Performance Tests of a Ferrite-Loaded Cavity under Operation Conditions

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Abstract:

The ferrite loaded, tunable reentrant-coaxial symmetric ($2\times\lambda/4$) accelerator cavity for the cooler synchrotron COSY is of the SATURNE type. For h=1, frequencies range from 450 kHz at injection to a maximum of 1.6 MHz, with a maximum rf power level of 50 kW. We have determined the cavity circuit properties both at low signal levels with standard rf test equipment, and at operation conditions, depending on frequency and power level. Moreover, the acceleration system was tested for its suitability to pass through gamma transition. For this end, a sudden phase jump of 180° was imposed at the input of the amplifier chain by means of the digital frequency synthesizer developed for COSY. At higher frequencies, a loss of Q was observed, partly aiding the transition crossing speed. Finally, a simple replacement circuit, incorporating the measured quantities, is used to model the cavity.

1. INTRODUCTION

Synchrotrons with non-relativistic injection energy require a large tuning range, to adjust to the continuously varying revolution frequency during acceleration. Tuning is achieved by biasing a ferrite material inside the cavity by means of a polarisation current. High-permeability ferrites are required to reduce wavelengths at low frequencies to a few meters. Thus, ferrite-loaded cavities are used with virtually every proton or heavy-ion synchrotron accelerator.

There exist a number of basic configurations of such cavities, the most predominant types being a single-sided $\lambda/2$ structure, as used in MIMAS/LNS or LEAR/CERN, and a double-sided symmetric (push-pull) configuration, as used in SATURNEII/LNS or PSBooster/CERN. For biasing, both the common figure-eight windings around the ferrite toroids inside the cavity, and an external quadrupole magnet is used. The latter method was proposed and developed, in cooperation with MPI Heidelberg, by one of us (S.P.) for TSR, to eliminate any possibility of rf-to-biasing crosscoupling [1].

Cavities are regularly coaxial reentrant, to provide the geometry for a beam tube on axis, and a suitable electric accelerating field in axial direction. Cavity characteristics are somewhat complex, depending on the nonlinear thermal and magnetic properties, the latter being also strongly frequency dependent. Measurements on such cavities, therefore, sensitively depend on the actual measurement and operation conditions.

In the following, we restrict ourselves to measurements made on the acceleration station for COSY [2], which is of the coaxial reentrant symmetric type, with a push-pull RF-power amplifier, consisting essentially of TTE TH120 power tubes, capable of dissipating 45 kW each, integrated directly into the acceleration station [3]: The power amplifier is coupled to the cavity capacitively and inductively (Fig. 1).

The station operates in the h = 1 acceleration mode, with frequencies ranging from 450 kHz to 1.6 MHz. Acceleration voltage amplitudes up to 5 kV are possible.

COSY very likely will have to pass transition in order to reach its topmost energy design values, this also poses demands on the performance of the acceleration system.
The entire station was, with the exception of all low-level rf signal synthesis components [4], manufactured by a consortium of Thomson Tubes Electroniques, and the Laboratoire National Saturne. Since its installation in 1992, the system was continually adapted to the needs of COSY, as they emerged during commissioning.

2. ELECTRIC CHARACTERISTICS

To define the acceleration station's electrical performance characteristics, we must first consider a suitable lumped-element circuit schematic.

2.1 Circuit Schematic

Main features of the circuit are the cavity itself, defined by an inductor and capacitor on each side, coupled via the gap capacitance, and the polarisation windings, which are fed by a slowly varying ("DC") current, as mandated by the tuning requirement (Fig. 1) The amplifier may, on each side, be simplified to a voltage source with a following load resistor, the rf tube's internal resistance, to act somewhat like a current source.

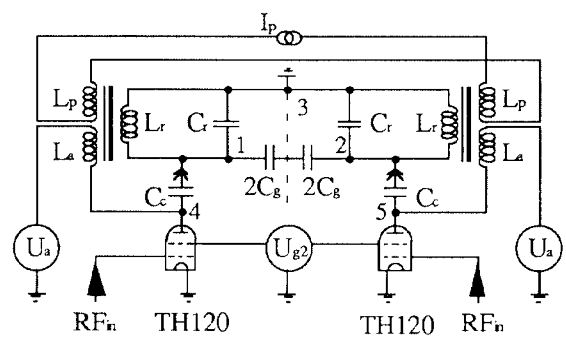


Fig. 1: Simplified circuit schematic of the COSY acceleration station

It was the goal of our measurements to either directly determine or derive from these measurements, the value of each of these circuit elements.

2.2 LCR bridge and vector impedance measurements

For both measurements a standard set up was used. However, care has to be taken to avoid errors induced by supplementary grounding loops.

The LCR-bridge and vector impedance meter both have to be supplied over a decoupling transformer

Also, due to the hysteresis of the ferrites, one has to establish specified magnetic conditions. In this case all measurements were taken by starting from the upper saturation point on the hysteresis loop.

Cavity inductance for low frequencies (f = 1 kHz) was measured directly via the LCR-Bridge connected across points 1 and 2 (Fig 1) by setting the polarisation current to the predetermined value required for saturation and then decreasing this current in small steps, taking down the inductance at each step.

To determine if the inductance of this cavity is also dependent on frequency, the impedance over polarisation current was measured across points 1 and 2 of Fig. 1 with a vector impedance meter for frequencies between 0.5 and 1.5 MHz, the operating range of our cavity. With a known value of C the, Inductance can be derived from frequency and the absolute value and phase angle of the complex impedance as given by the vector impedance meter. The results of these measurements are given in Fig. 2.

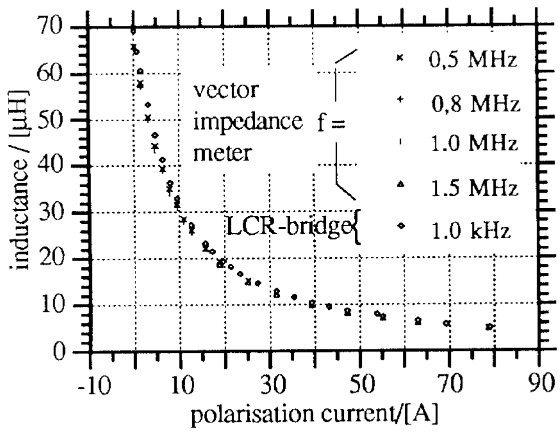


Fig. 2: Inductance over polarisation current

2.4 High-Power Measurements

Cavity Q i.e power dissipation and the response of the cavity to a phase jump of 180° were measured over a variety of frequencies between 540 kHz and 1.5 MHz and RF-voltages between 1 and 5 kV_p. The measurement set up is depicted in Fig. 3.

One evident method of determining Q is switching off the power generator and observing the decay of gap voltage. Here, an alternative method is used, employing the response of the resonator to a phase jump as is necessary when crossing transition energy. This method has the advantage of determining Q at operating conditions, and also, we get the variation of the gap voltage after the phase switch. For these measurements, the phase and amplitude control were switched off, since they would falsify the measured Q value.

The phase of the NCO's signal is switched 180° at the zero crossing t_0, of the gap voltage. The oscillogram of the resulting gap voltage is digitally recorded by a digitizing oscilloscope of the type HP DSA 602A.

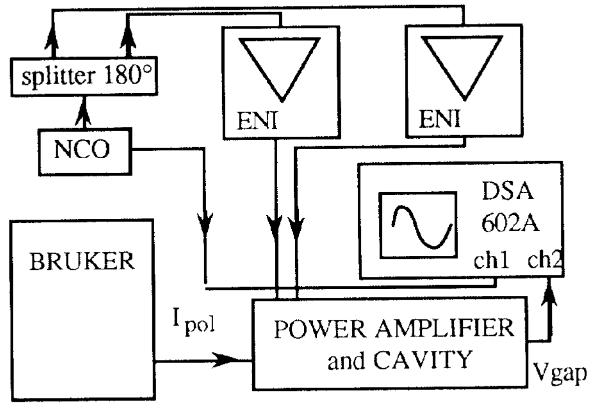


Fig. 3: Set up for testing phase jump of 180°

For low frequencies and moderate RF-amplitudes (Fig. 4) the gap voltage over time after the phase switch is given by the solution of the standard differential equation for forced oscillations:

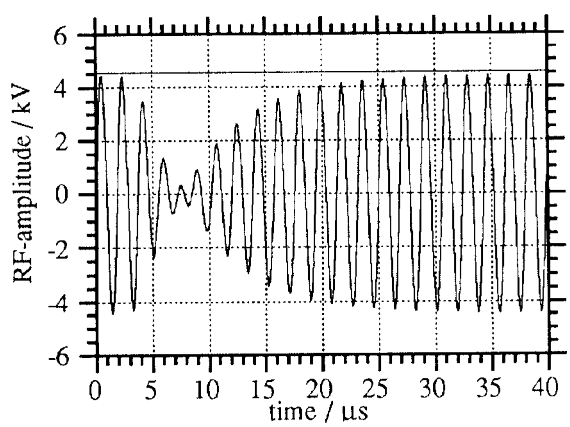
$$V(t) = V_0 \cdot \exp\left(\frac{-\omega}{2Q} t\right) \cdot \sin(\omega_r t + \varphi_0) + \hat{V} \sin\left(\omega t + \pi\right)$$

$$\text{with } \omega_r = \omega \sqrt{1 - (2Q)^{-2}} \qquad (1),$$

V_0 and φ_0 being determined by initial conditions. For a phase jump of 180° at zero crossing one obtains for the damped oscillation:

$$V(t) = 2 \cdot \hat{V} \cdot \sin(\omega t) \cdot \exp\left(\frac{-\omega}{2\,Q} t\right) \qquad (2).$$

Above some critical value ≈ 6 kV · MHz of $f \cdot V_{RF}$ (Fig. 5) there is sudden breakdown of cavity Q, resulting in a serious overshoot (Fig. 6)of the gap voltage .The behavior of the cavity can no longer be described by (1). The amplitude over time of the transient solution is some function f(t), as Q now strongly depends on frequency and RF-amplitude. At 1.5 MHz and an amplitude of 5 kV, approximately the RF-parameters when crossing the transition energy at COSY, the amplitude stabilizes to the initial value only after about 2 ms (not depicted here). By switching on the control loop, settling time can be considerably reduced



0.54 MHz / 4.5 kVp overshoot 0%

Fig. 4: Gap voltage over time after phase switch

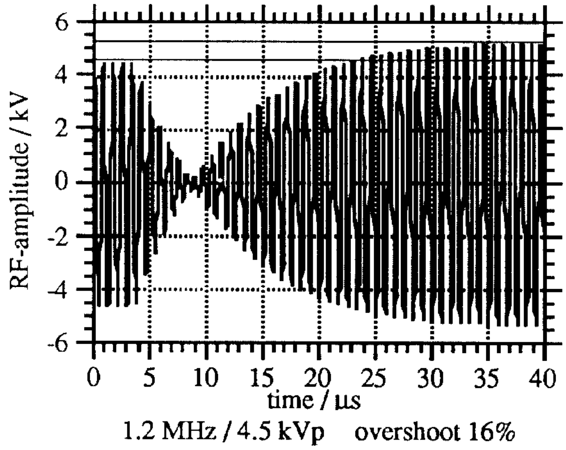


Fig. 5: Gap voltage over time after phase switch

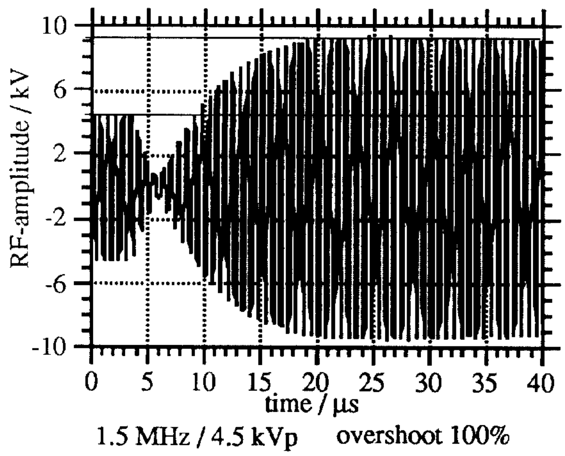


Fig. 6: Gap voltage over time after phase switch

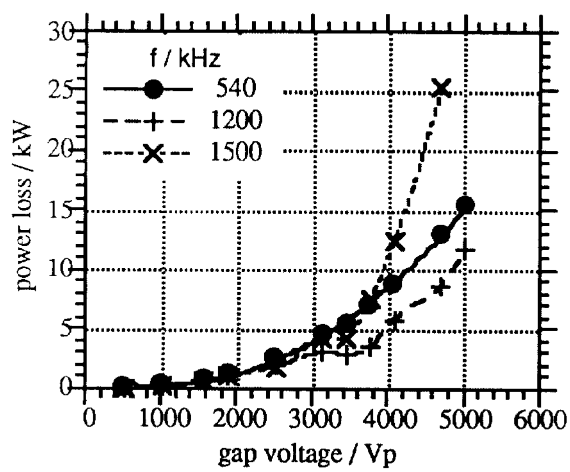


Fig. 7: Power dissipation over gap voltage

From the measurements mentioned above, parameters were derived for a SPICE model of the resonator, which is capable of simulating some aspects of the non linear response characteristics shown here

3. Thermal Characteristics

Under normal operating conditions the power disssipated in the resonator's ferrites is considerable (in excess of 10 kW), i.e. they have to be efficiently cooled. Each ferrite is intercalated between two copper cooling discs. There are four groups of six cooling disks with a serial water flow connection for each side of the cavity. The water temperature at the output from each of the 48 cooling discs is depicted in Fig. 8 for f = 1.6 MHz at Vgap = 3.7 kVp, cw mode and a water input temperature of 21.9°C.

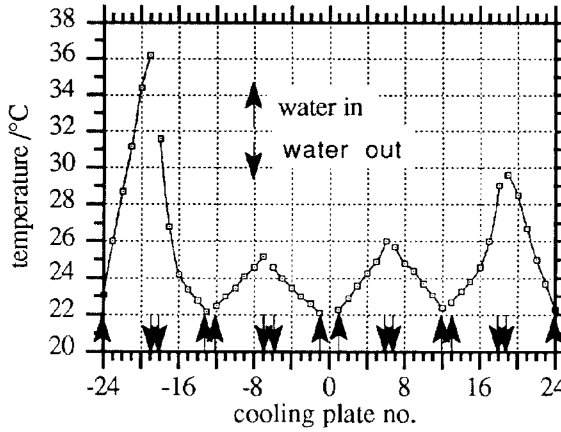


Fig. 8: Cavity cooling water temperature repartition

We can observe an asymmetry in the dissipated power between the left and the right side of the resonator which is probably due to the difference in the RF-characteristics of the ferrites. An increase of Vgap of only 5% produces the Q-loss effect in our ferrites resulting in a continuous rise of the cooling water temperature. In order to obtain higher cw gap voltages, we improved cooling at the shorted end of the cavity. The results for power dissipation derived from these measurements are in rough agreement with those derived from the measurements of Q mentioned in this paper.
We will report on the improvements obtains hereby and on further measurements elsewhere.

4. References:

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[3] C. Fougeron, Ph. Guidée, and K.C. N Guyen, *RF System for SATURNE II*, PAC, San Francisco 1979.

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[5] Ch. Hamm, *Ein SPICE Modell der COSY h=1 Be schleunigerstation*, Diploma Thesis 1993 Univ. Bonn