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Electrostatic chopper for Super MuSR muon beamline

Abstract: The upgrade to the MuSR muon beamline at ISIS will include an electrostatic chopper, designed to improve the timing resolution of muon experiments. The chopper is required to switch from +80 kV (±40 kV on each plate) to -80 kV in 10 ns, sweeping the beam across an aperture at a precise time. A feasibility study has been undertaken and a design based on thyratrons is being developed. This talk will present our conceptual design, some of the problems we expect to face and potential solutions. Beneficial discussion around this topic will include the experiences of designing and operating similar systems at other facilities.

12th March 2018

Jonny Ranner

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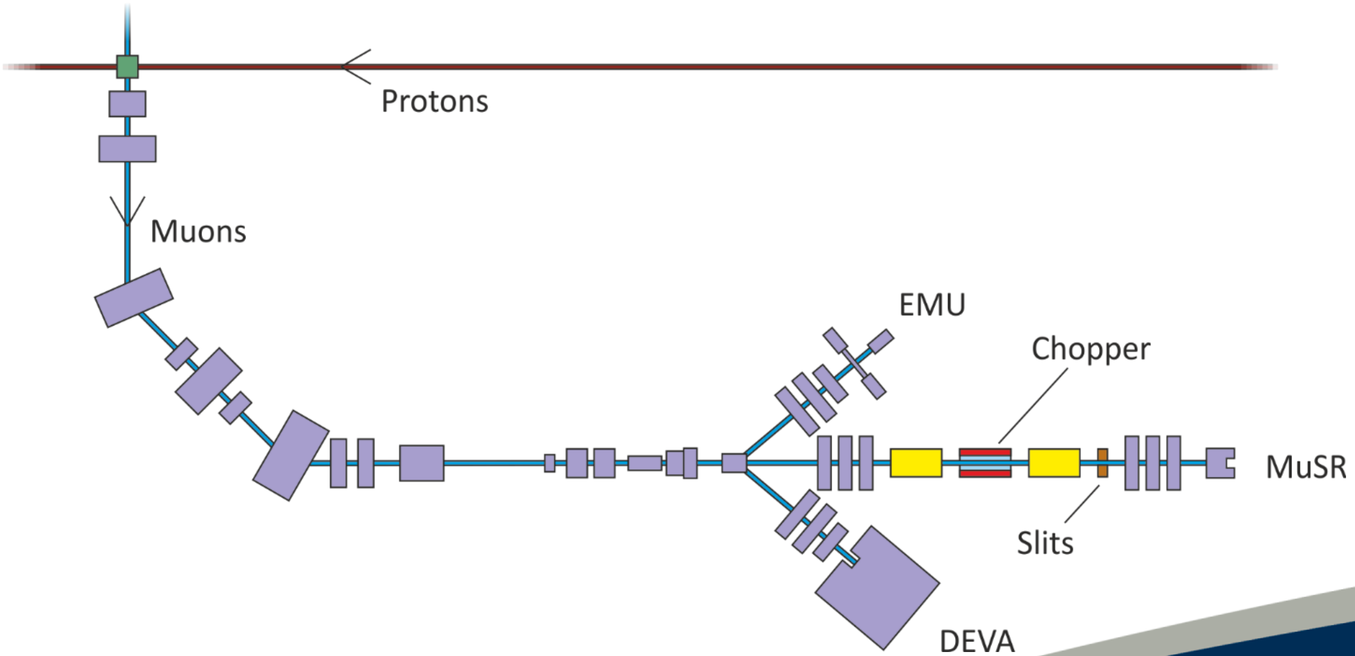
Aim of project

Super MuSR is an upgrade to the existing muon spin spectroscopy beamline at ISIS.

The Muon chopper will provide increased time resolution by reducing the spread of implanted muons.



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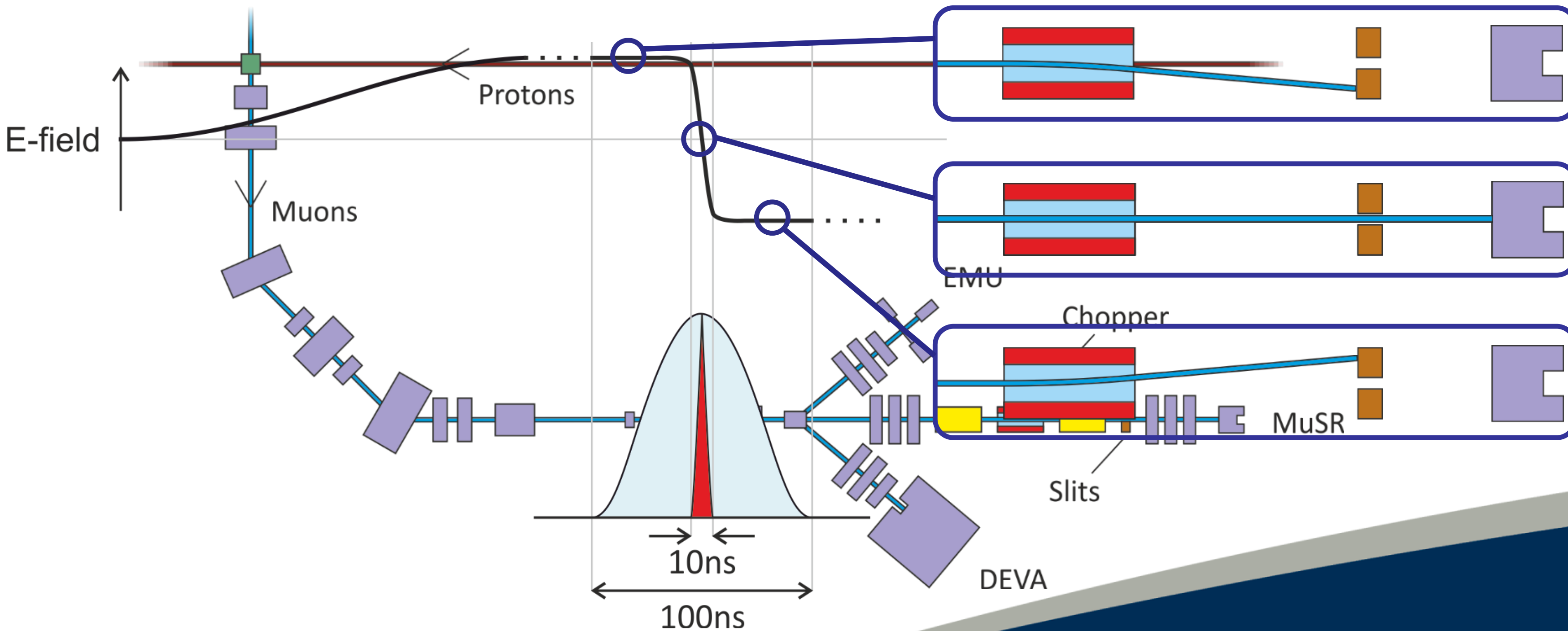

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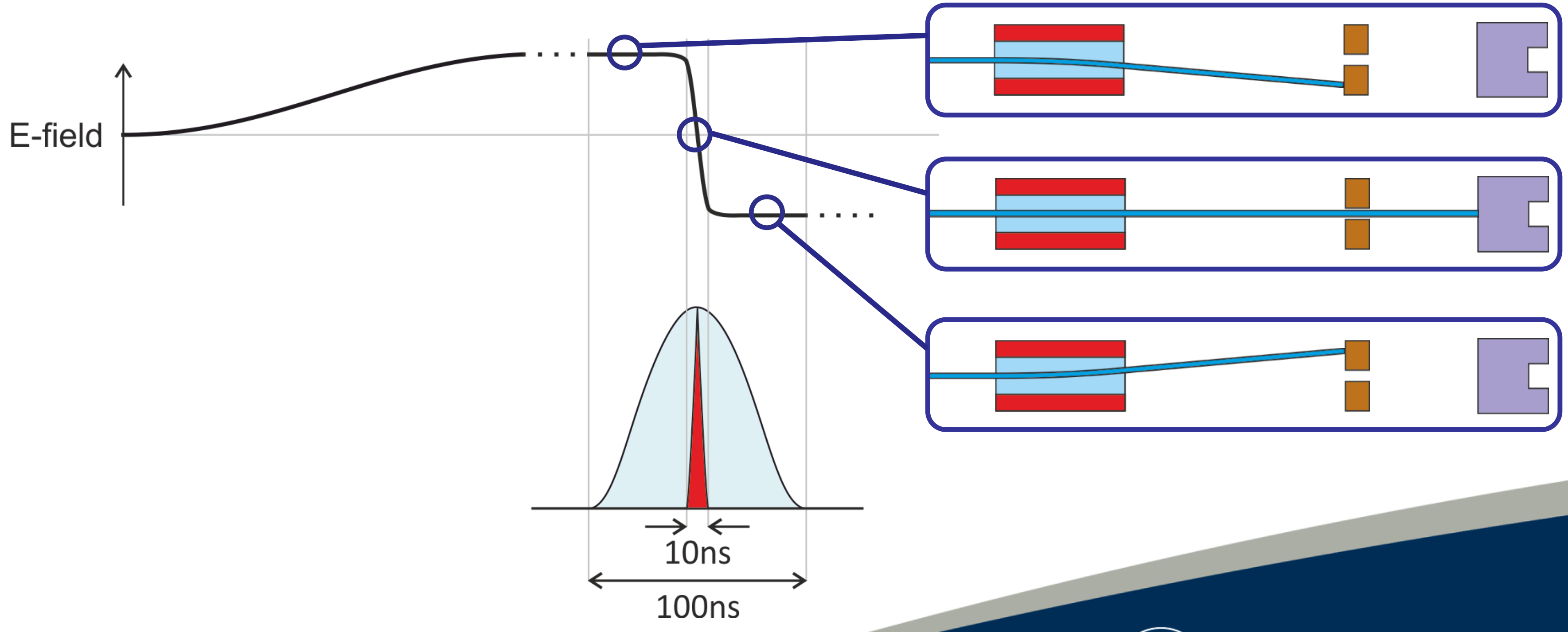


Starting point

Muon

Mass (m_0)	105.66 MeV/c^2
Momentum (p)	28.63 MeV/c
Velocity (v_x)	0.262c
Charge (q_μ)	-e (1.6×10^{-19} C)
Profile	100 mm
Bunch length	100 ns
Lorentz factor (γ)	1.036

Chopper

Length (L_1)	500 mm
Height	250 mm
Separation (D)	120 mm

Slits

Distance from chopper (L_2)	2 m
Aperture	150 mm

Displacement due to E field at end of chopper plate:

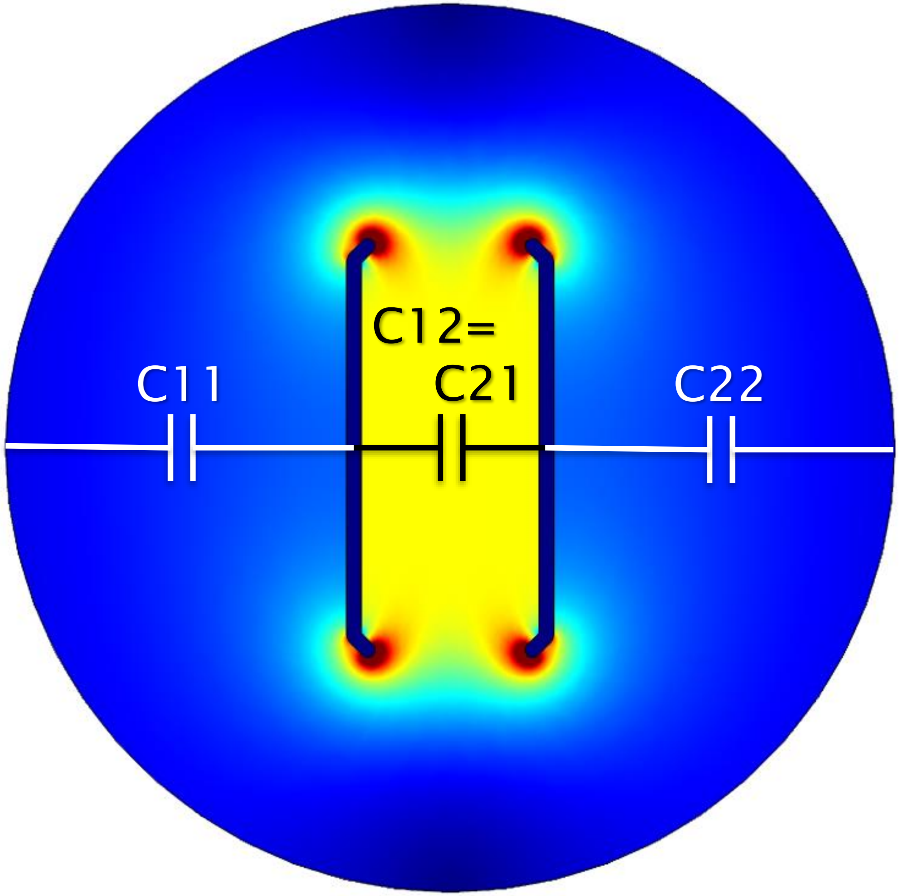
$$S_{E\_L_1} = \frac{q_\mu . V . {L_1}^2}{2. D . \gamma . m_0 . {v_x}^2}$$

Angle of velocity after chopper due to E field:

$$\varphi_E = \text{atan}\left(\frac{q_\mu . V . L_1}{D . \gamma . m_0 . {v_x}^2}\right)$$

To achieve 150 mm displacement at slits (44.488 mrad) requires:
V = 120 kV

Starting point



Per plate

Voltage	±60 kV
Charge	2.74 μC
Energy	82.1 mJ

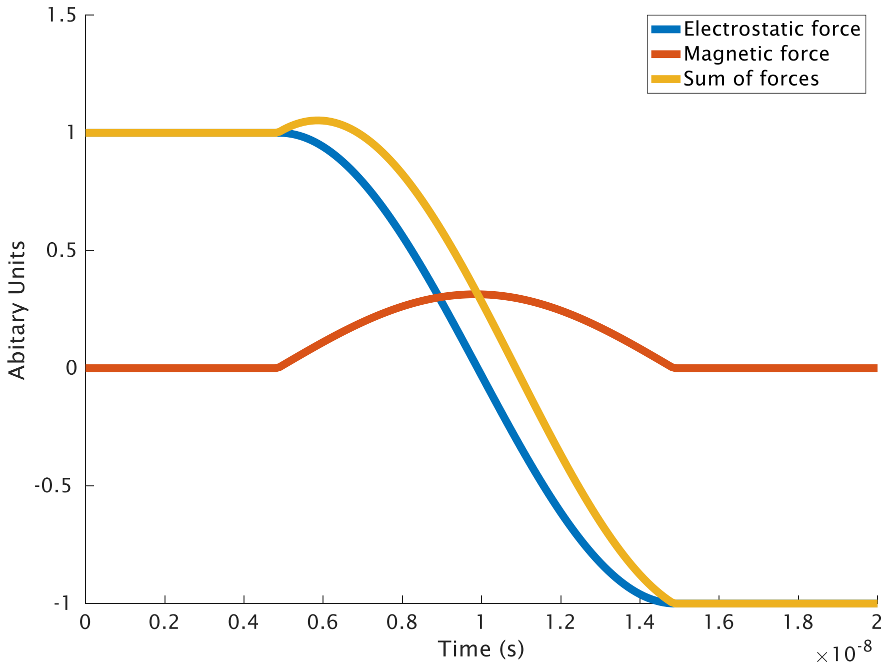
Capacitance:	
C12 plate to plate	12 pF
C11 plate to ground	21.6 pF

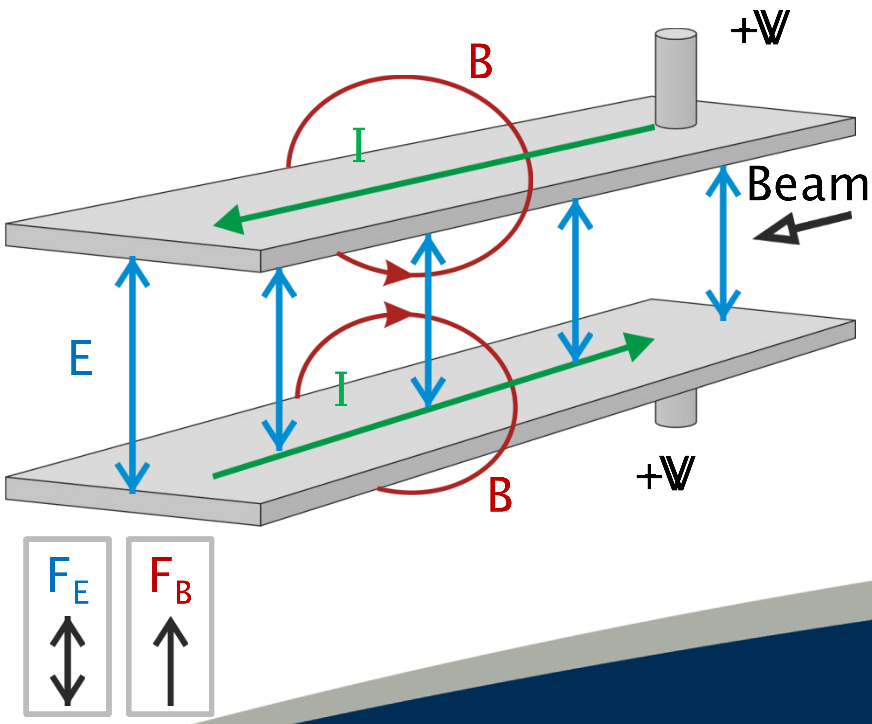
The plates will not be terminated so there will be no/little current outside of the voltage transition period.

Starting point

The effect of the magnetic field has not yet been properly considered.

If the force due to the magnetic field is aligned to add to the electrostatic force, then the beam direction transition will be faster.





Methods considered

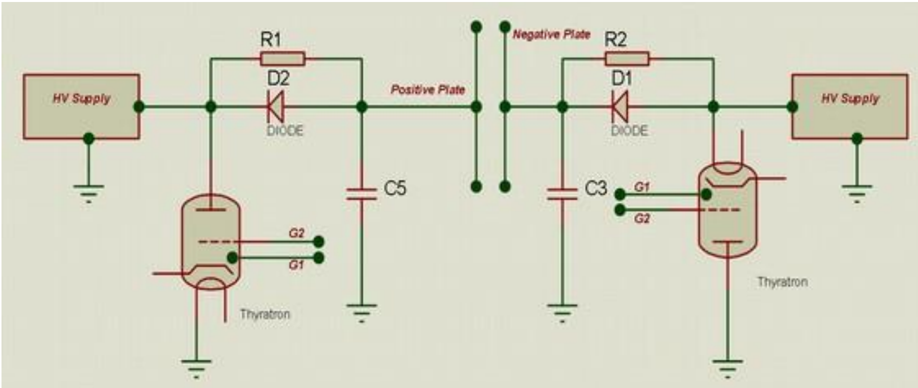
Previous work:

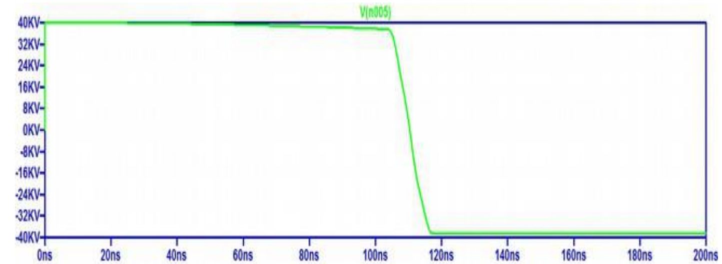
- High frequency measurements at a pulsed muon source: beating the pulse width!, A. D. Hillier et al
- Muon Beam Slicer at J-PARC MUSE, W. Higemotoa et al
- ISIS High Energy Drift Space chopper

Feasibility Study:

- Concept feasibility was carried out with an 80kV specification
- It suggested several designs and indicated which would give us the best chance of sucess
- Study conducted by Richard Adler of North Star High Voltage, USA

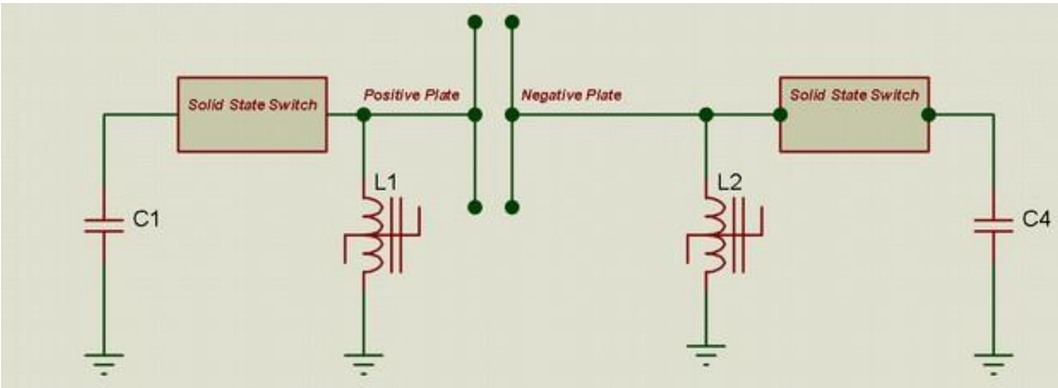
Methods considered

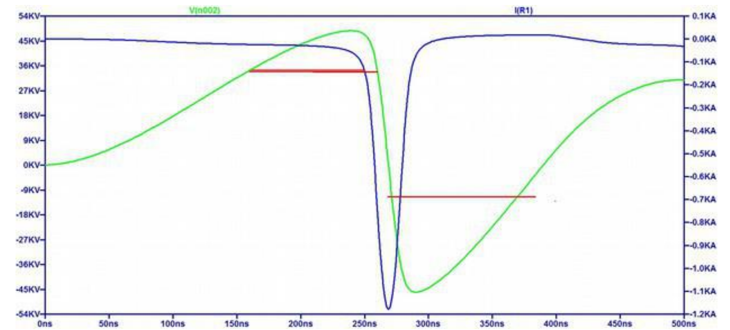




- Plates charged to ±60 kV.
- Switch closes to short plate to 0 V.
- Reflected wave causes plate voltage to invert.
- Inductance of switch and diode turn-on time are critical.
- Diodes were tested but the fastest voltage reversal was found to be 30 ns (Dean UX-F30).

Methods considered





- L1 and L2 are initially high inductance, blocking changes in current.
- >100 ns after solid-state switch closes, inductors saturate and inductance drops, allowing current to flow.
- Droop in voltage is expected to be high (~50% for μ_r=1000).

$$\frac{\delta V}{V} \approx \frac{\pi^2}{2\mu_r}\left(\frac{t_o}{t_c}\right)^2$$

t_o is duration that the magnetic switch open
t_c is closed duration
μ_r is relative permeability of core
$\frac{\delta V}{V}$ is the voltage droop

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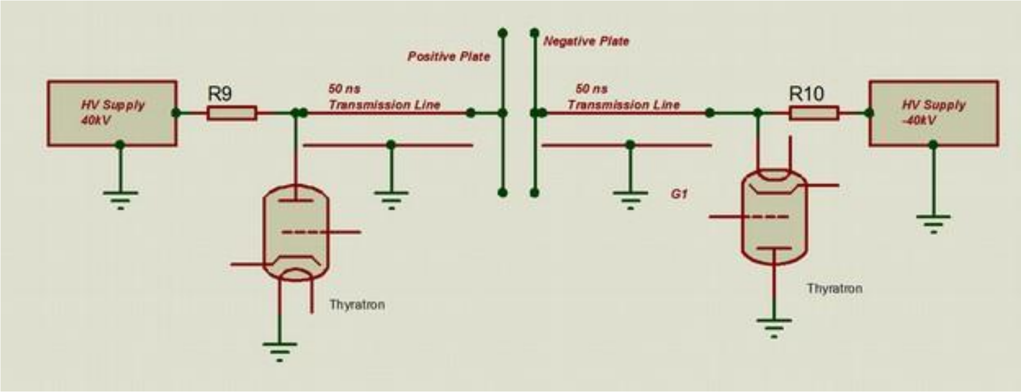
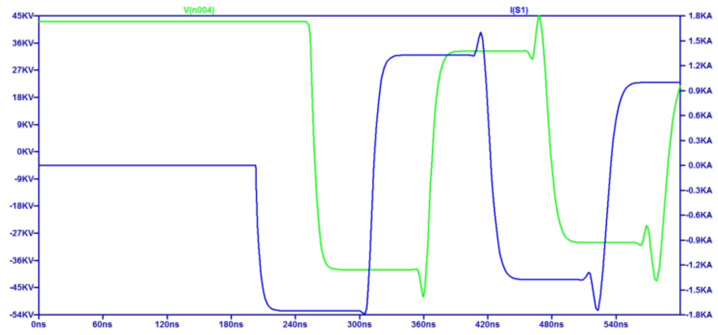
Methods considered





- Transmission line chosen to have a propagation delay of 50 ns so that the muon bunch has passed before the reflection returns.
- Line and plate are initially charged to ± 65 kV.
- Switch closes and holds one end of the line at 0 V.
- Wave travels along the line and inverts the voltage of the plate.
- The critical requirement for creating this waveform is to keep the thyratron inductance below 70 nH with a 25 Ω transmission line, or less than about 90 nH at 40 Ω.

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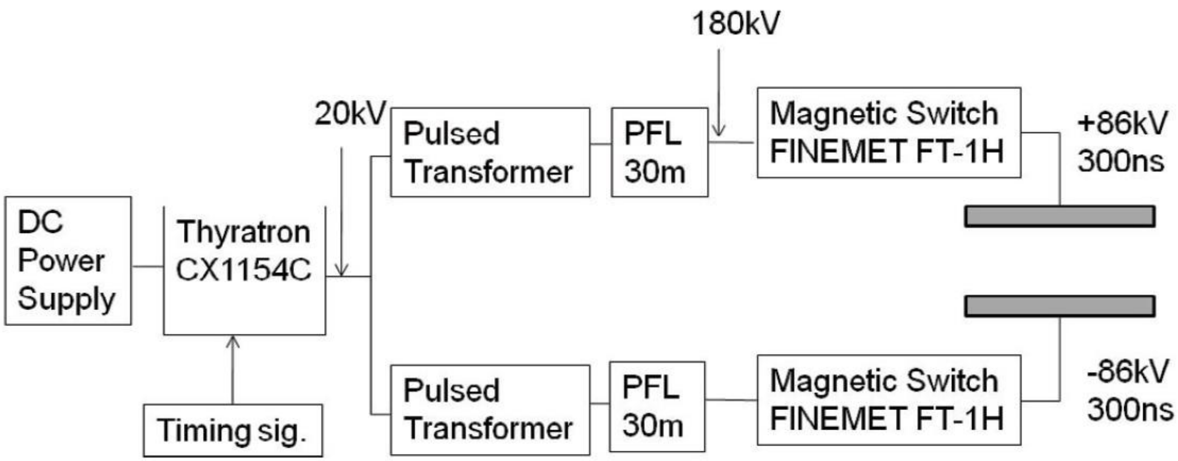
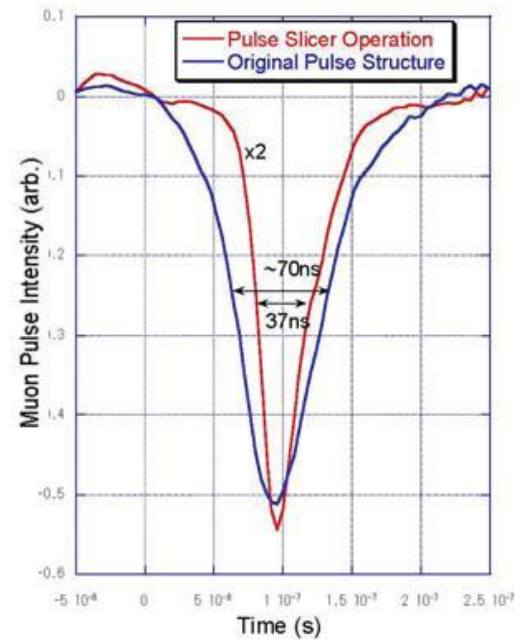
Methods considered

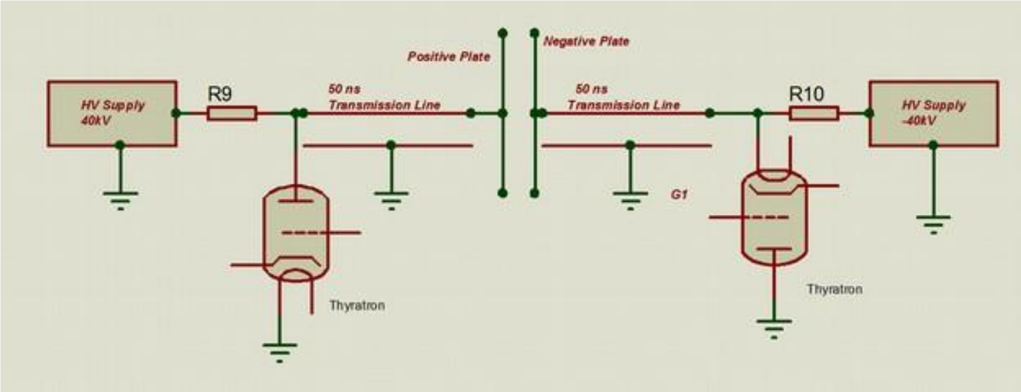




- “Muon Beam Slicer at J-Parc MUSE”, W Higemoto, T U Ito, K Ninomiya, R H Heffner, K Shimomura, K Nishiyama and Y Miyake.

- 20 ns rise time (10-90%), 300 ns pulse width
- 172 kV
- plate length 600mm, separation 150mm
- 80.29 mrad

Preferred Method



The shorted line method, with magnetic pulse sharpening, is an attractive solution and has been demonstrated at J-Parc.

A test circuit was built as a proof of principal of this method. A load of 50 pF to ground was used to emulate the plate capacitance.

In the first test both Si and SiC FETs were tested, both using a Ixys IXDD604 gate driver. In the second a low voltage thyratron was used. Pulse sharpening was not used in either test.

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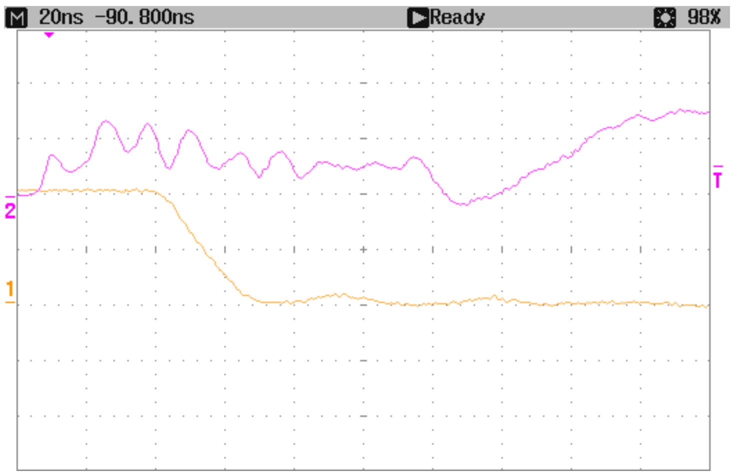
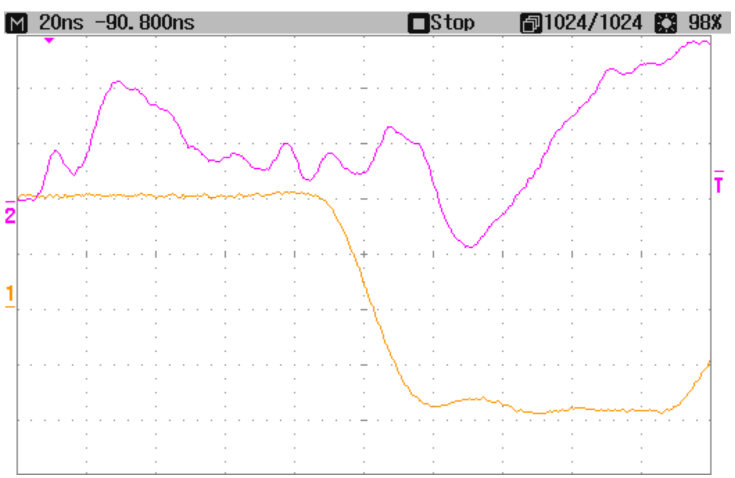
Preferred Method – Si FET





The FET (Microsemi APT12060LVFR) switches slower than we would like – 19 ns from 1050 V to 60 V.

Top plot shows output of FET (orange) and gate driver (magenta).

Lower plot shows plate voltage (orange) at the end of a 9.1 m RG-223 cable (45 ns) and the same gate driver (magenta).

80% voltage reversal is achieved.

1 kV to -800 V in 28 ns.

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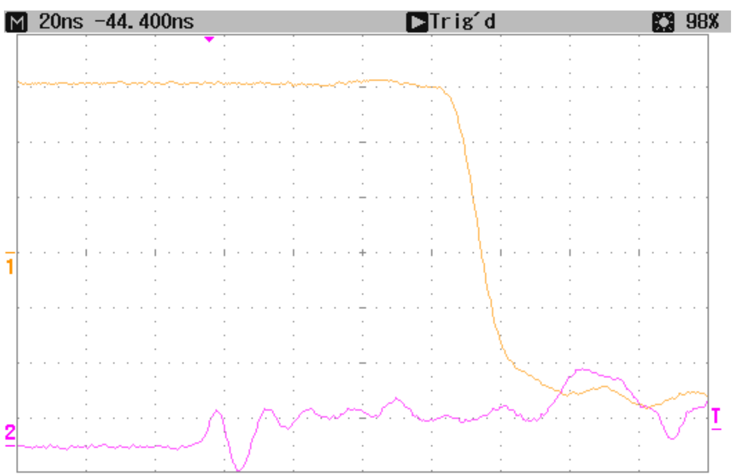
Preferred Method – SiC FET



Other FETs were investigated. By using a SiC FET (Cree 1700V C2M1000170D) we were able to improve performance.

Top plot shows output of FET (orange) and gate driver (magenta).

Lower plot shows plate voltage (orange) at the end of a 9.1 m RG-223 cable (45 ns) and the same gate driver (magenta) (x5 scale).

80% voltage reversal is achieved.

1.5 kV to -1.2 kV in 20 ns.

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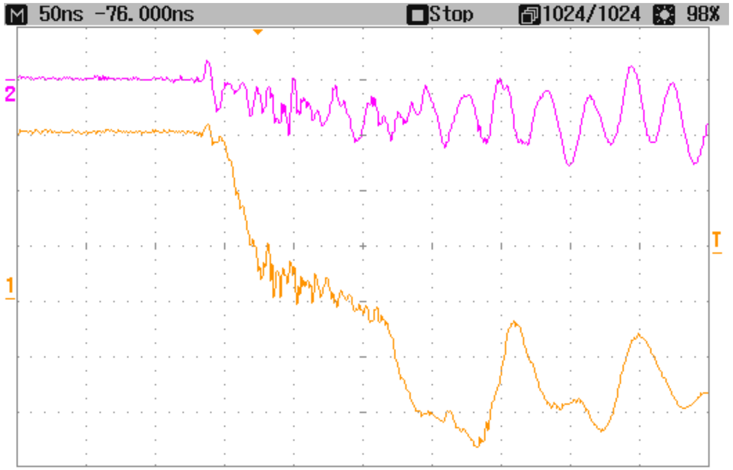
Preferred Method – Thyratron

The switching to zero for a 6 kV input with an EG&G JAN-CCYT-8613 thyratron is shown.



Top plot shows output of thyratron and lower plot shows plate voltage. Note: Time scale is now 50 ns/div.

The negative voltage reflection is seen at the switch as the thyratron does not reverse conduct.

The switching time is about 20 ns for this tube, and 30 ns at the plate. The latter is probably due to a poor cable.

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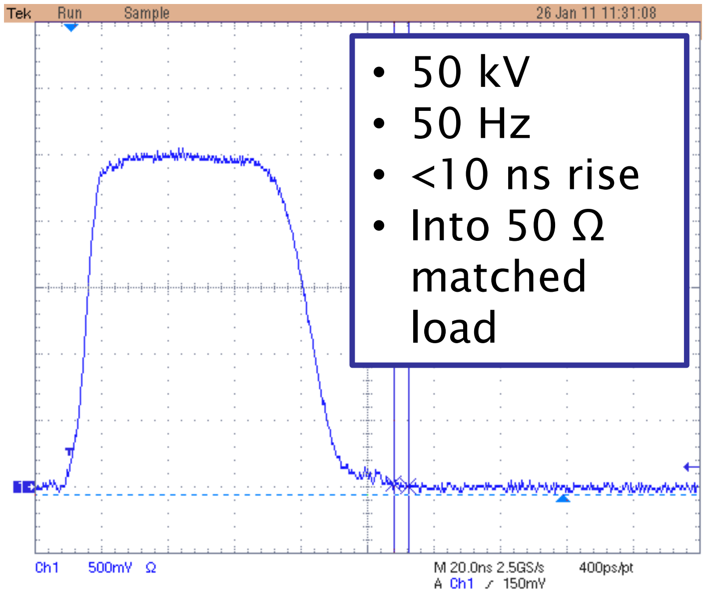
Preferred Method – FID



- 50 kV
- 50 Hz
- <10 ns rise
- Into 50 Ω matched load

Fast Ionization Dynistor (FID) is not a common technology choice.

Offered by a small number of suppliers. Reliability, longevity and availability are a concern.

Datasheets and published literature suggest output voltages up to 1 MV with a rise time of 1-2 ns and pulse width of 1-100 ns.

I contacted Alexey Efanov, MD of FID GmbH (Germany). He offered a complete system, including two switch devices for €98k.

Discussion

- Experience of switching >60 kV in <10 ns.
- Use of 70-80 kV thyratron for ~10 ns rise time.
  - CX1175C is 70 kV two gap with ceramic envelope
  - CX1925X is 80 kV three gap with metal/ceramic envelope
- Use of magnetic pulse compression and nonlinear transmission lines.
- Experience of manufacturers with capability in this area.
- Talks later today and tomorrow:
  - Experience of solid state modulators – Patrick Alexandre
  - Marx generators for kickers – Luis Redondo
  - Superfast thyristor based switches – Anton Gusev
  - Ultra fast kicker with a FID pulse generator - Marc Dubrulle