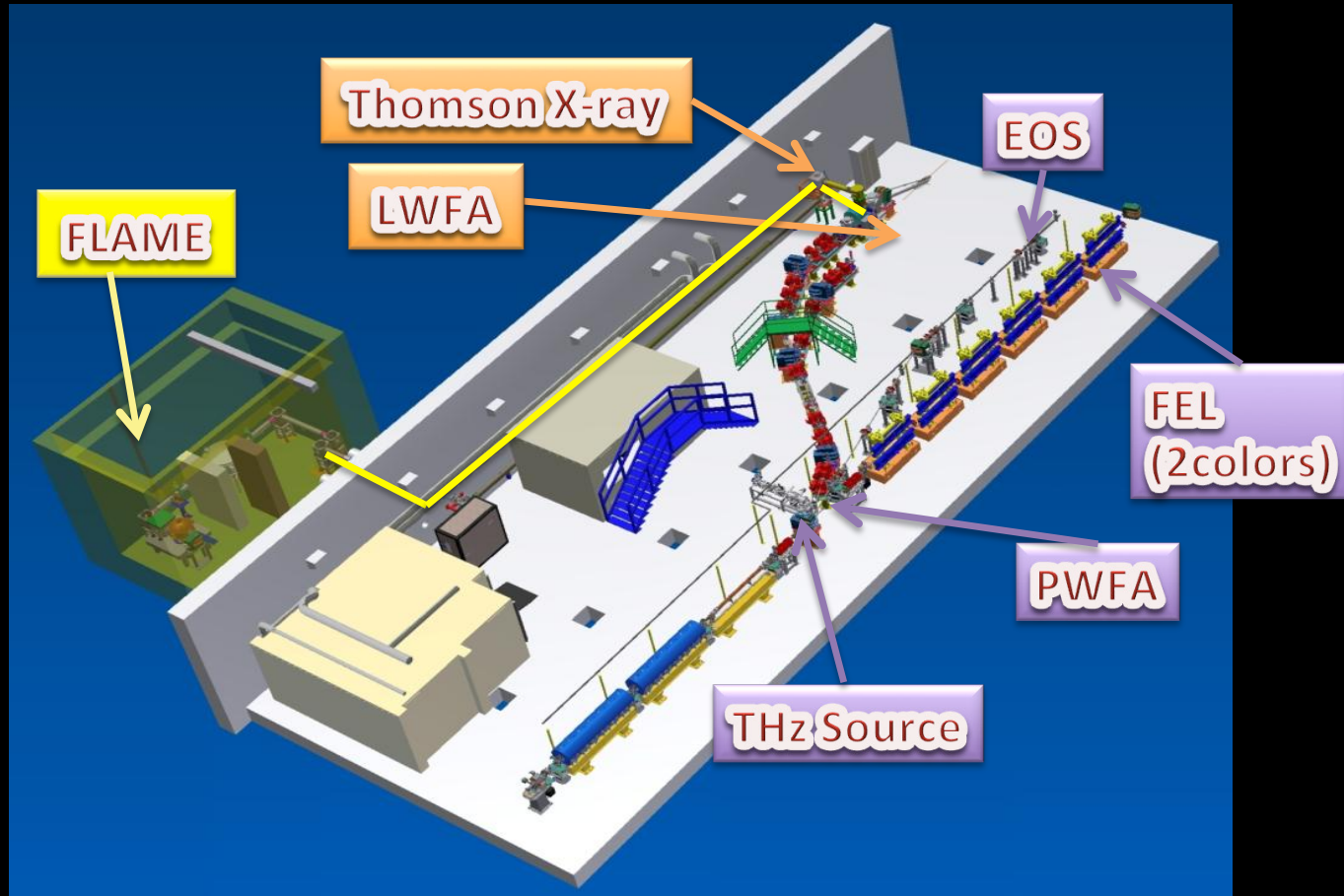


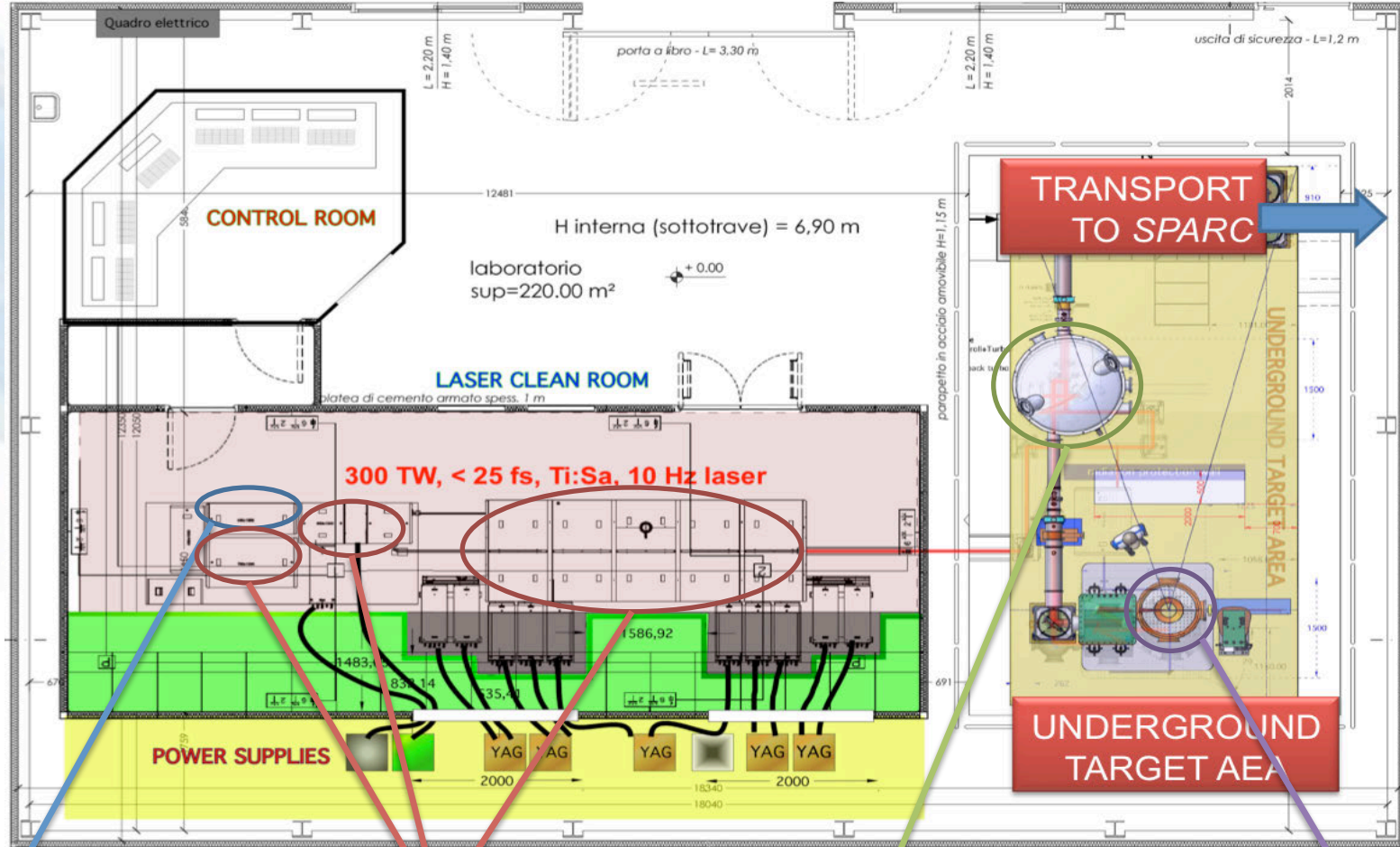
# Advanced Acceleration at SPARC\_LAB

Sources for Plasma Accelerators and Radiation Compton with Lasers And Beams

Massimo.Ferrario@LNF.INFN.IT



# Ti:Sa FLAME laser



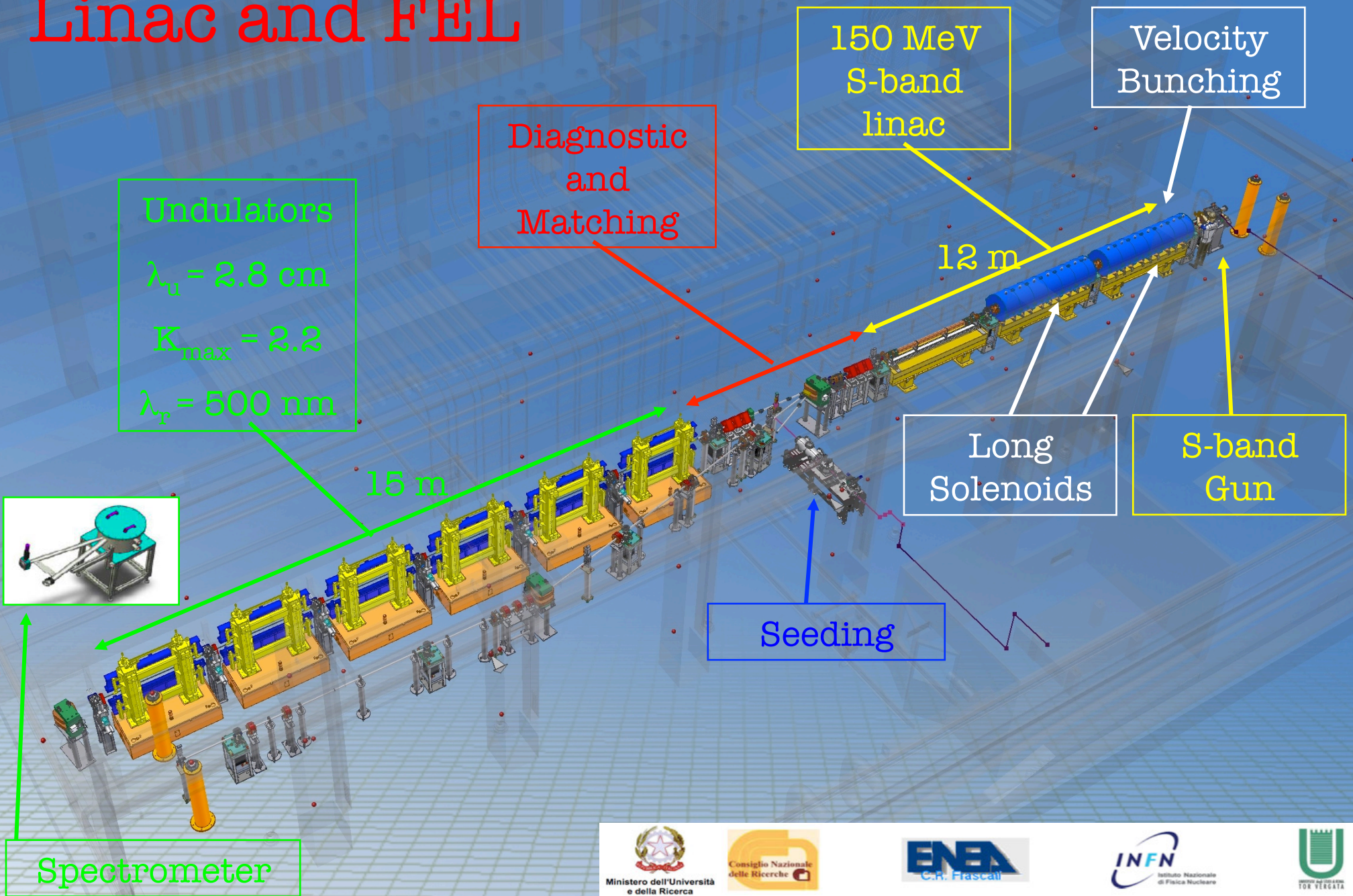
Stretcher

Amplifiers

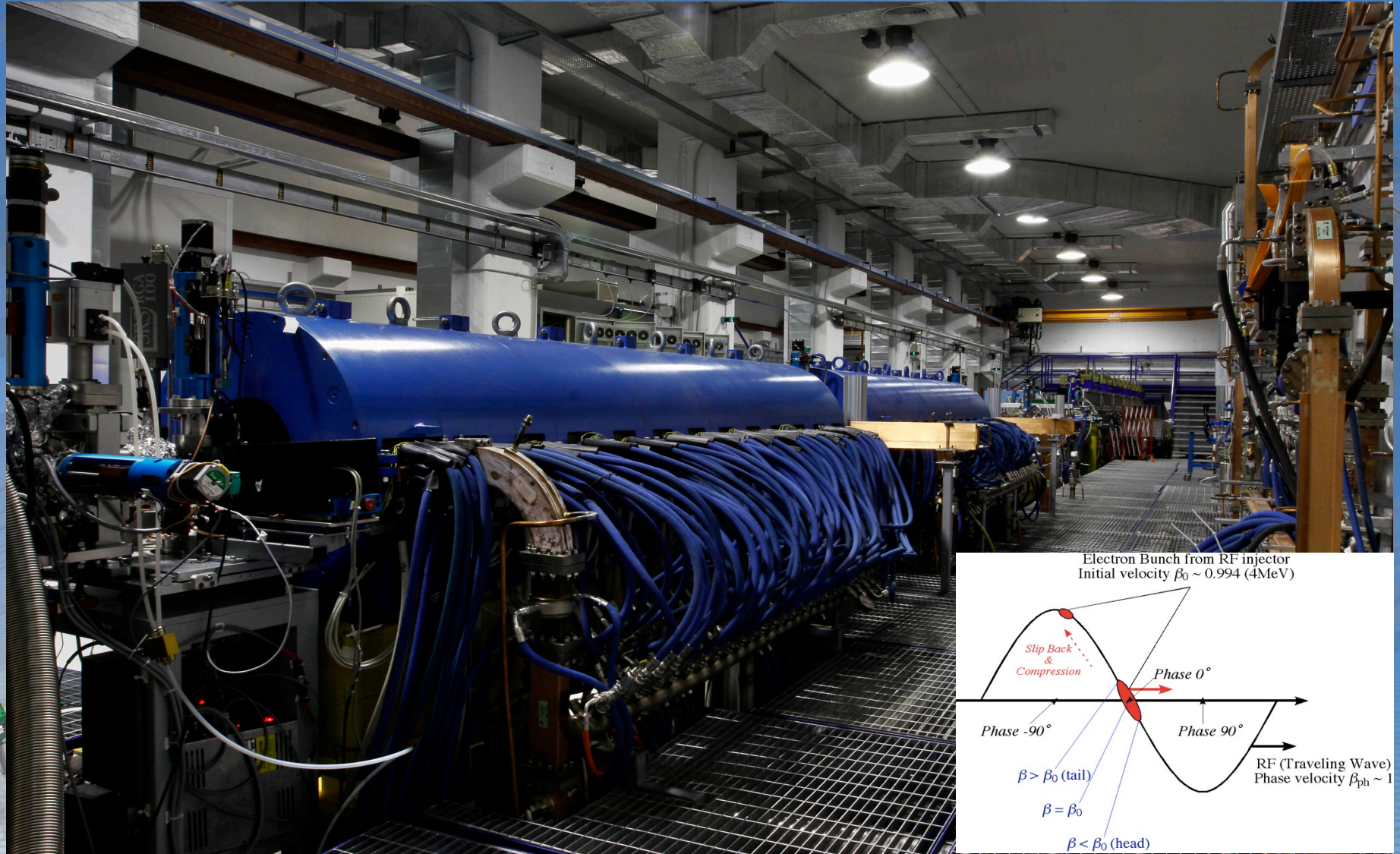
Compressor

LWFA  
Electron Self Injection  
And  
Protons

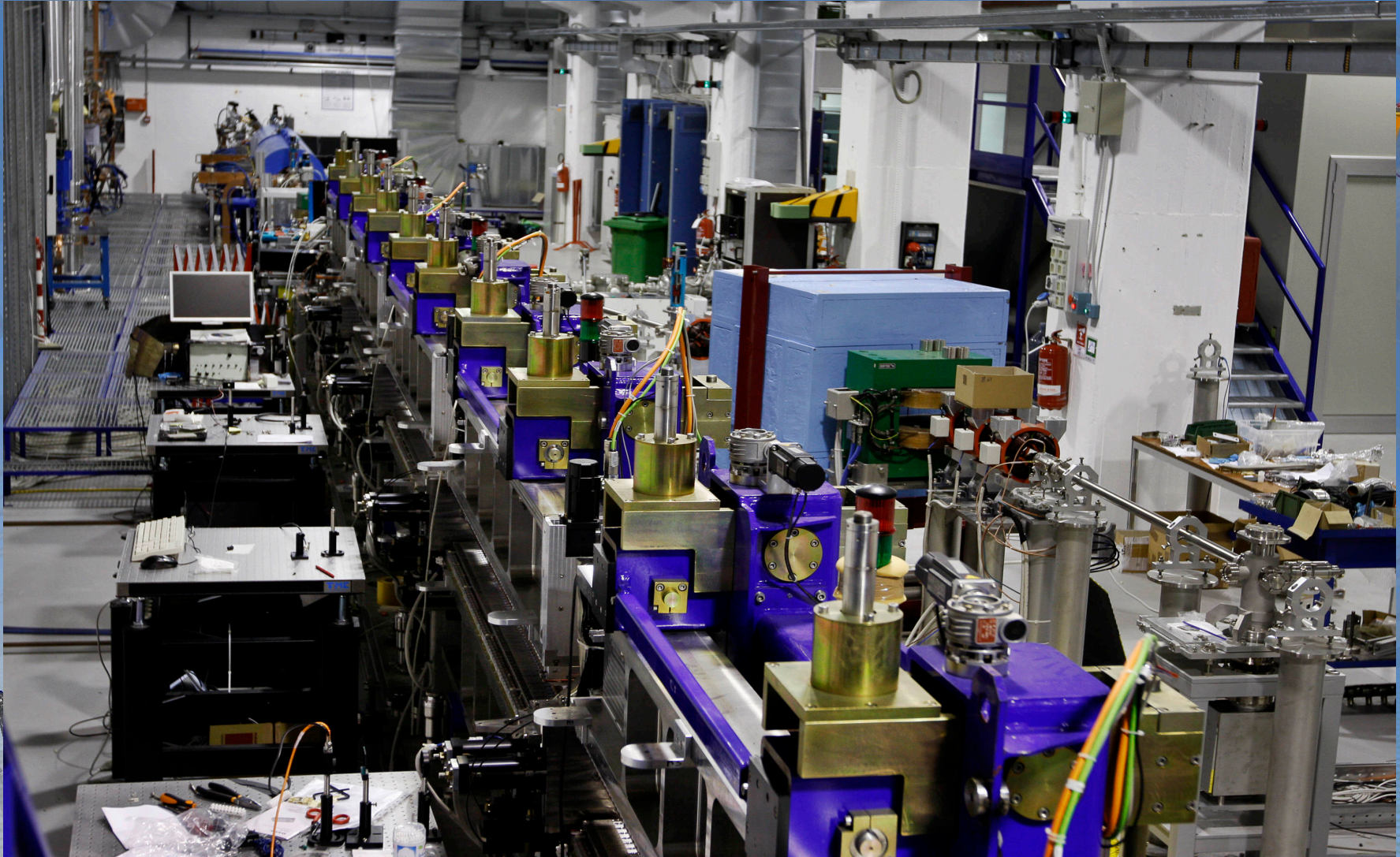
# Linac and FEL



# HB photo-injector with Velocity Bunching



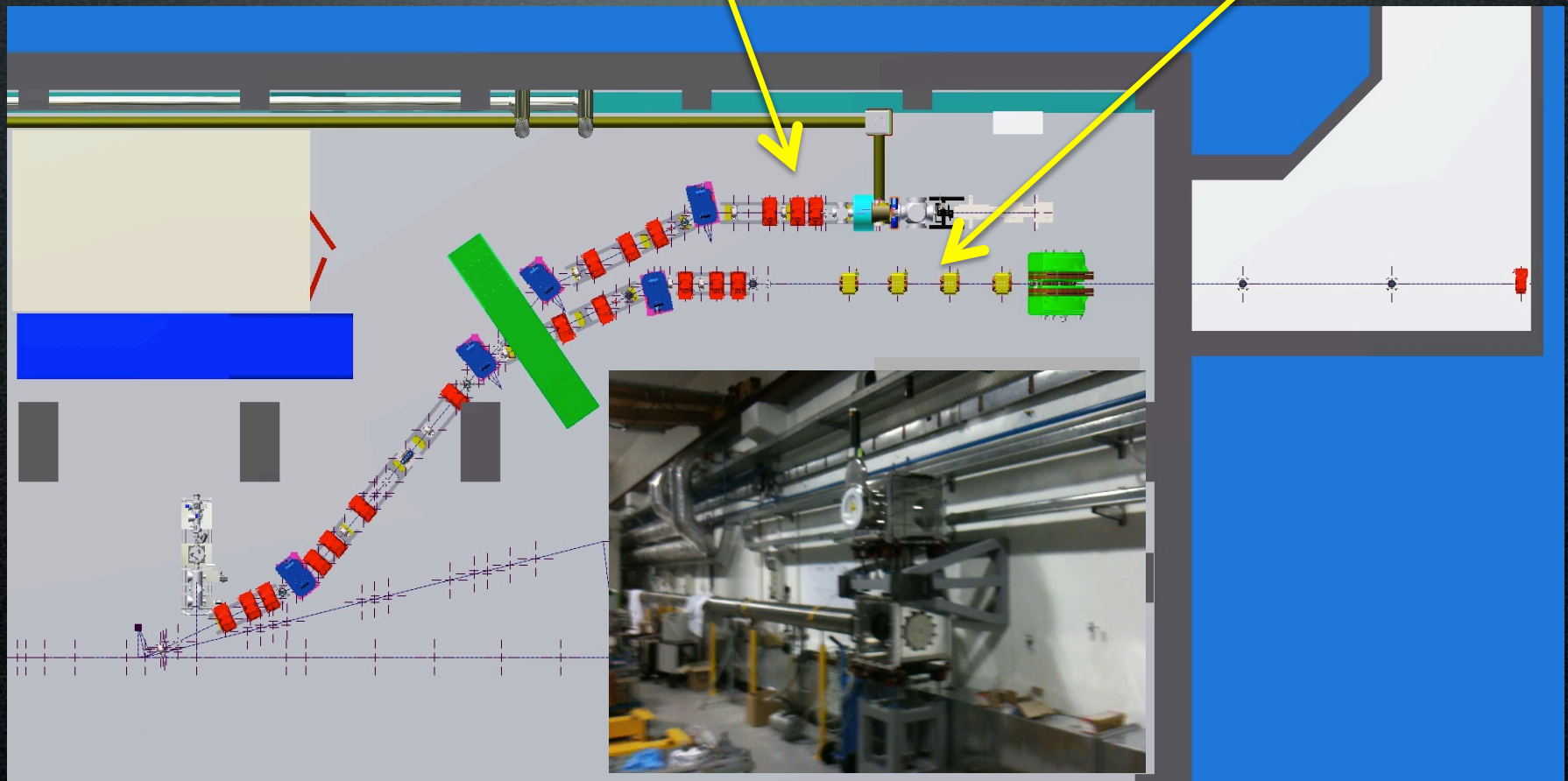
# Undulator chain



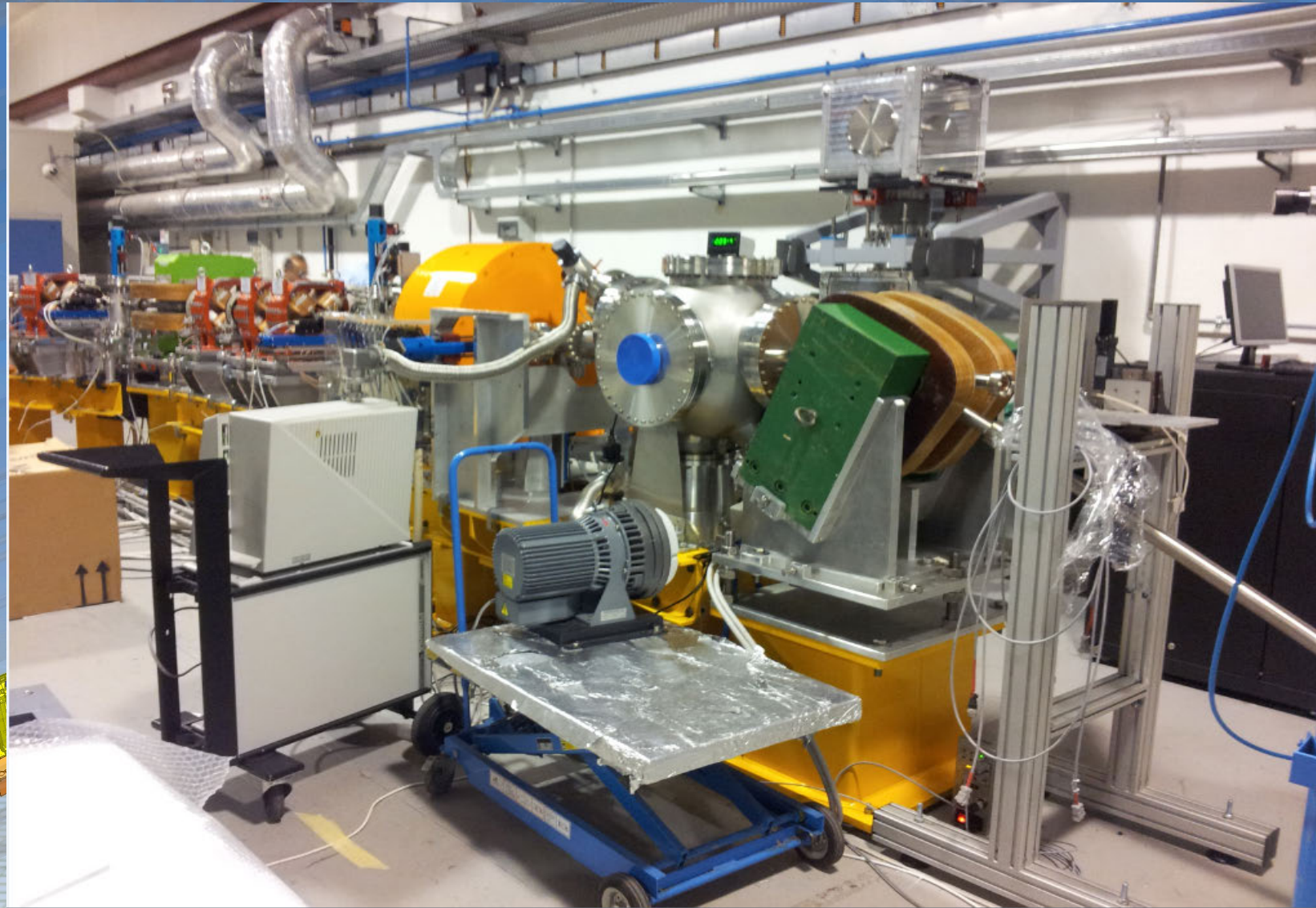
# New installations

Thomson source

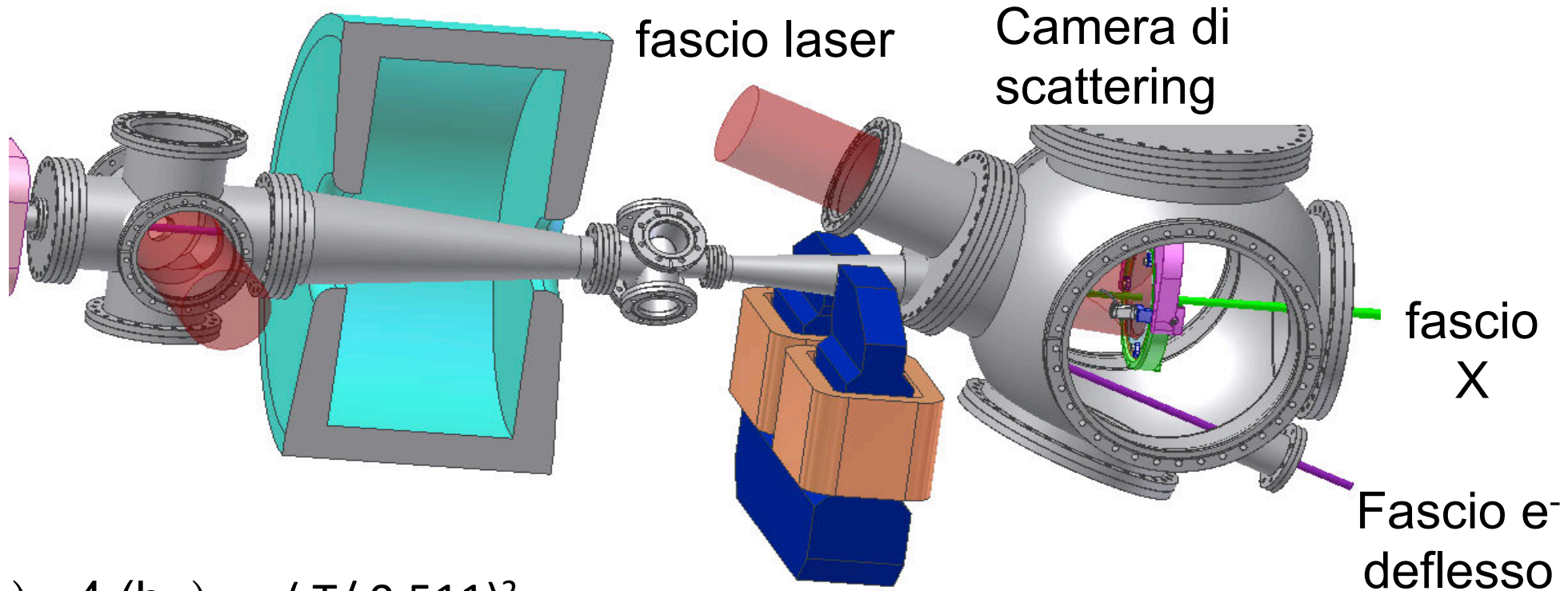
Plasma acceleration



# Thomson back-scattering source



# Thomson Interaction region (20-550 keV)



$$(h\nu)_X = 4 (h\nu)_{\text{laser}} (T/0.511)^2$$

$$(h\nu)_{\text{laser}} = 1.2 \text{ eV}$$

$$T = 30.28 \text{ MeV}$$

$$(h\nu)_X = \mathbf{20 \text{ keV mammografia}}$$

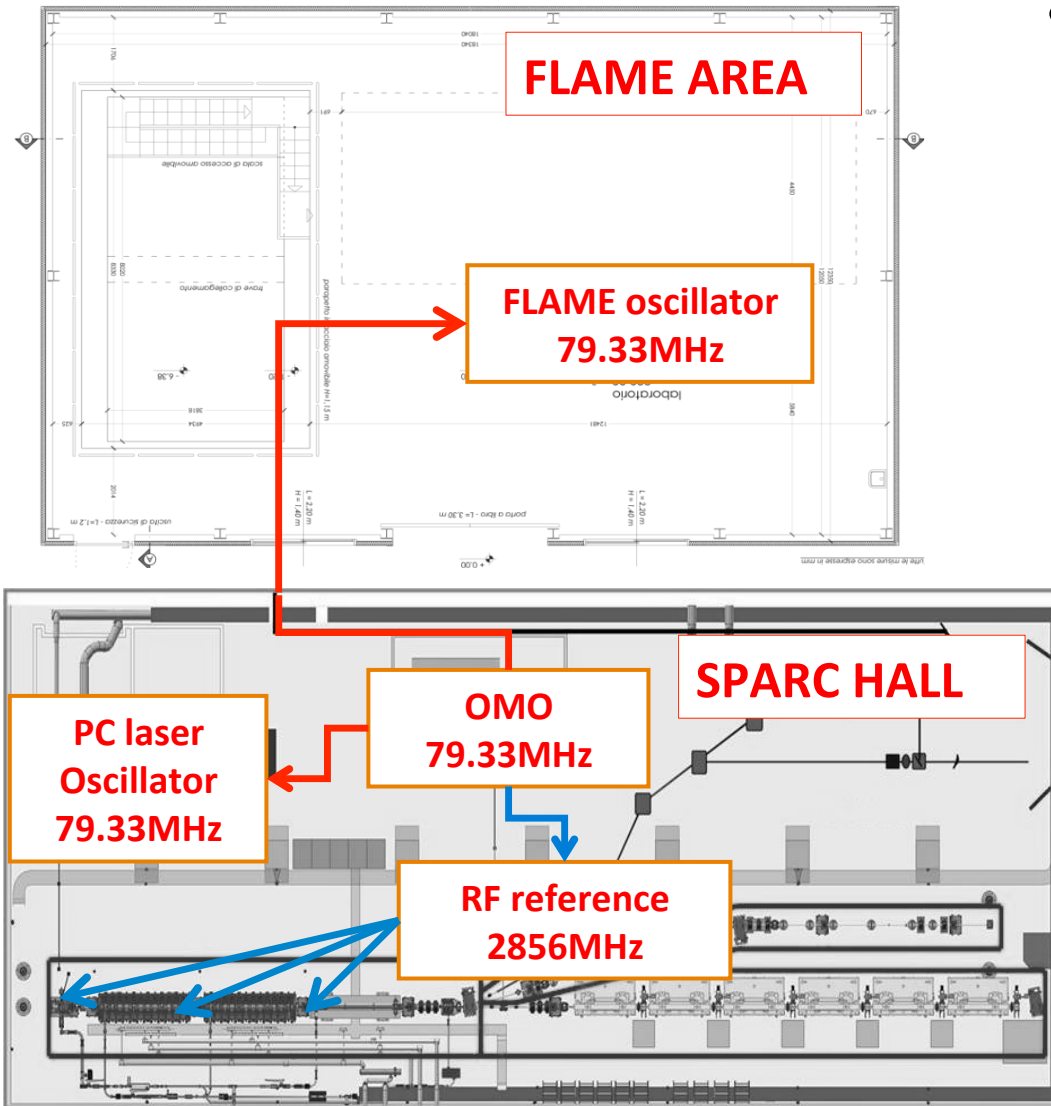
Impulso laser: 6 ps, 5 J

pacchetto e<sup>-</sup> : 1 nC , l: 2 mm (rms)

Impulso X: 10 ps, 10<sup>9</sup> fotoni

α emissione: 12 mrad

# SPARC-FLAME synchronization



- Optical reference distribution
  - Fiber laser OMO (Optical Master Oscillator) installed and tested
  - Fiber links to distribute the signal partially installed
  - High resolution optical phase monitor (cross-correlators) in house and ready to be tested
- **Sub-50fs<sub>RMS</sub> relative jitter synchronization**



# Laser Comb technique: generation of a train of short bunches

(Parmela code)

Charge vs. Time

Energy vs. Time

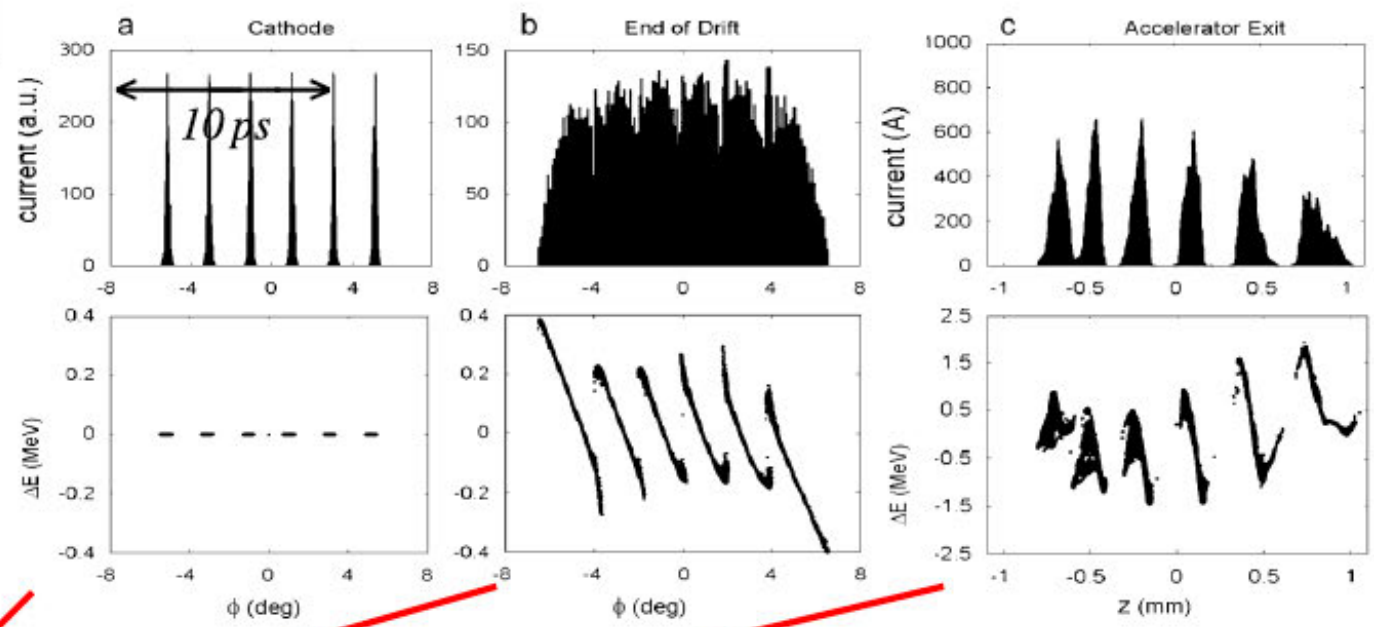
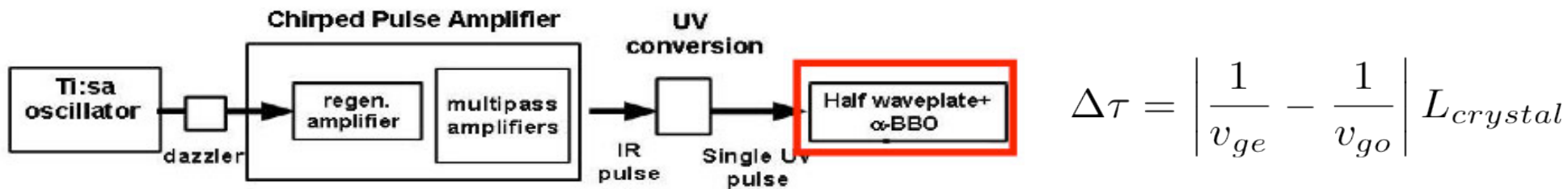


Fig. 1. Evolution of a six bunches electron beam train: the columns from left refer, respectively, to (a) the cathode, (b) the end of the drift at 150 cm and (c) the end of linac at 12 m far from cathode. The rows from top refer, respectively, to longitudinal profile and to energy modulation  $\Delta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



- 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

# Laser Pulse Train Generation



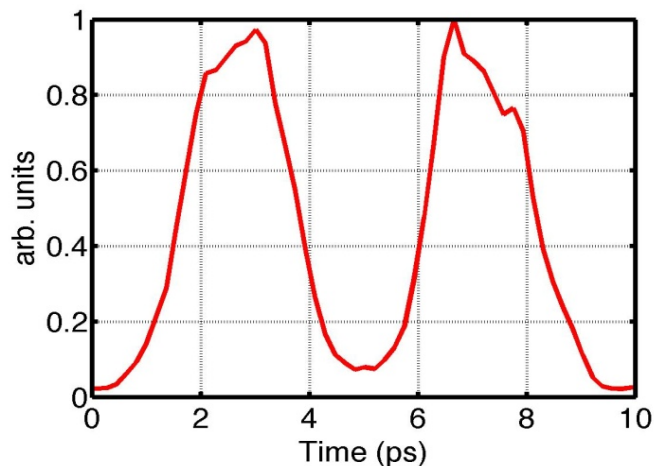
LASER



Crystal  
4 ps

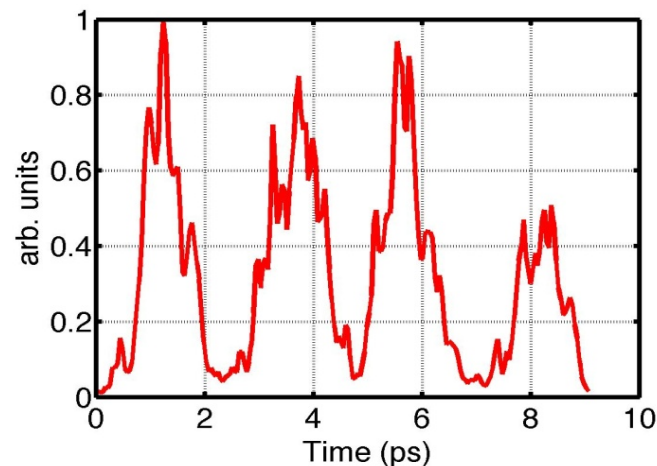
Crystal  
2 ps

UV pulses



Streak camera

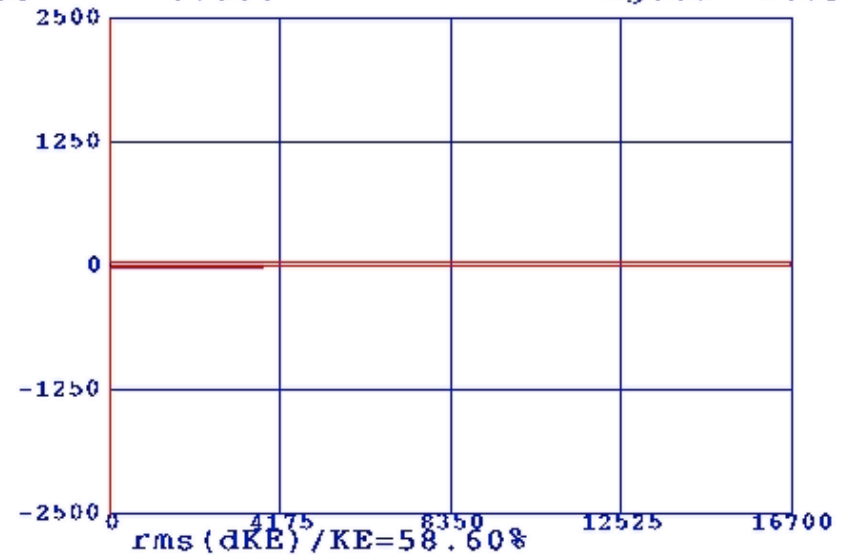
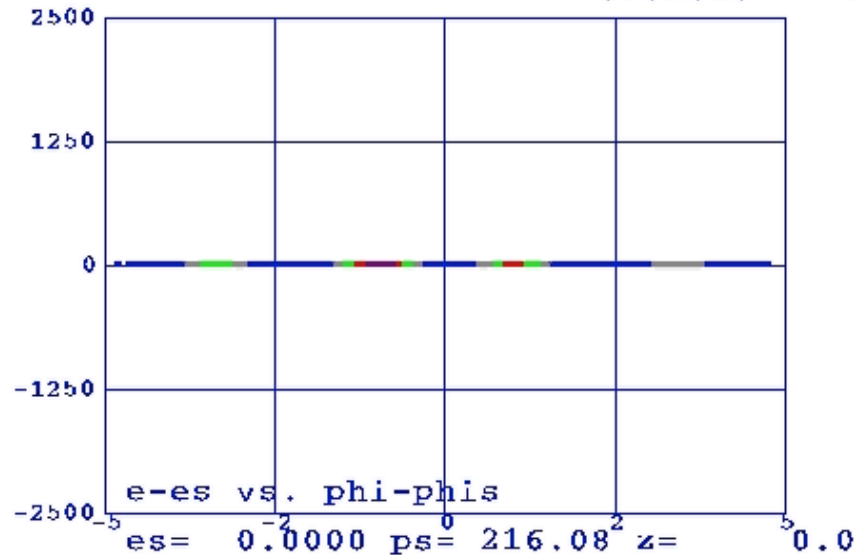
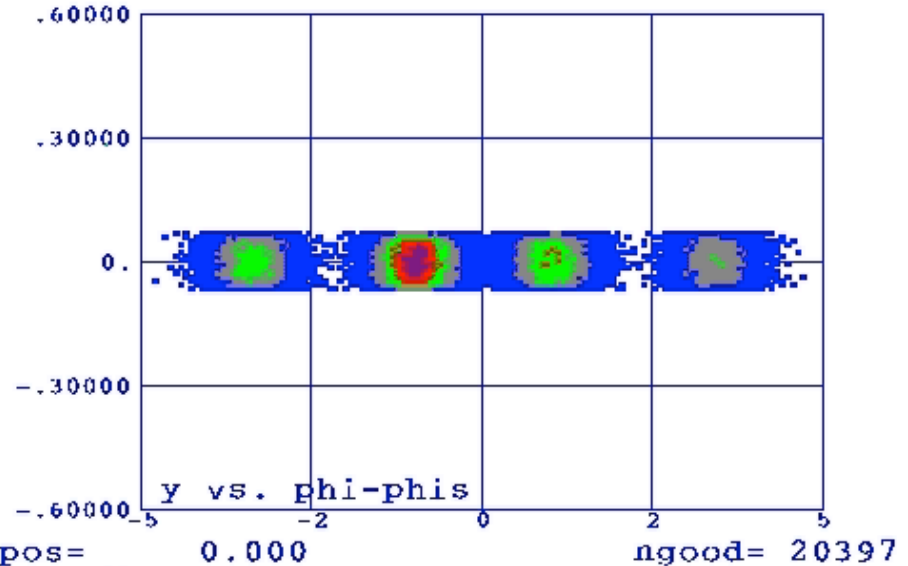
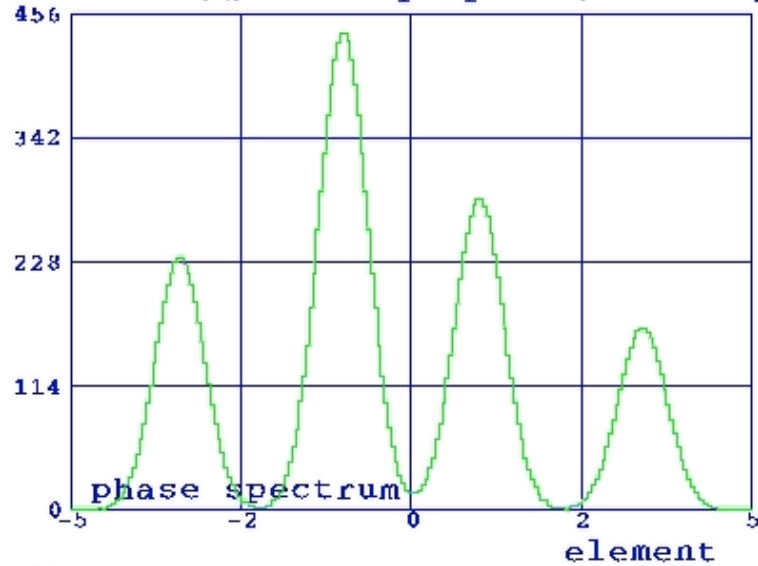
UV pulses



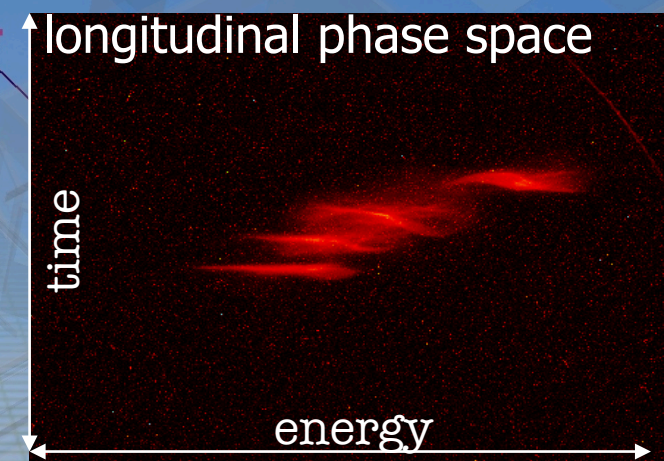
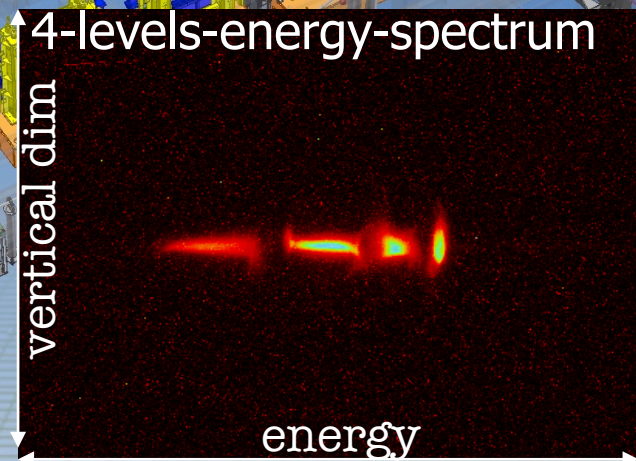
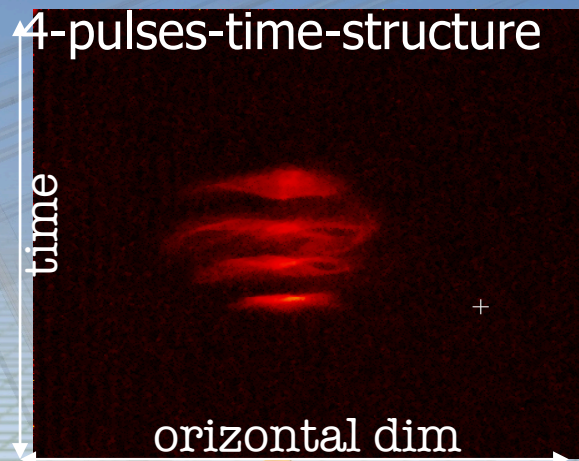
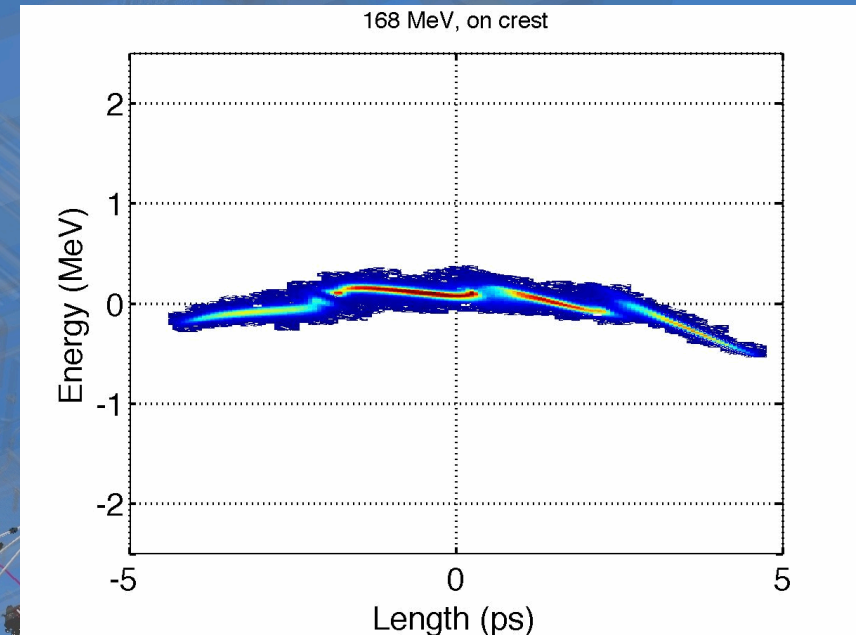
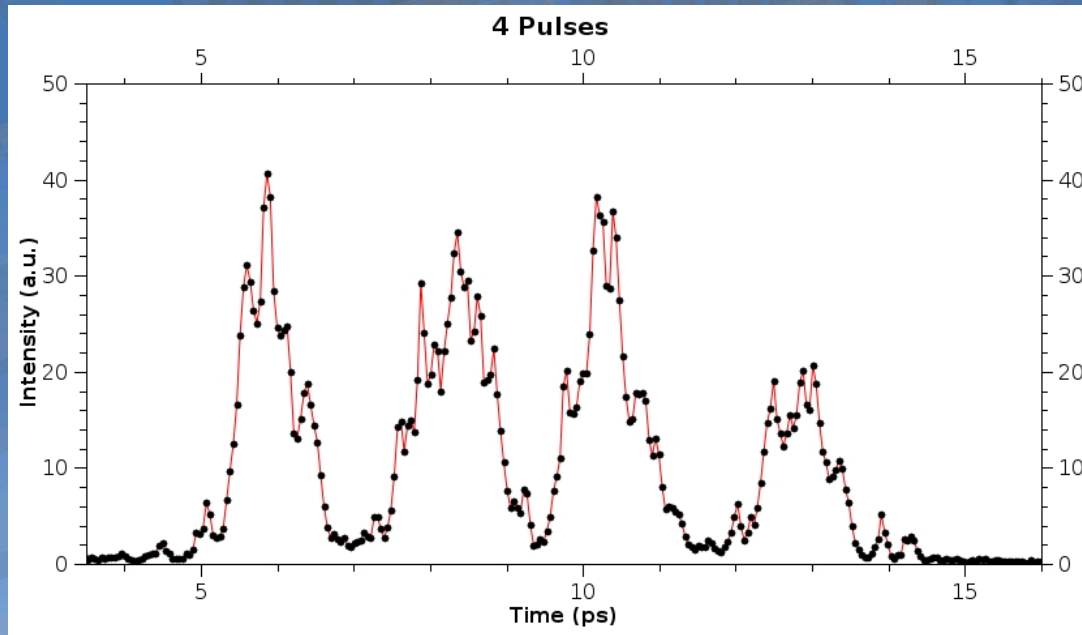
Streak camera

# Overcompression

SPARC COMB,  $Q_{tot}=220\text{pC/pulse}$ ,  $d=4.27\text{ psec}$



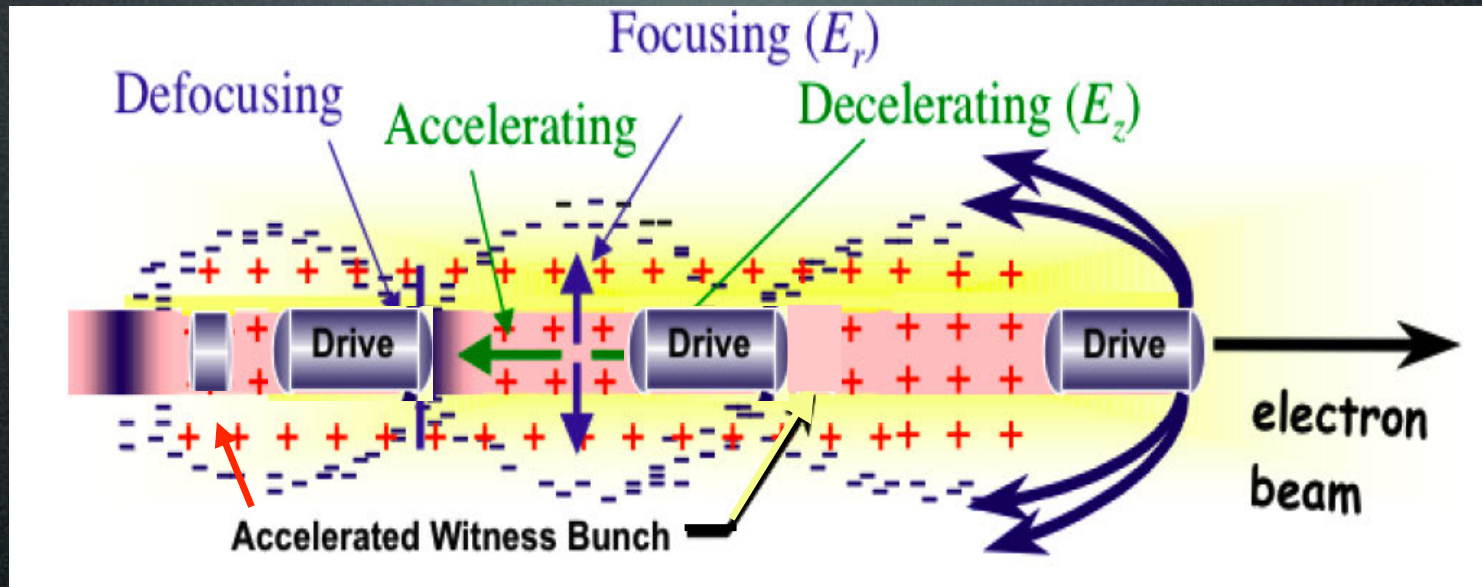
# Laser COMB: experimental results



- M. Ferrario et al., Nucl. Inst. and Meth, A 637 (2011)
- A. Mostacci et al., Proc. of IPAC 2011, Spain



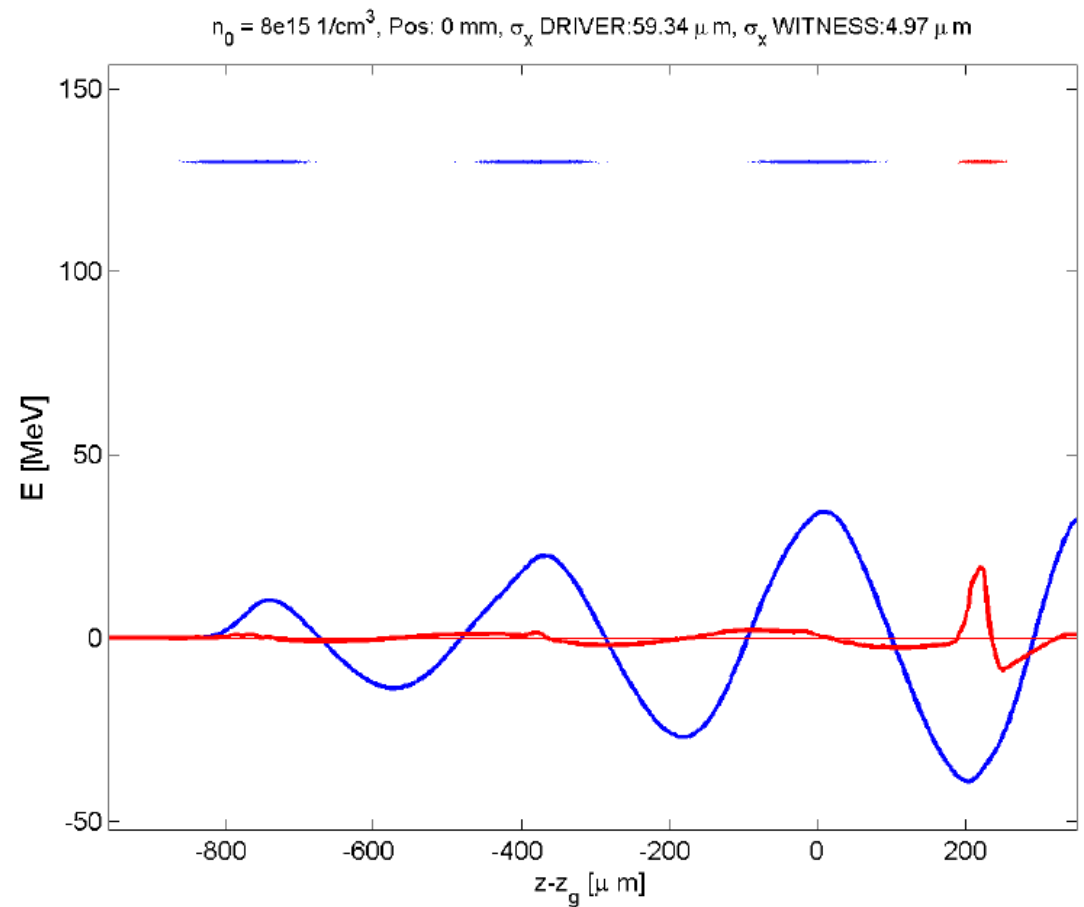
# Resonant plasma excitation by a Train of Bunches



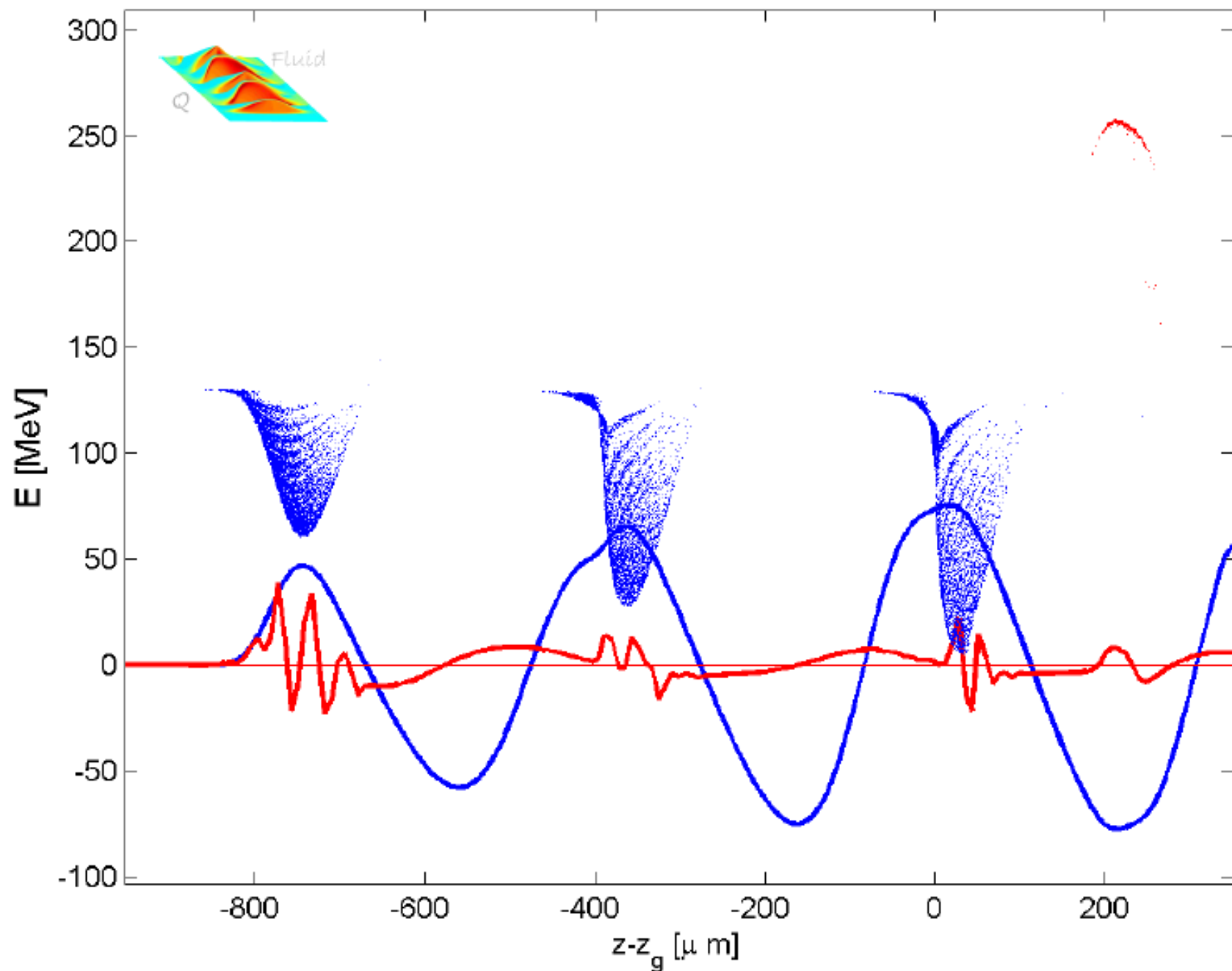
- **Weak blowout regime** with resonant amplification of plasma wave by a train of high Brightness electron bunches produced by **Laser Comb** technique?
- **Ramped bunch train configuration** to enhance transformer ratio?
- **High quality bunch** preservation during acceleration and transport?


$n_0=0.75e16 \text{ 1/cm}^3$   $\lambda_p=383 \text{ }\mu\text{m}$ ,  
 $L_{acc}=10\text{cm}$   $E_z=1.2\text{GV/m}$

	DRIVER (each, pC)	WITNESS
Charge (pC, each)	200	20
$\sigma_x$ ( $\mu\text{m}$ )	<b>60</b>	<b>5</b>
$\sigma_z$ ( $\mu\text{m}$ )	25	10



$\eta_0 = 8e15 \text{ 1/cm}^3$ , Pos: -100 mm,  $\sigma_x$  DRIVER: 369.91  $\mu\text{m}$ ,  $\sigma_x$  WITNESS: 42.87  $\mu\text{m}$

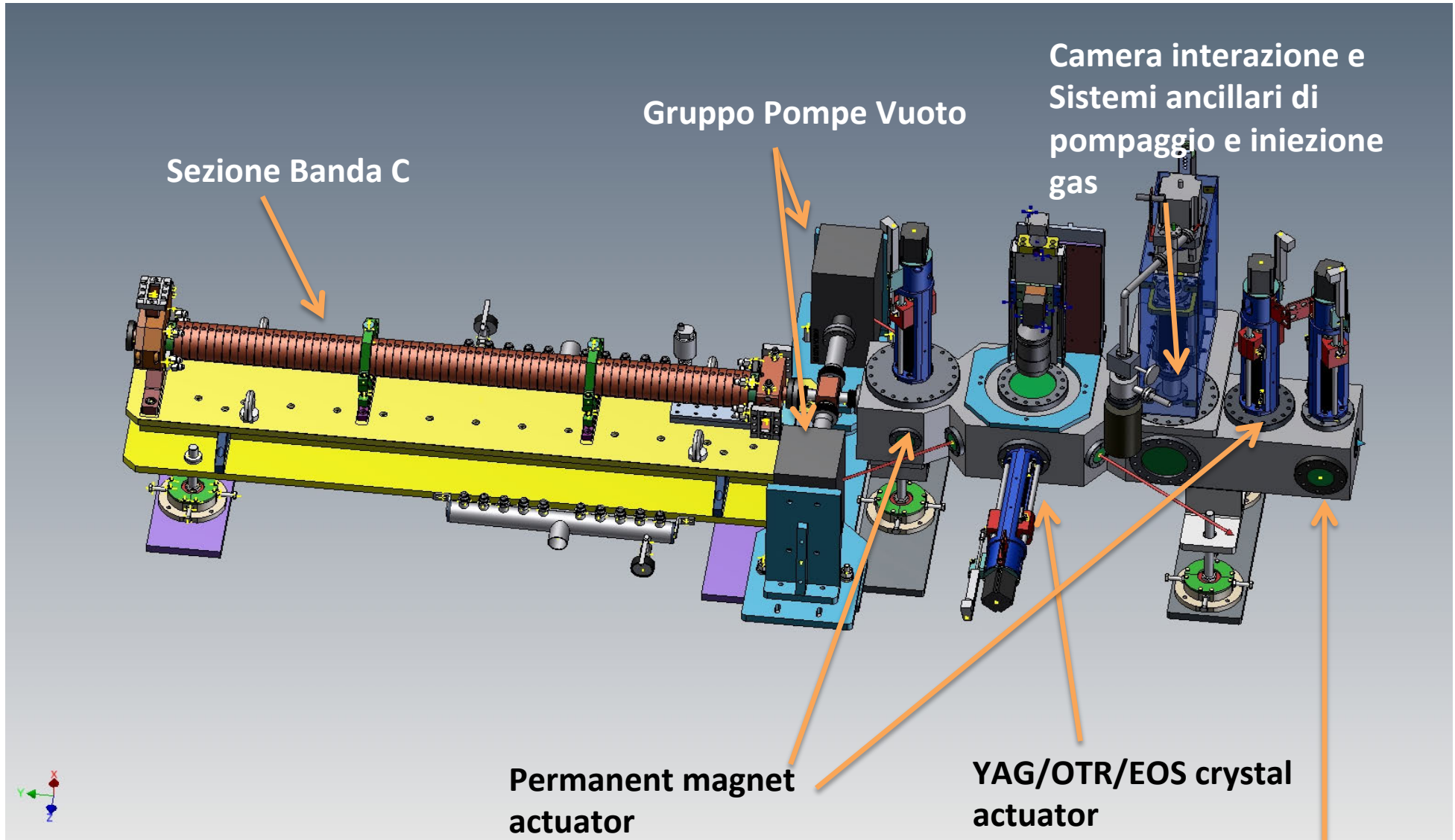


	DRIVER (each, pC)	WITNESS
energy (mean, MeV)	90	255
energy spread	35	0.9% 
norm. emittance (um)	303	1.6
sigma_x (um)	370	3.5

# A FEL driven by Plasma Accelerator at SPARC\_LAB?

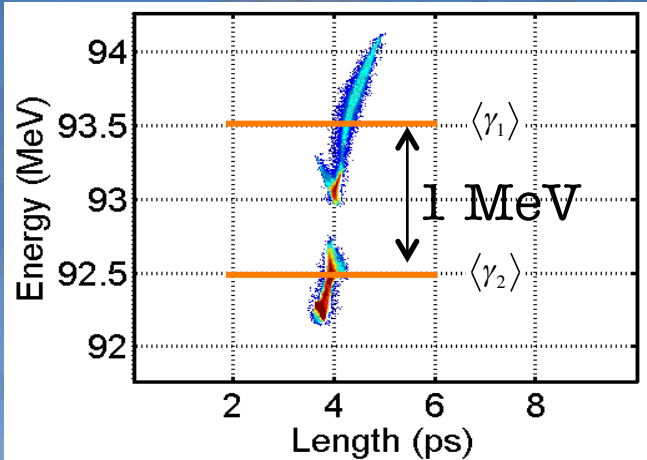


# COMB plasma interaction chamber



TWO COLORS FEL

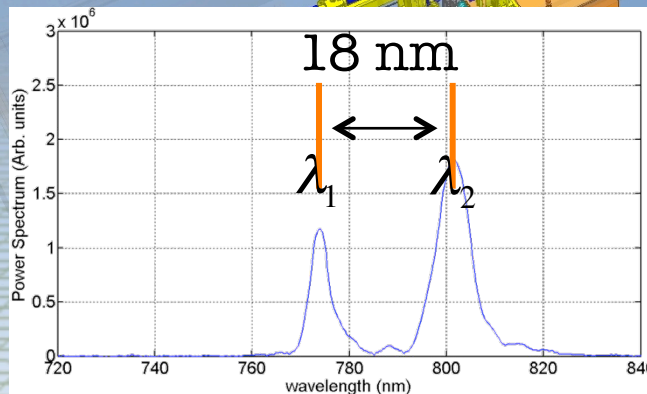
# NEW: TWO COLOURS SASE FEL



two bunches with a two-level energy distribution and time overlap (Laser COMB tech.)

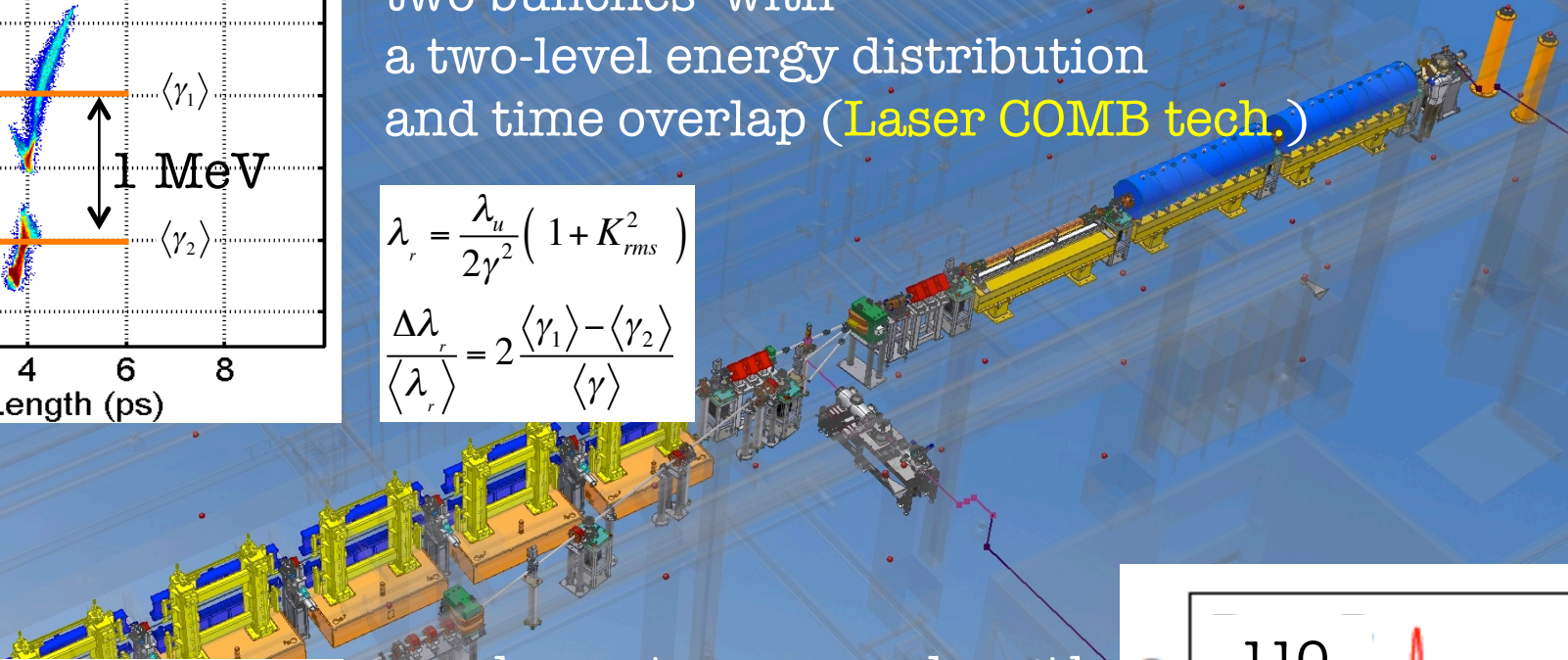
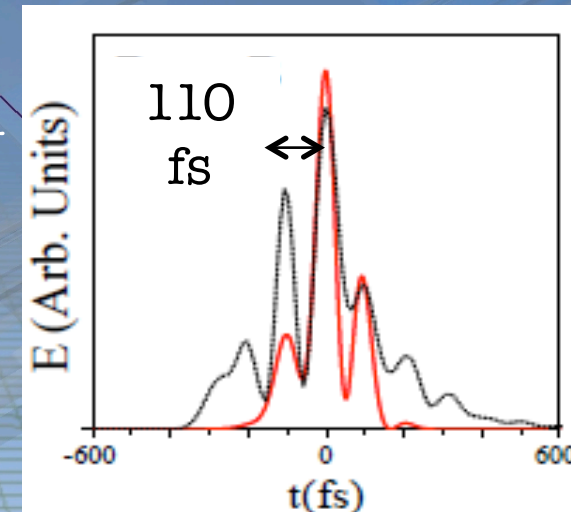
$$\lambda_r = \frac{\lambda_u}{2\gamma^2} (1 + K_{rms}^2)$$

$$\frac{\Delta\lambda_r}{\langle \lambda_r \rangle} = 2 \frac{\langle \gamma_1 \rangle - \langle \gamma_2 \rangle}{\langle \gamma \rangle}$$

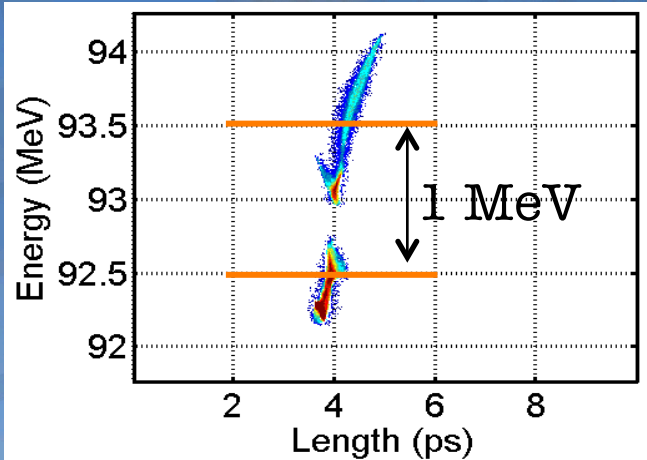


produce two wavelength SASE-FEL radiation with time modulation

$$\Delta t = \frac{\lambda_u (1 + K_{rms}^2)}{4c \langle \gamma \rangle \langle \gamma_1 \rangle - \langle \gamma_2 \rangle}$$



# Electron beam requirements



two bunches with a two-level energy distribution and time overlap (Laser COMB tech.)

- Lasing condition:

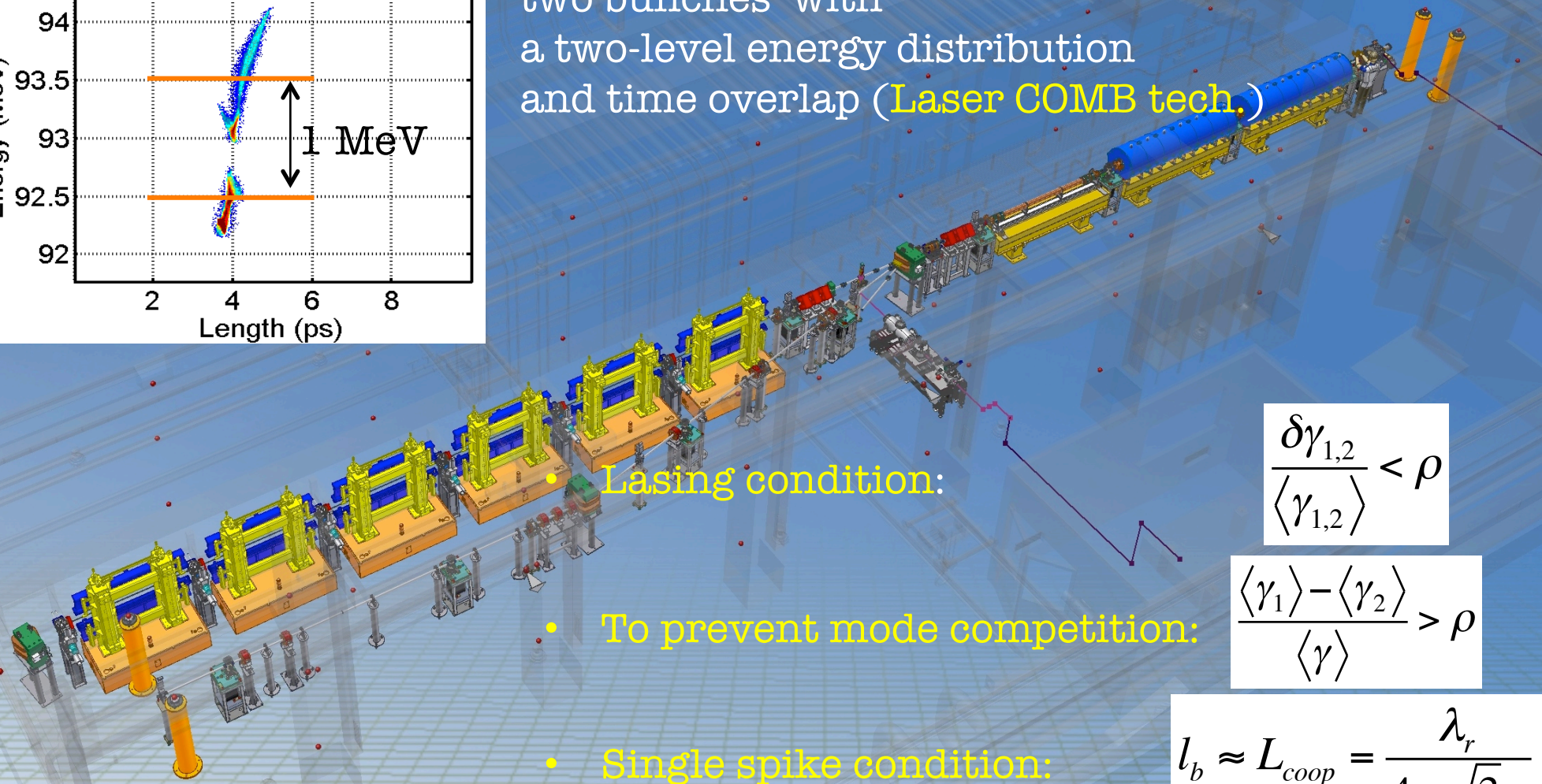
$$\frac{\delta\gamma_{1,2}}{\langle\gamma_{1,2}\rangle} < \rho$$

- To prevent mode competition:

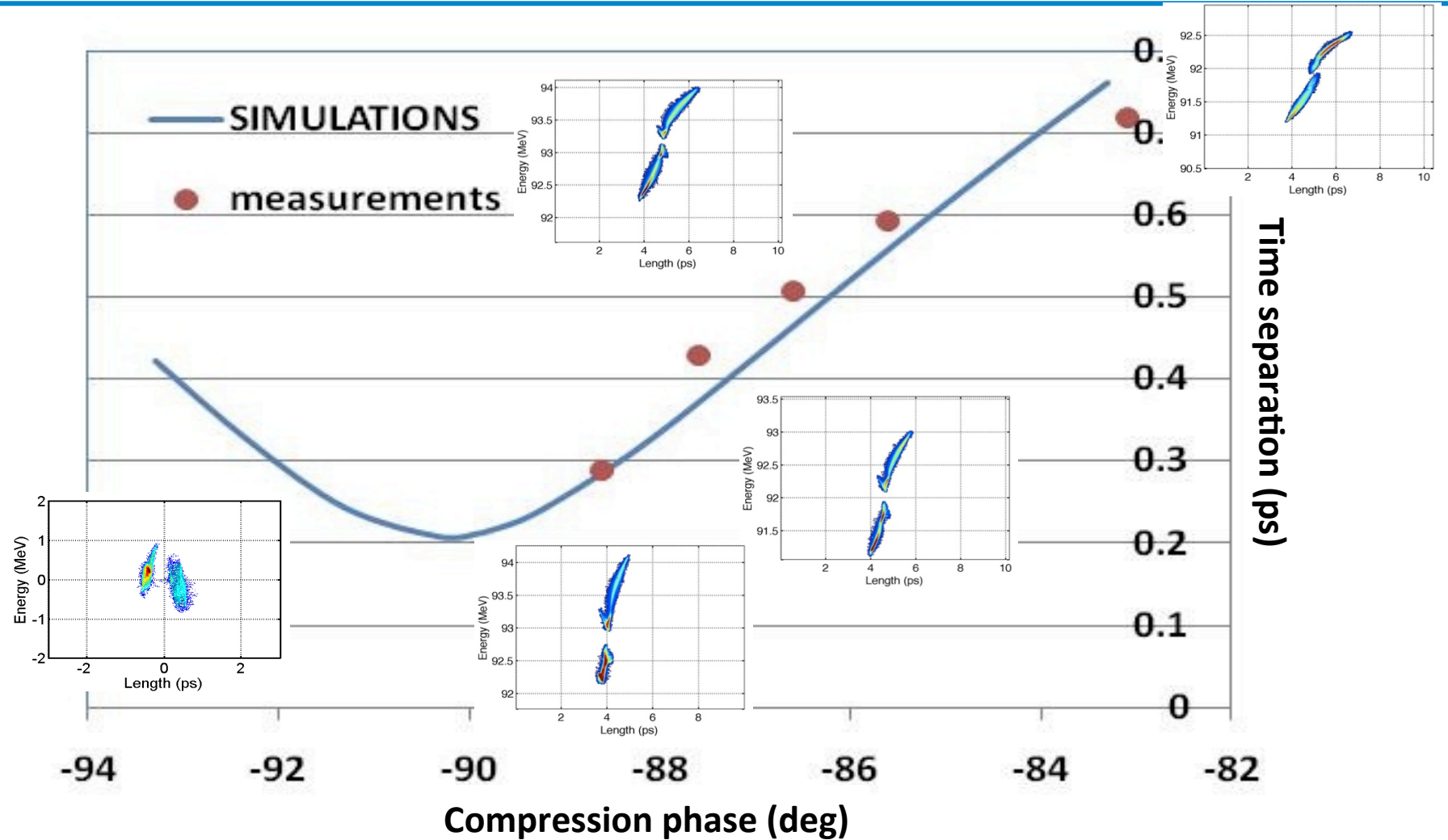
$$\frac{\langle\gamma_1\rangle - \langle\gamma_2\rangle}{\langle\gamma\rangle} > \rho$$

- Single spike condition:

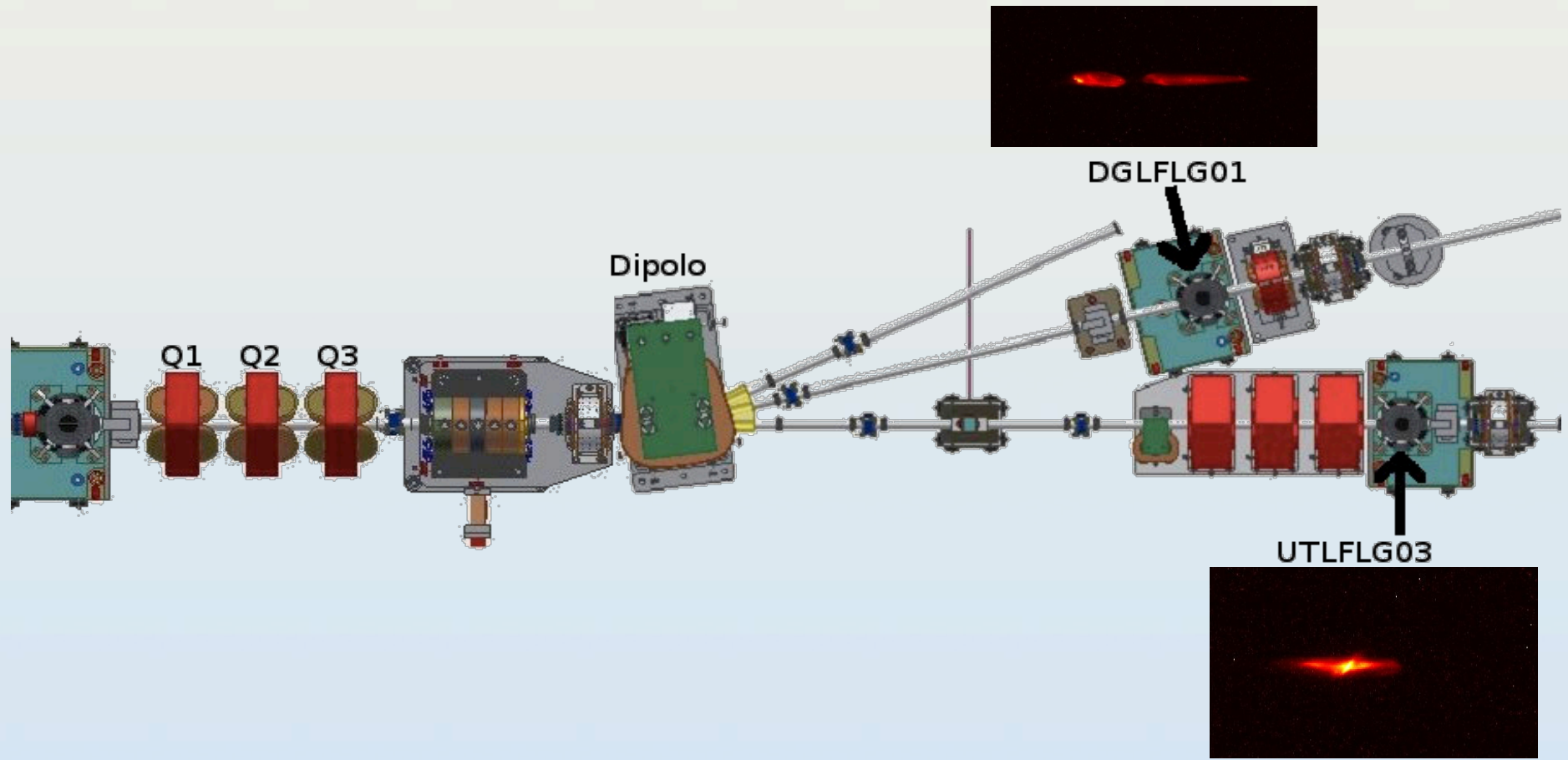
$$l_b \approx L_{coop} = \frac{\lambda_r}{4\pi\sqrt{3\rho}}$$



# Measured 2 bunches distance versus VB phase



# Measuring single beam properties



# Emittance measurements comb beams

*First bunch*

$$\varepsilon = (1.77 \pm 0.05) \text{ mm mrad}$$

$$\alpha = -2.1 \pm 0.1$$

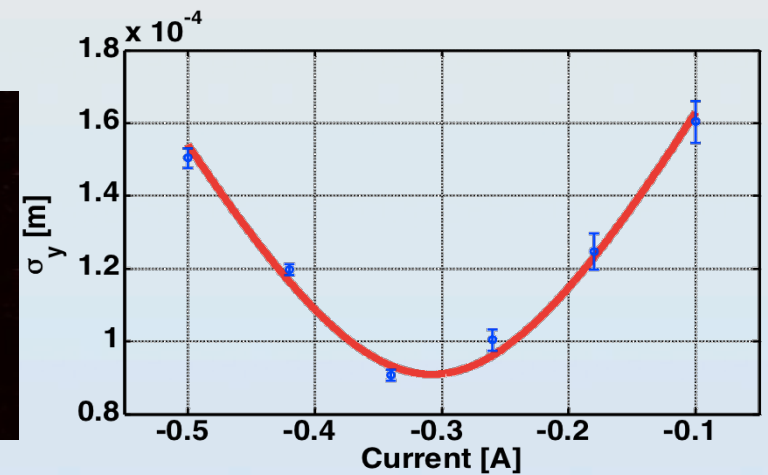
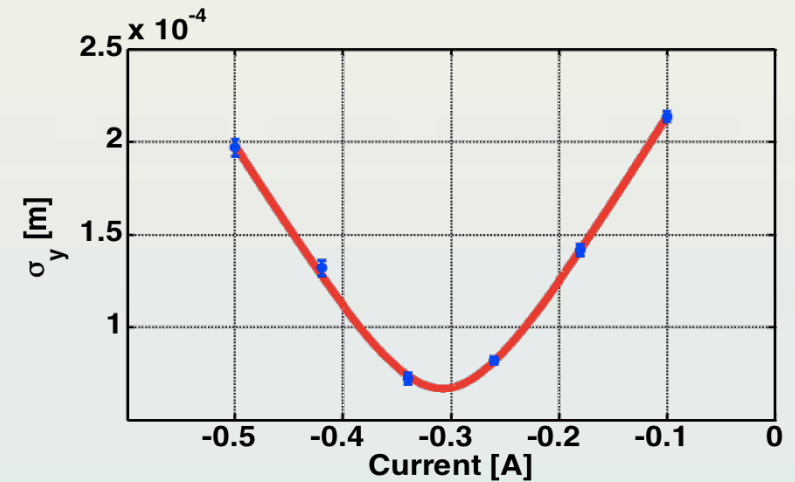
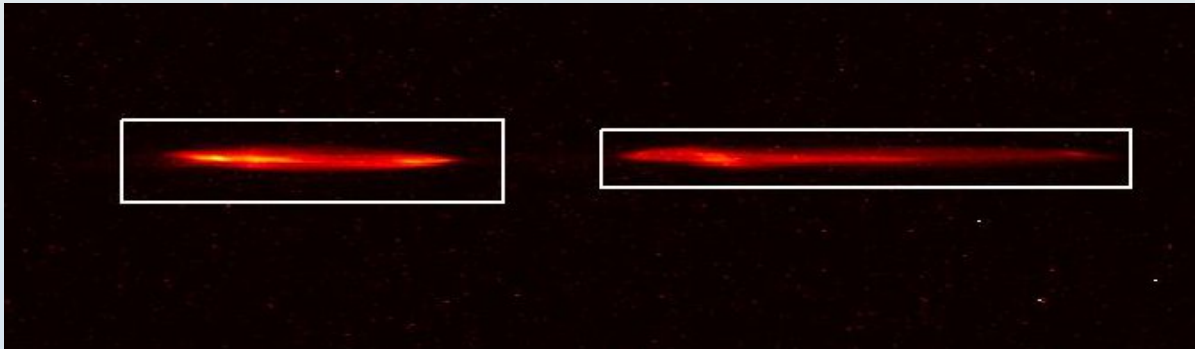
$$\beta = (27 \pm 1) \text{ m}$$

*Second bunch*

$$\varepsilon = (1.62 \pm 0.04) \text{ mm mrad}$$

$$\alpha = -0.94 \pm 0.05$$

$$\beta = (13.4 \pm 0.5) \text{ m}$$



L. Innocenti

# Achieved Electron Beam Performances

## Whole beam

- Peak current: 300 A (with 160 pC)
- Bunch duration: 300 fs
- Normalized emittance: 1.7 (0.1) mm mrad
- Energy spread: 0.6%
- Energy: 93.04 (0.03) MeV

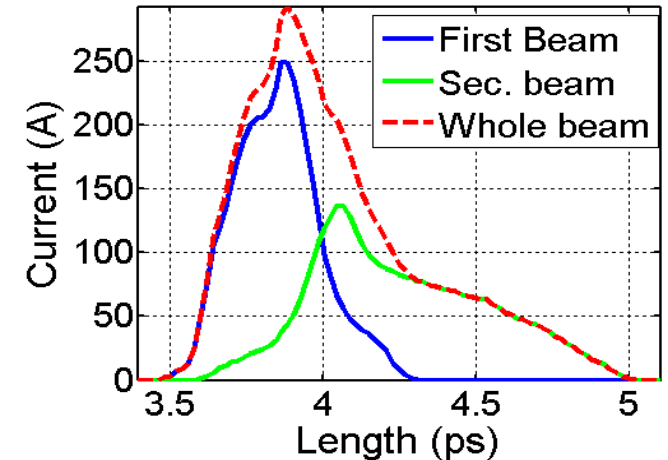
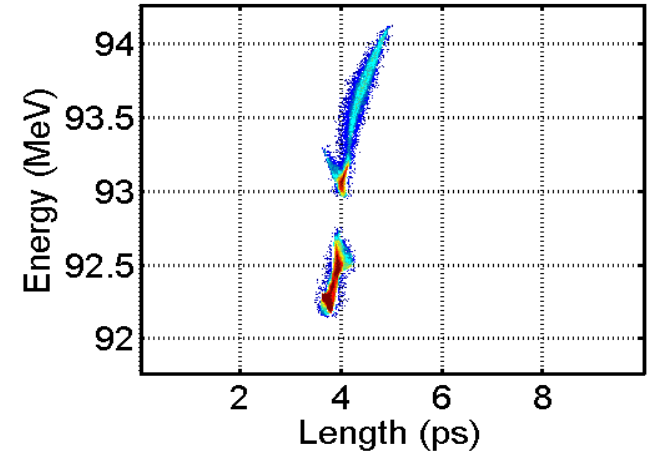
## Single bunch

- Energy spread: 0.2% / 0.3 %
- Bunch duration: 100 fs / 250 fs

**Energy separation:** 1.07 (0.05) MeV

**Time separation:** 0.42 (0.03) ps

**FEL parameter  $\rho$ :**  $6.7 \times 10^{-3}$



# FEL Photon Diagnostics

## Fiber Spectrometer

- Resolution: 1.2 nm @ 800 nm
- Window: 200-840 nm

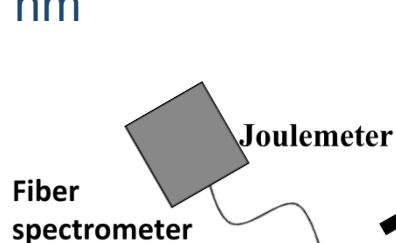
## Joulemeter

- Minimum detected energy: 1 pJ
- Calibration:  $5.96e8$  V/J @  $1\mu\text{m}$
- Optical density filters

## FROG: NIR-Grenouille

- Time-bandwidth product:  $<\sim 10$
- Spectral resolution: 0.7 nm @ 800nm
- Single shot sensitivity:  $1\mu\text{J}$

Period	2.8 cm
Undulator length	2.156.m
No of Periods	77
Gap (nom./min/max)	0.958 / 0.6 / 2.5 cm
K (nom./max/min)	2.145 / 3.2 / 0.38
Remanent field	1.31 T
Blocks per period	4
Block size (h x l x w)	2 x 0.7 x 5 cm

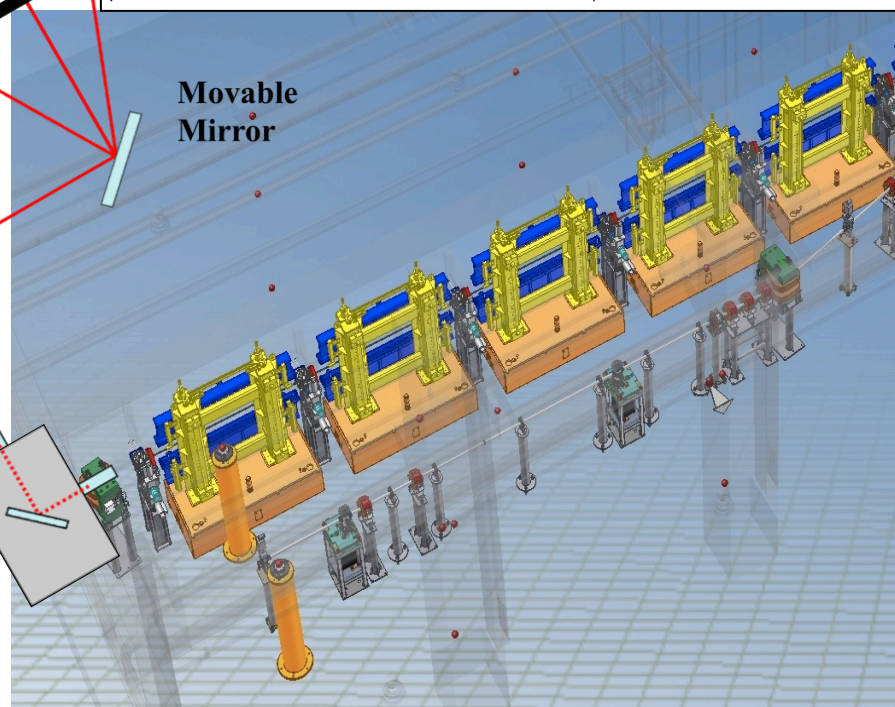


Fiber spectrometer

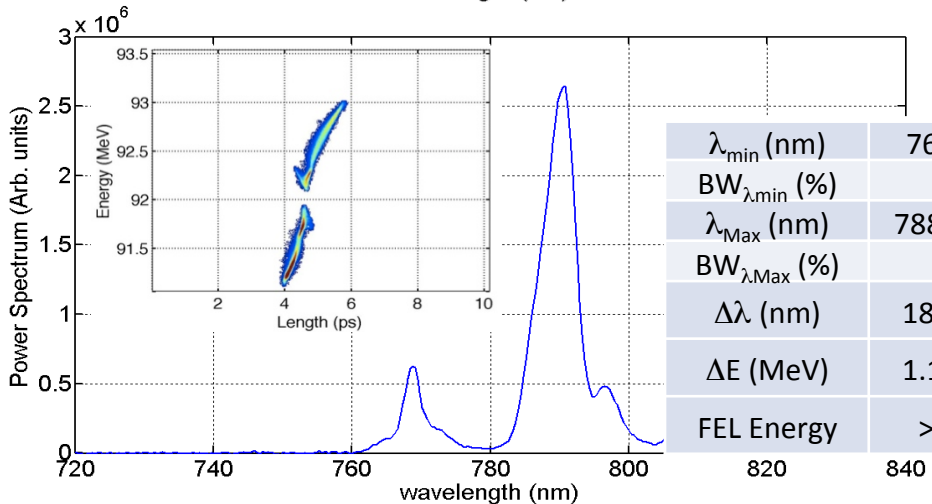
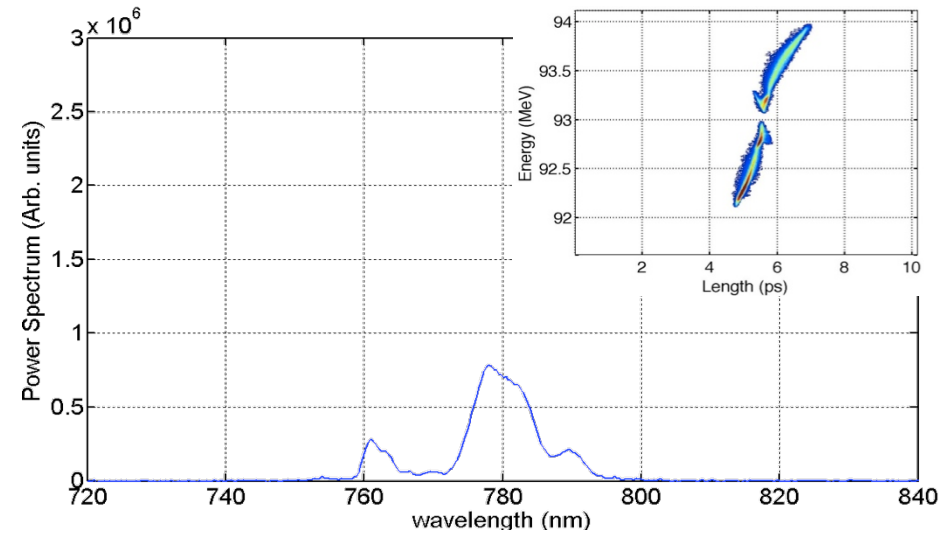
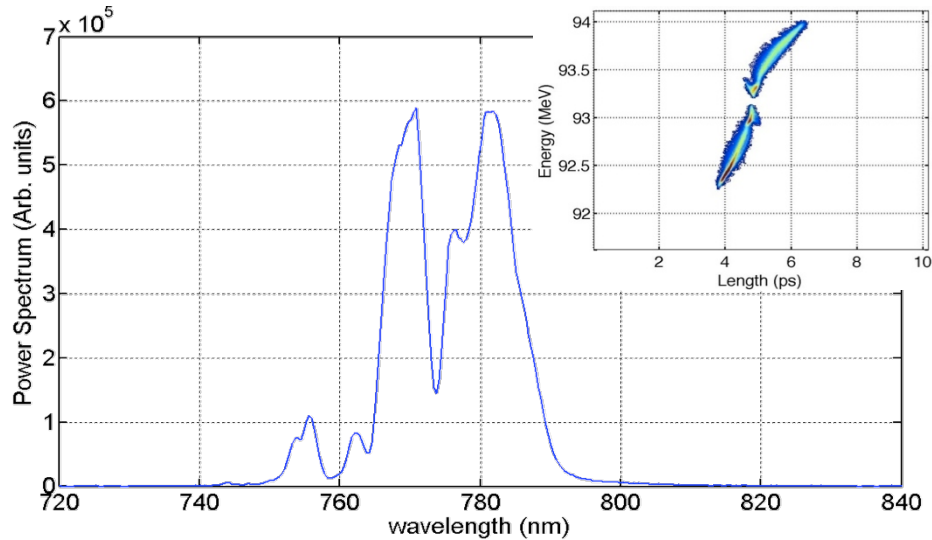
Filter Wheel Chamber

filters

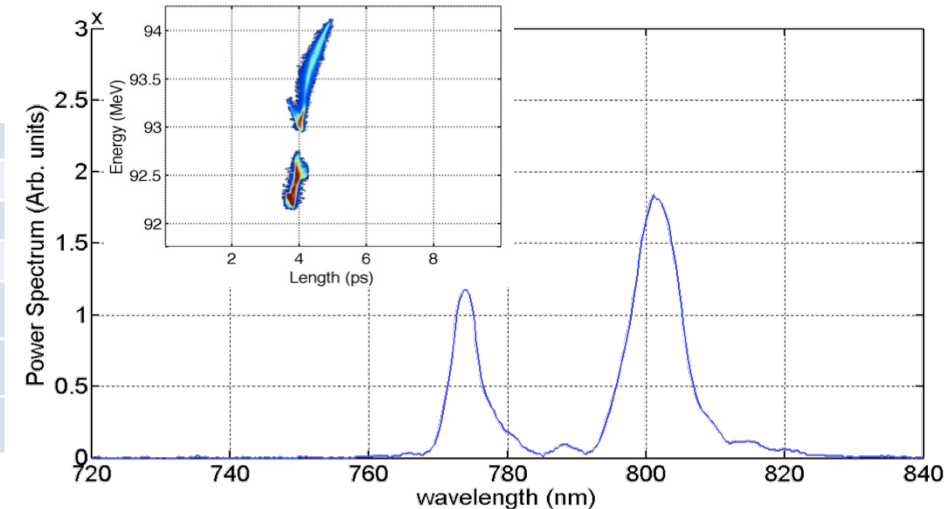
Movable Mirror



# FEL Experiments: Two-levels radiation spectra

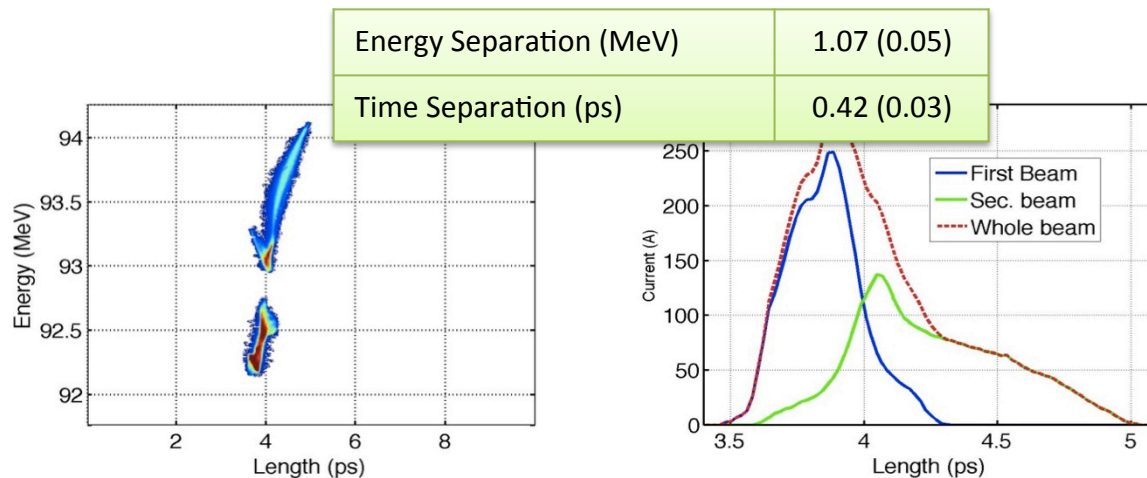


$\lambda_{\min}$ (nm)	769.8 (2)
$BW_{\lambda_{\min}}$ (%)	0.5
$\lambda_{\max}$ (nm)	788.6 (1.3)
$BW_{\lambda_{\max}}$ (%)	0.7
$\Delta\lambda$ (nm)	18.8 (2.9)
$\Delta E$ (MeV)	1.1 (0.17)
FEL Energy	> 37 $\mu\text{J}$

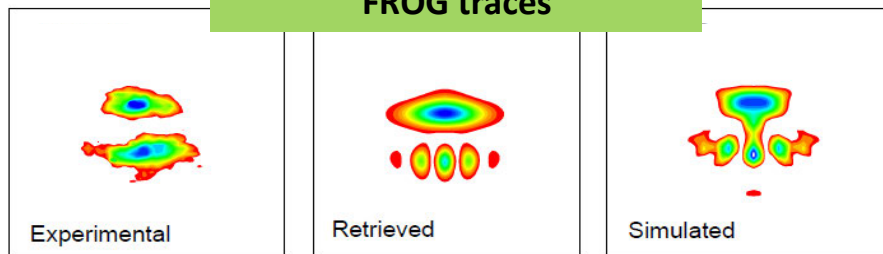


# FEL Experiments: Time-modulated pulses

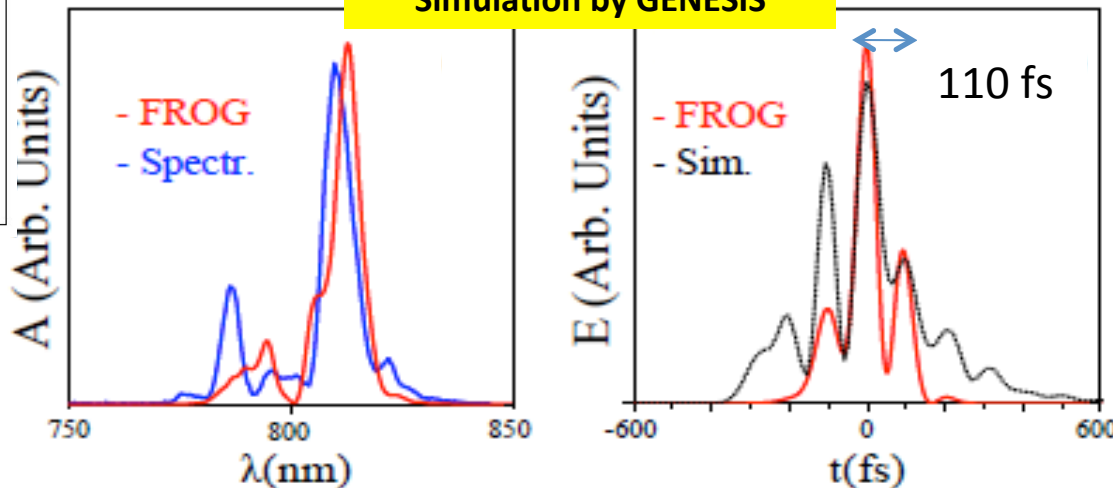
	Energy (MeV)	En. Spread (%)	Length (ps)	Charge (pC)
<b>First Beam</b>	92.515 (0.033)	0.174 (0.005)	0.147 (0.002)	82.15 (1.58)
<b>Second Beam</b>	93.588 (0.033)	0.317 (0.005)	0.283 (0.003)	77.85 (1.56)
<b>Whole Beam</b>	93.038 (0.032)	0.631 (0.003)	0.305 (0.004)	160.00 (3.10)



FROG traces



Simulation by GENESIS



$\Delta\lambda$ (nm)	BW (%)	RMS Time duration (fs)	Time separation (fs)
18	0.86	80	110

## Observation of Time-Domain Modulation of Free-Electron-Laser Pulses by Multi-peaked Electron-Energy Spectrum

V. Petrillo,<sup>1</sup> M.P. Anania,<sup>2</sup> M. Artioli,<sup>3</sup> A. Bacci,<sup>1</sup> M. Bellaveglia,<sup>2</sup> E. Chiadroni,<sup>2</sup> A. Cianchi,<sup>4</sup> F. Ciocci,<sup>3</sup> G. Dattoli,<sup>3</sup> D. Di Giovenale,<sup>2</sup> G. Di Pirro,<sup>2</sup> M. Ferrario,<sup>2</sup> G. Gatti,<sup>2</sup> L. Giannessi,<sup>3</sup> A. Mostacci,<sup>5</sup> P. Musumeci,<sup>6</sup> A. Petralia,<sup>3</sup> R. Pompili,<sup>4</sup> M. Quattromini,<sup>3</sup> J. V. Rau,<sup>7</sup> C. Ronsivalle,<sup>3</sup> A.R. Rossi,<sup>1</sup> E. Sabia,<sup>3</sup> C. Vaccarezza,<sup>2</sup> and F. Villa<sup>2</sup>

## Dual color X-rays from Thomson/ Compton sources

V. Petrillo<sup>1,2</sup>, A. Bacci<sup>1</sup>, C. Curatolo<sup>1,2</sup>, M. Ferrario<sup>3</sup>, G. Gatti<sup>3</sup>, C. Maroli<sup>2</sup>, J.V. Rau<sup>4</sup>, C. Ronsivalle<sup>5</sup>, L. Serafini<sup>1</sup>, C. Vaccarezza<sup>3</sup>, and M. Venturelli<sup>2\*</sup>

<sup>1</sup> INFN Milano, Via Celoria, 16 20133 Milano, Italy

<sup>2</sup> Università degli Studi di Milano, Via Celoria, 16 20133 Milano, Italy

<sup>3</sup> LNF, INFN Via E. Fermi, 40 Frascati (Roma), Italy

<sup>4</sup> ISM-CNR Via del Fosso del Cavaliere, 100 00133 Roma, Italy and

<sup>5</sup> ENEA Via E. Fermi, 45 Frascati (Roma), Italy

We analyze the possibility of producing two color X or gamma radiation by Thomson/Compton back-scattering between a high intensity laser pulse and a two-energy level electron beam, constituted by a couple of beamlets separated in time and/or energy obtained by a photoinjector with comb laser techniques and linac velocity bunching. The parameters of the Thomson source at SPARC\_LAB have been simulated, proposing a realistic experiment.

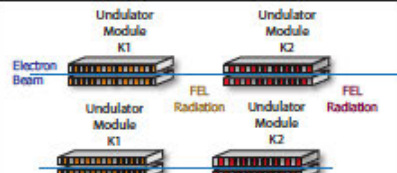
A. Marinelli, A.A. Lutman, J. Wu, D. Ratner, S. Gilevich, F. J. Decker, J. Turner, H. Loos, Y. Ding, J. Krzywinski, Y. Feng, H. D. Nuhn, J. Welch, T. Maxwell, C. Behrens, R. Coffee, Z. Huang, C. Pellegrini

## Introduction

Two color x-FELs have received considerable attention at fourth generation light sources [1-4], since they enable a wide range of applications from bio-imaging to time-resolved studies of atomic physics. Many schemes have been developed to achieve two-color operation. While no individual scheme can meet all the requirements set by the large x-ray user community, each scheme can meet a set of requirements for some specific applications.

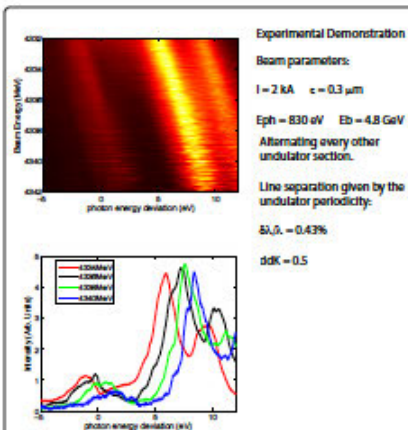
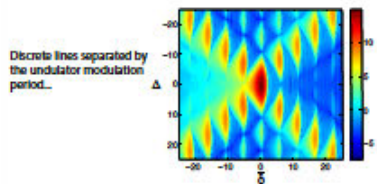


## Multicolor FEL via Gain-Modulation

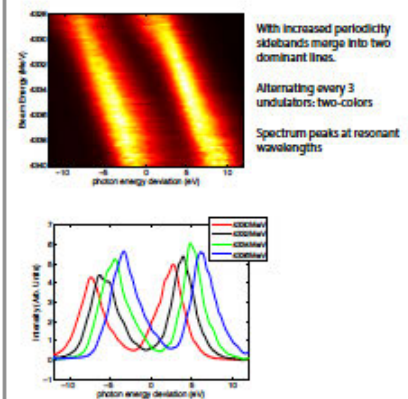


Alternately amplify 2 resonant wavelengths in a long undulator  $\rightarrow$  2 color spectrum  
Linear FEL dynamics in each undulator.  
Detuning changes by a fixed amount  $\Delta$

$$\begin{pmatrix} B \\ P \\ A \end{pmatrix} = \prod_{n=1}^{N_u} M_{r,n}(\bar{\delta} + (-1)^n \Delta) \begin{pmatrix} B_0 \\ P_0 \\ A_0 \end{pmatrix}$$



Experimental Demonstration  
Beam parameters:  
 $I = 2 \text{ kA}$   $\epsilon = 0.3 \mu\text{m}$   
 $E_{ph} = 830 \text{ eV}$   $E_b = 4.8 \text{ GeV}$   
Alternating every other undulator section.  
Line separation given by the undulator periodicity:  
 $\Delta\delta, \delta = 0.43\%$   
 $\delta dK = 0.5$

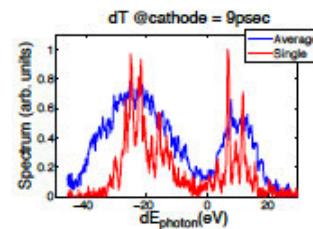
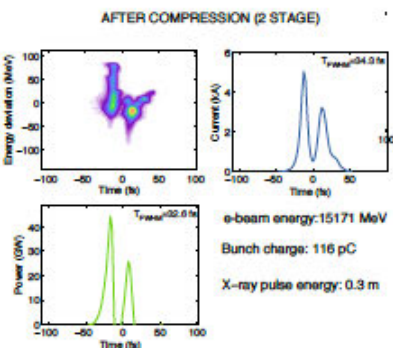
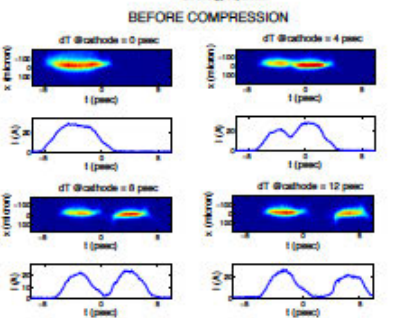
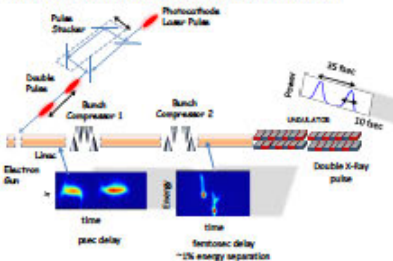


With increased periodicity sidebands merge into two dominant lines.  
Alternating every 3 undulators: two-colors  
Spectrum peaks at resonant wavelengths

PHYSICAL REVIEW LETTERS  
Multicolor Operation and Spectral Control in a Gain-Modulated X-Ray Free-Electron Laser  
A. Marinelli, A.A. Lutman, J. Wu, Y. Ding, S. Gilevich, H.D. Nuhn, F. J. Decker, J. Turner, H. Loos, Y. Ding, J. Krzywinski, Y. Feng, H. D. Nuhn, J. Welch, T. Maxwell, C. Behrens, R. Coffee, Z. Huang, C. Pellegrini  
\*Department of Physics and Astronomy, University of California Los Angeles, Los Angeles, California 90095, USA  
ACCEPTED

## Double-Bunch Operation at LCLS

Generate double pulse at cathode and compress. Similar concept demonstrated at SPARC in the infrared [4]



Spectrum around 9.1 keV  
Spectrum clearly shows appearance of two separate spectral lines.  
Tunability up to several tens of eV is a key feature for bio-imaging experiments based on MAD techniques.

## Conclusions

The generation of multicolor X-FEL pulses with gain-modulation has been demonstrated experimentally. This technique has already been used in user experiments and has proved to be a valid alternative to 2-color SASE in cases in which full time overlap of the two colors is a crucial feature.

Two-bunch operation is currently under development. Preliminary experimental results at hard x-rays show the key advantages of this method: full saturation power and possibility to diagnose the x-ray time structure with the x-tvcc on a single shot base.

## Bibliography

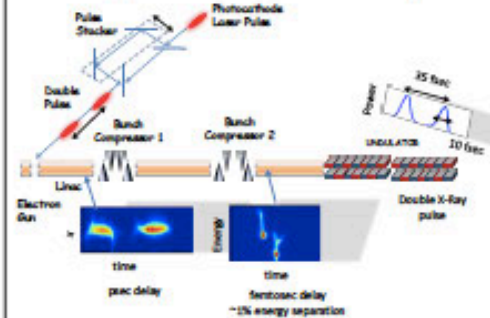
- 1) A. Lutman et al. Experimental demonstration of femtosecond two-color x-ray free electron lasers. Phys. Rev. Lett. 110, 134801 (2013).
- 2) G. De Ninno et al. Chirped seeded free-electron lasers: Self-standing light sources for two-color pump-probe experiments. Phys. Rev. Lett. 110, 064801 (2013).
- 3) A. Marinelli et al. Multicolor Operation and Spectral Control in a Gain-Modulated X-Ray Free-Electron Laser. Phys. Rev. Lett. (in production)
- 4) V. Pavlos et al. Observation of time-domain modulation of free-electron-laser pulses by multi-pulsed electron-energy spectrum. Phys. Rev. Lett. (in production)

# Double-Bunch Operation at LCLS

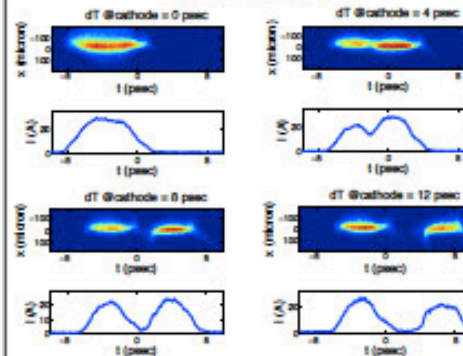
Generate double pulse at cathode and compress.  
Similar concept demonstrated at SPARC in the Infrared [4]

## Double-Bunch Operation at LCLS

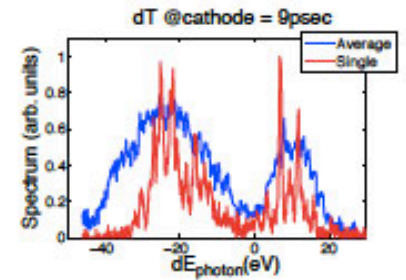
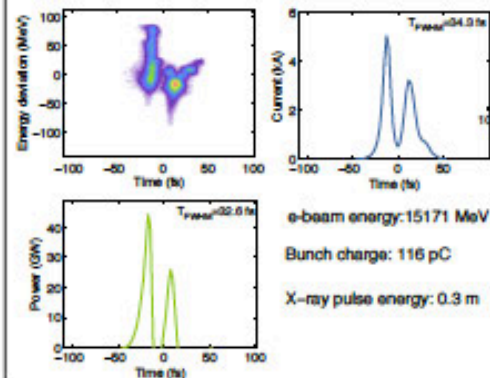
Generate double pulse at cathode and compress.  
Similar concept demonstrated at SPARC in the Infrared [4]



BEFORE COMPRESSION



AFTER COMPRESSION (2 STAGE)



Spectrum around 9.1 keV  
Spectrum clearly shows appearance of two separate spectral lines.  
Tunability up to several tens of eV is a key feature for bio-imaging experiments based on MAD techniques.

## Conclusions

The generation of multicolor X-FEL pulses with gain-modulation has been demonstrated experimentally. This technique has already been used in user experiments and has proved to be a valid alternative to 2-color SASE in cases in which full time overlap of the two colors is a crucial feature.

Two-bunch operation is currently under development. Preliminary experimental results at hard x-rays show the key advantages of this method: full saturation power and possibility to diagnose the x-ray time structure with the x-tcav on a single shot base.

## Bibliography

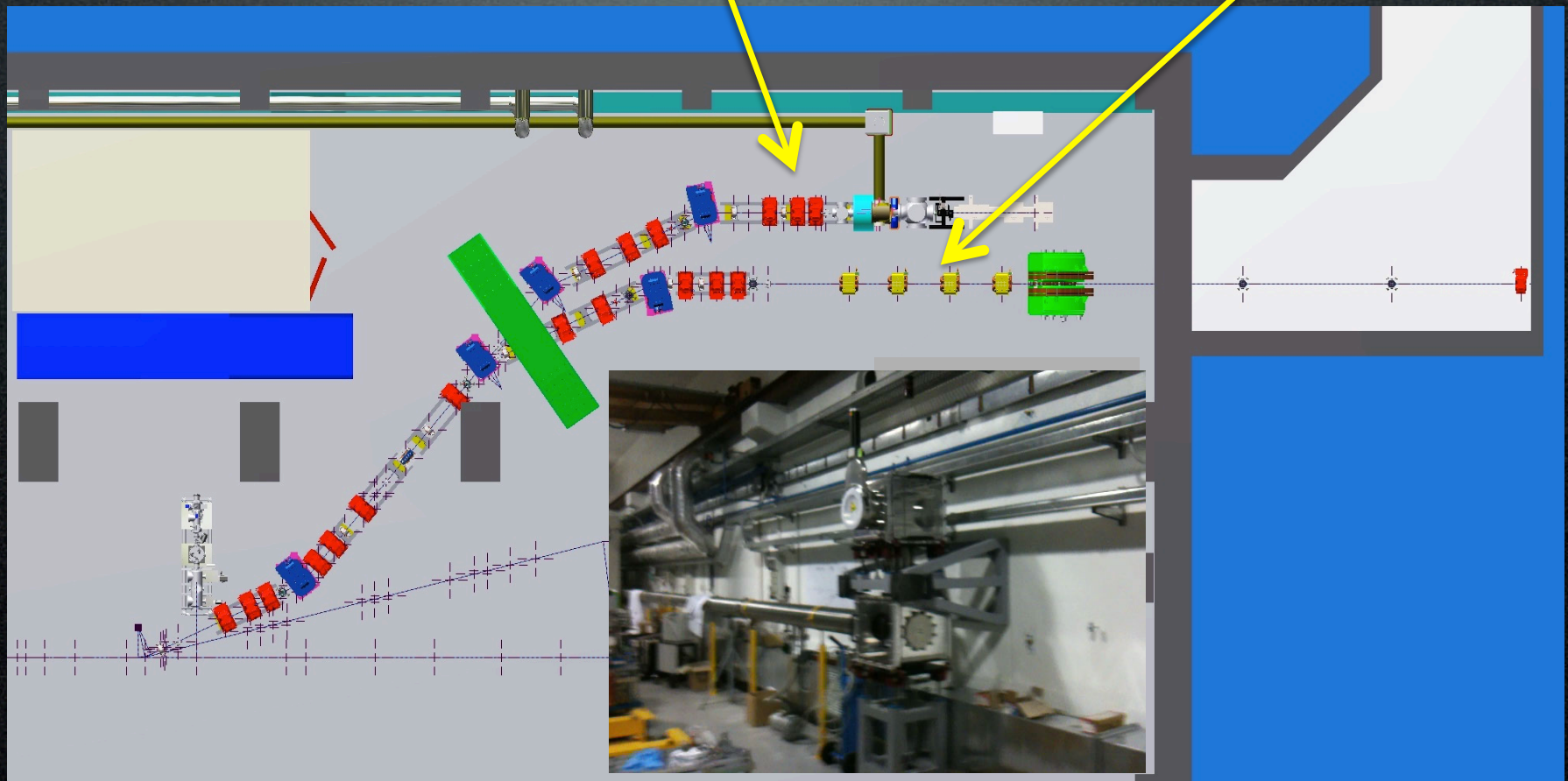
- 1) A. Lutman et al. Experimental demonstration of femtosecond two-color x-ray free electron lasers. *Phys. Rev. Lett.* 110, 134801 (2013).
- 2) G. De Nino et al. Chirped Seeded Free-Electron Lasers: Self-Standing Light Sources for Two-Color Pump-Probe Experiments. *Phys. Rev. Lett.* 110, 064801 (2013)
- 3) A. Marinelli et al. Multicolor Operation and Spectral Control in a Gain-Modulated X-Ray Free-Electron Laser. *Phys. Rev. Lett.* (in production)
- 4) V. Pettillo et al. Observation of time-domain modulation of free-electron-laser pulses by multiplexed electron-energy spectrum. *Phys. Rev. Lett.* (in production)



# New installations

Thomson source

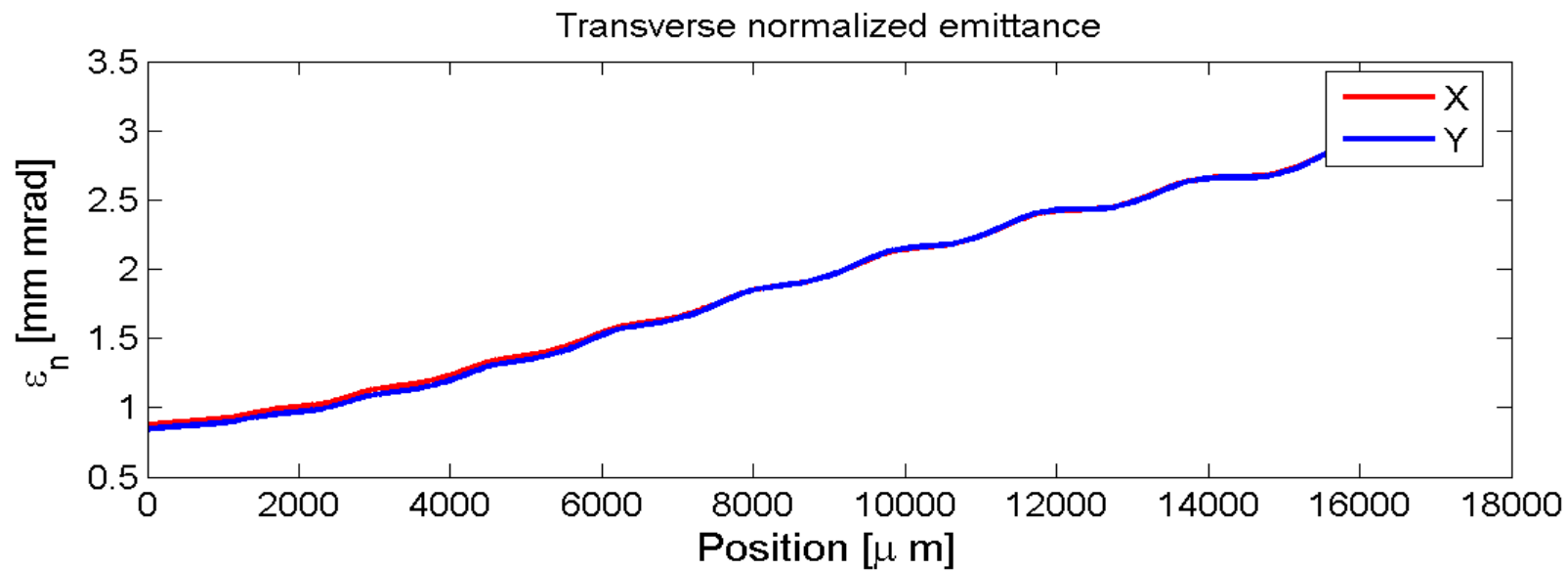
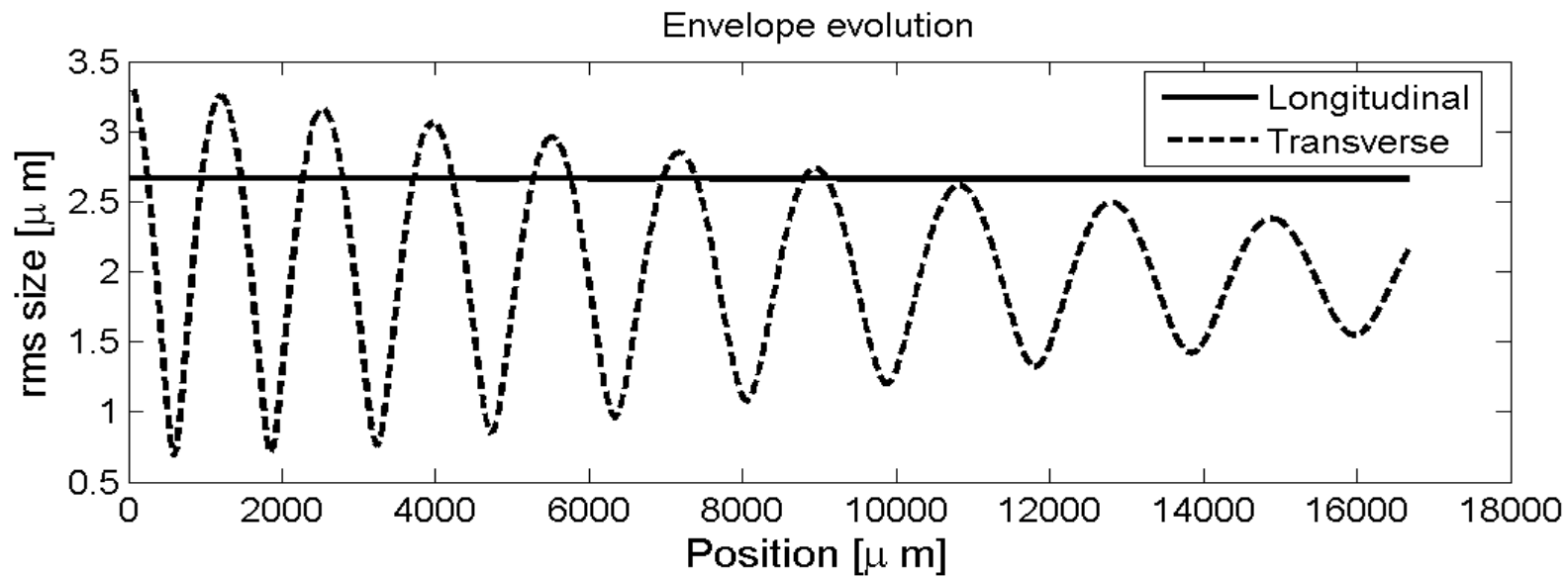
Plasma acceleration



## EXIN goals

- Produce a high brilliance e-beam, peak or global.
- Stability.
- Reproducibility.
- Everything above in the easiest way (leading philosophy).

Highest energy record in LWFA is NOT a goal!



When  $\eta = \frac{4\gamma k_p^2}{3\gamma'^2} \gg 1$

$$\rho = \frac{k_{sc}^0 \sigma_x^2}{\gamma_o \varepsilon_n^2} \ll 1$$

$$\gamma'' = 0$$

$$\gamma' \neq 0$$

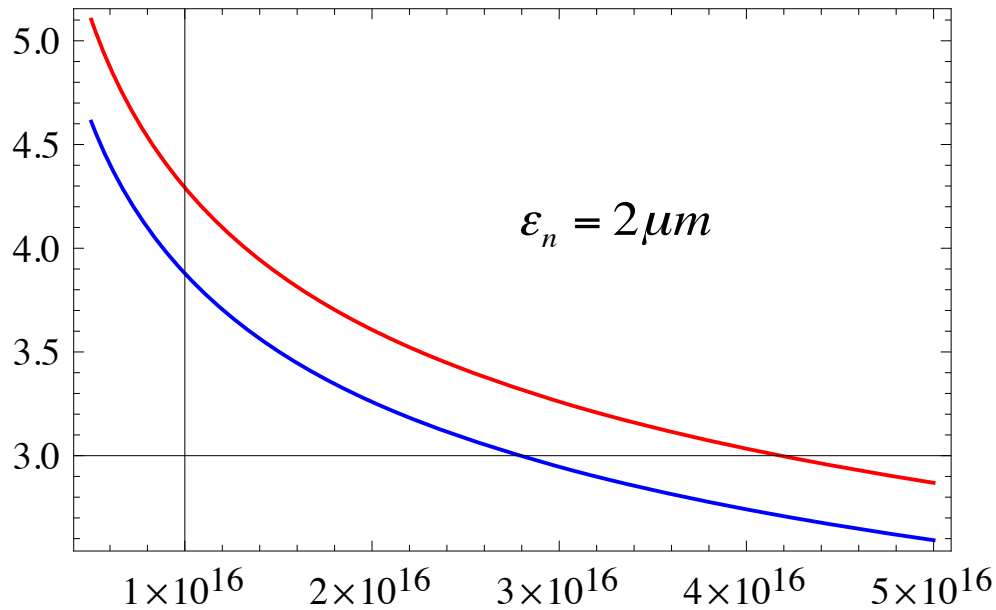
$$\sigma_x'' + \frac{k_p^2}{3\gamma} \sigma_x = \frac{\varepsilon_n^2}{\gamma^2 \sigma_x^3}$$

Looking for an equilibrium solution of the form:

$$\sigma_\varepsilon = \gamma^n \sigma_o$$

We get the matching condition with acceleration:

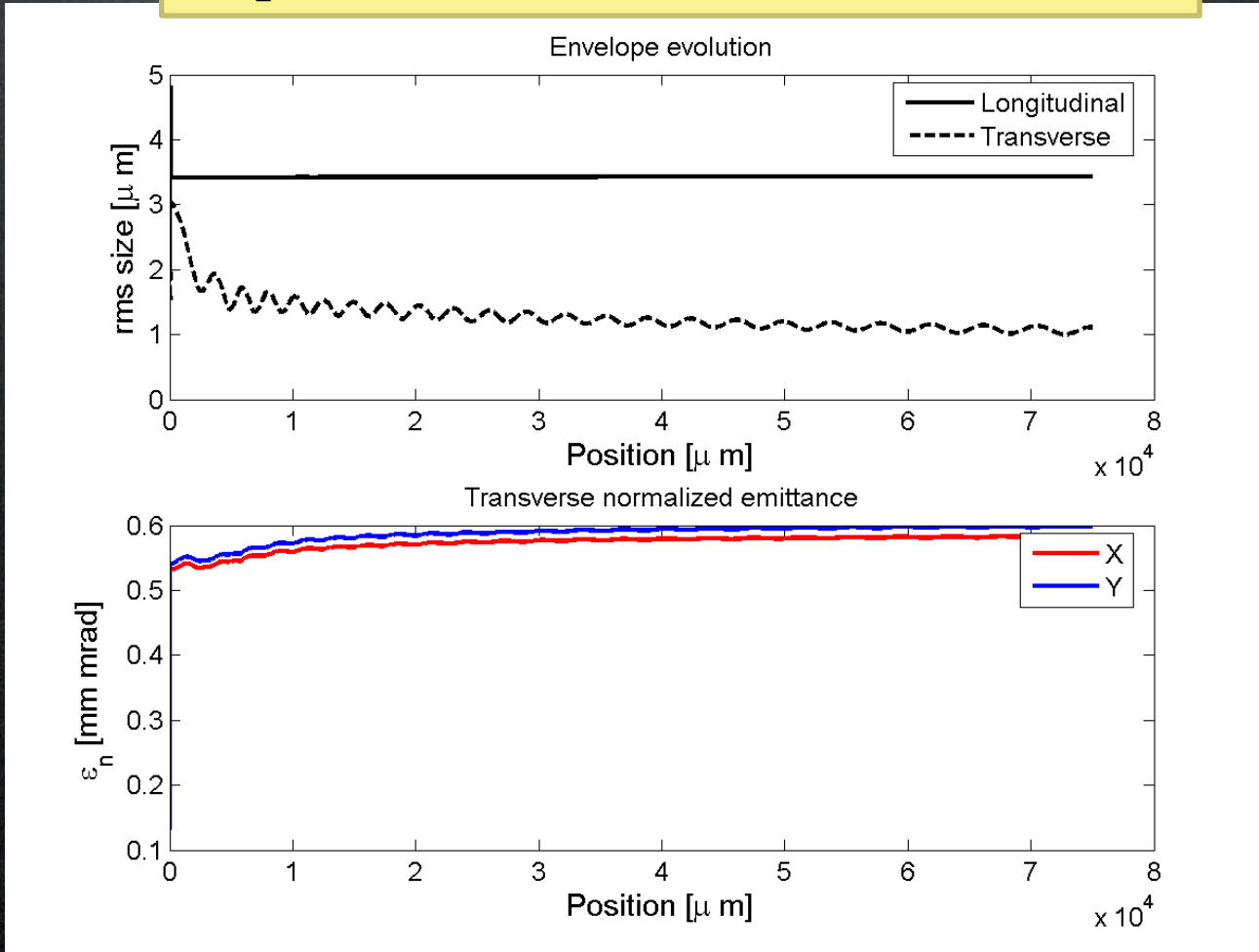
$\sigma_{\varepsilon}$  [um]



$n$  [cm<sup>-3</sup>]

$$\sigma_\varepsilon = \sqrt[4]{\frac{3}{\gamma}} \sqrt{\frac{\varepsilon_n}{k_p}}$$

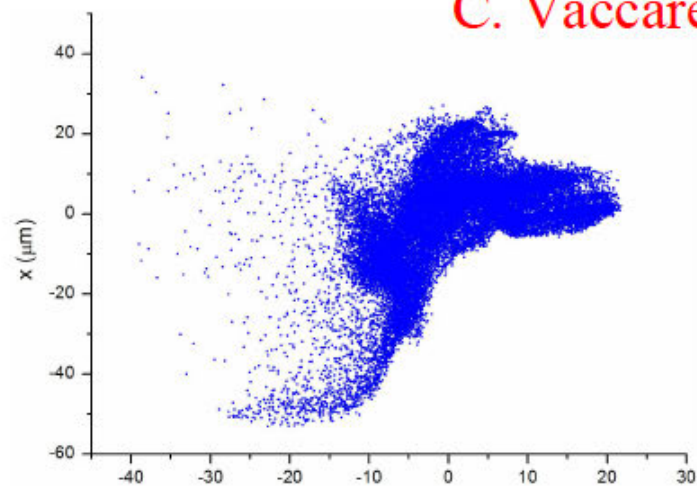
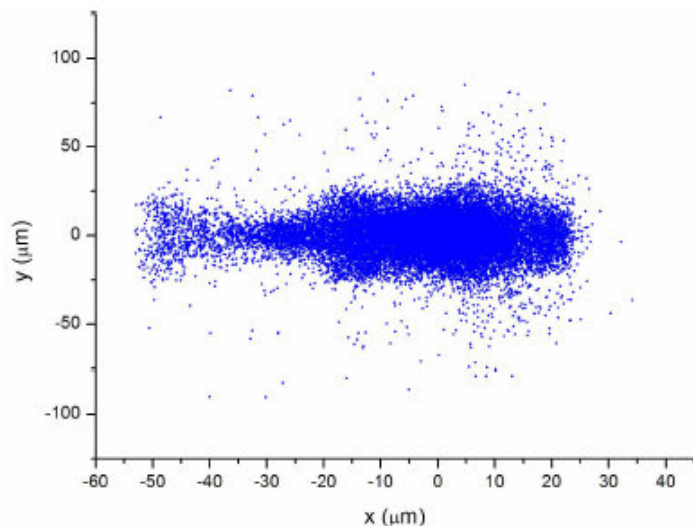
$$\sigma_\varepsilon = \sqrt[4]{\frac{3}{\gamma}} \sqrt{\frac{\varepsilon_n}{k_p}}$$



## S2E simulation: beam production and transport

Production has been simulated using ASTRA together with the genetic optimizer GIOTTO up to injector's end. ELEGANT has been used for the transport inside the dogleg.

By A. Bacci  
and  
C. Vaccarezza

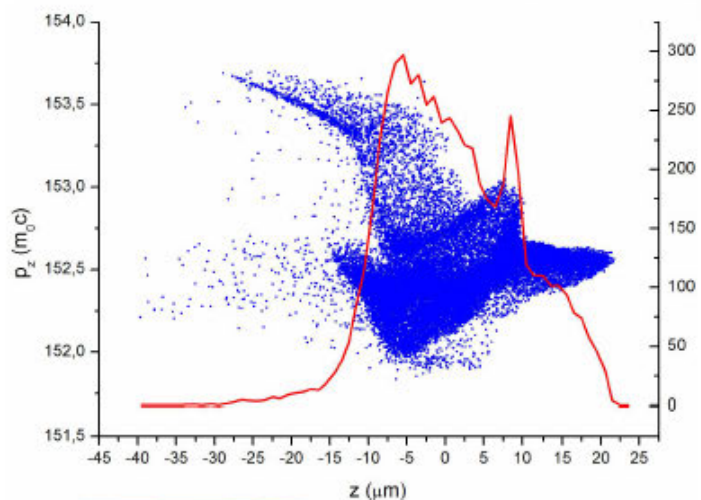


Final beam parameters:  $\sigma_x \approx \sigma_y = 12.7 \mu\text{m}$ ,  
 $\epsilon_x = 2.7 \mu\text{m}$ ,  $\epsilon_y = 0.4 \mu\text{m}$ ,  $E = 78 \text{ MeV}$ ,  
 $\delta\gamma/\gamma = 0.2\%$ .

Total compression:  $cf = 16$  (8 by VB and 2 by dogleg).

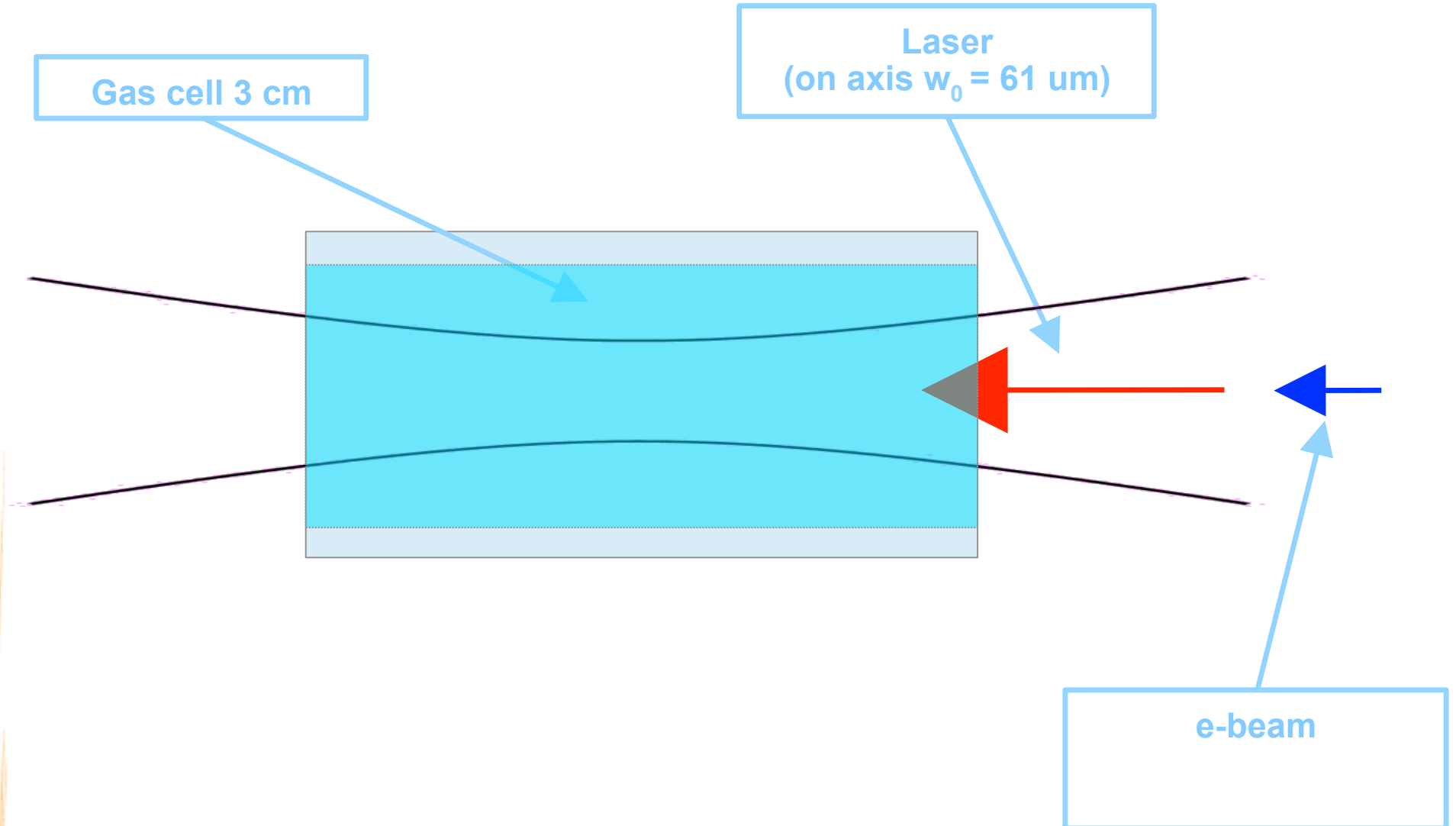
Non particular optimization in dogleg.

X emittance overestimated!



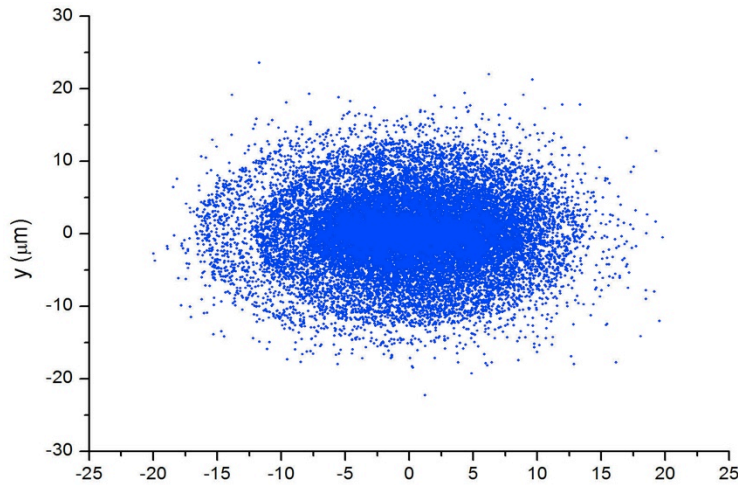
## S2E simulation: plasma acceleration

No laser guiding: gas cell, very easy from the experimental point of view.



# S2E simulation: plasma acceleration

Sample beam with gas cell (**VERY PRELIMINARY**):  $\Delta t = 157$  fs,  $\sigma_x = 3.8$   $\mu\text{m}$ .



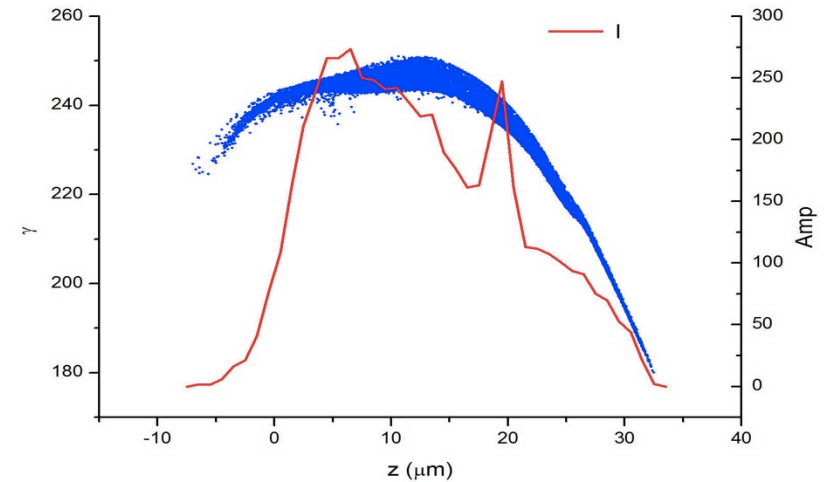
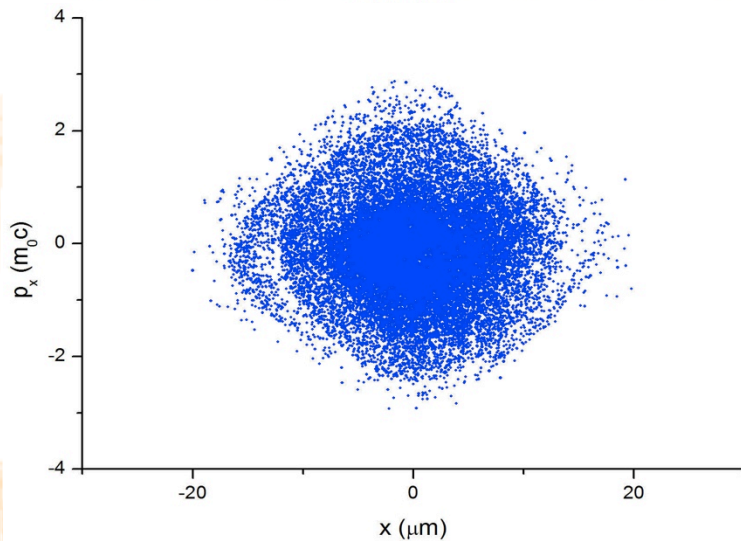
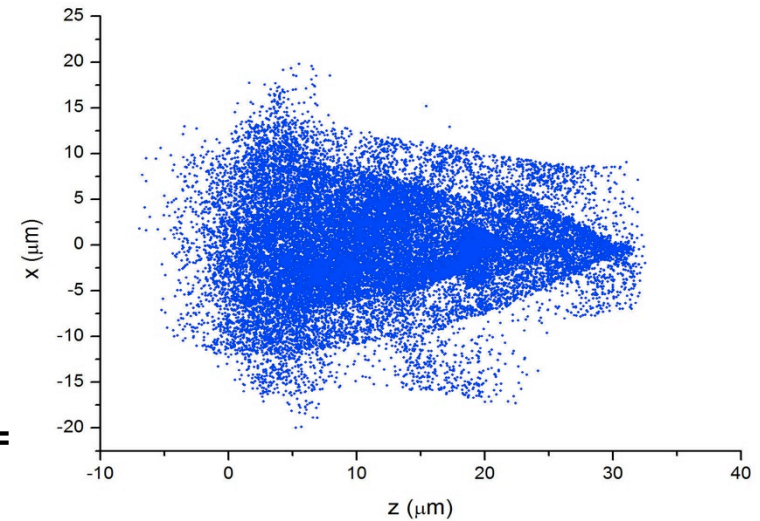
$$\sigma_x = 5.4 \mu\text{m}$$

$$E = 120 \text{ MeV}$$

$$\text{Charge loss} = 8\%$$

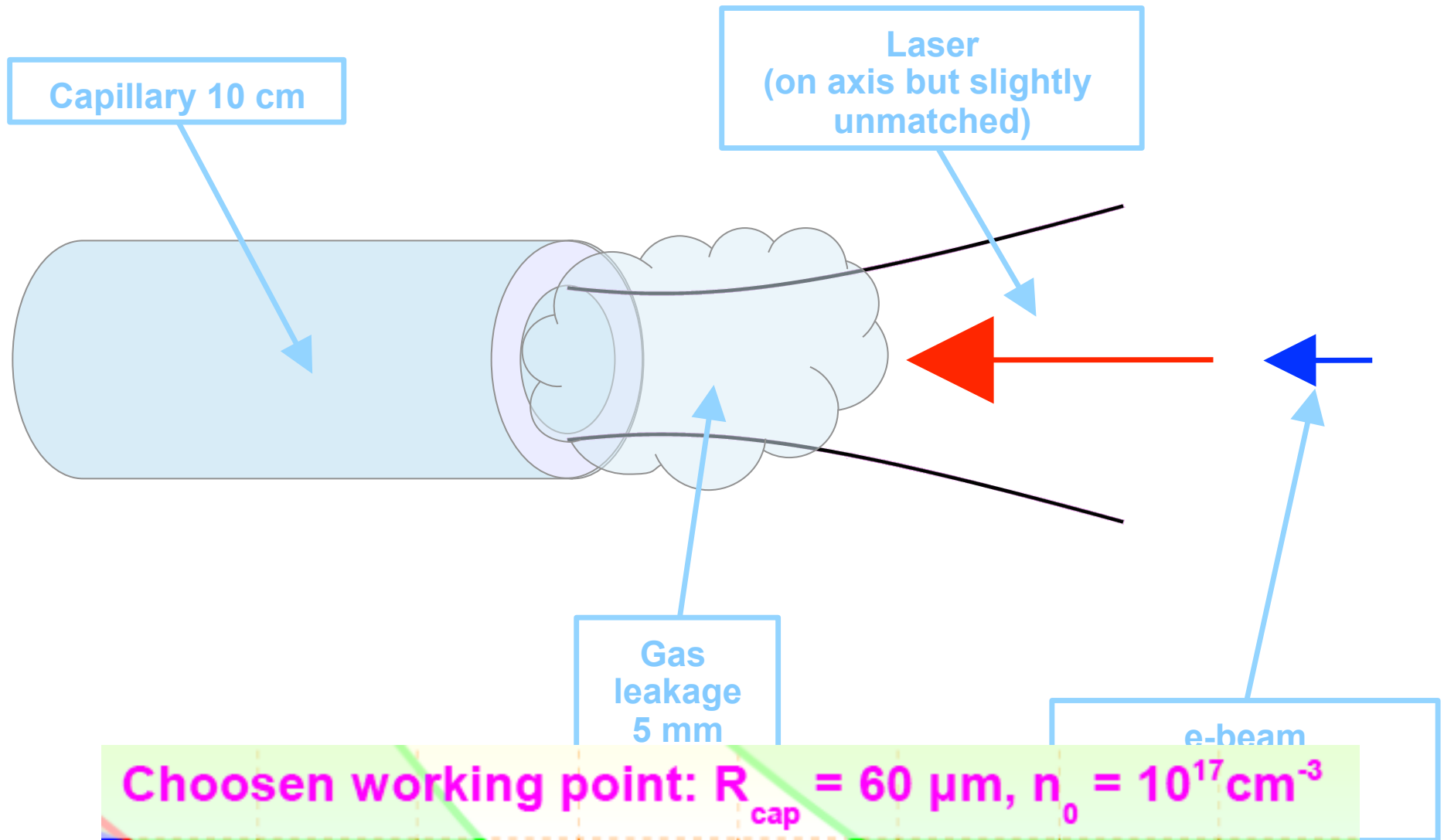
$$\varepsilon_{nx} = 4.5 \mu\text{m}$$

$$\Delta\gamma/\gamma = 4.5 \%$$



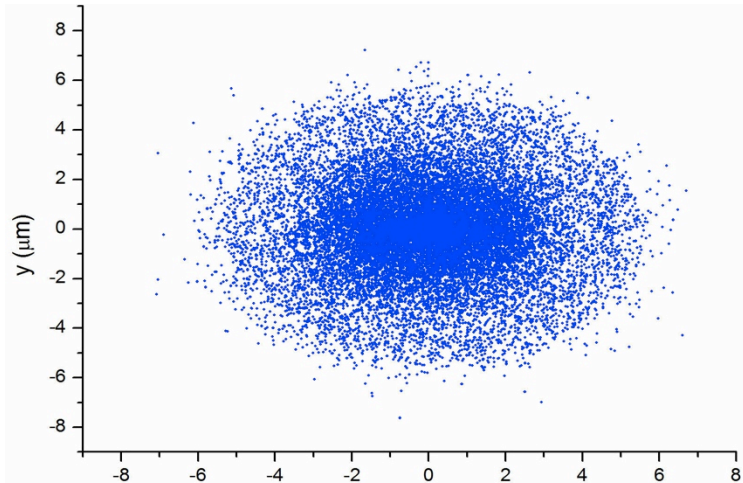
## S2E simulation: plasma acceleration

Laser guided by a capillary tube: more performances but much harder to implement



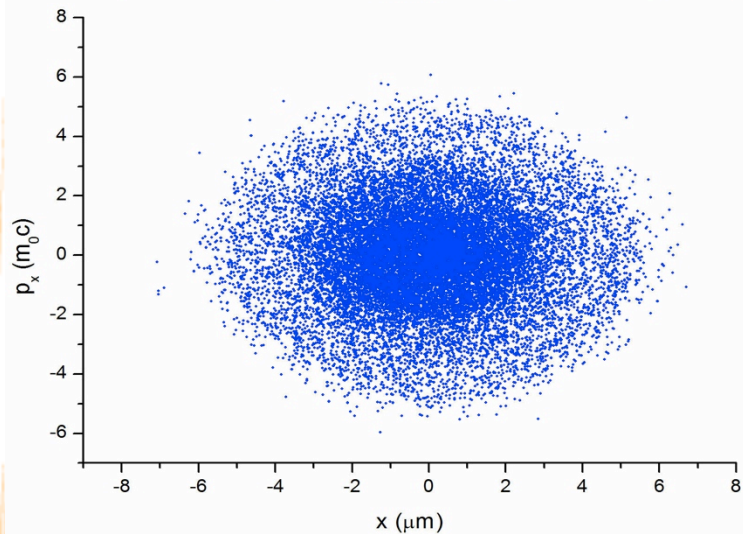
# S2E simulation: plasma acceleration

Best beam:  $\Delta t = 182$  fs,  $\sigma_x = 3.8$   $\mu\text{m}$ .



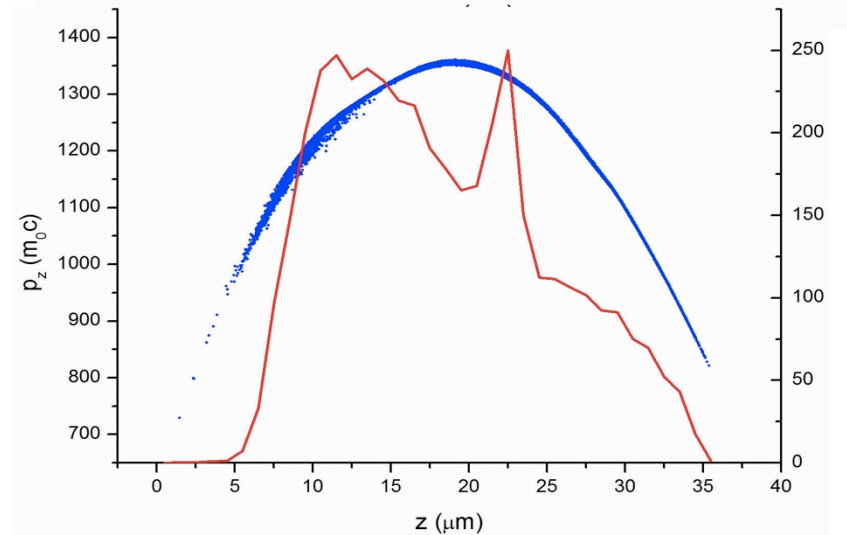
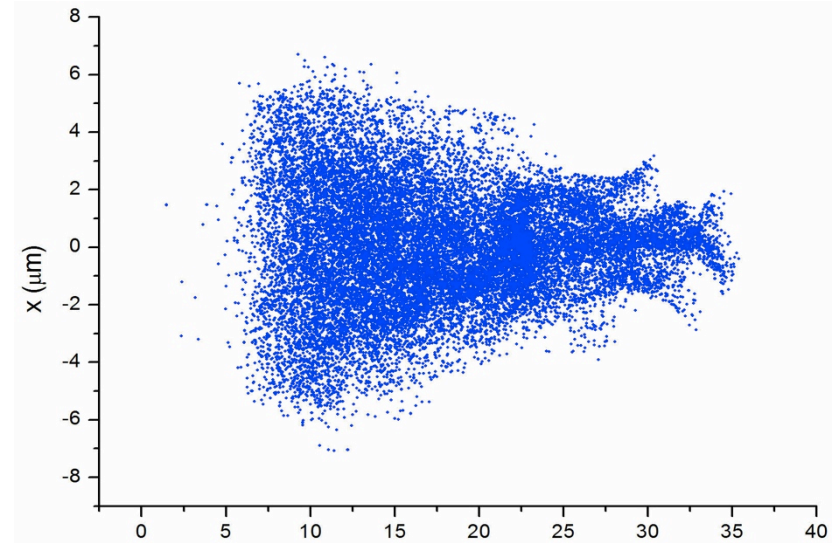
$$\sigma_x = 2.0 \mu\text{m}$$

$$E = 630 \text{ MeV}$$



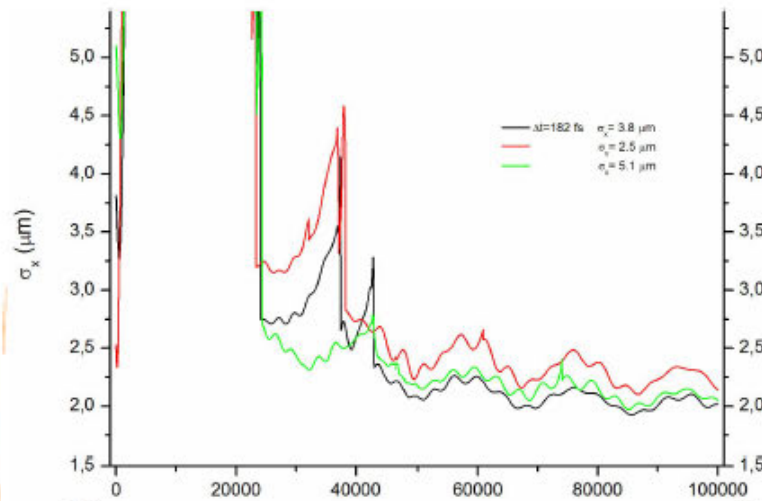
$$\varepsilon_{nx} = 3.5 \mu\text{m}$$

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



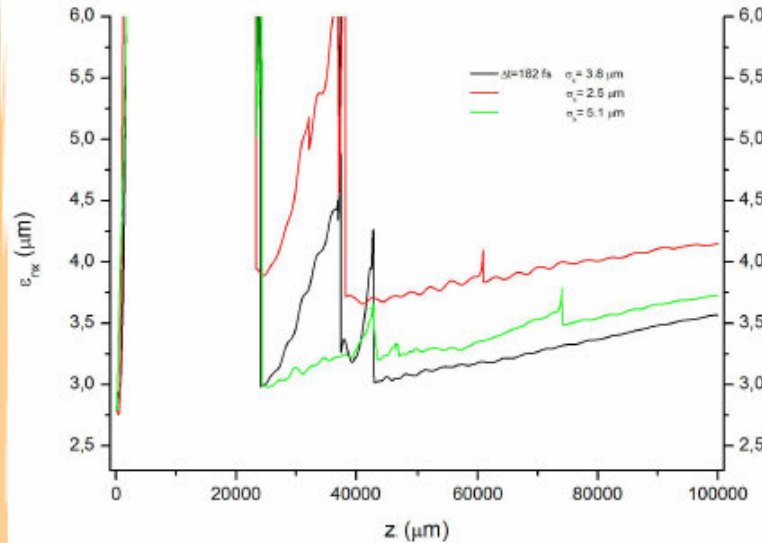
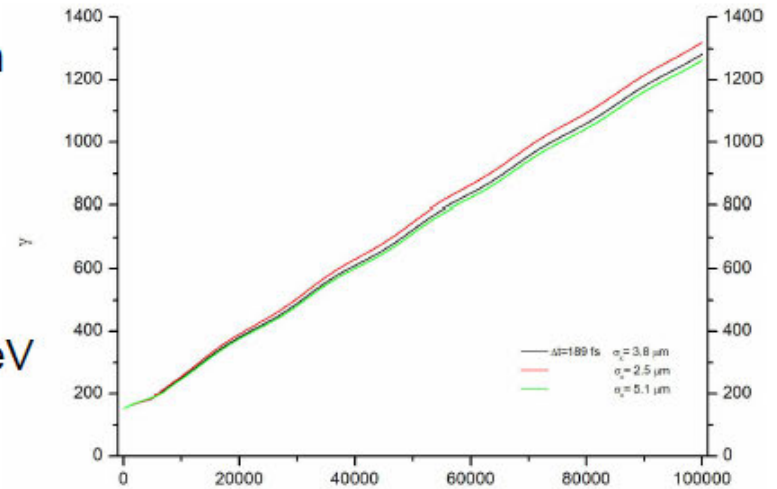
# S2E simulation: plasma acceleration

## Best beam transport and parameters



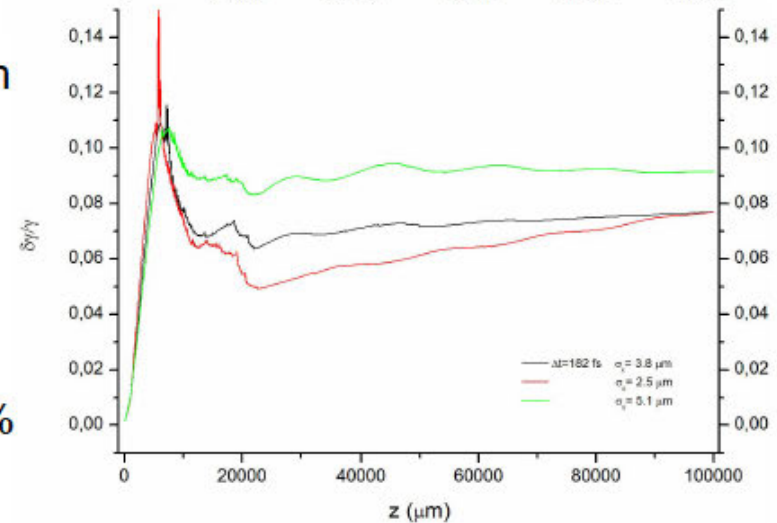
$$\sigma_x = 2.0 \mu\text{m}$$

$$E = 630 \text{ MeV}$$



$$\epsilon_{nx} = 3.5 \mu\text{m}$$

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



FLAME activities

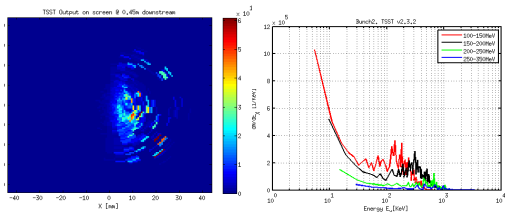


# γ-RESIST



## Inverse Compton scattering of self-injected, LWFA sub-GeV electrons<sup>1,2</sup>

Exp'ed: 2E8 photons/shot

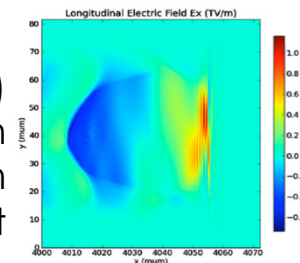


Montecarlo TSST:  
expected angular  
and spectral  
distribution

SIMULATIONS

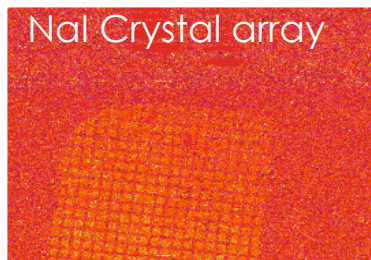
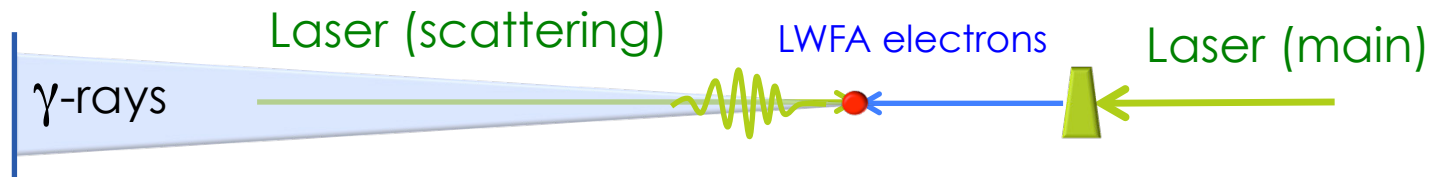
e<sup>-</sup> bunch

PIC (Jasmine)  
self-injection  
on a 4 mm  
gas-jet



Photons at screen: image and spectrum

γ-photons



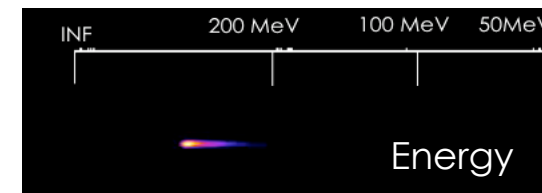
First measured (July 2013) γ-ray signal: low S/N ratio.

**Higher shielding,  
collision stability and  
laser beam energy  
needed**

EXPERIMENT

e<sup>-</sup> bunch

Measured bunch  
fully established  
July 2013 run:  
monoenergetic+  
**low emittance**



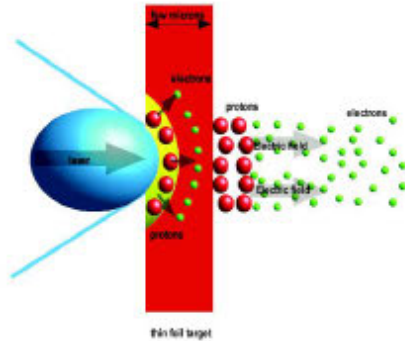
γ-photons

<sup>1</sup>L.A. Gizzi et al., NIM B 309, 202-209 (2013); <sup>2</sup>T. Levato et al., NIMA A720, 95-99 (2013) <sup>3</sup>P. Tomassini et al., [Appl. Phys. B](#) **80**, 419-436 (2005)



# LILIA: Solid target

Collaboration: Milano, Milano Bicocca, Bologna, Pisa, Lecce, LNS, LNF.



**Goal: Production of a proton beam suitable for injection into (conventional) accelerating structures**

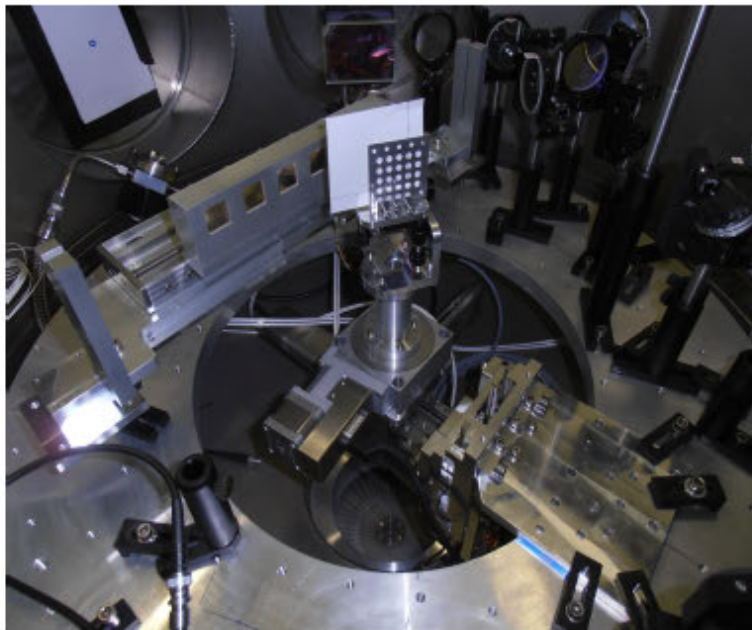
TNSA in the regime  $1E18 < I < 1E20 \text{ W/cm}^2$

-Metallic target of 1-10 microns

-GAFchromic and CR39 films have been used  
Solid state detectors (PIN) in order to investigate  
Noise baseline.

-Last run: Thomson parabola (ELIMED LNS)

-Detected protons  $< 4 \text{ MeV}$



Possible higher intensity  
For the next run

OAP F=1 mt  OAP F= 0.5 mt

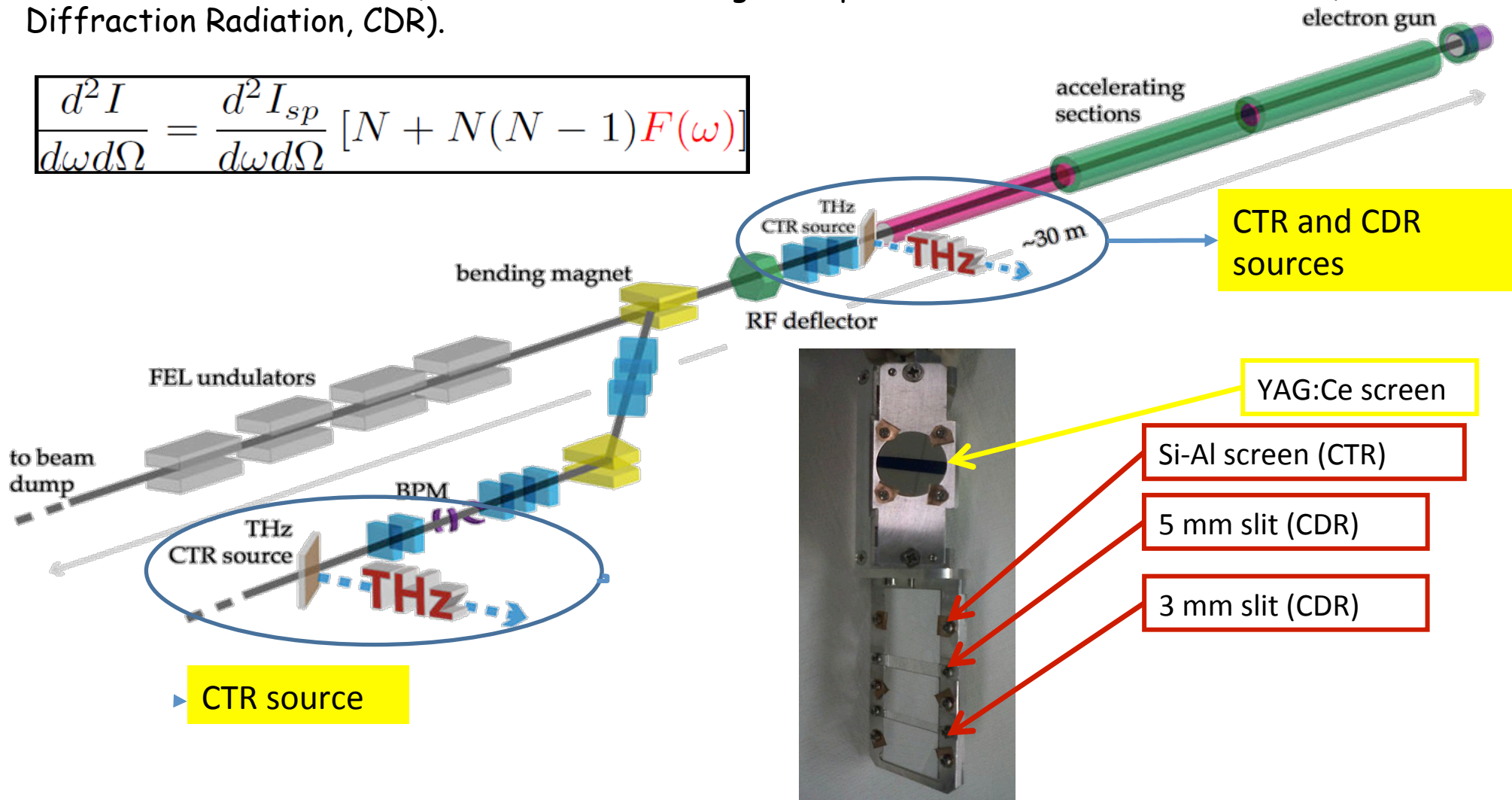
# THz Source

Courtesy E. Chiadroni, S. Lupi

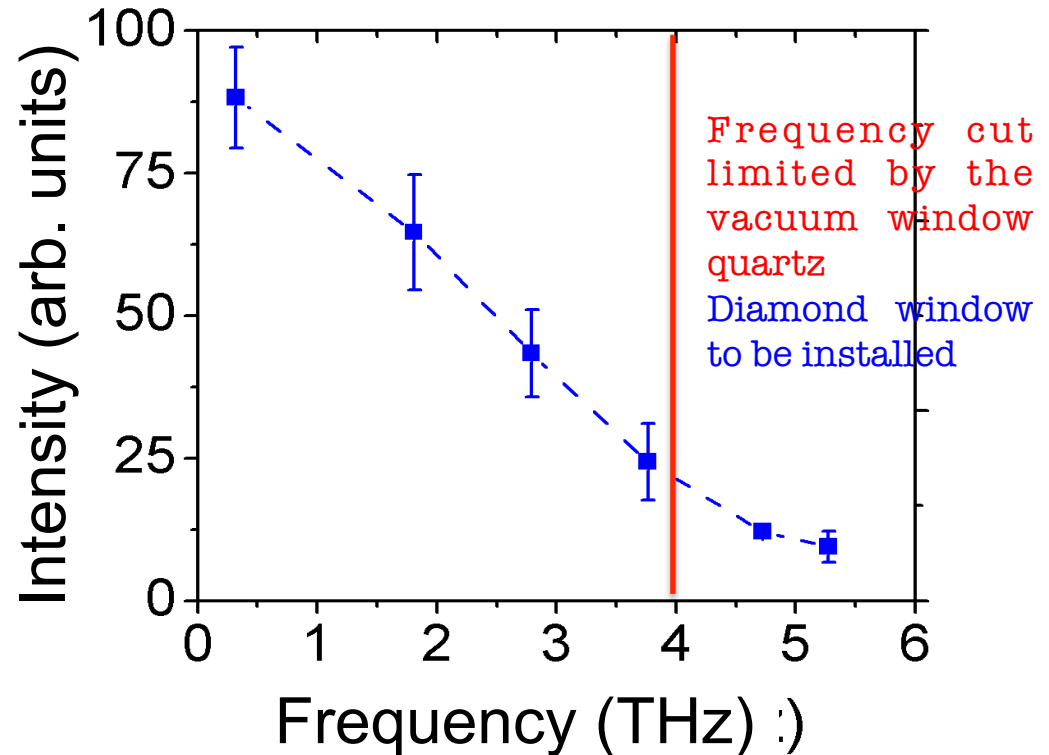
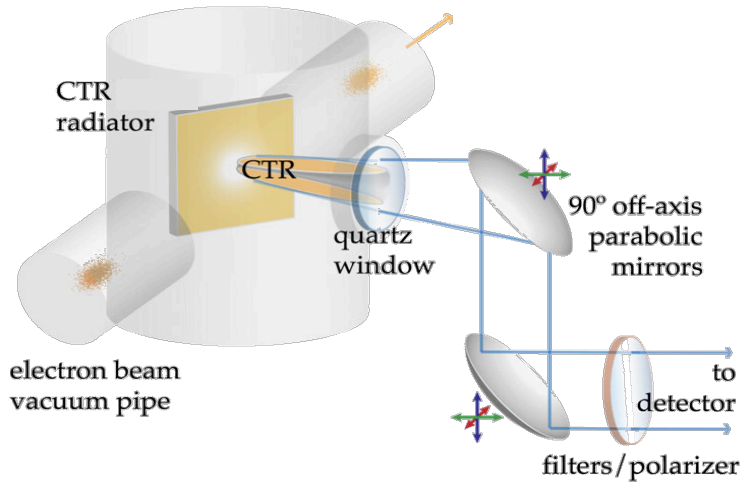
# The SPARC\_LAB THz beam lines

**Linac-based source:** Coherent Radiation from an aluminum-coated silicon screen (Coherent Transition Radiation, CTR) and from a rectangular aperture in the metallic screen (Coherent Diffraction Radiation, CDR).

$$\frac{d^2 I}{d\omega d\Omega} = \frac{d^2 I_{sp}}{d\omega d\Omega} [N + N(N - 1)F(\omega)]$$



# Broad-band THz radiation: Measurements



## Electron beam parameters

Energy (MeV)	100
Charge (pC)	260
RMS bunch length (fs)	260

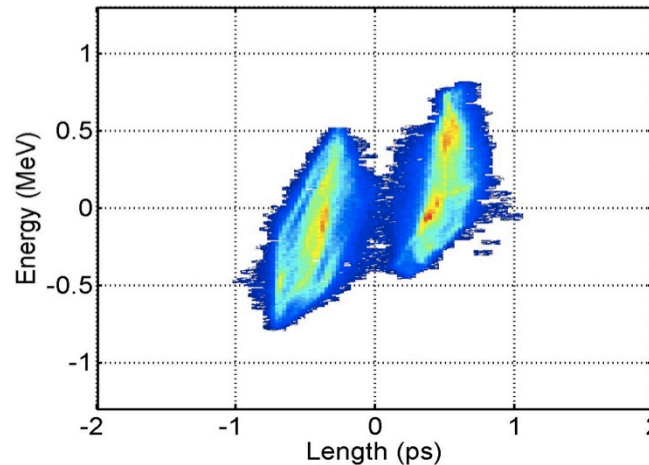
E. Chiadroni et al., Appl. Phys. Lett. 102, 094101 (2013)

# Narrow-band THz radiation: 2-bunches train measurements

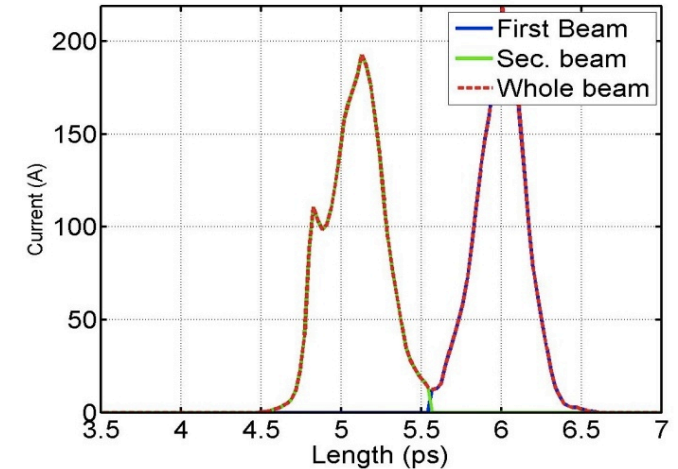
## Electron beam parameters

Energy (MeV)	122
Charge/bunch (pC)	80
RMS bunch 1 length (fs)	150
RMS bunch 2 length (fs)	165
Time distance (ps)	0.91 (0.019)

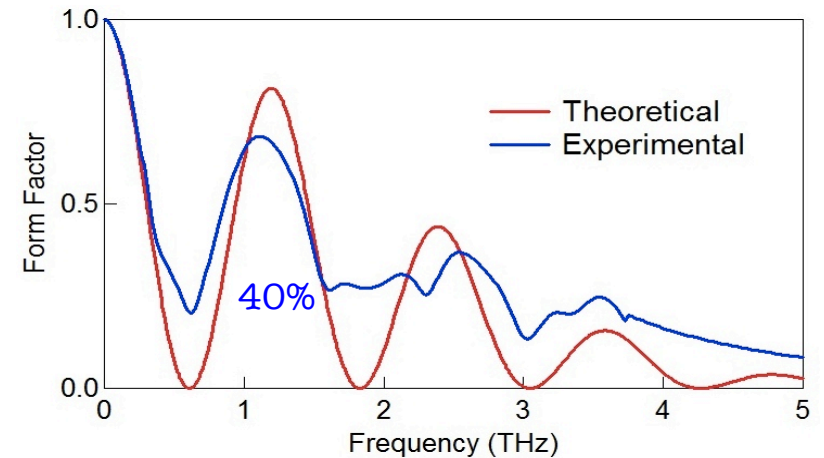
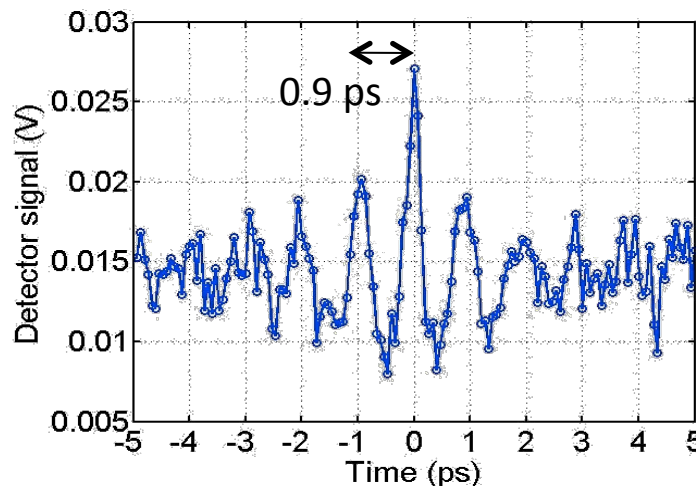
Measured Longitudinal Phase Space (LPS)



Current profile as measured at the end of the linac



Autocorrelation measurement of CTR with a Michelson interferometer



# Achieved THz Performances

Electron beam parameters	Single bunch (VB mode: max compression)	4-bunches per train (VB mode + laser comb)
Charge/bunch (pC)	300	50
Energy (MeV)	130	100
Bunch length (fs)	160	200
Rep. Rate (Hz)	10	

Radiation parameters	SPARC (single bunch)	SPARC (4-bunches/train)
Energy per pulse (J)	$40 \cdot 10^{-6}$	$0.6 \cdot 10^{-6}$ (@ 1 THz)
Peak power (MW)	> 100	3 (@ 1 THz)
Average power (W)	$1.8 \cdot 10^{-4}$	$6 \cdot 10^{-6}$
Electric field (kV/cm)	500	> 10
Pulse duration (fs)	160	< 100
Bandwidth (%)	broadband	< 25