RESONANT CHARGING AND PULSE SHARPENING FOR THE PROTON INJECTION KICKER: TEST RESULTS FROM MKS-90 MAIN RING SYSTEM

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ABSTRACT

The purpose of this note is to describe progress on a prototype unit for a resonant charging and pulse sharpening system to be used in the Main Injector proton injection kickers. The operating principle and the progress to date are described. The MKS-90 power supply has been evaluated and probably can not be used due to the large physical inductance of the thyratron housing.

INTRODUCTION

Currently, Fig. 1, a high voltage DC power supply, ~60 kV, and resistor are used to charge the pulse forming line at MKS-90. This system is required to operate with pulses spaced at 66 ms intervals, so a large current is required to charge the capacitance of the pulse forming line. This large current keeps the thyratron conducting following the pulse. The current through the tube is never low enough to let the tube turn off. To make the thyratron to turn off under these conditions, it is run with a low reservoir voltage which results in a long turn on time.

The resonant charging system would replace the high voltage DC supply. Since this is a command charging system, charging of the pulse forming line can be delayed between pulses. This permits the use of a higher reservoir voltage and faster rise time for the thyratron. The reservoir can be increased until either of two limits are reached. If the tube has too high a reservoir voltage, conduction will occur spontaneously, a prefire. If the inductance of the thyratron housing is high (greater than 10 - 20 nH), then that inductance becomes the limiting factor in rise time. If the decrease in rise time is still not sufficient, a pulse sharpener may be required.

The pulse sharpener is a ferrite loaded transmission line that operates as a magnetic switch. Initially, the ferrite is unsaturated and has a high reactive impedance. During this time, energy in the rising edge of the pulse is reflected back into the thyratron pulser. Upon saturation, the sharpener is a 25 Ω transmission line matched to the impedance of the system. This allows the rest of the pulse to pass through unaffected by the pulse sharpener. Theoretically, the pulse sharpener also reduces the "pre-pulse" which occurs in a multigap thyratron during switching.

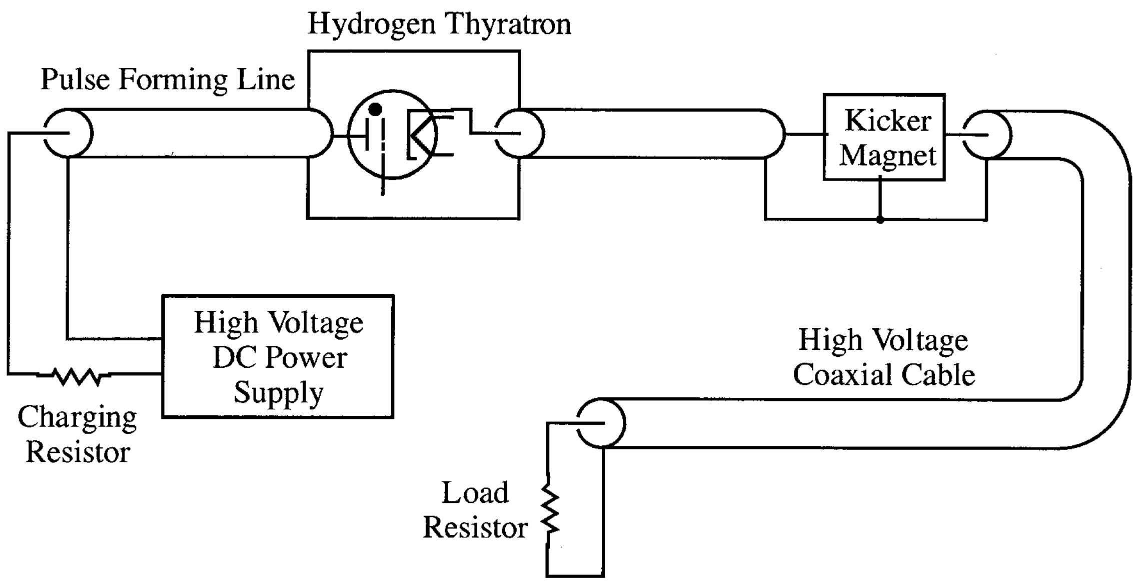

Figure 1
Existing MKS-90 Kicker System

RESONANT CHARGER DESIGN

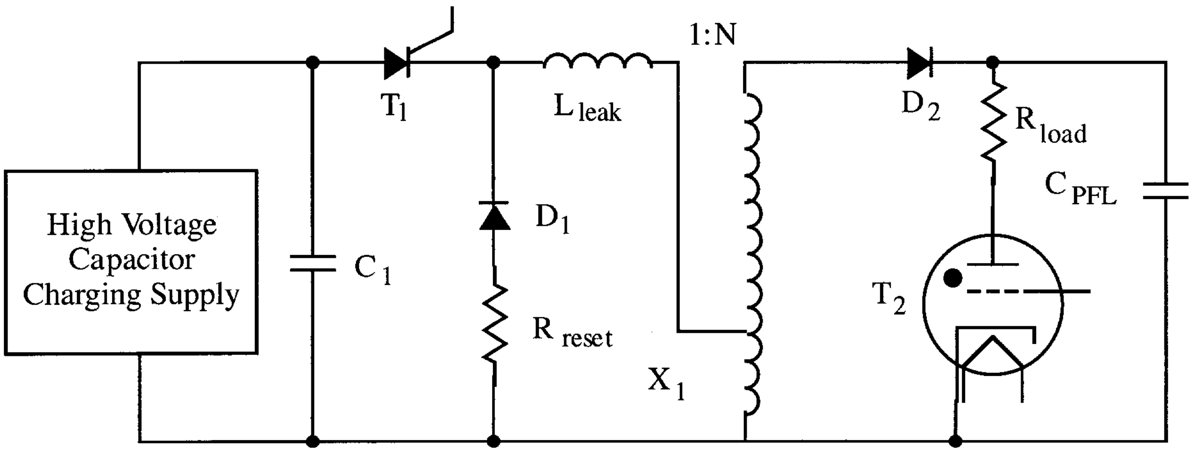

Figure 2
Resonant Charging System

The capacitor, C_1 Fig. 1, is charged to the desired voltage with a high voltage capacitor charging power supply, ~5 kV. When the thyristor, T_1, is triggered, all the energy is transferred from C_1 to C_{PFL}. The leakage inductance of the transformer makes this happen in a resonant fashion so that the current in T_1 and diode D_2 is a half sinusoid. Transformer X1 is used to step the voltage up to the required pulse forming line voltage. When the diode D_2 switches off it traps the energy in C_{PFL}. The hydrogen thyratron, T_2, is switched on after this time and transfers the energy from the pulse forming line through the magnet and into the resistive load. The magnetization energy of the transformer is then used to reset the transformer via D_1 and R_{reset}. The thyristor T_1 turns off sometime after the diode D_1 has started blocking. Capacitor C_1 can then be charged in ~40 ms for the next pulse.

The given parameters for this design are the output voltage, the pulse forming line capacitance and the repetition rate. There are essentially two free design parameters; the charging time that is determined by C_1, C_{PFL} and L_{leak}, and the C_1 charge voltage that is determined by the turns ratio. The charge time and charge voltage determine the characteristic impedance and hence the peak currents. The charge voltage and output voltage determine the turns ratio of the transformer.

The shorter the charge time, the smaller the transformer. The smaller the charge voltage, the higher the peak current. The cost of the transformer increases directly with the volt seconds given a fixed leakage inductance, or inversely with leakage inductance given a fixed volt seconds. The cost of the semiconductor increases roughly with the amp seconds required.

The charge time has other limitations. For charging cable, the charge time shouldn't be faster than ~10 times the round trip time of the cable for 10% overshoot, or ~100 times the round trip time for 1% overshoot. Also, there must be time allowed for the reset of the transformer and the control system must be able to tolerate the delay and jitter in the charging.

The design as built and tested has the following component values:

C_{PFL}	1.6 μs cable (520 ft, 158m) at 25 Ω has a total capacitance of 30.7 nF
V_{cable}	60 kV, possible to run at 66 kV continuously, or 72 kV intermittently
T_{charge}	300 μs
V_{C1}	3.75 kV nominal, 5 kV maximum (turns ratio of 16:1)

PULSE SHARPENER DESIGN

Design of the pulse sharpener is more complicated, however there are fewer variables. The core material, geometry and overall length determine the pulse sharpener characteristics. The prototype pulse sharpener uses the NiZn ferrite CMD5005 from Ceramic Magnetics. This high frequency ferrite has a saturation flux density that was recently measured for use on a different project. The geometry is a coaxial transmission line with a 0.44" copper conductor in the center and toroidal ferrite cores surrounding it. Then the outer conductor, 2" copper pipe, with standard copper pipe fittings used to accommodate high voltage connections. The cores are held between the center and outer conductor by a silicone rubber dielectric.

The pulse sharpener is designed so that its characteristic impedance is matched to the system impedance once the ferrite has gone into saturation. The entire pulse sharpener unit is passive, and is installed between the cathode of the thyratron and the magnet. Although a reset pulse is not necessary to reset the ferrite, the pulse sharpener is made shorter if one is used.

The cores are selected to have a Volt•second rating equal to the area under the rising edge of a typical pulse. The pulse is assumed to have a 60 kV peak with a 35 ns rising edge having a raised sinusoidal shape. The 25 Ω prototype sharpener used in conjunction with the resonant charging system is approximately 24 inches long. The cross-sectional area of the ferrite is approximately 0.5 in^2. The cores are relatively thin radially, allowing the domains in the ferrite to align uniformly in time when field is applied. While many other labs have shown good increases in 10% – 90% rise times, there are no results for pulses with the 1% – 99% rise time specifications and the 1% flatness apparently required for this kicker.

TEST RESULTS

In Fig. 3, the thyratron, T_2, was not triggered so that the amount of overshoot could be determined. The voltage is flat within 1% 40 μs after charging is complete. The charge voltage is also repetitive to within ±0.5%, the tolerance of the C_1 capacitor charging supply. The resonant charger was run at 66 kV for a short time without any problems. Table I shows a comparison of 10% to 90% and 5% to 95% current rise times when running at 60 kV and several reservoir voltages. Figure 4 compares the rise time of the current into a matched load resistor with several reservoir voltages. The reservoir voltage level on the kicker during the last run was approximately 4.6 V_{rms}. The improvement in rise time is obvious. The wider spread in rise times at low reservoir voltage is due to pulse to pulse variation in rise times.

Table I
Magnet Current Rise Times *vs.*
Reservoir Voltage
$V_{AK} = 60$ kV

	Reservoir Voltage				
	4.6 V_{rms}	5.0 V_{rms}	5.2 V_{rms}	5.4 V_{rms}	5.5 V_{rms}
10% – 90%	140 ± 50 ns	94 ± 5 ns	68 ± 1 ns	57 ± 1 ns	53 ± 1 ns
5% – 95%	–	116 ± 5 ns	92 ± 1 ns	78 ± 1 ns	78 ± 1 ns

Further decrease in rise time may be possible by increasing the reservoir voltage. This would require a permanent rework to the existing system since higher reservoir voltages are not currently possible.

Figure 5 shows the result of adding a pulse sharpener. Unfortunately, these results can not be directly compared with those of the resonant charging alone. A change in thyratrons was required and the system had to be returned to operational status before further tests could be run. While the pulse sharpener does reduce the 10% - 90% rise time, it is unclear whether is will decrease the 5% - 95% rise time and it will probably not decrease the 1% - 99% rise time. A further increase in reservoir voltage is also required for more effective pulse sharpening testing.

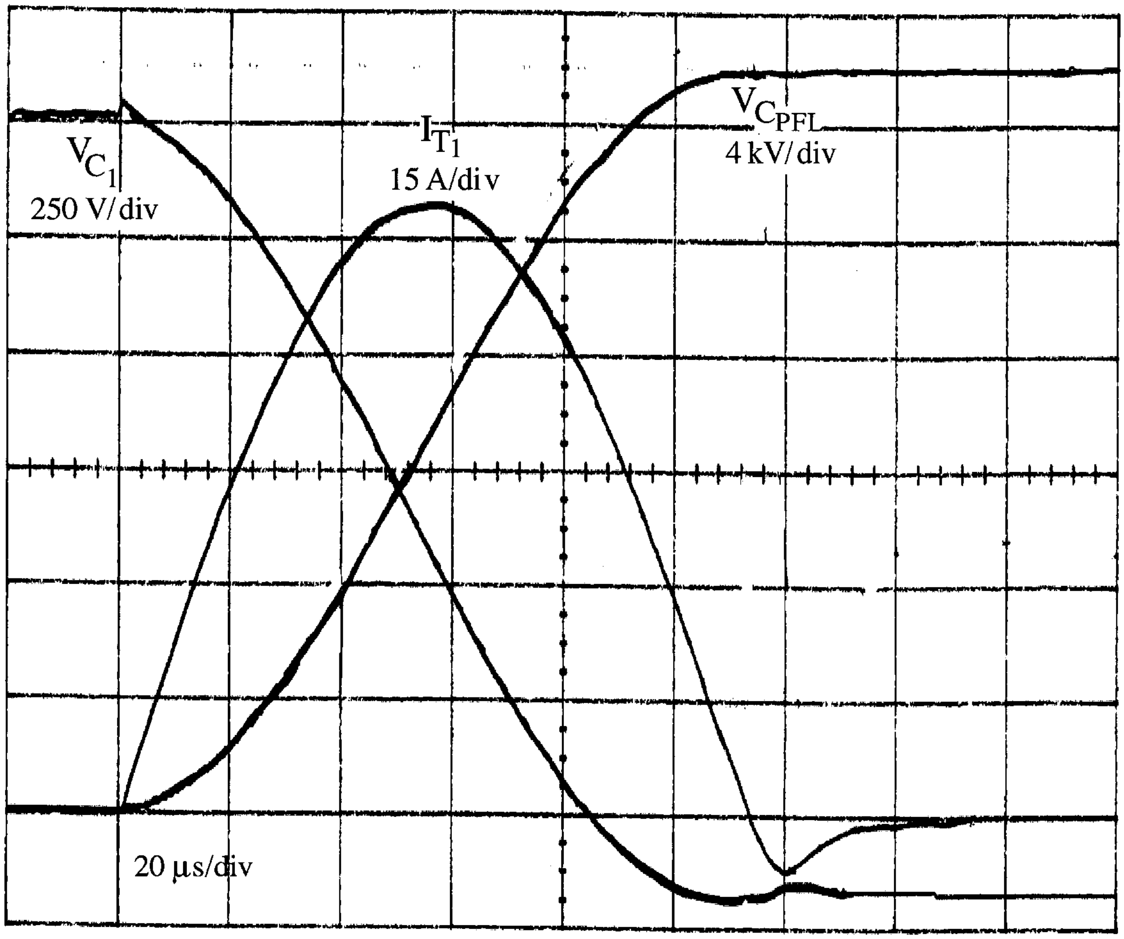

Figure 3
Resonant Charger Waveforms

The resonant charging system was run for 10 days at 60 kV without any lifetime problems showing up. One small problem that occurred during a fault was found and fixed. The pulse sharpener has also been operated overnight on various occasions at voltages up to 60 kV without any apparent lifetime failures.

SUMMARY

Resonant charging works and can be used to reduce the 10% – 90% rise time of the current into the 50 ns range by increasing the reservoir voltage. Decreasing the rise time much further would seem to require a redesign of the power supply to reduce inductance. This is in agreement with the initial assessment, note MI-0034. Lifetime tests were started, with the charging system running in a 5 pulse burst every 3 seconds at 60 kV for 10 days without any problems.

Pulse sharpening is still inconclusive. Preliminary test results showed an impressive speed up in 10% – 90% rise times in a 50 Ω system. Results on the 25 Ω system are less promising. To build a single 25 Ω pulse sharpener costs approximately $2500, including materials and labor. Experience from other laboratories has shown that experimentation with the location of the pulse sharpener and variations in ferrite material and size will affect performance.

A rise time (5% – 95%) of ~80 ns has been shown for the power supply with resonant charging alone. The requirements for the system, based on MI Notes 0015, 0034 and March 91 memo from Phil Martin, is a system rise time (1% – 99%) of less than 40 ns. A decision based on accelerator performance must be made on how much further to decrease rise time and at what cost and effort.

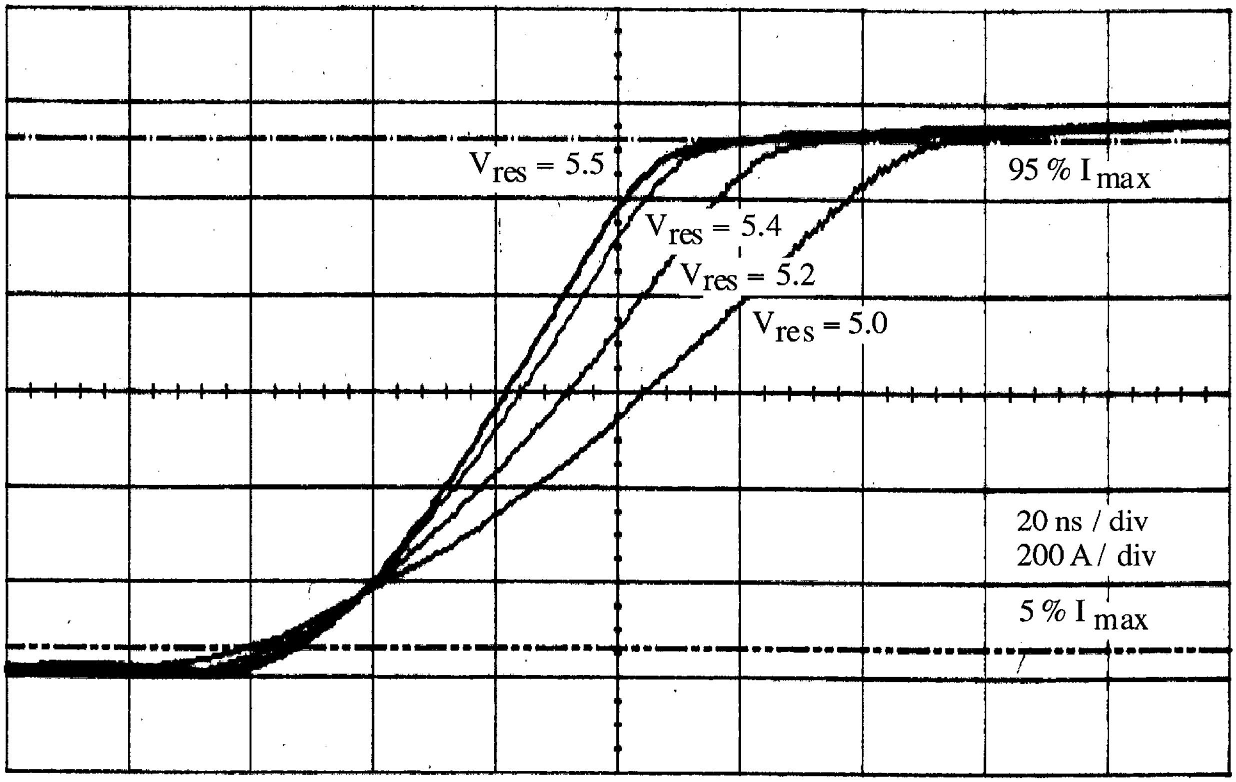

Figure 4. New Thyratron with Various Reservoir Voltages

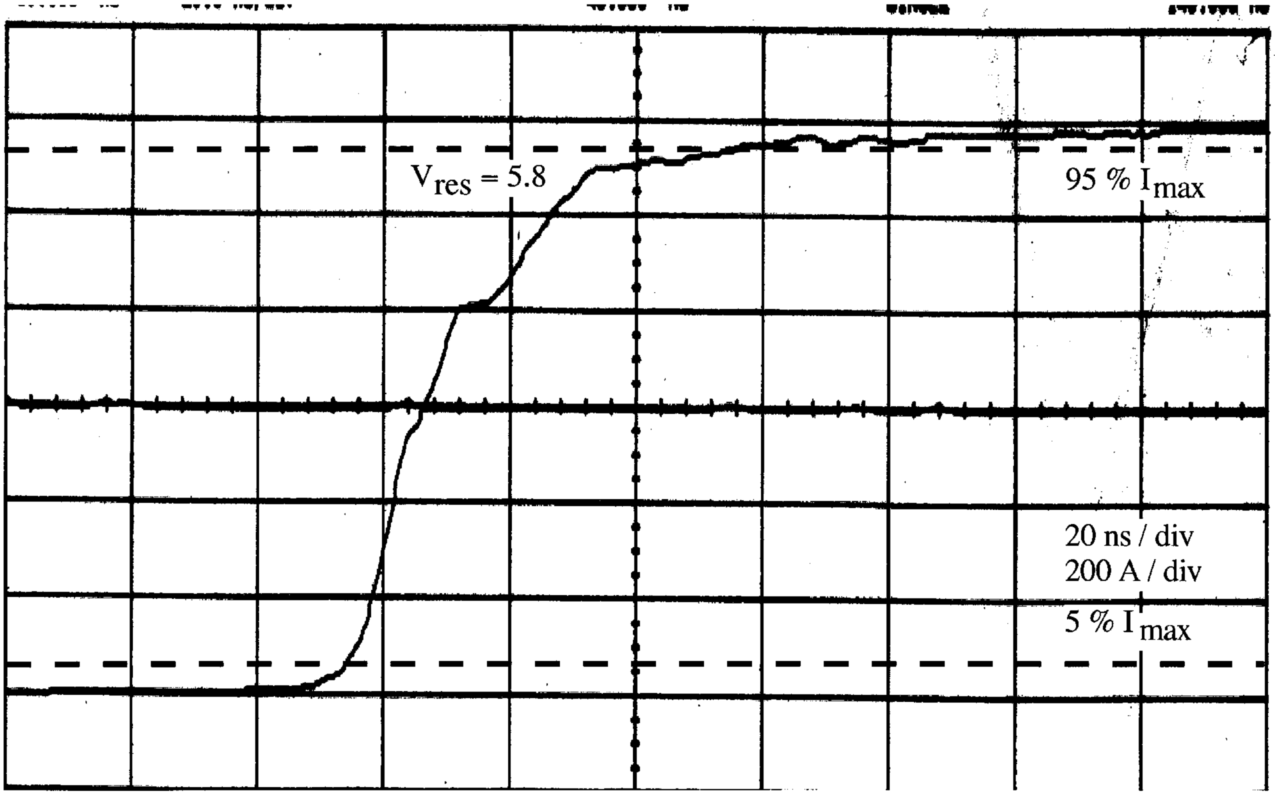

Figure 5. Old Thyratron with Pulse Sharpener