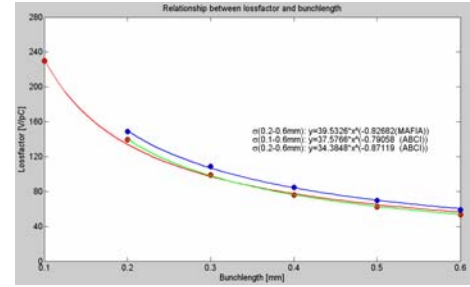


Figure 5: Relation between loss factor and bunch length.

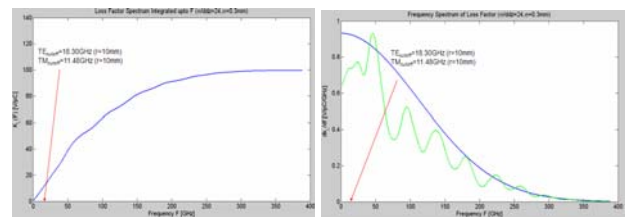
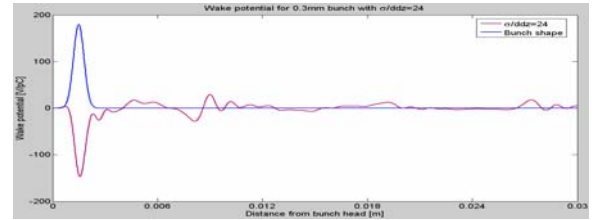


Figure 6: Long range wake and spectrum ($\sigma_z=0.3\text{mm}$).

Table 1 shows the summary of the analytical estimation and numerical simulation, including the power loss estimation for ILC nominal parameters with 369ns bunch interval and bunch population of 2×10^{10} [1], ABCI result is used to estimate the power loss. Both the pulse power and the average power are calculated for electron and positron beam, the total pulse power loss of which are [7]

$$P_{pulse} = k \tau_b \left\{ \left(I_{e^+} \right)^2 + \left(I_{e^-} \right)^2 \right\} \quad (6)$$

We can see the total power for different bunch length left in the chamber is almost constant.

Table 1. Loss factor and power loss for different bunch length

σ_z /mm	$k_{\text{analytical}}/V/pC$	$k_{\text{MAFIA}}/V/pC$	$k_{\text{GDFIDL}}/V/pC$	$k_{\text{ABCI}}/V/pC$	P_{pulse}/kW	P_{average}/W	Percentage and P_{average} of power left in chamber / (%/ W)
0.6	57.57	59.07	51.36	53.59	2.97	14.39	~20/2.88
0.5	69.08	69.75	65.81	62.54	3.47	16.80	~16/2.69
0.4	86.35	84.94	78.97	76.22	4.23	20.47	~12/2.46
0.3	115.13	108.60	98.55	99.00	5.49	26.59	~9/2.39
0.2	172.71	148.75		139.42	7.74	37.44	~7/2.62
0.1	345.41			230.03	12.77	61.78	~4/2.47

ALTERNATIVE GEOMETRIES

Besides the structure shown in Fig. 1, we also calculated the wakefield effect in another two alternative geometries shown in Fig. 7. The results are shown in Table 2. For ABCI, $\sigma_z/ddz=24$, while for MAFIA, $\sigma_z/ddz=18$. From Table 1 and 2, we can see the three geometries have almost same loss factors for different bunch length ranging from 0.1m to 0.6mm.

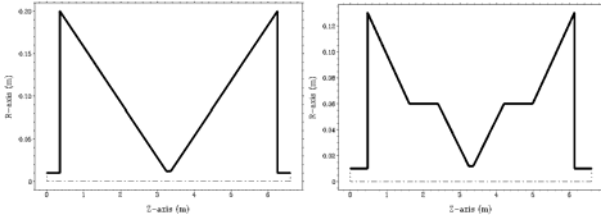


Figure 7: Alternative geometries of ILC Interaction Region chamber (Geo-2 & Geo-3).

Table 2: Loss factor for the two alternative geometries

σ_z /mm	Geo-2		Geo-3	
	$k_{\text{ABCI}}/V/pC$	$k_{\text{MAFIA}}/V/pC$	$k_{\text{ABCI}}/V/pC$	$k_{\text{MAFIA}}/V/pC$
0.6	52.51	58.87	49.80	56.92
0.5	63.03	69.73	59.33	67.82
0.4	77.06	85.37	73.53	83.32
0.3	100.30	109.67	95.37	107.29
0.2	142.30	150.93	135.50	147.95
0.1			227.10	

CONCLUSION

It has been shown that in the IR region the pulse power loss resulted from IR chamber is at the level of ~kW, while the average power loss is about tens of Watt, which is not so high. However, in order to operate the collider stably, beam pipe absorber [8][9] needs to be placed between the IR chamber and the final doublet. For different geometries mentioned in this paper, there is no big difference of the wakefield effect. For the wakefield left in the IR chamber, most

of them are trapped modes. Fig. 8 shows the wakefield spectrum for 10mm bunch in Geo-1, we can see there are many resonant modes below the beam pipe cut-off frequency. Fortunately, the total loss factor of these modes is not so large, however, careful design of the IR chamber shape still need to be done with consideration of detector requirements.

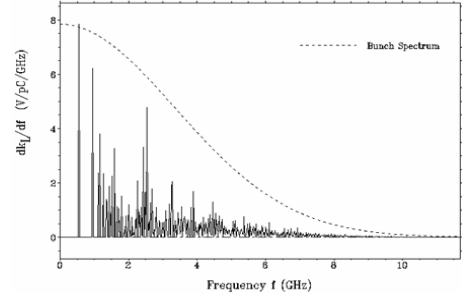


Figure 8: Spectrum for 10mm bunch in Geo-1.

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