EXPERIENCE WITH THE PSI- CYCLOTRON RF-SYSTEM UNDER HEAVY BEAM LOADING

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ABSTRACT

The projected proton beam of 1.5 mA from the 590 MeV ring cyclotron requires extensive replacement of RF-system components. Up to now, one of four amplifier chains on the accelerating cavities has been upgraded to provide for the necessary beam power as well as a 40% higher accelerating voltage. This required a new RF-control system and a new, more powerful final amplifier stage. In addition, everything but the cavity had to be replaced on the flattopping system; this in view of the expected heavy beamloading.
Both of these systems are now operational, and first experience with beam intensities up to 500 μA has been gained.
Serious restrictions will be imposed on our existing acceleration cavities. A new copper cavity design is therefore under investigation, with a first 1:3 scale prototype ready for power testing in 1993.

1. INTRODUCTION

The concept and reasons for expanding the PSI - meson facility to very high beam currents have been described previously.[1)2)] Furthermore, a paper presented at this conference by T. Stammbach[3)] deals with the current status of our upgrading program.
This paper will concentrate on the RF-system of the 590 MeV ring cyclotron and discuss the necessary improvements as well as our first operational experience with beam currents up to 500 μA.
These beam currents were obtained with only one accelerating cavity equipped with the new amplifier chain and operating at an increased cavity voltage of 700 kV_p; this corresponds to a power dissipation of approx. 300 kW. It is an increase of 40% in voltage (and 100% in power) over the existing RF-cavities, which continue to operate at their previous voltage levels of 480 kV_p, until they too, will be equipped with new equipment at the rate of one new system per year. One problem remains to be solved by that time, however: the RF-power coupling loops on the cavities work quite reliably at the previously required power levels of < 220 kW (including beam power), but now, at at power levels > 350 kW, the loop on cavity # 1 fails often.
The flattopping cavity, operating at 150 MHz, also received a completly new amplifier chain, RF-transmission line with power divider, absorber and RF-control system.

2. ACCELERATING CAVITIES, 50 MHz

Cavity # 1 was the first one to be equipped with a new amplifier chain and control system. The previously used final stage with 250 kW output power was converted into a driver stage for the new 800 kW final stage. At the same time, the location of the final stage was changed from inside the accelerator vault (close to the cavity) to a location outside and above the vault, about 40 m away, and a new transmission line of higher power rating was installed. This was done in view of the anticipated, much higher radiation dose levels at higher beam currents.

2.1. RF-Control System

The control system is an upgraded and adapted version of the modular concept that has been designed for the Injector 2 cyclotron. It consists of the RF-amplitude, phase, and resonance tuning circuits. The amplitude controller has been expanded by a beam- intensity controlled fast clipping circuit, which limits the maximum output power. This is necessary because of the high output power potential of the new final amplifier. For protection, the maximum power limiter always rides 20 kW **above** the required power level, which will vary from 300 kW (no beam) to about 520 kW @ 1.5 mA beam current. Measurements have shown that the specified amplitude- and phase stability limit (better than 10^{-4}_{pp} resp. less than 0.01°_{pp}) is not exceeded at 500 μA beam current. Figure 1 shows amplitude voltage rest modulation spectrum, at 500 μA, measured with an **independent** pickup loop and demodulator on cavity # 1.
In addition to the increased noise modulation, loop gain is reduced as a function of the beam current; if we neglect an eventual effect of variing load impedance on the final amplifier gain, we get:
$\Delta G = -4.8\, dB, \quad @ \quad I_{beam} = 1.5\, mA.$
Looking at the gain margin in our measured spectrum again (Fig. 1), we see that this gain reduction still keeps all spectral components below the specified limit of 10^{-4}_{pp}.

2.2. Power Amplifiers

The 800 kW final amplifier stage is built in a 'grounded grid' configuration; the advantage of this concept lies mainly

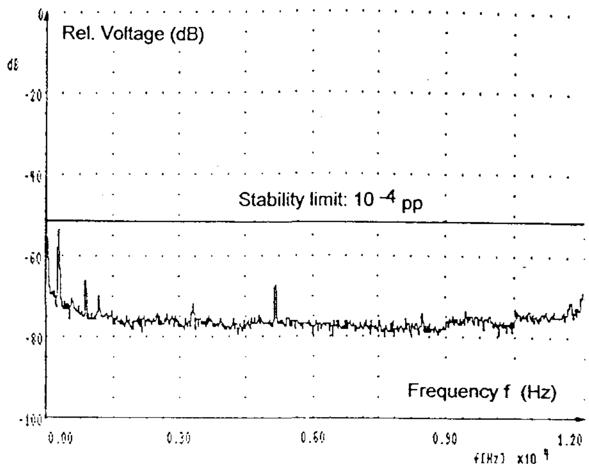

Fig. 1. Cavity voltage rest modulation spectrum, measured on cavity #1, @ I_{beam} = 500μA

in a more stable mode of operation, that is, less tendency to oscillate at parasitic frequencies, and a wider range of tolerable mismatch, since load variations of 1:2 will have to be handled in the future. Furthermore, no neutralisation network is necessary. The disadvantage of reduced power gain (G = 11..12 dB) can be countered by using the 'old' grounded cathode type final amplifier as a driver; it can easily provide the necessary driving power of ~60 kW. Since this stage is equipped with the same type of power tetrode [RS 2074 HF by Siemens] as the new final stage, older tubes with decreasing cathode emission can be transferred from the final- to the driver stage to extend their lifetime. This concept permits the reuse of all existing RF-amplifiers; they were of course rebuilt and power supplies and interlock systems were replaced by new designs.
The amplifier chain has been operated successfully into a wideband 50 Ω load at power levels up to 850 kW, and has delivered 400 kW into the cavity with only minor adjustments.

2.3. Results of first Operation, Problems

After commisioning of the cavity #1 RF-system in June 1991, beam current was gradually increased over the next half year, up to 500 μA (at an increased cavity #1 voltage of 700 kV_p) for about 2 weeks at the end of the year.
The new system performed remarkably well, this is especially true for the 800 kW amplifier, which, up to now has a perfect record.
Unfortunately, the same cannot be said about the RF-power coupling loop on the cavity: it has been an almost continuous source of trouble by causing a lot of unscheduled down time on the accelerator. This loop , which has been improved over the years to perform reliably on the existing power amplifiers, seems to have reached a limit in power-handling capacity. This despite the fact that we have continuously made improvements and modifications to eliminate weak spots over the past year. Some of these were:

- 'Field gradient rings' at both ends of the ceramic cylinder to lower E-field gradients and shield the edges of the ceramic-to-metal seal. These rings are made of the same material (Vacon) as the water-cooled metal rings at the ends, in order to have identical thermal expansion characteristics; and are silver-plated. The rings have been installed on all 4 acceleration cavities.
- Ionisation detection electrode; a DC voltage of 400 V connected to an electrode near the coupling loop, equipped with current monitoring to shut off the RF-drive if a certain 'dark current' is exceeded. This system proved to be effective in detecting multipacting and sparking in the coupling loop region. In fact, since it has been installed on the other 3 cavities, we have not let the machine up to air accidentally by cracking ceramic windows. Unfortunately, it did nothing to improve life expectancy at higher power levels in cavity #1; that is: it prevented breaking the vacuum all right, but shut off continuously.
  At inspection, the ceramic cylinder then turned out to be partially metal-film coated, and traces of pitting could be seen on metal parts.
- Additional water cooling at the base plate of the coupling loop installation, effective RF-filtering and shielding of the DC-bias connection.
- Amplitude clamp electronics: modifications to prevent up to 30% cavity voltage overshoot after a 'microspark'.

Tests on a loop indicated that overvoltage or multipacting at the loop could not be responsible for the failures. It is now suspected that the problems are caused, at least partially, by the high RF-currents in the cavity wall around the coupling hole.
Temperature tests show that dielectric losses in the ceramic material cannot be the sole source of the problem; we found temperatures of the ceramic cylinder (vacuum side) to be between 110° and 140° C, and lower everywhere else, due to the extensive water cooling.
Since it is doubtful that the existing design can ever reach the required power handling capacity in excess of 500 kW, a completely new concept has to be considered. Some ideas are:

- Remove the ceramic vacuum window (cylinder) from the inside of the cavity back into the coaxial transmission line; this has been tried before with a disk-shaped window, with catastophic results due to multipacting.
- Use two coupling loops of the present type, and install them symmetrically about the median plane, with a power splitter in the RF-feed line.

- Change the dimension of the ceramic cylinder in the present design, that is: make it **longer** or **change** the diameter, or both.

3. FLATTOPPING CAVITY, 150 MHz

In April 1992, the new flattopping amplifier - system became operational. It contains several completely different components, compared to the 50 MHz systems. The reason is that the flattopping cavity has to **absorb** power induced by the beam at the rate of ~65 kW/mA; this figure has to be compared to the resonator losses of < 75 kW, at 320 kV_p flattopping voltage. A simplified block diagram can be seen in Fig. 2. One key element in this concept is an high power 50 Ω load, coupled to the transmission line between final amplifier and cavity via a variable ratio 'power divider': a system of λ/4 - impedance transformation sections and variable length 50 Ω- line sections. A detailed description can be found in.[4]
The basic idea of the concept is to lower the Q - value of the cavity such that the critical limit (that is: when the beam - induced power gets into the range of the loaded resonator losses), shifts towards higher beam currents. Above this limit (1 mA), the amplifier tube should act as a variable resistive load to maintain the proper cavity voltage.

The amplifier has to deliver maximum power at no - beam condition and becomes 'unloaded' as beam power is tranferred to the cavity. It is important in this configuration that the line length be adjusted such that the electrical length between cavity and tube is $n \cdot \lambda/2$ (1 : 1 transformation). The cavity impedance always remains resistive due to the resonance tuning system. Even so, the amplifier works into a (resistive) mismatch except at one operating point. The transmission lines have to be considerably overrated to handle the high SWR. Nominal power losses on a mismatched transmision line are by a factor SWR (> 1) **higher** than with a matched line; this requires careful load coupling adjustments to keep transmission line dimensions (and costs) to reasonable levels.
Another problem develops even before the final stage is operated in absorbtion mode: the amplitude - and phase control loops will loose 'controllability' of the cavity voltage. Therefore, in order to keep the amplitude controller in its linear range and operate it in the small signal domain, we **subtract** from the RF - signal between controller and amplifier stages a second RF - signal, with an amplitude proportional to the beam current. This is done with a 0°/180° power combiner, as can be seen in Fig. 2. Such a concept has been successfully operated (at lower overall power levels) on our Injector 2 cyclotron; and although the system on the ring cyclotron has only worked at low beam currents up to 500 μA, we feel confident about its performance above the critical level of ~1 mA.

3.1. Control System

In principle, the control system is composed of the same modular units as are used in our 50 MHz controls, although

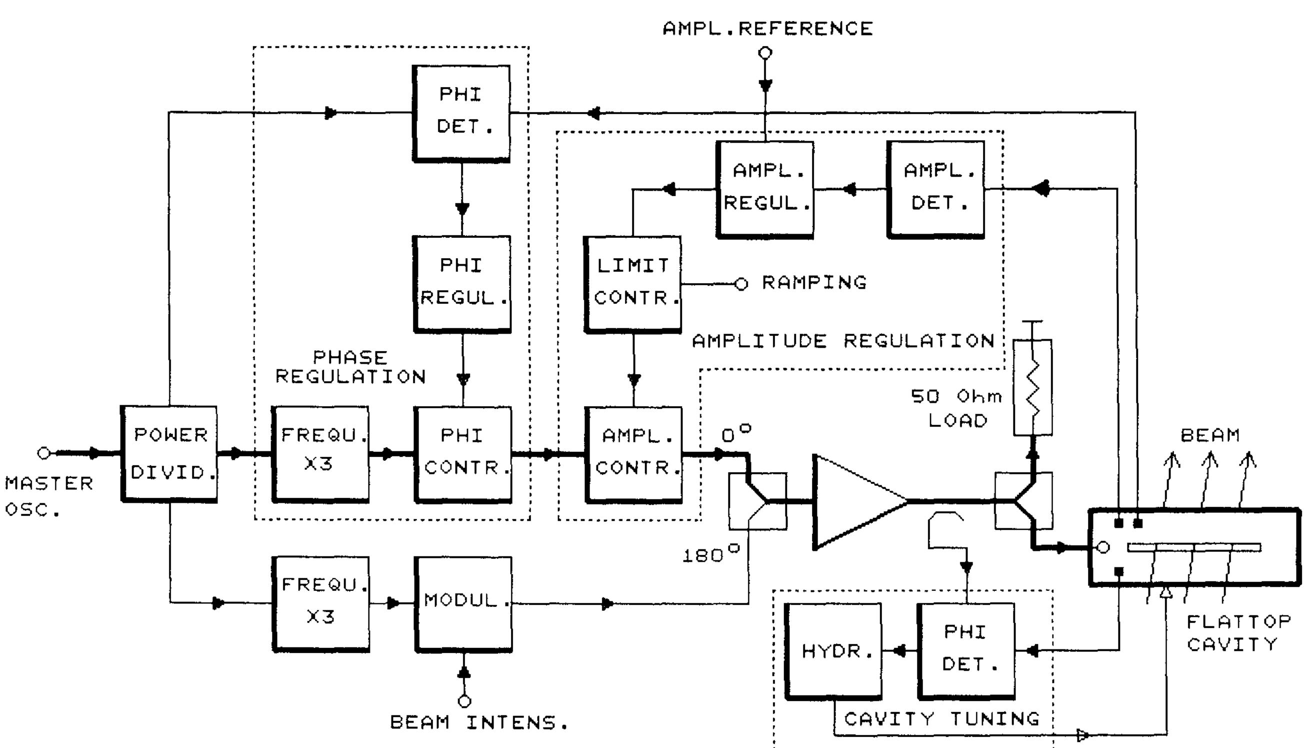

Fig. 2. Simplified block digram of the 150 MHz flattopping cavity control system

some modules had to be adapted to 150 MHz operation. The block diagram (Fig. 2) shows the differences; these are mainly: $3 \cdot f_0$ frequency multiplier, phase locked to the fundamental frequency f_0 , as well as the beam intensity modulator circuit and the $0°/180°$ power combiner used to subtract the beam intensity vector from the (modulated) RF-signal.

3.2. Power Amplifier

A new power amplifier has been designed and built; it uses the same tube as our previous flattopping amplifier, that is: a Siemens power tetrode, type RS 2004 J. Its configuration is 'grounded grid', the mechanical layout is very similar to the 50 MHz amplifier, and the RF-power output is 120 kW @ 150 MHz into a 50 Ω load. In absorbtion mode, the maximum absorbed power is limited by the max. plate dissipation and comes out to be ~42 kW (RF).

3.3. Test Results

There is only limited experience available with the new flattop- system, because beam current in the ring cyclotron was limited to about 500 μA. The flattopping voltage is not yet at its full level; it always operates at ~11% of the total accelerating voltage (ideal flattopping).
The weak element is again the coupling loop; the situation is even more critical than in the 50 MHz cavities, even though total power levels are considerably lower (< 75 kW). Shortly after starting up again after the long shutdown in mid-1991, and still operating with the old amplifier system, the loop failed. Metal surfaces of the loop assembly were coated with a flaky, magnetic film which easily could be wiped off. The 'metal films' were created when arcing caused sputtering of stainless steel and 'Vacon' surfaces. A second failure at the end of 1991 showed similar effects, so a replacement loop will be equipped with an ionisation detector (electrode) similar to the concept used in the 50 MHz loops. (comp. Section 2.3)
This coupling loop is hampered by its smaller size compared to the 50 MHz types used in accelerating cavities; this is due to the high field at the loop location plus the fact, that it has to provide 50 Ω coupling impedance for matching of the cavity to the transmission line at 150 MHz. One way to improve that situation is to increase the overall size of the loop by designing it for a higher coupling impedance, of say, 118 Ω, and then add a $\lambda/4$-transformation section ($l = 0.5$ m, $Z_0 = 77\,\Omega$) to the outside of the coupling loop flange to match it to the 50 Ω transmission line.
Another method might be to move the loop to a different location (with less field) on the cavity.

4. NEW ACCELERATION CAVITY (PROTOTYPE)

The present cavity voltage of 700 kV_p is considered to be the maximum safe voltage for continuous operation. The corresponding power dissipation of 300 kW presents a thermal and mechanical limit. The original concept was designed to dissipate 130 kW, it was built from aluminum, with integrated cooling. This makes the cavity very sensitive to changes in atmospheric pressure and temperature; furthermore, temperature gradients across the cavity walls make it impossible to turn on the cavity to the higher operating voltage in one step. Instead, a two step (or ramping) turn- on procedure has to be followed each time the cavity has been turned off for more than 1/4 hr. This will produce lenghty interruptions in beam production at a time when all four cavities will be operating at full accelerating voltage. Should one cavity fail mechanically, there is no spare available; for that reason alone, we are quite interested in a new cavity. The following points should be considered and improved in a new cavity design:

- The mechanical support structure designed to hold up the cavity against an atmospheric pressure has to be separated from the cooling system, this should drastically reduce thermal influences on the resonance tuning system.
- Using copper instead of aluminum for the cavity's inner surface as well as changing the shape of the cavity allows us to obtain a calculated 10 to 15 % higher Q-value, which translates into considerable savings in RF power.
- Integrated acceleration gap electrodes, instead of bolted-on units as in our present design, allow direct water cooling and eliminate the present contact- and thermal conductance problems.

We hope that using copper as our RF-surfaces, as well as a different geometry, will lead to an improvement in multipacting behaviour and turn-on characteristics as well.
We are at present in the design stage of a 1:3 model cavity prototype for power testing, since we now have a spare 150 MHz/60 kW amplifier chain available. It will furthermore allow some limited coupling loop design testing. The cavity prototype is scheduled to be available for first measurements by the end of 1992, and power testing should hopefully start sometime in 1993.

5. REFERENCES

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