A FLAT-TOP ACCELERATION SYSTEM FOR THE NAC LIGHT ION INJECTOR CYCLOTRON

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A 5th-harmonic flat-top system, which makes use of the main resonators and dees of the light ion-solid pole injector cyclotron (SPC1) of the NAC has been designed and installed to limit the energy spread acquired during acceleration. The system consists of additional amplifiers and transmission lines, operated near the fifth harmonic of the main rf frequency, and capacitively coupled to the main resonators. Interference between the two rf-systems is negligible in the frequency range of interest. The maximum beam current extracted from SPC1 increased by a factor of two with this system and the energy spread improved significantly.

1 Introduction

To increase the beam intensity and beam quality which can be obtained from SPC1, a flat-top acceleration system was installed. Although it is possible to use only a single dee for the generation of an harmonic voltage, as has been done at the PSI[1], there is not enough space in SPC1 for the installation of such a dee. A single dee would also cause a shift in the orbit centre. With ν_r, the radial betatron oscillation, close to 1, as is the case in SPC1 where ν_r is approximately equal to 1.003, the shift in the orbit centre would add up over many turns. For a single dee the displacement of the orbit centre at extraction can be several cm, depending on the harmonic number which is used for the flat-topping. Such a large centre displacement would complicate beam extraction, and is therefore not acceptable. The possibility of resonating each of the two main dees simultaneously at two frequencies, i.e. the fundamental dee frequency and a harmonic frequency was investigated.

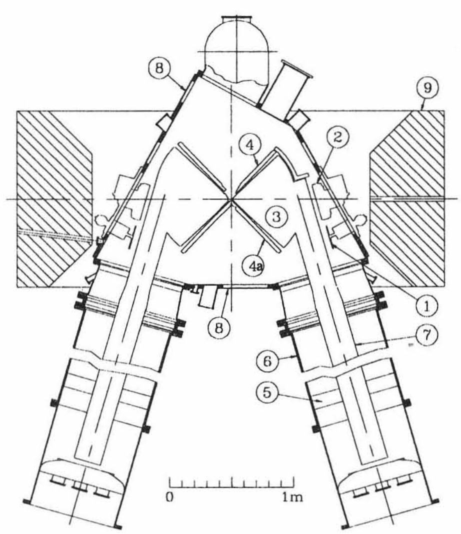

Figure 1. A top view of the SPC1 resonators, showing: (1) The main coupling capacitor, (2) the trimmer capacitor, (3) the dee, (4 and 4a) the dummy dee, (5) the short-circuit plate, (6) the outer conductor of the coaxial section, (7) the inner conductor, (8) the vacuum chamber, and (9) the magnet..

The layout of the SPC1 rf system is shown in figure 1. Each of the two 90-degree dees is connected to a coaxial transmission line with an adjustable short-circuit plate for rough tuning of the main resonance frequency. Trimmer capacitors are used for fine tuning. A dee voltage of 60 kV is required in the frequency range of 8.6 to 26 MHz. A sinusoidal voltage, generated by a frequency synthesiser, is amplified by the driver and power amplifier. The amplifiers are coupled through capacitors to the dees. In order to design a flat-top system for SPC1, the resonance frequencies and other resonator characteristics have to be determined. The irregular shape of the dees and the connecting sections between the dees and the cylindrical parts of the transmission lines makes an analytical analysis of the resonators difficult. A computer program FLATOP, was developed to calculate the resonator characteristics by numerical methods[2]. The assumption is made that, although the dees and connecting sections are not homogeneous, they can be divided into a number of short, homogeneous sections, connected in series[3] . To calculate the voltage and current distributions along the homogeneous cylindrical section, it is split up into 5 equal lengths. The remaining part of the resonator is divided into 11 segments.

2 Calculation of the Characteristics of the Different Resonator Segments

The inductance per meter, L, the capacitance per meter, C, and the characteristic impedance, Z_0, of the round coaxial section for a lossless line are given by[4] . The fact that the field in a homogeneous transmission-line, operated in the TEM mode, is transverse, and that the field distribution in a plane perpendicular to the direction of propagation is described by Laplace's equation, can be used to determine the characteristic impedance of the sections with complicated boundaries. The computer program POISSON[5] was used to calculate the inductance and capacitance per meter of sections one to eleven by solving the two dimensional Laplace equation numerically for the given boundary conditions. The program divides the space between the inner and outer conductors of each section into curvilinear transmission line cells by plotting field and equipotential lines. Without any medium between the conductors, as is the case for SPC1, the capacitance and inductance per meter and the characteristic impedance of the field cell are given by Kraus[6].

3 Calculation of the Resonance Frequencies of the Resonator

A cyclotron resonator has many resonance frequencies. Of interest for particle acceleration are resonances at which the impedance between the dee tip and the vacuum chamber wall has a high value. To determine at which frequencies resonances occur for a given position of the short-circuit plate, or the position of the short-circuit plate for a given resonance frequency, the impedance at the dee tip is calculated.

The calculation starts at the short-circuit plate and proceeds segment by segment to the dee tip. The position of the short-circuit plate at which the reactance is zero and the resistance has a maximum value, is determined by varying the position for which the impedance is calculated, according to the Bisection algorithm[7]. The impedance distribution along the resonator, at the main resonance frequency, is now known and can be used for the calculation of the voltage and current distributions in the resonator. Instead of varying the short-circuit plate position, the frequency can be varied to determine the resonance frequency for a specific position of the short-circuit plate with the program FLATOP. The largest difference between the measured and calculated frequencies is less than 8%. To determine the second resonance frequency of the resonator tuned to a given main frequency, the same method is used. The only difference is that the frequency (and not the length of the resonator as before) at which the parallel impedance is calculated, is varied in the region between the first and sixth-harmonic of the main frequency. The second resonance frequency is close to the fifth harmonic of the main resonance frequency. The reduction in the radial beam width as a result of the lower energy spread with a fifth harmonic flat-top system is shown in figure 2.

4 Tuning of the Second Resonance Frequency to a Harmonic of the Main Frequency

The next resonance frequency above the main resonance frequency does not in general occur exactly at a harmonic of the main frequency. To adjust the second resonance frequency, of the SPC1 resonators in order to coincide with an harmonic of the main frequency, two systems were considered. In the first case a tuned loop, tuned to a frequency close to the desired harmonic frequency, is coupled inductively to a main resonator. In the second case an additional co-axial transmission line, also tuned to a frequency close to the desired harmonic frequency, is coupled capacitively to a main resonator.

4.1 Tuning of the Second Resonance Frequency to a Harmonic of the Main Frequency with a Tunable Loop

The loop consists of an adjustable capacitor and an inductance is mounted inside the outer wall of the resonator. The loop reflects an impedance into the main resonator. The reflected impedance changes the impedance distribution in the main resonator. By controlling the reflected impedance it is possible to adjust the second resonance frequency to coincide with an harmonic of the main frequency, without detuning the main resonance frequency appreciably. In practice the capacitor is adjusted until the second resonance frequency of the resonator coincides with the 3rd or 5th harmonic of the main frequency. The main resonance frequency is detuned due to

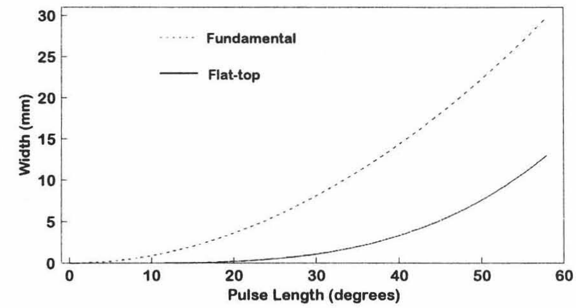

Figure 2. The increase in the beam with due to energy spread at extraction in SPC1 with and without a fifth harmonic flat-top sytem.

the presence of the loop, but because the resonance frequency of the loop is much higher than the main frequency, the reflected impedance at the main frequency, and therefore the amount of detuning, are small and can in practice be compensated for by a slight change in the position of the main trimmer capacitor. Although the reflected impedance is spread along the length of the loop, it is assumed that the effect of the loop can be simulated by inserting the impedance between two resonator segments, at the loop position.

Calculations have shown that the current in the loop and the voltage across the loop capacitor will be too high at some frequencies. The optimum position for the loop is also occupied by existing cyclotron components of the main resonators. For these reasons this method was discarded.

4.2 Tuning of the Second Resonance Frequency to an Harmonic of the Main Frequency with an Additional Transmission Line Resonator

The additional resonator developed from the idea to tune the second resonance frequency to the fifth-harmonic frequency with a variable parallel capacitor, in the conical section of the resonator. This method can only be used if the reactance of the main resonator, at the position of the capacitor, is positive at the 5th-harmonic frequency, so that it can be cancelled by the negative reactance of the capacitor. This is the case when the second resonance frequency is higher than the 5th harmonic frequency, as it is for the SPC1 resonators in the frequency range of 65 to 105 MHz. Above 105 MHz the resonator reactance is negative. With a variable capacitor connected in series with an inductor, both positive as well as negative reactance values can be obtained at the fifth-harmonic frequency. Instead of using an inductor, an additional transmission line with an adjustable short-circuit plate can be coupled to the main resonator through a series capacitor, as shown in figure 3. A copper plate mounted at the lower end of the inner conductor, forms the coupling capacitance between the two resonators. The largest part of the additional resonator, including the short-circuit plate, is at atmospheric pressure. The program FLATOP was extended to calculate the resonance frequencies, the voltage and current distributions and the power dissipation in the two capacitively coupled resonators. The flat-top system was greatly simplified by capacitively coupling the power amplifier directly to the additional resonator at a point outside the vacuum system i.e. without an intermediate transmission line. The power dissipation and other resonator characteristics at the fifth harmonic frequency are summarized in table 1.

Tabel 1: The calculated power dissipation and other resonator characteristics at the 5th harmonic frequency.

Main frequency (MHz)	Coupling capacitor between two resonators (pF)	Length of additional resonator (mm)	Total power dissipation at the fifth harmonic (W)
16	10	538	206
18	10	407	248
20	5	486	145
22	5	333	91
24	10	474	152
26	10	358	384

In contrast at a third-harmonic frequency of 78 MHz, the calculated length of the additional resonator and the total power dissipation are respectively 0.433 m and 45 kW. This power dissipation, which is about three times higher than dissipation in the resonators at the main frequency, is partly due to the higher dee voltages that have to be used at the third-harmonic frequency compared to those used at the fifth-harmonic frequency. It is further due to the fact that the second resonance frequency of the SPC1 resonators is not close to the third-harmonic frequency. The power dissipation is unacceptably high and cannot be handled by the existing cooling pipes of the resonators. The design of a third-harmonic flat-top system for SPC1 was therefore not pursued further.

To determine the tolerances on the amplitude and phase of the main and harmonic dee voltages, expressions derived by Joho[8] were adapted for 2 dees with 4 acceleration gaps and a flat-top system which works at the fifth-harmonic frequency. The tolerances on the amplitude of the main and 5th harmonic voltages are, 0.3% and 7,5% resectively and on the phase 0.3° and 1.5° respectively.

To determine the influence of a flat-top system in SPC1 on the beam quality an orbit code computer program was used. This program was modified to include the harmonic dee voltage and its radial distribution. In the central region of SPC1, where there is little magnetic vertical focusing because of the small flutter, the electric field can have a considerable effect on the vertical motion of the particles. It is therefore important to look at the electric focusing in the central region to determine whether the beam is defocused by the flat-top voltage. From these calculations it is clear that there will be no beam blow-up in SPC1 in the vertical direction due to the flat-top system. In fact a slight improvement in the vertical focusing can be expected.

To determine the effect of the flat-top system on the radial motion the same procedure was followed as for the axial motion. Eight particles with the same starting phase, were distributed around the circumference of an ellipse with an emittance of 20 π mm mrad in the r-r' phase space. These particles were tracked from the centre to the extraction radius of SPC1. To simulate a beam with a pulse of length $2\Delta\theta$, the eight particles were tracked for three starting phases: A starting phase θ_0, which gives the maximum energy at extraction, a starting phase of

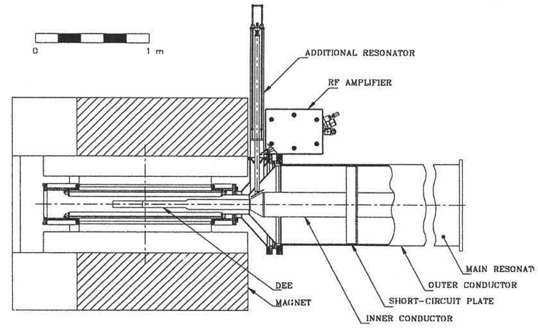

Figure 3. An additional transmission-line resonator, capacitively couple to an SPC1 resonator. The additional resonator is 1.2 meter long, and the diameter of the inner and outer conductor are 40 mm and 120 mm, respectively.

$(\theta_0 - \Delta\theta)$ and a starting phase of $(\theta_0 + \Delta\theta)$. These calculations were performed with the flat-top system and the results are shown in figure 4. The radial position of the three ellipses for the different starting phase are practically the same for each turn, which indicates a small energy spread. There is, however, an offset in the divergence of the three ellipses. This is due to the asymmetrical distribution of the fifth-harmonic dee voltage on the different acceleration gaps as shown in figure 5.

5 Results of Measurements with the Flat-top System

Measurements were made to test some of the calculated results of the program FLATOP. The 5th-harmonic voltage as a function of the radius along the two acceleration gaps of the dee, was measured on a full scale model. The results of these measurements as well as the calculated values are shown in figure 5. At frequencies higher than 100 MHz the dee voltage drops with increasing radius along the acceleration gap 2, and goes to zero before it increases again at higher radii. This indicates a change in phase of the dee voltage along the dee gap.

The measured main voltage at the position of the coupling capacitor of the fifth harmonic is 270 V, compared to the calculated value of 282 V at a main frequency of 16.37 MHz. The difference between the calculated and

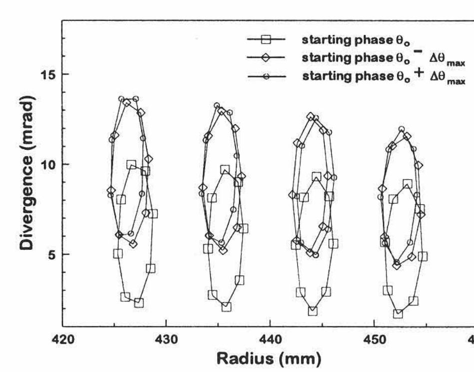

Figure 4 The calculated phase ellipses in the r-r' phase space at the of the last four turns at the extraction radius of SPC1 with the flat-top system. The three ellipses for each turn correspond to phases of -30°, 0° and 30° respectively. The turn separation between the last two turns is 4.5 mm.

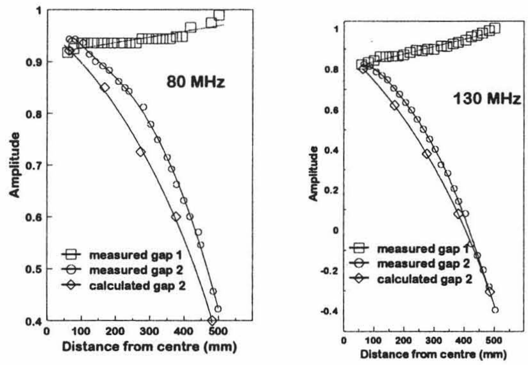

Figure 5. The measured and calculated fifth-harmonic voltage distribution along the acceleration gaps for the full-scale SPC1 resonator model at 80 MHz and 130 MHz. Gap 1 is indicated by no 4 and gap 2 by no 4a in figure 1. In the program FLATOP it is assumed that the voltage along gap 1 is constant.

measured length of the additional resonator as a function of the resonance frequency is less than 30%. The power dissipation of the fifth harmonic at 81.5 MHz is 450 W compared to the calculated value of 205 W. The difference between the measured and calculated values is due to imperfect contact between the different sectors of the short-circuit plates as well as the higher than assumed surface resistance of the resonators due to lack of fine polishing.

Tuning the additional resonators to the fifth harmonic has little influence on the main frequency. By varying the fifth harmonic frequency by 56 kHz with the short-circuit plate of the additional resonator, the position of the trimmer capacitor of the main system changes by only 20% of its full range, to keep the main system in resonance at 16.37 MHz. The system was first tested at a main frequency of 16.3 MHz. With the main voltage off, the harmonic dee voltage was limited because of multipacting. When the main system was switched on the required flat-top voltage could easily be obtained. The mutual interference between the two systems is negligible.

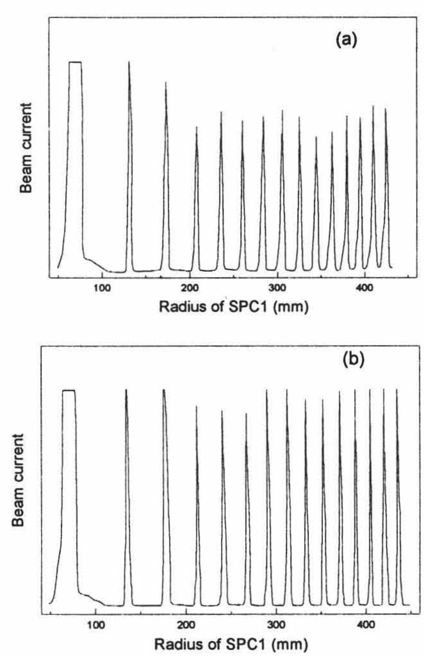

Figure 6. The beam pattern in SPC1 without (a) and with (b) the fifth-harmonic flat-top system. The beam width decreased from 12 to 8 mm at the extraction radius due to the reduced energy spread with the flat-top system for a beam intensity of 190 μA.

At 26 MHz problems were experienced due to a mechanical fault of the series capacitor. A circular ring was soft soldered, instead of hard soldered, onto the outer diameter of the plate. The soft solder melted in the rf field causing the deposit of a solder layer onto the surfaces of parts of the main and additional resonator.

6 Measured Results of the Influence of the Flat-top System on the Beam Quality and Intensity

The maximum beam current from SPC1, for the same slit size in the central region of SPC1, increased from 320 to 650 μA when the flat-top system was switched on. The extraction efficiency increased from 82% to 92%. The measured beam pulse length (full width at half maximum) at extraction of SPC1 increased from 10.8° to 20.2°. A comparison of the SPC1 orbit patterns at the same beam intensities with and without the flat-top system shows a reduction in the beam width at extraction from 12 mm to 8 mm as shown in figure 6. The increase in the beam width, due to energy spread, from the second turn to extraction with the flat-top on is negligible. Without the flat-top system the increase is 4 mm. These measurements show that the flat-top system is working according to our expectations.

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