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Sub-Microsecond Beam Notching at Low Energy

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A technique for creating a burst of 100 ns notches (beam extinctions) in an H^- beam at 454 kHz has been developed at $\leq$ 20 keV utilizing a Magnetron ion source with a slit extraction system and a split extractor. Each half of the extractor is treated as part of a 50 ohm transmission line which can be pulsed at ± 700 volts creating a 1400 volt gradient across the extractor. A beam current reduction of better than 95% has been observed at the end of the Fermilab 400 MeV Linac. Notched multi-turn charge-exchange injection into the Booster, a 400 MeV to 8 GeV synchrotron, has been demonstrated with a charge reduction in the resulting beam gap of 83%. Presently, the trailing edge of the notch may be adversely affected by space charge resulting in a beam recovery with two different time constants. Efforts to minimize this effect are discussed.

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Introduction

The expanding neutrino program at Fermilab has created a demand for proton intensities greater than the existing injector complex (400 MeV Linac, 8 GeV Booster synchrotron and 120 GeV Main Injector synchrotron) has ever produced[1]. Component activation

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associated with proton losses at high-energy, particularly in the Booster, is one of the factors limiting increases in the number of protons per minute. Efforts to minimize or control losses in the Booster including enlarging magnet apertures, beam collimation, and improving alignment have begun. However, losses associated with beam extraction from the Booster and Linac, which are directly tied to repetition rate, have not yet been addressed. Because the Booster extraction magnets have relatively slow rise and fall times the protons in 3 of the 84 acceleration buckets, representing 78 ns of beam at 400 MeV, are kicked into the Booster beam pipe prior to acceleration to minimize losses during extraction at 8 GeV. The Linac extraction problem is similar; in this case the beam is simply swept across the septum magnet with no effort at beam loss mitigation. In both of these cases localized losses are created at 400 MeV, which was only acceptable because of the low repetition rates of these machines, < 5 Hz. These high-energy extraction losses in both the Linac and Booster can be reduced or eliminated by notching the low-energy beam at the ion source.

Several laboratories have pursued low energy beam modulation. In the late 80's a traveling wave chopper at 35 keV was developed at BNL[2]. However due to emittance growth associated with space-charge neutralization this effort was abandoned. H^- beam chopping utilizing a biased plasma-electrode collar in a Penning source was investigated at LANL and beam rise and fall times of 400 ns and 2 μs[3] were achieved. At the SNS beam chopping of a 15 mA beam at 65 keV has been achieved[4]. The final lens of the SNS electrostatic LEBT (low energy beam transport) is separated into 4 parts which can be independently pulsed at ± 3 keV. The electrical rise and fall times are around 25 ns.

Work in this area has also been carried out at KEK where they have successfully modulated the converter voltage of a surface-plasma converter ion source. Beam rise and fall times of approximately 70 ns have been achieved[5].

Fermilab utilizes a Magnetron ion source to provide H^- ions for Linac operation. The ion source duty factor is 0.135%, producing a 90 μs beam pulse at 15 Hz. Beam currents up to 100 mA have been observed at 750 keV while 50 mA is typical for Linac operations. The magnetron utilizes a slit extraction system which is mounted 2.3 mm from the Magnetron anode (see Fig. 1 in Ref. 6) and operates between 12-20 keV. Upon exiting the anode aperture (0.9 × 10 mm), ions travel through a 90 degree bending/focusing magnet, with roughly an 8 cm path length. Within the magnet the beam size blows up due to space charge roughly forming a circular beam[6]. Exiting this region the ions are subsequently accelerated through a 750 keV high voltage (HV) column.

To notch the H^- beam, the extractor has been split length wise and the two halves are connected to 50 ohm transmission lines which can be pulsed to ±700 V creating a 1400 V gradient across the extractor[7]. This system electrically floats on top of the pulsed extractor voltage and is controlled using a fiber optic network. Figure 1 in Ref. 7 shows an early variant of the split electrode system and the leads of the 50 ohm transmission lines. Glass insulators are now used for electrical isolation because the Kapton sleeves, originally used, gradually became conductive along their surface while being exposed to the ion source environment. A custom built dual-polarity, pulsed HV power supply utilizing FET's was developed for this application. The sum of the dual- polarity voltage transition time (0 to 700 V), T_{elec}, is around 40 ns (~100%). Adjustment of the differential time between positive and negative pulses can make slight improvements to the rise and fall times, however to achieve the desired 10 ns transition time improvements to the pulsed HV power supply will be necessary.

The sum $T_{beam} = T_{elec} + T_{ion} + T_{bend}$ describes the expected transition time of the beam and includes the voltage transition time, T_{elec}, the ion transit time through the deflection plates, T_{ion}, and the path difference through the bend magnet, T_{bend}. Ignoring fringe fields the extractor is 15 mm wide relative to the ion path so at 20 kV the ions move through the deflector in, $T_{ion} = 8$ ns. Because the beam is magnetically bent perpendicular to the deflection direction the difference in path lengths through the magnet contributes to the effective beam transition time. The results from a SIMION model of the magnet suggests that at 20 keV there is roughly a 10 ns time spread between the short and long paths. Based on these estimates the expected transition time should roughly be $T_{beam} = 58$ ns.

Experimental Results

Notch Tail Minimization

Until recently beam notching has been studied primarily in the transport line following the 750 keV HV column using current transformers with 50 ns response times. A series of notches in a 60 mA beam is shown in Fig. 1a. The notch period is 2.2 μs, closely matching the ion revolution period at injection in the Booster. In this measurement, the beam extinction is around 70%. Three meters upstream the extinction is only 55%

suggesting that ions continue to fall out of the notch in transit, most likely due to off axis trajectories leading to collisions with beam pipe apertures. The notch fall times are consistently around 56 ns, in good agreement with T_{beam}. Unfortunately, the full recovery time is comparable to the notch period resulting in an average reduction in current of roughly 2-3 mA. This slow recovery also means that the Booster fill will not be uniform. In this case, the Booster accelerating buckets just after the notch will be under filled by as much as 50% (See Fig. 4 below). A closer view of a single notch is shown in Fig. 1b for five different pulse input widths between 0 and 120 ns. The first thing of note is there are two distinct time constants involved in the beam recovery. The fast rise times are similar to the fall time at 56 ns while the slow recovery times are several microseconds. Secondly, the slow recovery depends on the notch width with narrower notches giving the best overall performance. This evidence suggests further improvements in the electrical rise and fall times will be beneficial as they ultimately limit the width of the HV pulse.

Under the assumption that the long notch tail is related to a space charge problem, similar to that observed by BNL[2], increasing the number of positive ions in the extraction region should reduce the recovery time. Achieving this requires increasing the pressure in the extraction region which linearly increases H^- stripping[8] and to some extent changes the source operating conditions. Figure 2 shows this linear reduction in beam current with increased operating pressure. In this case, the pressure rise was achieved by increasing the hydrogen gas flow through the Magnetron. Free-hand digital area analysis of the space above each beam trace in the slow recovery region of the notch out to 700 ns after the fast rise was carried out using ImageJ[9]. In a plot of these results, roughly a linear improvement in the beam recovery is observed with increased pressure. Furthermore, notching efficiencies at this location improved from 83% for the 60 mA beam to 91% and 93% for the 51 and 40 mA beams respectively. Reducing the beam current by retuning the extraction voltage and/or bending magnet did not produce changes in the recovery time. Attempts were also made to increase the pressure in the source region independently of the source gas using hydrogen and krypton. To date, these tests have lead to sparking of the extractor before any change in the beam recovery time was observed. Nonetheless, since a clean Magnetron runs well up to about 4.0 mPa, optimization of the notch may be achieved by maximizing the gas flow through the source assuming the average beam current remains sufficient for operations.

Beam induced capacitive-loading can be discussed in terms of a simple circuit diagram of the ion source region, shown in Fig. 3, which includes the HV isolation, pulsed power supplies, 50 ohm loads, capacitances between the electrodes, and the location and direction of the beam. Based on this circuit, it is clear that independent beam loading of one extractor electrode should not occur and that possible ring times should be in the 10's of ns range. To verify this conclusion a differential measurement of the voltage across the split extractor was carried out using an oscilloscope floated at the extraction potential. No more than 2 volts appeared on the plates after HV pulsing, sufficiently small to be ignored.

Discussion

There are several possible reasons for a slow beam recovery after the notch and among these are: a) Space charge forces associated with creating a hole in a neutralized beam b) disruption of the plasma meniscus by the deflection voltage, c) ringing of the HV pulse, or d) differential beam loading of one of the deflection electrodes. Beam induced capacitive-loading problems appear to be ruled out, based on the circuit diagram in Fig. 3 and electrical diagnostics show that ringing is not a problem. The experiments at higher pressures as well as the experience of BNL, in Ref. 2, seem to point toward space charge effects but the external gas tests did not appear to help, nor did a modification to reduce the fringe field in the extraction region. One additional modification was made in order to place the deflection plates after the extractor. However since the beam begins to rapidly diverge after the extractor the plates reduced the beam intensity and produced such a poor notch that this configuration was abandoned. Nonetheless, this suggests that the split extractor approach takes advantage of the very low beam rigidity as the ions exit the source and thus maybe affects the plasma meniscus. Despite the available data, the cause for the slow beam recovery time after the notch remains unresolved with both space-charge and plasma meniscus effects being difficult to clarify.

Booster Experiments

Testing of Linac and Booster operations with notched beam from the ion source has just started. In Fig. 4, five turns (a turn is ~2.2 μs of Linac beam which after charge-exchange injection into the Booster can occupy the same phase space as previously injected beam[10]) were sent to the Booster injecting $2.0e^{12}$ protons with the notched beam and $2.4e^{12}$ protons with un-notched beam. The resulting beam extinction in the Booster was 83% representing an improvement of 50% from earlier work, reported in Ref. 7. The principle improvement made was better synchronization of the notch with respect to the Booster revolution period. The 17% reduction in intensity is crudely accounted for by the 2.5 mA average reduction in Linac current (8%), 3 bunches in the notch reduced by 83% (3%) and approximately 8 bunches in the notch tail reduced by an average of 50% (5%). In these tests, efforts were made to add a partial turn to compensate for the uneven fill of the Booster acceleration buckets. The effect of this can be seen in Fig. 4 by the increased amplitude on both sides of the notch. This proved only partially successful as the extra turn falls exactly on the next notch limiting the charge that can be added to these bunches. In future experiments the notch will be turned off prior to injecting the partial turn, software limits on the notch width will be removed to take advantage of the better recovery times shown in Fig. 1 and the pressure will further be optimized to minimize the long notch tail.

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FIG. 1a. A 61 mA beam with multiple notches 2.2 μs apart. FIG. 1b. A comparison of five notches with input pulse widths of 0, 40, 60, 90 and 120 ns top down (200 ns/div horizontal).

FIG. 2. Beam current and notch recovery as a function of operating pressure. The pressures are 1.9, 2.7 and 3.8 mPa with corresponding beam currents of 60, 51 and 40 mA, top down (200 ns/div horizontal).

FIG. 3. This circuit diagram models the extraction region of the ion source.

FIG. 4. A notch in the Booster 2.2 ms into the acceleration cycle. Each period represents a beam bunch at roughly the Booster RF frequency of 38 MHz.

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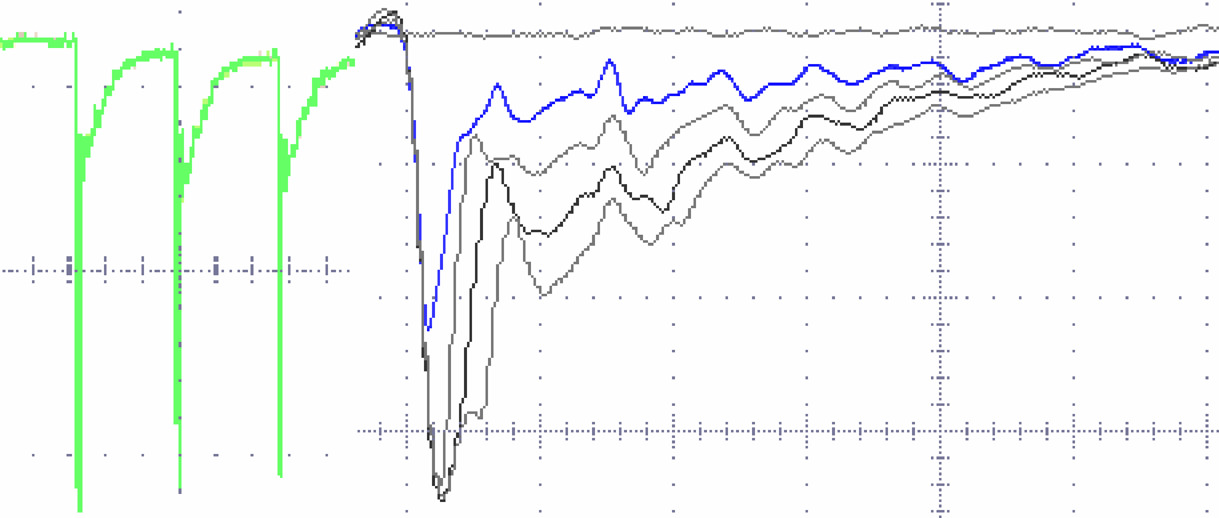

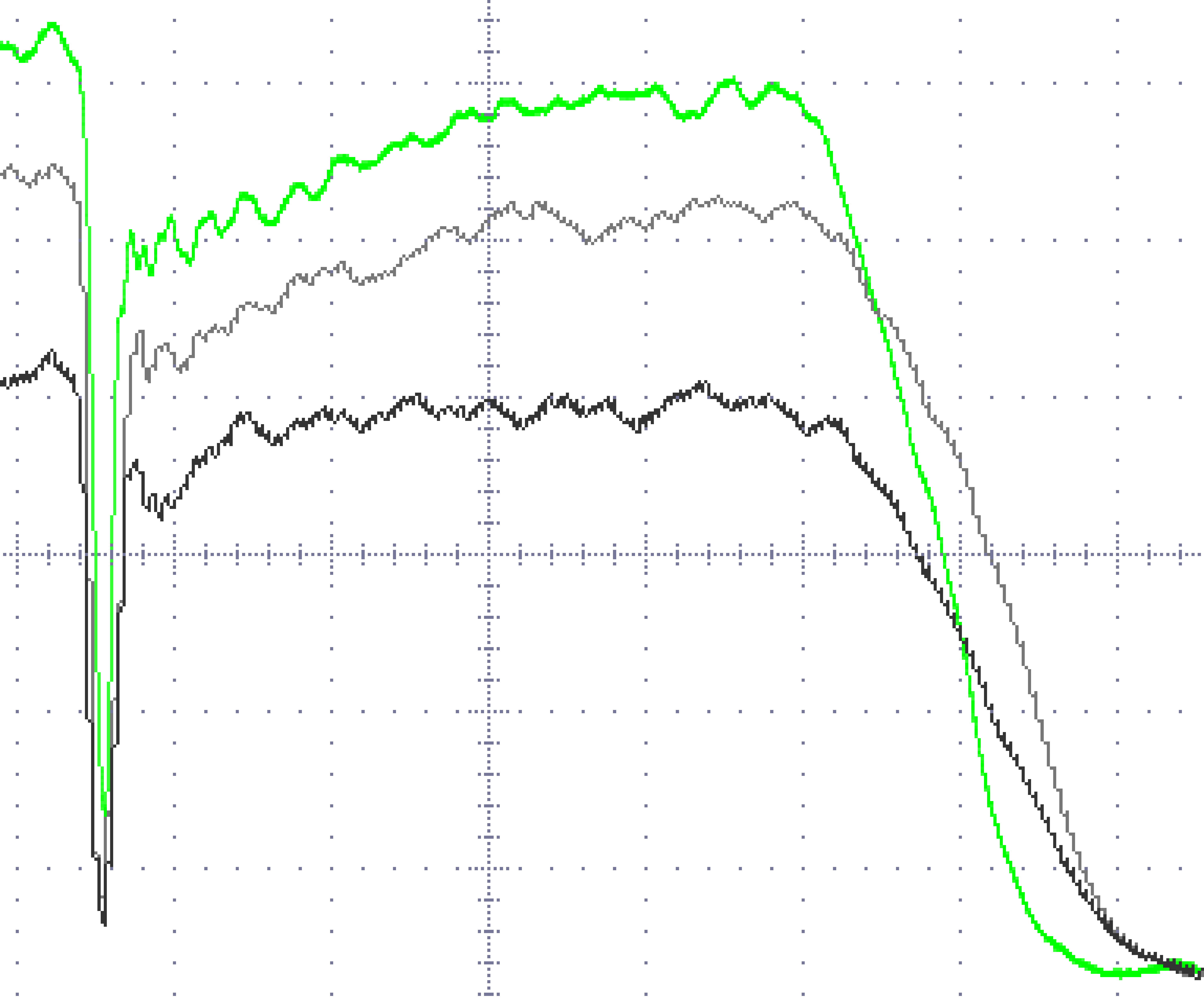

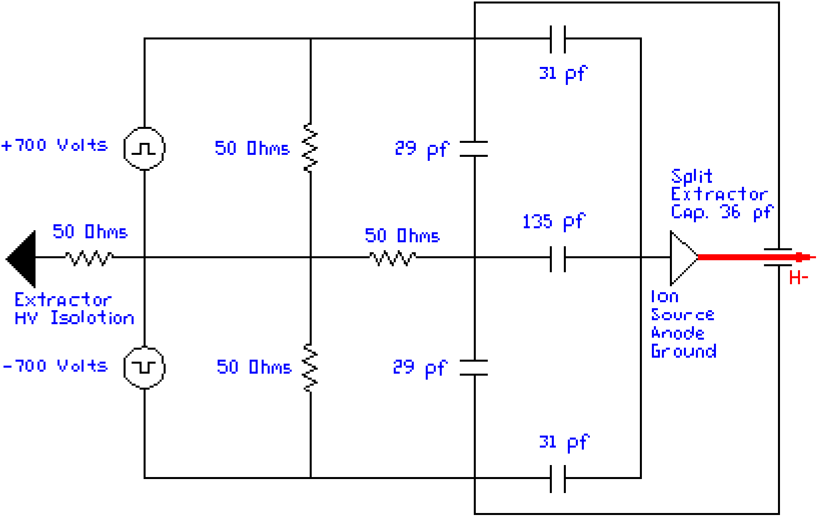
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