ALAN

Active pLAsma for beNding

Consiglio di Laboratorio | Presentazione preventivi 2026
Laboratori Nazionali di Frascati
14 luglio 2025

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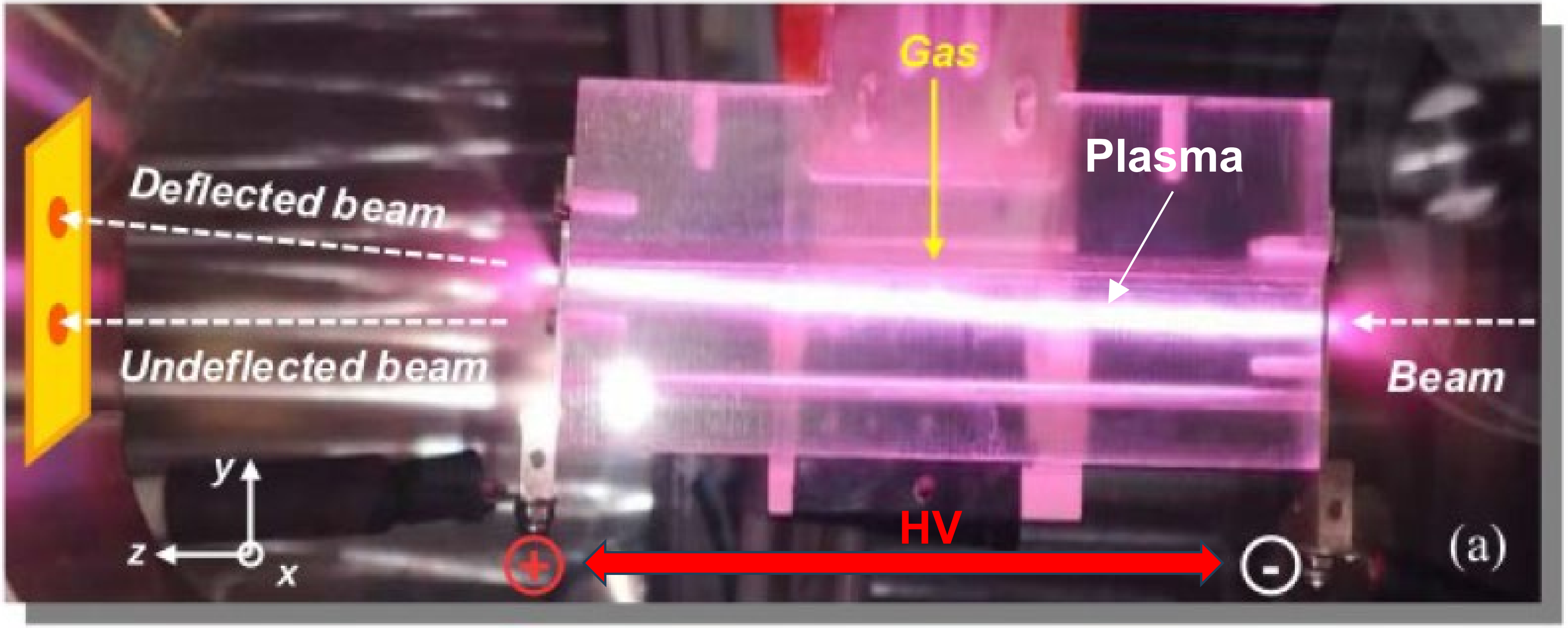
Guiding of charged particle beams in curved plasma discharge capillaries



Title: **ALAN (Active pLAsma for beNding)**
Research area: **Accelerators (Plasma accelerators)**
National responsible(LNF): **Angelo Biagioni**
Local responsible(INFN-Milano): **Andrea Renato Rossi**
Partecipants: **LNF (Laboratori Nazionali di Frascati), INFN-Sezione di Milano**
Total Budget: **195.000 € over a three-year period**
Budget 2026: **60.000 €**

PHYSICAL REVIEW LETTERS 132, 215001 (2024)

Guiding of Charged Particle Beams in Curved Plasma-Discharge Capillaries

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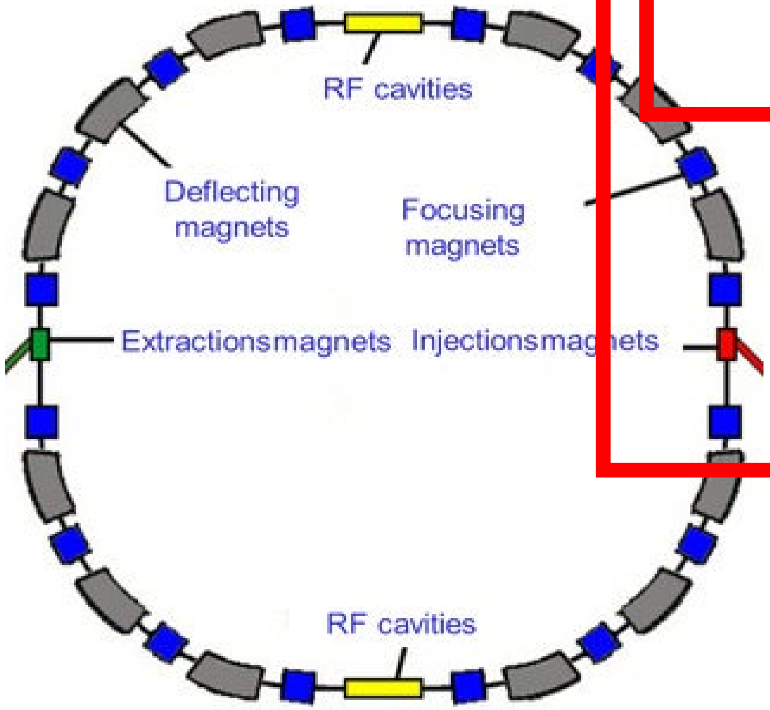
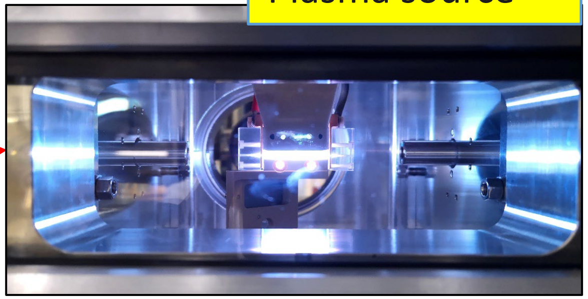
Schematic of a typical accelerator

An accelerator is made of
- Accelerating cavities
- Focusing magnets
- Deflecting magnets

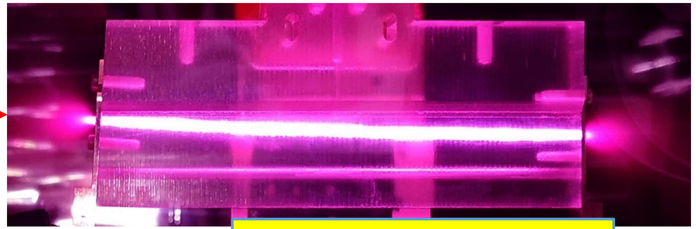


Plasma source



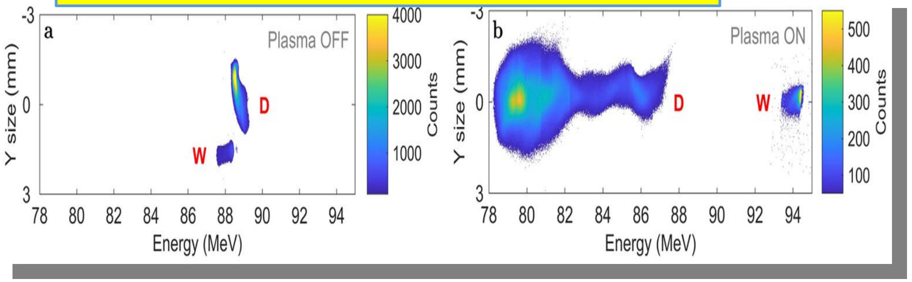
All-in-one Capillary

2023: Patent (INFN-LNF) Nr. 102023000012714

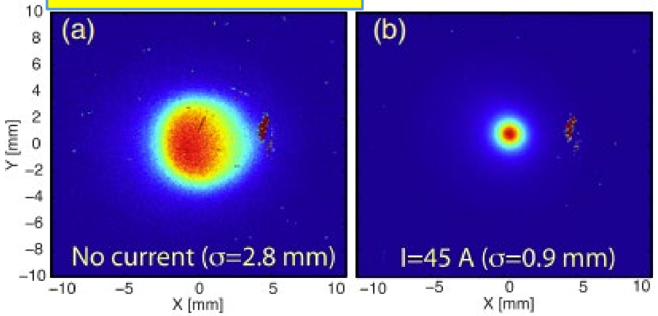


Curved Capillary

Plasma acceleration (EuPRAXIA)



Plasma focusing

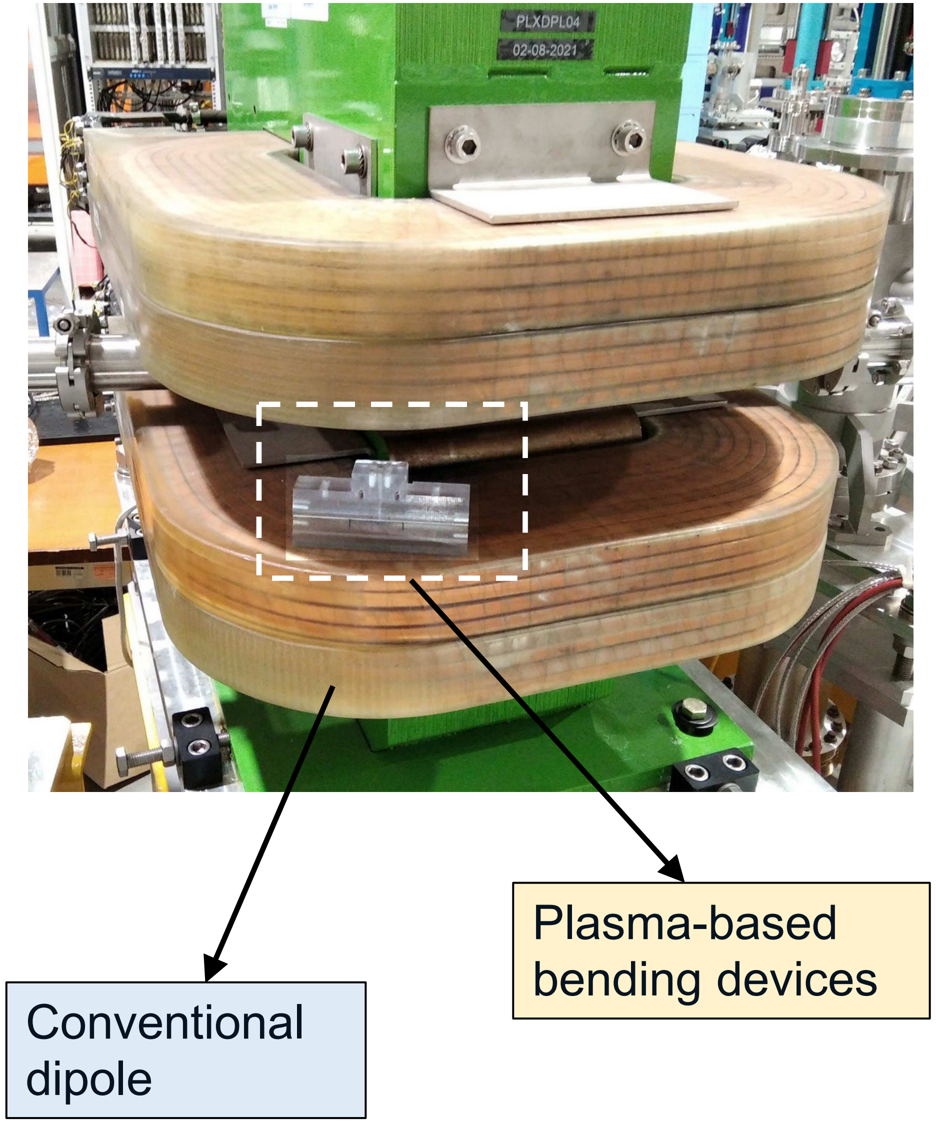


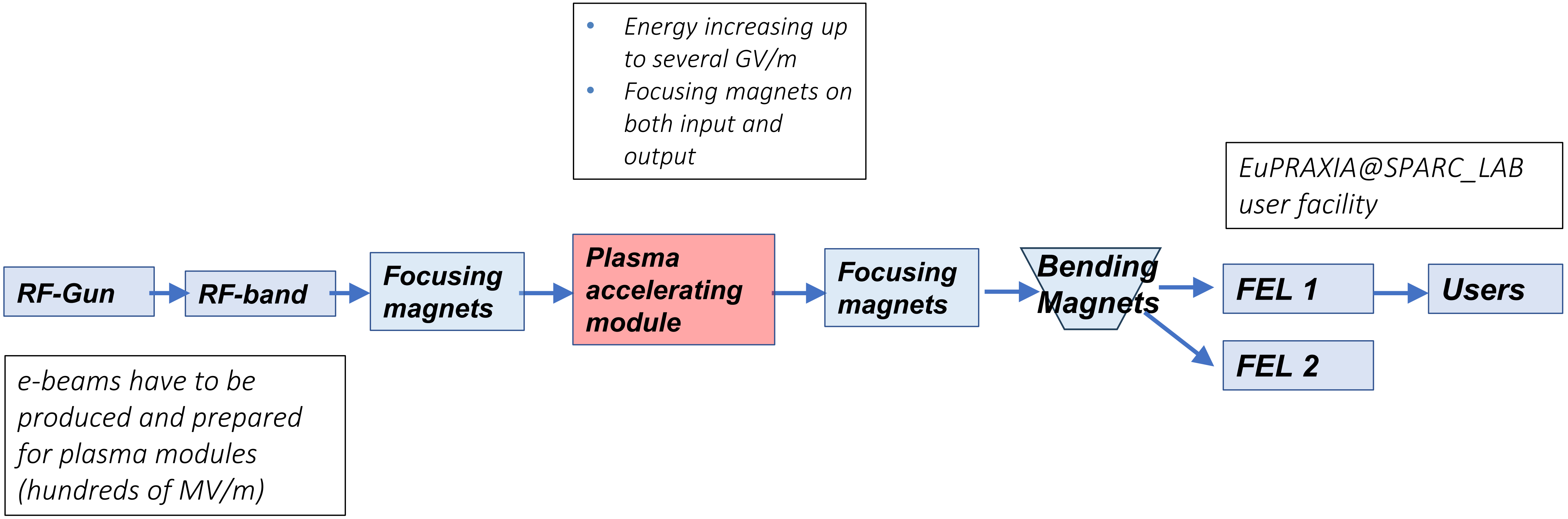
- We can tremendously reduce the accelerator size using plasma accelerators. We **still use conventional magnets to guide the beam**
- 2/3 of the 27 km long LHC ring is filled by magnets!
- **Can we reduce their size too?**

Why a plasma dipole?

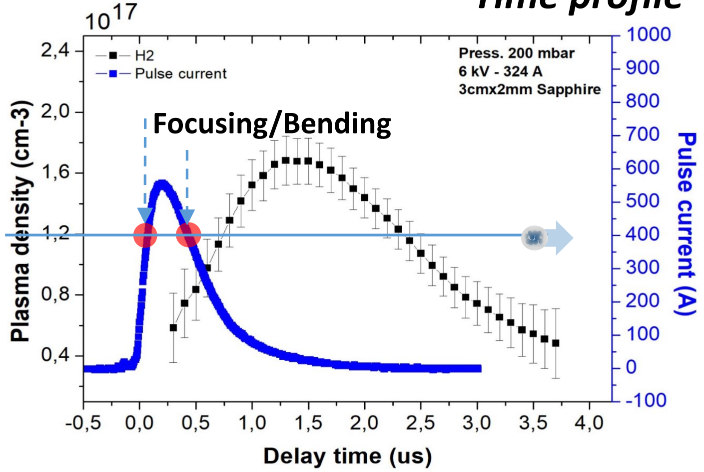
- New proposal for plasma-based approach of compact, achromatic **bending devices**, paving the way for next-generation high-energy accelerators.

- Currently, in particle accelerators, the deflection of charged particle beams is accomplished using large electromagnets driven by high currents:
  - high currents resulting in severe problems in terms of the thermal energy dissipation
  - Large dimensions lead to high implementation costs
  - The high costs of operation and implementation make these devices one of the most impactful elements in the design of particle accelerators.
  - In the GeV to TeV energy range, these magnets occupy a considerable part of the accelerator footprint, as demonstrated by the Large Hadron Collider (LHC).




Energy increasing up to several GV/m
Focusing magnets on both input and output
EuPRAXIA@SPARC_LAB user facility
RF-Gun
RF-band
Focusing magnets
Plasma accelerating module
Focusing magnets
Bending Magnets
FEL 1
Users
FEL 2
e-beams have to be produced and prepared for plasma modules (hundreds of MV/m)

Time profile



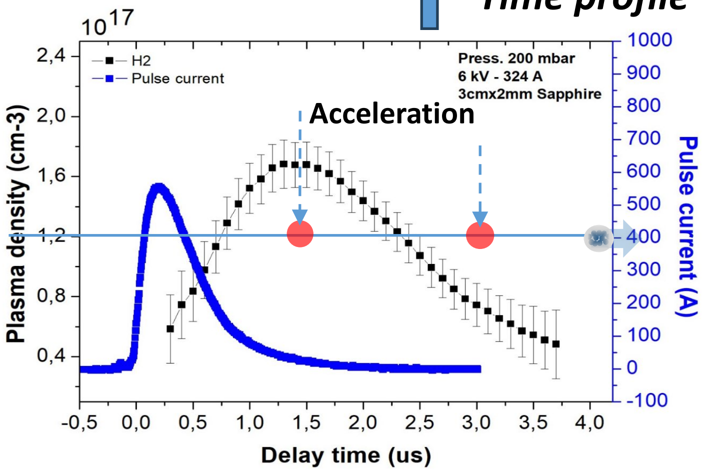
EuPRAXIA@SPARC_LAB user facility

RF-Gun → **RF-band** → **Plasma focusing** → **Plasma accelerating module** → **Plasma focusing** → **Plasma dipole** → **FEL 1** → **Users**

Plasma dipole → **FEL 2**

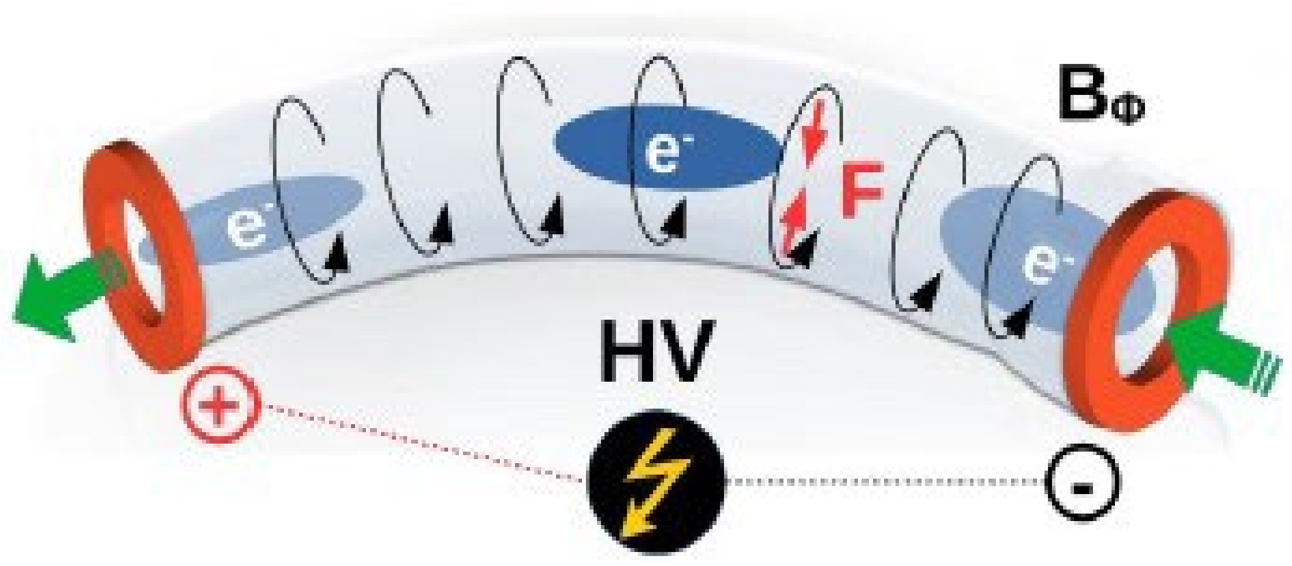
e-beams have to be produced and prepared for plasma modules (hundreds of MV/m)

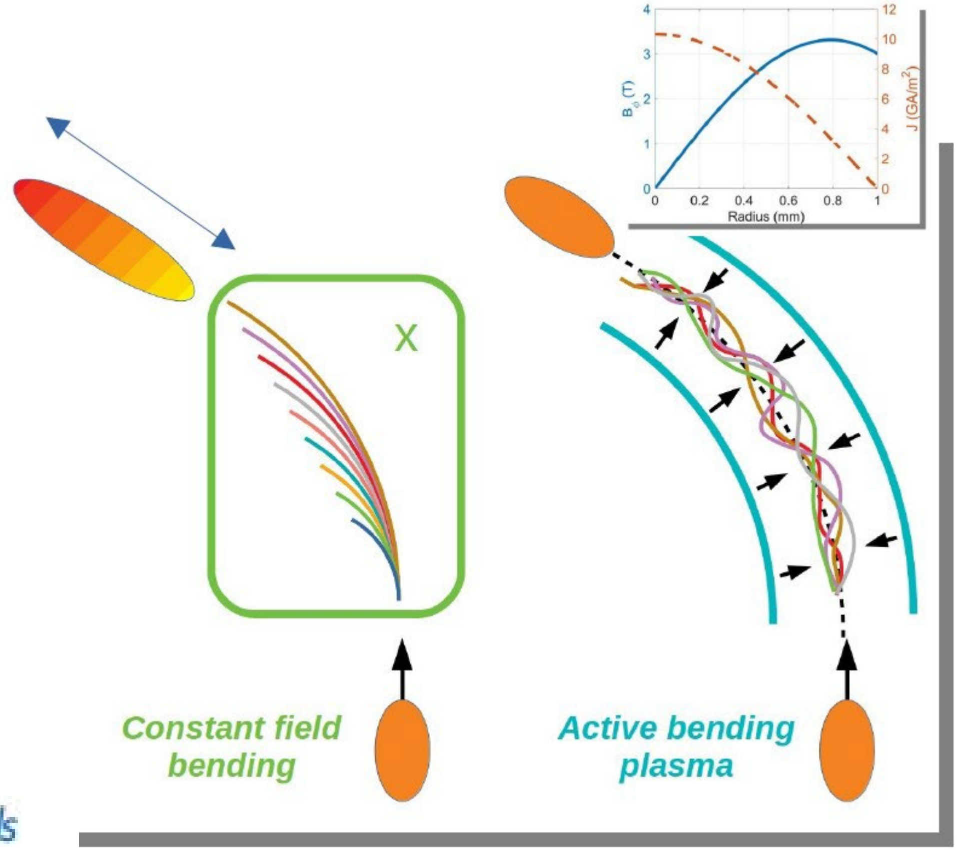
Time profile



- *Valid for plasma-based accelerators, maximum compactness as several components can be driven by the same HV-sources (EuPRAXIA@SPARC_LAB)*
- *Can also be applied to conventional accelerators*

*Active pLAsma for beNding (ALAN)*_**How it works**





Curved active-plasma lens: an alternative to classic bending magnets

- *Plasma can sustain large currents, E.g., 15 kA currents produce ~4 T magnetic fields*
- *Compactness. Large deflection angles, no need of cryogenic systems*
- *Tunability. The bending is tuned by adjusting the discharge-current*
- *Cheap solution (capillary+discharge pulser)*
- *Tunable dispersion (dispersion-free also possible) by changing the discharge current*

$$B_{\phi}(r) = \frac{\mu_0}{r}\int_0^r J(r')r'dr'$$

Requests for the use of *Plasma dipoles*

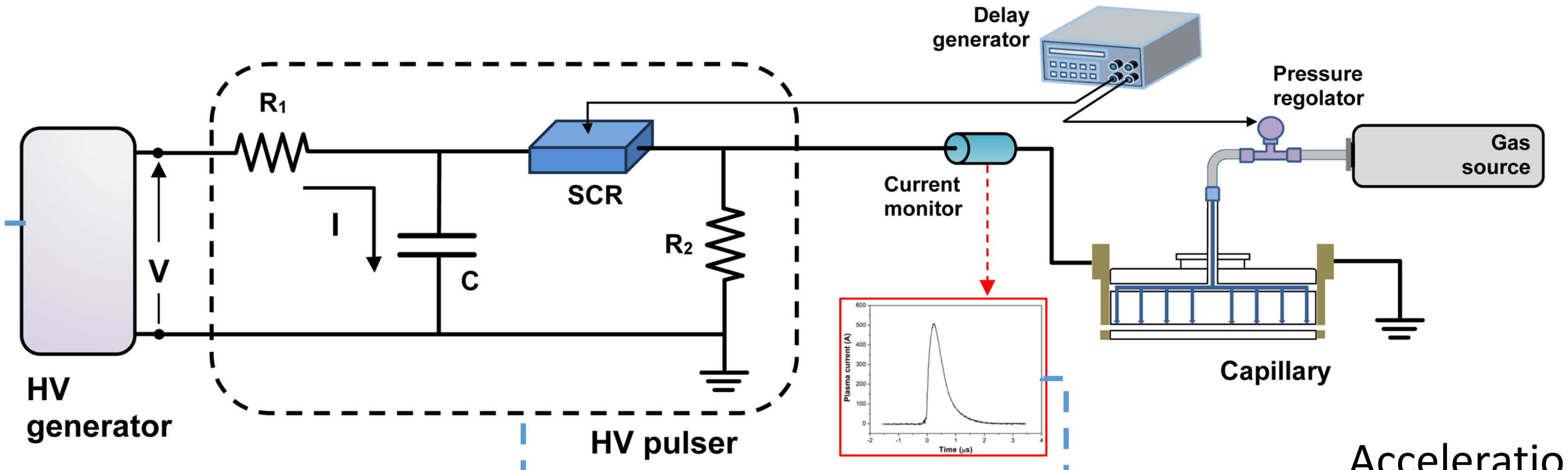
- Very high voltage pulses and especially currents (from few kA up to tens of kA)

- Design of HV systems to produce appropriate current pulses
  - High peak currents
  - short pulses to preserve capillary structures

- Capillary structure design
  - Geometry of the plamsa source
  - Studies on new materials that can withstand both high currents and, in the future, high repetition rates.

- These topics are closely linked to the EuPRAXIA project.

- Cost reduction
- Compactness
- Low energy consumption



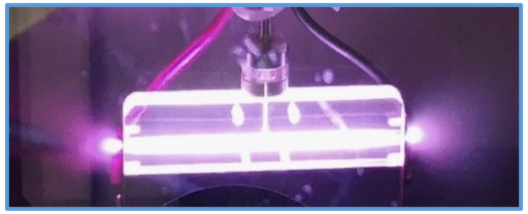
HV generator

- **High voltage for plasma formation (Max 30 kV)**

$Q=CV=10kV \times 40nF = 0.4\times10^{-3}$ C
$I=dQ/dt$

V = 25 kV
*I*p = 2.5 kA
Δt = 600 ns FWHM

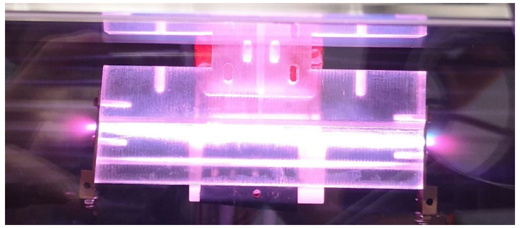
Acceleration/focusing



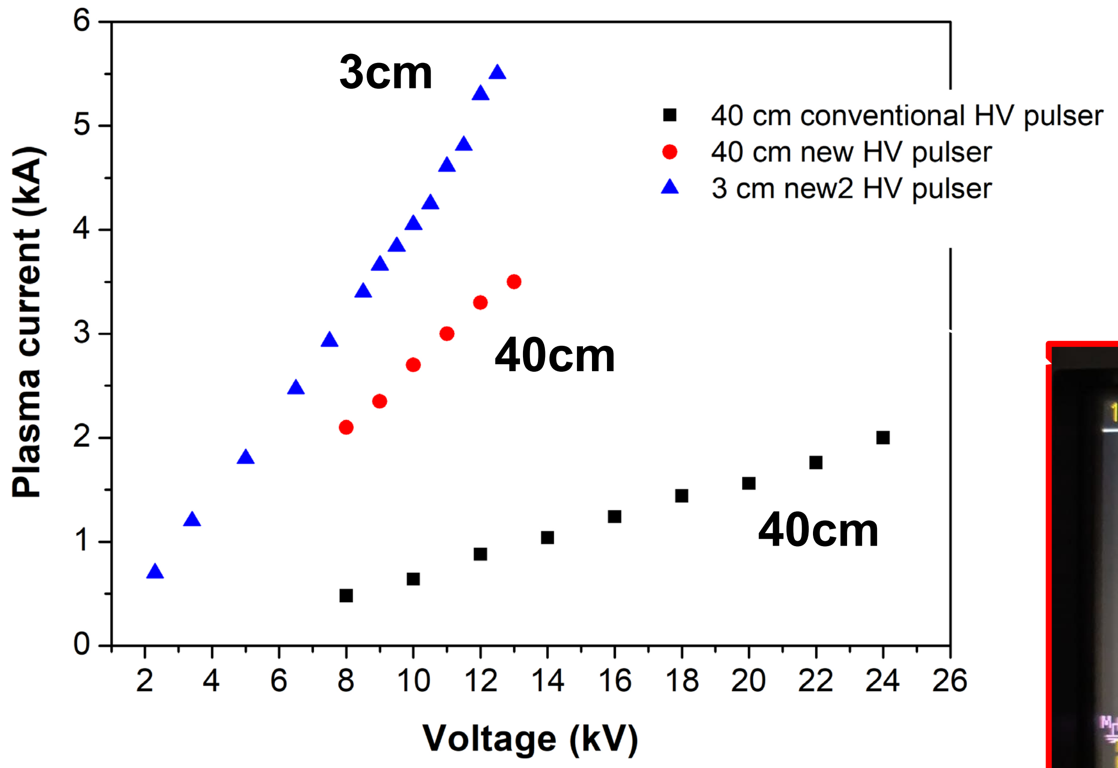
- **New design of the HV pulser**
- **Materials**
- **machining for curved channels in hard materials (ceramics)**

V = 30-50 kV
*I*p = 10-15 kA
Δt = 100 ns FWHM

Dipole



Design of HV systems to reach very High currents



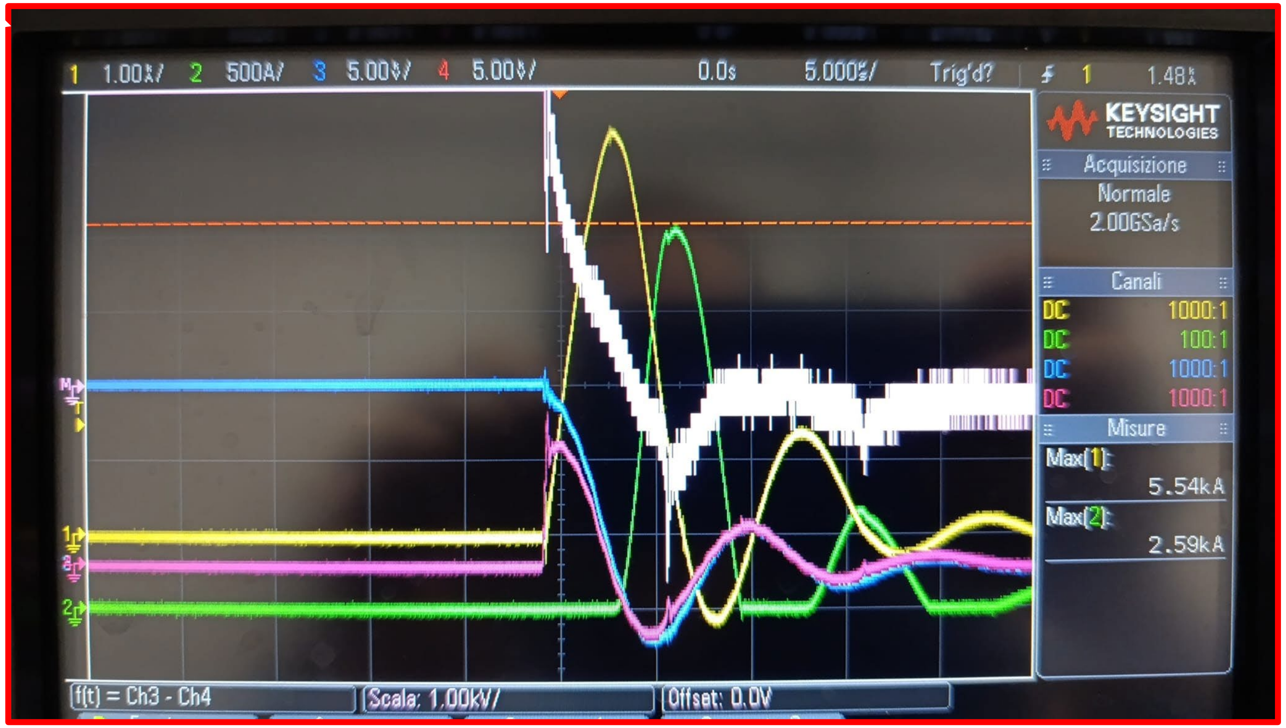
3 cm long capillary

Positive pick 5.54 kA

Negative pick 2.5 kA

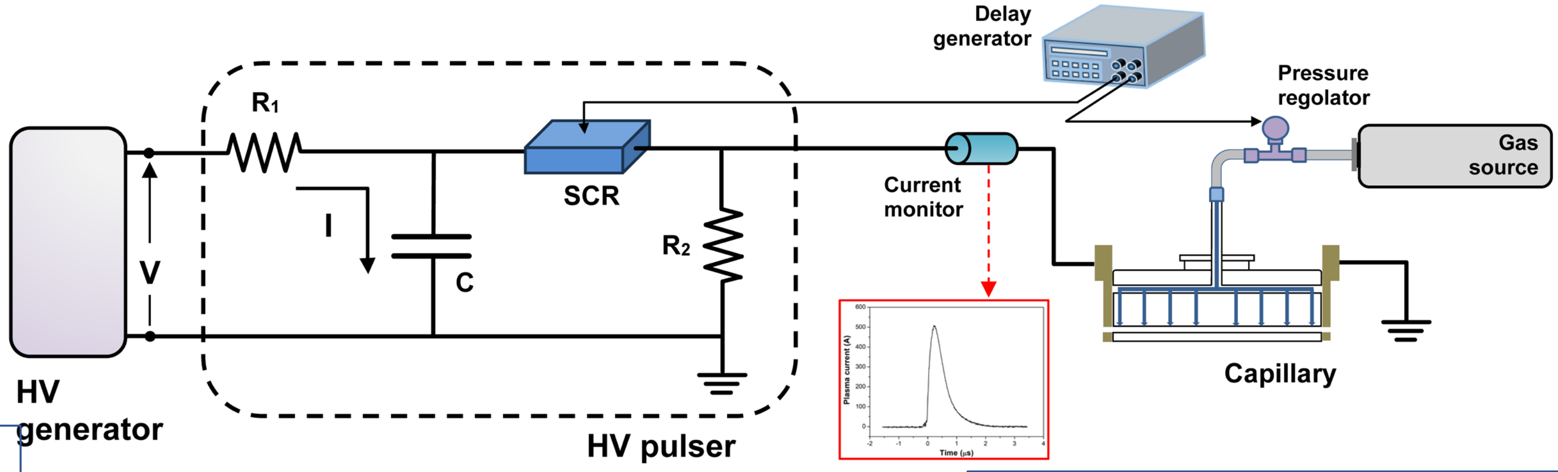
C = 1 uF

Δt > 5 us



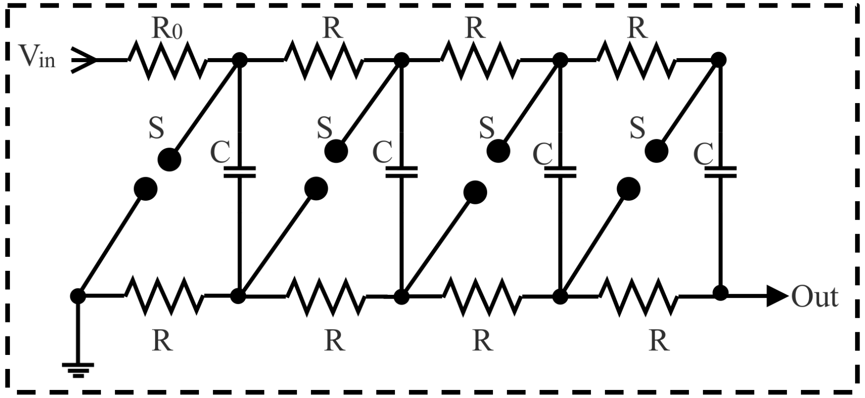
- **Optimization of the current shape**
- **Negative oscillations**
- **C = 1 uF, Δt > 5 us** → **Capillary damage**

First goal: **Design of HV systems to produce appropriate current pulses**

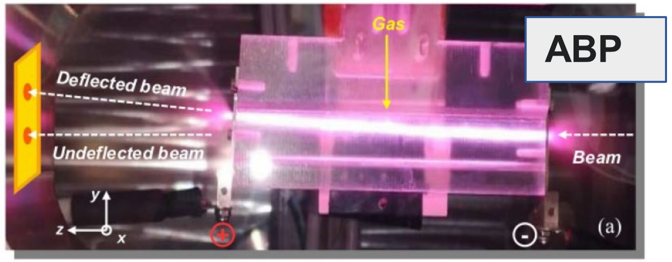


- HV pulses pulse from a low-voltage DC supply
- Very short pulses (tens of ns)
- charging *N* capacitors in parallel at Vc (output *NVc*)
- Discharge *N* capacitors in series (short pulse)
- Laser ignition for spark gaps
- new high-voltage cable design to limit inductive effects (oscillations and pulse duration)

Marx generator



- HV pulses/High currents pulse from a low-voltage DC supply



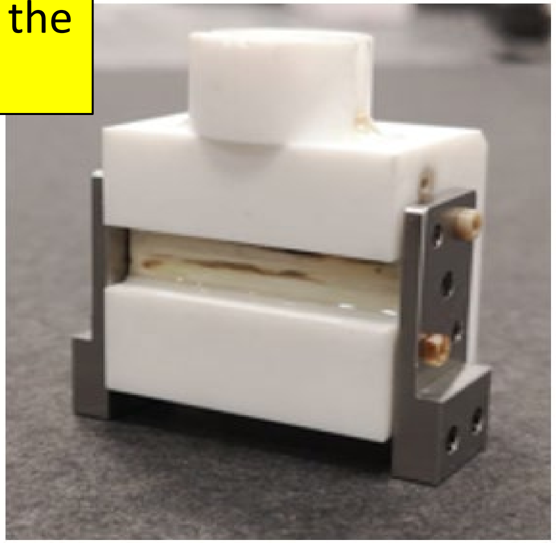
- **Very short pulses (tens of ns)**
  - **Lower Thermal energy per pulse**
  - **Higher repRATE/high peak**

Second goal: **Capillary structure design**

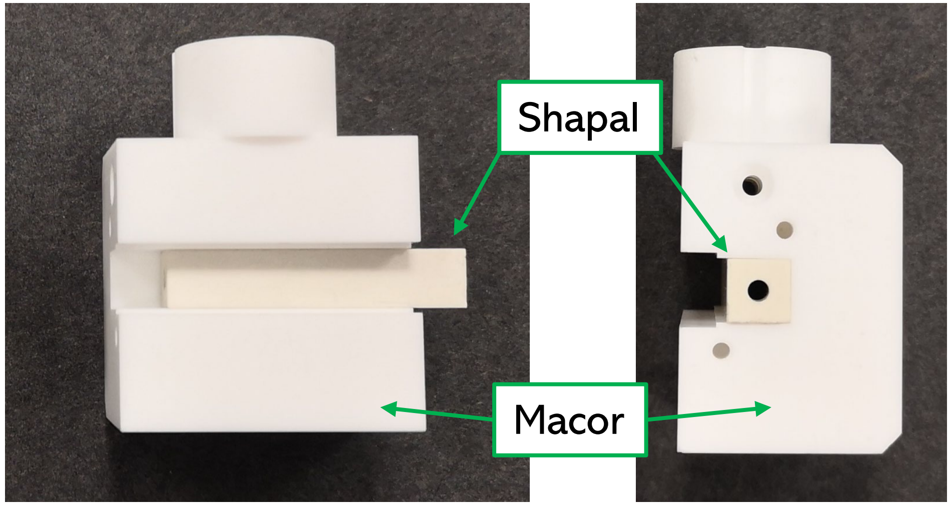
- High thermal conductivity
- High max operating temperature
- Good machinability, cost-effectiveness and availability for large geometries
- New materials for electrodes

$$T_e(\mathrm{eV}) = 5.7\left[\frac{I(\mathrm{kA})}{r_{\mathrm{cap}}(\mathrm{mm})}\right]^{2/5}$$

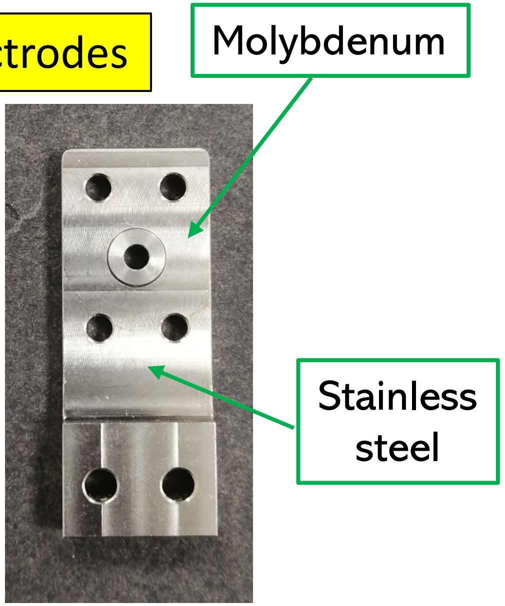
First prototype of the ceramic capillary



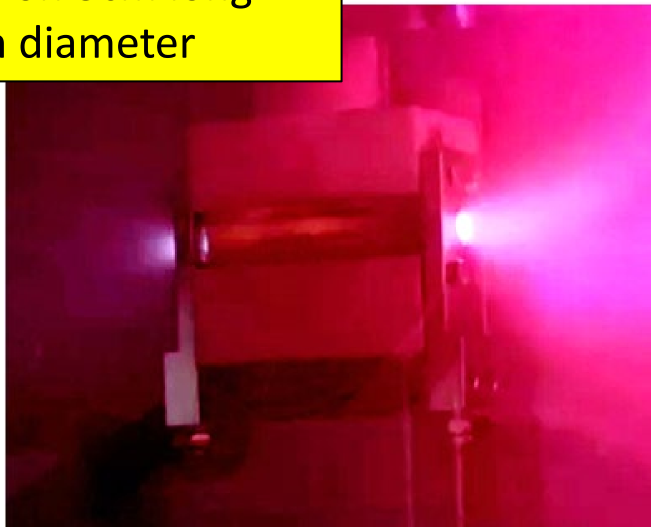
Capillary



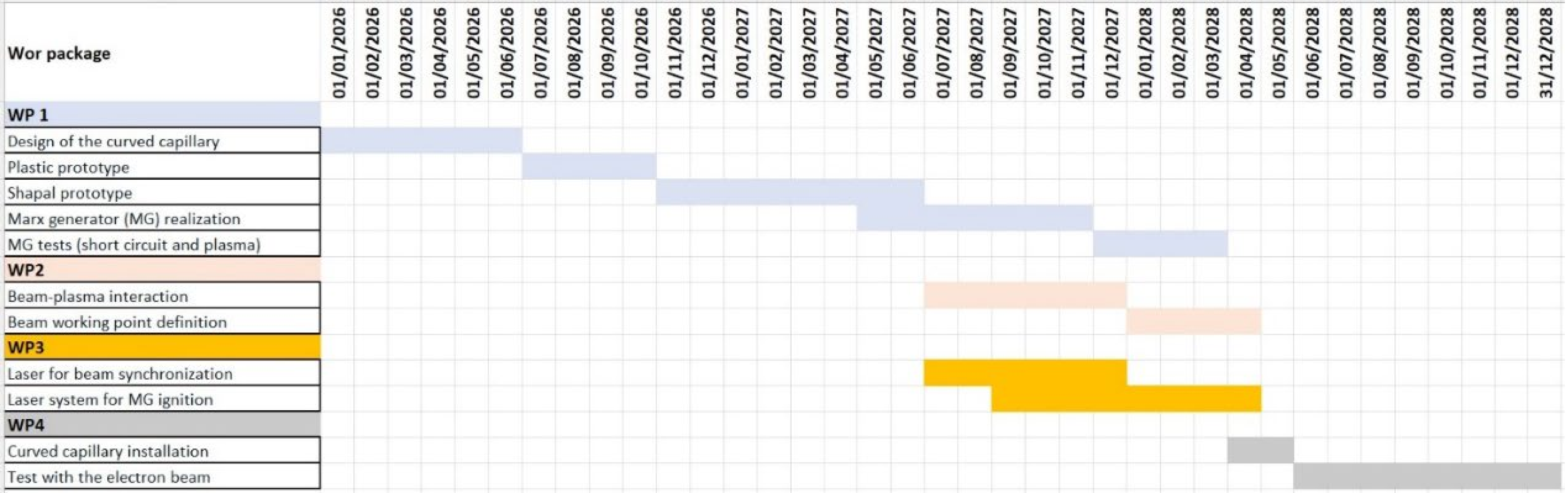
Electrodes



Tests on 3cm long-2mm diameter



Tab.6 Gantt chart of the ALAN project



Unit	**Work package**	**Researchers**	**FTE**
1st Unit INFN-LNF			
	WP1	Dr. Angelo Biagioni	0.3
		Dr. Lucio Crincoli	0.2
	WP3	Dr. Mario Galletti	0.3
		Dr. Gemma Costa	0.3
		Dr. Maria Pia Anania	0.3
	WP4	Dr. Riccardo Pompili	0.2
		Dr. Alessio Del Dotto	0.2
		Total INFN-LNF	**1.8**
2nd Unit INFN-Milan			
	WP2	Dr. Andrea R. Rossi	0.3
		Prof. Vittoria Petrillo	0.1
		Dr. Marcello Rossetti Conti	0.15
		Dr. Andrea Frazzitta	0.5
		Total INFN-Milan	**1.05**
		TOTAL	**2.85**

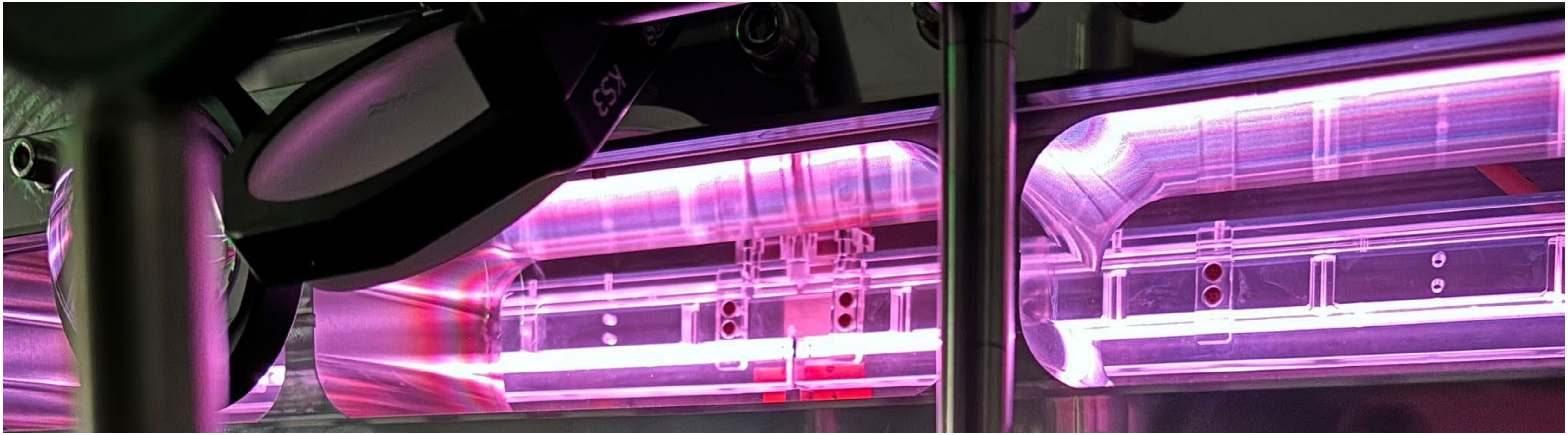
Work Package	**WP Leader**	**WP activity**
WP 1	Angelo Biagioni (LNF)	WP1 will lead the mechanical realization and characterization of the curved capillary and the HV sources for plasma formation.
WP 2	Andrea R. Rossi (INFN-Milan)	The WP1 activity will be focussed on the study of the beam-plasma interaction, The WP1 will also pursue the definition of the SPARC_LAB accelerator working point.
WP 3	Mario Galletti (LNF)	WP3 will work on the synchronisation of electron beam and plasma by means of a laser system. It will also study a laser system for triggering the discharge in the Marx generator.
WP 4	Riccardo Pompili (LNF)	The activity of WP4 will cover the integration of the curved capillary and particle beam bending experiments in the SPARC_LAB accelerator

*Active pLAsma for beNding (ALAN)*_**Project organization**

Unit	Work package	Year 1	Year 2	Year 3
1st Unit INFN-LNF				
	WP1	CapillariesP 10.000	CapillariesS 15.000	
		Capillaries S 10.000	MGprototype 40.000	
		Travel 5.000		
	Tot	**25.000**	**55.000**	**0**
	WP3	Lenses 15.000	Travel 5.000	
		Lens support 10.000		
	Tot	**25.000**	**5.000**	**0**
	WP4		Capillary support 20.000	Travel 10.000
			Movements 15.000	
	Tot	**0**	**35.000**	**10.000**
2nd Unit INFN-Milan				
	WP2	C. equipment 5.000	S. licence 10.000	S. licence 10.000
		Travel 5.000	Travel 5.000	Travel 5.000
	Tot	**10.000**	**15.000**	**15.000**
	Sum	**60.000**	**110.000**	**25.000**

195.000 €

Risk	**RPN**	**Mitigation**
Durability of the capillary material	**3**	The use of ceramics with high thermal conductivity has so far, in experiments at SPARC_LAB, yielded excellent results regarding the life of discharge capillaries for repetition frequencies up to over 200 Hz. Capillary life is significantly extended by reducing the frequency of operation, so the ALAN device can be tested at low frequencies.
Plasma discharge stability	**2**	The use of an external laser system with remotely controlled optics improves the stability of the discharge trigger.
Reaching high peak currents with short pulse durations	**2**	A current peak of 15 kA is a relatively low value of the current obtainable with the Marx generator, this is used to achieve much higher values. The complexity of the circuit depends on the triggering system of its capacitor sections. Initially, even just three capacitors may be sufficient to achieve the parameters required by the ALAN design.
Synchronisation and triggering of the discharge in the Marx generator	**2**	Laser synchronisation of the Marx generator ignition can be more complicated than the classical method based on an auxiliary voltage pulse, although more stable and reproducible. However, the latter is the solution to be used initially for tests on ALAN device
Control of the electron beam parameters to be matched with plasma and discharge current	**1**	According to preliminary numerical simulations, the electron beam parameters must precisely match those of the plasma and discharge. Furthermore, advanced techniques such as *machine learning* could be employed to automatically adapt the electron beam parameters in response to the evolving state of the plasma, accounting, for example, for capillary wall erosion and resulting changes in plasma density.



Thank you for your attention

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