Half-Integer Fast Resonant Extraction with Quasi Rectangular Spill

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Abstract

Neutrino experiments at the SPS require short bursts of protons which are extracted by a fast resonant mechanism once or twice per cycle. The extraction process is triggered by a thyristor controlled pulse generator, discharging a capacitor bank into an extraction quadrupole. The beam being pushed onto resonance at nearly constant speed during the "*linear*" part of the rising ramp, the time signal of the *spill* (i.e. the number of particles extracted per time unit) is almost *Gaussian*, according to the particle distribution in the momentum and horizontal tune (Q_H) space.

A relatively simple and inexpensive modification of the pulse generator allowed to improve this Gaussian spill time structure such as to become more rectangular.

1. INTRODUCTION

For fixed target experiments, the *instantaneous* intensity of particles hitting the target has to be kept as low as possible in order to reduce the thermic stresses in the target and to diminish the load on trigger and read-out electronics. Since the capacity of the latter is limited, an increase of the particle flux (and therefore number of interactions !) above a certain level only adds to the dead time of the apparatus, without any gain of recorded data. Therefore the flux of particles spilling out of the accelerator and being directed towards the target is required to be *constant* over a time interval as long as possible.

In practice however, spills with *ideal rectangular* time distribution are not possible and their duration is limited by the flat-top time of the acceleration cycle. For some experiments an even more restrictive upper bound may be imposed on the spill time by the equipment used in the generation of secondary beams, as e.g. pulsed magnetic lenses in a neutrino beam line (neutrino horn).

Neutrino experiments are therefore particularly sensitive to the spill structure, since the duration of the extraction is comparably short, namely a few milliseconds only. Consequently, the slightest improvement of the spill quality may significantly reduce the dead-time losses. In the case of the CHARM II detector operating at the CERN wide band neutrino beam, these losses could be reduced by a factor of 2 to 4 compared to those before the modification of the pulse generator and the resulting spill improvement.

2. EXTRACTION MECHANISM

The extraction mechanism of a "classical" half-integer fast resonant extraction is described thoroughly in [1]. It can briefly be summarized as follows:

The radial tune of the machine is brought close to the half-integer ($Q_H \approx 26.55$) and a local closed orbit deformation approaches the circulating beam to the septa in the extraction channel, which are placed outside the machine aperture. After exciting a set of suitably distributed octupoles, a capacitor bank is discharged through an extraction quadrupole which, together with these octupoles, defines a stable area in the radial phase space. With increasing quadrupole current, this area shrinks rapidly such that particles with a larger emittance start unstable betatron oscillations with a fast growing amplitude and with a phase locked to that of the extraction quadrupole. Particles, whose horizontal amplitude has grown sufficiently, will then enter into the field of the electrostatic septum which deflects them into the field region of the two subsequent magnetic septa and into the extraction beam line.

Since the resistance of the quadrupole is *negligibly small*, the quadrupole current is practically an undamped sinusoidal. Because either all particles have been pushed through the resonance, or in order to stop the extraction process, this current is usually " *clipped off* " before reaching its maximum value.

The particles are driven onto resonance at almost constant speed defined by the quasi linear ramp of the quadrupole current. According to their distribution in momentum and tune space, this results in a "Gaussian" shaped spill of typically 3 to 5 ms duration as shown in Fig. 1 from [1].

In order to provide a *constant* flux of extracted particles, the speed with which the beam is driven onto resonance, would have to be inversely proportional to this "quasi Gaussian" distribution function. This is not feasible, since infinite speeds would be required. A first order approximation of this requirement consists in "pushing faster" at the beginning of the extraction process and "slowing down" when the high density part of the beam probes the stop band. This can be achieved with two well distinct slopes of the current wave form in the extraction quadrupole yielding the spill improvement shown in Fig. 1:

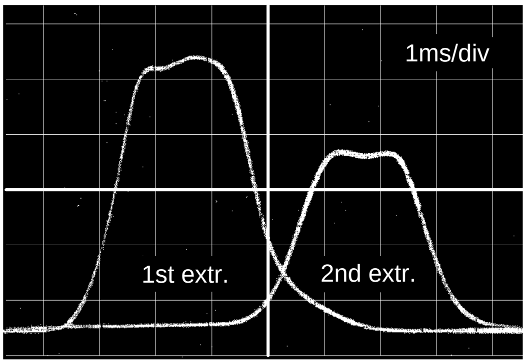

Fig. 1. Improved spill signals of the two fast resonant extractions at the beginning and at the end of the flat top.

3. Hardware Description

3.1. Design principle

The pulse generator which is connected to the extraction quadrupole used for fast resonant extraction, has originally been designed to produce a quasi triangular current wave form and is described in detail in [2]. In order to achieve spill time signals of more *rectangular* shape, this pulse generator has now been modified such that during the extraction process, the current in the extraction quadrupole shows two well distinct slopes.

This can be realized by connecting a Gate Turn-Off thyristor (GTO) with a parallel resistor R_B in series with the capacitor bank discharge thyristors, both being switched on simultaneously at time t=0. Switching off the GTO at time t_G introduces its parallel bypass resistor into the LC - circuit of the capacitor bank and the quadrupole, causing an additional damping of the practically undamped oscillation which immediately changes the slope of the magnet current i_M :

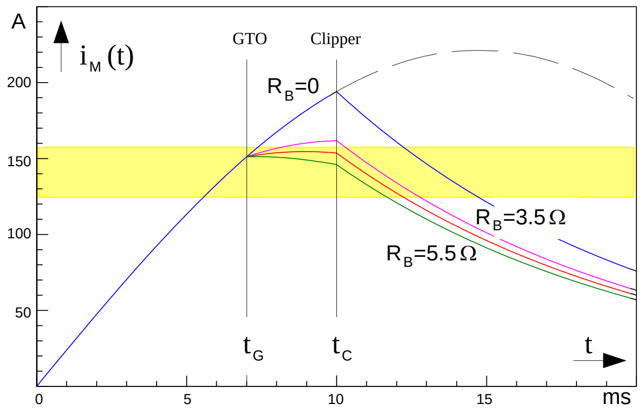

Fig. 2. Wave forms of the current in the extraction quadrupole for different bypass resistors R_B

After the whole beam is extracted or in order to stop the extraction process, the current is " clipped off " by opening the thyristor switch at time t_C .

3.2. Description of the pulse generator circuit

The equivalent circuit diagram of the pulse generator with its load is shown in Fig. 3. The extraction quadrupole is represented by its inductance L and its practically negligible resistance R_M. When the thyristor switch S closes and the GTO is turned on, the capacitor C discharges into the inductance L and during the first few milliseconds the current rises almost linearly at a rate given by U/L ($\approx$ 24 A/ms). Opening the thyristor switch by commutation as described in [2] reverses the slope of the current, which is now forced to flow through the parallel freewheel diode D_C which is in series with the crowbar resistor R_C. The maximum negative magnet voltage is given by the product of the resistor value and the magnet current at the time of commutation t_C of switch S. After this moment the current decreases exponentially with the time constant $\tau \approx L/R_C$.

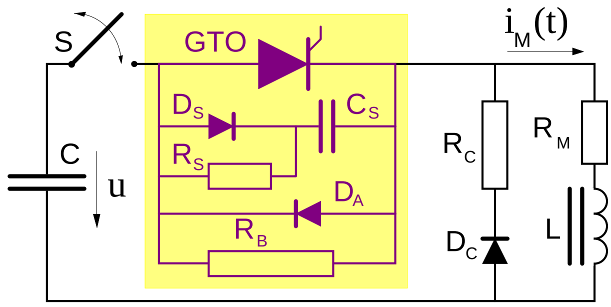

Fig. 3. Equivalent circuit of the modified pulse generator with its magnetic load

The additional "new" circuit (enclosed in the dashed box) is connected in series with the commutable switch S and essentially consists of a 4.5 kV GTO, a parallel resistor R_B and a protecting *snubber* circuit. The discharge of the capacitor is triggered by turning on simultaneously the thyristor switch S and the GTO. When the magnet current has reached the required value to change its slope, the GTO is turned off. During its turn-off period, the GTO anode current falls very rapidly with -di/dt≈1000 A/µs and the circuit current is instantly transferred to the GTO snubber circuit and charges the snubber capacitor C_S through the snubber diode D_S. This capacitor C_S , which during the ON state of the GTO is discharged through the resistor R_S , must be chosen such that the rate of the voltage rise over the GTO during turning-off is limited to maximum 500 V/µs. In order to suppress excessive voltage spikes across the GTO during the current transfer, a snubber diode D_S with a fast PIN junction proves to be most appropriate. For the same reason, the stray inductance of the snubber circuit must be kept very low. After the GTO is turned off completely, the circuit current is flowing through resistor R_B. At this moment the GTO must be able to support the forward voltage drop over resistor R_B. A second diode D_A is connected antiparallel to the GTO to limit reverse voltage transients across the GTO.

3.3. Circuit parameters and analysis

Table 1: **Main Parameters**

Capacitor bank C	1.8 mF
Maximum operating voltage $\hat{U}_o$	3.0 kV
Normal operating voltage U_o	1.2 kV
Magnet inductance L	50 mH
Magnet resistance (incl. cables) R_M	190 mΩ
Maximum magnet current $\hat{\imath}_M$	570 A
Normal maximum magnet current i_M	210 A
Resistance of GTO	~ 5 mΩ
Crowbar resistor R_C	4.7 Ω
Bypass Resistor R_B	3.5 Ω
Snubber Resistor R_S	5 Ω
Snubber Capacitor C_S	2 µF

The circuit is mainly a free oscillating LC - resonator with its *characteristic impedance* Z_o and the *natural angular frequency* ω_o :

$$Z_o = \sqrt{L/C} \quad \text{and} \quad \omega_o = \frac{1}{\sqrt{LC}} \tag{1}$$

The oscillation is damped with a damping constant δ (or damping factor ξ), reducing the oscillating frequency to ω :

$$\delta = \frac{R}{2L}\ ,\quad \xi = \frac{\delta}{\omega_o} = \frac{R}{2Z_0} \quad \text{and} \quad \omega = \sqrt{1-\xi^2}\cdot\omega_o \tag{2}$$

Neglecting the resistance of the thyristor switch S and of the GTO, the damping resistance is either $R=R_M$ or $R=R_M+R_B$, depending on whether the oscillation before or after time t_G is considered. For $t \le t_G$ and with U_o being the initial voltage of the capacitor C, the current in the magnet can be written as :

$$i_M(t) = \frac{U_o}{Z_o\sqrt{1-\xi^2}}\cdot e^{-\delta t}\sin\omega t \tag{3}$$

With $\Delta t = t - t_G$ and Z being the dynamic impedance at t_G :

$$Z = \frac{u(t_G)}{i_M(t_G)} = Z_o\left\{\xi + \sqrt{1-\xi^2}\cdot \mathrm{ctg}(\omega t_G)\right\} \tag{4}$$

(ξ and ω corresponding to the damping resistor $R=R_M$) and neglecting the transients during the finite time of switching off the GTO, the discharge current for $t_G < t \le t_C$ becomes :

$$i_M(t) = i_M(t_G)\cdot\left[\left(\frac{Z}{\omega L} - \frac{\delta}{\omega}\right)\cdot\sin\omega\Delta t + \cos\omega\Delta t\right]\cdot e^{-\delta\Delta t} \tag{5}$$

where δ and ω now refer to the total resistance $R=R_M+R_B$.

The rate of rise of the OFF state voltage of the GTO after turning off is given by the ratio $i_M(t_G)/C_S$ and in this case is limited to 250V/µs.

When the commutable switch S opens ($t > t_G$) the magnet current will flow through the crowbar circuit and decay exponentially with the time constant $\tau \approx L/(R_M+R_C)$.

3.4. Future improvements

In order to no longer limit the available voltage for the second extraction to the rest voltage of the first one, it is foreseen to build two independent generators, one for each extraction. Both generators may have a different bypass resistor R_B and their voltage U_o can be adjusted individually. This will allow better optimization of the current wave forms of the two extractions.

Since nowadays the GTOs have become very reliable, the commutable thyristor switch will be replaced by a GTO.

4. OPERATIONAL ASPECTS

An optimum spill time signal requires an optimum current wave form in the extraction quadrupole. However, once the bypass resistor is chosen (hardwired), the only two other parameters to be varied remotely are the initial voltage U_o of the capacitor bank, which defines the initial slope of the current, and the time t_G when the GTO is switched off. This latter can be adjusted with a precision of a tenth of a microsecond. Up to now, if two such extractions were to be performed during the same cycle, the available voltage for the second one had been limited by the rest voltage of the first one. A compromise had therefore to be made for the two spill signals. As mentioned in 3.4., this restriction will drop once each extraction has its proper pulse generator.

The (insufficiently) small number of parameters can partially be compensated by carefully trimming some of the machine parameters during the time of extraction, such as the (slope of the) horizontal tune Q_H, the chromaticity etc. However, the spill is very sensitive to the slightest variation of any of these parameters which not only changes the extraction time but the whole wave form, such that all generator settings have to be reoptimized thereafter. This is a very tedious, iterative process which requires not only a very stable machine but also a lot of expertise.

5. CONCLUSIONS

The method described in this paper and which had been applied during the whole fixed target run in 1991 considerably improved the spill quality for the neutrino experiments. However, a lot of time had to be spent on constant reoptimization and, since the process is too fast, it can not be envisaged to provide a feedback or learning system which automatically will adapt itself to the ever changing conditions.

6. ACKNOWLEDGMENTS

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7. REFERENCES

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