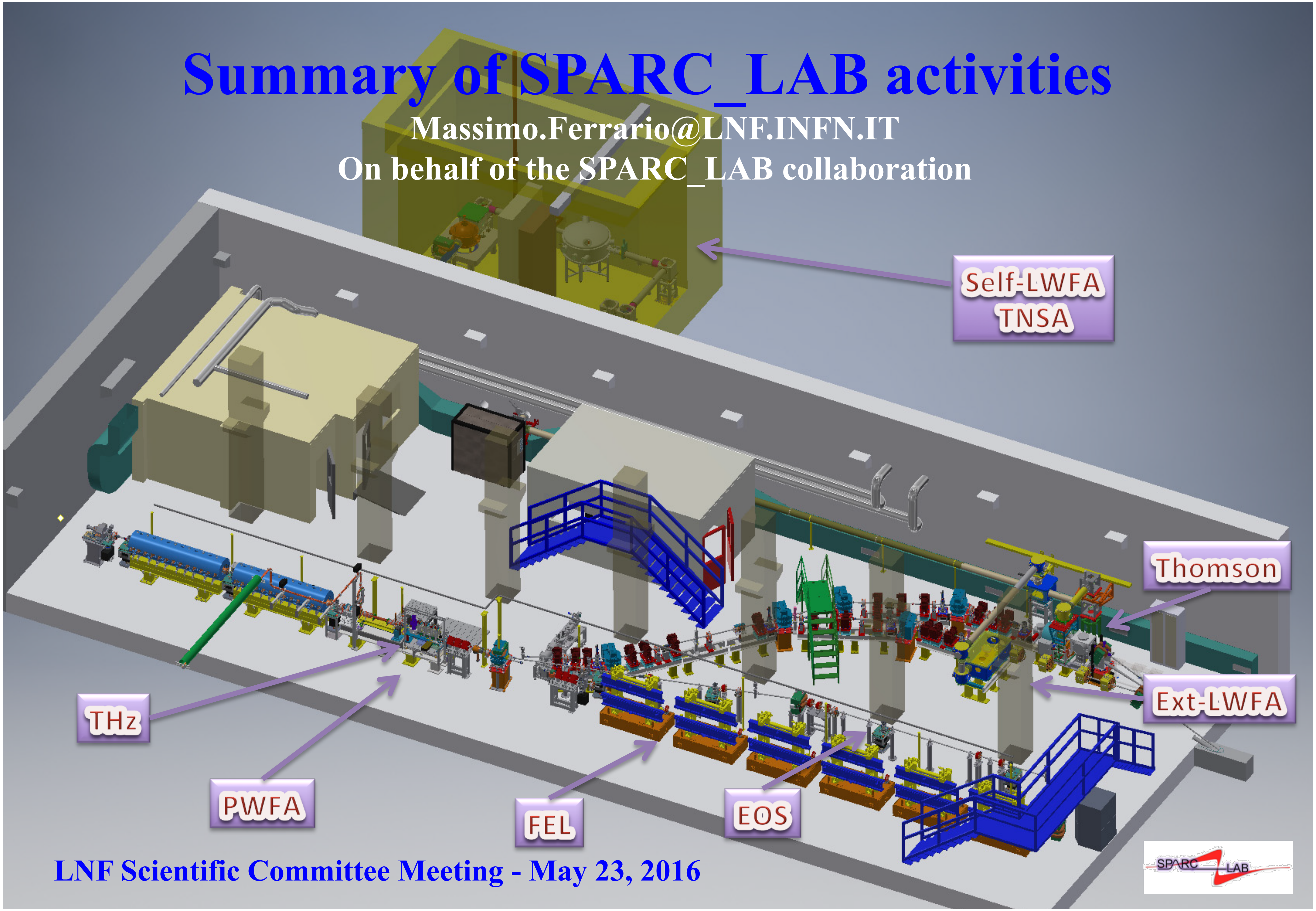
Summary of SPARC_LAB activities

Massimo.Ferrario@LNF.INFN.IT
On behalf of the SPARC_LAB collaboration



LNF Scientific Committee Meeting - May 23, 2016

Highlights

- THz: results published Nature Communications

- PWFA: first beam injected in to the plasma

- LWFA: self-injected beam accelerated up to 170 MeV, betatron radiation detected, emittance measurments in progress

- TNSA: results submitted to Nature Physics


nature COMMUNICATIONS

ARTICLE

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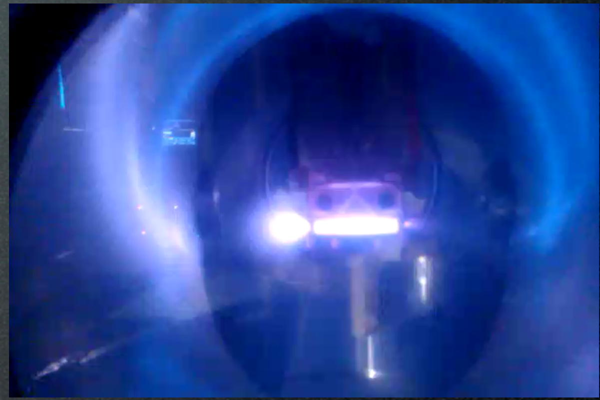
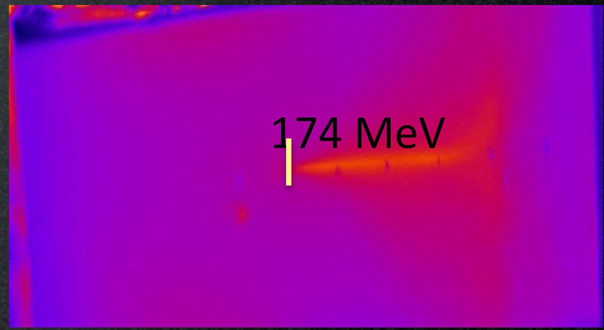
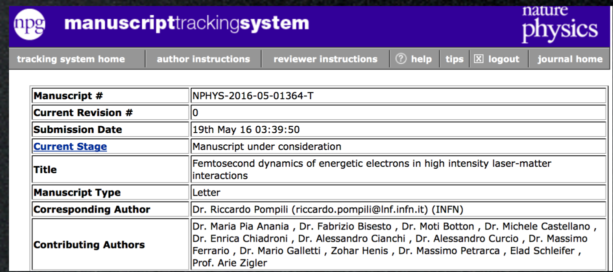
Strong nonlinear terahertz response induced by Dirac surface states in Bi_2Se_3 topological insulator

Flavio Giorgianni[1], Enrica Chiadroni[2], Andrea Rovere[1], Mariangela Cestelli-Guidi[2], Andrea Perucchi[3], Marco Bellaveglia[2], Michele Castellano[2], Domenico Di Giovenale[2], Giampiero Di Pirro[2], Massimo Ferrario[2], Riccardo Pompili[2], Cristina Vaccarezza[2], Fabio Villa[2], Alessandro Cianchi[4], Andrea Mostacci[5], Massimo Petrarca[5], Matthew Brahlek[6], Nikesh Koirala[6], Seongshik Oh[6] & Stefano Lupi[1]



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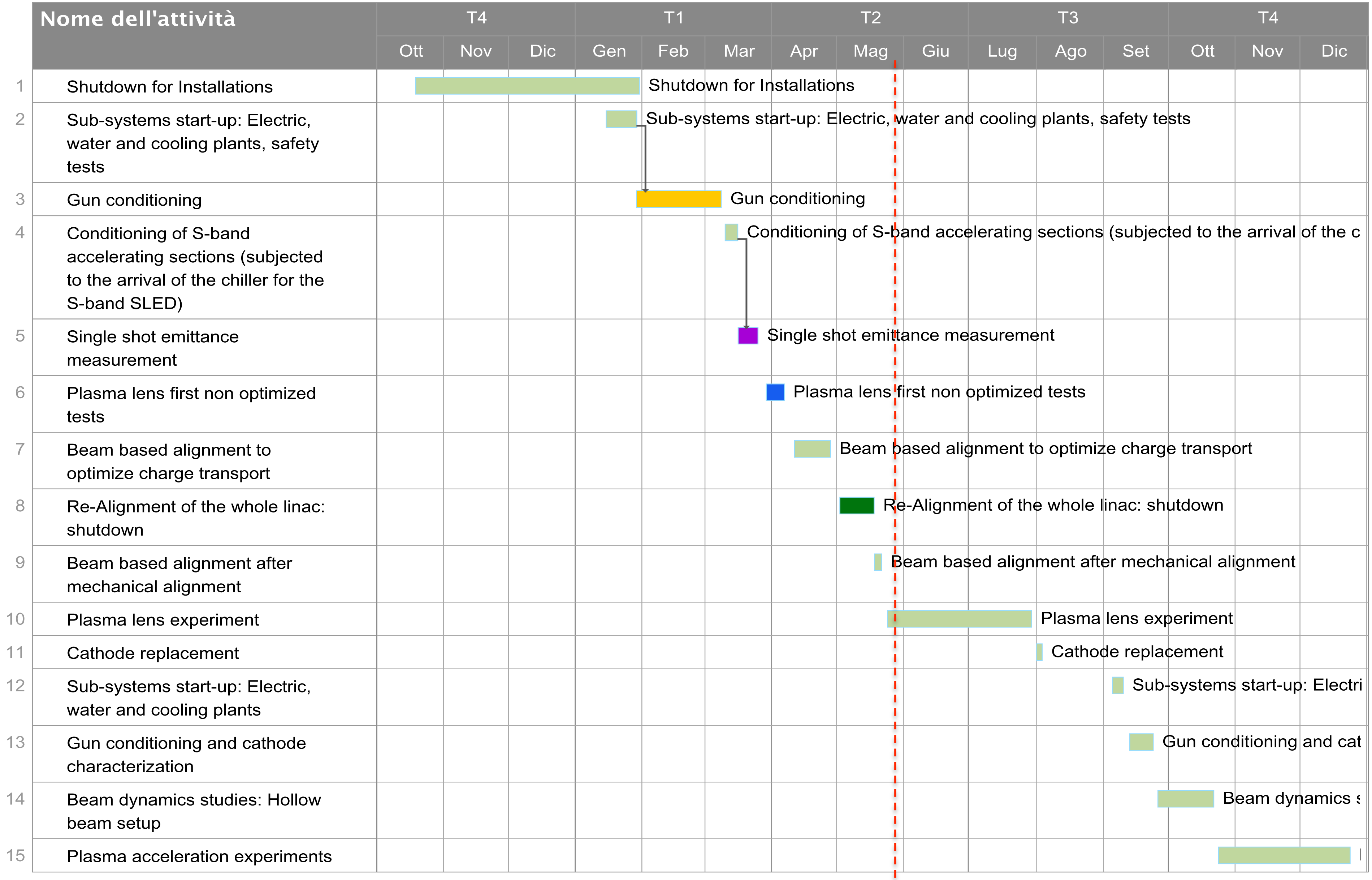
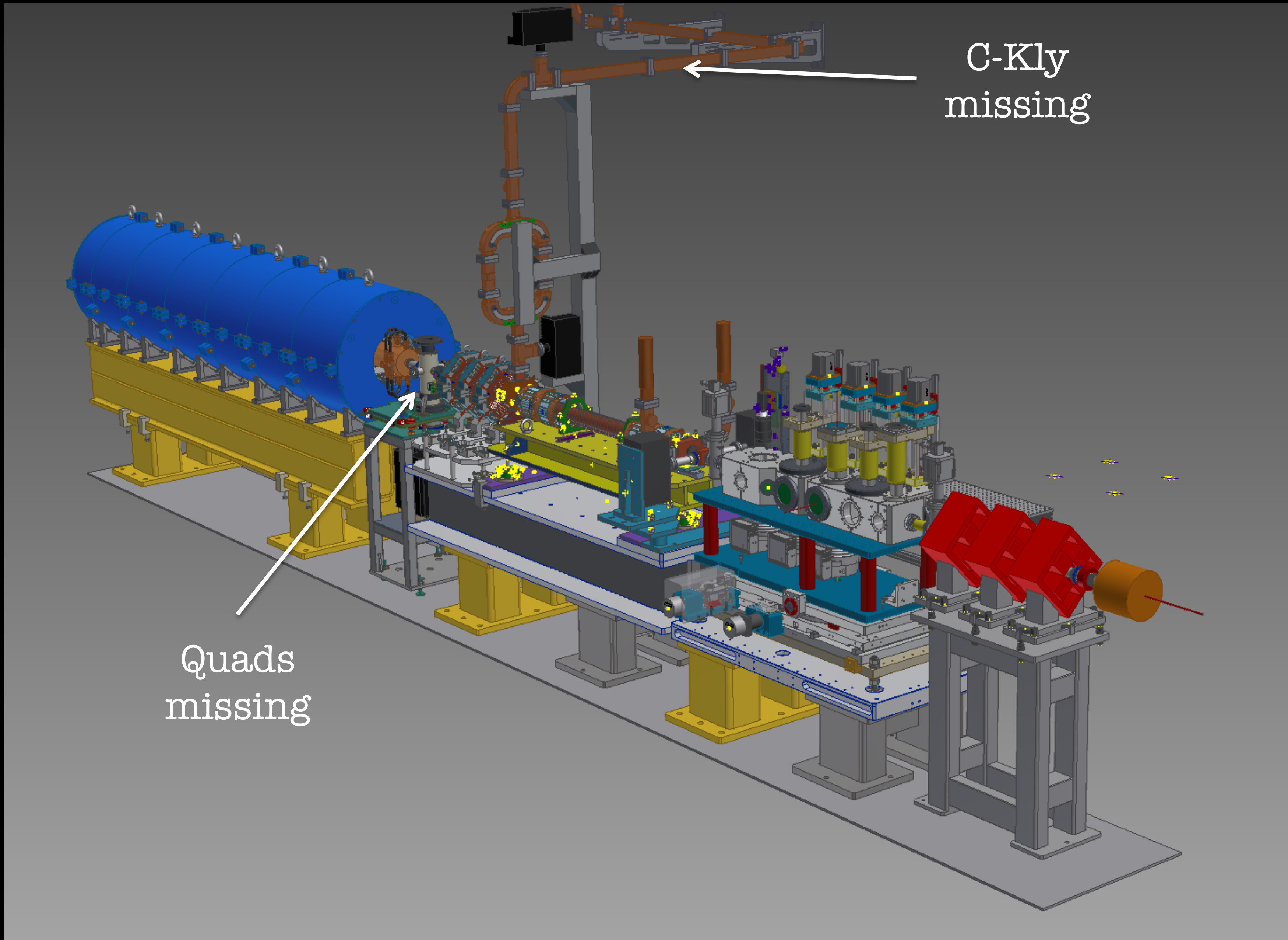
Manuscript #	NPHYS-2016-05-01364-T
Current Revision #	0
Submission Date	19th May 16 03:39:50
Current Stage	Manuscript under consideration
Title	Femtosecond dynamics of energetic electrons in high intensity laser-matter interactions
Manuscript Type	Letter
Corresponding Author	Dr. Riccardo Pompili (riccardo.pompili@lnf.infn.it) (INFN)
Contributing Authors	Dr. Maria Pia Anania , Dr. Fabrizio Bisesto , Dr. Moti Botton , Dr. Michele Castellano , Dr. Enrica Chiadroni , Dr. Alessandro Cianchi , Dr. Alessandro Curcio , Dr. Massimo Ferrario , Dr. Mario Galletti , Zohar Henis , Dr. Massimo Petrarca , Elad Schleifer , Prof. Arie Zigler

15 October 2015 – 23 December 2016



Installations almost completed: layout as it is now:



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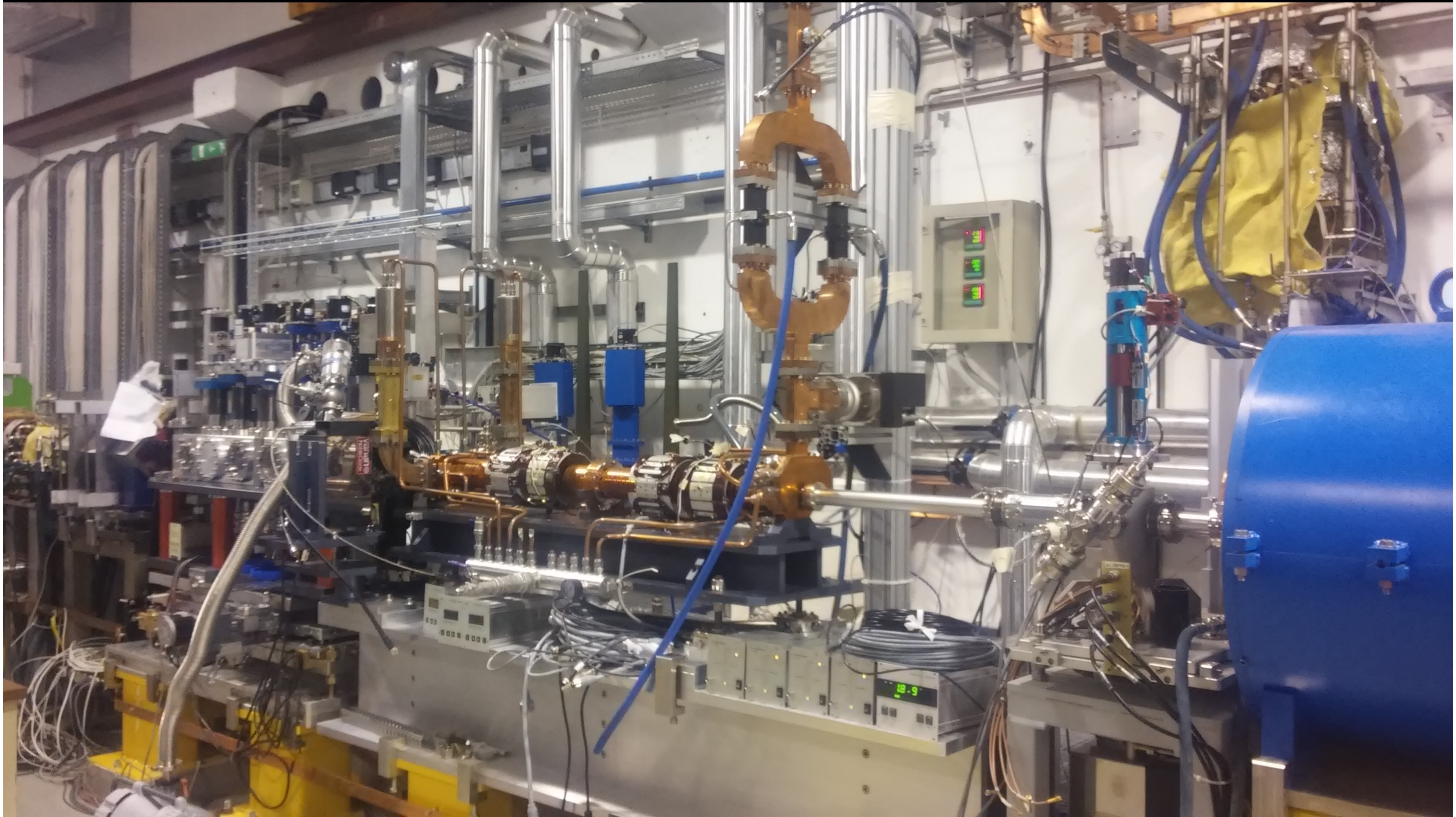


Pictures directly from CARRIER

TILT

FALL, IMPACT >25g

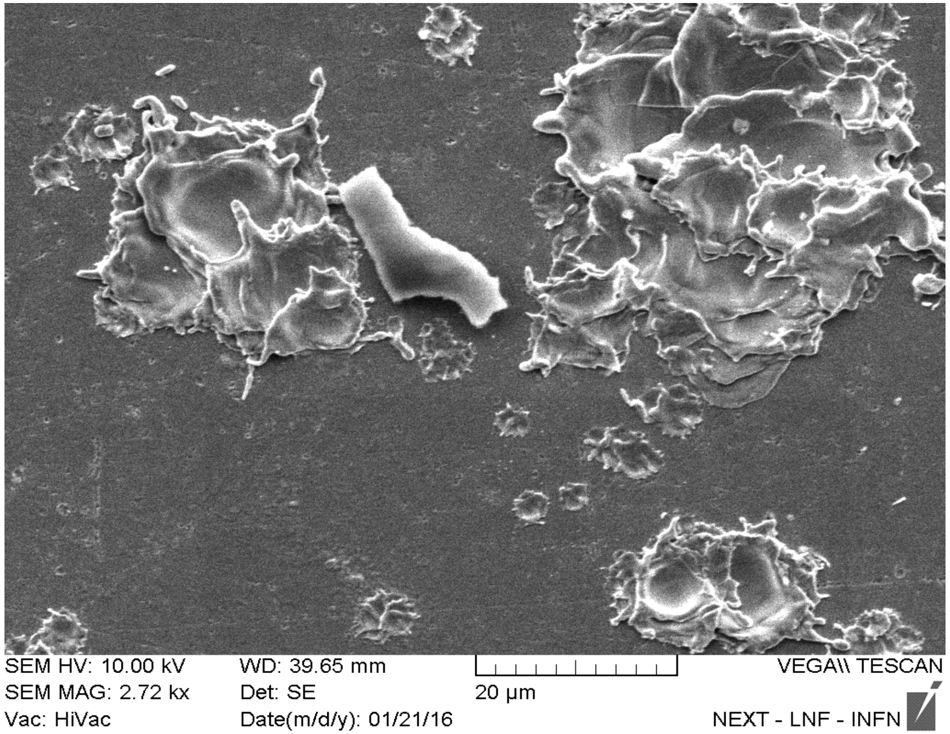
Cathode replacement

- Very low QE 5 10-6
- High breakdown rate, because of poor surface quality

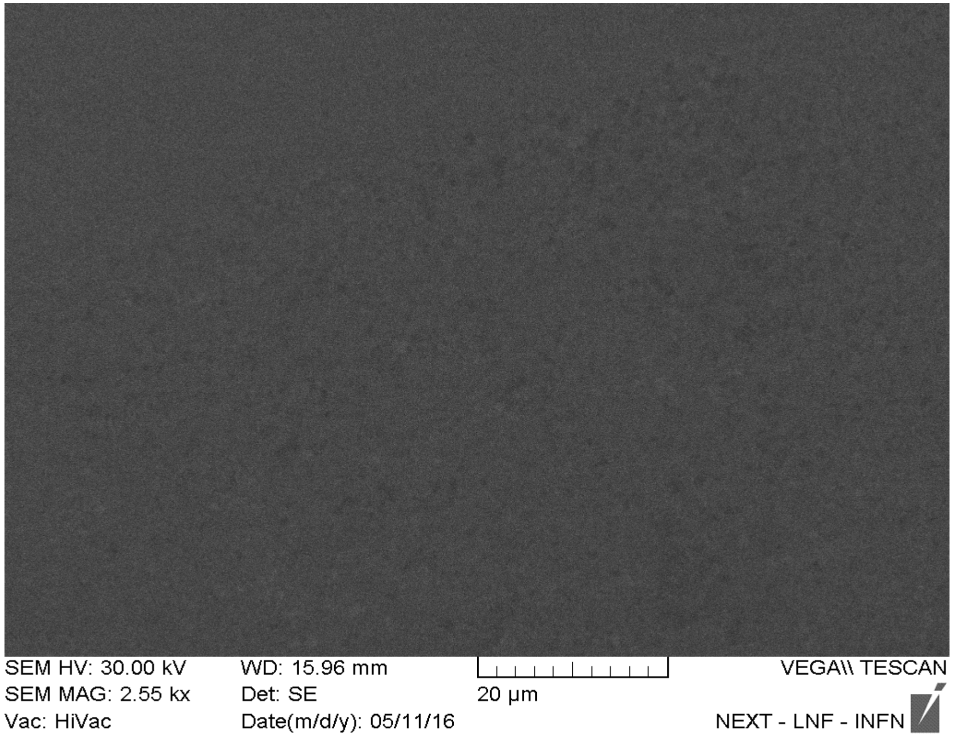
A research activity is already started to improve cathode performances and limit the breakdown rate

New cathode ready to be installed

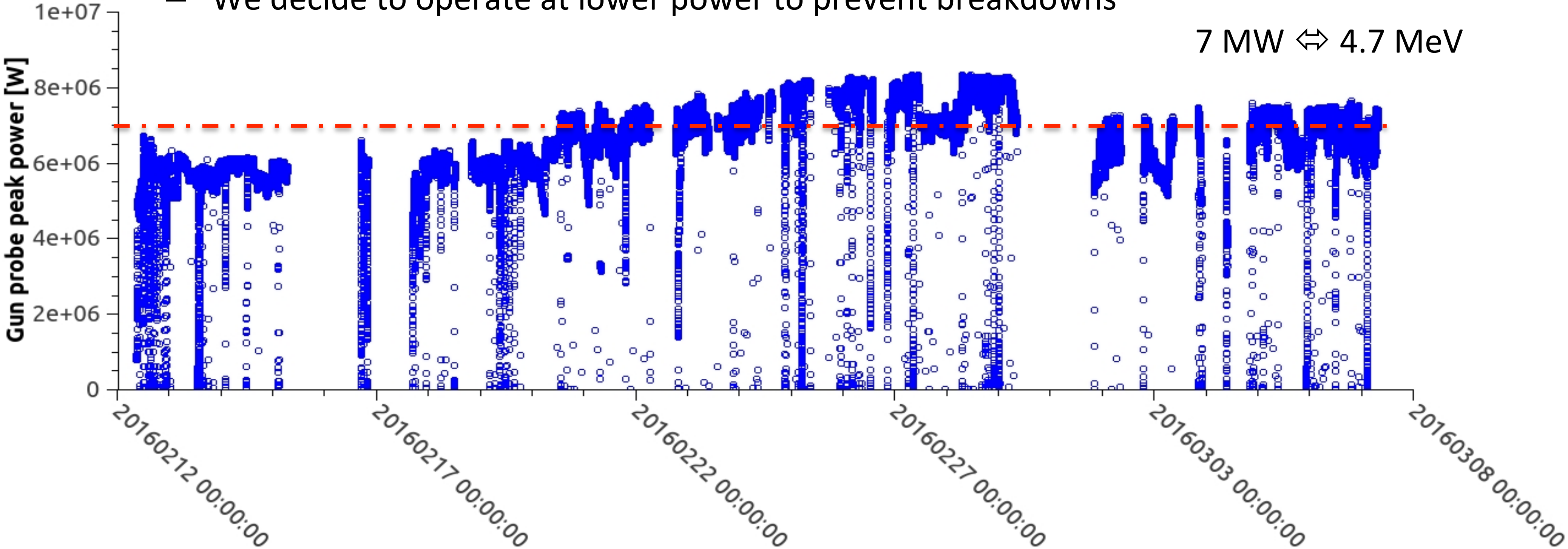
BEFORE MACHINING



AFTER MACHINING

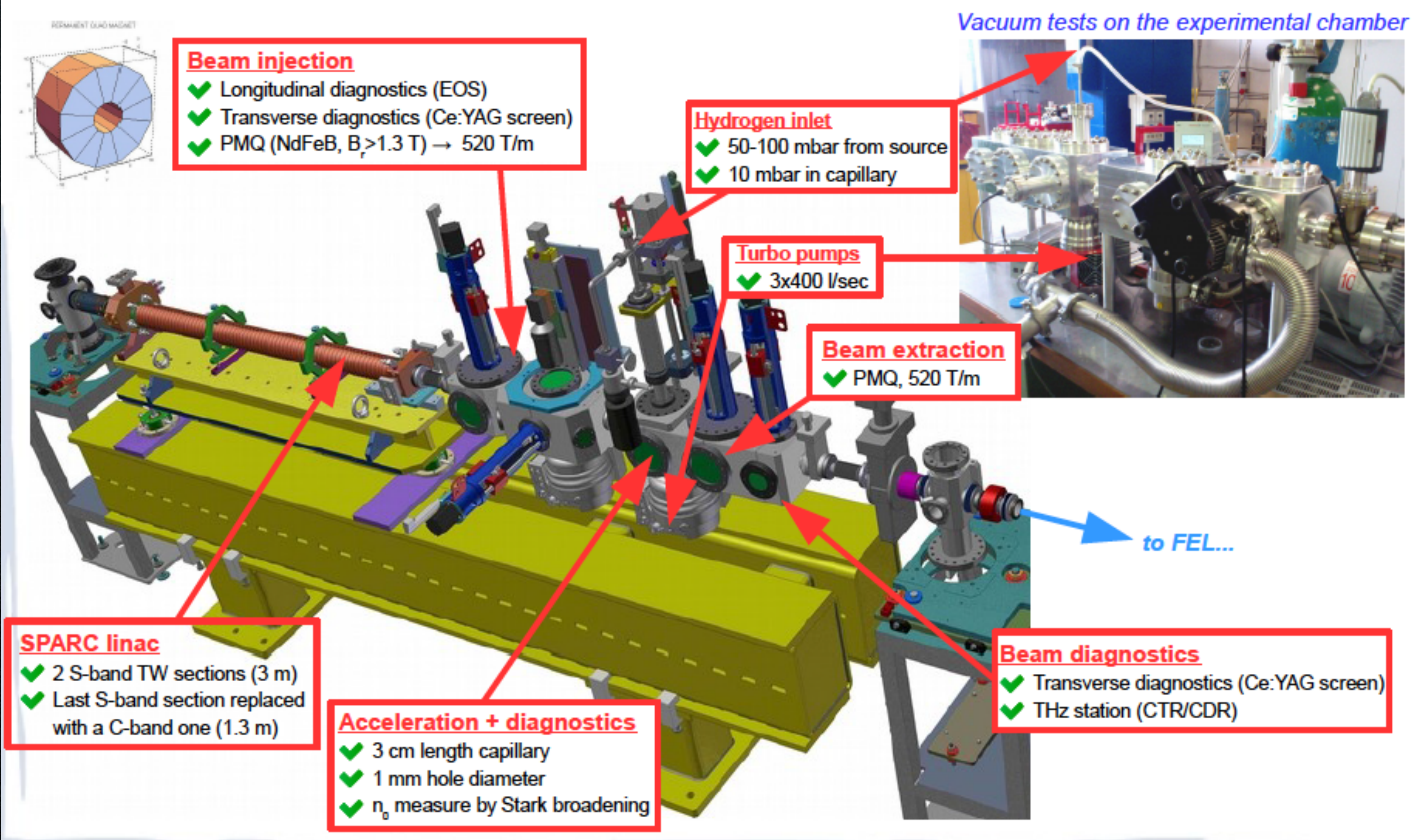


- **Gun conditioning** (Feb 2nd – Mar 7th)
  - In the night and during the weekends from Dafne control room with the help of Dafne crew
  - Full power in the gun with modest breakdown rate has been achieved after one month of conditioning
  - We decide to operate at lower power to prevent breakdowns

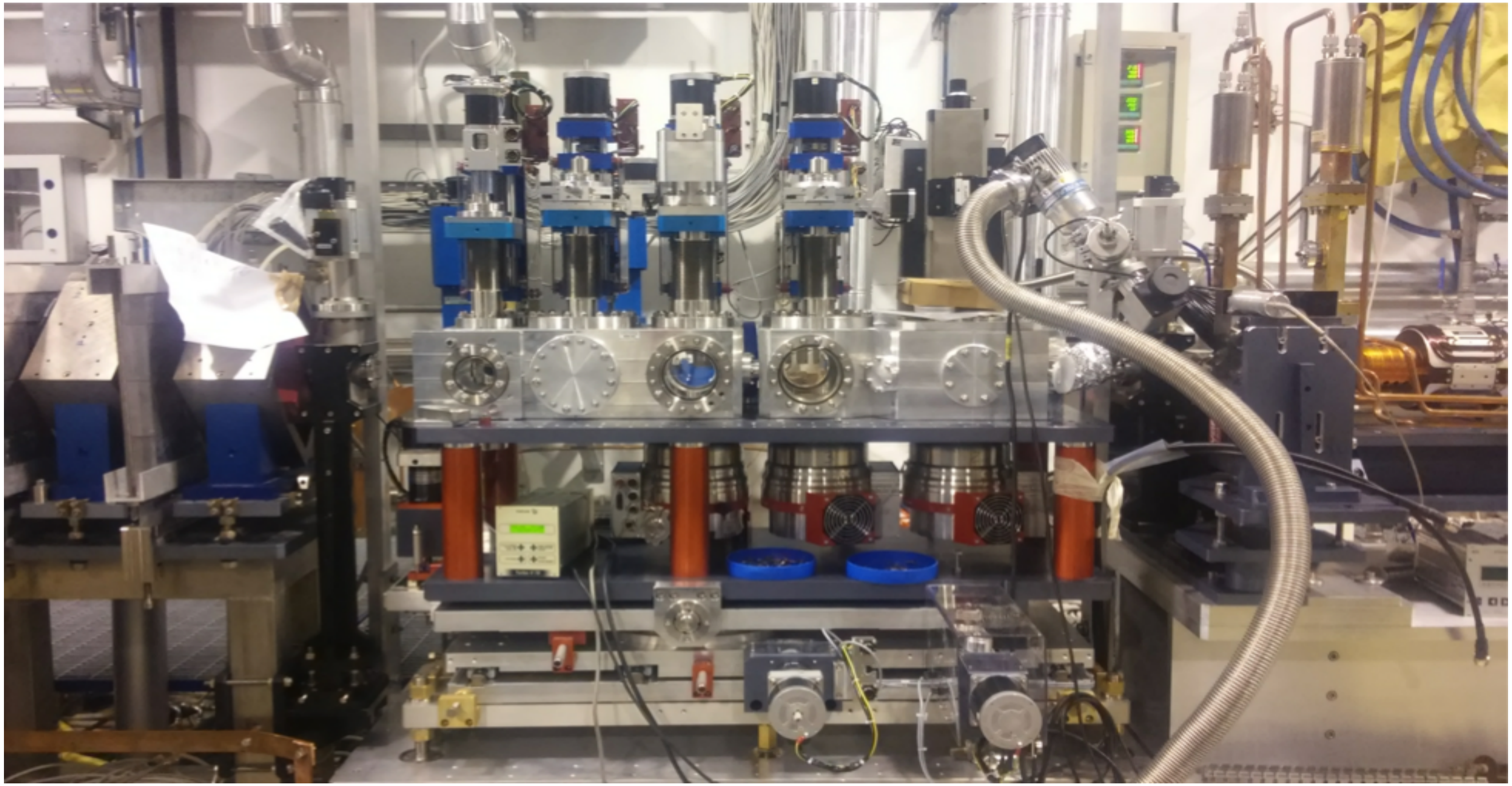


- **Conditioning of the S-band accelerating sections** (Mar 9th – Mar 15th)

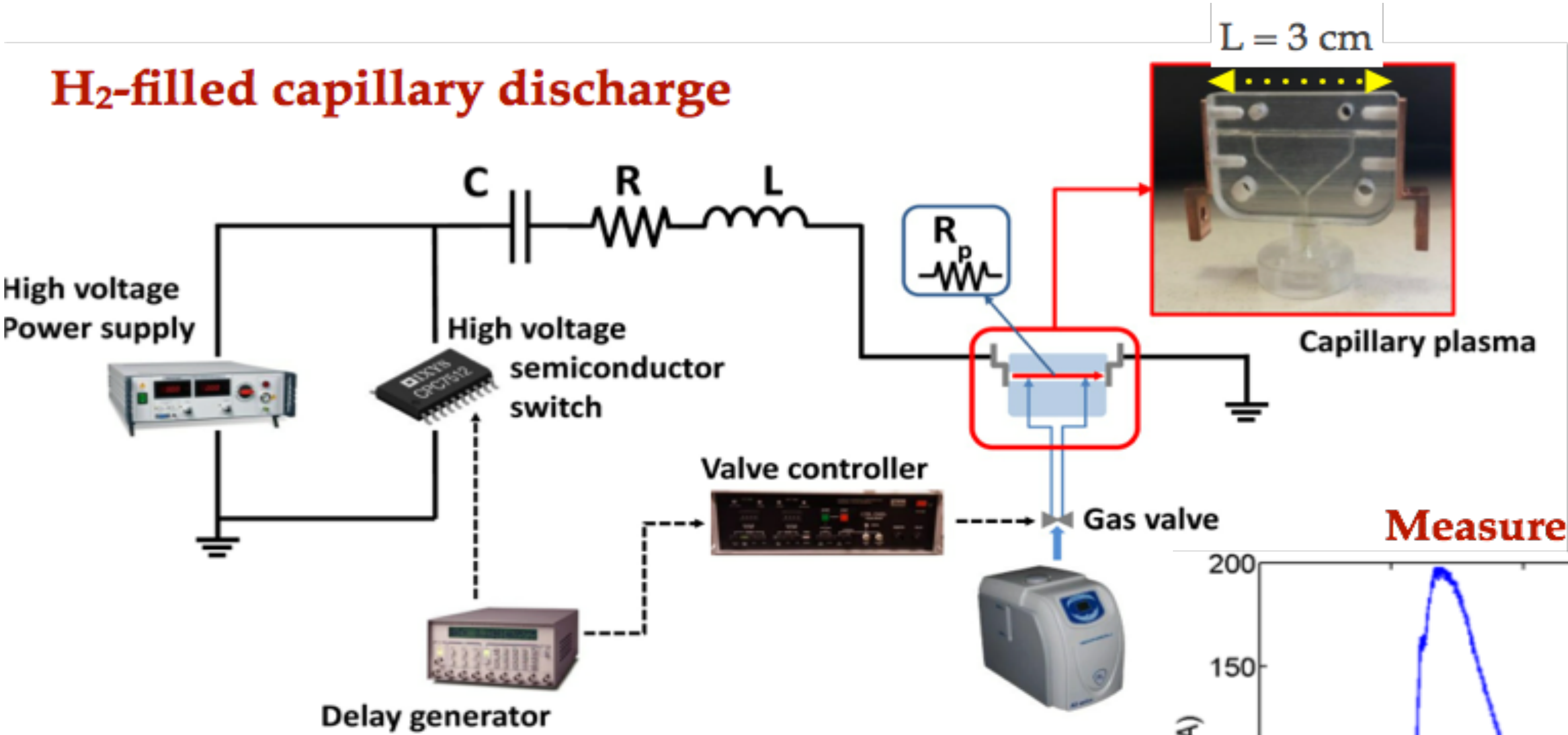
PWFA chamber installed and tested

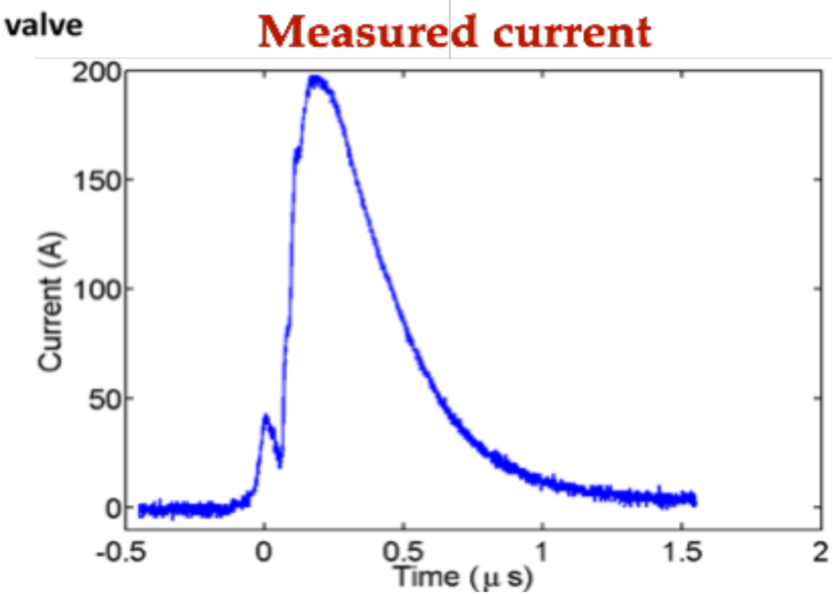


- COMB interaction chamber installed and fully equipped with PMQs and transverse diagnostics
  - EOS camera installed → transverse diagnostics @ COMB chamber entrance
  - OTR target below the capillary → transverse diagnostics at the plasma entrance with micrometer scale resolution



Plasma Source





P_{H2} = 10 mbar
Total discharge duration: 800 ns
Voltage: 20 kV
Peak current: 200 A
Capacitor: 6 nF

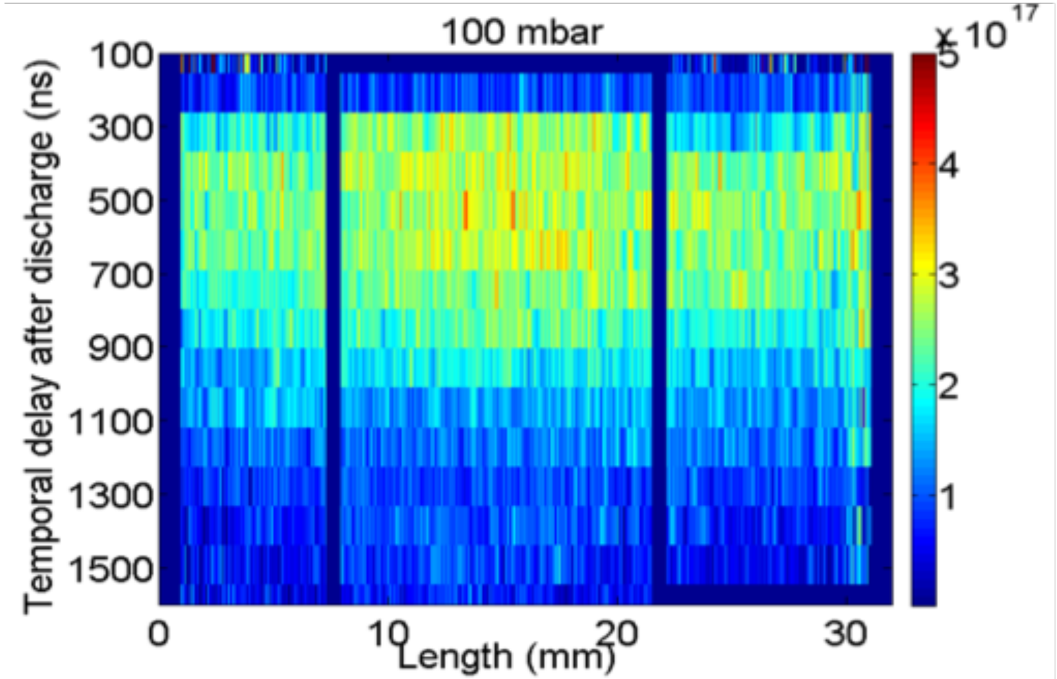
Courtesy of M. P. Anania, A. Biagioni, D. Di Giovenale, F. Filippi, S. Pella

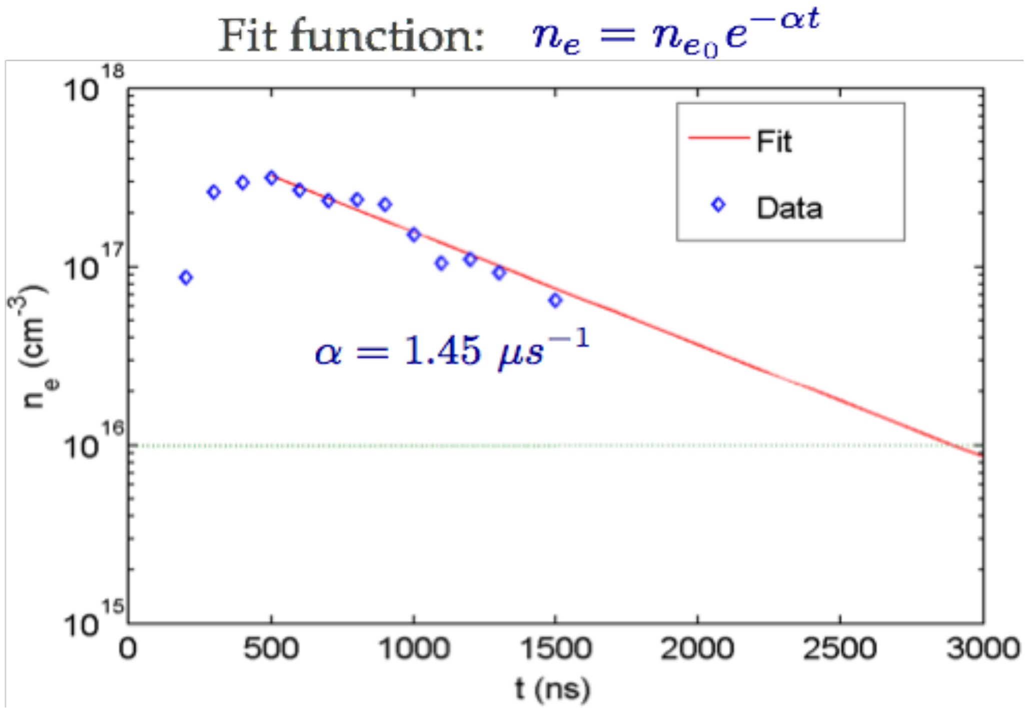
- Plasma discharge circuit tested online
  - Vacuum tests with discharge done @ 1-5-10 Hz

Plasma Characterization

Plasma density measurement from H_α Stark broadening

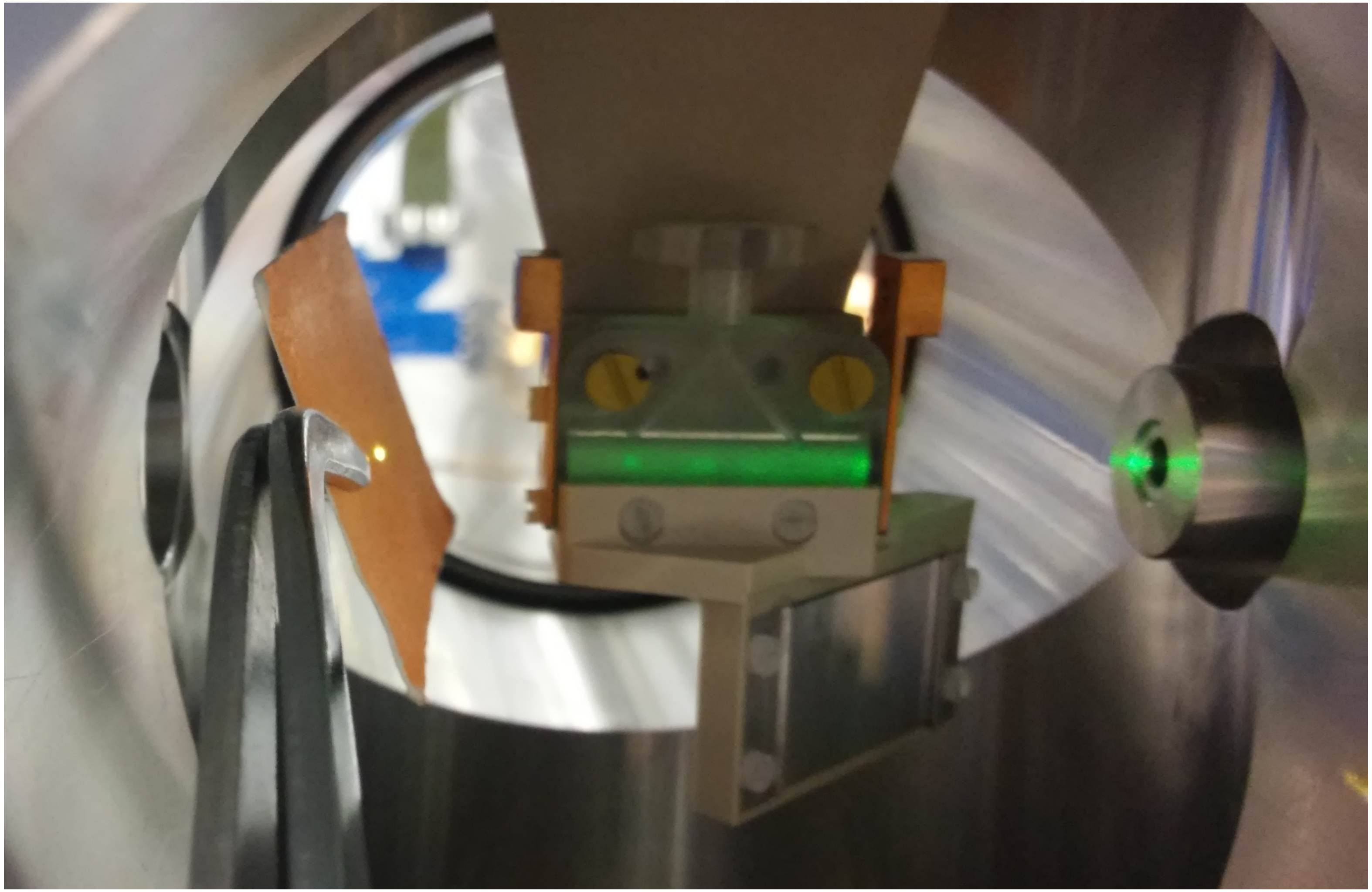
The plasma density is controlled through the delay after the discharge





Courtesy of M. P. Anania, A. Biagioni, F. Filippi, A. Ziegler

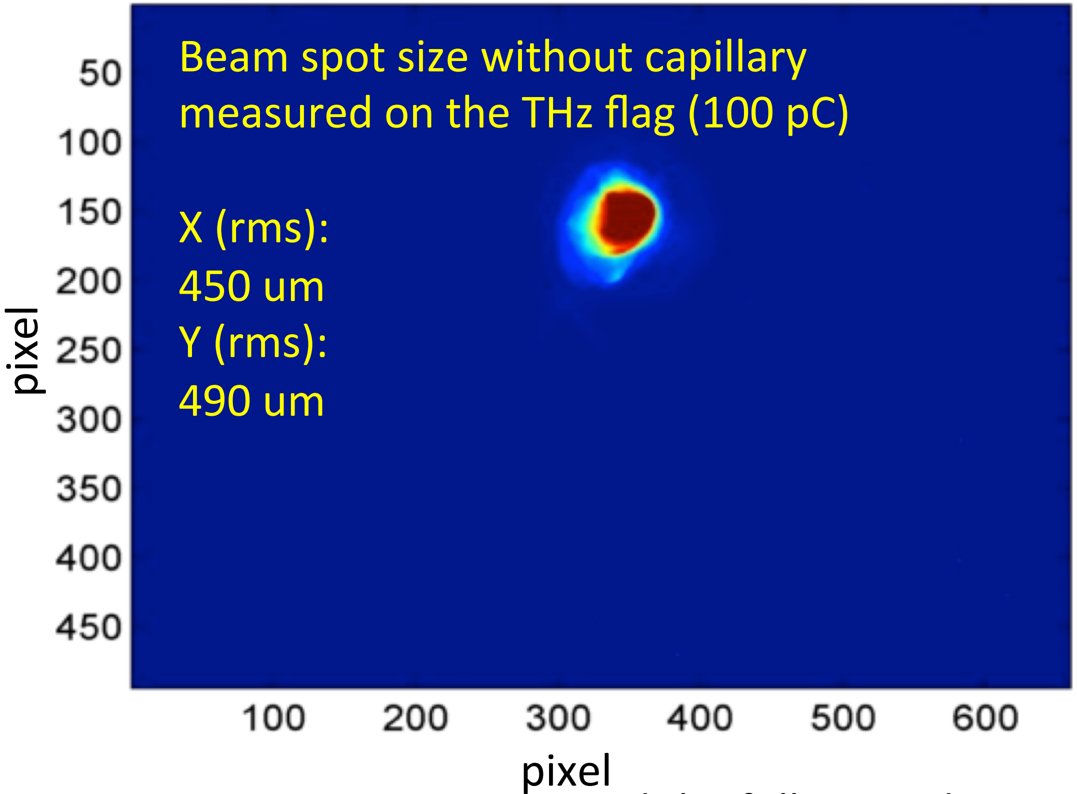
- Preliminary alignment of capillary, PMQs and plasma OTR with a laser through the linac



- # PWFA: first beam injected in to the plasma

Electron beam parameters
100 pC (at the cathode)
118 MeV

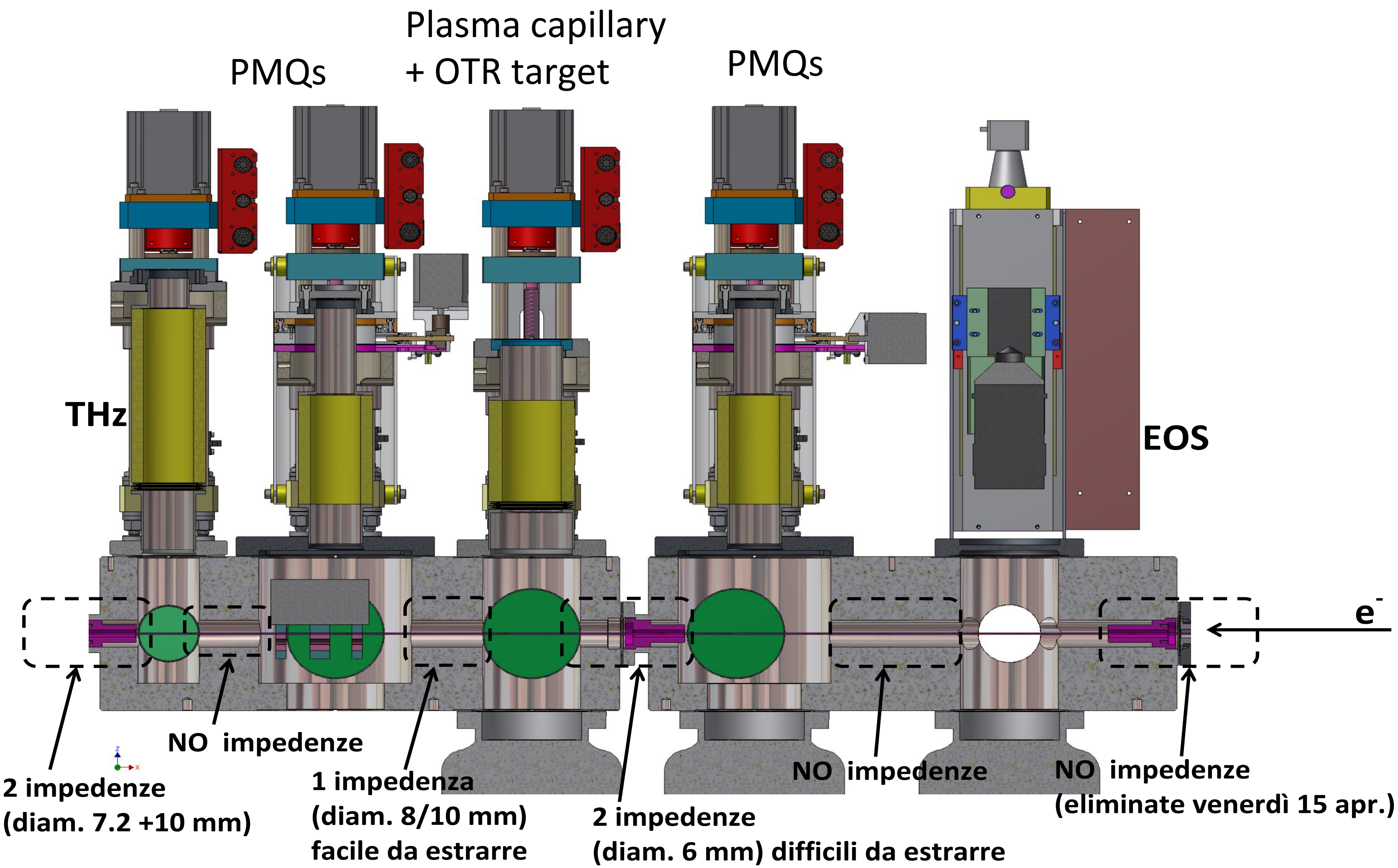
No capillary – no discharge



Through capillary with discharge varying the time delay

Measurements were repeated the following days with different injection parameters. The charge at the plasma exit was maximized to improve transmission, but still few pC were measured on the downstream BCM

- In order to preserve the vacuum level at 10^{-8} mbar in the C-band section, several irises have been installed between each module
  - Perfect alignment of the beam is mandatory in order to transport 100% of the charge



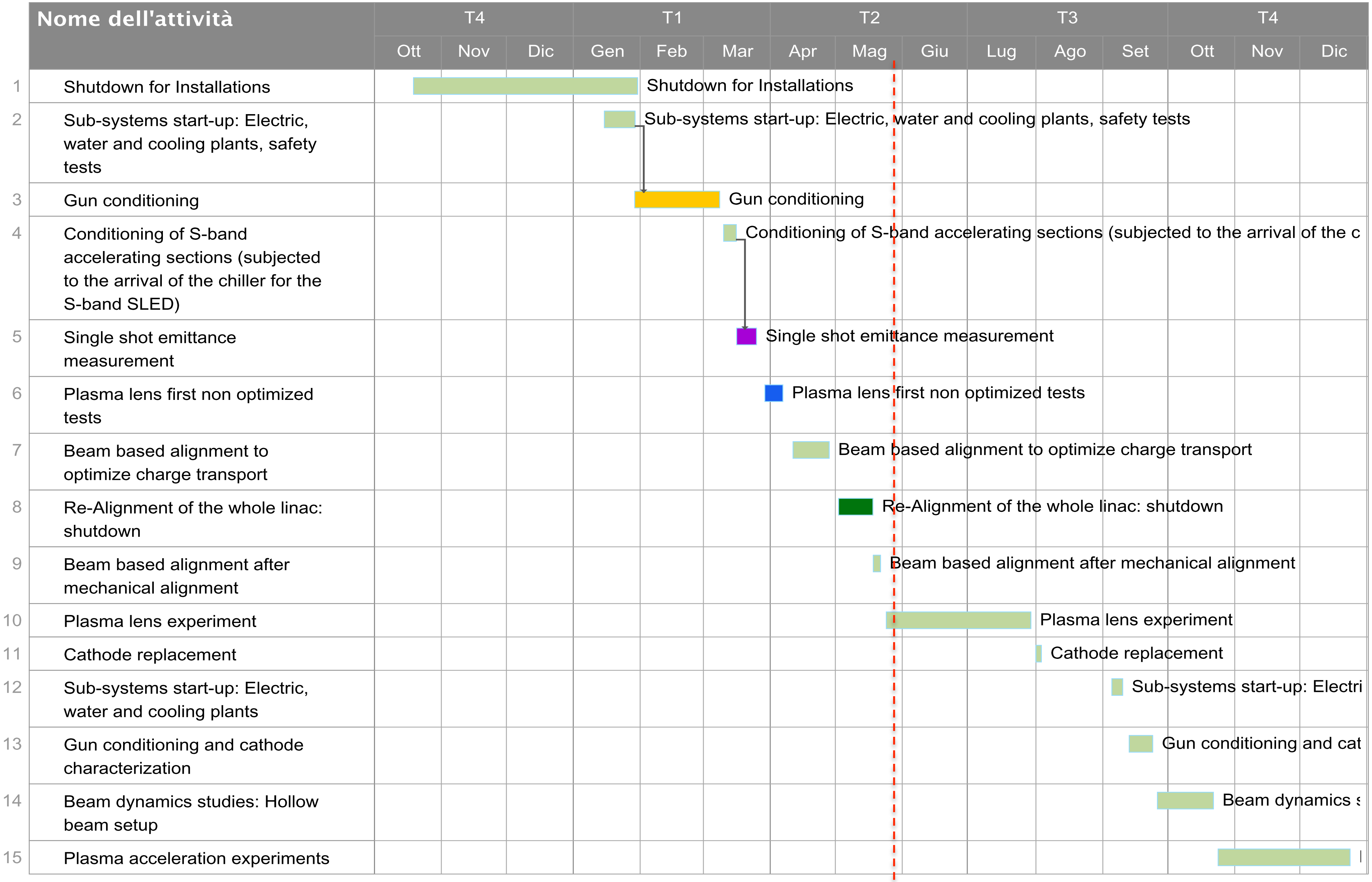
Milestones achieved so far

- **31-03-2016**
  - Commissioning of the COMB chamber installed on the SPARC main line
- **31-03-2016**: working point with 1 driver and 1 witness
  - Beam dynamics simulation studies from the gun, transport and matching to the plasma
  - interaction with the plasma and first beam focusing observation
  - Successful operation at 1 Hz
- **30-04-2016**
  - Fully setup of the plasma diagnostics based on Stark effect to measure the plasma density

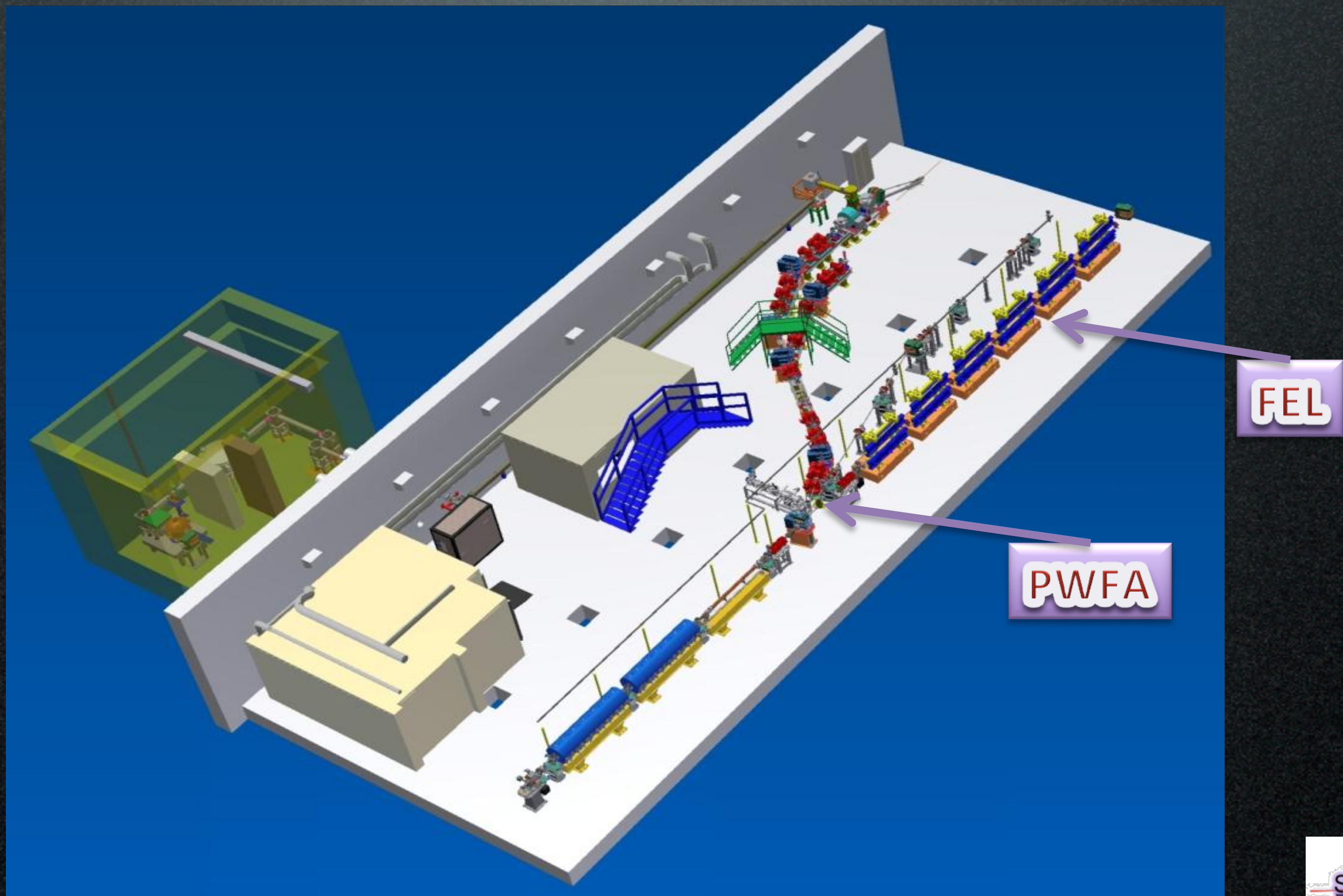
Critical Issues

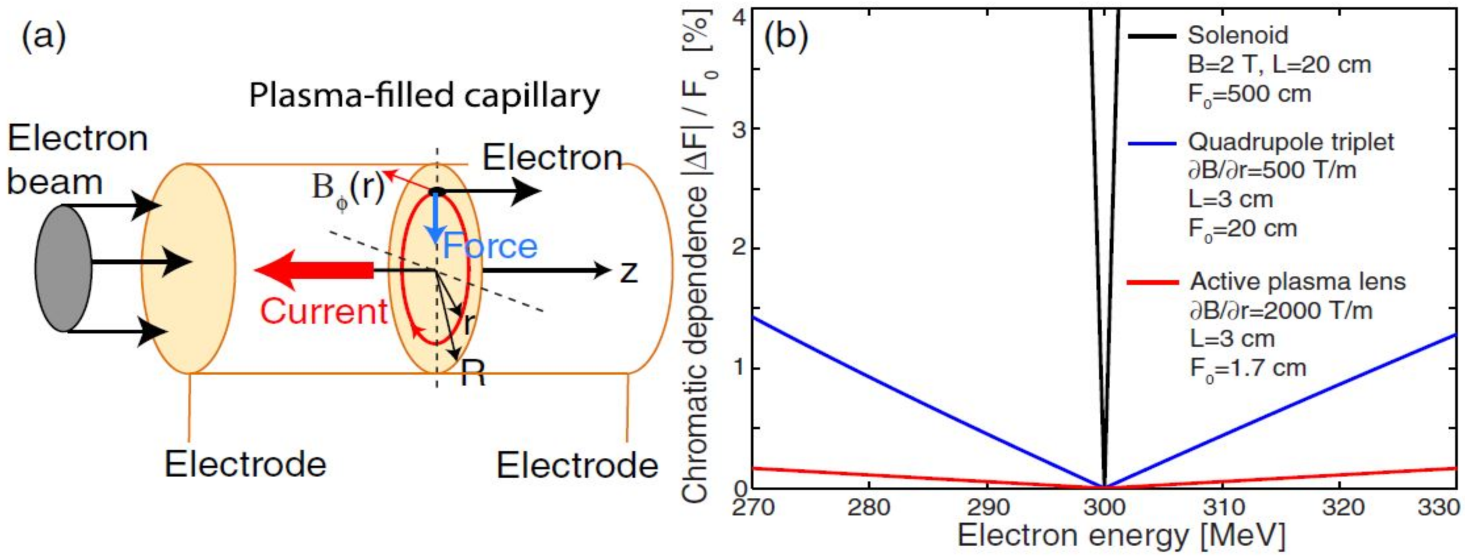
- E.M. Quadrupole triplet
  - Only 1 over 3 met the specifications
    - new production which means further delay
- C-band Klystron
  - Old one repaired: box arrived damaged
    - Waiting for instructions from Toshiba
  - New one: arrival expected in October
- ✓ Alignment of accelerating structures
  - ✓ Steering positioning at the beginning of the S1 and S2 sections to improve beam trajectory before injection

15 October 2015 – 23 December 2016



SL_COMB: Beam Driven Plasma Wake Field Acceleration





$$F_r = ec\left(\frac{\mu_o I_c}{2\pi R_c^2}\right) r = ecB'_\vartheta r$$

$$\frac{K_{cap}}{\gamma} = \frac{eB'_\vartheta}{\gamma mc} = \frac{2I_c}{\gamma I_A R_c^2}$$

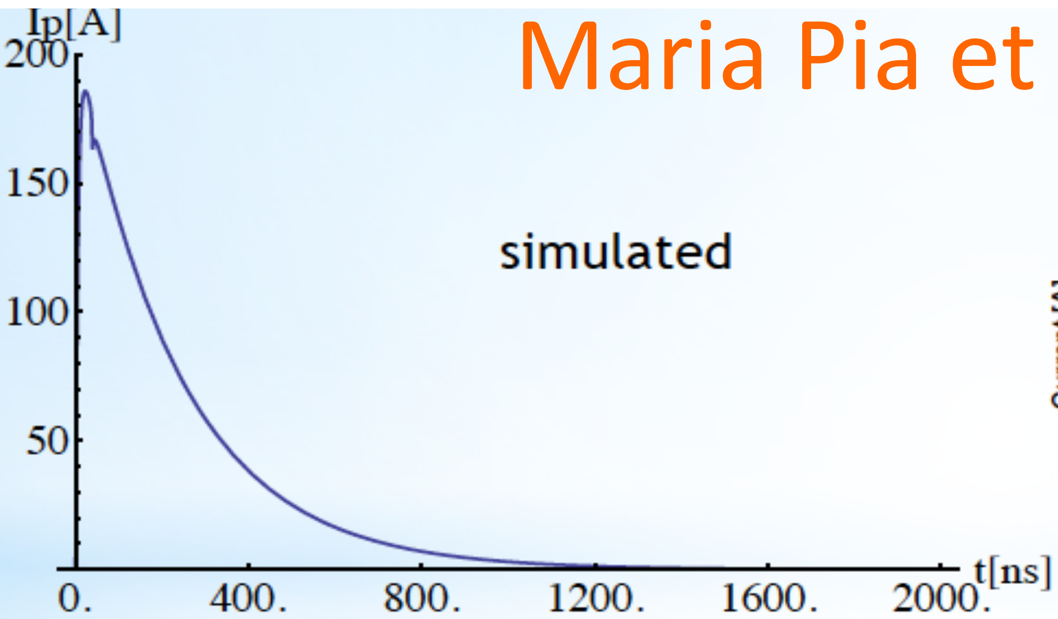
$$I_A = \frac{4\pi\varepsilon_o m_o c^3}{e} = 17kA$$

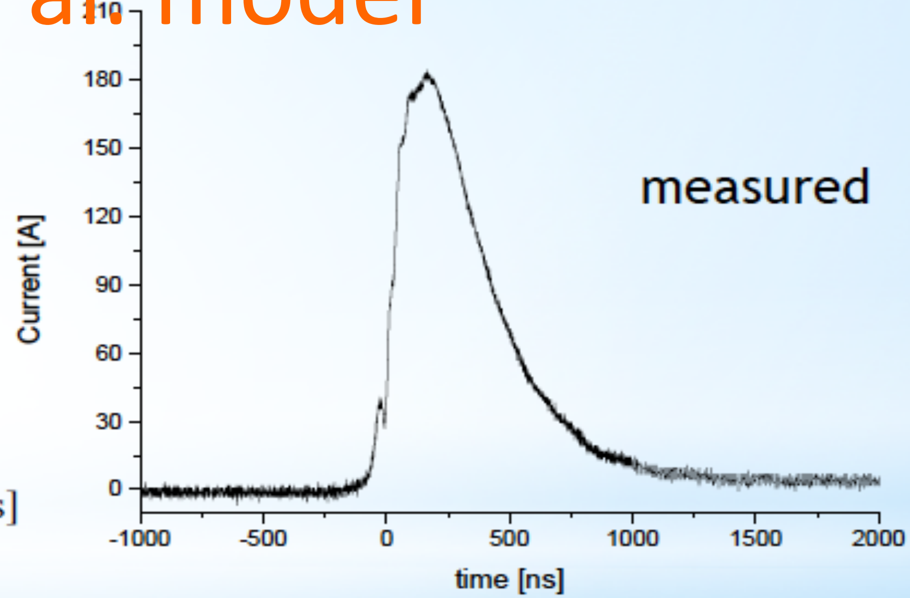
$$\sigma''_x + \frac{\gamma'}{\gamma}\sigma'_x + \frac{K_{cap}}{\gamma}\sigma_x = \frac{\varepsilon_n^2}{\gamma^2\sigma_x^3} + \frac{k_{sc}^o}{\gamma^3\sigma_x}$$

Focal Length

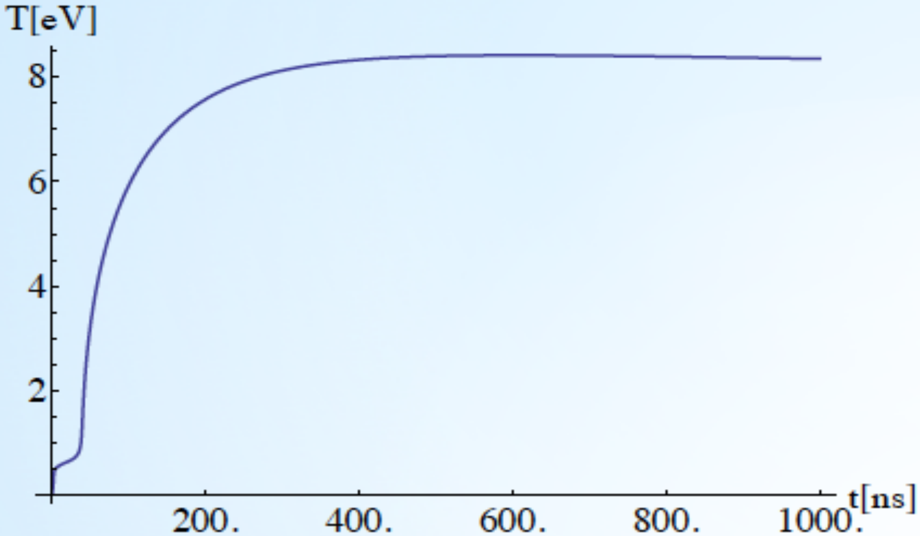
$$\frac{1}{f} = \frac{K_{cap}L_{cap}}{\gamma}$$

Maria Pia et al. model

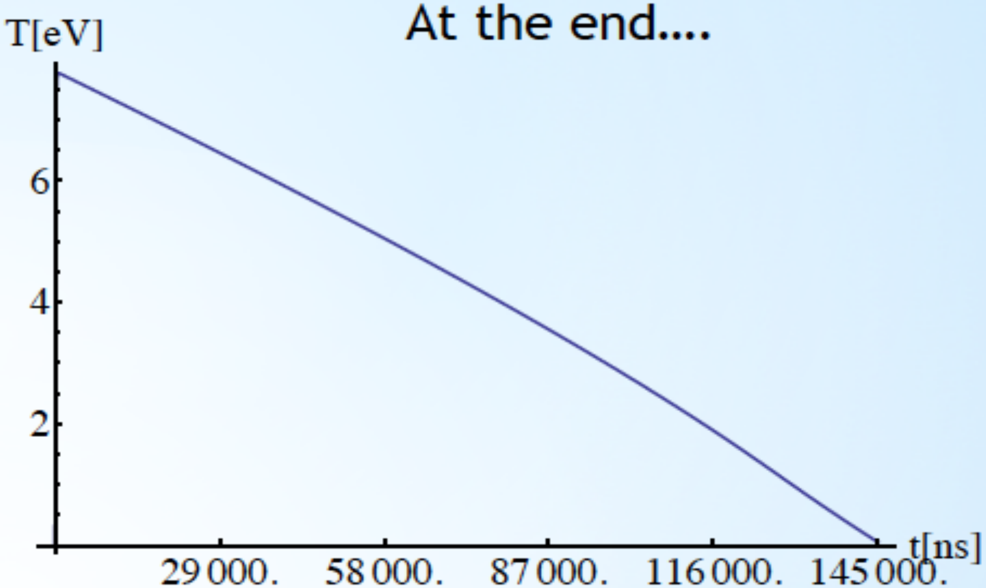




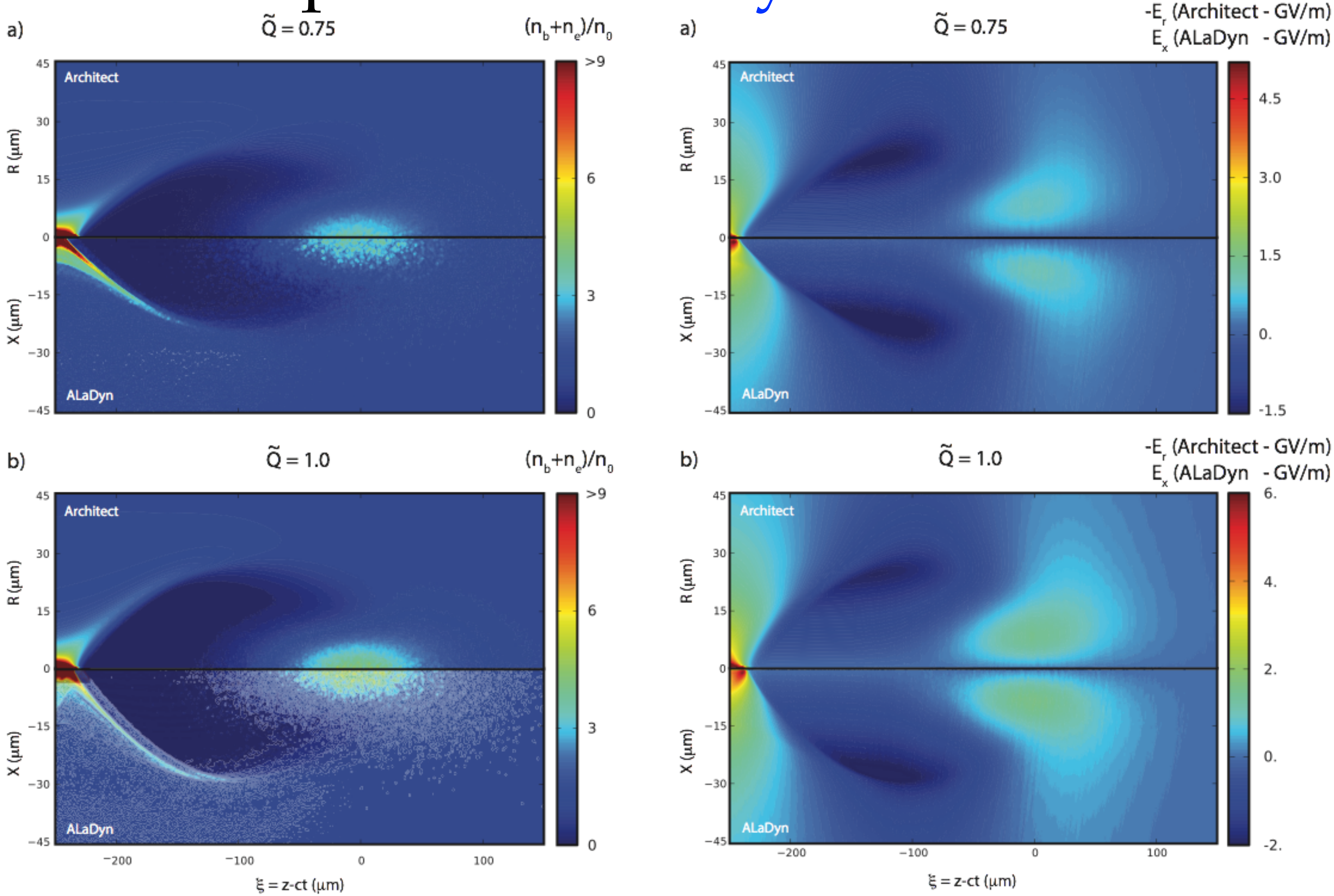
At the beginning....



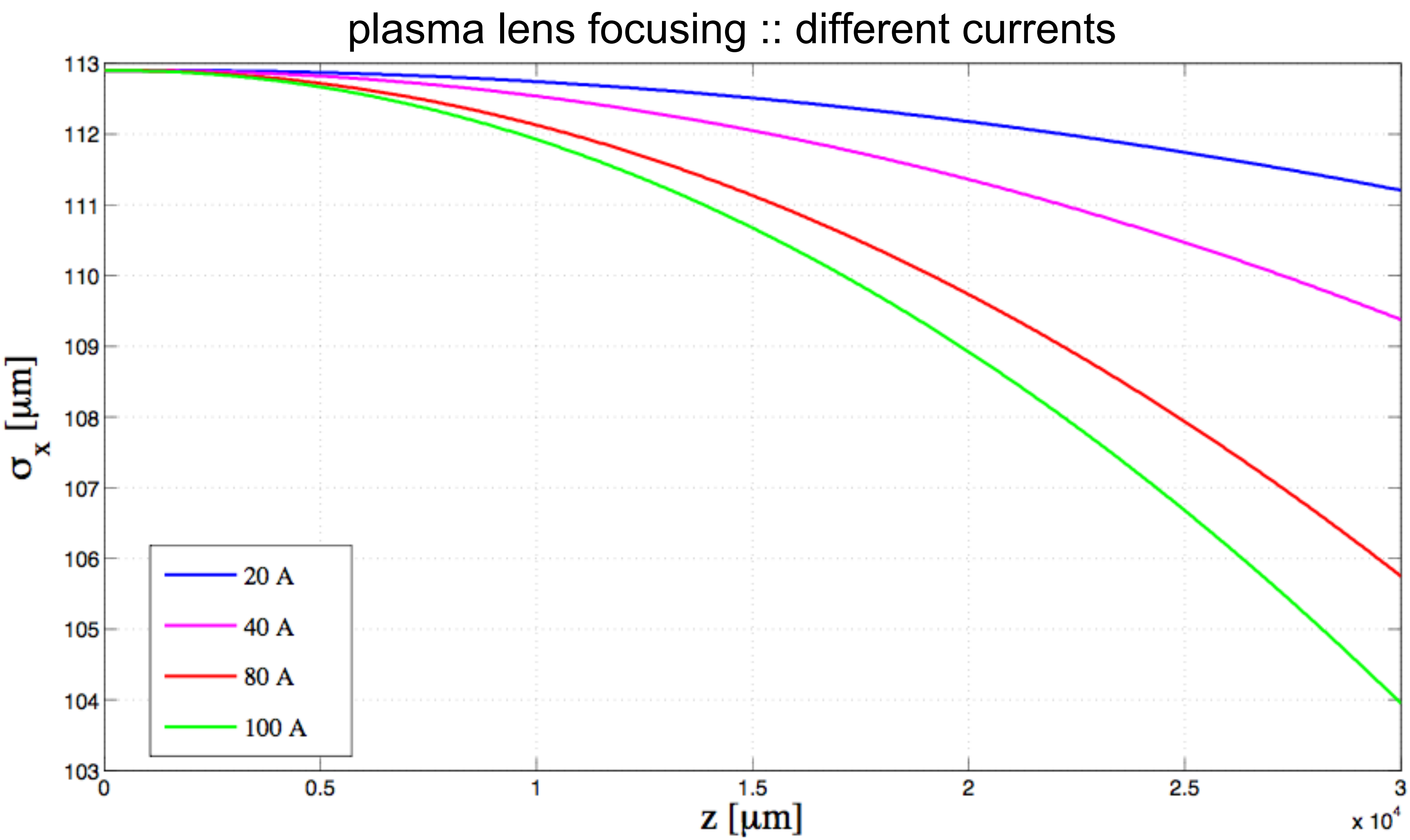
At the end....



comparison ALaDyn Architect

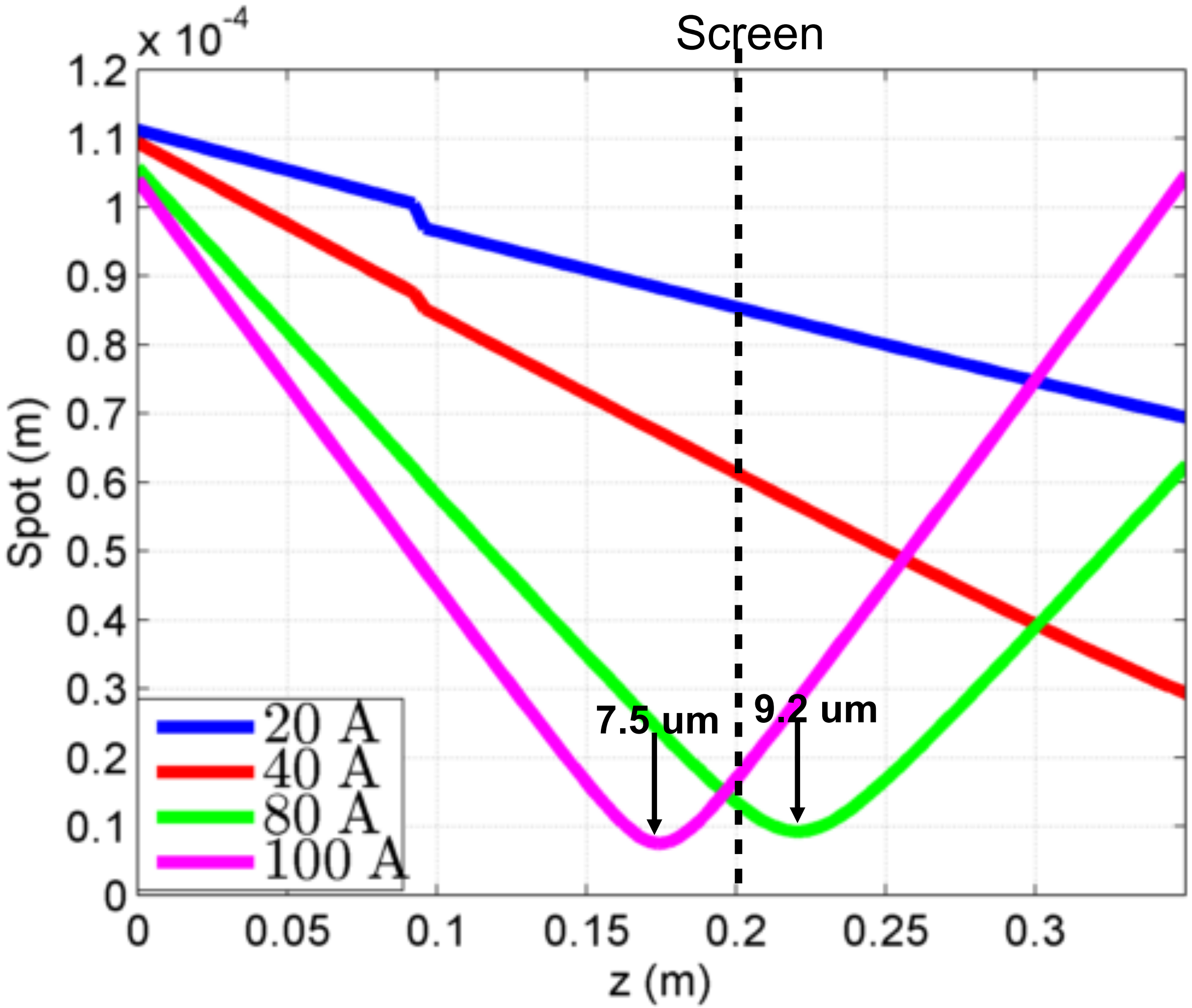


ALADYN simulations



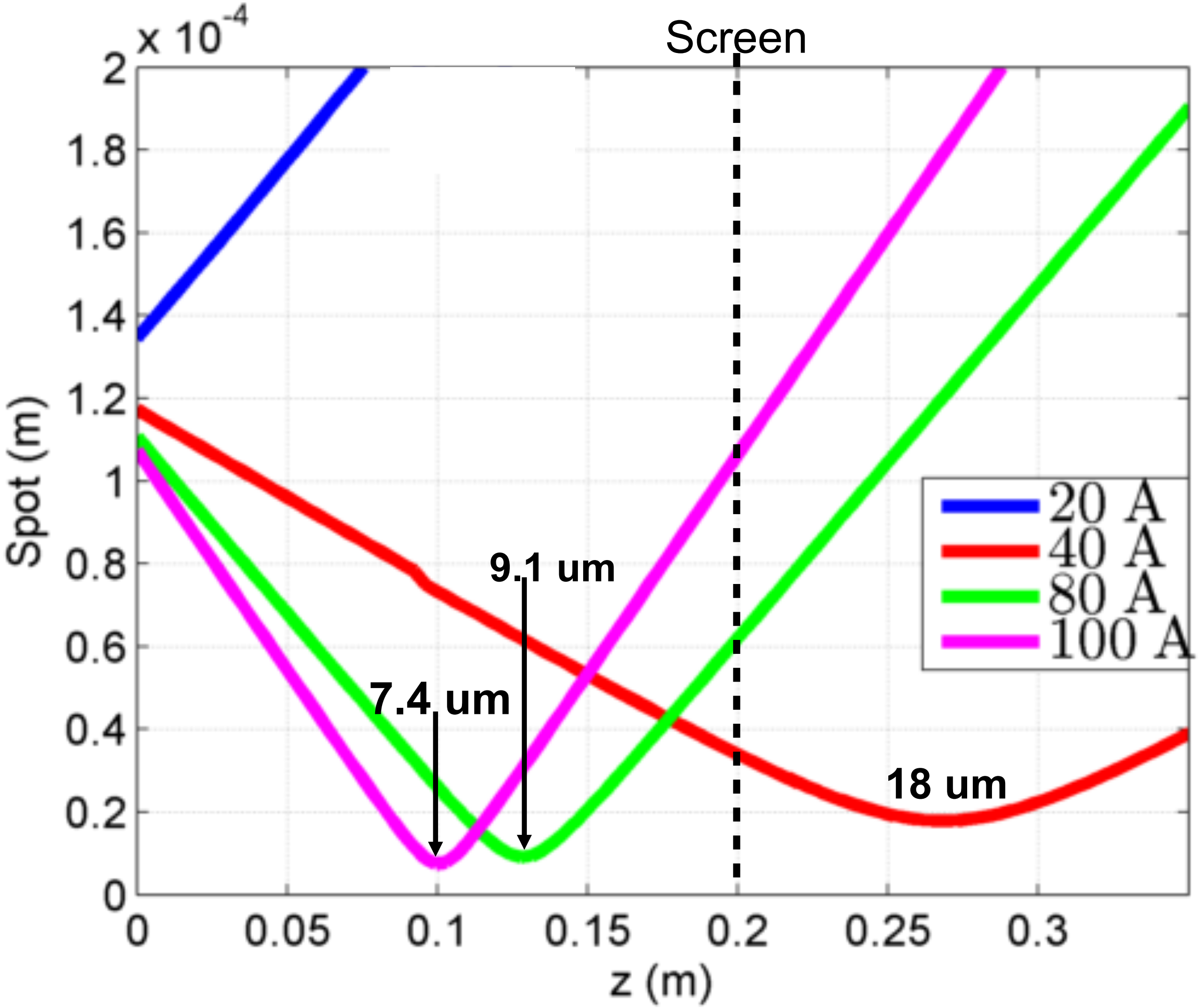
GPT – long bunch

Charge:	50 pC
Length:	**224 um** (750 fs)
Emittance:	1.1 um
Energy:	127 MeV
Spot:	113 um

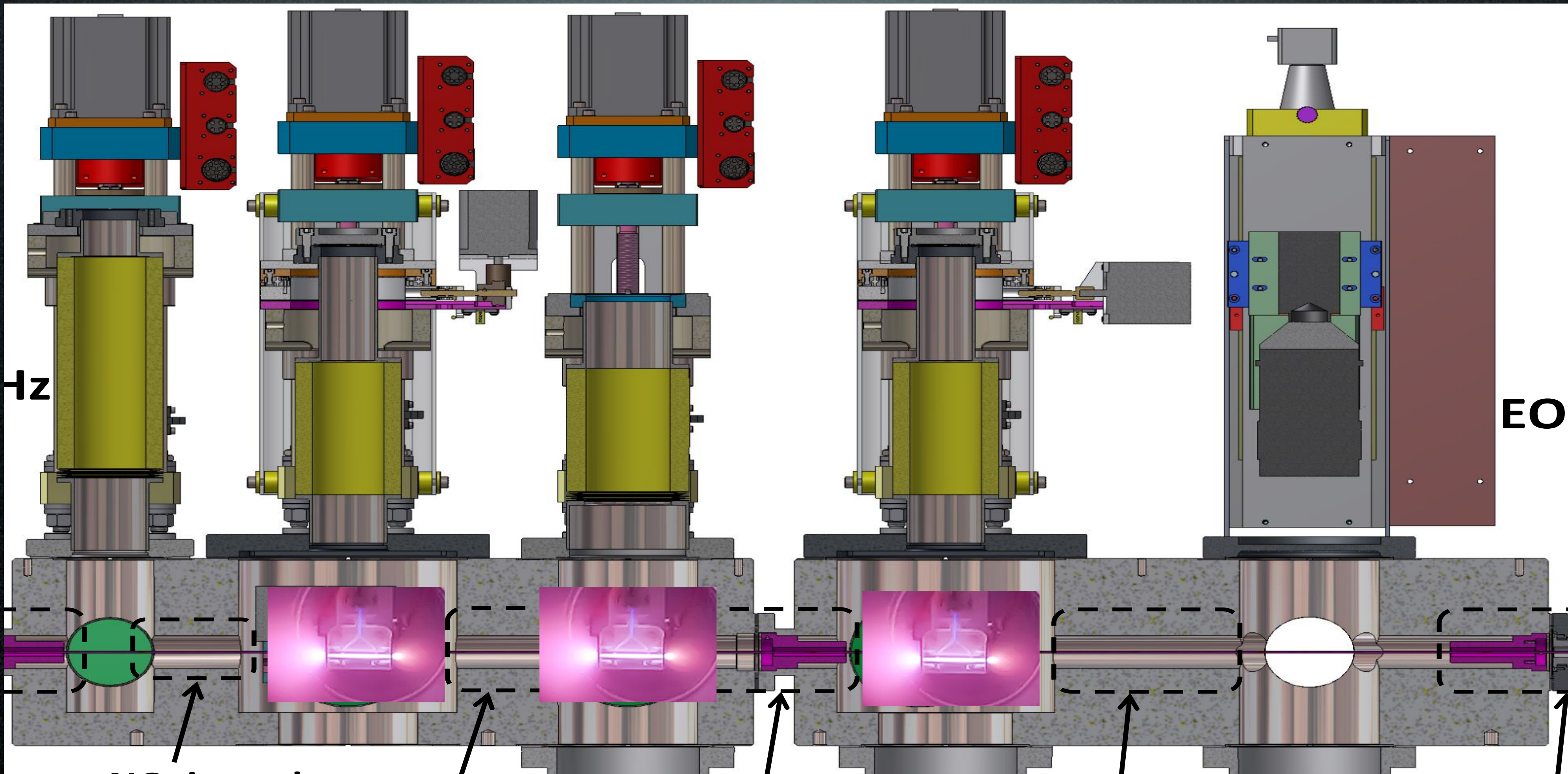


GPT - short bunch

- Charge: 50 pC
- Length: **18 um** (60 fs)
- Emittance: 1.15 um Energy: 77 MeV
- **Spot: 123 um**



Plasma Driven FEL under investigation

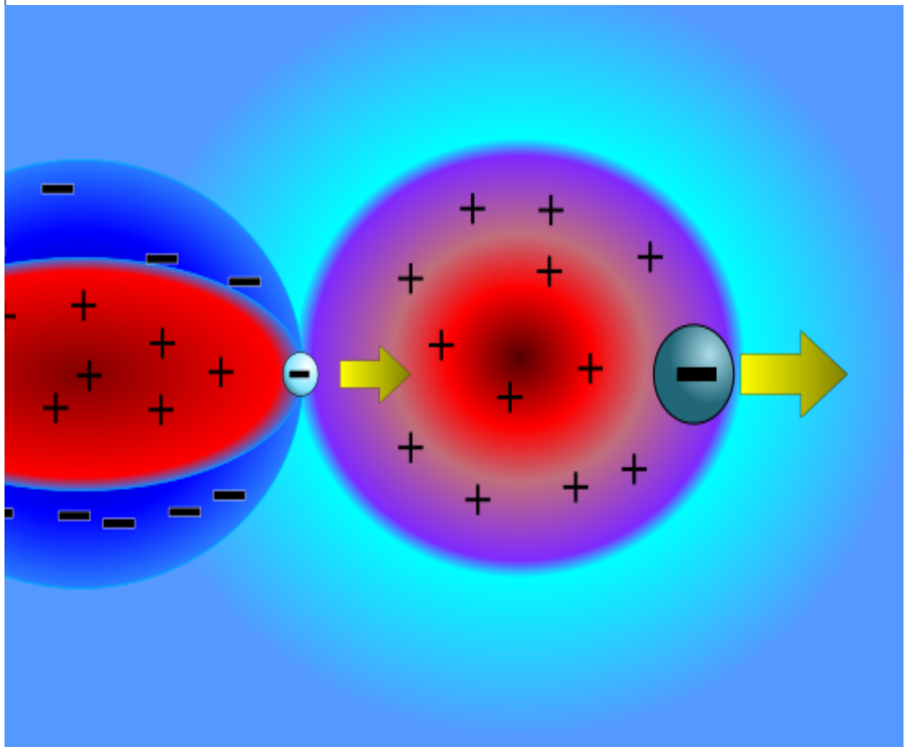


Focusing Plasma Lens

PWFA module

Capture Plasma Lens

New concept: hybrid scheme



Within the new hybrid scheme

- ➢The driver generates a linear field
- ➢The witness:
  - Is highly non linear ($\alpha \gg 1$)
  - Is injected in the region of the crest
  - Is mainly focused by the wakefields generated by the witness itself

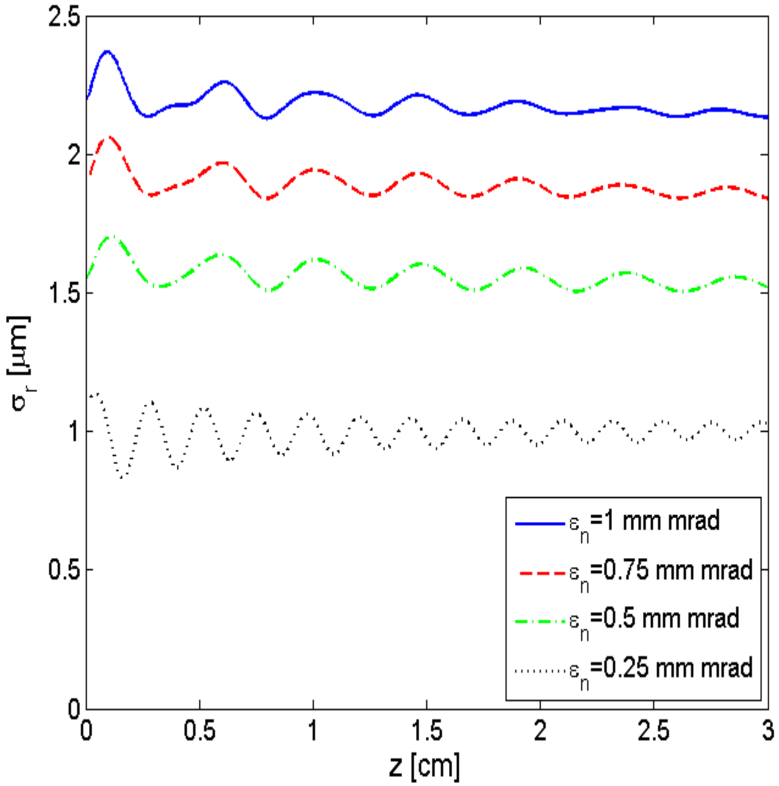
Simulation parameters

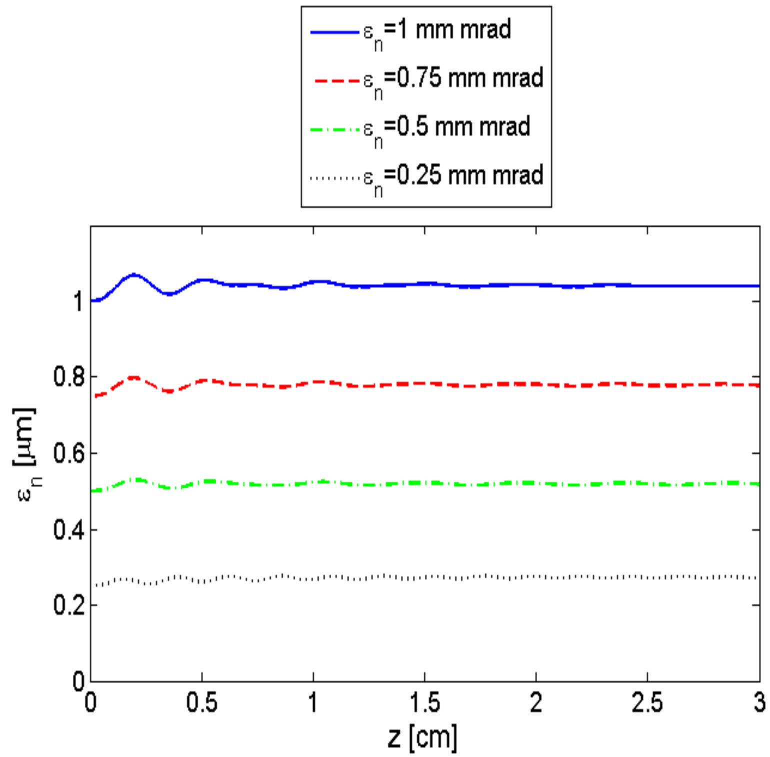
- Plasma density $n_0 = 2 \cdot 10^{16}$
- **Driver:**
  - Energy $\gamma = 240$
  - Charge $Q = 120pC$
  - Length $\sigma_z = \frac{1}{k_p}$
  - $\alpha = 0.5$

800 MV/m

- **Witness:** 20 pC
  - Energy $\gamma = 240$
  - Length $\sigma_z = 5.31\mu m$
  - $\alpha = 25$ (1° scan) or variable (2° scan)
  - Emittance variable (1° scan) or $\varepsilon_n = 0.5\ mm\ mrad$ (2° scan)
  - Spot size $\sigma_r = \sqrt[4]{\frac{1}{\gamma}} \sqrt{\frac{2\varepsilon_n}{k_p}}$

Matching conditions check (1)



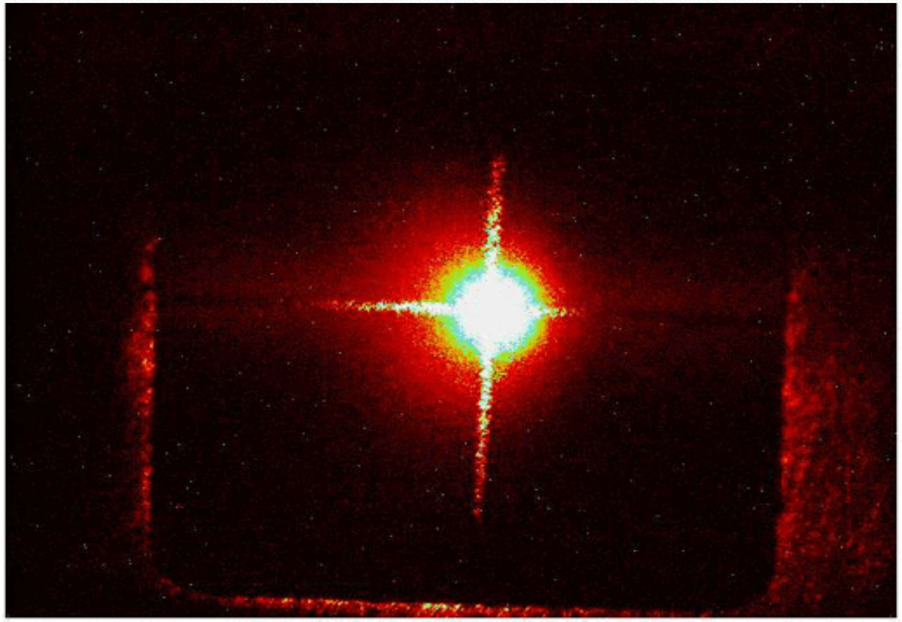


The matching condition we used gave a good result in a simulation scan at various emittances

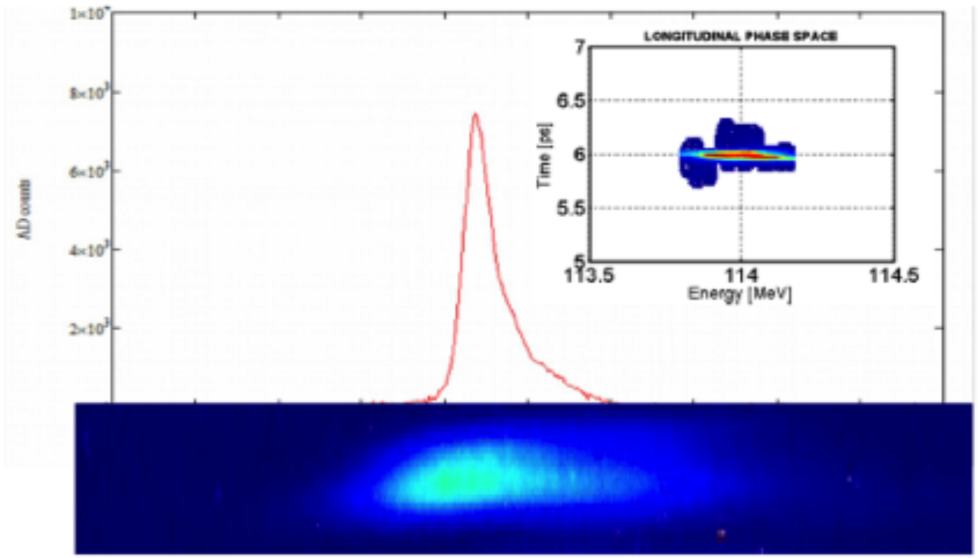
Electron bunches with properties similar to the one produced by plasma, have been sent into the SPARC FEL in the SASE regime and lasing has been observed.

Bunch parameters

Charge (pC)	Energy (MeV)	Energy Spread (%)	Duration (fs)	Emittance (μm)	Peak current (A)
20	114	0.1	26	1.2	400

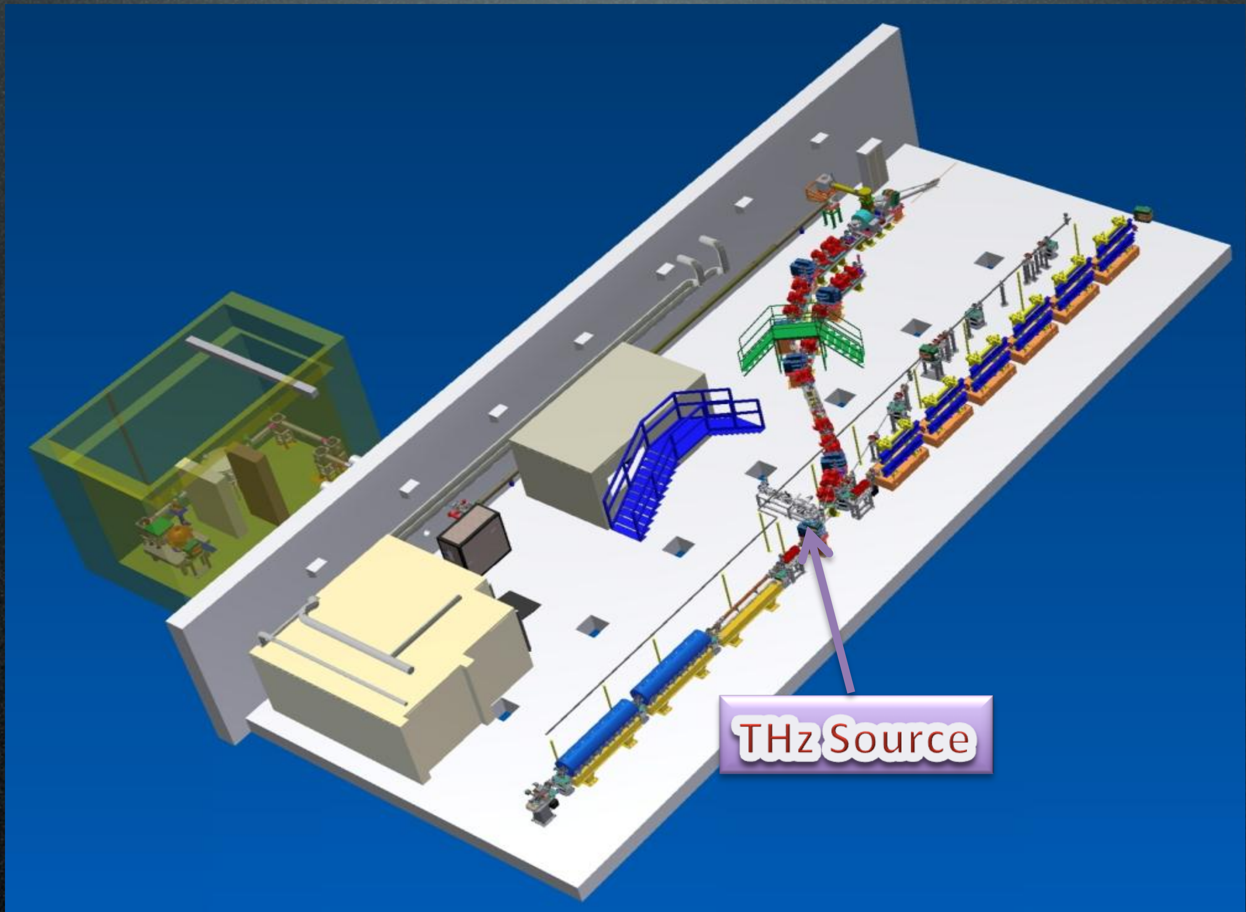


Single-spike FEL means high quality ultra-short beam!



Collected FEL light, 100 fs (rms), 40 μJ

THz Source



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ARTICLE

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OPEN

Strong nonlinear terahertz response induced by Dirac surface states in Bi_2Se_3 topological insulator

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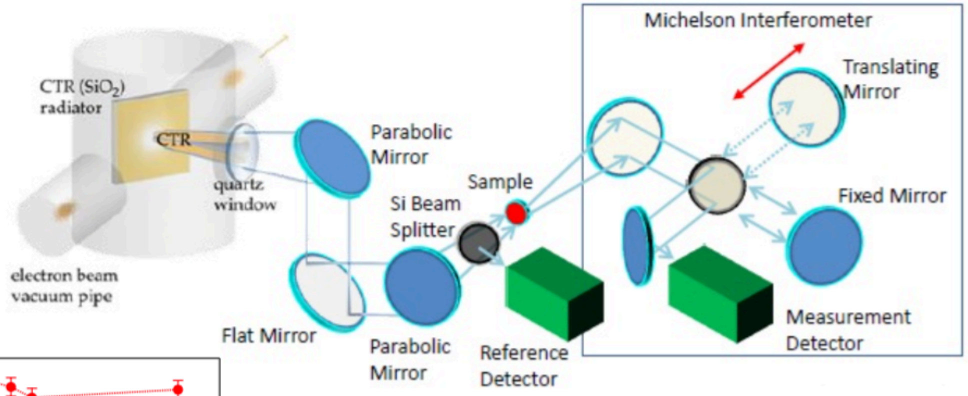
Electrons with a linear energy/momentum dispersion are called massless Dirac electrons and represent the low-energy excitations in exotic materials such as graphene and topological insulators. Dirac electrons are characterized by notable properties such as a high mobility, a tunable density and, in topological insulators, a protection against backscattering through the spin-momentum locking mechanism. All those properties make graphene and topological insulators appealing for plasmonics applications. However, Dirac electrons are expected to present also a strong nonlinear optical behaviour. This should mirror in phenomena such as electromagnetic-induced transparency and harmonic generation. Here we demonstrate that in Bi_2Se_3 topological insulator, an electromagnetic-induced transparency is achieved under the application of a strong terahertz electric field. This effect, concomitantly determined by harmonic generation and charge-mobility reduction, is exclusively related to the presence of Dirac electron at the surface of Bi_2Se_3, and opens the road towards tunable terahertz nonlinear optical devices based on topological insulator materials.

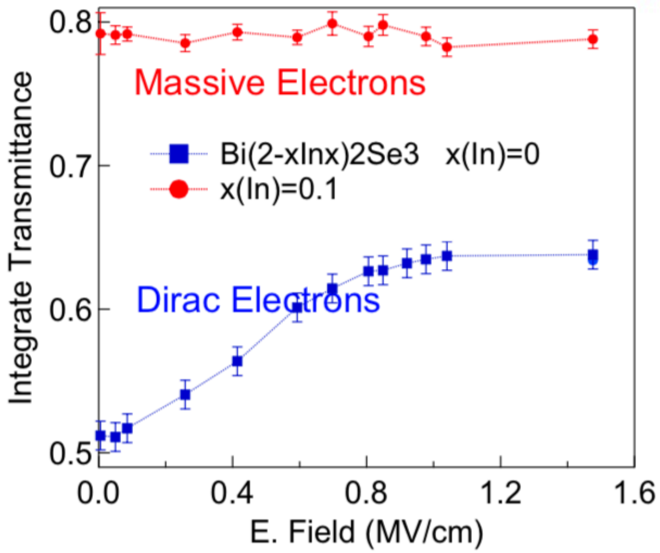
Nonlinear THz response of Bi_2Se_3 Topological Insulator

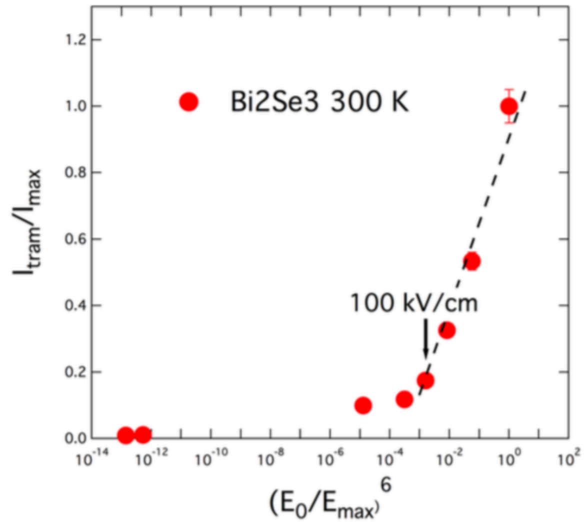
A Topological Insulator is an exotic electronic material showing an insulating bulk and intrinsic metallic surfaces.

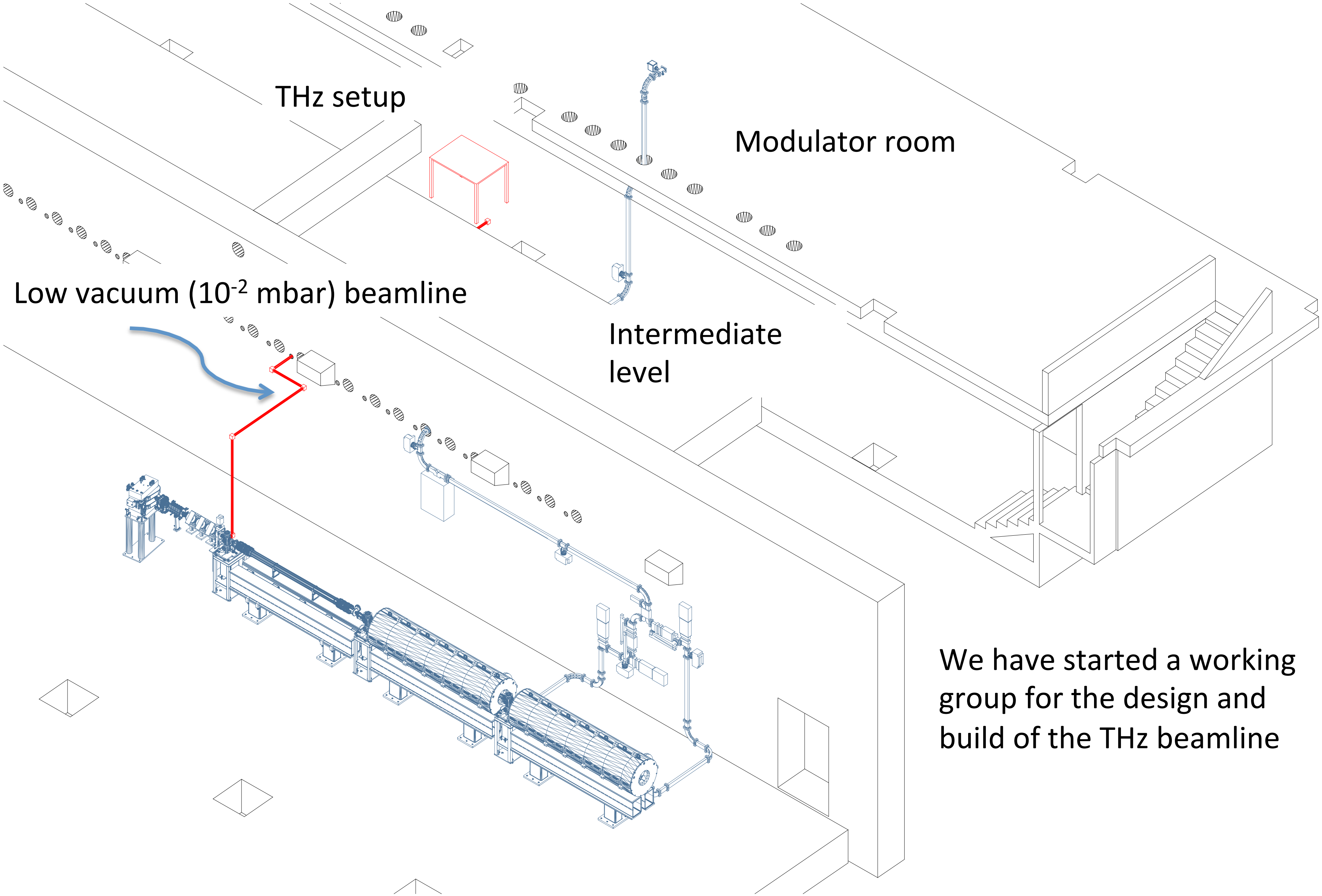
The metallic surfaces are characterized by a gas of Dirac electrons, *i.e.* having a relativistic dispersion: $E(k)=v_F k$ where v_F is the Fermi velocity.

In this experiment we observe a nonlinear optical behavior of Dirac electrons over 6 orders of megnitude of the THz electric field and characterized by THz harmonic generation



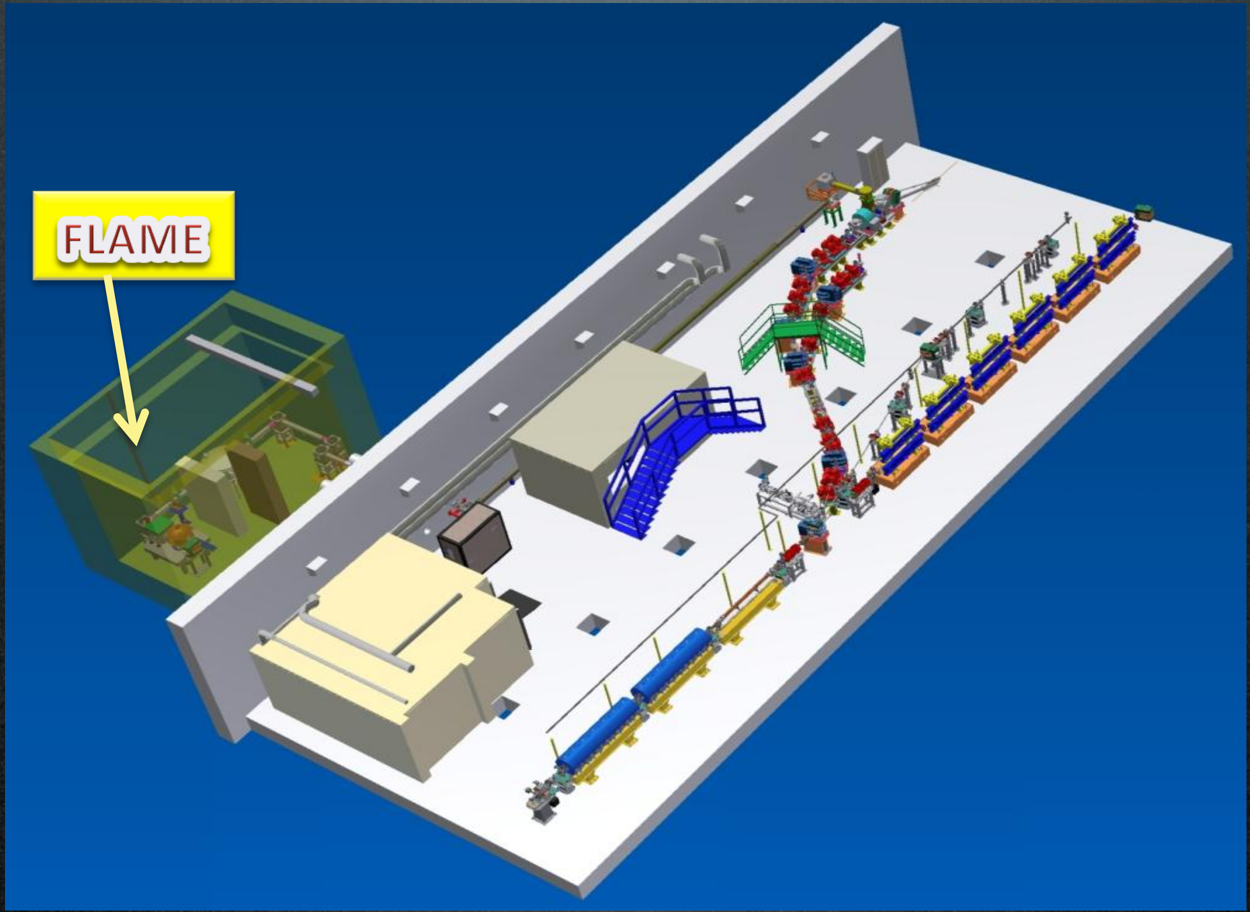




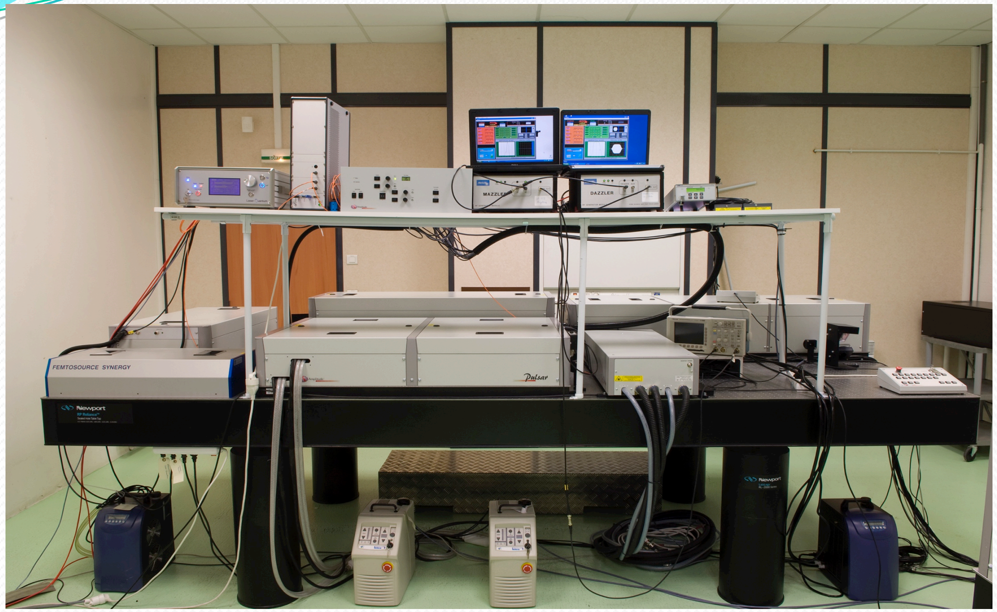


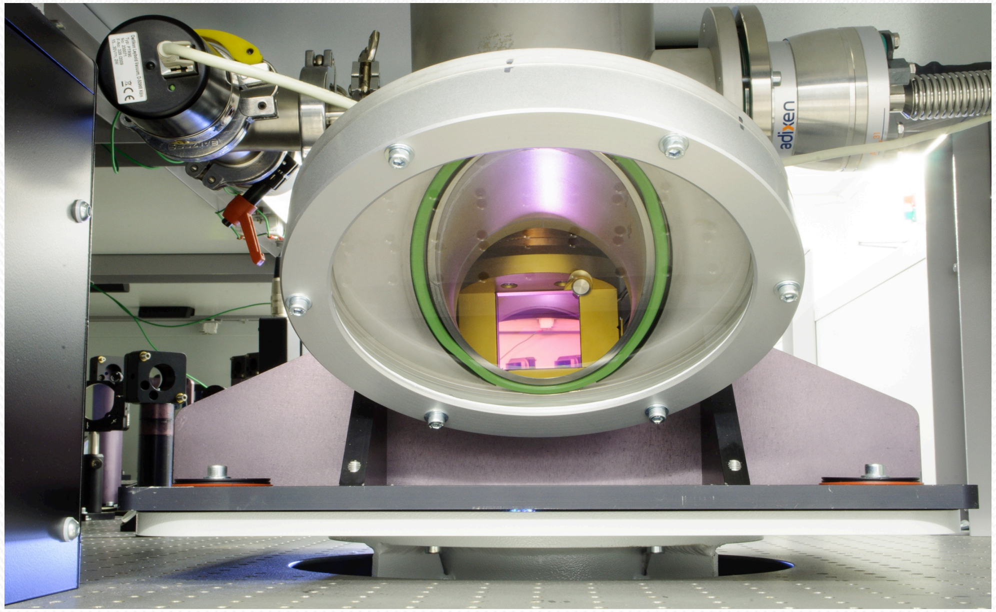
We have started a working group for the design and build of the THz beamline

FLAME Laser



FLAME @ SPARC_LAB





FLAME status: program

From January to now…

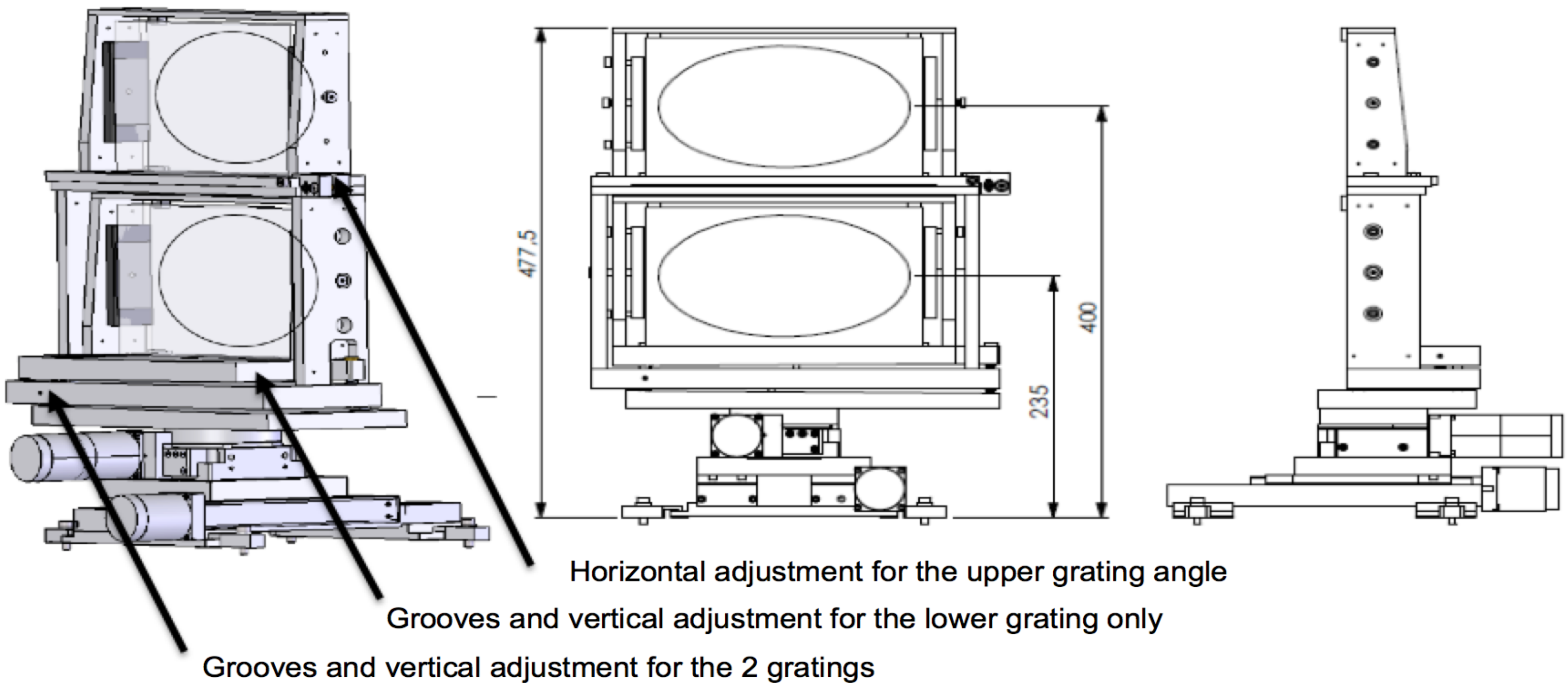
Activity	Start date	End date
Restart after Christmas	11/01/2016	22/01/2016
Single shot emittance measurement – phase 1	25/01/2016	21/03/2016
Compressor chamber optimization	28/03/2016	10/04/2016
Amplitude visit and compressor optimization	11/04/2016	15/04/2016
Compressor reassemble after Amplitude visit	15/04/2016	1/05/2016
Single shot emittance measurement – phase 2	04/05/2016	15/06/2016
Optimization of one of the YAGs	15/04/2016	15/06/2016

After Amplitude visit we had to realign the compressor completely because Amplitude alignment was done on a random line which was not the correct entering line of the compressor.

FLAME status

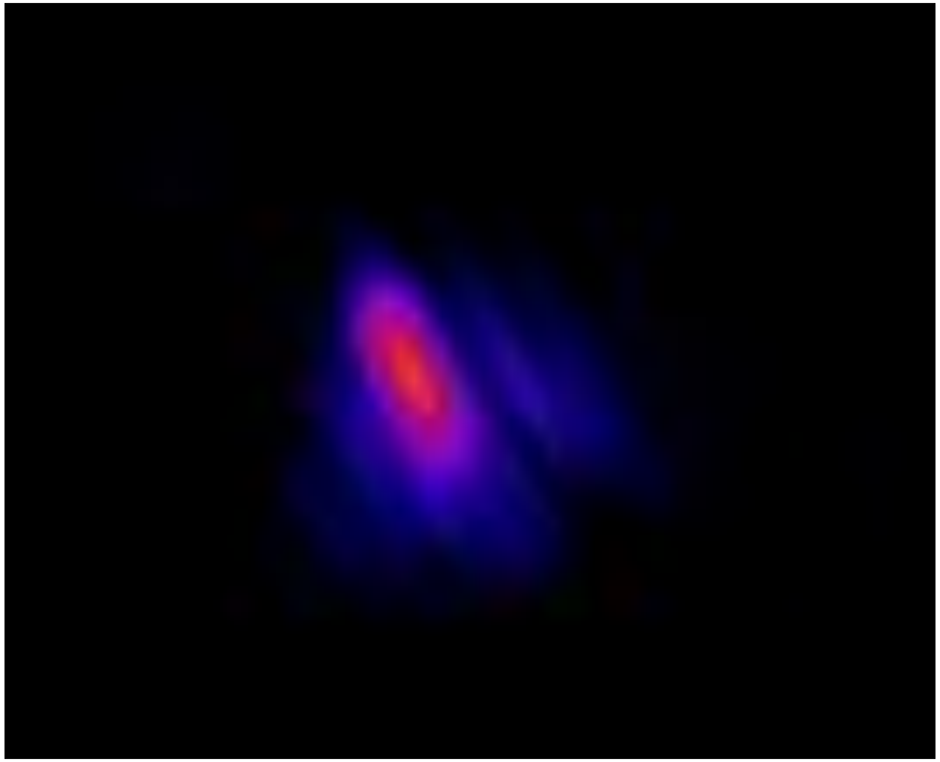
In general the laser is working fine, **delivering 5-6 J in 35-40 fs.**

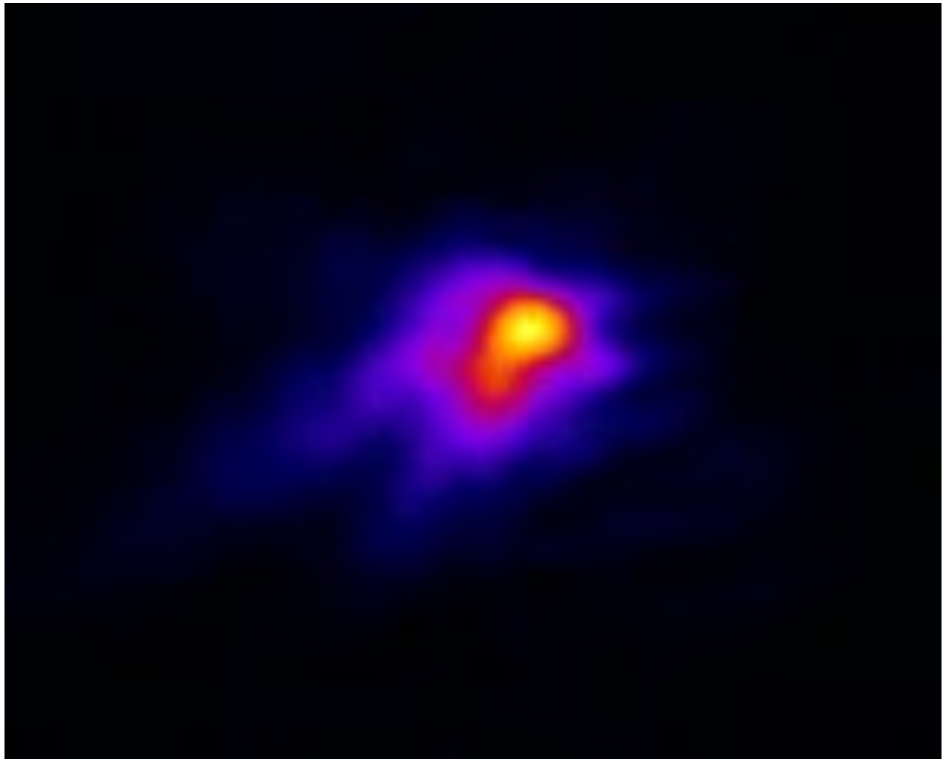
The main improvement in the last months has been to change the compressor's mount in order to be able to completely remove the spatial chirp which was giving a very bad focal spot. The new mounts have all the possible movement for each grating, allowing for an easier alignment.



FLAME status

The focal spot has improved a lot passing from an elliptical spot with a dimension ($1/e^2$) of 60x20 micron to a **circular 20x20 micron.**





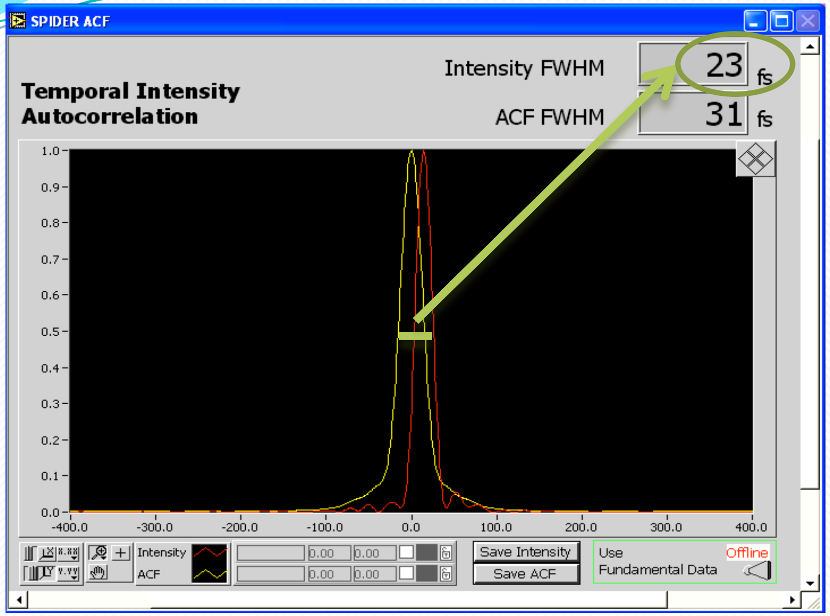
The energy in the focal spot is between 40 to 60%.

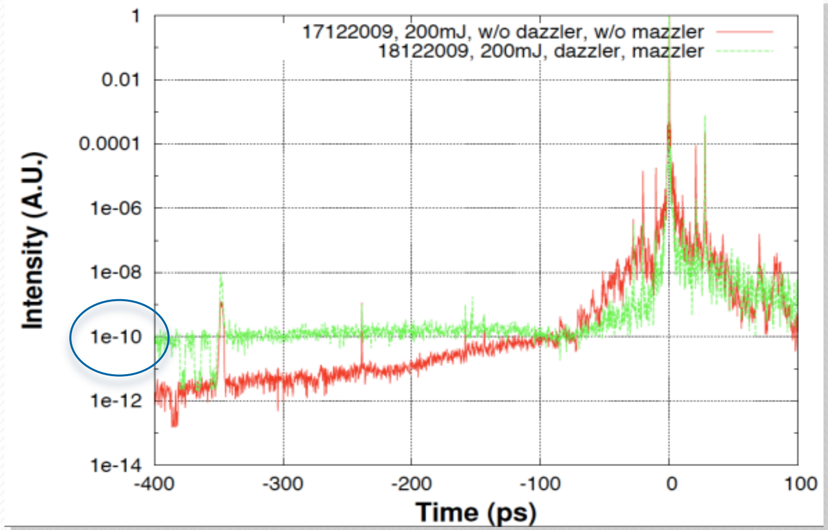
FLAME status

The problem of YAGs is under final solution. **The first YAG has been sent to Amplitude for upgrade.**

We are now evaluating with Amplitude the final solution which includes a replacement of the rods with bigger rods (not the exact size of the beam) so to be less sensitive to small misalignments. However, this will change slightly the efficiency of the YAG and so we are evaluating if to change also the 2^{nd} harmonic crystal in order to have the some efficiency we have now or if to loose a bit of efficiency and keep the some 2^{nd} harmonic crystal.

FLAME @ SPARC_LAB





BEST LASER PERFORMANCES:

Max energy before compression: 6J

Max energy on target: ~5J

Min bunch duration: 23 fs

Wavelength: 800 nm

Bandwidth: 60/80 nm

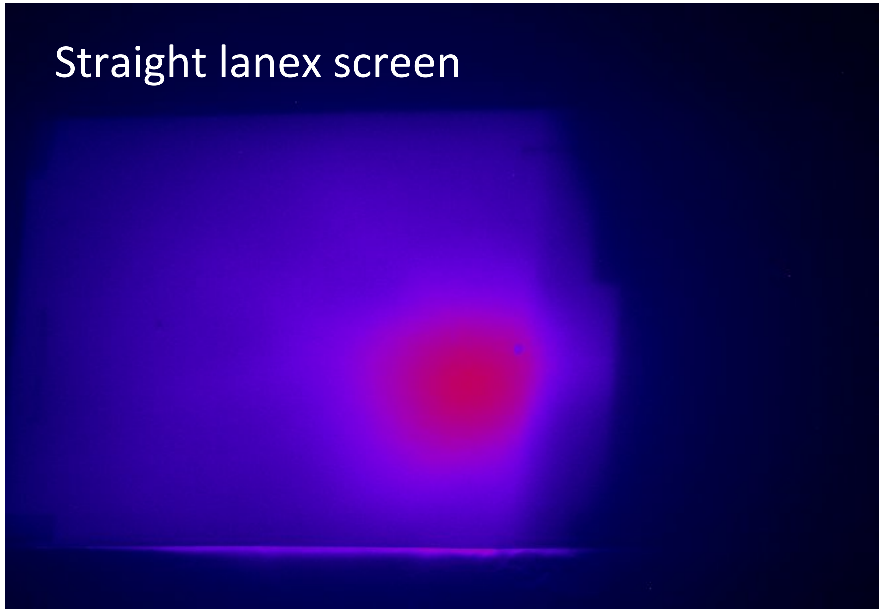
Spot-size @ focus ($1/e^2$): 20 μm

Max power: ~200 TW

Contrast ratio: 10^{10}

FLAME status: OSE' experiment

The experiment is under way.



Electrons have been accelerated up to an energy of about 170 MeV in 4 mm Helium gas-jet.

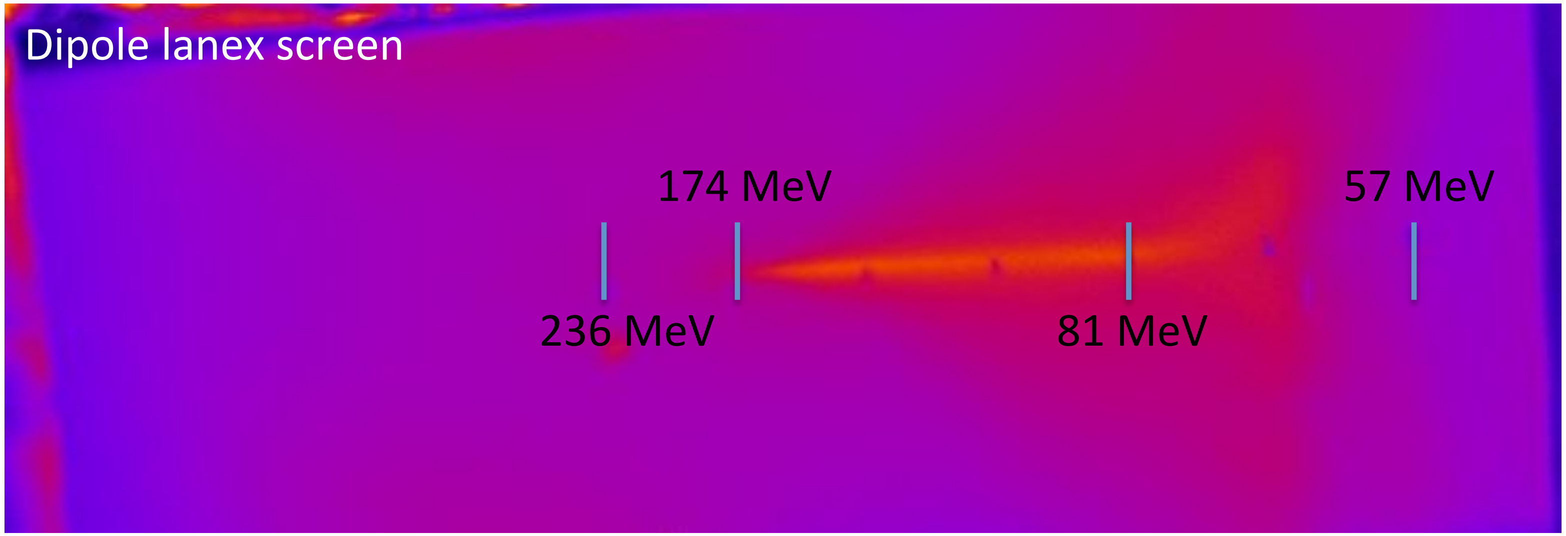
Laser parameters:

Focal spot size (1/e2): 20 x 20 micron

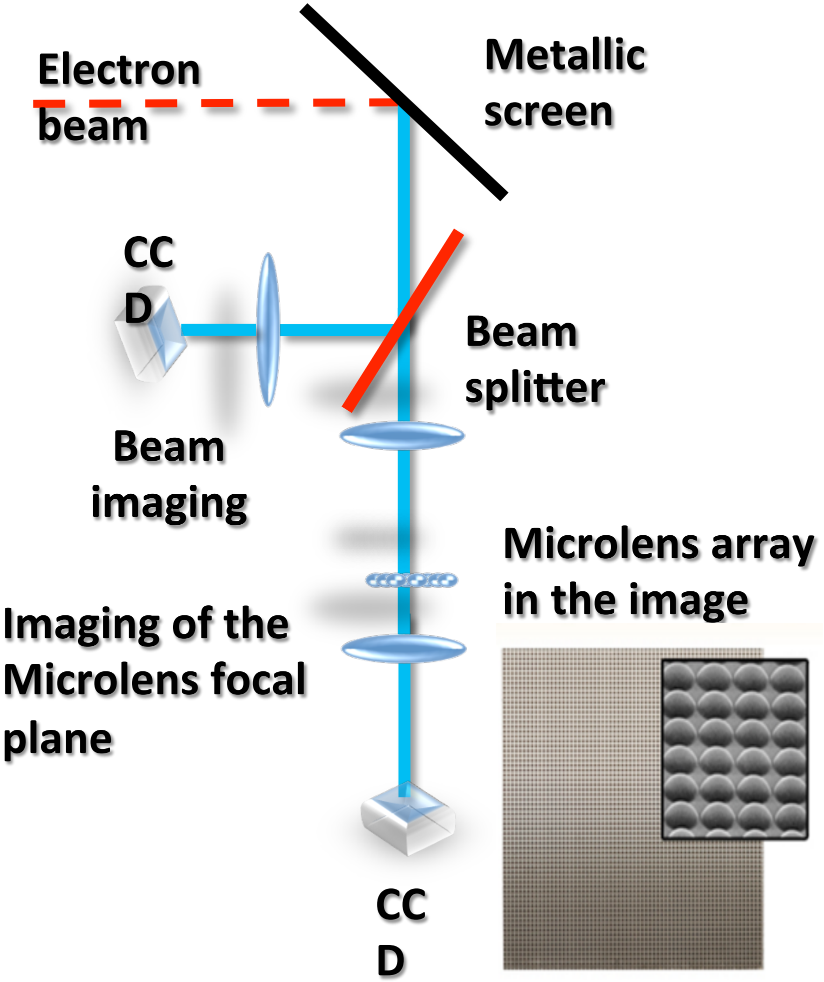
Energy: 2 J

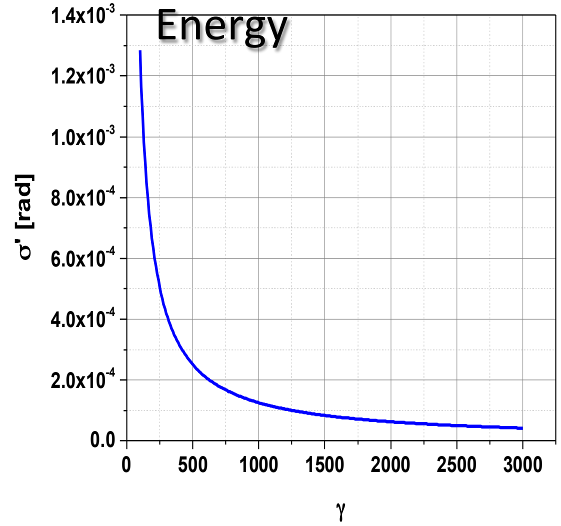
Duration: 35-40 fs.

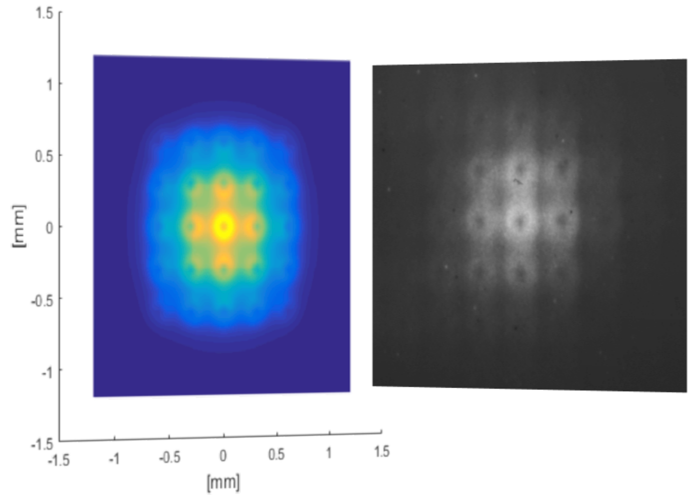
The quality of the electron bunch is not high, but optimization is under going.



OSE (One Shoot Emittance)

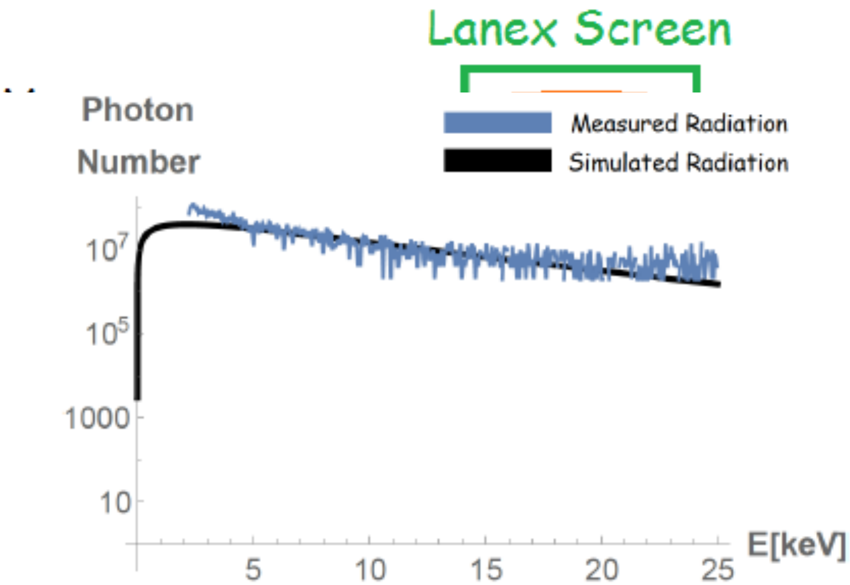


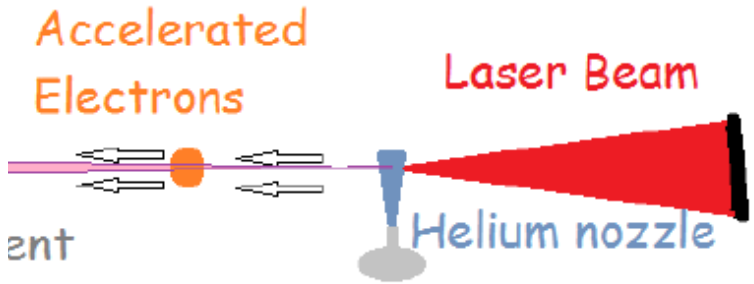




Simulation Measurement

Ongoing self-injection LWFA experiment/2





Electron Parameters:

Max Energy: 200 *MeV*

Energy Spread: ∼ down to 30%

Divergence: ∼ down to 10 *mrad*

Charge: 10-100 pC

Laser Parameters:

Energy in the focus: 1.5 *J*

Pulse duration: 35 – 40 *fs*

Focus radius: 10 μm

FLAME status: EOS experiment

We have written a paper on the measurement done last year and submitted it to Nature.

npg **manuscript**tracking**system** nature physics

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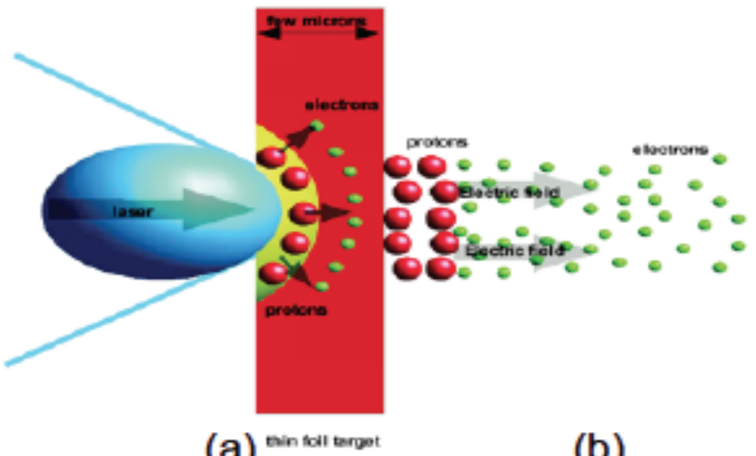
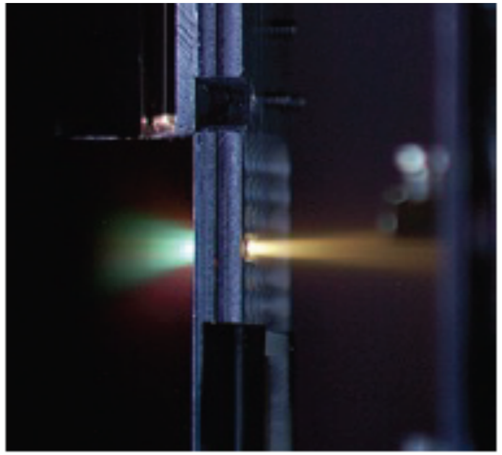
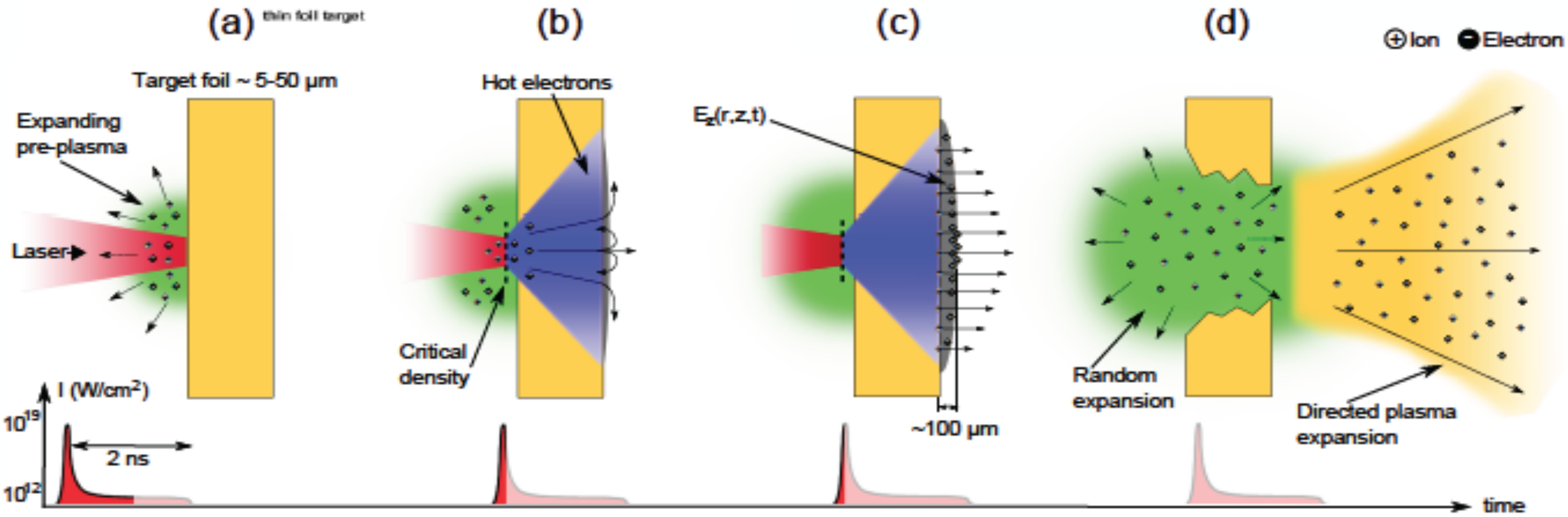
Manuscript #	NPHYS-2016-05-01364-T
Current Revision #	0
Submission Date	19th May 16 03:39:50
Current Stage	Manuscript under consideration
Title	Femtosecond dynamics of energetic electrons in high intensity laser-matter interactions
Manuscript Type	Letter
Corresponding Author	Dr. Riccardo Pompili (riccardo.pompili@lnf.infn.it) (INFN)
Contributing Authors	Dr. Maria Pia Anania , Dr. Fabrizio Bisesto , Dr. Moti Botton , Dr. Michele Castellano , Dr. Enrica Chiadroni , Dr. Alessandro Cianchi , Dr. Alessandro Curcio , Dr. Massimo Ferrario , Dr. Mario Galletti , Zohar Henis , Dr. Massimo Petrarca , Elad Schleifer , Prof. Arie Zigler

Target Normal Sheath Acceleration field enhancement studies





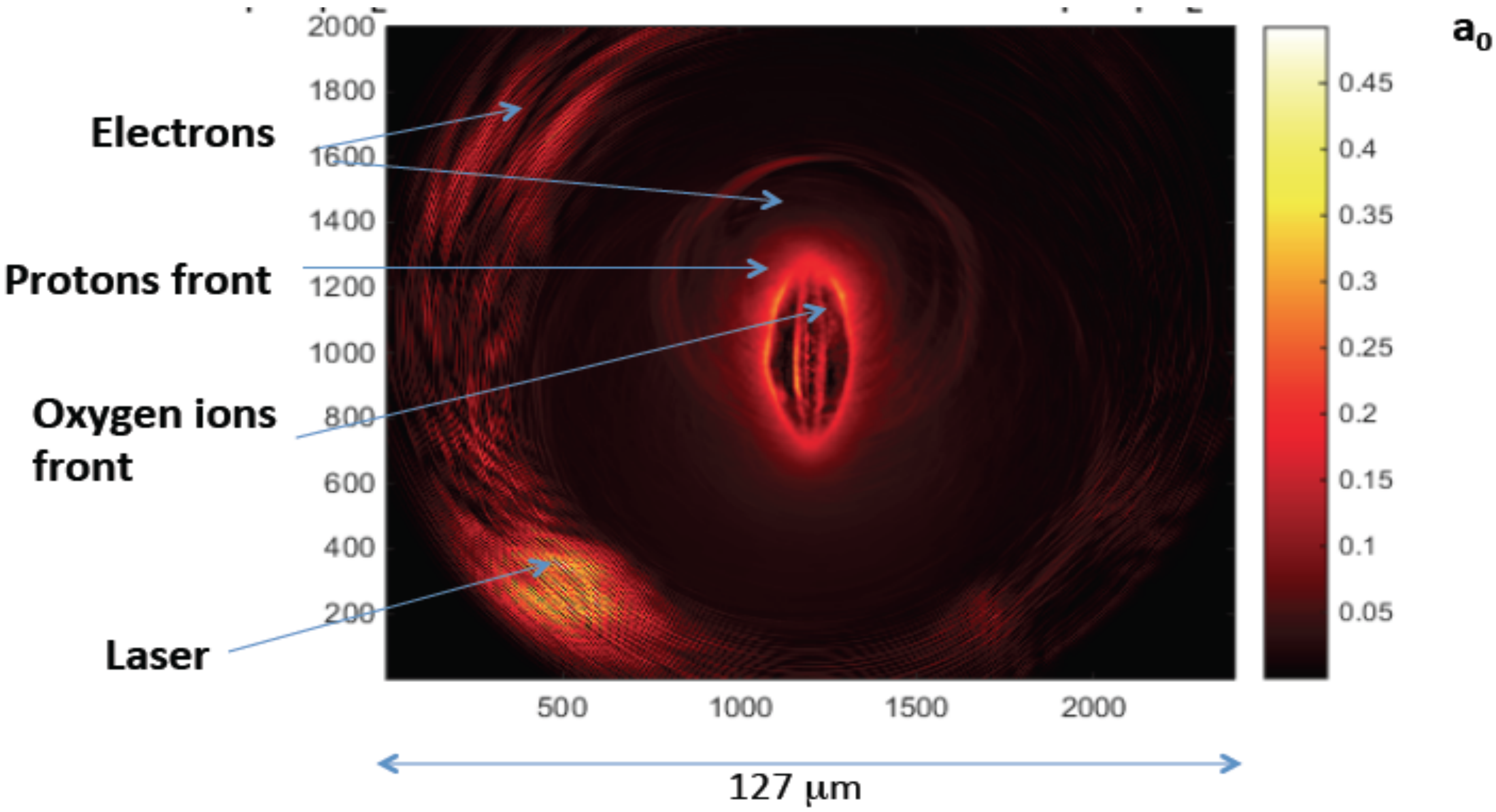


The electric field in units of a_0

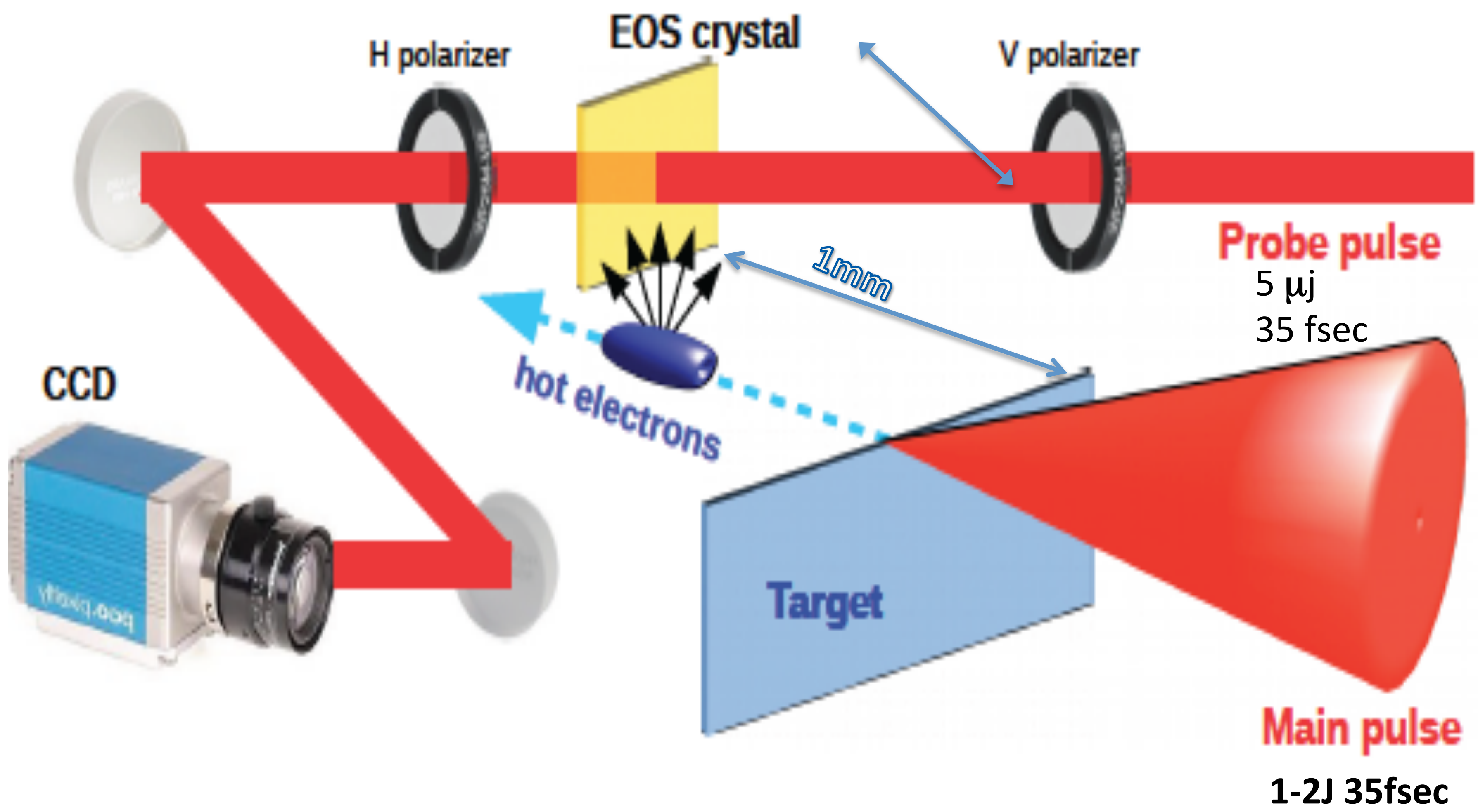
(x $1.37\cdot10^{11}$ V/cm) $I_L = 2.5\cdot10^{19}$ W/cm^2

after 200fsec

$$a_0 = \frac{eE}{mc\omega}$$



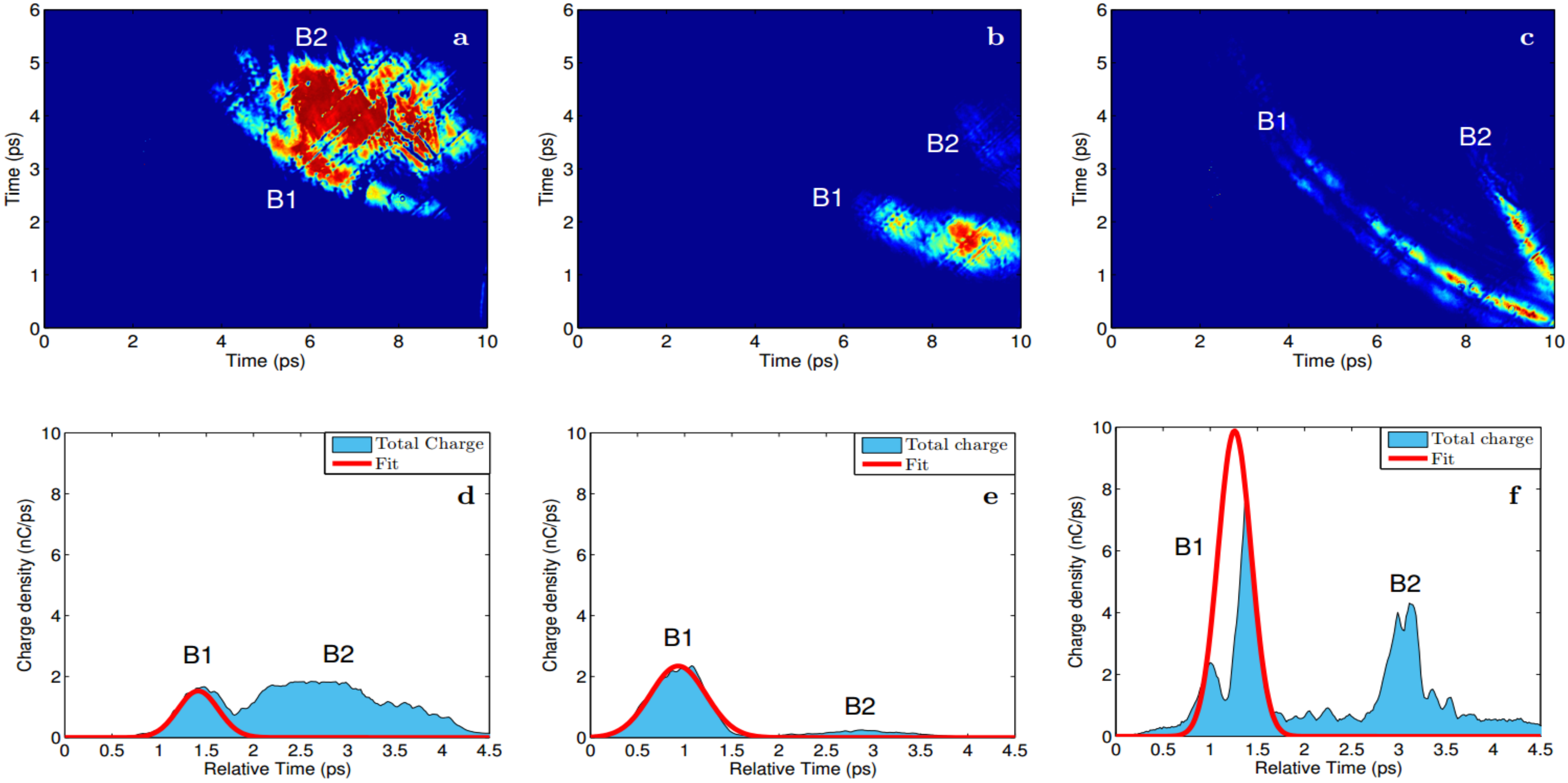
SINGLE-SHOT ONLINE MONITOR FOR THE HOT ELECTRON CLOUD



Schematics for measuring quantity and temporal evolution of the escaping electrons

Influence of the target shape on the escaping electrons

Planar (Foil) **Wedge (blade)** **needle**



(d-f) Corresponding longitudinal charge profiles.
The main laser parameters are the same in all cases.

Influence of the target shape on the escaping electrons

Charge (first “bunch”)

(a) planar	- 1.3 nC
(b) wedge	- 2 nC
(c) needle target	- **7 nC**

The mean energy of the emitted electrons is:
7 MeV in (a) and (b)   12 MeV in (c).

The main laser parameters are the same in all cases.

FLAME status: program

From now to the summer.

Activity	Start date	End date
Test of the first optimized YAG in FLAME	06/06/2016	30/06/2016
Optimization of the other 10 YAGs	10/06/2016	30/06/2016
Single shot emittance experiment – phase 2	21/05/2016	03/06/2016
EOS experiment – phase 2	06/06/2016	30/06/2016
Laser maintenance	01/07/2016	05/05/2016
Capillary guiding and acceleration for EXIN in FLAME bunker	05/06/2016	31/07/2016

The 10 YAGs will be shipped to Amplitude 2 by 2. Every 2 YAGs will be upgraded in one week.

Possibly, all the YAGs will be upgraded and working before the beginning of the summer holidays.

FLAME status: next experiments

EOS experiment - phase 2.

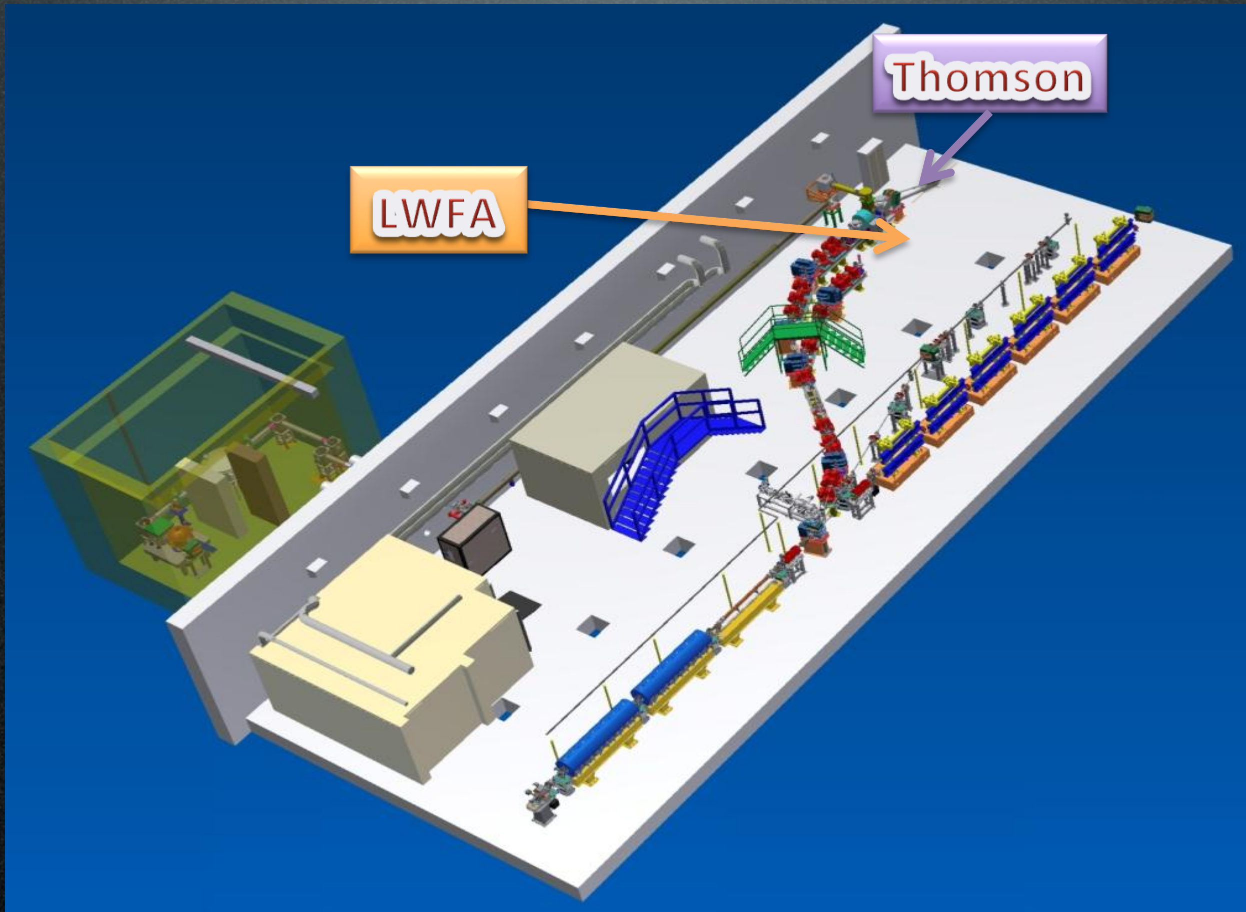
The aim of this experimental campaign is to add more diagnostic to the previous experimental campaign. Examples of diagnostic that will be included in this experimental campaign are electron charge and energy.

Moreover, a more comprehensive study of the potential barrier will be carried out.

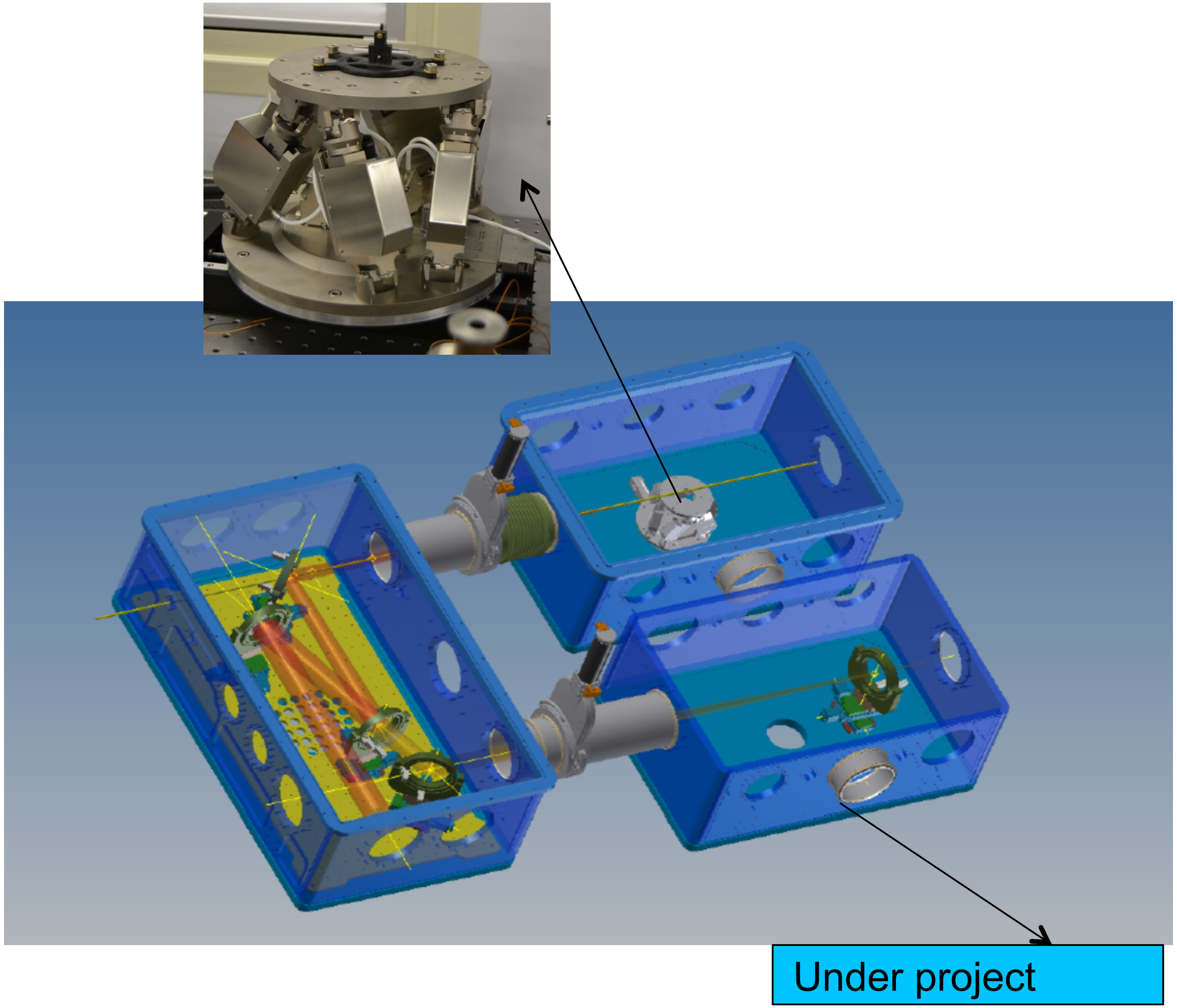
EXIN – capillary guiding at FLAME.

The goal of this experiment is to start working with the capillaries overseen to be used for the external injection experiment that will take place at SPARC. It is of paramount importance, for the experiment success, to have the abilities to align the capillaries; in particular, in the first part of the experiment, we will start using empty capillaries in order to see the capillary modes trying to optimize transmission and modes. Then, we will go to gas filled capillaries and we will finish using pre-formed plasma capillaries.

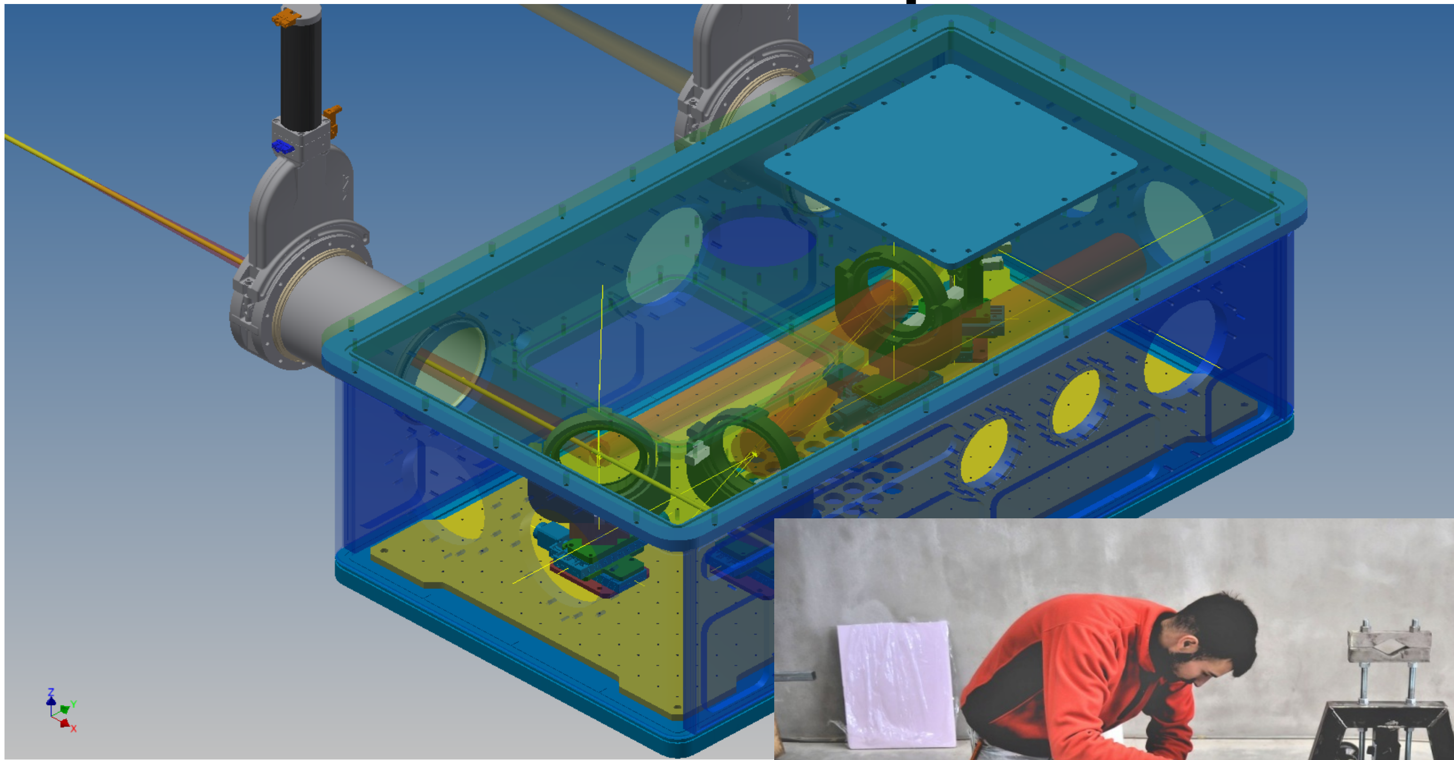
SL_EXIN & SL_Thomson



Interaction Chamber

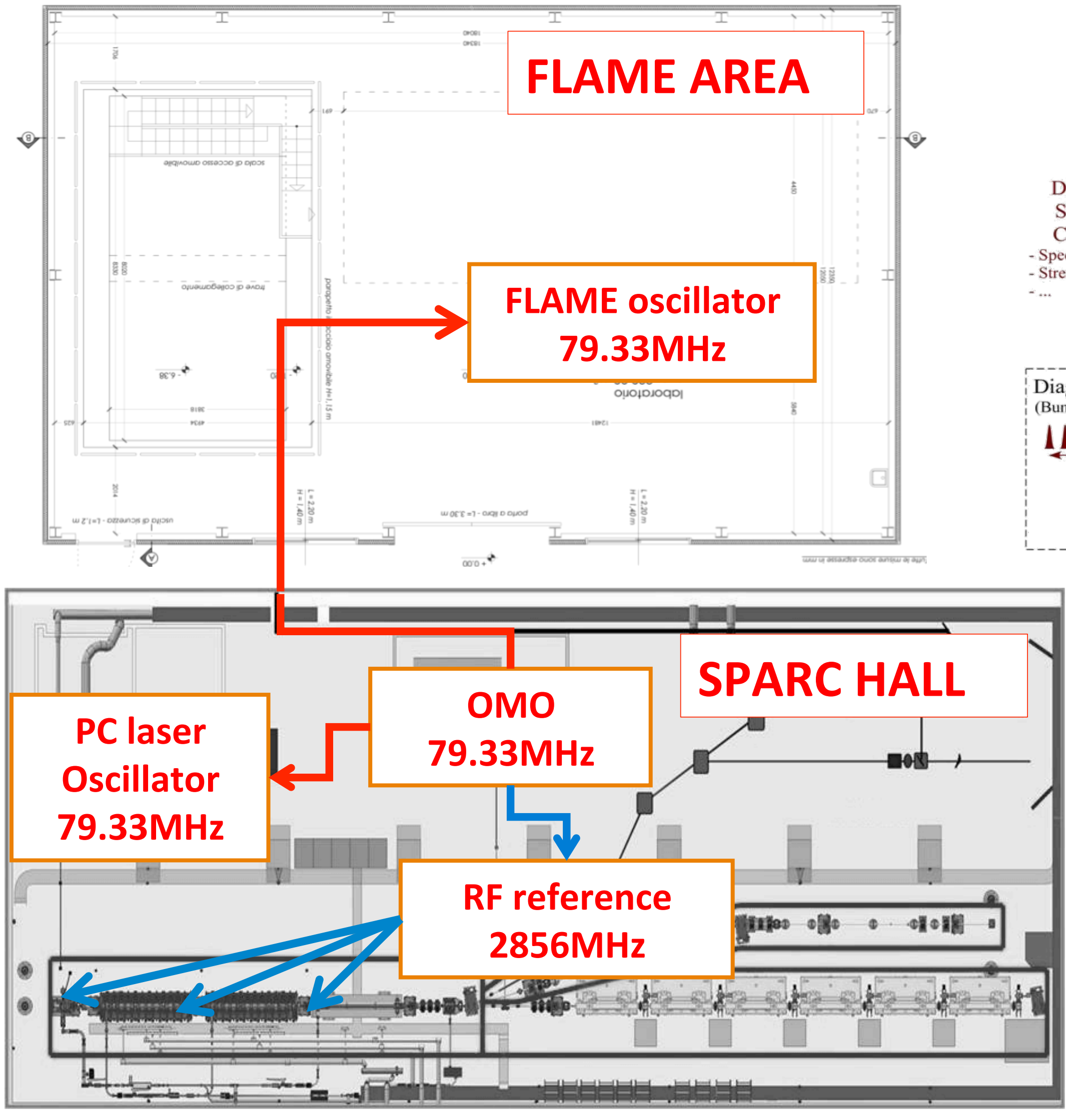


Laser transport chamber

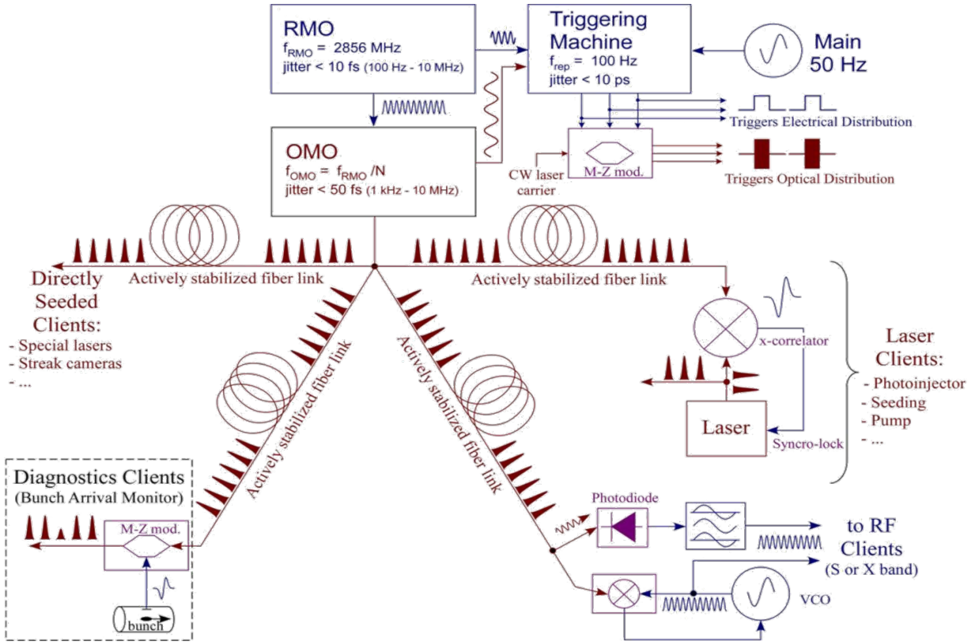


General layout of SPARC_LAB synchronization system upgrade

Optical architecture foreseen at SPARC_LAB

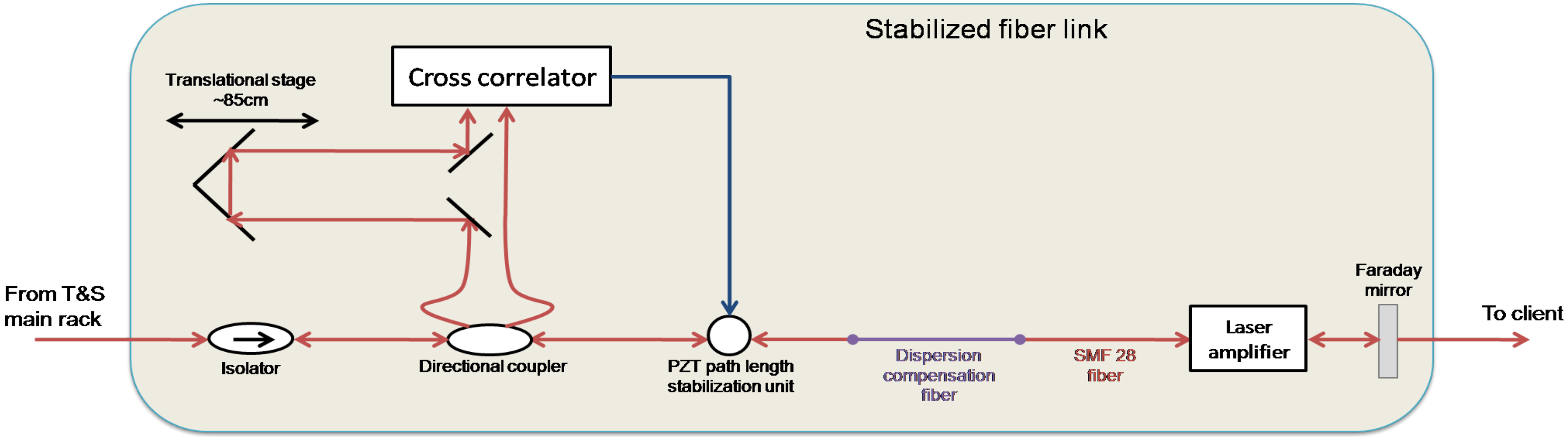


Typical modern synchronization system layout



- Present relative jitter performance <50fs RMS (coaxial distribution)
- Upgrade to optical reference signal distribution towards <10fs RMS
- Fiber stabilized link installed and commissioned
- Optical phase detectors (x-correlators) under test @LNF

Fiber link installed and commissioned



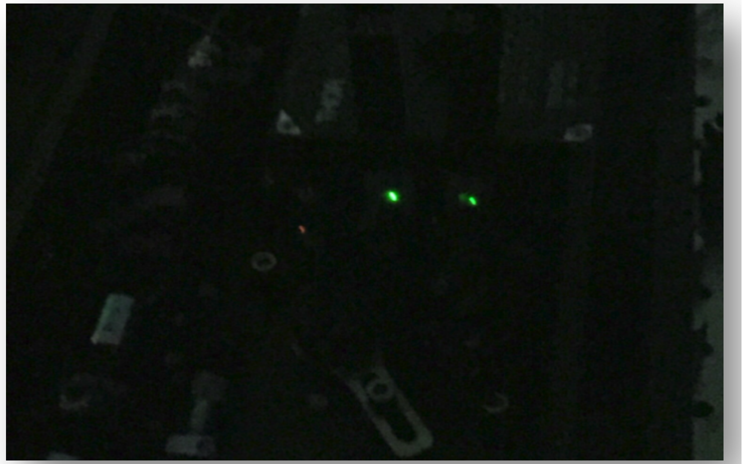
General drift-compensated fiber link layout

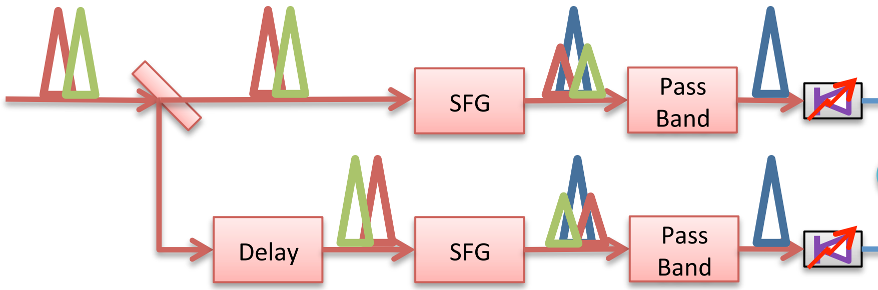
- Installed and fully commissioned @SPARC_LAB
- All the noise in the DC÷10kHz band (thermal drifts, mechanical vibrations, mains disturbances, …) corrected.
- No major noise contributions outside the loop BW of the link stabilizers are expected
- Signal distributed with jitter <10fs towards FLAME laser oscillator (~40m long link)

Commissioning of optical phase detectors

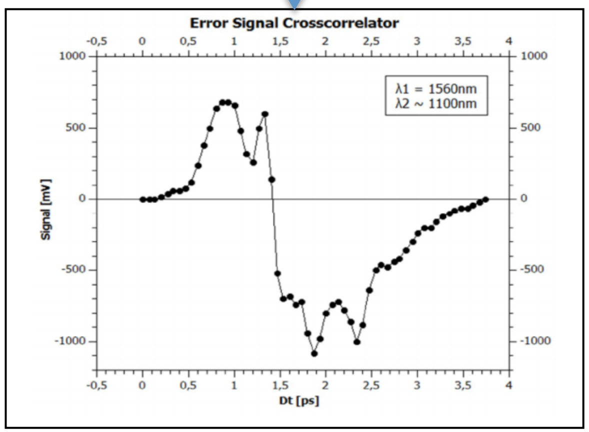
- Used to detect relative timing jitter between Optical Master Oscillator (OMO) and slave laser system
- sensitivity up to **10mV/fs** (~3 order of magnitude better than standard electronic mixing technique)
- commercially available product (see picture below from Menlo Systems)
- commissioning of the device in progress @LNF
- Estimated closed loop jitter reduced to <u><10fs RMS</u>

Detected signal from one of the SPARC_LAB x-correlators





Typical x-correlator characteristics (measured at MENLO Systems GMBH)




Thank you