CONCEPTUAL DESIGN AND TEST OF THE PHASE PROBES FOR THE MILAN K800 CYCLOTRON

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ABSTRACT

The design of the phase probes which will be installed in the Milan Superconducting Cyclotron is reported. Analytical and numerical approaches in order to obtain 50 Ω impedance for the phase probes are presented. Beam signal parameters is evaluated and read-out electronics is described.

A test bench of the phase probe system with low energy electrons beams is described and some preliminary results are presented and discussed.

INTRODUCTION

As described elsewhere[1)] the heavy ion Superconducting Cyclotron of Milan will be equipped with 16 non intercepting phase probes which would assure a precise adjustment of the magnetic field topology for all particles and energies, in order to obtain the proper phase law. Furthermore the phase measuring system could be used to control the long term drifts of the magnetic field and of the cavities and bunchers RF voltages, since any drift of this quantities induces a beam phase shift. A phase resolution better than 0.2° ÷ 0.3° is required for relative measurements while an accuracy of about 1° is instead sufficient for comparative measurements between probes, with low beam intensity (1÷10 enA) and a bad beam signal to RF disturbance ratio. These performances have been achieved in compact and separated sectors cyclotrons[2,8)] which, however, present more favourable operating conditions with respect to the very compact superconducting cyclotrons.

The lack of experience with capacitive phase probes in operating superconducting cyclotrons and the actual impossibility of testing the operating conditions of the machine, have suggested us to accurately design probes and read-out electronics and to realize a test bench with RF pulsed electrons beams in order to check the system performances for different operating conditions.

CYCLOTRON AND BEAM FEATURES

The K800 Superconducting Cyclotron can accelerate axially injected beams from an external ECR source or radially injected beams from a 15 MV Tandem. In the first case long bunches (up to about 40° RF) can be injected and the acceleration of different ions at various energies is carried out in constant orbit mode and second RF harmonic. In the second case short bunches (less than 10° RF) are injected and the acceleration can be carried out at the maximum RF voltage for all particles and energies by using second or first RF harmonic.

The expected beams intensities range from a maximum of a few 10^{13} p/s (typically 1÷10 eμA for light ions) to a minimum of a few 10^{9} p/s (typically 1÷10 enA for heaviest ions).

The RF accelerating system consists of three dees placed into the valleys, each dee being the high voltage part of a coaxial resonator. The working frequency range is between 15 and 48 MHz.

PICK-UP PROBE DESIGN

Passive pick-up probes (low input impedance) have been chosen for the Milan cyclotron because of some advantages such as continuous and easy access to the electronic components, more precise comparative absolute measurements between probes and no damages caused by radiations.

The pick-up probes design with a precise 50 Ω impedance has been carried out in two steps. An analytical approach has been used in the first step to determine a suitable probe geometry and to study the influences of geometrical errors on the characteristic impedance. In the second step numerical calculations of the electrostatic potential among the pick-up plate, the grounded case and the liner have defined with more precision the most suitable probe geometry. The scheme of the probe and the liner used for analytical calculations is shown in Fig. 1.

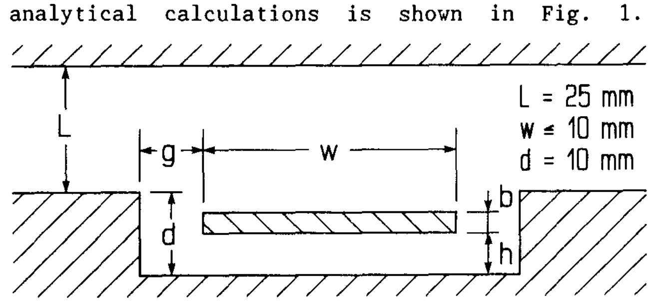

Fig. 1. Pick up plate model.

The characteristic impedance Z of the pick-up plate can be calculated as follows:

$$Z = 1/vC \qquad (1)$$

where C is the capacitance per unit length and v is the light speed. The capacitance C has been calculated by applying the analytical formulas obtained for rectangular transmission lines[9]:

$$C = \varepsilon_0 (w/h + w/L_1 + 2b/g) + \frac{2\varepsilon_0}{\pi}\left[\frac{2h+b}{2h}\ln\left(\frac{4h+b}{b}\right) + \ln\frac{b(4h+b)}{4h^2}\right]\frac{\ln[1+\coth(\pi g/2h+b)]}{\ln 2} + \frac{2\varepsilon_0}{\pi}\left[\frac{2L_1+b}{2L_1}\ln\left(\frac{4L_1+b}{b}\right) + \ln\frac{b(4L_1+b)}{4L_1^{2}}\right] \qquad (2)$$

where $\varepsilon_0 = 8.854 \cdot 10^{-12}$ F/m and $L_1 = L + (d-h-b)$.

The pick-up plate capacitance has been calculated as a combination of parallel-plates condensers constituted by the conductors walls plus the excess capacitance caused by the disturbances of flux lines close to the corners. The probe dimensions for a 50 Ω impedance and the impedance changes produced by 1% variations of the dimensions are reported in Table I.

Table I

x	Analytical formula x(mm)	Analytical formula ΔZ/Z*	Numerical results x(mm)
L	25.0	-0.46%	25.0
w	10.0	-0.99%	10.0
d	7.5	-0.18%	7.7
h	3.5	+0.36%	3.7
g	2.6	+0.31%	2.7
b	2.0	-0.20%	2.0

* Impedance change due to Δx/x = + 1%

This electrode configuration, assuming a median plane symmetry, has been analyzed by numerical codes which solve the Laplace's equation by relaxation method. The specific capacitance is obtained simply as:

$$C = \varepsilon_0 \Phi(E)/\Delta V \quad (F/m) \qquad (3)$$

where Φ(E) is the electrostatic field flux through a surface line enclosing the pick-up plate and ΔV the potential difference between the electrodes.

The potential distribution and the normal component of the electrostatic field along the flux integration line are shown in Fig. 2

The characteristic impedance obtained by numerical calculations is about 2% lower than the expected calculated value. Some probe dimensions (gaps h and g and depth d) have been changed, as reported in Table I, in order to obtain a precise 50 Ω impedance. A probe exploded view is shown in Fig. 3. The electrode length has been reduced to about 60 mm to limit the picked up RF noise disturbance.

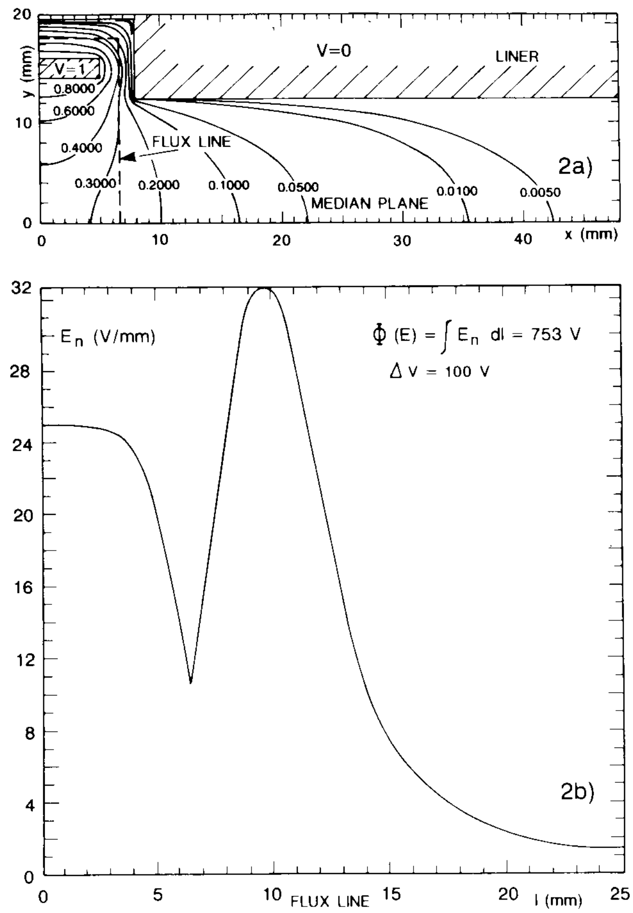

Fig. 2. Equipotential lines and electric field along flux lines as calculated by numerical codes.

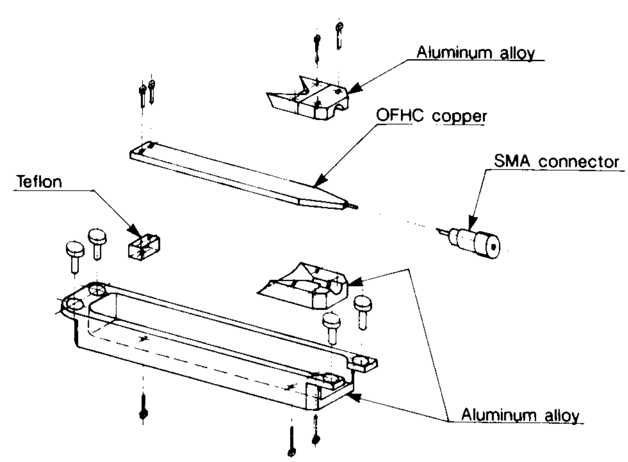

Fig. 3. Exploded view of the phase probe.

The expected amplitude of the signal picked up by the probe is given by:

$$V = 4nw_1A_1\gamma ZI/r_0{}^2 = 2M\Delta\theta n\gamma ZI \qquad (4)$$

where

w_1, A_1 are respectively the equivalent radial width and azimuthal length of the pick up plate,
Z is the characteristic impedance,
n is the n^{th} harmonic component of the beam current $I(t)$,
γ is the relativistic factor,
r_0 is the radius of the first orbit,
M is the number of turns seen by the pick-up,
$\Delta\theta$ is the azimuthal length of the plate,

and

$$I = 2/T \int_{-\alpha T}^{+\alpha T} I(t)\, \cos(2\pi nt/T)dt \qquad (5)$$

where T is the particle period and $2\alpha T$ the burst duration. The burst intensity $I(t)$ is related to the average beam intensity I_{av} by the simple relation:

$$I_{av} = 1/T \int_{-T/2}^{+T/2} I(t)\, dt \qquad (6)$$

As shown by the relations (4), the signal amplitude is almost constant at any radial pick-up position (the only variation being due to the γ factor).

Assuming $A_1 = 70$ mm , $w_1 = 20$ mm , $n = 2$, $\alpha = 0.03$ and an energy gain per turn of 250 keV/nucleon, the expected beam probe sensitivity should be:

$$V/I_{av} = 350\ \mu V/\mu A$$

This signal amplitude should assure a good resolution in the phase measurements up to low beam intensities (10 ÷ 1 enA).

ELECTRONICS DESIGN

The read-out electronic has been designed by using the homodyne solution, which has been preferred to the heterodyne one, in order to standardize it with the accelerating voltage phase control system of the cavities.

The block diagram of the whole system is shown in Fig. 4.

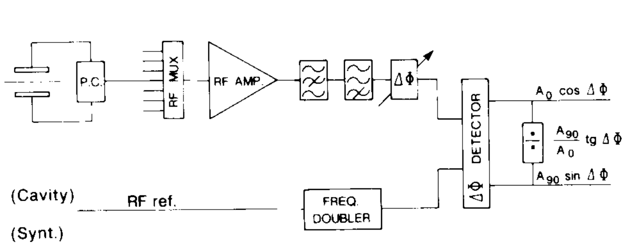

Fig. 4. Block diagram of the read-out electronics.

As previously explained, the signals detected by each pick-up plate are summed into a power combiner to reduce the RF noise. A computer controlled RF multiplexer connects the required probe to the first stage of a processing chain where the signals are amplified by a low noise device and passed through a filtering block. Here the second harmonic component is extracted and a phase shifter ensures a fixed working point for the phase detector independent from the frequency. The second harmonic of the detected signal is finally compared in phase with a sample of the accelerating voltage duplicated in frequency. Sine and cosine functions of the phase angle are available at the phase detector output. An analogic divider is further used to get phase informations in spite of input signal amplitude variations.

This procedure is described in details in the literature[4]. It is instead interesting to describe the filtering stages. An expanded view of the two filtering blocks is shown in Fig. 5.

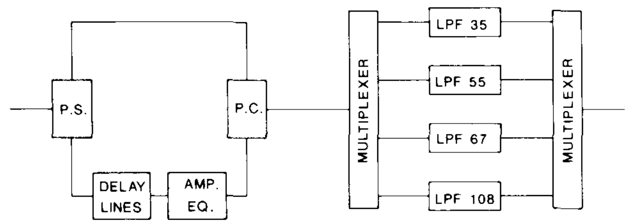

Fig. 5. Detailed diagram of the two filtering blocks.

The first stage is an interference filter and it is used to reject the odd harmonics. A computer controlled stepping delay line is used to achieve 180° phase shift on one branch of the splitted signal. The signals are recombined, after amplitude equalization, with the odd harmonics strongly reduced. The amplitude equalizer is a precise voltage controlled amplitude attenuator amplifier. The equalization is necessary to increment the odd harmonics interference suppression.

The second filtering stage is needed to reject all even harmonics higher than the second, still present after the interference filter. A set of four coaxial low pass filters, selected via a multiplexing system, is used to cover the wide operating range (30-96 MHz).

Two different devices for the frequency duplication system are under test. The first solution uses a phase locked loop, while the other uses a simple passive frequency doubler (MCL FD 2) followed by a low pass filter. The performances/costs ratio and the complexity of the two devices will determine the final choice.

ELECTRONS BEAM TEST BENCH

A test bench has been realized in order to test the phase probes and the read-out electronics. The test bench scheme is shown in Fig. 6. The electrons beam (0÷2 mA - 0÷5 keV) delivered by the gun is swept by a RF voltage (up to 200 V_{pp}) applied to the deflection plates. The beam profile and position (for the centering) can be measured by a movable thin wire (0.2 mm diameter).

The collimator produces electrons bunches

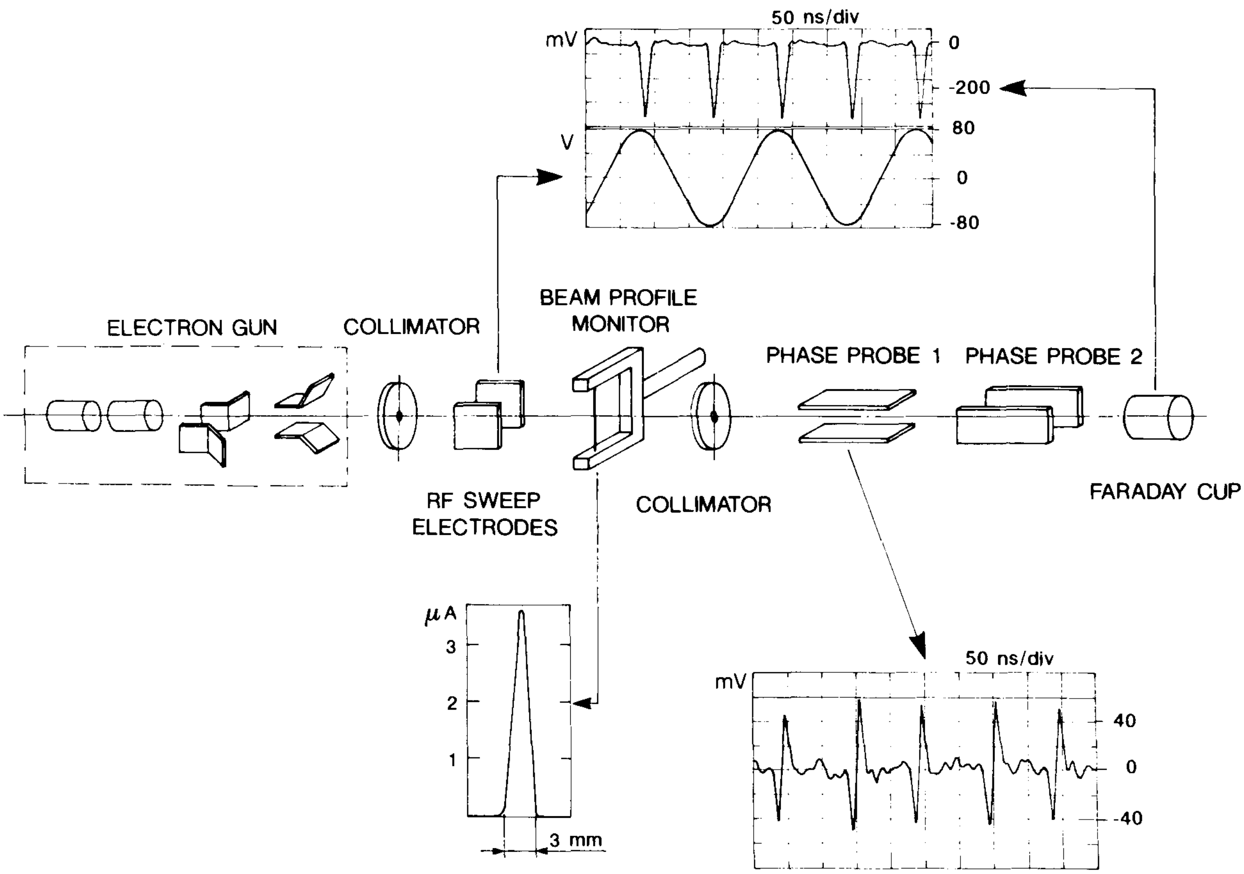

Fig. 6. Schematic view of the electrons beam test bench.
Typical device parameters measurements are shown in the inserts.

whose intensity and time length are depending on the electrostatic accelerating voltage and on the RF amplitude and sweeping frequency.

The pulsed electrons beam passes through two phase probes whose gaps can be varied in order to verify the influence of this parameter on the beam signal and on the RF noise. Furthermore the phase probe system can be displaced with respect to the beam position in order to evaluate the equivalent width of the pick-up plates.

The beam signals frequency is twice the RF sweeping frequency. RF noise can be introduced on the probes via a suitable antenna to analyze the picked-up signal to noise ratio. The electrons beam is finally stopped in a Faraday cup.

The expected beam signal from the phase probe is given by:

$$V = 4\pi n(L_1/\lambda)ZI = (4\pi n L_1 \nu Z I)/(0.563\ E^{\frac{1}{2}}) \qquad (7)$$

where $\lambda = vT$ being v the electrons speed, ν the frequency of the RF voltage, E the electrons energy whereas the other quantities have been previously defined.

For an accelerating voltage of 2 kV and a RF frequency of 20 MHz ($n = 2$, $Z = 50\ \Omega$) the beam phase probe sensitivity will be:

$$V/I = 130\ \mu V/\mu A \qquad (8)$$

Typical measured features of the electrons beams and the phase probes (beam size before the collimator, time structure of the bunches at the Faraday cup and beam signal from the pick-up plates) are reported in Fig. 6.

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