DAΦNE TECHNICAL NOTE
INFN - LNF, Accelerator Division

Frascati, April 6, 1992
Note: **G-13**

RF ENERGY LOSSES AND IMPEDANCE OF THE DAΦNE ACCUMULATOR RING VACUUM CHAMBER

S. Bartalucci, L. Palumbo, M. Serio, B. Spataro, M. Zobov

Introduction

A particle beam in an accelerator generates an electromagnetic field while passing through discontinuities and variations in the cross-sectional shape of the vacuum chamber. This field acts back on the beam and it is responsible for energy losses and instabilities.

We must know the amount of energy lost during the radiation process to design a reliable RF system having enough power and voltage to compensate the energy loss. Moreover, criteria of stability of coherent motion usually use the low-frequency limit of the longitudinal impedance Z(n)/n, where n is the harmonic number $n = \omega/\omega_{rev}$ and knowledge of the longitudinal loss factor k_l allows us to estimate this quantity on the basis of the broad-band impedance model.

In this paper we present the results of numerical simulations of the RF energy loss with TBCI and MAFIA codes in the DAΦNE accumulator ring (Fig. 1) and give an estimate of the vacuum chamber impedance.

RF energy loss

Preliminary comments:

1) The vacuum chamber in the bending magnets has an elliptical shape with semiaxes of 15 and 51 mm. The cut-off frequency for such a geometry is about 6 GHz. For a bunch length $\sigma > 2.5$ cm ("natural" bunch length in the accumulator) almost all bunch spectrum lies below this value. This means that the RF energy radiated in the vacuum chambers of the straight sections between the bending magnets does not flow into the neighbouring straight sections. So, by neglecting the interference of waves diffracted in the different straight sections, we can consider the energy loss as a sum of energy losses in the vacuum chambers between the bending magnets.

2) The radius of the beam pipe between vacuum chamber elements, within each straight section, is rather large (a = 5 cm) and we must take into account the interference of waves diffracted in these elements. Therefore to evaluate the loss factor for the straight section we consider it as a single element.

3) Since the vacuum chamber in the straight sections is not azimuthally symmetric it is necessary to use 3D simulations.

4) The contribution of bellows and diagnostic elements to the total loss factor (and impedance) is much less than the one due to kickers, RF cavity and step transitions. Therefore we do not include the bellows and diagnostics in 3D simulation, but we simply add their contribution, previously computed by TBCI code or analytically.

5) In some cases, we reduce the length of the beam pipes with a constant cross - section to decrease the CPU time of 3D calculation and checking that this reduction does not change the loss factor. TBCI code is used for this purpose.

Straight sections

The geometry of the straight section with 2 kickers and RF cavity used for 3D simulation is presented in Fig. 2. It is a rather complicated structure and so we show also the cut along the longitudinal axis (Fig. 3). Table 1 gives the longitudinal loss factor versus the bunch length for this part of the accumulator vacuum chamber.

Table 1

σ, cm	2.5	3	4	5	6
kl, V/pC	0.4235	0.2975	0.1617	0.09595	0.06177

The other straight section is the array of 2 kickers. 3D MAFIA plot of it is shown in Fig. 4, while the longitudinal loss factor is reported in Table 2.

Table 2

σ, cm	2.5	3	4	5	6
kl, V/pC	0.1977	0.1144	0.04136	0.01718	0.00587

There are 2 injection straight sections. Steps and tapered transitions in the vacuum chamber cross-section are shown in Fig. 5. These sections have a longitudinal asymmetry. A bunch passes the first injection section entering the tapered transition between elliptical and cylindrical beam pipes.

In the second injection section, the bunch goes entering the step transition and exiting the tapered one. But for our case the loss factor does not depend on the direction along z-axis in which a bunch travels, because the entrance and exit beam pipes have the same cross-sections (theorem [1]). The longitudinal loss factor for different bunch length for both injection sections is given in Table 3.

Table 3

σ, cm	2.5	3	4	5	6
kl, V/pC	0.04077	0.01741	0.00232	0.00021	0.000016

There are 4 sections where quadrupole and sextupole magnets have to be installed. The loss factor for their vacuum chamber (Fig. 6) is reported in Table 4. For these sections too, it does not depend on the direction in which bunch travels.

Table 4

σ, cm	2.5	3	4	5	6
kl, V/pC	0.02205	0.00803	0.000784	0.00010	0.000068

Bellows

The geometry of the bellows is shown in Fig. 7. Parameters of the bellows used in simulations are: beam pipe radius is equal to 50 mm, height of convolution is 25 mm, bellows period - 4 mm. The accumulator has bellows with different numbers of convolutions. The bellows installed between kickers have 13 convolutions, which is the maximum number. Figure 8 shows the dependence of the loss factor on the number of the convolutions for $\sigma = 3$ cm. We can see that the loss factor scales linearly with the number of the convolutions. Table 5 shows the loss factor versus the bunch length for the bellow with 13 convolutions.

Table 5

σ, cm	2.5	3	4	5	6
kl, V/pC	0.01957	0.0093	0.00254	0.00083	0.00030

The loss factor is rather small. In our calculation we consider 2 bellows with 13 convolutions and 2 bellows with 5. If some bellows are added we can get the loss factor of any of them by using the linear scaling.

Vacuum ports

There are 16 vacuum ports in the accumulator, which are placed near the ends of the bending magnets. To reduce the losses a vacuum port is shielded with a perforated screen. One of the possible design of the screen is a structure with a number either round holes or longitudinal slots. It is easy to show that the contribution of the shielded vacuum ports is negligibly small in comparison with that of kickers, RF cavity and tapered transitions.

For estimates we use the formula [2] for the loss of N_h holes with a radius $r << \sigma$:

$$k_l = 0.00715 \frac{r^6}{a^2 \sigma^5} g N_h \tag{1}$$

Here "a" is the beam pipe radius and $g = \sigma/l$ is the coherence factor depending on the average distance "l" between holes, $g > 1$. For our case the equivalent beam pipe radius is a = 2 cm. If we choose N_h = 156, r = 0.5 cm, g = 3, σ = 3 cm, we get k_l = 0.0008 V/pC for 16 shielded pumping ports.

It worth noting that k_l drops very fast with r and with increasing σ. So we can neglect influence of the shielded vacuum ports in the impedance calculation.

Diagnostics

There are 8 beam position monitors (BPM) of the 4 buttons type, 4 strip-line BPM (4 strips), 1 pick-up (4 strip-lines) and 1 kicker (4 strip-lines) used for the transverse feedback/tune monitor in the accumulator ring. For these diagnostic elements we estimate the longitudinal impedance at low frequencies and we add it to the total impedance of the ring.

For strip-line BPM, pick-up and kicker, the formula for 4-electrode design is used [3]:

$$\frac{Z}{n} = j\, 4\, Z_s \left(\frac{\Phi_0}{2\pi}\right)^2 \frac{l}{R} \tag{2}$$

where Z_s - characteristic impedance of a strip-line; l - length of one strip-electrode; $\Phi_0/2\pi$ - represents the fraction of the image current that flows along the strip-electrode; R - radius of the accumulator ring.

Z_s for all diagnostic elements is equal to 50 Ohm; $\Phi_0 = 18^0$. The length of the strip-lines in the pick-up and in the kicker is about 50 cm and in the BPMs - 15 cm. By using (2) we get Z/n = 0.0483 Ohm for both the pick-up and the kicker and Z/n = 0.0145 Ohm for each BPM.

The longitudinal impedance at low frequencies for one button in the button BPM is [4]:

$$\frac{Z}{n} = j\,4\left(\frac{r}{4a}\right)^2 \frac{r^2}{R\,c\,C_l} \tag{3}$$

where r - radius of the button-electrode; a - effective radius of the vacuum chamber; C_l - capacitance between the electrode and the vacuum chamber; R - averaged radius of the accumulator.

The BPMs are situated in the elements of the vacuum chamber with the equivalent radius a = 1.9 cm. r = 0.5 cm and C_l = 4 pF. Putting these parameters in (3) we get Z/n = 0.000278 Ohm per one 4-button BPM.

The total contribution of diagnostics to the longitudinal impedance is Z/n = 0.1545 Ohm.

Impedance estimates

The dependence of the total longitudinal loss factor in the DAΦNE accumulator ring (without diagnostics) on the bunch length is given in Fig.9. The longitudinal impedance Z can be estimated from the above numerical results for k_l . To obtain Z/n from k_l we use a relation between the loss parameter of a Gaussian bunch with rms length σ and broad-band model impedance:

$$k_l\left(\sigma\right) = \frac{1}{p}\int_0^\infty d\omega\,\mathrm{Re}\left\{Z\left(\omega\right)\right\} e^{-\left(\omega\sigma/c\right)^2} \tag{4}$$

$$Z\left(\omega\right) = R_s \frac{1 + jQ\left(\frac{\omega_r}{\omega} - \frac{\omega}{\omega_r}\right)}{1 + Q^2\left(\frac{\omega_r}{\omega} - \frac{\omega}{\omega_r}\right)^2} \tag{5}$$

We find the shunt impedance R_s, angular resonant frequency ω_r and quality factor Q of the model broad-band resonator by fitting the analytical dependence $k_l(\sigma)$ by numerical results. It is easy to see that the analytical dependence $k_l(\sigma)$ with Rs = 1.5268 kOhm, Q = 0.82, $\omega_r/2\pi$ = 4.14 GHz fits well the numerical one (See Fig. 9). At low frequencies $Z/n = R_s\,\omega_0/\omega_r\,Q$. For the accumulator ring $\omega_0\ /2\pi$ = 0.0092 GHz and hence Z/n = 4.135 Ohm. By adding the diagnostics contribution the total DAΦNE accumulator longitudinal impedance is equal to 4.3 Ohm.

For Z/n = 4.3 Ohm a bunch is in the turbulent regime and its equilibrium length is equal to 5 cm and rms energy spread σ_p = 9.15E-04 at the average current of 130 mA and RF voltage of 200 kV. The loss factor in the accumulator that corresponds to this bunch length is k_l = - 0.115 V/pC. This means that if the number of particles in a bunch is $N = 9*10^{10}$ (corresponding to 130 mA of the average current in the accumulator) than the bunch loses 1.66 keV ($U = e\ N\ k_l$) per turn because of the RF radiation.

Conclusions

The total RF energy loss is 1.66 keV/turn at I_{AV} = 130 mA and V_{RF} = 200 kV. The main contribution to the loss factor comes from the kicker cavities and RF cavity (almost 80%). According to our estimate, the vacuum chamber impedance Z/n is ~ 4.3 Ohm.

References

[1] S. A. Heifets and S. A. Kheifets, "Coupling impedance in modern accelerators", SLAC-PUB-5297, September 1990(A).

[2] S. Heifets, "Preliminary estimate of the B-factory impedance", SLAC/AP-84, December 1990(AP).

[3] King-Yuen Ng , " Impedances of stripline beam-position monitors", Particle Accelerators, 1988, Vol.23, pp. 93-102.

[4] M. Serio, to be published.

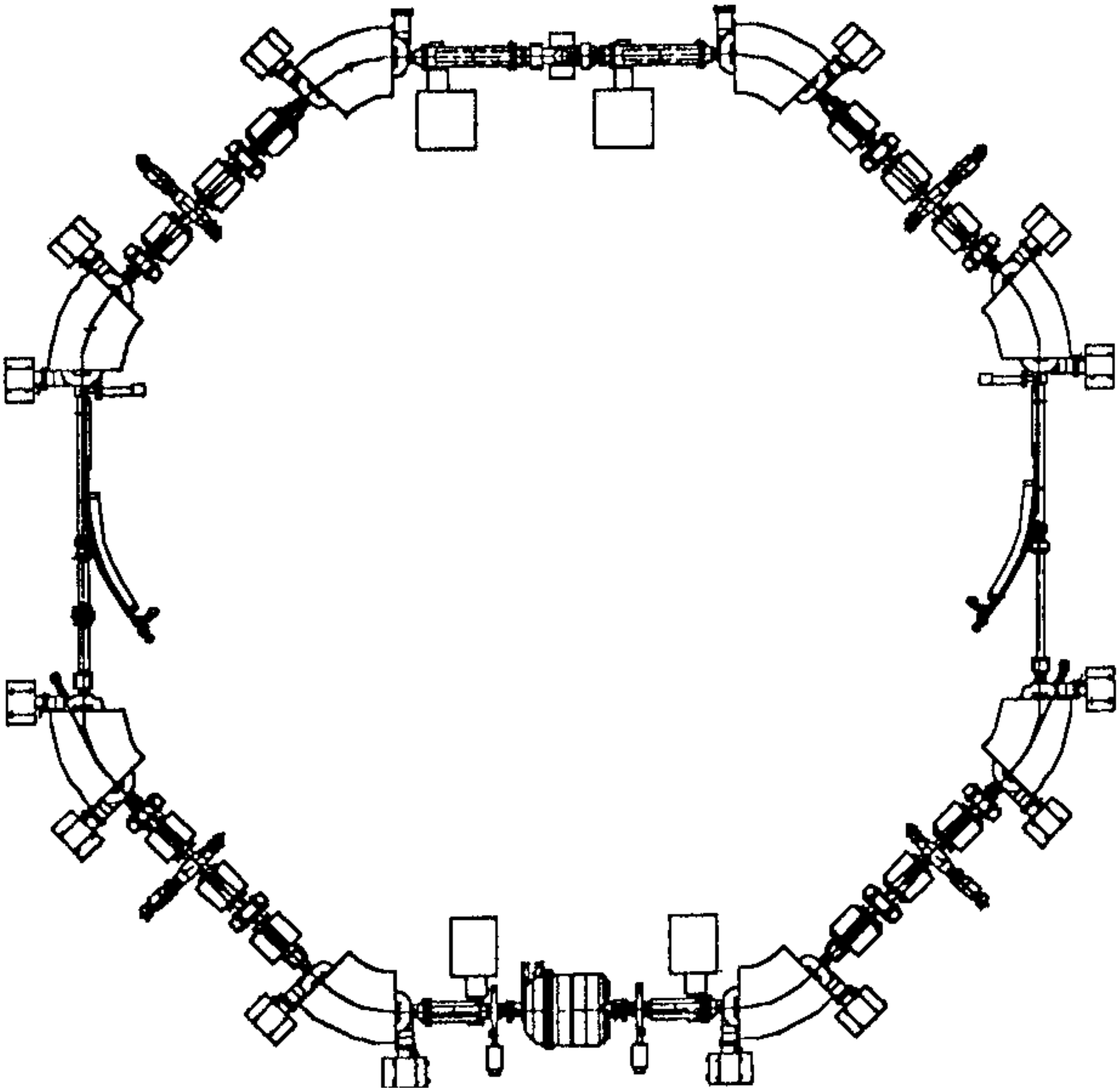

Fig. 1 - Layout of the DAΦNE accumulator ring.

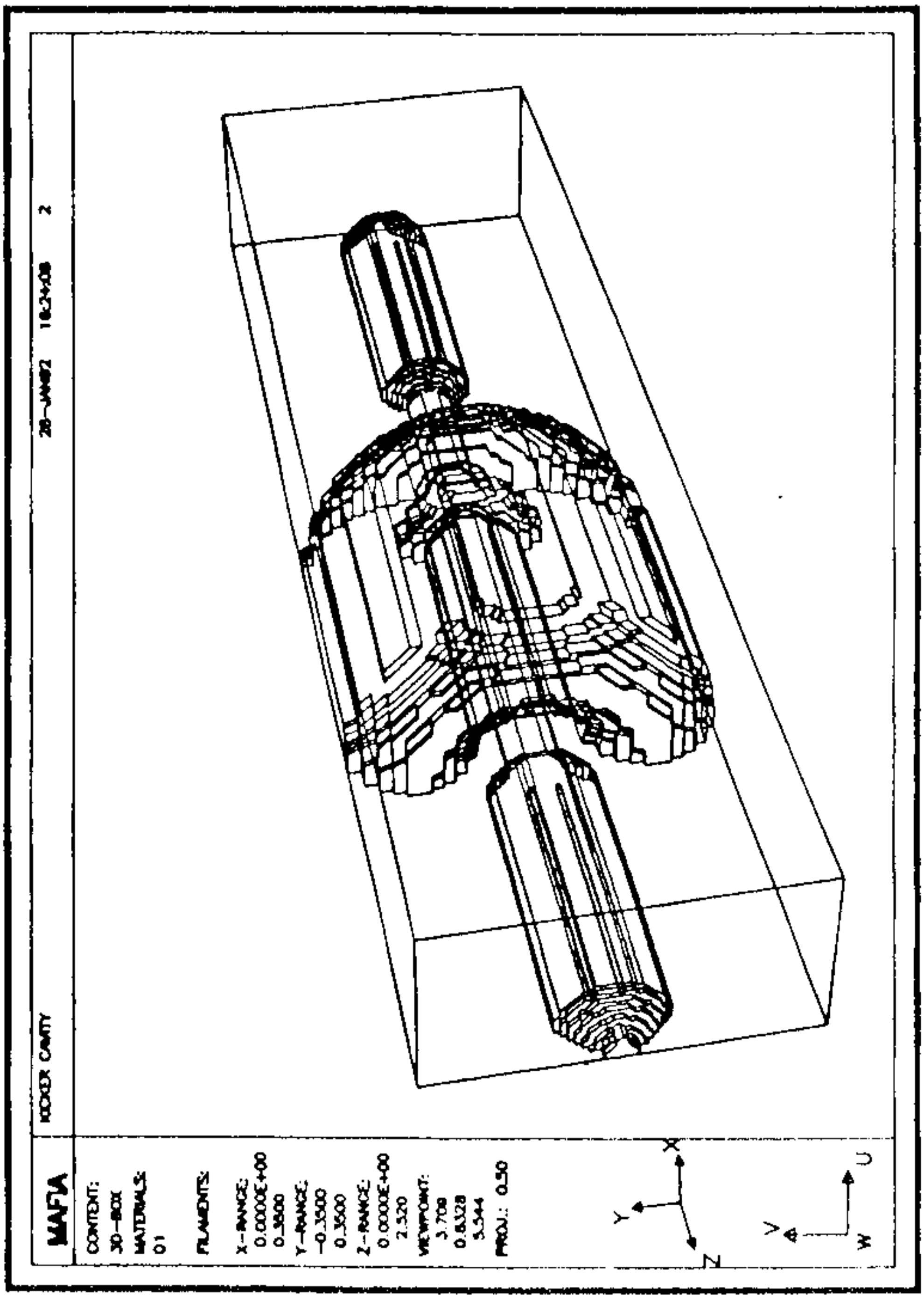

Fig. 2 - Straight section with 2 kickers and RF cavity (MAFIA code input).

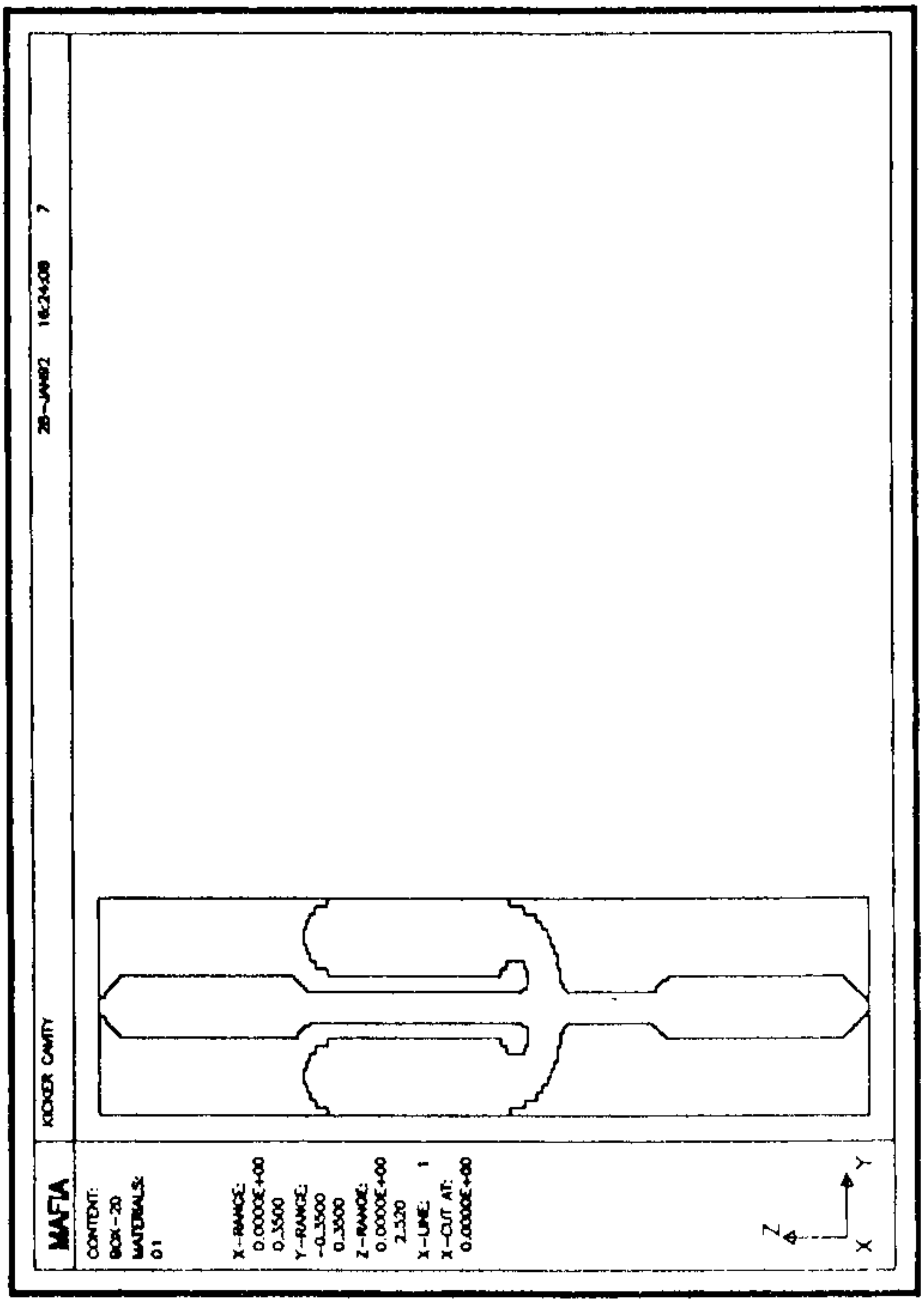

Fig. 3 - Cut along the longitudinal axis of the straight section with 2 kickers and RF cavity (MAFIA code input).

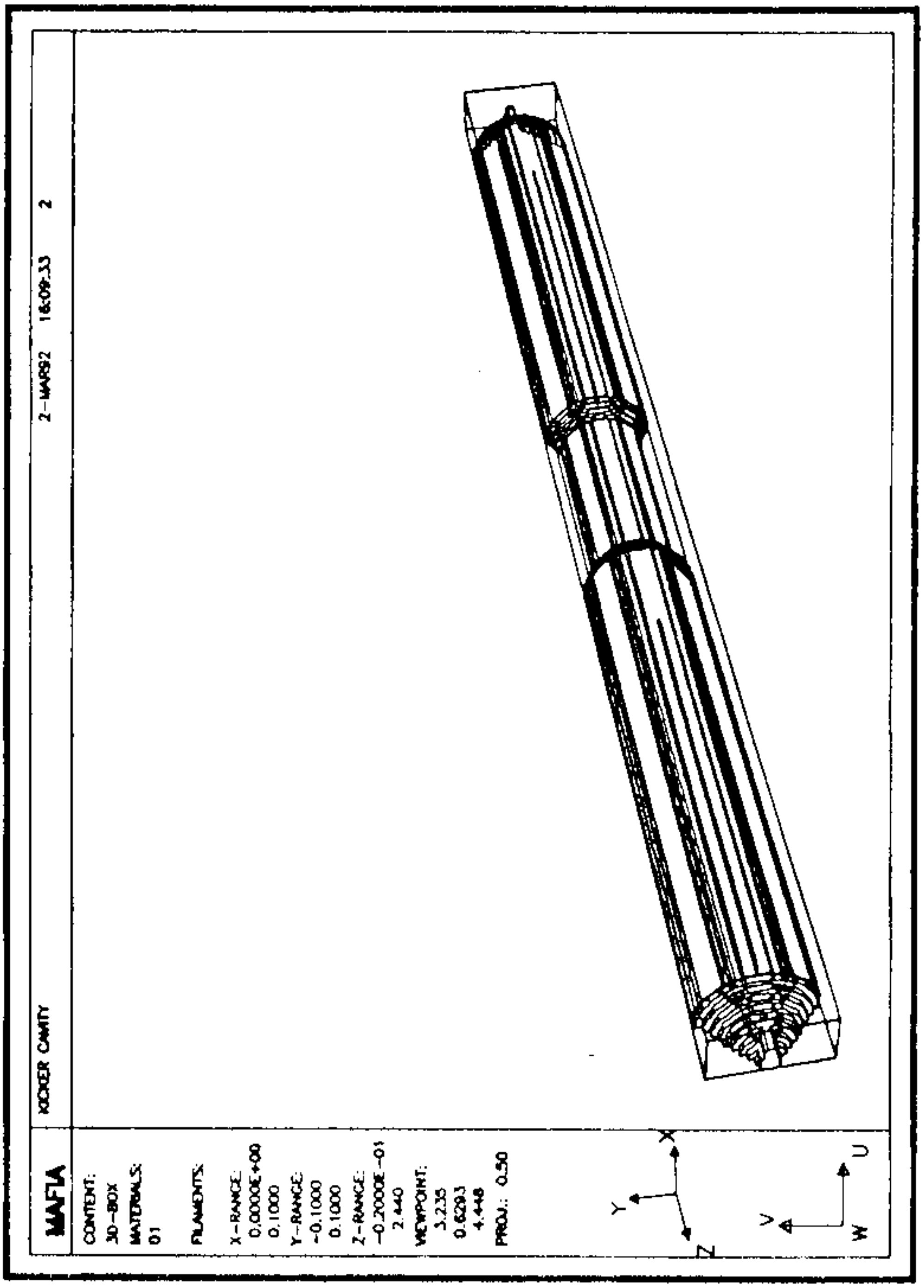

Fig. 4 - Straight section with 2 kickers (MAFIA code input).

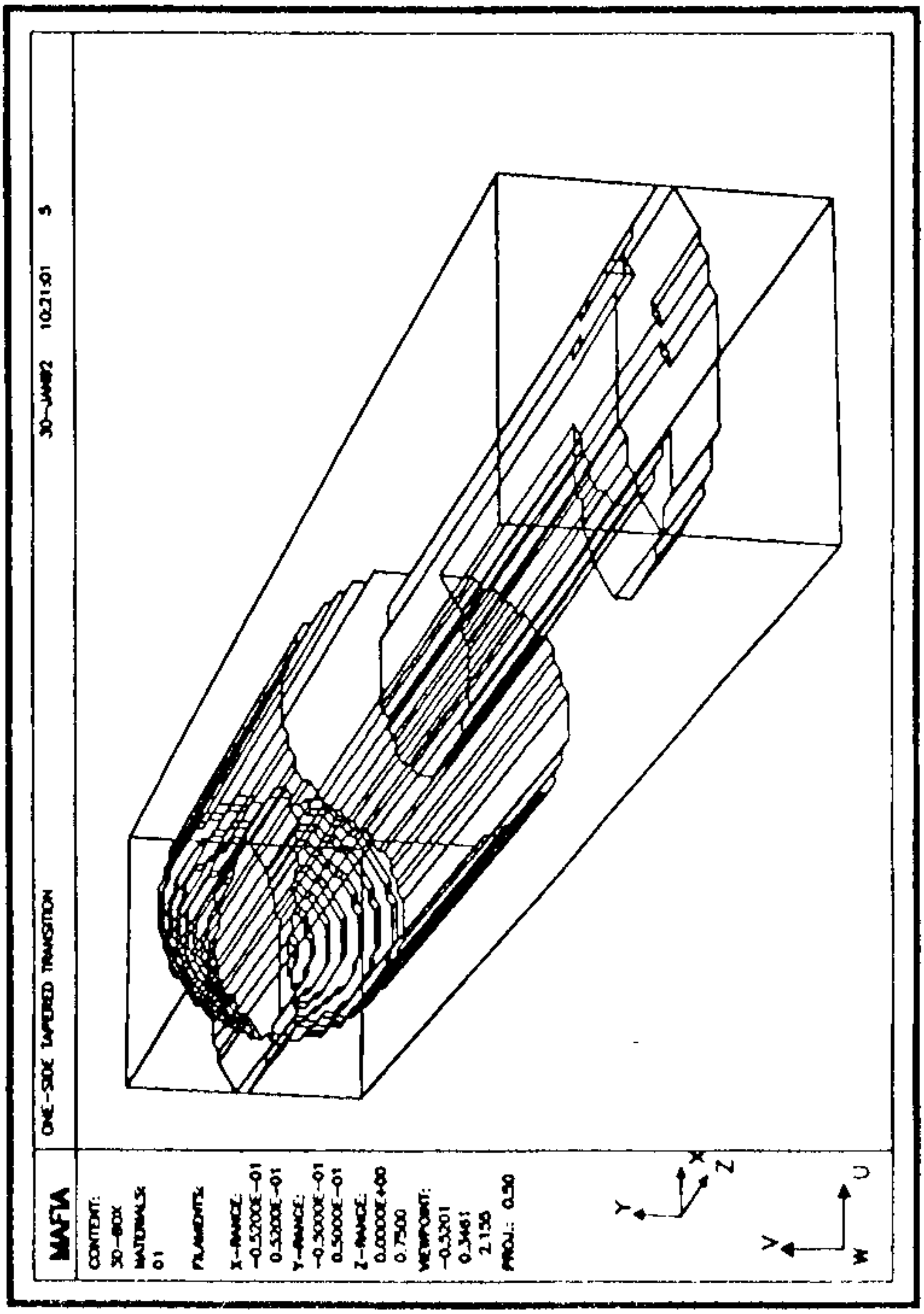

Fig. 5 - Vacuum chamber of the injection straight section (MAFIA code input).

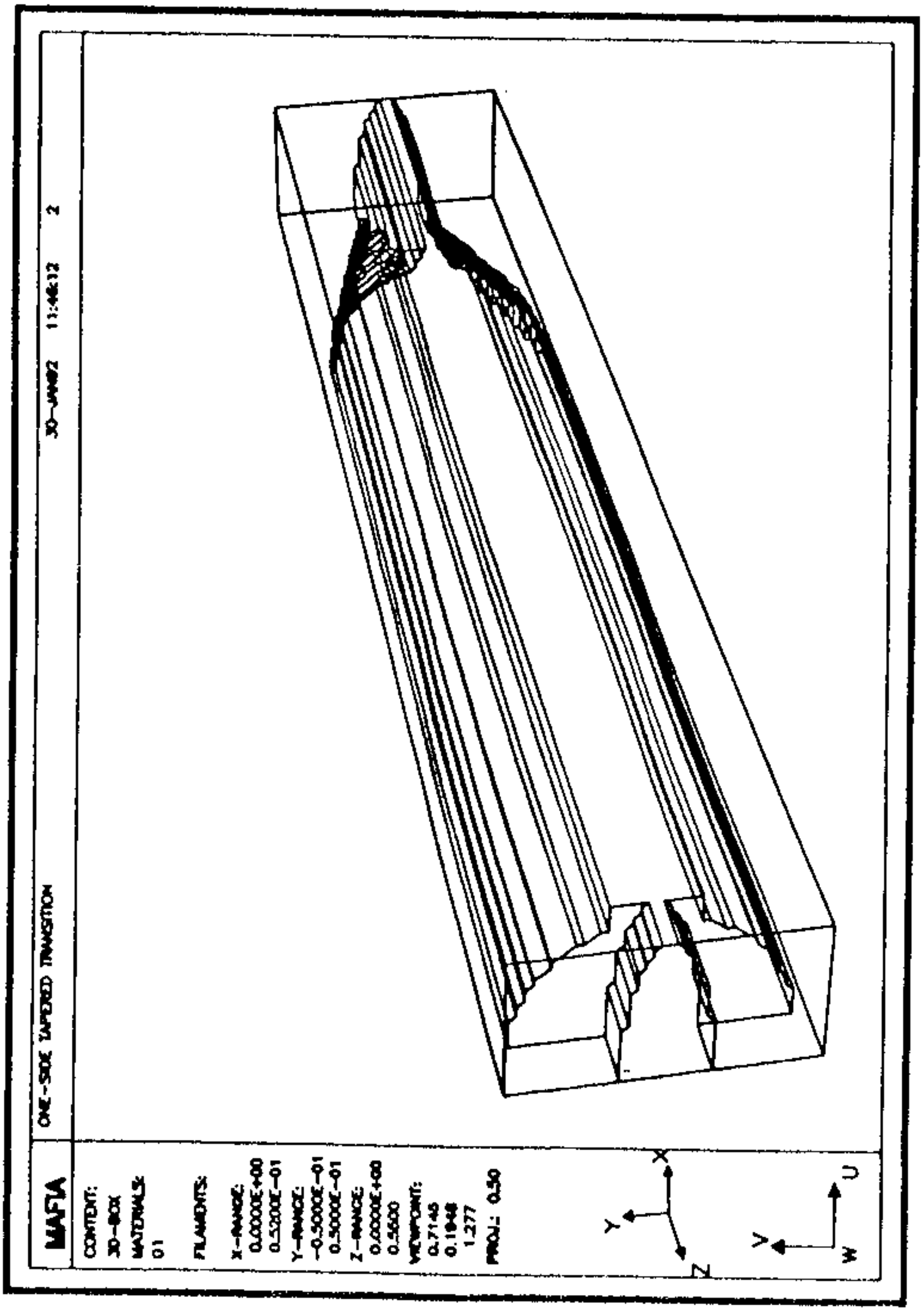

Fig. 6 - Vacuum chamber of the straight section with quads and sextupoles (MAFIA code input)

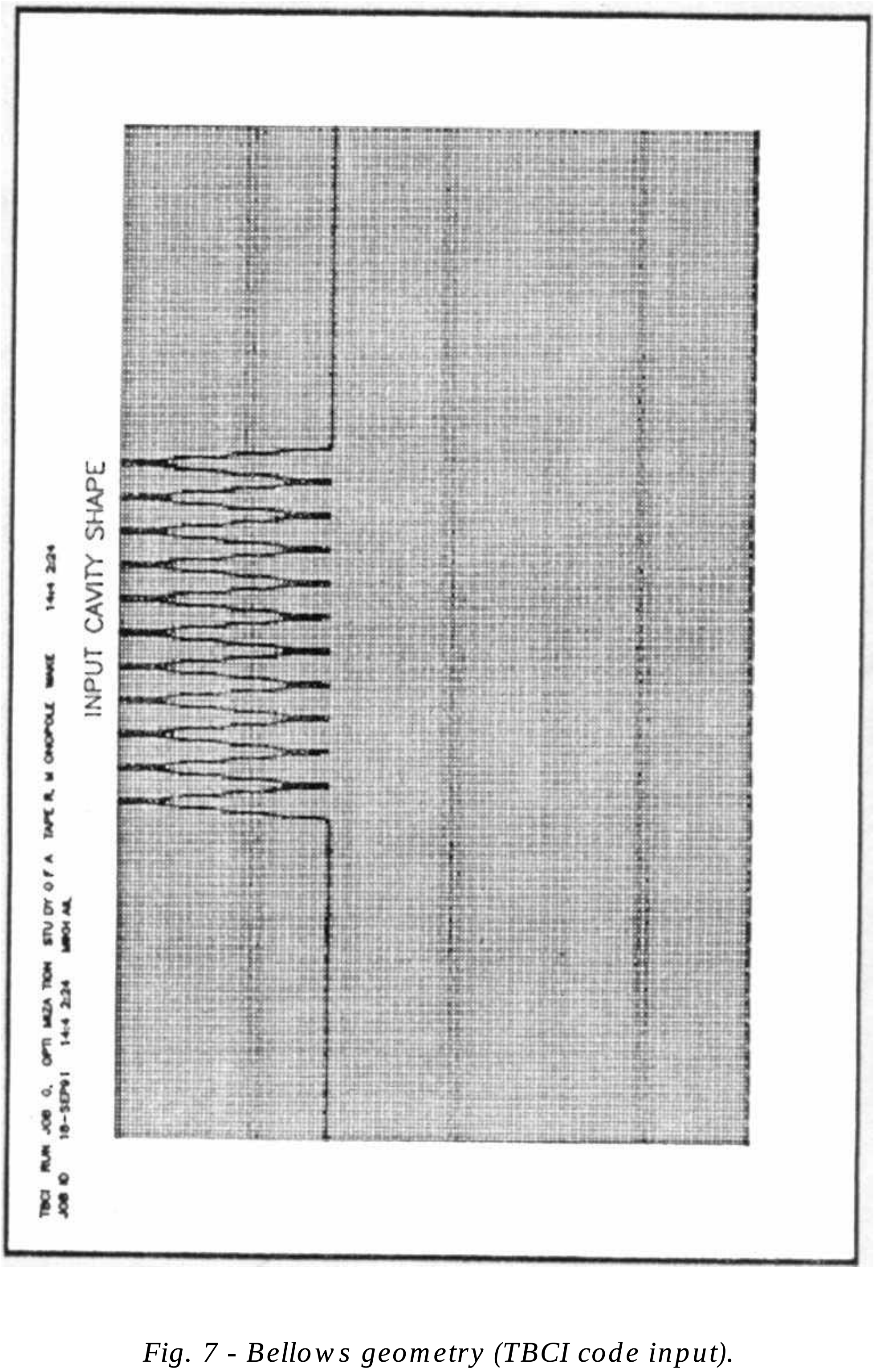

Fig. 7 - Bellows geometry (TBCI code input).

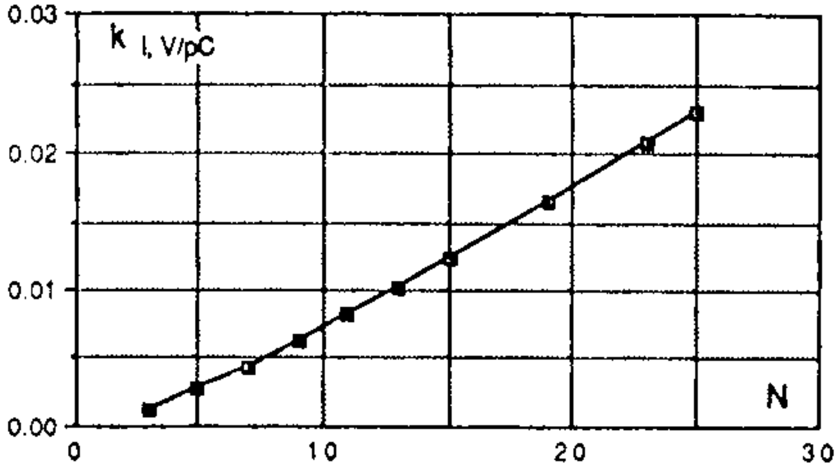

Fig. 8 - Dependence of the loss factor on the number of bellows convolutions.

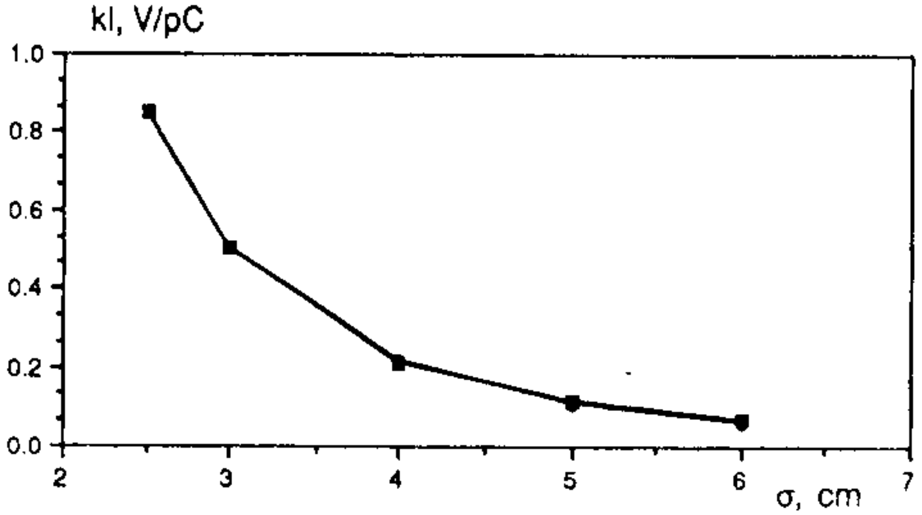

Fig. 9 - Broad-band resonator model fit: Z/n = 4.135 Ohm; Q = 0.82;
$\omega_z/2\pi$ = 4.14 GHz
(numerical and analytical dependences coincide)