EuPRAXIA@SPARC_LAB - The plasma section

R. Pompili, A. Biagioni

February 22, 2021

On behalf of the WA5 and SPARC_LAB collaboration

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

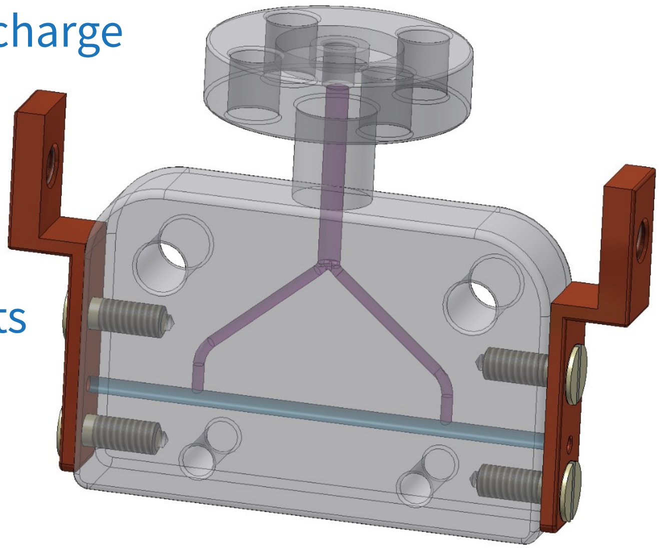
Plasma source – experience @ SPARC_LAB

During past 5 years we have employed the following setup

- 3D-printed capillaries with different geometries (length, hole, number of inlets)
- Fast electro-valve (3 ms opening) used to inject Hydrogen
- Hydrogen is produced by electrolytic generator
- Ionization by high-voltage (10-20 kV) high-current (100-1kA) discharge
- Operation @ 1 Hz

So far some major upgrades have been done

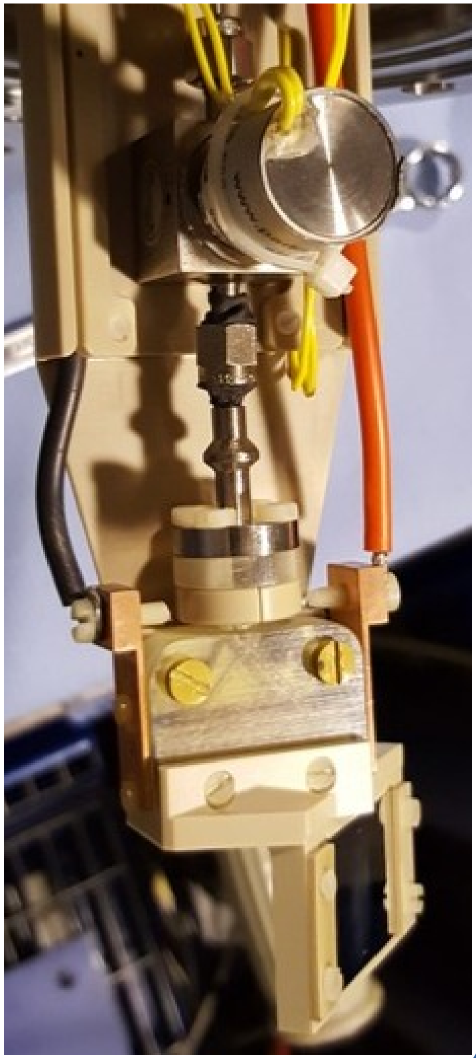
- Elongations above the electrodes (aka “spacers”) guiding the jets
- External laser stabilization to reduce the timing-jitter
- Electro-valve insulation to remove discharge instabilities



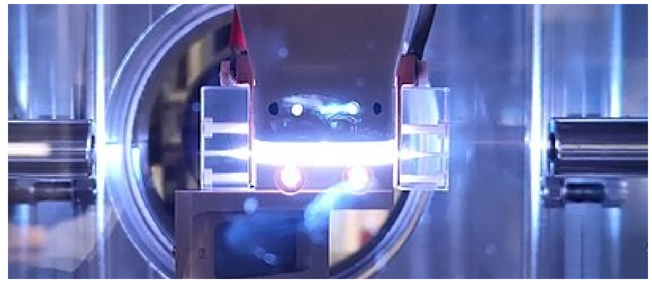
For EuPRAXIA we’ll start by extending such technology to longer capillaries

Plasma source – experience @ SPARC_LAB

Original setup

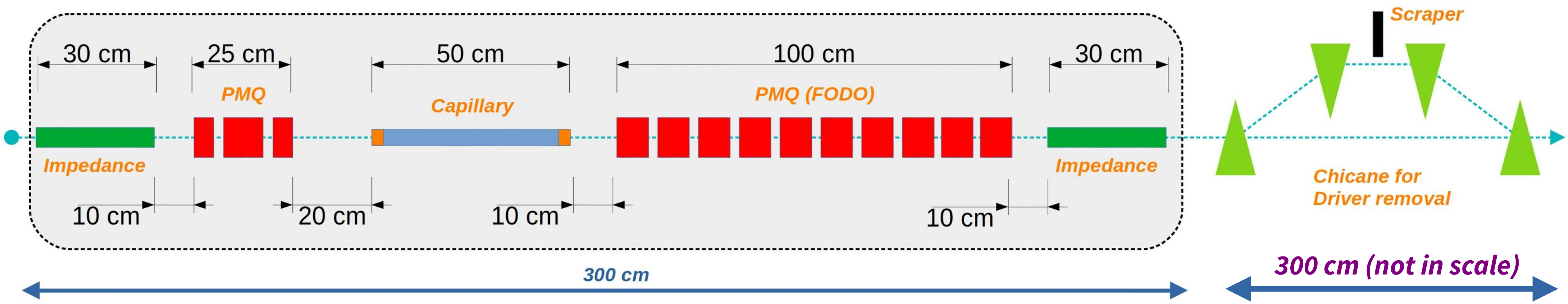


Use of "spacers"



Additional insulation

Plasma layout – option #1

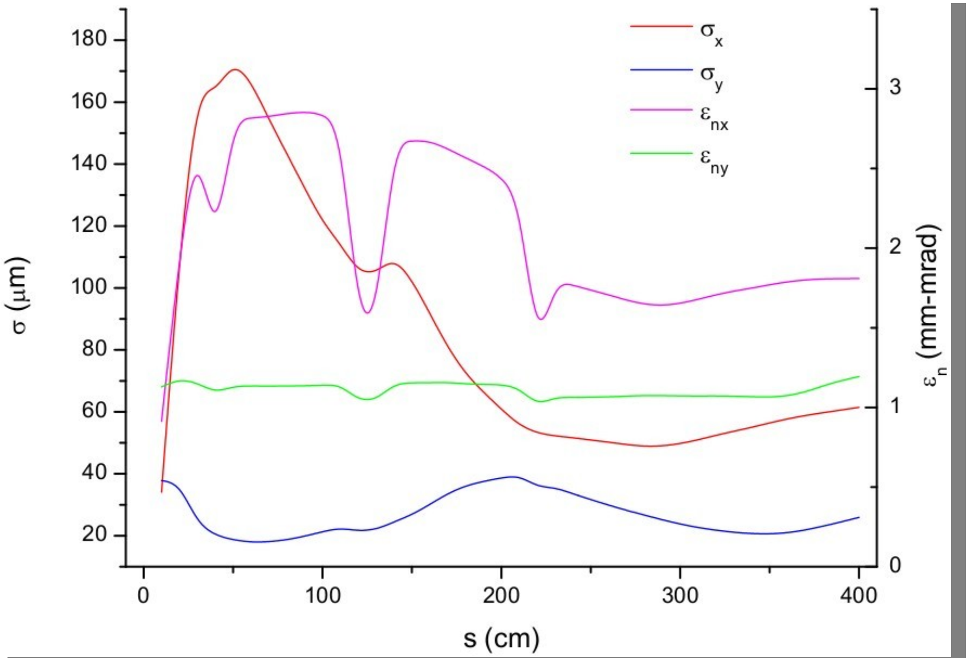


From CDR, first idea is to use a long "gentle" FODO to extract the witness.

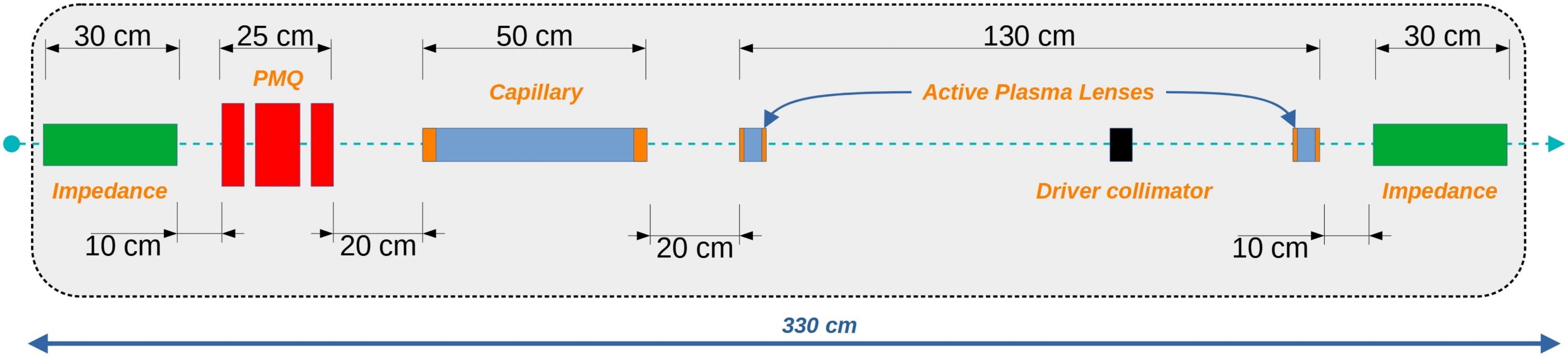
Major part of the driver is still transported

A magnetic chicane must be used to separate witness and driver in energy and cut the latter with a scraper

Simple solution but require some space and single independent tuning for each PMQ



Plasma layout – option #2



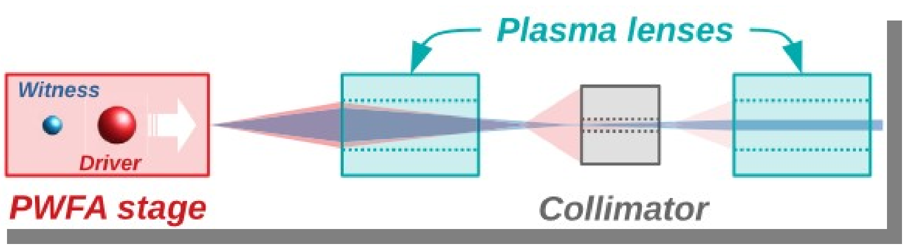
Active-Plasma lenses to extract the witness and remove driver

- Witness is catch and transported without loss of charge
- Driver is over-focused at the collimator entrance and its charge removed

Pompili, R., et al. "Plasma lens-based beam extraction and removal system for plasma wakefield acceleration experiments." Physical Review Accelerators and Beams 22.12 (2019): 121302.

Study performed on the EuPRAXIA@SPARC_LAB reference working point

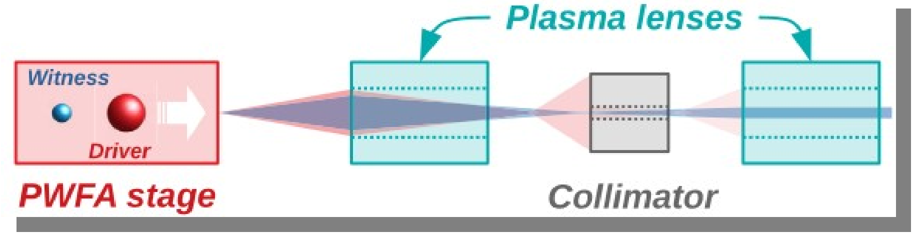
- It requires two active-plasma lenses and a lead collimator.
- Solution would benefit of compactness and tunability.
- However puts more load on the vacuum



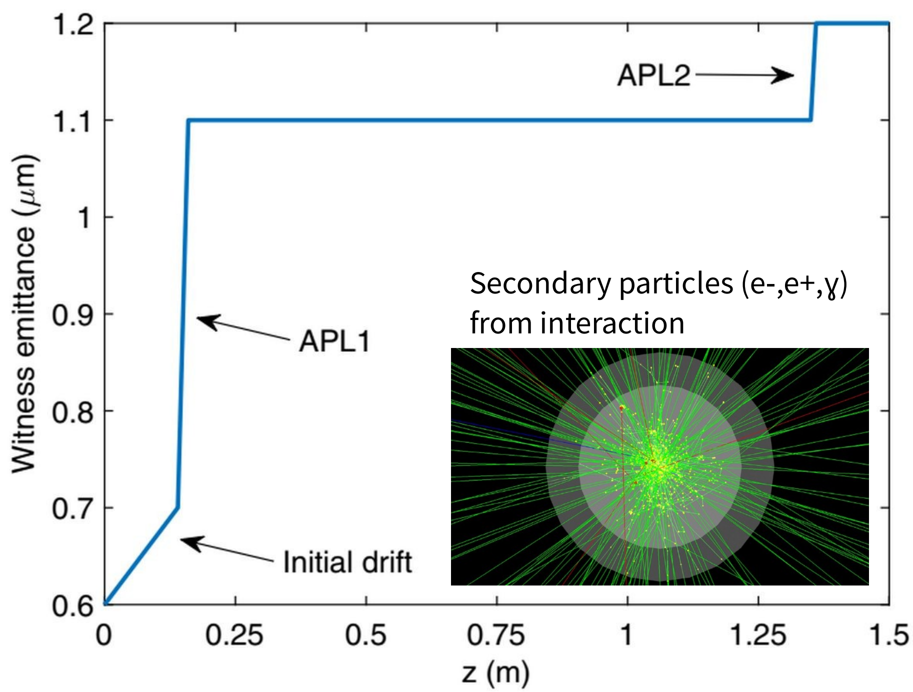
Driver removal system

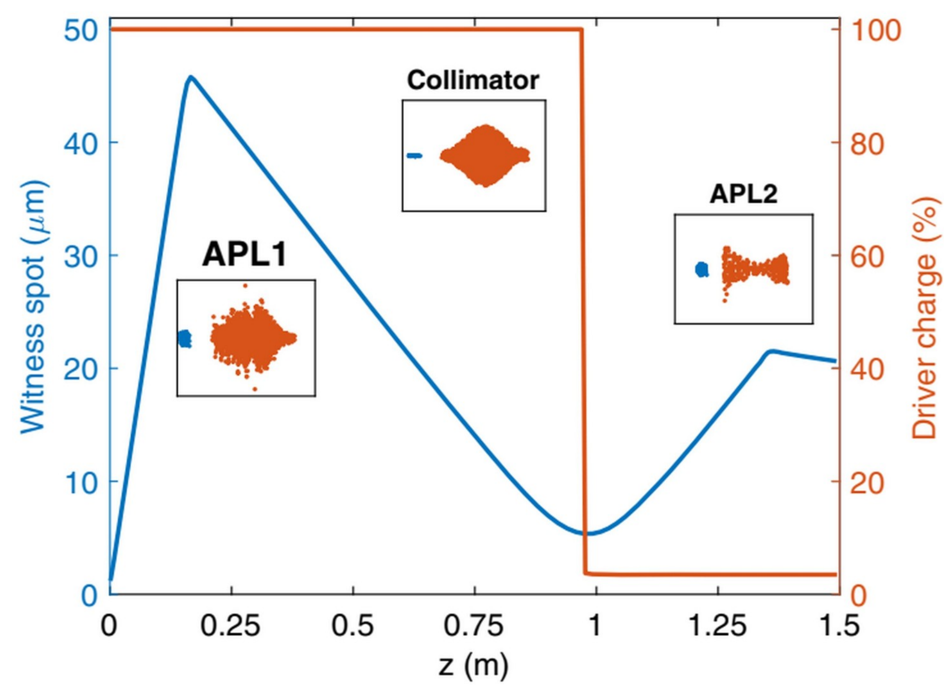
The study showed two main effects

- Emittance growth due to active/passive lenses
- Physics simulation for the collimator (GEANT4)
- No wakefield from small aperture collimator (CST)



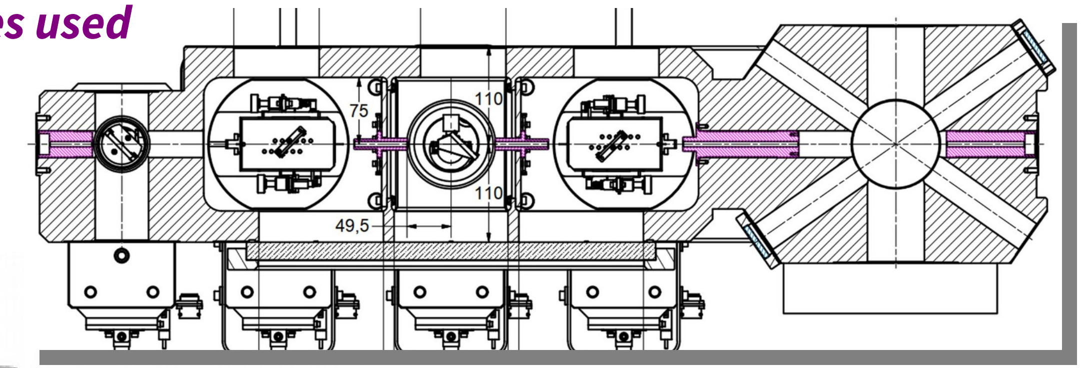
	Size (cm)	Radius (mm)	z (cm)	I_D (kA)	n_p (cm^{-3})
APL 1	2	0.5	15	1	10^{16}
Collimator	3	0.2	97		
APL 2	1	0.5	135	0.6	10^{16}

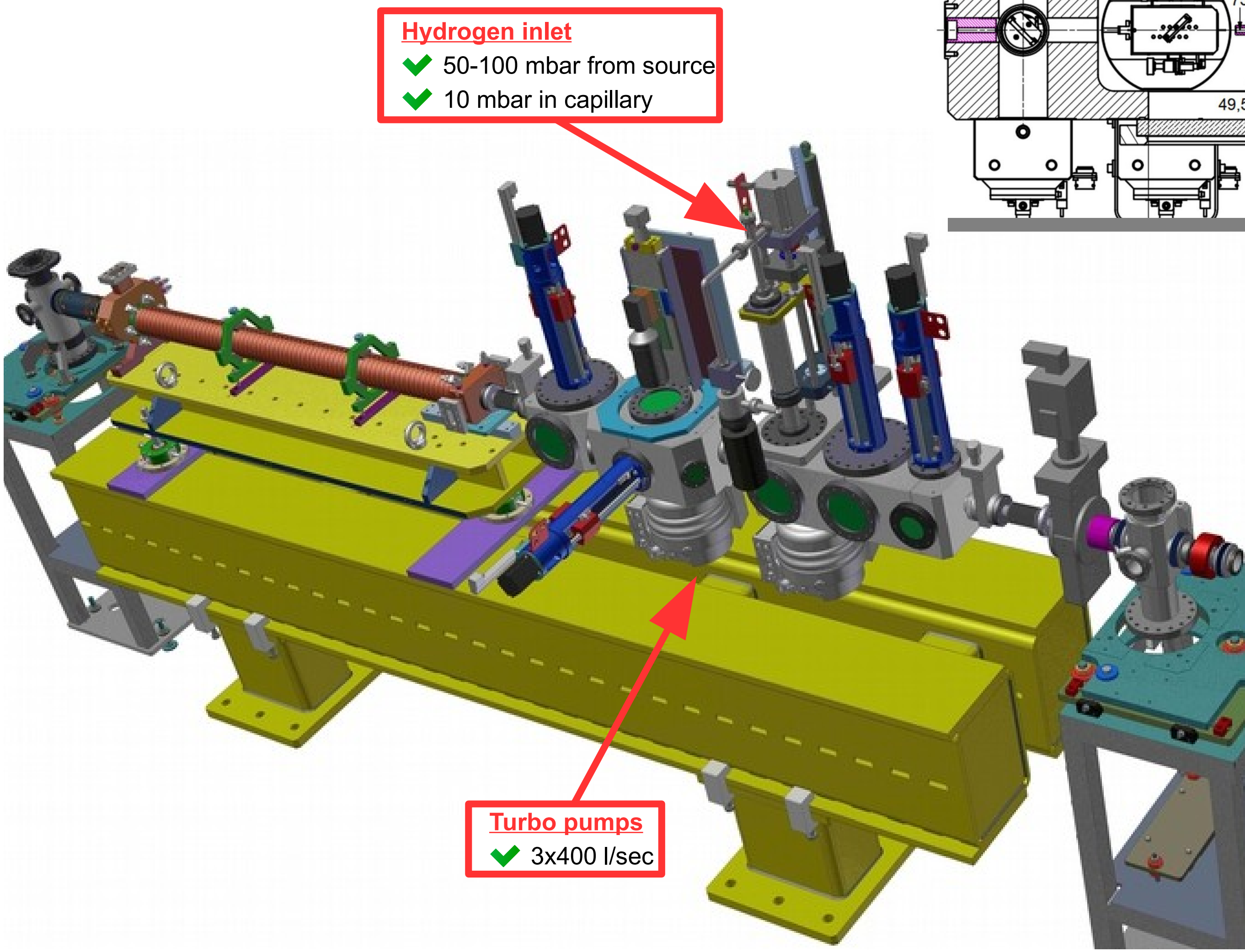




Differential pumping system @ SPARC

5 vacuum impedances used





At SPARC we already use differential pump system

- Three-stages windowless
- 10^{-8} mbar H2 pressure at 0.5m from the capillary

Stable operation @ 1 Hz

- Can be extended to 10-100 Hz as required by EuPRAXIA?

Vacuum R&D

SPARC_LAB

Stable operation of differential pumping system @ 1 Hz with 10-20 mbar Hydrogen pressure in the capillary. It required 5 impedances (6 mm hole diameter, 5-10 cm length) upstream and downstream the capillary to better separate its environment from rest of the machine.

Vacuum of the linac is preserved

Window-less system. Emittance degradation due to multiple scattering avoided

EuPRAXIA

Needs to operate at 10-100 Hz. Long plasma structures will be employed, much more gas will be injected. Differential pump system would be great, but is it practicable?

Possible mitigation solutions/alternatives:

- Use of different gases. Argon, Nitrogen are more vacuum "friendly".
- Use of thin windows (mylar, kapton, etc) before/after the capillary. Effects on the beam must be checked before.

Ongoing studies, R&D

PLASMA_LAB, offline measurements

Tests with long capillaries (20-40 cm)	→ September 2021
Tests with different gases (N, Ar)	→ May 2021
Tests with high currents (~kA)	→ April 2021
Tests with closed capillaries	→ June 2021

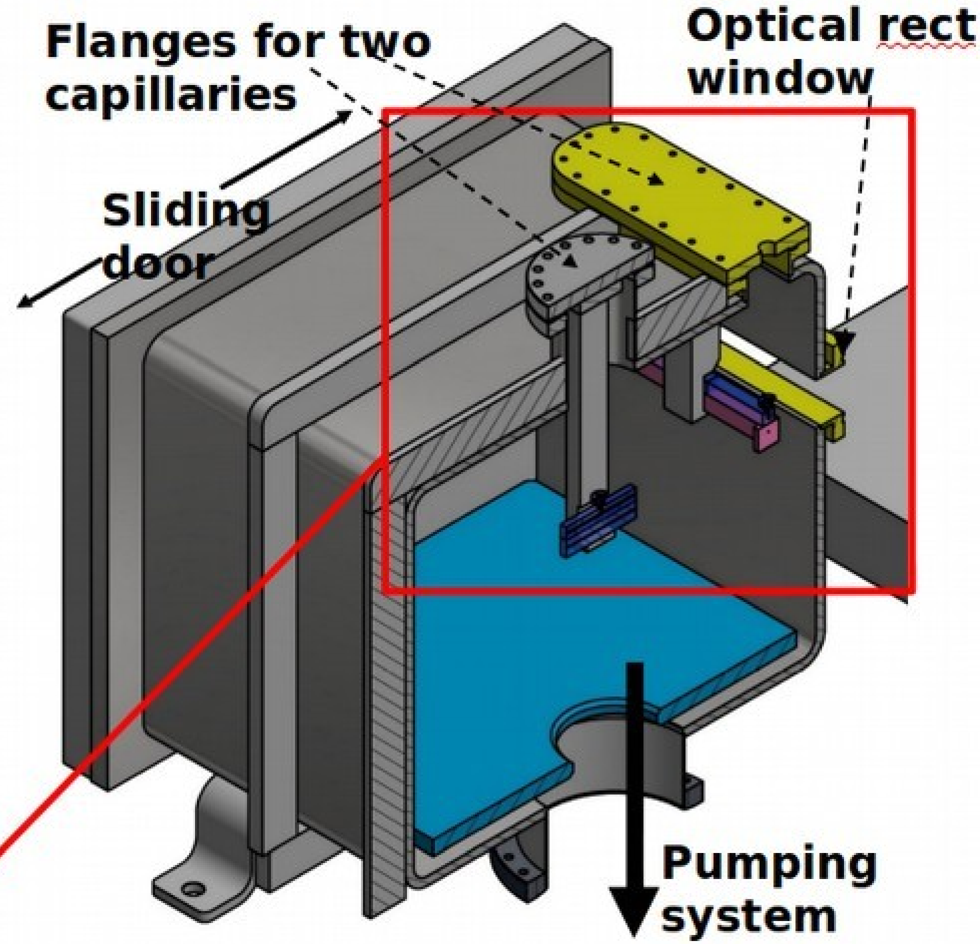
SPARC, beam-based measurements

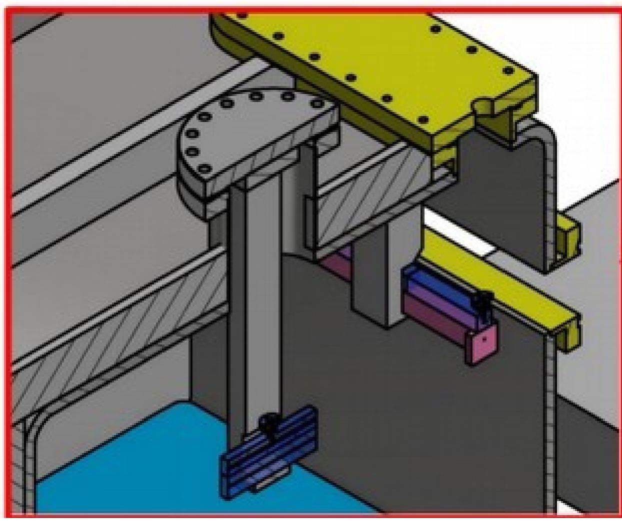
Study of plasma instabilities with beam-based measurements	→ July 2021
Determination of maximum repetition rate within the SPARC environment	→ May 2021
Study of beam interactions with thin mylar/kapton windows	→ July 2021
Driver/witness separation	→ ongoing
Determination of maximum witness energy-chirp	→ June 2021

Vacuum chamber for offline tests

thanks to V. Lollo

- Test of longer capillaries up to 400-mm length
  - Eupraxia 1.1 GeV (400 mm-10E16)
  - Eupraxia 5GeV: it is possible to study the segmented capillary (2-3 meters)
- New gas injection system and so new capillary shape to optimize plasma formation
- Two chambers in plasma lab with two acquisition systems

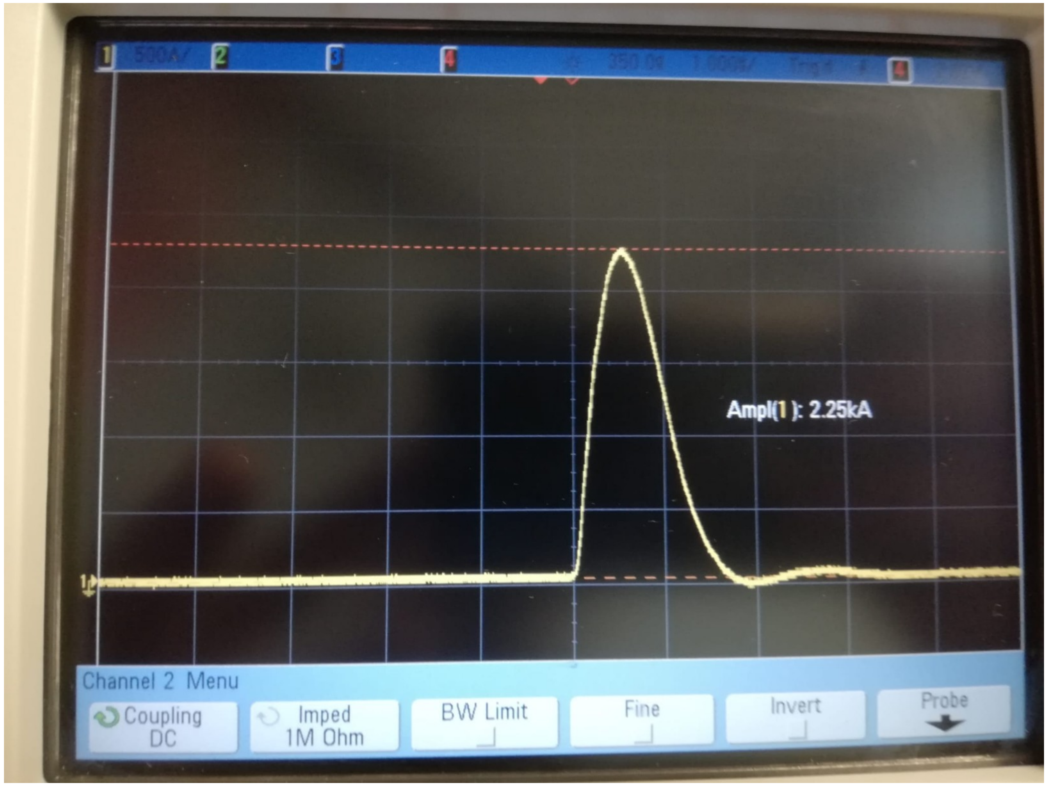




- Larger dimensions: 800x480x700 mm
- Sliding doors
- Two different settings for capillaries
- Rectangular window for diagnostics (50 cm)
- Side windows for other applications (Laser, etc)

High-current discharge

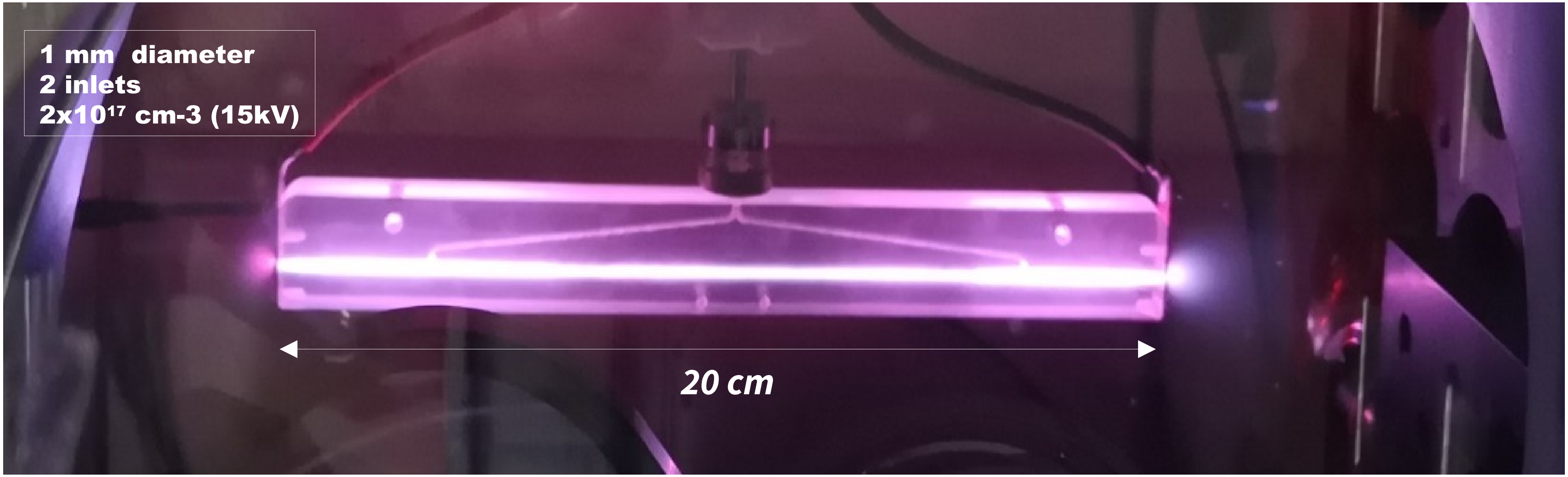
HV pulser (thanks to D. Pellegrini)



First results @ 2.25 kA

Long capillaries study

***First Eupraxia goal*:** 1.1 GeV (1.5 GV/m - 40-cm capillary – Plasma density 10^{16} cm-3)



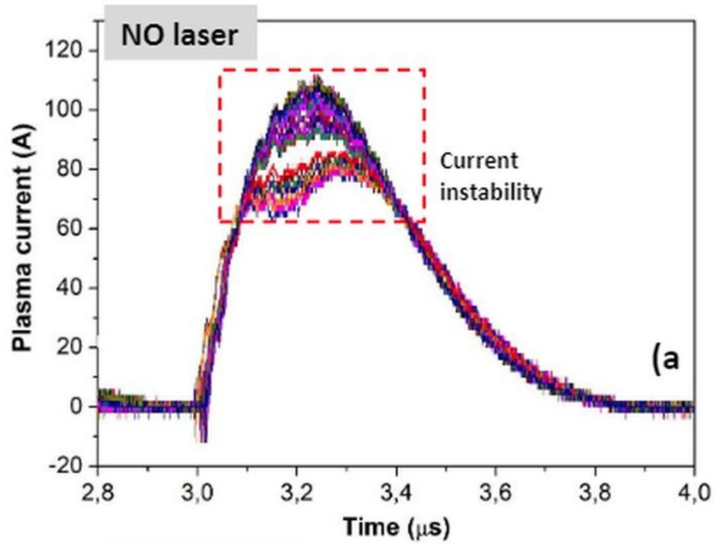
Longest capillary that Has been studies was 20 cm (limited by Available space in the Vacuum chamber)

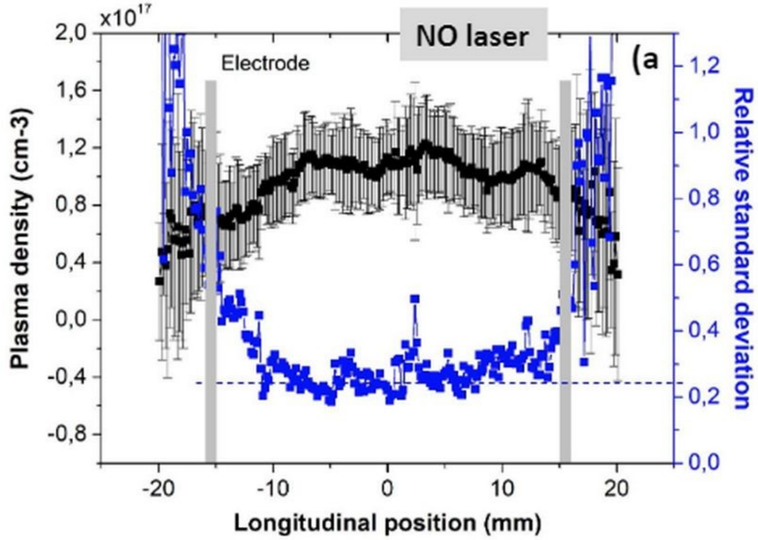
Length	*Density*	*Vb*
3 cm	3×10^{17} cm-3	2 kV
10 cm	3×10^{17} cm-3	6 kV
20 cm	3×10^{17} cm-3	10 kV
40 cm	3×10^{17} cm-3	20 kV

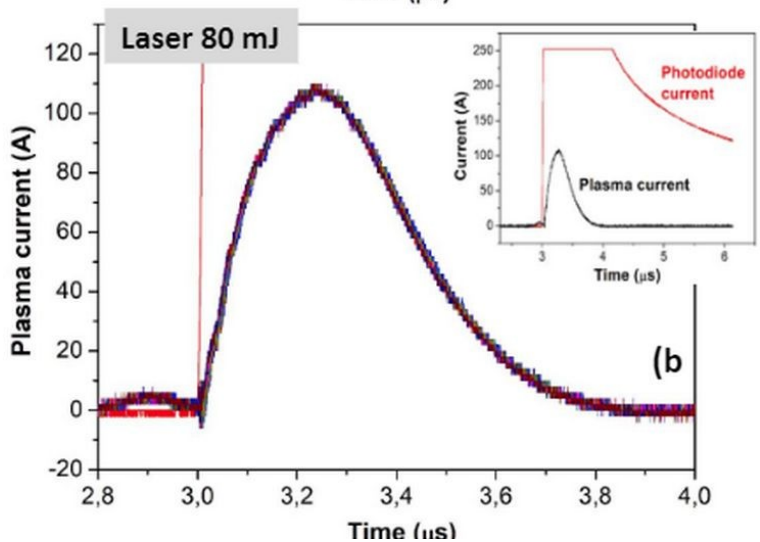
Paschen law

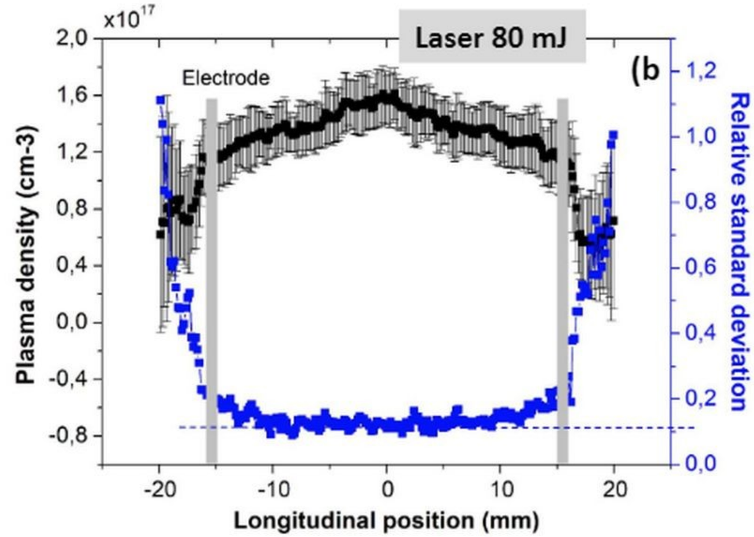
External laser stabilization

Plasma density instability reduced from **25% to 11% @ 5 kV**
Instability of **~5%** when operating at >8 kV (from Stark meas)

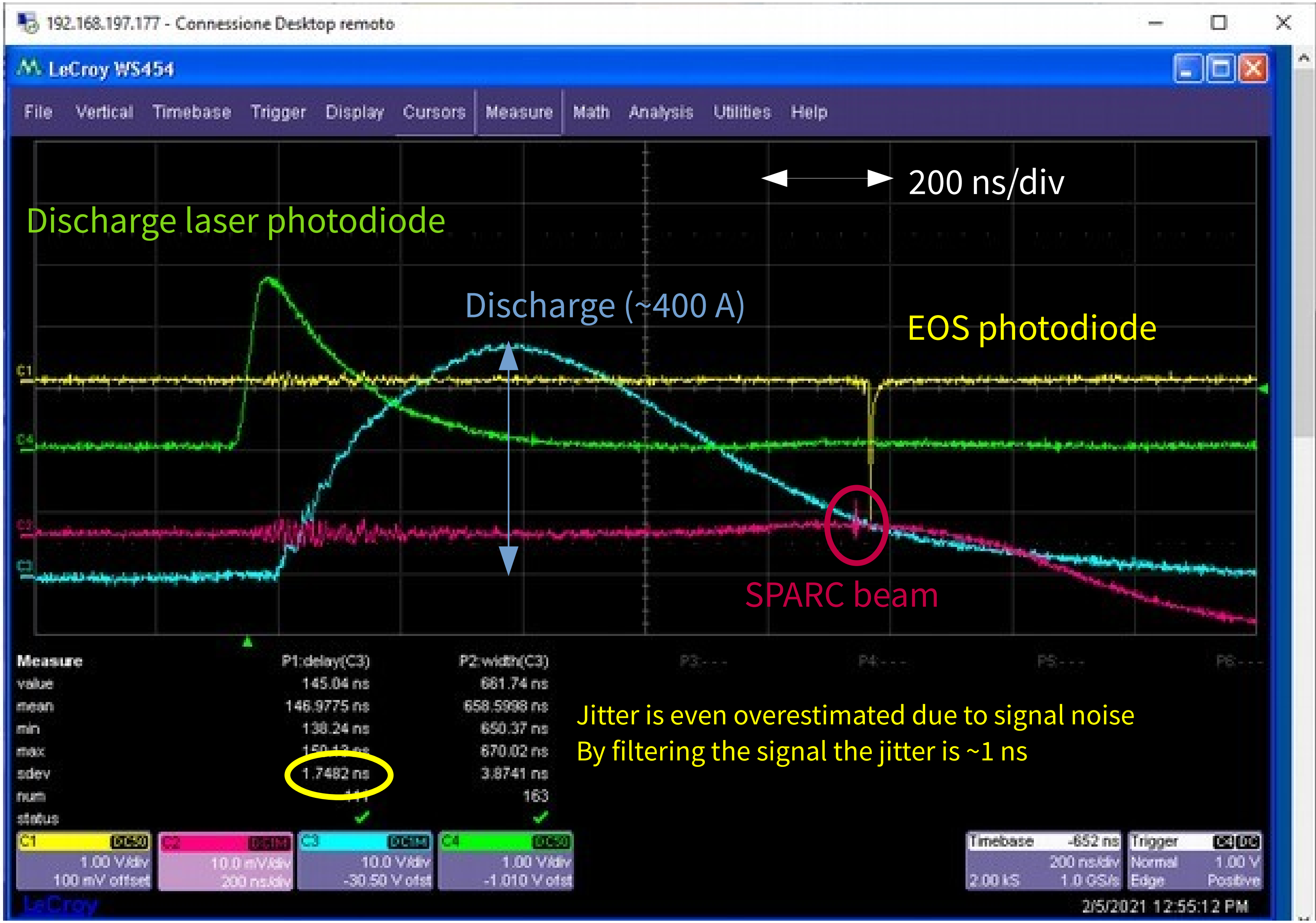




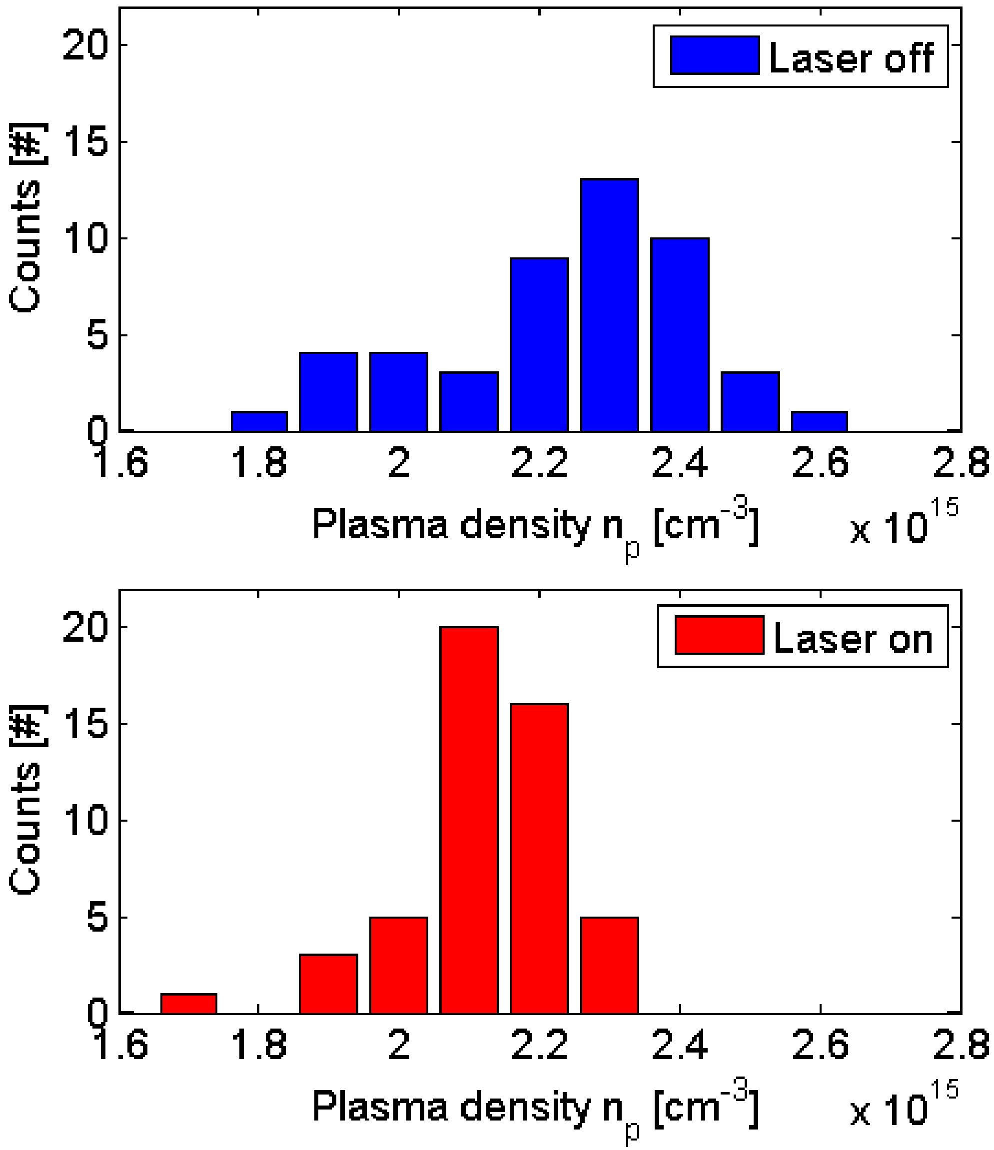




External laser stabilization



Beam-based study (preliminary)



Plasma density was measured via LPS (50 images) in the new capillary at the delay -2600 ns with trigger laser on and off (11 kV HV)

Laser OFF results

$$n_p = 2.2 \cdot 10^{15} \pm 18\%$$

Laser ON results

$$n_p = 2.1 \cdot 10^{15} \pm 6\%$$

Thanks to S. Romeo

Thanks

February 22, 2021

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Preliminary calculations

Operation with gas is different from the SPARC_LAB scenario

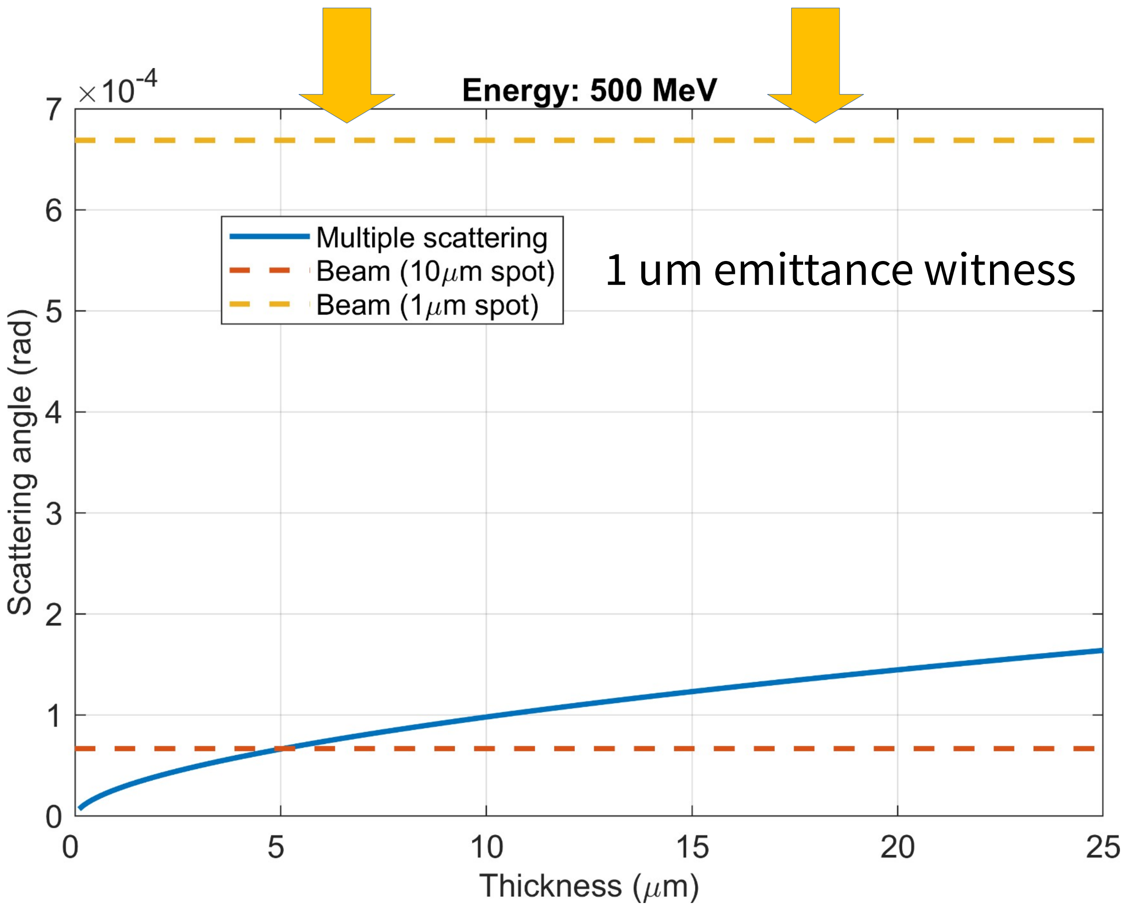
For EuPRAXIA we will have much more gas flowing into the env.

- 10 Hz rep. rate (maybe 100 Hz)
- 0.5-1.0 m long capillaries

To relax vacuum constraints

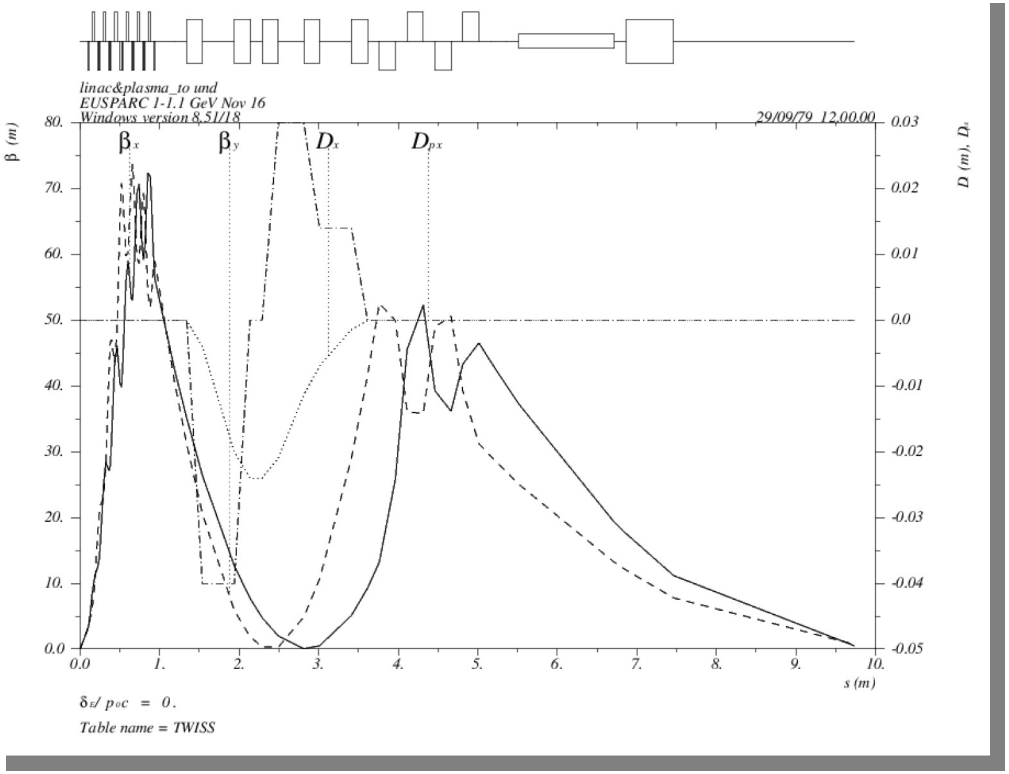
- Nitrogen/Argon instead of Hydrogen
- Long vacuum impedences
- Thin vacuum windows

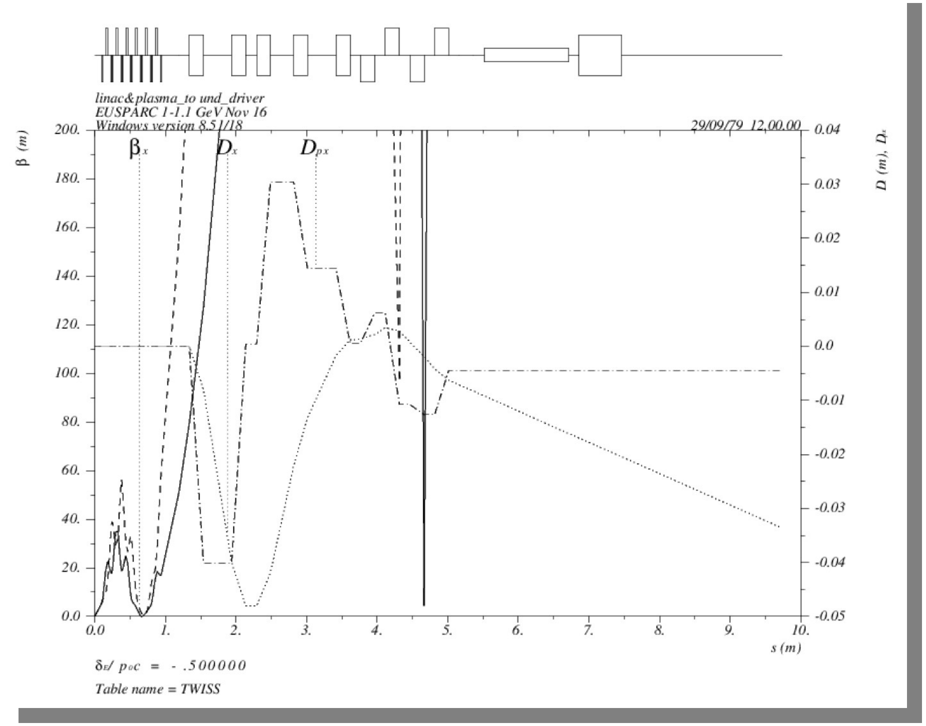
Window close to beam waist has negligible effects on emittance



Kapton window @ plasma entrance

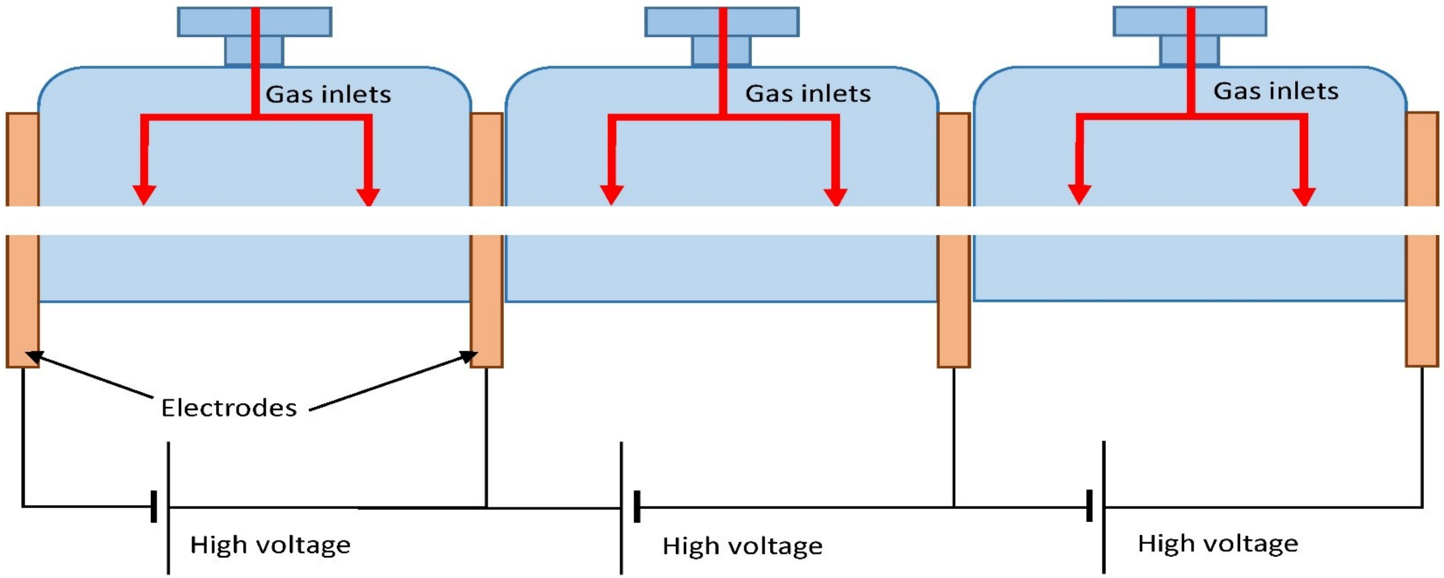
Extraction FODO





Long capillaries study

Second Eupraxia goal: 5 GeV (1.5 GV/m – 3-m capillary – Plasma density 10^{16} cm-3)



To increase the length of the capillary, an alternative to make one very long structure is to merge several shorter capillaries

Assisted beam-loading technique

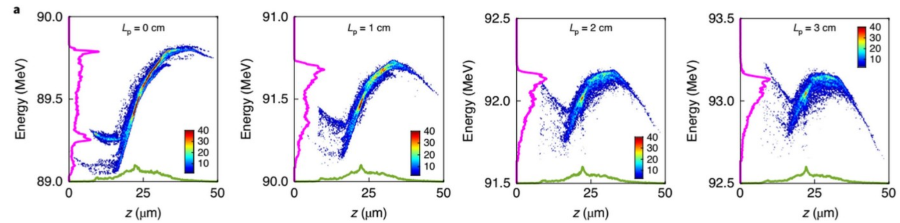
The method allows to assist the beam-loading effect in wakefield flattening and energy spread reduction

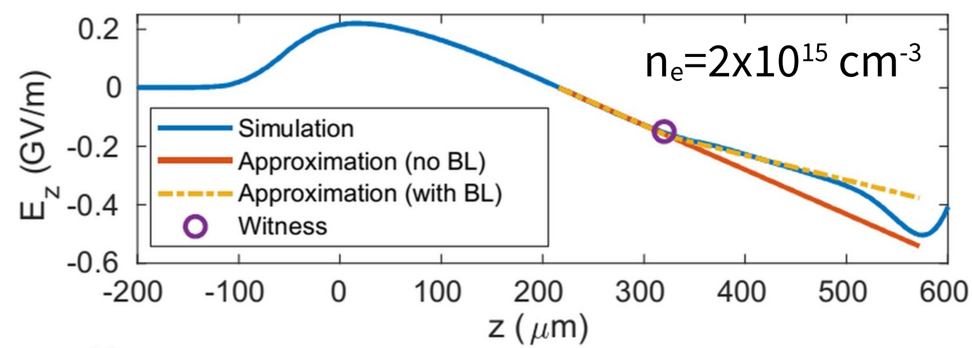
- Make use of an externally imprinted energy-chirp on the witness. It can be potentially large thanks to velocity-bunching
- The chirp slope must counteract the plasma wakefield one

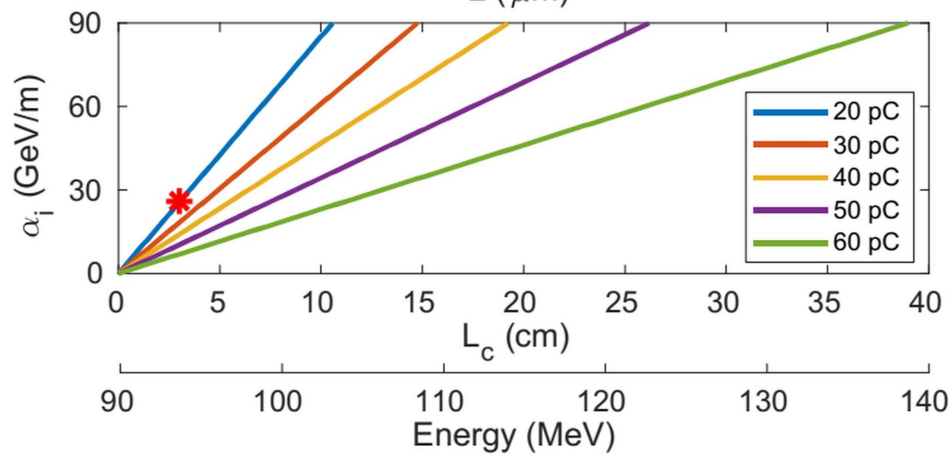
Engineered formula (valid for QNL)

$$\alpha_i\left[\frac{\mathrm{GeV}}{\mathrm{m}}\right] \approx 4L_{\mathrm{c}}[\,\mathrm{cm}\,]n_{\mathrm{p}}[10^{15}\mathrm{cm}^{-3}]\left(\sqrt{\frac{Q_{\mathrm{d}}[\,\mathrm{pC}\,]}{\sigma_{z,\mathrm{d}}[\mu m]}}-\frac{1}{2}\sqrt{\frac{Q_{\mathrm{w}}[\,\mathrm{pC}\,]}{\sigma_{z,\mathrm{w}}[\mu m]}}\right)$$

- EuPRAXIA: with 1 GV/m and 40 cm acceleration the required chirp is ~1.2 TeV/m







Extension of the method @ SPARC_LAB