Development of a Marx Generator Discharge Circuit for High-Current Plasma Capillary Discharges

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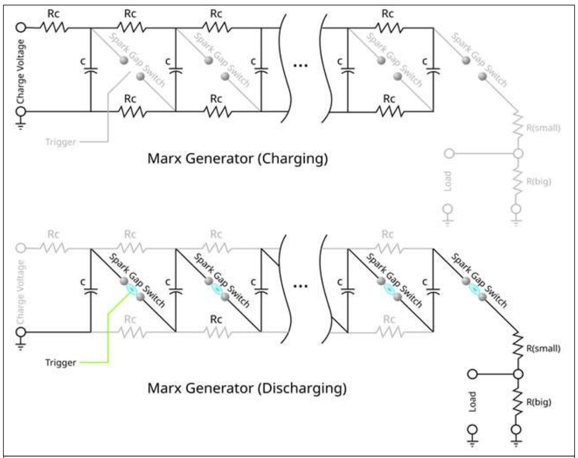
Abstract

In the context of plasma-based accelerators, one of the main advantages lies in their compactness and lower overall cost compared to conventional machines. Beside particle acceleration, plasma can also be used to focus (plasma lens) [1,2], and bend particle beams [3,4] within compact structures such as plasma discharge capillaries [5]. Beam bending in such devices requires a tailored capillary geometry and a dedicated discharge circuit capable of delivering high currents — typically above 10 kA — through the plasma. In this work, we present the development of a new type of discharge system based on a Marx generator, specifically designed to deliver more than 50 kV and 10 kA into a 20 cm-long capillary.

Additionally, numerical simulations are conducted to estimate the magnetic field distribution produced by such current discharge, and beam dynamics studies are performed to evaluate the guiding effect on a charged particle beam.

Marx Generator Principle



Operating principle of a Marx generator: capacitors charged in parallel are discharged in series through spark gaps, delivering a short high-voltage pulse to the plasma capillary (load).

A Marx generator is designed to deliver very short, high-voltage and high-current pulses to a plasma capillary.
Its operation is based on a two-step process:

- **Charging phase (parallel):** Each capacitor is charged in parallel at a moderate voltage V_c, through charging resistors R_c.
- **Discharge phase (series):** When the spark gaps (or fast switches) are triggered, the capacitors are suddenly reconfigured in series, producing an output voltage of approximately $N \times V_c$.

This high-voltage pulse is then delivered to the **plasma capillary (load)**, driving large discharge currents (kA–10 kA range) within tens of nanoseconds.

Benefits of Marx circuit

Why Marx instead of a classical RLC pulser?

Classical RLC pulser:

- Single capacitor charged and discharged through a switch.
- Pulse durations in the **hundreds of ns to µs** range.
- Limited peak current (hundreds of A).
- Higher energy per pulse → **thermal stress** at high repetition rates.

Marx generator:

- Capacitors charged in parallel, discharged in series → **voltage multiplication**.
- Produces **short pulses (hundreds of ns and lower)** with much faster rise times.
- **Higher peak current** → stronger plasma density and magnetic fields.
- Reduced energy per pulse → **thermal management**, enabling **operation >400 Hz [6].**

Discharge simulation

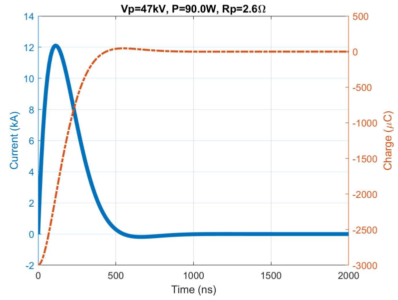
Parameters	Value	Comments
Numbers of gaps (*N*)	2	Equivalent to 2 stages at 30 kV each
Output voltage (*V*)	60 kV	From 2 × 30 kV
Capacitance per stage (C_i)	100 nF	Equivalent capacitance = 50 nF
Inductance per stage (L_i)	18 nH	Total inductance ≈ 36 nH + plasma contribution
Cable length	~0.1 m	≈0.05 m effective half-length per side
Capillary length	20 cm	Radius = 1 mm
Effective resistance (*R*)	~2.6 Ω	Approximated load (plasma) resistance

The voltage delivered to the plasma is evaluated as

$$V_{plasma} = V_{tot} \cdot \frac{R}{R_{tot}} = 47 \text{ kV},$$

and under the chosen parameters it satisfies all breakdown conditions (**Paschen law**):

- Below the breakdown of individual gaps,
- Above the breakdown threshold of the capillary.



With the chosen parameters, the current reaches a **peak of 12 kA** at **t ≈ 112 ns**.
The pulse **FWHM** is ≈ **244 ns**, i.e. the 6 kA level is crossed at **t_1 ≈ 27.4 ns** and **t_2 ≈ 271.4 ns**.
(For reference, **FWHM** with **RLC** pulser is ≈ **1000 ns**.)
This satisfies the breakdown conditions and delivers a transient B-field sufficient to bend a 60 MeV-class electron beam by **~90°**.

Active Plasma bending simulations

- A **discharge current of 12 kA** generates an azimuthal magnetic field up to **~2.6 T** inside the capillary (Fig. 1).
- A weak **energy–position correlation (dispersion)** is observed at the exit, quantified by **R_{16} ≈ 0.46 mm** (Fig. 2).
- The 60 MeV electron bunch is bent by **≈90°** over the 20 cm long curved plasma channel (Fig. 4).
- The transverse beam distribution at the exit shows clear displacement while remaining well confined (Fig. 4).
- **Emittance growth remains limited** (<10%) and transmission is 100% (Fig. 4, bottom panel).

Parameter	Value
Nominal energy	60 MeV
Energy spread (RMS)	1.5 MeV (~2.5 %)
Charge	50 pC

Transverse spot size (RMS)	10 µm
Bunch length (RMS)	100 fs (~30 µm)
Normalized emittance	1.0 mm·mrad

Capillary radius	1.0 mm
Bending radius	0.15 m
Effective length	0.235 m
Plasma current	12 kA

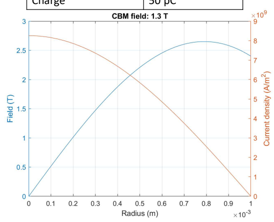


Fig 3. Radial distribution of current density and induced B-field (peak ~2.6T)

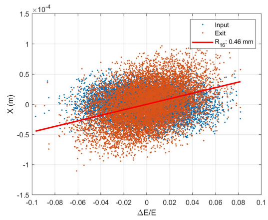


Fig 2. Energy–position correlation at exit: extracted R_{16} = 0.46 mm

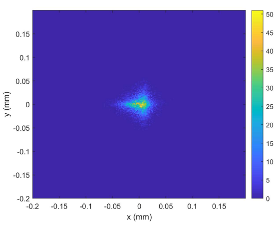


Fig 4. Exit beam profile (x–y distribution, mm scale)

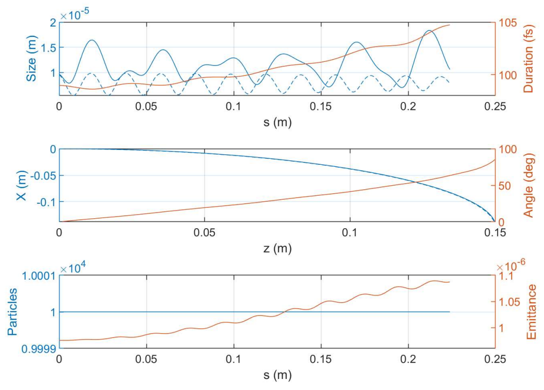


Fig 4. Beam evolution along the capillary: size, centroid trajectory, angle, emittance.

Conclusions

- A 2-gap Marx generator has been designed and simulated, delivering **≈47 kV** to the plasma and producing **peak currents of ~12 kA**.
- The generated current pulse (FWHM ≈ 240 ns) provides the required transient magnetic field (effective dipole ~1.3 T).
- Beam dynamics simulations confirm that such a discharge can **bend a 60 MeV electron beam by ~90°** while preserving beam quality.
- These results demonstrate the feasibility of plasma-based bending devices powered by tailored Marx generators, paving the way for compact, high-repetition-rate plasma beam optics.

References

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