A FLAT-TOPPING SYSTEM FOR THE SEPARATED SECTOR CYCLOTRON AT ITHEMBA LABS

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Abstract

At iThemba LABS (previously the National Accelerator Centre) proton beams, accelerated in a K=200 separated sector cyclotron (SSC) with a K=8 solid-pole injector cyclotron, to an energy of 66 MeV are utilized for the production of radionuclides and neutron therapy. Proton therapy is done at an energy of 200 MeV. Low intensity beams of light and heavy ions as well as polarized protons, pre-accelerated in a second injector cyclotron with a K-value of eleven, are available for nuclear physics research. Additions and improvements to the facilities currently in progress [1, 2], for increasing the beam intensity for radioisotope production, include flat-topping systems for the light-ion injector and separated-sector cyclotrons, and an additional buncher. The design, construction and commissioning of the flat-topping system for the separated sector cyclotron are discussed.

INTRODUCTION

At present the intensity of the 66 MeV proton beam, accelerated at an RF frequency of 16.373 MHz, is limited to 150 µA by beam losses at extraction in the separated sector cyclotron [3]. The maximum beam intensity that can be obtained from the injector cyclotron is 320 µA. At this intensity the effect of longitudinal space-charge forces is noticeable and an increase in the internal beam intensity does not lead to an increase in the external beam current. In the past [4], experiments with a flat-topping system showed that a 600 µA beam can be extracted from the injector cyclotron with such a system. The longer beam pulses extracted with a flat-topping system fall outside the linear range of the buncher in the transfer beam line. A second buncher, operating at a harmonic frequency of the existing one, is therefore planned. To prevent the longer beam pulses from acquiring excessive energy spread in the separated-sector cyclotron a flat-topping system for this cyclotron is also required. The main reasons for the choice of a resonator type as well as the main parameters have been reported before [5]. The design has since been refined and completed. The resonator and power amplifier have been built, commissioned and tested with beam.

THE RESONATOR

Choice of a Resonator Type

In order to keep the cost involved low the resonator has to be installed through an existing port in one of the valley vacuum chambers and leave sufficient space for both existing and planned equipment in the chamber. Access for maintenance and replacement of cyclotron components has also to be considered in the design and location of the resonator. These prerequisites severely restrict the design of the resonator and limit the width of the resonator to less than half the width of a valley vacuum chamber. This implies a harmonic number of three or more, i.e. a frequency of 49.12 MHz or more, unless a single gap resonator is used. A single gap resonator has been ruled out by the higher RF power and therefore more expensive power amplifier required in comparison with double gap resonators. A horizontal quarter-wave resonator, as is frequently used in cyclotrons, would cover only half the radial length of the SSC and would therefore drastically reduce the orbit separation at extraction, since the resonator has to operate out of phase with the main resonators. A vertical half-wave resonator has also been considered and it would have been a good option except for the fact that it would be very difficult to install the resonator in the restricted space of the valley. A horizontal half-wave resonator, as shown in the 3D drawing in fig. 1, has therefore been decided upon. At injection, i.e. the narrow part of the resonator, and at extraction the dee voltage is zero. The orbit separation in these critical regions is therefore not influenced by the flat-top system. In between the voltage has a maximum value. The step in the resonator, at extraction, has been made to leave space for the electrostatic extraction channel.

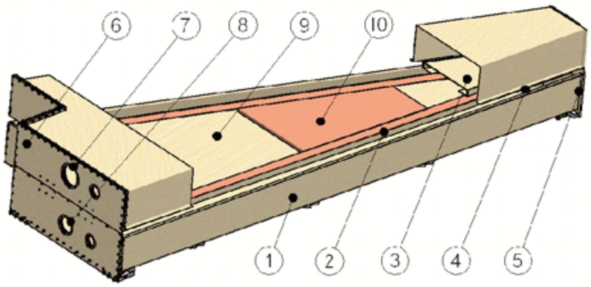

Figure 1: Three-dimensional drawing of the flat-top resonator with the top part cut away showing: 1. lower dee housing 2. acceleration gap 3. top of the upper dee plate 4. beam gap 5. short-circuit plate at injection 6. short-circuit plate at extraction 7. and 8. ports for coupling and tuning components 9. top of the bottom dee plate 10. plate for detuning of an unwanted resonance mode.

Resonator Dimensions and Characteristics

The angle between the centerlines of the accelerating gaps has to be 16.5° for acceleration on the peak of the dee voltage. The resonator height is 0.465 m to allow installation through the port in the vacuum chamber. To fit the resonator into the vacuum chamber and leave ample clearance for the beam at injection and extraction a resonator length of 3.017 m has been decided upon. The accelerating gap increases from 60 mm at injection to 100 mm at extraction to prevent excessive sparking. The transit time factor is close to one.

Orbit calculations have shown that a peak voltage of 62 kV is necessary for minimum energy spread at extraction. The electrical characteristics of the resonator were calculated with the computer program Soprano from the company Vectorfields [6], and with a computer program in which the resonator is modelled as twenty homogeneous but different transmission line segments, with short-circuit plates at the end points, at injection and extraction. The calculated power dissipation and Q-value are 8.6 kW and 11000, respectively, without beam. With beam the power dissipation will be less, since the beam will supply power to the resonator. With a 500 μA beam a power input of only 5.3 kW will be required. The peak current and current density in the dee at injection for dee voltage of 62 kV are 2100 A and 100 A/cm, respectively.

For coarse tuning, before installation, two round capacitor plates with a diameter of 21 cm are mounted inside the dee housing, above and below the dee at the radial position where the maximum in the dee voltage occurs. For fine-tuning a rotatable short-circuited loop at the back of the resonator near extraction and above the dee, is used. The tuning range with the loop is 30 kHz. Another loop, at the same position, but below the dee provides a 50-ohm input impedance to the resonator. Two smaller ports at the back of the resonator are used for two loops for dee voltage measurement.

Calculations with the computer program Soprano have shown that the resonator has two oscillation modes with almost identical frequencies. In the desired mode the voltages on the top and bottom dee plates are in phase, whereas in the unwanted mode the voltages are 180° out of phase. To visualize the two modes the resonator can be considered as consisting of three parallel plate lines with short-circuits at their end points: one formed by the top dee plate and the top part of the dee housing and the second similarly by the lower half of the resonator, whereas the third is formed by the two dee plates. Since the lengths of the three lines are equal the two resonance frequencies should also be the same. Any asymmetry in the resonator construction, coupling and tuning systems would therefore lead to excitation of the unwanted resonance mode causing unwanted energy loss, due to currents flowing on the inside of the dee surfaces, and a vertical electrical field component which would tend to deflect the beam out of the median plane.

The effect of asymmetrical coupling and tuning has therefore been investigated by modelling the three inductively and capacitively coupled parallel plate lines with lumped-circuited L, C and R parameters in a circuit analysis computer program. Calculations based on this model showed that with two resonance frequencies being almost identical even small deviations from top-bottom symmetry in the coupling and tuning systems or in the construction of the resonator would indeed increase the vertical electrical field and the power dissipation to unacceptable levels. It was therefore essential to tune the resonance frequency of the unwanted mode away from the operating frequency. This was done by installing the 800 mm long plates, shown in fig. 1 inside the dees in the region where the voltage maximum occurs. With these plates the frequency of the unwanted mode is now 43.4 MHz compared to the 49.12 MHz operating frequency and the resonator is no longer sensitive to deviations in symmetry in the coupling and tuning systems, which are inherently asymmetrical. The capacitor plates for coarse tuning are further adjusted to cancel any asymmetry in the dee and dee housing construction.

Resonator Construction

Fig. 2 shows the resonator during installation. The front and back short-circuit plates as well as the dee lips have been made from machined 10 mm thick solid copper. The large flat copper surfaces were made from 2 mm copper plates welded together to obtain the required length. The top and bottom dee plates are welded to the two halves of the short-circuit plate at extraction. Near injection home made contact fingers are used to connect the dee plates to the short-circuit plates.

Figure 2: The flattop resonator during installation through a port in the south valley vacuum chamber of the cyclotron. The last two quadrupole magnets of the transfer beam line are visible on the right.

The highest current density occurs on the lips of the dee and dee housing. Special care has therefore been taken to polish these parts of the resonator in the direction that the current flows to a surface finish of 4 µm.

The cooling pipes are soft-soldered to the inside of the dees and the outside of the dee housing and are spaced for a maximum temperature rise of 10 °C above the inlet water temperature.

The capacitor plates for coarse tuning are cooled through heat conduction to the dee housing. The closed tuning loop and coupling loop are shown in fig. 3. Both loops can be rotated through 90°. The 234 mm long tuning loop, made from 16 mm copper tubing, has an internal width of 82 mm. The length and width of the coupling loop, made from the same material, are 170 mm and 42 mm, respectively.

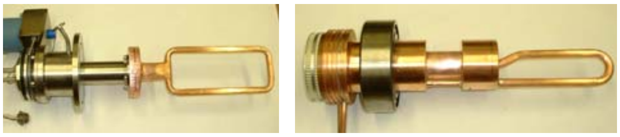

Figure 3: The tuning and coupling loops on the left and right, respectively.

Measured Resonator Characteristics

The resonator characteristics were measured with a network analyser. The measured Q-value is 8335. From this value and the calculated stored energy in the resonator for a peak dee voltage of 62 kV the power dissipation is calculated to be 9.6 kW. Measurements were initially made before the capacitor plates inside the dees were installed. Under these circumstances the resonance frequencies of the two modes practically coincided and the capacitor plates for coarse tuning had to be adjusted to within a fraction of a mm to obtain the Q-value mentioned above. The resonance frequency of the two modes were measured by inserting a loop, connected to the network analyser, into both the accelerating gap and the dee, at the narrow part of the dee where the current is high, at an angle of 45° with respect to both the median plane and the dee edge.

THE POWER AMPLIFIER

The fixed-frequency power-amplifier uses an Eimac 4CW25000A tetrode vacuum tube in class AB, grid-driven configuration. The available power output is 15 kW, and can be increased if required by readjusting the anode circuit resonant impedance. The amplifier gain is 18 dB. The anode tuned-circuit uses a short-circuited transmission-line, configured as a conductor-above-ground, as an inductance. This is tuned to a quarter-wave resonance by the vacuum-tubes anode capacitance and a parallel tuning capacitor. A fixed tapping point on the transmission-line connects to the 50-ohm output flange. The moveable short permits the coupling to the load and hence the resonant load impedance to be set whilst the tuning capacitor corrects the resonance frequency.

The tuned-grid circuit uses an adjustable inductor in the form of a parallel-plate transmission-line with an adjustable short circuit. A variable tuning capacitor is connected from one plate to ground and a coupling capacitor connects the other plate to the grid. The tuning capacitor therefore provides an anti-phase point to apply bridge-neutralization in order to minimize grid-anode reaction. The grid load is a fan-cooled carbon resistor and a fixed tapping point on the inductor serves as input. The latter is set to a 50-ohm match by means of the adjustable short and the tuning capacitor.

COMMISSIONING OF THE SYSTEM

The resonator and power amplifier were first tested outside the vacuum system where stable operation at a power input of 3 kW could easily be achieved. The resonator strongly radiated RF power with the capacitor plates for coarse tuning out of balance, due to the vertical electric field over the beam gap that exists in this condition. After installation in the cyclotron time for testing was limited to a few hours per week. Initially multipacting limited the input power to 1 kW, above which the reflected power became too high. This continued for several hours, spread intermittently over days before the power level was increased to 10.5 kW at which stable operation over hours without sparking was attained.

With beam stable operation up to a power level of 10.5 kW could be obtained. There is no indication of vertical deflection of the beam due to voltage differences between the top and bottom dee plates. A 50 µA beam passed without any losses through the cyclotron and for an 180 µA beam with a much longer pulse length than used up to now the beam loss in the extraction system was a quarter of a micro-amp.

CONCLUSIONS

A fixed-frequency flat-topping system, using a horizontal half-wave resonator, for the separated sector cyclotron at iThemba LABS has been completed and tested with beam. The improvement in the measured beam characteristics with the flattop system so far agrees with expectations. Further measurements, at higher beam intensities, are planned. The flat-topping systems, buncher, beam stop and vertical beam line are scheduled for completion by the end of 2004.

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