CNAO RF SYSTEM: HARDWARE DESCRIPTION

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Abstract

CNAO foundation is the Italian National Center of Oncological Hadrontherapy in Pavia. Proton beams are accelerated in the synchrotron and extracted in the energy range 60 to 250 MeV/u and carbon ion beams in the energy range 120 to 400 MeV/u. Trapping at the injection energy of 7 MeV/u and acceleration up to the extraction energy are done by an RF cavity which covers the needed range of frequency (0.4 to 3 MHz) and voltage (50 V to 10 kV) thanks to the use of an amorphous alloy. RF Gymnastics, including phase jumps to increase the momentum spread and empty bucket channelling, is requested and has been performed with optimum results on proton beams in the full energy range and with several beam intensities. A description of the hardware characteristics of the CNAO RF system and of its performances in terms of dynamic and static behaviour are reported in this paper.

INTRODUCTION

The purpose of CNAO is to cure tumors via the principle of hadronterapy [1] using proton and carbon ions beams. The layout of the accelerator consists basically of two sources, a 7 MeV/u linac, a 77.65 m long synchrotron and 4 transfer lines. The beam energies required by medical protocols need an RF cavity in the synchrotron able to cover a wide range of frequencies with moderate voltages. For this reason the solution adopted in CNAO project for acceleration is a coaxial resonator loaded with Vitrovac 6025, a ferrite-like amorphous material with a broadband frequency response produced by VACUUMSCHMELZE. The voltage that is generated across the accelerating gap is obtained by a push-pull amplifier in which two 70 kW tetrodes are installed. The skeleton of both resonator and amplifier, have been constructed at SATURNE for MIMAS [2] to validate the use of Vitrovac in an accelerating cavity; TERA foundation bought and modified it at CERN [3] to make tests in the frame of the PIMMS project [4]; finally, in the CNAO foundation, changes were performed in order to cure some weaknesses of the system and to guarantee the needed performances of the RF cavity. The description reported below for both the resonator and the amplifier shows the result of these changes and the present system in its actual status that has been successfully tested with proton beams [5].

CNAO RF CAVITY SPECIFICATIONS

For the proton acceleration in their full energy range the RF frequency changes from 0.46 to 2.4 MHz; the upper limit increases to 2.8 MHz considering Carbon ions. The beam is injected in the ring with a multi-turn injection, and then bunched by RF with an adiabatic trapping: this makes a good control of low voltages in the gap (from 50 V peak-peak to 200 V) necessary. The acceleration ramps are characterized by a rate of 23 kV/sec for the voltage and of 7 MHz/sec for the frequency; the maximum voltage is 3 kV for protons and 5 kV for Carbon ions. After acceleration, the RF phase jump, i.e. a sudden jump of 180° of RF voltage, is used to increase the beam energy spread up to the extraction value with an uniform distribution: to optimize this RF gymnastic, the cavity has to be able to limit the ringing of the voltage in the jump. The ringing of the voltage must be limited also during the sudden RF switching off needed to debunch the beam before extraction preserving beam momentum distribution. The last stress for RF system is the empty bucket channelling, an efficient technique to greatly reduce ripple spill: the higher the voltage the more efficient is the technique; furthermore the slew rate of the voltage must be as high as possible to reduce unwanted rebunching of the beam. The dynamic performances obtained are shown below.

RESONATOR CHARACTERISTICS

Resonator Design

In CNAO RF cavity, the vacuum chamber is the central coaxial conductor; the beam is accelerated across a ceramic gap placed in the middle of the chamber. The middle of the gap is a virtual RF ground because the two sides of the gap are connected to two tetrodes whose outputs are in anti phase. 28 vitrovac disks (14 for each half resonator) surround the vacuum chamber; every two vitrovac disks there is a copper disks in which a water flow of about 4l/min allows Vitrovac cooling keeping temperature below 90° (Vitrovac Curie temperature). The bias field for Vitrovac is supplied by a circuit arranged as a figure of eight with windings that go in and out Vitrovac disks to balance RF voltages on each winding; this circuitry creates a strong RF coupling between the two halves of the resonator affecting cavity impedance. Considering this description, in terms of the classification for the ferrite cavities reported in [6], CNAO RF cavity resonator belongs to the type 3 cavity.

Vitrovac Characteristics

The physical principle of broadband cavities exploiting the magnetic hysteresis cycle of ferrite-like materials are well described in [6]. Vitrovac is an amorphous Co-based alloy sold as a 25 micron thin ribbon wound in a ring with an internal diameter of 355 mm and external diameter of 510 mm. With respect to the standard ferrite:

- the dependence of μ from temperature is smaller;

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- permeability is higher (10^5 at 0.4 MHz and 10^3 at 10 MHz) as well as the figure of merit μQf [6];
- the magnetic sensibility is 40 times higher so the bias current is much slower (few tens of amperes instead of thousands), which implies cheaper and simpler bias power supply;
- the number of disks can be halved so the length of the cavity can be reduced (CNAO cavity is 1.5 m long).

Cavity Impedance

The impedance of the resonator has been measured with an Agilent network analyser E5061A adding different capacitors across the accelerating gap and varying the polarization current. Such measurements have revealed that the cavity response has always the bell-shaped frequency response of a resonator but it has the effective trend of a resonator (12 dB/octave) only increasing the polarization current: nevertheless we will describe the circuit with the usual characteristics of a resonator (resonance frequency, R_{shunt}, Q) [7] for easiness of explanation. Without polarization and extra capacitor, the resonance frequency is near 1 MHz: above this value the response has a trend of 6 dB/octave and below is $\ll$ 6 dB/octave. According to this measurement the resonator is equivalent to the parallel of a 125 pF capacitance, a non linear (versus frequency) resistance and a nonlinear inductance. Figures 1 and 2 show respectively the response without extra capacitor and with an extra capacitor (850 pF) across gap at different polarization currents. We can see that adding capacitor lowers both the shunt resistance and the resonance frequency (then it is not preferable) but reduces the Q of each resonance giving an accelerating voltage with smaller spurious harmonics. A compromise has been chosen adding only 250 pF across the gap. In this configuration: only 10.3 A are needed to tune the cavity at 3 MHz at low gap voltage (gap voltage influences the tuning condition), Q goes from 1 (0 A) to 5 (10 A) and the shunt resistance goes from 900 Ω (0 A) to 500 Ω (10 A). When the vitrovac temperature approaches 80° the resonance frequency becomes 5% higher and R_{shunt} increases by 20%. As shown in the figures 1 and 2, another element that encouraged the introduction of a great capacitance across the gap was the damping of a resonance of the circuit near 9 MHz.

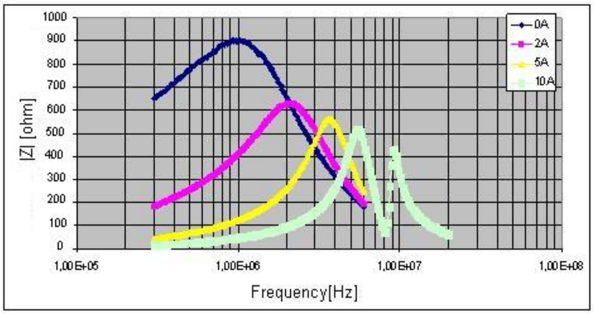

Figure 1: Absolute impedance without extra capacitor.

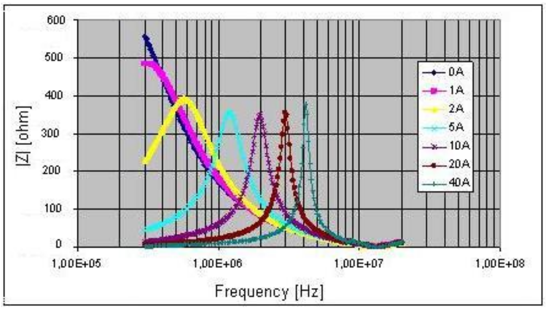

Figure 2: Absolute impedance with 850 pF across gap.

AMPLIFIER SCHEME

The tetrodes installed in the cavity amplifier are two Thales RS1084CJ [8] used in a grounded cathode configuration and bias in class B. The chosen working point is: anode voltage 11 kV, screen grid voltage 900 V; control grid voltage -180 V. The maximum RF power deliverable to the control grids comes from two class C solid state amplifier of 500 W (driver amplifiers). Considering the push-pull configuration the impedance seen by each tetrode is one quarter of the total impedance. Therefore, considering the previous paragraph, the RF power of each tetrode at 3 MHz needed to have a peak-peak voltage of 10 kV (the value corresponding to 500 W in the control grid) is about 25 kW. In this condition the anode current of each tube is about 6 A giving a DC power consumption of 66 kW; the power dissipated in each screen grid is about 180 W. While the grids power supplies are quite commercial, the anode power supply is more critical: it is a 12 kV-12 A power supply with a ripple of 1%. It has an output filter and a control loop able to avoid great undershoot and overshoot of the DC voltage when the RF voltage in the cavity decreases or increases rapidly. The control grid power supply is floating in order to connect the positive output to the filament through a resistor: this creates an anti-hum system able to decrease the 50 Hz modulation of the accelerating RF voltage. The air cooled filament is heated with a variac system that guarantees the slow heating during the switching on and off.

The anode of each tetrode is connected to the gap through 30 nF to block the DC voltage that arrives from the anode power supply through a cable passing between the resonator and the vitrovac disks and creating a "natural" choke for the RF voltage.

The RF power is injected in the grid through a second order low pass RF filter (cutoff frequency 6 MHz) that exploits the natural capacitance of the control grid and a water cooled 50 Ω resistor. Accurate filter design was required to avoid exciting parasitic resonances at high frequencies (above 10 MHz) experienced by tests with all-pass filters. Additional instabilities damping is provided by 2 Ω resistors between screen grid and tetrode socket (250 MHz resonance) and 10 Ω along the anode connection (1 MHz resonance across the DC blocking capacitors).

Considering cavity geometry, at the maximum power delivered by the tetrodes, each vitrovac disks must dissipate about 600 W.

Several strategies are implemented to protect tetrodes from damaging situations: screen grid overvoltage protector (gas discharger), screen grid over current protector (1 Ω-1 W resistor), rapid anode over current protector (ignitron circuit with a raise time of 10 µsec), automatic slow control (realized with home-programmed NI fieldpoint) of several interlocks (water cooling, air cooling, presence of high voltages and so on).

CAVITY SERVO LOOPS

The RF signal for the two driver amplifiers is generated by a DDS inserted in a custom low level RF (LLRF) card hosting an FPGA and two DSPs. The general electronic scheme of the LLRF can be found in [9]; the architecture of the system in the management of all the signals will be dealt with in a future publication. Using dedicated software for FPGA and DSPs of the LLRF, a rough calibration of the system has been done searching the DDS input and the vitrovac polarization current to obtain several set points of frequency and gap voltage. Such a calibration is not sufficient: a voltage loop and a tuning loop are digitally implemented in one of the two DSPs of the LLRF. The voltage loop is a digital PI controller that acts on the DDS signal amplitude using as an input the signal obtained by a capacitor divider (1/2000) mounted across the gap. A divider 1/50, realized by a ferrite transformer, is used as a pick-up for the RF signal injected in the tetrode grid: the phase between this signal and the RF gap signal is the input for the tuning loop. Indeed the tuning PI loop changes the vitrovac current to adjust the grid-gap phase to the value that minimizes the power needed for the gap voltage and the gap superior harmonics. For a real resonator with phase-compensated pick-ups, this phase would be 180°; in our case a calibration has been performed to obtain the best phase at each frequency and voltage. The parameters of the PI of both loops depend on the frequency because the open loop response of the system depends strongly on it. The tuning loop is active only above 0.7 MHz; below this value, vitrovac is not polarized. Voltage loop is always active; the only condition in which the voltage loop, together with the tuning loop, is switched off is about 20 microseconds after the RF phase jump because the jump causes a discontinuity in the calculation of the grid and gap signals. With the use of both loops in a static condition, the gap voltage amplitude oscillates within 3% of its value while the phase is stable within 0.3 degrees. The maximum slew rate of the voltage depends on the frequency because the sampling period of the loops is limited to the DSP speed then it is higher for higher frequencies: at 0.4 MHz we have 32V/µsec while at 3 MHz we have 120V/µsec; at each frequency the integral part of the PI voltage loop has been set choosing a compromise between the maximum voltage slew rate and the overshoot of the voltage. Figure 3 shows the gap voltage amplitude during a machine cycle: we can distinguish the adiabatic trapping ramp; the proton acceleration ramp; the RF switching-off to debunch beam; the empty bucket. Figure 4 shows the RF signal during a phase jump: we can see that ringing is limited to only few oscillations.

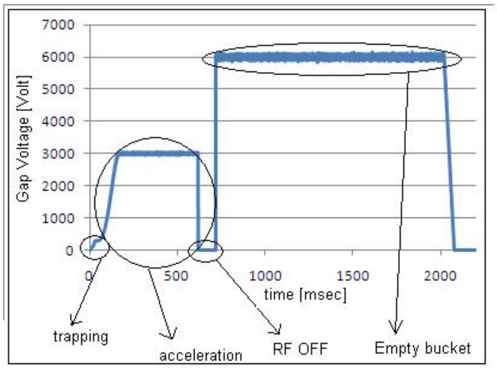

Figure 3: Gap voltage during a proton machine cycle.

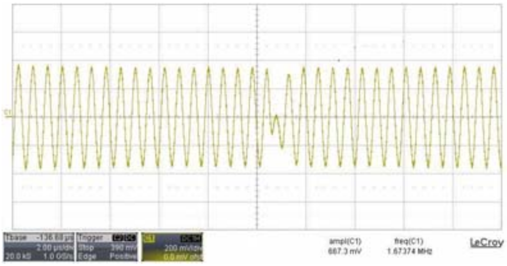

Figure 4: RF gap signal during phase jump.

CONCLUSIONS

The CNAO RF cavity has been commissioned and tested with proton beams performing acceleration and RF gymnastics. Recently also the first carbon beam has been accelerated up to its maximum energy of 400 MeV/u.

REFERENCES

[1] S. Rossi, Eur. Phys. J. Plus, (2011) 126:78.
[2] C. Fougeron et al., "Very wide range and short accelerating cavity for MIMAS", PAC'93.
[3] M. Crescenti et al., "The vitrovac cavity for the TERA/PIMMS medical synchrotron", EPAC'00.
[4] "Proton Ions Medical Machine Study (PIMMS)", CERN/PS 99-010.
[5] M. Pullia et al., "CNAO synchrotron commissioning", these proceedings.
[6] L.S.K. Gardner, "Ferrite dominated cavities", CAS'92.
[7] H. Klein, "Basic concepts 1", CAS'92.
[8] Thales electron devices, "Technical specifications tetrode type RS1084CJ".
[9] O. Bourrion et al., "LLRF Electronics for the CNAO Synchrotron", EPAC'08.

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