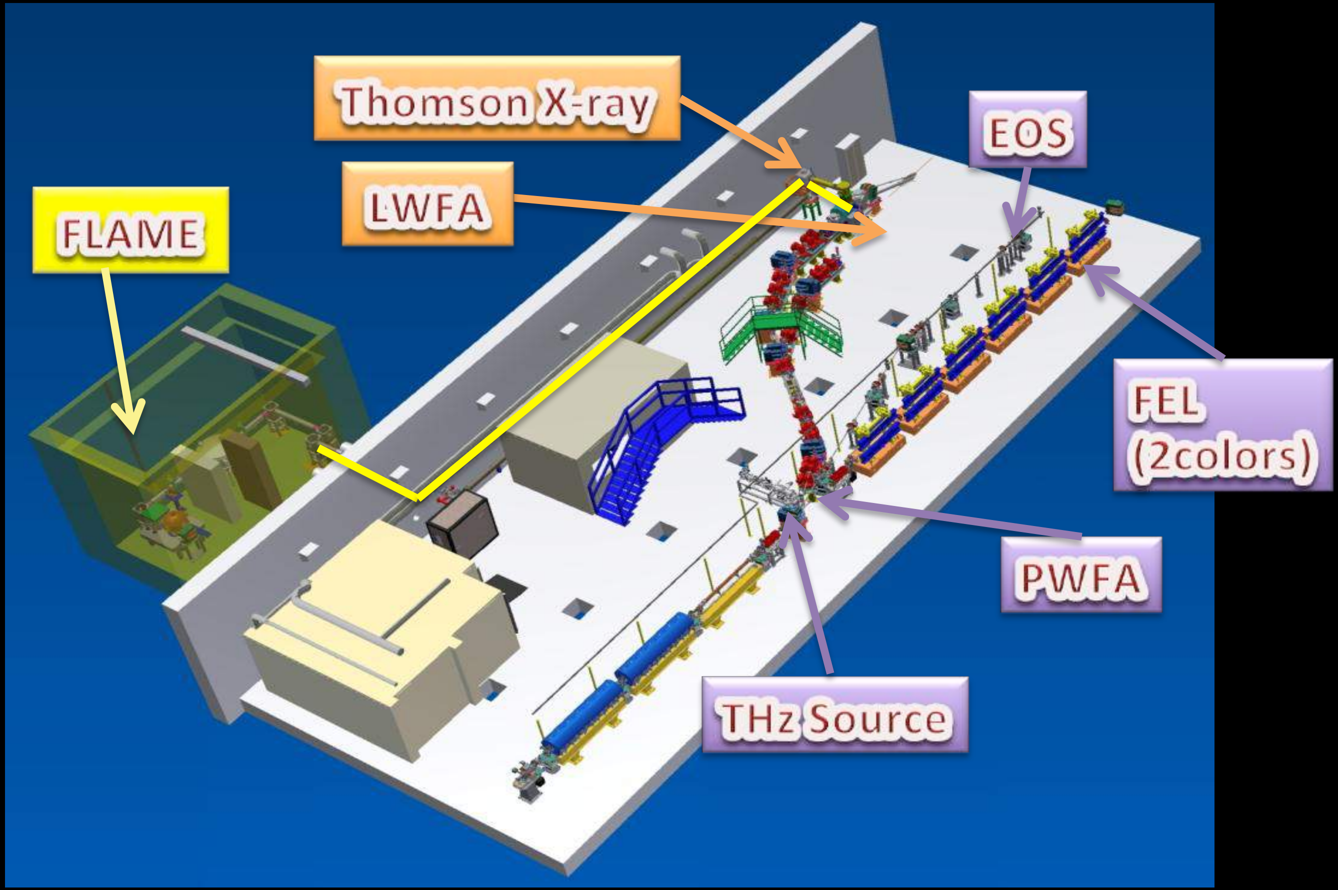
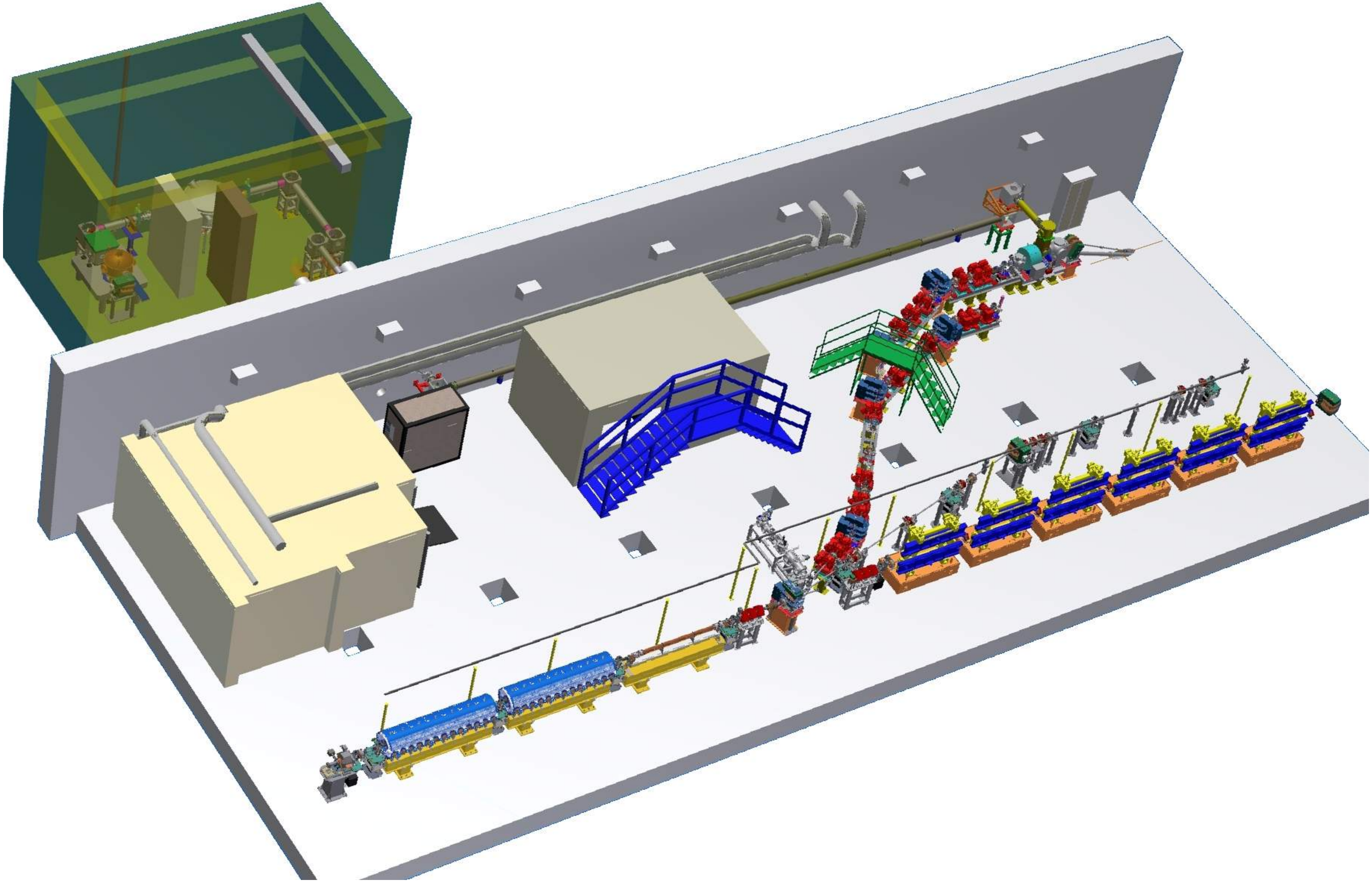
SPARC_LAB

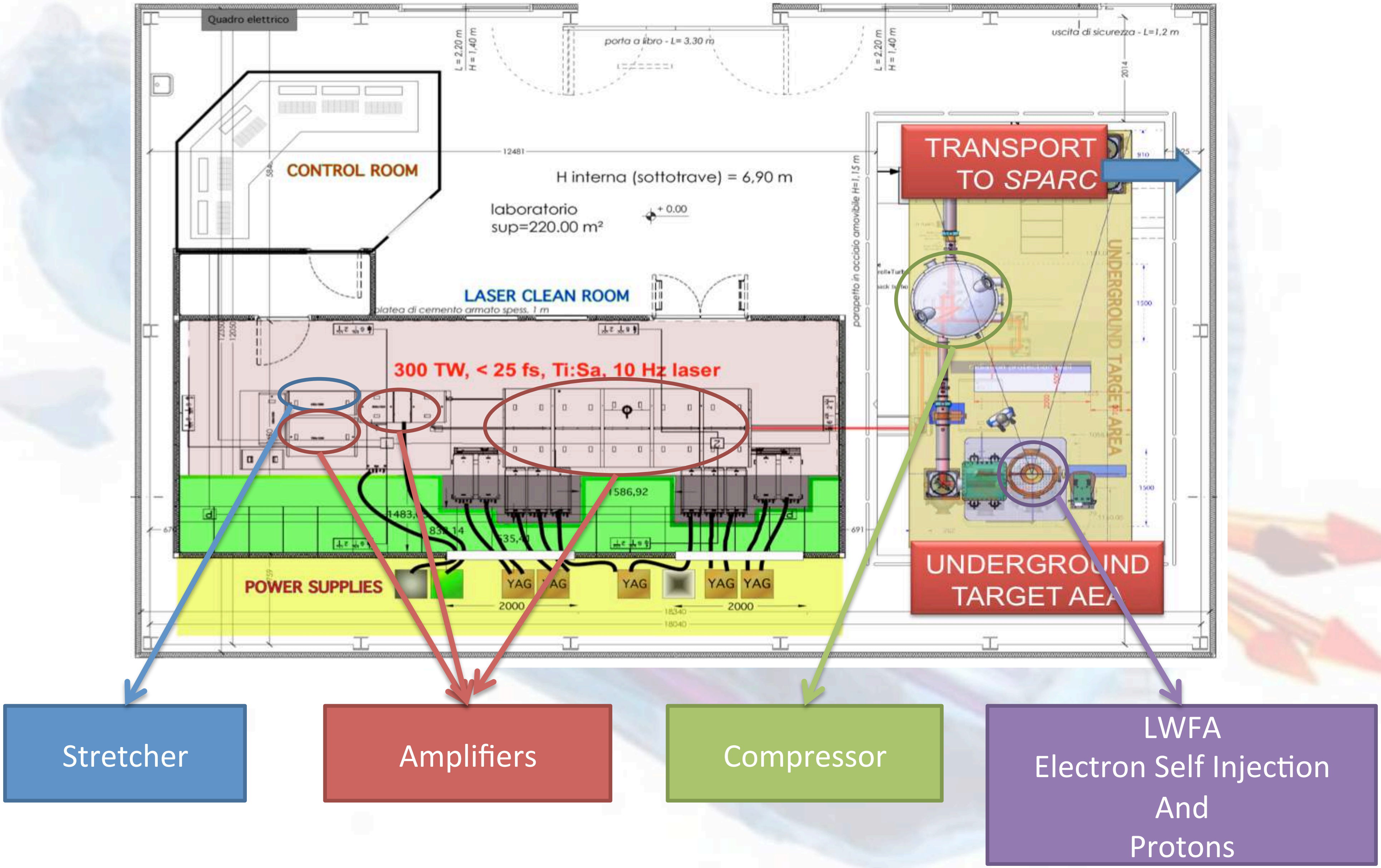
Sources for **P**lasma **A**ccelerators and **R**adiation **C**ompton with **L**asers **A**nd **B**eams

Massimo.Ferrario@LNF.INFN.IT





Ti:Sa FLAME laser



Stretcher

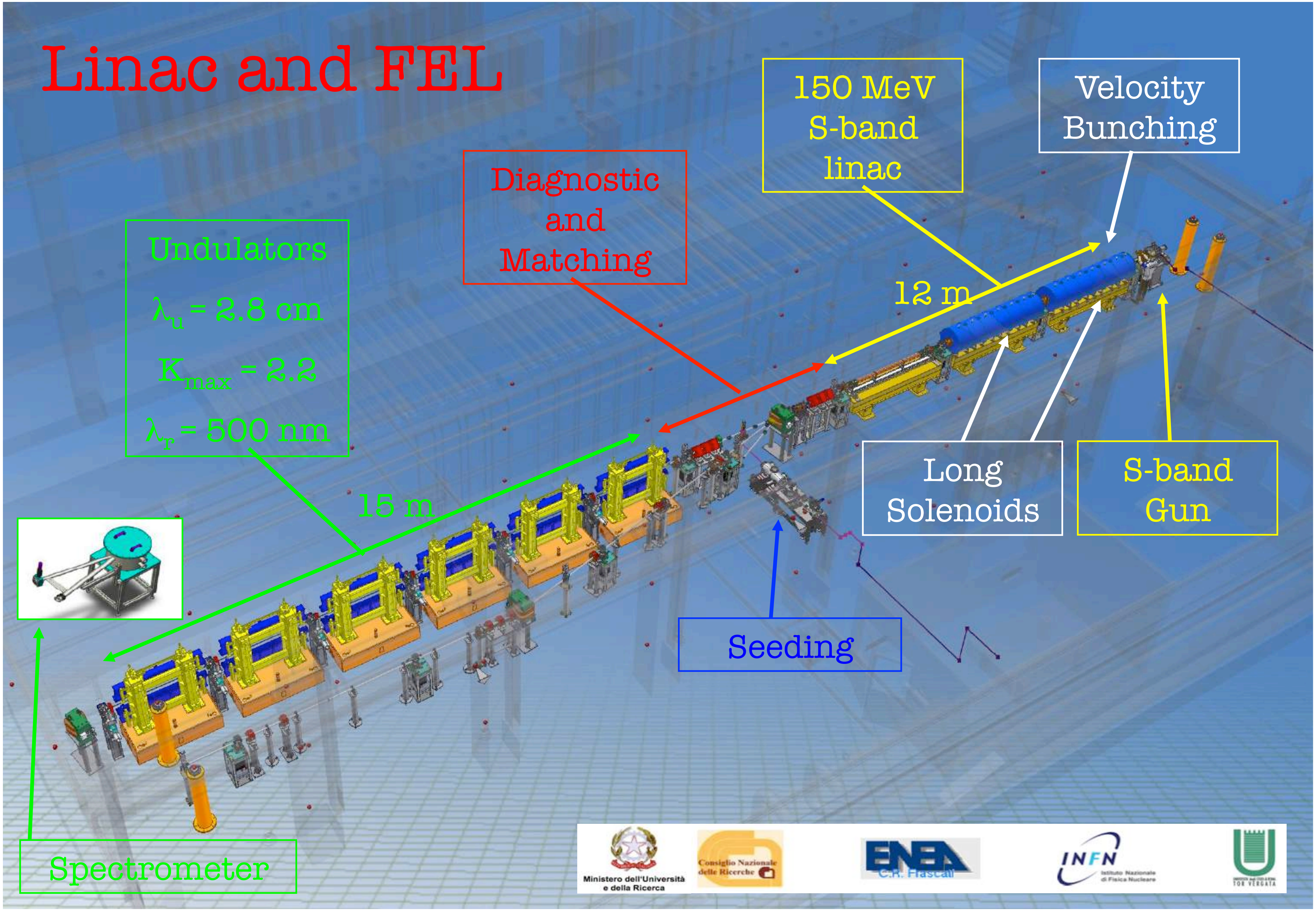
Amplifiers

Compressor

LWFA
Electron Self Injection
And
Protons

FLAME @ SPARC_LAB

Linac and FEL



150 MeV
S-band
linac

Velocity
Bunching

Diagnostic
and
Matching

Undulators

$\lambda_u = 2.8$ cm

$K_{max} = 2.2$

$\lambda_r = 500$ nm

12 m

15 m

Long
Solenoids

S-band
Gun

Seeding

Spectrometer

Ministero dell'Università
e della Ricerca

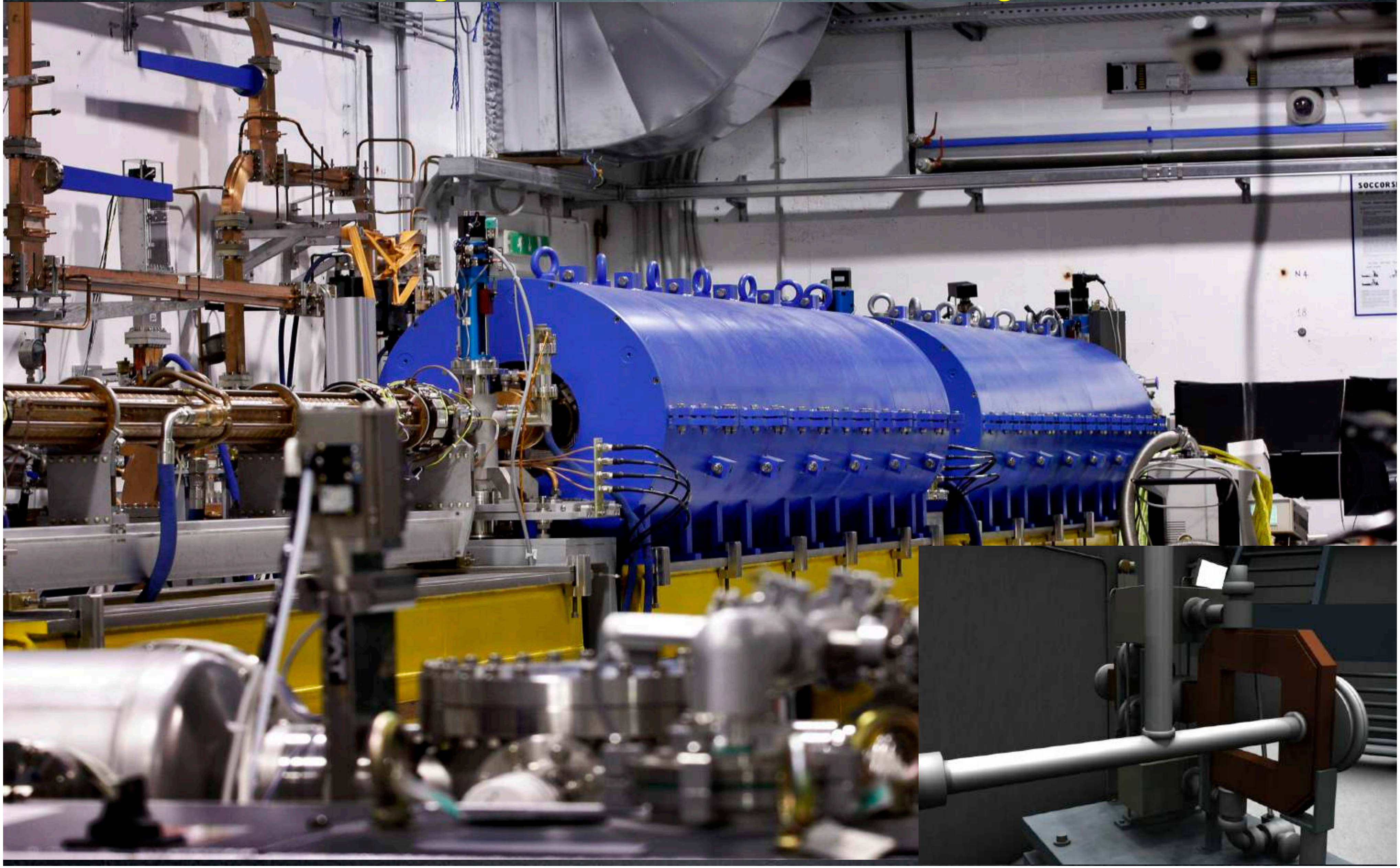
Consiglio Nazionale
delle Ricerche

ENEA
C.R. Frascati

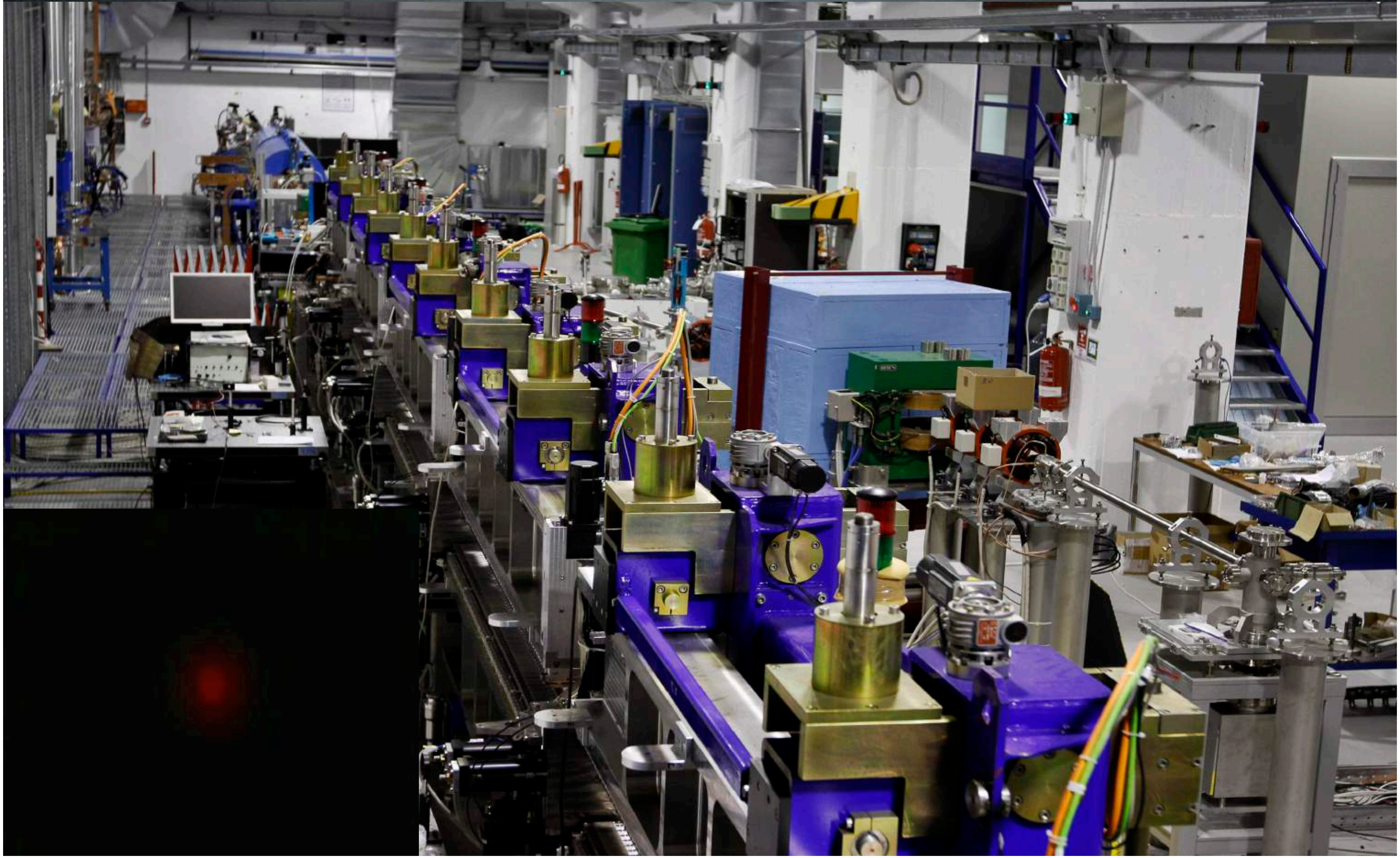
INFN
Istituto Nazionale
di Fisica Nucleare

Tor Vergata

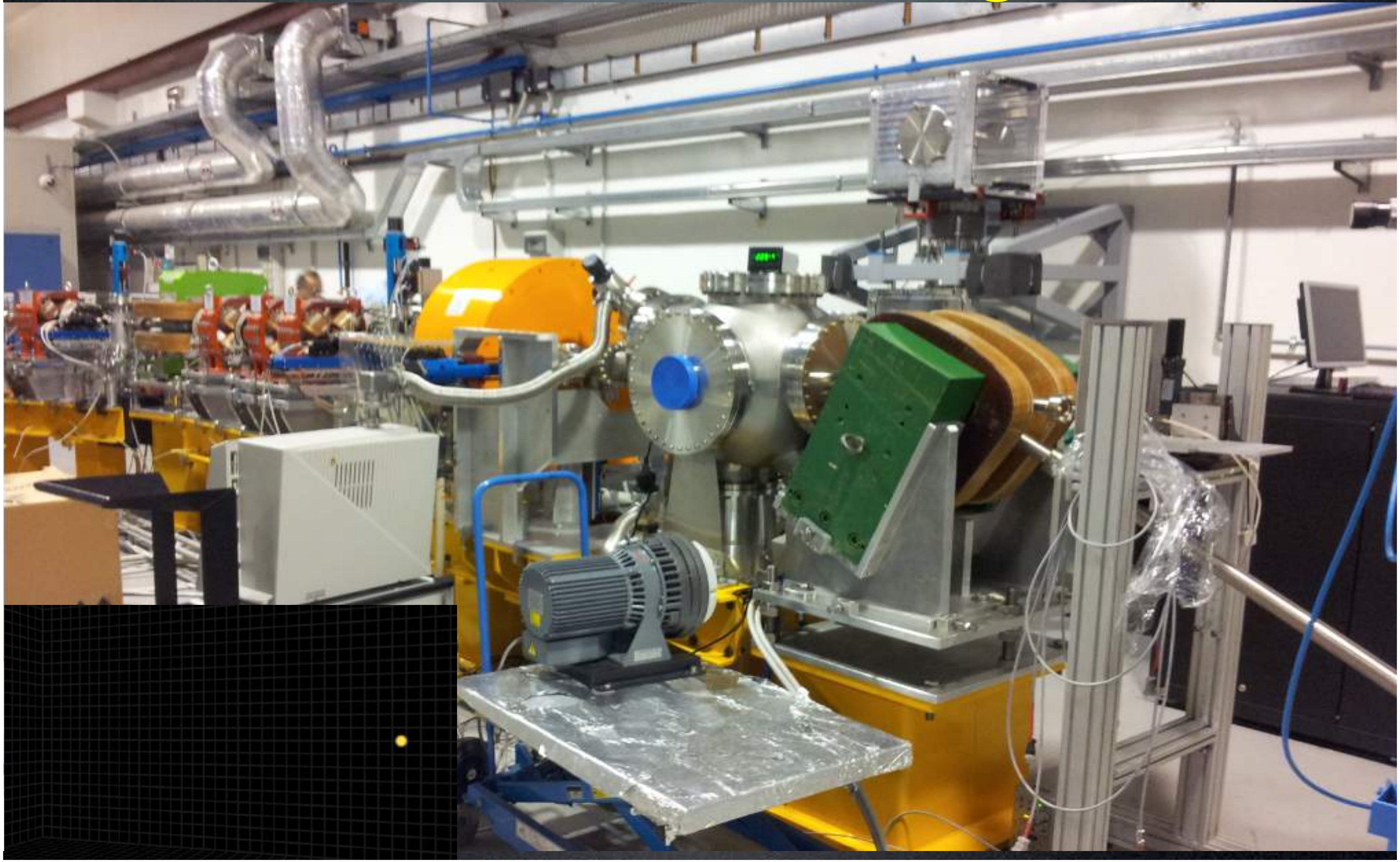
HB photo- injector with Velocity Bunching



Free Electron Laser

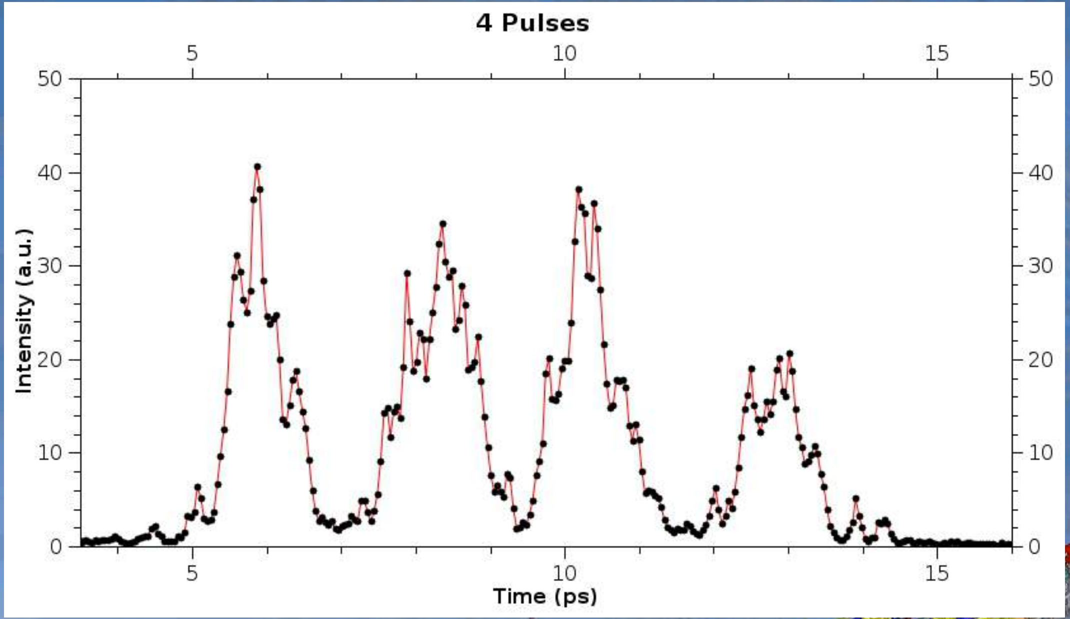


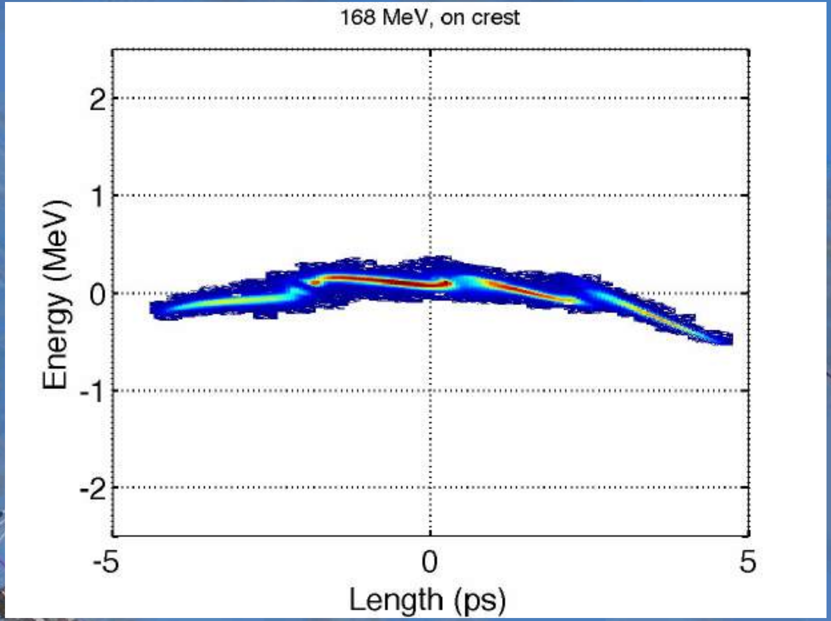
Thomson back-scattering source

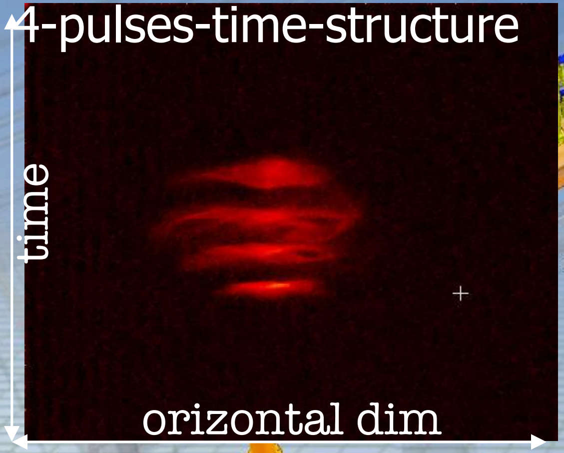


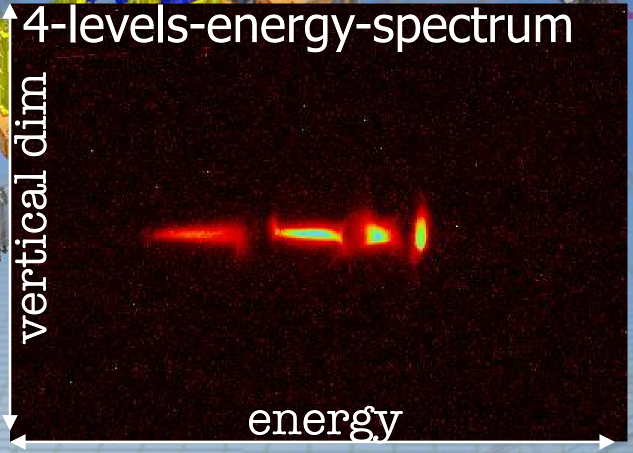
Laser Comb Technique

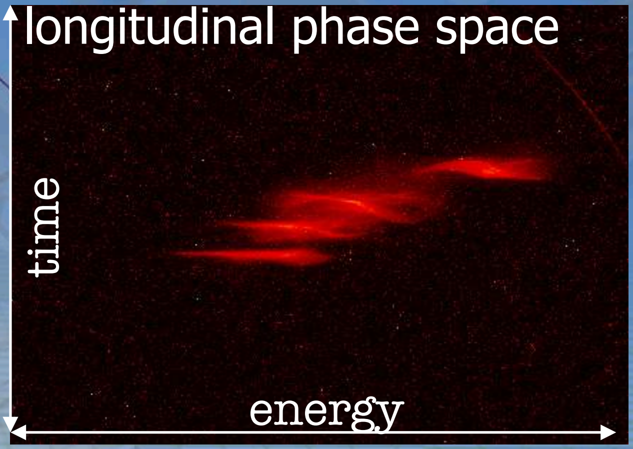
Laser COMB: experimental results







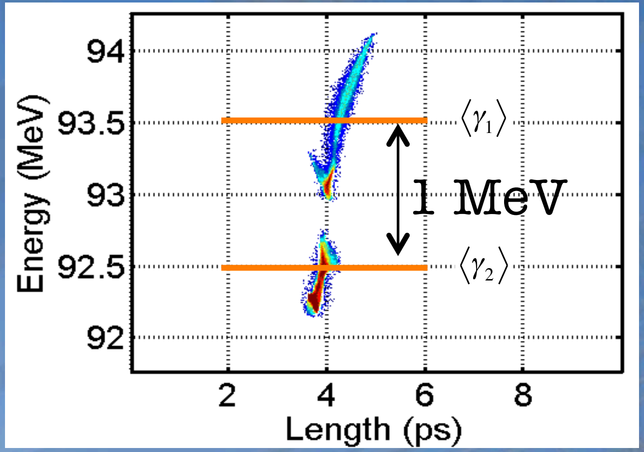




- M. Ferrario et al., Nucl. Inst. and Meth, A 637 (2011)

TWO COLORS FEL

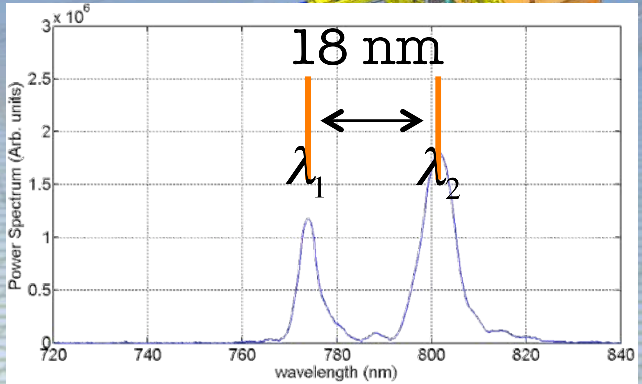
TWO COLORS SASE FEL



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

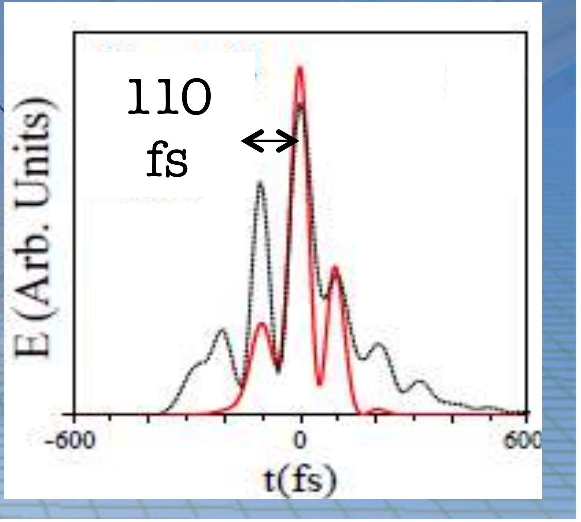
$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1+K_{rms}^2\right)$$

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



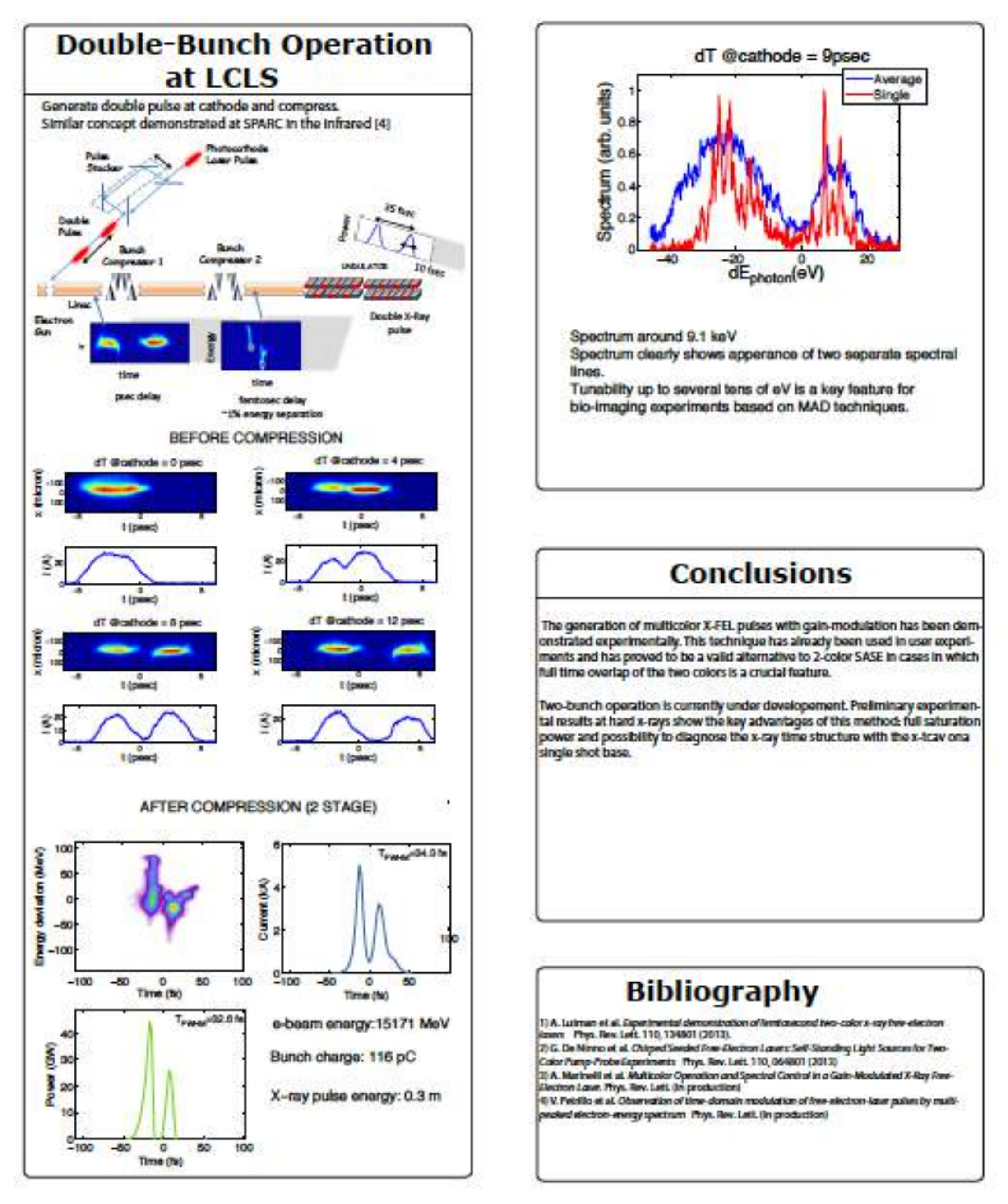
produce two wavelength
SASE –FEL radiation
with time modulation

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



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)

e-beam energy:15171 MeV

Bunch charge: 116 pC

X-ray pulse energy: 0.3 m

Spectrum around 9.1 keV
Spectrum clearly shows apperance 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.

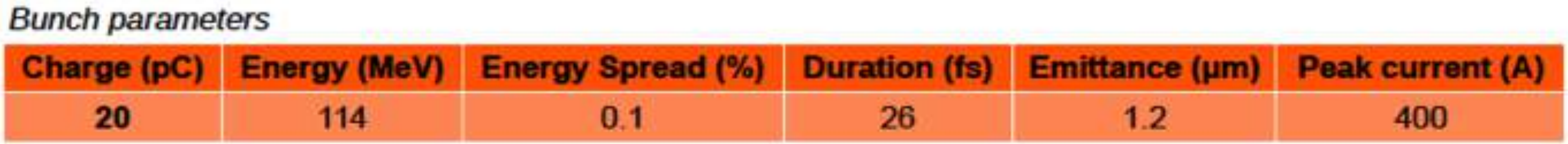
Two-bunch operation is currently under developement. Preliminary experimental results at hard x-rays show the key advantages of this method: full saturation power and possibility to diagnose the x-ray time structure with the x-tcav on a single shot base.

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 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. Petrillo et al. *Observation of time-domain modulation of free-electron-laser pulses by multi-peaked electron-energy spectrum* Phys. Rev. Lett. (in production)

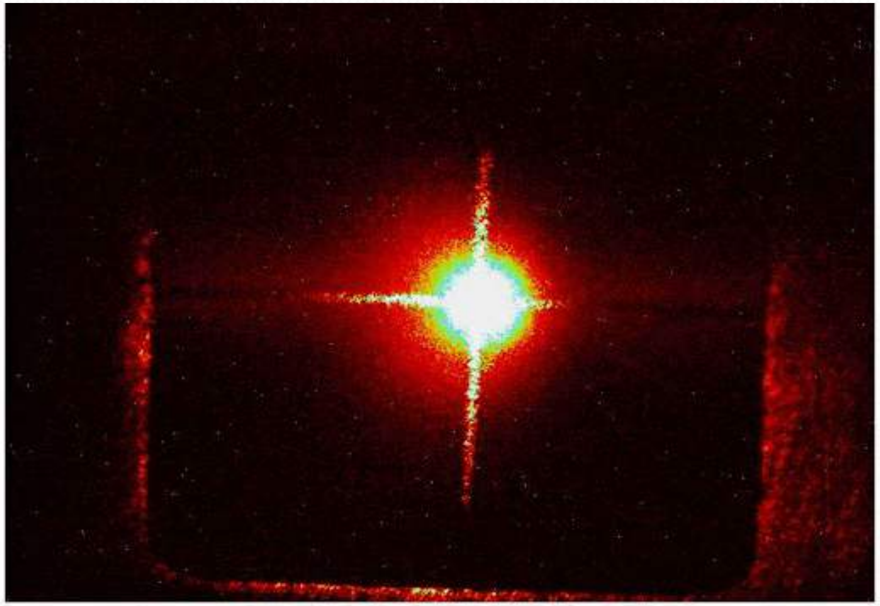
Single Spike FEL

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.

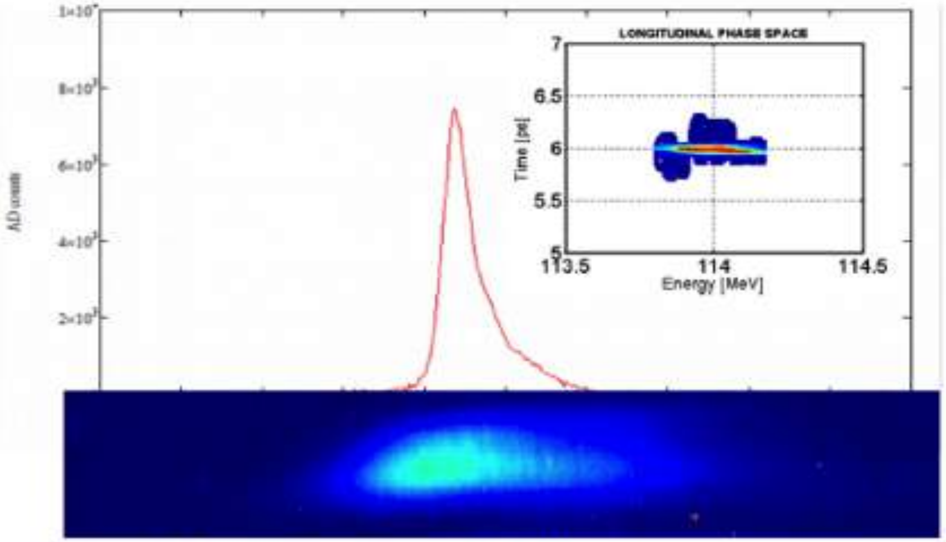


Bunch parameters

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

SPARC_LAB: Some achievements

Beam Dynamics

Direct Measurement of the Double Emittance Minimum in the Beam Dynamics of the SPARC High-Brightness Photoinjector
M. Ferrario et al., PRL **99**, 234801 (2007)

Experimental Demonstration of Emittance Compensation with Velocity Bunching
M. Ferrario et al., PRL **104**, 054801 (2010)

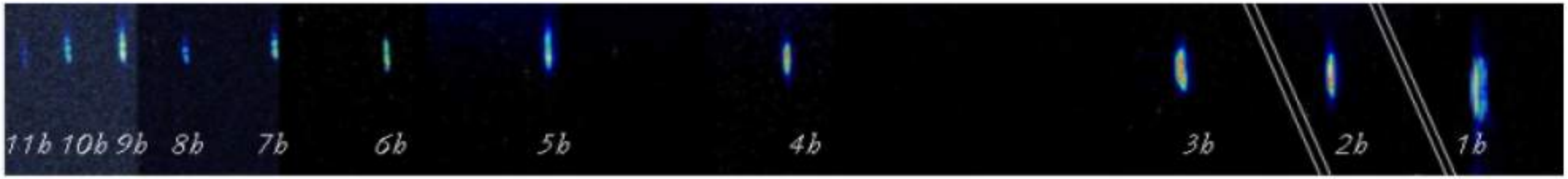
FEL

Self-Amplified Spontaneous Emission Free-electron Laser with an Energy-Chirped Electron Beam and Undulator Tapering
L. Giannessi et al., PRL **106**, 144801 (2011)

Seeded FEL

High-Gain Harmonic-Generation and Superradiance Free-electron Laser Seeded by Harmonics Generated in Gas
M. Labat et al., PRL **107**, 224801 (2011)

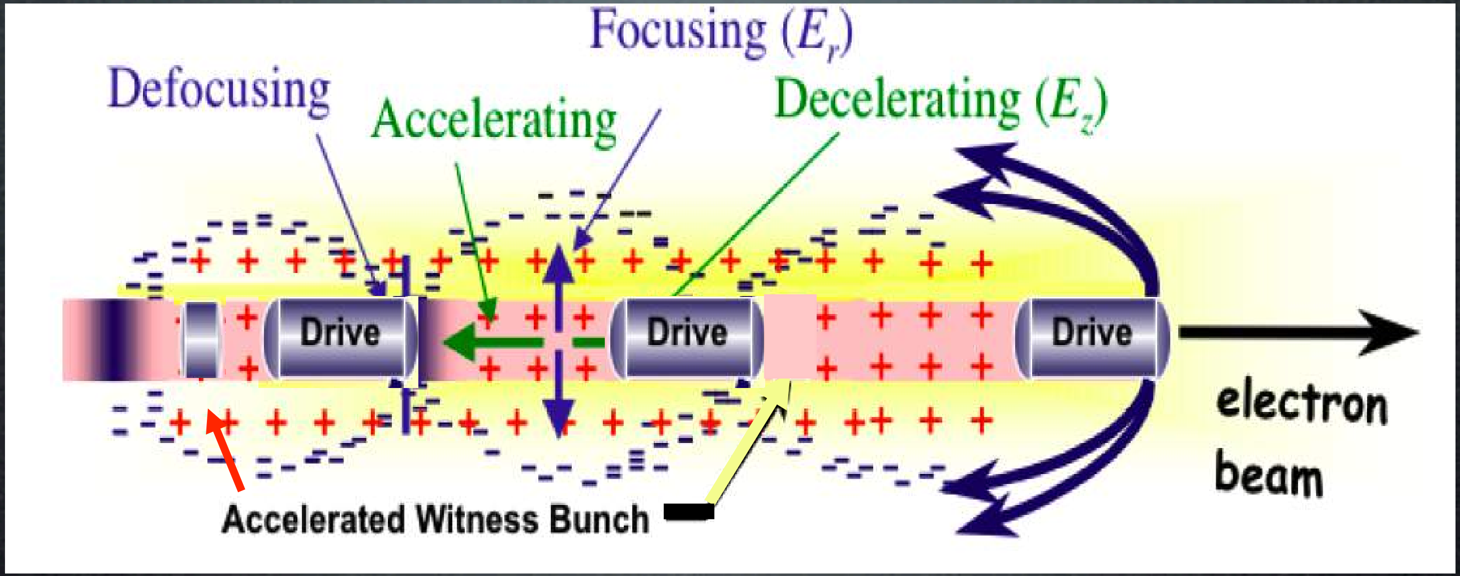
High-Order- Harmonic Generation and Superradiance in a Seeded Free-electron Laser
L. Giannessi et al., PRL **108**, 164801 (2012)



Superradiant Cascade in a Seeded Free-electron Laser
L. Giannessi et al., PRL **110**, 044801 (2013)

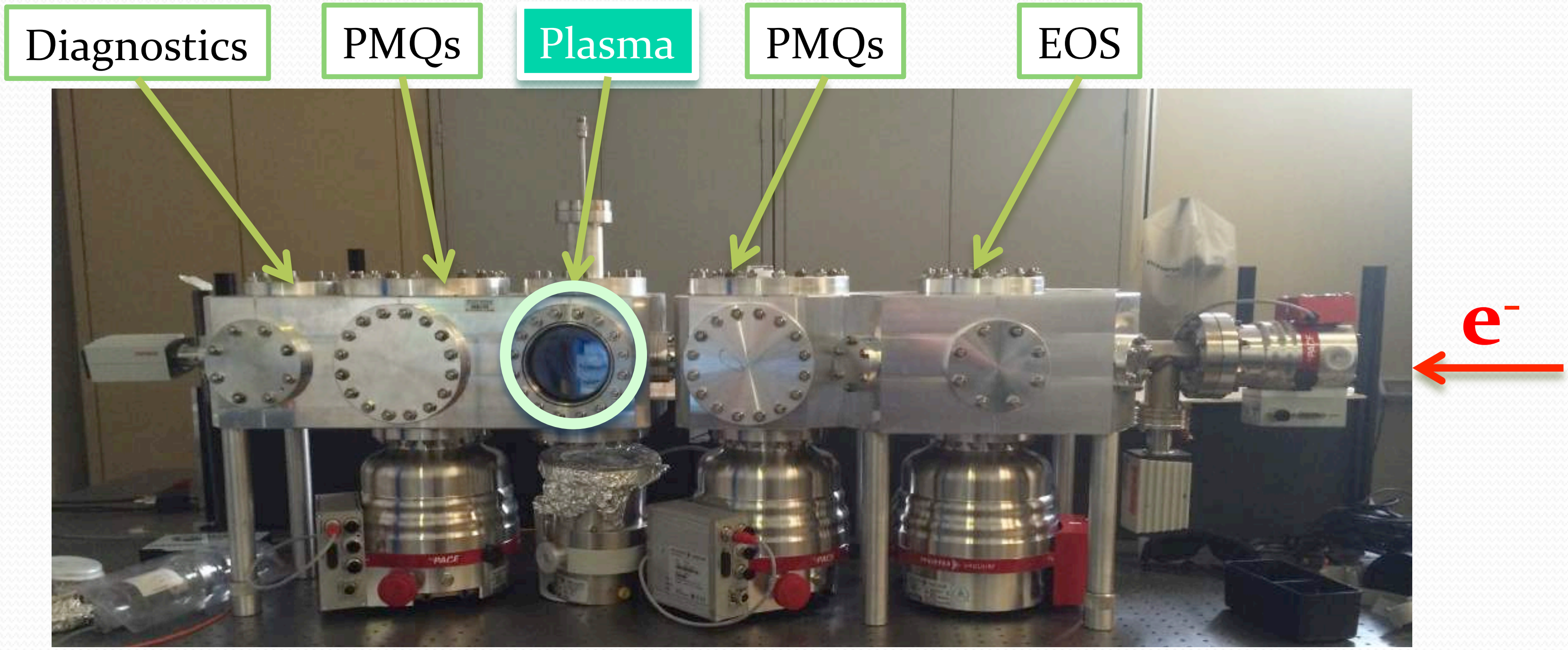
Particle Wake Field Acc.

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 tranformer ratio?
- **High quality bunch** preservation during acceleration and transport?

Plasma based acceleration

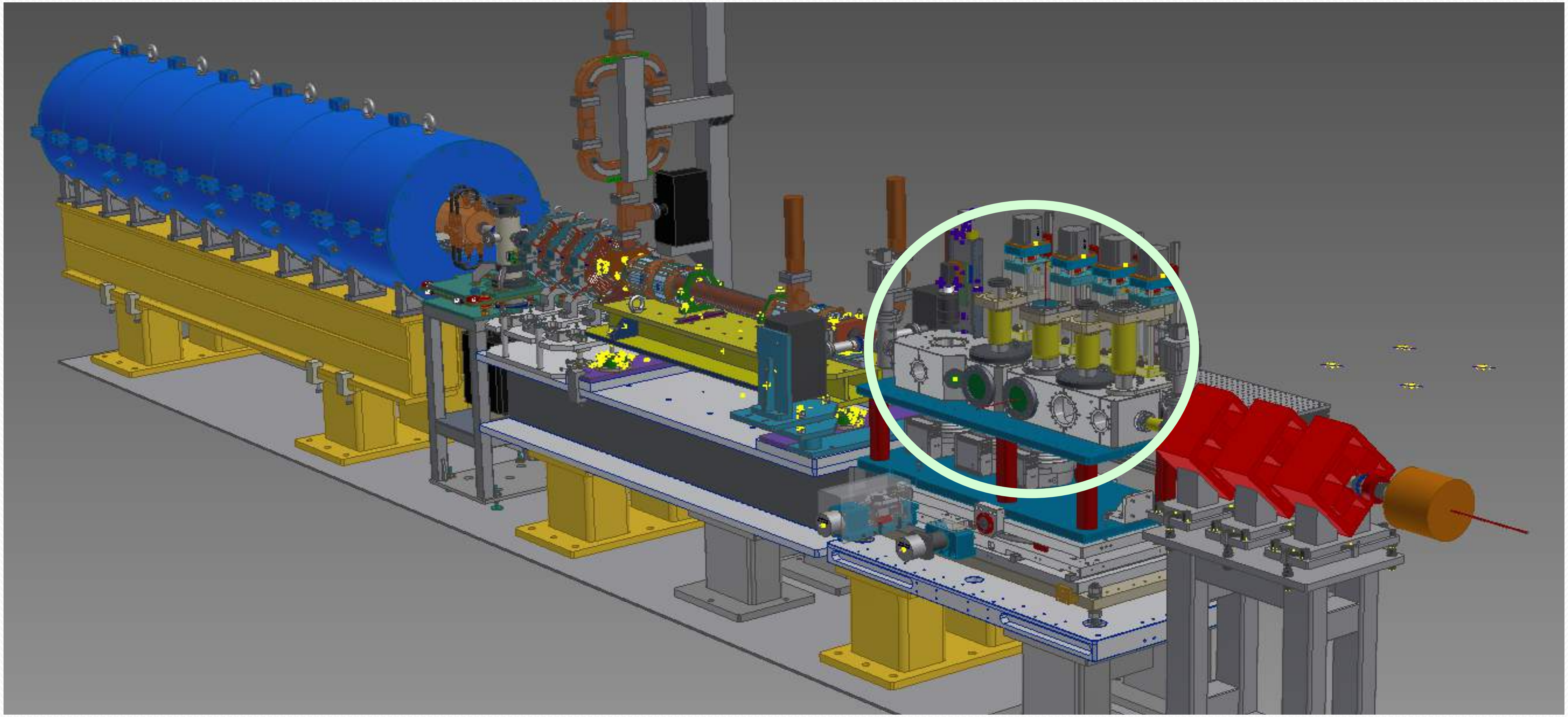


The vacuum chamber has been designed to have the best vacuum performances, in order to guarantee the ultra-high vacuum level at the exit of the last accelerating structure ($5*10^{-8}$ mbar).

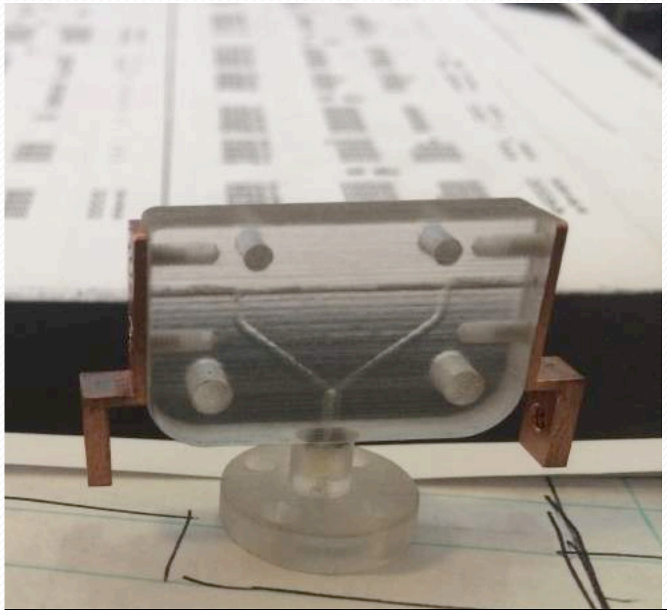
Vacuum tests show that we can run the plasma at 5 Hz without problems (vacuum level $7*10^{-8}$ mbar), while 10 Hz operations seems feasible, but – in case – will need to be tested on the machine (vacuum level $1*10^{-7}$ mbar achieved)!

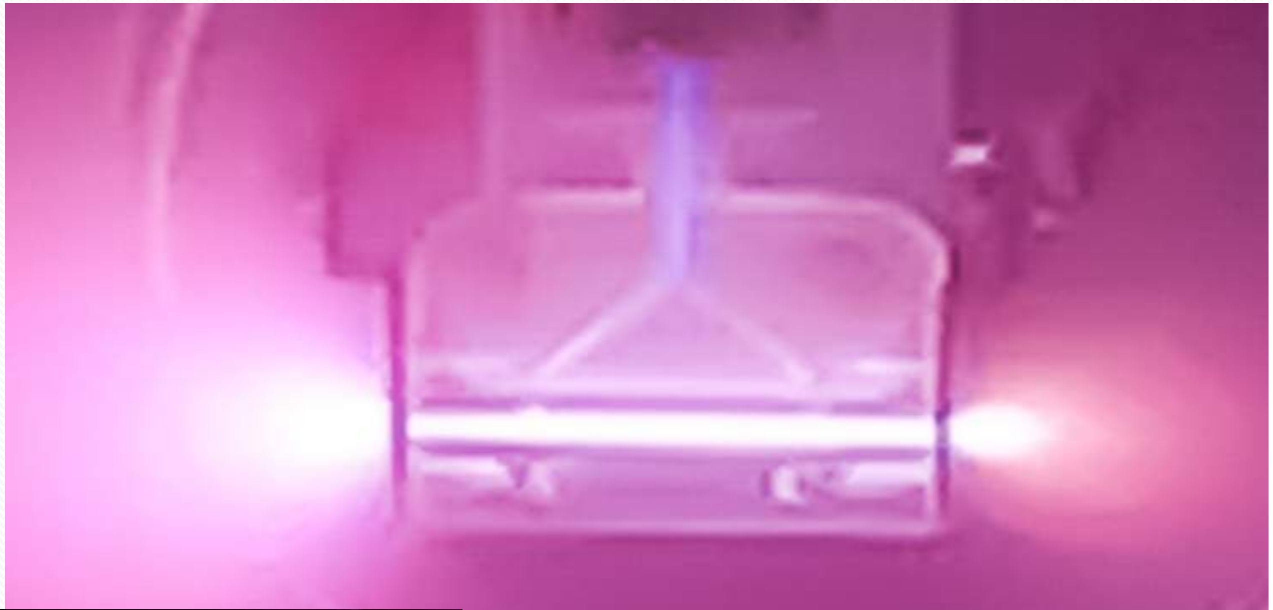
Plasma based acceleration

Final layout: 2 S-band cavities, 1 C-band cavity + 1 plasma stage.



Plasma based acceleration

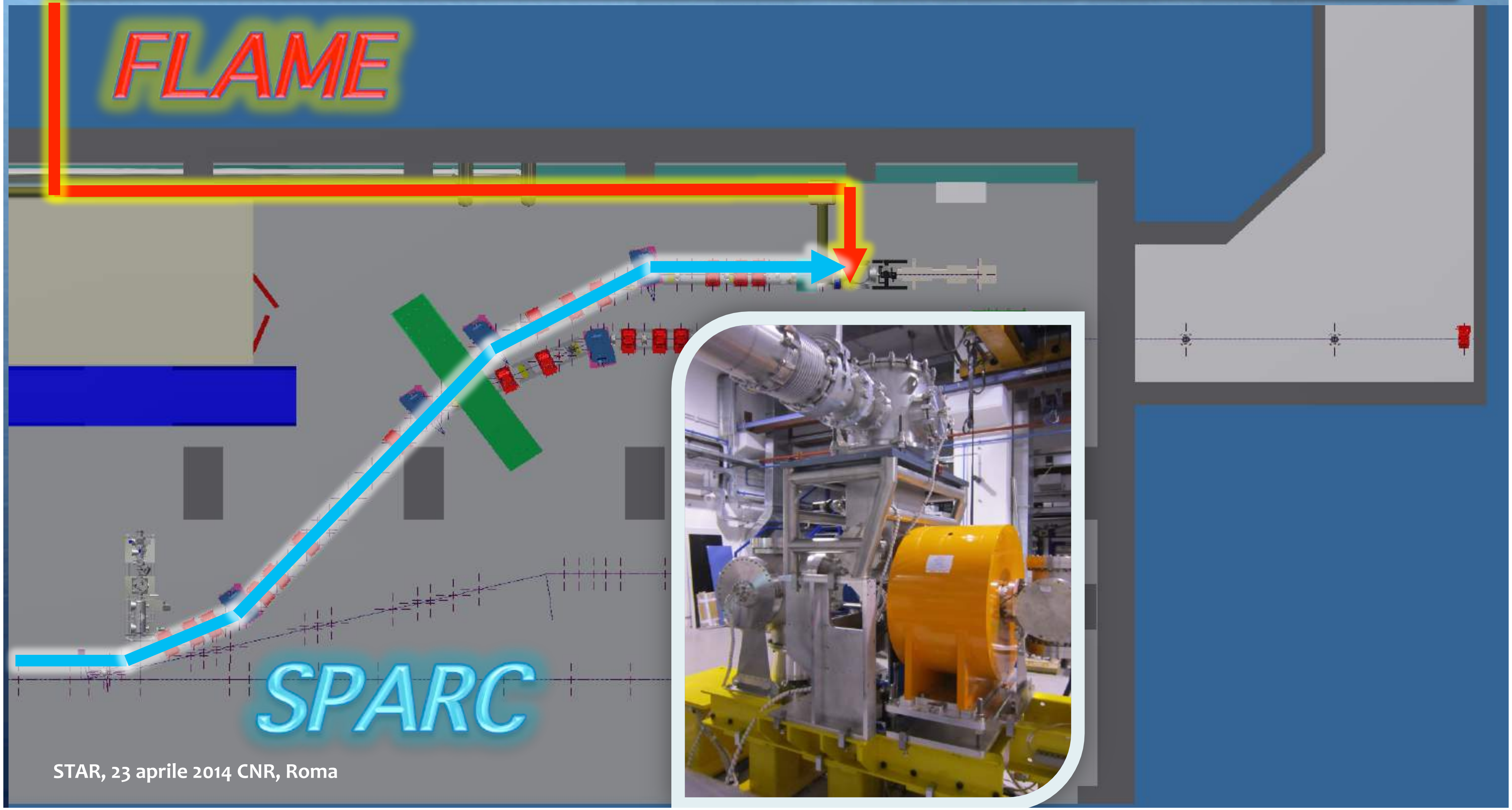




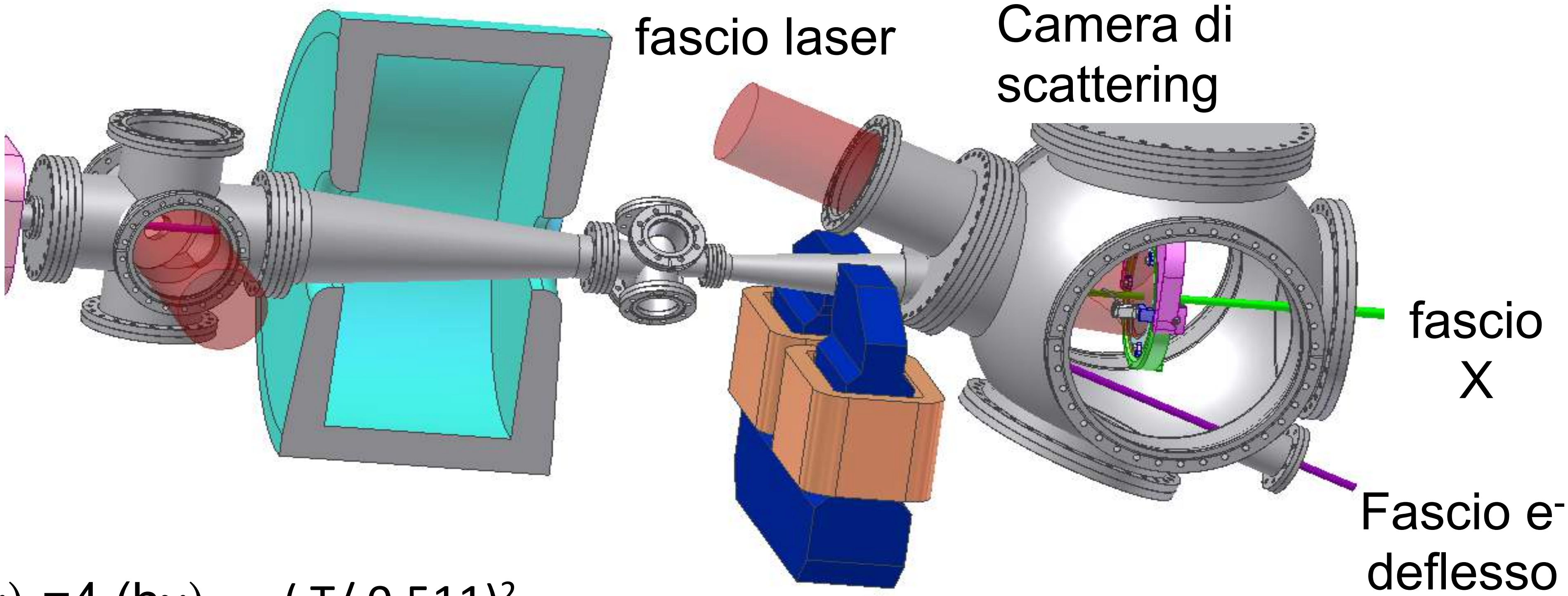
First plasma discharges.

Thomson backscattering

SL-Thomson Source at SPARCLAB



Thomson Interaction region (20-550 keV)



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

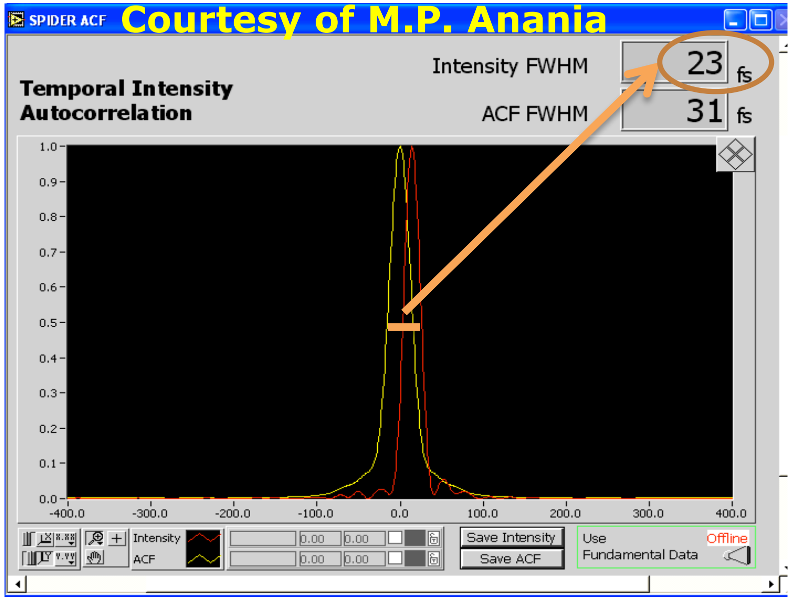
$(h\nu)_{laser} = 1.2$ eV
T =30.28 MeV
$(h\nu)_X$ = 20 keV mammografia

Impulso laser: 6 ps, 5 J
pacchetto e$^-$: 1 nC , l: 2 mm (rms)
Impulso X: 10 ps, 10^9 fotoni
α emissione: 12 mrad

Thomson back-scattering source

Electron Beam Experimental Studies

- Thomson backscattering experiments



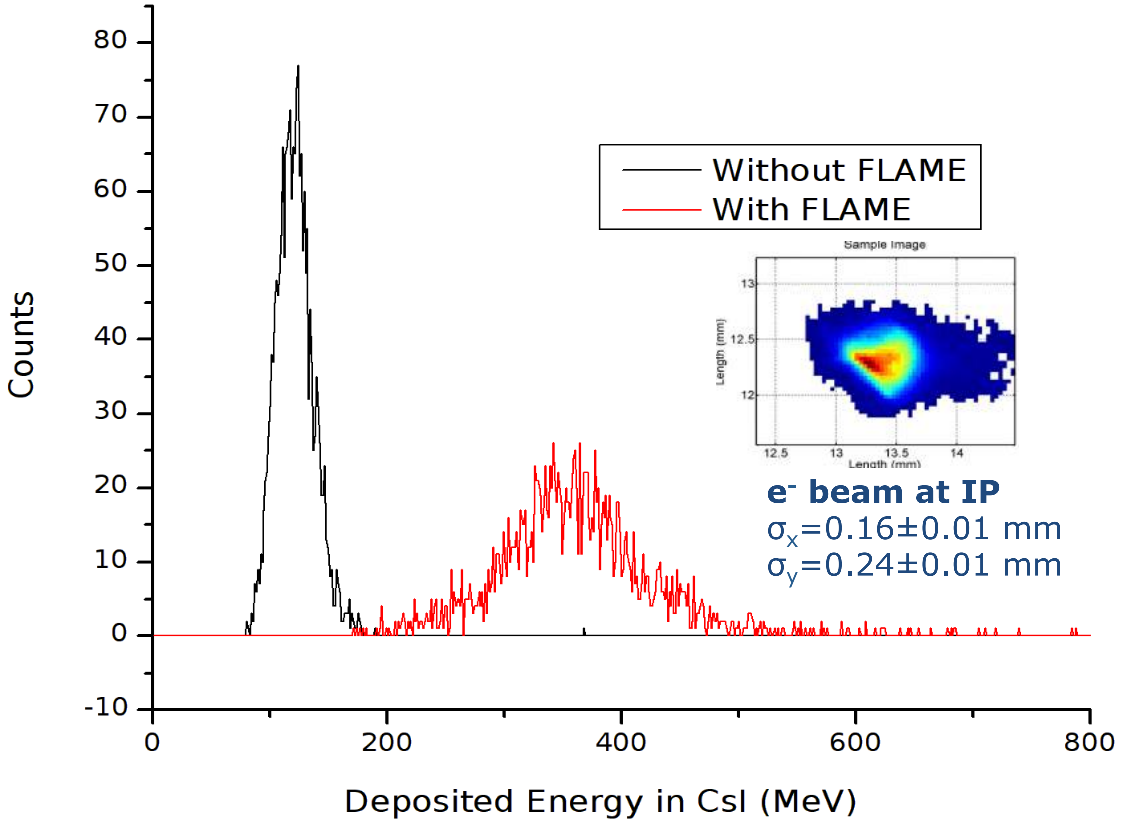
Courtesy of M.P. Anania

Temporal Intensity Autocorrelation

Intensity FWHM 23 fs

ACF FWHM 31 fs

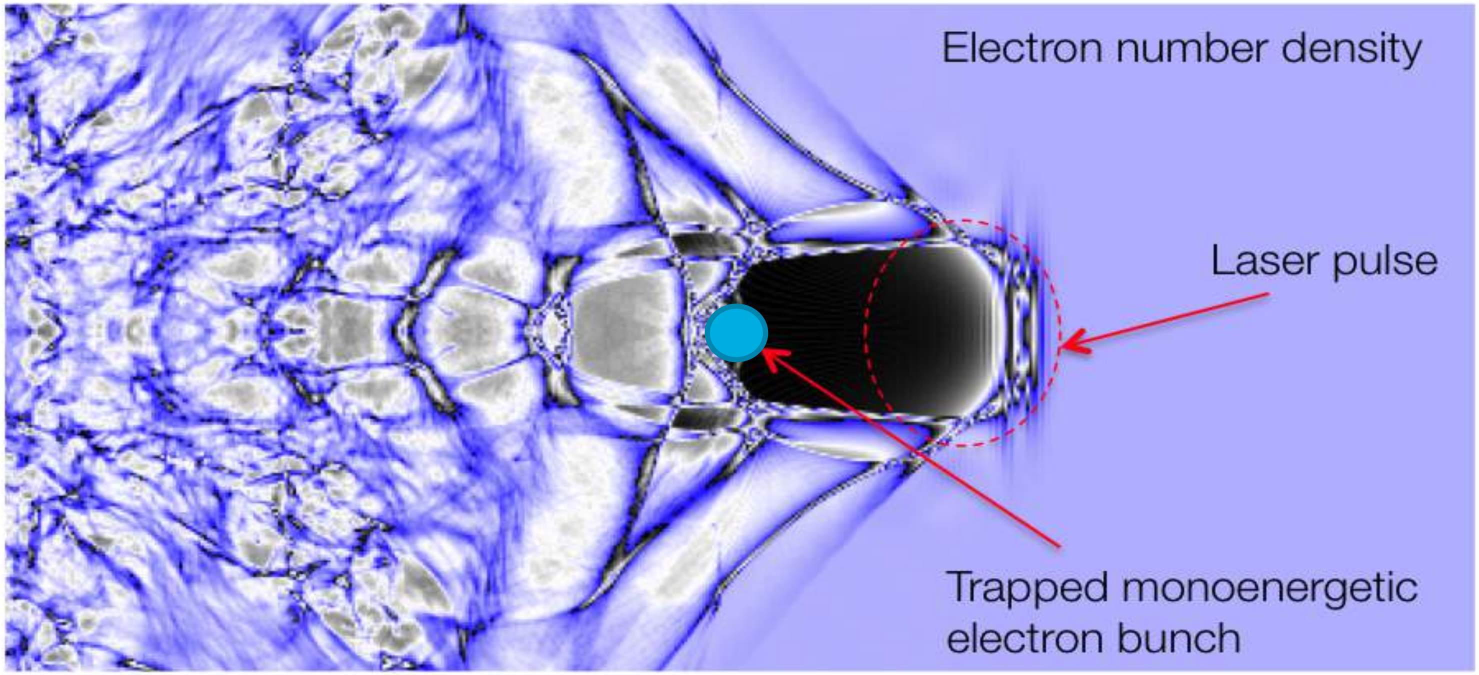
Max energy: 7J
Max energy on target: ~ 5J
Min bunch duration: 23 fs
Wavelength: 800 nm
Bandwidth: 60/80 nm
Spot-size @ focus: 10 μm
Max power: ~ 300 TW
Contrast ratio: 10^{10}



e^- beam at IP
$\sigma_x = 0.16 \pm 0.01$ mm
$\sigma_y = 0.24 \pm 0.01$ mm

Laser Wake Field Acc.

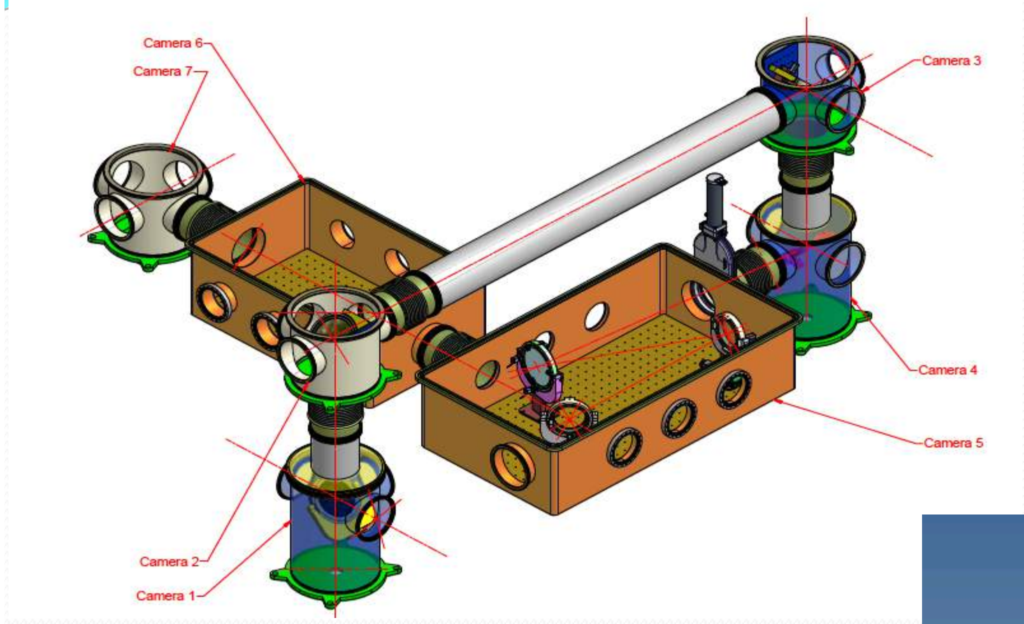
External injection



Electrons accelerated by the linac injected with the right phase on the creast of the wakefield to be further accelerated.

Expected electrons at the plasma exit with a higher energy and a quality comparable to that of incoming electron beam.

External injection



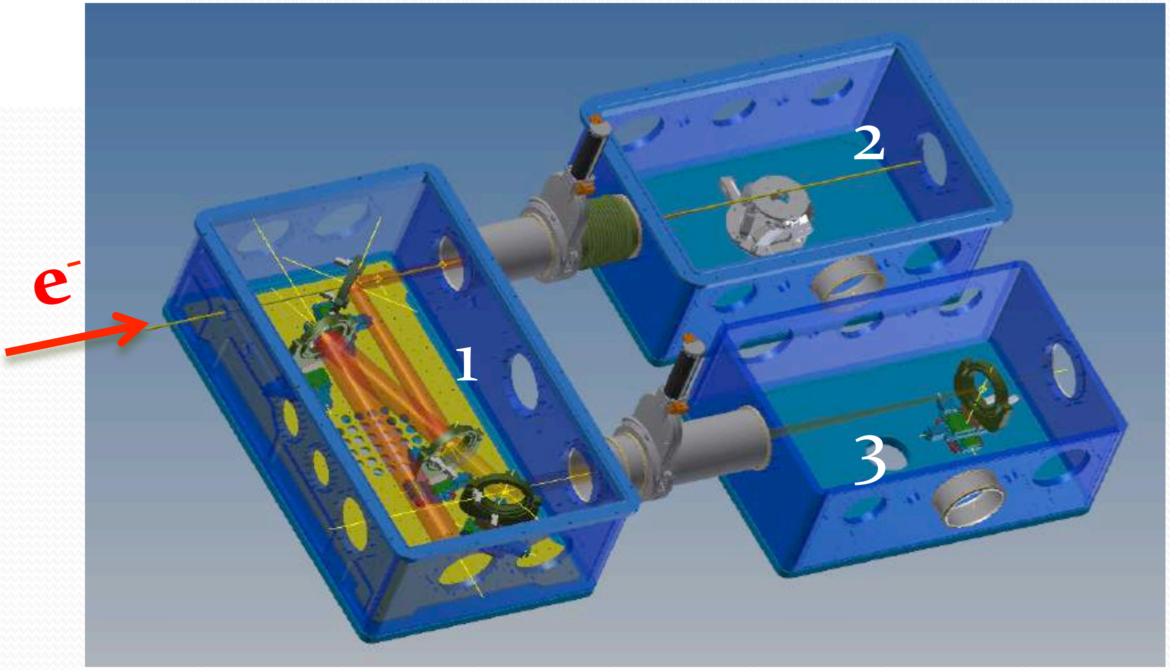
Design of the vacuum chamber for the laser transport.

1st chamber is for mirrors and 3 m focal length off-axis parabola,

2nd chamber is for interaction and 3rd chamber is for diagnostics.

Movements of the capillary (filled with H2) will be made with hexapod.

Synchronization: needs to be at the fs level.

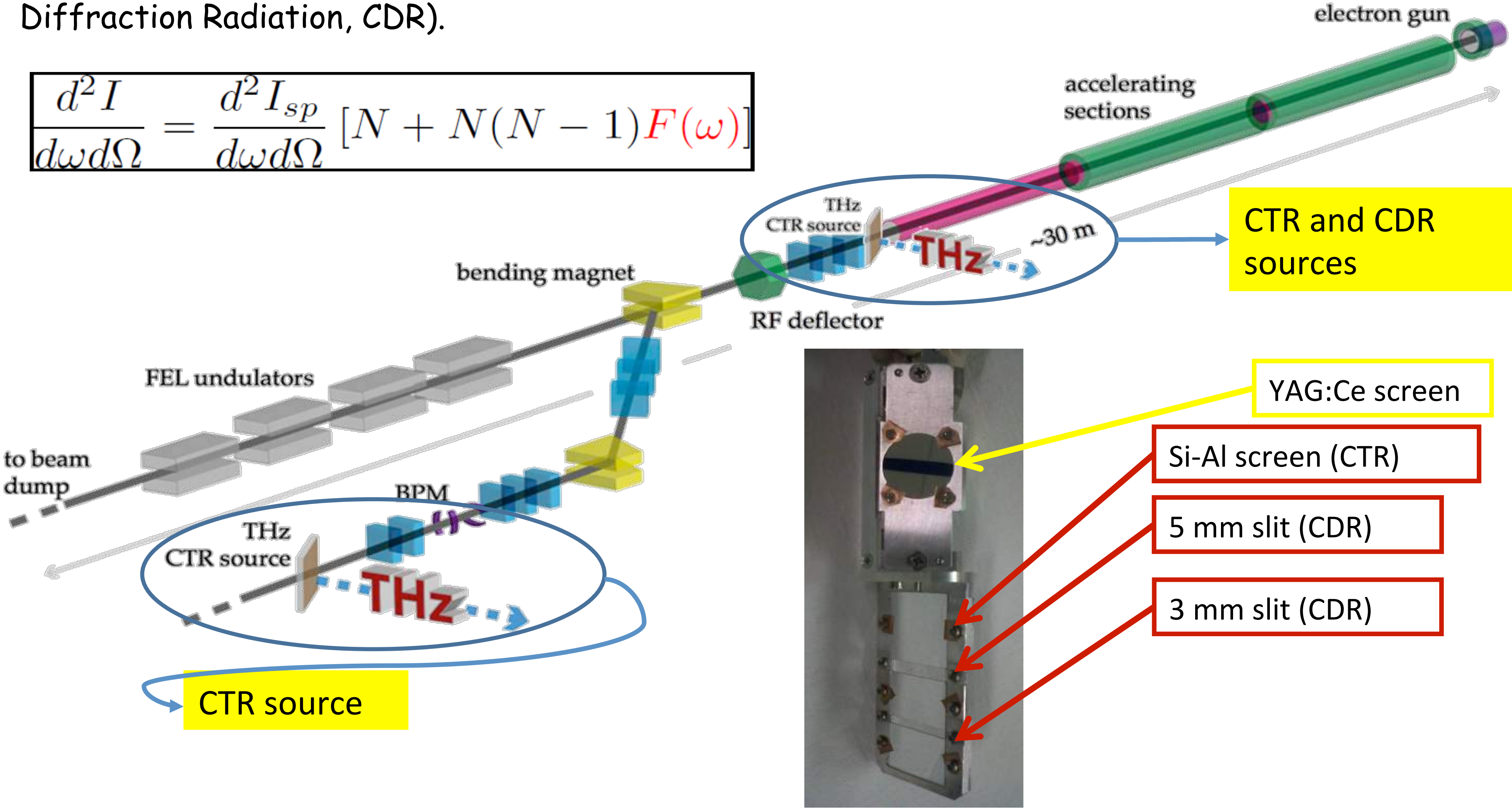


THz Source

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).

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



CTR and CDR sources

CTR source

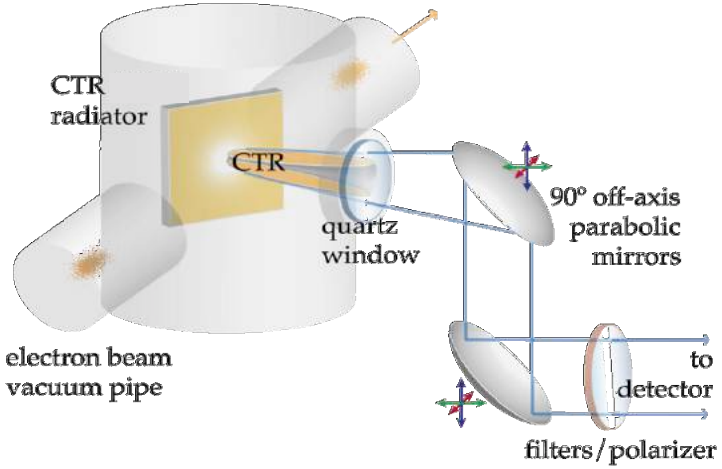
YAG:Ce screen

Si-Al screen (CTR)

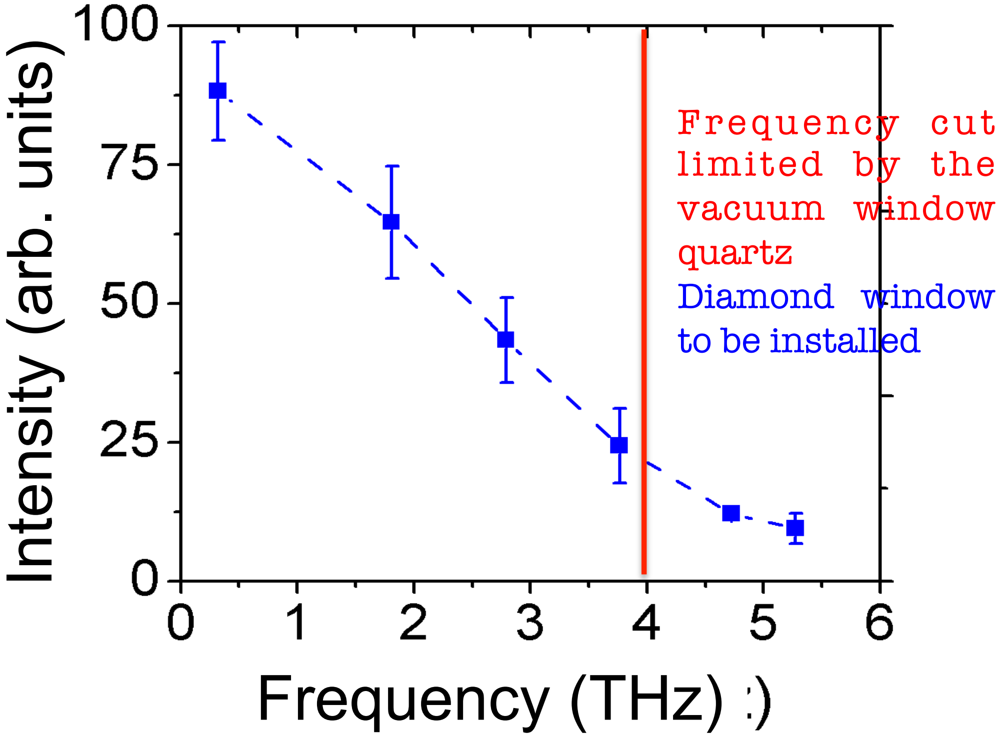
5 mm slit (CDR)

3 mm slit (CDR)

Broad-band THz radiation: Measurements



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



Frequency cut limited by the vacuum window quartz

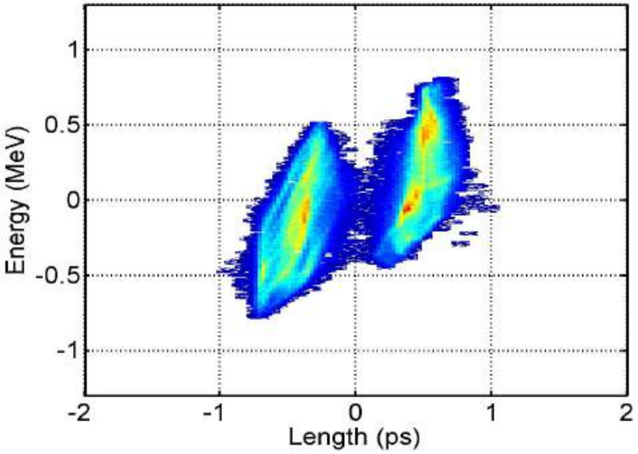
Diamond window to be installed

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

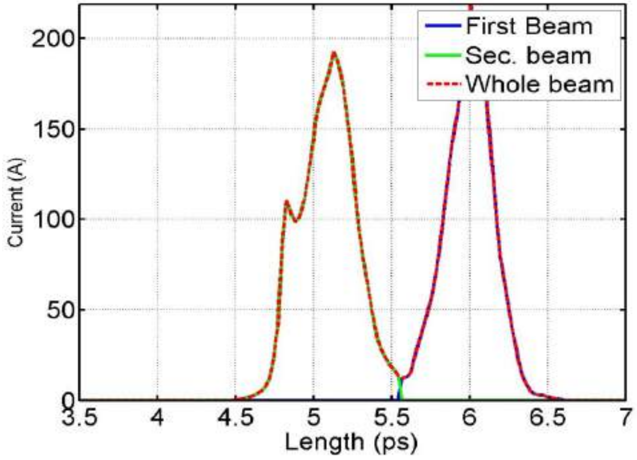
Narrow-band THz radiation:
2-bunches train measurements

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)

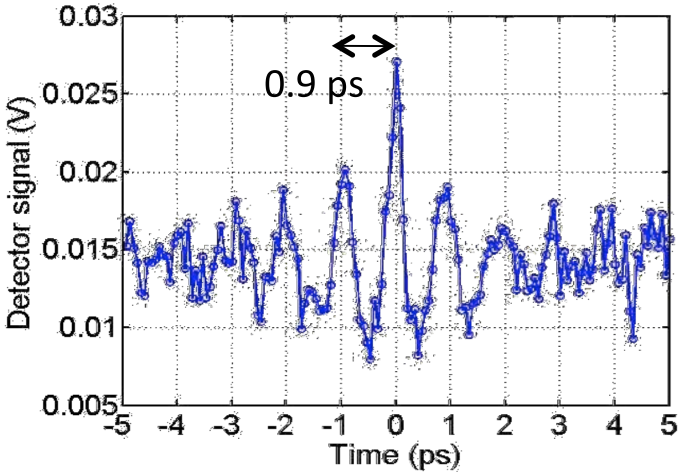
Measured Longitudinal Phase Space (LPS)

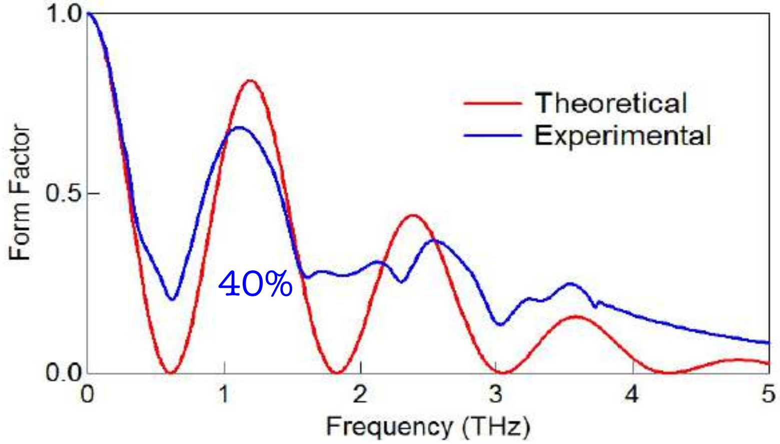


Current profile as measured at the end of the linac



Autocorrelation measurement of CTR with a Michelson interferometer





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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)	$40\ 10^{-6}$	$0.6\ 10^{-6}$ (@ 1 THz)
Peak power (MW)	> 100	3 (@ 1 THz)
Average power (W)	$1.8\ 10^{-4}$	$6\ 10^{-6}$
Electric field (kV/cm)	500	> 10
Pulse duration (fs)	160	< 100
Bandwidth (%)	broadband	< 25

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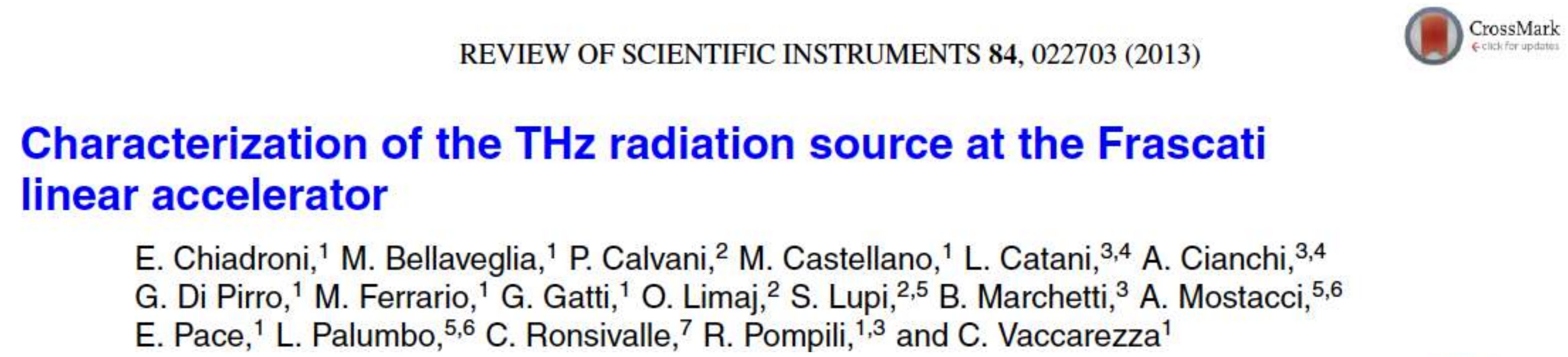
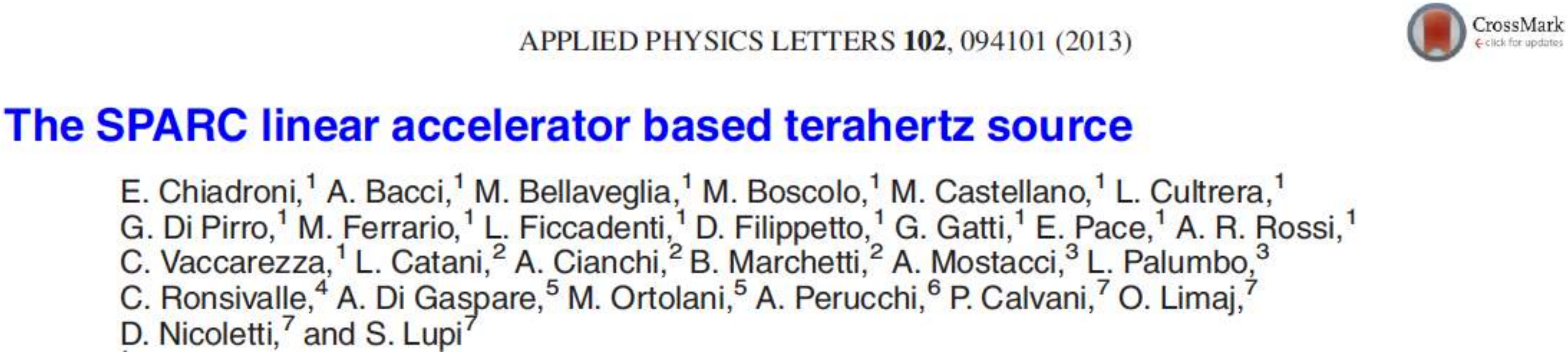


REVIEW OF SCIENTIFIC INSTRUMENTS **84**, 022703 (2013)

Characterization of the THz radiation source at the Frascati linear accelerator

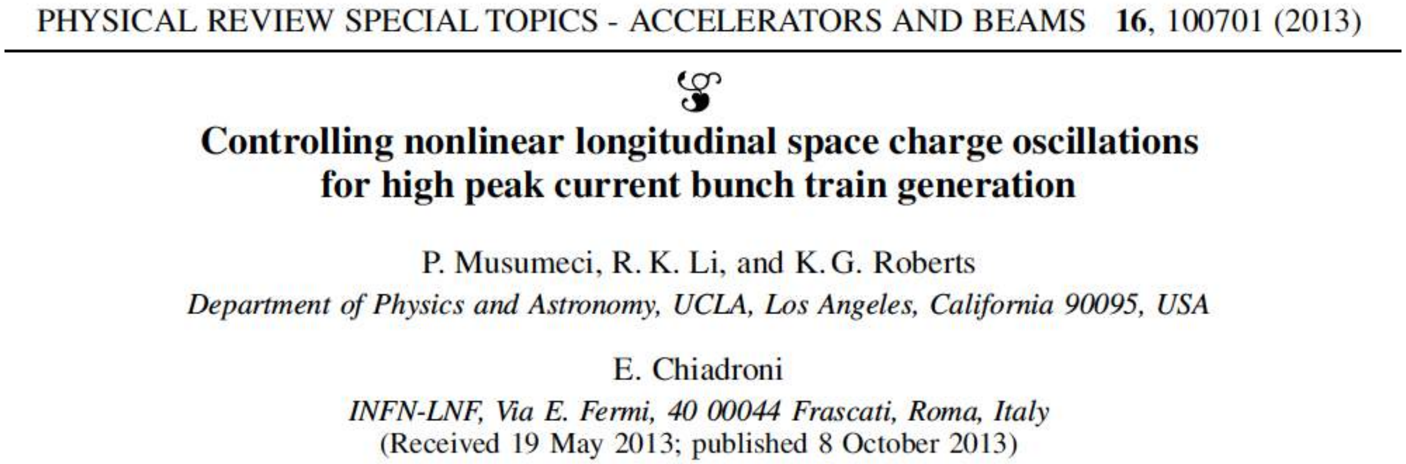
E. Chiadroni,[1] M. Bellaveglia,[1] P. Calvani,[2] M. Castellano,[1] L. Catani,[3,4] A. Cianchi,[3,4]
G. Di Pirro,[1] M. Ferrario,[1] G. Gatti,[1] O. Limaj,[2] S. Lupi,[2,5] B. Marchetti,[3] A. Mostacci,[5,6]
E. Pace,[1] L. Palumbo,[5,6] C. Ronsivalle,[7] R. Pompili,[1,3] and C. Vaccarezza[1]



APPLIED PHYSICS LETTERS **102**, 094101 (2013)

The SPARC linear accelerator based terahertz source

E. Chiadroni,[1] A. Bacci,[1] M. Bellaveglia,[1] M. Boscolo,[1] M. Castellano,[1] L. Cultrera,[1]
G. Di Pirro,[1] M. Ferrario,[1] L. Ficcadenti,[1] D. Filippetto,[1] G. Gatti,[1] E. Pace,[1] A. R. Rossi,[1]
C. Vaccarezza,[1] L. Catani,[2] A. Cianchi,[2] B. Marchetti,[2] A. Mostacci,[3] L. Palumbo,[3]
C. Ronsivalle,[4] A. Di Gaspare,[5] M. Ortolani,[5] A. Perucchi,[6] P. Calvani,[7] O. Limaj,[7]
D. Nicoletti,[7] and S. Lupi[7]



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **16**, 100701 (2013)

Controlling nonlinear longitudinal space charge oscillations for high peak current bunch train generation

P. Musumeci, R. K. Li, and K. G. Roberts
Department of Physics and Astronomy, UCLA, Los Angeles, California 90095, USA

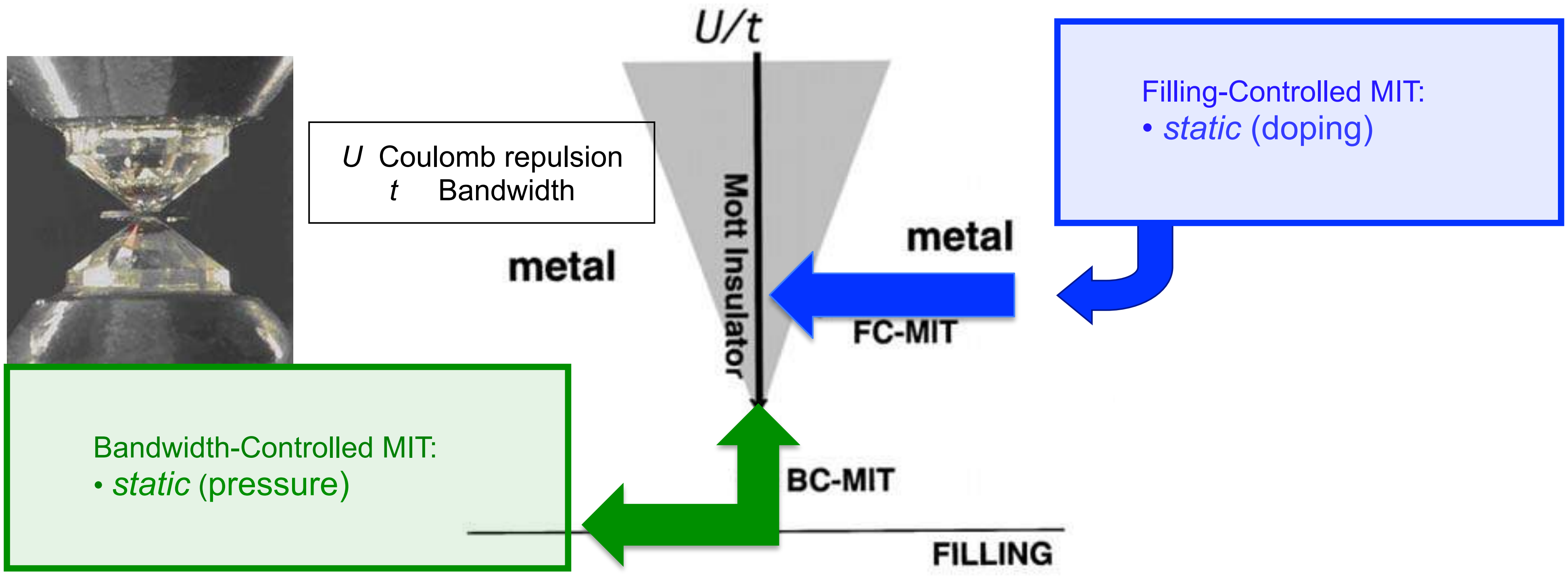
E. Chiadroni
INFN-LNF, Via E. Fermi, 40 00044 Frascati, Roma, Italy
(Received 19 May 2013; published 8 October 2013)

Insulator to Metal Transitions

Many materials are insulating although band theory suggests a metallic ground state: V_2O_3, VO_2, NiO, $NiSe_2$, La_2CuO_4, Cs_3C_{60}

→Strong Electronic Correlations

(Basic Ingredient for High-Tc Superconductivity)



U Coulomb repulsion
t Bandwidth

Filling-Controlled MIT:
- *static* (doping)

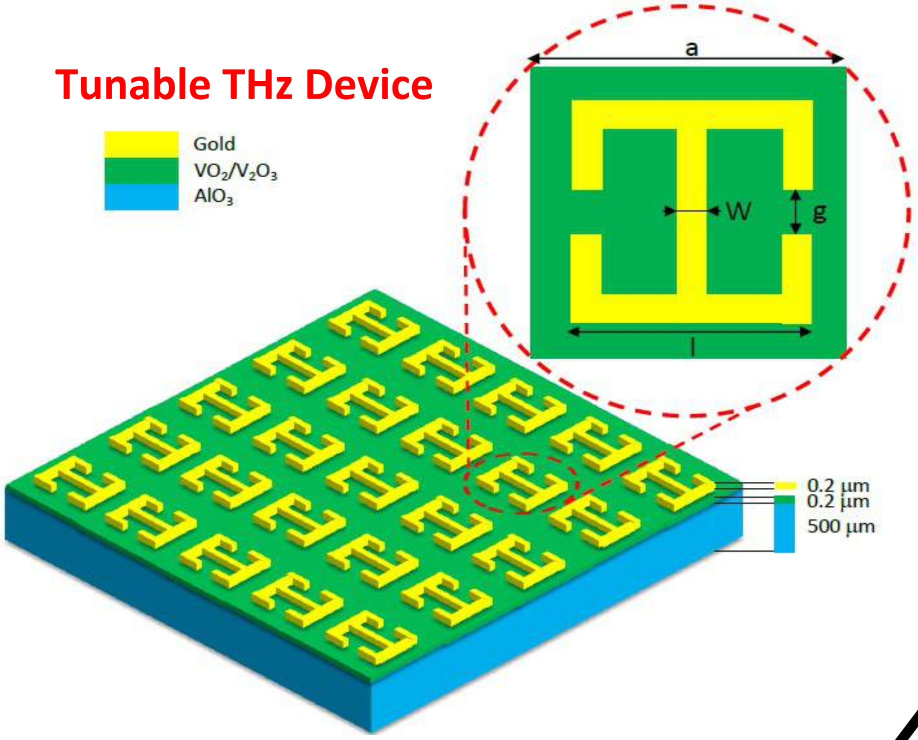
Bandwidth-Controlled MIT:
- *static* (pressure)

THz Controlled MIT in V_2O_3

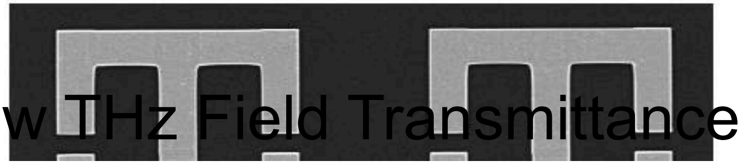
(in collaboration with University of Pavia and IIT)

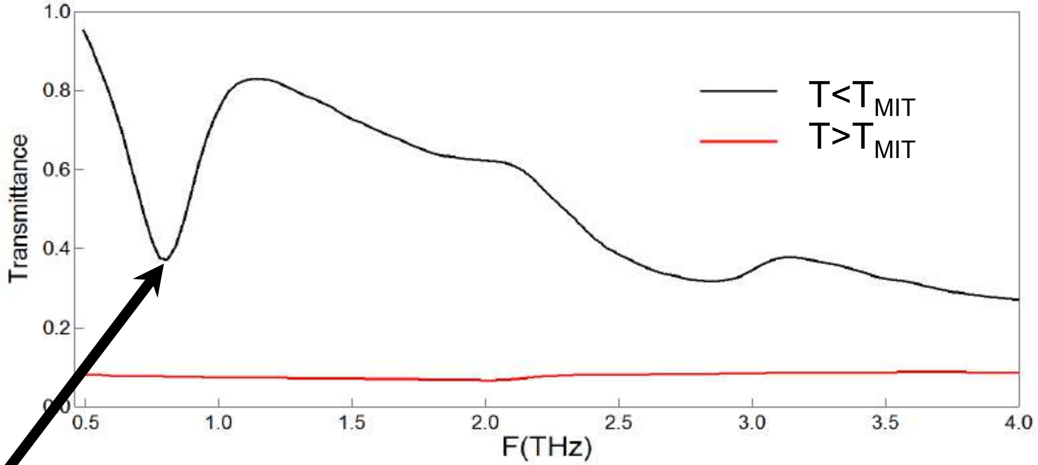
Study of transmittance vs THz intensity of V_2O_3 resonators

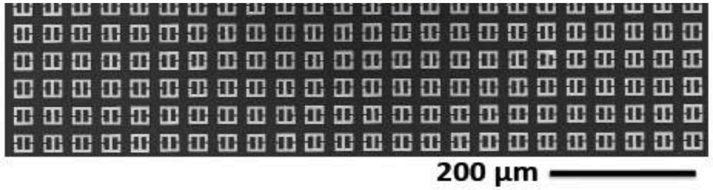
Tunable THz Device



Low THz Field Transmittance



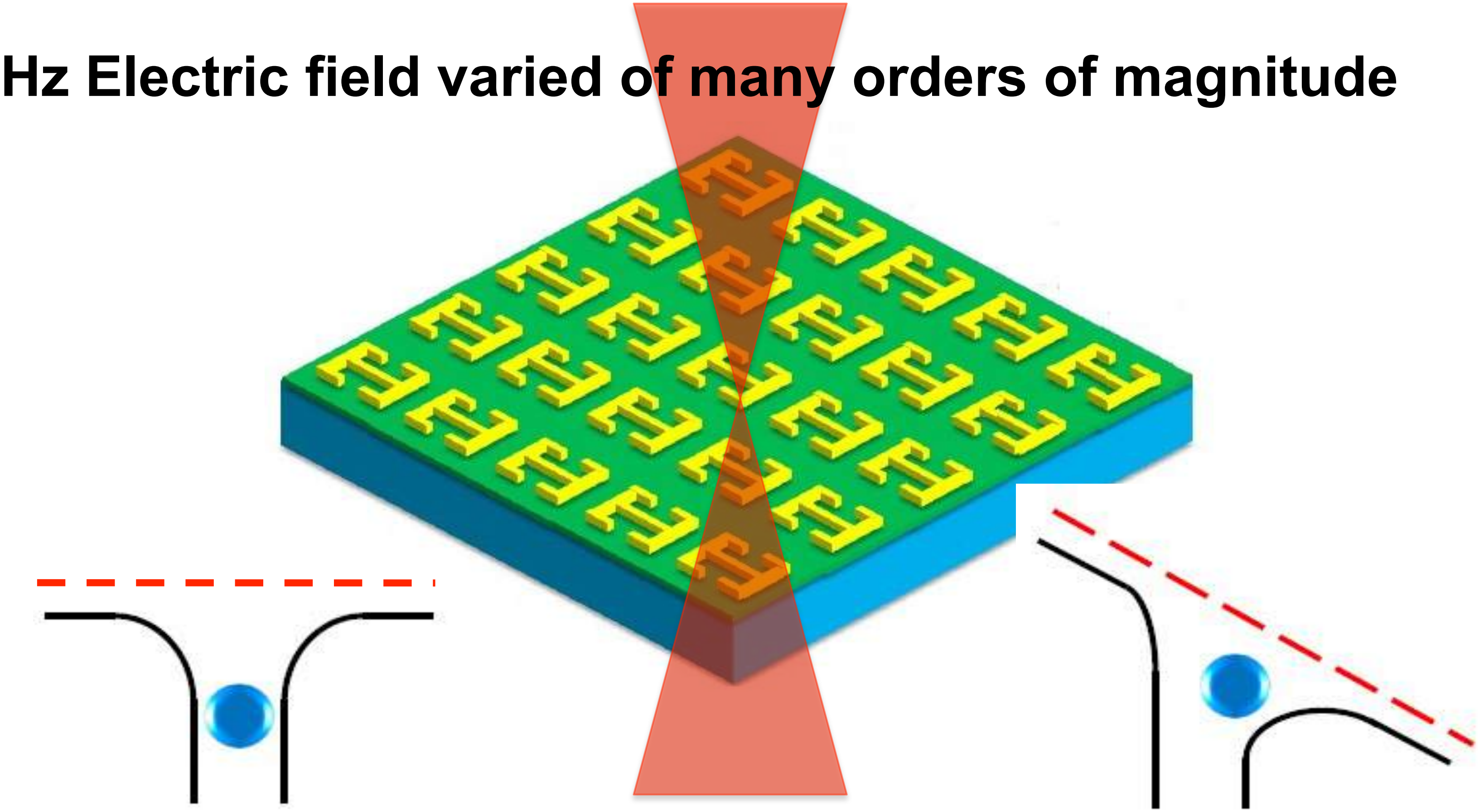




LC Resonance

THz Controlled MIT in V_2O_3

THz Electric field varied of many orders of magnitude



Localized Charge Carriers
at low THz Field→Insulator

Mobile Charge Carriers
at high THz Field→Metal

FLAME activities

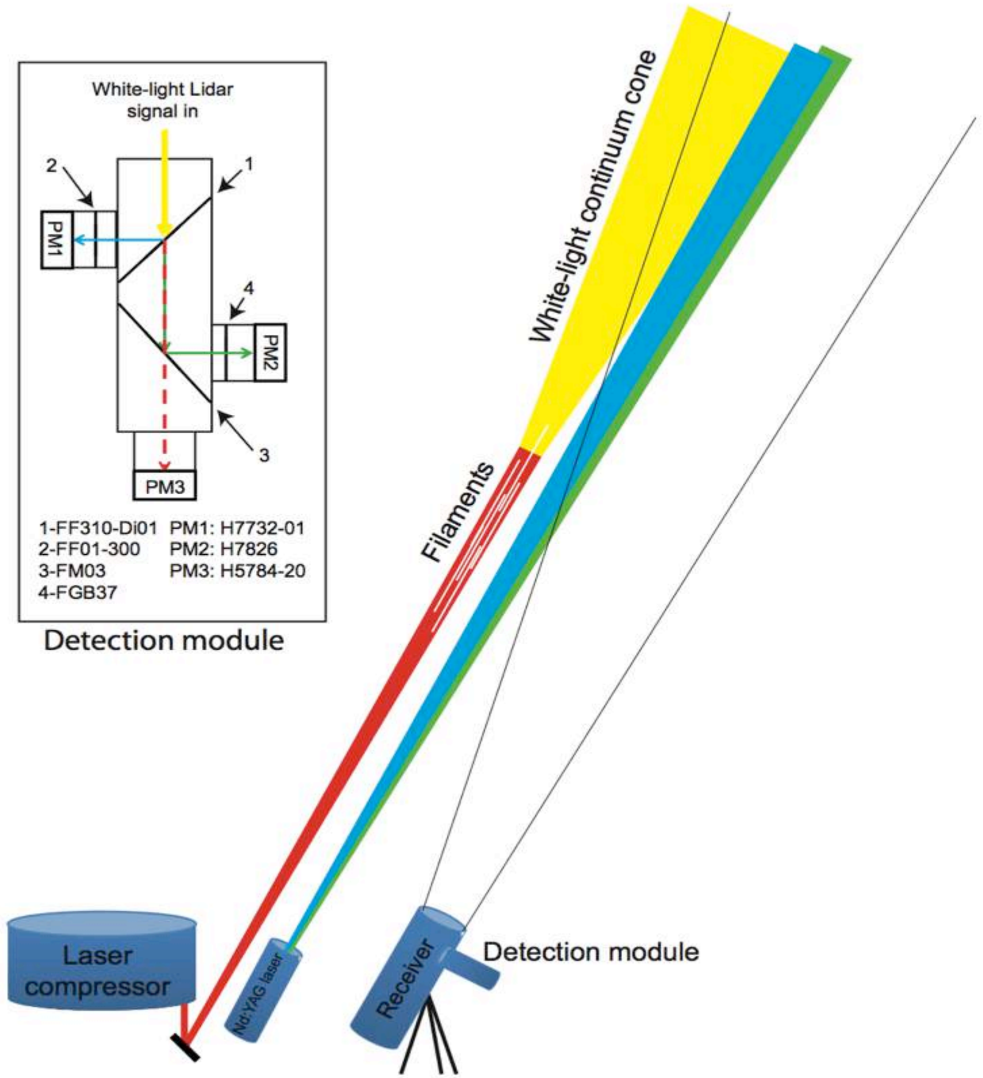
Laser propagation in air

High-power systems are commonly used in atmospheric research (LIDAR – *Light Detection and Ranging*) for measuring many atmospheric parameters: the height, layering and densities of clouds, cloud particle properties, temperature, pressure, wind, humidity, trace gas concentration, etc.

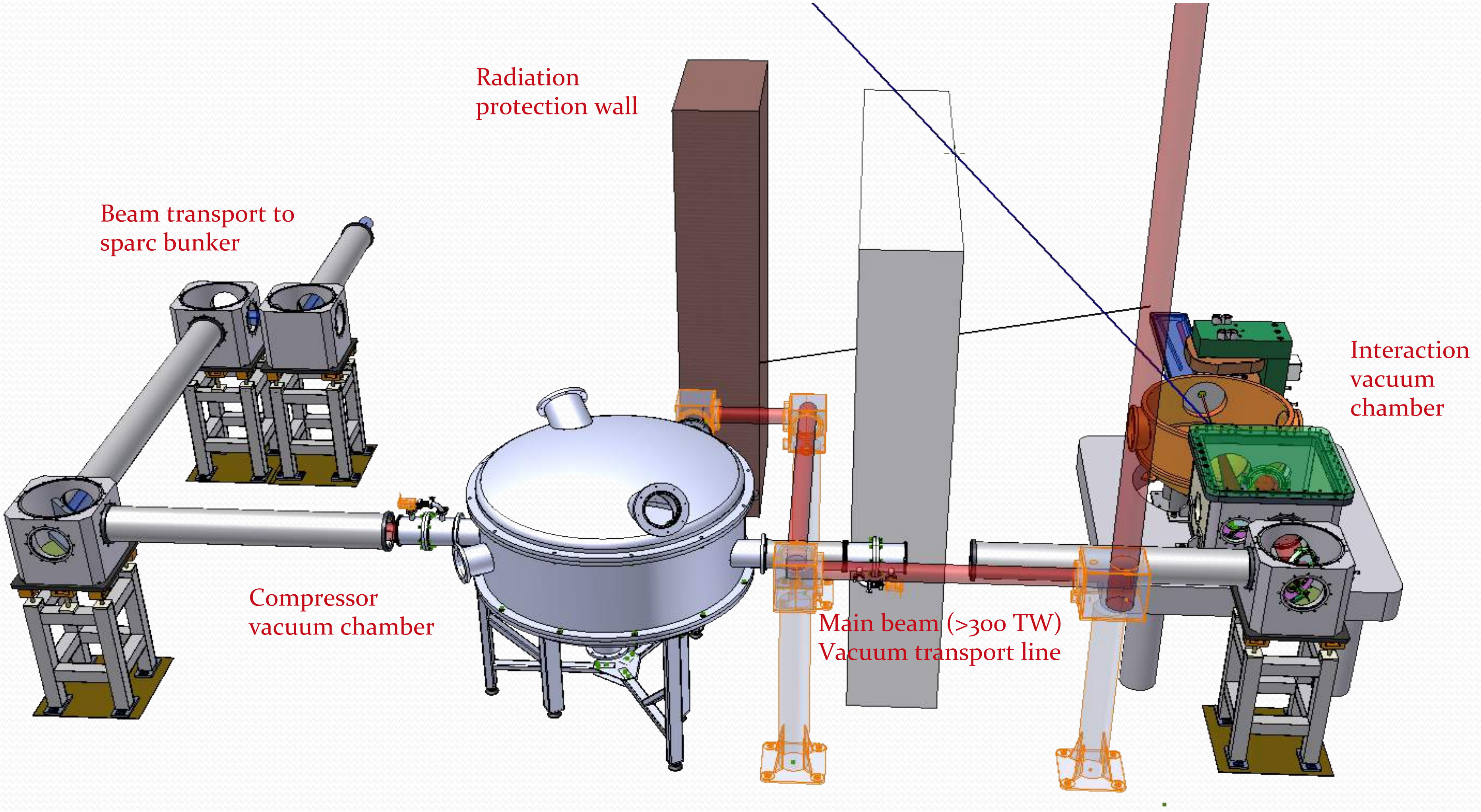
High power lasers propagated in air give rise to multiple plasma lines (filaments which are due to Kerr lens effects) and can propagate in atmosphere up to a few hundreds of meters by controlling the chirp and the duration of the laser beam.

By analyzing the light emitted by the plasma filaments, different species can be detected and analyzed, i.e., industrial incidents, leakages, fires, as well as unknown aerosols, since it does not require any priori knowledge of the species present in air.

Laser propagation in air



FLAME target area



Radiation protection wall

Beam transport to sparc bunker

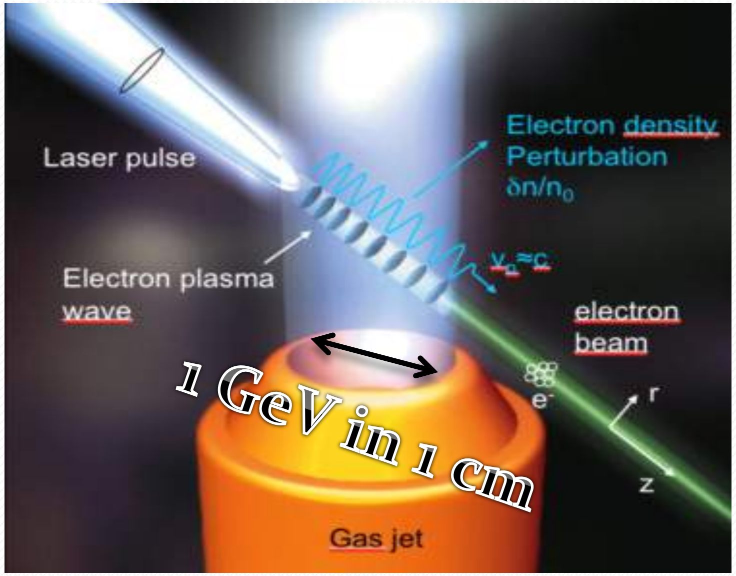
Interaction vacuum chamber

Compressor vacuum chamber

Main beam (>300 TW) Vacuum transport line

Self-injection

Laser wakefield accelerators (LWFA) are a novel type of accelerators capable to produce accelerating field up to 100 GV/m. This feature gives the possibility to have very compact accelerators able to accelerate electrons to GeV energies in few **centimetres**.



PROS:

1. Costs of the facilities;
2. Compactness: key-word is TABLE TOP!

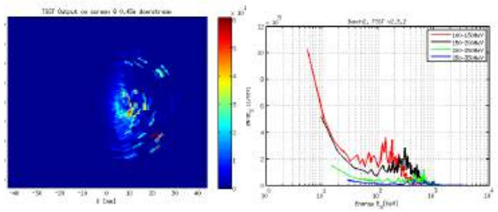
CONS:

1. Instability of the electron bunches → necessary to study new accelerating structures to control the beam (PWFA?);
2. Quality of the electron bunched are not comparable to that of conventional accelerators → research undergoing.

γ-RESIST

Inverse Compton scattering of of self-injected, LWFA sub-GeV electrons[1,2]

Exp'ed: 2E8 photons/shot



Montecarlo TSST: expected angular and spectral distribution

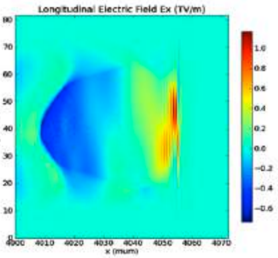
Photons at screen: image and spectrum

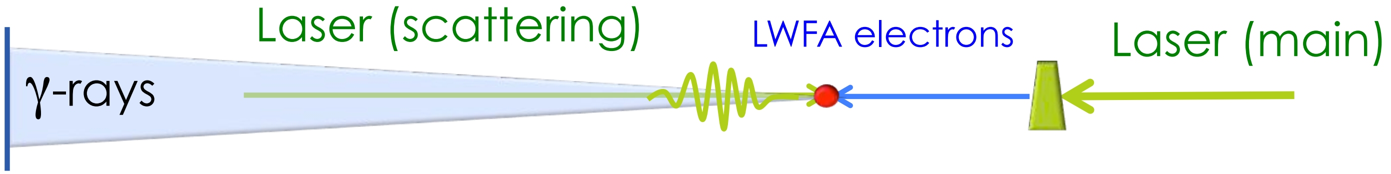
γ-photons

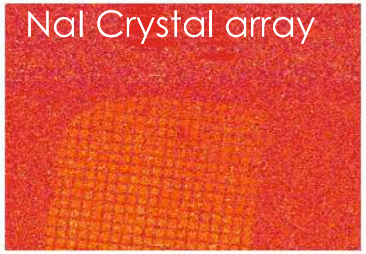
SIMULATIONS

e^- bunch

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







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

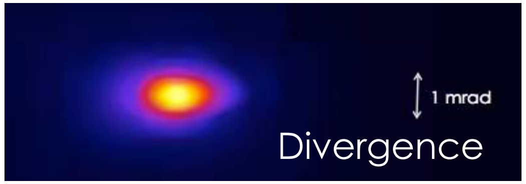
Higher shielding, collision stability and laser beam energy needed

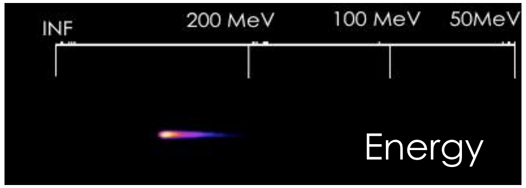
γ-photons

EXPERIMENT

e^- bunch

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

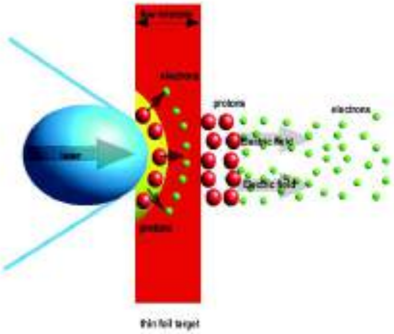


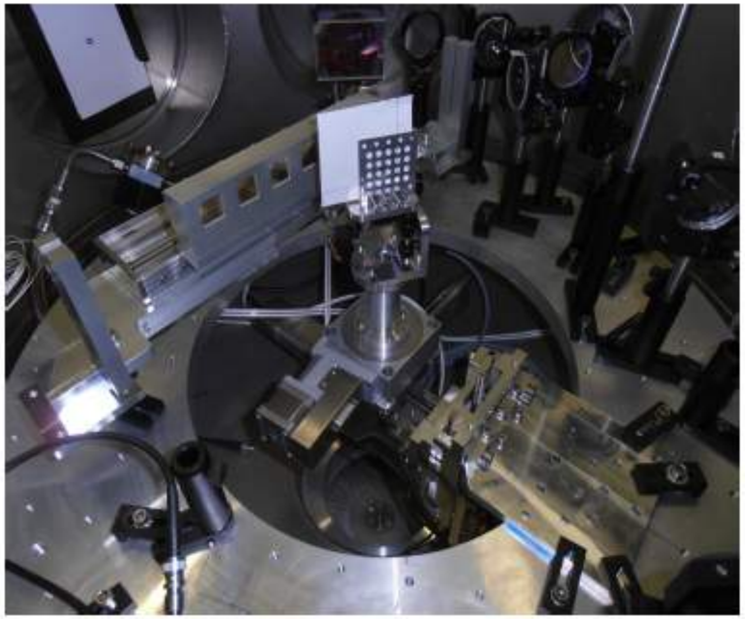


[1]L.A. Gizzi et al., NIM B 309, 202-209 (2013);[2]T. Levato et al., NIMA A720, 95-99 (2013) [3]P. Tomassini et al., Appl. Phys. B **80**, 419-436 (2005)

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 $1E18 < I < 1E20$ 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 MeV

Possible higher intensity
For the next run

OAP F=1 mt → OAP F= 0.5 mt