ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-WEPMA021

EFFICIENT PULSED QUADRUPOLE *

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Abstract

In order to raise the focusing gradient in case of bunched beam lines, a pulsed quadrupole was designed. The transfer channels between synchrotrons as well as the final focusing for the target line are possible applications. The quadrupole is running in a pulsed mode, which means an immense saving of energy by avoiding standby operation. Still the high gradients demand high currents. Hence a circuit had to be developed which is able to recover a significant amount of the pulsing energy for following shots. The basic design of the electrical circuit of the quadrupole is introduced. Furthermore more energy efficient circuits are presented and the limits of adaptability are considered.

ELECTRICAL CIRCUIT

As described in detail before, a pulsed quadrupole lens was designed [1] and a prototype was built (cf. Fig. 3) to prove the feasibility of the design. While the final system is supposed to handle currents up to 400 kA, the first prototype setup should operate at ~ 30 kA.

Its electrical circuit design is sketched in Fig.1. In this prototype, a 450 µF capacitor was charged to a voltage of 4700 V and discharged, producing a current pulse of ~ 33 kA and a pulse duration (FWHM) of ~ 60 µs (cf. Fig. 2).

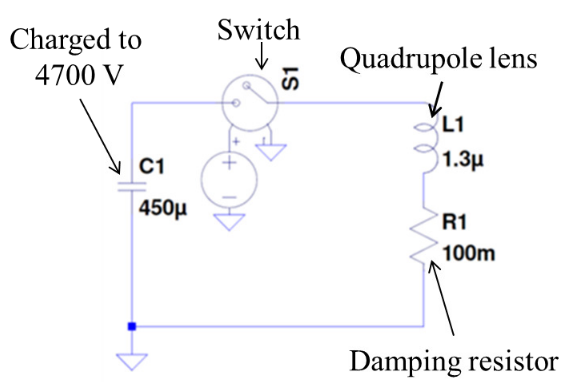

Figure 1: LTSpice[2] model of the electrical circuit of the prototype. The circuit is nearly critically damped to avoid oscillations.

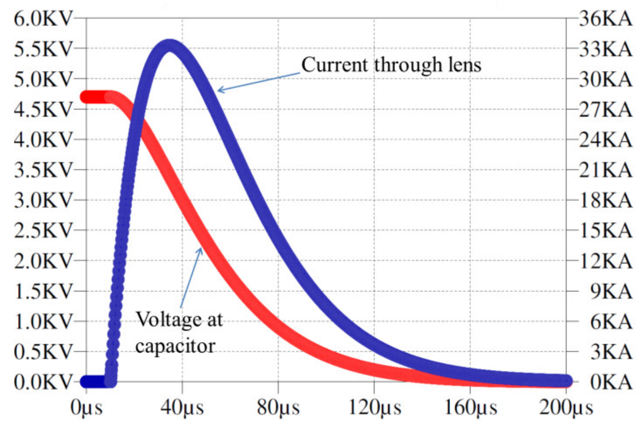

Figure 2: Pulsed current and voltage (Result of simulation in Fig. 1).

The electrical circuit presented in Fig. 1 is not suitable for a system with currents much higher than the 30 kA aimed for in this setup. Due to the damping resistance R1, a quite high voltage is required to realize high currents. For 400 kA operation, nearly 60 kV would be required. Also power dissipation (~ 16 GW at peak current) in the resistor and its cooling would be a serious issue, especially at higher repetition rates. Additionally, at 400 kA, the voltage drop across the 100 mΩ resistor would be 40 kV. Alternative electrical circuits will be discussed below. For the test circuit presented here, the resistance was a very simple possibility to damp the current critically and prevent a ringing discharge which would harm the capacitors lifetime. Due to the low repetition rate (1 shot in ~ 4 minutes) and the lower power input, cooling of the resistance was not an issue.

PROTOTYPE

To test the applicability of the design presented in [1], a prototype was built. The setup can be seen in Fig. 3. The upper part above the rectangular rack is the quadrupole lens itself. In the center of the lens is the vacuum tube. Inside the lens, this tube is made from alumina. The tube is positioned ~ 2 m above ground. Below the quadrupole lens, the pulsed power unit, i.e. capacitor, switch and damping resistor, is situated. It can be seen in more detail in Fig. 4. During operation, the rack is enclosed to prevent accidental contact with high voltage.

*Work supported by EuCARD-2-WP03-EnEfficient. EuCARD-2 is co-funded by the partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453
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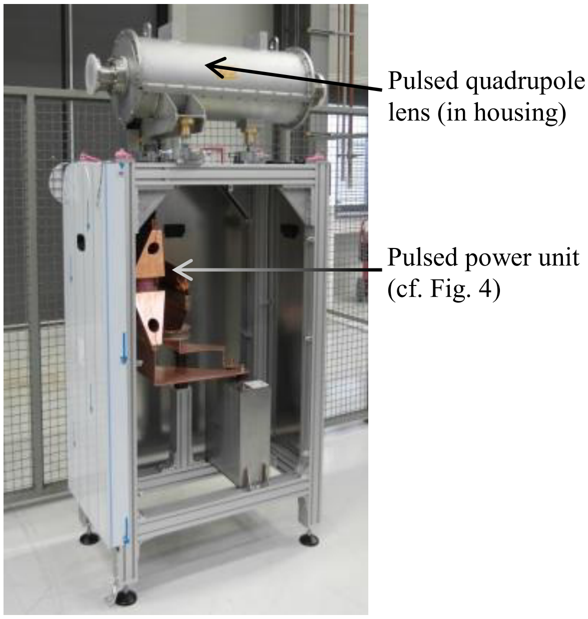

Figure 3: The prototype of the pulsed quadrupole lens. The pulsed power unit is situated below the lens.

REAL ELECTRICAL CIRCUIT

The schematic of the electrical circuit of the prototype is shown in Fig. 1 and most of the realization can be seen in Fig. 4. In the latter, the 450 µF capacitor can be seen in the lower right part of the picture. At the nearer contact of the capacitor, the high voltage is applied. The pink element on the left hand side is the switch that was used, a Pulsetech cold-cathode thytratron TDI1-200k/25H. It can handle currents of up to 150 kA and voltages of up to 20 kV [3].

Between the switch and the quadrupole, the current is divided onto the single wires of the cable and coming back from the lens itself it is damped in the green disc resistor that can be seen in the middle of Fig. 4.

The current reached in this setup was ~ 26 kA.

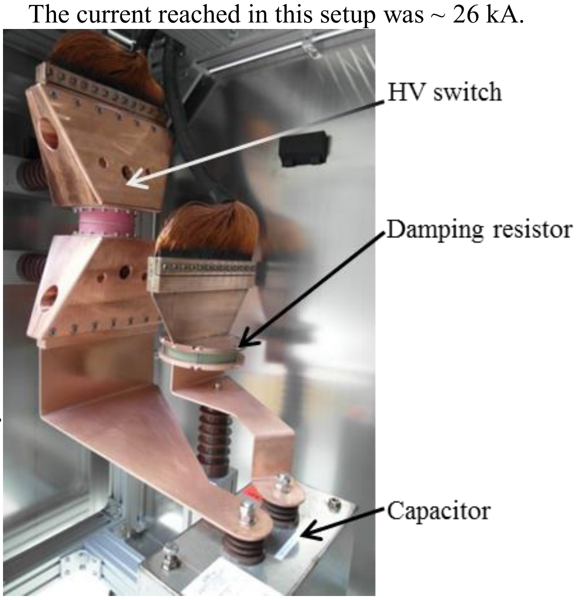

Figure 4: Pulsed power of the prototype.

ENERGY EFFICIENCY

For a real application, the gradient of the magnetic field produced by the lens has to be increased. Therefore the current has to be increased. To reduce the losses, the damping resistor shall be avoided. To avoid a ringing discharge without the damping resistor in the main circuit a scheme as shown in Fig. 5 can be used. Compared to the circuit in Fig. 1, the current rises by more than a factor of 3 to ~ 80 kA using a voltage of 4500 V.

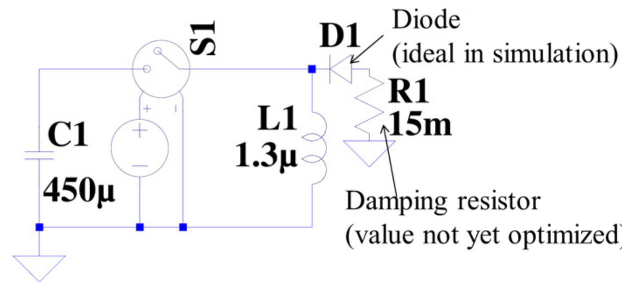

Figure 5: Improved circuit for quadrupole lens, LTSpice [2].

To realize this circuit will be the next step in our development. The value of the damping resistor has to be optimized for an acceptable compromise between reverse voltage at the capacitor, peak current through the diode and pulse duration. While this circuit is more efficient than the circuit in our prototype, it still dumps the whole energy after every pulse.

Ideally, an energy recovery circuit should be used to reduce the required energy. This can be done by using a capacitor that is insensitive to voltage reversals, a second switch, two diodes and a second inductance as shown in Fig. 6.

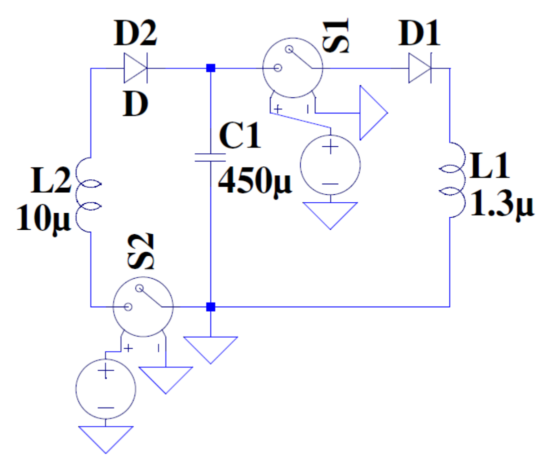

Figure 6: Energy recovery circuit, LTSpice [2].

The right hand side of the circuit just works like before, D1 prevents ringing. After the half-wave, C1 is charged to opposite polarity. This can be inverted by using the left hand circuit. The results can be seen in Fig. 7. Using the

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circuit above (not taking into account ohmic resistances except 1 mΩ per switch), the capacitor is charged to ~ 4300 V. This means, about 4160 J were recovered and the external power supply has to deliver only the 810 J difference to charge up the capacitor to 4700 V again.

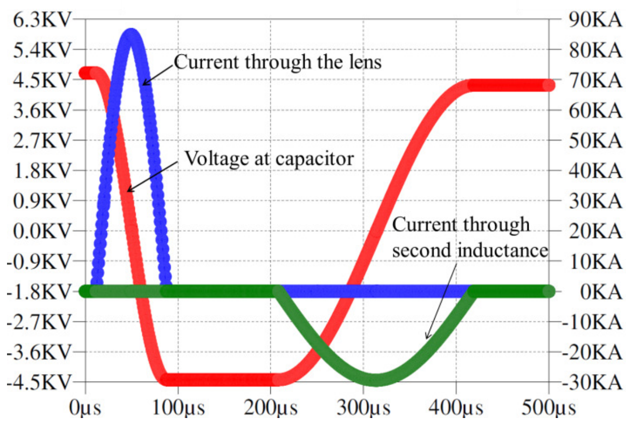

Figure 7: Results of the circuit simulation shown in Fig. 6.

In this simulation, the second inductance was chosen larger than the first to reduce the peak current through S2. This lower peak current reduces cost for this branch of the circuit, because a cheaper switch can be utilized.

Of course, a pulsed lens is only beneficial when there is no continuous ion beam to be focussed. This is shown in Fig. 8. A conventional DC quadrupole is compared to our pulsed system. The aperture of the conventional quadrupole in this comparison is about 15% larger (65 mm instead of 56 mm), but apart from that the systems are comparable [4].

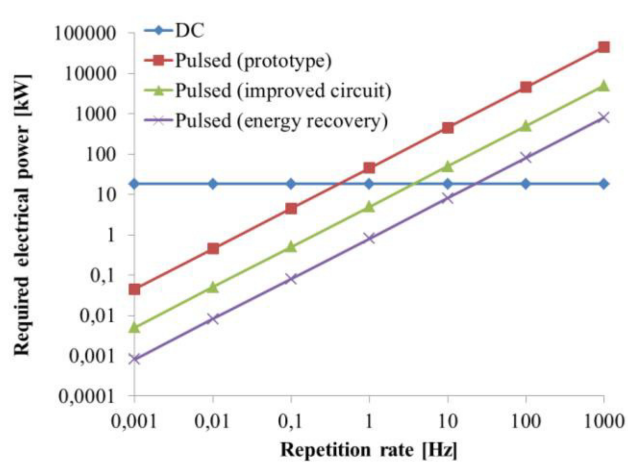

Figure 8: Power saving depending on the repetition rate of the pulsed lens.

For the DC quadrupole, the repetition rate is not relevant for the required power. The other curves show that in the case of our prototype circuit (cf. Fig. 1) only repetition rates below 0.6 Hz and for the improved circuit (cf. Fig. 5) below 6 Hz lead to an energy saving. Using the energy recovery scheme at repetition rates below 40 Hz energy can be saved. This theoretical approach does not take cooling of the lens and additional internal losses into account.

As mentioned before, in the simulation of the energy recovery circuit (cf. Fig. 6, Fig. 7 and Fig. 8) the only ohmic component was 1 mΩ included in each switch. To estimate its feasibility in a real application, the simulations were repeated after adding another 2 mΩ in the left and the right hand branch of the circuit. From the originally stored 4970 J, 3600 J were recovered under these circumstances. Raising these additional resistors to 4 mΩ each, the recovery is still a significant value of about 3000 J, still saving ~ 60% of the energy. For this situation, every repetition rate below ~ 9 Hz will save energy compared to the DC system.

While the energy recovery circuit is really efficient, for very low repetition rates the circuit in Fig. 5 seems more reasonable due to the simpler and cheaper setup (no additional switch required, capacitor without full voltage reversal capacity can be used) because operating at 0.1 Hz, the difference in average power consumption between this simpler circuit and the energy recovery circuit is only ~ 400 W dropping to ~ 40 W at 0.01 Hz.

CONCLUSION

For quadrupole lenses with a low duty cycle, a pulsed system can significantly save energy, e.g. when requiring only one shot every 10 seconds, the average power in our example can be reduced from ~ 18 kW to ~ 100 W or ~ 500 W depending on the circuit (Fig. 6 or Fig. 5, resp.). Operating 6500 h per year one quadrupole could save more than 110 MWh in this timeframe.

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