CHAPTER 6

BOOSTER RF SYSTEMS

6.1 NEW PSB RF CAVITIES *H* = 1 (0.6 – 1.8 MHz)

The addition of cavities accelerating on RF harmonic $h = 1$ and supplemented with a $h = 2$ system, contributed to the reduction of harmful space charge effects and avoided the coupled bunch instabilities observed with the former acceleration scheme on $h = 5$ [1]. These advantages apply equally well for all other proton beams handled in the PS accelerator chain [2]. The system properties are summarised in Tab. 6.1.

A nominal peak RF voltage of 8 kV with ample margin is required, since high-intensity beams beyond 10^{13} particles per pulse and per PSB ring are to be handled. Vertical installation space is scarce due to the construction of the PSB with four superimposed rings which restrict the vertical size of any equipment. For this reason the idea to squeeze four cavities in one PSB straight section was abandoned and a second section had to be sacrificed to allow usage of large size ferrite rings.

Table 6.1: Main parameters of C02 RF system.

Frequency range	MHz	0.6 - 1.8
Cav. equiv. capacitance[1]	pF	700
Quality factor[1] @		
0.6MHz		6.5
1.2MHz		16
1.8MHz		28
Cav. shunt res.[1] @	kΩ	
0.6MHz		2.5
1.2MHz		3.0
1.8MHz		3.4
Beam impedance at resonance (with FB)	Ω	~ 300
Ferrite type (Philips)		4A11

Permeability at remanence		~ 600
Tuning bias	A · turn	0 - 500
Power density	mW/cm^3	64
Magn. RF flux density	mT	4 - 12
Cooling air flow	m^3/s	1
Ferrite ring size	cm	48×24×3
Total ferrite length	cm	1500
Nominal gap voltage	kV	8.0
Max. gap voltage	kV	10.0
Power loss	kW	13.0
Peak power	kW	50
CW power	kW	20
RF feedback loop gain	dB	20

6.1.1 Cavity Design

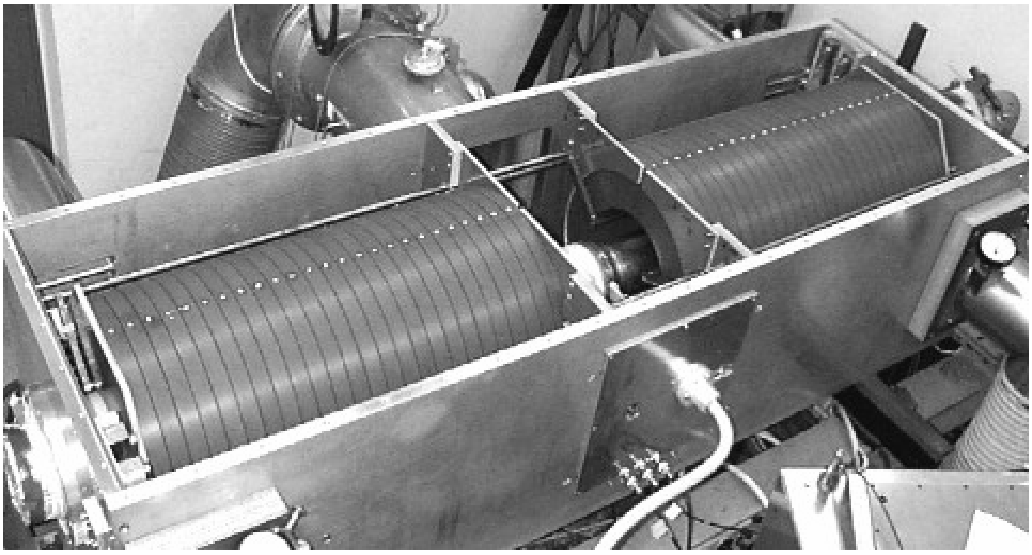

Figure 6.1: Ferrite loaded cavity C02.

[1] As seen across the gap at nominal voltage, with final amplifier and all accessories connected.

A classical and conservative NiZn ferrite-based design was chosen, essentially replicating the design of the one-gap type with virtual ground symmetry in the gap mid plane used for the other two PSB RF system cavities (Fig. 6.1) [3]. Air cooling of the ferrite through 1 mm spacing between rings gives the best ferrite filling factor, keeps the mechanical construction simple and is very cost effective compared with water cooling. The choice of Philips ferrite material grade 4A11 was made after tests on several small size ring samples. The absence of resonant absorption phenomena in the required working area was the main criterion.

PSB operation implies synchronisation of the four rings with the PS cycle on a magnetic flat top (duration up to 60 ms) at constant or very slowly changing RF frequency around 1.8 MHz. It is known that under such conditions ferrite can jump into the so-called High Loss Mode (HLM) at critical excitation and disturb the servo control of the RF voltage amplitude [4]. The onset of HLM appears to arrive earlier at higher DC saturation of the ferrite, i.e. towards the high frequency end of the tuned cavities. Fig. 6.2 shows the measured effect. The ferrite volume and cross section was chosen to stay safely below HLM onset at nominal RF voltage (8 kV_p). The ferrite grade selected exhibits a smooth and fairly stable transition into HLM and experience has shown that safe operation well beyond nominal voltage is possible. A temperature check of the individual rings in the operational cavities replaced laborious ferrite reception testing.

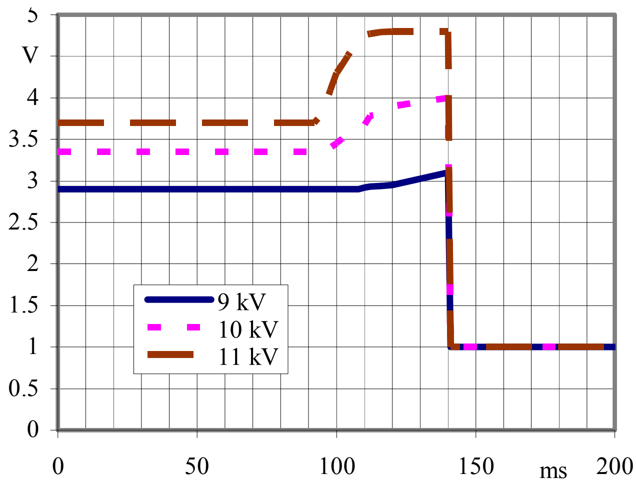

Figure 6.2: Final cathode current vs. time and gap voltage at $f = 1.8$ MHz.

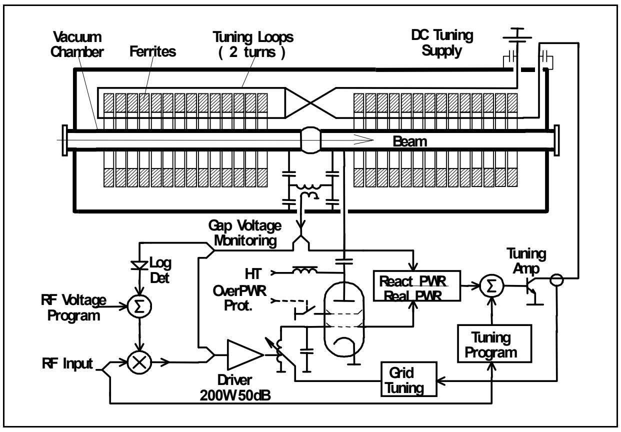

Figure 6.3: C02 system layout.

6.1.2 RF amplifier Chain

A conservatively-rated power amplifier was developed using the tetrode RS1084CJ, already widely used in the PS 10 MHz RF systems. Two newly developed wide-band transistor amplifiers plus a power combiner (100 kHz...100 MHz) serve both as driver and fast feedback amplifier. The whole unit is water-cooled. Feedback of the gap RF signal provides reduction of the cavity impedance to the beam by about 20 dB. Higher values are possible when needed. A particularity of the design is the use of a tuned low-Q resonant grid circuit [5], synchronised with the DC tuning current of the cavities. Advantages are higher gain, smaller drive power and the possibility to program phase response for increased feedback loop stability. The movable amplifiers are placed near to the cavities and can be easily replaced in case of a repair. The system layout is sketched in Fig. 6.3.

6.1.3 System Electronics Layout

The system electronics were developed to cover the frequency range of 0.5-20 MHz and are used in all PSB RF systems. Servo control of RF voltage amplitude is provided by logarithmic detector and modulator electronics (Fig. 6.3). The detector has a 70 dB dynamic range and ~0.5 dB absolute precision in the working range. Frequency response to modulation is 200 kHz for the detector and 40 kHz for the voltage control loop. The cavity tuning uses a novel IGBT linear current amplifier, which is controlled by a reactive power detection module. Maximum current is 400 A and tuning loop response to small perturbations extends to 500 Hz. The frequency to tuning current relationship is pre-programmed in a memory; fine tuning is handled in the analogue feedback loop which automatically turns on when the gap voltage exceeds ~100 V. An RF overpower detector acts rapidly on the final tube screen grid to prevent system trips. Two systems like those shown in Fig. 6.4 are installed in PSB straight sections 10L1 and 7L1.

Figure 6.4: C02 test mount for PSB rings II and IV.

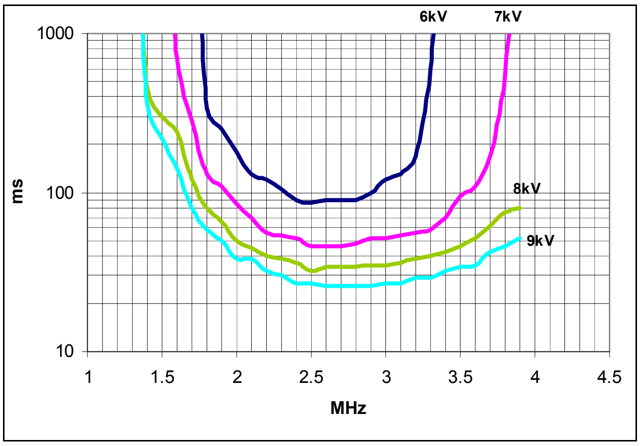

Figure 6.5: High loss mode on-set time.

6.2 CONVERTED PSB *H* = 2 CAVITIES (1.2 – 3.9 MHz)

With the abandoning of RF harmonic $h = 5$ it became possible to modify the existing equipment for $h = 2$ operation at little cost. Cavity modifications mainly consisted in increasing the gap equivalent capacitance, to shift the working frequency range to 1.2 – 3.9 MHz and replacing the gap voltage divider with a calibrated, wide-band unit.

Although the gap voltage required for $h = 2$ operation is only 2/3 of the previously used voltage at $h = 5$ (8 kV instead of 12 kV), the frequency decrease by a factor 2/5 results in an RF induction increase given by the ratio of the two factors (~ 1.7). This pushes the ferrite (Philips 4L2) more to its limits and the nominal RF voltage is reached without much margin. Ferrite entering into HLM, which with this ferrite grade appears to be unstable, is the critical parameter. Operation at constant frequency (~3.5 MHz) for synchronisation of the four rings with the PS RF system, has to be limited in duration as shown in Fig. 6.5.

The existing push-pull power amplifiers, using two RS2012CL tetrodes, have been retained without modifications. They are air-cooled and share the cooling system with the cavities (Fig. 6.6).

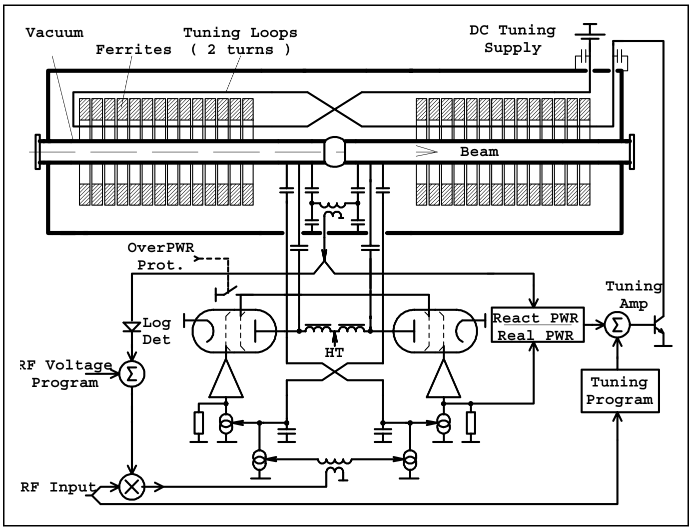

Figure 6.6: C04 system layout.

Standard 100 W wide band amplifiers already used in the C02 systems have been added as fast feedback power drivers. Feedback of the gap RF signal provides reduction of the cavity impedance to the beam by 26-32 dB.

Although most of the heavy hardware has been retained, control and servo electronics have been replaced with the new, wide-band standard electronics developed for the C02 system. The system properties are therefore similar to those already described in the previous section. The system properties are summarised in Tab. 6.2.

Table 6.2: Main parameters of C04 RF system.

Frequency range	MHz	1.2 – 3.9
Cav. equiv. capacitance	pF	650
Quality Factor @		
1.2 MHz		85
2.5 MHz		130
3.9 MHz		190
Cav. shunt res. @	kΩ	
1.2 MHz		17.5
2.5 MHz		12.5
3.9 MHz		12.0
Beam Impedance (with FB):	Ω	
1.2 MHz		< 440
2.5 MHz		< 440
3.9 MHz		< 600
Ferrite Type (Philips)		4L2
Permeability at remanence		~200

Tuning bias	A · turn	0 – 1800
Power density	mW/cm^3	31
Magn. RF flux dens.	mT	3.2 – 9.4
Cooling air flow	m^3/s	1
Ferrite ring size	cm	20×35×3
Total ferrite length	cm	1500
Nominal gap voltage	kV	8.0
Max. gap voltage	kV	9.0
Power loss	kW	3.0
Peak power	kW	20.0
CW power	kW	10.0
Feedback loop gain @	dB	
1.2 MHz		> 32
2.5 MHz		> 29
3.9 MHz		> 26

6.3 PSB BEAM CONTROL MODIFICATIONS

The PSB is composed of four superimposed rings, each having three cavities described in Tab. 6.3.

Table 6.3: PSB cavities.

Cavity	Frequency range	Maximum voltage	Use (for protons)	Use (for ions)
C02	0.6 → 2 MHz	8 kV	Acceleration on h=1	Acceleration h=4 up to 1.8 MHz (f_{rev}=450 kHz)
C04	1.2 → 3.9 MHz	8 kV	Bunch flattening Bunch splitting (h=1→2) at 1.4 GeV Acceleration on h=2	Acceleration on h=4 from 1.8 MHz (f_{rev} =450 kHz) up to 3.86 MHz (f_{rev} =965 kHz)
C16	5 → 16 MHz	6 kV	Controlled longitudinal blow-up during acceleration	Acceleration of 4 bunches of Indium on h=8 up to f_{rev}=1.13 MHz

The present beam control was installed in 1998 within the framework of the harmonic change from h = 5 to h = 1 and/or h = 2. Its structure is based on one digital frequency synthesiser per cavity, each digital frequency word being directly derived from the main magnetic field measurement (B to f conversion). The present architecture is represented in Fig. 6.7. For one PSB ring, LHC beam parameters are:

one single proton bunch, 190 ns long, obtained with longitudinal blow-up (momentum spread), $\Delta p/p = \pm 2.5 \times 10^{-3}$ ($\pm 2\sigma$).

6.3.1 Hardware Layout

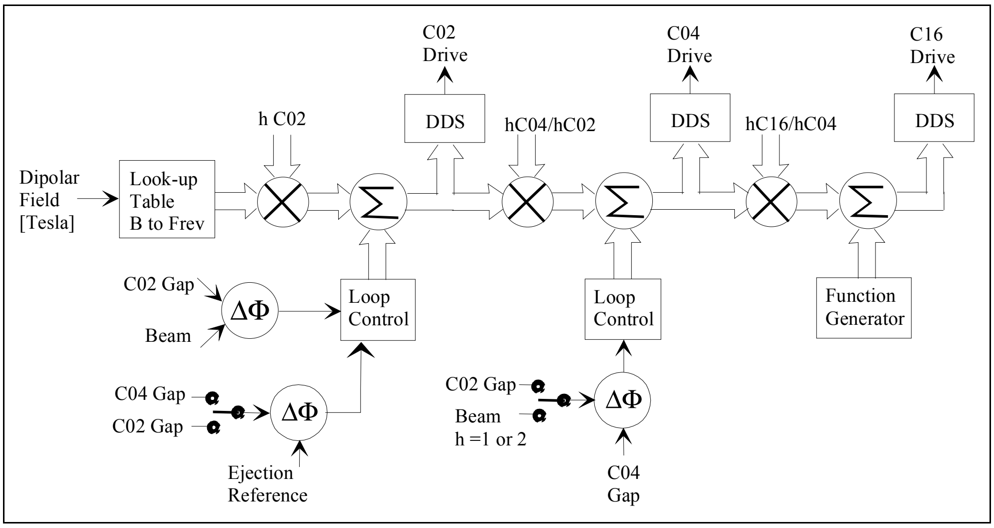

Figure 6.7: PS Booster Beam Control layout.

Fig. 6.7 shows that the measured value of the bending field ("*B*-train") is used for generating the frequency words feeding all three cavities. The revolution frequency (f_{rev}) is obtained from a look-up table (typically a read only memory) and multiplied by the harmonic number aimed for C02 (h = 1 for LHC beams). The resulting frequency is summed with the loop (phase and synchronisation) error signals, to obtain the actual C02 RF value sent to the cavities via a digital synthesiser.

C16, when used as a "controlled blow-up" cavity, is not included in any loop. Its harmonic value is just set to different integer values during acceleration so as to be the highest possible. A phase modulation (at a rational multiple of f_S) is then applied to obtain the desired emittance growth in the same way as in the PS or SPS [6]. When accelerating Indium on h = 4, the required RF–frequency at extraction (4.52 MHz) is above the limit of the C04 system, while still below the C16 frequency range. Therefore, the h = 4 beam, hold by C04, is captured (hand-over process) in every second h = 8 bucket of C16 and accelerated until extraction.

The main advantages of the digital structure are:

- The look-up-table on the left-hand side of Fig. 6.7 sets the RF frequency to keep the beam on orbit for any magnetic field. This feature makes it possible to accelerate a beam with all loops open (albeit with some losses and instabilities). In the previous (analogue) version, only the radial loop could establish the required frequency to keep the beam centred but the position detectors were quite hard to run with low intensity beams (e.g. lead ions).
- All cavities are naturally locked in frequency even with loops open; this avoids the presence of an integrating type of corrector in the different phase loops (simplified correctors and more stability margins).
- In the old system, the loss of beam led to saturation of the different loops and erratic behaviour of the frequency and voltage programmes necessitating security interlocks to protect the power equipment which were quite heavy to handle. In the new system the loops only have to act on a small frequency range and do not provoke cavity trips.

6.3.2 The Transition to *h = 1*

Since its running-in period in 1972, the PSB machine was subject to many improvements. The most important was the introduction of a second harmonic cavity on each ring in 1983. The peak accelerated intensity levelled off from that time at about 3.4×10^{13} protons per pulse (ppp) with all four rings (1.1×10^{13} on ring 2). The introduction of a fast feedback on the cavities in 1985 improved the reliability of operation, but did not improve the record value.

During the first h = 1 run in 1998, operation was disturbed by the impedance of the vacuum flanges around the ring. The resonances of these flanges gave a total (integrated around the ring) longitudinal coupling impedance of 450 Ω at 750 kHz [7] which is the RF frequency range at the beginning of the cycle. The return voltage generated by the beam current was coupling to different electronic devices which therefore had to be equipped with common mode rejection circuits. Some coupling between rings remained, implying adjustment of the radial position to avoid beating between cavities near the synchrotron frequency. After some flanges had been short-circuited during the 1998-99 shutdown the total impedance was lowered to about 200 Ω (still higher than the maximum value for $h = 5$ which was 130 Ω). This eliminated the frequency beating from one ring to the other as a source of trouble and helped to reach a new intensity record in September 1999: 4.1×10^{13} protons per pulse accelerated in the PSB with 1.2×10^{13} in ring 2. New RF decoupling flanges were introduced in the 1999-2000 machine shut-down to further reduce the impedance [7].

The transition to $h = 1$ eliminated the coupled bunch mode instabilities (not present with a single bunch) and thus made the complex feedback system as well as the “Hereward” damping system (tackling quadrupolar bunch-shape oscillations) superfluous. This last effect, not formally studied, might be explained by a criterion given in [8, 9] that relates the loss of Landau damping to the beam current. The current threshold, proportional to V_{RF}/h, has been improved by a factor 3.3 when moving from $h = 5$ to $h = 1$. The absence of the quadrupolar loop indirectly permitted an increase of the $h = 2$ versus $h = 1$ voltage ratio limited to 50% in the former system where beam amplitude detection was misled by double peaked bunches.

Another improvement came from the C04 ($h = 2$) cavities. These were obtained from the conversion of the older C08 cavities that were used as the main $h = 5$ drive cavities. They have more voltage and power margin than the previous C16 cavities used at $h = 10$ and thus run more reliably whenever the phase relationship between $h = 1$ (C02) and $h = 2$ (C04) is critical in terms of power demand from $h = 2$.

All these improvements certainly contributed to the record intensity increase. In summary, the main advantages of the $h = 5$ to $h = 1$ conversion are:

- Feasibility of two-batch filling of the PS as required for the LHC beam.
- Increase of longitudinal acceptance (proportional to $\sqrt{V_{rf} / h}$).
- No need of coupled bunch mode feedback system.
- Less longitudinal space charge effect ⇒ no need for Hereward damping at present intensities.

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