3rd Topical Workshop on Novel Acceleration Techniques

28-30 April 2014, HZDR

Plasma-based acceleration experiments at SPARC_LAB

Abstract

The current goal of the world wide R&D programs is to **demonstrate the stable and repeatable acceleration of high brightness beams** (HBEBs).

The scheme proposed at the **SPARC_LAB test facility** is based on the **external injection of the electrons inside the plasma**.

Two different mechanisms are proposed: an **external injection laser wakefield acceleration** (LWFA), by combining the multi-hundreds power laser (Flame) and the HBEB from the SPARC photo-injector, **and** a **resonant plasma wakefield acceleration** (PWFA), by using a train of high brightness electron bunches.

Enrica Chiadroni (INFN – LNF)
on behalf of the SPARC_LAB group
http://www.lnf.infn.it/~chiadron/index.php

Outline

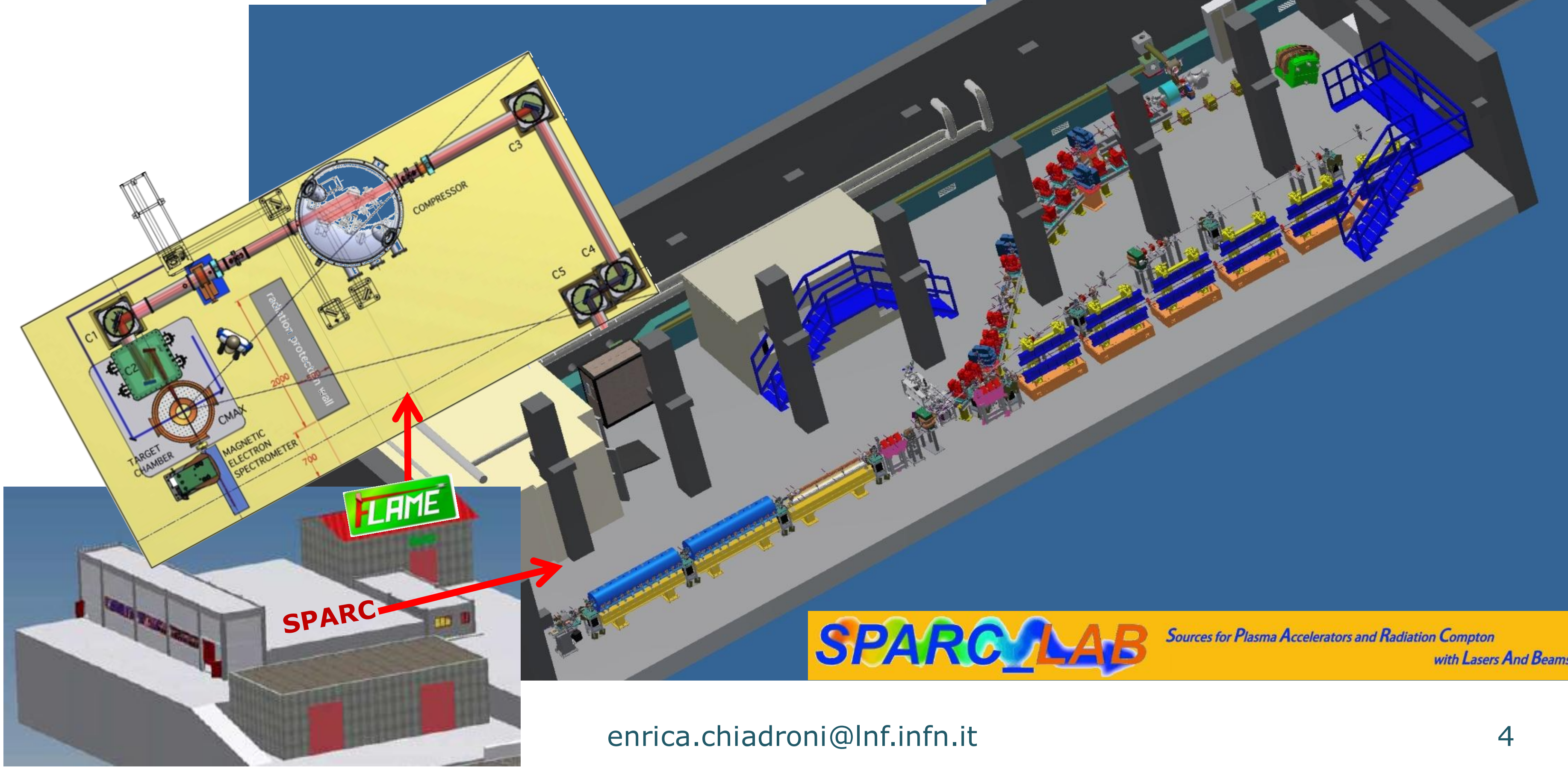
- Scientific Motivation
- Plasma-based experiments at SPARC_LAB
  - Introduction to the SPARC_LAB Test Facility
- Milestones
- External injection based schemes
  - Resonant particle-driven plasma wakefield acceleration (**r-PWFA**)
  - Laser-driven plasma wakefield acceleration of externally injected HBEBs (**LWFA**)
- Achievements so far
  - Manipulation of trains of high brightness electron bunches (HBEBs)
    - Generation of two-color Free-Electron Laser (FEL) radiation
    - Production of narrow band, tunable THz radiation
  - Transport of high power laser in the SPARC bunker
- Conclusions

Scientific Motivation

- Plasma-based acceleration has been already demonstrated
  - P. Muggli et al, in Proc. of 2011 Particle Acc. Conf., New York, NY, USA, TUOBN3
  - I. Blumenfeld et al., Nature 445, p. 741 (2007)
  - W. P. Leemans, Nature Physics vol. 2, p.696-699 (2006)
  - V. Malka et al., Science 298, 1596 (2002)
- The main issue is now on the beam quality
  - Demonstrate the acceleration of **HBEBs**
    - High peak current, low emittance, small energy spread, stability, repeatability
  - The highest energy record in both particle and laser driven experiments is not the goal
- Future applications
  - Drive FELs
  - Build multi-staging compact colliders
  - Advanced radiation sources

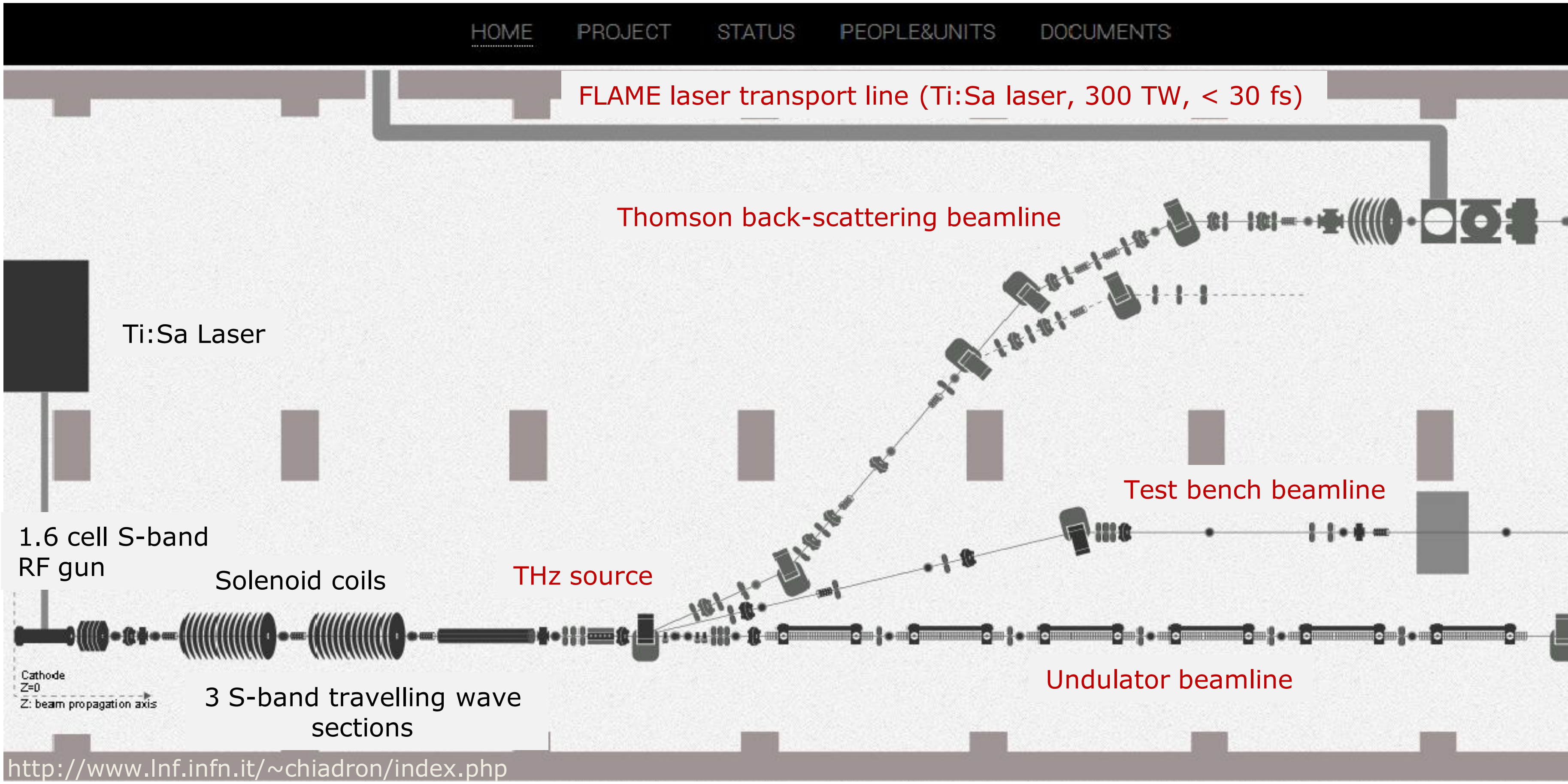
SPARC_LAB

SPARC_LAB is a test facility based on the **combination of high brightness electron beams, from** the **SPARC** photo-injector, **with high intensity ultra-short laser pulses, from FLAME**.



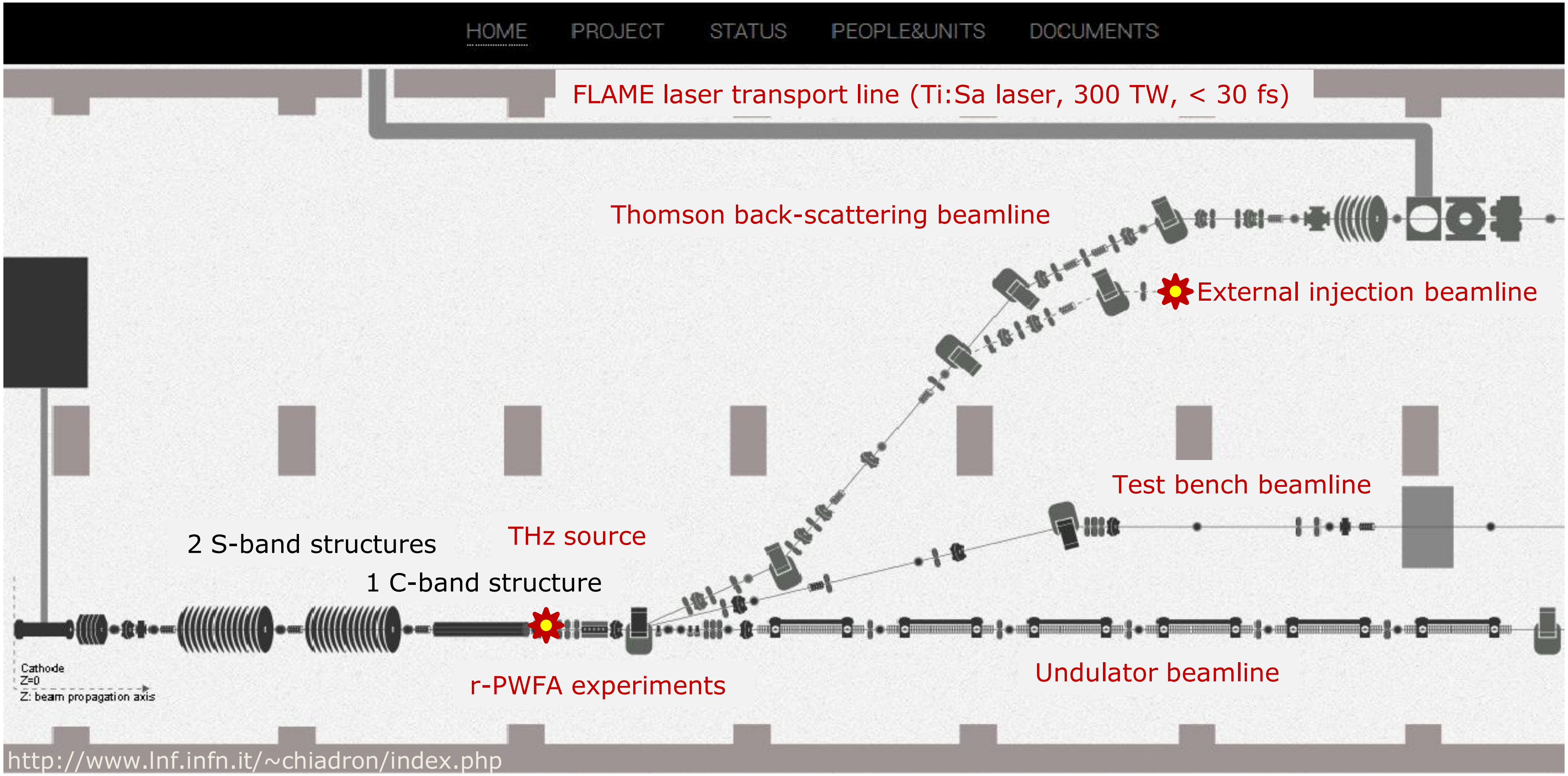
The SPARC_LAB Test Facility

Present



The SPARC_LAB Test Facility

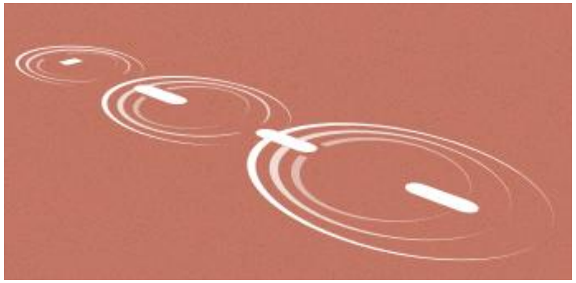
Next Future



The Project

External injection of electrons to be accelerated in the plasma

- **r-PWFA**



- Bunch trains generation with the *comb technique* based on RF Velocity Bunching (VB)
- Resonant plasma wave excitation in a capillary discharge
  - Advanced electron beam and plasma diagnostics test
  - Beam dynamics studies

- **external injection LWFA**

- VB and magnetic mixed compression to deliver HBEBs
- Laser parameters
  - $E \leq 3.5$ J on target, 20 – 40 fs (FWHM), $\sigma_r \geq 10$ μm
- Electron beam parameters
  - E = 70 - 150 MeV, 7 – 40 fs (FWHM), ε_n: few μm, $\sigma_r < 20$ μm, Q = 5 – 30 pC

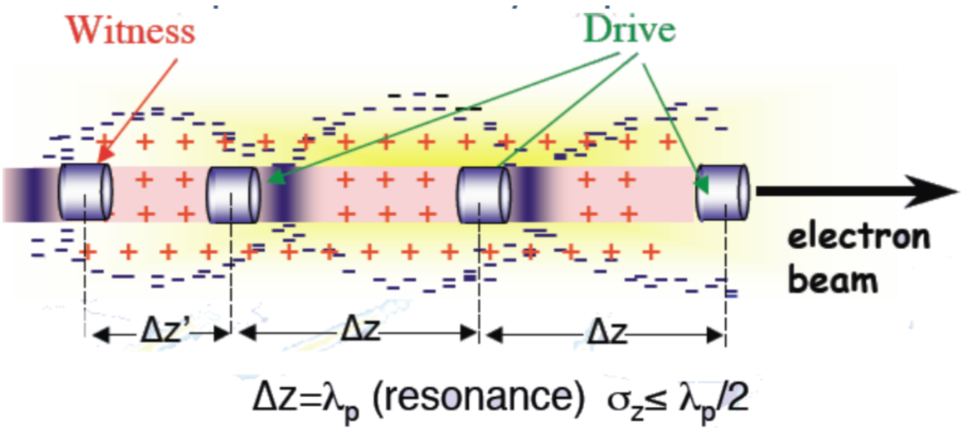
Milestones

- Start-to-end simulations
  - Set working points
  - Guide during experiments
  - Validate experimental data
- Design and construction of plasma chambers
- Transport and shaping of both Flame laser and SPARC electron beams
  - from their generation down to the injection into the plasma chamber
- Study and the realization of diagnostics devices for both electron beams and plasma
  - Non-intercepting longitudinal diagnostics based on EOS
    - Single shot measurement of electron beam time distribution
    - Electron beam and laser synchronization
- Run LWFA and resonant PWFA experiments
  - Generation of high brightness, stable and repeatable electron beams

RESONANT-PWFA

Resonant Plasma Oscillations by Multiple Electron Bunches

- Weak blowout regime with resonant amplification of plasma wave by a train of HBEBs injected into the preformed plasma (by electric discharge)
  - 5GV/m with a train of 3 bunches, 100 pC/bunch, 20 μm spot size, n_e 10^{22} e/m^{-3} at λ_p = 300 μm



- Ramped bunch train configuration to enhance transformer ratio
- Synchronization with an external laser is not needed
- Challenge: creation and manipulation of driver bunches and matching all the bunches with the plasma
  - High quality bunch preservation during acceleration and transport

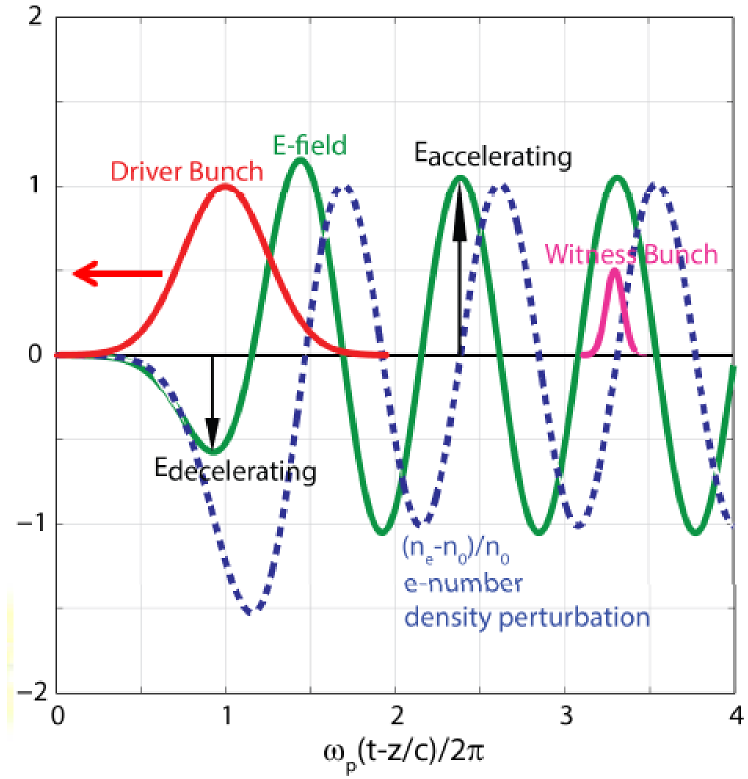
Transformer Ratio Studies

The **key parameter** that determines the energy gain is the **Transformer Ratio**, defined as the ratio of the maximum accelerating field behind the driving bunch and the maximum decelerating field inside the driving bunch

$$R = \frac{E_{accelerating}}{E_{decelerating}}$$

A test charge injected in correspondence of $E_{accelerating}$ gains an energy approximately equal to

$$\Delta W = R\gamma_{driver}$$

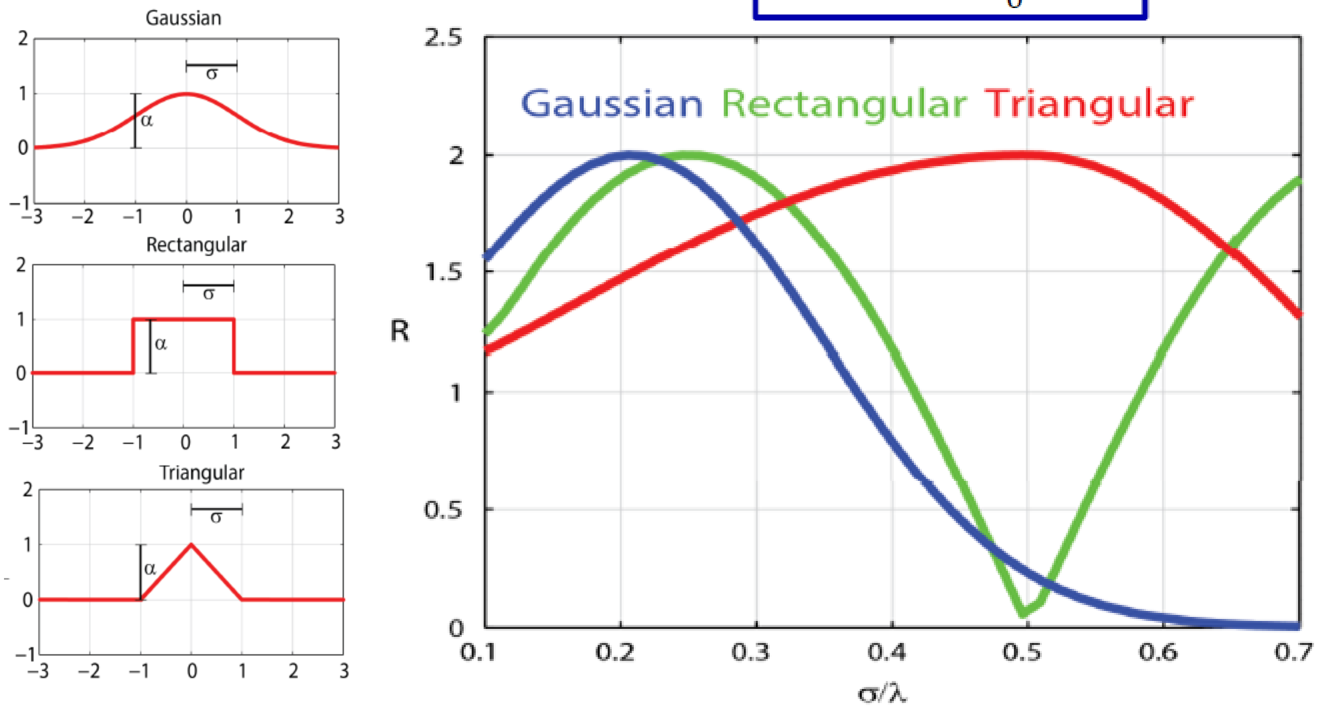


F. Massimo et al., NIM A **740**, 242–245 (2014)

Transformer Ratio Studies

It is found that the transformer ratio critically depends on the bunch shape and on the density ratio.

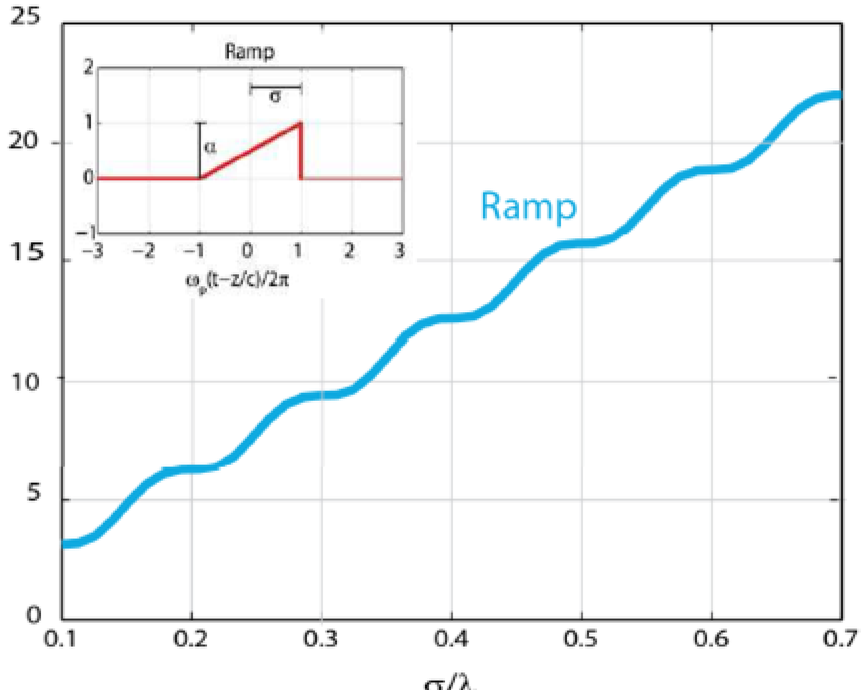
Linear regime: $\alpha = \dfrac{n_{driver,peak}}{n_0}$ **= 10^-4**



F. Massimo et al., NIM A **740**, 242–245 (2014)

Ramped Bunch Train

Asymmetric driver bunches can reach even in linear regime R>2
➔ Ramped bunch train configuration to enhance transformer ratio



F. Massimo et al., NIM A **740**, 242–245 (2014)

Generation and Manipulation of Bunch Trains

P. O. Shea et al., Proc. of 2001 IEEE PAC, Chicago, USA (2001) p.704.
M. Ferrario. M. Boscolo et al., Int. J. of Mod. Phys. B, 2006

(Parmela code)

Charge vs. Time

Energy vs. Time

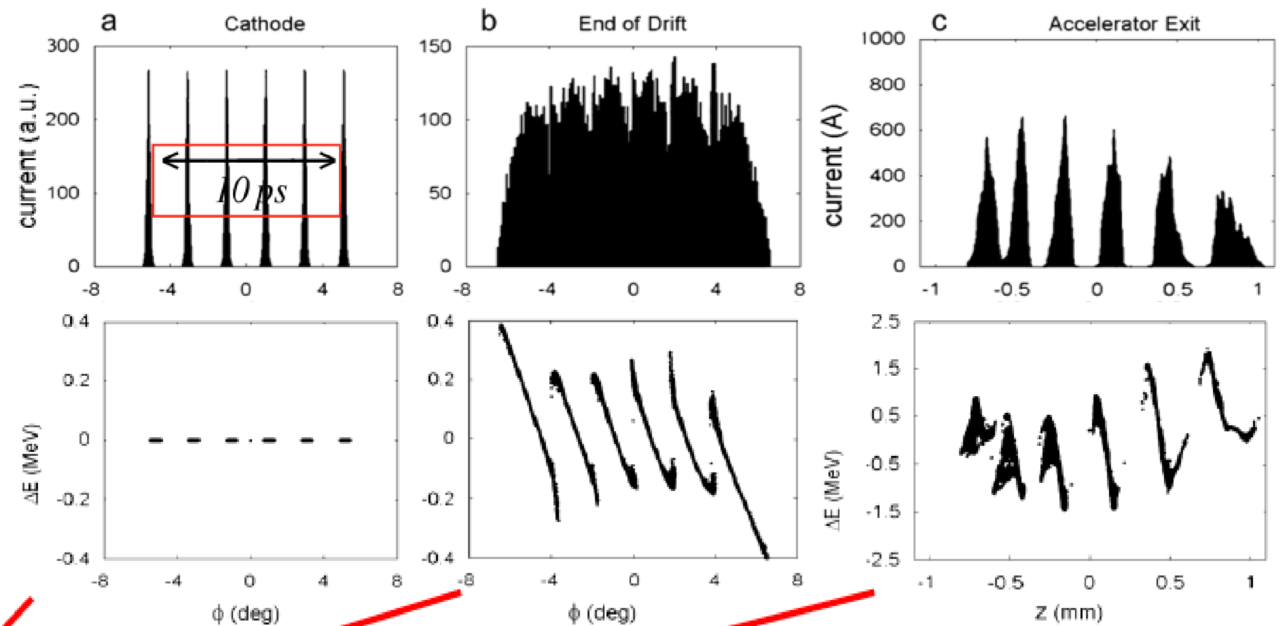
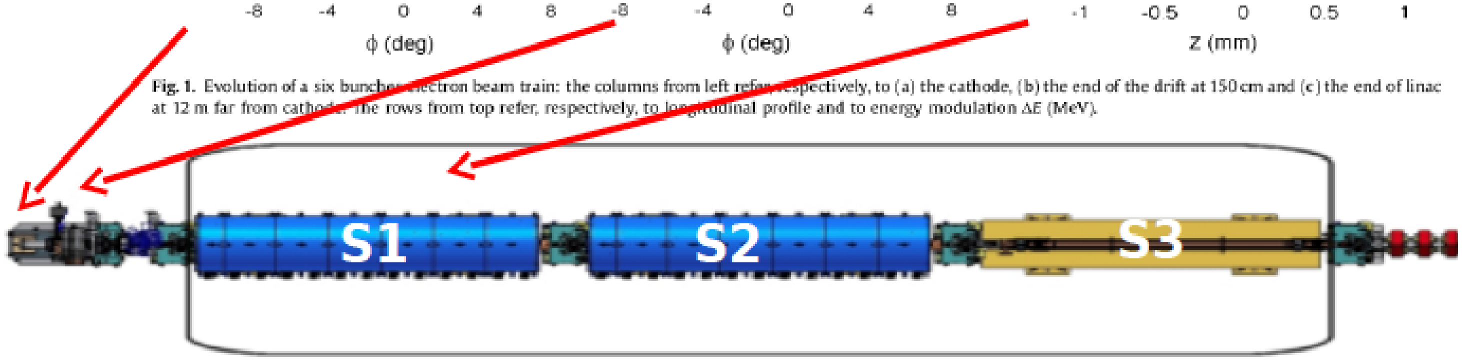


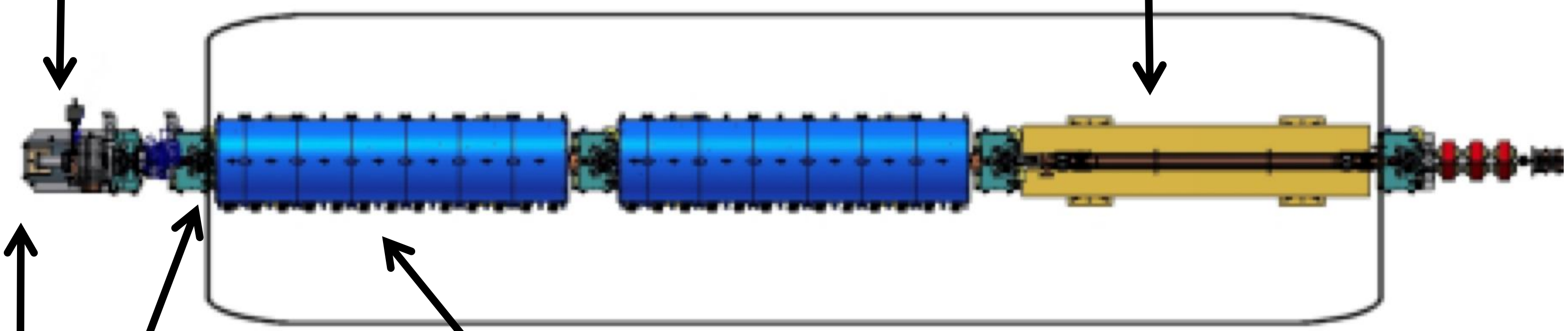
Fig. 1. Evolution of a six bunches electron beam train: the columns from left refer, respectively, to (a) the cathode, (b) the end of the drift at 150 cm and (c) the end of linac at 12 m far from cathode. The rows from top refer, respectively, to longitudinal profile and to energy modulation ΔE (MeV).



Manipulation of Bunch Trains

Gun focusing field (~3kG)
Emittance
Bunches current, length

Accelerating field
Energy separation



Injection phase
Bunch spacing
Train length

TW focusing field (~300G)
Emittance
Bunches current, length and their max compression phase

Gun exit energy
Beam brightness

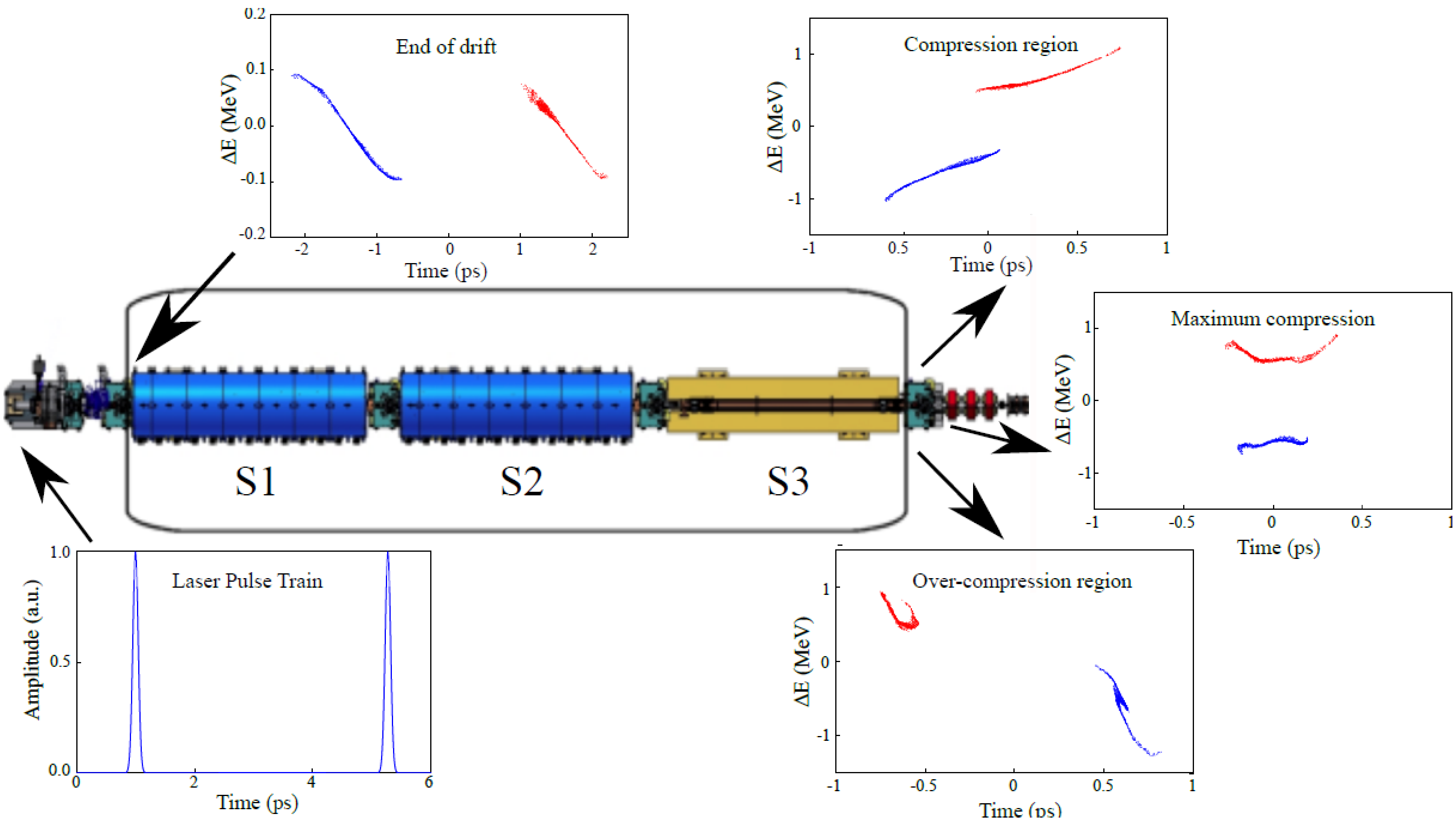
Compression phase stability
Bunch separation stability

Gun injection phase and space charge
Bunches distance at the linac entrance

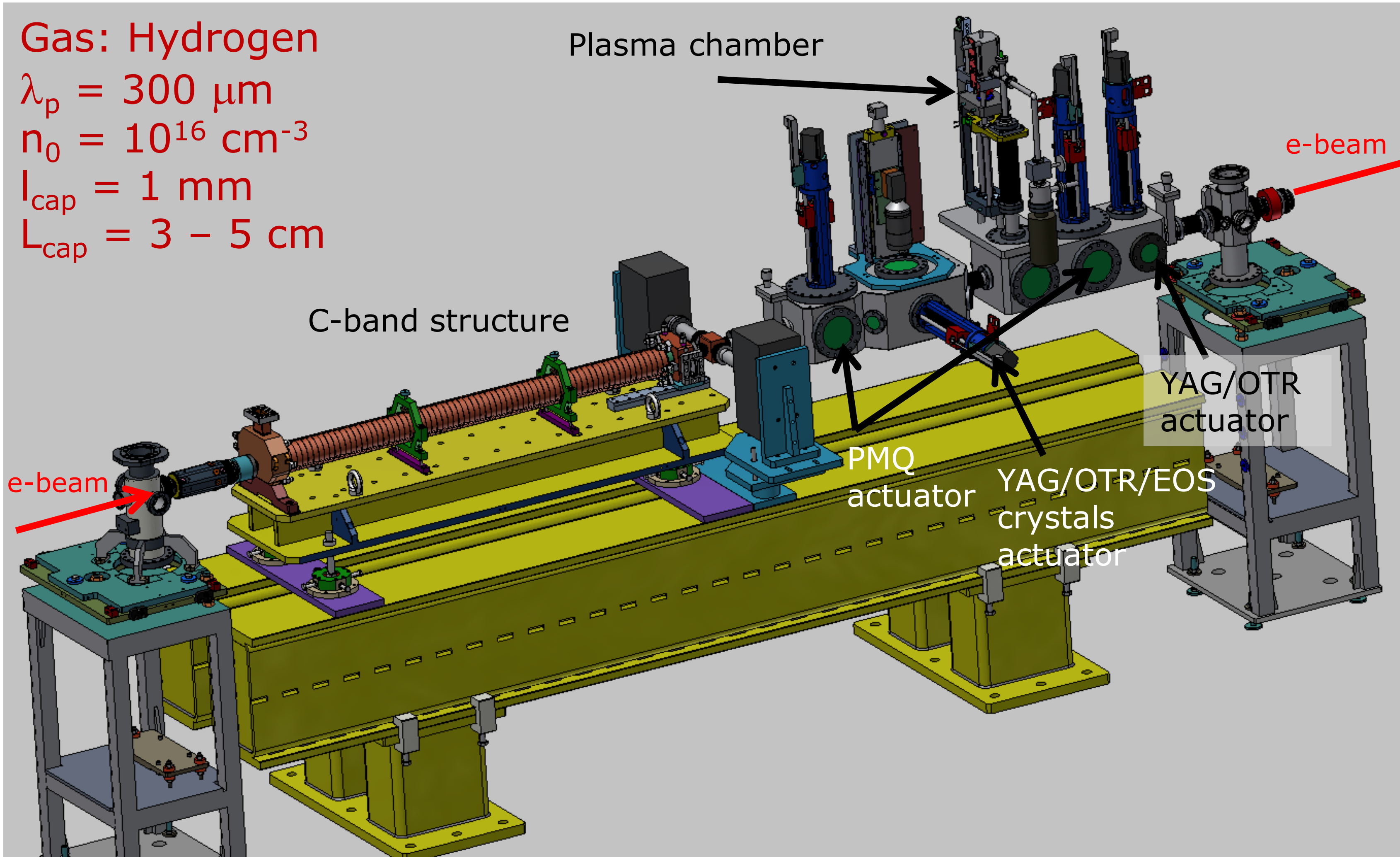
enrica.chiadroni@lnf.infn.it

Evolution of two-bunch Trains

RF compression ➔ S1 phase



Interaction Layout

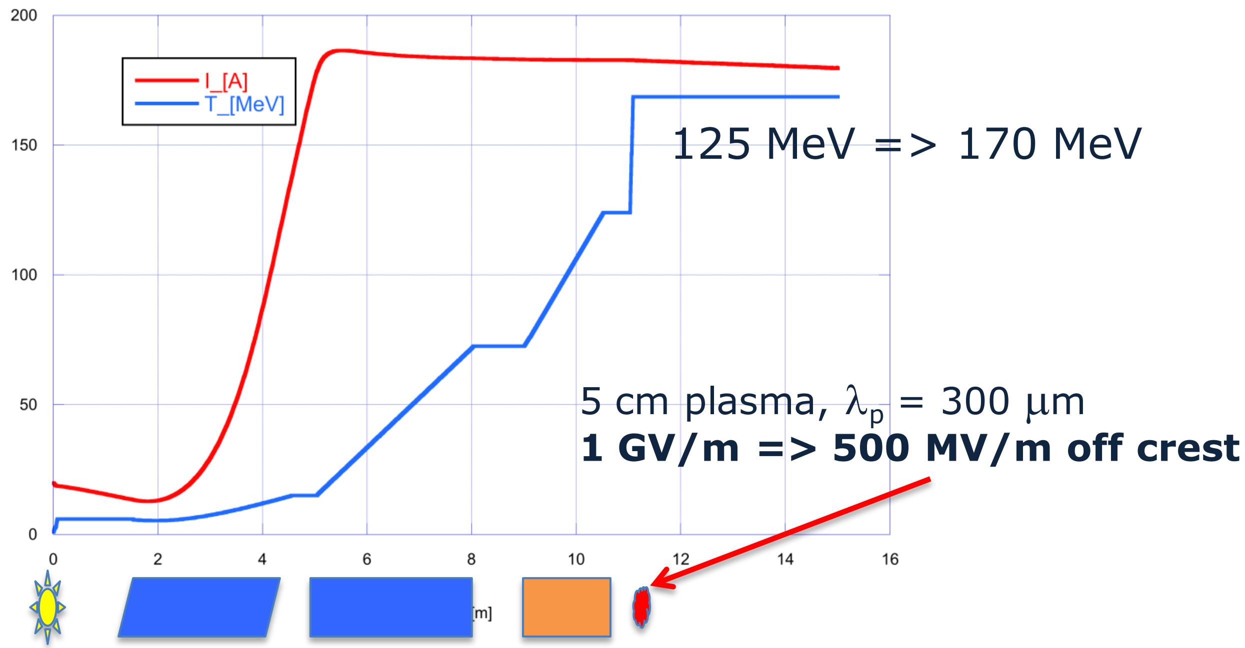


Courtesy of V. Lollo

Preliminary Start-to-End Simulations

Homdyn simulation for the witness bunch

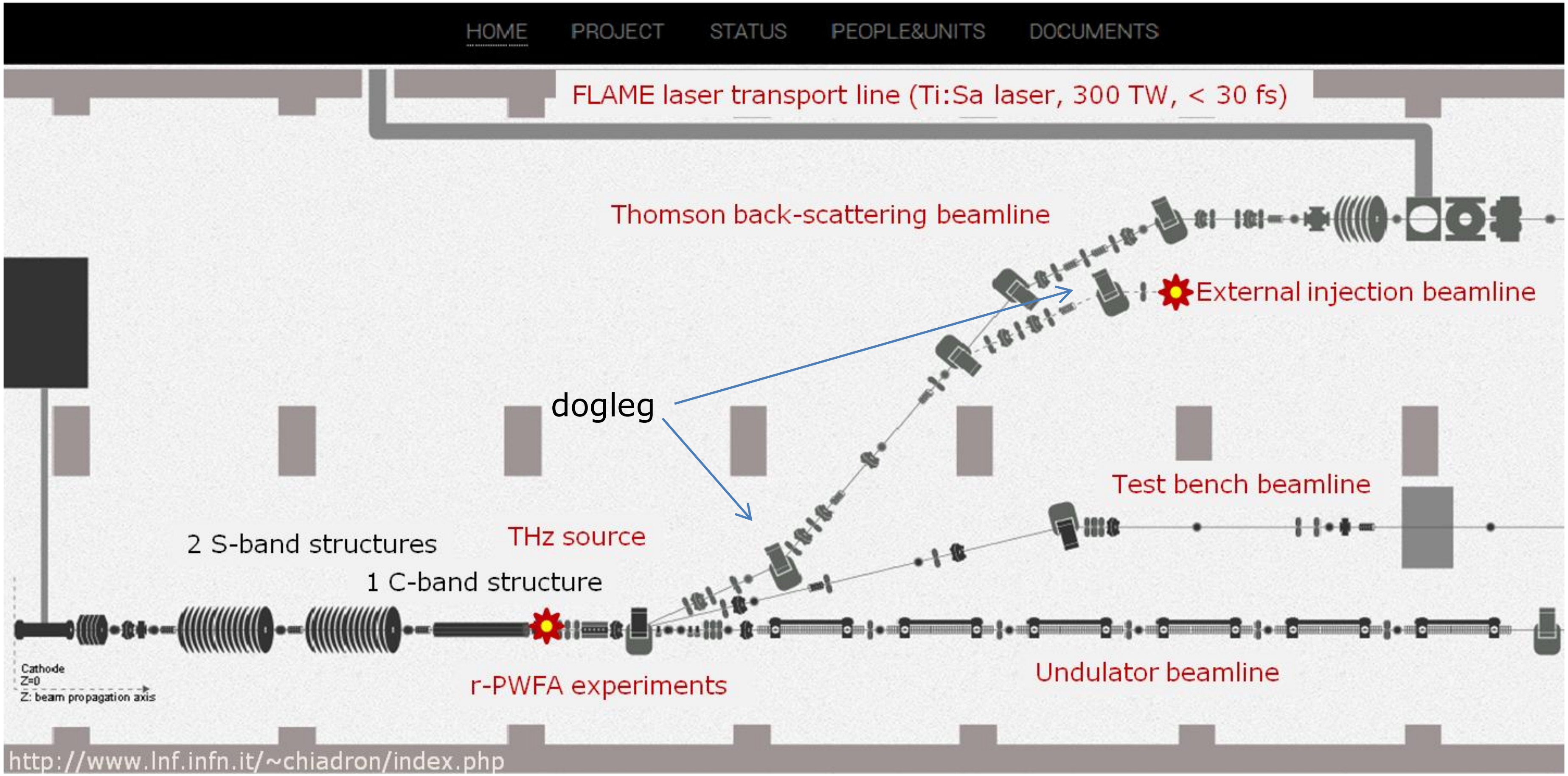
Laser pulse length	300 fs (FWHM)
Laser spot at cathode	370 μm
Witness bunch charge	25 pC
Acc. Sect. Gradients	20,20,35 MV/m



Courtesy of M. Ferrario

LWFA:
EXTERNAL INJECTION

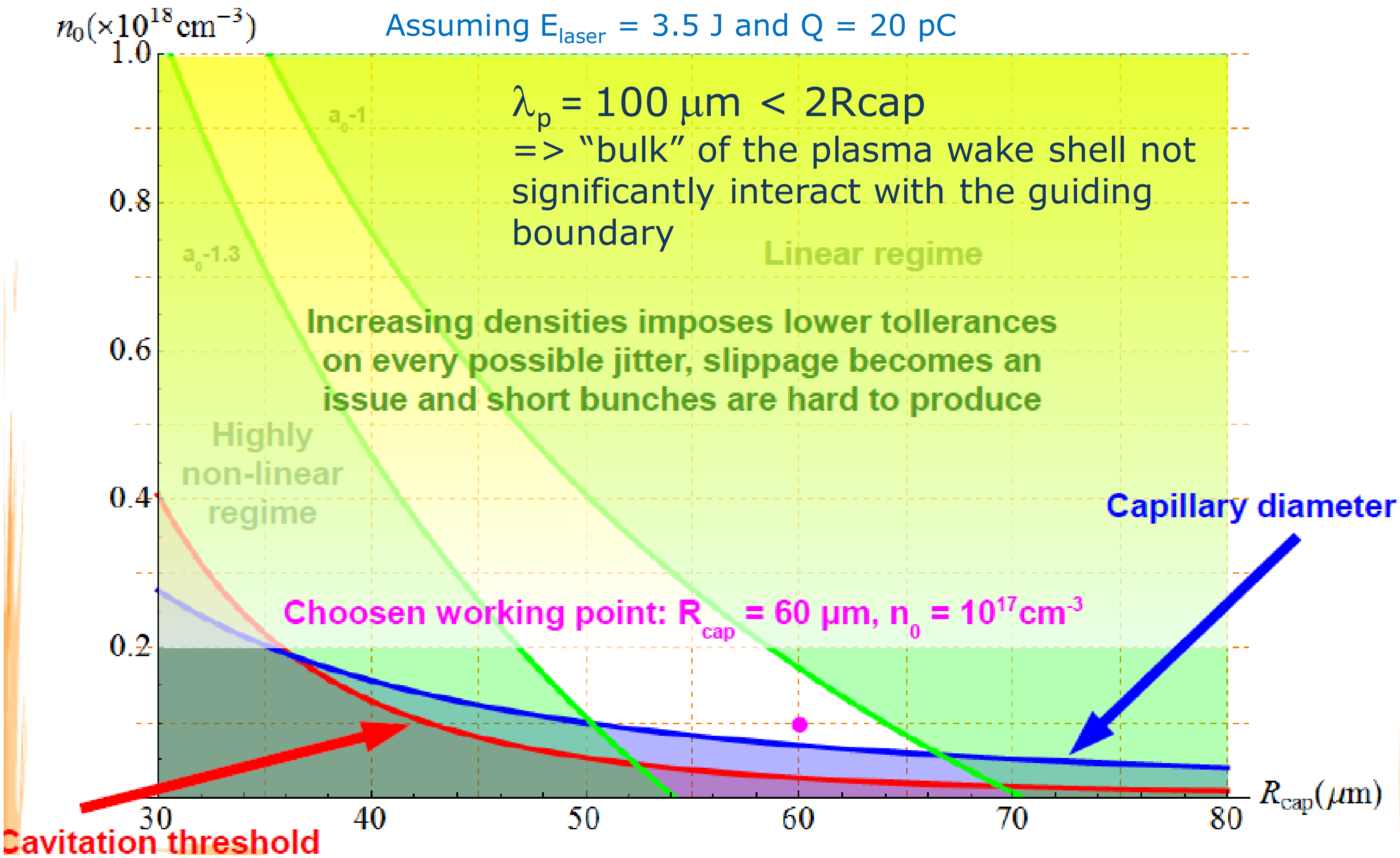
Experimental Layout



RF and magnetic mixed compression to deliver HBEBs

Working Point

Coloured exclusion areas come from physical and practical constraints



A. R. Rossi et al., NIM A **740**, 60-66 (2014)

Start-to-End Simulations

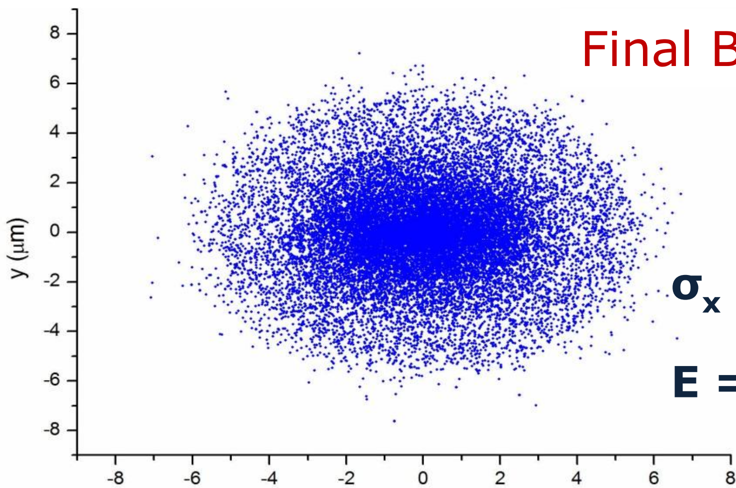
Start-to-end simulations for the External-Injection experiment are performed using three different numerical codes
- ASTRA for the bunch generation at the photocathode and acceleration down to the linac end (by A. Bacci)
- ELEGANT for the transport inside the dogleg (by C. Vaccarezza)
- QFLUID2 for the acceleration in plasma (by P. Tomassini)

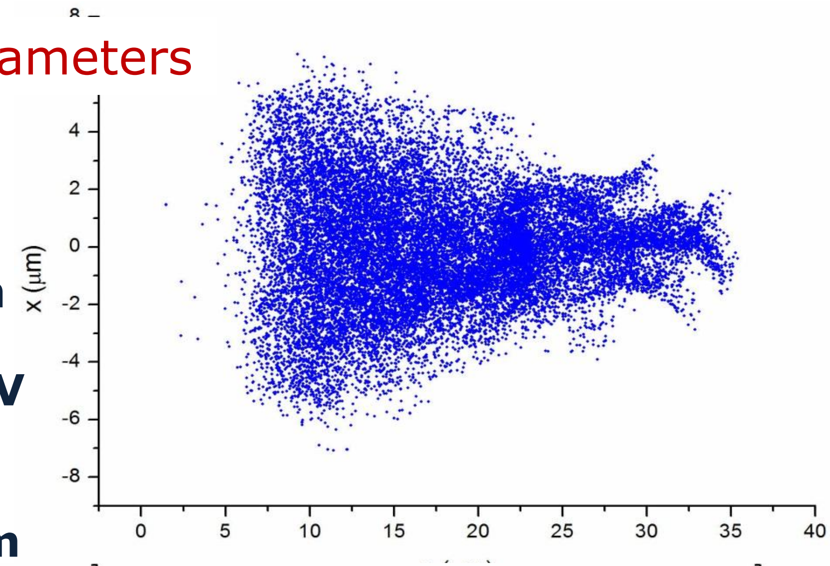
The simulation geometry is a capillary

Beam parameters
$\sigma x \approx \sigma y$=12.7 μm,
εx= 2.7 μm, **εy**= 0.4 μm, **E**= 78 MeV,
$\delta\gamma/\gamma$= 0.2%.
Total compression factor = 16 (8 by VB and 2 by dogleg).
Non particular optimization in dogleg
X emittance overestimated!

Start-to-End Simulations

Final Beam parameters



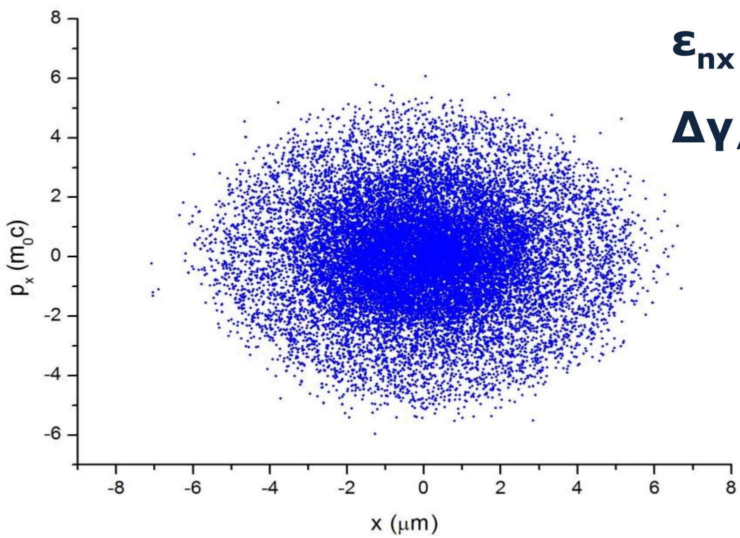


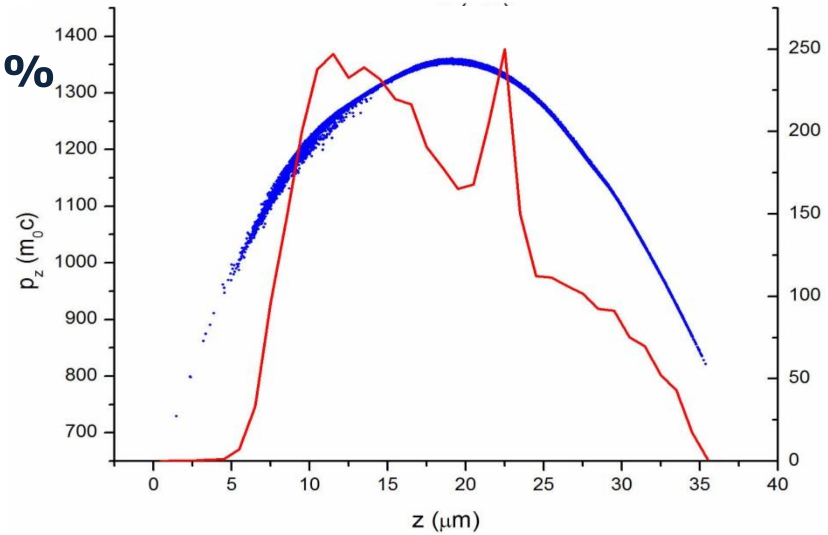
σ_x = 2.0 µm

E = 630 MeV

ε_{nx} = 3.5 µm

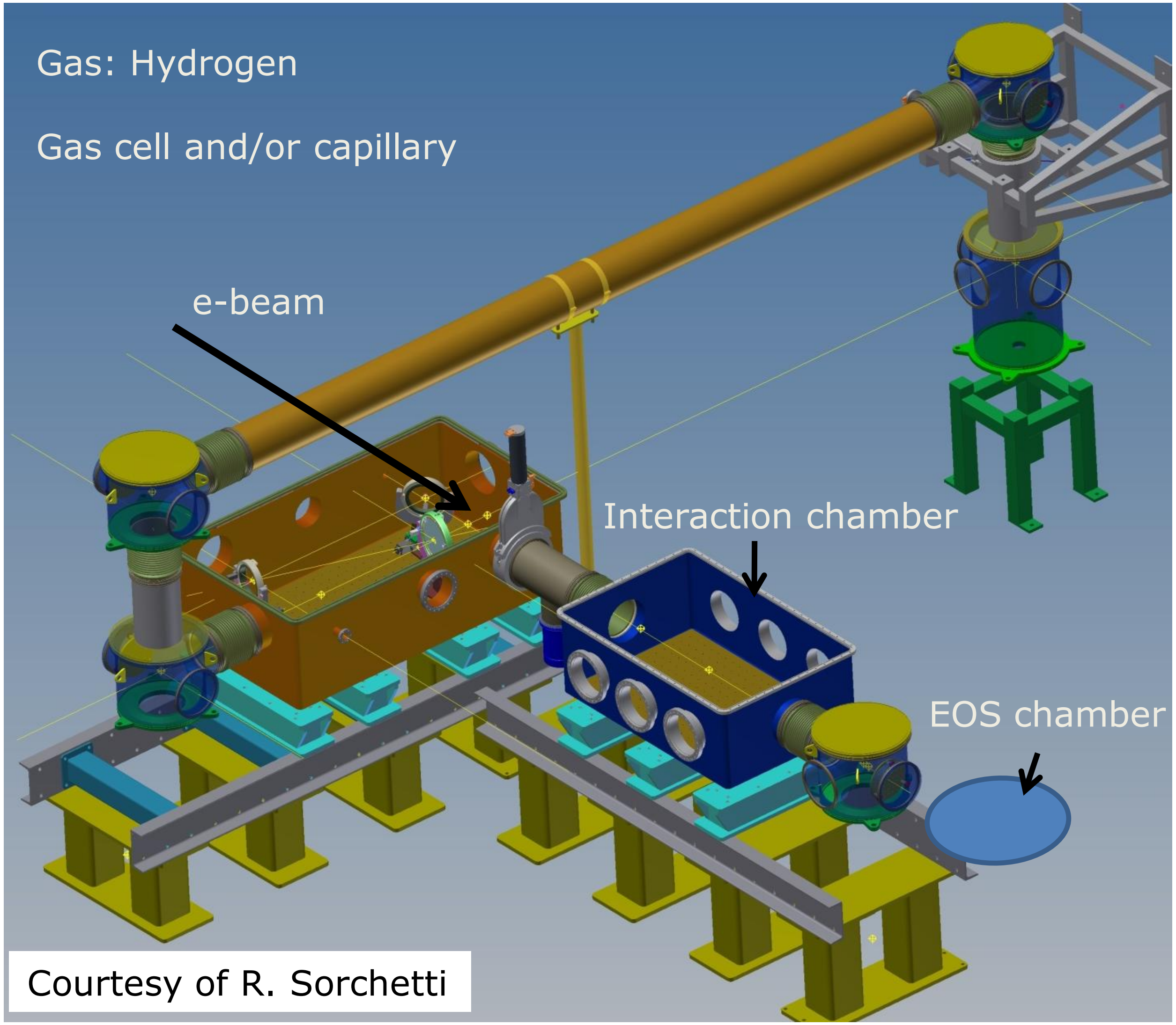
$\Delta\gamma/\gamma$= 7.7 %





A. R. Rossi et al., NIM A **740**, 60-66 (2014)

Interaction Layout



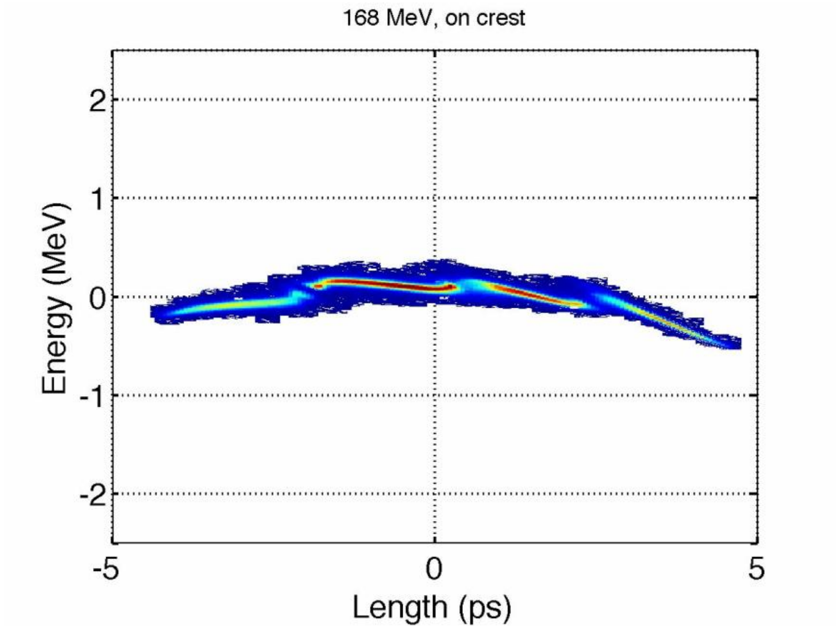
Achievements so far

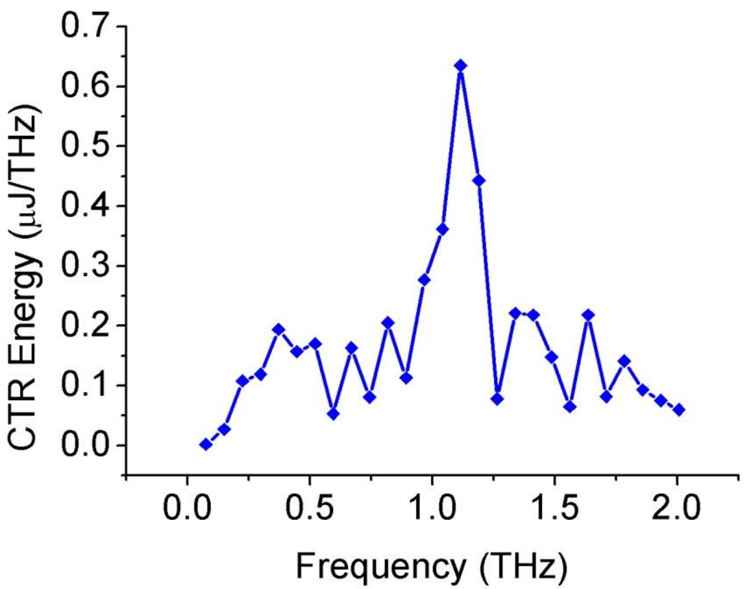
- Electron beam studies
  - Manipulation of trains of electron bunches, i.e. *comb beam*
    - Narrow band and tunable THz radiation
    - Two-color FEL radiation
  - Low energy electron beam transport and Flame laser transport along the Thomson beamline

- Electron beam diagnostics
  - EOS
    - Longitudinal diagnostics of multi-bunch trains
    - Synchronization tool in external injection LWFA

Electron Beam Experimental Studies

- COMB 4 pulses
  - Narrow band, tunable THz radiation

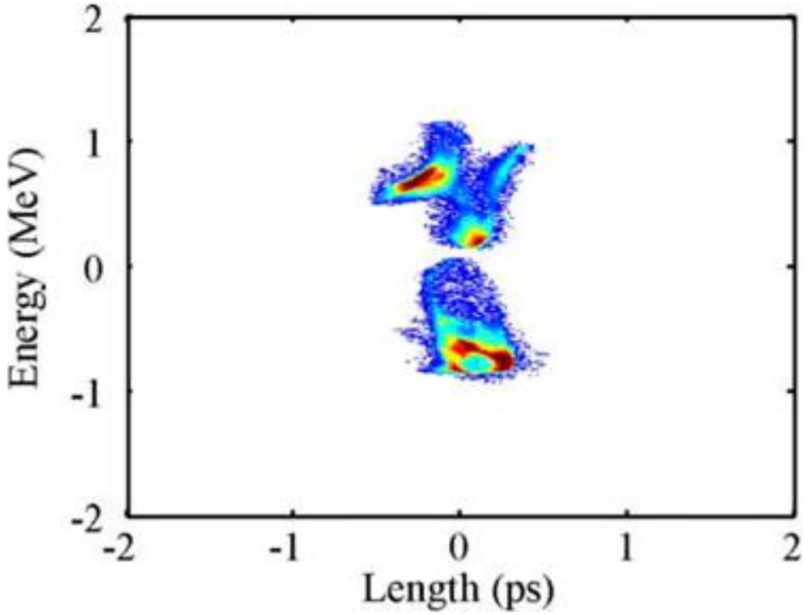


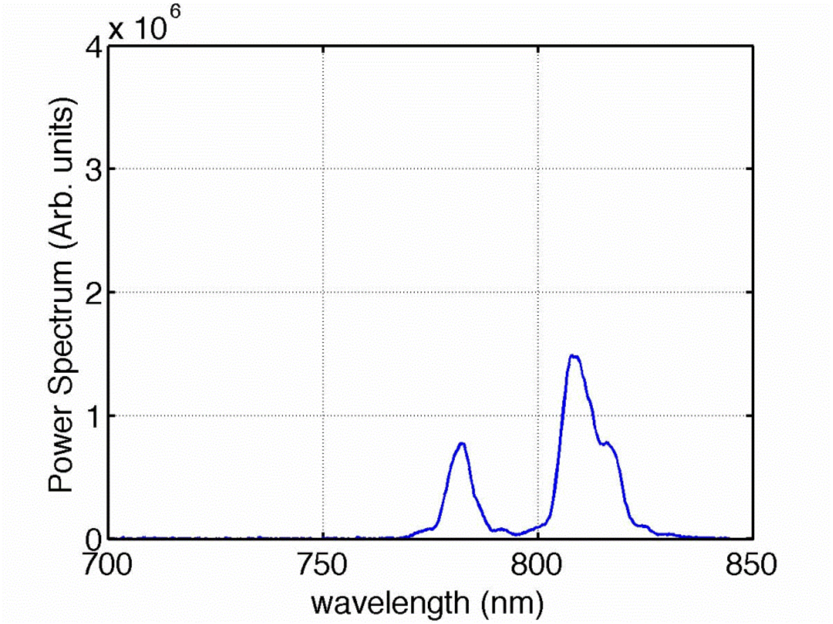


E. Chiadroni et al., Rev. Sci. Instrum. **84**, 022703 (2013)

Electron Beam Experimental Studies

- COMB 2 pulses
  - Injection of a two bunches train with a two-level energy distribution into the FEL undulator
    - Two-color FEL radiation

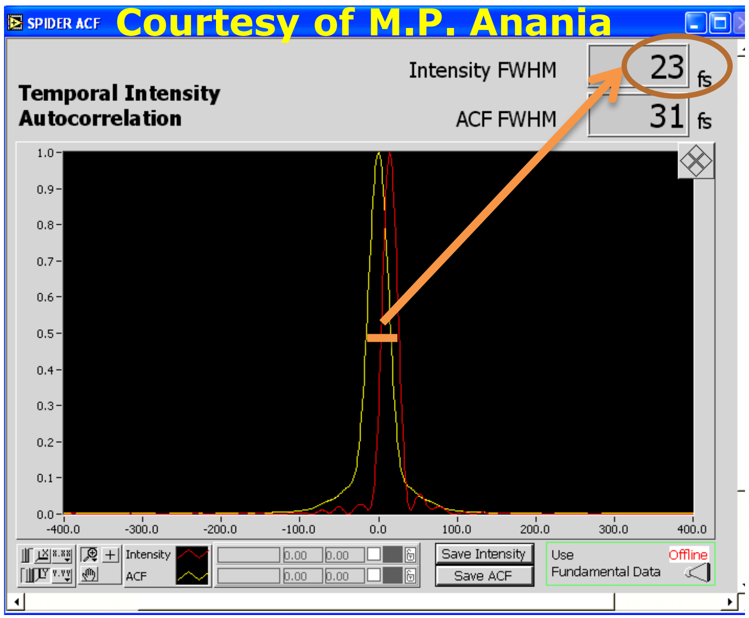


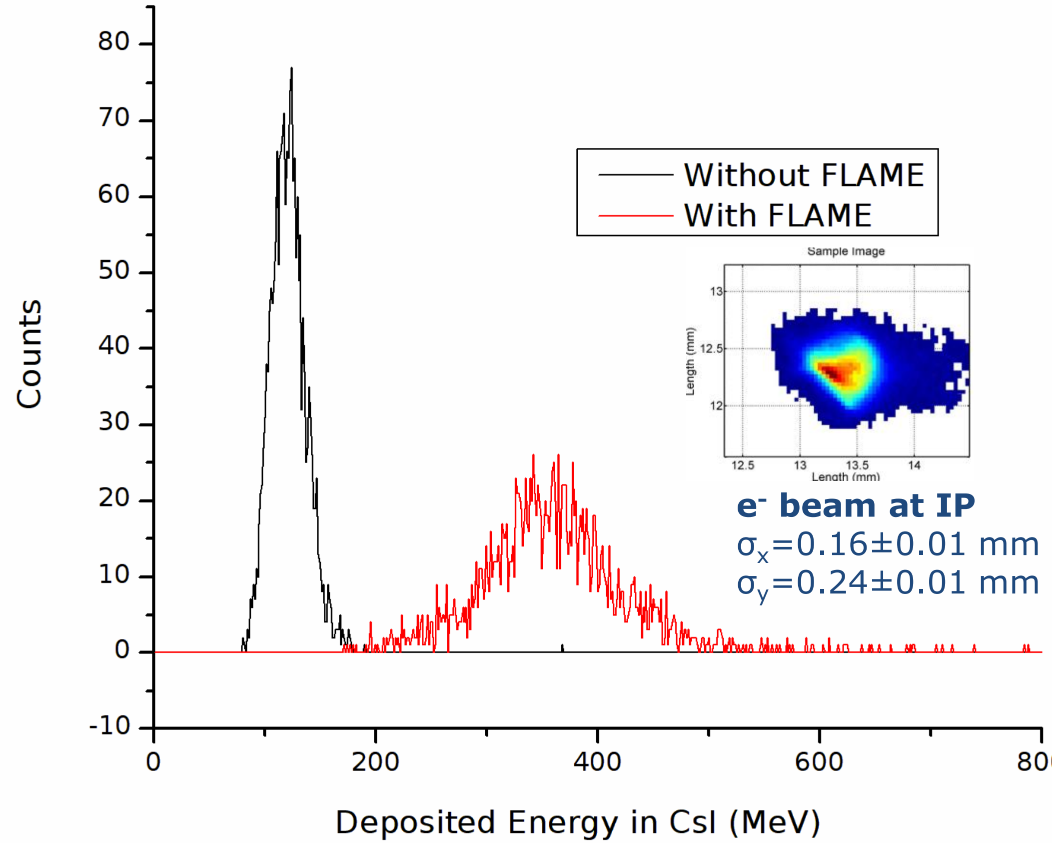


V. Petrillo et al., PRL **111**, 114802 (2013);
E. Chiadroni et al., New Jour. Phys. **16**, 033018 (2014)

Electron Beam Experimental Studies

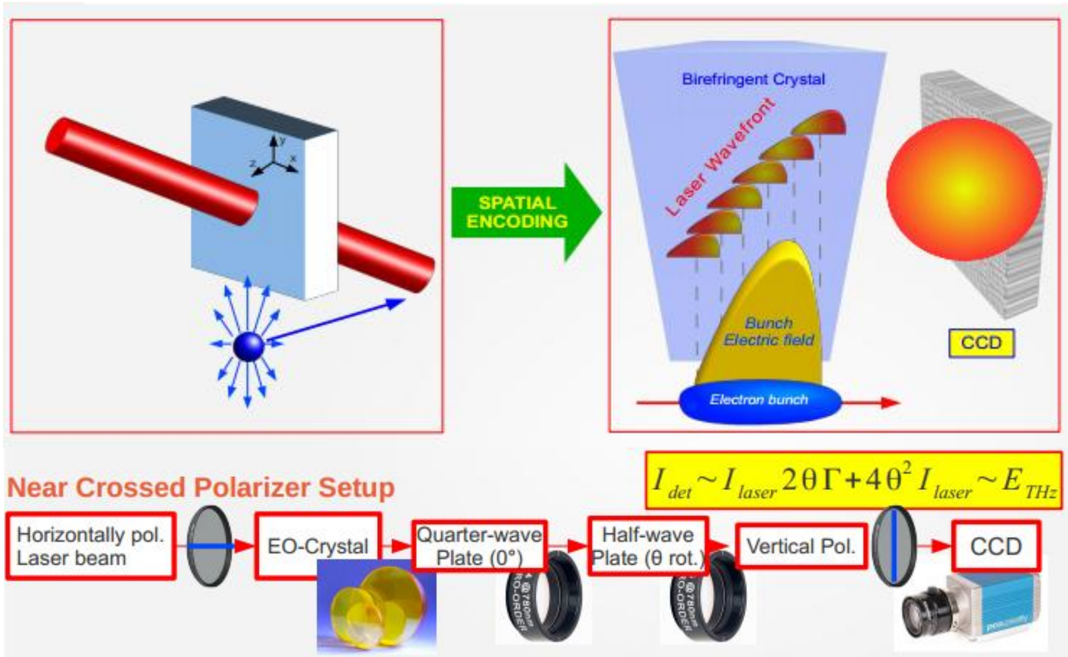
- Thomson backscattering experiments

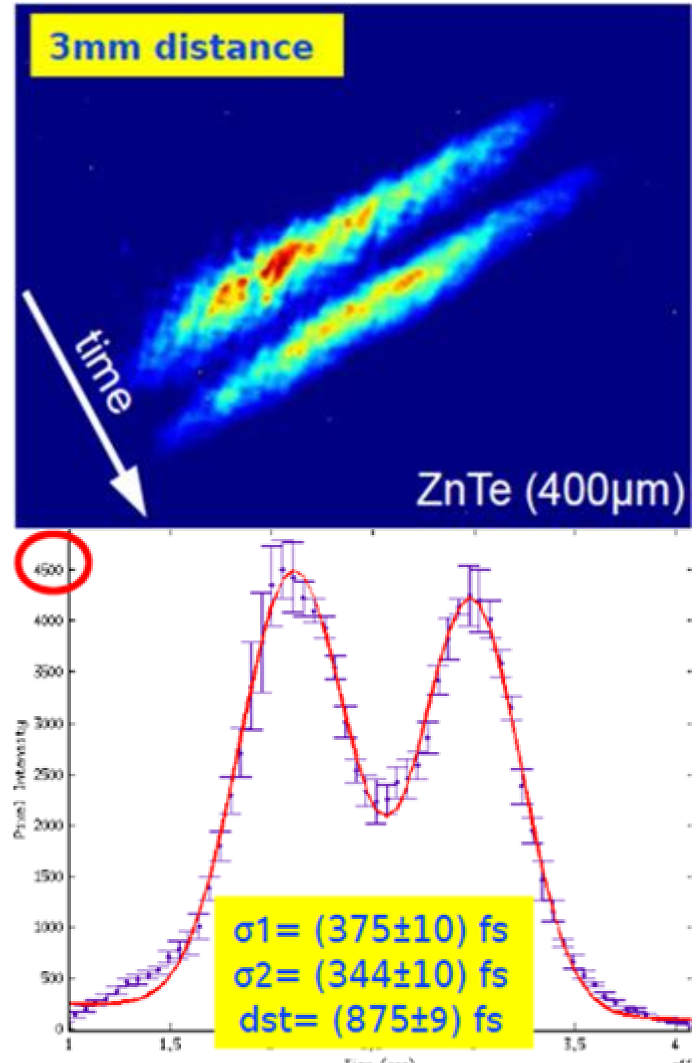




Max energy: 7J
Max energy on target: ~5J
Min bunch duration: 23 fs
Wavelength: 800 nm
Bandwidth: 60/80 nm
Spot-size @ focus: 10 μm
Max power: ~300 TW
Contrast ratio: 10^{10}

Electron Beam Diagnostics





- Laser crosses the crystal with an incident angle of 30deg
  - one side of the laser pulse arrives earlier on the EO crystal than the other by a time difference ΔT
- Coulomb field inducing birefringence is encoded in spatial profile of laser pulse

R. Pompili et al., NIM A **740**, 216–221 (2014)

Conclusions

- SPARC_LAB hosts several beam lines and experiments
- Advanced beam dynamics manipulation is the basis for the production of high brightness single and multi-bunch train
  - The possibility to control time and energy separation of *comb* beam has been demonstrated at SPARC_LAB
  - *Comb* beams have been already used for the production of two-color FEL radiation as well narrow band THz radiation
- Simulations for both external injection based experiments at SPARC_LAB are ongoing and yield promising results
- rPWFA and external injection LWFA experiments are the next

Acknowledgment

- This work has been partially supported by
  - the Italian Minister of Research in the framework of *FIRB - Fondo per gli Investimenti della Ricerca di Base*, ***Project n. RBFR12NK5K***
  - the EU Com236 mission in the Seventh Framework Program, **Grant Agreement 237 312453 EuCARD-2** and Contract n.283745-CRISP

Thank you all for the attention!