Design, construction and tuning of an RF deflecting cavity for the REGAE facility

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Abstract. Extraordinary emittance requirements in the nm range (normalized) and pulse lengths down to a level of ~10 fs for REGAE bunches demand both operation at low bunch charges on the sub-pC scale and a very careful beam handling. The S-band RF deflecting cavity is intended for diagnostics of the longitudinal bunch parameters. For the first time a deflecting structure, specially developed and optimized for bunch rotation has been realized for the REGAE RF deflector. The developed cavity provides a minimized level of aberrations in the distribution of the deflecting field combined with an improved RF efficiency. The main steps in the cavity design, construction and tuning are described.

1. Introduction

The scientific program of the Relativistic Electron Gun for Atomic Exploration (REGAE) facility [1] focuses on investigations of femtosecond electron diffraction with respect to the most venerable concepts in chemistry and biology. Extraordinary emittance requirements in the nm range (normalized) and pulse lengths down to a level of ~10 fs demand both operation at low bunch charges on the sub-pC scale and a very careful beam handling. The S-band RF deflecting cavity is designed for diagnostics of the longitudinal bunch parameters. For the first time a deflecting structure, specially developed and optimized for bunch rotation has been realized for the REGAE RF deflector. The developed cavity provides a minimized level of aberrations in the distribution of the deflecting field combined with an improved RF efficiency. The main steps in the cavity design, construction and tuning are described.

2. Optimized structures for bunch rotation

Initially introduced for deflection of charged particles, in modern applications the deflecting structures operate for rotations of bunches of charged particles. They are used for luminosity enhancement in circular colliders, beam lines for emittance exchange and longitudinal bunch diagnostics. In this case the deflecting structure is applied for transformation of particles distribution in a 6D phase space and
should provide as minimal own distortions, as possible. The concept of special deflecting structures with a minimized level of aberrations, preferable for distribution transformation, was presented in [2].

Analysis of electron bunch dynamics and distribution of a deflecting field was presented in [3,4], indicating non linear additions mostly caused by higher spatial harmonics in the periodical deflecting field as the main source of emittance deterioration. For structures optimization a parameter $\psi_{\text{max}}$ was proposed, [2], in the physical sense the maximal deviation of the phase of a deflecting field $E_d(r, \varphi, z)$ from the phase of a synchronous spatial harmonic

$$E_d(r, \varphi, z) = \tilde{E}_d(r, \varphi, z) e^{i\omega_0(t, \varphi, z)}$, $\psi_{\text{max}} = \max(|\psi_d(0,0,z) - \frac{\theta_0 z}{d}|), -\frac{d}{2} \leq z \leq \frac{d}{2}, \quad (1)$$

where $\tilde{E}_d(r, \varphi, z), \psi_d(r, \varphi, z)$ are the amplitude and the phase of deflecting field, correspondingly, $d$ is the structure period and $\theta_0$ is the operating phase advance, see [4] for details. For the end cells design the similar procedure with a zero rise in transverse momentum during bunch rotation was adopted, [5]. The leading idea in the developed procedures is to keep the central particle in the bunch near the structure axis and simultaneously decrease the level of higher spatial harmonics in the $E_d(r, \varphi, z)$ distribution. Guided by these ideas, deflecting structures with a minimized level of aberrations have been developed, [6]. For conventional deflecting structures the conditions of equation (1) are additional requirements and result in deterioration of other parameters, in particular RF efficiency. To maintain a high RF efficiency and combine it with a minimal level of aberrations a deflecting structure with separated control of parameters was proposed, [5].

3. Cavity design parameters

The structure with a separated control of the RF efficiency and the level of aberrations was investigated and optimized more thoroughly, [7], and one option was selected for realization. The cells of the accepted structure and a childlike face - distribution of the magnetic field between irises are shown in Figure 1a,b, respectively. The short cavity has three regular cells and two identical end cells, Figure 1c. In Figure 1d are shown distributions of a deflecting field along the structure axis for bunch deflection, $\phi = 0$, and bunch rotation, $\phi = 90$, see [4] for details. The main design parameters of the cavity are listed in Table 1.

| Parameter                        | Definition                  | Unit  | Value  |
|----------------------------------|-----------------------------|-------|--------|
| Operating frequency              | $f$                         | MHz   | 2997.925 |
| Operating phase advance          | $\theta_0$                  | radian | $\pi$ |
| Quality factor, calculated       | $Q$                         |       | 12550  |
| Maximal phase deviation          | $\psi_{\text{max}}$        | grad  | 1.8    |
| Effective shunt impedance, structure | $Z_e$                      | MΩ/m  | 43.2   |
| Effective shunt impedance, total cavity | $Z_et$                     | MΩ  | 7.58   |
| Maximal input RF power           | $V_d$                       | kW    | 5      |
| Maximal deflecting voltage       | $V_d$                       | kV    | 190    |
| Particles energy                 | $V_d$                       | MeV   | 5      |

Table 1. The main design parameters of the cavity.
3

Figure 1. (a) The cells of the deflecting structure, (b) magnetic field distributions between irises, (c) the model of the deflecting cavity, (d) deflecting field $E_d$ distribution along the axis for bunch deflection (blue curve) and bunch rotation (red curve).

4. Cavity technical design and manufacturing

As compared to a widely used deflecting structure, based on a disk loaded waveguide, the applied structure has more complicated, hence more difficult for processing, shape of cells. It is the price for better physical performances. The coupling coefficient $k_f = \frac{f_f^2 - f_0^2}{f_f^2 + f_0^2} \times 100\% = -5.04\%$ is not high, leading to a narrow passband with negative dispersion. But the cavity is rather short – the length from flange to flange is 270 mm and has only three regular cells and two end cells. On the operating dispersion curve there are only five modes and the separation in frequency with the nearest mode is 13.5 MHz. To simplify cells processing, we can specify reasonable tolerances for cells treatment. The procedure of tolerances estimations is described in [7]:

$$\sigma_E = 2\sigma_f \left( \frac{1}{N} \sum_{m=0}^{N} \left( \frac{f_m^2 - f_f^2}{f_m^2 + f_f^2} \right)^{1/2} \right), \quad \sigma_f = \frac{1}{f_f} \left( \sum_{n=1}^{N} \left( \frac{\partial f_x}{\partial X_{nd}} \right)^2 \sigma_{nd} \right)^{1/2},$$

Taking into account a more complicated shape of the cell, for this short cavity the tolerances for internal cell dimensions were specified as $\pm 20 \mu m$, resulting in the expected standard deviations of the cells frequency $\sigma_f \approx 700 kHz$ and the related standard deviation of the deflecting field distribution $\sigma_E \approx 1.8 \times 10^{-2}$.

Figure 2. (a) Aluminum test cells, (b) diagram of CMM measurements and (c) distribution of frequency sensitivity $\mu (\mu_0 H^2 - \omega_0 E^2)$.

To develop and test procedures of cells processing with Numerically Controlled (NC) hardware, the test cells, shown in Figure 2a, were produced and their dimensions were measured, Figure 2b. The measured dimensions of test cells appeared to lie within tolerances. The measured frequency of operating mode, normalized for air evacuated conditions, was 3001.9 MHz. To reduce extra positive reserve in frequency at $\pm 2 MHz$, the cells diameter was increased up to $0.11 \ mm$. For frequency tuning after cells brazing blind holes with central pins were introduced in the cavity design. The thread allows pins to be pushed and pulled, thus providing deformation of the cell surface and a related shift of the operating frequency in both directions.
Figure 3. (a) Cavity elements after manufacturing and (b) brazed cavity before RF tuning.

Regular cells of the cavity are produced of OFHC copper by using hard tools and NC hardware, showing a high quality of surface treatment, Figure 3a. The high temperature cavity brazing was done in a vacuum oven with silver alloys. The brazed cavity before RF tuning is shown in Figure 3b.

5. RF measurements and tuning

After cavity brazing the measured operating frequency, recalculated for vacuum conditions and temperature $T = 20^\circ C$, was estimated to be 3001.5 MHz, higher than expected. Dimensions correction made after test cells measurements give the calculated value of cell frequency as 2995.86 MHz. The reason for this big deviation is not completely clear yet. The most probable reason is the shape deviation due to residual stress relaxation during high temperature brazing, which is simultaneous annealing of forged copper.

Multiple repeated bead pull measurements of field distribution, after averaging the results, indicate a very similar distribution for $E_r$ values in the middle of four iris 100:100.08:100.04:99.86 – with a relative deviation from the average value $\approx 0.145\%$. Field values in the middle of iris are practically identical. It means very narrow spread in the own frequencies of the cells.

Figure 4. (a) assumed spherical surface deformations (b) with blind holes 1,2 on the cavity surface, (c) calculated for spherical deformation (blue curve) and estimated from measurements (red line) frequency shift and (d) – final pins positions after frequency tuning.

Each cell is equipped with four blind holes for frequency tuning, Figure 4b. Assuming a spherical shape for surface deformation, Figure 4a, the plot of the expected frequency shift is shown with blue curve in Figure 4c. The shape deformation was performed in two steps. The depth of pins extraction $dh$ was defined by the angle of external nuts, because the thread M8 has a pitch of 1.25 mm. All pins were extracted at the same depth. The treatment of the results showed more linear dependence of the frequency shift on the pin extraction, red curve in Figure 4c. Finally, with a sufficiently large depth...
of pins extraction \( dh = 2.1 \text{ mm} \), see Figure 4d, the frequency value of 2997.91 MHz was obtained assuming vacuum conditions and operating temperature \( T = 35 \text{ C} \). In the case of this surface deformation the vacuum tightness of the cavity is not violated.

The cavity will be powered from a solid state amplifier with a rather moderate RF power value of 5 kW. Coaxial cable as a transmission line is used with turning vacuum tight feed through. The cavity has RF driving and RF signal loops. To minimize self inductance, the RF driving loop has small dimensions and is produced with 3D printing technology. Preliminary measurements with driving RF loops showed a possibility of matching \( S_{11} \leq -30 \text{ dB} \). The value of the own quality factor is estimated to be \( \approx 80\% \) from value calculated in 3D approximation. The final measurements will be performed after plating the loop with a thin layer of gold and mounting the cavity at the beam line.

6. Summary
For the first time was realised the deflecting cavity specially optimized for minimal level of aberrations in the distributions of deflecting field. As compared to conventional deflecting structures, the cavity provides physical benefits in applications for transformation of particle distributions in the bunch. These cavity performances are requested in the facilities with unique bunch parameters. As the price for better physical performances this structure requires more attention during construction and RF tuning.

The experience acquired during construction and tuning of the first cavity is sure to help us replicating this deflecting structure with improved parameters.

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