DEVELOPMENT OF HIGH POWER GRIDDED TUBE CW RF SYSTEMS WITH EXCELLENT RELIABILITY AND MAINTAINABILITY

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Abstract

In the course of expanding the PSI proton accelerator complex towards very high beam currents, the entire RF system (except cavities) was redesigned. Aside from the set beam intensity goal, higher reliability became a prime objective. Analysing problem areas and failure mechanisms led to a much improved overall system. New power amplifiers and coupling loops were designed, together with improved protection, spark detection and RF recovery systems. This paper shows and explains the recently obtained results in performance and discusses means for further improvements.

1 INTRODUCTION

As a first step in the upgrade of the 590 MeV(p) PSI accelerator complex, from initially 200 µA to 1.5 - 2 mA; the conventional injector cyclotron (72 MeV(p)), was replaced by a different design: a separated sector cyclotron [1]. This concept allows more energy gain per turn and therefore, lower beam losses at injection and extraction (< 0.02 %). An extracted beam current of 1.5mA @ 72 MeV(p) was first obtained in 1991 [2].

Extensive changes on the 590 MeV ring cyclotron RF system were required. Total beam power increased from 60 kW to 1 MW, calling for 250 kW beam power per cavity. To stay clear of the expected longitudinal space charge limit at these elevated beam currents, the cavity voltage was raised from 480 kV_{peak} to 730 kV_{peak}, thus increasing cavity losses from 120 kW to 300 kW.

Therefore, new power amplifiers were needed, each to deliver > 600 kW (CW) @ 50 MHz. To facilitate maintenance, and to reduce the number of activated components, these new final amplifiers were planned to be placed outside the cyclotron vault, even though this called for RF power lines of 20 to 45 m in length between amplifiers and cavities. The amplifiers were designed with ease of maintenance and high reliability in mind. The net result is a much shorter MDT (Mean Down Time) in case of amplifier or power tube failure.

Additionally, the flattop system (3^{rd} harmonic RF) was completely redesigned, in order to obtain stable operation of the amplifiers and control system over a wide power range of 30 kW to 120 kW [3].

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In all RF systems, the MTBF (Mean Time Before Failure) of the power coupling windows was inadequate at power levels above 200 kW. Analysis of the sparking phenomena on RF windows led to a better understanding of the voltage breakdown mechanisms [3]. This resulted in the design of new coupling windows, capable of handling RF power levels in excess of 600 kW, and life expectancies of 3 years or more.

2 BEAM INTERRUPTIONS

Next to beam quality, the *frequency of occurrence* and the *length of beam interruptions* during scheduled beam production time are **the** measures of accelerator performance.

2.1 Classes of Beam Interruptions

One way of defining classes of beam interruptions is acc-ording to the length of the 'beam-off time': three groups seem to be sufficient in the case of the PSI accelerators.

Table 1: Classification of beam interruptions (trips)

DURATION OF BEAM INTERRUPTION	CLASS
Short beam trips (duration ≤ 1 min)	**1**
Medium length beam trips; between 1 min to about 1 hr	**2**
Long interruptions, lasting > 1 hr (mostly component failures !)	**3**

Analysing the beam trip data base and consulting the accelerator log book (maintained by the cyclotron operating group) allows an assessment of the sub-systems involved. The following table lists the cyclotron subsystems (both accelerators) and the classes of beam trips they contribute to most frequently.

Table 2: Cyclotron subsystems and beam trip classes

SUBSYSTEM	CLASS
Electrostatic beam deflection devices	1&3
Beam monitoring devices, interlocks	1
RF SYSTEMS	**1&2&3**
All other systems (magnets, power supplies, vacuum & cooling, controls)	3

2.2 Beam Interruptions Caused by RF Systems

The presumption that RF systems do contribute heavily to the total unscheduled beam-off time is confirmed by the accelerator operating statistics. Take, for example, the year 1997, the last year before all new RF system components were installed, calibrated, and operational.

The RF systems of the ring cyclotron were to blame for ≈ 23 % of the accumulated (unscheduled) down time; all RF systems together (both accelerators) accounted for ≈ 34 %. This corresponds roughly to the percentages of previous years. In 1998 however, the ring cyclotron was responsible for a mere 0.2 % (with a bit of luck !); the share of all RF systems decreased to 14 %. The figures in table 3 - accumulated class 2 and 3 events - have to be attributed mostly to component failures.

Table 3: Cumulative beam down times (hrs), and their percentages of total scheduled beam time

Cumulative Beam Down Time	**1997** hrs	**1997** %	**1998** hrs	**1998** %
Ring Cyclotron RF	160	2.7	**10**	**0.2**
Inj. II Cyclotron RF	80	1.35	81	2.0
Total, RF	240	4.1	91	2.2
Total, all Systems	705	12.0	648	15.9
Sched. Beam Time	*5870*	*100*	*4080*	*100*

The reduction seen for the year 1998 reflects, for the first time, the full effect of the RF system improvement pro-gram, with one exception: *45 hrs* of the injector cyclotron down time had been caused by the need to convert the last of the old RF power coupling windows on a resona-tor to the new design after it had failed. In the future, we anticipate the beam-off time to be approx. *8 hrs* in the case that an RF- window has to be replaced; most of this time will now be used for the cyclotron vacuum pump-down.

2.3 Class 2 & 3 Beam Trips in RF systems

Class 2 beam interruptions triggered by RF system inter-locks are mainly caused by multipacting in cavities after a spark, combined with thermal effects affecting the cavity geometry, which, in turn, prevent the build-up of the acceleration voltage for up to ½ hrs. The latter effect is caused by the limited range of the cavity resonance tuning system and occurs in the case that the cavity voltage cannot be restored within ≈ 2 min. after a spark. The number of these events has now been drastically reduced (see Fig.1), mainly because of a new cavity tuning, power pulsing and turn-on concept [4], but also due to additional 'Aquadag' coating in some cavities that were not previously treated.

Beam interruptions of class 3 (component failures) are now the dominant contributors to the Cumulative Down Time (CDT), as well as the mean down time (MDT).

2.4 Short Beam Trips of Class 1 (Sparking !)

Trips of < 1 min. duration are quite frequent in RF systems and electrostatic beam deflection devices. They contribute very little to the cumulative down time (CDT); they are, however, mainly responsible for poor Mean Time To Failure (MTTF) performance of the cyclotrons, and become increasingly important in applications of accelerators which demand extremely stable beam conditions.

RF- triggered short beam trips are almost exclusively caused by sparking in cavities and around RF power coupling windows. Depending on the duration (and location) of a spark (or discharge), two different spark-handling procedures are employed:

- *Spark in cavity, of < 650 μs duration*; this is what we call a 'micro-spark' (μ- spark):
  → RF drive stays on;
  → **beam stays on**.
- *Spark in cavity, but of > 650 μs duration:*
  → **beam is turned off** after 650 μs, then:
  → after 3 ms: RF drive is turned off, followed by:
  → 'Auto Start' procedure: tuning, pulsing and ramping to full voltage, within 4 to 6 sec.

A special case is the following:

A spark at the coupling window (vacuum side) is detected by the electron (e^-) detection probe:
→ RF drive is suppressed within 3μs, for 150 μs; then *turned back on to full power* immediately.

In the event that the beam is turned off, the time needed to turn on and ramp up the beam to full intensity dominates; taking about 45 sec.

2.5 New Data on Cavity Voltage Trips

In Nov. and Dec. 1998, we monitored the cavity voltage, and several related parameters with a fast, multi-channel digital oscilloscope connected to a computer for storage of **all** events (μs resolution) in cavity No. 4, for 40 days. This allowed us to get statistical data on the frequency of sparks: in a (well conditioned) cavity, on the RF coupling window, as well as on all other interlocks .
After analysing every event individually, it turned out that, of a **total** of **60** RF trips in 40 days, **20** were so-called (self-recovering) **μ- sparks** of < 650 μs duration, which did not even turn off the beam. This results in a *MTTF of ≈ 45 hrs* for μ-sparks, comparing very well with ≈ 10 min on the first days after a cavity has been exposed to air! Only **one** spark of longer than 650 μs (= **non-recovering spark**) was recorded. **25** events were caused by **external** non-RF interlocks (RF 'off' and 'on', including scheduled interruptions for maintenance, etc.). The remaining 15 events were due to faults in the RF system, 10 of them caused by a malfunctioning crowbar unit in the final amplifier HV supply (these events do not show up in Fig. 2, because they occurred during set-up -

and not operation - of the cyclotron). Obviously **absent** were sparks at the **coupling loop**, a fact confirmed by an independent event counter on the spark monitoring device. The remaining cavities, during that same period, accumulated 1, 0, 2 and 14 such events.

Since it is not clear now whether we were fortunate with the choice of this particular cavity for this monitoring project, nor if and how these results are dependent on conditioning and other influences, it is proposed to install such monitoring on all RF systems. The biggest disadvantage, aside from equipment cost, is the fact that event viewing and screening still has to be done manually; some automation might be needed in the future. Furthermore, such a database should also conform to the cyclotron operation database, which collects data with a sampling rate of ≈ 1 min., and the device interlock statistics, which only count events during scheduled beam time.

3 RELIABILITY OF RF SYSTEMS

A simple definition of *reliability* first: During the scheduled beam production time of an accelerator: we want a minimal number of beam trips and, *if* they occur, minimal time to restore beam again!

Or, using statistical terminology: *decrease* the frequency of fault occurrences in a cyclotron, that is: *lengthen* the MTTF; and *decrease* the time to repair, corresponding roughly to the MDT .

3.1 *Increasing the Mean Time Before Failure (MTBF)*

- Reduce the influence of sparks:
  Do *not turn off beam* during short, self-recovering μ- sparks in cavity (duration: ≤ 650 μs).
- Reduce the absolute number of sparks: This can be achieved by *conditioning* RF cavities. It is a very time-consuming process, and it has to be repeated after each breaking of the cyclotron vacuum. Controlled filling of the cyclotron with nitrogen makes a big difference in the conditioning time required, compared to the (uncontrolled) filling with (moist) air, as is the case when an RF window breaks during heavy sparking across the ceramic surface! Important goal:
  ⇒ **Avoid cracking windows altogether !**
  In the case of our aluminium cavities: by using 'Aquadag' coating inside and on metallic coupler surfaces, we reduce multipacting and facilitate conditioning dramatically.
- Reduce Component Failure Frequency (1/MTBF): Improve and refine the *protection circuitry*, especially of high power/high voltage components (RF amplifiers, HV- supplies), but also for RF windows.
  Generally speaking: use high quality components if possible (with power tubes: choice is based on past experience). Employ reliability engineering methods and ample safety margins in design

That such measures can result in dramatic improvements in MTBF is best illustrated by the following figure (1), showing the cavity voltages for the four ring cyclotron acceleration cavities recorded during two typical 10-day intervals. Typical in this context means: comparable beam intensities (1.5 mA), no breakdown of non-RF systems, and no scheduled maintenance- or other beam-off periods planned during this time.

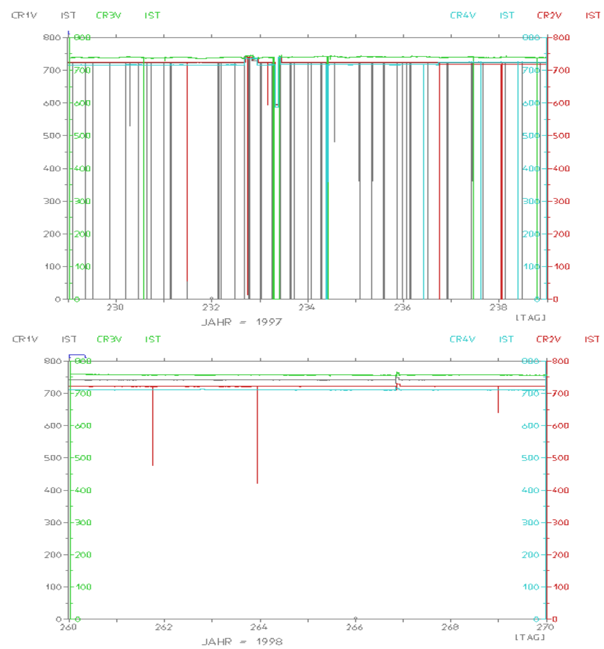

Figure 1: Ring cyclotron cavity voltages in kV_p for two typical 10-day beam production periods;
- Upper trace: 10 days in August 1997,
- Lower trace: 10 days in September 1998

3.2 *Reducing the Mean Down Time (MDT)*

As is the case for MTBF, only spotty statistical data is presently available on past and present MDT data for individual subsystems of the cyclotrons. Nevertheless, maintenance experience for individual components allowed us to pinpoint weak spots. Several measures were then taken to alleviate the most obvious ones, and to derive some rules to improve the replacement- and/or repair times of most critical systems:

- ***Speed up cavity voltage recovery*** in the case of sparks that do not extinguish for > 3 ms; because, in that case, the *amplifier protection circuits* will turn off the RF drive and the beam. *Resonance tuning, pulsing and ramping* procedures will now re-establish full resonator voltage within 4..6 s, (compared to 2..25 min with the old system).

- ***Reduce spark damage*** to coupling windows:
  Redesign the RF-coupling windows, include *ionisation detection pick-ups* at the couplers. The protection system turns off the RF-drive for 150 µs immediately (within 3µs) after electrons of a spark at the window are detected. This way, the amount of material evaporated, and deposited on ceramic insulator surfaces with each spark is strongly reduced.
  ⇒ *Lifetime of all types of RF coupling windows is now > 3 years !* (better than most power tubes)
- ***Reduce repair times:***
  Design quick *fault diagnostic tools*, provide test points to facilitate fault location; both on a system level *and* on device levels.
  Allow *fast exchange* of components by employing suitable mechanical design and fast connectors for RF-, electrical-, HV-, cooling water and air cooling hook-up.
  Provide *ready-to-operate replacement units* (hot spares), from power supplies to final amplifiers (tuned and calibrated) !
  Specify all units to use a strictly *modular design* (or: convert to modular design). At PSI, this has been done for amplifiers, coupling windows, power supplies, amplitude-, phase-, and frequency control systems and RF-interlock devices.
- ***Identify components with limited lifetime***;
  include them in *preventive maintenance* schedules, and design them for ease of replacement and minimal adjustment work (starting with components like: RF power tubes, RF coupling windows, etc)

Again, there is some data available to compare the effect of the measures mentioned above to the time before they were all operational. However, since many features were introduced in the course of several years, data on the contribution of individual measures would be difficult to extract reliably. Also, since this is an ongoing process, and the first steps were certainly the most effective, it is unlikely that such spectacular improvements can be demonstrated in the future. (Fig. 2)

This figure confirms the message of Fig. 1 (significant reduction of *number* of beam trips), but also clearly shows the second effect of the improvement program: the reduction in the cumulative down time (CDT). It is inter-esting to notice that the only significant data point in the lower diagram (marked by *) can attributed to one single problem: a cooling water safety interlock switch of a replacement amplifier being set too close to the limit. It took 13 beam trips to locate and solve the problem.

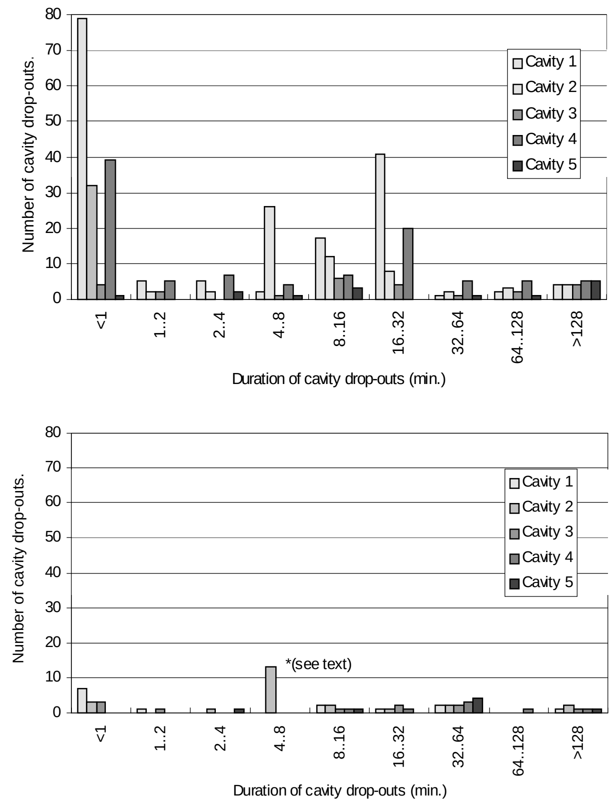

Figure 2: Ring cyclotron cavity drop-out distribution, during scheduled beam time; compiled for 3 months (Sept. to Nov.) in 1997 (upper chart), and the same time period in 1998 (lower chart).

4 RF POWER EQUIPMENT

4.1 Amplifier Design Considerations

The power amplifier chain of a PSI ring cyclotron RF system consists of 4 stages, of 1 kW, 10 kW 100 kW and 800 kW nominal output power (CW). All tubes are power tetrodes of metal-ceramic design. The 1 and 10 kW amplifiers are forced-air cooled, while the 100 & 800 kW amplifiers each use the same tube type, and are water cooled.

In case of a tube failure, the air cooled tubes are replaced directly, within about 1 hour (to full power operation); while in the case of a 100 or 800 kW stage failure, the entire amplifier is exchanged. Total time to operation in this case takes about 2 hrs., and requires at least two qualified persons from the RF group.

This is only possible because all amplifiers are designed and built with very tight mechanical specifications, allowing quick 'plug-in' connection of HV-, RF-, power- and control signals; as well as air- and water cooling hook-up, as can be seen in figure. 3.

Further contributing to the reliability of the amplifiers were external measures to reduce any tendency for parasitic oscillations. They are mostly caused by load changes

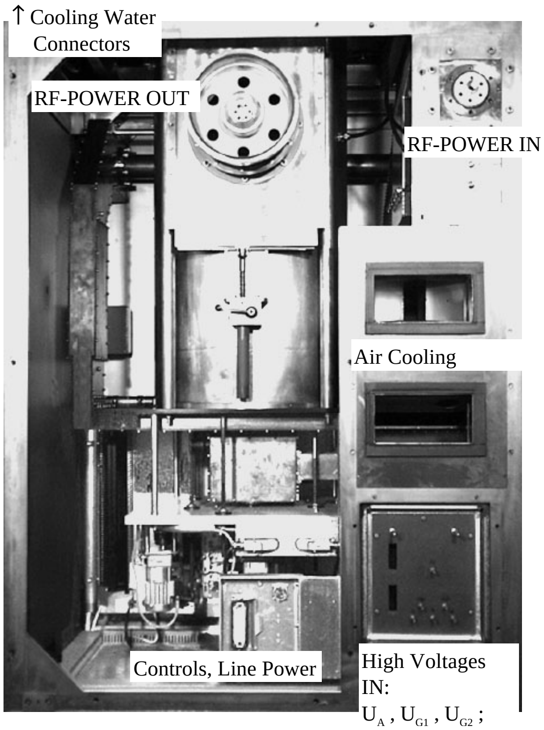

Figure 3: Connector Side of 850 kW Final Amplifier (cover removed)

and output mismatch for higher harmonics, and do occur despite careful internal circuit design, generous cooling, etc. In the past, damage by parasitics was also caused by unreliable (water cooled) power absorbers, employed in some grid input circuits and on transmission line higher order mode absorbers. Any fixed frequency RF amplifier connected to a narrow-band and/or variable load works best if the line length between amplifier and load is adjusted to integer multiples of $\lambda/2$. At higher harmonic- and parasitic frequencies, multiple reflections due to mismatch will occur on such a line, possibly resulting in parasitic oscillations in the amplifier. This effect can be countered by inserting directional 3 dB couplers between amplifiers, with integral band-stop filters for the fundamental frequency inserted between incident- and reflected power ports and 50 Ω power absorbers. These absorbers dampen signals over a wide frequency range on the transmission line (outside the fundamental frequency band) by ≤ 6 dB, and prove to be very effective in providing stable amplifier operating conditions and preventing damage due to uncontrolled parasitic oscillations.

4.2 Tube Lifetime

Average tube lifetime differs little between small and large tubes. Despite the start of the high power operation (I_{BEAM} = 1.5 mA) some 3 years ago, tube replacement data still indicate an average tube life time of 18'000 hrs (corresponding to ≈ 3 years of cyclotron operation).

Unfortunately, the 800 kW tube (RS 2074 HF) showed very large fluctuations in life time for a while, varying between 1000 hrs. and 27'000 hrs.,('record holder': > 60'000 hrs !) and failing for different reasons as well; from breaking of the filament to shorts between control-grid and cathode. In any case: the sample sizes for the different tube types are just too small to get a reliable statistical data base. Normally, tubes 'die' slowly of low cathode emission, thus giving ample lead time to plan a replacement during regular maintenance periods (bi-weekly), provided they are monitored regularly. Life time of cathodes is dependent on limiting the turn-on current pulse (to ≈ 150 %) and constant filament power; we employ passive power control systems to achieve this goal.

Manufactures of power grid tubes have improved reliability through better understanding of the chemical and physical processes inside the tubes, employing new materials and new, computerised manufacturing methods, allowing very tight internal tolerances. Standard lifetimes are now quoted to be > 15'000 hrs, corresponding well to our own observations. [5]

5 OUTLOOK, CONCLUSIONS

Improved statistical data, allowing us to better correlate sparking with all other activities in the cyclotron and across all cavities, will hopefully help to increase our comprehension of the underlying phenomena of sparking. (Compare sub-section 2.5) Additional studies might be needed in this field, but the goal will be worthwhile: to improve accelerator reliability and availability further, eventually preventing sparking in cavities during accelerator operation completely !

Another reason for the high reliability of our RF systems may be found in an organisational - rather than a technical - aspect: we do not employ separate groups for development and for maintenance of the RF systems. Whoever designed equipment will remain responsible for it during operation, and will therefore be much more inclined to improve or redesign, instead of just repair; thus assuring a continuous improvement of all systems.

At present, we are developing a new cavity with higher acceleration voltage (1 MV_p) for our ring cyclotron. In the future, such cavities will allow us to further decrease the turn number in the cyclotron, raise the space charge limit, and to produce extracted beam currents in excess of 2 mA @ 590 MeV(p). [6]

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