Plasma sources design for plasma-based accelerators

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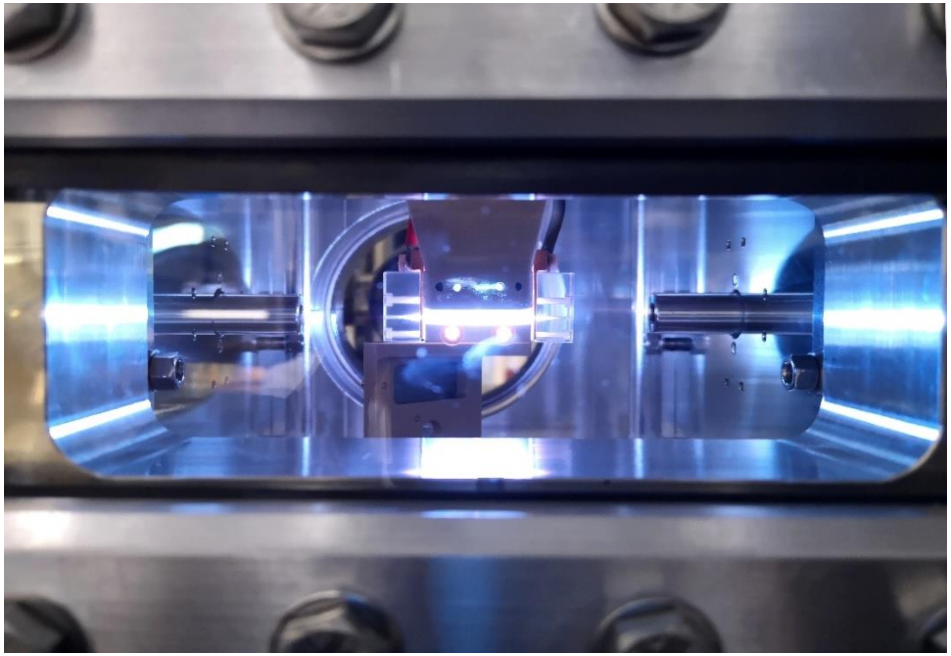

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Outlines

- *Motivations*
- *Plasma Wakefield acceleration*
  - *Plasmas for accelerator machine*
  - *Plasma-based devices*
- *Plasma module to confine and control plasmas*
  - *Gas-filled capillary plasma source*
  - *Gas cells*
- *Plasma sources characterization*
  - *Density measurements*
  - *Plasma instabilities*

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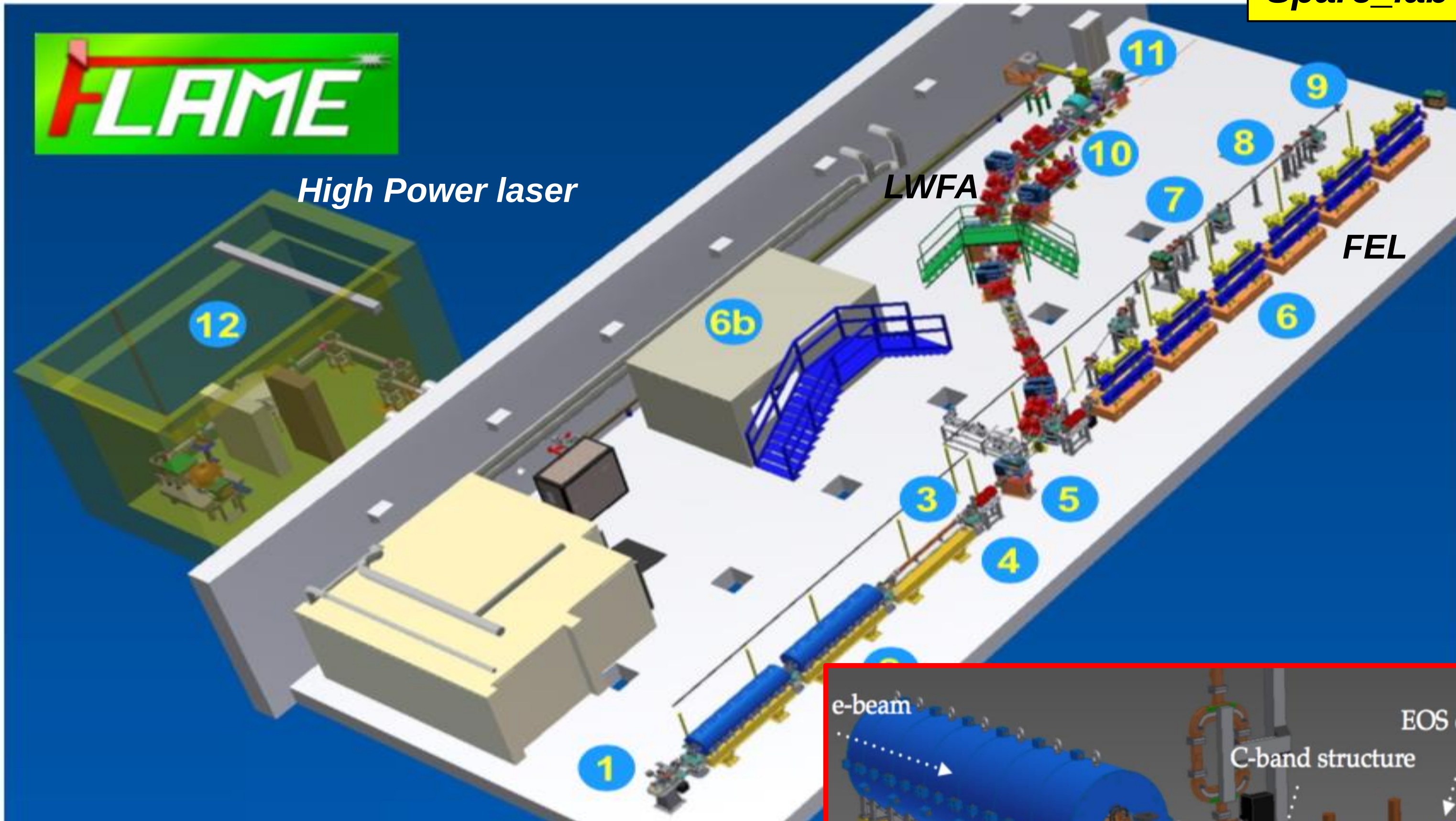
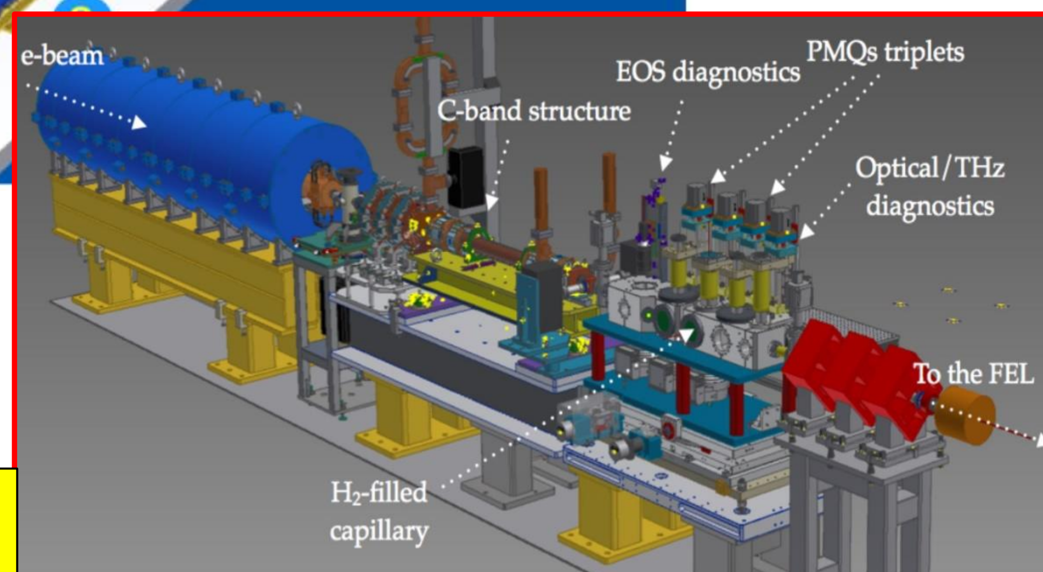
Sparc_lab test facility



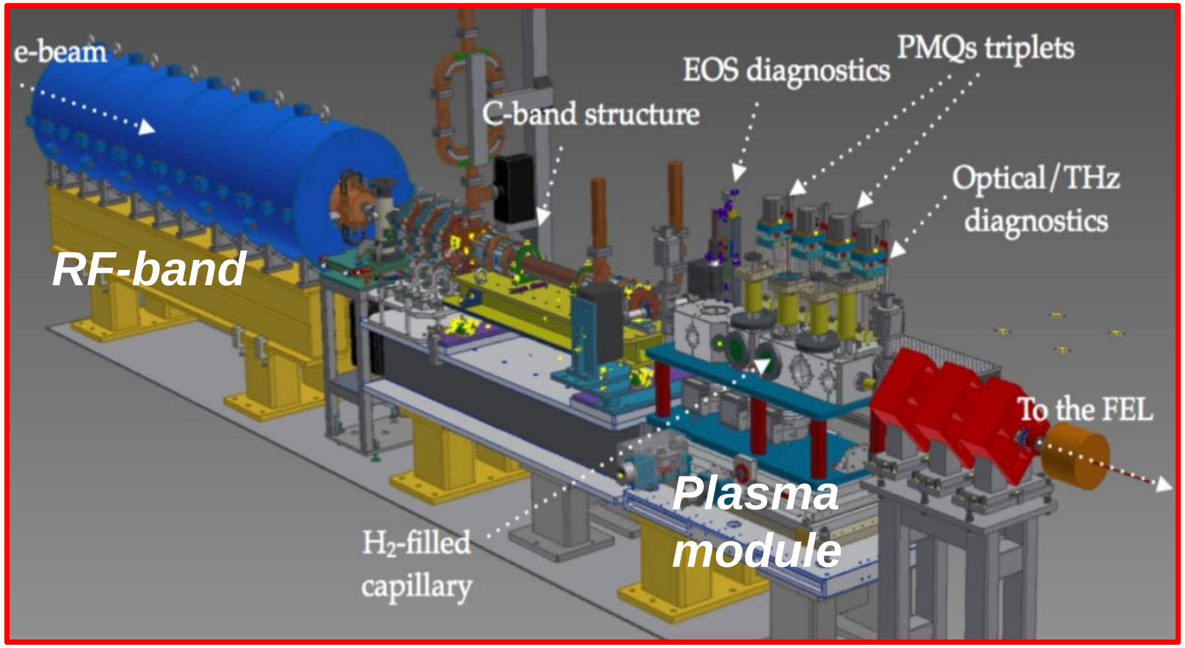


- ***Compactness***
- ***Accelerating gradient***

S-band accelerating structres: **20 MV/m**
C-band accelerating structures: **35 MV/m**

Up to **10-100 GV/m** for Plasma-based accelerating structures

Motivations

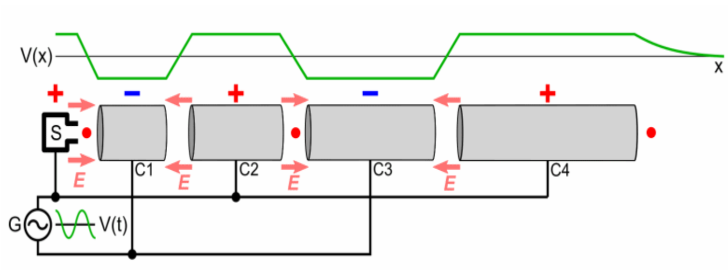


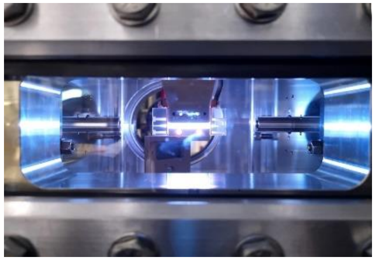
RF-Gun → **RF-band** → **Plasma module** → **FEL** → **Users**

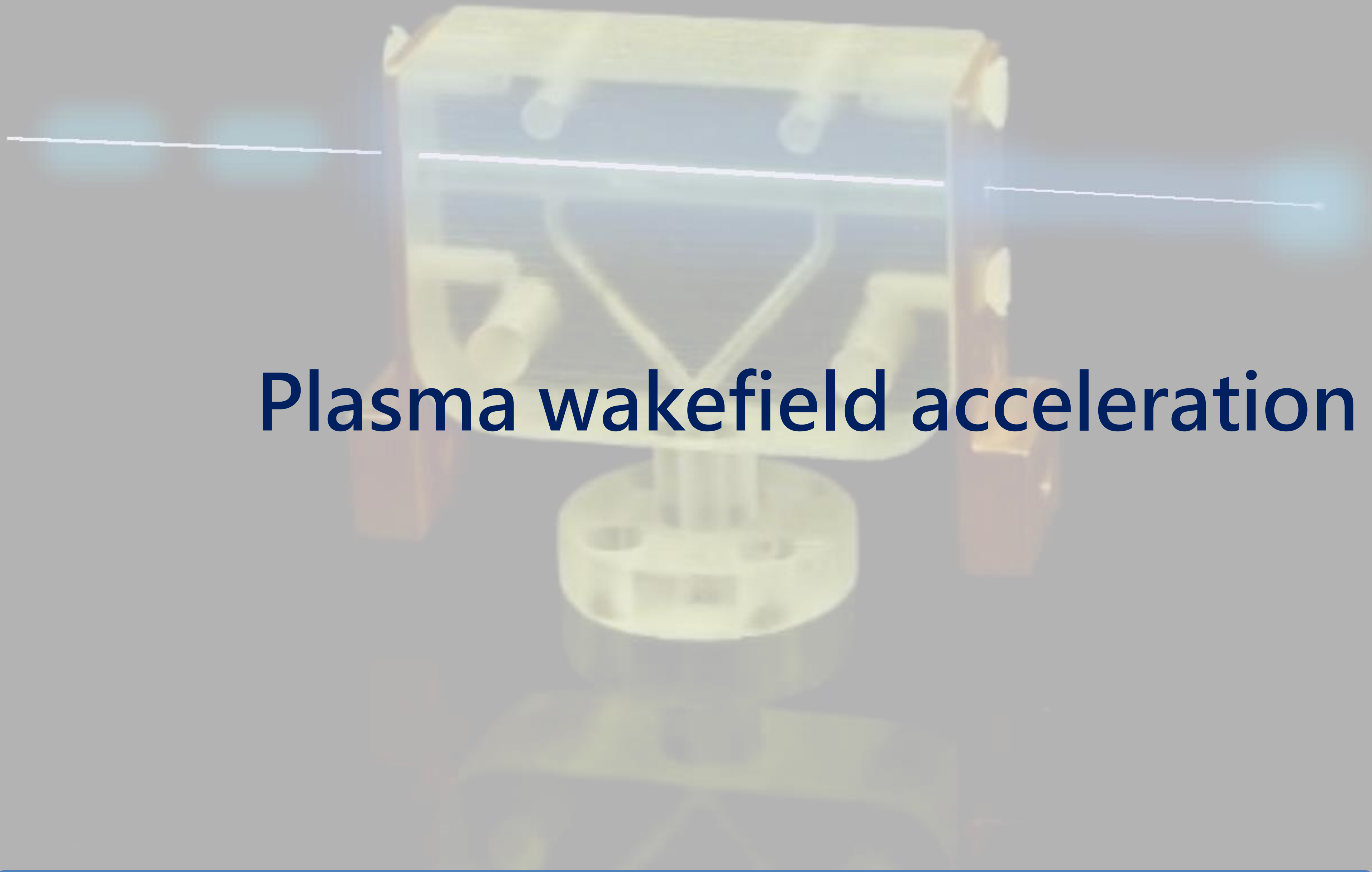
e-beams have to produced and prepared for plasma modules (hundreds of MV/m)

Energy increasing up to several GV/m:
PWFA
LWFA

At **Eupraxia@Sparc_lab** user facility

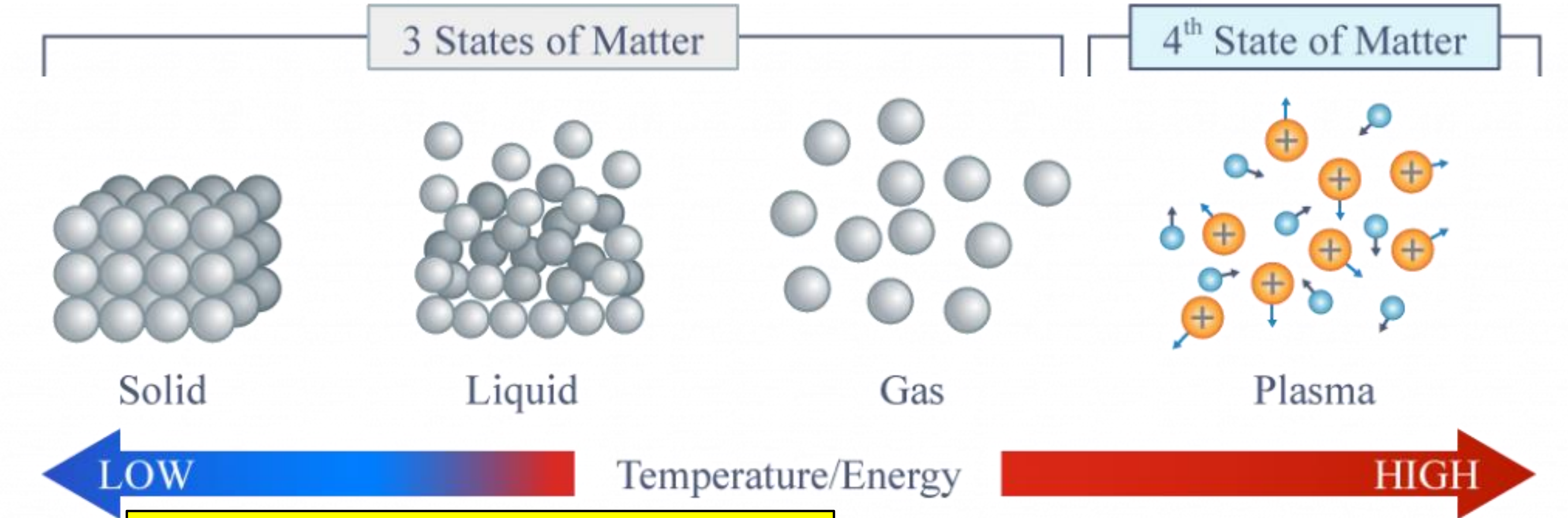






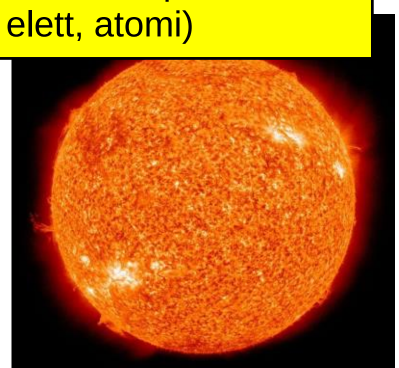
Plasma wakefield acceleration

IL PLASMA

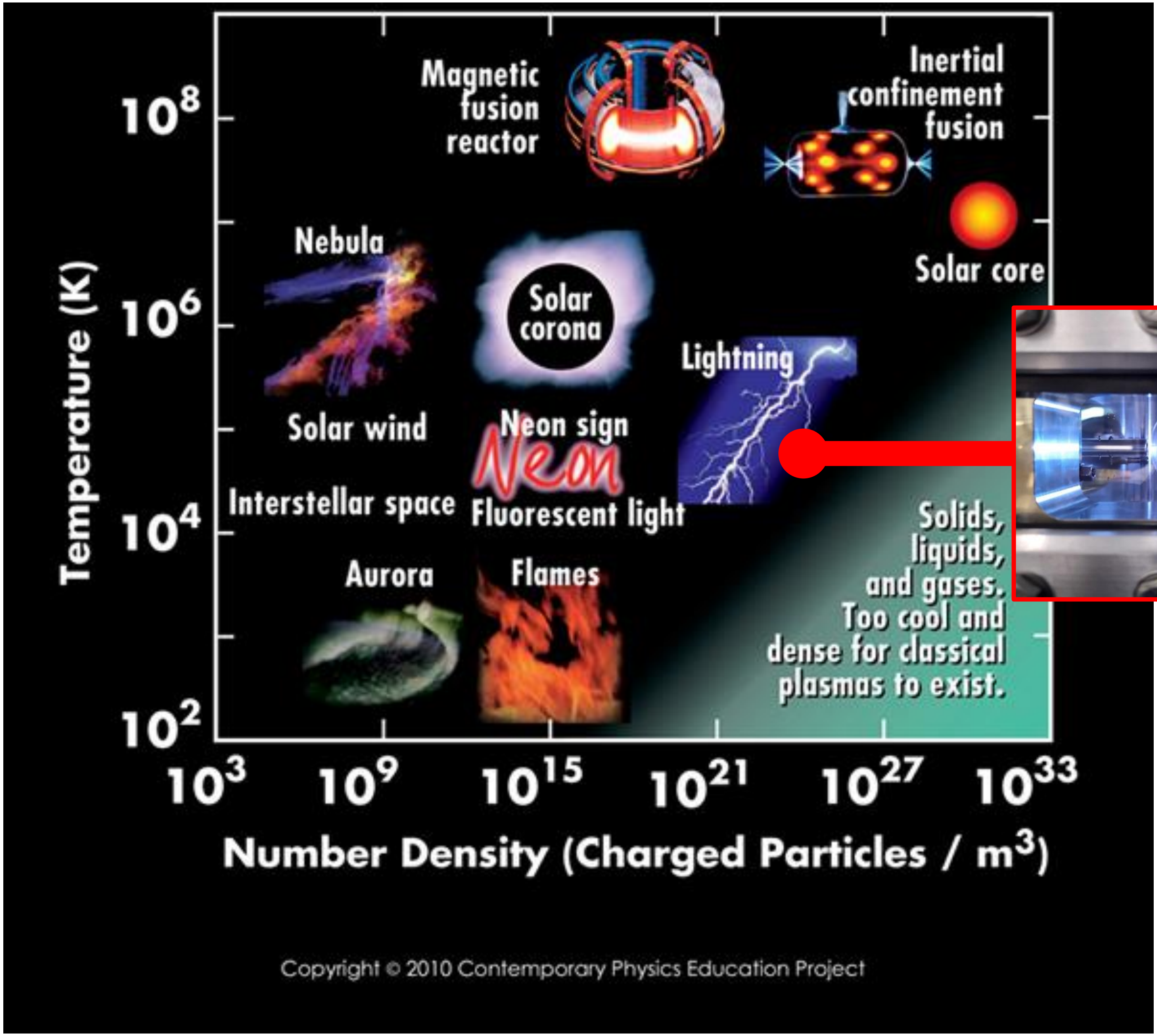


Confinamento e formazione del Plasma

- Breve durata (decine di microsecondi)
- Instabilità
- Alte temperature
- Disuniformità
- Equilibrio termodinamico tra particelle di diverso tipo (ioni, elett, atomi)

IL PLASMA



Magnetic fusion reactor
Inertial confinement fusion
Solar core
Nebula
Solar corona
Lightning
Solar wind
Neon sign
Neon
Interstellar space
Fluorescent light
Aurora
Flames
Solids, liquids, and gases. Too cool and dense for classical plasmas to exist.
Temperature (K)
10^8
10^6
10^4
10^2
10^3 10^9 10^{15} 10^{21} 10^{27} 10^{33}
Number Density (Charged Particles / m^3)
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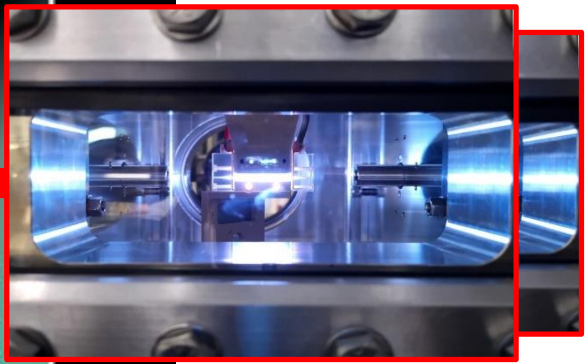
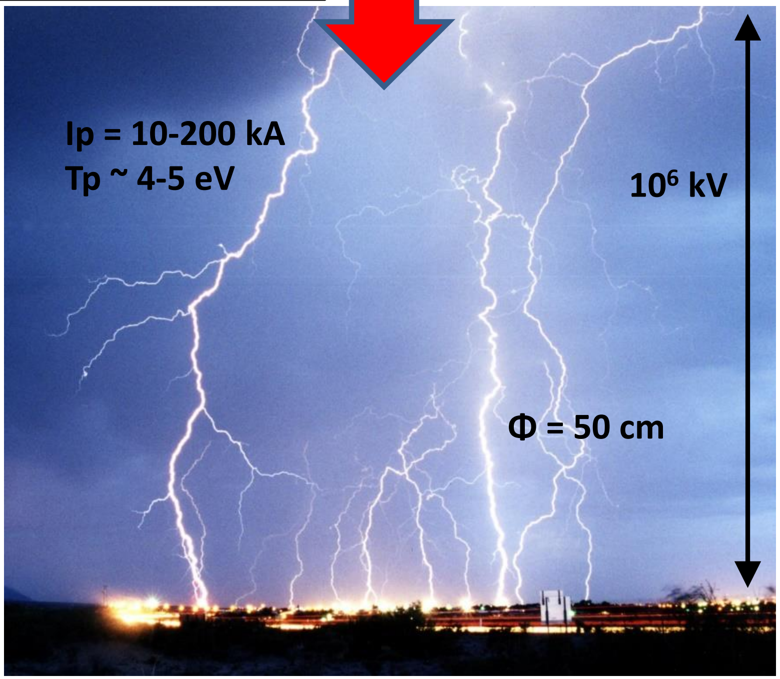
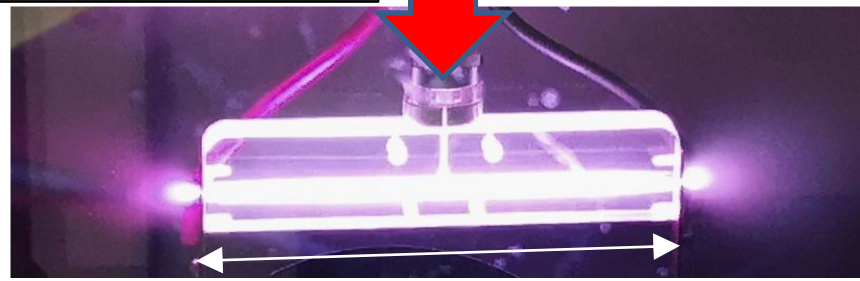


Natural plasmas



Artificial plasmas



Ip = 0.3 – 1 kA
Tp ~ 2-10 eV
Vp = 5-20 kV
Φ = 1-2 mm

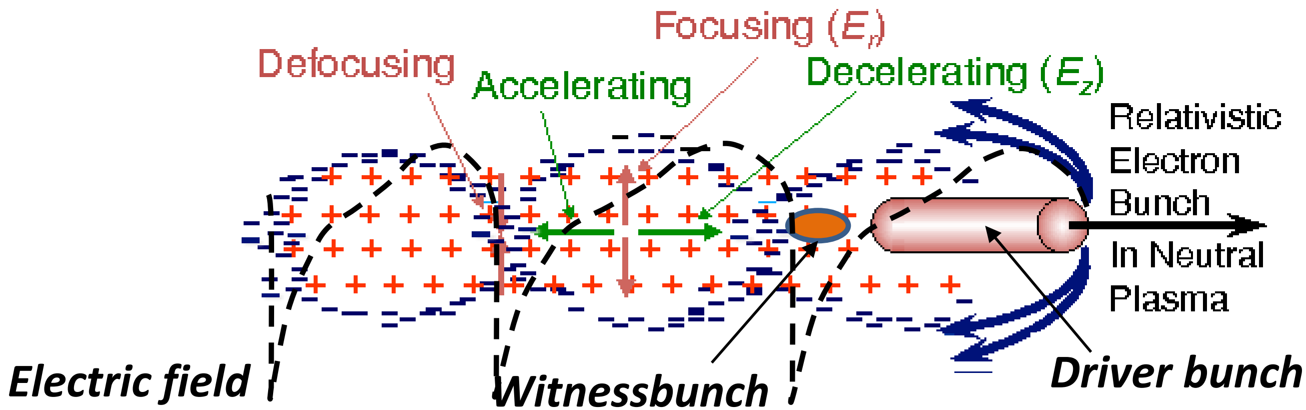
$$T_e(0) \approx 5.7 \left(\frac{I_{peak}[\text{kA}]}{r_{cap}[\text{mm}]} \right)^{2/5} \text{eV}$$

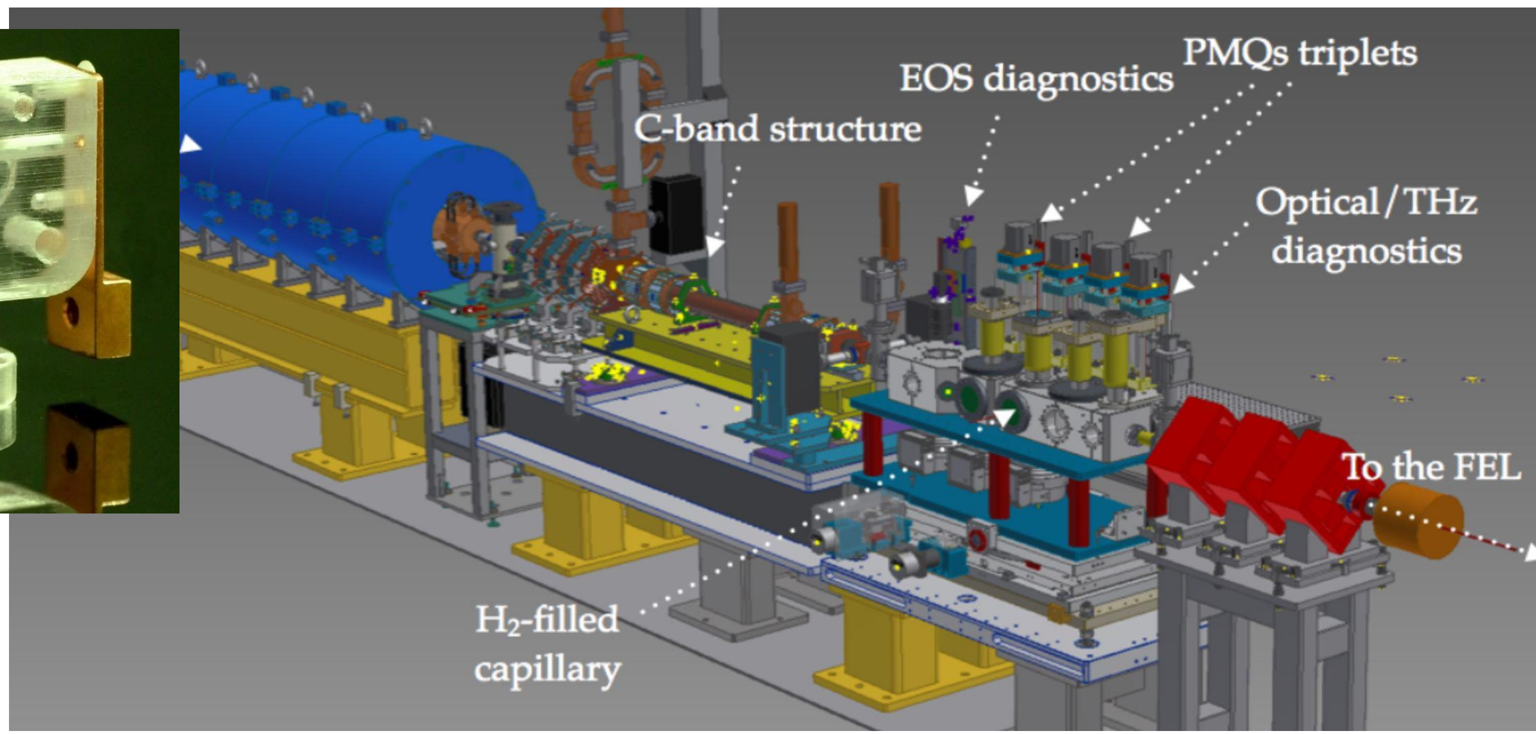
$T_{lightning}$ **~ 4 eV**
$T_{plasma\ source}$ **~ 5.7 eV**

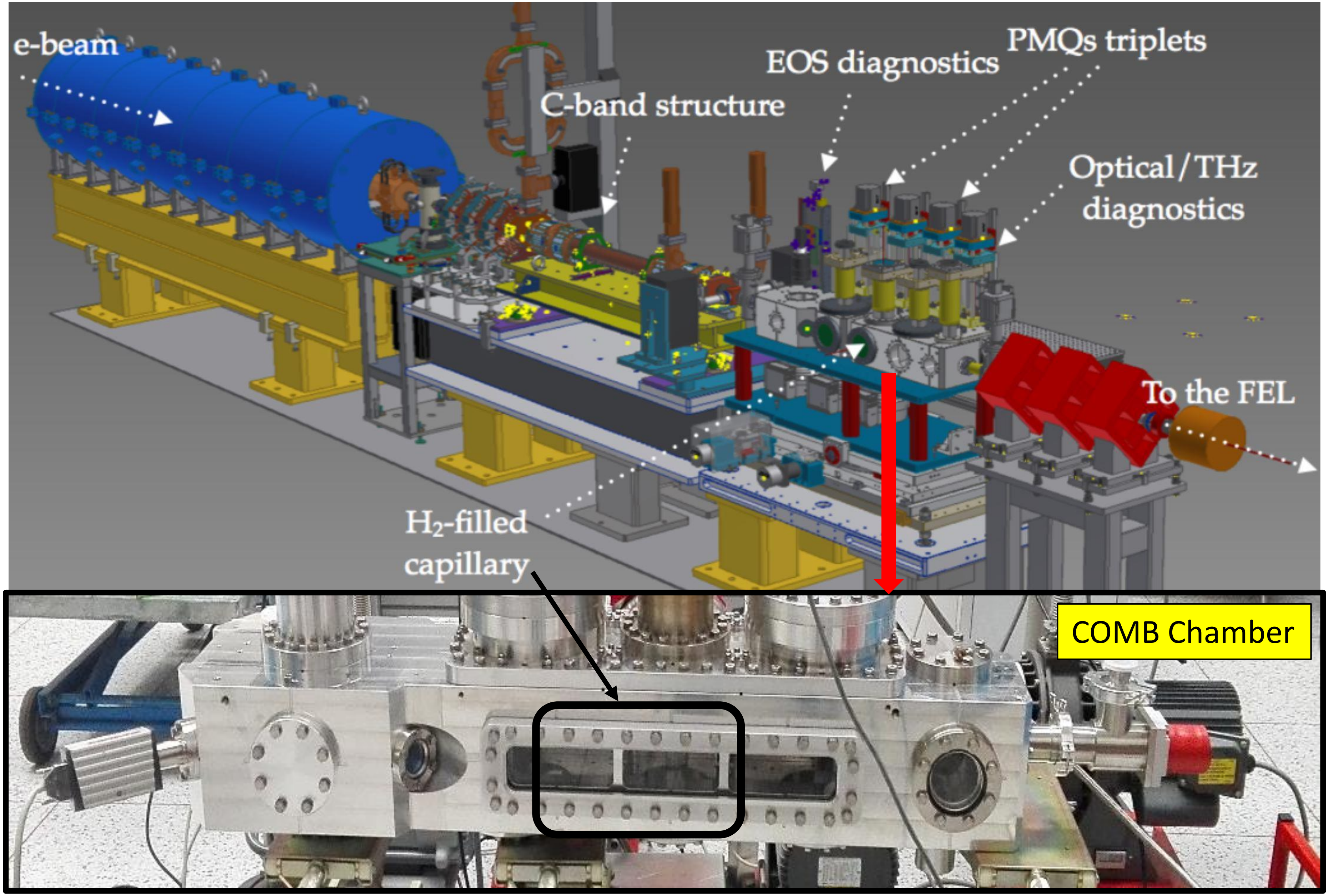
With each Debye length, charges are increasingly electrically screened. Every Debye-length, the electric potential will decrease in magnitude by 1/e.

•**Bulk interactions**: The **Debye length** is much smaller than the physical size of the plasma. This criterion means that interactions in the bulk of the plasma are more important than those at its edges, where boundary effects may take place. When this criterion is satisfied, the plasma is quasineutral.

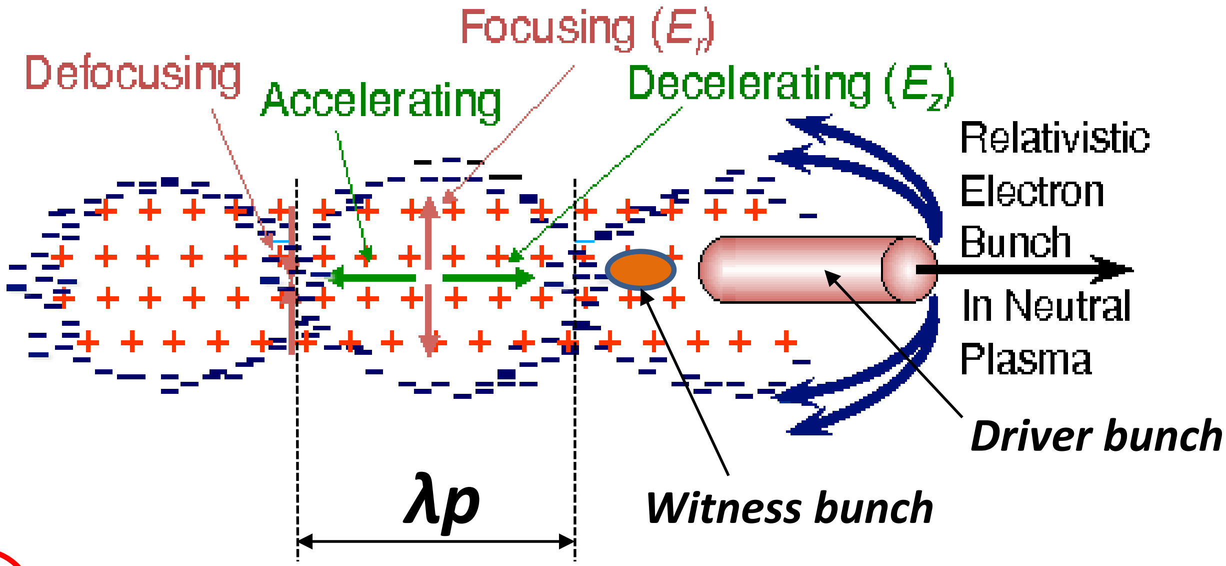
•**Collisionessless**: The electron plasma frequency (measuring plasma oscillations of the electrons) is much larger than the electron–neutral collision frequency. When this condition is valid, electrostatic interactions dominate over the processes of ordinary gas kinetics. Such plasmas are called collisionless.


Focusing (E_r)
Defocusing
Accelerating
Decelerating (E_z)
Relativistic Electron Bunch In Neutral Plasma
Electric field
Witnessbunch
Driver bunch


PMQs triplets
EOS diagnostics
C-band structure
Optical/THz diagnostics
To the FEL
H_2-filled capillary


e-beam
C-band structure
EOS diagnostics
PMQs triplets
Optical/THz diagnostics
To the FEL
H_2-filled capillary
COMB Chamber

$$\omega_p = \sqrt{\frac{n_p e^2}{m_e \varepsilon_0}}$$



$$\lambda_p = \frac{2\pi c}{\omega_p}$$

$$E_{cold,wb}[V/m] = \frac{m_e \omega_p c}{e} \approx 96\sqrt{n_0[cm^{-3}]}$$

$$\alpha = \frac{n_{bunch}}{n_p}$$

Linear regime	***(nb < np)***
Weakly NL regime	***(nb = np)***
Non-linear regime	***(nb>>np)***

Plasma density measurement represents a crucial point to implement plasma-based devices:

- **Accelerators**
- **Plasma lens**

$$n_p = 10^{17}\ cm^{-3}$$

$$\omega_p = 2\times 10^{13}\ Hz$$

$$E_0 = 30\ \frac{GV}{m}$$

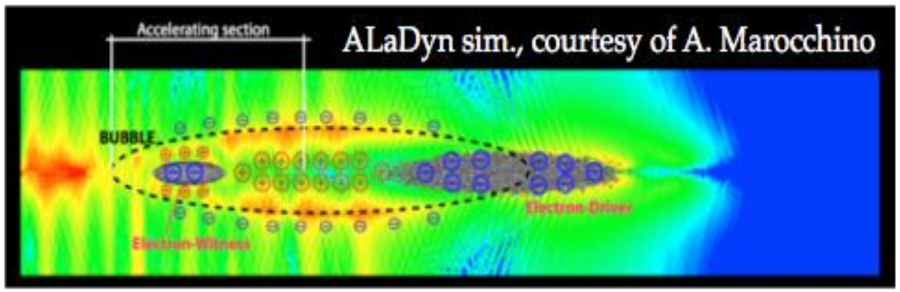
$$\lambda_p = 100\ \mu m\ (300\ fs)$$

$$\sigma_{zD} \approx 25\ \mu m\ (75\ fs)$$

$$\sigma_{xD} \approx 2\ \ \mu m$$

PWFA

- High quality $\varepsilon_n \ll 1mm\ mrad, I_{peak} \sim kA, \frac{\Delta\gamma}{\gamma} \ll 1\%$
- External injection of high brightness electron beams

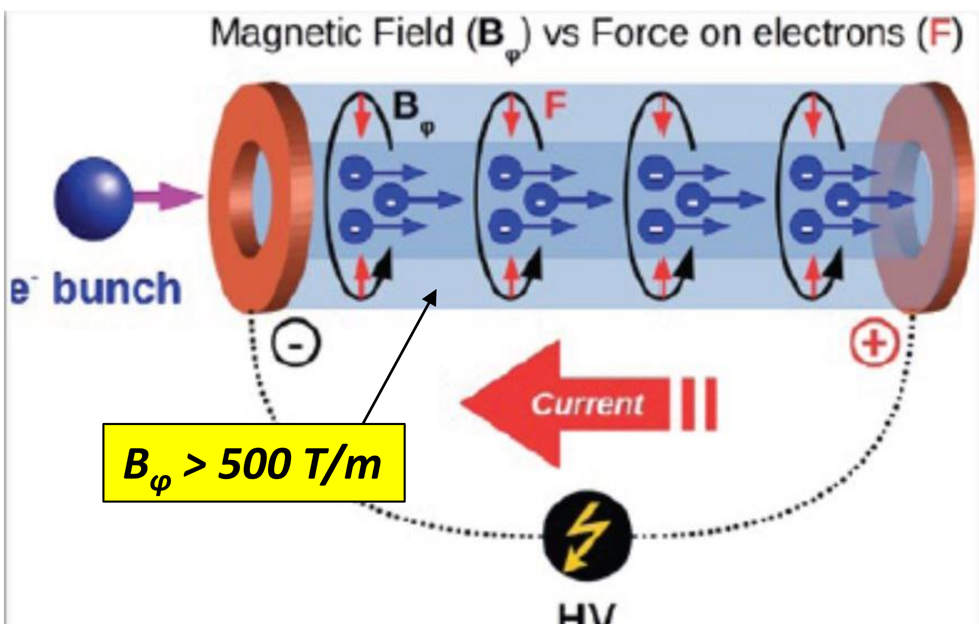


$n_e = 10^{16}$-10^{18} cm^{-3}
V = 15-20 kV
Imax = 50-1200 A
R = 1-2 mm
L = 1-100 cm

$$\lambda_p(\mu m) \approx 3.3 \cdot 10^{10} n_p^{-1/2}(cm^{-3})$$

$$\lambda_p \approx 330\mu m\ @\ n_p = 10^{16} cm^{-3}$$

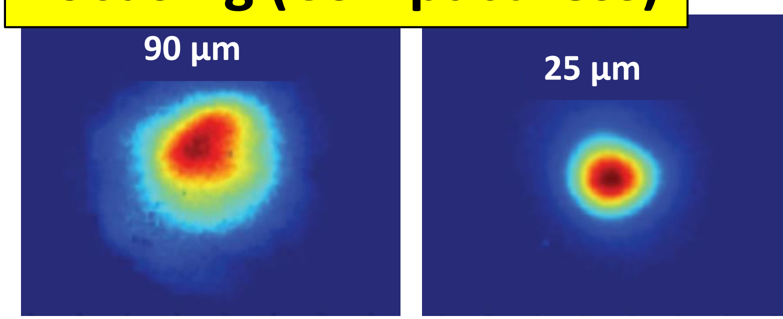
Plasma lens

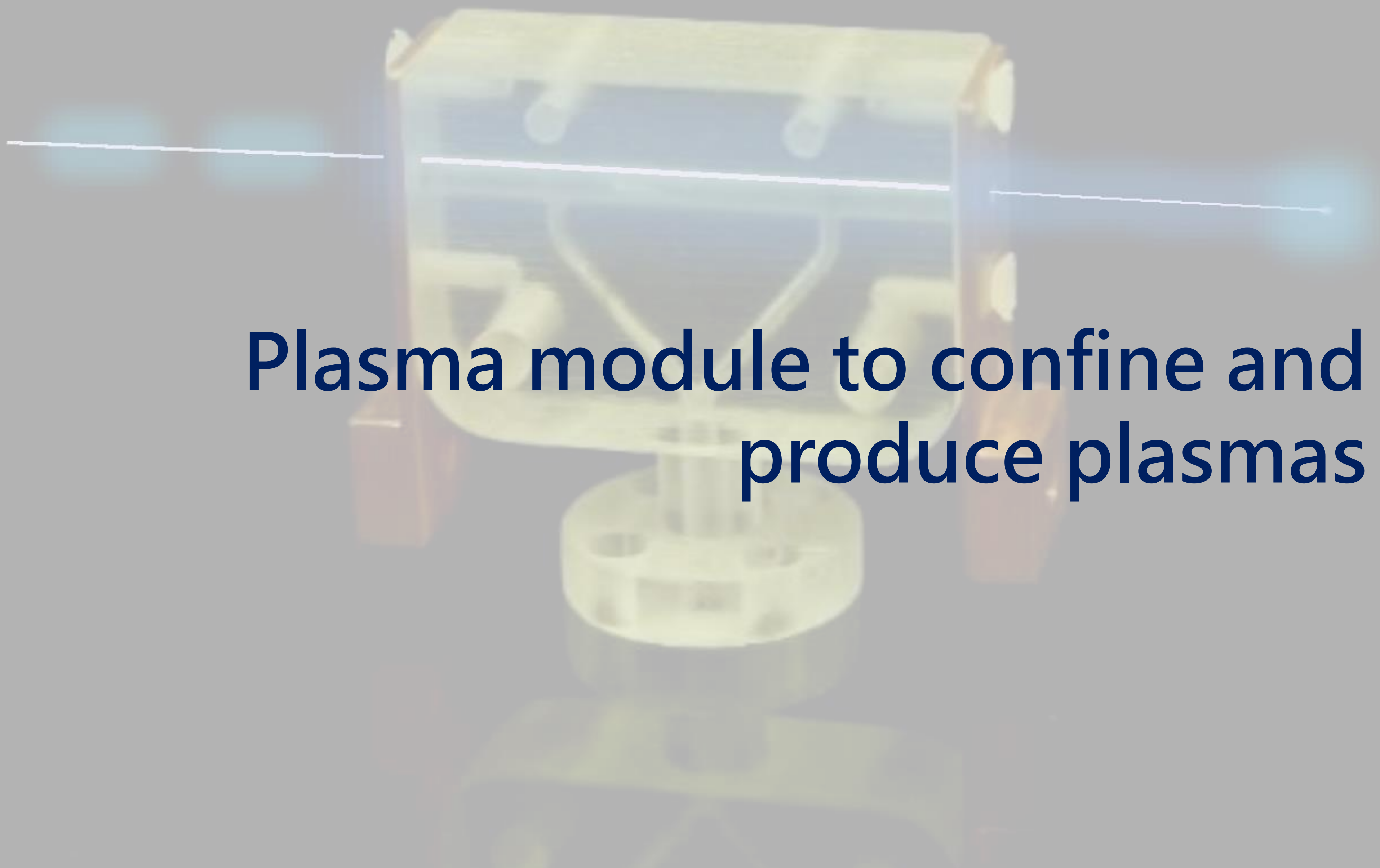


$$B_\phi(r) = \frac{\mu_0}{r}\int_0^r J(r')r'dr'$$

$$B_{cost}(r) = \frac{\mu_0 r i}{2\pi R^2}$$

Focusing (Compactness)





Plasma module to confine and produce plasmas

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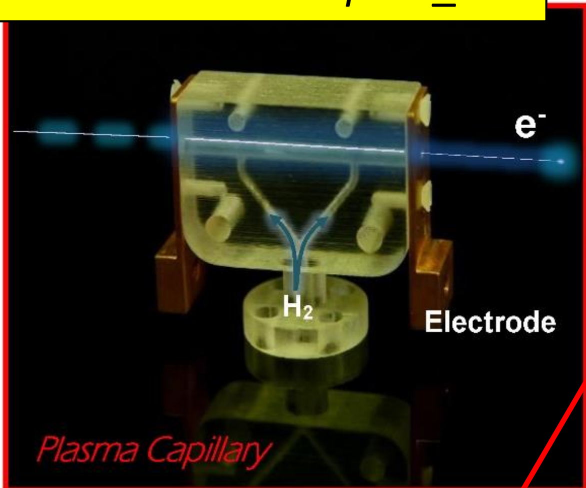
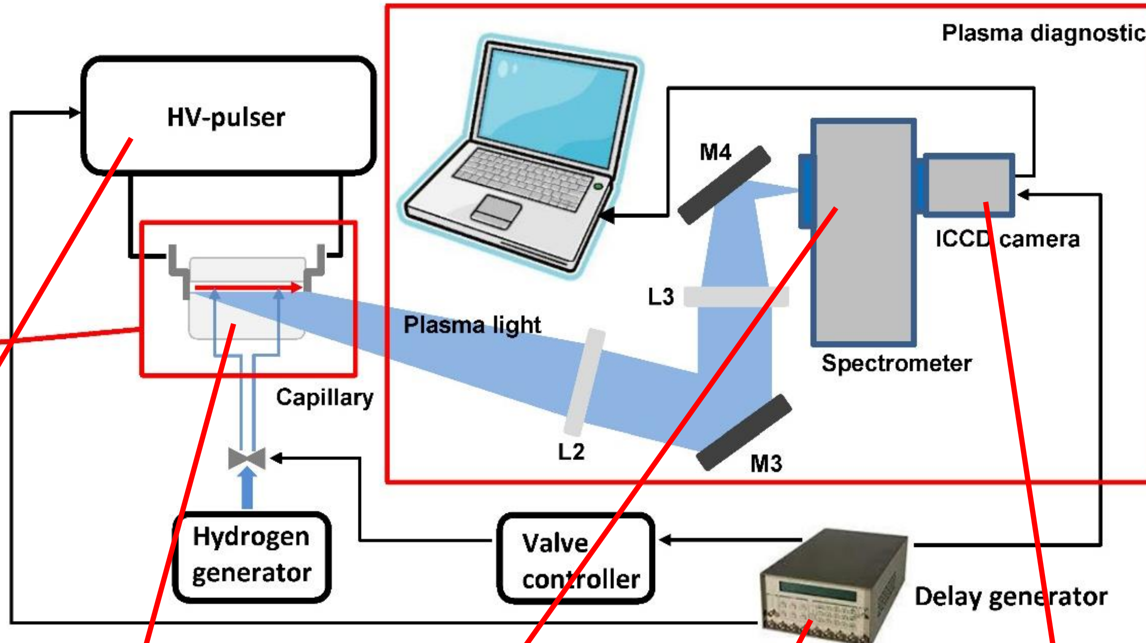
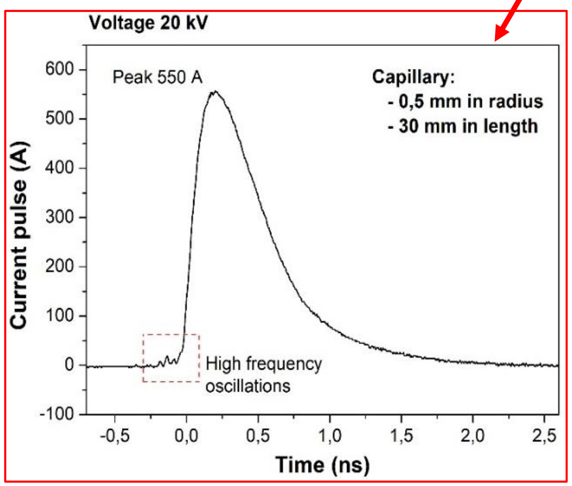
Plasma source at Sparc_lab







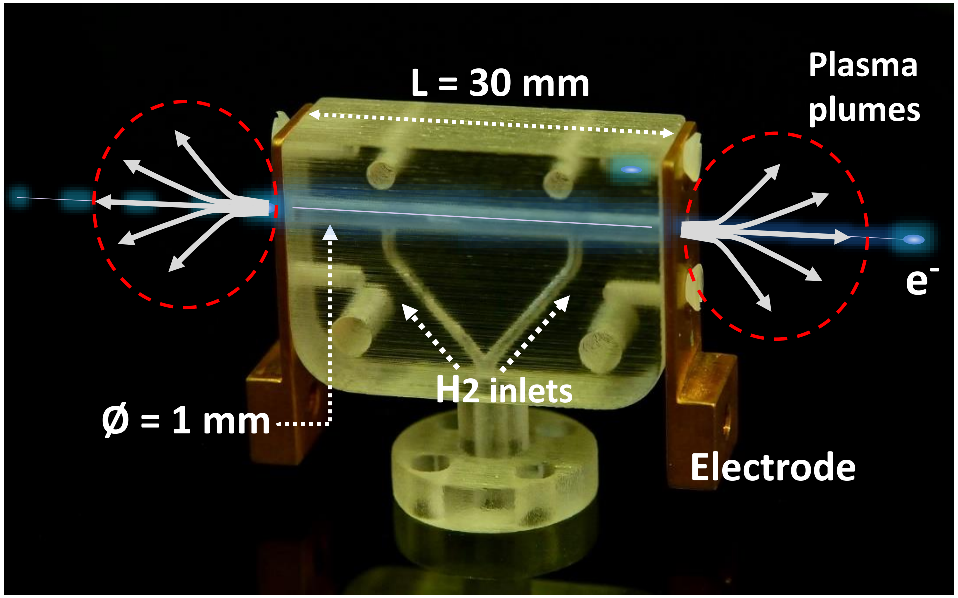
Capillary shapes:
- **Length (Energy)**
- **Radius (Density)**

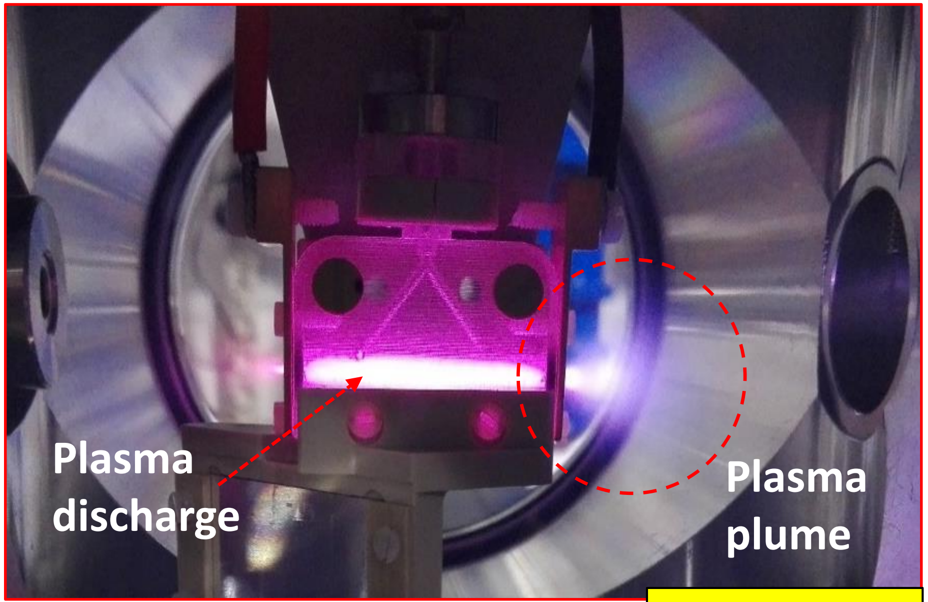
Timing:
- **Valve opening time**
- **Voltage delay time**
- **Trigger of ICCD camera**

Spectrometer:
- **Grating**
- **Optical alignment**

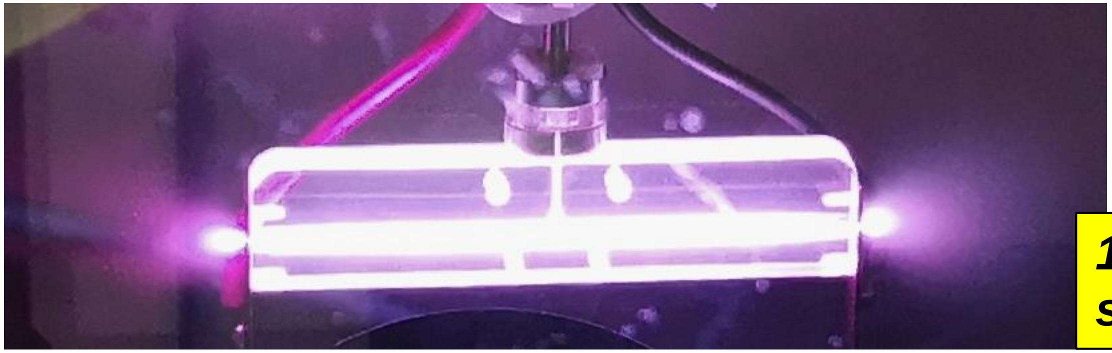
Camera timing:
- **Delay time**
- **Gate time**

Plasma sources: gas-filled discharge capillary





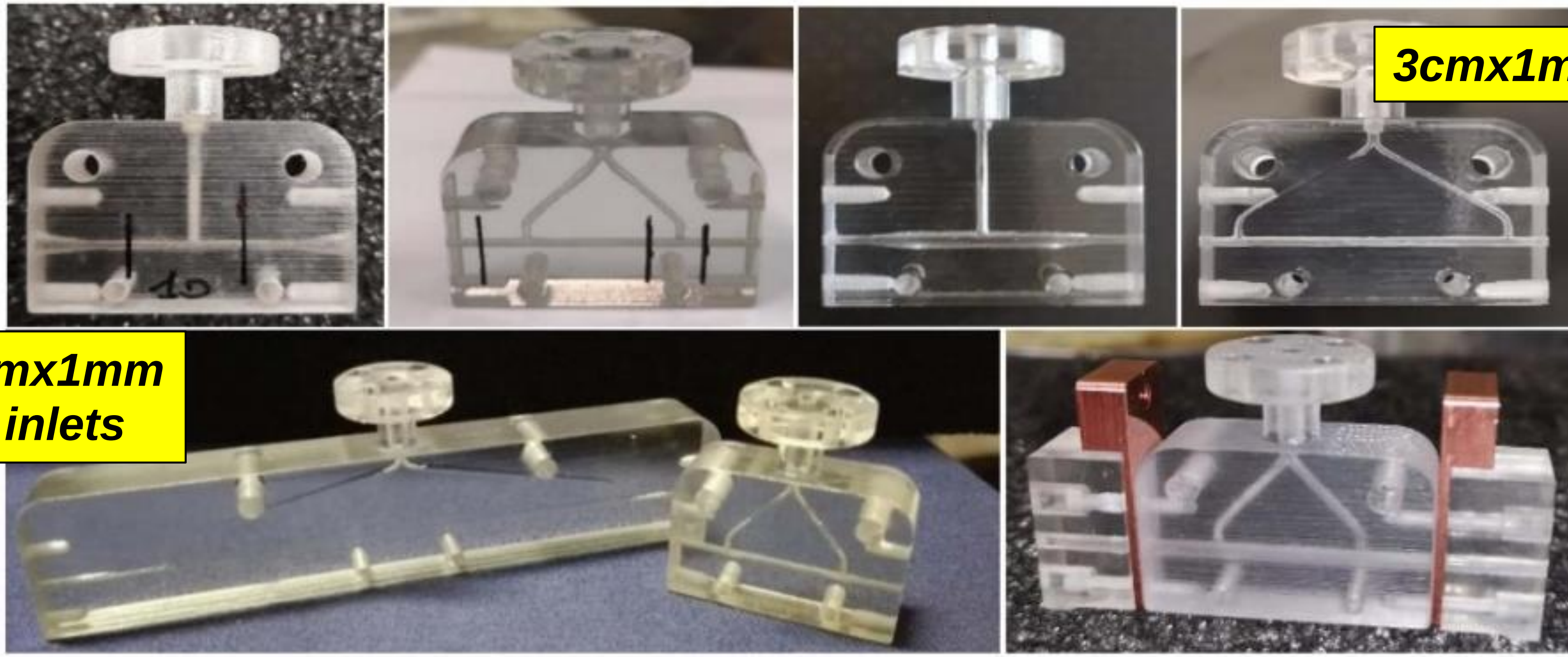
3cmx1mm two inlets



10cmx1mm single inlet

- Plasma plumes depend on different conditions of pressure, temperature and density between inside and outside (vacuum) of the capillary
- The expansion velocity and so the plume lengths depends on several terms as the dicharge voltage and the geometric properties of the capillary

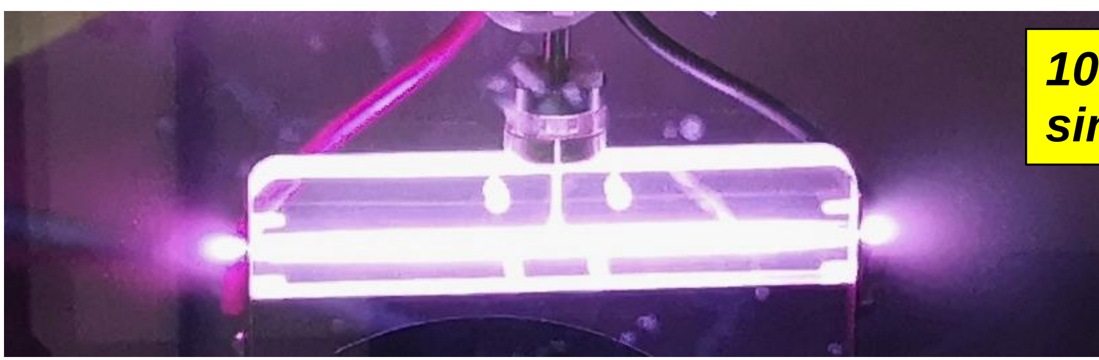
Plasma sources: gas-filled discharge capillary



3cmx1mm

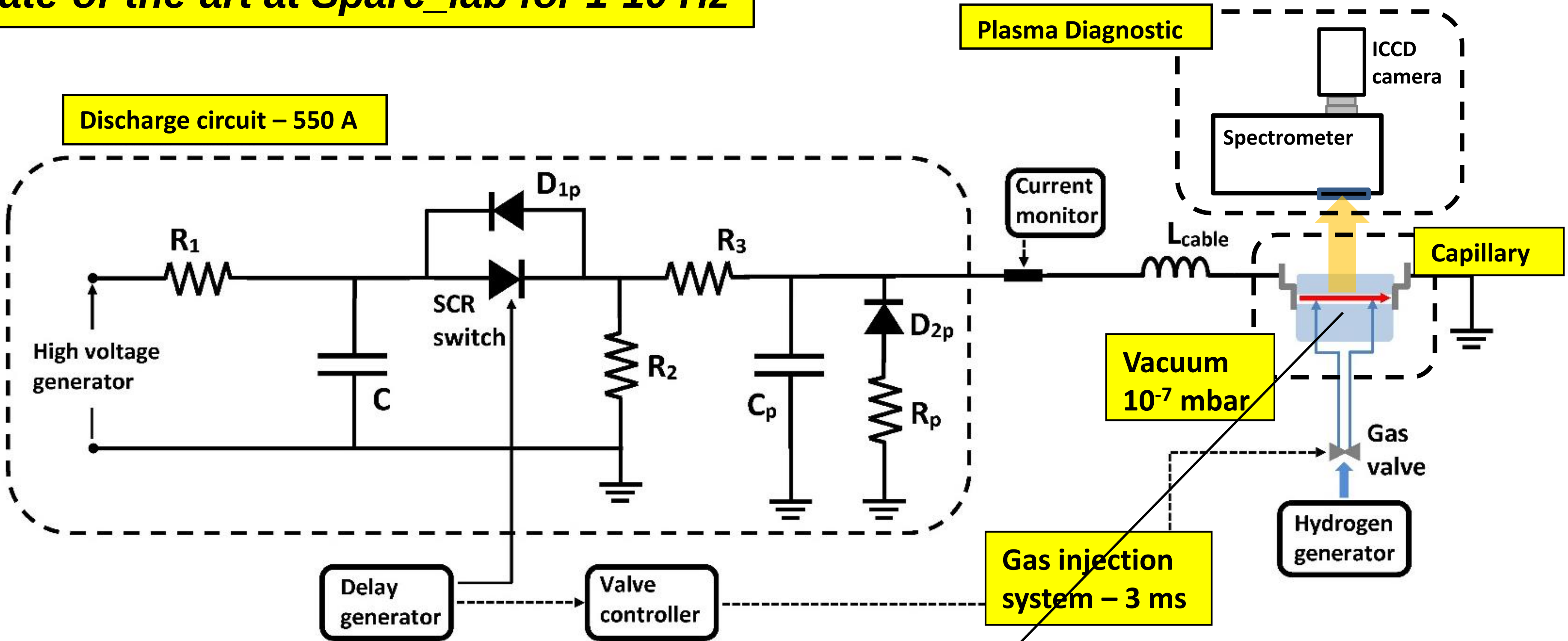
20cmx1mm two inlets

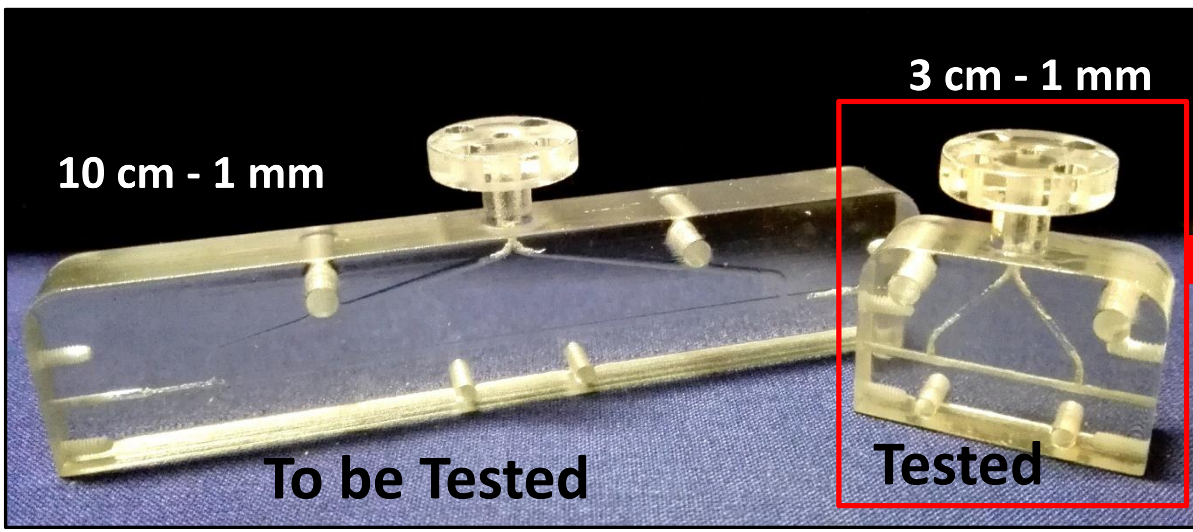
Plasma source characterization means to study the plasma behaviour as a fuction of many parameters: discharge voltage, position and number of the gas inlets, plasma channel shape and so on, that in turn will affect the quality of the accelerated beam



10cmx1mm single inlet

State-of-the-art at Sparc_lab for 1-10 Hz

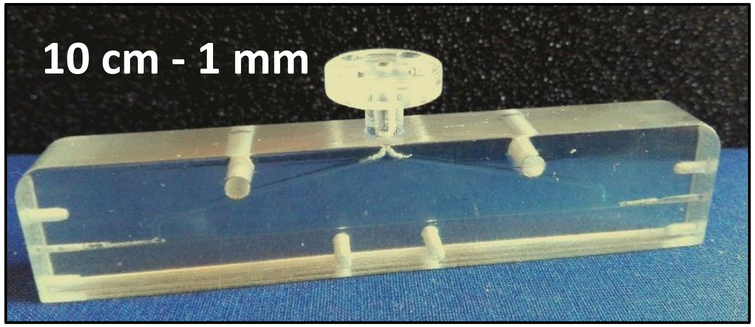




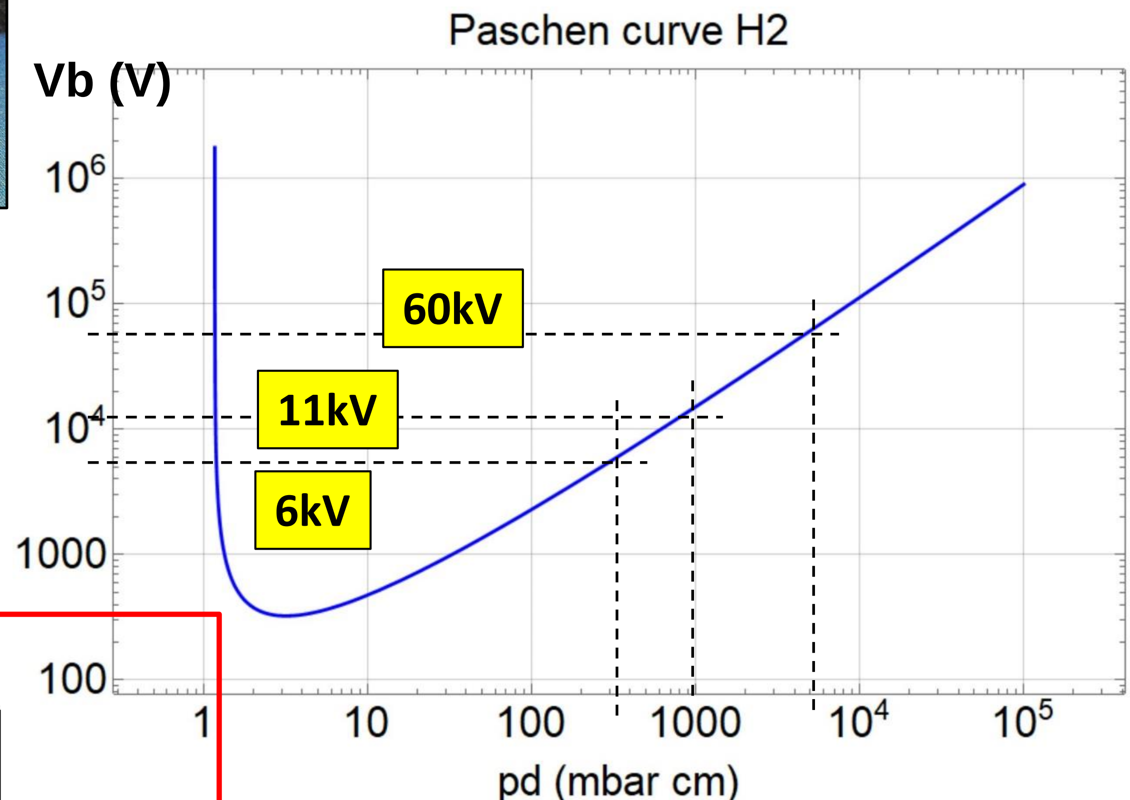
1-10 Hz

- 3 cm - 1 mm
- 3 cm - 2 mm
- 1 cm - 1 mm
- 2 cm - 1 mm

Plasma density (Stark broadening) 10^{16}-10^{17} cm^{-3}



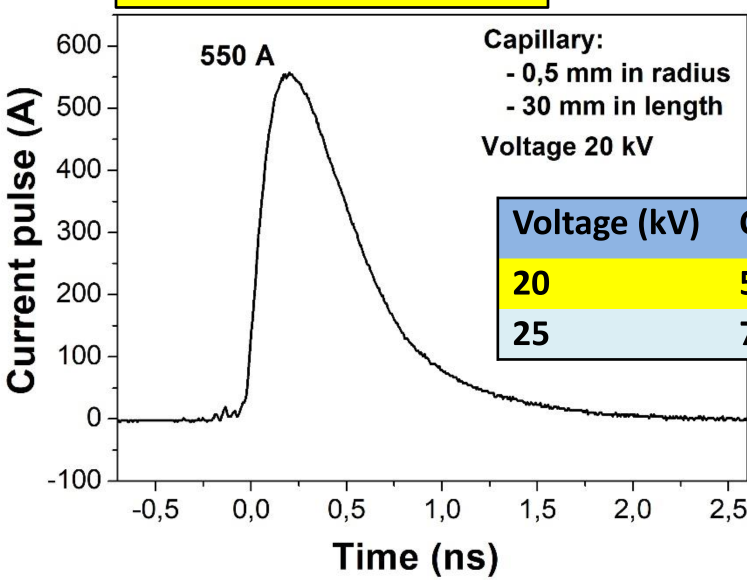
We will start to characterize longer capillary to reach the EuSPARC conditions (PWFA): 40 cm - 1.1 GV/m



Vacuum

Parameters: 10 Hz/3 ms	
Duration	**Vacuum (mbar)**
Starting values	1.3×10^{-9}
t_0	4.3×10^{-8}
60 min	6.4×10^{-8} (10^{-8})

Discharge circuit



Voltage (kV)	Current (A)
20	550
25	700

Gas injection

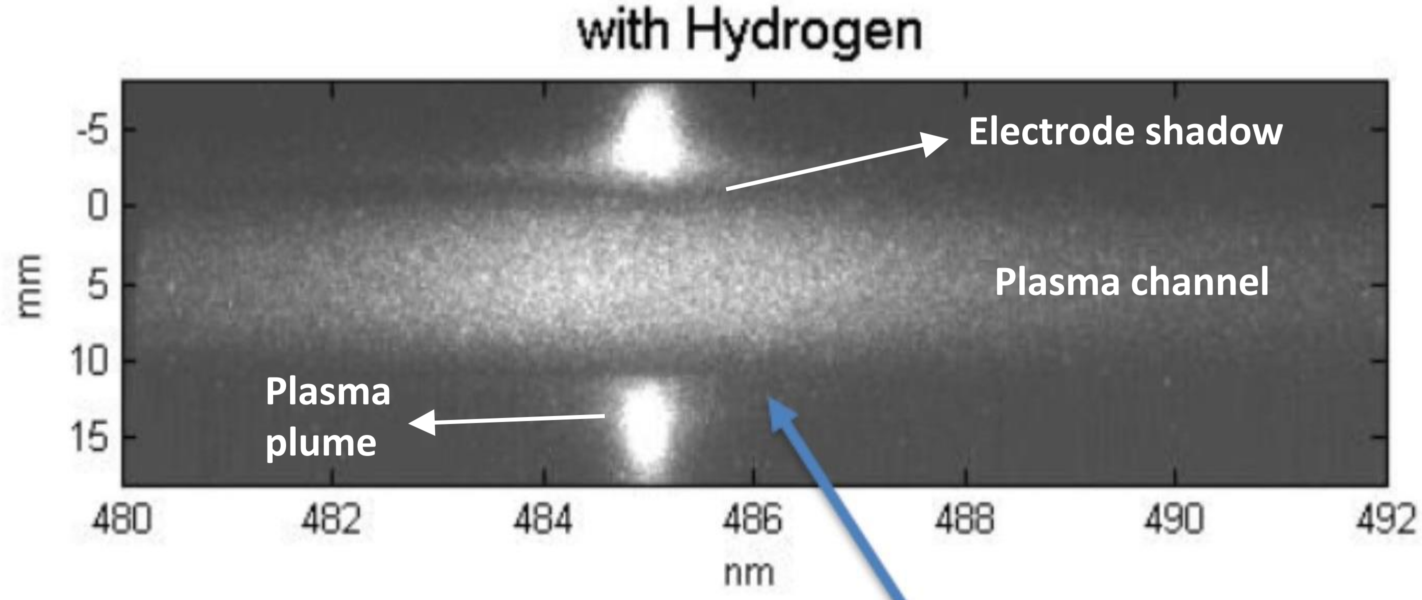
Capillary shape	3 cm 1mm	10 cm 1mm	40 cm 1mm
Opening time	5 ms	14 ms	48 ms
Voltage	6 kV	11 kV	60 kV

Density measurements

Stark broadening method

$$n_e = 8.02 \times 10^{12} \left(\frac{\Delta\lambda}{\alpha} \right)^{3/2} cm^{-3}$$

By using the Stark broadening method to measure the plasma density, we obtain the below result: the larger is the Balmer line (Δλ), the higher is the electron density of plasma



Balmer Beta line B_β due to transitions from the outer orbit n=4 to the orbit n=2

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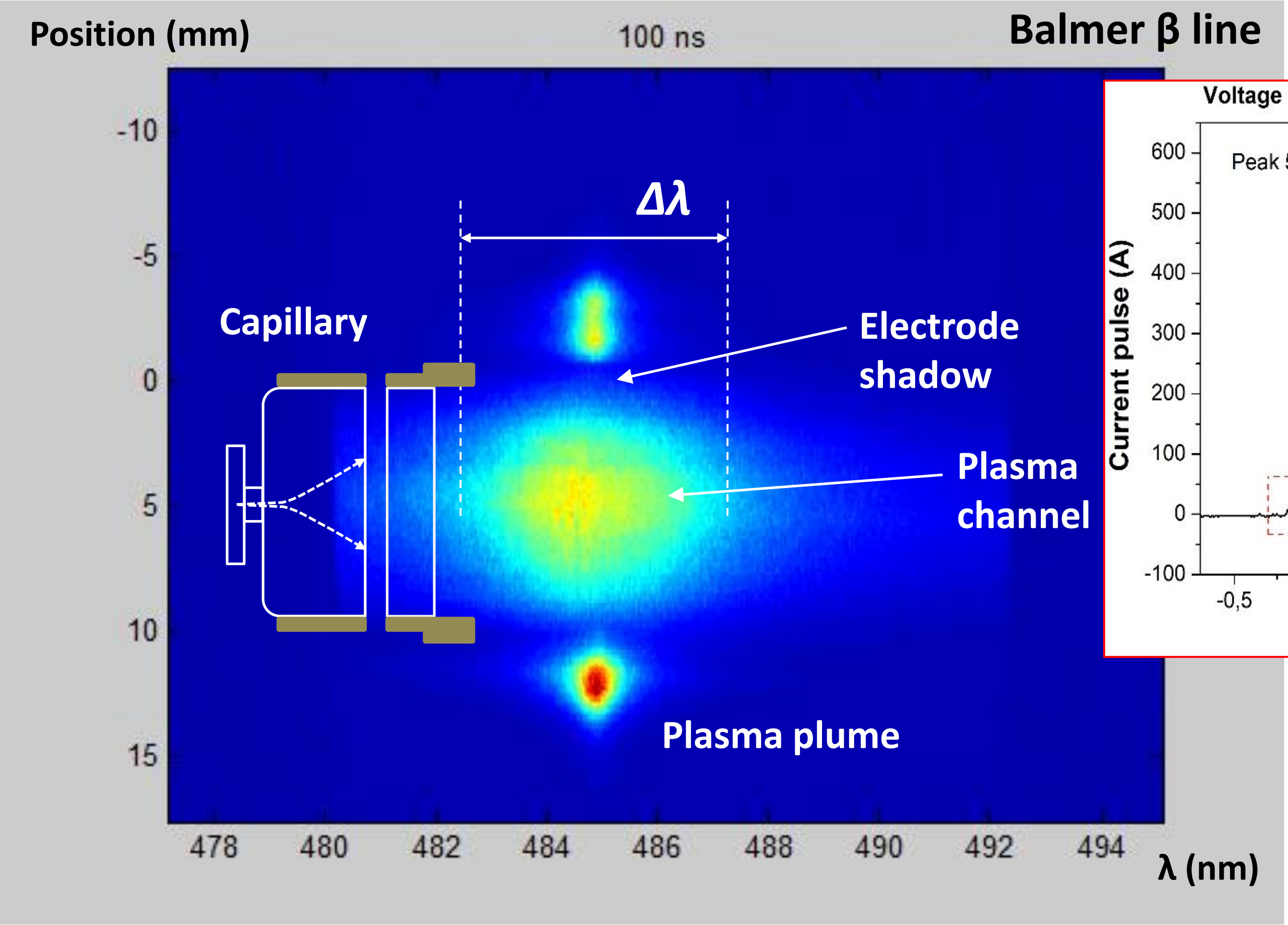
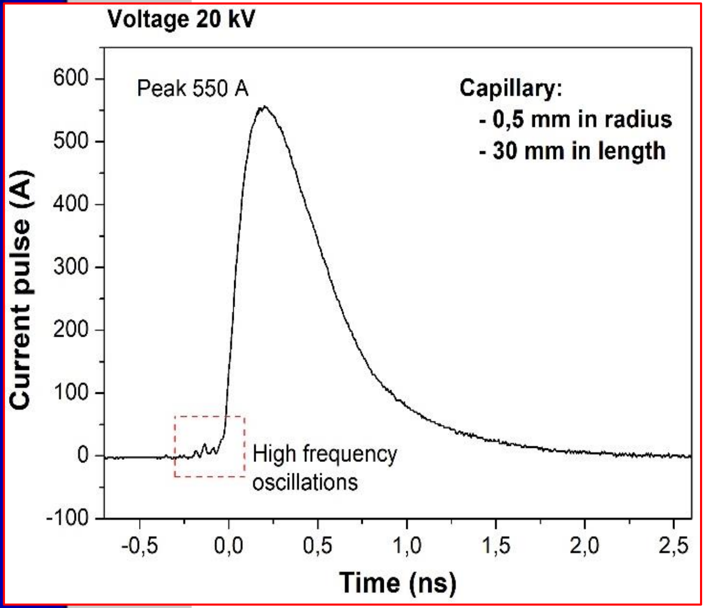
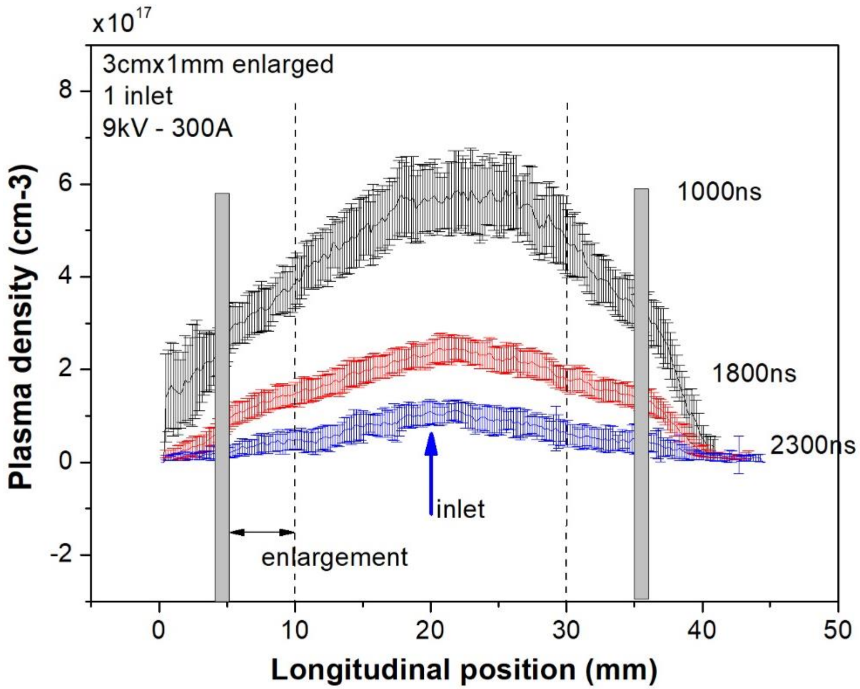
Density measurements

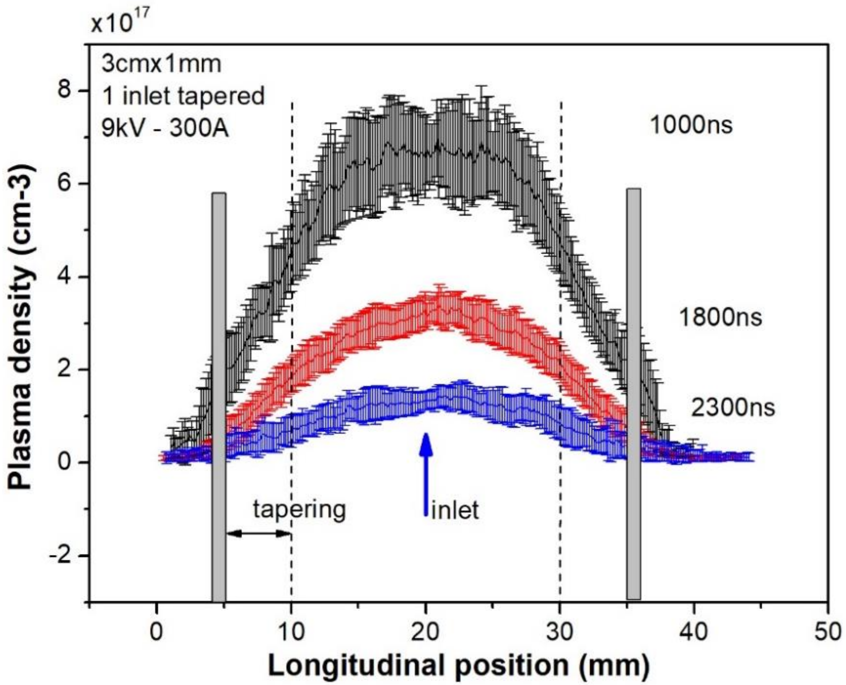
Plasma density inside and outside the capillary will change during the current pulse: such a behaviour it is very important to select when inject the electron bunch

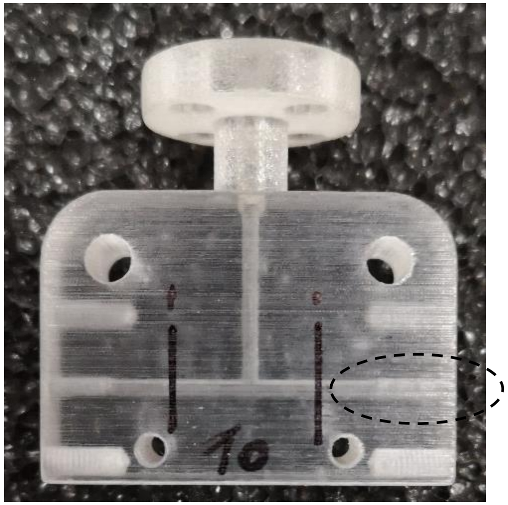


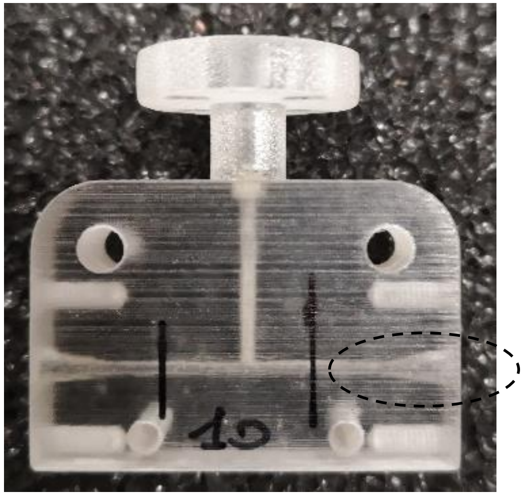


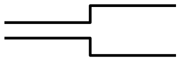
Density measurements: Longitudinal profiles

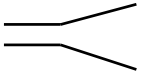






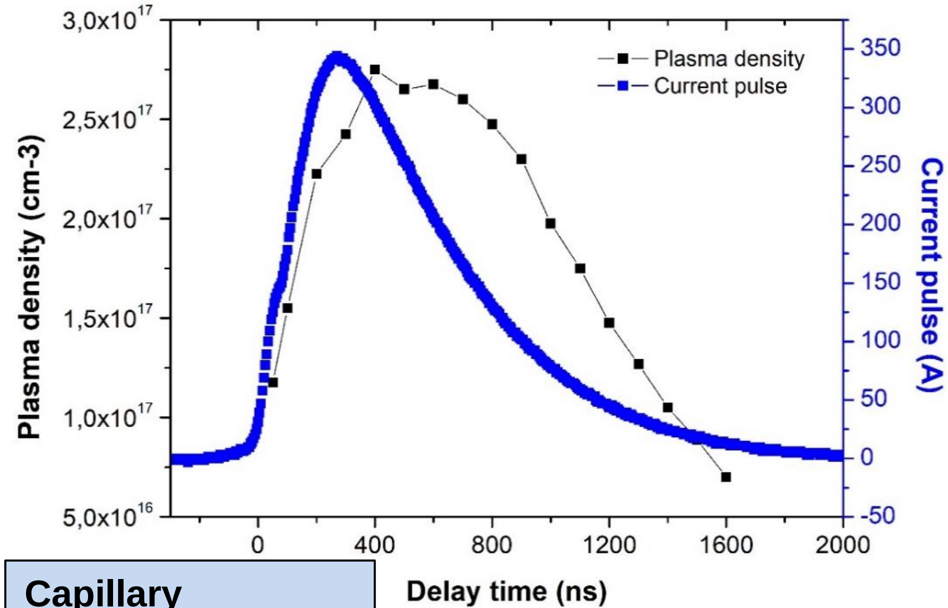




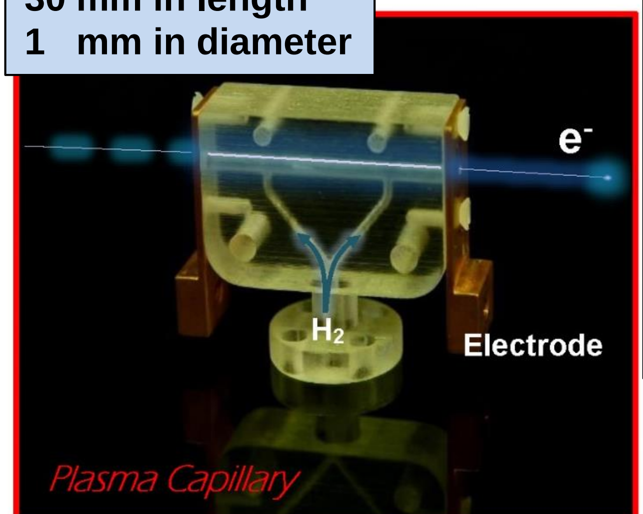


Plasma density measurements

Time-resolved measures



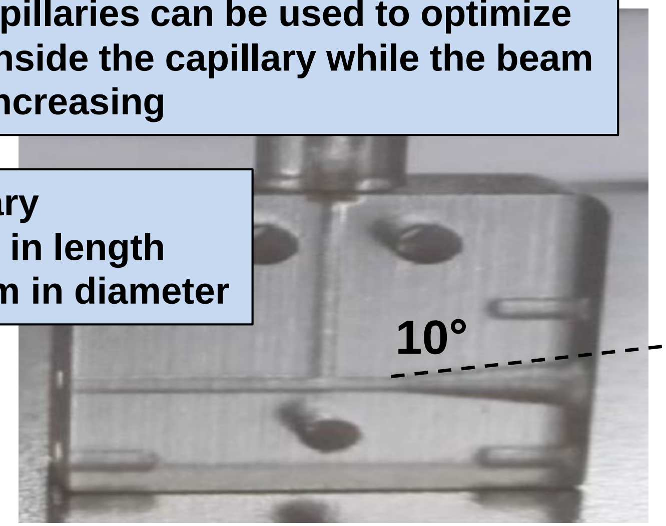
Capillary
30 mm in length
1 mm in diameter



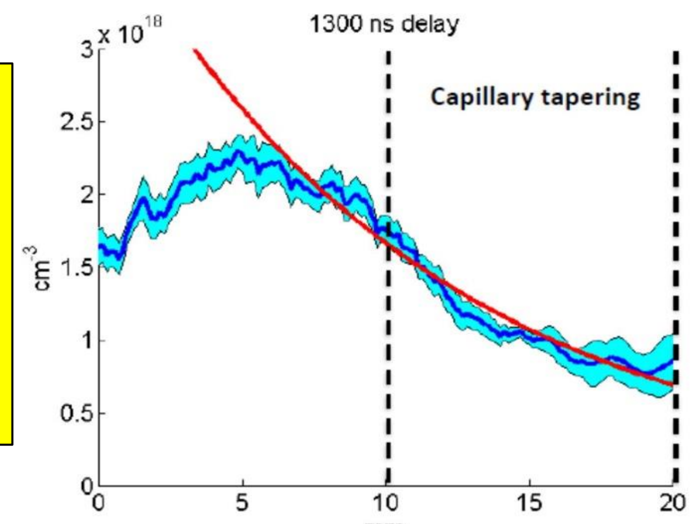
By using the Stark broadening method we measure plasma densities as a function of the delay time from the zero-time of the current pulse and for each one we obtain a longitudinal profile of the density itself

Space-resolved measures

Tapered capillaries can be used to optimize matching inside the capillary while the beam energy is increasing

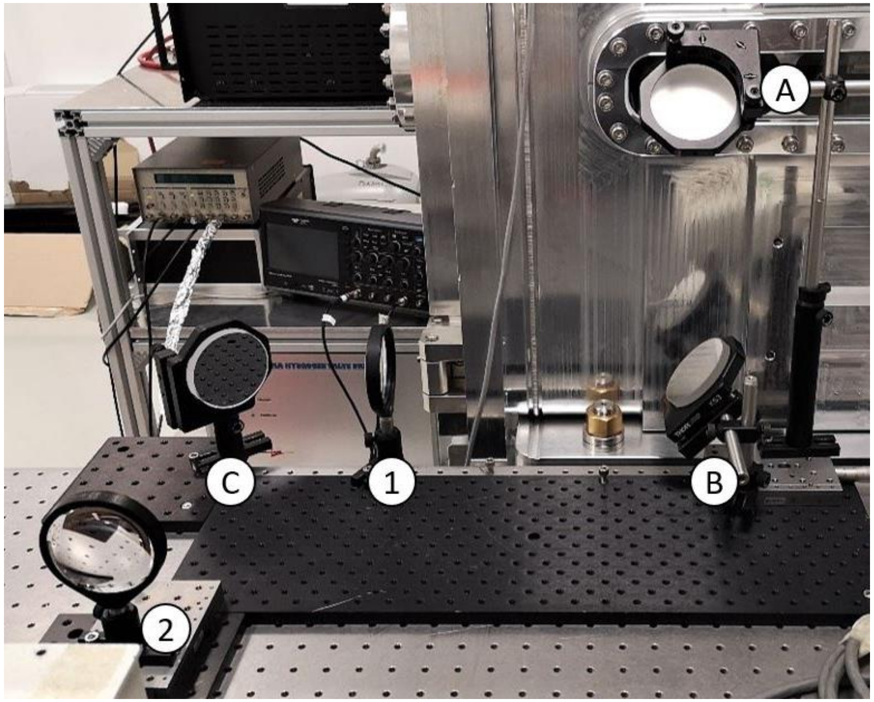


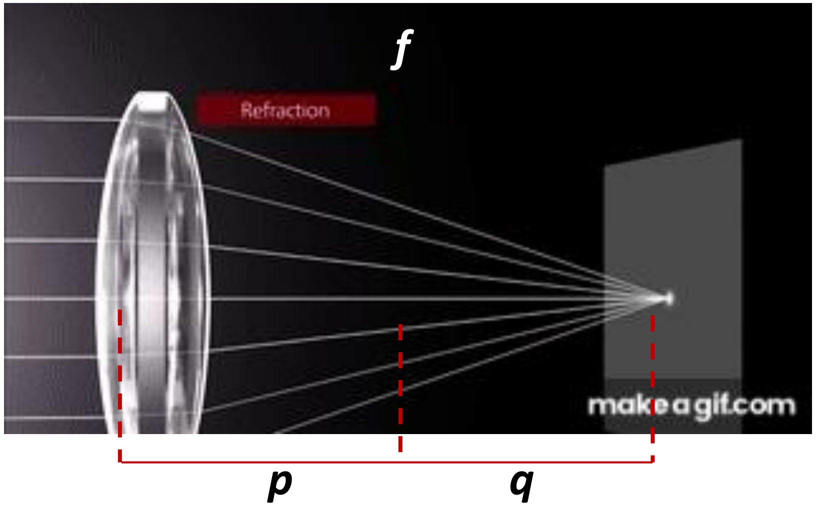
Capillary
30 mm in length
0.5 mm in diameter



Filippi et al. NIMA(2018), DOI: 10.1016/j.nima.2018.04.037

HOW IS THE CAPILLARY CHARACTERIZED?





A. Mirror 1
B. Mirror 2
C. Mirror 3

1. Lens 1
2. Lens 2

LENSMAKER'S EQUATION:

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{q}$$

MAGNIFICATION FACTOR:

$$M = \frac{q}{p}$$

In case of two lenses, there will be p1 and p2, q1 and q2, f1 and f2

Thank you for your attention

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