BNL-101808-2014-TECH

AD/RHIC/RD/26;BNL-101808-2013-IR

On the Possible Use of the CERN 200-MHz Cavities for the RHIC Beam Storage System

R. McKenzie-Wilson

April 1991

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

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April 22, 1991

1. INTRODUCTION

The beam storage system foreseen for RHIC is presently specified to provide a total voltage of 4.5 MV at 160 MHz from 6 RF cavities in each ring. The system design shares many similarities with the standing wave or "SWC" system used for Lepton acceleration in the former CERN SPS machine. This system provides for a total voltage of 32 MV at 200 MHz generated by 32 RF cavities.

CERN is developing a plan to replace part of the SWC system with superconducting RF cavities for operation in 1992. When this plan is implemented the replaced cavities will become available for use elsewhere. This note will describe the CERN SWC system together with some information on the availability of these cavities. It will also discuss options for the modifications required to adapt this system for use on RHIC.

2. SHORT DESCRIPTION OF THE CERN SWC SYSTEM

A detailed description of the CERN SWC system can be found in several conference papers (Annexes 1, 2 and Ref 1,2) and in CERN internal reports (available from the authors of this note). Key features are:

- Each cavity is equipped with a dedicated power amplifier and can deliver an effective voltage of 1 MV to the beam at 200 MHz.

- A pneumatically actuated damping loop is fitted which reduces the beam induced voltage in inoperative cavities by a factor greater than 500.

- Groups of eight cavities share a common driver and a common power supply.

3. AVAILABILITY OF THE CERN SWC SYSTEM

Sixteen out of the 32 SWC cavities that are presently operating in the former SPS-ring will be replaced by two superconducting units in early 1992. The remaining 16 cavities will stay in the ring as a backup until a later unspecified date; only if the decision is made to increase the LEP injection energy from 20 GeV to 22 GeV, these cavities will also be replaced by superconducting units.

CERN is ready to sell the cavities and associated amplifiers with or without the power supplies. The power supplies are designed for an input voltage of 18 kV/50 Hz and would need dedicated input transformers for connection to the US standard voltage of 13.5 kV/60 Hz; the procurement of new power supplies may be an advantageous alternative.

One complete cavity/amplifier assembly could be removed earlier to serve as a high-power test unit at Brookhaven when equipped with a power supply. In addition, a low-level cavity not capable of high power could be made available.

4. CONSIDERATION OF OPERATING FREQUENCY

4.1 CERN Cavities

The 200 MHz operating frequency of the CERN SWC-system is determined mainly by the geometry of the cavity. If major surgery is to be avoided, the possibilities for frequency alteration are limited practically to the modification of the distance separating the nose cones (Fig 1a). Several methods have been considered to achieve this end:

- Stretching or compressing the cavity by plastic deformation of the copper body.

- Shortening of the nose cone by machining.

- Insertion of a reducing cylinder in the bore of the nose cone, exploiting the fact that the available aperture of the CERN cavities is 144 mm whereas the aperture needed for RHIC is only 73 mm (Fig 2).

- Insertion of a separate, doughnut-shaped annular ring in the equator plane between the nose-cones (proposal of Mr. J. Griffin at Fermilab).

Fig. 1a shows the result of SUPERFISH calculations, giving the available voltage of a single cavity as a function of frequency over a range that can be obtained by the methods enumerated above. Three different mechanisms have to be considered:

- For constant amplifier power the voltage is proportional to the square root of the effective shunt impedance of the cavity, which has a maximum around 200

MHz. It is reduced at higher frequencies by deterioration of the transit-time factor and at lower frequencies by additional losses due to the currents from the capacitive loading.

- The electric field strength at the nose cone increases rapidly at lower frequencies due to the reduced gap distance. The full available amplifier power can only be applied down to 183 MHz, where the safe limit of 120 kV/cm starts to be exceeded at a gap voltage of 980 kV.
- The RF current density at the contacts of the reducing cylinder reaches 51 A/cm at the above mentioned operating conditions, and also increases rapidly at lower frequencies. Standard flexible contacts can only be used up to about 30 A/cm. Therefore, specially designed prestressed contacts or welded-in inserts or a separate annular ring have to be considered instead. The problem can be avoided if the cavity is used close to 200 MHz where the detuning can be achieved by plastic deformation of the cavity body.

It can be seen that the cavities have been well optimized for 200 MHz. Their operation at 160.5 MHz would necessitate relatively involved interventions to overcome the problem of the high current density at the contacts. In addition the operating voltage would still be restricted to about 700 kV due to the electric field strength limitation. Above 183 MHz, almost 980 kV per unit can be expected but the contact problem remains to be solved up to a frequency of about 195 MHz; from there on the tuning can be safely performed by plastic deformation.

4.2 Power Amplifier

The CERN power amplifier uses narrow-band resonant line sections in the plate, screen and cathode circuits as well as in the feedthrough blockers; the feeder-line is also tuned to optimum length at 200 MHz. Shifting of the operating frequency is possible, but requires some RF design work followed by mechanical modifications.

The output power is limited by the permissible dissipation of the screen grid at 200 MHz; the latter increases with the square of frequency, so that operation at higher frequency would lead to a reduction in available power.

4.3 Modification of the RHIC Frequency

The nominal frequency of the RHIC RF storage system has been settled at 160.5 MHz as a compromise between several competing factors. It is possible to raise this frequency provided the following elements are taken into account:

a.) NUMEROLOGY. The circulation of n times 57 bunches requires an RF frequency which is a modulo-n multiple of 4.457 MHz, the repetition frequency for 57 bunches. The possible frequencies are shown in fig 1b, with marks for those who allow the circulation of 2* and 3*57 bunches, respectively.

b.) RF VOLTAGE REQUIREMENTS FOR THE STORAGE SYSTEM. Strong longitudinal focussing is required to maintain a short bunch length during the storage process in presence of intrabeam scattering.

According to earlier studies the required RF voltage is approximately proportional $f^{1.5}$ for a given beam growth rate (see AD-RHIC-AP-66). Recent evaluations led to a voltage requriement proportional to f^2 (Ref. 4). Tracking studies performed by J. Wei, takingn the beam loss during storage as the main criterion, confirmed the f^2-Law (see Fig. 16). Admitting a beam loss of 11% after 10 hours of storage, an RF voltage of 8 MV at 200.6 MHz is equivalent to a voltage of 5.2 MV at 160.5 MHz.

c.) RF VOLTAGE REQUIREMENTS FOR THE ACCELERATING SYSTEM. Higher frequencies of the storage system lead to a shorter length of the receiving bucket and consequently to higher requirements of bunch-shortening before the transfer. This bunch shortening is performed by non-adiabatic bunch rotation, provoked by a fast amplitude step going from voltage U1 to U2 in the accelerating system. U2 is proportional to $U_1^{-2} \cdot f^2$. J.Wei has shown that satisfactory bunch transfer into a 160.5 MHz bucket can be achieved by the voltage step U1=20 kV and U2=300 kV (Ref 3). With these values as a starting point and the assumption that U2 is limited to 350 kV, the voltage U1 can be expressed as a function of frequency, as shown in fig. 1b.

The following conclusions may be drawn.

- The frequency of 200.6 MHz would allow the use of virtually unchanged CERN-cavities; it offers the possibility of accelerating 57 or 3*57 bunches; the bunch rotation is expected to require a step going from 11.2kV to 350 kV which is well within the specified capabilities of the accelerating RF system.

- Frequencies higher than 200 MHz are not attractive, for reasons of hardware and beam dynamics.

- Going substantially lower than 200 MHz will not lead to significant advantages. The operating frequency should remain close to that value to limit the hardware modifications to a minimum. The frequency of 196.1 MHz should be considered if the circulation of 2*57 bunches is required; 187.2MHz should be chosen if the possibility of circulating 2*57 bunches and/or 3*57 bunches is to be maintained.

5. COPING WITH THE BEAM-INDUCED VOLTAGE

Analytical and multi-particle tracking studies carried out by Mr. J. WEI (Ref 3) have led to the specification of upper limits for the total beam induced voltage at different points during the machine cycle. These limits are 10 kV at transition and V/4 during the bunch rotation process, where V stands for the total voltage of the 26.7 MHz acceleration system. The table below translates these limits into maximum permissible cavity impedances. This table assumes a set of 8 cavities, a DC-beam current I0= 56 mA and rectangular bunch shape for the determination of the 200-MHz component I1.

Points during cycle	max. tot. [kV]	voltage cavity [kV]	bunch length [nsec]	I1/I0	I1 [mA]	max. impedance [kOhm]
Transition	10	1.25	2	1.52	85.2	14.7
Flat-top before bunch rotation	4	0.5	10	0.2	11.2	44.6
End of bunch rotation	75	9.37	2	1.52	85.2	110.1

As the nominal impedance of a cavity together with the amplifier is about 5 MOhm, a reduction factor in the order of 340 has to be implemented at transition. Counterphasing groups of cavities can result in a factor of about 10, since precise cancellation of the individual group voltages is less than perfect in the presence of significant beam induced voltages. The amplifiers have to be kept operating to allow control and counterphasing, and this regime can in fact be considered as a special form of feedforward-compensation. "Strong" RF feedback with a loop gain of about 34 has to be used to cover the full missing factor at transition.

The damping loops currently installed in the cavity allow a significant simplification. Moved pneumatically in their activated position at the very beginning of the machine cycle they reduce the induced voltages by a factor of 500, up to and through transition where the requirements are most demanding. They must be withdrawn before the beam transfer process, but the requirements are less stringent for the rest of the cycle. "Weak" RF feedback with a loop gain around 10 is then sufficient.

Reported reliability of these loops has been marginal for actuation times of 1/2 second, as compressive shock waves were induced in the bellows which then developed microleaks. In the present application, however, actuation is slow. The insertion time can be made arbitrarily long, and the withdrawal occurs just prior to bunch rotation in the period of lowest RF voltage. This may be extended to at least 5 seconds (J.Wei, private communication). Fully satisfactory reliability can be expected under these conditions.

RF feedback not only reduces beam induced voltages, but also amplifier imperfections such as parasitic modulations at 60 Hz. Loop gains in excess of the minimum of 10 needed for "Weak" feedback may therefore be desirable; a factor of 63 can theoretically be reached for an overall delay of 500 nsec (equivalent to 150 m of air-cable). Although measured data on the delay could not be obtained, the simulation of the circuit by PSPICE give confidence that the final amplifier will not be a limiting factor. A comfortable margin sufficient for a 6-fold increase in beam intensity is therefore available.

6. AREAS NEEDING FURTHER ATTENTION: HOM-COUPLERS, TUNER SPEED, MULTIPACTOR

The SWC cavities are equipped with 2 water-cooled HOM couplers in the equator plane, which are reportedly effective up to a frequency of 1 GHz but had not been specified for storage-ring application. The cavities themselves are optimized for highest shunt impedance rather than lowest beam-equipment interaction, exhibiting a relatively high R/Q of 180 Ohm. This basic disadvantage is enhanced by the fact that 8 instead of 6 cavities are needed; further studies of the longitudinal impedance characteristics are therefore necessary.

Tuning of the cavities during operation is performed by a motor-driven mechanical tuner. The tuning speed of the assembly may not be sufficient for the planned counterphasing-gymnastics so that the incorporation of a fast ferrite tuner may become necessary.

Multipactor in the cavity has been a problem from the beginning; extended conditioning is necessary, attempts to cure the problem have been only partially successful.

It is worth commenting that HOM and multipactor problems are common to all new cavity designs and would almost certainly be present for any new design develop for RHIC. Therefore, although the CERN SWC cavities, when applied to RHIC, may present new problems, there is the advantage of the CERN previous experience in these areas which can be built on.

7. A POSSIBLE SCENARIO

The most advantageous solution for the first stage of RHIC would be the use of 2*8 CERN cavities near to their original design frequency, i.e. at 200.6 MHz. The beam induced voltage can be lowered to acceptable values by the use of the damping loop together with "Weak" feedback and counterphasing. Storage system performance at least equal to the original proposal with a 160.5 MHz system can be safely expected.

The use of 8 cavities in a group seems a natural choice since such a group is designed to share a common driver and common power supply. The argument is weakened by the necessity of individual drivers and the option of using new power supplies, but remains basically valid because of the availability of the SWC units in these groups. Space in the RHIC-tunnel is adequate .

Future increase in beam current can be covered by converting the "Weak" to a "Strong" feedback. 3*57 bunches can be handled directly, 2*57 bunches would require the change of operating frequency with noticeable hardware modifications.

The following main modifications are necessary to adapt the basic system to the RHIC environment:

- Development of the RF feedback using individual drivers with output powers of about 5 kW and a gains of 40 dB

- Manufacture of the drivers (16 operating units)

- Procurement of:

    - power supplies for the drivers

    - predrivers 100W at 200 MHz

    - interfaces from the CERN G64 control bus to a RHIC-compatible bus

    - 2 power transformers 2.5MW together with 13.5 kV switchgear (or entirely new 10-kV DC supplies).

The total cost of these modifications is estimated roughly at 1 000 000 $. This sum does not include the cost of purchase and transportation.

8. CONCLUSION

Use of the CERN-SWC cavities for the RHIC storage system seems technically feasible and holds the promise of a cost-effective solution, at least for the first phase of the project. The ultimate potential of RHIC may be best exploited in later phases by the incorporation of a small number of high-voltage superconducting cavities.

More detailed studies should be carried out to determine all implications to RHIC beam dynamics; this note is intended to trigger that process.

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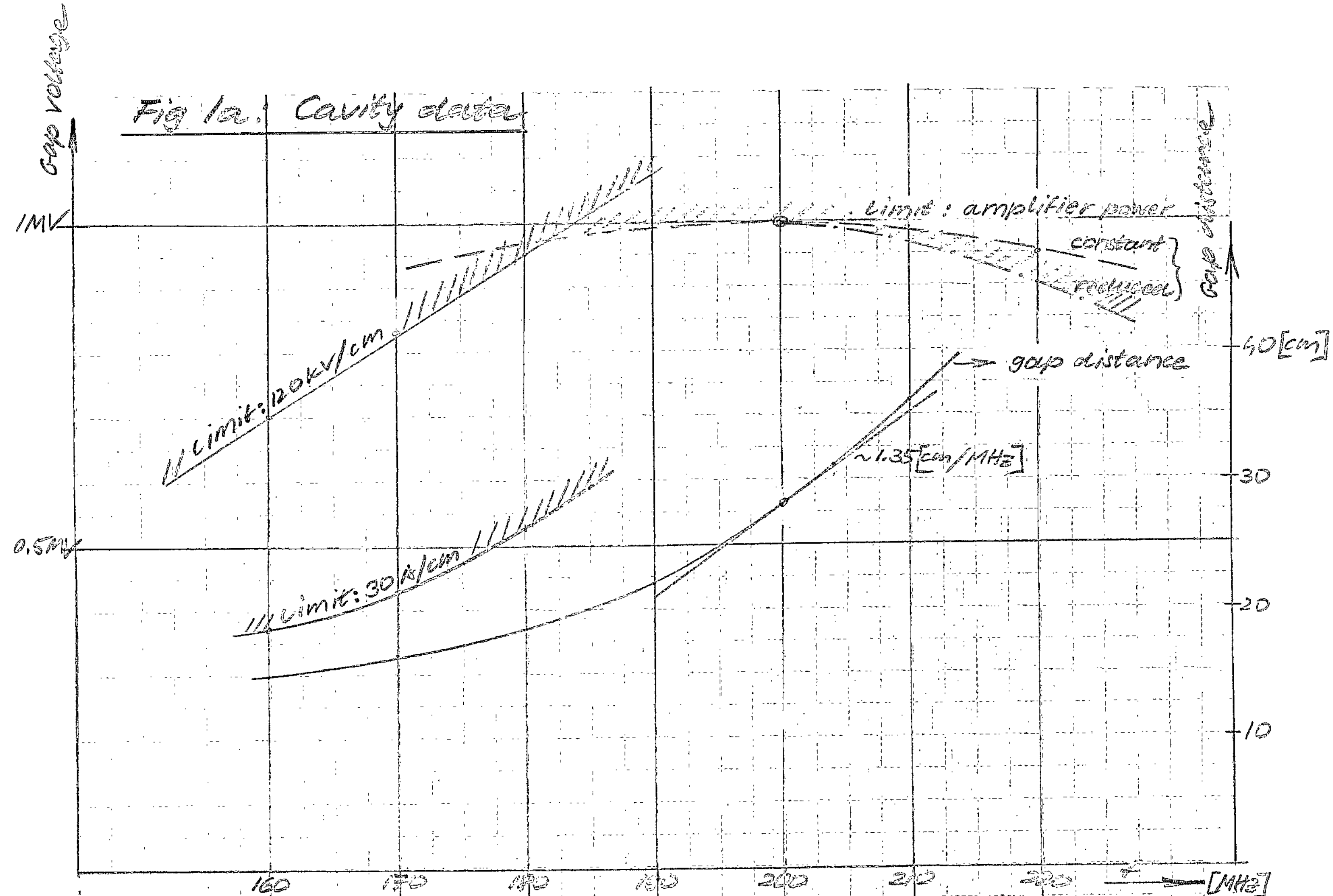
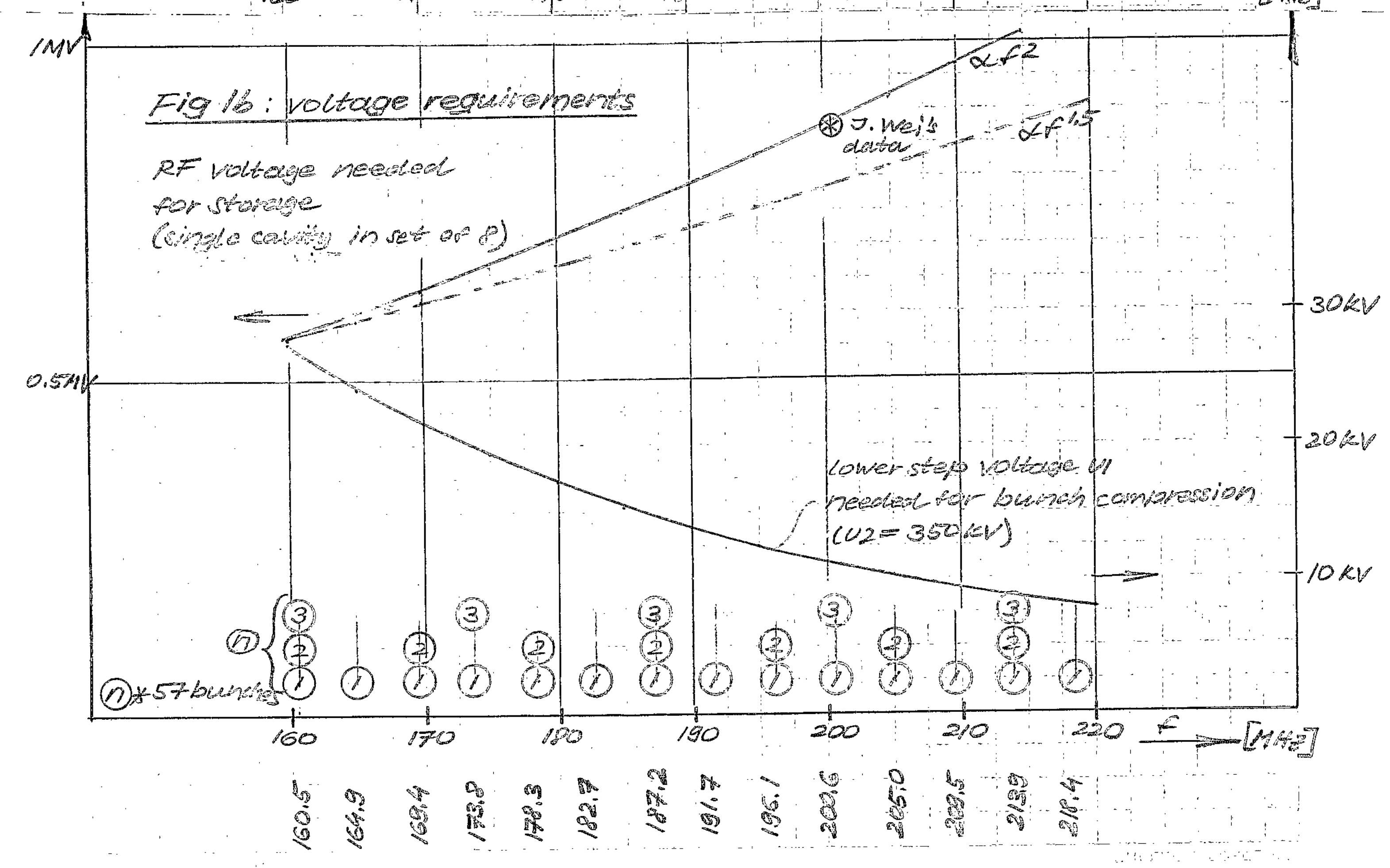


Fig 1a: Cavity data
gap voltage
gap distance
1MV
0.5MV
Limit : amplifier power
constant
reduced
Limit: 120kV/cm
Limit: 30kV/cm
gap distance
~1.35 [cm/MHz]
40 [cm]
30
20
10
160
170
180
190
200
210
220
f [MHz]


1MV
Fig 1b: voltage requirements
∝f²
J. Wei's data
∝f^1.5
RF voltage needed
for storage
(single cavity in set of 8)
30kV
0.5MV
20kV
lower step voltage U1
needed for bunch compression
(U2= 350kV)
10kV
n
n * 57 bunches
160
170
180
190
200
210
220
f [MHz]
160.5
164.9
169.4
173.8
178.3
182.7
187.2
191.7
196.1
200.6
205.0
209.5
213.9
218.4

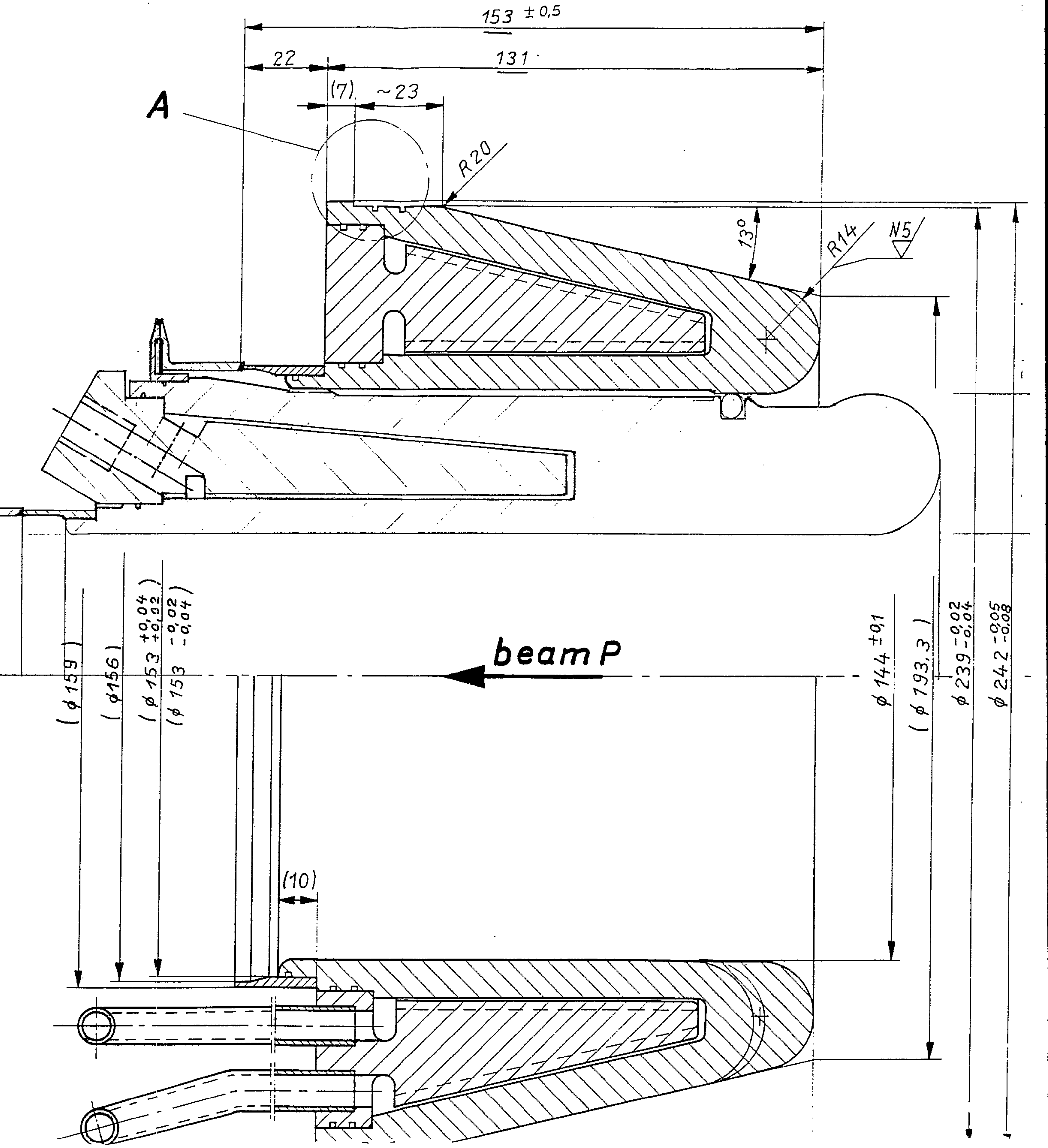


Fig 2 Lowering the frequency by an insertion (courtesy G. Rogner / CERN)

Annex I

THE NEW RF SYSTEM FOR LEPTON ACCELERATION IN THE CERN SPS

P.E. Faugeras, H. Beger, H.P. Kindermann, V. Rödel, G. Rogner, A. Warman

European Organization for Nuclear Research (CERN), CH - 1211 geneva 23, Switzerland

Summary

The use of the SPS accelerator as an injector for LEP requires a new radio-frequency system which is being built and installed in the machine. This system is made of 32 single-cell copper cavities, each one being fed by its own 60 kW RF power amplifier, mounted on top of the cavity, thus providing a peak RF voltage of 1 MV per cavity at 200 MHz. The interleaved acceleration of leptons and of intense proton beams in the SPS, as well as collider operation have required the design of special damping and tuning devices, mounted on each cavity. Performances of the first accelerating modules are described, with some emphasis on the effects of the very high surface electric field in the cavity.

Introduction

For the acceleration of electrons and positrons in the SPS to an energy of 20 Gev, a peak RF voltage of about 30 MV is needed at 200 MHz to compensate for the energy lost by synchrotron radiation and for parasitic mode losses and to adapt the bunch shape to the LEP buckets. The existing travelling wave structures of the SPS, which were designed for accelerating intense proton beams, can provide 9 MV at most and cannot be extended for practical and economical reasons.

As the lepton intensity will be low in the SPS and the beam loading not severe, the new RF system which has to be built for lepton acceleration can make use of high Q cavities. 32 single-cell copper cavities, each fed by its own power amplifier, will then provide a much higher energy gain per meter, thus permitting the installation of the new accelerating system in the two medium straight sections on either side of LSS3. The standard SPS frequency of 200 MHz was chosen for this system which can then also be used for collider operation to increase the available RF voltage during acceleration and beam storage.This frequency leads to accelerating modules whose dimensions are compatible with the SPS tunnel cross section: see fig. 1 , which shows the main components of a module.

The single-cell cavity

Fig. 2 is a cross section of a single-cell cavity, whose shape has been optimized with standard computer codes[1],for an outer diameter limited to 1.0 m and a beam hole diameter of 144 mm : the calculated unloaded Q reaches 53,000 and the shunt impedance 11.5 MΩ, but this implies a fairly high peak surface electric field of $\approx$ 12 MV/m on the radius of the drift tubes, for a total integrated gradient of 1 MV on the cavity axis. The distance between the centres of adjacent cavities is half a wavelength, i.e. 748 mm.

High-conductivity, oxygen free copper is used for the fabrication of the cavities: two half shells are cold-formed first from thick copper sheets. Holes are also cold-drawn on the cylindrical part of the longer half shell. The two shells are assembled by electron-beam welding to form the cavity body. Two nose-cone inserts and six output flanges are then brazed onto the cavity body in a vacuum oven at 800 °C . Finally, the cooling channels are soft-soldered on the outer wall of the cavity.

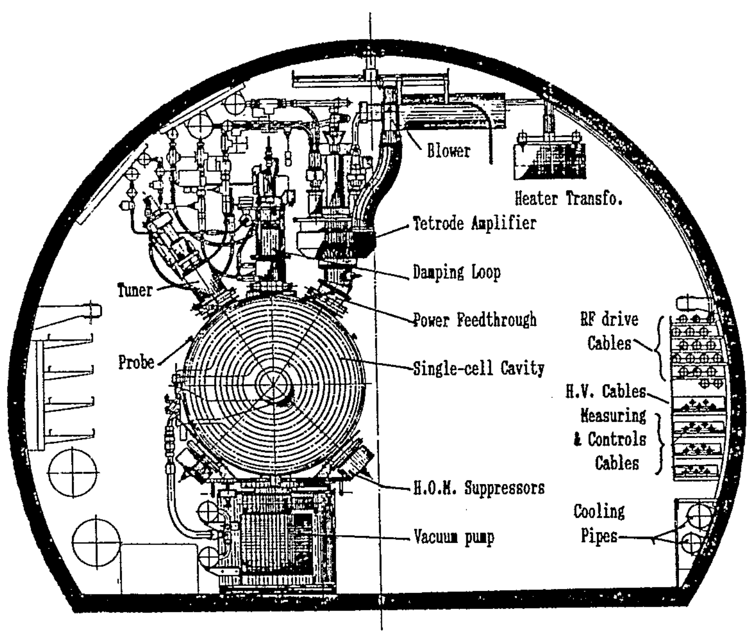


Fig. 1: Cross-section of the SPS tunnel with a new acceleration module

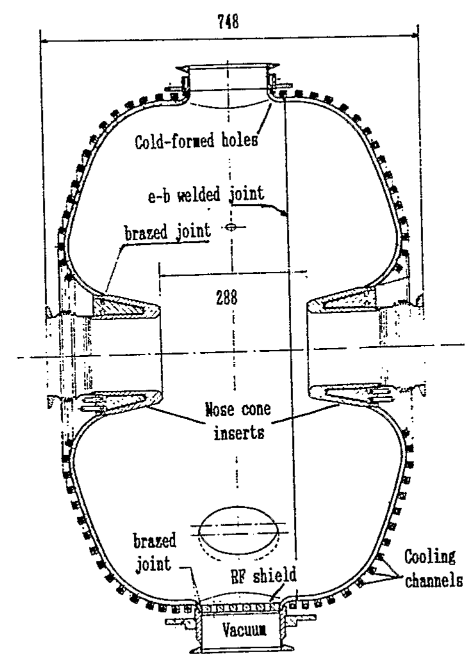


Fig. 2: Cross-section of a single-cell cavity

CH2387-9/87/0000-1719 $1.00 © IEEE

This manufacturing procedure was successfully tested at CERN on prototypes, but led to difficulties during the series-production: cracks developed in the main circumferential weld during the high temperature vacuum-brazing. However, the finished cavities were still vacuum-tight and could then be repaired by rewelding them with a small rotating electron gun mounted inside the cavity.

When a cavity is finished, its resonant frequency is adjusted by small axial deformations which change the gap length. Then the cavity is cleaned by complete immersion in a bath with a special detergent at 50 °C, agitated with ultrasound, rinsed in demineralized water, dried out and pumped down. After two days of bake-out at 135 °C, the base pressure in the cavity is better than 10^{-8} Torr.

All cavities have a measured Q_0 higher than 49,000 and a shunt impedance around 8.5 MΩ. 60 kW of RF power are then necessary to reach the design voltage of 1 MV per cavity.

Tuning and damping devices

Piston tuner

Each cavity has a servo-controlled piston tuner which corrects for mechanical tolerances, thermal expansion and varying beam conditions : the available stroke allows a tuning range of 400 kHz which is large enough to also cover the frequency swing required for collider operation.

Damping loop

These new cavities cannot be used when the SPS is accelerating intense proton beams and must be damped sufficiently in order to insure beam stability, [2]. The principle of a resonant damping loop,[3], is shown in fig.3. A rectangular loop of 120*60 mm² strongly couples to the magnetic field of the cavity and is connected to the outside with a coaxial feedthrough. The reactance of the circuit is compensated with a short-circuited line (stub). The resulting real low impedance is then transformed via a $\lambda/4$ line to a 50Ω load resistor which is water-cooled, to cope with the beam induced power(≈3kW for $3*10^{13}$ protons in the SPS).

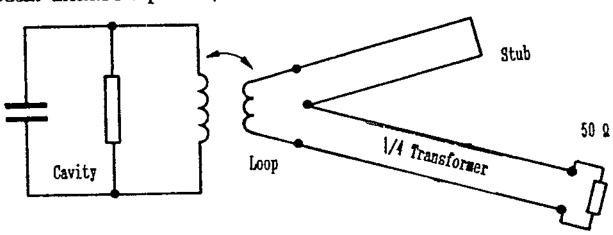


Fig. 3: Schematic of the damping loop.

Before proton acceleration starts, the loop is moved into the cavity, with a pneumatic actuator, thus providing a damping factor greater than 500 at 200 MHz whereas the loop is retracted for lepton operation. This 100 mm movement takes 0.5 sec and is made under vacuum, thanks to thin-wall bellows, which have been specially developed for this application and which are one of the most critical components of the whole system: the operation of the SPS as an injector for LEP, interleaved with its usual running for fixed target physics implies for each damping loop more than one million cycles per year. This damping device is mounted on the vertical top port of each cavity, so as to minimize the effects of shocks induced by the loop movement.

H.O.M. suppressors

Each cavity has an infinite number of resonating modes, some of them being harmful for the stability of the beams, in particular those at 306,396 and 600 MHz. Two types of higher order modes suppressors have been studied and are described elsewhere, [4]. After tests, we have chosen the resonant type as sketched in fig.4

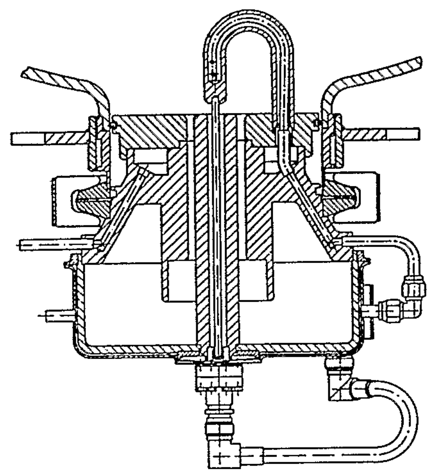


Fig. 4 : Section of the H.O.M. suppressor

This type of suppressor has the advantage of lower losses on the fundamental than the waveguide type . It is also more compact , cheaper to manufacture and easier to adjust, as it is made of machined copper pieces brazed together. Note that this device requires water-cooling, in particular for the coupling loop, because of the ohmic losses induced by eddy currents on the loop surface . Two such suppressors are mounted on each cavity, to take care of the two polarizations. Measurements on a fully equipped cavity, as in Fig.1, have shown that all modes up to 1 GHz and which may be of concern for the beam stability are sufficiently damped.

RF power amplifier and feedthrough

The 60 kW of RF power, which are necessary at the cavity input to reach the design voltage of 1 MV per cavity, are obtained with a tetrode amplifier, which has already been described, [5]. As shown on fig. 5, the amplifier is mounted on a skew port of the cavity, through a coaxial elbow, which is terminated by the power feedthrough and coupling loop,(see also fig. 1). This arrangement allows a quick exchange of the whole amplifier in case of problems and keeps the tetrode in the upright working position.

A coaxial design is used for the power feedthrough because of the short length available: a ceramic disc is brazed onto two thin and hollow copper conductors. The ceramic disc and the inner conductor are air-cooled, and the outer conductor water-cooled. All copper parts of the window in contact with the cavity vacuum are covered by a layer of ≈ 0.5 µm thickness of titanium deposited by sputtering, for lowering the secondary electron emission coefficient.The insulation resistance of the ceramic disc is also lowered down to 10 MΩ with a similar titanium deposit, which allows electrostatic charges to flow away during operation. The orientation of the coupling loop is adjusted to match the cavity impedance to that of the amplifier output (16 Ω for CW operation at 60 kW).

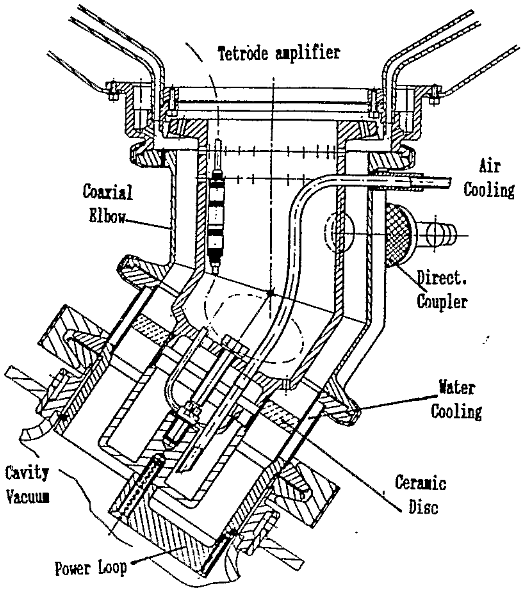


Fig. 5: The coaxial elbow and power window

Cavity conditioning

RF conditioning is done in the lab for each cavity individally and can be started when the base pressure is better than 10^{-8} Torr : RF power is then gradually applied and increased as long as the pressure does not exceed $3*10^{-8}$ Torr. Between this value and 10^{-7} Torr the RF power is kept constant but is reduced above, and stopped, if the pressure rises above $5*10^{-7}$ Torr, to avoid any damage of the power window.This process is done manually up to 3 kW of RF power and then under computer control.

At low power, the conditioning speed is limited by multipactoring on the ceramic window, which occurs at 300 W, 800 W and 2 to 3 kW. Once these limitations are overcome, the RF power can be relatively easily raised up to a level $\approx$ 20 kW, where horizontal light strips start to appear on the ceramic disc of the window. At the same time, electrons are detected (with a Faraday cup on the cavity axis) and are accompanied by X-rays and short small bursts on the vacuum pressure. One has to wait until the vacuum pressure is quiescent before being able to increase slightly the RF power. It may then take two to three days to reach 40 kW, but above this level the pressure stabilizes around $10*^{-8}$ Torr. The radiations increase with the RF power and reach an average of $\approx$ 50 rad/h at 1 m distance on the cavity axis for 60 kW in the cavity. Fig. 6 shows the light strips on the window at that power level.

Electrons produced by field emission are likely at the origin of these phenomena. One has then tried to suppress the emitting spots by RF processing: 60 kW of RF power are fed into the cavity filled with Helium or Argon at a pressure of $2*10^{-5}$ Torr. After a few hours the radiation level decreases by a factor 5 and the light on the window is strongly attenuated. However, this beneficial effect disappears after 24 hours of running with the cavity at the normal pressure.

Copper coating of the brazed joints which are in contact with the cavity vacuum looks more promising: the brazing alloy has indeed a high content of silver, which is known to be electron emitter under vacuum. 15 µm of copper have been electro-deposited locally on the two brazed joints between the cavity body and the nose-cones of a cavity.The X-rays and the light on the

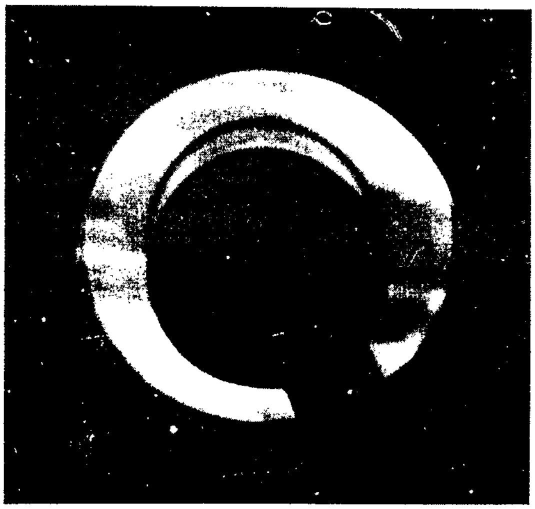


Fig. 6: TV picture of a ceramic window at 60 kW RF

window are much lowered, but further investigations are necessary to confirm these results.

Each module is filled with dry nitrogen after its conditioning and goes in the SPS tunnel fully equipped but without its amplifier and damping loop. In this way, its exposure to air during its installation is kept to a minimum. Eight modules are going to be put into operation this year to gain some experience. The other 24 modules will be installed during the next two SPS winter shutdowns, to be ready for LEP in 1989.

Acknowledgements

This project has benefited from the constant support of B. de Raad and E. Picasso. We also would like to thank all members of the SPS who contributed to this project, in particular G. Bérard, L. Dumas, J.M. Giguet, M. Goujon, J. Grieger, P. Griessen, R. Gueissaz, W. Herdrich, F. Oude Moleman, G. Patti, G. Pistolato, W. Sinclair, B. Sutton and F. Weierud.

Thanks are also due to A. Boulmier,J.P. Bacher, R. Bellone, P. Sievers, B. Thony and B. Trincat for their expertise and help in solving some of our problems.

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Annex II

INSTALLATION AND OPERATION OF THE NEW RF SYSTEM FOR LEPTON ACCELERATION IN THE CERN SPS

P.E. Faugeras, H.P. Kindermann, T.P.R. Linnecar, V. Rödel, A. Warman

European Organization for Nuclear Research (CERN), CH - 1211 Geneva 23, Switzerland

Summary

32 accelerating modules, each made of a single-cell copper cavity, fed by its own tetrode amplifier, have now been installed in the SPS tunnel. These modules are arranged in groups of 8, each sharing the same HV power supplies and with a common RF driver chain, installed on the ground surface. Each module has its own controls crate, and 4 independent beam control circuits have been built, one for each group of modules. Three groups have already been put into operation and have allowed acceleration of leptons in the SPS up to 18 GeV for the LEP injection tests of July 1988, and up to the design energy of 20 GeV at reduced intensity. First operational experience of this system in the interleaved mode of operation of the SPS is also reported.

Introduction

In order to adapt the SPS accelerator as an injector for LEP, a new radio-frequency accelerating system has been built and installed in the machine, which can provide a peak RF voltage of up to 32 MV at 200 MHz. As already reported,[1], this system makes use of 32 identical accelerating modules, each one being made of a single-cell copper cavity fed by its own tetrode amplifier which is mounted on top of it. In this paper, we will describe the overall installation, the power part and RF driving chain of the system, the associated beam control electronics and the computer control equipment and will also give the results of the lepton acceleration tests performed in July 1988.

General layout

As a general rule, a minimum of equipment has been installed in the SPS tunnel, which is not accessible during beam operation, whereas a maximum has been left at surface level to ease operation and maintenance of the system. Therefore, only the 32 accelerating cavities, each with its tuner and damping devices,

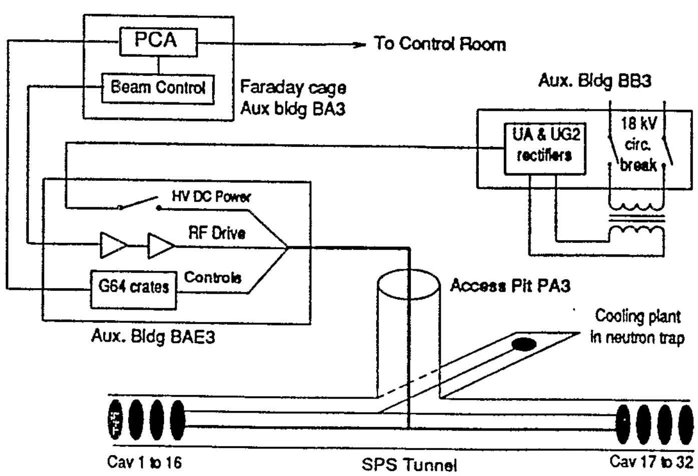

Fig.1 : Overall layout of the system

together with the RF power part of the final power amplifiers, [2], are installed in the SPS tunnel, 60 m underground, in the two missing magnet straight sections on either side of the long straight section 3. All the other equipments, such as DC power supplies for the tetrodes, RF driving chains, computer controls and low level circuitry are housed in existing surface buildings.

The overall layout of the system is sketched in Fig. 1. The Faraday cage contains the low level beam control electronics and the computers which are linked to the main control room. In the auxiliary building BB3 are housed the HV mains circuit breakers which feed the rectifier transformers (outside the building) and the HV anode and screen grid supplies. The DC voltages from these supplies are transported about 80 m to building BA3 where HV isolating and grounding switches provide the distribution to the individual power amplifiers. RF drive equipment and controls racks for all cavities and amplifiers are also installed there, as well as auxiliaries for the final amplifiers, (400 Hz generators for powering the blowers, regulated supplies for the filament transformers, ...). An impressive number of cables, which carry the HV DC power, the RF drive power, the controls and various measurements, leave this building, run down the 60 m access pit, to reach the individual modules in the SPS tunnel, some 280 m away from BA3.

The 60 kW RF final power amplifiers had to be mounted on top of each accelerating cavity: there is not enough space available in the SPS tunnel and access pit to install 32 high power transmission lines, not to mention the cost. Some of the water-cooled elements like the power tetrodes and the cavity damping devices, do not withstand high water pressure. To eliminate the 6 bars pressure due to the 60 m high access pit, a water cooling plant with pumps and heat exchanger, has been placed in a small cavern at the bottom of the pit ("neutron trap"), together with a clean air compressor for cooling the cavity damping loops and RF power windows. The final amplifiers are also air-cooled, but because of the required air flow, with individual small size 400Hz blowers mounted on the tunnel wall, beside the filament transformers, near each amplifier.

The power plant and RF driver

The 32 cavities have been arranged into 4 identical groups: a common RF driver (identical to a final amplifier) feeds the 8 final amplifiers and one common anode power supply, (10 kV, 1.1 MVA), feeds this driver and its group of 8 final amplifiers. Since the screen grids of the power tetrodes are physically grounded, the use of a common anode supply requires also a common screen grid supply for these 9 tubes. However, each tetrode has its own regulated control grid bias supply, equipped with an active bleeder, using transistors. Anode and screen grid power supplies are equipped with thyristor crowbar circuits, which diverts the stored energy in case of a tube arc.

Motor-driven isolating and grounding switches are included in the anode and cathode lines to the 9 tubes to allow operation of the plant with any amplifier off line. All HV switches of one group are mounted on a common shaft and magnetic clutches control the switching of the individual tubes. DC current transformers are also installed in the cubicles of the HV switches to monitor the anode current I_a and screen grid current I_{g2} of each tetrode, the latter requiring a differential transformer.

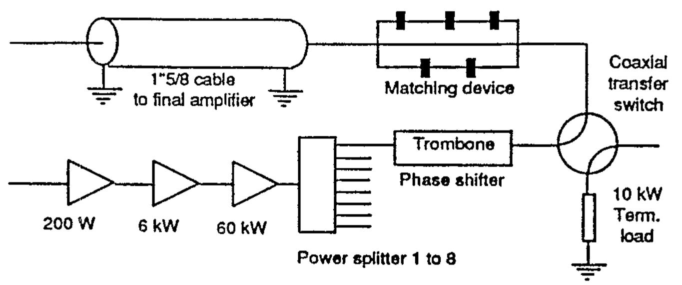

Fig.2 : RF driver chain for a group of 8 cavities

The RF driver chain for one group of 8 cavities is shown in Fig. 2. The predriver consists of a 200 W transistorized amplifier and of a 6 kW TV amplifier. The output power of the 60 kW driver is split into 8, two $\lambda/4$ coaxial transformers matching the 8 50 Ω outputs to the driver output impedance. Each of the 8 outputs feeds one final amplifier via a coaxial transfer switch, a phase shifter, a matching device and a 1 5/8" Flexwell cable. The motor-driven transfer switch is connected to a water-cooled 10 kW 50 Ω load, which absorbs the corresponding drive power whenever the final amplifier is switched off line. The phase shifter is a coaxial trombone and permits the precise adjustment of the 180 degree phase shift between two successive cavities. The matching device uses a line section with 5 adjusting screws, and allows elimination of any amplifier and cable mismatch, which is important for equal power distribution at the output of the power divider.

The low-level electronics

The design of the beam control circuitry is influenced by the :ed for compatibility with the existing SPS accelerating systems as well as by features defined by the power hardware, as described above, and by specific requirements for lepton acceleration in the SPS. As shown on Fig. 3, the low-level system divides naturally into the cavity control electronics concerned with each group of cavities and the beam control electronics related to the interaction of the beams with the RF wave.

The majority of the cavity control electronics is designed at an intermediate frequency of 10.7 MHz, and input and output mixers to the SPS frequency of 200 MHz, are used with a local oscillator, LO, which is controlled by the beam control electronics. Cavity control is done globally on all eight cavities of a group, which have the same driver amplifier. Nonetheless individual cavities must be monitored to prevent, e.g., overdrive of the final amplifiers. A linear detector working at 200 MHz with a linearity of 1 % over more than 40 dB dynamic range is employed to monitor the forward power to each individual cavity. The result is used for limiting, by hardware, the RF power to 1 kW at switch on and subsequently , as soon as the tuner of each cavity of a group is locked to its correct position, to a maximum power level of 60 kW, defined by the capabilities of the hardware.

The tuner position of each cavity is servoed with a loop which uses the phase error detected between the forward power and the cavity signal. Also, an amplitude loop holds the sum of the eight cavities to the level required within the single cavity hard limitation values. Note that each cavity has a high quality cable librated in amplitude and phase from the monitoring loop to the .ectronics, whereas each group of cavities has its own local oscillator at 10.7 MHz, used in a phase loop to keep the relative phases of the different groups to the required values.

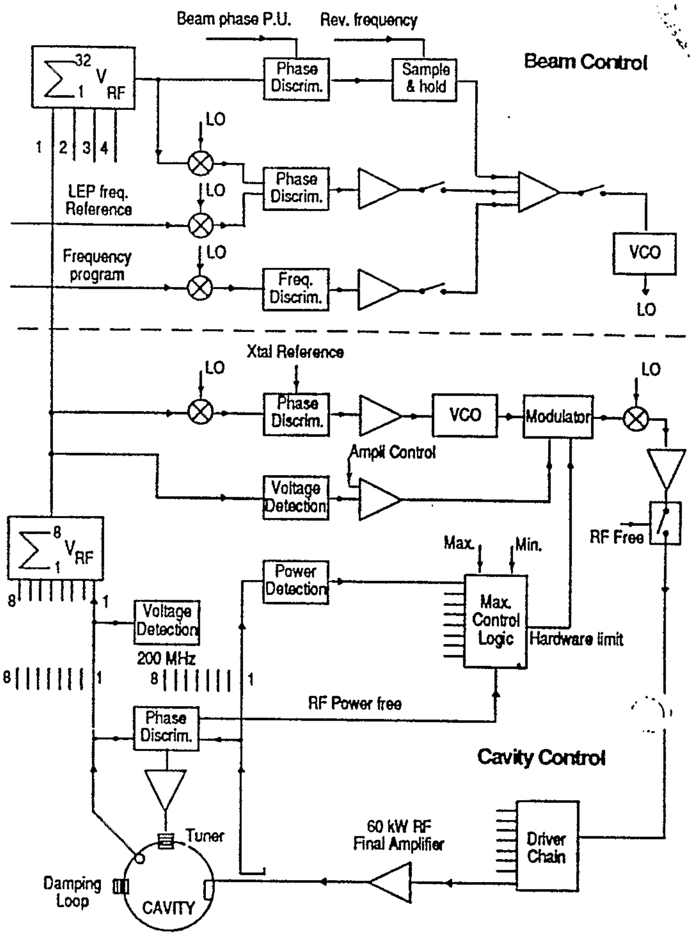

Fig. 3: Low level beam and cavity control

At injection into the SPS, the synchrotron radiation dampin time is 5 s. The beam control system has therefore a phase loo RF-beam, to damp injection oscillations and maintain longitudin stability on the first dipole mode. Up to eight bunches are injecte and the 200 MHz fast phase detector of Fig. 3 is followed by sample-and-hold circuit, triggered at the revolution frequency. Th signal thus obtained from the first injected bunch is used t control the local oscillator at 189.3 MHz via the loop amplifier. Th complete loop response time is approximately 150 μs.

The match voltage for the injected beam is 500 kV, wh th peak accelerating voltage with 32 modules goes up to 30 MV. Th amplitude loop provides this range, but lower voltages value imply counterphasing between groups via the 10.7 MHz referenc The frequency which is constant in lepton operation is maintaine by locking the local oscillator to the LEP reference in bot frequency and phase using a synchronisation loop. A frequenc loop is also provided for diagnostic purposes like chromatici measurements.

The microprocessor controls

The controls of this new acceleration system have been bui according to the design principles for the LEP controls, [3], an their architecture, sketched on fig. 4, reflects the hardwa construction and is based on two main pieces:

- G64 control crates connected to the equipments,
- a Process Control Assembly, PCA, for communication ar synchronisation.

For each group of 8 cavities, there are 11 control crates i total, one for each accelerating module, one for the anode and th screen grid power supplies, one for the driver chain, and one for a common services of the group. These crates are fully independent, are built in the G64 standard and make use of two types of cards:

- system cards, which comprises the CPU card, the timing card and the interface with the multidrop bus,
- cards directly connected to the hardware, for digital inputs and outputs, analog I/O and interlocks.

The hardware cards, 6U high, have been specially developed for our needs with a view of minimizing the wiring, junction boxes and electronic interfaces with each equipment, while being fully changeable in between different types of crates. For instance, the interlock card can have up to 54 interlock signals on its input and can deliver up to 8 stop signals. The matrix link between interlocks and stops is made by PAL's, which combine easy programing and changing of the matrix if needed while keeping reliability of hardware interlocks. Any stop coming out of this card can either be directly connected to a digital I/O card or be input on another interlock card, such that crates can be linked by hardware from the interlock point of view.

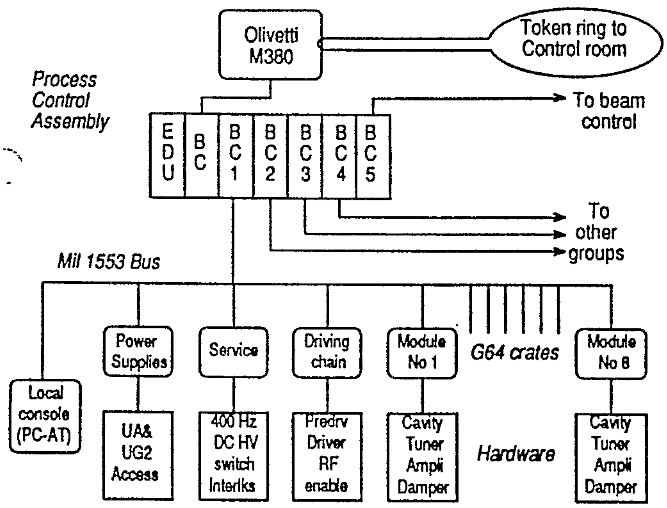

Fig. 4: Principles of the computer controls

The digital I/O card can drive up to 24 different equipments, through floating and insulating Darlington transistors, and makes use of Erasable Programmable Logic Devices which allow any sophisticated equation. The analog I/O card can input up to seven differential signals and 2 times 4 temperature measurements on 2 12 bits ADC's and can give 2 outputs with 12-bits DAC's. Each analog signal may be compared with min and max values set by 8-bits DAC's to provide interlocks.

All G64 crates run programs written in PASCAL under AMX, a small multitask operating system. The microprocessor is actually a 6809 but will be changed for 68000 type with OS9 as operating system. The 11 crates of a group are linked together by a Mil 1553 multidrop bus, driven by a bus controller which resides in the Process Control Assembly. This PCA is a VME crate associated with a PC and houses the five bus controllers together with the Equipment Directory Unit, which allows synchronisation of the action of the G64 crates on a link as well as of the full system. By connecting the PC, (actually an Olivetti M380C), to a token ring, one can access the equipment from the control room and from any place via the CERN local network. The PCA software is written in "C" and runs under XENIX.

Commissioning and operation

The first eight cavities were installed in the SPS ring in 1987, the next sixteen during the winter shut-down of 1988, and the last group of eight just now in 1989. Part of the SPS shut-downs had to be reserved for commissioning and RF conditioning of the instal-led modules, before restarting the machine. Because of the large distances between the different components, parasitic oscillations of the whole amplifier chains were observed at frequencies between 10 and 500 kHz during commissioning, but could be suppressed by adequate filtering in the anode and control grid leads.

Although the cavities were conditioned in the lab, they had to be reconditioned after their installation. RF conditioning started at a base pressure of lower than 10^{-8} Torr. With a small amount of RF at the nominal frequency applied to a cavity, the position of the piston tuner is adjusted for the minimum of reflected power at the cavity input before closing the servo-loop which keeps the cavity in tune. The level of the RF power which is then applied to the cavity is controlled by a fast reacting loop from the pressure which must not exceed 10^{-7} Torr. It takes about 8 hours before 10 kW of RF power can be applied on each individual cavity. All eight cavities of the same group are then conditioned together to the full nominal power of 60 kW, which requires typically a further 16 hours.

Three groups have been commissioned so far with beam. This was done by using lepton cycles interleaved with the normal SPS cycles for high intensity proton operation. Note that during the proton part of the supercycle, all the damping loops had to be inserted into the cavities, and then retracted before lepton injection. The lepton cycles were tuned first up to 14 GeV/c with the existing travelling waves structures, then the SWC groups were commissioned one after another with little trouble. For the LEP injection tests of July 1988, the 3 groups provided reliably 18 GeV positrons. Although the four groups are needed for accelerating high intensity lepton bunches to 20 GeV, 3 groups allowed to reach this energy at a somewhat reduced intensity. To verify the voltage calibration of the cavities, one or more groups were switched on and off and the beam loss point during the cycle was recorded for each condition. Knowing the energy loss per turn from the B-field and dB/dt, the total voltage at the beam loss time can be found. This agreed to within 5% with the RF voltage calculated when knowing the R/Q, the RF power and the various cable calibration factors.

Acknowledgements

This work has benefited from the support of D. Boussard, B. de Raad and E. Picasso. It is a pleasure to also acknowledge the contribution to this project of many members of the SPS division, and in particular G. Bérard, L. Dumas, J.M. Giguet, M. Goujon, J. Grieger, P. Griessen, R. Gueissaz, W. Herdrich, G. Lambert, F. Oude Moleman, G. Patti, G. Pistolato, W. Sinclair, D. Stellfeld, B. Sutton, U. Wehrle and F. Weierud.

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