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RF KICKER AT THE CYRCÉ FACILITY IN STRASBOURG

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Abstract

The Cyrcé facility of IPHC in Strasbourg operates a TR24 cyclotron to produce medical isotopes, lead radiobiology programs and qualify detectors. After installation of a first chopper operating with a switched high voltage (see [1] and [2]) an RF kicker was developed to halve the frequency of the beam bunch frequency so as to obtain a rate close to 40MHz (the Large Hadron Collider bunch frequency). An RF voltage at a quarter of the cyclotron frequency applied to a deflector in the injection line allows to reach that goal. The 30keV DC beam from the ion source is discarded except at the zero crossing of the RF. With a proper phase difference between the two RF (kicker and cyclotron), only one accelerating phase of the cyclotron over two is populated resulting in a bunch rate of 42.5MHz.

A second need for radiobiology is to switch the beam on and off with the highest raise and fall times. This is done by adjusting the phase of the kicker to block the beam.

The kicker is made of a collimator (diam. 8 mm), followed by 2 deflectors (55 mm long, 50 mm wide) spaced by 40 mm and a second collimators (diam. 6mm) at 160 mm downstream the deflectors, also used as a beam dump for the deflected ions.

The high voltage is achieved by a resonant circuit consisting of a coil and a deflector acting as a capacitor, excited by a second coil. A second variable capacitor is added for tuning. The excitation coil position allows to adjust the matching.

Scintillators associated with fast electronics has shown that the bunch rate was half the cyclotron frequency as expected. The beam rejection was measured to values up to 2 10^{-5}. The raising and falling times of the beam was measured to 10µs.

BASIC CONCEPT OF THE RF KICKER

An RF voltage at a quarter of the cyclotron frequency is applied to deflectors plates in the injection line. The 30keV DC beam from the ion source is discarded except at the zero crossing of the RF, see Fig. 1 for global overview. With a proper phase difference between the two RF, only one accelerating phase of the cyclotron over two is populated (first mode) or the beam is completely switch off (second mode). This later mode is used to control irradiation times to guarantee precise dose deposits in radiobiology projects.

Figure 2 shows the cyclotron RF (Radio Frequency) superimposed on the kicker RF in the "one over two bunch" mode. The green areas indicate the phase acceptance of the cyclotron and the red areas when the beam is deflected. Bunches are accelerated every two periods of the cyclotron RF.

Figure 3 shows the beam suppression mode. The phase between the two radio frequencies is adjusted to eliminate all bunches. To switch from one mode to the other, a 45° phase shift must be applied to the kicker RF.

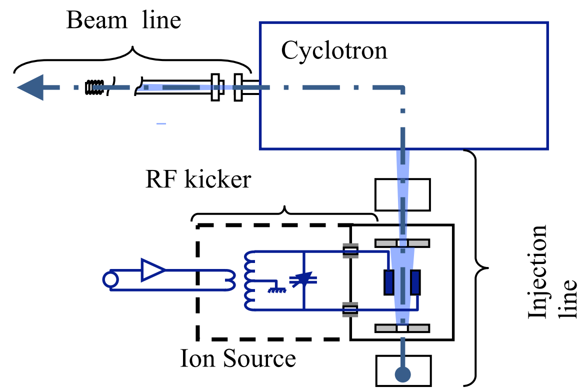

Figure 1: Overview of kicker implementatio into the cyclotron injection line.

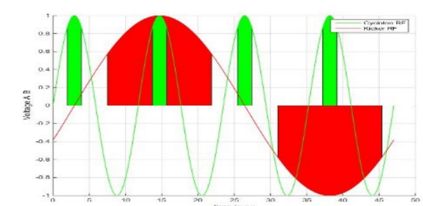

Figure 2: One over two bunch mode.

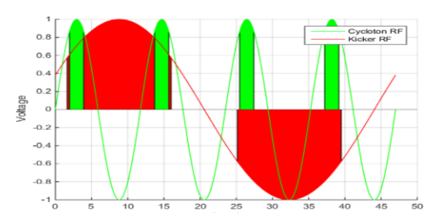

Figure 3: All bunches suppressed mode.

OVERALL DESIGN

A synthesizer locked to the cyclotron synthesizer generates an RF signal at a quarter of the cyclotron frequency. This signal feeds a resonant circuit composed of lumped elements which synospsys is given in Fig. 4.

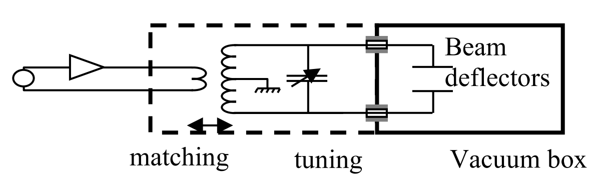

Figure 4: High voltage RF circuit diagram.

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Coil Design

To reduce the effect of parasitic capacitance, the centre point of the main coil has been grounded. The main capacitance comes from the feedthoughs, the deflectors, the coil vs the box. The overall capacitance is of the order of 15pF to which a variable capacitance of 15pF has been added.

A standard annealed copper plumbing pipe with silver plating was used for the coil. The NAGAOKA formula Eq. (1) was used to optimize the design of the coil.

$$L=\frac{\pi N^2 D^2}{h\left(1+0.45\frac{D}{h}+0.005\frac{D^2}{h^2}\right)}10^{-9}\mathrm{H} \tag{1}$$

With D, the diameter of the coil in cm, h its height in cm and N its number of turns.

Equations (2) and (3) give the resistance R of the coil.

$$R=2k\rho N\sqrt{\frac{\pi V_{coil}}{h}}\ \Omega \tag{2}$$

With Vcoil the volume of the coil, h its height, N the number of turns, ρ the silver conductivity and k a proximity coefficient defined as :

$$k=1+0.5u\left(\frac{d}{c}\right)^2 \tag{3}$$

With d the diameter of the conductor, c the coil step (c=1 meaning contiguous turns) and u being a parameter depending on the ratio h/D (height/diameter of the coil) derived from the following values

h/D	0.4	0.6	0.8	1	2
u	4.06	4.5	4.93	5.29	6.58

The main ohmic resistance of the coil is given by the length of the conductor. The k-factor accounts for an additional resistance that occurs as the coil turns get closer together. On the one hand, the tightening of the turns reduces the total length of the conductor and thus the resistance, but on the other hand the k-factor increases it. There is therefore an optimal geometry for a given coil volume that minimises the resistance while maintaining the value of the inductance.

Figure 5 shows the quality factor (green) of the coil as a function of the number of turns for a given volume. For each value of the number of turns, the corresponding height and diameter (red and blue plots) give a coil with the right inductance value.

As expected, this curve shows a maximum corresponding to the best coil geometry. In practice, the measured Q-factor for the whole circuit is much lower than this optimum value and is around 650 instead of the theoretical value of 3526. This difference is mainly due to feedthroughs and other connections resistance.

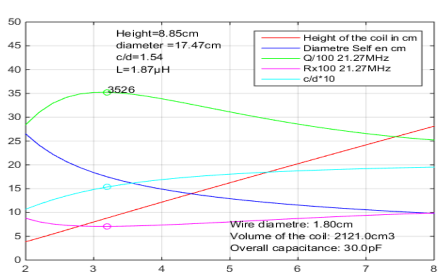

Figure 5: Coil Quality factor vs number of turns.

The coil is coated with 15µm silver and its geometry is maintained with PEEK supports, see Fig. 6.


Figure 6: Coil made from standard copper plumbing, silver coated.

Implementation

Figures 7 and 8 show the mechanical overview of the kicker as it is implemented in the injection line. The beam must be collimated upstream and downstream of the deflectors before the kicker can be used. The collimators can be removed for normal operation by a pneumatic actuator. Two motorised actuators are used to adjust the tuning and matching of the resonant circuit. A blower at the bottom of the resonance box cools down the coil.

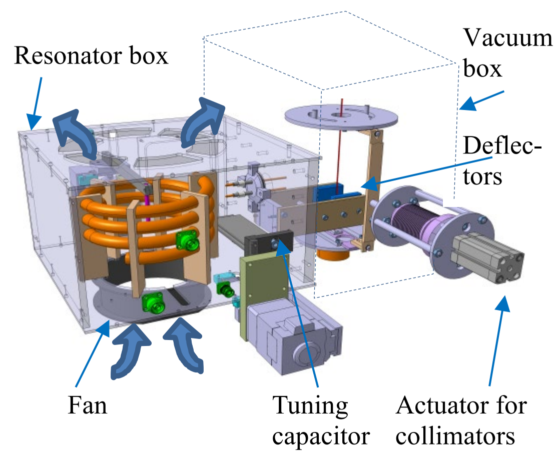

Figure 7: View of the entire mechanical assembly.


Figure 8: View of the Rf kicker box opened.

The collimator apertures are respectively 12 and 8 mm diameter. To reduce beam diffusion conical shaped collimators have been designed as shown in Fig. 9.

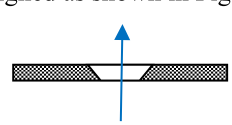
Figure 9: collimator schematics.

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A negative voltage of 100V is applied to the collimators in order to reduce beam interaction.

Electronic Control

Figure 10 shows the schematic diagram of the control and command electronics. The HMS synthesizer provides the RF frequency for the kicker and for other controls. It allows to adjudt the level and phase of the RF signal to maximize the beam current. A controllable phase shift of around 45° allows to switch between the two modes (beam on and off). This function is physically implemented with a fast SPDT switch that allows the RF signal to be routed over 2 paths, one of which has a delay corresponding to the desired phase jump. A phase comparator gives an indication of any phase drift of the radio frequency. It can be inserted into a phase control loop to maintain the correct setting of the resonant circuit.

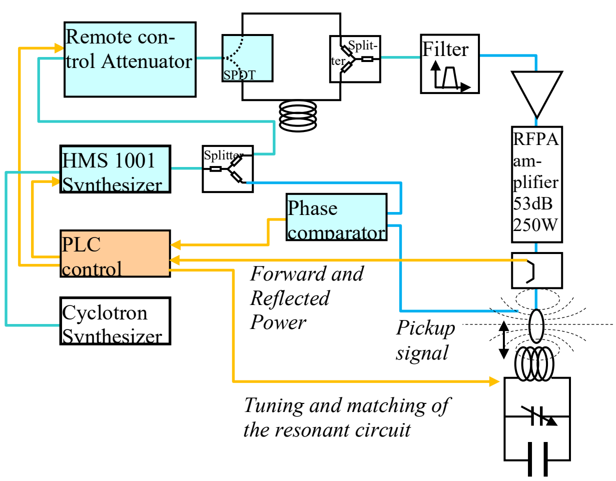

Figure 10: Synopsis of the electronic control system.

Settings

Beam current is measured during constant phase ramping (from the HMS synthesizer). Ramping is stopped when the beam current reaches a maximum. Typicall periodical diagram of beam current is given in Fig. 11.

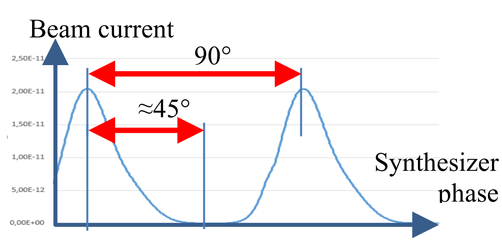

Figure 11: Beam current vs RF phase.

RESULTS

Mode beam on

As expected when the phase is adjuted to get the maximum beam current, one can observed that the repetition rate is half the cyclotron frequency as can be seen on Fig. 12. To qualify this first mode, analog scintillators associated with fast electronics has been used to quantify the time structure of the beam. Average beam bunches arrive at a rate of 23.5 ns as expected. Beam current of 50fA was used for this result.

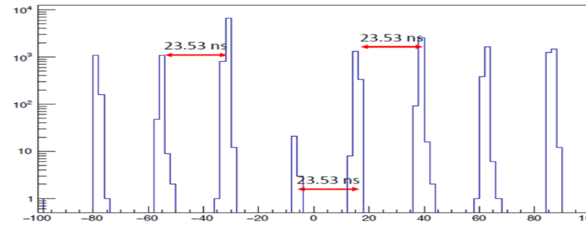

Figure 12: Beam current vs time.

Mode Beam Off

The second mode is evaluated by measuring the ratio between the maximum and minimum currents obtained with the phase scan. Beam rejection ranges from 50.10^4 and 10^5.

Beam Cut-Off and Restoration Time

SPDT switch reacts in the range of ns, yet RF phase change is much longer due to poor coupling between excitation and main coils of the resonant circuit. It has been measured to be a bit less than 10 µs (see Fig. 13)

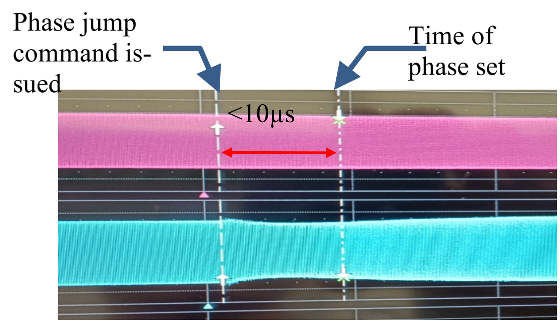

Figure 13: Retauration time after a phase jump.

CONCLUSION

The RF kicker has been in operation for about 2 years, working as intended in its two modes, either for radiobiology or for detector qualification. The rejection rate is sufficient for most radiobiology applications, but should be further improved for flash type applications with very high dose rates and high currents (several tens of nA).

The great advantage of this equipment over systems using electronic switches is its insensitivity to neutron flux, which is present in particular during isotope production shots. The equipment is permanently installed on the injection line and is never removed.

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[3] ACSI website, http://www.advancedcyclotron.com