Using an Inertial Electrostatic Confinement (IEC) Nuclear Fusion Device as a Pulsed Neutron Source: Optimizing the Pulse Shape

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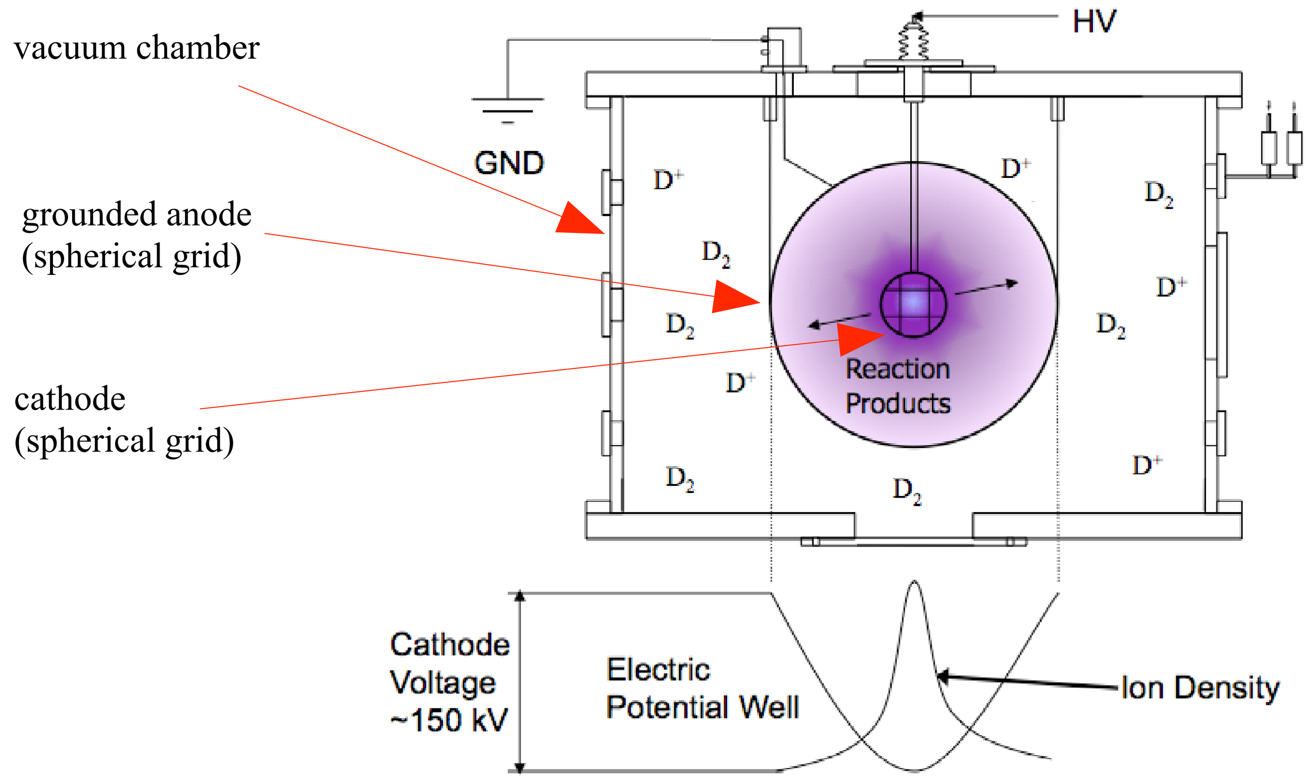
Abstract:
Pulsed neutron sources may prove to be valuable for detecting illicit nuclear materials in items being smuggled across borders or checkpoints. Work already accomplished by Sorebo et al. (1) at the U. of Wisconsin demonstrated the basic detection concept by successfully detecting delayed U-235 fission neutrons using neutron pulses generated by an IEC fusion device. Numerical studies imply the detection of the much more copious prompt induced-fission neutrons would be preferable; the experimental detection of prompt neutrons represents a challenge: the prompt, fission-produced neutron and interrogating neutron pulses may overlap. After IEC device operation and past work by Sorebo et al. are reviewed, efforts to produce a properly shaped interrogating neutron pulse are described. Efforts drawing, in part, on techniques used in hard-switched power inverters are highlighted.

(1) J.H. Sorebo, G.L. Kulcinski, R.F. Radel, and J.F. Santarius, "Special Nuclear Materials Detection Using IEC Fusion Pulsed Neutron Source," Fusion Science and Technology 56, 540 (2009).

* Work funded by the Grainger Foundation

Background: Device Operation



Ionized deuterium is accelerated toward the center by radial electric field produced by spherical electrodes. The UW IEC device is capable of producing a 10 Hz source of 2.45 MeV neutrons at 5×10^9 neutrons/s in a 110µs pulse at a -120 kV cathode potential and 6 amperes of D+ current.

$D + D \rightarrow T$ (1.01 MeV) + p (3.02 MeV)
$D + D \rightarrow {}^3He$ (0.82 MeV) + n (2.45 MeV)
The reactions split approximately evenly between the branches

Background: HEU* Detection (Sorebo/Radel results) motivated by Homeland Security needs

Delayed Neutron Analysis (DNA)

- Interrogating, thermalized neutron induces fission of U-235 nucleus.
- After a short delay, immediate fission products undergo Beta-decay, emitting neutrons.
- These neutrons are then detected.

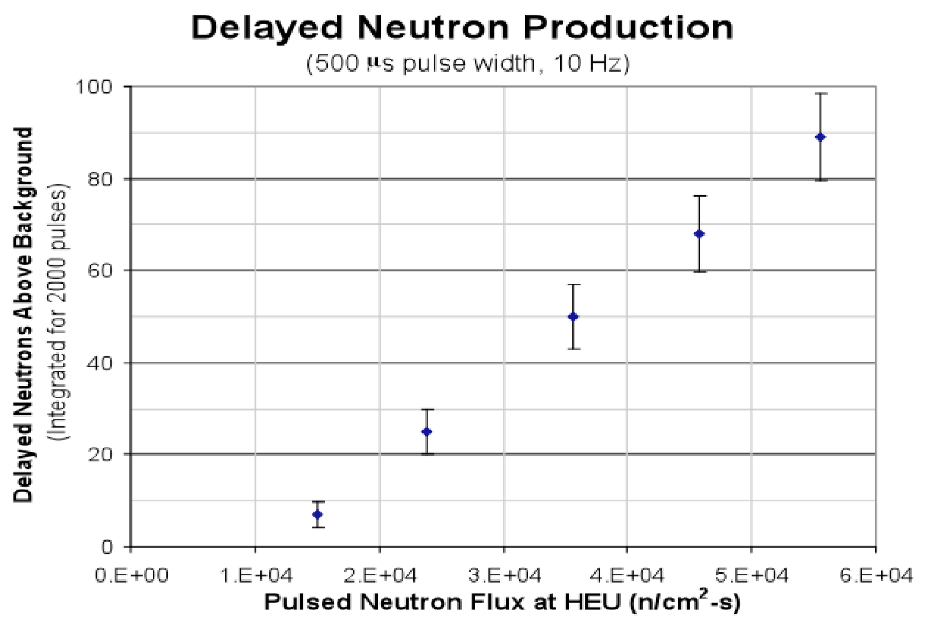
Differential Die-away Analysis (DDA)

- Interrogating, thermalized neutron induces fission of U-235 nucleus.
- many neutrons are released as direct products of the fission.
- these neutrons are sensed immediately after the interrogating neutrons have dissipated.

Note: fission neutrons are much more copious than delayed neutrons!

* -- HEU: Highly Enriched Uranium

DNA Results with HEU



Experimental data for delayed neutron production above background versus interrogating neutron flux. As expected, the number of delayed neutrons increases with increasing interrogating neutron flux.

The Challenge:

"Immediate" neutrons, i.e. neutrons which are the direct product of induced fission reactions, though more copious, will be emerging from the specimen under test immediately after and perhaps during the interrogating neutron pulse. Detection of the immediate neutrons will require an interrogating neutron pulse with a sharp cut-off.

Neutron pulse forming techniques with "beam-background" IEC devices:

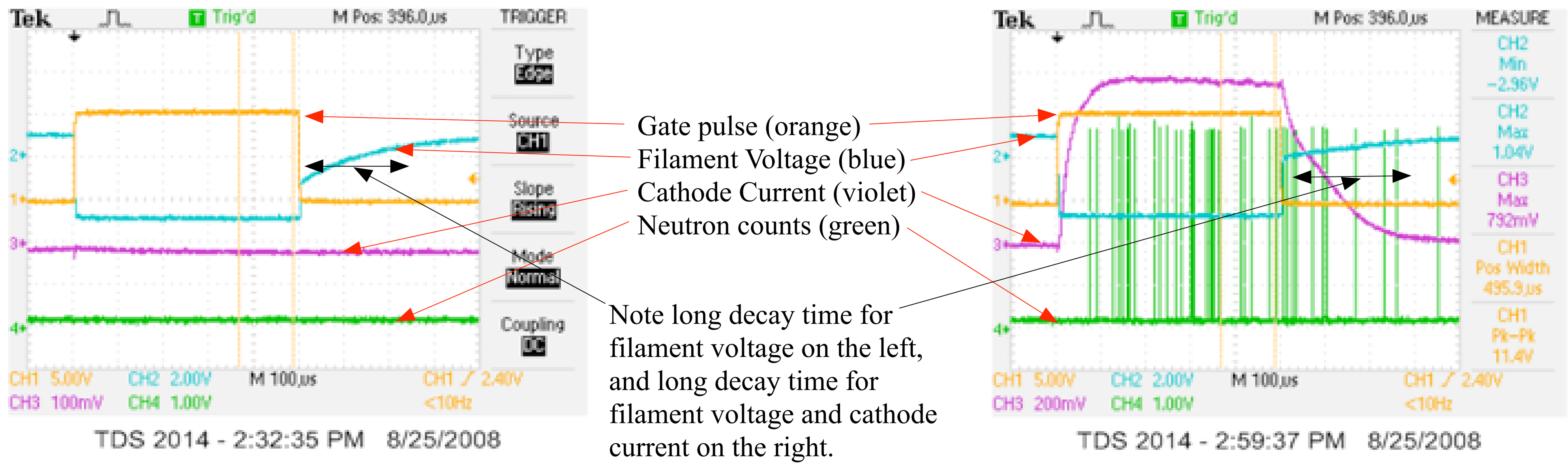
Cathode pulsing: This method would most likely be the most effective way of producing neutron pulses with short rise- and fall- times. However, this means designing a system which can supply well-formed pulses of approximately 150 kV amplitude and several amperes of current to a load of an ill-defined and variable impedance. Accomplishing this in a manner which is consistent with the eventual need to produce these devices with footprint, weight, and power requirement consistent with field deployment respresents a substantial challenge and expense.

Filament pulsing: This method involves keeping the heated filaments perhaps 100 V positive most of the time, and then pulling them down to a substantial negative voltage for the duration of the pulse (e.g. 500 µsec.). While the filament is positive, fusion reactions do not occur, as there are no free electrons to produce ions to fall into the potential well formed by the cathode. Pulsing the filaments to a large negative voltage, briefly, produces a burst of electrons which produces a burst of free ions which then fall into the potential well. Some of these will undergo fusion, producing a neutron burst. This method has the advantage of simplicity, and relative ease of implementation, but it is not clear that this method can produce sufficiently "sharp" neutron pulses because of the natural time delays involved in the drop of ion population. **This experiment is concerned with determining if this simpler-to-implement method can be made to work.**

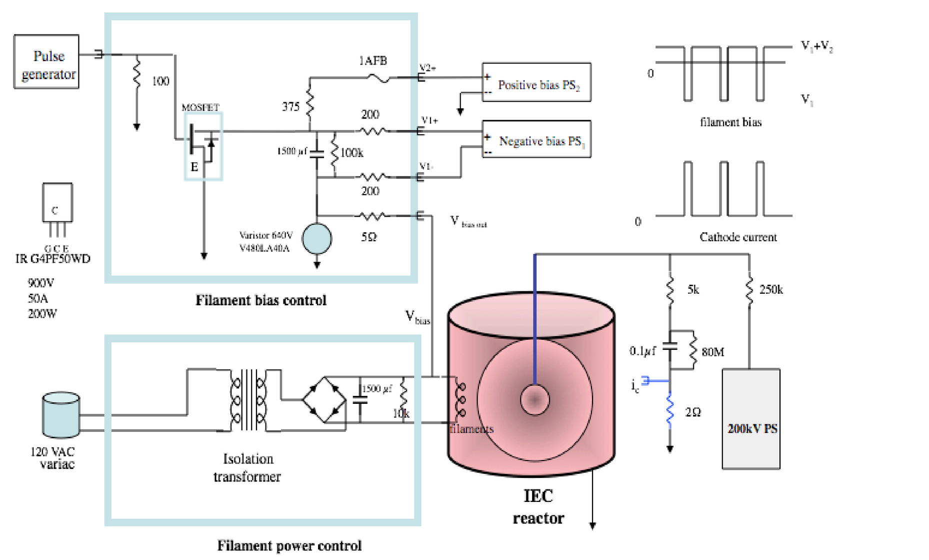
Pulse Shape with Original System:

With cathode at ground potential

With cathode at negative potential



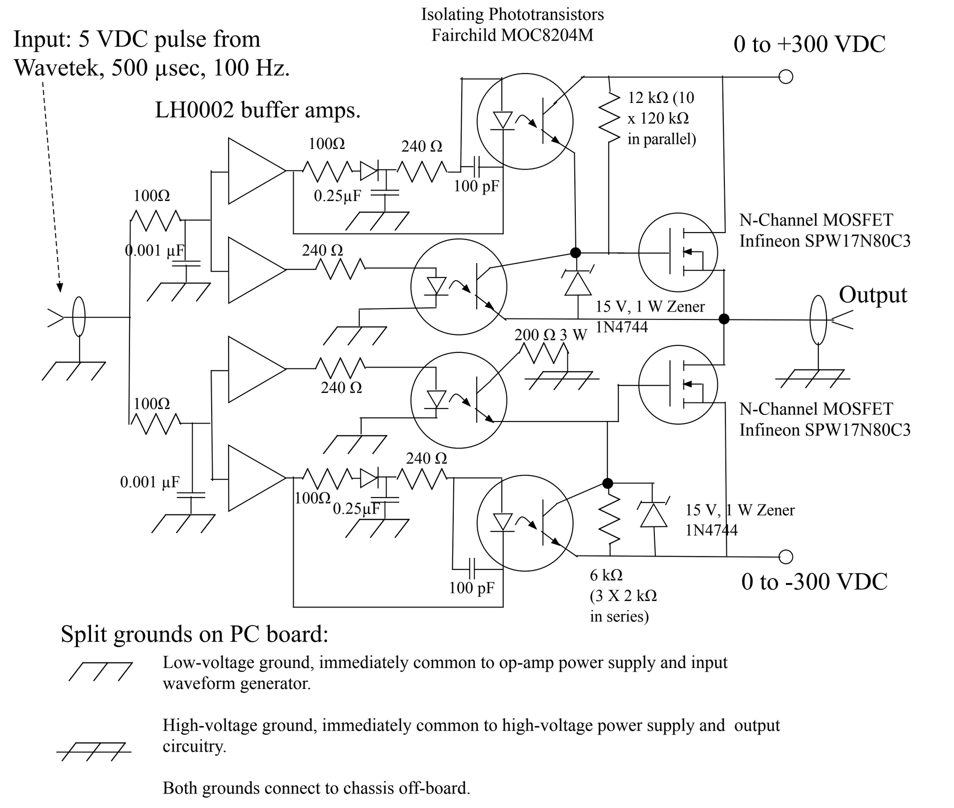
IEC Pulsing Circuit



The original filament-bias pulsing circuit employed two independent power supplies to provide bias voltage to the heated filaments. One power supply is set up to provide a large positive voltage to the filament, while a second power supply is connected to the first in such a manner as to "buck" the first power supply with a negative voltage of lesser magnitude, thus the net voltage biasing the filaments is positive when the system is quiescent. When the MOS-FET is turned "on," it pulls the junction between the power supplies suddenly to ground, suddenly giving the filaments a negative bias. During the short pulse, the capacitor will be able to maintain the filament bias voltage at the level of the negative power supply.

When the transistor is switched "off ," the power supplies' junction is allowed to return to its prior voltage. This process takes some time, perhaps as the space-charge around the filament is drained via the 375 Ω resistor on the positive power suppply.

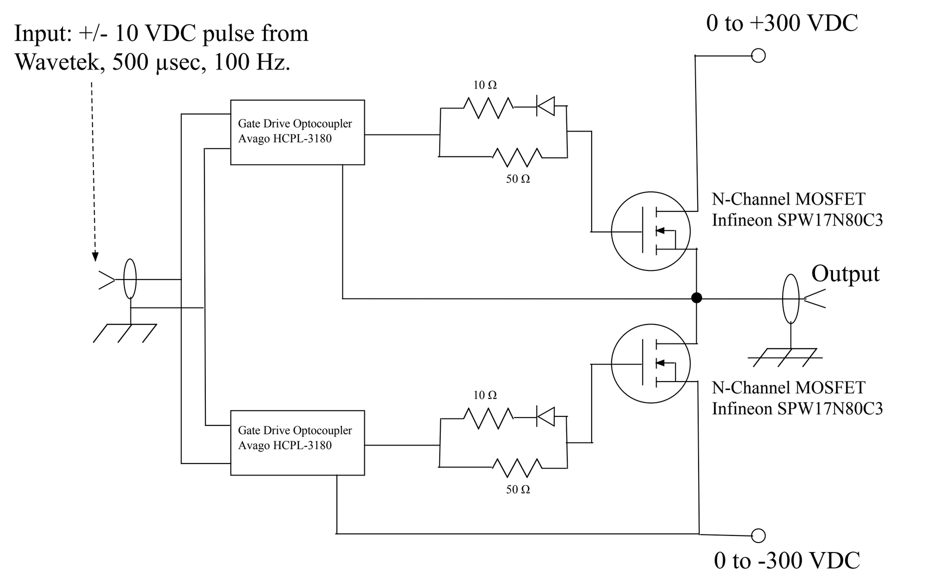
First attempt at a redesign using MOSFETS in a "push-pull" configuration:



- Attempts to actively return filament bias voltage to positive state by using two MOSFETs in a "push-pull" arrangement.
- When the input signal is low, the phototransistors are all off, thus causing the upper MOSFET to be switched on, and the lower MOSFET to be switched off, thus leaving the filament bias positive.
- When the input signal goes high, the central phototransistors are switched on, turning the upper MOSFET off and turning the lower MOSFET on, thus causing the output to be positive.
- Also, when the input signal is high, the 0.25 µF capacitors connected to the ouputs of the upper and lower are charged to 5 VDC.
- When the input returns to the low state, the central phototransistors are again switched off, allowing the upper MOSFET to switch on and the lower to switch off.
- Additionally, when the input returns to the low state, the 0.25 µF capacitors discharge through the upper and lower phototransistors, briefly turning them on, and thus permitting them to accelerate the switching of the MOSFETs by momentarily bypassing the MOSFET gate resistors, and more rapidly discharging the internal gate-source capacitance.

This version of the device failed bench testing. While it performed well at up to about +/- 50 VDC, at higher voltages there would be substantial instability in the output, especially near the transitions. When it became apparent that this was not going to work, it was decided to seek out the expertise of the Wisconsin Electric Machines and Power Electronics Consortium (WEMPEC) at the U.W. department of Electrical Engineering.

Second redesign, using techniques used by motor drive designers (with thanks to WEMPEC):



- This design makes use of off-the-shelf components optimized for and intended for this particular task of switching MOSFETS in power applications, for example in switching power supplies or in inverters.
- The gate driver integrated circuits are each powered by a separate and isolated DC/DC converter, each converter output being referenced to the common output terminal of the gate driver it is powering.
- This particular device was recently pressed into service to power an ultrasonic transducer for an ad-hoc ultrasonic cleaning system used to clean an IEC device vacuum chamber.

This second attempt at a redesign passed bench testing, and neither showed sign of instability nor showed evidence of "shoot-through" (i.e. both transistors being "on" or in active region at the same time).

Future Work:

- Test this system on the IEC device (HOMER) for which it is intended, and determine if it does, in fact, switch the filament bias voltage between the set positive and negative limits quickly.
- If the bias voltage switching speed appears to be adequate, proceed with further experiments to determine if the generated neutron pulse is sufficiently sharp to allow the distinguishing of immediate fission neutrons from the interrogating pulse.
- If the bias voltage switching speed appears to be NOT adequate, determine what steps may be taken to improve the switching time.