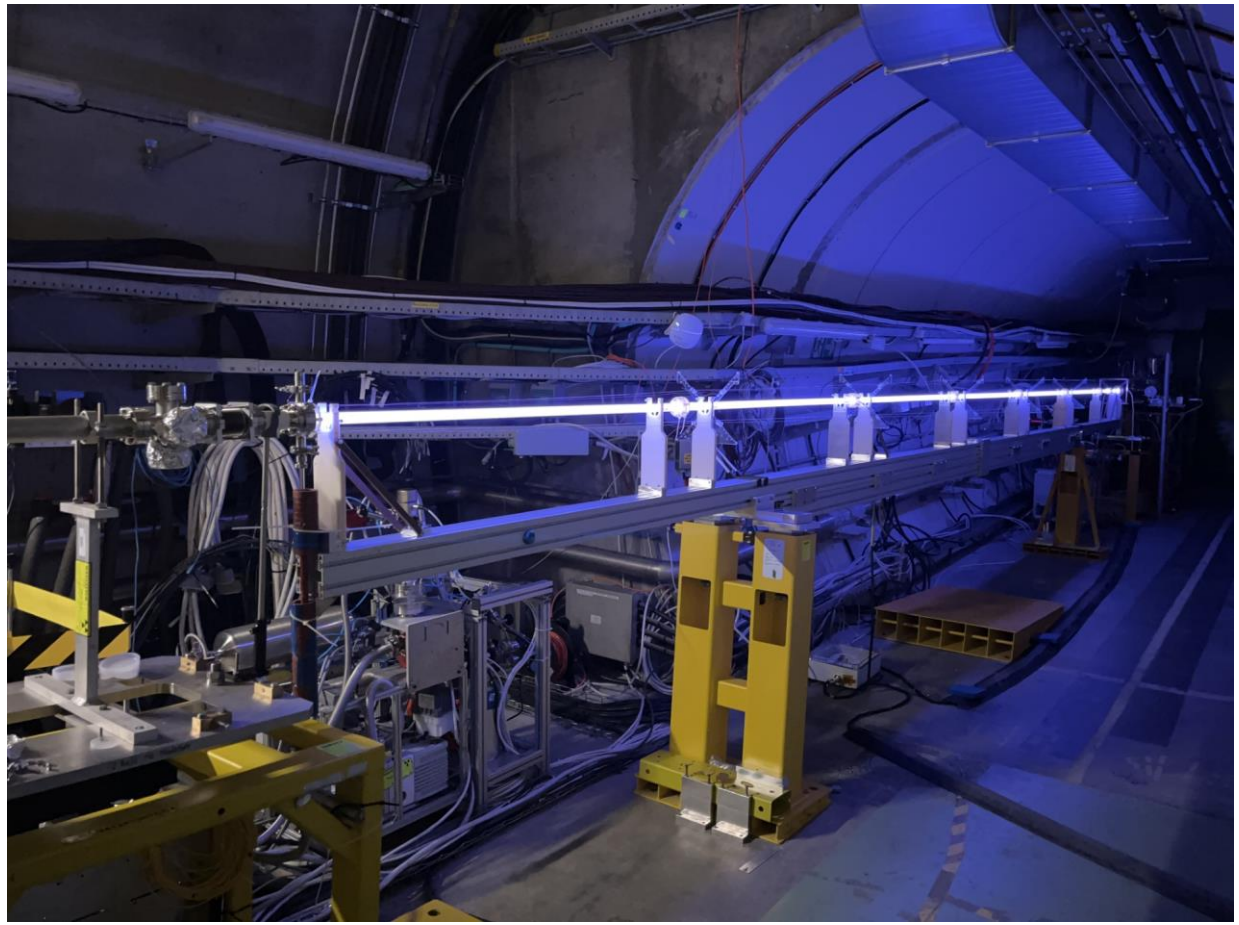
Electrical design of AWAKE scalable discharge plasma source



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FCT Fundação para a Ciência e a Tecnologia

AWAKE

TÉCNICO LISBOA

CERN *Vacuum, Surfaces & Coatings Group* Technology Department

Outline

1. AWAKE scalable plasma sources
    - Motivation
    - Requirements
    - Electrical challenges

2. Double pulse generator
    - Fast Ignition
    - Density target
    - Operation

3. May 2023 proton run
    - Current reproducibility
    - Operation range
    - Double plasma

Outline

1. **AWAKE scalable plasma sources**
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   - **Electrical challenges**

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AWAKE scalable plasma sources

Motivation

One of the core components of a plasma wakefield accelerator is the plasma source

Currently AWAKE uses a laser ionisation plasma source

Due to laser beam diffraction, this plasma source is limited to a 10 m length

Longer lengths are required to reach higher particle beam energies

Alternative scalable plasma sources are being investigated: Discharge Plasma Source (DPS) and Helicon Plasma Source (HPS)

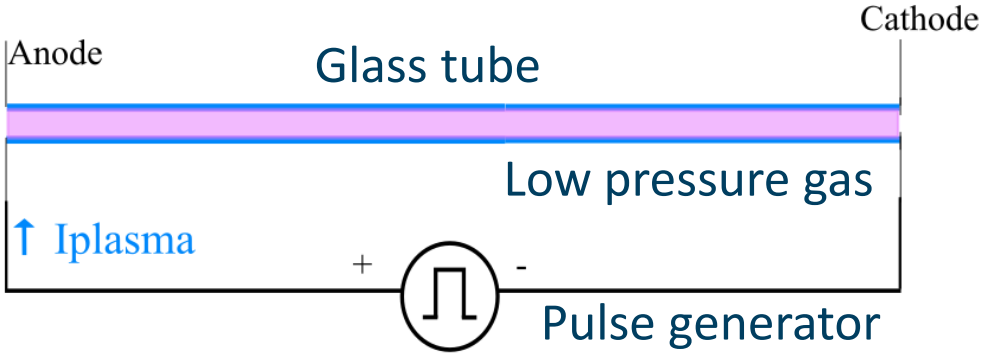
AWAKE scalable plasma sources

Requirements

1. Nanosecond time reproducibility
2. AWAKE plasma density 7×10^{14} cm^{-3}
3. Plasma density reproducibility
4. Plasma density uniformity < 0.25% along 10 m
5. Length scalability

AWAKE scalable plasma sources

Requirements



Proposed solution → Discharge Plasma Source

1. Nanosecond time reproducibility
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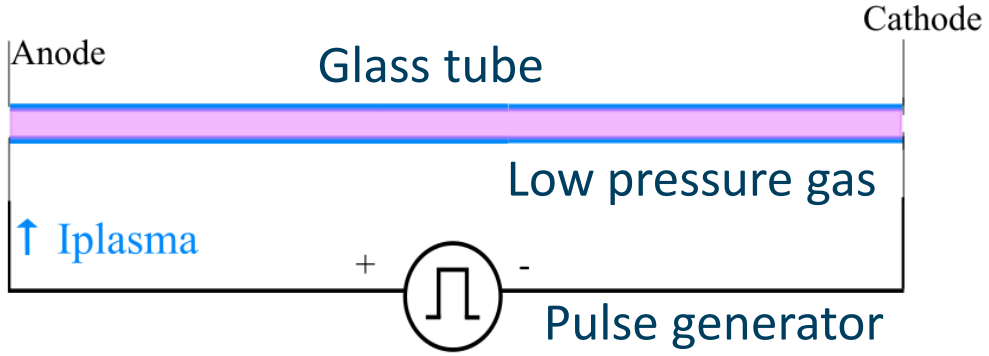
AWAKE scalable plasma sources

Electrical challenges



Proposed solution → Discharge Plasma Source

1. Nanosecond time reproducibility → Fast ignition

2. AWAKE plasma density 7×10^{14} cm^{-3} → High current discharge

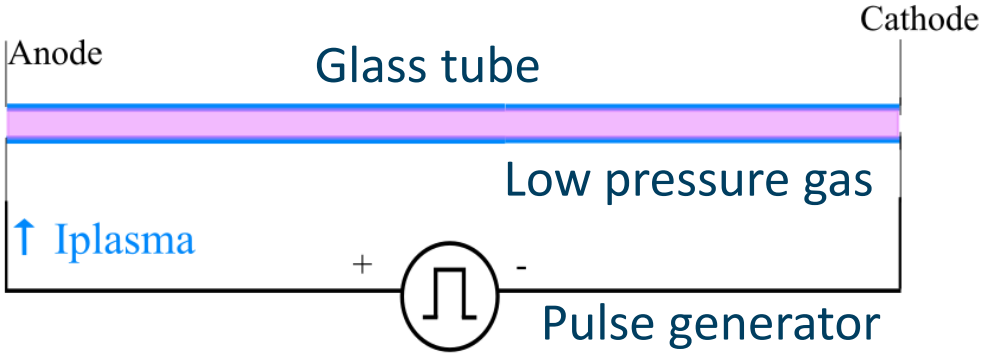
3. Plasma density reproducibility → Current reproducibility

4. Plasma density uniformity < 0.25% along 10 m → Electrode design

5. Length scalability → Series assembly with common electrodes

AWAKE scalable plasma sources

Electrical challenges



Proposed solution → Discharge Plasma Source

1. Nanosecond time reproducibility → Fast ignition

2. AWAKE plasma density 7×10^{14} cm^{-3} → High current discharge

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1. AWAKE scalable plasma sources
   - Motivation
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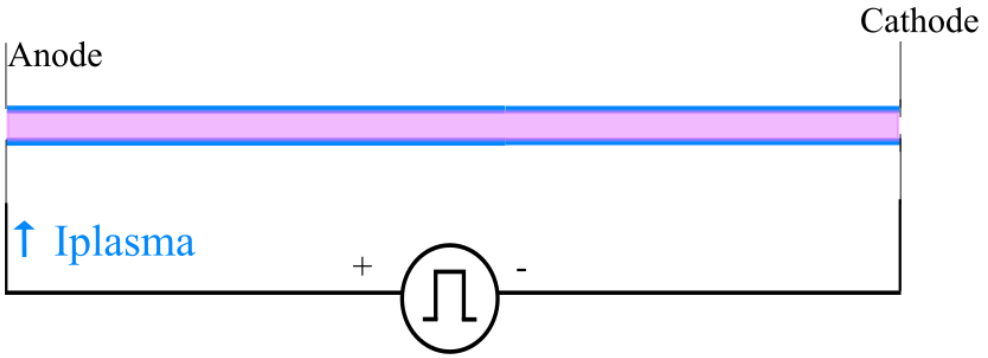
2. **Double pulse generator**
   - **Fast Ignition**
   - **Density target**
   - **Operation**

3. May 2023 proton run
   - Current reproducibility
   - Operation range
   - Double plasma



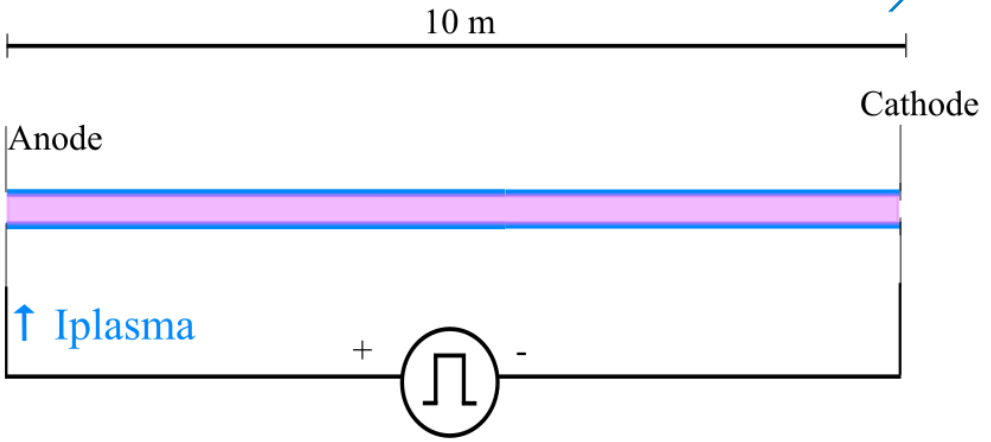
Double pulse generator

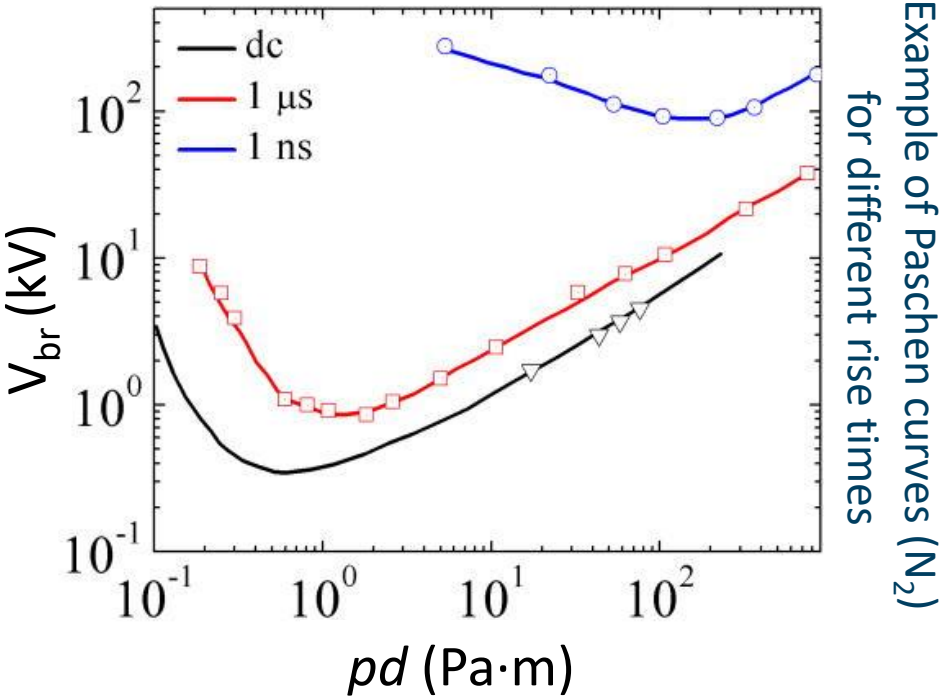
Fast ignition

Gas discharges are performed typically with cm lengths

10 m lengths require very high voltages (tens of kV)

Fast ignition demands even higher voltage (hundreds of kV)





Example of Paschen curves (N_2) for different rise times

Levko et. al, Phys. Plasmas 26 (2019)

Double pulse generator

Fast ignition

Gas discharges are performed typically with cm lengths

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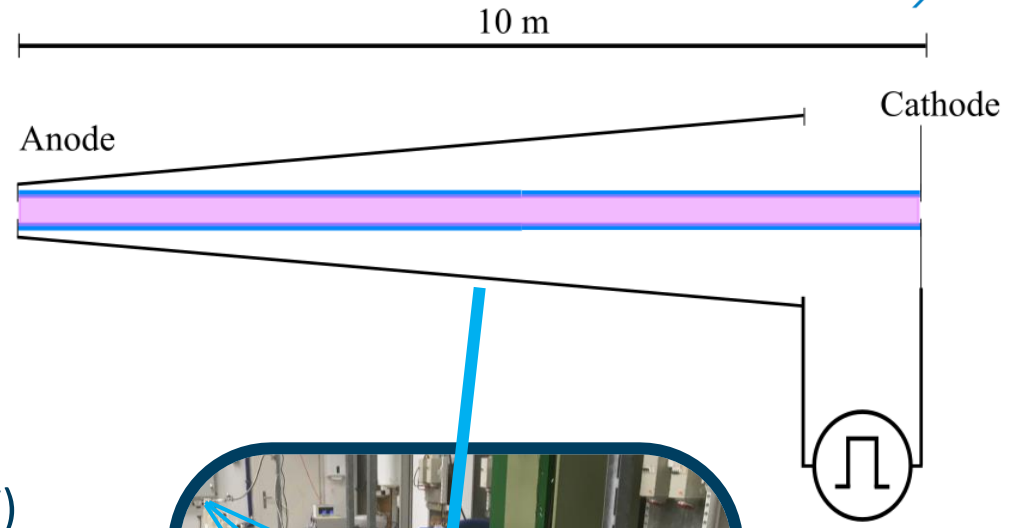
Fast ignition demands even higher voltage (hundreds of kV)

→ Introducing an “anode cage”

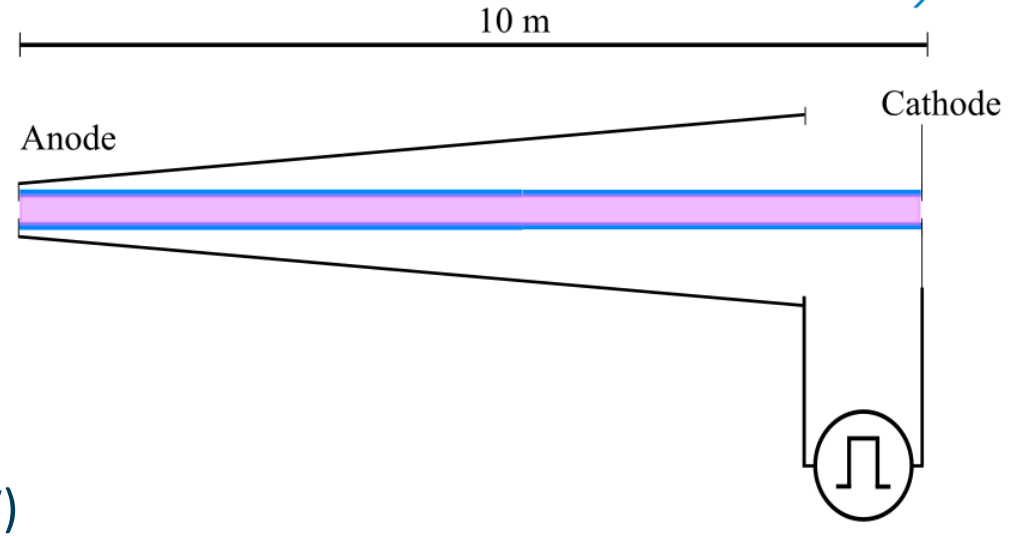
Reduces breakdown voltage

Improves longitudinal uniformity



Double pulse generator

Fast ignition



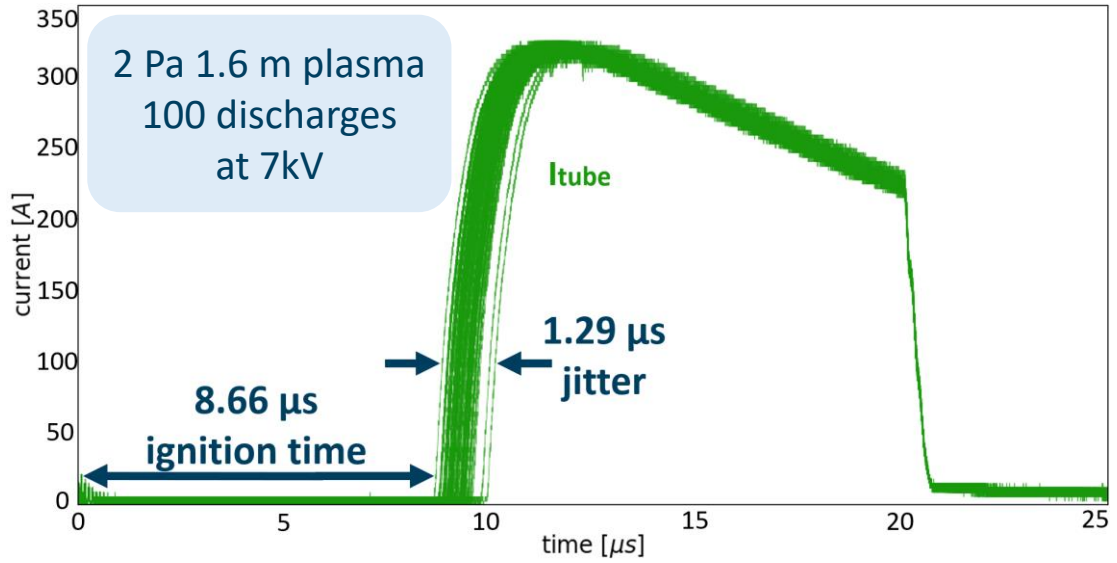
Gas discharges are performed typically with cm lengths

10 m lengths require very high voltages (tens of kV)

Fast ignition demands even higher voltage (hundreds of kV)

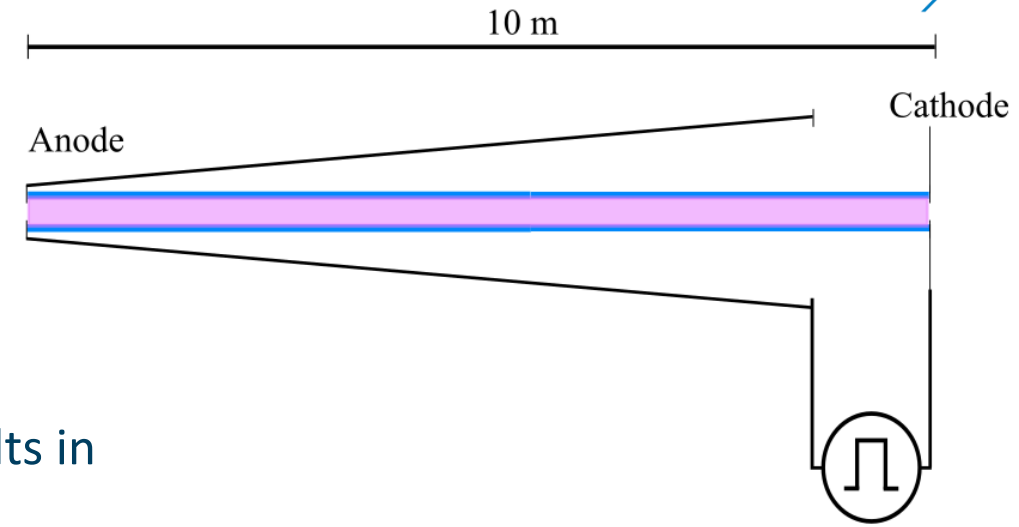
→ Introducing an “anode cage”
Reduces breakdown voltage
Improves longitudinal uniformity

Still requires very high voltages for nanosecond jitter



Double pulse generator

Density target

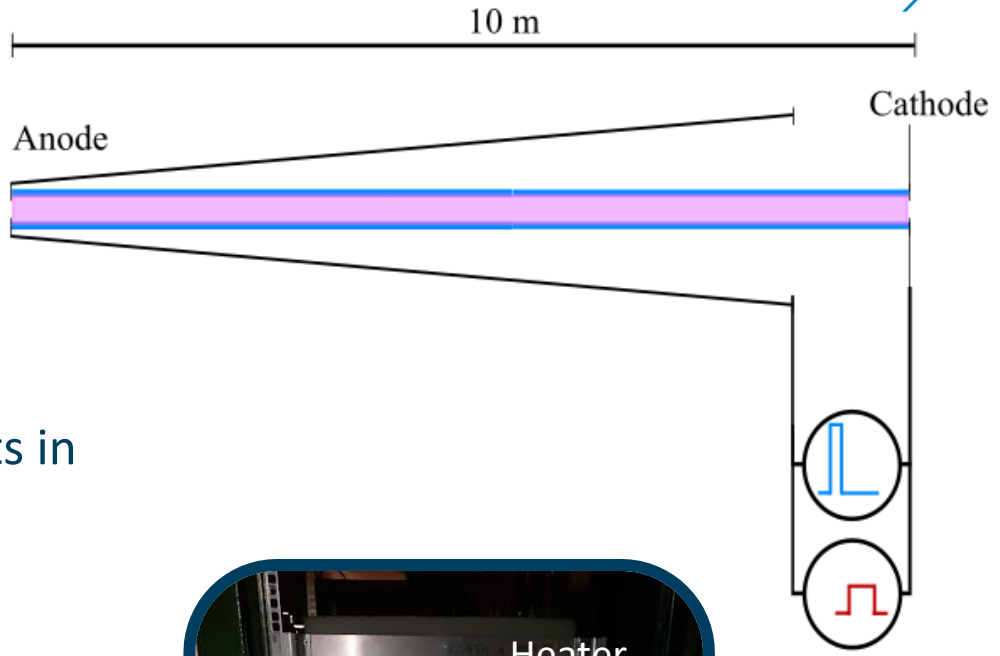


AWAKE densities and the uniformity targets demand high current plasma – around 500 A

Combining a single pulse with about 20 kV and 500 A results in 10 MW of power

Double pulse generator

Density target



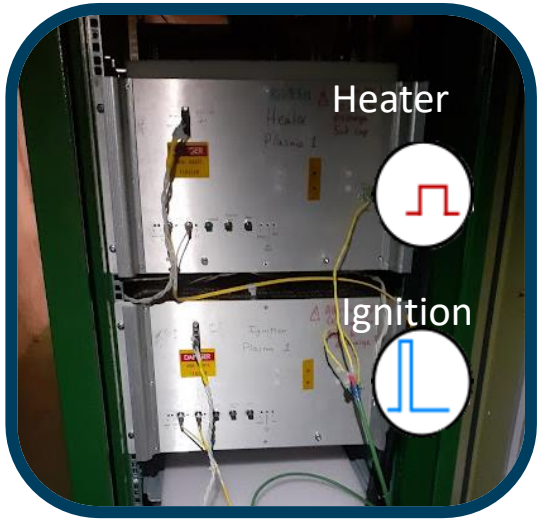
AWAKE densities and the uniformity targets demand high current plasma – around 500 A

Combining a single pulse with about 20 kV and 500 A results in 10 MW of power

→ Double-pulse solution:

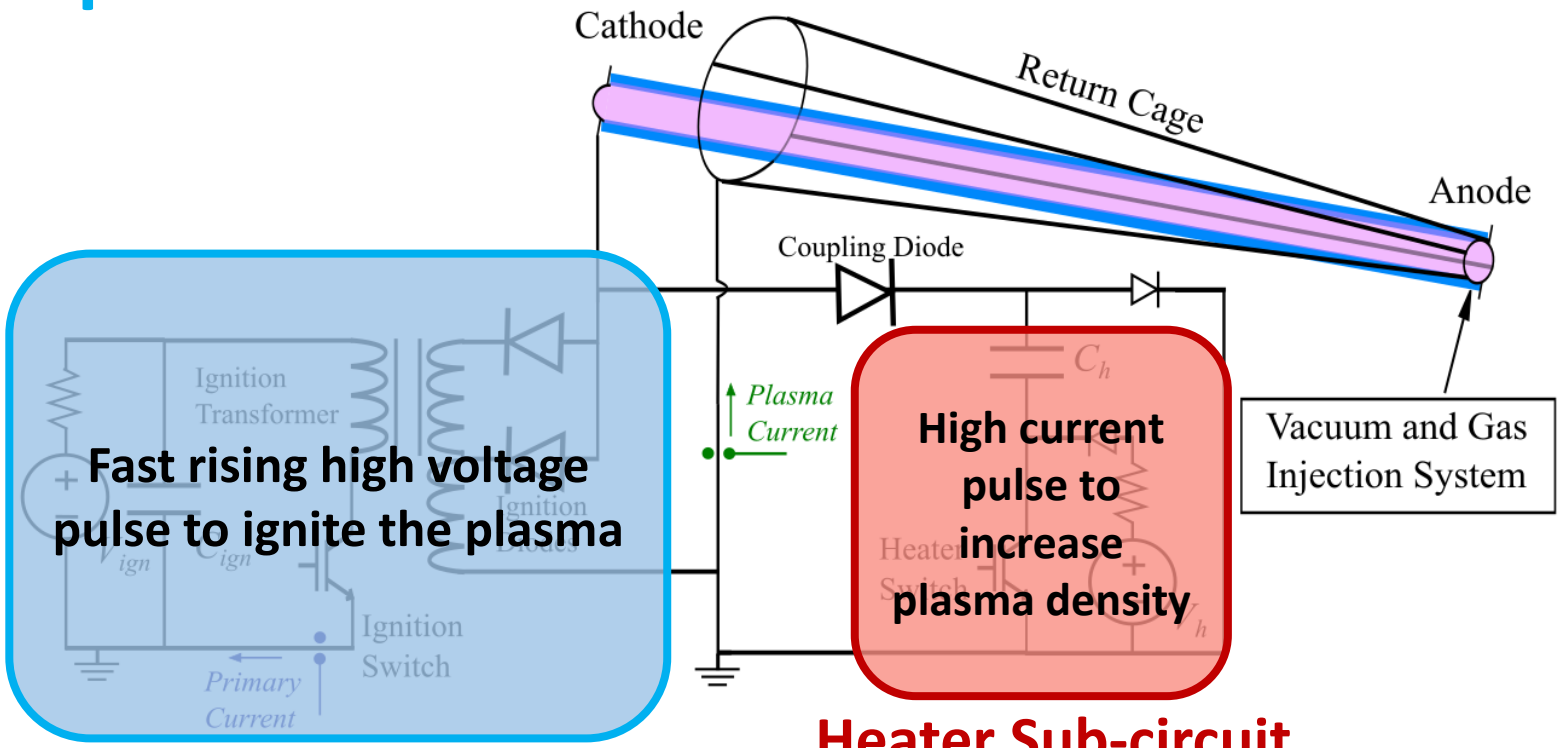
High-voltage **ignition pulse**

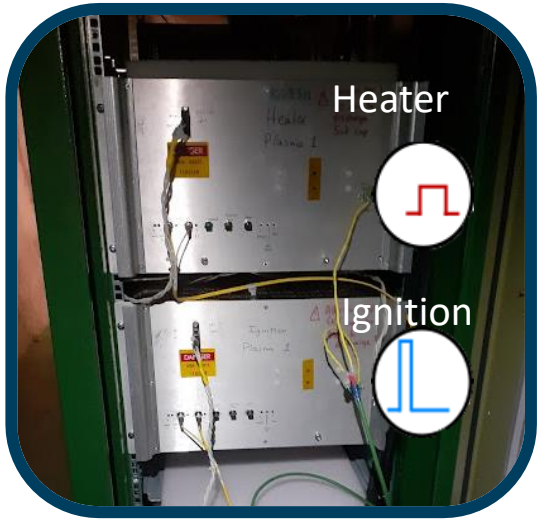
High-current **heater pulse**



Double pulse generator

Operation

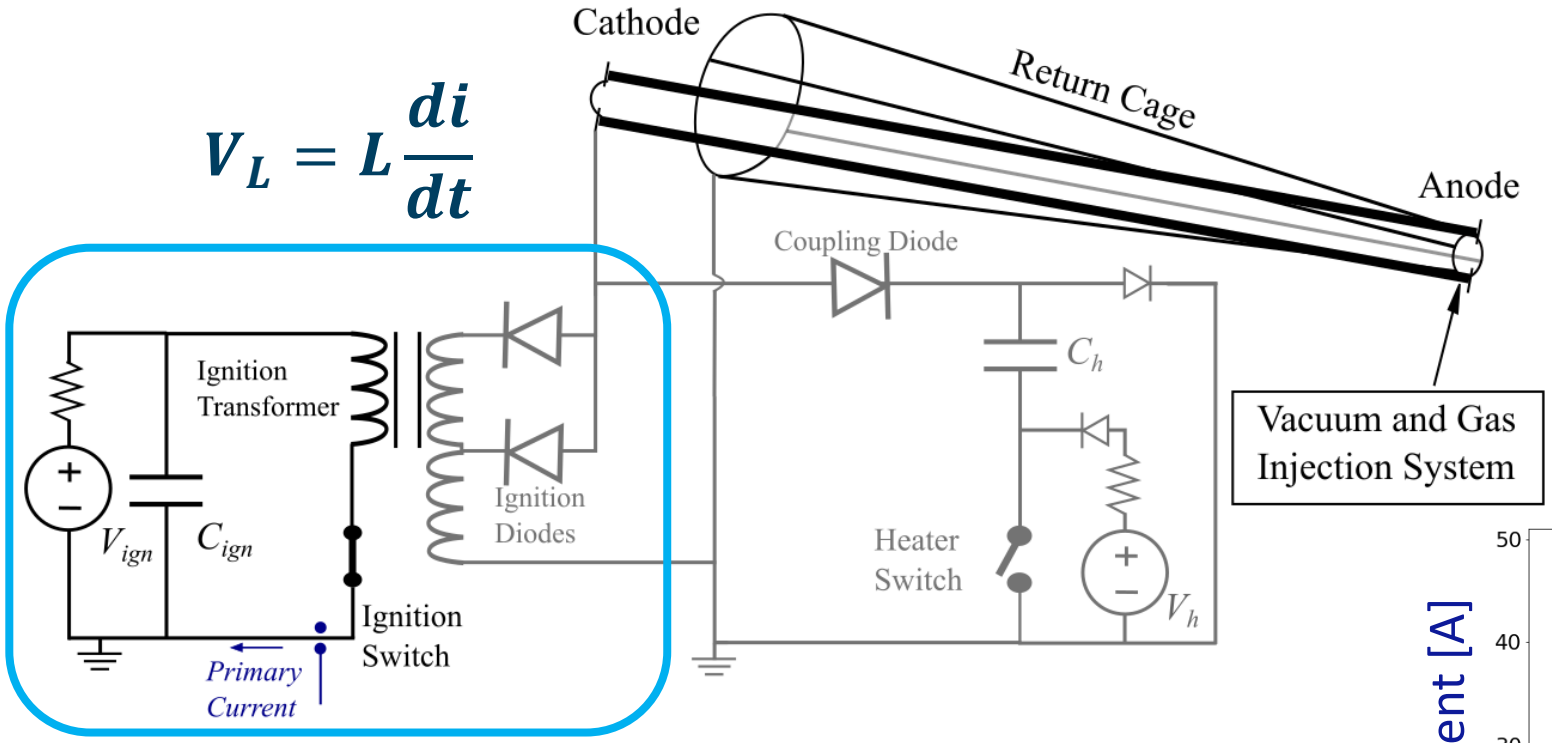




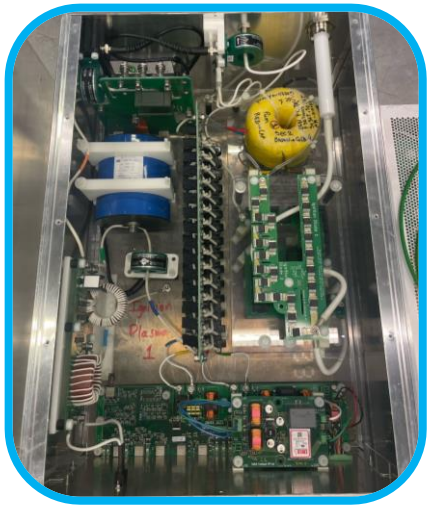
Double pulse generator

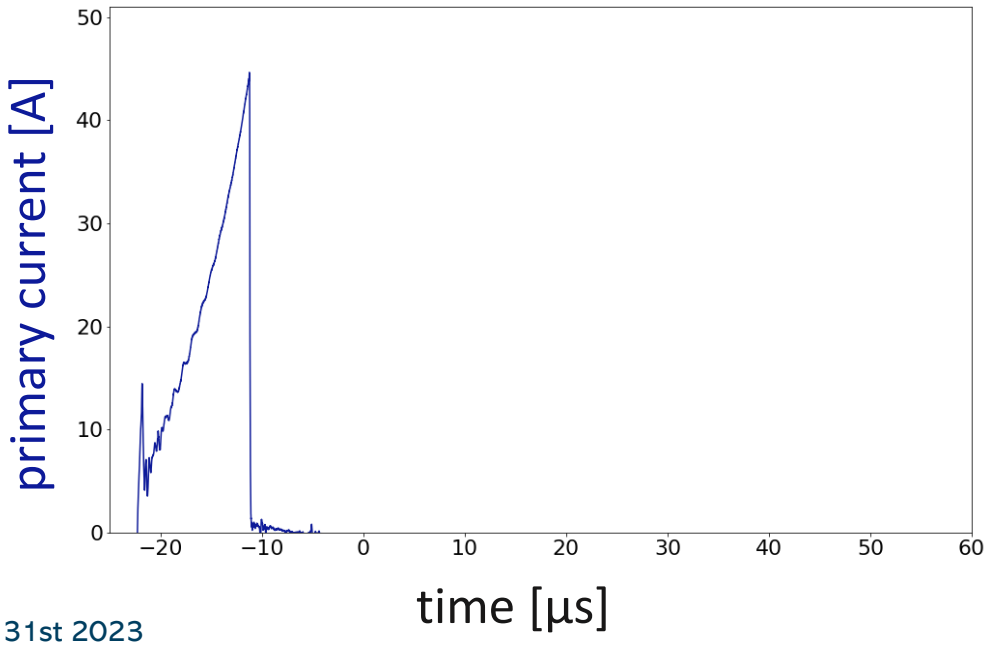
Operation

$$V_L = L\frac{di}{dt}$$



Ignition Sub-circuit



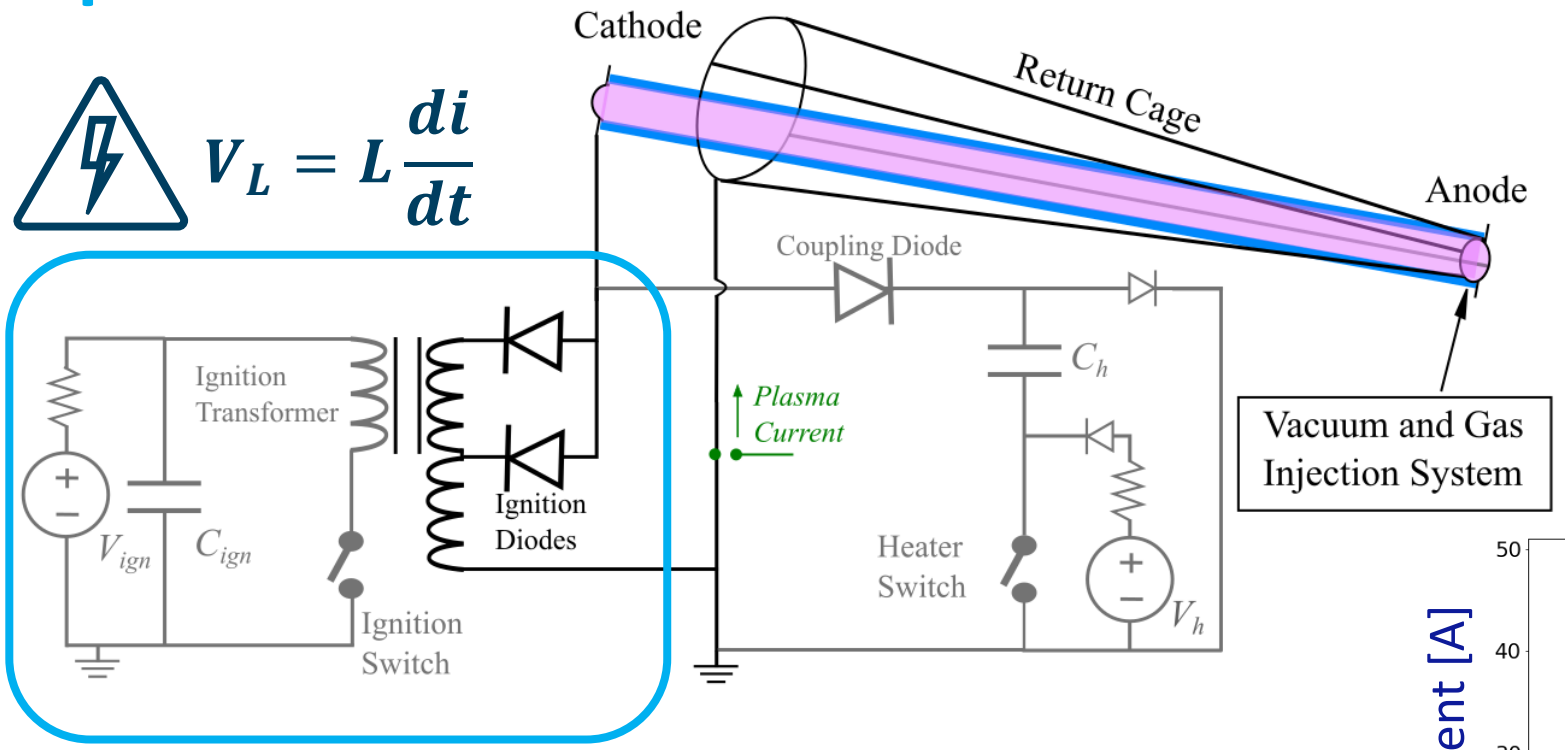


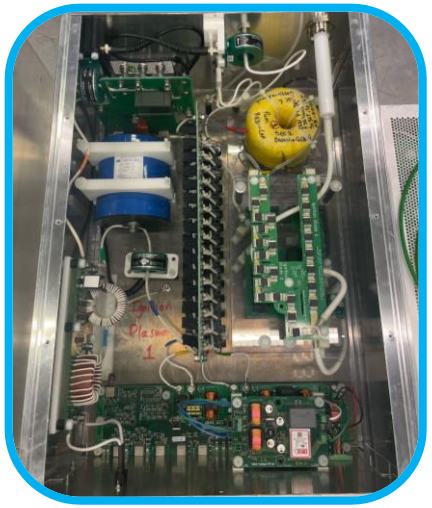
The ignition transformer's magnetizing inductance charges during switch ON (primary current)

Double pulse generator

Operation

$$V_L = L\frac{di}{dt}$$

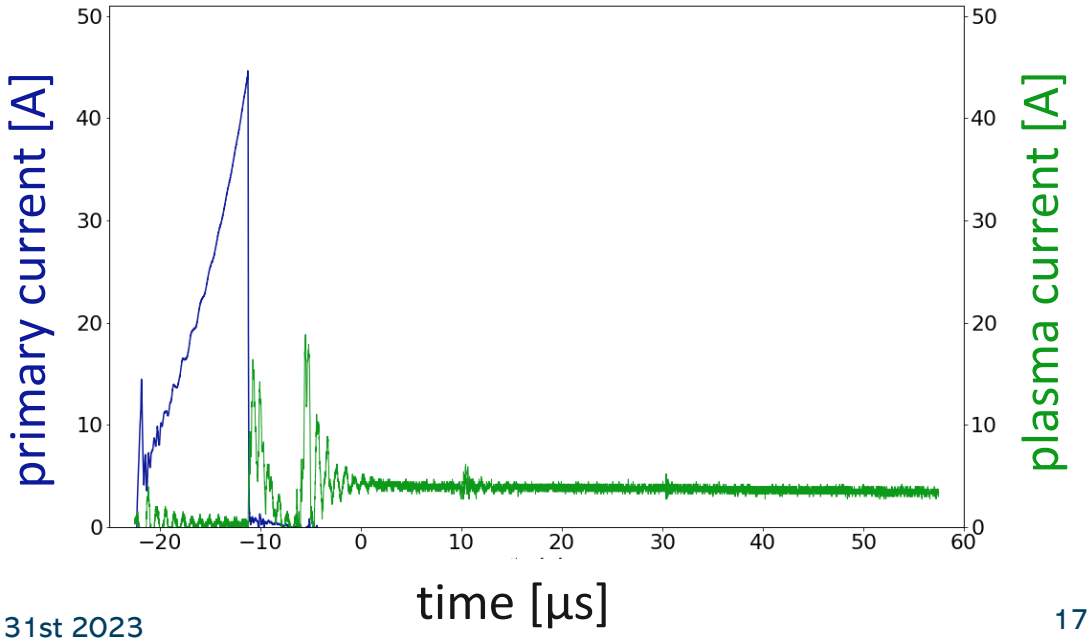




Ignition Sub-circuit

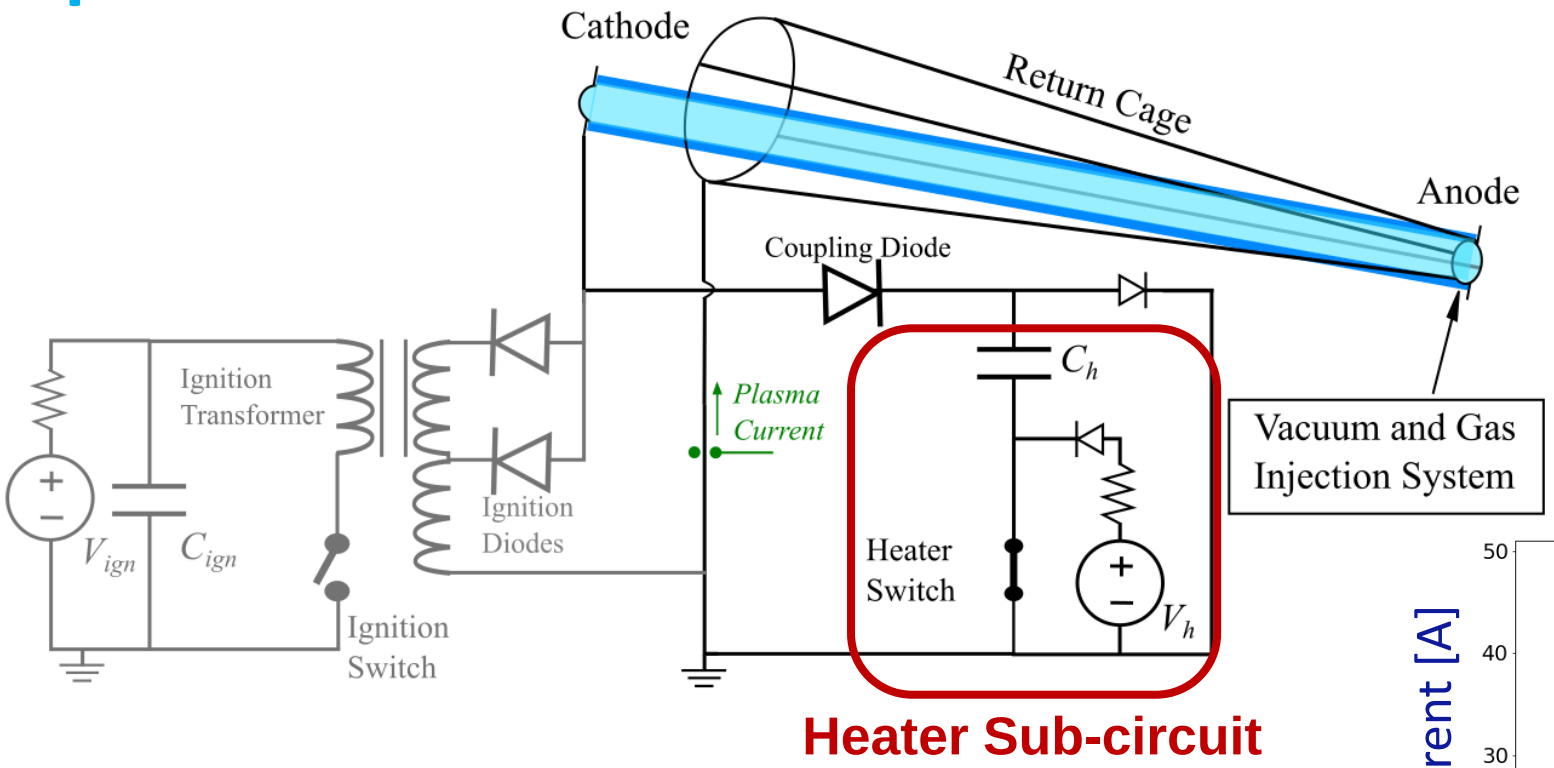
Turning OFF the switch generates a high-voltage pulse (20 kV) across the electrodes

The high-voltage ignition pulse establishes a low-current (~10 A) arc

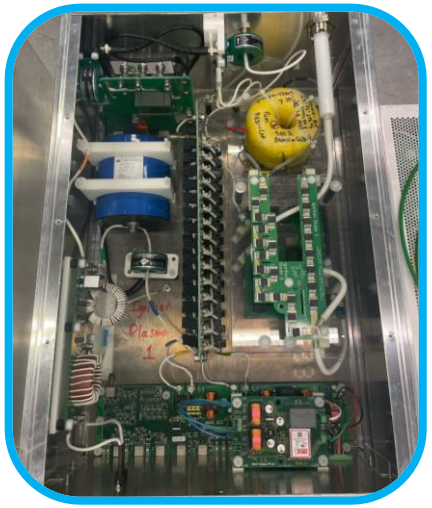


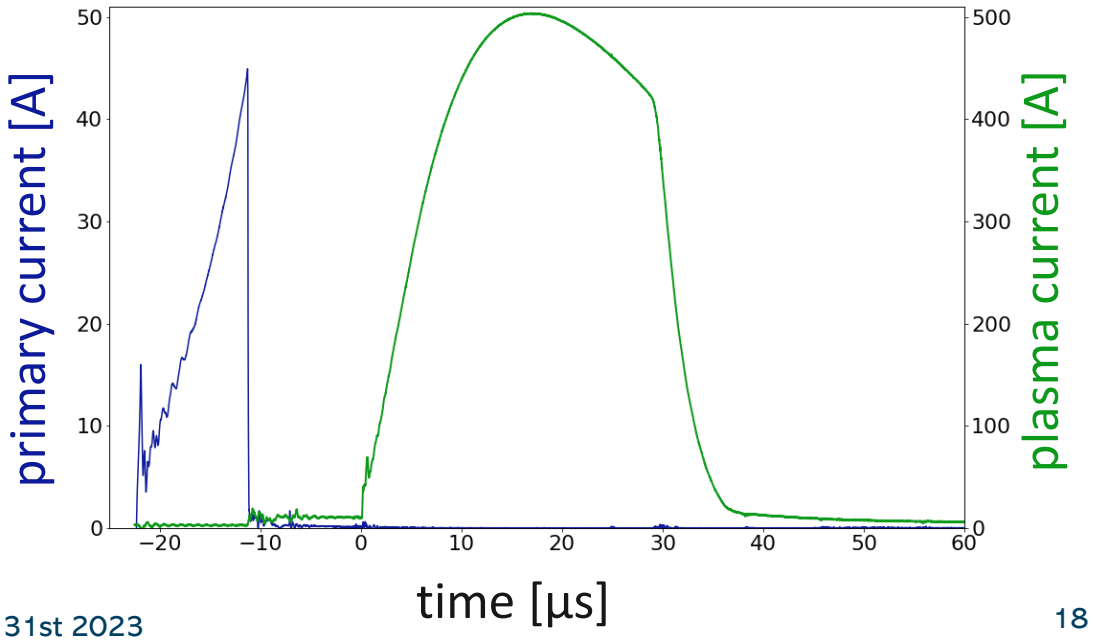
Double pulse generator

Operation



Heater Sub-circuit





The heater pulse raises the current (up to 600 A) and consequently the plasma density

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3. **May 2023 proton run**
   - **Current reproducibility**
   - **Operation range**
   - **Double plasma**

May 2023 proton run

Motivation

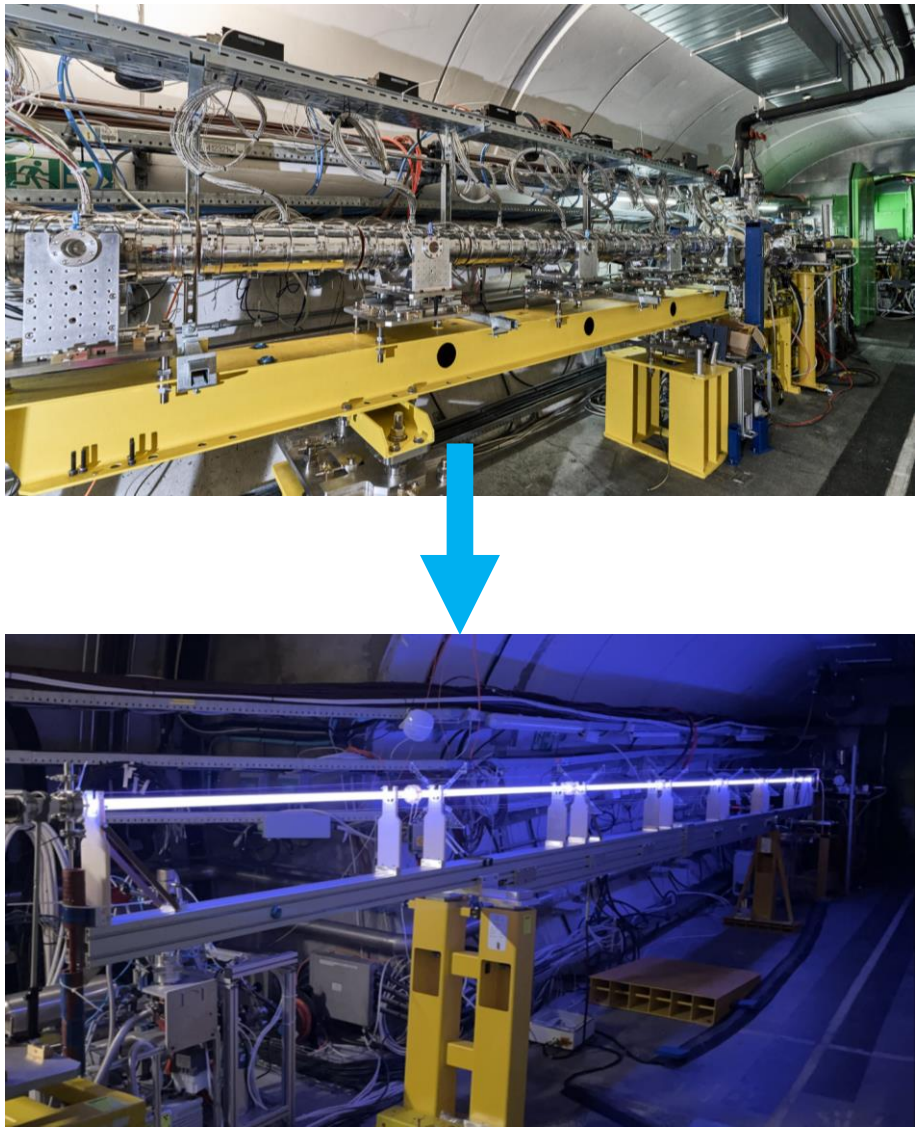
Use the DPS in the AWAKE tunnel with proton beams

Show that it can be used as an alternative source for AWAKE

Take advantage of the operation range of the discharge plasma source

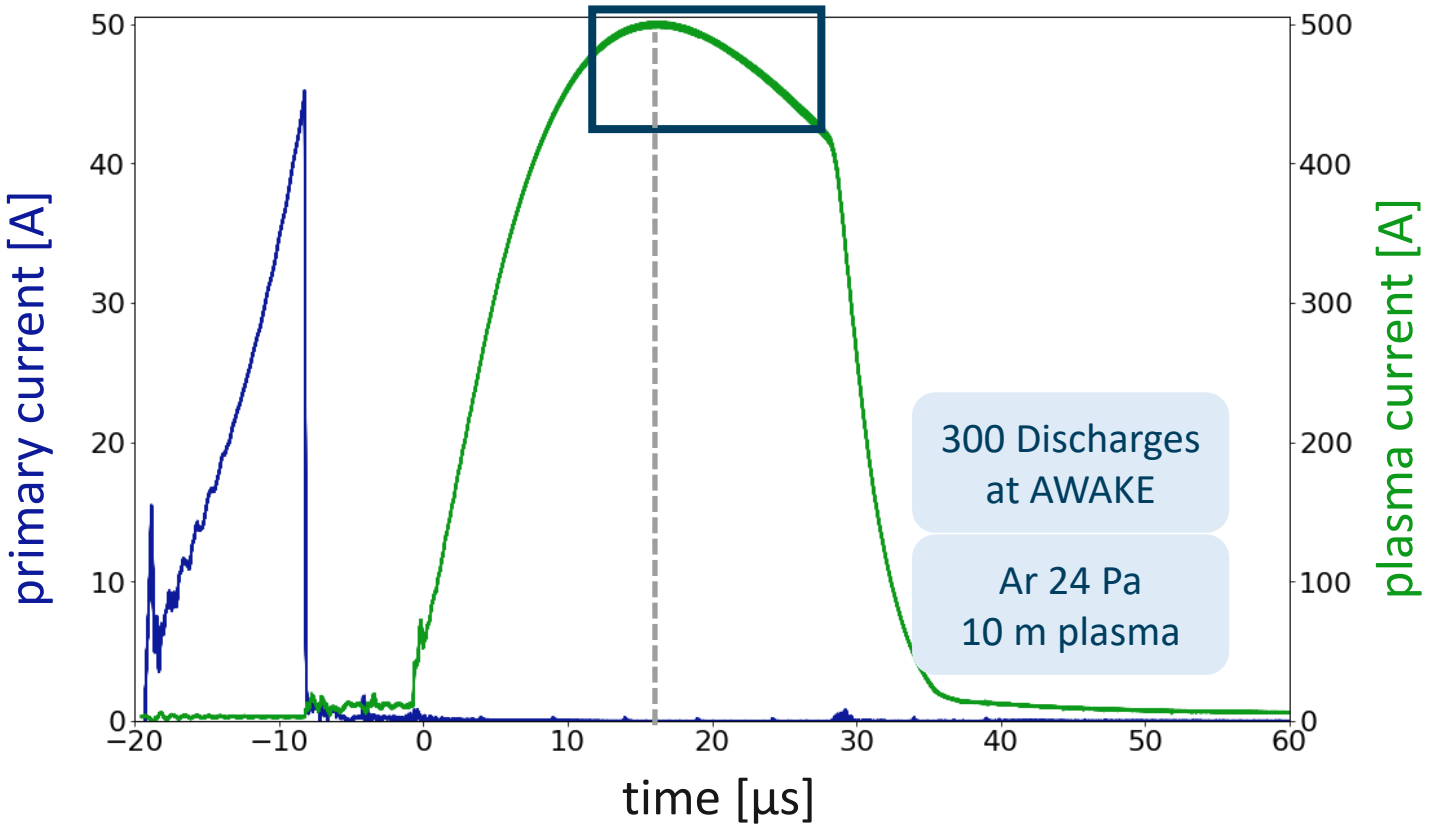
Three different plasma lengths: 3.5, 6.5 and 10 m

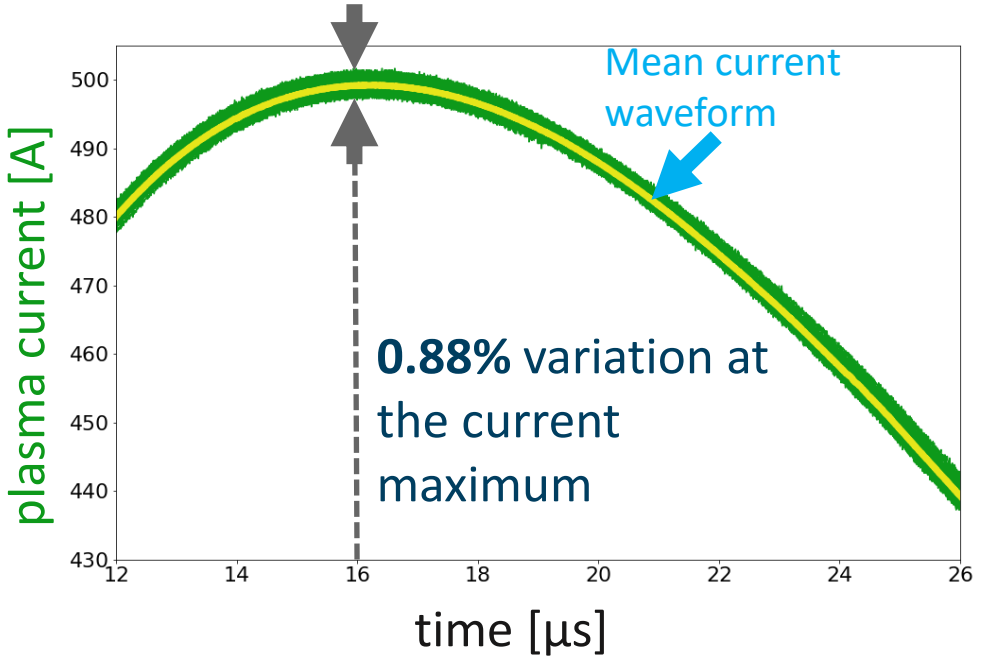
Three different gases: Xe, Ar and He



May 2023 proton run

Current reproducibility





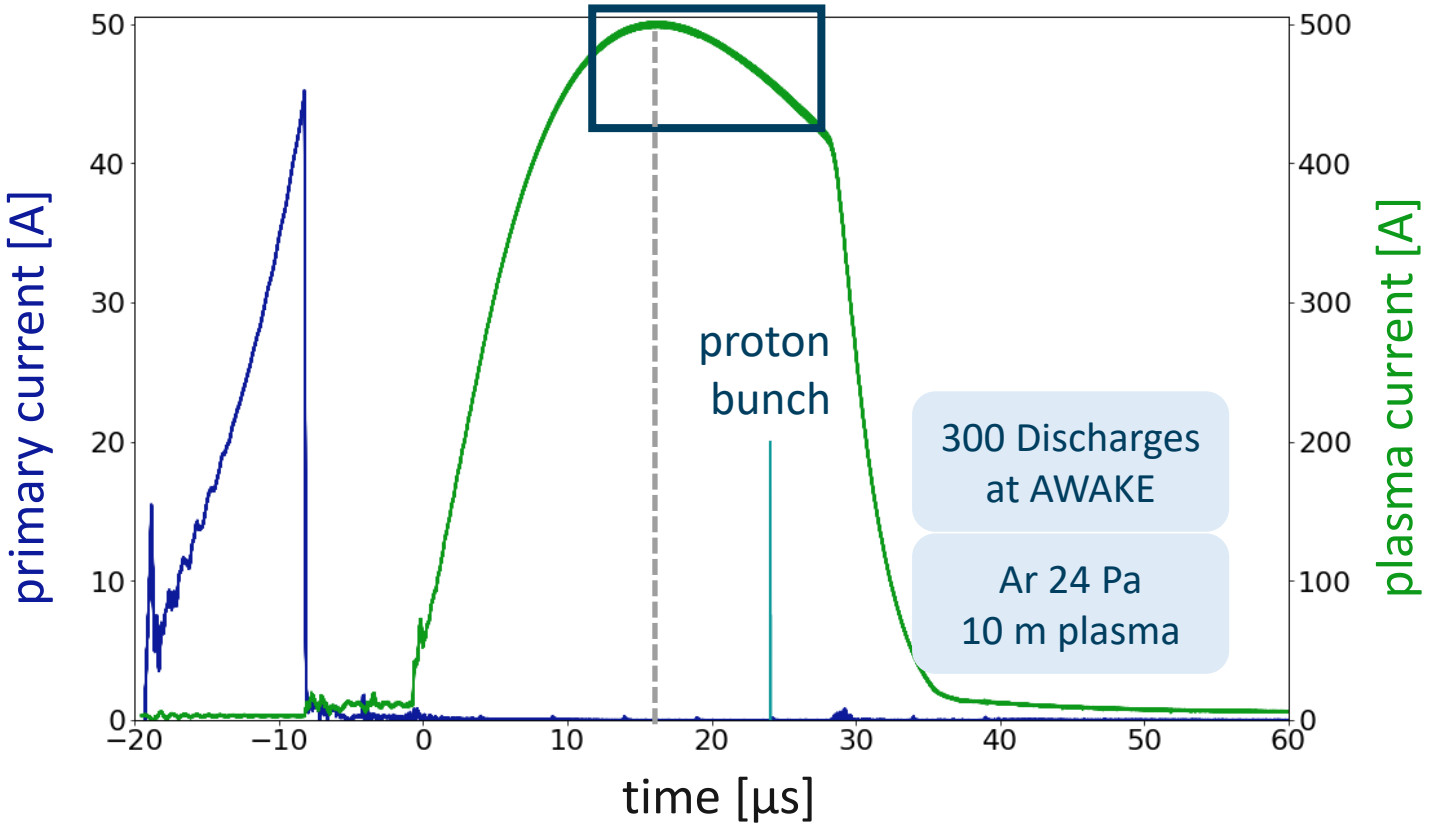
Good electrical reproducibility over 300 discharges

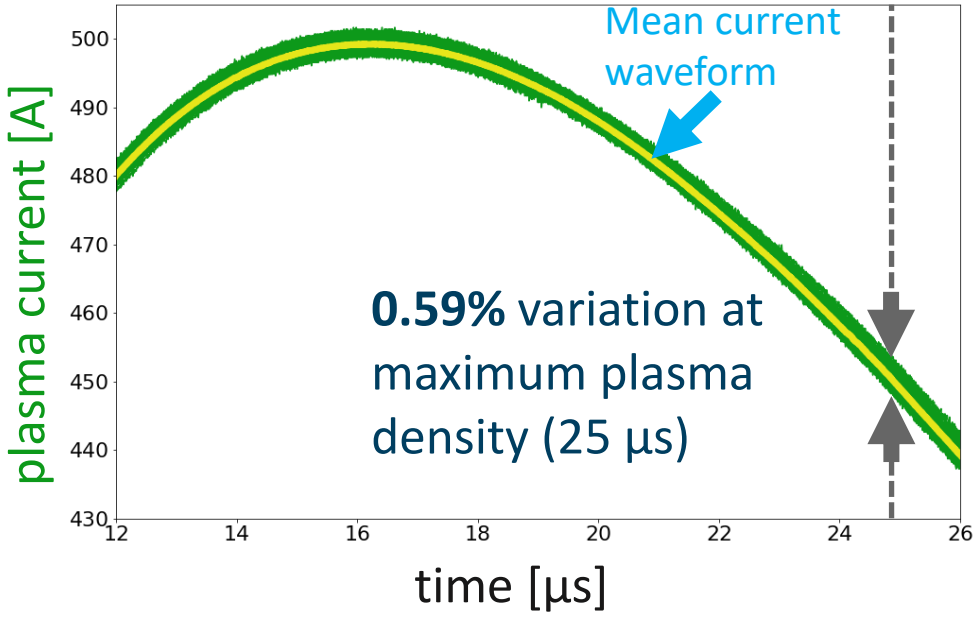
Current maximum variation of 0.88%

DPS proton run results - May 2023

May 2023 proton run

Current reproducibility

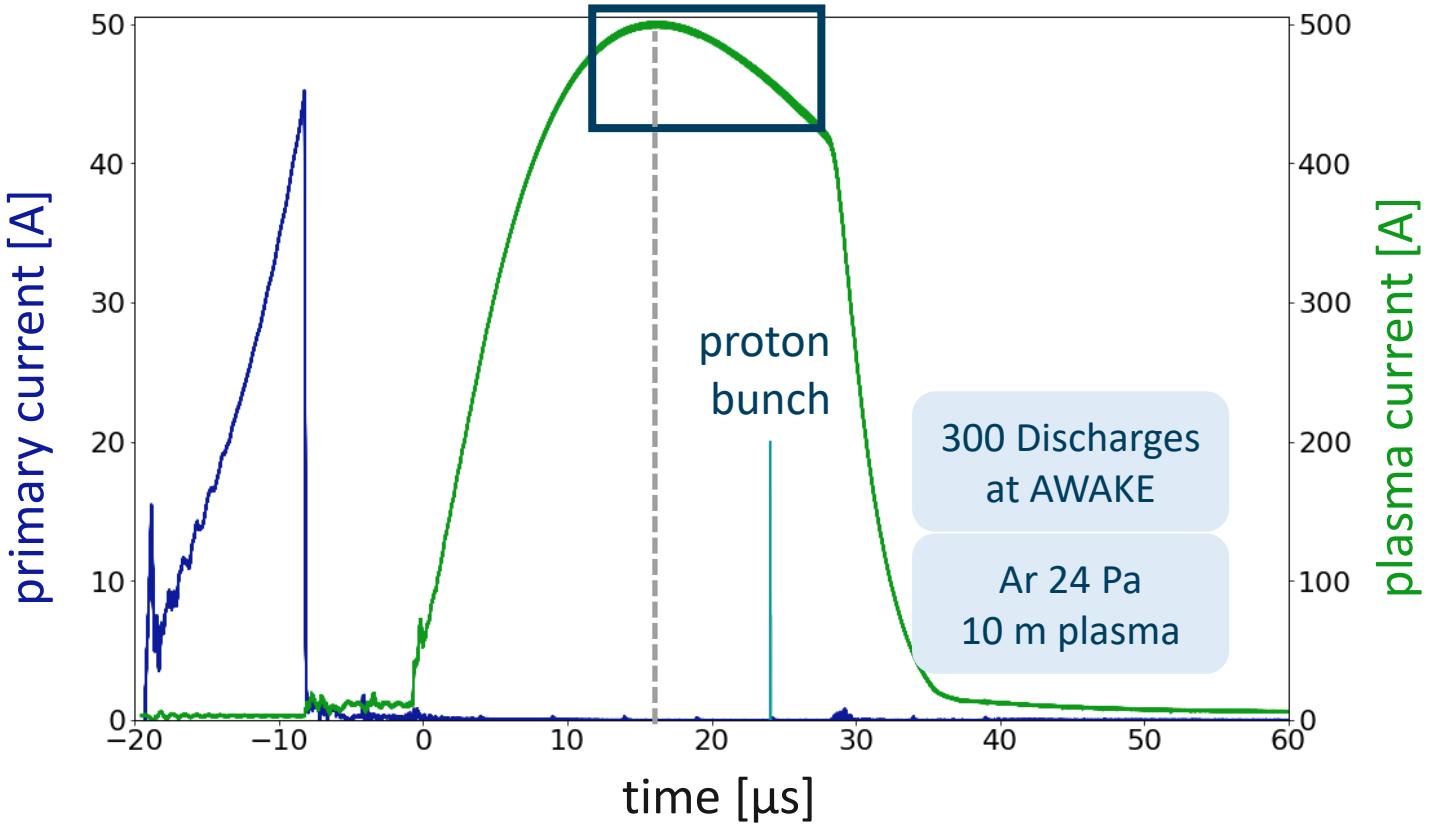


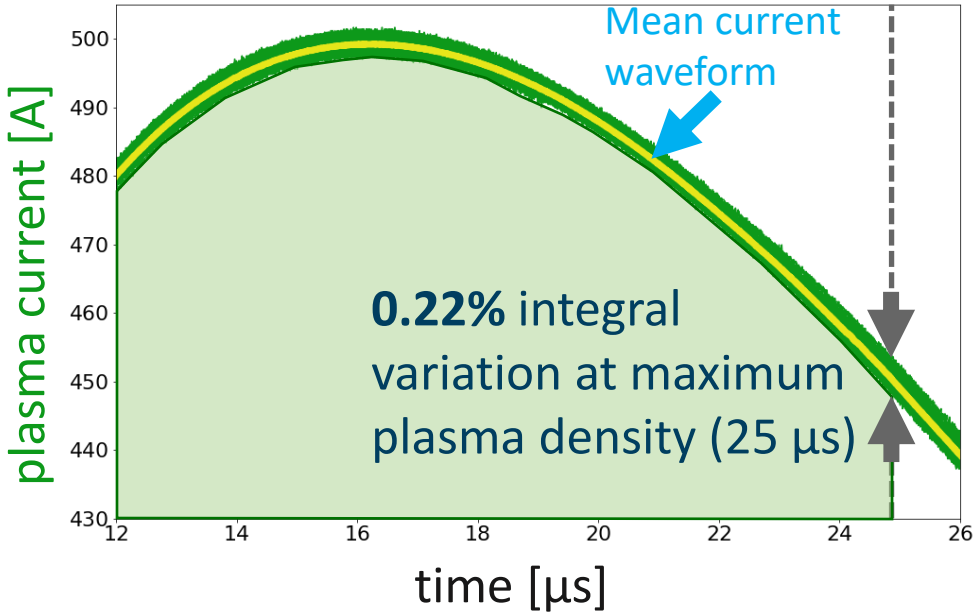


Good electrical reproducibility over 300 discharges
Current maximum variation of 0.88%
Maximum plasma density current variation of 0.59%

May 2023 proton run

Current reproducibility



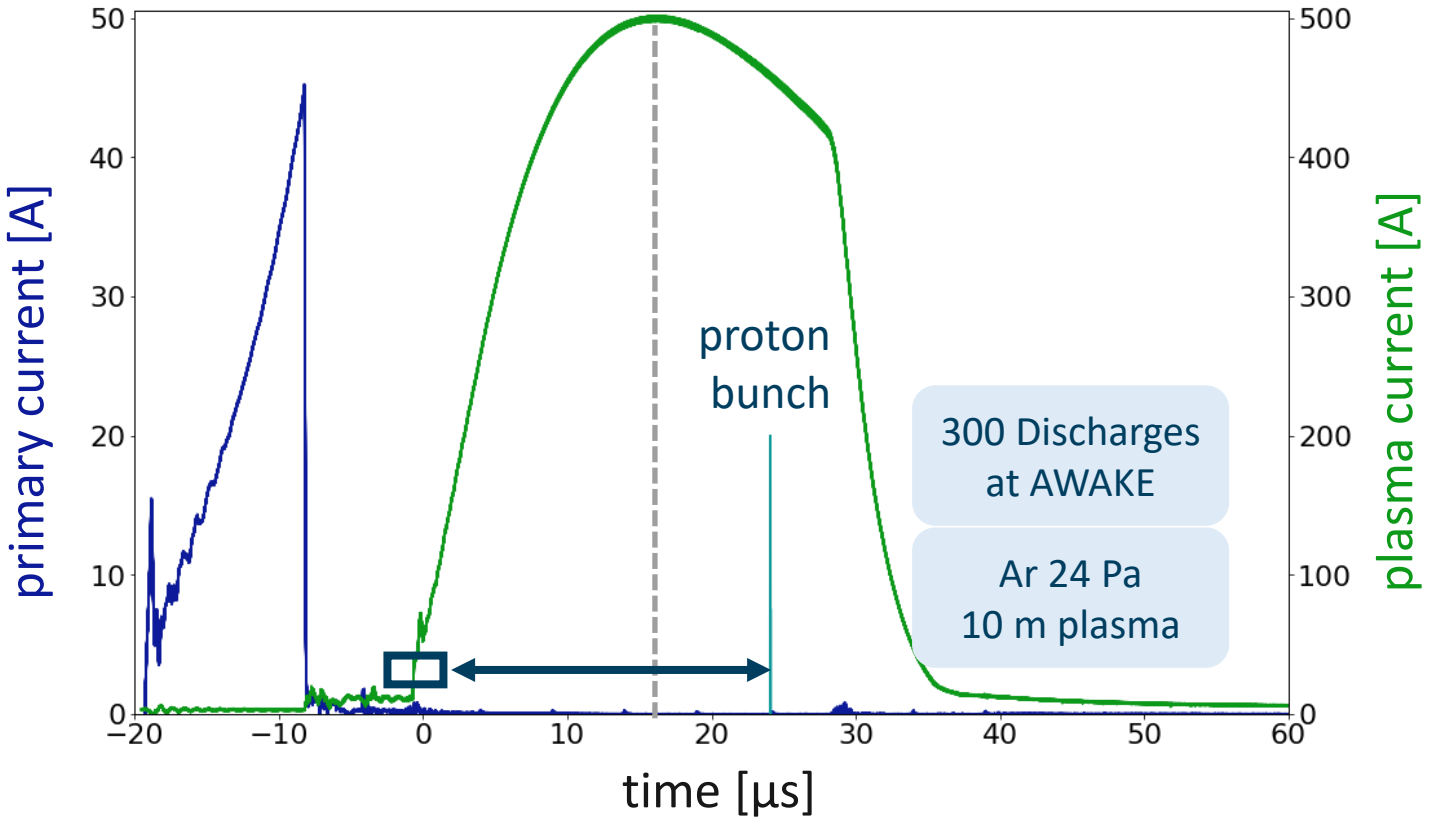


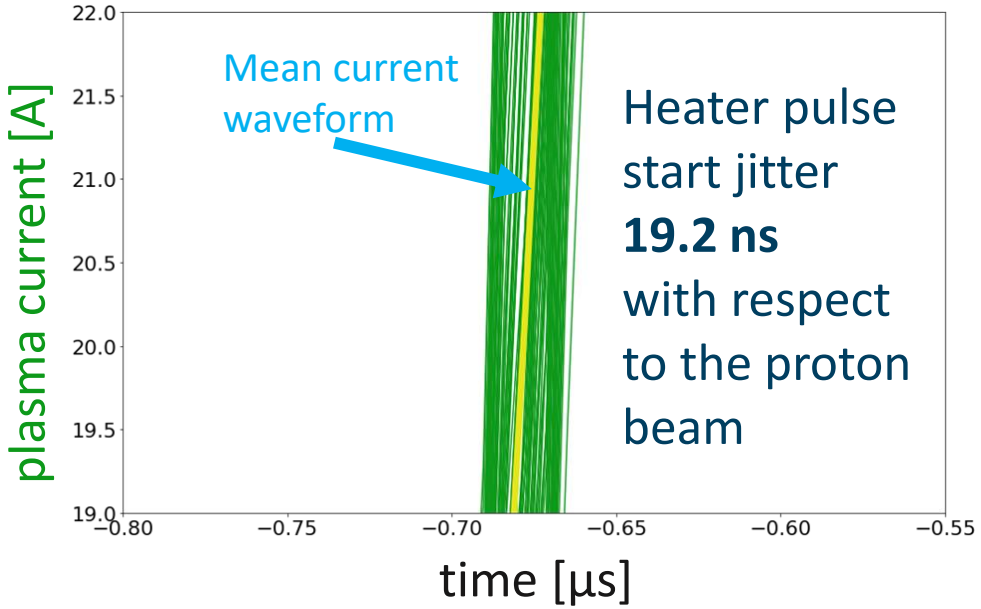
DPS proton run results - May 2023

Good electrical reproducibility over 300 discharges
Current maximum variation of 0.88%
Maximum plasma density current variation of 0.59%
Plasma current integral variation of 0.22%

May 2023 proton run

Nanosecond jitter



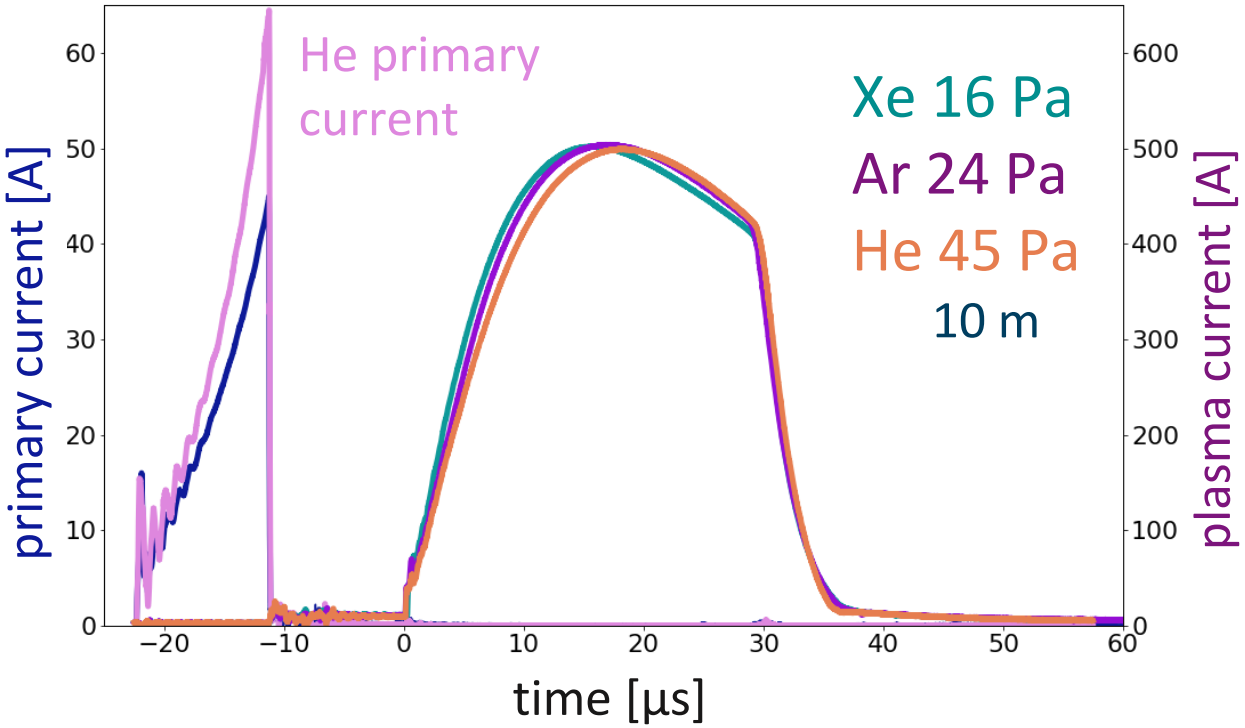


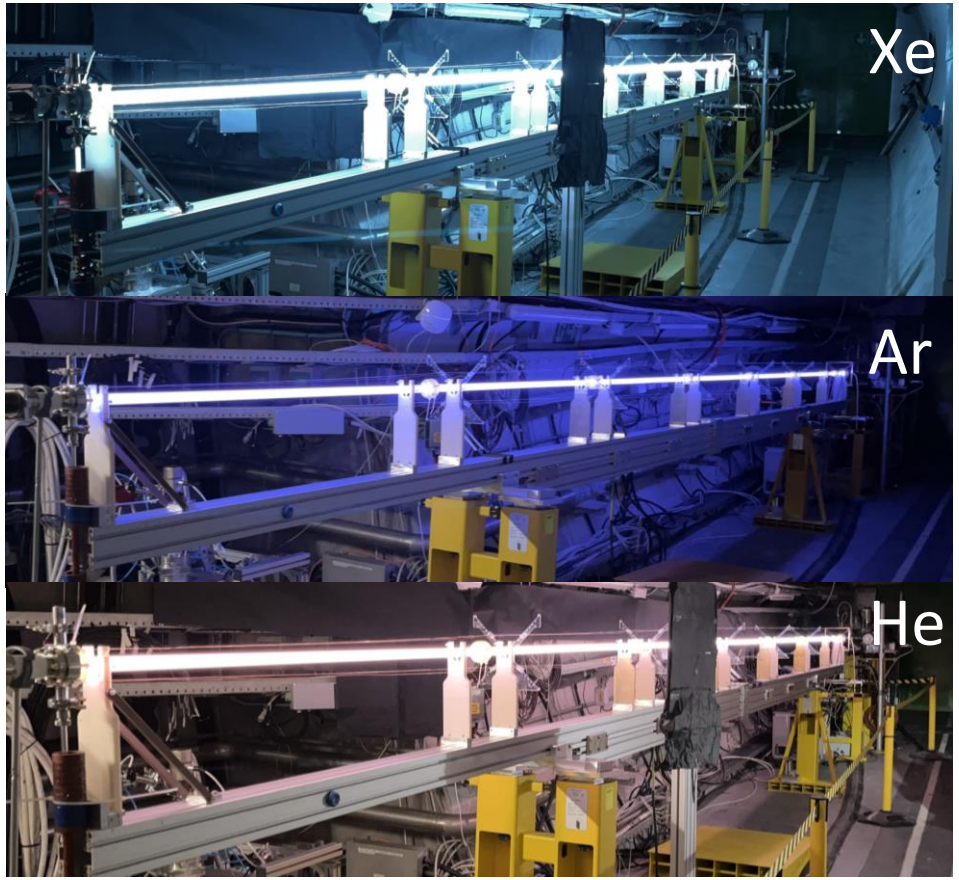
Good electrical reproducibility over 300 discharges
Current variation of <1%
Current pulse jitter of 19.2 ns

DPS proton run results - May 2023

May 2023 proton run

Operation range – Gases



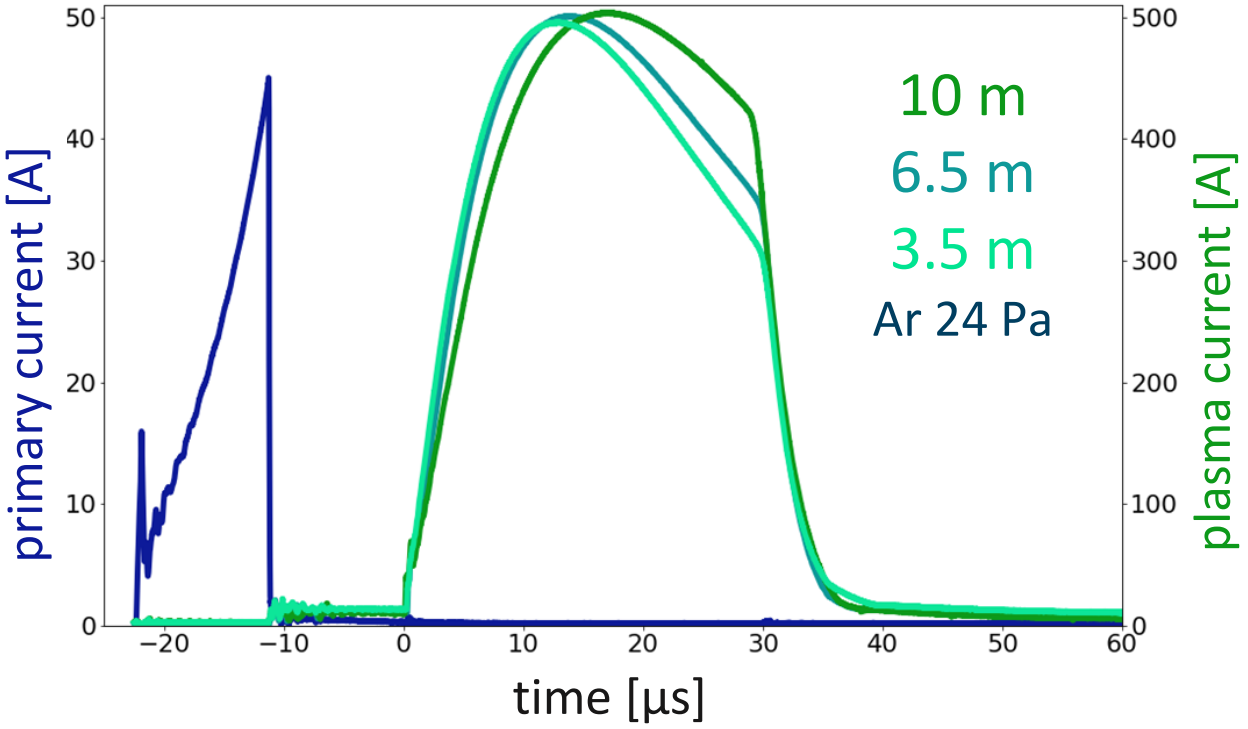


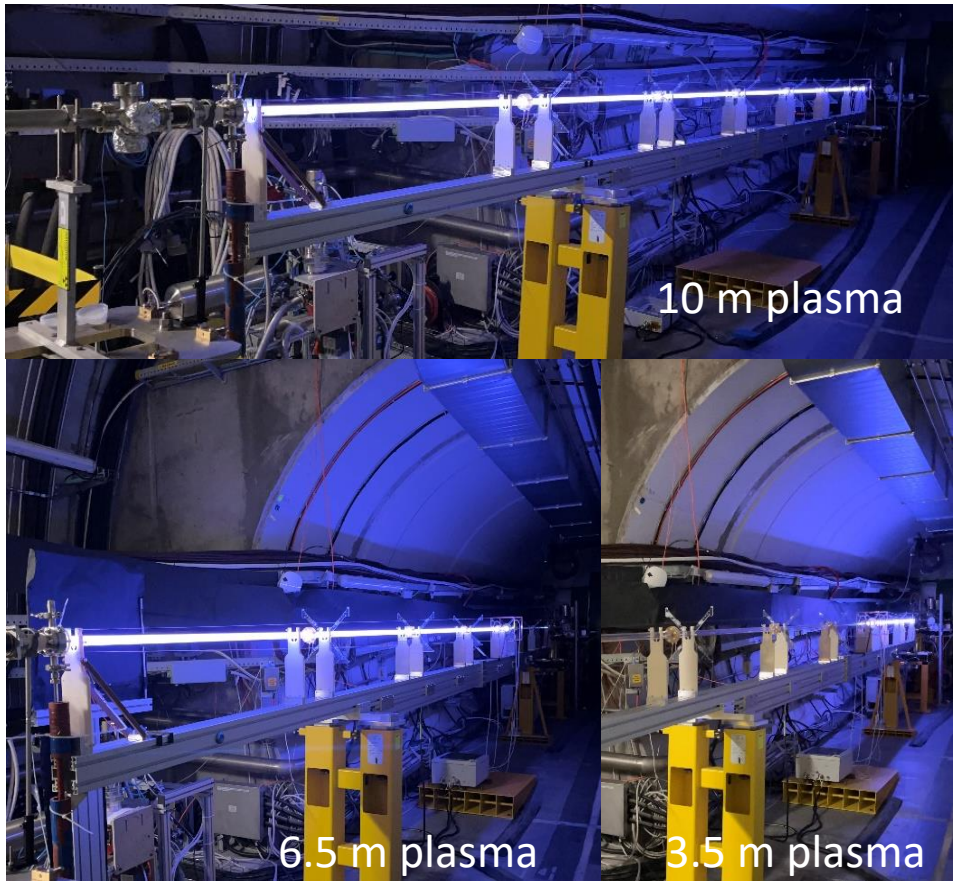
The pulse generators reach the target currents in all three gases

Gas affects mostly the ignition voltage required, leading to a higher primary current for He

May 2023 proton run

Operation range – Length





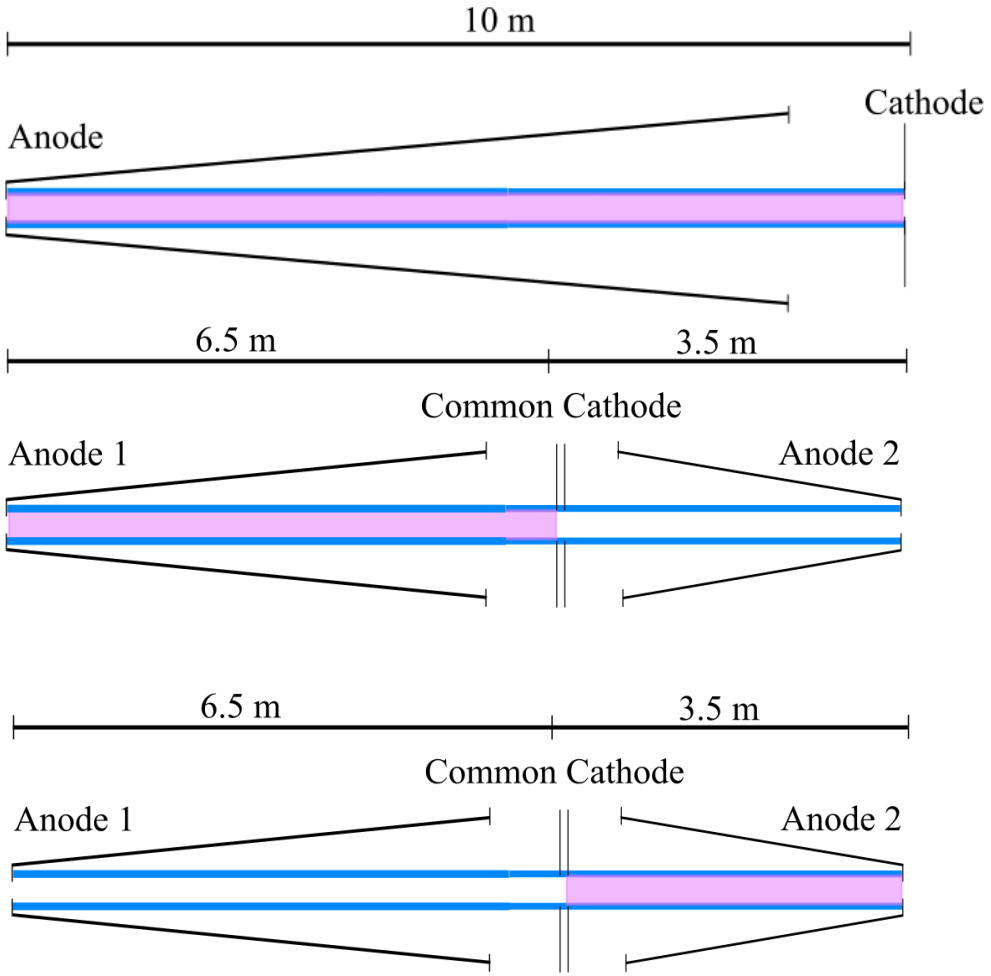
The pulse generators reach the target currents in all three gases and lengths

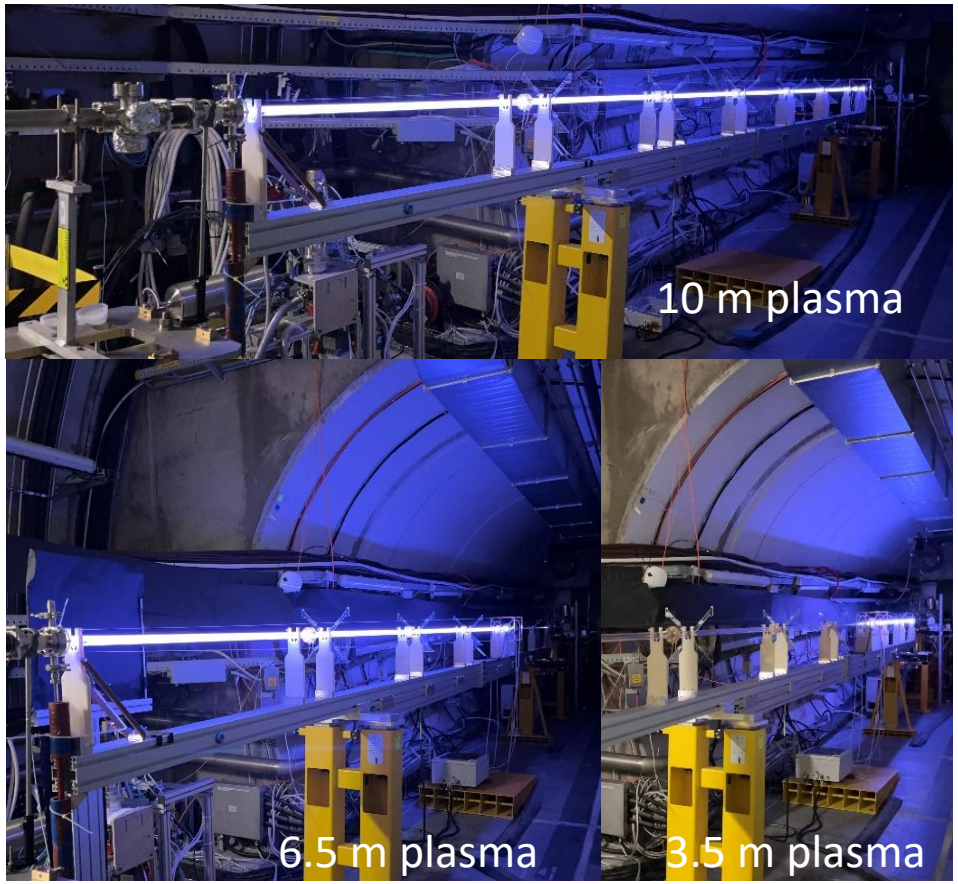
Gas affects mostly the ignition voltage required, leading to a higher primary current for He

Plasma length affects the load impedance, thus causing differences in the pulse shape

May 2023 proton run

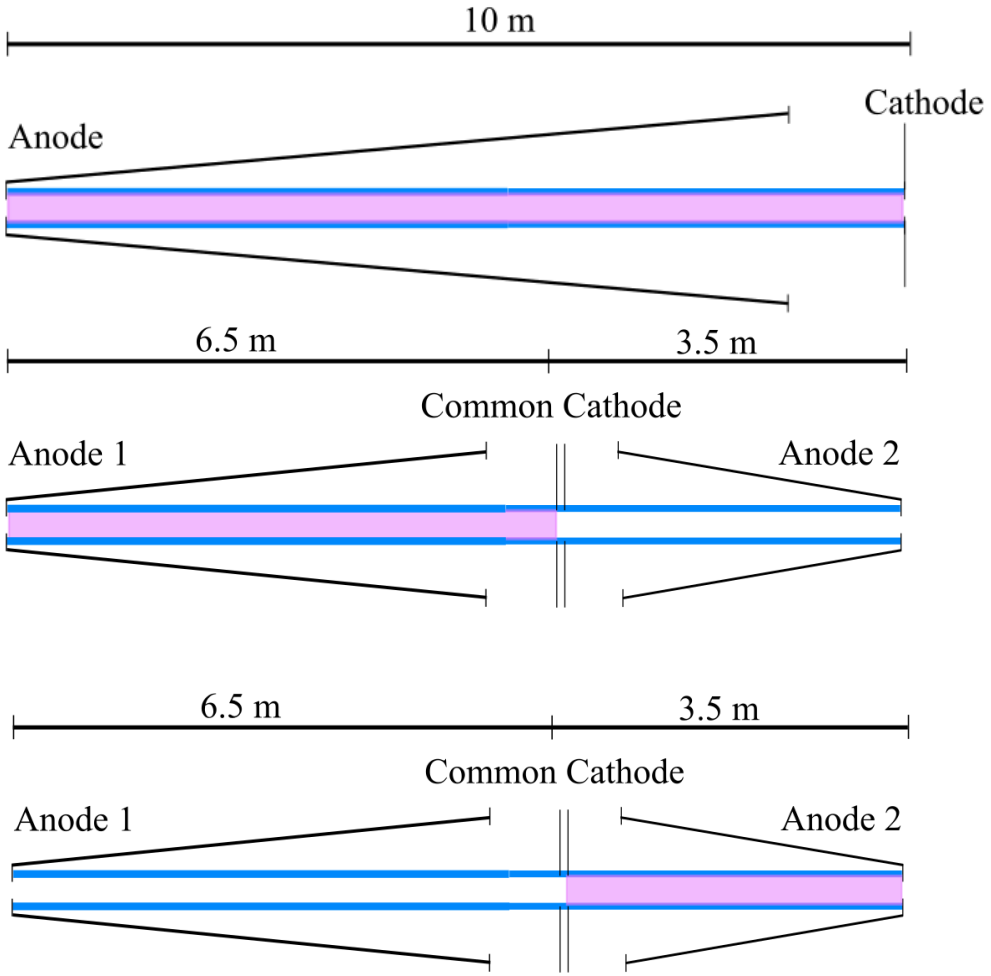
Operation range – Length

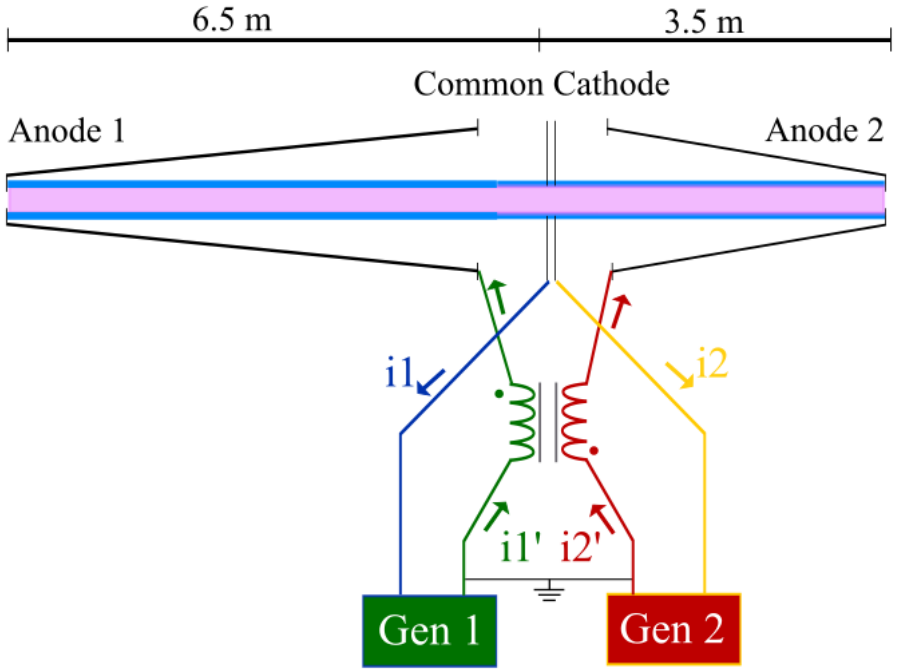




May 2023 proton run

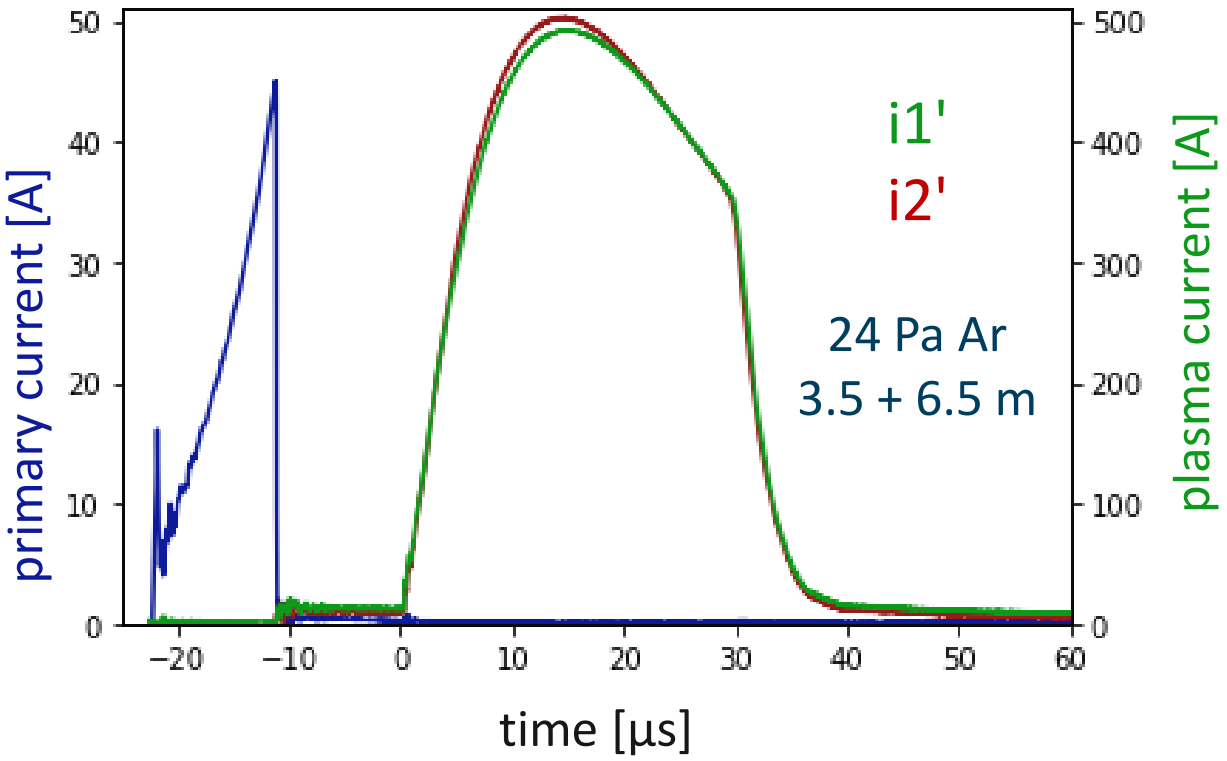
Operation range – Double plasma

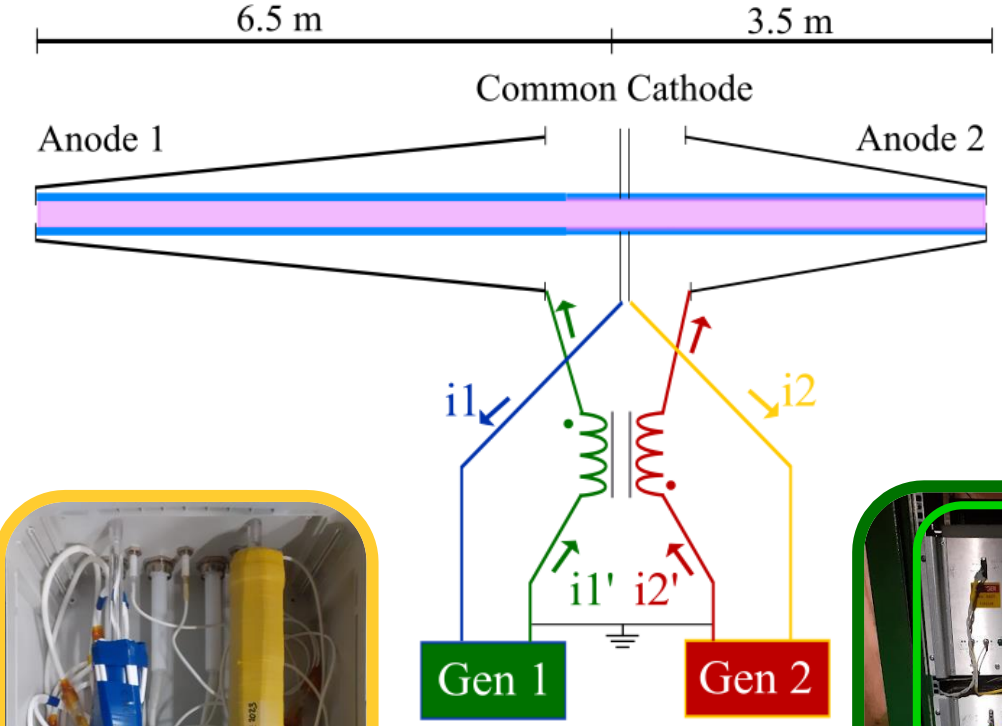


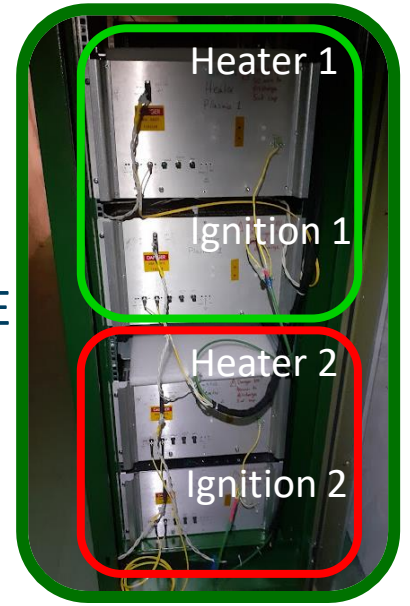


May 2023 proton run

Operation range – Double plasma







The double plasma current is equalized by a current balancing module: a high-current and small leakage inductance magnetic choke

The high-frequency impedance of each winding adjusts, forcing current symmetry between both plasmas

Tested in the AWAKE tunnel delivering symmetric currents, even with asymmetric plasma lengths

Next steps

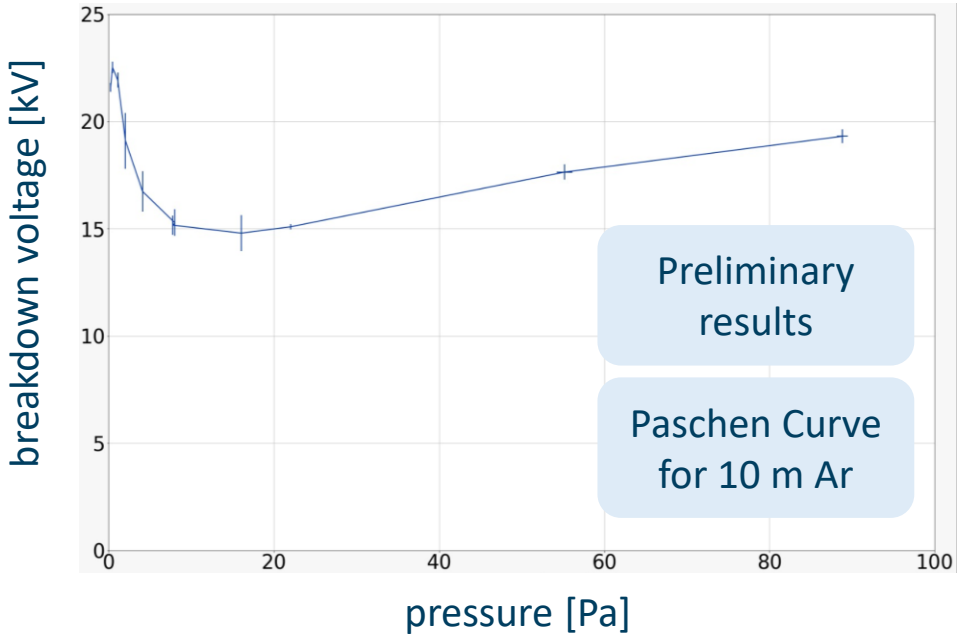
Back to the lab

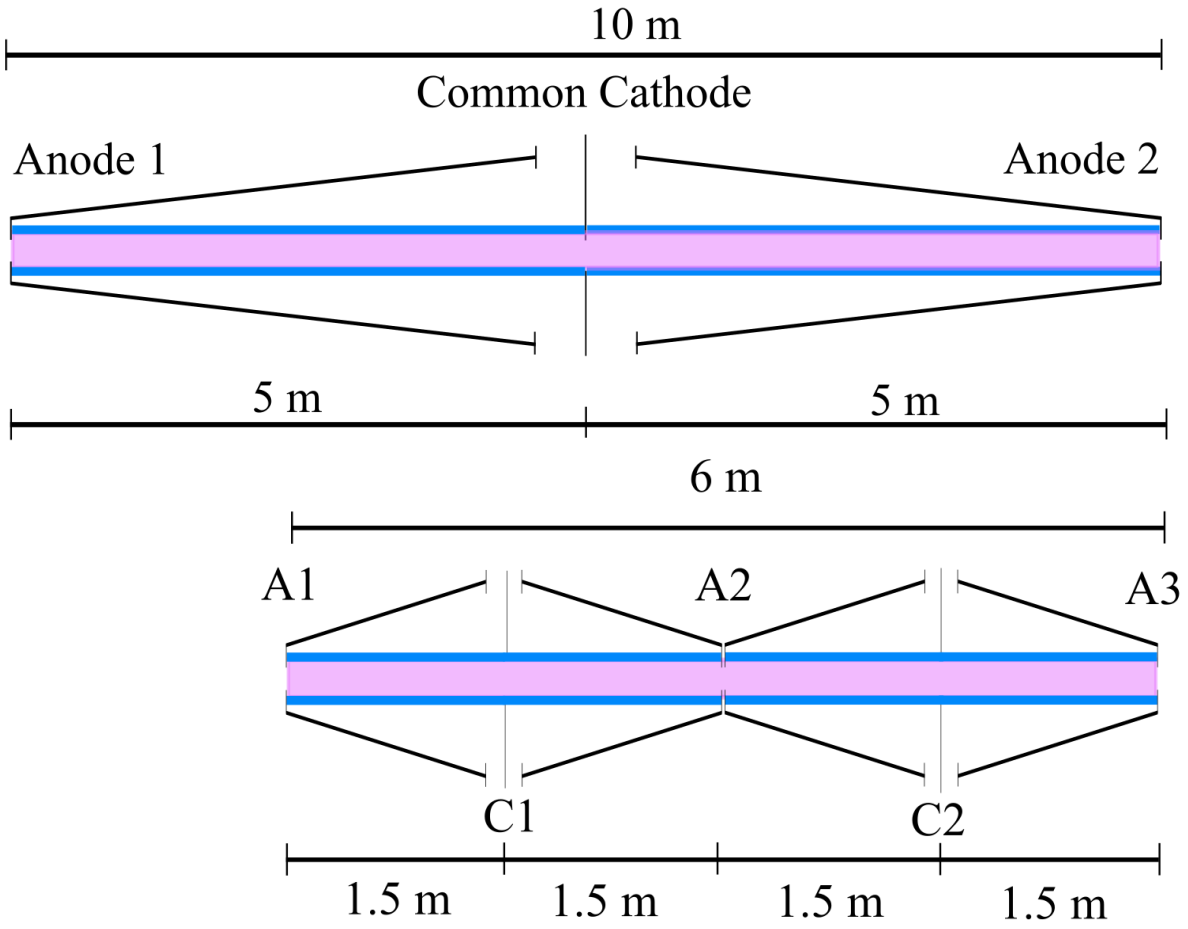
Scalability tests with different configurations:

5 + 5 m

1.5 + 1.5 + 1.5 + 1.5 m

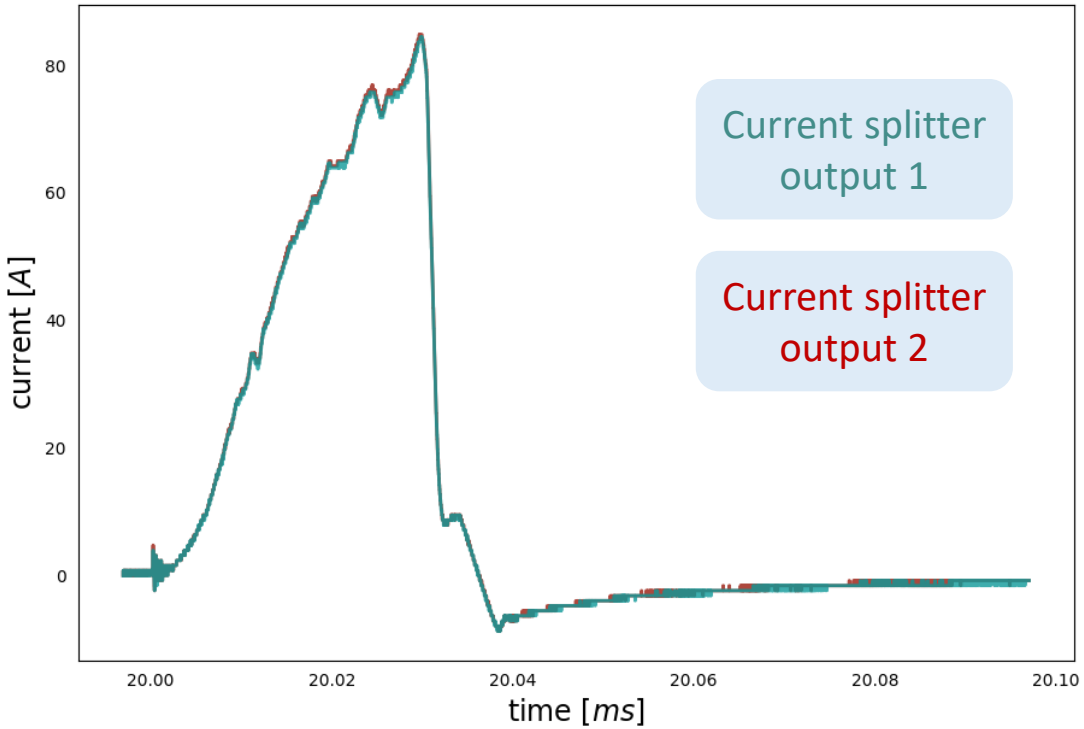
Optimization and characterization of the pulse generators





Next steps

Other applications



Similar current balancing modules were developed for the Wide-Open Waveguide (WoW) cavity coating, to split the current of three pulse generators into six outputs (HiPIMS)

Conclusions

The discharge plasma source design is suited for the AWAKE requirements

The nanosecond jitter, the density targets and the current reproducibility are made possible by combining two pulses for ignition and heating

The double pulse generator can accommodate a variety of plasma loads, which allows a large spectrum of operation

Scalability is potentially achievable by introducing current balancing modules

The next steps include further characterization of the pulse generator and scalability tests