HIGH INTENSITY BEAM ACCELERATION WITH THE SIN CYCLOTRON FACILITY

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Summary

Since 1985 the Injector II cyclotron is used routinely together with the 590MeV ring cyclotron for production runs. With this new injector SIN can provide simultaneously proton beams of 220μA for the meson production targets, 18μA for the medical pion irradiation facility and about 100μA for isotope production at 72MeV. At these current levels extraction from both cyclotrons is very clean, the losses beeing below 0.01%. The intensity records stand at 310μA for the 590MeV cyclotron, corresponding to 180kW of beam power, and 1mA for the 72MeV injector. At 590MeV the present intensity limit is given by the target, beam dump and the available RF-power. In the injector the extraction losses increase drastically with current due to space charge forces. To increase the intensity limit from 1mA to the design value of 1.5mA we plan to install higher harmonic resonators and metallic plates tightly above and below the median plane. Another challenge is the problem of beam loading in the 50MHz RF-system and beam power absorption in the 150MHz flattop system. Polarized beams are still produced with the original Injector I cyclotron and proton currents of 5μA at 72MeV and 2μA at 590MeV have been achieved.

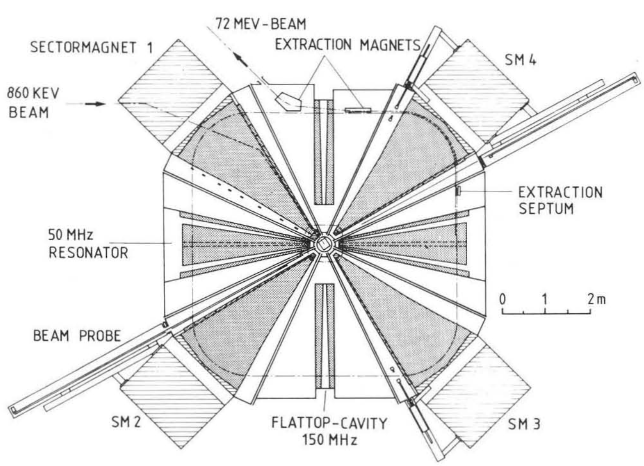

Fig. 1: Layout of Injector II cyclotron. The four sector magnets produce the 'almost- square' shaped orbits. The two 50MHz resonators are responsible for the acceleration over 100 revolutions to 72MeV. The two flattop cavities (operating at 150MHz) produce a practically monoenergetic beam for a wide phase range. At high beam currents they are used to compensate the linear part of the longitudinal space charge forces.

Introduction

The SIN accelerator facilities with a 72MeV Injector Cyclotron and a 590MeV Ring Cyclotron for protons have been in operation since 1974. During 1984 the new "Injector II", consisting of a 870keV Cockcroft-Walton pre-injector and a four sector cyclotron, has been commissioned and been brought into routine operation in 1985. The original Injector was fabricated by Philips (NL) and is able to produce (with an internal source) close to 200μA of CW beam on target (the design value was 100μA). Since the main ring cyclotron can handle much higher intensities than this, the new Injector was designed to produce currents of 1-2mA and recent beam experiments indicate that this goal is achievable: A beam of 1mA has been extracted to a 72MeV beam dump and in a 1:3 pulsed mode a current of 0.4mA corresponding to 1.2mA peak current has been obtained. The concept of Injector II and its commissioning has been described at previous conferences [1,2,3,4,5] and figure 1 shows a layout of this accelerator.

Results of Beam Tests

Due to our flattop RF-systems we have completely separated turns in both the injector (107 turns) and the main cyclotron (344 turns). This results in a 1:1 image of the source onto the target over a path length of 8km. Below we describe the results of our beam development efforts for some sections along this path.

Cockcroft-Walton Pre-Injector, 870keV Beamline

The 60keV ion source is of the magnetic-cusp type with a four electrode extraction system, and has been designed for a total beam current of 50mA. At present the ion source has a rather low proton efficiency of 36% giving a maximum proton beam of 18mA DC with a normalized emittance of 0.5 pi mm mrad. Work is under way to improve the proton ratio to at least 50% leading to the design goal of 25mA protons. A pair of solenoids focuses the protons through a 6mm diameter hole placed about 1m in front of the accelerating column of the CW pre-injector. In this way most of the parasitic molecular ions coming from the source are eliminated from the beam before it enters the acceleration tube. The measured beam envelopes agree quite well with the calculated ones assuming a beam neutralization of more than 99% outside the tube and full space charge forces inside it. Maintenance of the source requires no venting of the column which helps to give very stable operating conditions. The ion source and CW pre- injector are described in more detail in another paper of this conference [6].

The 18m long 870keV beamline between the CW and Injector II works very reliably. Recently, a buncher has been added, enhancing the intensity but increasing the beam emittance slightly. From a comparison of measured beam profiles with calculated ones we have to conclude to our surprise, that the proton beam is practically unneutralized. This is in complete contrast to the 60keV section, where we have full neutralization. The origin of this clearing effect for background electrons is not understood yet. At the moment the 870keV beam line is well matched to the Injector II for beam currents up to about 11mA. For higher currents we still have not found complete agreement between calculated and observed beam profiles. Nevertheless a maximum of 16mA has been injected into the cyclotron, from which about 3mA could be accelerated over the first 6 revolutions to 4MeV.

Performance of Injector II and New 72MeV Beamline

Due to two flattop RF-resonators we have well separated turns up to extraction for a wide phase acceptance of 30 to 40 deg. (see figure 2). The increase of the beam diameter with current is due to the longitudinal space charge force, which produces an energy spread of about 1.5MeV/mA which can be reduced to about 450keV/mA (see figure 3) by the flattop system [9]. For currents up to about 0.3mA extraction losses are less than 0.01% .During routine operation with 0.2mA the radiation level inside the cyclotron vault is 7mrem/h, with 5mrem/h alone coming from the RF-system! At higher beam intensities the losses increase drastically due to longitudinal space charge forces (see figure 4), and reach about 0.2% at the present maximum current of 1mA.

Setting up the cyclotron for high current operation requires reliable diagnostic equipment supported by computer programs, and SIN has developped some new beam probes which allow a quick tomographic reconstruction of the beam properties (see fig. 5 and ref. [7, 8]. A novel method for measuring the time structure and correlations in longitudinal phase space of the beam was developped by T. Stammbach (see figure 6). Protons are elastically scattered from thin carbon wires, which can withstand beam currents as high as 1mA. The new 72MeV beamline between Injector II and the ring cyclotron has two interesting features: An electrostatic septum which can peel off part of the primary beam for online isotope production and a diagnostic section for measurement of the transversal phase space properties (see figure 7).

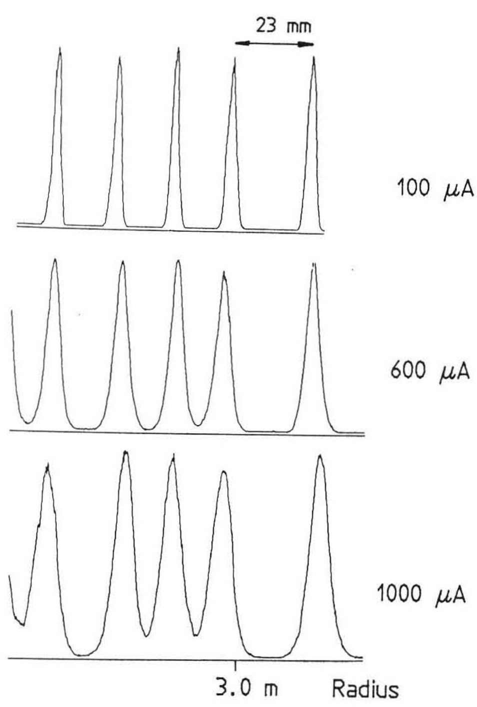

Fig. 2: The last 5 turns in the Injector II at 72MeV for three different current levels. Shown is the intensity, as measured on a metal finger, versus radius in front of the first extraction magnet. The average radius gain is 16mm/turn coming from an energy gain of 1MeV/turn. An electrostatic septum placed about 60 deg upstream from the extraction magnet provides an extra orbit separation of 8mm. At high currents the beam is injected into the cyclotron slightly excentric to enhance the orbit separation further. The increase of the beam size with current is obvious and is due to an energy spread induced by longitudinal space charge forces.

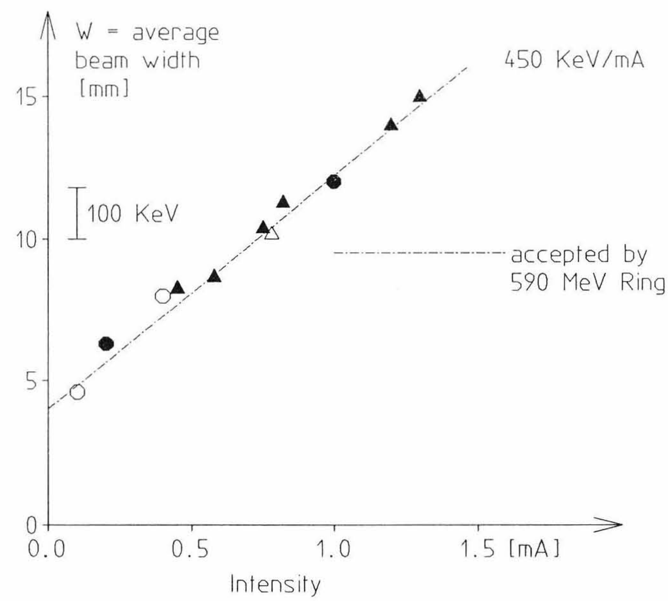

Fig. 3: Average beam width w versus intensity for the last few turns in Injector II. The increase of w comes from an energy spread induced by the nonlinear part of the longitudinal space charge forces. The linear part has been compensated already by adjusting the phase of the third harmonic RF-system. The minimum width of 4mm at zero current corresponds to a normalized emittance of 0.8 pi mm mrad. The triangular points were obtained with a beam where only 1 out of 3 micropulses were transmitted through the cyclotron; the missing two beeing eliminated by an 8.3MHz deflector on the first revolution at 1MeV. In this case the average current was multiplied by three to obtain the peak current relevant for space charge effects. Points in full black were obtained with the 870keV buncher in operation. For each intensity only the smallest beam sizes ever achieved are displayed. Shown is also the present acceptance limit of the 590MeV ring cyclotron given by a beam spill tolerance of 1 μA at extraction.

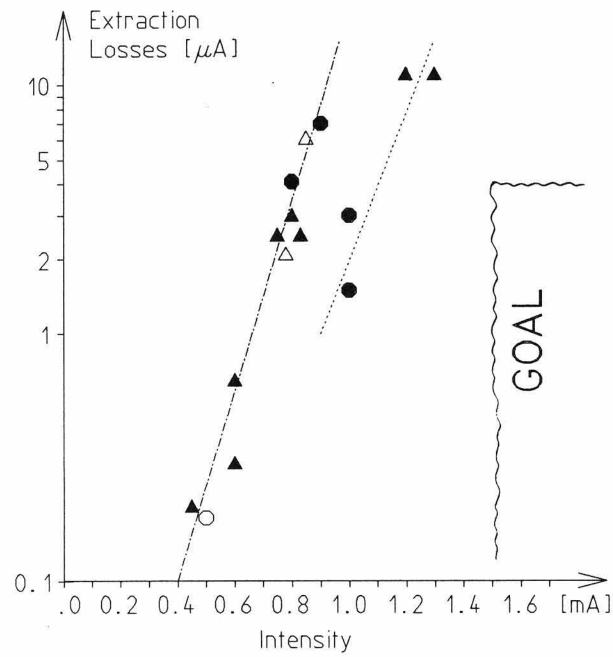

Fig. 4: Extraction losses in Injector II as a function of beam intensity. Beam losses occur both at the 0.1mm thick electrostatic septum and the 7mm thick magnet septum. While extraction is very clean up to currents of 0,4mA, beam losses increase dramatically afterwards. The 4 good points with highest intensities are the most recent ones from beam developments in summer 1986. Labeling of the points is as in figure 3.

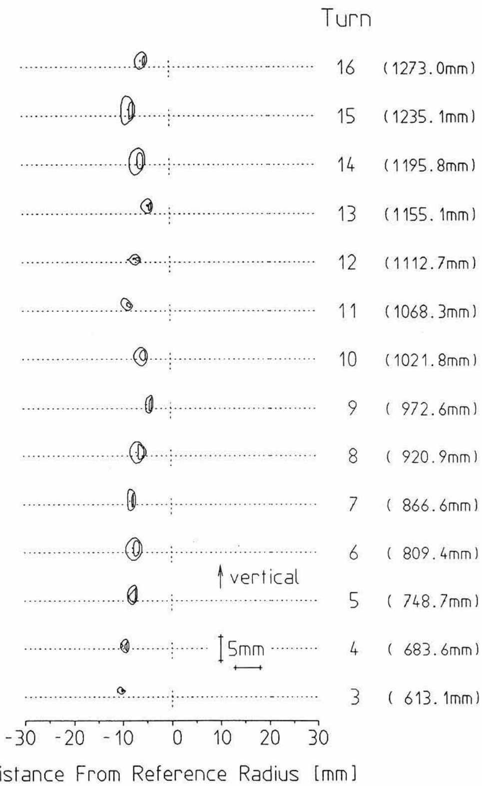

Fig. 5: Beam cross sections of turns 3-16 in Injector II. Shown are the contour lines corresponding to 20 and 50% of the peak intensity. These profiles were reconstructed tomographically using a beam probe with three wires oriented differently in the x-y-plane. From such a beam measurement the coherent horizontal and vertical oscillation amplitudes are automatically calculated by the control computer. Matching of the incoherent amplitudes is quite good as indicated by the relatively weak pumping of the beam diameter. Comparing the measured radial beam position with reference values allows a calibration of the effective acceleration voltage.

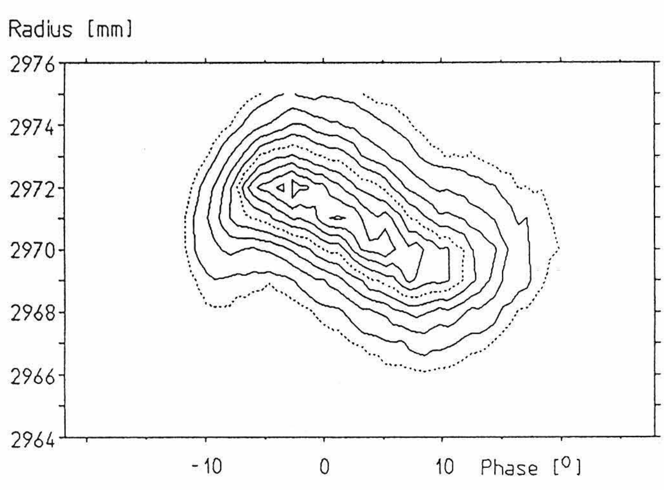

Fig. 6: Time structure measurement with high radial resolution in the last turn of the Injector II cyclotron for a 0.25mA beam. 72MeV protons scattered from a 30μ carbon fiber are detected in a fast scintillator and photomultiplier as a function of radius. Contour lines of equal intensity show an S-shaped correlation between phase and radius (or energy), attributed to the effect of longitudinal space charge forces. The linear part of this correlation can be compensated with the phase of the third harmonic flattop voltage.

590MeV Cyclotron

In a production run a beam of 0.31mA has been accelerated through the main cyclotron and guided onto the pion production targets. At this level extraction losses in the main ring were still as low as 0.03%. The limitation to higher currents was not in the accelerator but rather in the temperature increase of a target flange. The next current limit comes at about 0.35mA from the target itself and the beam dump. Unfortunately this limitation will persist until the target station will be rebuilt during a big shutdown in 1989 in preparation for the installation of a spallation neutron source. In the Injector II we have the possibility to suppress 2 out of 3 bunches and thus see the effect of space charge forces at reduced average intensities. In this mode we could accelerate an average current of 0.2mA to 590MeV, the limit given by extraction losses. This indicates, that the energy spread coming from the injector would presently limit the acceptance by the main cyclotron to about 0.6mA.

Besides serving as a backup, the old injector is now used more extensively for low energy physics mainly with polarized beams. For 72MeV polarized protons the record intensity is now 5μA, and 2μA of this beam has been accelerated further to 590MeV. In addition Injector I routinely supplies beam for the treatment of eye tumors.

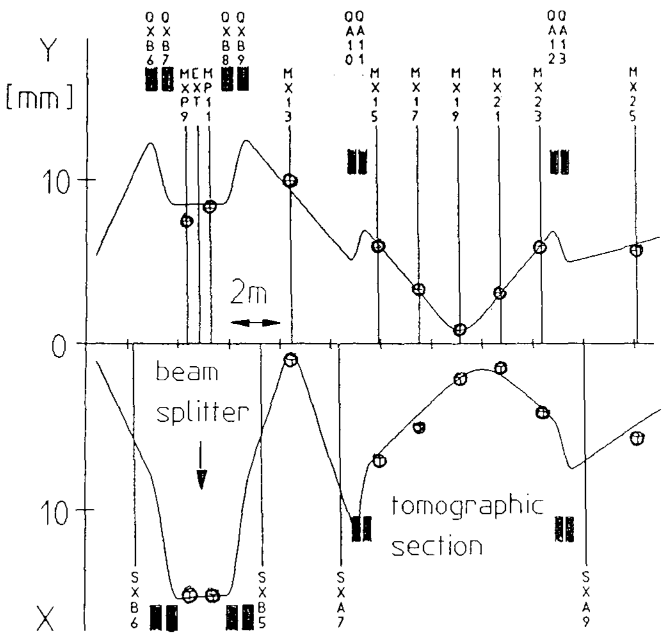

Fig. 7: Partial section of the 72MeV beamline between Injector II and main cyclotron. The first part of this section shows how the beam is blown up horizontally as well as vertically in order to ease the separation of up to 0.1mA for online isotope production. The second part of this beamline section contains a long drift with a battery of 10 profile monitors used for tomographic reconstruction of the horizontal and vertical beam emittances. In this example the corresponding normalized values are 0.8 pi resp. 0.6 pi mm mrad.

RF-Systems

In both the Injector II as well as the 590MeV ring cyclotron we have in addition to the accelerating 50MHz system a flattop RF-system. The corresponding RF- resonators operate at the third harmonic i.e. at 150MHz and decelerate the beam. At the design goal of 1.5mA we have thus the following situation summarized in table 1 including future developments:

From this table we can see that there are two distinct problems, which have to be solved before we can reach our design current:

a) Increase of the available RF-power for the 50MHz system of the ring cyclotron.
b) Handling the beam power absorption in the 150MHz RF-systems of both cyclotrons.

Table 1

	INJECTOR II		590MEV RING	
	50MHz	150MHz	50MHz	150MHz
number of resonators	2	2	4	1
peak voltage [kV]	250	65	500	350
future			700	490
resonator loss [kW]	120	4	150	35
future			340	75
absorber loss [kW]		4		40
power delivered to beam per cavity [kW]	61	-7	220	-100
RF-power per cavity for 0 to 1.5mA [kW]	120..181	4..-3	150..370	35..-65
future incl. absorber loss [kW]	120..181	8..1	340..560	115..15

50MHz RF-Power for the Ring Cyclotron

Each of the four 50MHz cavities is driven by its own final amplifier with a capacity of about 200 kW. This is enough to cover the cavity losses of 150kW at 500kV and to provide beam power for about 0.34mA. To reach higher currents the original idea was to upgrade these transmitters, which are operated in a grounded cathode configuration, to 500kW, using Siemens tetrodes RS2074. This scheme was successful on acceptance tests with a resistive load. The operation with a high Q cavity however gives problems with the onset of parasitic oscillations and would limit the available RF-power to about 300kW.

The new concept foresees the development of a new final amplifier designed in a grounded grid configuration with a capacity of 600kW. The present final amplifiers will be used as driver stages delivering about 60kW. To ease service access all amplifiers will be placed outside the cyclotron vault and power will be fed to the cavities by new transmission lines. The available RF-power will enable us in the future to increase the cavity voltage from 500 to 700kV, which will have the following beneficial effects:

- increase of the turn separation at injection and extraction, leading to the acceptance of a higher energy spred from the injector and giving lower extraction losses.
- smaller longitudinal space charge effects due to the reduced number of revolutions.
- reduction of the variation in RF-power between zero and maximum current (smaller relative beam loading).

Going from 500 to 700kV increases the losses in the cavity walls more than quadratically because of the increased surface resistance with temperature. The present cavities are thus limited by the cooling capacity to about 700kV. For higher voltages we would have to build new cavities.

Beam Power Absorption at 150MHz

The beam delivers power to each flattop resonator at a a rate of 4.5kW/mA in the Injector II and 65kW/mA in the 590MeV ring. With the present resonator losses (see table 1) we have thus a situation, where above a certain current (0.9mA in the injector and 0.5mA in the ring) the 150MHz systems should absorb RF-power rather than deliver it! The whole system works then like a proton klystron, with power beeing fed into the beam at 50MHz and part of it coupled out at 150MHz. The main problem is, that the RF-system has to cope with the whole range of possible beam currents. Two ways for handling this situation are under consideration at SIN.

In the first case, investigated by P. Sigg, one plans to have a relatively constant power output from the RF- generator. The beam power absorbed by the resonator is coupled out to an external variable load. The second case is beeing investigated by M. Maerki and discussed below in more detail. Here the RF-system itself is adapted to handle the big load variations and the corresponding reflections in the transmission line. Since mechanical adjustements of an impedance matching system would be too slow, the idea is to make the transmission line and generator relatively immune against power reflections. Figure 8 shows a schematic representation of this system and the analysis which follows in table 2 shows how one can minimize reflections over a selected range of beam currents. This analysis, which has been copied from an internal SIN report [10], assumes a purely resistive load. This is very realistic for any decent isochronous cyclotron, where the beam is always accelerated on the peak of the RF-voltage. Figure 9 shows an example of the behaviour in the flattop system of Injector II. The system is optimized for a maximum current of 2mA, i.e. for minimum reflections at 1mA. The generator power has to cover the whole range of beam power, or about 9kW between 0 and 2mA in our example. Since the generator should work in a linear regime over this whole range, the RF-tube has to operate in either the A- or the AB-class. With external absorbers one can preload the resonators and optimize the working line for the RF-tube. To avoid an oversized generator one can design the system to operate with a zero or even slightly negative load at the maximum beam current, i.e. the generator works then in an absorber mode. In this situation care has to be taken to avoid parasitic oscillations.

Another challenge is the design of the control loop for amplitude and phase of the resonator. In the regime of very small generator power the phase of the feedback signal can vary widely between 0 and 360 deg. (see bottom part of figure 10) and the amplitude- and phase-loops are strongly coupled. With a compensation scheme as outlined in figure 10 this difficulty can be avoided. A prototype of this scheme has been tested successfully on one of the Injector II flattop cavities. By adjusting the external absorber correspondingly one could create a situation, where a 1mA proton beam alone generated the required voltage of 65kV on the cavity. Although the RF- generator delivered practically no power, the feedback loop was able to keep the cavity voltage and phase constant.

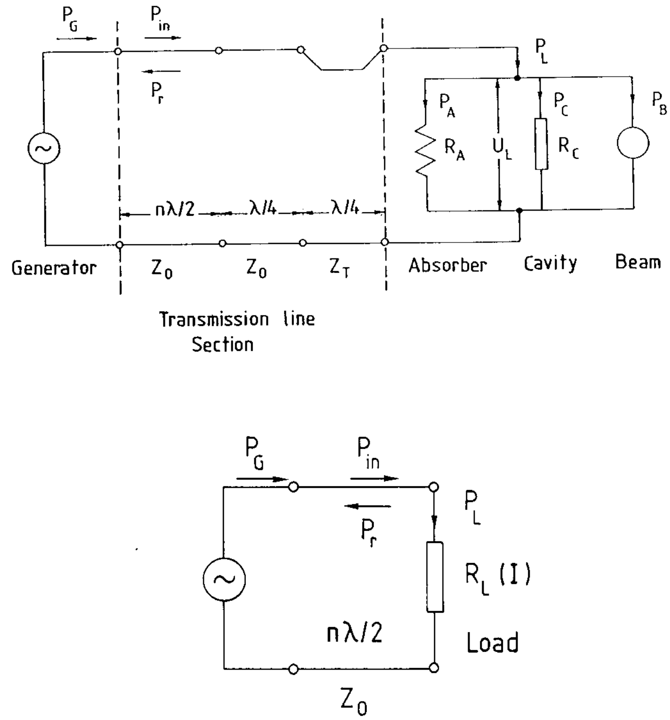

Fig. 8: *Simplified diagram of RF-cavity fed by generator via a transmission line (top part of figure) and further reduction into lumped circuit with current dependent load impedance $R_L(I)$ (bottom part). The 150MHz flattop cavities are decelerating the beam and power is absorbed by the cavities from the beam. The range of acceptable beam current can be extended by preloading the cavities with an external absorber. The 50MHz resonators on the other hand are delivering power to the beam by accelerating it. In this case there is no need for an absorber.*

Power balance:

$$P_G = P_L = P_{in} - P_r$$
$$= P_A + P_C + P_B(I)$$

Where

P_G = generator power

P_L = total power in load (positive or negative)

P_{in} = incident power

P_r = reflected power

P_A = power loss in absorber (only for flat-top cavity)

P_C = power loss in cavity

$P_B(I)$ = power delivered to beam (< 0 for flat-top cavity)

I = average beam current

U_L = transformed cavity voltage, regulated to be constant

Table 2

Minimize reflected power over the whole range of beam power with free choice of:
P_K = beam power at which total load impedance is matched (no reflection)

Introduce:
$P_{AC} \equiv P_A + P_C, \qquad P_\circ \equiv P_{AC} + P_K$
$\Delta P_B(I) \equiv P_B(I) - P_K$
Condition for load impedance at zero current is:

$$R_L(0) = Z_\circ \cdot P_\circ / P_{AC}$$

Condition for transformer impedance Z_T :

$$Z_T = Z_\circ \sqrt{\frac{R_A \cdot R_C}{(R_A+R_C)R_L(0)}}$$

$$r(I) = -\frac{\Delta P_B(I)}{2P_\circ + \Delta P_B(I)} = \frac{R_L(I) - Z_\circ}{R_L(I) + Z_\circ} = \text{reflection coefficient}$$

$$SWR(I) = \frac{P_\circ}{P_\circ + \Delta P_B(I)} = \frac{R_L(I)}{Z_\circ} = \text{standing wave ratio}$$

$$P_L(I) = P_{AC} + P_B(I)$$
$$P_r(I) = \Delta P_B^2(I)/(4P_\circ)$$
$$P_{in} = P_L + P_r$$

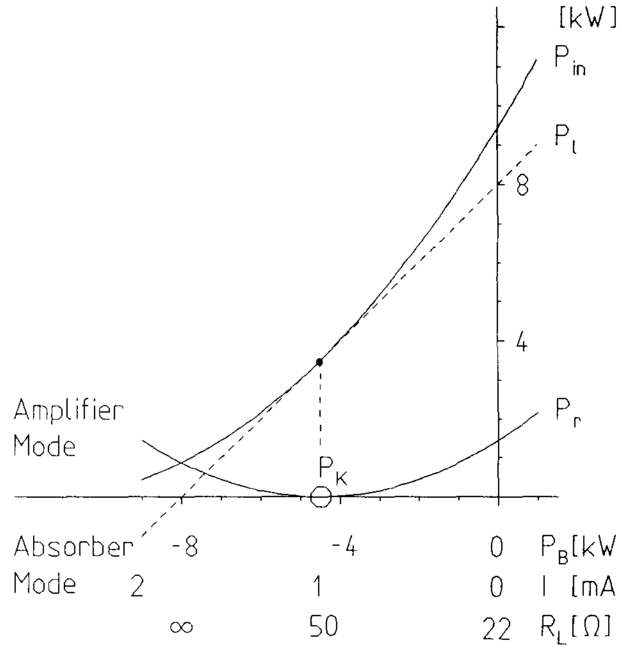

Fig. 9: Incident, reflected and total power as a function of beam power for the flattop cavities of Injector II. The zero current load impedance is adjusted to give optimum matching at a beam current of 1mA, corresponding to a beam power of 4.5kW per cavity. This results in a maximum reflected power both at 0 and 2mA. Above a beam power of 8kW, corresponding to 1.8mA, the total load is negative and the generator tube has to absorb the extra power of 1kW coming from the beam.

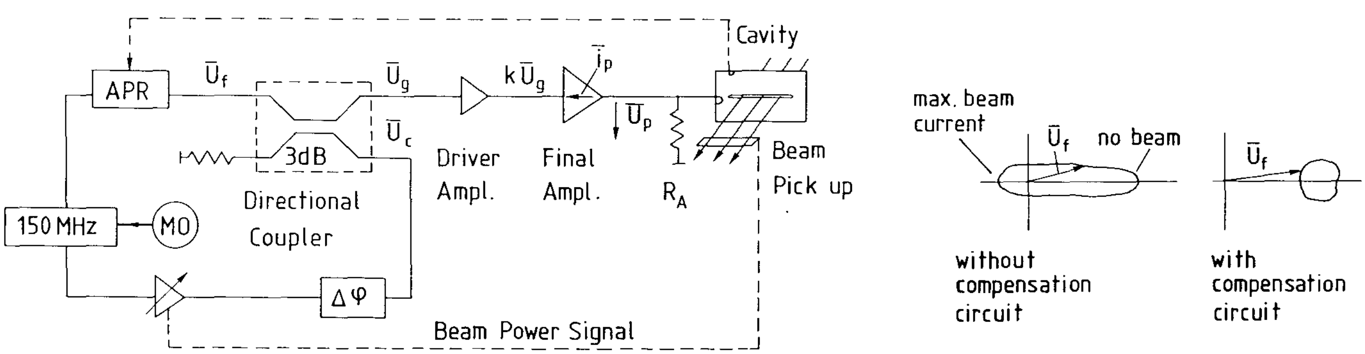

Fig. 10: Compensation scheme for 150MHz flattop cavity and trace of feedback voltage Uf under different beam power conditions. In the 3dB directional coupler a feedback signal Uf, coming from the amplitude and phase regulator, is combined with a beam pickup signal. The outgoing grid control signal is related to the difference between the two ingoing signals. This compensation ensures that the feedback signal has always about the same magnitude and phase for all beam power levels. In this situation we have a socalled "small signal behaviour" with decoupled amplitude- and phase-loops.

MO = Master Oscillator
APR = Amplitude and Phase Regulator
$\Delta\varphi$ = Phase Adjust
$\overline{U_f}$ = Feedback Control Voltage
$\overline{U_c}$ = Compensation Voltage (Beam Power)
$\overline{U_g}$ = Grid Control Voltage
$\overline{i_p}$ = Plate Current
$\overline{U_p}$ = Plate Voltage

Future Plans

The first priority in the near future is to increase the beam intensity of Injector II up to 1.5mA or more, with beam qualities which can be safely accepted by the 590MeV ring as well. This means that we have to compensate the space charge produced energy spread by an additional factor of at least 2.5 down to the level of 0.2MeV/mA. We plan to do this with the installation of two additional RF-resonators: The first will extend the range of the flat-top system to the first few turns after injection. This will help to increase the current threshold for the socalled longitudinal spiral instability (see fig. 11), which was discovered by numerical space charge calculations due to S. Adam [11]. The second resonator will have a frequency of 500 to 600MHz tailored to the expected azimuthal charge distribution. In addition we hope to reduce the space charge forces further with the help of socalled metallic mirror plates (see fig. 12) to be installed into the injector cyclotron.

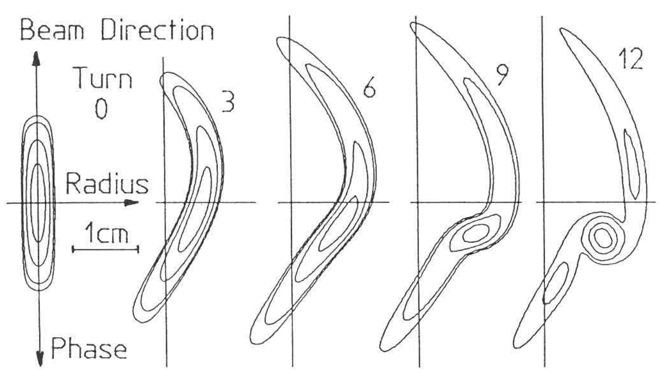

Fig. 11: Distortion of beam bunches at the low energy end of Injector II, simulated with the space charge program PIC2 [11] for a 2mA beam. During acceleration the bunches of constant phase width increase in physical length with radius and become curved from the time dependent energy gain. The general tilt at turn 3 and 6, the kink in turn 9 and the thickening of the bunch center at turn 12 are due to space charge forces.

Acknowledgements

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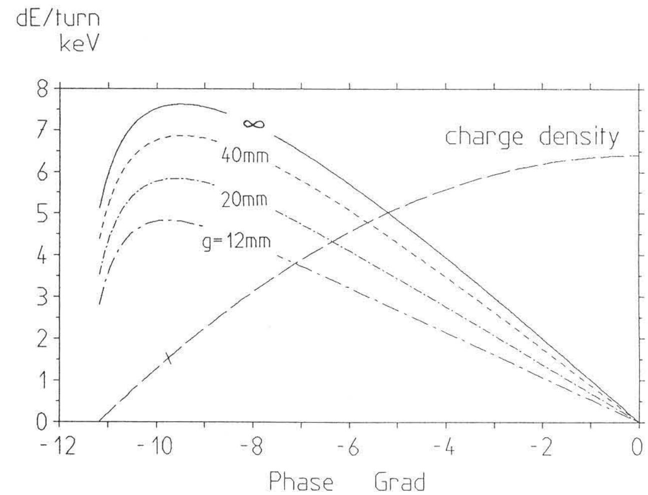

Fig. 12: Effect of image charges on the energy spread induced by longitudinal space charge forces. The curves correspond to different gaps g between metallic plates. Presently we have an average gap of about 40mm in the magnets, RF-resonators and the vacuum chamber. Installation of socalled mirror plates with a spacing of 15mm could give a further reduction of the energy spread by about 30%. The numerical calculations were done for a 1mA beam at a radius of 2.3m assuming a parabolic charge distribution .

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