HIGH BEAM POWER RF- SYSTEMS FOR CYCLOTRONS

P.K. SIGG, J. CHERIX, H.R. FITZE, H. FREI, M. MÄRKI, U. SCHRYBER

Paul Scherrer Institute (PSI), CH- 5232 Villigen, Switzerland.

If beam currents in cyclotrons are to be increased into the mA range, conventional RF systems will have to be redesigned completely. Beam power in the order of hundreds of kW has to be supplied through the accelerating cavities and becomes comparable to the dissipative power losses of such cavities. In case 'flat-topping' is employed in order to increase the phase acceptance in the cyclotron, such flat-topping becomes increasingly difficult to implement. Here we present the necessary modifications to 'normal' cyclotron RF systems, which are required to achieve high beam currents in cyclotrons. We use as an example the upgrade from 100 µA to 1.5 mA (@ 590 MeV_p) of the PSI ring cyclotron. The RF-upgrade program is presented and results are discussed, along with progress made since the last status report in 1992. The complete upgrade program is presented elsewhere at this conference. Finally, an outlook is given on some future improvements desirable in the present design, including the possibility of replacing the acceleration cavities.

1 Introduction

The PSI - facility for the production of high intensity proton beams consists of two stages of separated sector cyclotrons. The first (injector-) cyclotron has an output energy of 72 MeV, the proton beam is then accelerated to the final energy of 590 MeV by four acceleration- and one flat-top cavity in an eight-sector ring cyclotron. Originally, the acceleration cavities where designed for a peak gap voltage of 450 kV_p (@ 50.63 MHz), with dissipative cavity losses of around 115 kW. The corresponding figures for the flat-top cavity were 300 kV_p (@ 151.9 MHz) and 23 kW.
When the decision was made to expand the facility to deliver high proton beam currents (>1mA) to a spallation neutron source [1,6], the RF system of the ring cyclotron, along with other major components, had to be redesigned and rebuilt.
After extensive testing for peak voltage limits and maximum cooling capacity on one of our acceleration cavities, it was decided that it would be safe to increase the cavity gap voltage to 730 kV_p, corresponding to cavity losses of about 300 kW. (It should be noted, however, that we have *not* reached a voltage breakdown limit, rather it is the cavity cooling system that prevents higher power dissipation)
This acceleration voltage increase was very much welcomed by our accelerator design people, most notably by W. Joho and S. Adam.They pointed out early that an increase of the acceleration voltage would, - through a reduction of the turn number in the accelerator - permit a respectable increase of the beam current, the limit of which is dominated by longitudinal space charge effects. [4].
One serious consequence of this decision was, however, that the flat-top cavity would turn into the weak link of our concept; with a required peak gap voltage of approx. 490 kV_p. This voltage was arrived at by taking the integral of the deceleration voltage over the gap range (required for flat-topping) to be 11 % of the total acceleration voltage.

Not only would the flat-top system have to handle by far the largest load swing of all RF systems; its amplifier, coupling loop and controls were also required to operate over a range where no such system had operated before. Decelerated particles act like an additional RF generator on a cavity, and this renders 'normal' amplifier- & control systems useless. They will turn unstable at high beam intensities. Generally speaking, it is the flat-top system as a whole that presents the most difficulties in achieving high beam currents.
Another problem area was the power handling capability of the RF coupling loops. In the case of the flat-top cavity, in particular, it was doubtful, based on past experience, that one coupling loop alone would ever be able to handle the much increased RF power flow into (and out!) of the cavity. The existing design, although improved over many years, still had a restricted life expectancy of somewhat over 1/2 year, so a solution was most needed there.
On the other hand, the injector cyclotron, already conceived with much higher beam intensities in mind, needed comparably little new hardware, although to achieve the desired current levels was by no means a routine operation [3]. The injector cyclotron was commissioned in 1985, the design goal of 1.5mA of proton beam current at 72 MeV was reached in 1991 [6].
Efforts therefore concentrated on the upgrade of the ring cyclotron RF system; the scope of the entire program has been described previously [1,6], along with an intermediate progress report in 1992. [2].
Since then, the program has reached completion, and we have gained first experience with high beam intensity operation up to 1.4 mA [1], with test periods at 1.5 mA.
It is therefore appropriate to summarize the experience gathered up to now, and derive some general recommendations and conclusions, adressing the design and operation of high beam current cyclotron RF systems.

2 Characteristics and Requirements

If a cyclotron is to be used for high beam currents, it requires special RF systems, or, to be a bit more specific: two different types of RF cavities (acceleration- and 3rd harmonic- [or *flat-top*] cavities), and amplifiers and control systems able to handle large load variations. It is assumed that such a cyclotron RF system is designed with the following key characteristics: *fixed frequency and cw operation*. This is a deviation from most conventional RF designs, which, in cyclotrons, usually allow for some energy range and therefore require variable RF frequency and voltage , or, in the case of synchrotrons or linacs, operate in pulsed mode.
Next follows a résumé of a few of the main specifications and features.

2.1 Acceleration cavities

- high cavity voltage, to obtain a large energy gain per turn and good turn separation.
- Efficient (that is: fast) conditioning of cavities after pumpdown of the cyclotron, the same condition applies to flat-top cavities !
- low losses (high Q-value); this results in less demanding cooling and reduced RF power requirements for a given acceleration voltage and increases the overall efficiency of the RF system.
- large power handling capability and high reliability of coupling loops; additionally, the loops should be easy to replace and repair.

2.2 Flattopping cavities

They have to absorb power from the beam; at high beam currents the beam *induces* more power in such a cavity than is required to compensate for cavity losses, that is: to maintain the proper cavity voltage. This poses some serious problems; several approaches have cristallized; but more than the cavity alone is involved in all suggested solutions.

a. A first way to solve the problem is to use a standard cavity (= high Q), an amplifier of the lowest possible power output (in our case: 40kW, to cover cavity losses only) and an additional, beam- intensity controlled RF power absorber stage, coupled to the cavity through a separate coupling loop. The feasability of such a solution has been investigated in a low power (8 kW) absorber model on one of the flattop cavities in our 72 MeV injector cyclotron. Tests, run without beam, have shown that such a system could indeed be built, using a power triode as a variable load, a so-called reactance tube.[5] It also became clear, however, that additional costs, comparable to the costs of a complete amplifier chain with the power rating close to the total of the induced beam power (approx. 80 kW), including all DC power supplies, could not be avoided.

b. Another possible solution - a heavily damped cavity - can be obtained either by coupling a fixed, external load to the cavity, or by using a cavity covered with very lossy inner surface material and appropriate cooling. This approach of course requires a very powerful RF amplifier (in our case: > 150 kW), but allows it to be operated in a fairly conventional way, albeit with a widely varying load.

c. And finally, a mixture of the above can be thought of: a moderately damped cavity; additional damping done with an external load, coupled to the transmission line between power amplifier and cavity. At high beam currents, the RF energy flow in the transmission line to the cavity will reverse, so the amplifier has to be able to operate as a controlled absorber. Special precautions have to be taken in that case, principally in order to maintain stability of the phase- and amplitude control loops when the system changes over to the absorber mode. The primary advantage lies in the fact that less RF power is needed when compared to version b), so costs should decrease, while overall efficiency will increase. Compared to version, a), we save a 'full size' amplifier chain (the absorber), but will require higher main amplifier power rating, plus a (relatively simple) fixed load. Overall,the result is a simpler design .

2.3 Amplifiers, Controls

- Final amplifiers for acceleration cavities have to handle wide load ranges, caused by beam power levels comparable to cavity losses. Furthermore, such amplifiers should be designed with high AC-to-RF conversion efficiency (η) as well as overall efficiency in mind.
- Since acceleration voltage stability requirements are very stringent, control loops have to be adaptive, that is: adjust their transfer-function characteristics according to beam loading to maintain best possible regulation.
- Special start-up and spark recovery schemes have to be implemented in order to minimise down-time after a spark occurs in a cavity or on a coupling loop; furthermore, special probes and fast circuitry for the coupling loop ceramic window protection are needed.
- As mentioned in the previous paragraph, flat-top control systems are particularly demanding, since the RF amplifier has to operate in absorbing mode at high beam current levels. Amplitude- and phase stability has to be maintained, even though the RF drive signal to the final amplifier may change its phase by 180°.

3 Upgrade of the PSI - 590 MeV- Accelerator:

Goal: Increase beam current from 100 µA → 1.5 mA; that is: beam power from 60 kW → 900 kW !

Total elapsed time: almost 10 years, from planning stage to operation at full current level.

Costs of **RF upgrade** : ≈ 10'000'000 sFr (≅ 8.8 M$); this sum was spent for:

- New, high power final amplifier stages (850kW @ 50MHz, into 50Ω load); which had to be developed in house, at PSI.
- Larger transmission lines between amplifier and cavity; this reconstruction was combined with the removal of the final amplifier stages from inside the cyclotron vault to a location on the roof of the vault, providing much better accessibility and preventing activation of the amplifier stages.
- New RF controls, new cavity tuning system, 'micro spark' interlock suppression and a new RF start-up system, designed to reduce cavity down time after a (non-recovering) spark occurrence from about 4 ...15 min. to a few seconds.
- Completely redesigned coupling loops (power windows) for the 50 MHz acceleration cavities, capable of handling four times higher RF power than previous designs (now: > 600 kW); and equipped with special pick-up probes (see figure 7) and protection circuitry. Basically the same concept is also applied to the new flat-top cavity loop design at 150 MHz.
- A New RF system for the flat-top cavity, with new amplifier and cavity-damping hardware, including a new coupling loop. It is designed to run in absorber mode at very high beam current levels.

4 The Flat Top System in a high Beam Current Environment

Table 1 shows the increase in power levels and dynamic range of the upgraded flat-top system; listed in this comparison are the 'no beam' and the 'maximum beam' figures for each system.

Table 1: Comparison of old and new flat-top system

F.T. - SYSTEM:	OLD		NEW	
I_{beam} (mA)	0	0.25	0	1.5
P_{beam} (kW)	0	15	0	96
V_{cav} (kVp)	300	300	490	490
P_{cav} (kW)	23	23	60	60
P_{load} (kW)	17	17	40	40
P_{AMP} (kW)	40	35	100	4
$P_{in}(=P_{cav}-P_{beam})$ (kW)	23	8	60	**-36**

As was mentioned earlier, a flat-top system is the most unconventional RF system in a high beam current cyclotron environment. The concept is best illustrated by a simplified block diagram (figure 1), which shows the way the beam current compensation (actually a feed-forward system), the 50 Ω load and the power splitting are implemented.

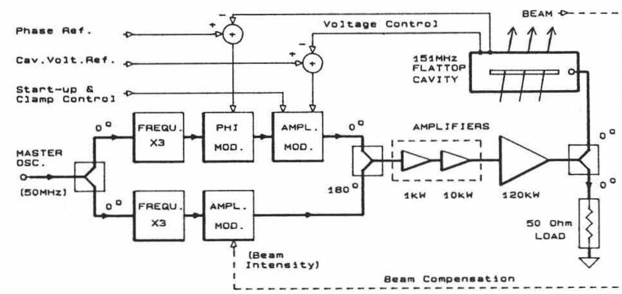

Figure 1: Block diagram of the PSI flat-top system

To understand the necessity for such an arrangement, one merely has to look at the RF energy flow at the 'no beam' condition and at 1.5 mA beam current. (fig. 2)

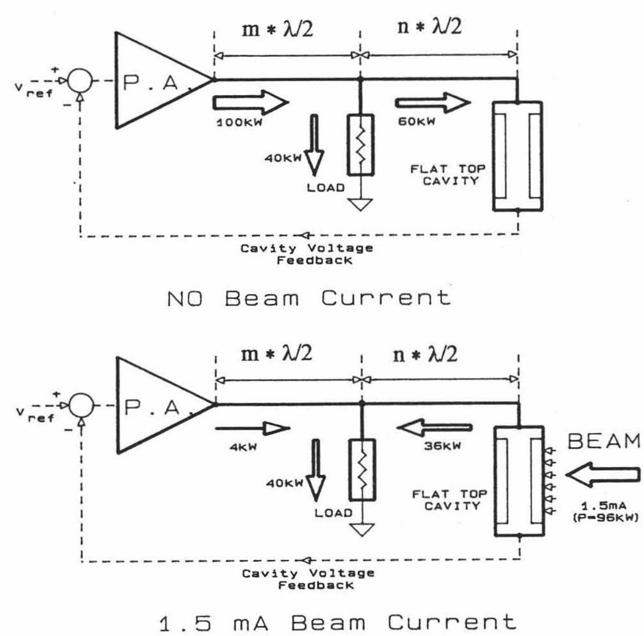

Figure 2: Symbolised RF energy flow at 0 and 1.5 mA beam levels

Power levels indicated in the above figure are actually deduced by superposition of incident- and reflected waves in the transmission lines; these signals can be measured separately, using directional couplers.

The following figure (3) shows graphs of RF power levels, (incident- and reflected power) at two points in the system, indicating the large variation of these parameters as a function of the beam current.

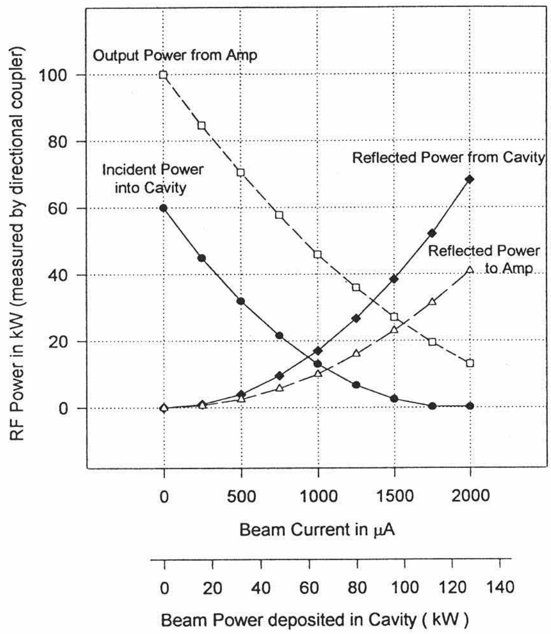

Figure 3: RF power levels as a function of beam current, showing extrapolated range to 2mA

The coupling of the high power load (several 100 kW) to the transmission line between final amplifier and cavity has been designed to allow a variable power splitting ratio; that is: something like a *variable ratio* power divider! This is done with passive devices; components like variable length transmission line segments (so-called 'trombones'), and variable impedance quarter-wavelength transmission line elements (λ/4-resonant impedance matching sections), as shown in figure 4.

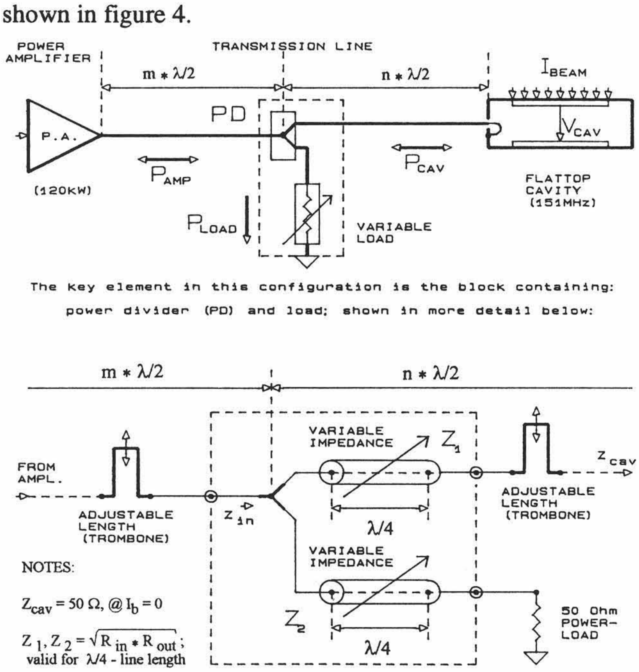

Figure 4: Schematic of the cavity loading network

Here one can see clearly the benefits of operating a cyclotron at a fixed frequency; such solutions would be even more complicated if one had to adjust all these parameters as functions of the operating frequency, just to keep the division ratio fixed.

In our case, all elements are adjusted once (manually) for a desired power split ratio and will then be left fixed.

To fully comprehend the function of the compensation system, it is quite important to notice, that the power delivered to the absorber load stays *constant* over the entire range of the beam current. This is due to the fact that, since cavity voltage is stabilised, so is the voltage at the power division point, because of 1:1 transformation between cavity and this point! (fig. 4)

To understand how RF signals under closed loop operating conditions behave as the beam power level increases, it helps to look at different phasors (RF signals as vectors) at several locations around the loop. The phasors are represented at a few selected beam currents, to show the ones that are most affected. As was mentioned before, some even reverse their polarity. (see fig. 5)

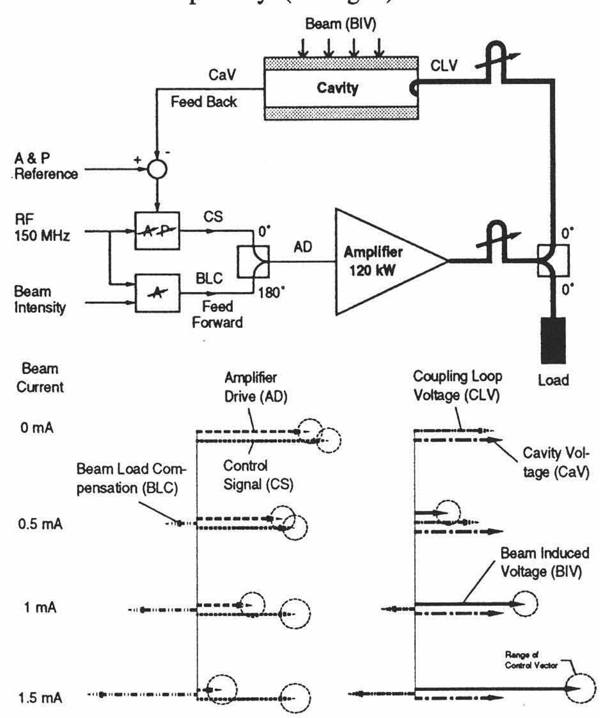

Figure 5: Phasor diagram, showing voltage phasors at different points in the system, for selected beam currents.

The ranges of distortion- and control vectors are also symbolically indicated. As the dotted circles show, high beam currents produce magnitudes of these signals comparable to the 'carrier' signal, at least in some cases. It implies that small signal operating conditions - which normally allow linear and stable operation - are no longer valid, and that non-linear behaviour of amplifiers and/or modulators will set in.

This effect is clearly shown in spectra of the cavity phase signal, which were taken a) without beam, b) with 1200μA and beam load compensation turned off, and finally c): with the compensation active, also at 1200μA beam current. (see figure 6)
This (feed forward) compensation operates with the following response:

V_{comp} = 0 | $I_B < 400$ μA,
= $a + b*I_B$ | 400 μA < I_B < 1.5 mA.

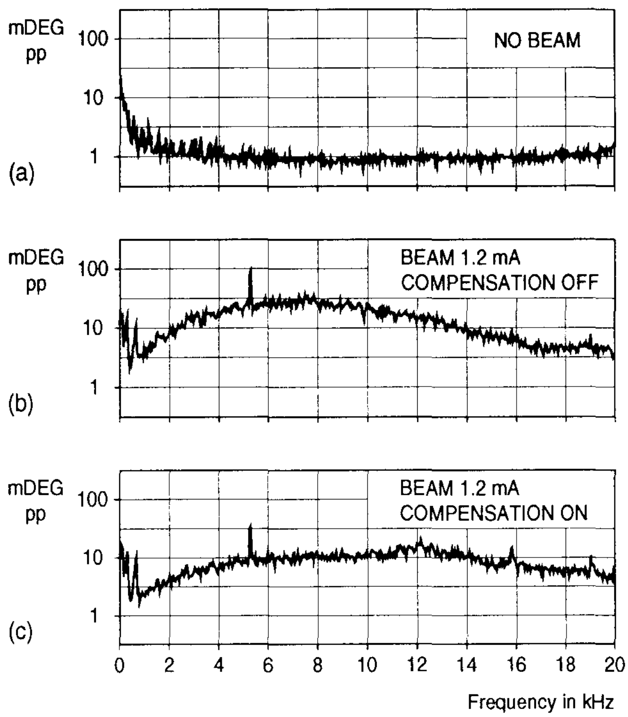

Figure 6 : Effect of beam load compensation on flat-top cavity phase spectra

5 What have we built, achieved and learned since the last progress report of June 1992 ? (ref. 2)

- Our new coupling loop design has proven to be quite successful indeed: the first model installed has operated at over 500 kW RF-power for over 2 years; furthermore, none of the other three identical couplers subsequently installed on the other 50 MHz accelerating cavities have failed as of this time.This progress is mostly due to knowledge gained by the use of special pick-up probes for electrons, mounted on the flange of a 50 MHz acceleration cavity coupling loop. They permit the analysis of sparking phenomena at the loop.
  The same concept was applied in the design of the power coupling loop on the 150 MHz flat-top cavity, where we additionally got rid of the strong influence of the coupler geometry on the cavity resonance frequency, which was immanent in the previous design. This new design turned out to be highly successful, considering our past experience with loops at this frequency (compare ref. 2, section 3.3); it has been installed in the spring of 1994, and has not been replaced since!

- Thanks to careful analysis of sparking events, by observing transient behaviour of cavity voltage signals, incident- and reflected power signals, as well as the above-mentioned pick-up probe signals, we think that we have gained a much better insight into the phenomena which control voltage breakdowns and discharges at the coupling loop ceramic insulators. The probe as well as a symbolised plasma 'bubble' is shown in figure 7. (See also: section 5.1)

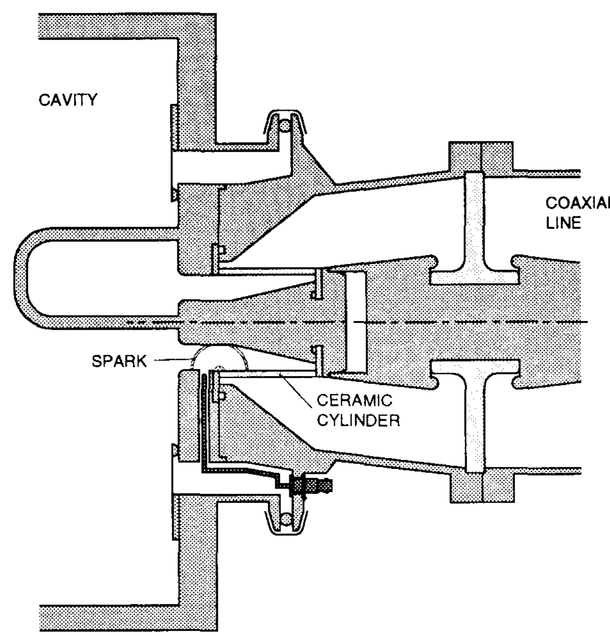

Figure 7: Coupling loop cross-section, with spark detection probe

This analysis allows us to define and adjust the special RF drive control circuitry and procedures in order to protect a coupling loop from failure due to cracking of the ceramic insulator.
The system operates as follows: If electrons are detected on the special pick-up probe (indicating a spark at the coupling loop), the RF drive is suppressed within microseconds and held down for ≈ 100 μs; before being released to *full power* again. This requires that the final amplifier and transmission line be able to withstand full (> 600 kW) reflected power for a few 100 μs.
As a result of this instantaneous suppression of the RF power from the power amp, the duration of a spark is

drastically reduced, along with total energy dissipated in such a spark; since only energy stored in the cavity is available as an energy source. (compare fig. 8 & fig. 9) It seems essential, that sufficient time is allowed to pass for clearing the area of the spark from ions before power is again applied to the loop and cavity; sufficient in our case being 100 µs. The following two figures show timing diagrams of signals from the spark detection probe, cavity voltage, and power levels in the transmission line; first, *without* the suppression circuit (fig. 8) and then, in fig. 9, *with* this circuit *operational.* Most of the time, fully stabilised cavity voltage is reestablished within less than 300 µs after the onset of a spark.

In case the arcing repeats within the next ≈ 20 ms, the RF drive is turned off indefinitely, and has to be turned on again by an operator.

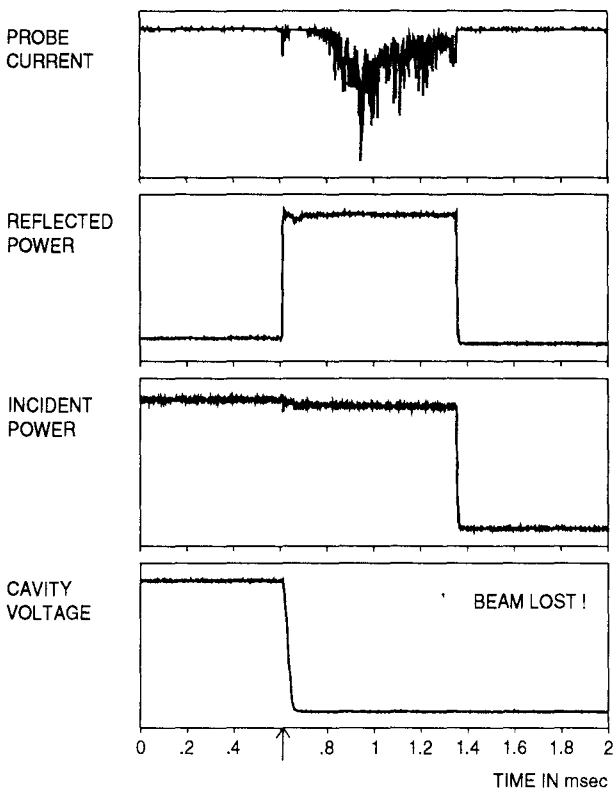

Figure 8: Timing diagram of signals from: spark detection probe, cavity voltage, and transmission line power levels; without suppression circuit.

- Subsequently, we obtained a significant overall reduction in the number of spark-triggered beam interlocks, by suppressing such interlocks for ≈ 650 µs. We called these events: 'micro- sparks', to set them apart from sparks that do not lead to automatic recovery within the given time window.

  Of course, components inside the cyclotron (extraction septa, for example) must be able to handle the beam spill resulting from the momentarily reduced acceleration voltage, and eventually, ionisation detectors of the interlock system may have to be bypassed for this time interval as well!

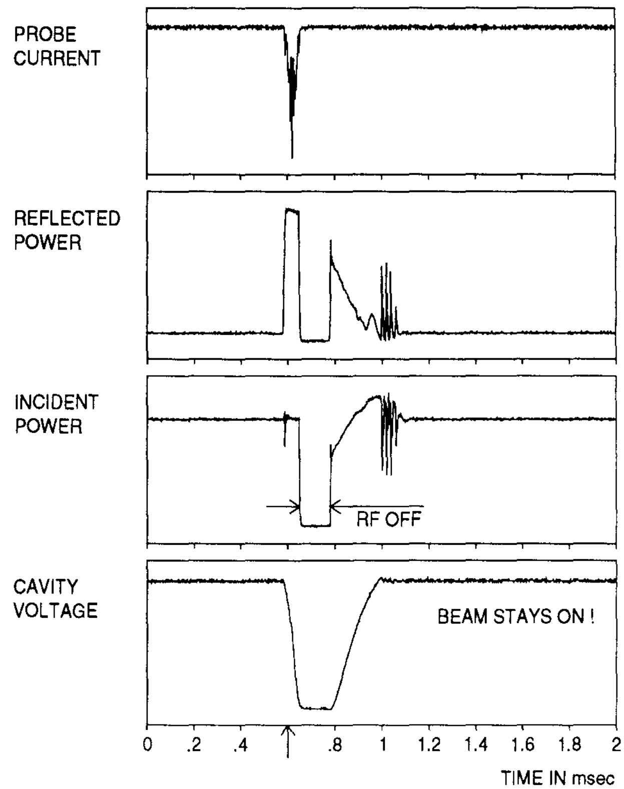

Figure 9: Timing diagram, same configuration as in fig.8, but with *suppression circuit active.*

- In the case of 'unrecoverable' sparks (no recovery of cavity voltage within 1.5 ms), RF drive is definitely suppressed and a special "start-up unit" takes over. This start-up unit permits the cavity voltage to be re-established within seconds, using 300 kW peak power RF-pulses of 100 µs width, at 10 ms repetition rate, until the cavity voltage breaks through the multipacting barrier. Then, CW operation resumes at a reduced power level, followed by ramping to the full cavity voltage.

  This compares very favourably to the old system's 4..15 min. recovery time. That time resulted from effects of temperature gradients in the cavity walls, which are so strong that, after power is removed from the cavity for more than a minute or two, they deform the cavity such that the range of its frequency tuning system is exceeded (compare fig. 10).The previous cavity sweeping and conditioning system, together with the less powerful final amplifiers, was unable to 'push' through the multipacting range of the cavity voltage fast enough, that is: before the limit of the tuning system was reached.

The start-up procedure and equipment is still under development, we feel that the system can be further improved and optimised, to catch even more of the 'unrecoverable' spark events.
At the moment, we are also in the process of building and testing a similar start-up system for 150 MHz, to be used on the flat-top cavity, if advantageous.

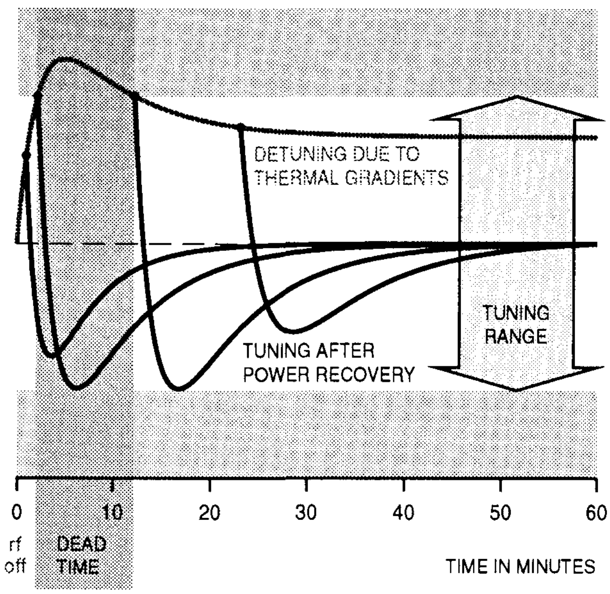

Figure 10: Cavity tuning behaviour, after RF-drive interrupt; for 4 different start delays. The starting-point curve shows the strong influence of thermal gradients in the cavity walls.

5.1 A Hypothesis for the spark generation process.

Over the past few years, we have gained better insight into the causes and mechanisms of sparking in RF cavities and, in particular, in the vicinity of power couplers; of the capacitive as well as inductive type. In particular, a hypothesis of the voltage breakdown mechanism emerged, showing good correspondence to observations. The (tentative) line of arguments runs as follows:
Nonconductive material (such as a dust speck, ceramic insulator surfaces, or an insulating surface layer on aluminium cavity walls, like Al_2O_3) inside a cavity is continuously exposed to showers of electrons from ionisation processes in the vacuum. Frequently, such spots or regions possess a relatively high secondary electron emission coefficient, leading to an accumulation of *positive charge* in such material.
As soon as such an 'island of charge' exceeds the voltage breakdown anywhere at its periphery, a discharge ensues towards some conducting material. This discharge produces high enough temperatures to melt and evaporate some material, and blow it off in the shape of a plasma 'bubble', with a determinable propagation speed. On expansion, this 'cloud' produces large amounts of electrons, which in turn lead to a complete mismatch in a cavity by detuning the cavity. This process is well understood and has been investigated in depth in reference[7]. When this plasma bubble finally reaches (and therefore in effect: *shunts*) a gap with high RF-field gradients, it may trigger a secondary breakdown at this location. This phenomenon seems to be the cause of sparking at the coupling loop, as visible traces on the loop components, as well as observations of probe signals (timing) and some simple computations of propagation velocities indicate. Statistical evaluation of the duration of 'micro sparks' reveals, that they can be categorised into a few sets of well defined time intervals.
These groups can be attributed with fair confidence to propagation delays of ionised 'bubbles' across certain geometrical structures inside a cavity; such as: the acceleration gap, cavity width, or accross components of the coupling loop.

6 The next step: A new acceleration cavity

What are our design objectives in such a concept? Given the fact that a new cavity would have to be fitted into the existing PSI ring cyclotron, the following design goals can be set:

- Increased gap voltage: go from $730kV_p$ to $1MV_p$, and, at the same time: try to reduce the overall number of sparks (and/or micro sparks). This may call for different cavity inner surface material (Cu or any other suitable surface layer, instead of Al). Continuing studies of discharge phenomena on our 1:3 scale cavity model will hopefully assist in making this decision.

- Higher efficiency (Q-value), partially achieved by choosing (for example) copper instead of aluminium as cavity surface material, and partially by using a different, optimised cavity shape; optimised for maximum shunt impedance (+ structural integrity?). This process will be limited, of course, by geometry constrains given by our existing ring cyclotron design!

- A different mechanical structure; to improve stability, cooling and facilitate tuning by decreasing the thermal frequency drift range (compared to our present cavity design; its behaviour shown in fig. 10).

- If necessary: multiple RF power coupling loops to handle the greatly increased RF power requirements.

As mentioned in ref. 2, we are in the process of building a 1:3 scale cavity (150 MHz), to operate under power and in vacuum, to test these concepts as well as the feasibility of

the manufacturing process. Welding of the raw cavity structure has now been completed, and cooling system tests (and sealing!) are about to be finished. Vacuum tests and first low power RF tests will begin shortly, and first high power tests are scheduled to begin sometime next year.
If a 1:1 scale cavity based on this design can indeed be built in the future - at present, this depends at least as much on financial- as on engineering aspects - then it is hoped that such a cavity will become an important stepping stone on the way to a 10 MW cyclotron, as mentioned in ref. 1.

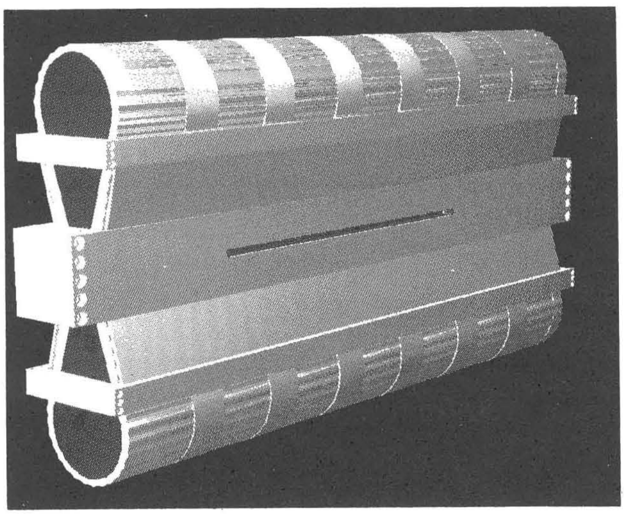

Figure 11: 150 MHz test cavity (1:3 scale model)

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