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RF AND RESISTIVE ENERGY LOSS IN THE INTERACTION REGION VACUUM CHAMBER

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Introduction

The interaction region (IR) vacuum chamber should allow to accommodate the IR quadrupoles with a bore radius provisionally set at 25÷30 mm, leaving a material-free cylindrical region ~100 mm long with a radius of at least 80 mm.

It is shown that the unavoidable cross-section variation leads to substantial energy losses localized in the IR vacuum chamber even if the steps in cross-section are tapered. The relatively short bunch duration furtherly exacerbates the losses. The resistive loss is also significant in the case of an internal metallic coating, but it can be reduced by a factor ~3 using Beryllium.

RF losses

The interaction of the beam with the surrounding environment gives rise to a power loss, usually written as

$$P = \frac{< I >^2 T_0}{n_b} k_l(\sigma_t) \tag{1}$$

where <I> is the average total current, n_b the total number of bunches, T_0 the revolution period and $k_l(\sigma_t)$ is the so-called loss parameter

$$k_l(\sigma_t) = \frac{1}{\pi}\int_0^\infty Z_R(\omega)\exp(-\omega^2\sigma_t^2)d\omega \qquad [V/C] \tag{2}$$

i.e. the resistive part of the coupling impedance weighted by the beam power spectrum. $Z_R(\omega)$ is the real part of the coupling impedance and σ_t the rms bunch duration.

The integral (2) can be evaluated in the frequency domain by knowledge of the function $Z_R(\omega)$ and analytical integration, or in the time-domain by solving the EM wake field (as done, e. g., with the TBCI code).

Figure 1 shows a preliminary design of the DAΦNE IR provided us by B. Dulach. Tapered cross-section variations result in the RF radiation of a traversing bunch. We estimated the longitudinal loss parameter for this preliminary design using the TBCI code. The estimated loss parameter k_l is 2.1 10^9 [V/C] for an rms bunch length σ_t of 3 cm. The power radiated in the interaction point (IP) at the nominal average current of 46 mA/bunch is ~2.7 Watt per pair of colliding bunches, resulting in a total radiated power of 324 W, in the case of 120 + 120 colliding bunches. If all this power is dissipated in the IR chamber wall, special cooling is required.

We tried to reduce the total amount of radiated RF by acting on the taper, but there are a number of constraints on the IR geometry:

- the outer radius at the IP is fixed and must be 80 mm:
- the distance from the first quadrupole of the IR triplet is defined and equal to 450 mm;
- the length of the flat part of the vacuum chamber near the IP should not be less than 100 mm (we have verified, however, that even in the case of a taper starting right at the IP, the RF losses are larger than in the case with a flat part);
- the outer radius of the first quadrupole, hence the beam pipe radius are limited by the angle (8° 30’) that is let free by the experimental apparatus; the bore radius is 25 to 30 mm. However we also considered bore radii of 35 and 40 mm.

The only way we could try to reduce the losses, according to the above constraints and to the original drawing, is to give up the flanges and to prolong the taper to the onset of the first quadrupole. The shape of this new taper is shown schematically in Fig. 2. With such a geometry, the radiated power decreases to 1.4 W per pair of bunches in the case of a bore radius a of 30 mm, down to 0.6 W in the case of a = 40 mm (results of the TBCI code, with an rms bunch length σ_t of 3 cm).

Now it is also necessary to estimate which amount of power is dissipated in the IR and which flows away through the beam pipe.

The tail of the wake field in Fig. 3 corresponds to the wake fields remaining in the IR. Unfortunately, most of the bunch spectrum lies below the TM cut-off frequency of the beam pipe. In fact the bunch cut-off at the nominal bunch length is approximately 2.3 GHz, while the beam pipe cut-off is ~3.8 GHz with a = 30 mm. This means that most of the RF energy radiated by the bunch will not flow out of the IR.

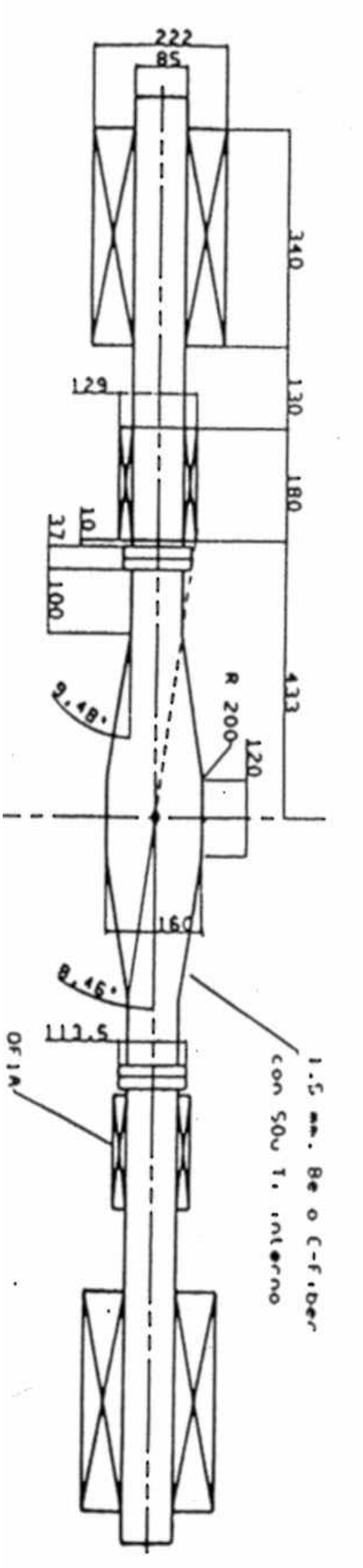

Fig. 1 - Preliminary design of DAΦNE interaction region (Provided by B. Dulach - SPECAS).

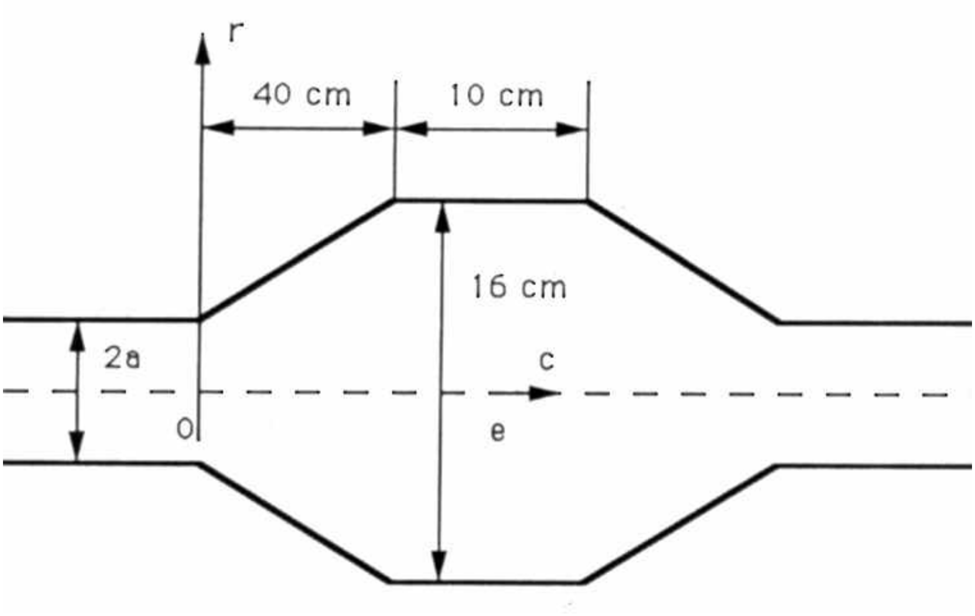

Fig. 2 - Geometry of the interaction region.

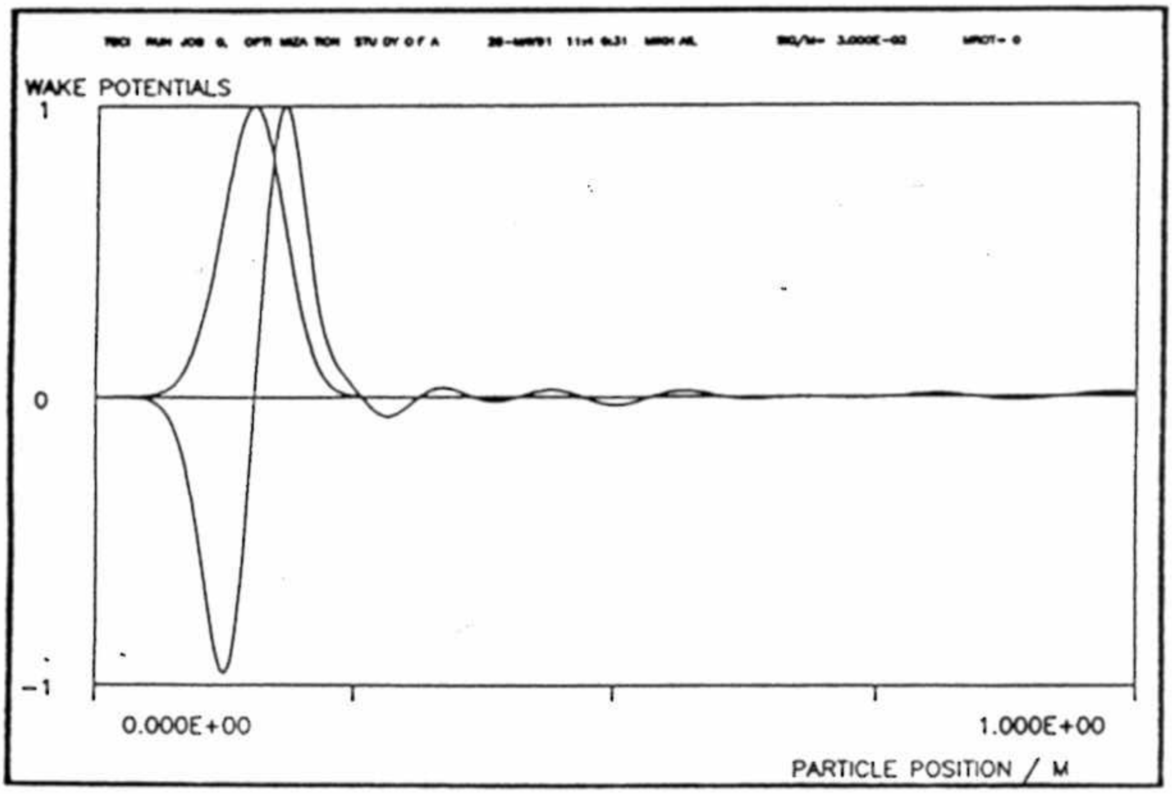

Fig. 3 - Results of the code TBCI: bunch current distribution and associated longitudinal wake.

We verified this fact: the loss parameter for all modes trapped in the IR is [1]

$$k_{br}(\sigma_t) = \sum_n 2k_n \exp(-\omega_n^2 \sigma_t^2) \qquad (3)$$

where $k_n = \frac{\omega_n R_n}{4Q_n}$

and ω_n is the resonating frequency of the n-th trapped mode, R_n the shunt impedance and Q_n the quality factor.

To get all the necessary values ω_n , R_n , Q_n , we used the code OSCAR-2D. These values for 15 trapped modes, calculated with a = 30 mm, are shown in Table I.

TABLE I - *Monopole modes in IR.*

Freq (MHz)	R_n (Ω)	Q_n	$(R/Q)_n$ (Ω)
1512.7	498.6	45562	1.09E-2
1704.6	6528.	45714	1.43E-1
1881.5	1519.7	45575	3.33E-2
2026.2	4996.5	44959	1.11E-1
2177.4	2820.4	45128	6.25E-2
2311.7	4435.3	44620	9.94E-2
2449.8	4240.4	44752	9.47E-2
2579.9	4125.9	44453	9.28E-2
2709.7	5290.2	44493	1.19E-1
2837.5	4258.9	44435	9.58E-3
2961.8	6297.5	44346	1.42E-1
3087.9	5111.9	44452	1.15E-1
3208.3	8792.6	44296	1.99E-1
3350.2	1858.6	69897	2.66E-2
3452.0	8882.1	44274	2.0E-1

The power loss calculated by using the results of OSCAR-2D for that case is P = 1.12 Watt per pair of bunches with σ_t = 3 cm. These results agree reasonably with those of TBCI and confirm the fact that the most part of the radiated energy remains within the IR.

For σ_t = 2 cm, 45% of the radiated power will flow through the beam pipe. Nevertheless the total power trapped in the IR will be larger since the total energy loss grows very rapidly (see Fig. 4) with σ_t (4.2 Watts per pair of bunches, according to numerical calculations).

An other important question is how the power loss is distributed in the IR. The code OSCAR-2D also gives the answer to this question: the most part of power (~91%) will be symmetrically distributed on the tapers, whereas the remaining part will be dissipated in the flat region of the IR.

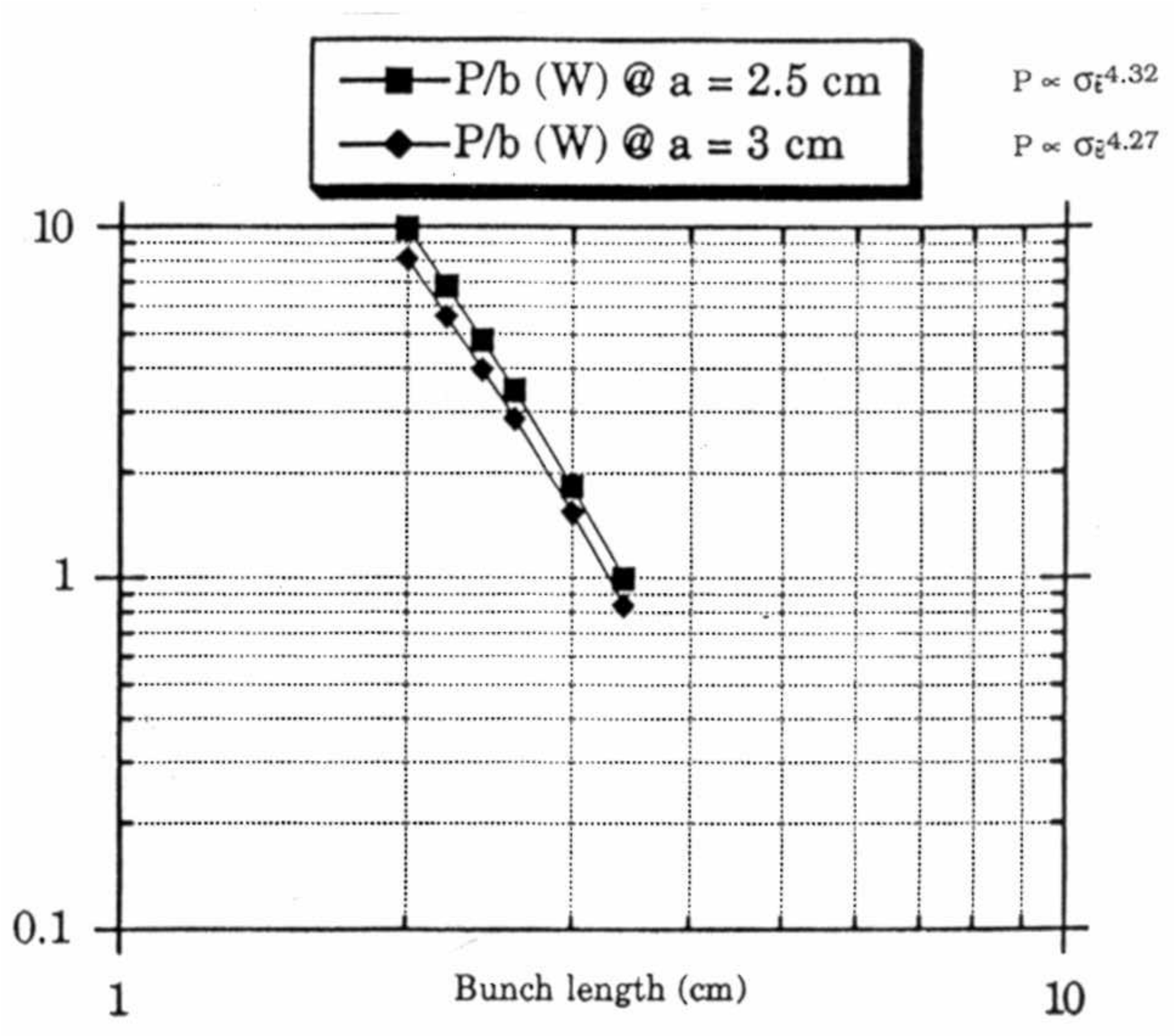

Fig. 4 - Power loss (per pair of bunches) in the IR vs. bunch length.

Resistive loss

The longitudinal impedance per unit length of a vacuum chamber of effective radius a, due to the finite resistivity ρ of the wall is

$$Z'_{RW}\ [\Omega/M] = \begin{cases} \dfrac{(1+j)}{2\pi a}\sqrt{\dfrac{\rho\mu_0\omega}{2}} & s > \delta_s \\[2ex] \dfrac{\rho}{s}\dfrac{1}{2\pi a} & s < \delta_s \end{cases} \tag{4}$$

where s is the thickness, and δ_s the skin depth

$$\delta_s = \sqrt{\frac{2\rho}{\mu_0\omega}}\quad . \tag{5}$$

Associated to this impedance, the loss parameter/ unit length is

$$k'_l(\sigma_t) = \frac{1}{\pi}\int_0^\infty \mathrm{Re}\{Z'_{RW}(\omega)\}\exp(-\omega^2\sigma_t^2)d\omega \quad =$$

$$(6)$$

$$= \frac{1}{2\pi^2 a}\frac{1}{\sigma_t}\left\{\frac{\rho}{s}\int_0^{\omega^*\sigma_t}\exp(-x^2)dx \quad + \sqrt{\frac{\mu_0\rho}{2\sigma_t}}\int_{\omega^*\sigma_t}^\infty \sqrt{x}\exp(-x^2)dx\right\}$$

where $\omega < \omega^* = 2\rho/\mu_0\sigma^2$ defines the frequency region where the conductor thickness is larger than the skin depth.

It can be seen that in both cases of 50 μm of Ti coating or 1.5 mm of Be, the first integral of (6) contributes very little to the resistive loss. So, for our estimation we take into account only the second term in (6).

We calculated the power resistive loss for the IR geometry presented in Fig. 2 for two kinds of materials: Be (1.5 mm, 50 µm) and Ti (50µm). For Be the loss is by factor 3.2 less than for Ti (See Tables IV and V).

Conclusions

The results of all our estimates are summarized in the following Tables:

- in the Tables II and III the total radiated power and RF power dissipated in the IR are given for different bunch lengths and bore radii;
- in the Tables IV and V the resistive power loss in Be and Ti metallic coating is presented. Resistive losses scale with σ_t as $(1/\sigma_t)^{3/2}$.

The RF and resistive losses must be added.

TABLE II - *Total power loss in the IR (W/pair of bunches).*

a (cm) \ σ_t (cm)	2	2.5	3
2.5	9.1739	3.7895	1.7038
3	7.4444	3.0918	1.4064
3.5	6.1812	2.4590	1.1375
4	4.9854	1.9327	0.8951

TABLE III - *RF power dissipated in the IR (W/pair of bunches).*

a (cm) \ σ_t (cm)	2	2.5	3
2.5	4.9963	2.6893	1.3587
3	4.1825	2.2174	1.1198
3.5	2.8037	1.5451	0.8009
4	1.8298	1.0826	0.5936

TABLE IV - *Resistive power loss in 1.5 mm of Be (W/pair of bunches).*

a (cm) \ σ_t (cm)	2	2.5	3
2.5	0.2456	0.1757	0.1337
3	0.2291	0.1693	0.1247
3.5	0.2156	0.1543	0.1174
4	0.2043	0.1462	0.1112

TABLE V- *Resistive power loss in 50 μm Ti metallic coating (W/pair of bunches).*

a (cm) \ σ_t (cm)	2	2.5	3
2.5	0.7923	0.5668	0.4313
3	0.7390	0.5287	0.4023
3.5	0.6925	0.4977	0.3787
4	0.6590	0.4716	0.3587

References

[1] T. Weiland, R. Wanzenberg, "Wake Fields and Impedances", DESY M-91-06, May 1991.