THE RF SYSTEM OF THE ACCELERATOR COMPLEX OF THE ENERGY AMPLIFIER

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This paper presents the satus of the studies concerning the RF system of the accelerator complex of the energy amplifier proposed by C. Rubbia at CERN. The accelerator complex consists of three stages of cyclotrons referred to as the injectors, intermediate and booster cyclotrons accelerating a high intensity (of the order of 10-12.5 mA) proton beam up to an energy of the order of 1-1.2 GeV. Following analytical and three-dimensional computations, the geometry of the flat-top and accelerating cavities of the injector, intermediate and booster cyclotrons has been determined. Models of these cavities have been built and measurements carried out in order to check the theoretical predictions.

1 Introduction

A new concept called "Energy Amplifier" for clean energy production through controlled nuclear fission has been developped by a team lead by C. Rubbia at CERN [1]. Its main features are extensively described in a companion paper [2]. Let us just recall here that the reactor is driven by an accelerator complex in order to produce nuclear reactions induced by fast neutrons.

The accelerator complex consists of three stages of cyclotrons referred to as the compact injector (CIC), intermediate separated sector (ISSC) and booster separated-sector (BSSC) cyclotrons accelerating a high intensity (of the order of 10-12.5 mA) proton beam up to an energy of the order of 1-1.2 GeV. It has been extensively described in a preliminary report [3]. Two versions of the accelerator complex have been studied depending on the beam power needed at the accelerator output (12.5 MW). In the first one (called version A) the energy steps at the various input and output of the stages are 0.1-10 MeV (injector), 10-120 MeV (intermediate) and 120-1000 MeV (booster). The respective figures for version B are 0.1-10 MeV, 10-200 MeV and 200-1200 MeV. We will focus in this paper on the various components of the RF system.

2 General Features

The main features of the RF system are summarized in Tables 1,2 and 3 in the following sections for both versions. In addition to the main cavities that provide the required energy to the beam, flat-topping cavities are also included in order to reduce space-charge effects. It is planned to use local flat-topping in both injector and intermediate cyclotrons, whereas global flat-topping might be considered for the booster cavities since this would enable to reduce the cavity radial extension. Due to the reduced beam phase expansion in the booster cyclotrons, fifth harmonic operation of the flat-top cavities has been selected in order to reduce the losses in the walls.

2.2 Computations of the cavity characteristics

The main tool that has been used in the design of the cavities is the electomagnetic computer-aided design code MAFIA [4]. RF characteristics (Voltage distributions, frequency , stored energy, losses and quality factor) of the various resonant modes can be obtained rather easily.

2.3 Measurements on models

Voltage ditributions are obtaimed from integration of the electric field maps in the median palne of the cavity. The local electric field intensity is measured by a volume perturbation technique with a small dielectric sphere [5]. The electric field is proportional to the square root of the frequency shift induced by the introduction of the spherical bead in the cavity. Such frequency shifts are automatically read for each sphere location in the model median plane (near the gaps) from a network analyzer and stored in a PC, thus enabling field mapping and subsequent data processing to get the voltage distribution with a dedicated software. The same kind of technique with a conducting sphere could be used in the future in order to obtain magnetic field (and then RF current) maps and check prediction with MAFIA near the short-circuit plane. These maps would be used as input for the design program of the cooling system.

2.4 RF Transmitters and beam loading

No thorough investigation of the RF transmitters has been carried out up to now. However, the global features can be extrapolated from existing devices and concepts [6] in particular for the amplifiers of the accelerating cavities of the booster ring (grounded-grid configuration, power tetrode, impedance matching between stages).

A frequent source of trouble in high power cavities is the coupling loop window between the transmission line and the cavity itself. Careful design of that region is necessary in order to sustain high power transmission. It is estimated that the maximal power per window (loop) for reliable operation is of the order of 600-700 kW. Four such loops would therefore be required for each booster cavity.

Possible solutions to handle the additional power produced by the beam in the flat-top cavities have been reviewed in ref. [7]. Depending on the ratio of the power dissipated in the cavity walls and the beam power, a different design strategy is recommended. If this ratio is close to unity, the design of the RF transmitter is based on an amplifier adapted to operation in absorbing mode at high beam levels. Such an amplifier is combined with an additional load to lower the cavity effective quality factor and accordingly overrated (to sustain high plate dissipation and RF output power) [8]. In this project, since the beam intensity is rather high, the beam power exceeds by far the losses in the cavities. Therefore it would not be suitable to use such a concept, except maybe for the injectors where power levels are low. Another possibility is to use a tetrode plate as a continuously varying resistive load coupled to the flat-top cavity as suggested in ref. [7]. A prototype based on a simpler design with a triode has been successfully tested at PSI.

3 Injector Cyclotron

The shape of the accelerating and flat-topping cavities of the injector cyclotron is shown in Fig. 1 and 2. They basically corresponds to a distorted coaxial $\lambda/2$ resonator.

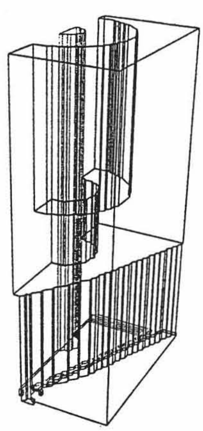

Fig. 1: MAFIA model of the RF accelerating cavity of the injector cyclotron

As far as the accelerating cavity is concerned, the liner diameter is reduced when crossing the magnet yoke in order not to affect too strongly the magnetic field distribution and to reduce the cavity height. This only slightly increases the RF losses compared to a configuration where no diameter reduction is imposed. The voltage distribution along the gap is constant within 3%.

The whole flat-topping cavities can be housed between the magnet yoke and sectors. A decreasing voltage distribution at low radii has been obtained in order to account for transit time effects in the gaps.

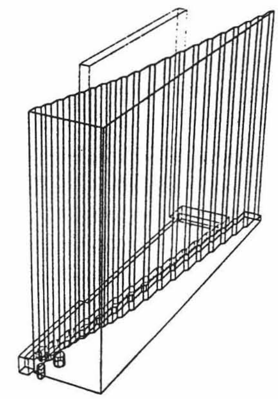

Fig. 2: MAFIA model of the RF flat-topping cavity of the injector cyclotron

Table 1: Main parameters of the RF system of the injectors

Injectors	Version A/B
Nb of accel. cavities.	2
Voltage	110 kV
Quality factor	7600
Total losses	50 kW
Beam power	62.0/51.5 kW
Nb of flat-top. cavities.	2
Harmonic	3
Voltage	12 kV
Quality factor	7500
Total losses	0.9 kW
Absorbed beam power	-6.8/-5.6 kW

4 Intermediate Cyclotron

The shape of the RF accelerating and flat-topping cavities of the intermediate cyclotron is visible in Fig. 3 and 5. Double-gap cavities have been selected (as opposed to single-gap ones) because their radial extension is much smaller, thus leaving more space in the centre of the machine for the bending and injection magnets and the beam diagnostics. They consist of a classical half-wave resonator with a delta-shaped resonant line (with a central dee and stem). In order to reduce the number of turns in the cyclotron and sufficient turn separation, accelerating voltages of 170 kV and 340 kV are required at injection and extraction. The required value of the frequency is mainly obtained by varying the cavity height, whereas the voltage distribution is mostly tailored by adjusting the stem expansion along the dee. A close agreement has been found between the measured and computed characteristics.

Table 2: Main parameters of the RF system of the ISSC

Intermediate	Version A	Version B
Nb of acc. cav.	2	2
Inject. voltage	170 kV	190 kV
Extr. voltage	340 kV	380 kV
Quality factor	13000	14400
Total losses	440 kW	630 kW
Beam power	1380 kW	1980 kW
Nb of f.t. cav.	2	2
Harmonic	3	3
Inject. voltages	20 kV	22 kV
Extr. voltage	40 kV	44 kV
Quality factor	11000	12000
Total losses	18 kW	22 kW
Absorbed beam power	-163 kW	-229 kW

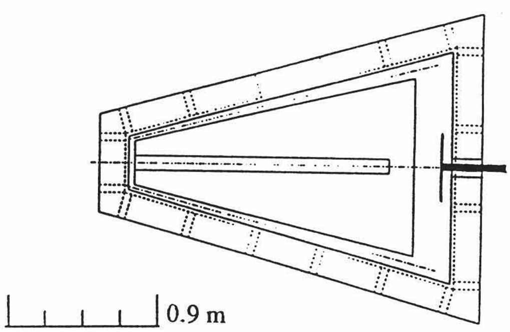

Fig. 3: Model of the intermediate cyclotron accelerating cavity

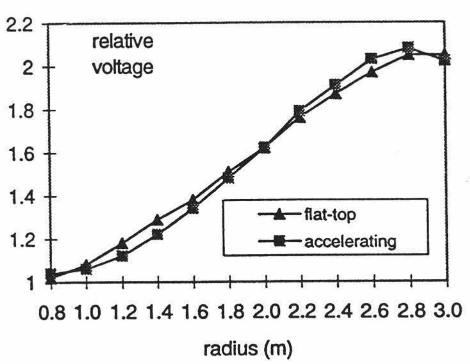

Fig. 4: Voltages distribution along the gaps of the intermediate cyclotron cavities

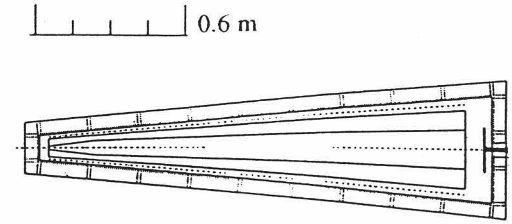

Fig. 5: Model of the intermediate cyclotron flat-topping cavity

5 Booster Cyclotron

Single-gap cavities are the most suitable candidates because azimuthal space is restricted and they have high inherent quality factors. This type would be used for both acelerating and flat-topping cavities. In order to reduce the number of turns in the cyclotron and sufficient turn separation at extraction, accelerating voltages of 550 and 1100 kV are required at injection and extraction.

Since the beam phase width is reduced to 15 degrees at the intermediate cyclotron exit, fifth harmonic operation has been selected for the flat-top cavities. This enables to decrease the flat-top cavity losses compared to operation on the third harmonic.

In a preliminary design for version A (10 sector cyclotron), it was decided to give them a simple basic shape (schematically a simple cylindrical box as shown in Fig. 6 with lips symmetrically added on each side of the median plane so as to reduce the time transit factor and planar upper and lower boundaries). They are operated in the fundamental TE110-like mode. It is advantageous from the power reduction point of view to depart from the basic cavity shape by allowing the cavity wall to extend azimuthally and benefit from the room available between the magnet sectors [2] even though this makes the design of the mechanical structure more complicated. This possibility is being presently investigated for version B (12 sector cyclotron). The estimated loss reduction due to this modification is larger than 30%, which means that the losses for the given voltages at injection and extraction could be reduced to a value lower than 400 kW for voltages at injection and extraction of 550 and 1100 kV. Reducing the RF power is certainly an important concern not only from the cost point of view but also makes the design of the cooling system an easier task. The gap voltage distribution computed with MAFIA in the optimised cavity confiuration is shown in Fig. 7. Measurements on a low-power model will be required in order to check the computational predictions.

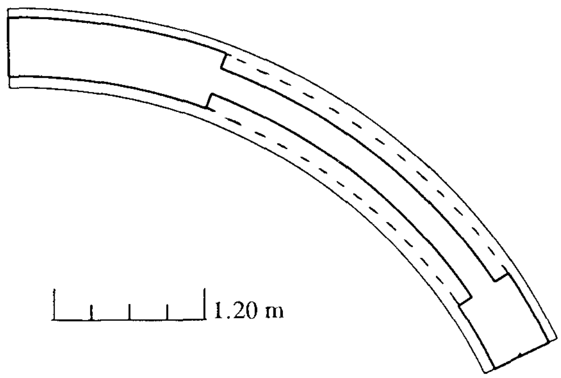

Fig. 6: Shape of the basic booster accelerating cavity

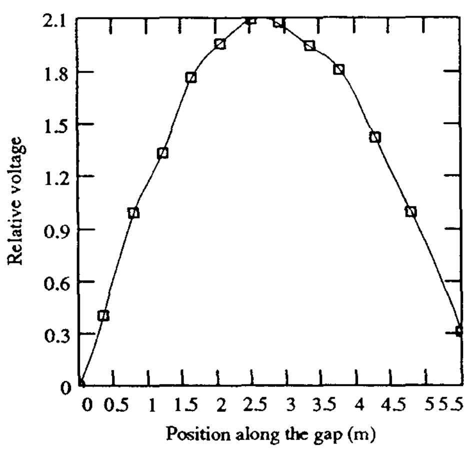

Fig. 7: Computed gap voltage distribution in the optimised booster accelerating cavity

Table 3: Main parameters of the RF system of the BSSC

Booster	Version A	Version B
Nb of acc. cav.	6	8
Inject. voltage	550 kV	550 kV
Extr. voltage	1100 kV	1100 kV
Quality factor	31000	36000
Total losses	3600 kW	3200 kW
Beam power	11000 kW	10400 kW
Nb of f.t. cav.	2	2
Harmonic	5	5
Absorbed beam power	-600 kW	-570 kW

6 Conclusion

The preliminary design of the RF system of the energy amplifier has been presented. Further investigations are presently carried out, in particular concerning the booster accelerating cavities, where wall losses should be reduced after optimizing the cavity shape. It is also necessary to start a detailed design of the mechanical structure, frequency tuning and cooling systems of the various cavities.of the accelerator complex. Low-level models of the accelerating and flat-top cavities of the injector cyclotrons should be built in the very next future. Further investigations should help in determining whether a single amplifier chain with power splitters should be allocated to each accelerating cavity or whether each loop would be associated with its own transmitter. A detailed design of the high speed beam absorber system of the booster flat-topping cavities should be carried out. In addition, it is planned to build a high-power prototype of the optimized accelerating cavities.

Acknowledgements

Various people have been involved in these studies and should be acknowledged : J.F. Di Carlo for the mechanical design studies and model construction with the help of J.C. Dupeux., P. Montalant for the mechanical part of the measuring system, J.M. Bergerot for preparing the software of the data acquisition system and for carrying out part of the model measurements, A. Susini and G. Primadei for their work on the design of the transmitters. In addition, P. Sigg of the Paul Scherrer Institute should also be thanked for helpful discussions

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