THE PANDA INSERTION IMPEDANCE IN HIGH ENERGY STORAGE RING OF FAIR

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Abstract

The PANDA detector [1] insertion creates a discontinuity due to the special shape of the vacuum pipe and two perpendicular shoot-pipes. This was expected to be the main contribution for impedances of the vacuum chamber, besides kicker and pickup. In this paper we present the results of computations dealing with this problem.

MAFIA METHOD OF THE IMPEDANCE CALCULATION

The high energy storage ring (HESR) is dedicated to the field of high energy antiproton physics. It has two arcs and two straight sections [2]. The PANDA experiment is supposed to be in one of the straight sections. Figure 1 shows the cross section of PANDA vacuum pipe.

First we solve the axial-symmetric problem and then add two perpendicular shoot-pipes to investigate their influence on the total impedance.

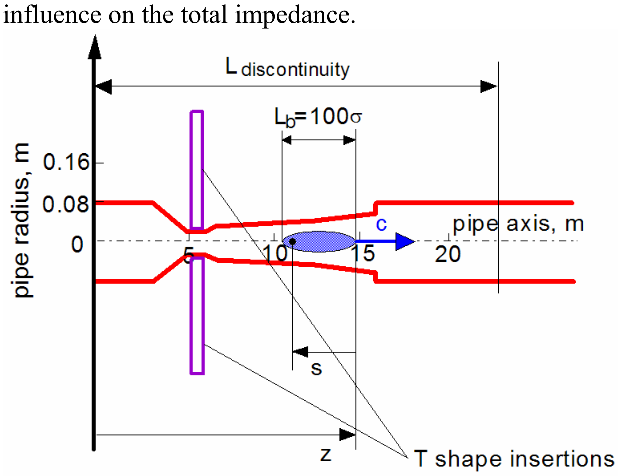

Figure 1: The longitudinal cross-section of PANDA.

Longitudinal Wake field

MAFIA [3] calculates the wake field irradiated by model particles in the bunch. It solves the Maxwell equations using the method of finite elements. The bunch distribution is approximated by the one dimensional Gaussian distribution with N model particles and the line longitudinal density $\rho=\rho_{peak}\exp\left[-(s-s_{center})^2/2\sigma^2\right]$, where ρ_{peak} is the maximum density in the bunch centre with the distribution dispersion σ. MAFIA determines the wake field in the time domain form (function of time τ) induced by all model particles in the bunch. For some number of "probe" particles with coordinate s counted off from the head of bunch (see figure 1) the wake field $E_i(z,s,\tau)$ moving together with these particles is calculated. Then the wake field $E\left(z,s,\frac{z}{c}\right)$ is integrated over the length of discontinuity and the longitudinal potential is calculated for each "probe particle" versus the distance s:

$$U_L(s)=\int_0^{discontinuity} E(z,s)dz \qquad (1)$$

The length of discontinuity is determined as the minimum length, when the calculated results of the wake field remain to be unchanged. The wake function is the normalized wake potential on the unit charge [4]:

$$W_L(s)=\frac{U_L(s)}{Q} \qquad (2)$$

It can be submitted through the Fourier integral

$$W_L(s)=\frac{1}{2\pi}\int_{-\infty}^{\infty} Z_L(\omega)\cdot\rho(\omega)\cdot e^{-i\omega\frac{s}{c}}d\omega, \qquad (3)$$

where the Fourier transform of the bunch density is

$$\rho(\omega)=\int_{-L_b/2}^{L_b/2}\rho_{peak}\cdot e^{-\frac{s^2}{2\sigma^2}}\cdot e^{i\omega s}ds=\rho_{peak}\cdot e^{-\frac{\omega^2\sigma^2}{2c^2}} \qquad (4)$$

Knowing the wake function from MAFIA calculation, we find the impedance $Z(\omega_n)$ for all frequency spectrum $\omega_n=n\cdot\omega_0$ in the frequency domain representation:

$$\frac{Z_L(\omega_n)}{n}=\frac{\int_{-L_b/2}^{L_{discontinuity}} W_L(s)e^{i\omega_n s}ds}{\rho(\omega_n)\cdot n}, \qquad (5)$$

where ω_0 is the revolution frequency.

All above expressions are for the axial beam location. In the common case the multi-pole expansion with the distance r and angle ϕ deviations of the beam is

$$Z_L(r,\phi,\omega_n)=\sum_{m=0}^{\infty} Z_{L,m}(r,\omega_n)\cos(m\phi), \qquad (6)$$

and in ultra relativistic case is:

$$Z_{L,m}(r,\omega_n)=r^{2m}\hat{Z}_{L,m}(\omega_n) \qquad (7)$$

The first term with m=0 is called the monopole term, and it gives the main contribution in the longitudinal wake field. The second term is called the dipole wake field. It does not make significant contribution in the longitudinal impedance, but its variation determines the transverse wake field.

Transverse Wake field

The transverse wake potential produced by the r axis-off deviation of the bunch in the transverse direction is:

$$W_T(r,s) = \frac{1}{q}\int_{-\infty}^{\infty} w_T(r, s-\hat{s}) i_b(\hat{s}) d\hat{s}\,, \tag{8}$$

where $i_b(s)$ is the bunch current, q is the total charge of the bunch, and the normalized value

$$w_T(r,s) = \frac{\int_{-\infty}^{\infty} F_\perp(r,\hat{s}) d\hat{s}}{q} \tag{9}$$

is the transverse kick per unit of charge. From the Panofsky-Wenzel theorem we find the relation between the transverse and the longitudinal impedances:

$$Z_T(r,\omega_n) = \frac{c}{\omega_n} Z_{L,1}(\omega_n) r \tag{10}$$

The Bunch Simulation

In HESR the bunch length is about 200 m. But since the wake field is calculated for the given value of the bunch length $L_b = 10\sigma$, the frequency range of the model validity is limited by the range of the bunch spectrum. Thus, the model parameters are independent on the bunch length only in the finite range of dispersion σ. For instance, if the bunch length is L_b=10σ=200m the frequency roll-off (the frequency in the bunch spectrum with the spectrum intensity equal 10% of maximum) for the bunch length 200 m is 2 MHz. Therefore we take the bunch length as minimum as possible, which one would cover the frequency region up to the cut-off frequency of the PANDA straight section $f_{\text{cut off}} = \dfrac{c}{2\pi r_{\min}} \approx 4.8$ GHz. Simultaneously, the bunch length has to satisfy to MAFIA requirements for the calculation accuracy (~4-10 mesh per bunch dispersion). Taking into account all these factors, it is reasonable to take the bunch length L_b=10 cm.

MAIN RESULTS OF PANDA STRAIGHT SECTION IMPEDANCE

The Mafia and ABCI Calculation

For reliability together with MAFIA we used the code Azimithal Beam Cavity Interaction (ABCI) [5]. ABCI solves the Maxwell equation directly in time domain when the bunched beam goes an axial symmetric cavity on or off axis. An arbitrary charge distribution can be defined in the code by the user.

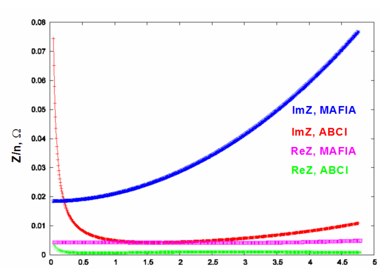

Figure 2: The PANDA insertion longitudinal impedance.

For the criteria of instability the normalized impedance $\dfrac{Z(\omega)}{n}$ is used. Figure 2 shows both parts of the longitudinal impedance. The imaginary part at frequency ~2GHz is $\mathrm{Im}Z_L/n \approx i$ 0.03 (MAFIA) and $\approx i$ 0.005 (ABCI). The real part in both calculations is smaller. Figure 3 shows the results of the transverse impedance imaginary and real parts at the same frequency: $\mathrm{Im}Z_T \approx i$ 7 kΩ/m (MAFIA) and $\approx i$ 3 kΩ/m (ABCI).

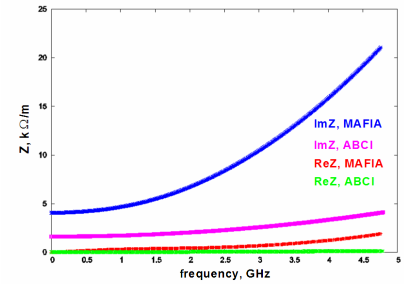

Figure 3: The PANDA insertion transverse impedance.

Yokoya's Formula Estimation of the Impedance

You can see that MAFIA and ABCI give the different results. For comparison we use Yokoya`s formula [6], which works well for soft tapering:

$$Z_L(\omega) = \frac{i\omega Z_0}{4\pi c}\int_{-\infty}^{\infty} dz \left(b'(z)\right)^2\,, \tag{11}$$

where Z_0 = 377 Ohm, b' is the taper slope. Using the HESR parameters and exchanging the integral by the sum, we get:

$$\frac{Z_L(\omega)}{n} = -i\frac{Z_0}{2L_{orb}}\sum_i (b_i')^2 l_i\,, \tag{12}$$

where L_{orb}=574m. From (11) and (12) the impedance value is $Z_L(\omega)/n = i\,0.012$ Ω, which is some average between MAFIA and ABCI results.

The transverse impedance is estimated by the formula [6]:

$$Z_T(\omega) = i\frac{Z_0}{2\pi}\int_{-\infty}^{\infty} dz \left(\frac{b'(z)}{b(z)}\right)^2 \tag{13}$$

Using the HESR parameters, we get the transverse impedance value ~i 2.5 kΩ/m of the PANDA straight section, which is very close to ABCI results.

THE T-SHAPE INSERTION IN PANDA STRAIGHT SECTION

Longitudinal Impedance

In the PANDA straight section there is the T-shape insertion (see figure 1), which gives the contribution into the total longitudinal and transverse impedances.

Only the MAFIA code solves the 3D problem wake field, but the accuracy depends on the object geometry complexity. We assumed the PANDA beam pipe radius is varying from 7.5 cm to 1cm and the tube inserted in the beam pipe has 3 mm radius. To simplify the T-shape insertion and increase the mesh number we have cut the tubes on the distance of 3-4 diameters. Then, since the MAFIA accepts two open ends only, we artificially have closed the vertical tubes.

Figure 4 shows the longitudinal impedance dependence on the frequency. We can see that the normalized longitudinal impedance has very low value for both components.

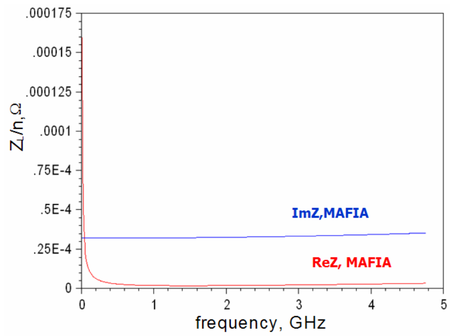

Figure 4: Longitudinal impedance of T-insertion (MAFIA).

Since the numerical calculation has been done with the above mentioned assumptions, we tested these results using of the theoretical formalism of the Bethe diffraction theory [7]. In this theory the hole is considered as the discontinuity of surface current and causes the irradiation in the hole. This theory works under assumption: the discontinuity typical size (radius a) is small in comparison with the chamber cross-section and the critical wave length, $a << \lambda_{cut}$ (λ_{cut} is the "cut off" wave length in the beam pipe). In our case the diffraction theory can be used for the frequency range ~0.6÷1.2 GHz.

Following the Bethe theory the irradiated field into the hole is shifted relative to the beam current by 90^0. Therefore the impedance has the inductive part only[8]:

$$Z_L(n)/n = iZ_0 \frac{a^3}{6\pi^2 b^2 R_{cir}}, \quad (14)$$

where b is the beam pipe radius and R_{cir} is the average radius of machine circumference. From (14) we can estimate the impedance for the PANDA case. It does not depend on the frequency, and it is similar to MAFIA results. But it gives ~70% higher value, which is very acceptable for the impedance calculation accuracy. Besides, MAFIA gives the real part as well, which is confirmed by the experimental measurements. The PANDA T-insertion has two vertical tubes, an upper and a lower one. Following the additivity law the later has the same contribution to the total impedance.

Transverse Impedance

Using the same approach, we have calculated the transverse impedance (see figure 5). Following to the same diffraction theory, we can estimate the transverse impedance using the formula [8]:

$$Z_T = iZ_0 \frac{2a^3}{3\pi^2 b^4} \quad (15)$$

In the PANDA case it equals ~0.07 kΩ/m, which has the same order of MAFIA results $Z_T \approx i$ 0.16 kΩ/m in the low frequency range. In the higher frequency the MAFIA gives the bigger impedance values. Besides, MAFIA produces both parts, the real and the imaginary, which more or less accords to the experimental measurement.

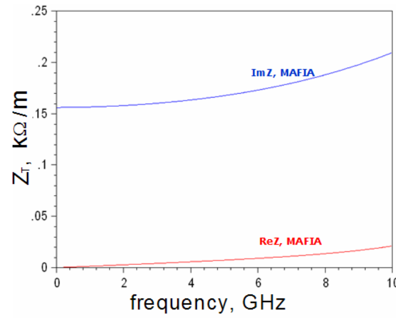

Figure 5: Transverse impedance of T-insertion (MAFIA).

CONCLUSION

We have investigated the impedance of the PANDA insertion. Table 1 shows the results obtained by the different methods.

Table 1: PANDA impedance

At frequency 2 GHz		MAFIA	ABCI	Theory
w/o T-insertion	Z_L/n, Ω	0.004 $+i$ 0.03	0.001 $+i$ 0.005	0.0 $+i$ 0.003
	Z_T,kΩ/m	0.5$+i$ 7	0.0$+i$ 3	0.0$+i$ 2.5
T-insertion	Z_L/n, Ω	(0.1$+i$3.2) $\cdot 10^{-5}$		(0$+i$ 1.9) $\cdot 10^{-5}$
	Z_T,kΩ/m	0.005$+i$0.16		0$+i$ 0.07

The T-insertions only contributed to the transverse impedance, but almost not to the longitudinal, since the fundamental component of the longitudinal wake field has axial symmetry.

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