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FIRST OPERATION OF A FLATTOP ACCELERATING SYSTEM IN AN ISOCHRONOUS CYCLOTRON

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Summary

In the 590 MeV SIN ring cyclotron a 150 MHz cavity operating on the third harmonic of the fundamental accelerating voltage is now in routine use at average beam currents up to 170 μA. Addition of this cavity resulted in an increased phase acceptance for the single turn extraction mode of over 40° compared to 9° without flattop system. The extraction efficiency is improved from a previous 99.9% to 99.98% while the energy spread is reduced to less than .05% or 300 keV (FWHM). The 150 MHz cavity has a voltage of 350 kV and requires 40 kW of RF power. An important feature is the tight tolerance of .03° on the phase stability.

Introduction

The addition of a flattop system for the SIN ring cyclotron[1] was studied in Ref. 2 and described in Ref. 3. In 1979 such a system came into operation for the first time on any cyclotron. Fig. 1 shows the effect of subtracting an 11.5% third harmonic component from the main RF voltage in order to achieve a constant acceleration over a broad phase range. In Fig. 2 the location of the single flattop cavity and the four main cavities is indicated. The radial voltage distribution of these cavities is sinusoidal (see Fig. 3). The peak voltage of the flattop cavity is relatively high due to its shorter length compared with the main cavities (see the table below).

	main cavities/	flattop cavity
frequency	50 MHz	150 MHz
peak voltage	500 kV	350 kV
RF power/cavity	120 kW	40 kW
Q	28'000	28'000
Length L	5.2 m	2.7 m
Height H	2.9 m	.96 m
gap g (no lips)	.45 m	.4 m
δV/V	$< 3\cdot10^{-4}$	$< 10^{-3}$
$\delta\phi_1$ (50 MHz)	< .01°	

Fig. 4 shows the block diagram for the 150MHz flattop system with the associated amplitude and phase feed back loops. The voltage V_1 of the 50 MHz cavities is kept constant independent of beam loading. The summed up voltage of these four cavities serves as the reference signal for the flattop parameters V_3 and ϕ_3. The ratio V_3/V_1 can be varied with an attenuator for the 50 MHz amplitude signal. The phase ϕ_3 can be changed and optimized with a coaxial phase shifter. The constraints on the phase stability are very strong (see Fig. 7) and measurements have shown, that the actual phase stability $\delta\phi_1$ with respect to 50 MHz is better than .01° (see Fig. 5). This is a factor 3 better than originally specified.

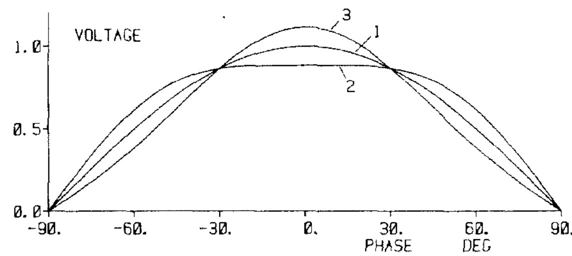

Fig. 1 Effective accelerating voltage waveforms as a function of phase or time. 1 represents the pure sinusoidal voltage of the main accelerating system. 2 is the resulting waveform with the subtraction of a 11.5% third harmonic component (ideal flattop). 3 is the result with a 180° phaseshift of the same third harmonic.

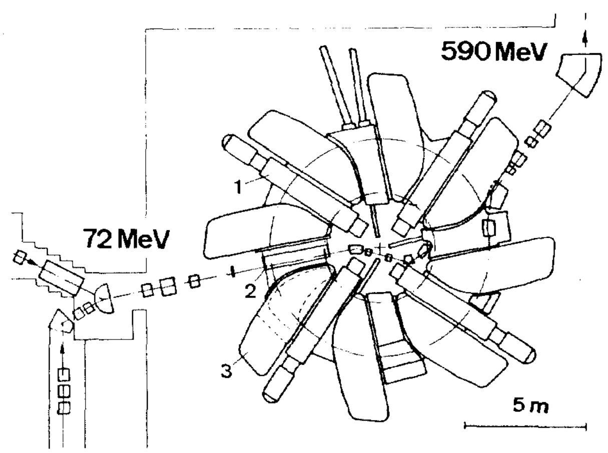

Fig. 2 Layout of 590 MeV ring cyclotron. The number labels are: 1 = one out of four 50 MHz cavities, 2 = 150 MHz flattop cavity, 3 = one out of eight sector magnets. The present injection path for the 72 MeV protons is from the left, the future injection from the new injector II will be from the lower part of the figure.

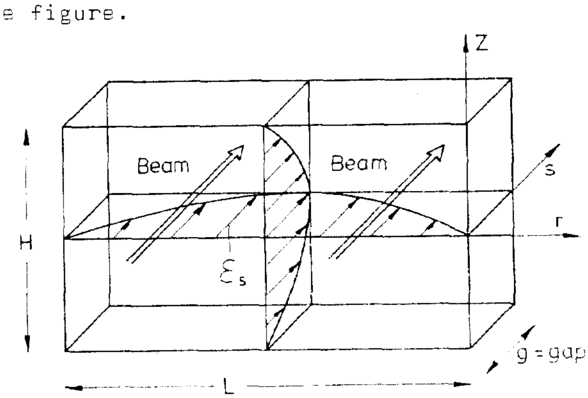

Fig. 3 Geometry of a rectangular cavity operating in the H_{101}-mode used for the 50 and 150 MHz system.

Beam Tests and Operational Experience

Initially we had some problems with the multipacting effect. By coating the inner aluminium surface of the flattop cavity with a thin layer of aquadac the secondary electron emission could be partially suppressed which cured the multipacting problem.
There are only two free parameters, amplitude V_3 and phase ϕ_3. These were optimized in a series of beam measurements with a radial current probe. The result is shown in Fig. 6 and 7 and was used to calibrate the voltage

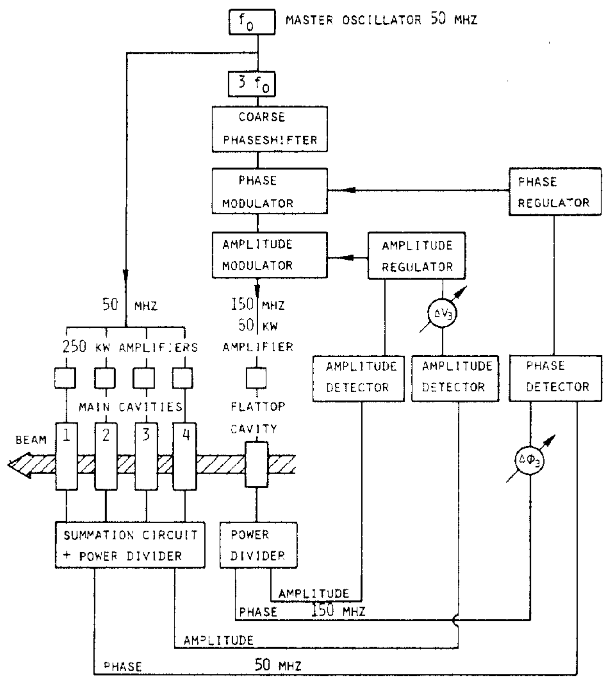

Fig. 4 Block diagram of flattop RF-system of ringcyclotron. The four 50 MHz cavities have all their own amplitude and phase regulation system (not shown). For the 150 MHz flattop cavity the control room operator has access to amplitude V_3 and phase ϕ_3.

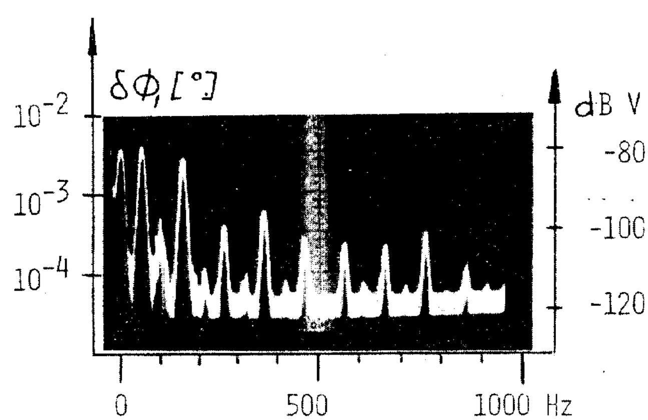

Fig. 5 Spectrum of phase error $\delta\phi_1$ (with respect to 50 MHz) between the flattop voltage and the summed up voltage of the four 50 MHz cavities.

to better than .05%. Since the present 72 MeV injector cannot produce a beam with a phase width above 10° FWHM we had to measure the phase acceptance by shifting the central phase ϕ_{in} of the whole beam at injection. The observed phase acceptance of 40° corresponds to a phase range of 30° at extraction due to the phase compression effect[4].

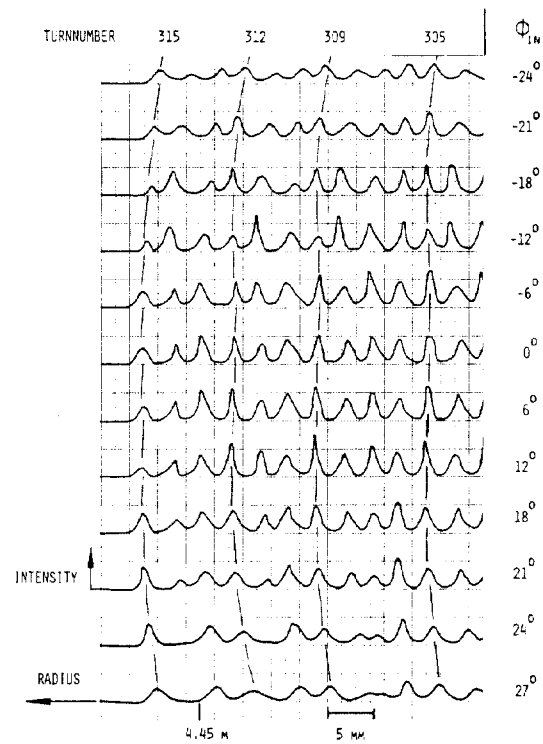

Fig. 6 Demonstration of large phase acceptance of flattop system. Shown are the last 11 out of 315 turns in the ring cyclotron for different injection phases ϕ_{in}. The phase range for single turn extraction is more than 40°. The clear distinction of separate turns for the extreme phases proves the excellent phase stability.

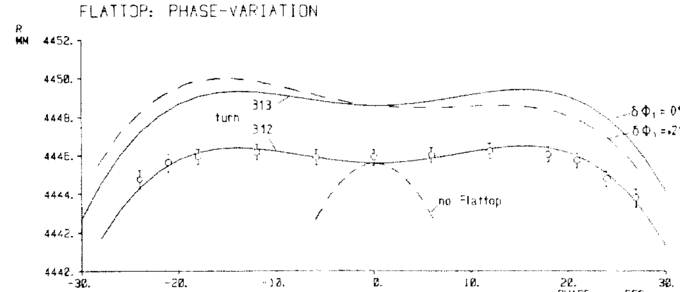

Fig. 7 Radial position of turn 312 versus injection phase ϕ_{in} as evaluated from Fig. 6. The curves for turn 312 and 313 are the result of numerical orbit calculations. The energy gain at extraction is 1.67 MeV. The upper broken curve shows the extreme sensitivity of the radial position against phase shifts. $\delta\phi_1$ is the phase of the 50 MHz system with respect to the 150 MHz system. The lower broken line shows the narrow phase acceptance without flattop.

The implementation of the flattop system had a very beneficial effect on the daily operation of the cyclotrons with the following consequences:

1. Minimum beam loss.
We obtain clearly separated turns from injection to extraction as seen in Fig. 8. Compared with an extraction rate of 99.8 to 99.9% without flattop we obtain now routine values of 99.98% and better. The beam losses and with it the activation of the ring cyclotron have thus dropped by a factor 5 to 10 against previous values. It was even possible to produce 100 µA with 3 main cavities only and losses below 10^{-3}!

2. Record beam intensity.
Thanks to the large phase acceptance of the ring one could open up a bit the internal phase slits of the injector cyclotron. This together with improvements made in the cyclotron center allowed the routine acceleration of 170 µA protons to 590 MeV. The short time record stands now at 190 µA.

3. Minimum energy spread.
The energy spread ΔE of the extracted 590 MeV beam cannot be measured directly. From the sharp turn pattern in Fig. 8 one can deduce an upper limit of

ΔE (FWHM) < 300 KeV or $\Delta E/E < 5\times10^{-4}$

With such a practically monoenergetic beam the beam loss in the proton channel between ring and target is below the detection limit of the ionization monitors.
If we would have a high resolution spectrometer at hand we could probably tune the cyclotron to an energy spread below 100 keV.

4. Short setup times.
With the flattop system the setting of the ring parameter and especially the main magnetic field is much less critical. This has made the setup of the cyclotron easier and faster.

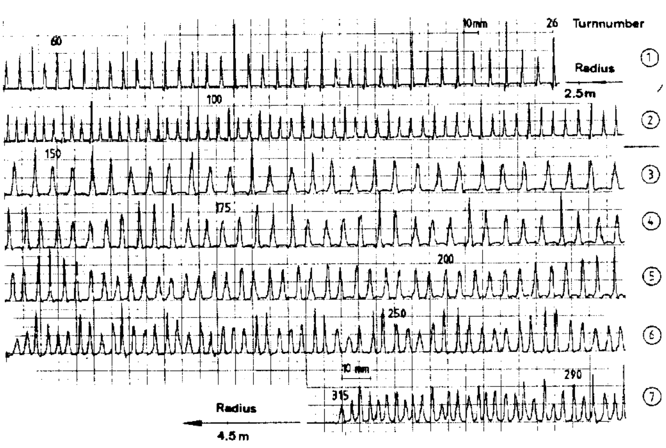

Fig. 8 Turns 26-315 in the ring cyclotron with flattop system. Shown is the current density on a .2mm thick secondary emission probe as a function of radius between 100 and 590 MeV. For traces 3-7 the radial scale has been doubled against traces 1 and 2. For routine production the beam is not as well centered as in this example but injected excentrically. This enhances the turnseparation at extraction and leads to extraction efficiencies of 99.96%.

Future Developments

A new 72 MeV injector II for currents of more than 1 mA is presently under construction[5]. For such high currents the longitudinal space charge forces will start to smear out the separated turn structure. It is possible to compensate the linear part of this effect by phase shifting the 3rd harmonic RF component with respect to the fundamental harmonic. Preliminary numerical studies have shown that a flattop system is absolutely essential in order to reach currents in the order of 1 mA.
With 170 µA on target the total beam power at 590 MeV is 100 kW. The flattop cavity absorbs about 10 kW from the beam, which corresponds to a noticeable beam loading factor of 25%. With increasing current it becomes more and more difficult for the regulation system to stabilize the cavity voltage. For a current of about 600 µA there is even no need to feed power from the transmitter into the cavity. A further problem is that the impedance of the coupling is current dependent which results in a reflected RF wave which could damage the power amplifier. In order to solve the above mentioned problems the following measures are under consideration:

- increasing the cavity voltages of the 50 MHz and 150 MHz systems.
- lowering the Q of the 150 MHz cavity.
- loading the flattop cavity with an external resistor which can be matched to the variable beam loading. This can be done by varying the coupling or by electronically adjusting the impedance.
- the RF power which is reflected from the flattop cavity is coupled out and dumped to a 50 Ω resistor. With presently available directional couplers only a fraction of the reflected power can be diverted.

Detailed calculations and tests will be carried out in the near future to see which method or combination of methods will be finally adopted in order to cope with this beam loading problem.

Conclusion

We strongly recommend the addition of a flattop RF system for cyclotrons with a special emphasis on high current or low energy spread.

References

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