DESIGN OF THE FLAT-TOP ACCELERATION CAVITY FOR THE LNS SUPERCONDUCTING CYCLOTRON

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Abstract

A 3rd harmonic Flat-top acceleration system for the K800 Superconducting Cyclotron of the Laboratori Nazionali del Sud (LNS) was designed to reduce the energy spread of the accelerated particles and to improve the beam quality and the extraction efficiency.

The Flat-top effect is realized by the superposition of the 3rd harmonic to the fundamental acceleration frequency. The 3rd harmonic frequency is produced by an additional resonator, capacitively coupled to the K 800 cavities. The Flat-top cavity was designed with the 3D electromagnetic codes Ansoft HFSS and CST MicroWaveStudio.

INTRODUCTION

The LNS K800 Superconducting Cyclotron (CS), is a compact three-sector accelerator. The cyclotron, in operation since 1995, delivers ions in the energy range 8÷80 AMeV. The acceleration is provided by three λ/2 coaxial resonators, with a maximum acceleration voltage of 100 kV [1]. The tuning of the cavities, between 15 and 48 MHz, is allowed by a sliding short system, about 3 meters long. The cyclotron is now used also to deliver a primary beam for the Excyt project, a facility for the production of radioactive nuclei [2]. The introduction of a Flat-top system modifies the shape of the acceleration voltage from sine to square wave, reduces the energy spread of the accelerated beam and improves the beam quality and the extraction efficiency in the perspective of delivering a 500 W beam power. A brief description of the system is here presented.

FLAT-TOP SYSTEM

According to the Fourier analysis, a square waveform shape is the result of the sum of all the odd harmonics of the fundamental frequency. The superposition of the main frequency with the 3rd or 5th harmonic, gives a more uniform acceleration voltage in a phase range of +/-30° around the phase of the reference particle [3].

If $V_0 = A_0 \sin(2\pi f_0 t)$ is the main resonance (f_0) acceleration voltage on the median plane and $V_n = \frac{A_0}{n^2}\sin(2\pi(nf_0)t)$ (n=3,5,7…) is the voltage of an odd n-harmonic frequency, the superposition of the fundamental and the harmonic n is:

$$V_{FLATTOP} = A_0 \sin(2\pi f_0 t) + \frac{A_0}{n^2} \sin(2\pi(nf_0)t)\,.$$

If n=3 the Flat-top voltage has the shape shown in Fig.1.

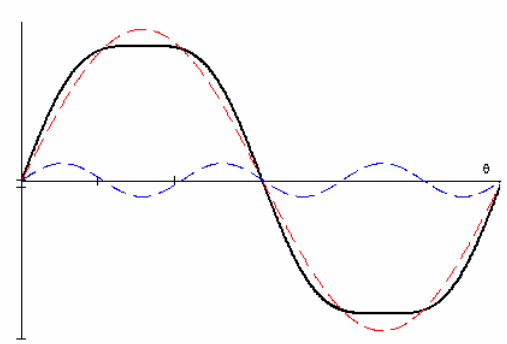

Figure 1: Main resonance (red line), 3rd harmonic (blue line) and flat acceleration voltage (black line).

As a general rule the result of the superposition between the fundamental frequency and a generic harmonic n f_0 produces a broader flattop region for lower harmonic number. On the other side the lower the harmonic mode, the higher the power dissipation, because the voltage amplitude is inversely proportional to the square of the harmonic number. According to the Fig.1 the energy gain for the particles inside a beam bunch with a length of about 10-20° will be uniform. The Fig. 2 shows the flattop voltage achieved adding a 3rd or a 5th harmonic to the fundamental frequency.

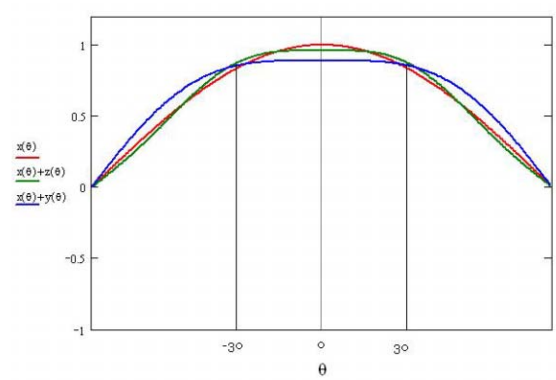

Figure 2: Not flat (red line), 3rd harmonic flat (blue line) and 5th harmonic (green line) acceleration voltage.

ELECTROMAGNETIC SIMULATIONS

The RF structures have been investigated with the 3D EM simulation codes CST MicroWave Studio[4] and Ansoft HFSS[5]. First of all the CS cavity was simulated to analyse its resonance modes and to evaluate its performances. The results of the simulation confirmed the λ/2 cavity behaviour in terms of electric and magnetic field distributions of the main mode and the higher modes

(3 λ/2, 5 λ/2…). Moreover further resonances identified as transverse resonance modes were found, see Fig. 3.

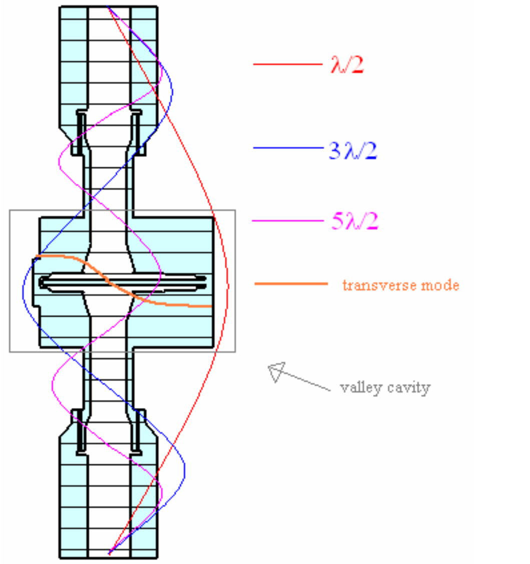

Figure 3: Electric field distribution of the main mode, the high harmonic resonances and transverse mode along a cross section of the cavity.

These further resonances occur ever at the same fixed frequencies (for example 98.0 MHz, 162.0 MHz, 220.0 MHz) and are not sensitive to the tuning change between 15÷48 MHz. So these frequencies are not related to the position of the sliding shorts of the cavities, but they are related to the geometry of the valley cavity, its shape and dimensions, which produces a transverse standing wave. The consequent modes are natural resonances of the cavity, which is confirmed by a simulation of the valley alone, without the coaxial structures. Due to the high frequency of these modes the usual operation of the cavity is not influenced, but a coupling between the transverse resonance mode and the 3rd or 5th harmonic of the fundamental (nλ/2) is possible. This coupling causes an energy transfer between these modes, thus in the frequency regions where transverse resonances are active it is not possible to generate a stable 3rd or 5th harmonic voltage to achieve a proper flat voltage distribution along the acceleration gap. A further effect related to the valley shape geometry is the electromagnetic distribution of the 3rd and 5th harmonic modes. The figure 4 shows the results of the simulations for three frequency regions. In the range 27.5÷30.0 MHz, the 3rd harmonic mode shows an electric field distribution on the median plane that allows to realize a flat-top effect at the extraction region. This frequency mode is a little higher than the right $3f_0$ value. In the range between 30.0 MHz and 33.5 MHz the 3rd harmonic mode is coupled to a transverse electric field, oscillating on the median plane, so the production of a flattop voltage is not possible. The values of the electric field at the injection and at the extraction are comparable but in opposite phase.

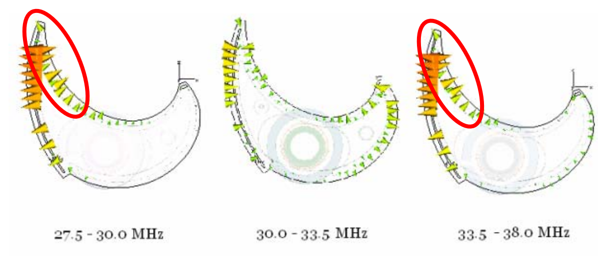

Figure 4: 3rd harmonic electric field distribution on the median plane for 3 frequency ranges. The red circled area is the region where the flat-top voltage is achieved.

A technical solution to overcome this problem, like a slotted Dee [6], has been studied without success. In the last range from 33.5 MHz to 38.0 MHz the transverse higher mode effect is attenuated. In this range it is always possible produce a Flat-top effect at the extraction region.

Unfortunately the 5th harmonic mode has an irregular distribution of the electric field on the median plane, for the whole frequency range due to the strong coupling with the transverse resonances, Fig. 5. So it is not allowed to use this mode to produce a flat-top effect.

Thus we analyzed a 3rd harmonic flat-top system only in the frequency range 27.5÷30.0 MHz and 33.5÷38.0 MHz. The figure 5 shows the resonance values of the 3rd and 5th resonant harmonic modes and of the transverse mode for the fundamental frequency range 22.0÷46.0 MHz.

DESIGN OF THE FLAT-TOP CAVITY

A λ/4 coaxial cavity with a plate has been chosen as Flat-top resonator. Only one additional cavity will be used to provide the flat-top effect for all the three CS resonators. The additional resonator will be installed inside an existing cylindrical hole in the top of the magnet which is connected with the valley of one RF Cavity. The RF cavity and the flat-top cavity are electrically connected by a capacitive coupling.

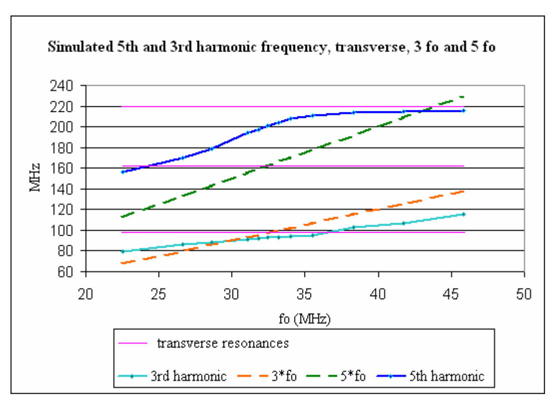

Figure 5: Simulated 3rd , 5th harmonic mode and transverse mode frequencies vs. frequency of the fundamental mode.

To tune the Flat-top cavity in all the frequency range, two different solutions have been investigated.

1^{st} Solution: Ffixed Plate, Sliding Short Circuit.

The first solution is a coaxial λ/4 cavity with a fixed distance plate from the median plane and a sliding short circuit system on the upper side of the cavity, as shown in Fig. 6. In this case the capacitance of the cavity is mainly due to the plate, while the inductance is adjustable by the sliding shorts. The geometrical main characteristics of the cavity are $\phi_{ext} = 90$ mm, $\phi_{int} = 24$ mm and the distance between the sliding short and the capacitive plate is in the range 587÷720 mm. The plate diameter and the distance from the dee are 180 and 100 mm respectively. This distance is enough to prevent electric discharges. The whole range of CS frequency is covered.

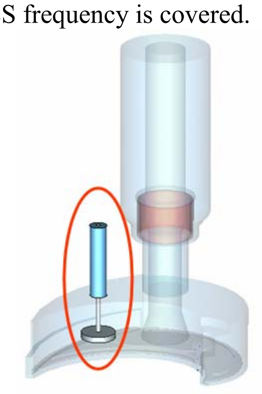

Figure 6: CS cavity and 1^{st} Flat-top cavity.

The additional cavity is used to reduce the 3^{rd} harmonic mode of the main cavity to the desired frequency value $3f_0$ in the frequency range 27.5÷30.0 MHz. While in the range 33.5÷38.0 MHz, we use the two cavities as one resonator where the frequency modes are the combination between the resonances of the original cavities. The positions of the sliding short of both the additional and the main cavity are used to find out the additional mode with the proper voltage distribution on the Dee and frequency $3f_0$.

To produce the Flattop effect a maximum voltage of 40 kV is required at the extraction region. To achieve this voltage value a RF power of 13 kW and a current density on the short circuit of 76 Amps/cm are required. The Q factor value is about 5000. The perturbation of the additional cavity on the main resonator is about 90.0 kHz at higher frequencies. It is easily adjustable with a slight retuning of the CS cavity. The Q factor and the main resonance acceleration voltage distribution do not change.

Unfortunately the high value of the current density on the sliding contacts makes this solution not reliable.

2^{nd} Solution: Variable Capacitance Plate

To avoid the previous problem a cavity with a fixed short circuit and a variable capacitance plate has been investigated. The tuning of this Flat-top cavity is allowed by a semicircular moveable plate system, as shown in Figure 7. The plate is composed by two symmetrical semicircular sections: one fixed, the other one rotating. The rotation from 0° to 180° of the moveable part allows to tune the capacitance of the Flat-top cavity.

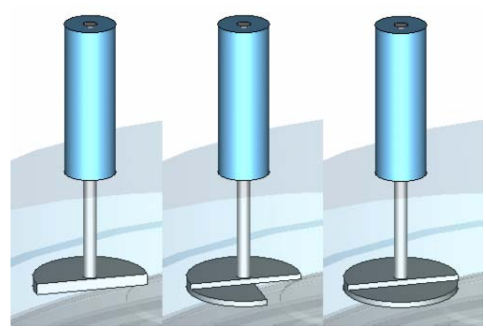

Figure 7: 2^{nd} Flat-top cavity on detail.

It is possible to obtain a frequency variation of the flat-top cavity up to 8 MHz with half plates of ϕ 200 mm and 100 mm far from the median plane. So we chose the parameters of this cavity to achieve a flat-top effect in the frequency range from 33.5 MHz to 36.2 MHz because this range allows us to accelerate the primary beams requested to operate of the EXCYT facility.

To achieve the maximum voltage of 40 kV for the frequency mode $3f_0$ a power of 7 kW is required. An inductive excitation coupler is under study.

CONCLUSIONS

A preliminary Flat-top cavity has been investigated and designed at LNS with the aid of 3D electromagnetic simulators. A λ/4 coaxial cavity with a variable capacitance plate has been chosen to realize a Flat-top effect in the CS frequency range 33.5÷36.2 MHz. Despite its short frequency range this technical improvement should produce an increasing of extraction efficiency just for the beams required for the EXCYT facility. We are planning to make this cavity in order to check the expected improvement on the beam. After these tests we shall decide to build a second cavity with a different operational frequency range. The new cavity can be installed in another valley so allowing to use one or the other cavity according to the working frequency.

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