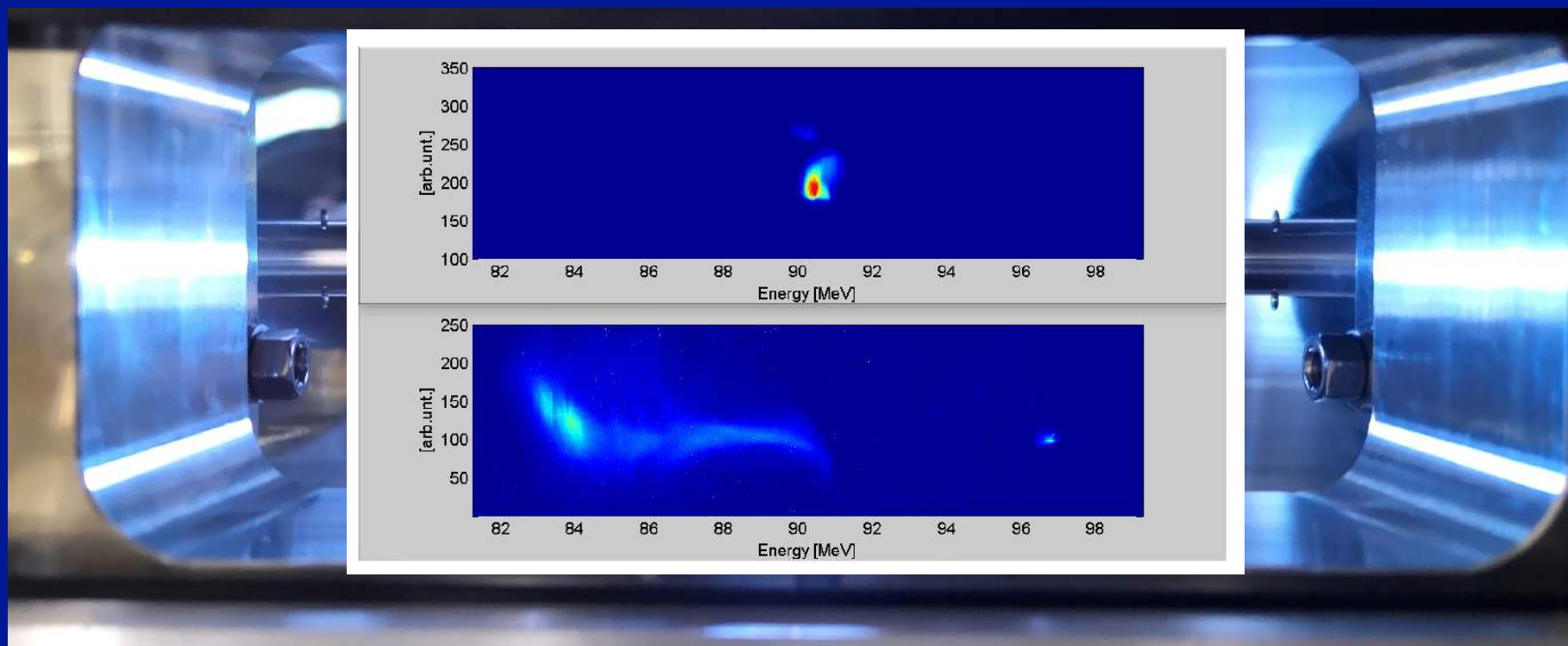


From SPARC_LAB to EuPRAXIA

Massimo.Ferrario@lnf.infn.it

On behalf of the EuPRAXIA@SPARC_LAB team



Recent Publications

1. R Pompili et al., “Energy spread minimization in a beam-driven plasma wake field accelerator”, **submitted to Nature Physics**
2. R Pompili et al., “Plasma lens-based beam extraction and removal system for plasma wakefield acceleration experiments”, **Physical Review Accelerators and Beams** 22 (12), 121302,1, 2019
3. F. Bisesto et al., “Simultaneous observation of ultrafast electron and proton beams in TNSA” – HPLSE – APR 2020;
4. M. Salvadori et al., “Accurate spectra for high energy ions by advanced time-of-flight diamond-detector schemes in experiments with high energy and intensity lasers” - arXiv: 2003.01442 – MAR 2020;
5. M. Galletti et al., “Direct observation of ultrafast electrons generated by high-intensity laser-matter interaction” – APL – FEB 2020;
6. F. Bisesto et al., “Zemax ray tracing model for plasma waveguides” – LPL – JAN 2020;
7. A. Curcio et al., “Modeling and diagnostics for plasma discharge capillaries” – **Physical Review E** – NOV 2019.

LNf SciCom Recommendations

- The committee strongly recommends that the latest funding by SABINA be used for a new klystron modulator and photo-cathode drive laser. These have been the source of significant down time and experimental difficulties over the past six months.
- As was recognized and recommended before, SPARC_LAB must be seen as a major component of the EuPRAXIA@SPARC_LAB project. As such, its operation time must be increased. The committee strongly recommends that plans for availability of spare parts be developed. The quality of the linac beam parameters must also be improved and made more reproducible. The committee recommends that strong effort and resources be put in improving the quality of the drive laser pulse at the photo-cathode through transverse and longitudinal shaping.
- The committee recommends that experiments driving the FEL, even with a beam with modest energy gain in a plasma, be performed soon to demonstrate that such a beam can lead to SASE operation and/or discover the necessary improvements (plasma density ramp, reduction of correlated energy spread, etc.)

SABINA:

SOURCE OF ADVANCED BEAM IMAGING FOR NOVEL APPLICATIONS



GOAL: strengthening of SPARC (increase of the uptime)

- Technological plants renewal (compressed air system, dry cooler, ATU, ...)
- Update of equipment (photocathode laser, injector, modulator, ...)
- Creation of two user facilities: THz and FLAME

THz: spectroscopic analysis (single point or imaging), also at cryogenic T

FLAME: surface coating tests (green, infrared), vacuum tests

BUDGET: about 6.1 M€ (4.5M€ Regional funds POR-FESR, 1.6M€ INFN)

STATUS: Kick off Sept. 2019, first progress report just submitted. Main items:

- Injector: designed, components purchased, now in assembling phase
- **Photocathode laser: the new one will be installed in a new clean room, outside the bunker (in order to reduce down time in case of fault)**
- Solenoids: definition of tech specs, now in purchasing phase
- **Modulator: in purchasing phase**
- THz: undulator specification has been fixed, THz line designed
- Network: 10Gb for the Sparc-FLAME area
- ...and there's more to come

Courtesy L. Sabbatini & M. Bellaveglia

SABINA: WORK IN PROGRESS

New photo cathode drive laser - Ongoing study on transverse shape quality

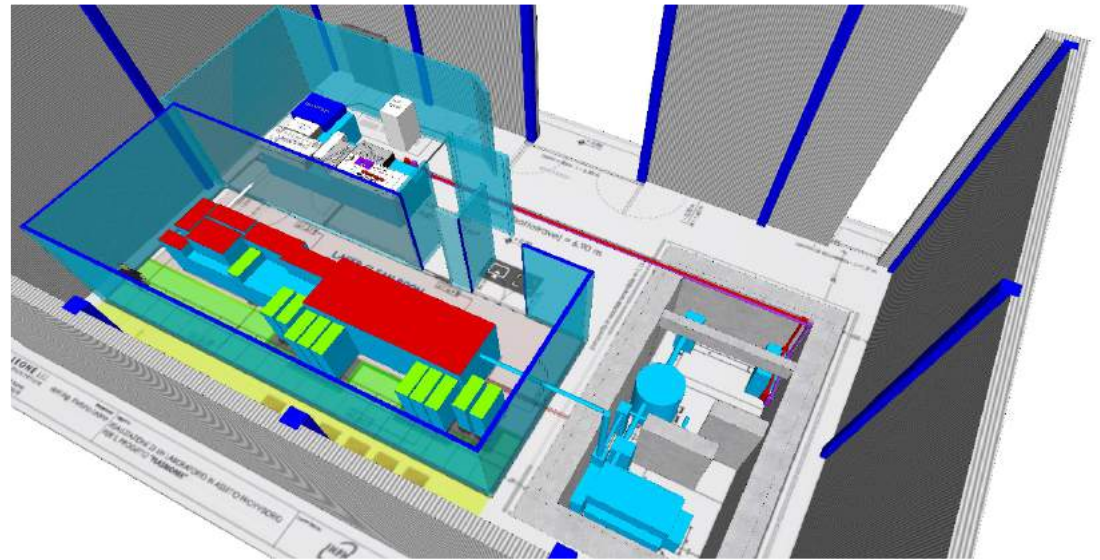
PARAMETERS	
Longitudinal shape (UV)	Gaussian, <50fs rms
Time jitter respect to reference (oscillator)	<6 fs rms (external piezo&stepper oscillator control)
Transverse shape (UV)	Flat-top, 0.2-2 mm diameter
Centroid pointing stability (UV)	<10 urad long term
Energy (UV) before shaping	>10 mJ (20?)
Energy jitter (UV)	<1% rms short term (5min), <2% rms long term (24h)
Repetition rate (UV)	10 Hz (internal/external trigger)
Wavelength (UV)	260-266 nm
Rep rate oscillator (oscillator)	79.3333 MHz (36 th S-band subharmonic)
Piezo actuator frequency response (oscillator)	>10kHz (3 dB bandwidth)
IR probe beam for EOS, seeding, xcorr... (IR)	Separate compressor, >5 mJ in the bunker (option)
Good oscillator 50/50 splitting (oscillator)	Same parameters on both lines
Control system	External access with protocol

(courtesy Fabio Villa)

SABINA: WORK IN PROGRESS

Photo cathode drive laser – new clean room

(courtesy Fabio Villa)

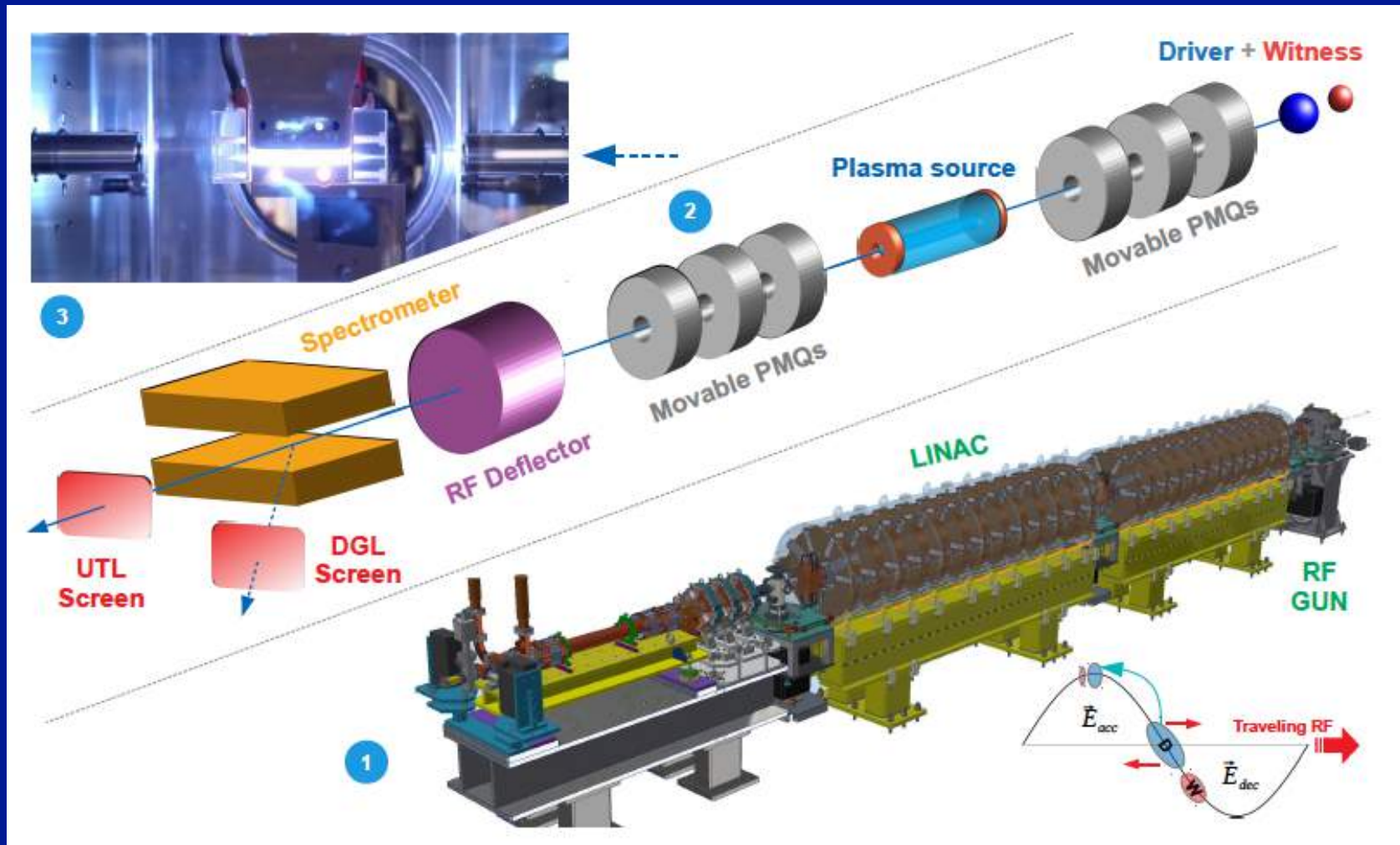


Modulator *(courtesy Scandinova)*

LNF SciCom Recommendations

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Experimental Setup



Courtesy R. Pompili

SPARC beam time dedicated to machine restart after laser failure of 2nd half 2019

Photo-cathode laser pulse compressor made remotely controlled

It allows to change the laser pulse duration on cathode and study beam-dynamics in different configurations

Preparation of the comb-beam setup with one driver (up to 400 pC) and witness (20 pC)

Some problems with C-Band modulator (water system, fake interlocks, etc.)

Beam time dedicated to the preparation of the COMB experiment. Dual bunch operation (driver+witness)

Beam dynamics of 1 driver (200 pC) + witness (20-50 pC)

Test with permanent magnet quadrupoles. Minimum spot obtained about 15 μm (rms)

Tests of plasma interaction with long beam

Observation of transverse modulations due to self-modulation instability. Studies on hose instability. Data analysis is currently ongoing.

Failure of the security devil (lost 2 days)

Studies of photo-emission process with pump-probe setup

Driver+witness (as probe) configuration.

Observation of largely increased quantum efficiency when the two pulses are close in time. Temporal scan done. Currently under study

Beam time dedicated to the COMB experiment. Dual bunch operation in velocity-bunching (driver+witness)

Beam dynamics of 1 driver (200 pC) + witness (20 pC)

We obtained up to 4 MeV acceleration (~ 130 MV/m) @ 2×10^{15} cm⁻³ plasma density in a 3 cm-long capillary

Parametric study done at different plasma densities. Data analysis completed

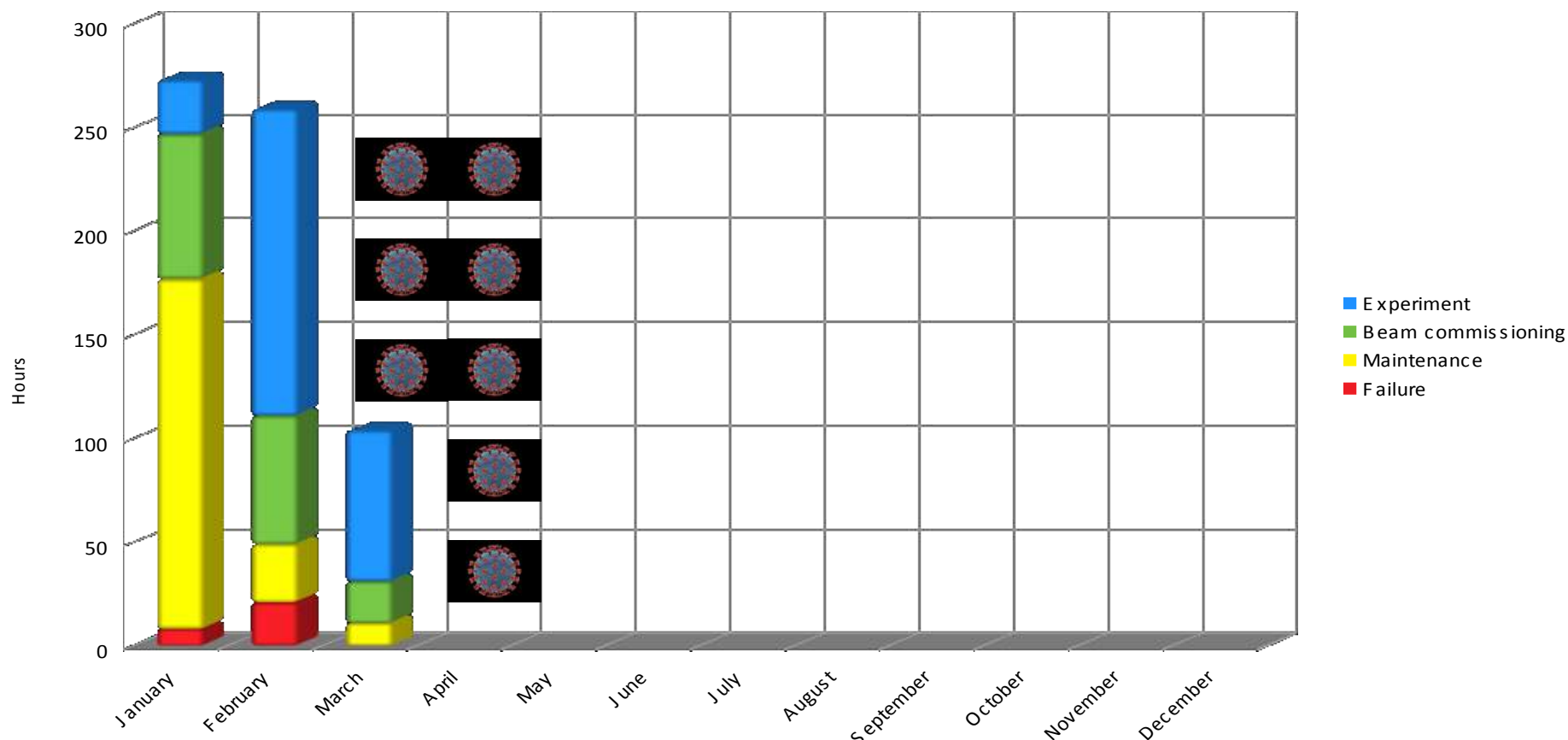
Beam dynamics of 1 driver (350 pC) + witness (20 pC)

We obtained up to 7 MeV acceleration (~ 230 MV/m) @ 2×10^{15} cm⁻³ plasma density in a 3 cm-long capillary

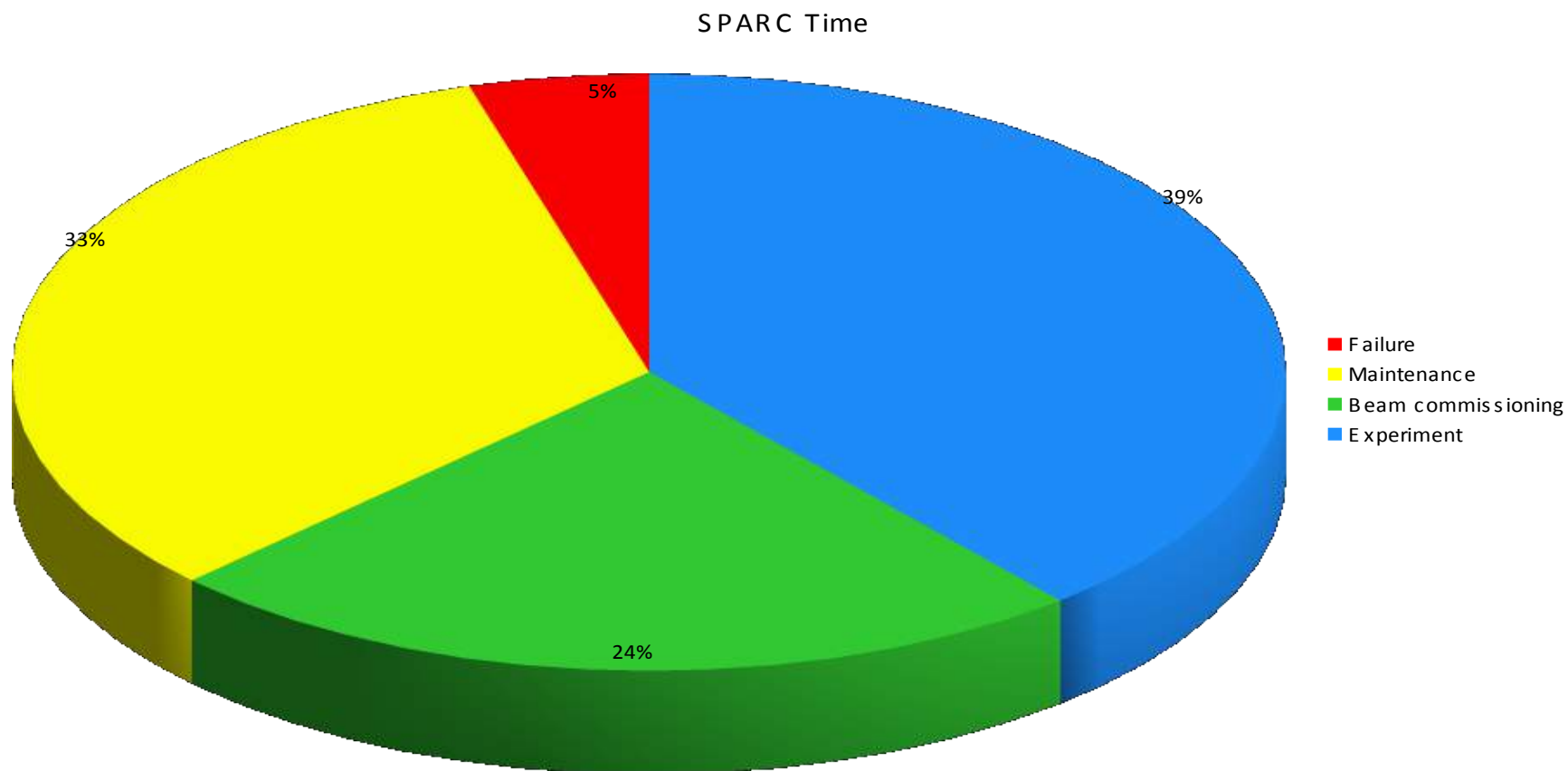
Parametric study done at different plasma densities. Data analysis completed

All activities have been stopped due to covid-19

SPARC - Monthly activity



Total Useful Hours: 620



Total Up-Time: 63%

We plan to change the current capillary with a new one

- Same length (3 cm)

- Same hole diameter (1 mm)

- Again with two 1 cm-long spacers attached to the electrodes (for plasma stabilization)

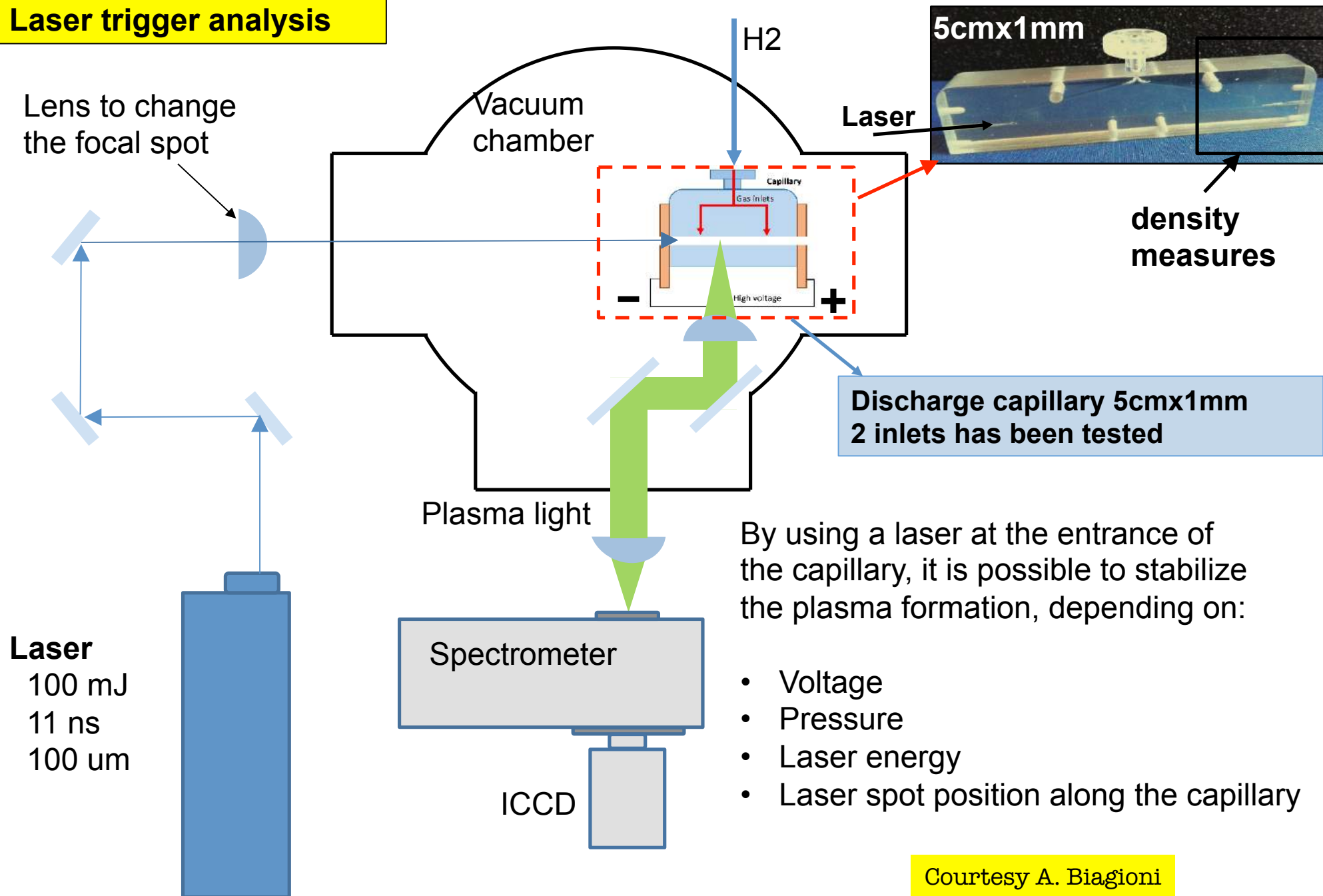
- Two gas inlets (instead of one)

The new capillary has already been characterized @ PLASMA_LAB in the 2nd half of April 2020

The new capillary should provide a more flat plasma density profile along the beam propagation axis. Larger accelerations expected

We are also planning to stabilize the plasma discharge process by triggering it with an external laser pulse (assisted plasma discharge)

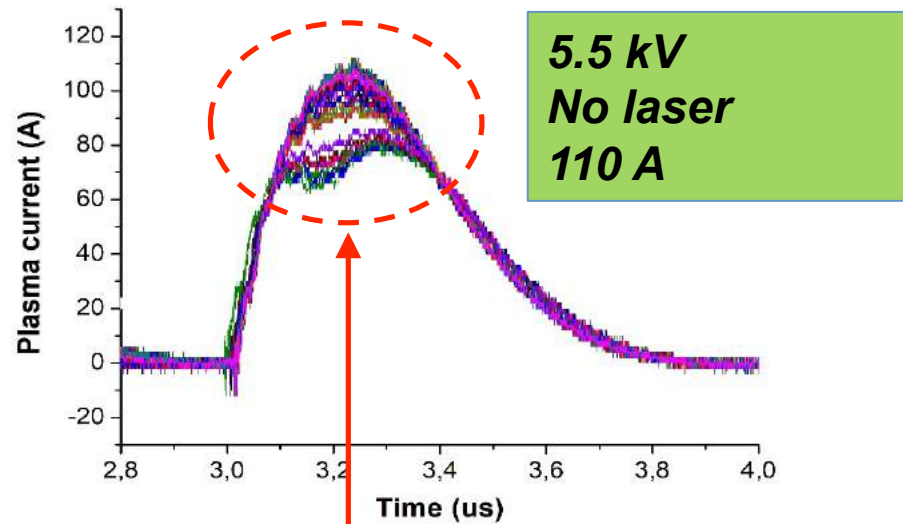
Laser trigger analysis



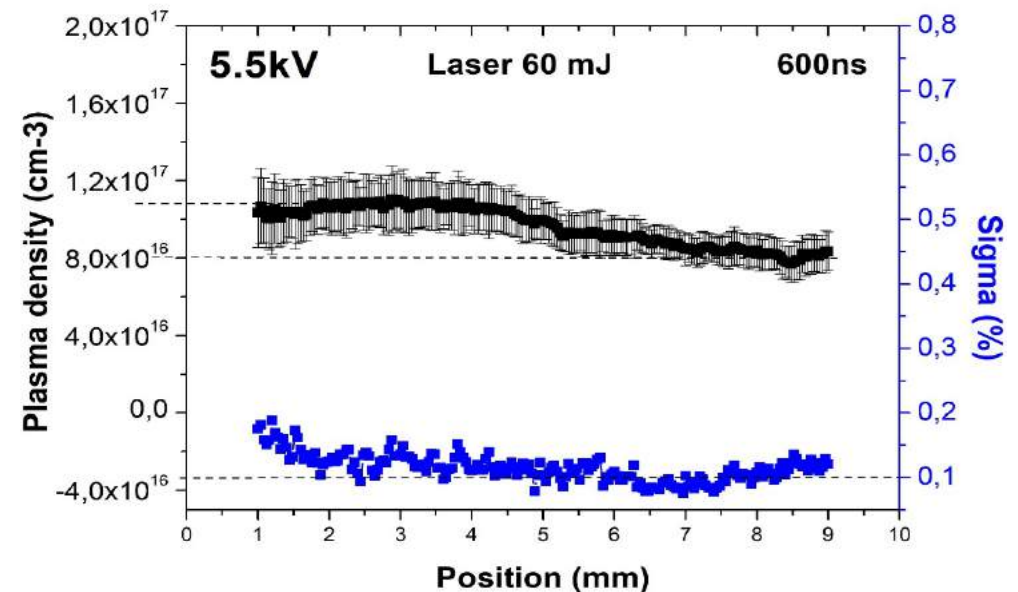
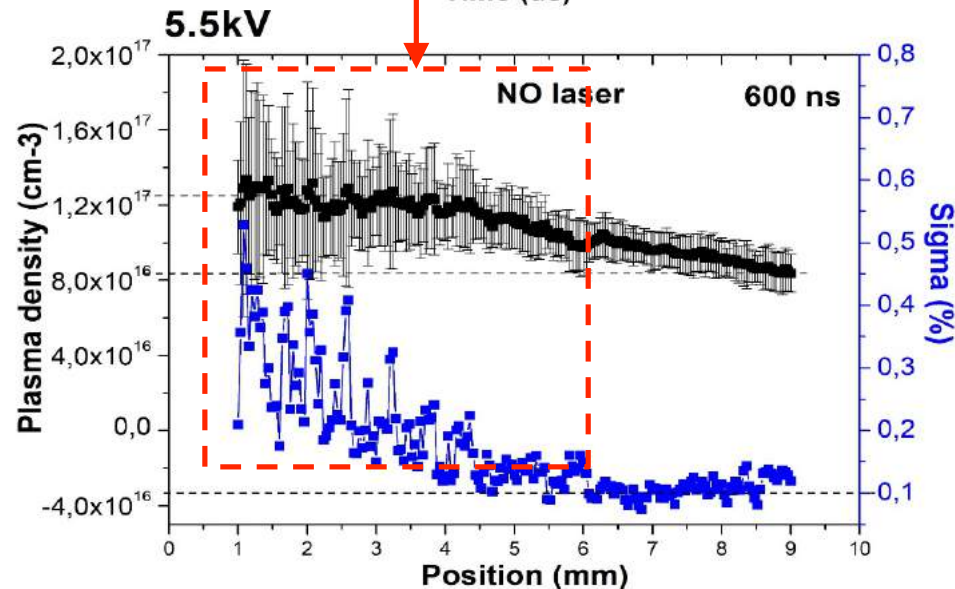
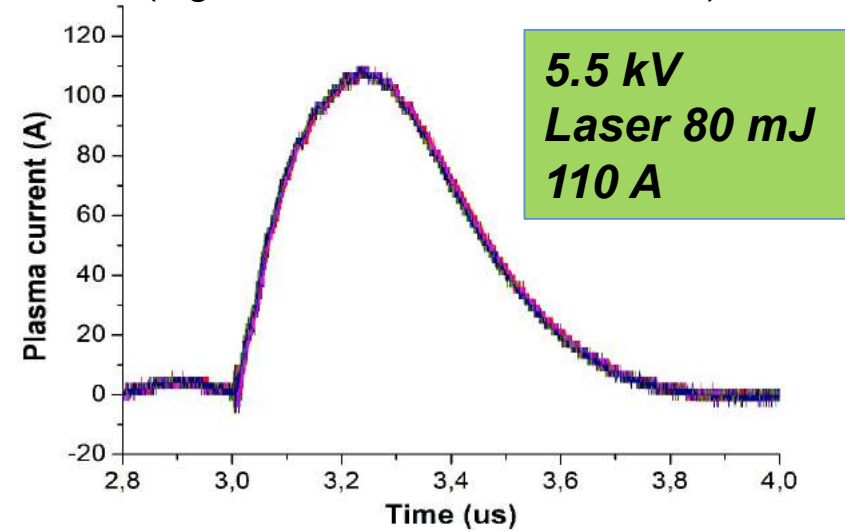
Courtesy A. Biagioni

Here are shown some measures about plasma density and plasma current inside capillary with and without laser trigger

Instability without laser (50 shots)
(sigma error reaches 40%)



Stability with laser (50 shots)
(sigma error is around 10-15%)





Plasma Lab: future planning

- Further experiments about spacers and different shapes of the capillary to optimize both the density and the stability
 - Changing of the plasma ramp profiles by using different diameter/tapering...
- Transverse density profile measurements to optimize capillaries for laser wakefield acceleration
- Further experiments to optimize the laser trigger technique used to reduce the timing jitter of the discharge and the stability of the plasma formation
- The new chamber will allow to test longer capillaries up to 40 cm (Eupraxia 1.1 GeV) and the segmented capillary technique to reach 2-3 m-long capillaries
- Closing windows to cut the plasma ramps and so redesign the gas injection system (continuously flow)

Subject to Clean Room access

May-July

Installation of the new capillary and acceleration tests. Energy spread and emittance investigation

Setup and tests of the OSE (one-shot emittance) experiment

Alignment on C-band and AC3QUADs

September

Calipso+ experiment (external users)

ELI-beamline experiment (external users)

October-December (if SABINA related installations will be postponed)

Acceleration optimization. Transport up to the FEL undulators

Preliminary tests with comb-beams with multi-drivers configuration

FLAME activities



Final amplification stage from ~600 mJ to 6J

Energy	6 J
Duration	23 fs
Wavelength	800 nm
Bandwidth	60/80 nm
Spot @ focus	10 μm
Peak Power	300 TW
Contrast Ratio	10^{10}

The main activity on FLAME has been electron acceleration through gas-jet.

The goal has been to test all the diagnostics needed for acceleration with capillaries (EXIN).

However, a problem with the clean room air conditioning has stopped the activities for long time (essentially full JAN and part of FEB).

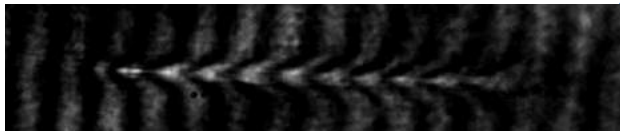
Courtesy M. P. Anania

In parallel to FLAME activities, we are working on the characterization of the capillaries needed for EXIN project.

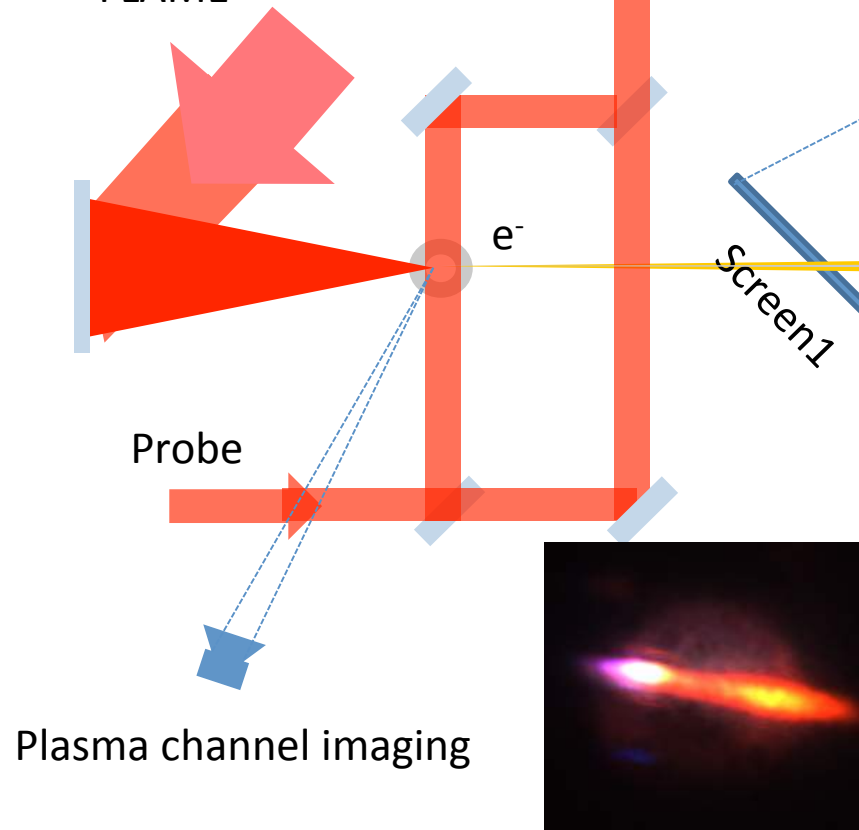
Those capillary are tested at low laser intensity with the intend to:

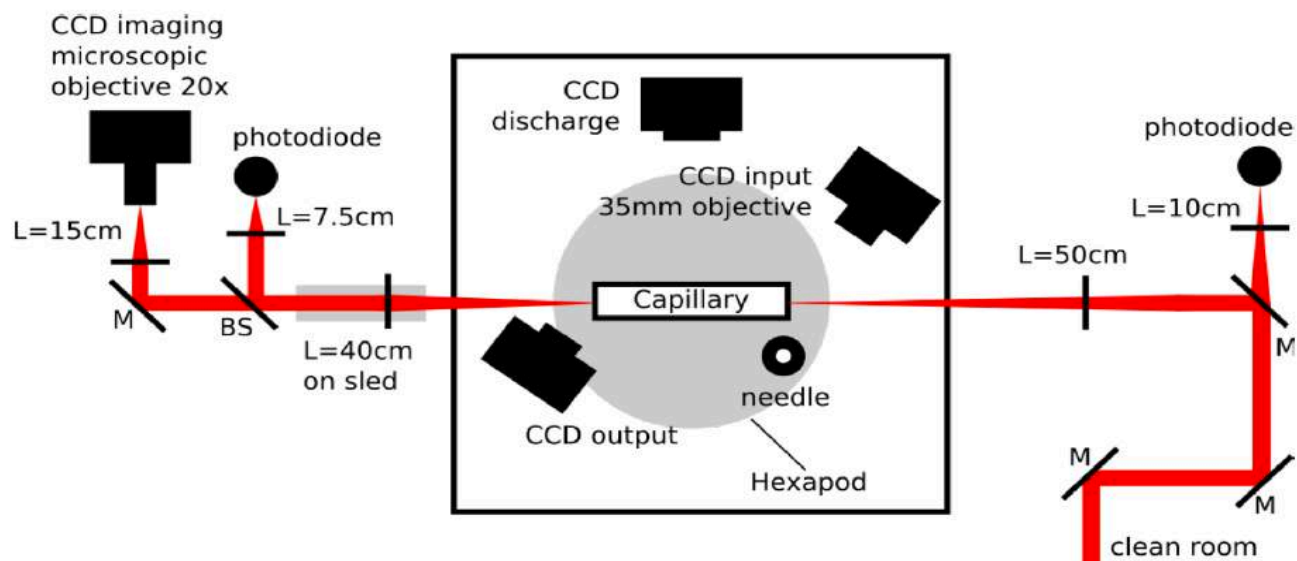
1. Learn how to align capillaries;
2. Design dedicated diagnostic;
3. Design capillaries with the right density request;
4. Characterize density (transverse and longitudinal);
5. Study timing and jitters (for guiding).

Interferometer

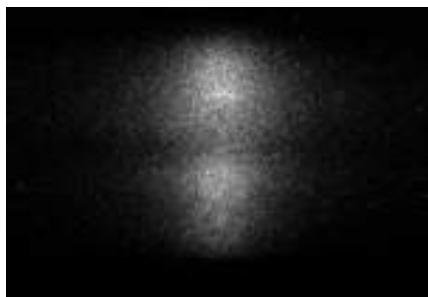


FLAME

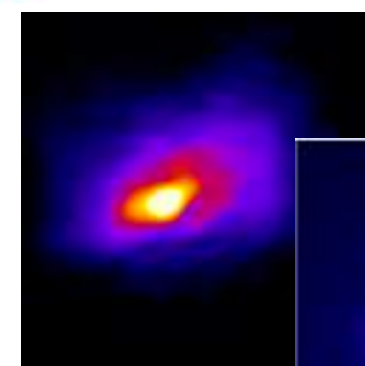
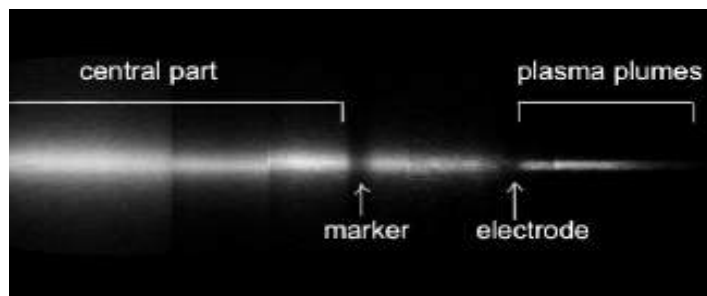




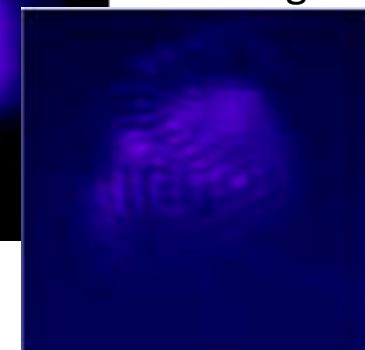
Transverse plasma density



Longitudinal plasma density

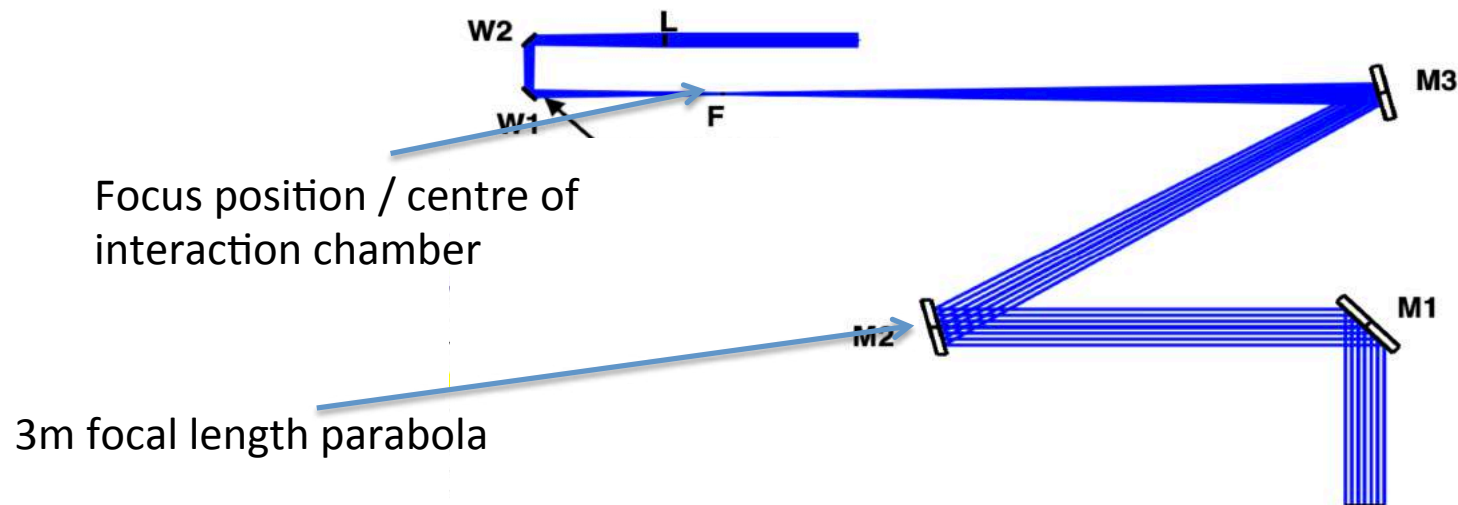


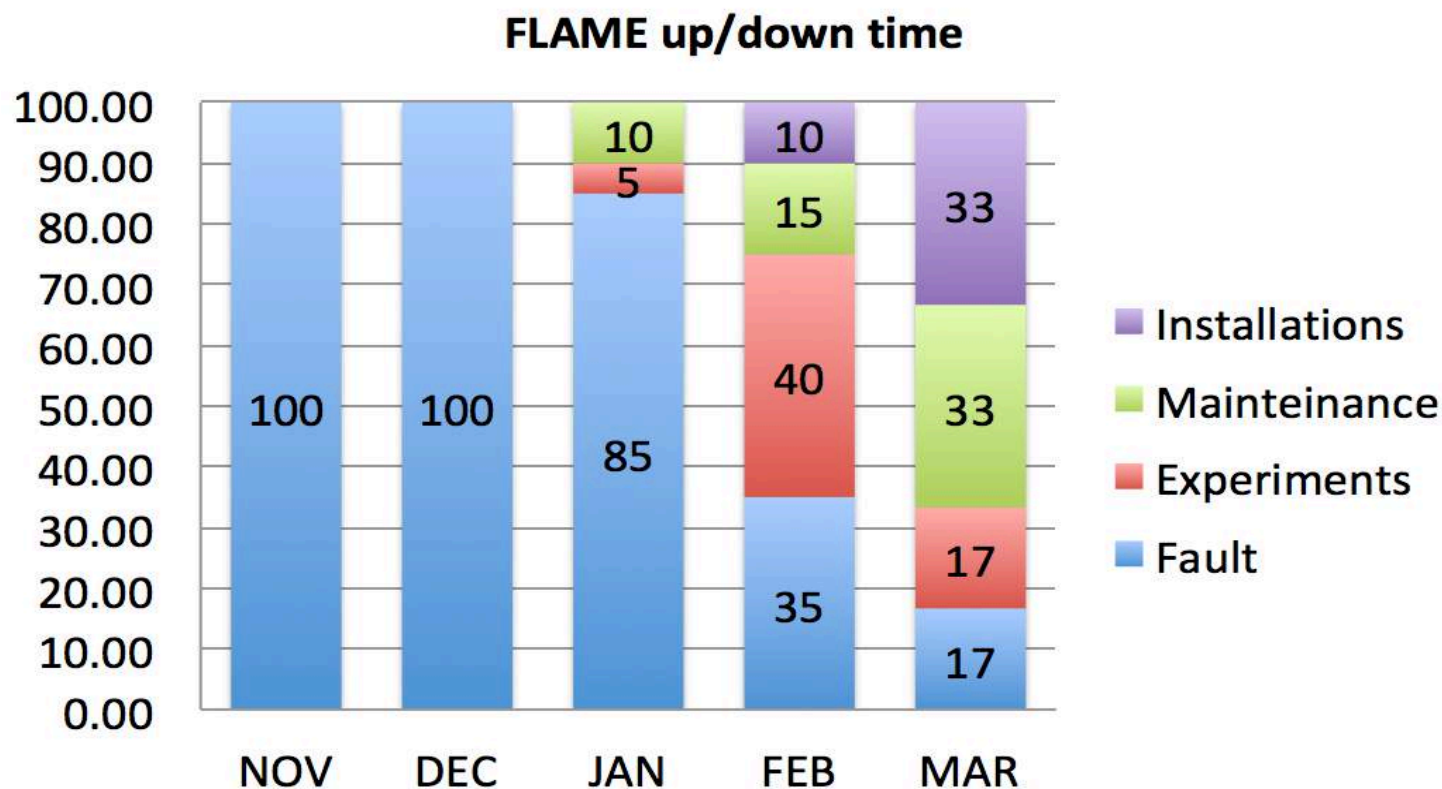
Guiding and timing



Capillaries have been almost totally characterized and soon will be installed in main FLAME interaction chamber for high intensity test.

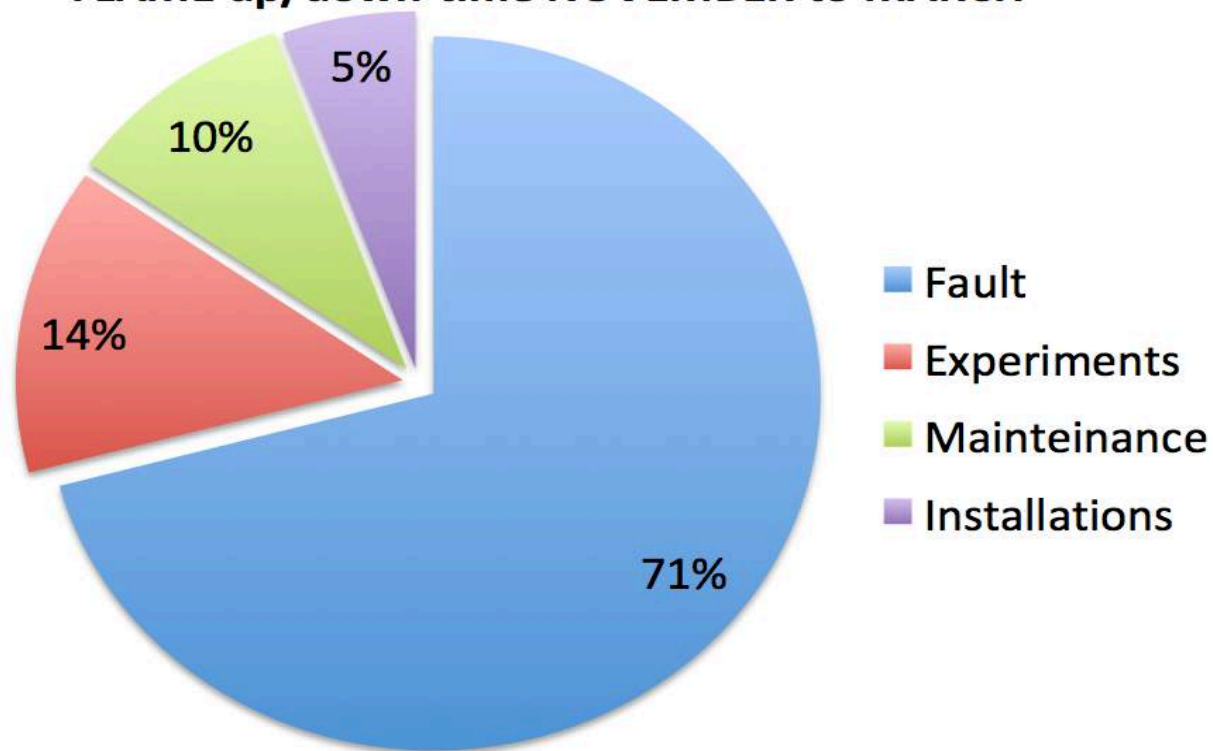
For this reason, a new optical set-up has been conceived in order to have the right beam size for capillary test (we need to use a longer focal length parabola in order to have larger spot dimensions).





Air conditioning are still causing some problems (in clean room there is a difference between night and day higher than 3°C).

FLAME up/down-time NOVEMBER to MARCH



Fault percentage in this chart is very large due to some work that have been done on clean room air conditioning system in (control system has been changed with a new one that had a lot of problems at the beginning (NOV and DEC).

Subject to Clean Room access

As soon as we will be able to restart the laser, we will conclude the characterization of the gas-jet.

Then we will install capillary set-up (both the new optical line and the diagnostics needed for this activity) and we will work on capillary guiding at high intensity. The main goal is to fully characterize at high intensity the capillaries that will eventually be installed in SPARC.

EuPRAXIA@SPARC_LAB



STATUS BUILDING

Contract with the engineering company for the design of the building is in place.

First productive meeting held in February.

Now activities stopped due to the current situation. Hopefully will be reactivated in the next weeks.

In the meantime:

- Building architectural requirements
 - Length of the accelerator hall
 - Size, number and requirements for the clean rooms (2 ISO7 CR).
- Primary utilities requirements:
 - Temperature, stability and RH
 - Water cooling temperature
 - Power dissipation in air
 - Electrical power overall consumption.

S2E simulations always running

New layout suitable for:

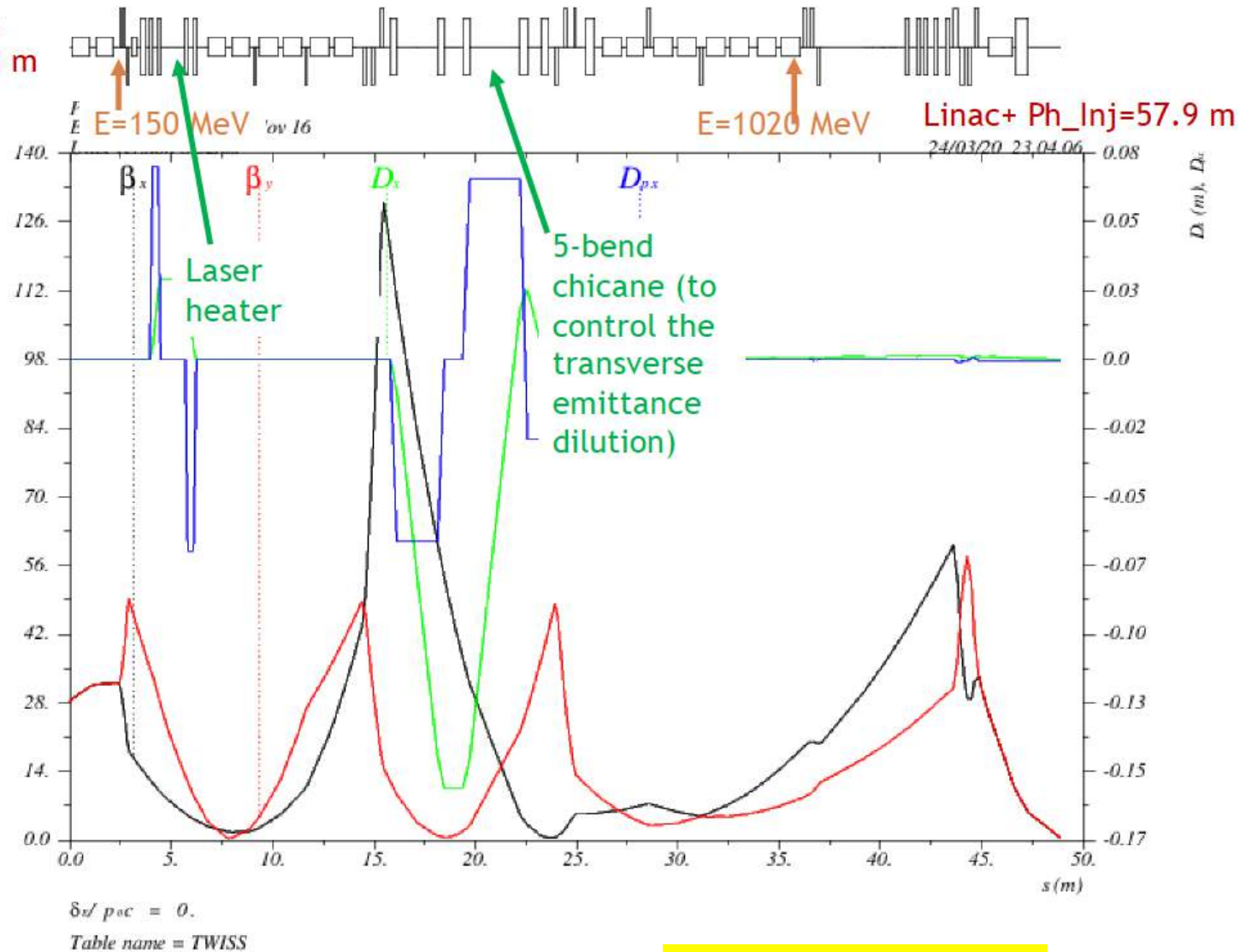
1° WP:

- 30 pC LWFA
- 200+30 pC Comb beam PWFA

2° WP:

- 200 pC all X-band

Ph_Inj exit
2 s-band=8 m



Courtesy C. Vaccarezza

EuPRAXIA@SPARC_LAB

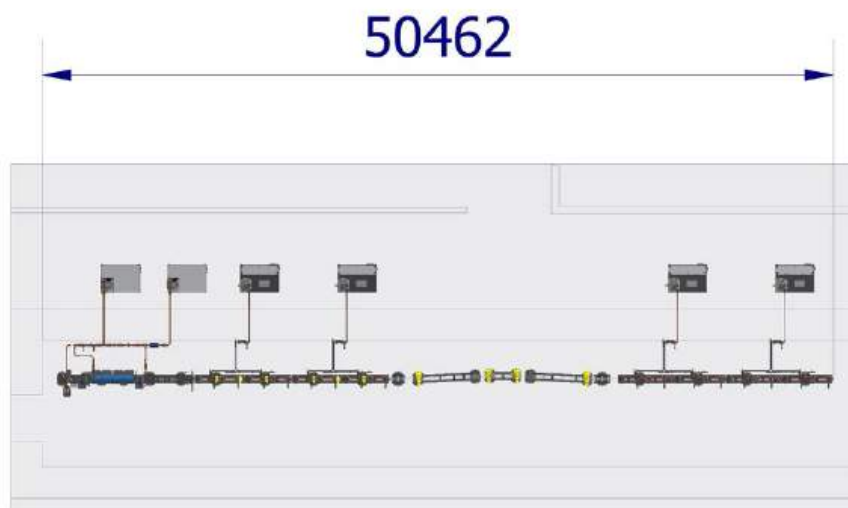
MECHANICAL LAYOUT UPGRADE - REV. B (14/04/2020)

ENRICO DI PASQUALE

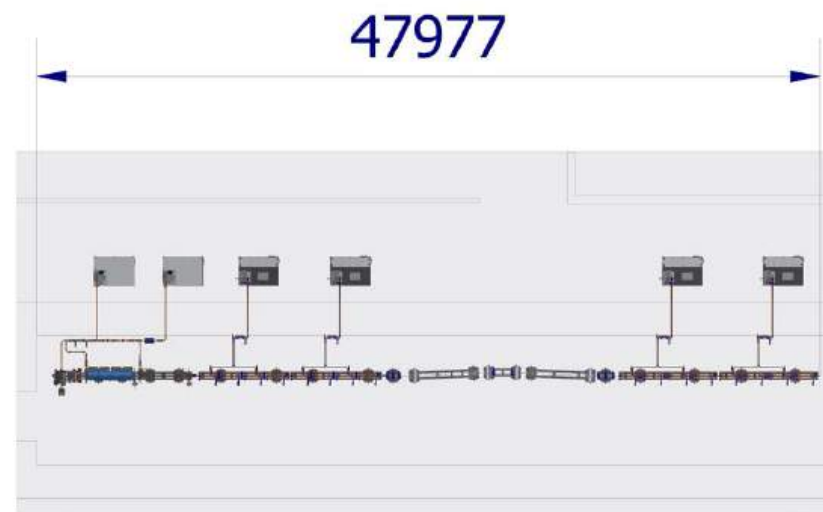
- INSERIMENTO NUOVO MODULO DI INIEZIONE SUL MODELLO SPARC
- INSERIMENTO CURRENT MONITOR
- NUOVA DISPOSIZIONE TARGHETTE CON TELECAMERA
- BPM STRIP PASSANTI NEI QUA
- INSERIMENTO POMPEA IN SEZIONE ACCELERANTE SOL B S BAND
- CONCLUSIONI

CONCLUSIONI

Al netto di tutte le modifiche apportate e mostrate in questo report si ha, rispetto al layout della versione precedente, un decremento della lunghezza del LINAC pari a 2485 mm.



EuPRAXIA@SPARC_LAB_Rev.A (OLD)



EuPRAXIA@SPARC_LAB_Rev.B (NEW)

ESFRI 2021 Roadmap application

ESFRI Application deadline has been extended to September 9th 2020 due to the COVID-19 emergency

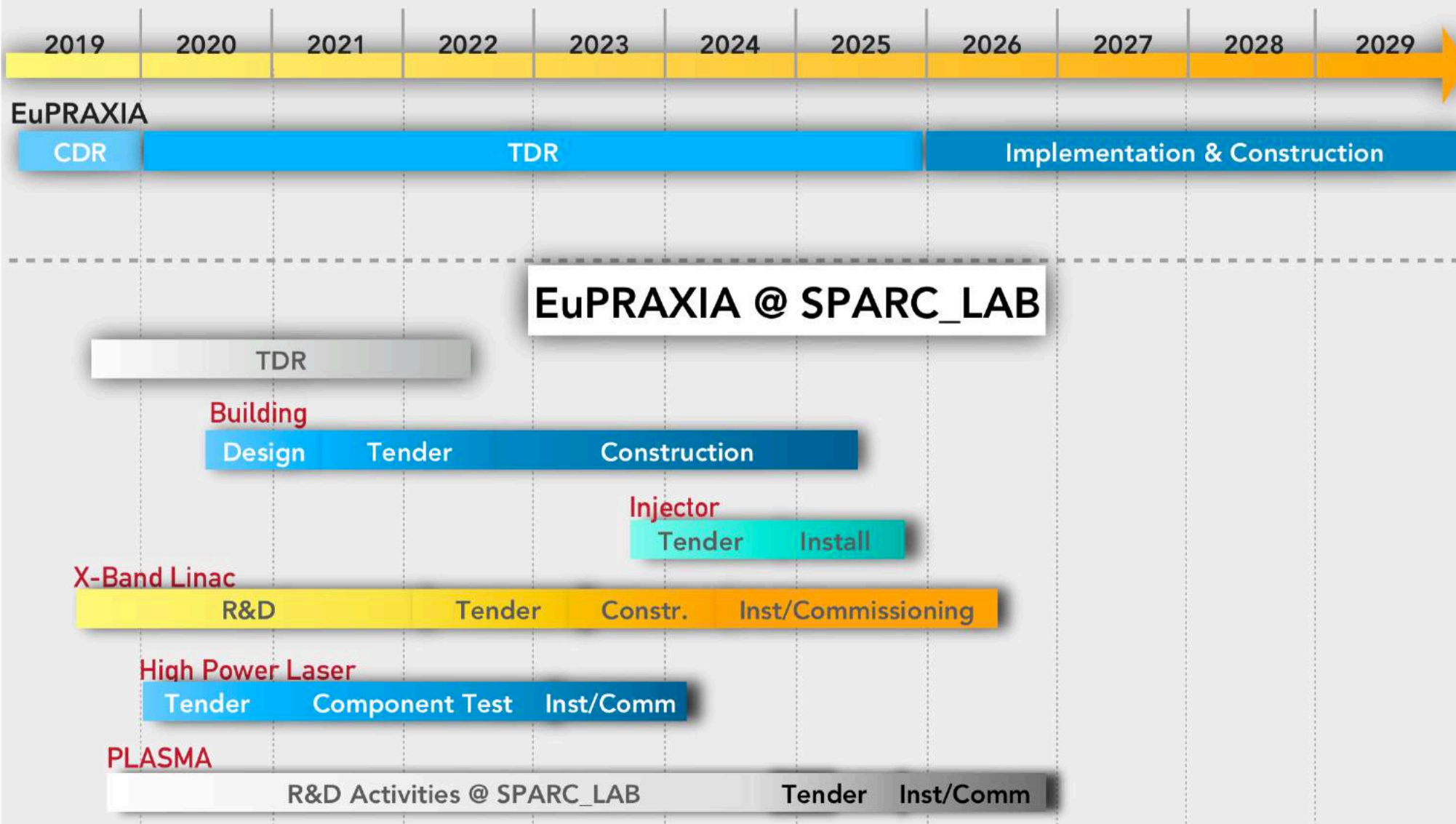
Application is almost ready.

- Consortium agreement:
A remarkable number of institutes and companies have been involved in the consortium.
A first round of agreement has been concluded.
A final version of the agreement is now ready to be submitted to all the institutions.
- Support from political countries:
Negotiations are ongoing. Positive feedback from a number of countries, hopefully (after the COVID-19 thunderstorm) we can get a broad consensus.

We are confident that we can prepare a very convincing application to be included in the 2021 ESFRI Roadmap.

Courtesy A. Falone

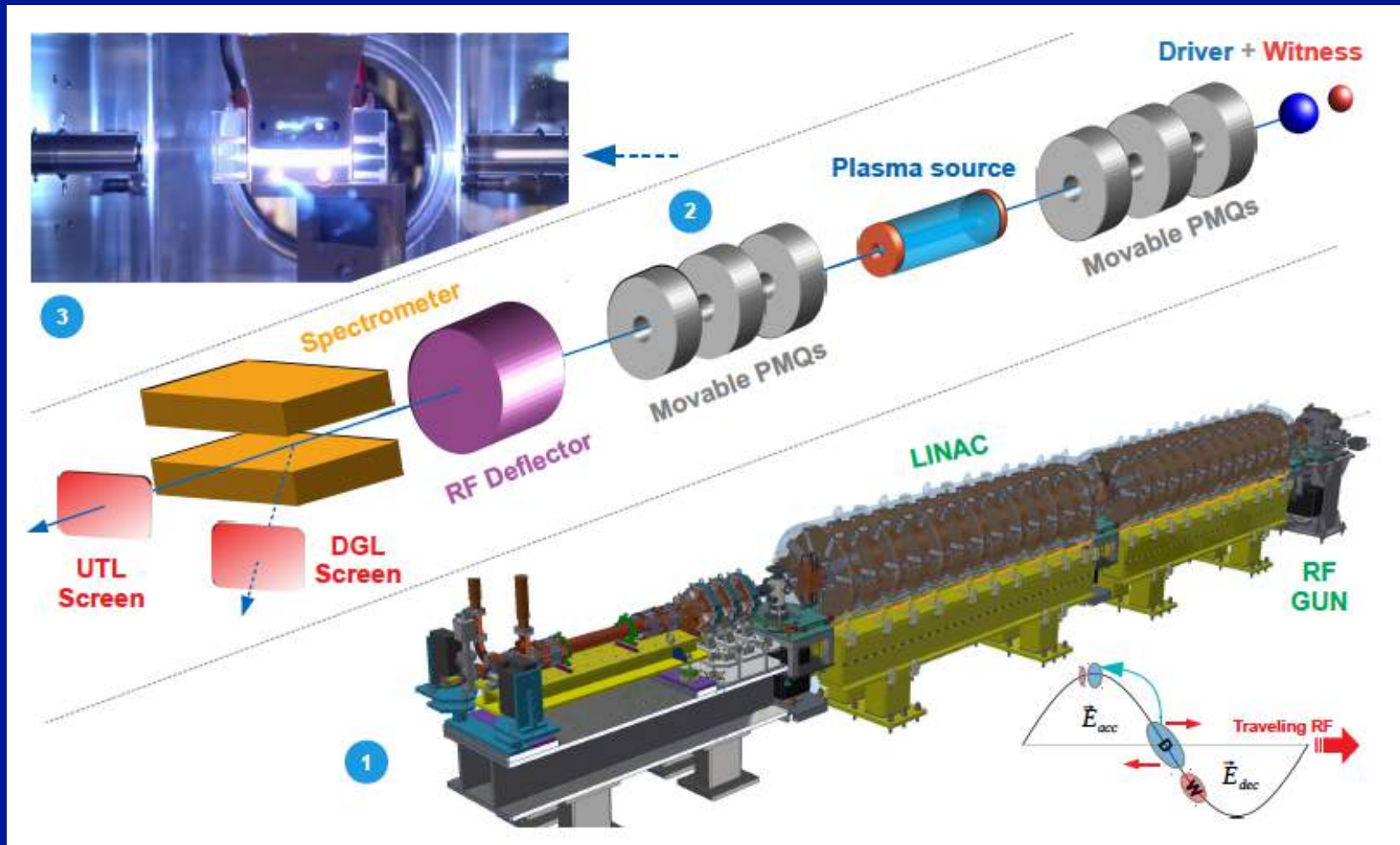
MASTER SCHEDULE CDR Update



LNF SciCom Recommendations

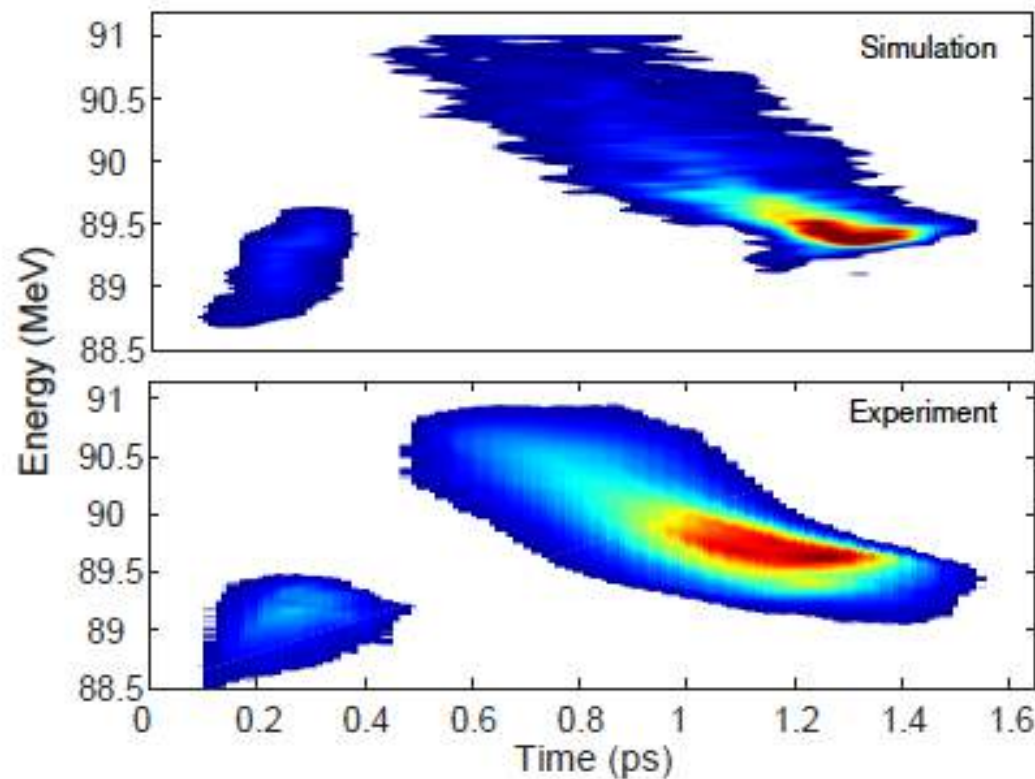
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- The committee recommends that experiments driving the FEL, even with a beam with modest energy gain in a plasma, be performed soon to demonstrate that such a beam can lead to SASE operation and/or discover the necessary improvements (plasma density ramp, reduction of correlated energy spread, etc.)

Experimental Setup



Courtesy R. Pompili

Beams at the Plasma entrance



Driver 200 pC

- Duration: 216 fs (rms)
- Energy spread: 0.4 MeV
- Emittance: 2.0 μm

Witness (20 pC

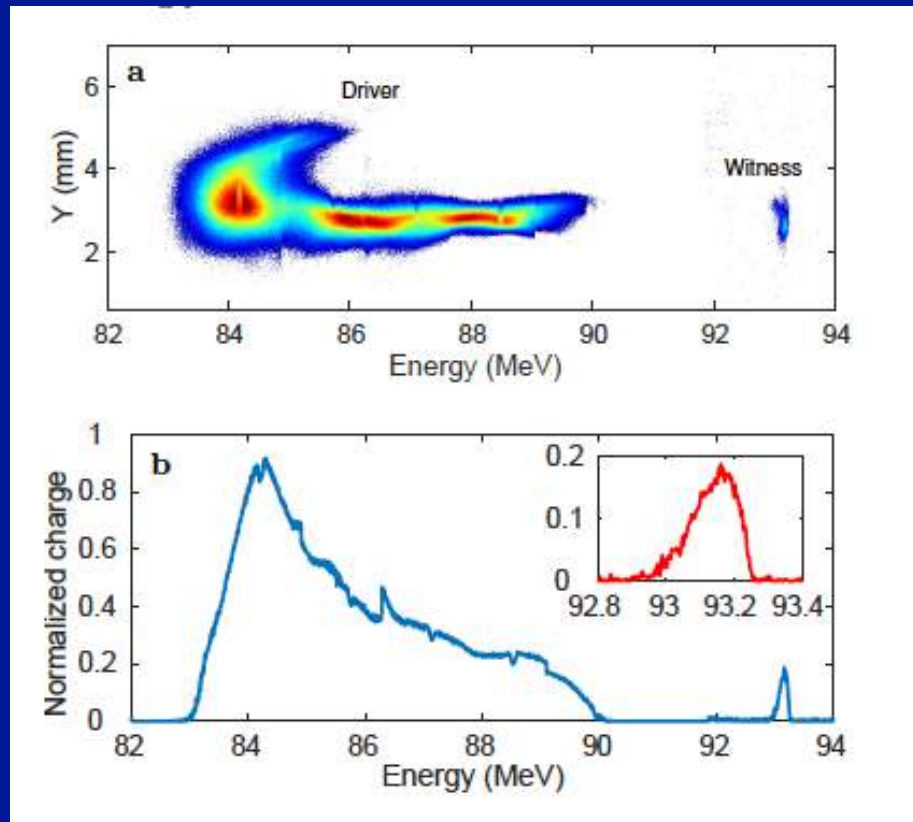
- Duration: 25 fs (rms) \rightarrow 30 fs without Driver
- Spread: 0.3 MeV \rightarrow 0.5 MeV without Driver
- Emittance: 0.7 μm \rightarrow 0.4 μm without Driver

D+W (entire beam)

- Distance \rightarrow 1.03 ps (330 μm), Duration \rightarrow 360 fs
- Energy spread: 0.54 MeV
- Emittance \rightarrow 2.0 μm

Plasma Density: $2 \times 10^{15} \text{ cm}^{-3}$

Beams at the Plasma exit



Witness
Energy
Spread:
0.1 %

First results obtained with well-known WP 200+20 pC

Energy spread of witness (plasma OFF) is 0.2 MeV

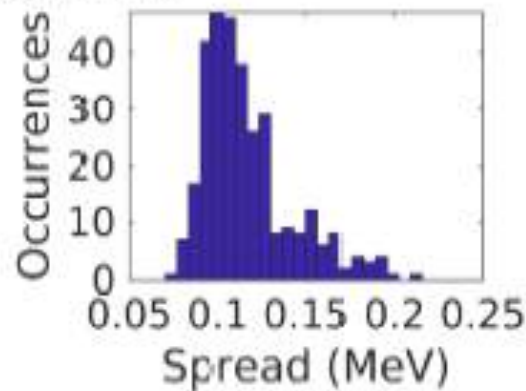
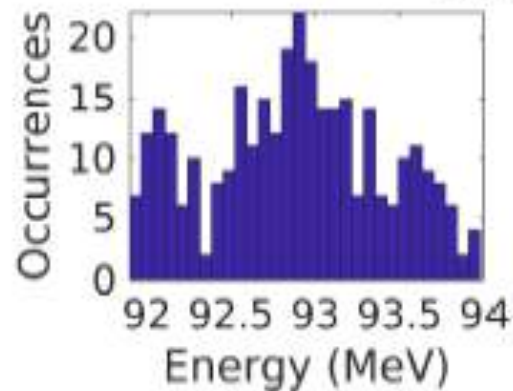
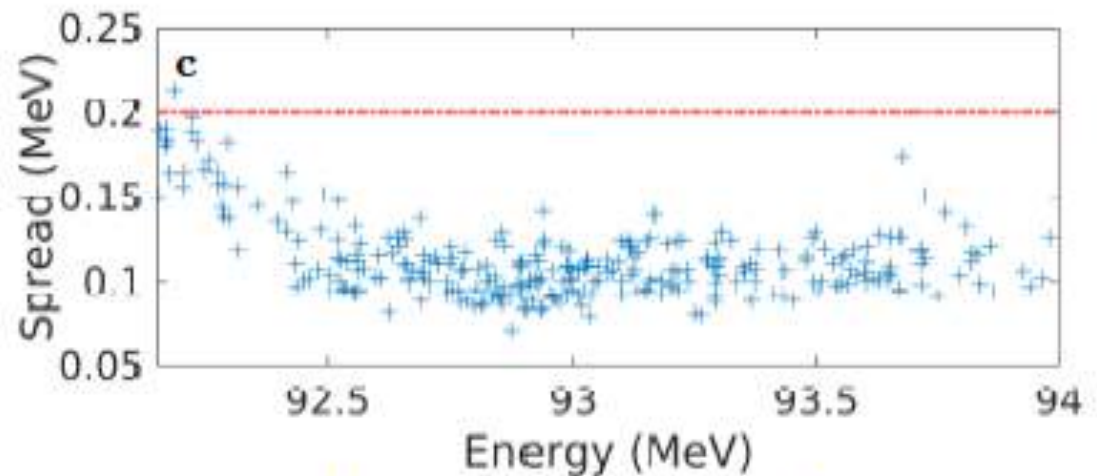
The achieved acceleration is of ~4 MeV

Corresponds to 130 MV/m

Energy jitter of the witness energy is 0.5 MeV

Energy spread after acceleration is 0.1 MeV, lower than the one with plasma off

Statistics



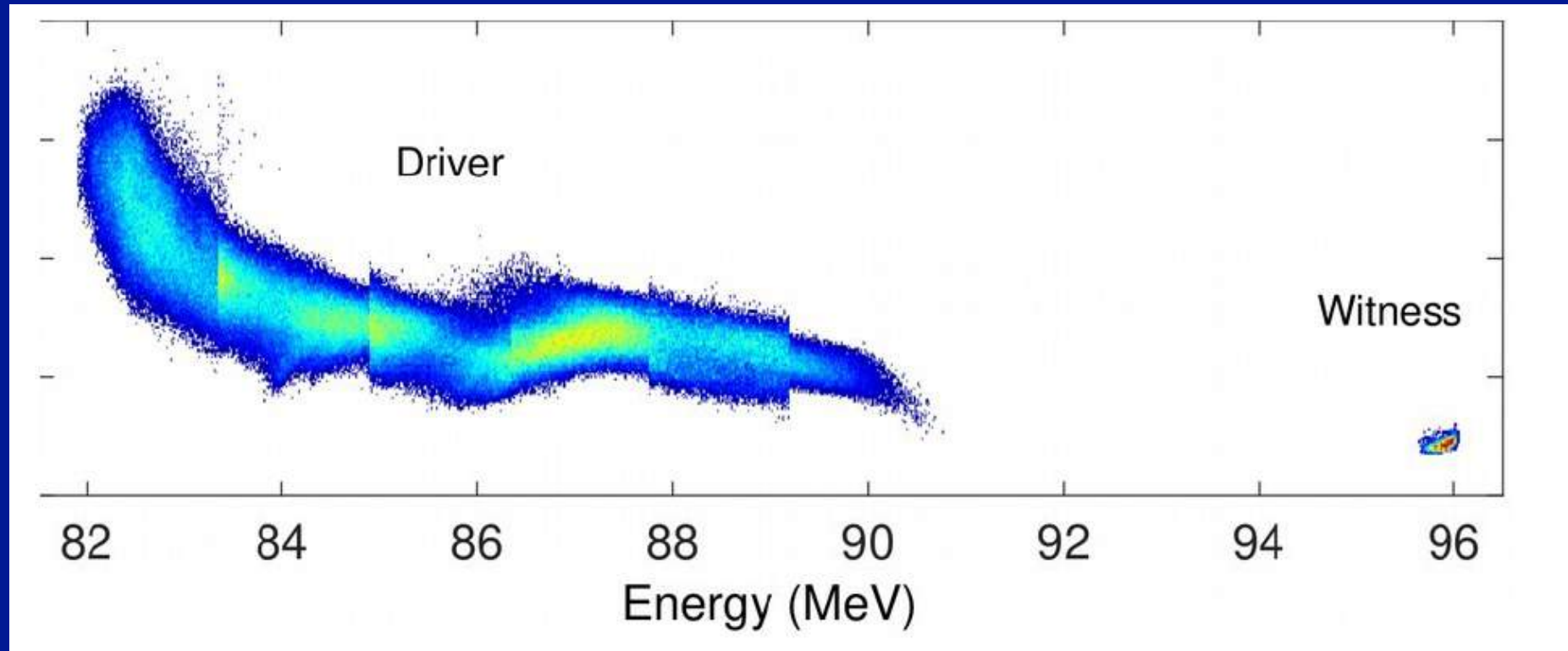
320 points

Red dashed line is the initial spread (plasma OFF)

Final spread is lower

→ chirped witness is rotated by the plasma wakefield

Higher Charge Driver 300 pC



Second configuration tested is WP 350+20 pC

Energy spread of witness (plasma OFF) is 0.2 MeV

The achieved acceleration is of ~7.5 MeV

Corresponds to 250 MV/m

Energy jitter of the witness energy is 0.6 MeV

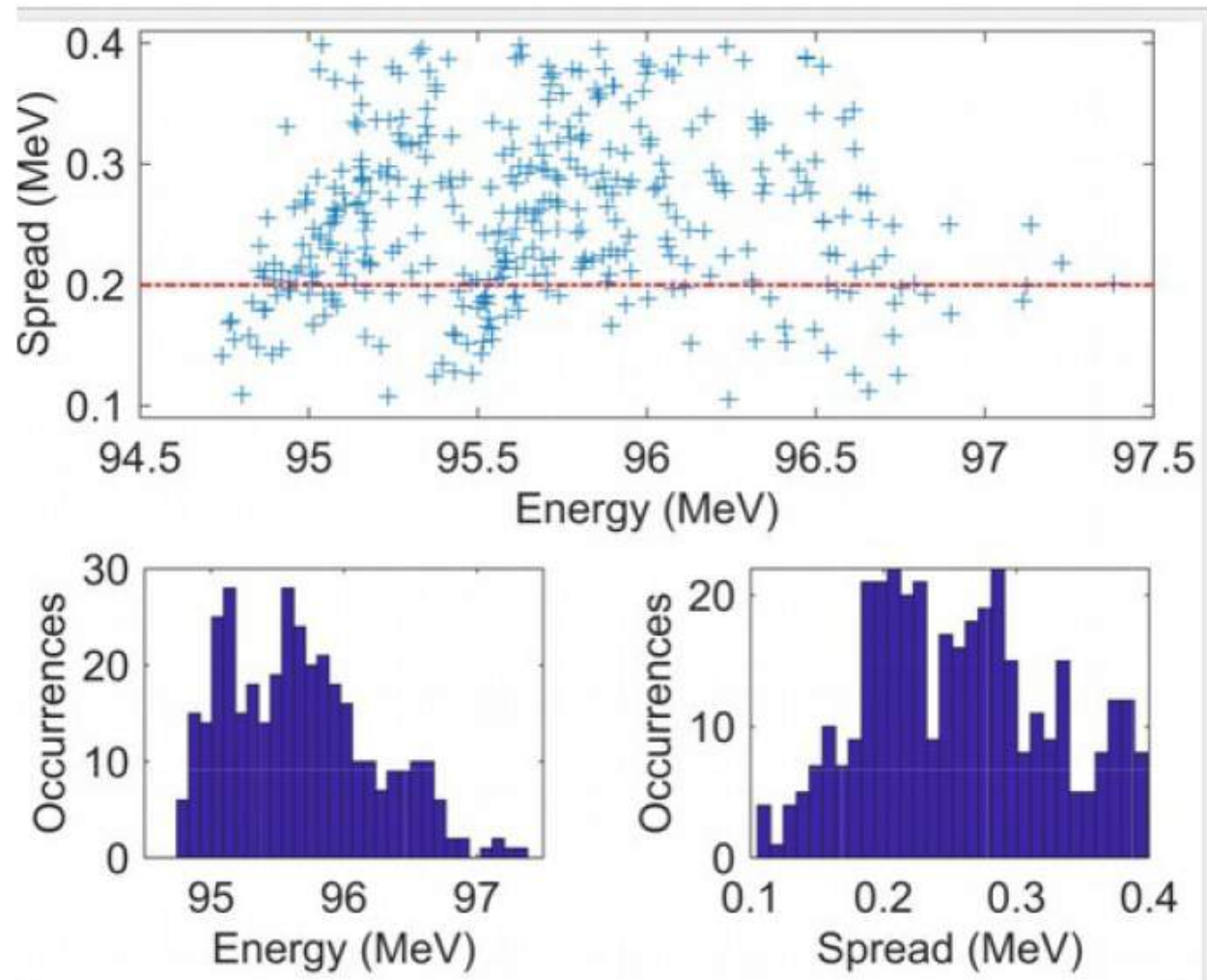
Energy spread after acceleration is 0.3 MeV, larger than the one with plasma off

Statistics

360 points

Red dashed line is
the initial spread
(plasma OFF)

Final spread is larger
→ chirped witness is
over-rotated by the
larger wakefield



SPARC_LAB lock-down started at the most
exciting moment, on March 11





LNF SciCom

LNF - 7 May 2020

SL_COMB2FEL

Resp. Naz.:
E. Chiadroni (LNF)

Other units:

LNF (Resp. Loc.: E. Chiadroni),
Roma1 (Resp. Loc.: A. Mostacci),
Roma2 (Resp. Loc.: A. Cianchi)
Milano (Resp. Loc.: V. Petrillo)
Lecce (Resp. Loc.: A. Lorusso),
Napoli (Resp. Loc.: R. Fedele)

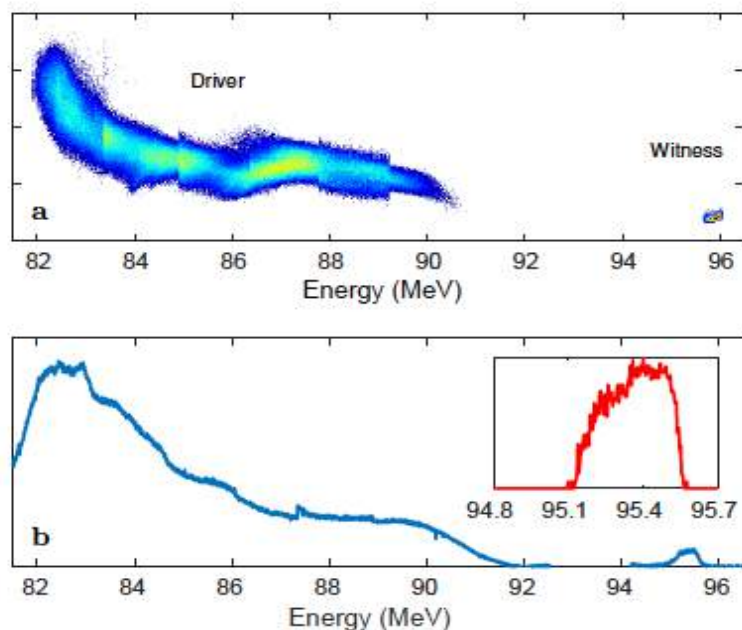


Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI



Experimental results

- ❖ Energy spread reduction in the beam driven PWFA experiment



	Driver	Witness	Plasma-accelerated witness
Energy (MeV)(MeV)	89.5	89.1	95.6
$\Delta E/E$ (%)	0.3	0.2	0.2
$\epsilon_{nx,y}$ (mm mrad)	2.5	0.7	0.9*
Q (pC)	350	20	20
σ_t (fs)	250	40	40

*The witness emittance has not been measured with plasma on, but it is assumed from simulations it is slightly degraded

R. Pompili et al., submitted to Nature Physics

enrica.chiadroni@lnf.infn.it

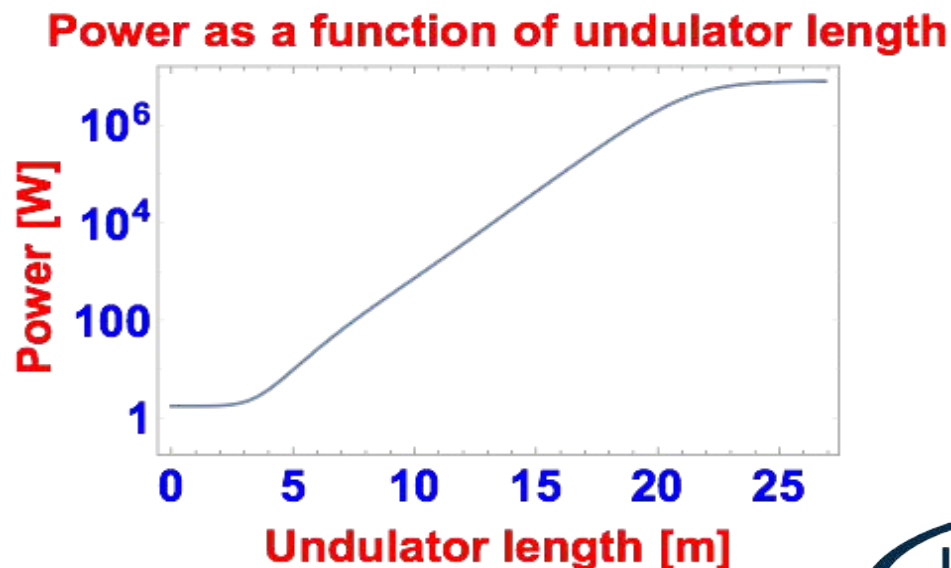
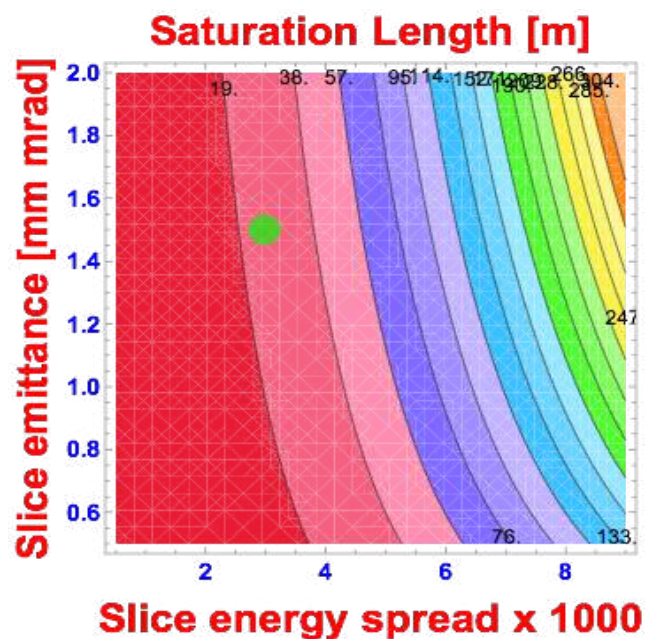
Radiation at 600 nm - Expected FEL Results



from measured accelerated beam parameters

Assuming a factor 2 transverse emittance degradation, a growth of the FEL gain could still be measured

Witness beam parameters		Undulator parameters	
gamma	188	λ_u (cm)	2.8
$\Delta E/E$ (%)	0.3	K	1
$c_{nx,y}$ (mm mrad)	1.5	FODO β function (m)	3
Q (pC)	20	λ_r (nm)	594
I_{peak} (A)	199.5		



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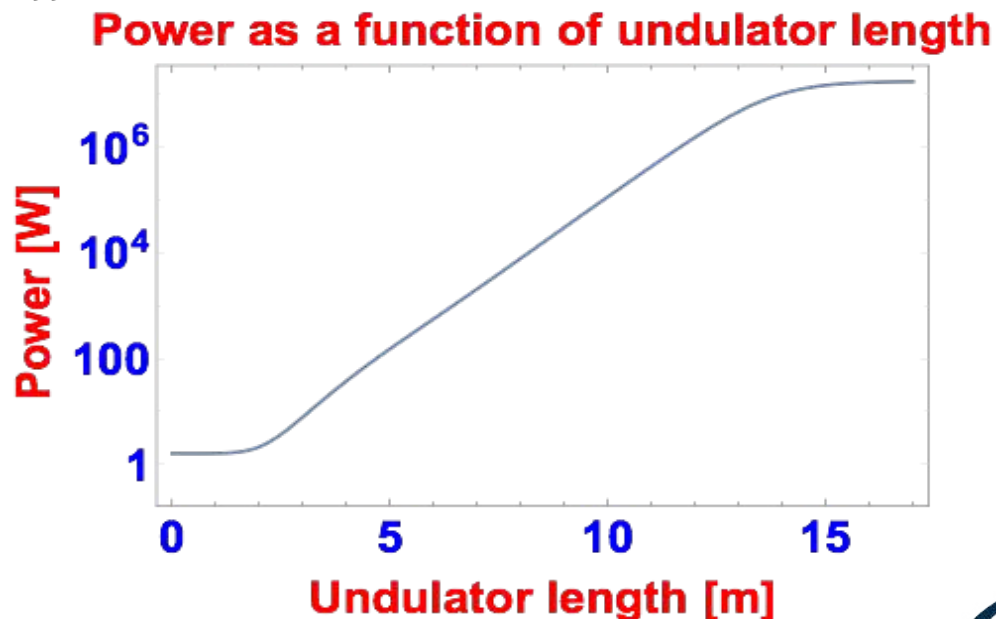
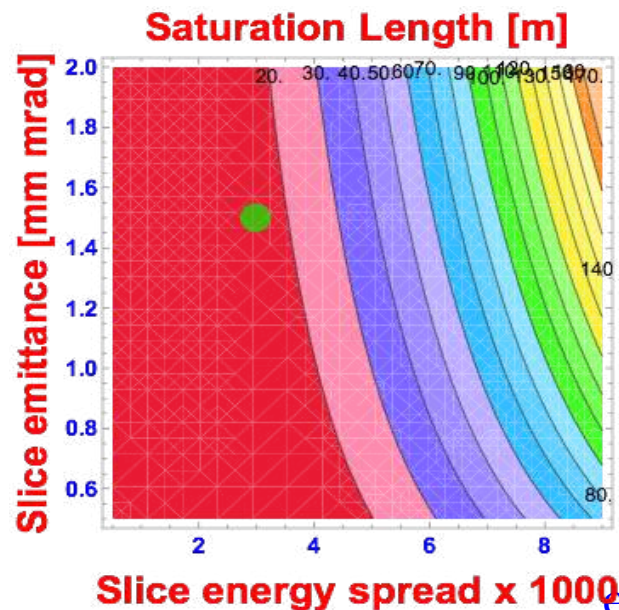
Radiation at 800 nm - Expected FEL Results



from measured accelerated beam parameters

Assuming a factor 2 transverse emittance degradation, a growth of the FEL gain could still be measured

Witness beam parameters		Undulator parameters	
gamma	188	λ_u (cm)	2.8
$\Delta E/E$ (%)	0.3	K	1.43
$c_{nx,y}$ (mm mrad)	1.5	FODO β function (m)	3
Q (pC)	20	λ_r (nm)	800
I_{peak} (A)	199.5		



enrica.chiadroni@lnf.infn.it





- ❖ Keep on both simulation and experimental studies going to **optimize the acceleration process** with particular attention to the **stability, reproducibility** and **quality** of the accelerated electron beam
- ❖ Study, design and **project of the transfer and matching line to the undulator** to remove the driver beam and preserve the the witness beam parameters
- ❖ **Experimental studies for witness beam and matching conditions optimization to drive FEL experiments**
- ❖ Optimization of experimental setup for single-shot bunch length and transverse diagnostics
- ❖ Design, project and procurement of material for compact beam position monitors

The background is a dark, abstract composition. A large, irregular, blue textured shape, resembling a rock or a piece of fabric, is positioned on the left side. To its right is a bright yellow-orange oval shape with a textured, almost crystalline interior. The overall lighting is dim, with some faint, wispy light trails or smoke-like effects in the upper right corner.

More Works in Progress
or
Thanks you for your attention

Hosing Instability Suppression in Self-Modulated Plasma Wakefields

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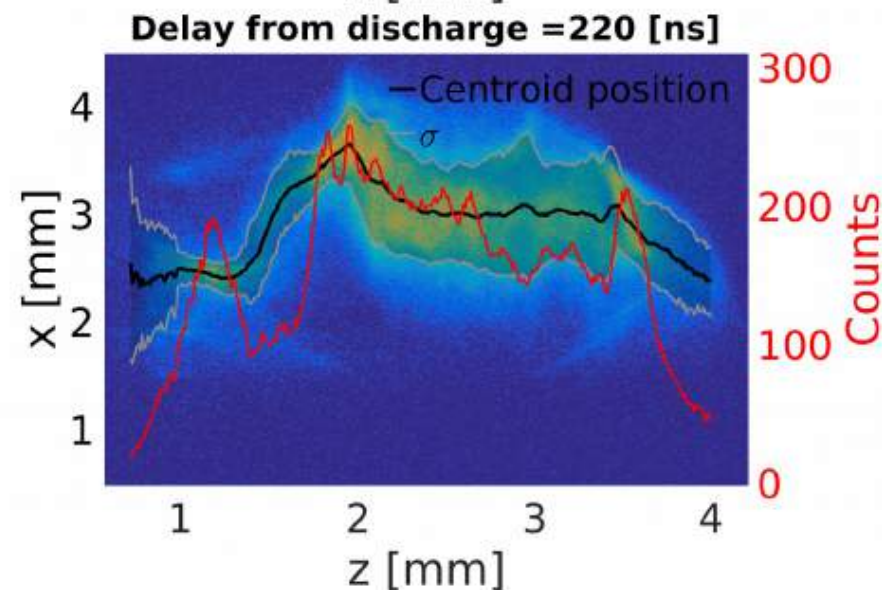
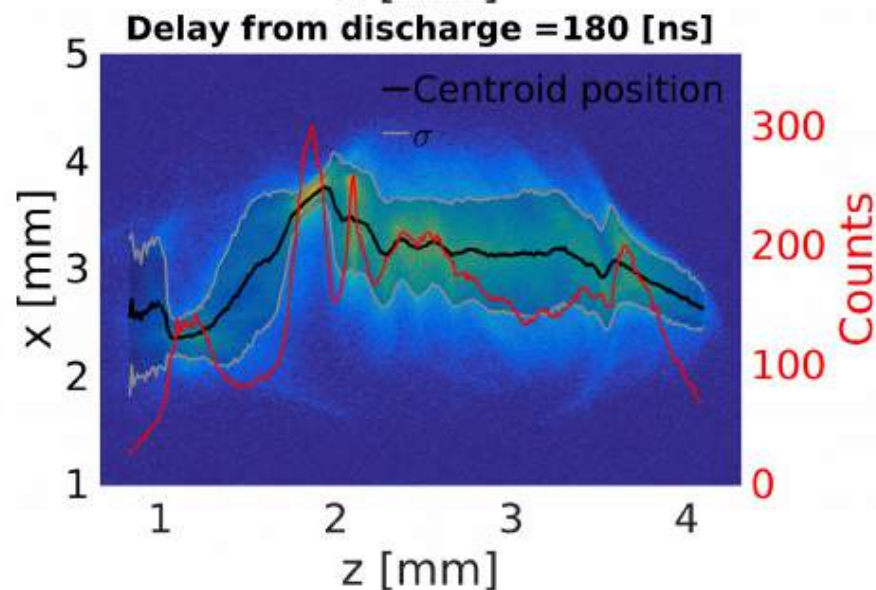
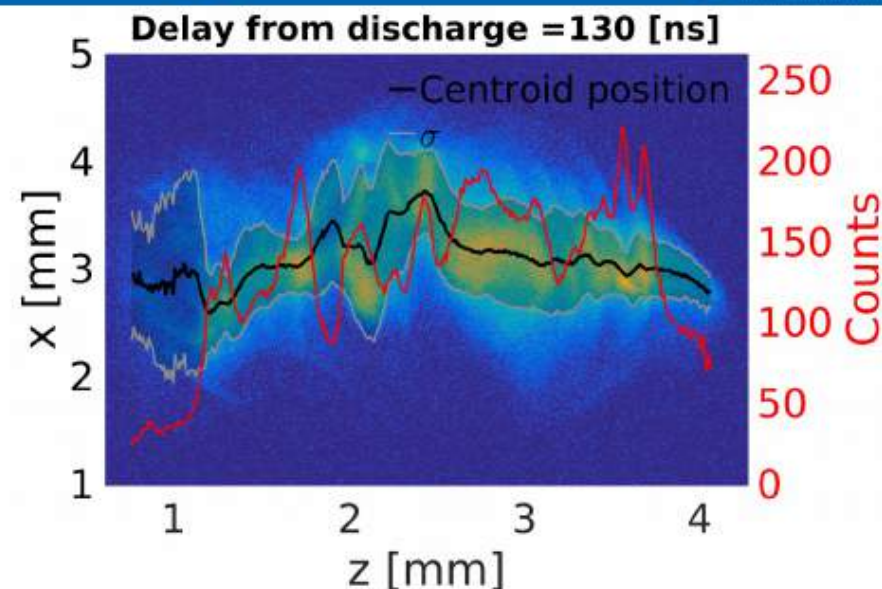
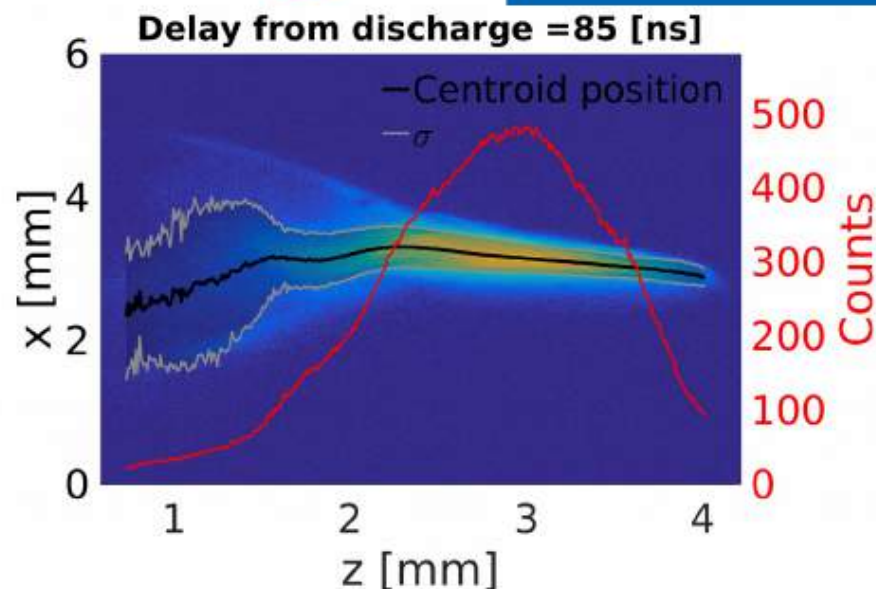
We show that the hosing instability can be suppressed after the saturation of the self-modulation instability of a long particle bunch if the plasma density perturbation is linear. We derive scalings for maximum bunch tilts and seeds for the self-modulation instability to ensure stable propagation beyond saturation of self-modulation instability. Numerical solutions of the reduced hosing equations and three-dimensional particle-in-cell simulations confirm our analytical findings. Our results may also apply when a train of particle bunches or laser pulses excites a linear wake.

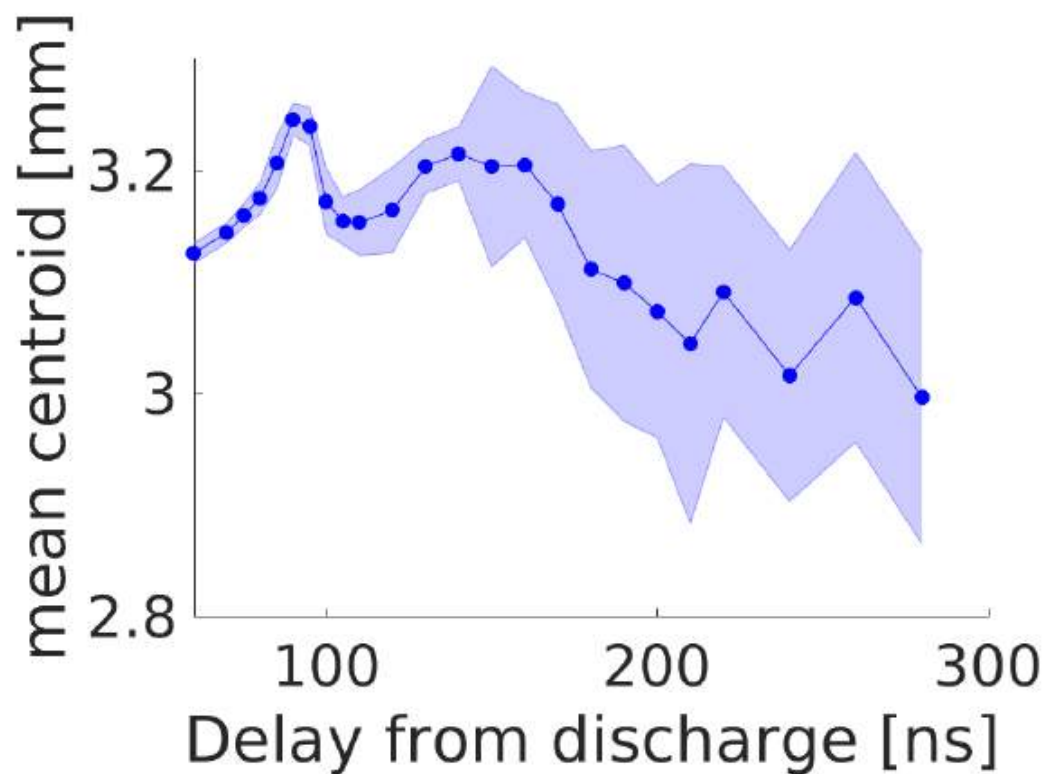
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PACS numbers: 52.40.Mj, 52.35.-g, 52.65.Rr

Phenomenology shown that a suppression of the hose instability should occur in linear overdrive regime, i.e. $n_b < n_p$.

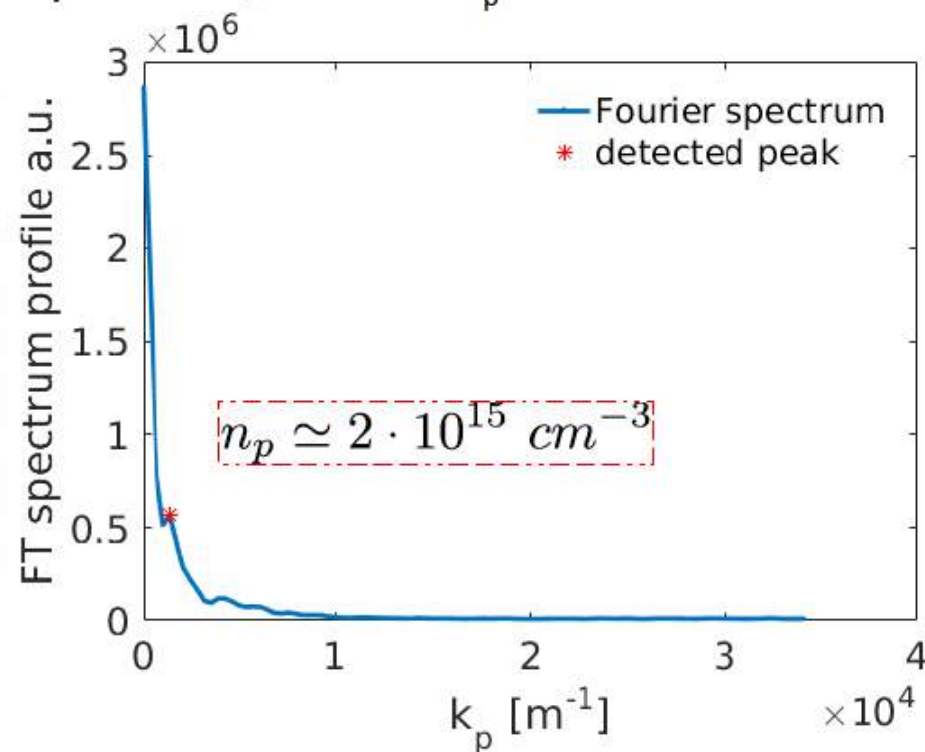
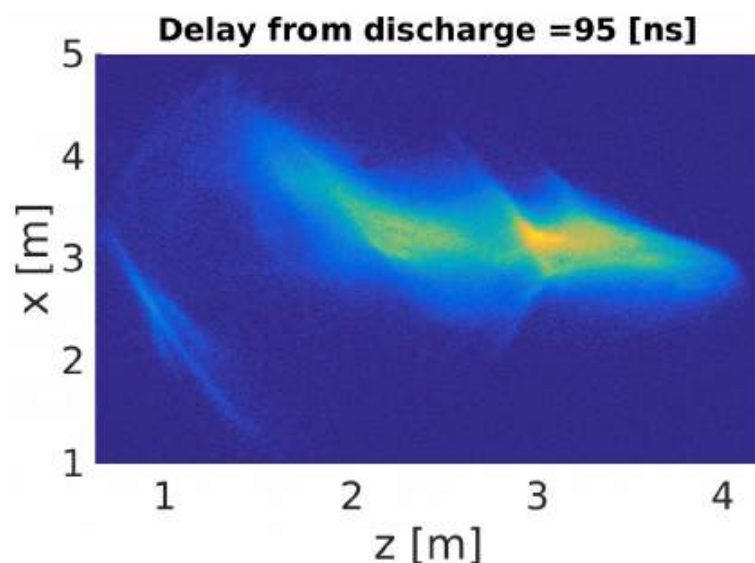
Courtesy A. Del Dotto





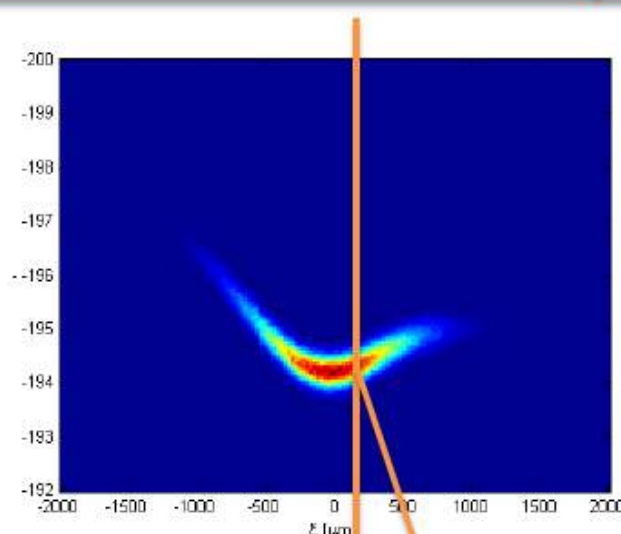
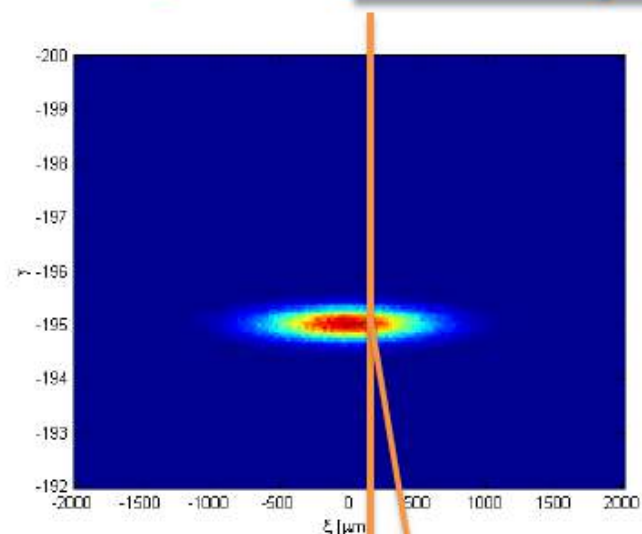
- After 100 ns, once the plasma density grows enough, we are in a regime where $n_b < n_p$ (n_b about 10^{14} cm^{-3})
- The self-modulation of the beam become relevant and the damping starts

Note: Delay used for the acceleration experiment, retrieved n_p used in the simulations

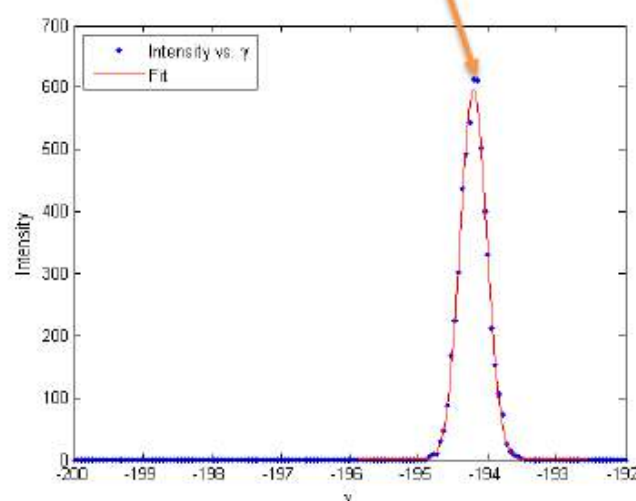
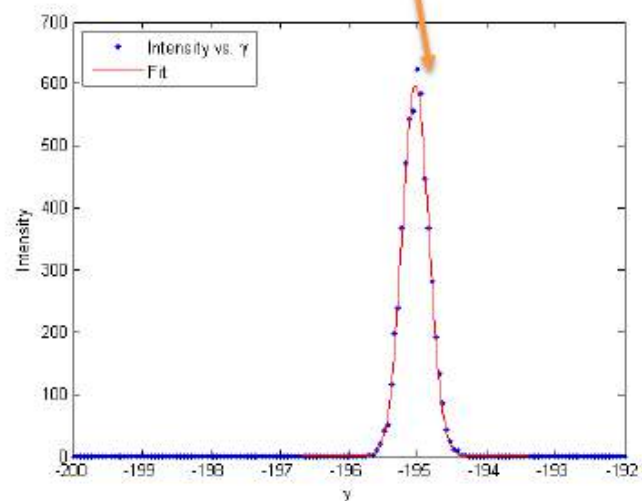


$$n_p = (c^2 \epsilon_0 m_e / e^2) k_p^2 \simeq (3.33 \cdot k_p)^2 \cdot 10^8 \text{ cm}^{-3}$$

Phase space measurement of plasma density



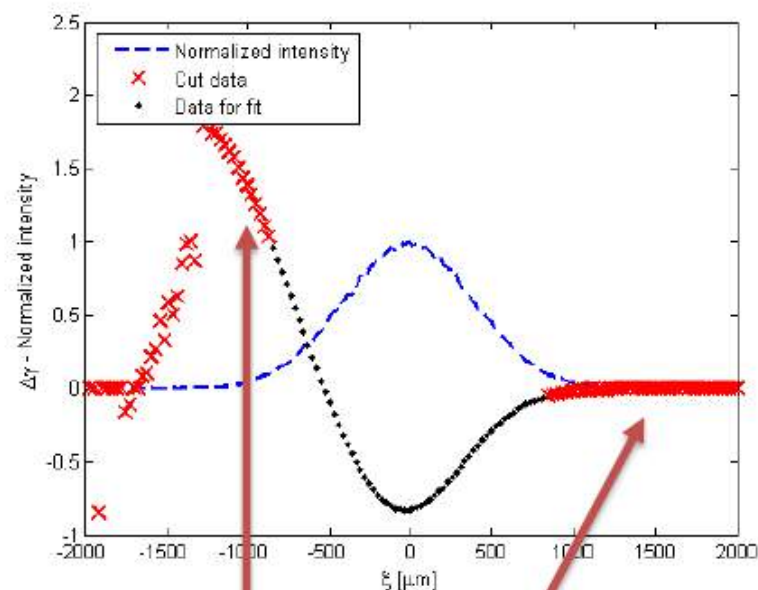
We analyze the phase spaces in order to retrieve the average γ vs. ξ



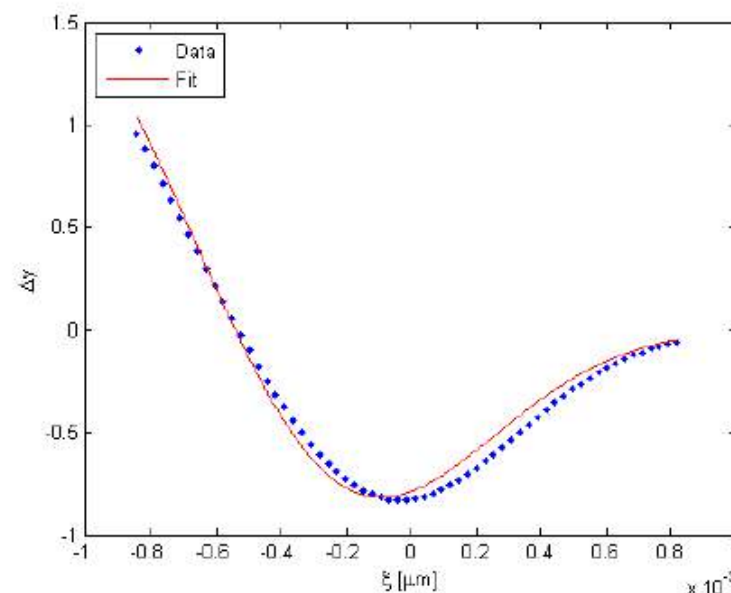
Subtracting the results with plasma ON/OFF in order to obtain $\Delta\gamma$ vs. ξ

Cut and fit (simulation example)

From fit we retrieve the value of k_p

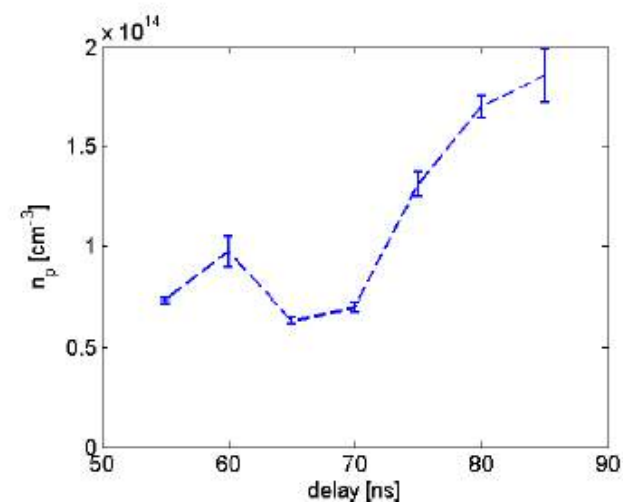
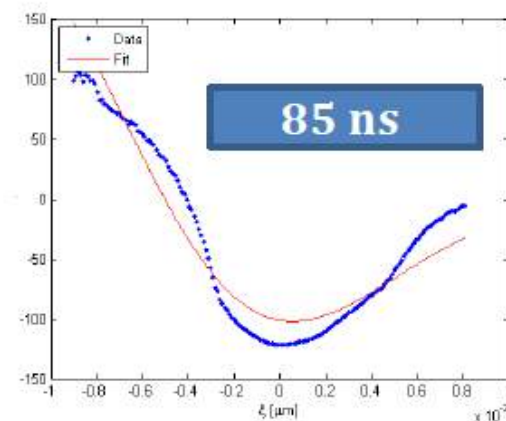
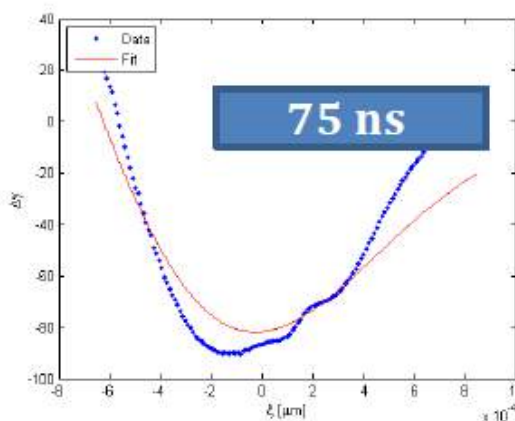
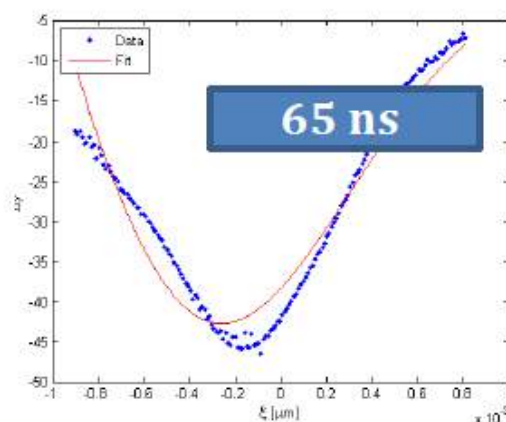
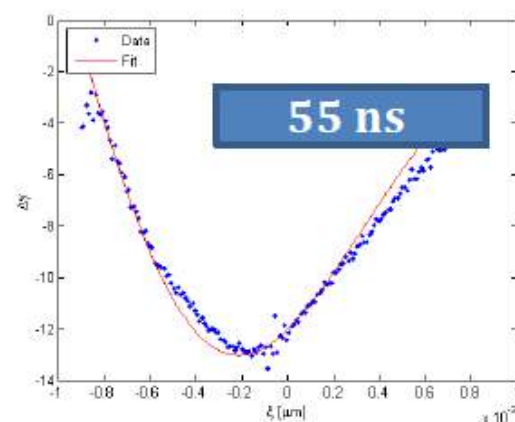


Cutting points where bunch intensity is lower than 10% of peak intensity and halos (handmade)



$$\Delta\gamma = \frac{E_z L}{m_e c^2} = a \operatorname{Re} \left[\exp i k_p \xi \operatorname{Erf} \left(\frac{\xi}{\sqrt{2} \sigma_z} - i \frac{k_p \sigma_z}{\sqrt{2}} \right) \right]$$

Fit of experimental data for different delays



From the value of k_p we retrieved n_p for different delays

An abstract digital artwork featuring a dark blue background with flowing, ethereal light trails in shades of blue and green. A prominent, glowing orange-yellow shape, resembling a stylized eye or a celestial body, is positioned in the lower right quadrant. The text "Thanks for your attention" is centered in a bold, orange-yellow font.

Thanks for your attention