BEAM-CHOPPING SYSTEM FOR LNS SUPERCONDUCTING CYCLOTRON

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Several experiments which foresee the measurement of time of flight require a bunched beam with a FWHM smaller than 1 ns and a temporal separation from 100 to 200 ns. An H.E. Chopper that achieves this temporal separation between the impulses has been installed along the beam extraction line of the cyclotron. The two electrodes, which deflect the beam and the inductance coil are both under vacuum. The operating frequency range of the LC resonant circuit is 4.5÷9 MHz and the maximum design voltage is 70 kV. The chopper selects only the beam bunches which cross the device at peak voltage, one bunch for cycle. A steerer magnet to recover the selected bunches on the beam axis is used. All the tests, measurements and chopper's performance, will be presented.

1. Introduction

The K800 superconducting cyclotron of the L.N.S. is able to deliver ion beams over a broad range of energies and mass [1]. These beams are meanly delivered to nuclear physicist users. A lot of nuclear experiments requires bunched beam with a FWHM smaller than 1 nsec. A bunching system consisting of buncher and rebuncher placed before and after the Tandem respectively is able to achieve the above beam time performance. Moreover a chopper is installed just after the Tandem accelerator to remove the unbunched beam current, to prevent stripper foil damage and to suppress the spurious bunches when the bunching system is operated in subarmonic 2 or 3 respect the RF Cyclotron. In figure 1 a layout of L.N.S. beam lines is shown. The position of bunching system elements and of the Low and High Energy Choppers are shown too. In the last years several experiments required longer times separation between beam pulses than the cyclotron and the bunching system usually provide. Since single turn extraction is very difficult to be guarantee to our cyclotron, the L.E. Chopper some time was not able to achieve the required bunch separation. Figure 2(a) shows the beam bunches delivered by the bunching system when it is operated at the Cyclotron frequency, h=1. In figure 2(b) the beam bunches delivered by the Cyclotron are shown, RF is operated in harmonic 2. Figure 2(c) shows the waveform applied to the L.E. Chopper to reduce the bunch repetition at 1/2 of the Cyclotron revolution frequency. The Chopper is operated at subarmonic frequency h=1/4. Figure 2(d) shows the beam bunches delivered by the Cyclotron, when the L.E. Chopper is on. Despite the L.E. Chopper is on, spurious bunches are present due to multi-turn extraction. Moreover in near future the present radial injection will be replaced with the axial injection [2], the beam will be produced by the superconducting ECR source SERSE [3]. Due to the central region design the cyclotron will be only operate in harmonic mode h=2 and in the frequency range 15÷48 MHz. An RF buncher, operate at the same frequency of cyclotron, will be placed along the axial injection line near the cyclotron

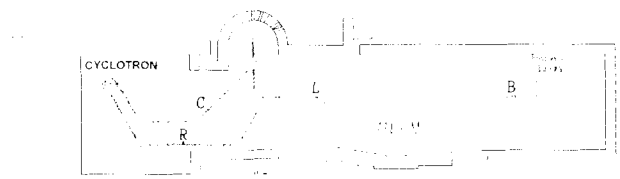

Figure 1: Layout of L.N.S. with Buncher (B), Rebuncher (R), Low Energy Chopper (L) and High Energy Chopper (C).

median plane. A beam chopper along the axial injection line will be installed, too This chopper will be able to perform beam suppression with frequencies of 1÷5 MHz, but with smooth rise time. It could not suppress the bunches with a temporal separation lower than ≈40 nsec. In this perspective the only way to achieve the required time separation between beam bunches is the use of an High Energy Chopper able to reduce the repetition rate of the beam bunches by a factor 2, 3 or 4. The High Energy Chopper is placed along the extraction line.

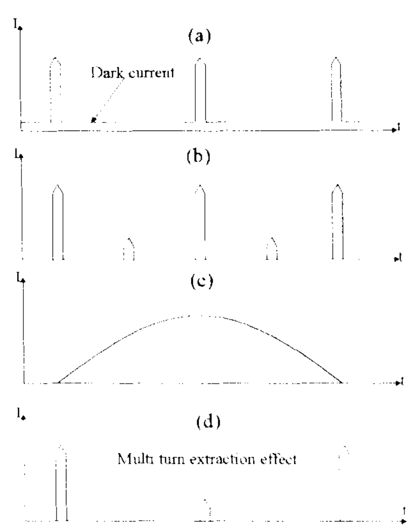

Figure 2: (a) Pulsed beam delivered by the buncher and the rebuncher; (b) Pulsed beam after the Cyclotron; (c) Waveform of the voltage applied to the L.E. Chopper; (d) Pulsed beam with Chopper on.

It has been successfully tested on the beam of ^{58}Ni at 45 MeV/amu last February to perform an experiment which required separation time between the bunches of 120 ns.

2. Design

Despite the frequency range of the RF cyclotron is 15÷48 MHz, the temporal separation between the bunches delivered to users is ranging from 100 to 35 nsec. This feature is obtained operating the bunching system in frequency range 10÷28 MHz, harmonic 1 or 1/2 of RF cyclotron, joint with the L.E. chopper which suppress the continuous unbunched beam current [4], see figure 2.

As earlier mentioned the difficulty to perform the single turn extraction from the cyclotron forbids to deliver bunches with a lower repetition rate than the Cyclotron revolution frequency. The cyclotron frequency bandwidth is 15÷24 MHz according to the energy range 5÷100 MeV/amu. To increase the temporal separation of the bunches until 100÷200 nsec for all the energies range it is mandatory to suppress the Cyclotron bunches along the extraction beam line by a H.E. Chopper. The feature of usual Chopper driven with a voltage $V=V_0\sin(2\pi ft)$ is to displace all the particles which cross with phases different of 0° and 180°. After the deflection plates of the chopper, at a distance L, a couple of slits are placed to stop all that particles outside the slits aperture, see figure 3. The bunches repetition rate of the beam after a chopper is then twice its frequency f. If a chopper is placed between two steerers, it is possible to adjust the bending angle of the two steerers, to balance the effects of the chopper for a chosen crossing phase. In this operation mode the chopper it is able to deliver, through the slit's aperture, the particles which cross with a phase different of 0° and 180°. The steerer balances the deviation of the chopper and recover the particles with a selected phase, on the beam axis. In particular the chopper and steerer system can be tuned to delivery the particles which cross the chopper when the voltage is maximum (phase=90°) or minimum (phase=270°). In these conditions only one bunch for cycle will be delivered. The main advantage of this unusual operation mode is a reduction of peak voltage required and then of RF Power. In fact the chopper plus steerer system can be driven with a frequency double respect than the usual chopper, and the phase distance among the bunches is then double. If we like to reduce the bunches frequency repetition of a factor 4, for an usual chopper the distance between two consecutive bunches will be $\Delta\phi=45°$, while in a chopper joint with a steerer magnet system the phase distance between two consecutive bunches will be $\Delta\phi=90°$.

In figure 4 are shown the two operations mode. When the chopper is operated in the usual mode the bunches 1, 5, 9,... are selected, while if the chopper is operated joint with a steerer the bunches 3, 5, 11,... are selected.

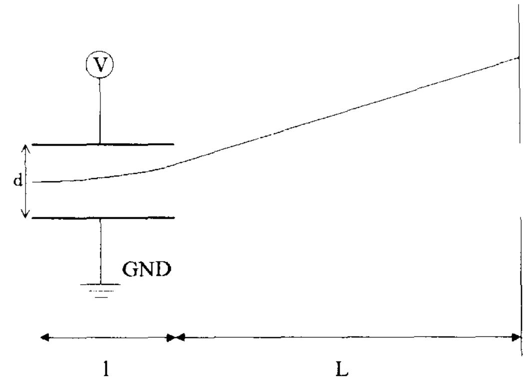

Figure 3: The layout of a beam chopping system.

The voltage difference, between the delivered and the consecutive suppressed bunches, for the standard chopper, driven by $V_0\sin\omega t$, is then:

$$\Delta V_{1\text{-}2}=V_2-V_1=V_0\sin 45°$$

while for the chopper plus steerer system, driven by $V_0\sin 2\omega t$, the voltage difference is:

$$\Delta V_{3\text{-}2}=V_3-V_2=V_0[\sin 90°-\sin(90°-90°)]=V$$

For the present case the chopper plus steerer system, needs then a peak voltage $1/\sqrt{2}$ lower than a conventional one. Moreover selecting the bunches which cross the chopper at the peak voltage, the vertical spread introduced by the chopper due to the bunch length is minimised. Now, let's evaluate the voltage required for our chopper-steerer system. The deflection of the beam in the slit plane can be written [5]:

$$y=\frac{qV}{md}sin(\phi)\left\{\left[\frac{1-\cos\left(\frac{2\pi l}{\beta\lambda}\right)}{\omega^2}+\frac{L}{\omega v}sin\left(\frac{2\pi l}{\beta\lambda}\right)\right]+\right.$$

$$\left.\frac{qV}{md}\cos(\phi)\left\{\left[\frac{\frac{2\pi l}{\beta\lambda}-sin\left(\frac{2\pi l}{\beta\lambda}\right)}{\omega^2}\right]+\frac{L}{\omega v}\left(1-\cos\left(\frac{2\pi l}{\beta\lambda}\right)\right)\right\}\right.$$

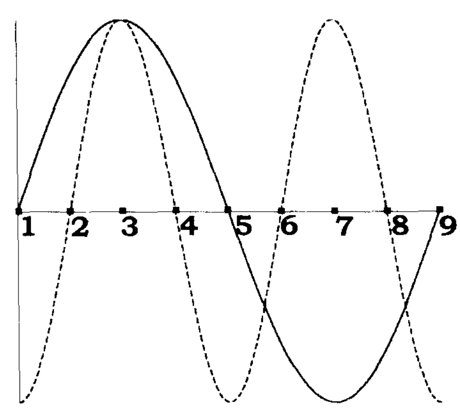

Figure 4: The two operation mode of the H.E. Chopper.

where:
v, q and m are velocity, charge and mass of particles respectively;
ω and V are the angular frequency and the peak voltage of the driven waveform;
ϕ is the phase angle of the sinusoidal voltage across plates when the particles enter the plates;
d, l are the gap distance and the length of the plates;
L is the drift length from the plates to the slit aperture.
If $l \leq \beta\lambda/10$ and in non-relativistic approximation ($E=1/2 \cdot mv^2$), the above general expression can be written as:

$$y = \frac{qV\sin(\phi)\, l(l+2L)}{4dE} = \frac{V\sin(\phi) l(l+2L)}{4dK_{foc}}$$

assuming an aperture of the slit of 7 mm, l 700 mm, L 3 m, d 30 mm and because for Cyclotron beam $\frac{E}{q} \leq K_{foc}$, with K_{foc}=200, the required voltage difference between two consecutive bunches is $\Delta V = V[\sin 90° - \sin(90° - \Delta\phi)]$=35 kV. If the chopper plus steerer have to suppress beam bunch with a phase separation of $\Delta\phi$=45°. The maximum voltage required at the plates is about 50 kV [6].

3. System description

The H.E. Chopper consists of a lumped L-C resonant circuit, the main components are shown in figure 5. The inductance is provided by a coil which consist of a tube, copper made, with 18 mm of diameter. The cooling water is inlet to the coil by an internal pipe of 8 mm, coaxial to the copper tube, while the water outlet is pass through the gap between the internal and external coaxial tube. In this way the inlet/outlet connection of the cooling circuit are on the grounded terminal of the coil, and the effect of the spurious water impedance is negligible. The coil has a diameter of 210 mm and a length of 500 mm. To minimise the required power and to cover the required frequency range from 4.5 to 9 MHz, two different coils, with 10 and 12 turns have been realised.

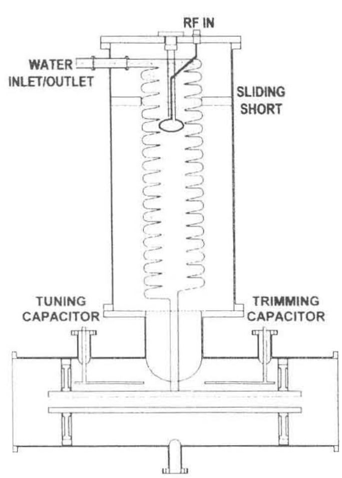

Figure 5: High Energy Chopper

The inductance of these two coils are 7 and about 11 nH. An interchangeable system has been studied to replace the two different inductance coils, which allows to use a fixed short. The capacitance of the system is mainly due to the parallel deflecting plates. The upper plate of the capacitor is connected to the H.V. end of the coil, while the lower plate is grounded. The electrodes are copper made, 10 mm tick, 100 mm width and 700 mm long. To prevent the use of H.V. feedthrough, both the coil and the capacitor are placed inside two cylindrical tanks under vacuum. The RF power is inductively coupled to the chopper at the shorting end of the coil. The connection between this power feeding coil and the power amplifier is made through a semirigid coaxial cable. The air vacuum feedthrough is presently realised by a vacuum-sealed N-type connector. The operation of changing the coil, needs approximately four hours, including the time to recover the vacuum in the line. Presently out of two trimming capacitors with a value from 4.4 to 44.2 pF are used, for one coarse tuning while the other like for trimming capacitor.

4. Tests and measurements

Power tests in air and under vacuum were carried out. A Q factor of 450 was measured with a network analyser. The voltage on the electrodes was measured, directly with a HF probe, and a shunt impedance of 190 kΩ was found. To achieve 50 kV peak at the electrodes a maximum power of 6.6 kW is then needed [6].
The High Energy Chopper, placed along the beam line is shown in the figure 6.

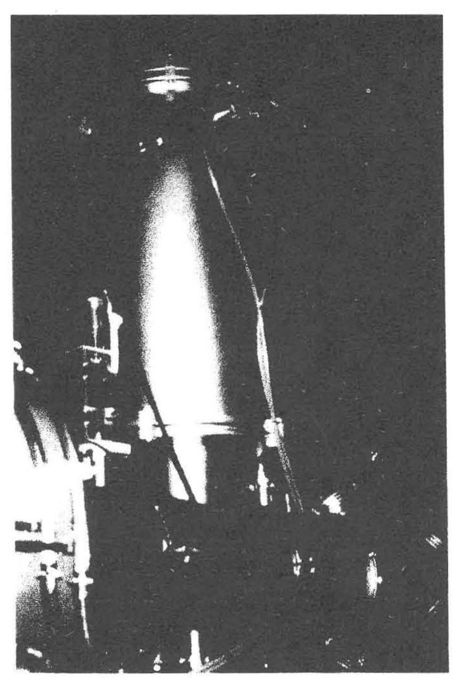

Figure 6: H. E. Chopper in the beam line.

At the same time the calibration of the pick-ups, placed in front of the H.V. electrode, was carried out to evaluate the voltage at high power. The calibration factor was found to be 4000. We could not go beyond 10 kV peak, in air, due to sparks/breakdown. The measurement under vacuum were accomplished up to 500 Watts, due to limits of our present power amplifier. During the tests, performed under vacuum the maximum voltage of 14 kV was reached without any multipactoring. During the operation with ^{58}Ni beam at 45 MeV/amu, the H.E. chopper was drawing around 350 Watts, for 12 kV on the electrodes, to achieved the required deflection, in good agreement with the evaluate values. After some hours of warm-up, the system run quite well without any automatic correction tuning loop.

5. Future plane

During test and measurements with the H.E. Chopper it has been necessary some manual adjustments of some parameters of the system. In the future we are planning to develop a proper control circuits unit as the figure 7 shows. We are introducing two different automatic loop systems for the trimming capacitor and for the regulation of the amplitude. A start/stop system connected to the protection circuits is also planned as the block diagram shows in the figure 7.

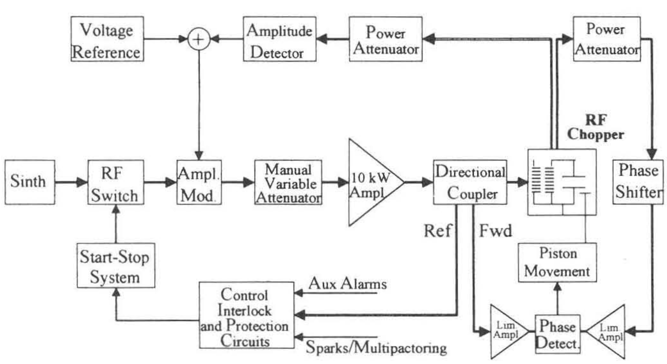

Figure 7: Block diagram of the H.E. Chopper.

Considering the higher voltage and RF power request, a 10 kW amplifier is under construction. It is a solid state amplifier based on modular design. Each module, see figure 8, can deliver 800 Watts and the combination of 16 such modules allows to achieve the required power.

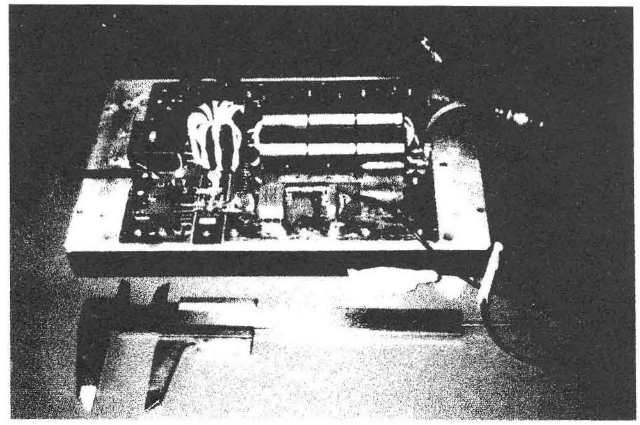

Figure 8: Single module of the 10 kW amplifier.

Satisfactory tests and measurements on a single module of this RF amplifier has carried out up to 1 kW on the bandwidth of 4÷9 MHz. To reduce system losses, the inner walls of the cylinders housing the coil and the capacitor will be copper plated. We are using the electrochemical deposition technique directly on the steel cylinders. The copper plating of both cylinders has already been successfully done in our laboratories.
In September the system will be replaced along the beam line to be tested together with the new 10 kW amplifier. For October and November experiments are selected which need chopper system are scheduled.

6. Acknowledgement

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