DIPOLE KICK DUE TO GEOMETRY ASYMMETRIES IN HWR FOR PXIE*

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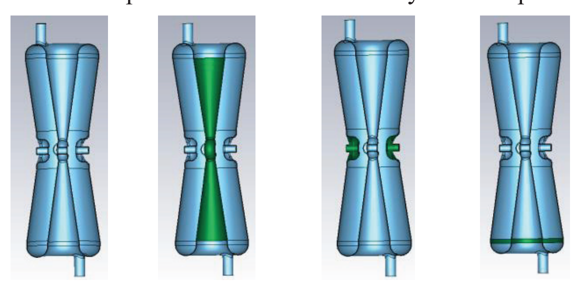
Abstract

Project X Injector Experiment (PXIE) will have a family of half wave resonators having frequency=162.5 MHz and beta optimal=0.11. During cavity production, when the niobium parts are assembled and welded together, it is fundamental to control the frequency of the accelerating mode in order to meet the specified operating value. For the HWR of PXIE the tuning will be achieved by trimming one end of the resonator only, this will introduce unwanted asymmetry in the cavity geometry leading to a dipole kick for the particles traveling through the cavity. The cavity geometry will be different from the ideal, once the cavity is assembled, because of small misalignment of the niobium parts and because of the welding shrinkage. Misalignments of the inner conductor and the beam pipes can be expected. The asymmetry due to tuning process along with production misalignments, have been simulated and the equivalent dipole kick has been calculated.

INTRODUCTION

PXIE is a CW linac to be built at FNAL, it consists of an ion source capable of delivering 5 mA (nominal) at 30 keV followed by a LEBT section, a 5 mA RFQ, a MEBT section with integrated wideband chopper. Two superconducting cryomodules are then used to accelerate the beam from 2.1 MeV, at the end of the MEBT, to 30 MeV [1]. The HWR cavities, designed and built by ANL [2][3], operating at 162.5 MHz and having optimal beta = 0.11, will bring the beam energy from 2.1 to approximately 10 MeV, and they will be placed before a section of spoke cavities SSR1 (frequency = 325 MHz and beta = 0.21). Spoke resonators are used for low and medium beta acceleration, since they have compact size at low frequency. Since coaxial resonators have an inner electrode which breaks the azimuthal symmetry, these structures show asymmetric transverse fields, even though the cavity shape is perfectly matching the ideal design [4][5]. For a real structure there will be some misalignment due to fabrication tolerances, weld shrinkage or, in some cases, the manufacturing process will require asymmetric trimming of the Nb parts. At FNAL one family of single spoke resonators has been built and tested and the transverse field perturbation due to geometry misalignments has been study and presented in [6]. The HWR for PXIE manufacture requires an asymmetric trim of one end of the cavity, in order to match the resonance frequency of the whole structure. As a result, one could expect to have cavities with up to 3 mm (worst case) asymmetry in the half-length: distance from beam tube to top or bottom of the resonator.

In this paper a study of the effects of geometry misalignments on the HWR transverse fields is presented. The Y-Z cross-section of the cavity is shown in Fig. 1(a). Different kinds of perturbation have been taken into account: displacements of the inner electrode, highlighted in Fig. 1(b), misalignments of the beam tubes, shown in Fig. 1(c), the asymmetry due to one end trim for final frequency match, the area to be trimmed is shown in Fig 1(d). The calculation of the transverse momentum gain has been carried out by direct integration of the transverse field components and by Panofsky-Wenzel's theorem. In addition the radial component of the transverse momentum gain has been expanded into multipoles to see what kind of perturbation to the beam dynamic is present.



(a) (b) (c) (d)

Figure 1: HWR geometry Y-Z section (a), inner electrode highlighted (b), beam tubes highlight (c), area of asymmetric trimming shown in green (d).

HWR GEOMETRY MISALIGNEMENTS

The RF fields have been simulated with Comsol Multiphysics, which allows local mesh refinement on lines, surfaces and domains. This feature is crucial in order to get precise values of the field amplitudes for geometry misalignments of the order of 1 mm. The displacements induce electric and magnetic transverse fields on the Z axis: a displacement along X perturbs Ex and Hy fields, while a modification along Y axis affects Ey and Hx. For example the transverse fields on Z axis for X and Y misalignments of the electrode are plotted in Fig. 2. The transverse momentum gain induced on the particles traveling on axis can be calculated by integration of the fields:

$$\Delta \boldsymbol{P}_{\perp} c = \int_{z_i}^{z_f} (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \frac{1}{\beta} e^{i\frac{kz}{\beta}} dz \qquad (1)$$

Panofsky-Wenzel's theorem gives an alternative formula:

$$\Delta \mathbf{P}_{\perp} c = \frac{i}{k} \int_{z_i}^{z_f} \nabla_{\perp} E_z \, e^{i\frac{kz}{\beta}} dz \,. \qquad (2)$$

When the inner electrode, Fig. 1(b), is displaced with respect to its ideal position the electric field on axis shows

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even amplitude, while the magnetic shows an odd profile. The transverse fields in case of 1 mm displacement of the inner conductor along X axis are shown in Fig. 2(a) and 2(b), for a displacement along Y axis the field amplitudes are reported in Fig. 2(c) and 2(d).

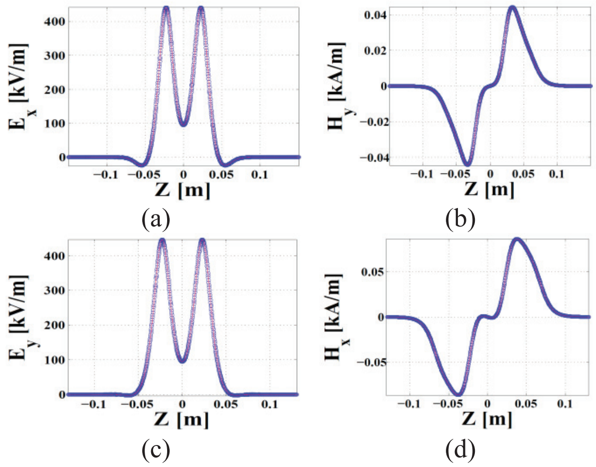

Figure 2: Transverse fields on axis for inner conductor displacement along X, (a) and (b), and Y (c) and (d).

The kick given by these fields is shifted by 90 degrees in phase with respect to the synchronous condition for acceleration. It has a sine shape having the amplitude calculated in (1) or (2), only part of $\Delta p_{\perp}c$ will be transferred to the particles, depending on the RF phase used in the linac.

Inner Conductor X and Y Displacements

Fig. 1(b) shows in green the electrode of the HWR that has been displaced of 1 mm in X and Y directions. Calculating the kick for just the optimal beta can be reductive; integrating the fields over the whole beta range for the HWR section of PXIE gives more general results. Fig. 3 reports the values of $\Delta p_{\perp}c$ calculated by direct integration and using Panofsky-Wenzel's theorem for particle energy ranging from 2.1 to 10 MeV.

A multipolar expansion of $\Delta p_r c$ has been performed:

$$\Delta p_r c(r,\varphi)= A_0 r + \sum_{n=1}^{\infty} A_n r^{n-1}\cos(n\varphi) + B_n r^{n-1}\sin(n\varphi) \quad (4)$$

The coefficients $A_n r^{n-1}$ and $B_n r^{n-1}$ are reported in table 1, cosine coefficients are associated with X asymmetries while sine coefficients with Y. Comparing the values of the ideal geometry with those calculated for the displaced inner electrode, one realizes that a small dipole perturbation arises. It is possible to introduce another parameter to assess the intensity of the dipole perturbation: $\alpha = \Delta p_{\perp}c/p_z c$ it is the ratio between the particle transverse momentum gain and the total momentum along the Z axis, which can be expressed in radians. In order to have a more accurate estimation of the transverse kick experienced by a particle traveling in the linac, one should take into account the RF phase and the amplitude used in each cavity. In Fig. 4(a) and 4(b) the angle α has been plotted for the whole HWR cryomodule, taking into account the RF phase of each cavity in the lattice but assuming maximum gradient for all the eight cavities. This can be considered as the upper bound for the dipole kick which will never happen during operation of the linac.

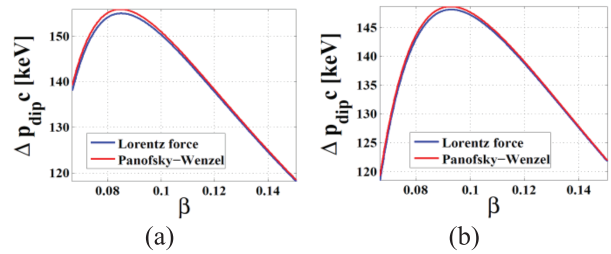

Figure 3: Transverse kick vs beta, (a) X and (b) Y electrode displacement.

Table 1: Multipoles coefficients of $\boldsymbol{\Delta p_{\perp}c}$ for inner electrode displacements, calculated at 10mm radius and for β=0.11.

Multipoles [keV]	Designed HWR	1 mm X spoke	1 mm Y spoke
n=1 dipole	8.22E-04	149.46	148.786
n=2 quadrupole	14.295	12.935	12.448
n=3 sextupole	8.22E-04	0.192	0.228
n=4 octupole	0.649	0.056	0.152

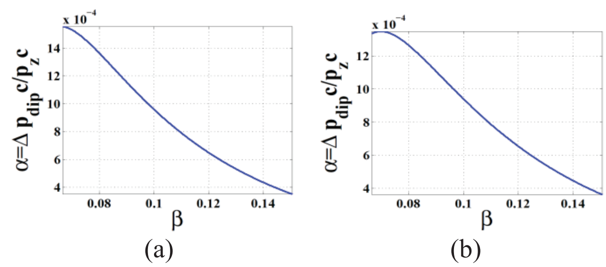

Figure 4: $\boldsymbol{\alpha}$ vs particle beta for HWR inner electrode displacement in X (a) and Y (b) axis.

The maximum of α due to misalignment of the inner post is well below 1 mrad, making its correction very easily achievable given the strength of the correctors of PXIE solenoids [7].

Beam Tubes Misalignments

In Fig. 1(c) the beam pipe area has been highlighted in green, the transverse fields on axis have been plot in Fig. 5 for both X and Y 1mm displacements. A displacement of the beam tubes induces higher perturbation on the electric field than on the magnetic, like a displacement of the central electrode. Table 2 compares the multipoles expansion of $\Delta p_{\perp}c$ of the perfectly built HWR and the cavity having the beam pipes displaced, again a small dipole is present. Fig. 6(a) and 6(b) show the dependence of dipole kick versus beta for the whole energy range in PXIE, $\Delta p_{\perp}c$ tends to be higher for low beta and then it drops sharply. Both the plots in Fig. 6 consider maximum gradient and 90 degrees synchronous phase, so maximum $\Delta p_{\perp}c$ value, which will never occur in the linac: the first two cavities of the cryomodule have very low gradient, to allow lattice matching. So one could expect to have

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values of $\Delta p_{\perp}c$ in the first part of the curve, as low as half of what is reported here.

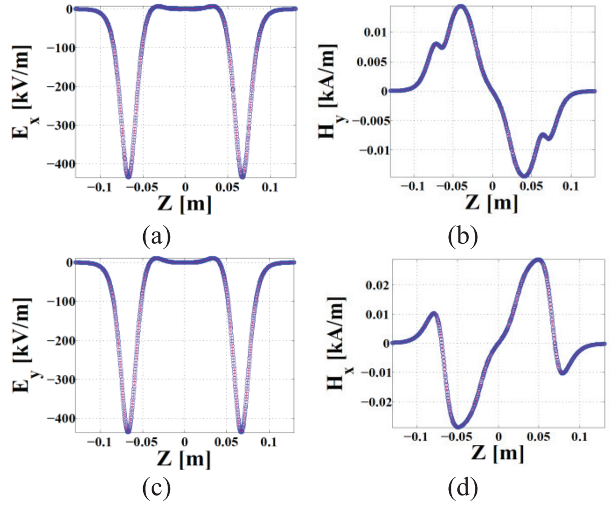

Figure 5: Transverse fields on axis due to beam pipe displacements (a) and (b) 1 mm X, (c) and (d) 1 mm Y.

Table 2: Multipoles coefficients of $\Delta p_{\perp}c$ for beam tubes displacements, calculated at β=0.11 and 10 mm radius.

Multipoles [keV]	Designed HWR	1 mm X BP	1 mm Y BP
n=1 dipole	8.22E-04	97.562	98.304
n=2 quadrupole	14.295	12.803	12.437
n=3 sextupole	8.22E-04	0.301	0.125
n=4 octupole	0.649	0.087	0.126

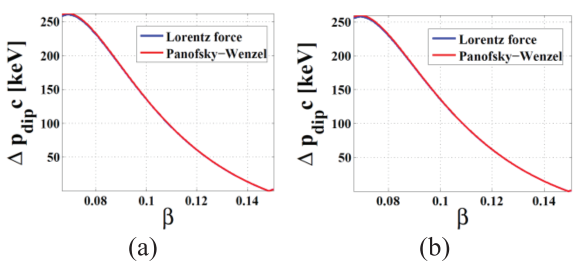

Figure 6: $\Delta p_{\perp}c$ vs β, Lorentz's force and Panofsky-Wenzel's calculation for beam pipes displacement X (a) and Y (b).

ASYMMETRIC TRIMMING

In order to match the goal frequency of 162.5 MHz for the cold cavity, the HWR requires to be trimmed before the final weld. This could lead to asymmetry will affect the half length of the cavity along the electrode axis: taking the beam pipe centre as reference, the distance to the bottom and the one to the top of the cavity could differ from up to 3 mm. Fig. 1(d) shows the area where the material is trimmed. Figure 7 shows the fields on axis due to a 3 mm trim of one cavity end, the amplitude of the electric field drops two orders of magnitude in comparison to the previous cases. The electric field shows some noise which is due to the very small amplitude of the perturbation on axis. The magnetic field is the only significant perturbation to the fields on axis; this is due to the fact that the geometry is trimmed where the electric field is very low while the magnetic has its maximum.

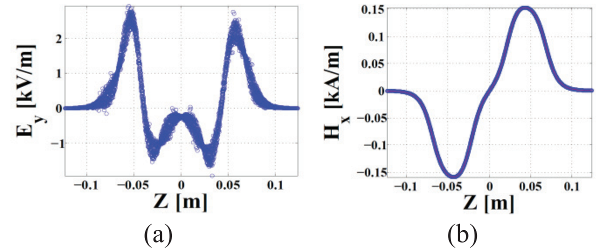

Figure 7: Electric (a) and magnetic (b) transverse fields on axis, due to asymmetric trim of the HWR.

The dipole kick on axis and the ratio $\alpha = \Delta p_{\perp}c/p_z c$ are plotted in Fig. 8 for the whole beta range. The values are considerably lower than for beam pipes or electrode misplacements. One could say that the asymmetry introduced by the trimming of one end of the cavity does not affect the beam significantly.

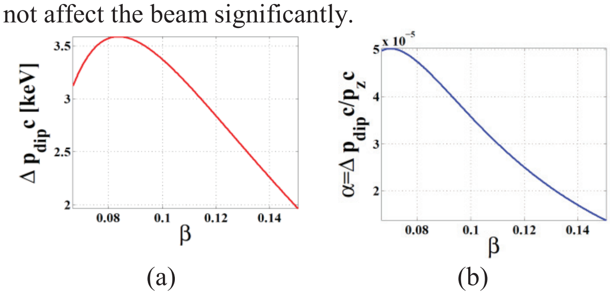

Figure 8: Dipole kick on axis (a) and $\Delta p_{\perp}c/p_z c$ (b) as function of beta for trimmed HWR.

CONCLUSIONS

The dipole field perturbation has been studied for the HWR of PXIE, different scenarios have been considered and none of them seems to be source of concern for the beam dynamic. Even the asymmetric trim of the cavity does not affect significantly the fields on axis. The correctors inside the solenoids will have separate leads for quadrupole and dipole corrections.

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