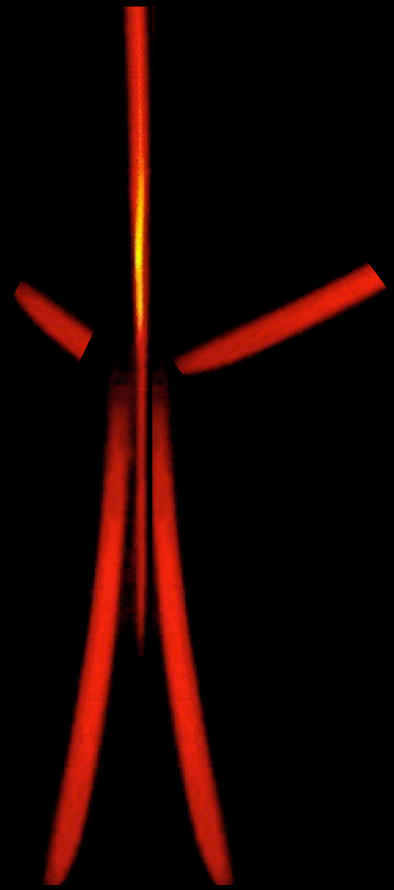
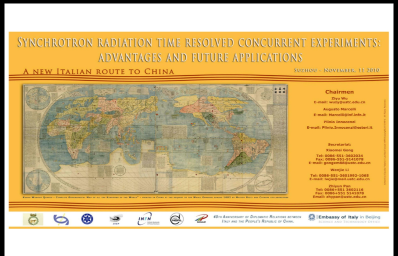
Collaboration Opportunities with the next generation Italian/Chinese FEL Sources

Massimo.Ferrario@LNF.INFN.IT



IHEP – INFN Collaboration Meeting – Roma, May 16, 2014



Bilateral Italian/Chinese Workshop

Low energy coherent light sources:
an Italian and Chinese strategy for Infrared Free Electron Laser

Beijing (P.R. China) 4-5 December 2013

Chairmen

Ziyu Wu
Augusto Marcelli
Stefano Lupi

Participants

Weiwei Gao - NSRL/USTC
Chen Gao - NSRL/USTC
Xueming Yang - DICP, CAS
Qika Jia - NSRL/USTC
Dong Wang - SINAP, CAS
Ziyu Wu - NSRL/USTC

M. Ferrario - INFN-LNF
L. Giannessi - ENEA/Elettra
E. Chiadroni - INFN-LNF
A. Perucchi - Elettra
A. Marcelli - INFN-LNF
S. Lupi - Sapienza University

Secretariat

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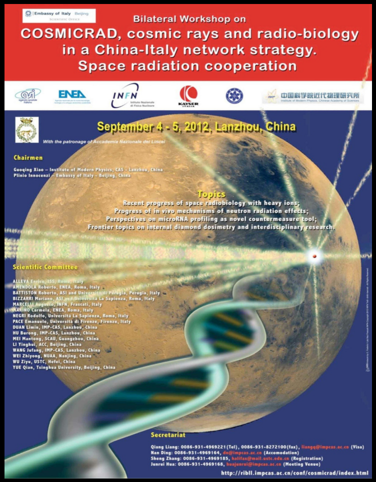
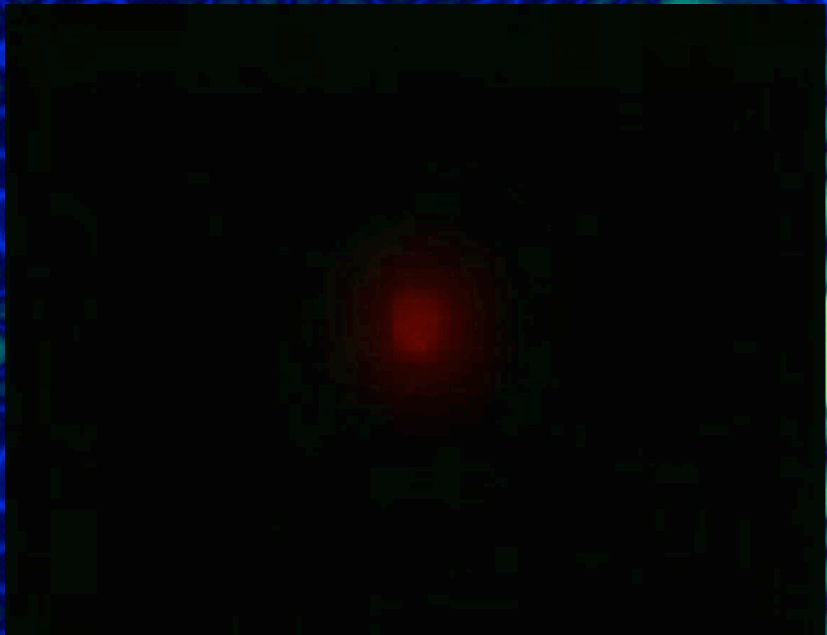
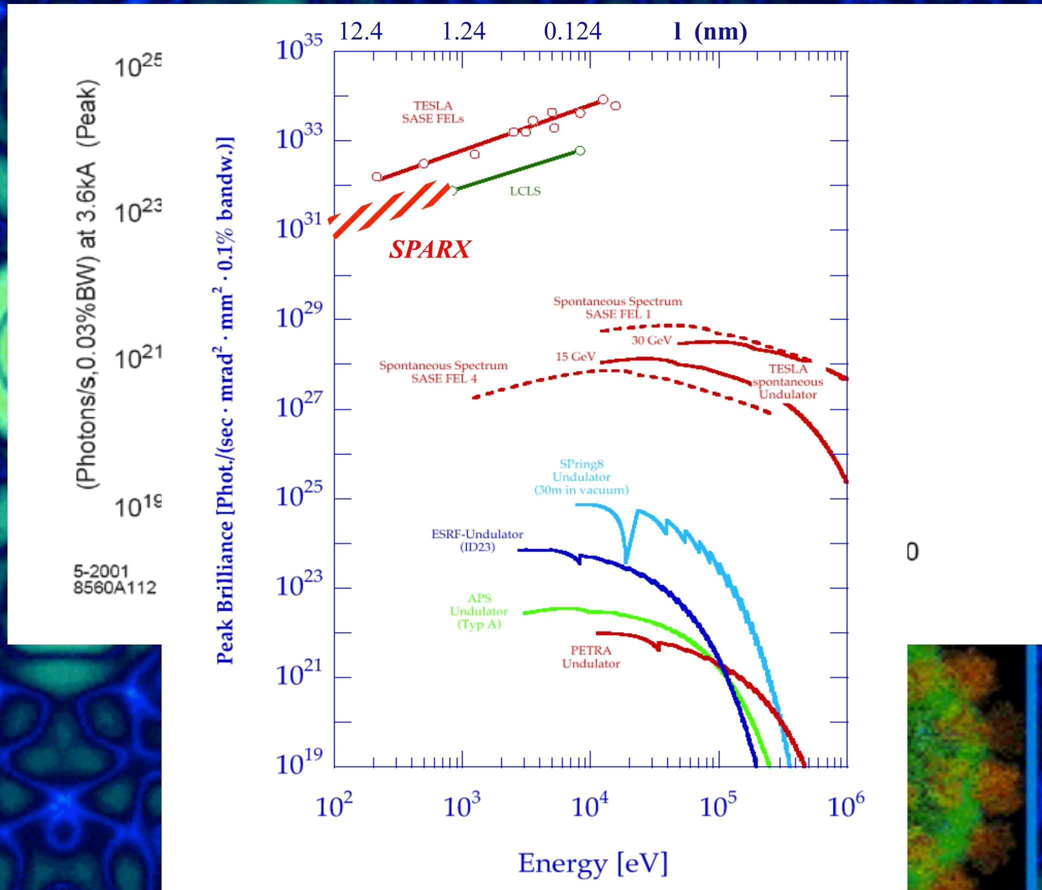


A Free Electron Laser is a device that converts a fraction of the electron kinetic energy into coherent radiation via a collective instability in a long undulator



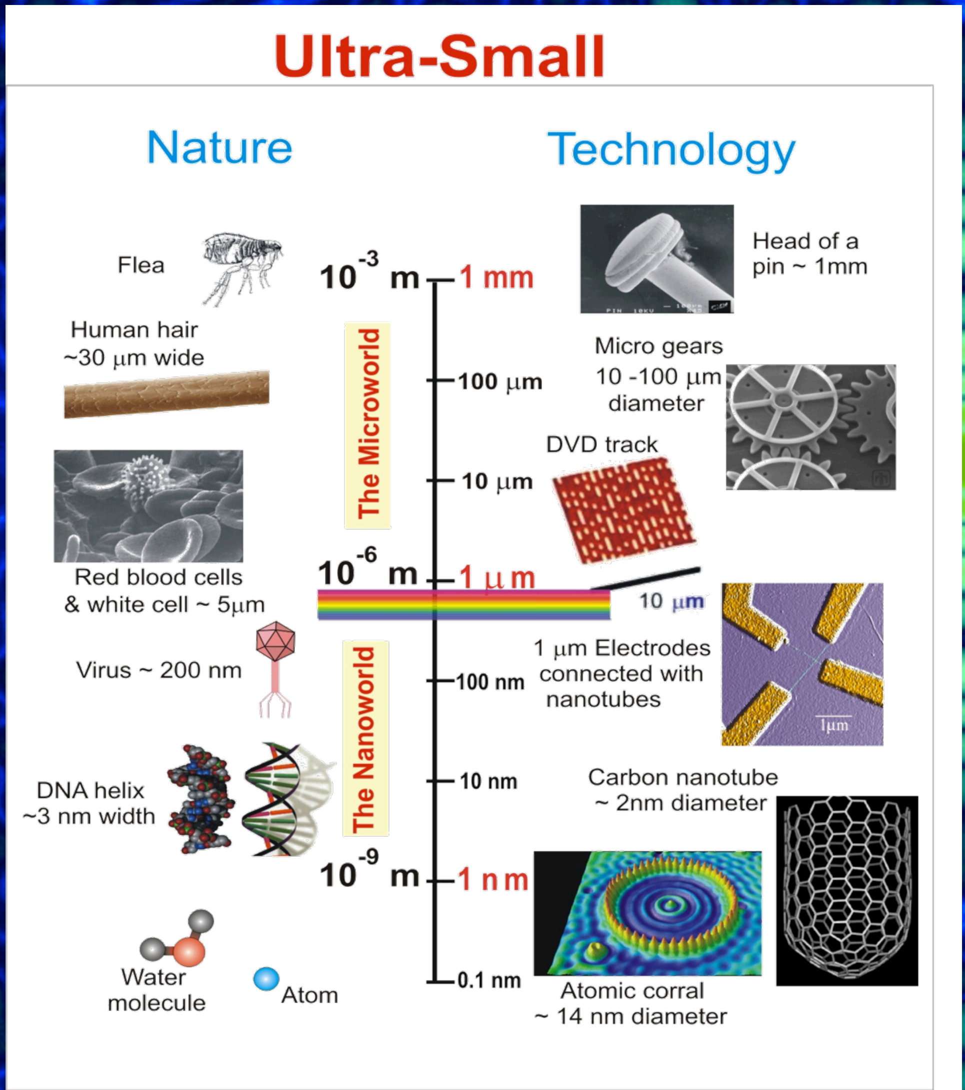


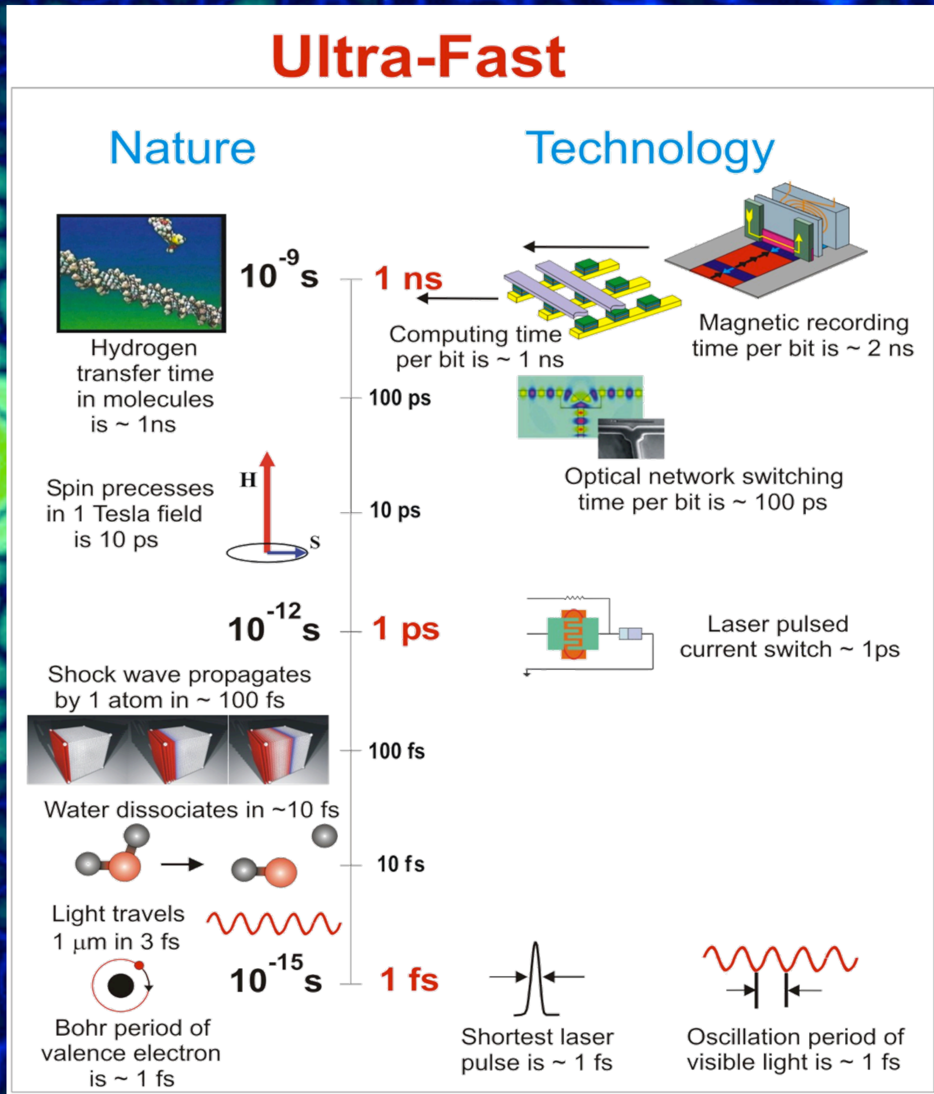
$$\lambda_{rad} \approx \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2 \vartheta^2\right)$$

Radiation properties:

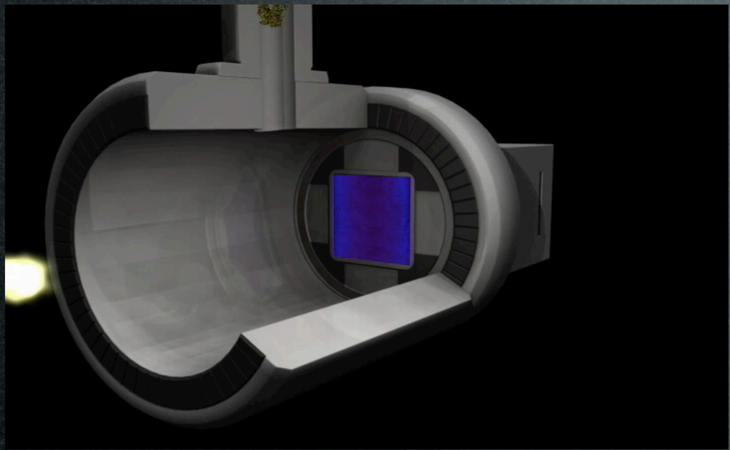
GW power - Monocromaticity - Tunability from IR to X– Short pulses

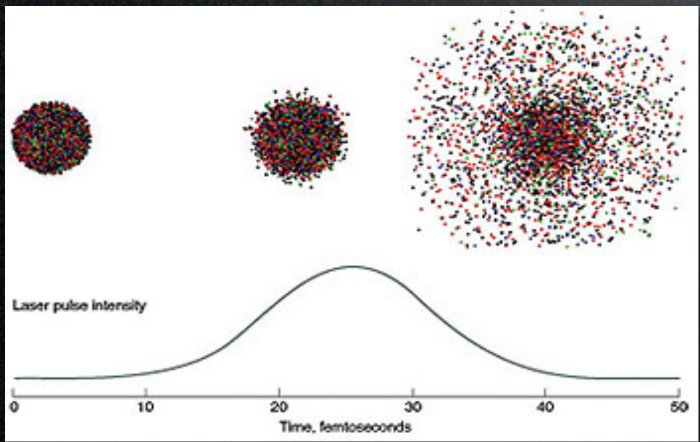
Science with FEL





Protein imaging





Lawrence Livermore National Laboratory (LLNL)

Using extremely short and intense X-ray pulses to capture images of objects such as proteins before the X-rays destroy the sample.

Single-molecule diffractive imaging with an X-ray free-electron laser.

Individual biological molecules will be made to fall through the X-ray beam, one at a time, and their structural information recorded in the form of a diffraction pattern.

The pulse will ultimately destroy each molecule, but not before the pulse has diffracted from the undamaged structure.

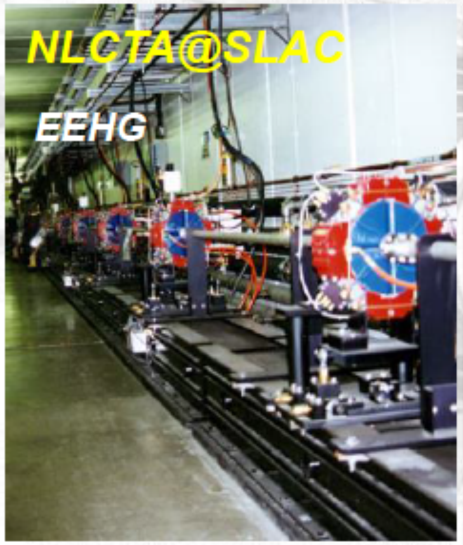
The patterns are combined to form an atomic-resolution image of the molecule.

The speed record of 25 femtoseconds for flash imaging was achieved.

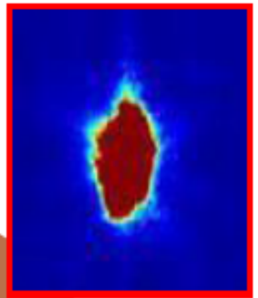
Models indicate that atomic-resolution imaging can be achieved with pulses shorter than 20 femtoseconds.

Worldwide hard X-ray FEL facilities (SASE)

Seeded FEL facilities

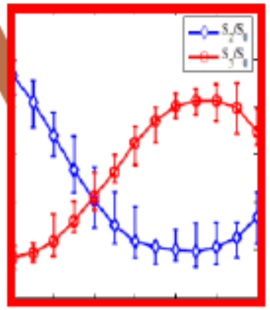


SDUV-FEL



HGHG & cascaded HGHG

Phys. Rev. ST-AB 16, 020704 (2013)

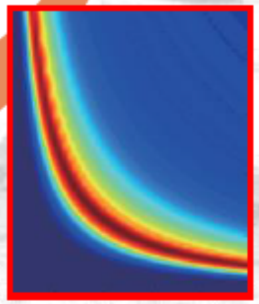


Crossed-undulator demonstration

Phys. Rev. ST-AB 17, 020704 (2014)

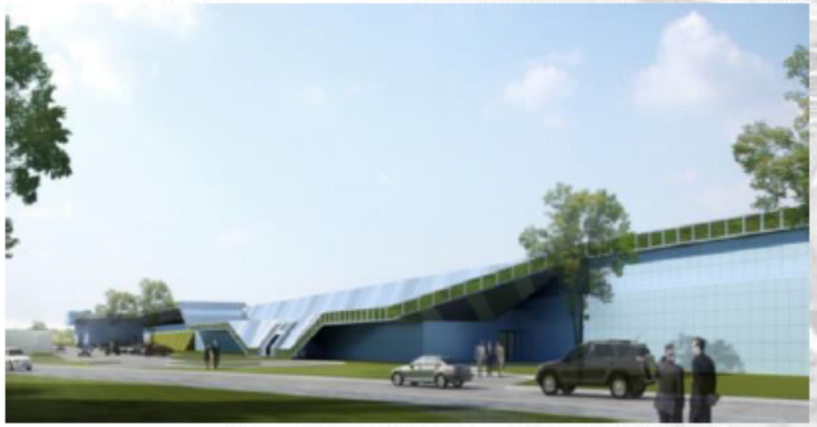
First lasing of EEHG-FEL

Nature Photonics 6, 360 (2012)



FEL Physics & Novel ideas

Phys. Rev. Lett. 111, 084801 (2013)



DCLS、SXFEL、XFEL

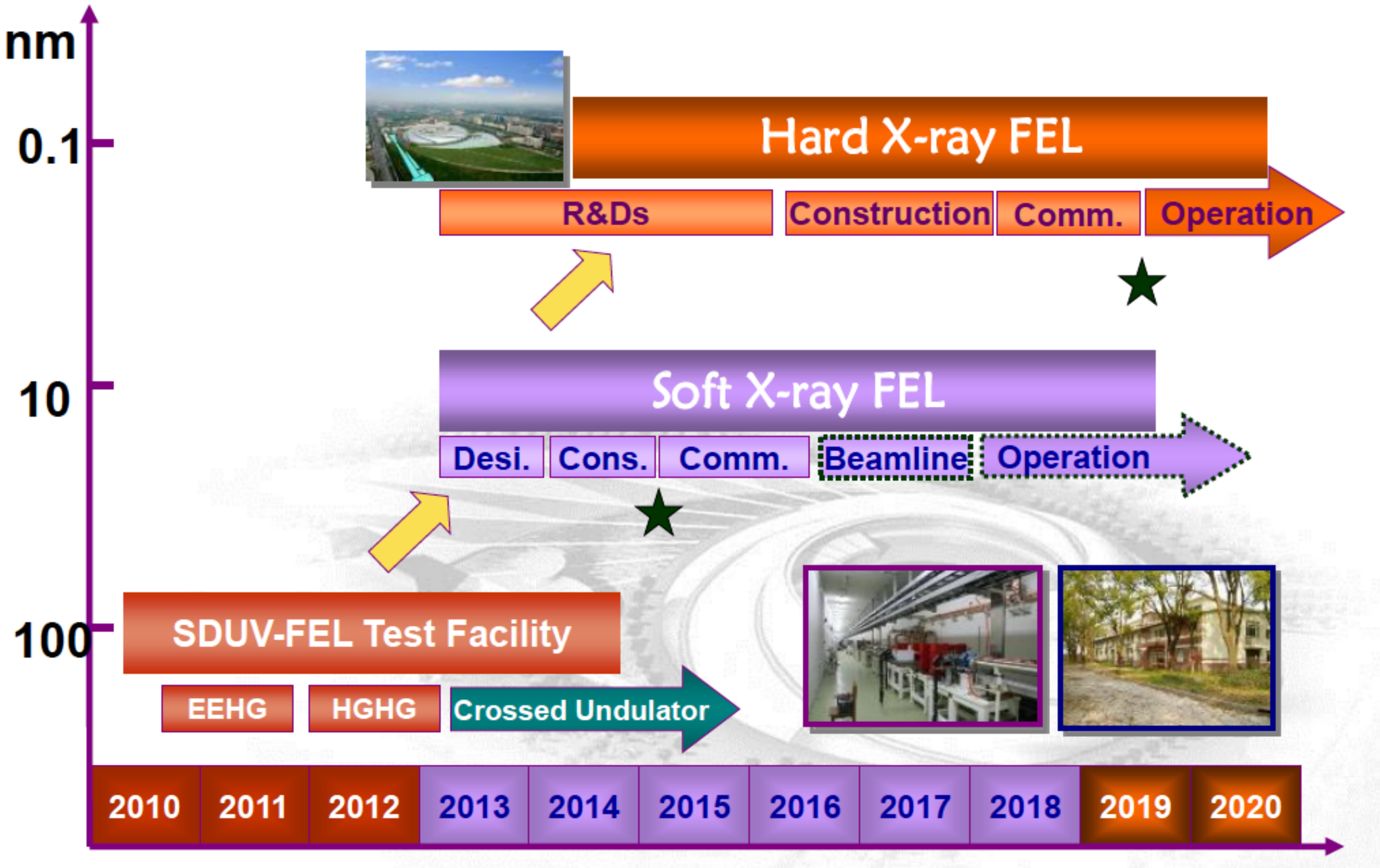
Courtesy Haixiao Deng

SDUV-FEL Program

- Shanghai Deep-UltraViolet Free-Electron Laser (SDUV-FEL) started as an 262 nm SASE / 88 nm HGHG FEL test setup around 2000.
- Funding partially supported by
  - Chinese Academy of Sciences / CAS
  - Ministry of Science and Technology of China / MOST
  - National Natural Science Foundation of China / NSFC
- Collaborating between USTC, IHEP, THUB and SINAP
- Be a test bed for the key technologies for XFELs

Courtesy Haixiao Deng

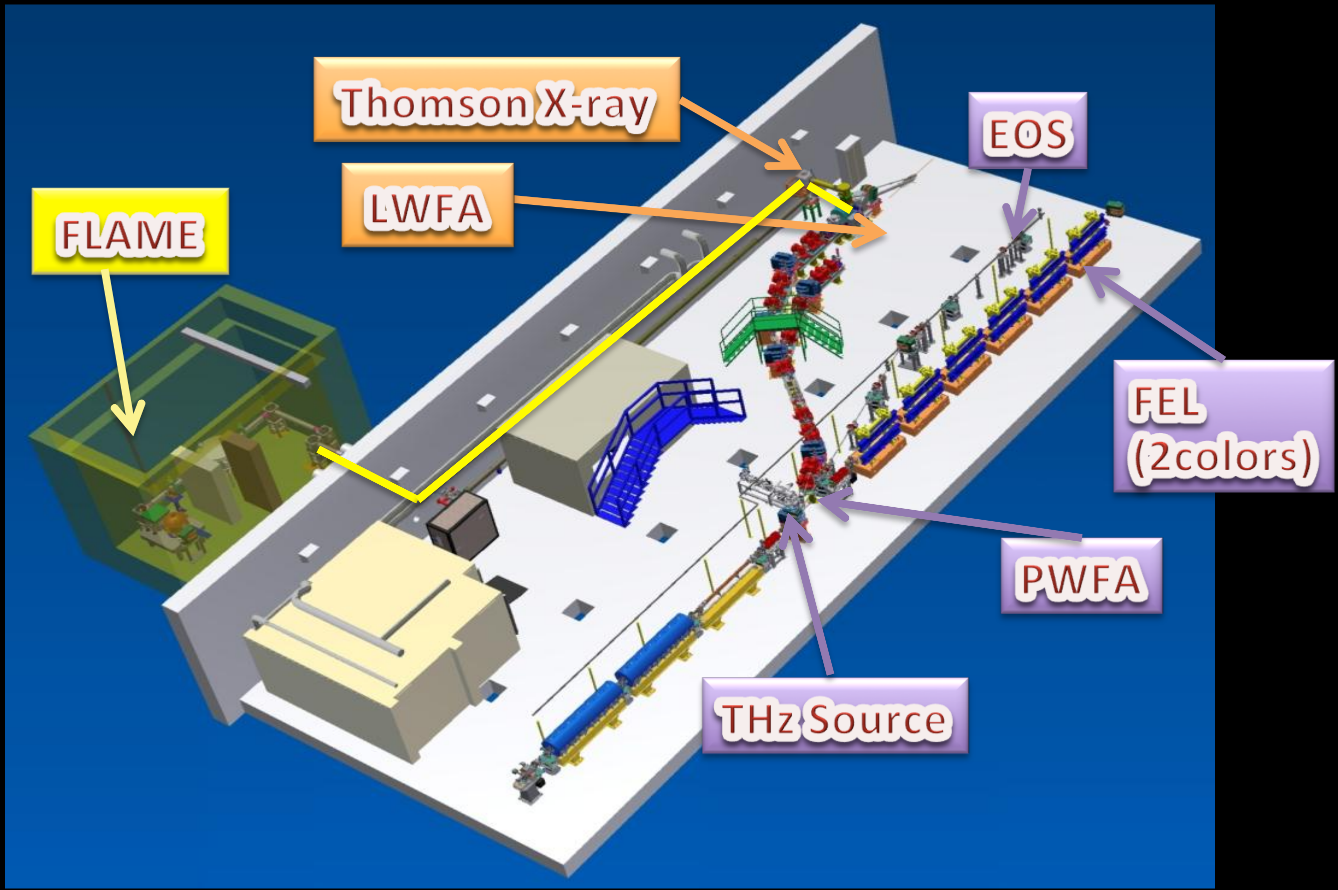
Roadmap of Shanghai FELs



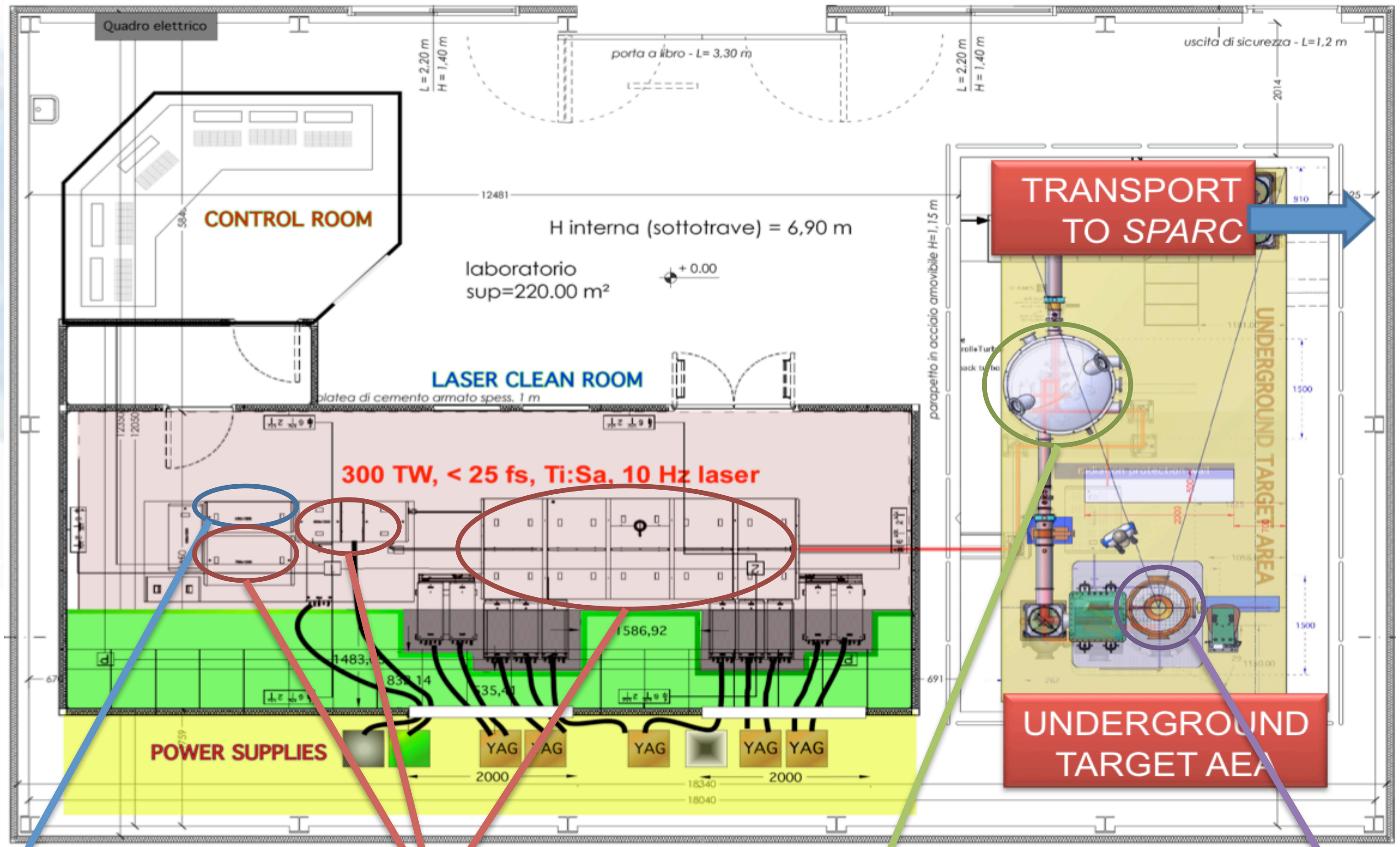
Courtesy Haixiao Deng

SPARC_LAB

Sources for Plasma Accelerators and Radiation Compton with Lasers And Beams



Ti:Sa FLAME laser

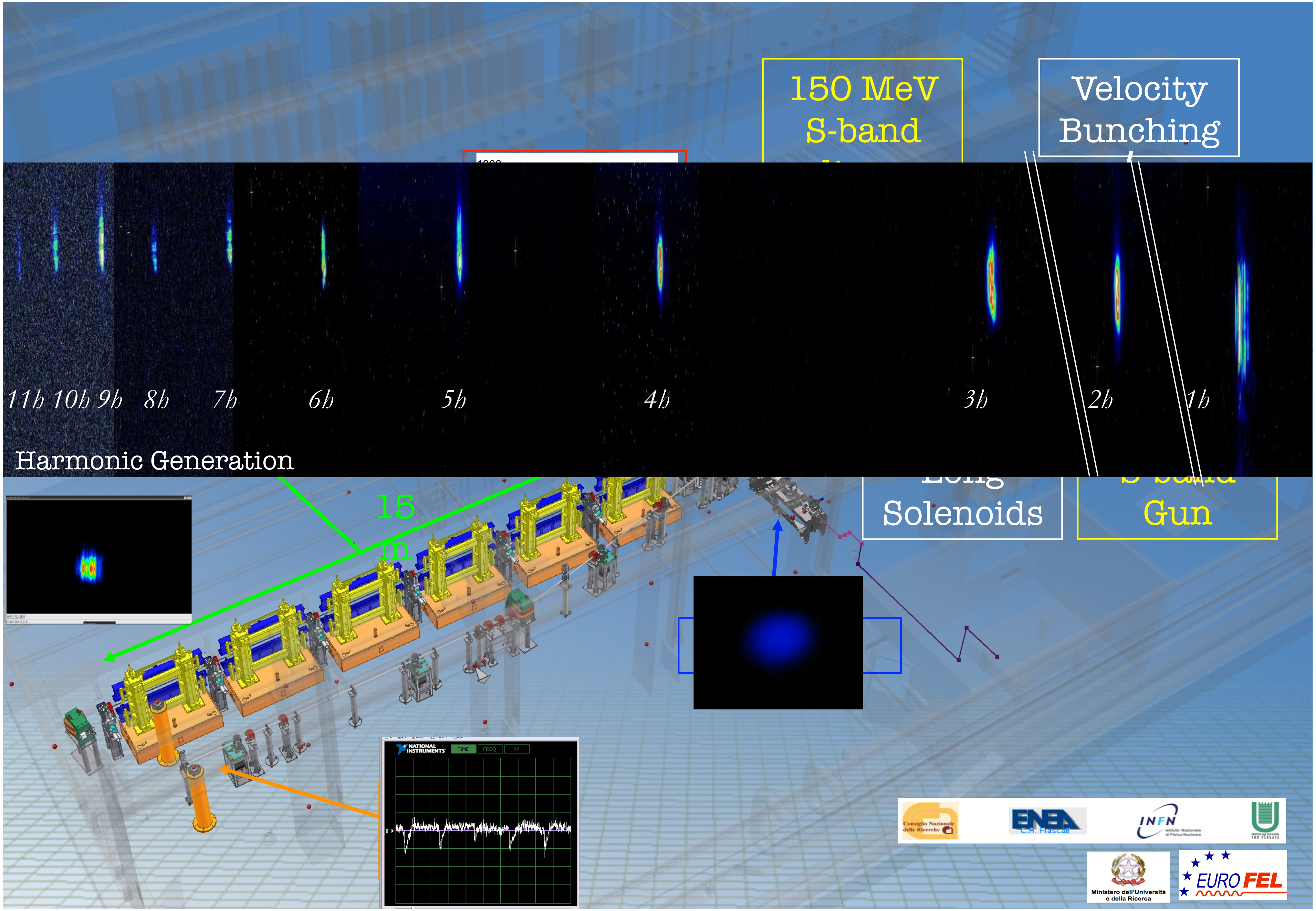


Stretcher

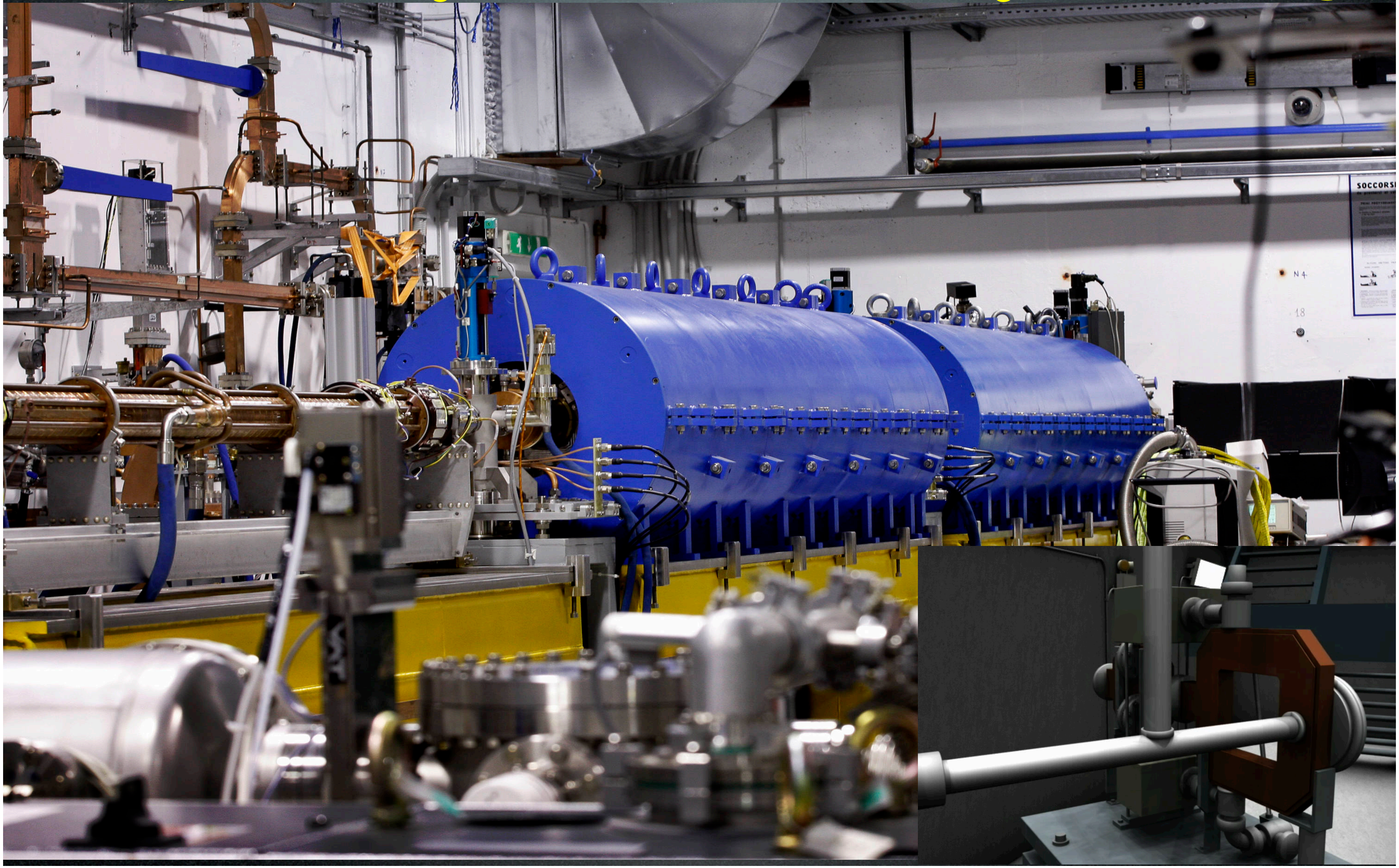
Amplifiers

Compressor

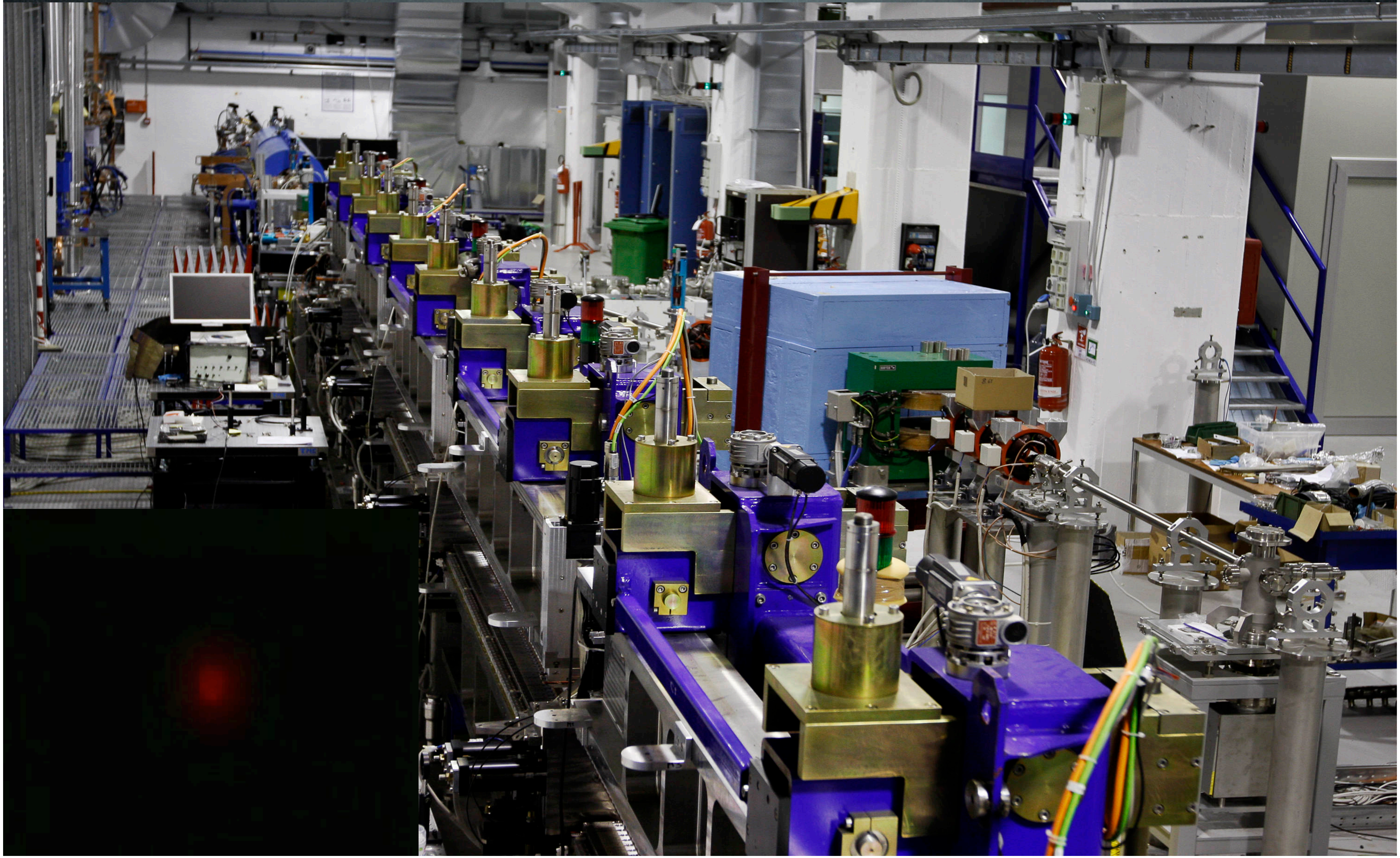
LWFA
Electron Self Injection
And
Protons


150 MeV
S-band
Velocity
Bunching
11h 10h 9h 8h 7h 6h 5h 4h 3h 2h 1h
Harmonic Generation
15
m
Solenoids
Gun
NATIONAL INSTRUMENTS
TIME
FREQ
XY
Consiglio Nazionale delle Ricerche
ENEA
C.R. Frascati
INFN
Ministero dell'Università e della Ricerca
EURO FEL

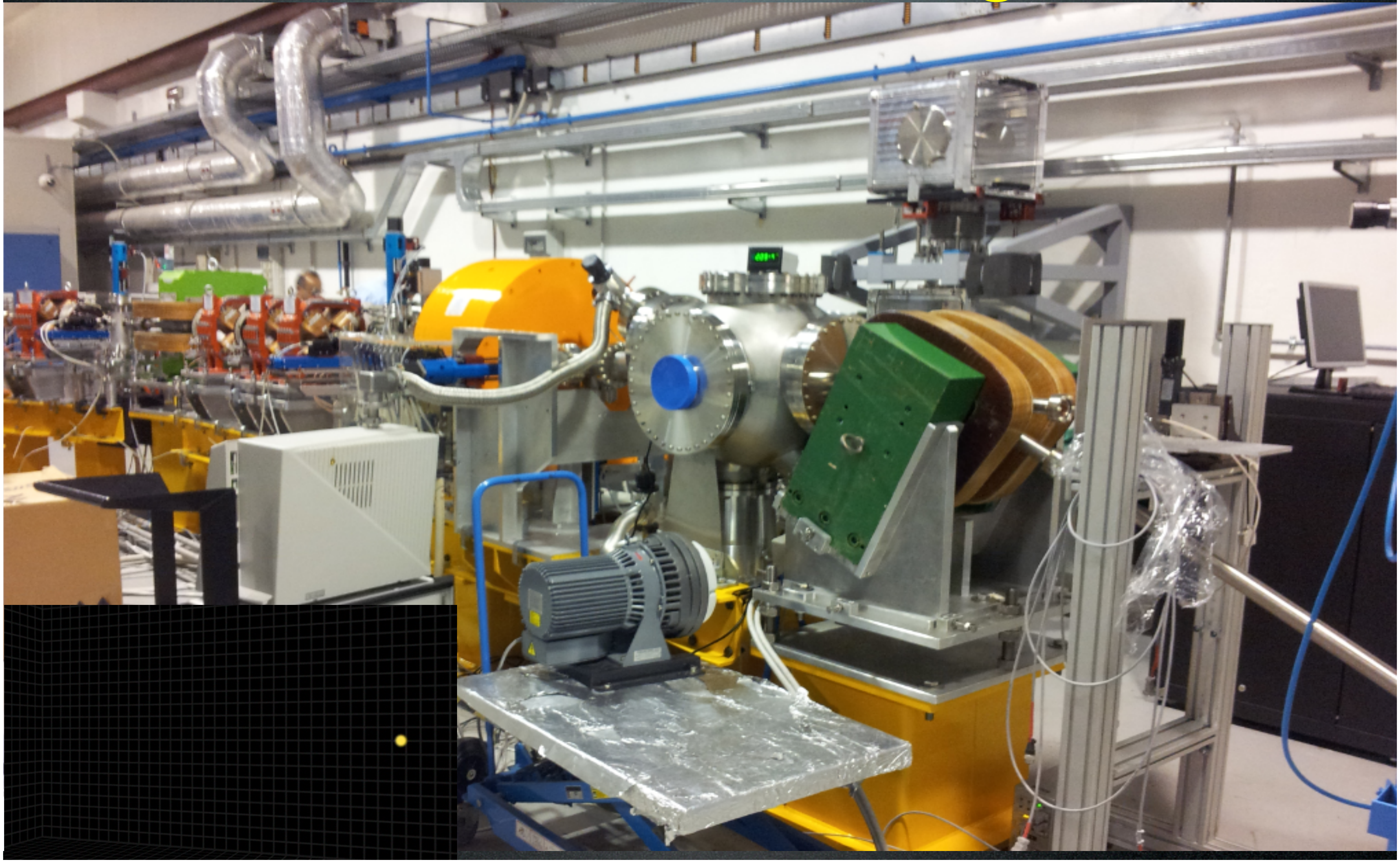
HB photo- injector with Velocity Bunching



Free Electron Laser



Thomson back-scattering source



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)

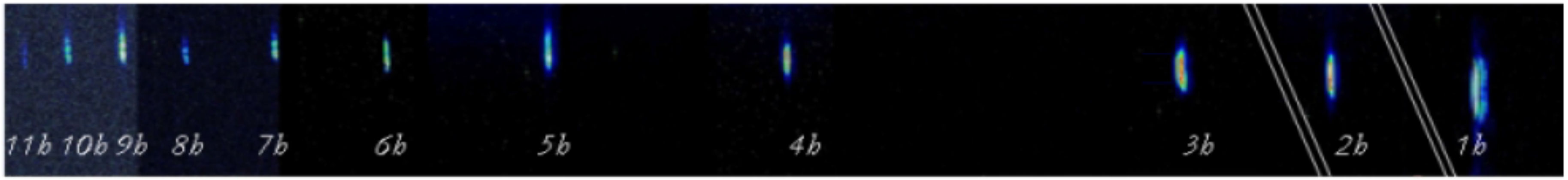
FEL

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

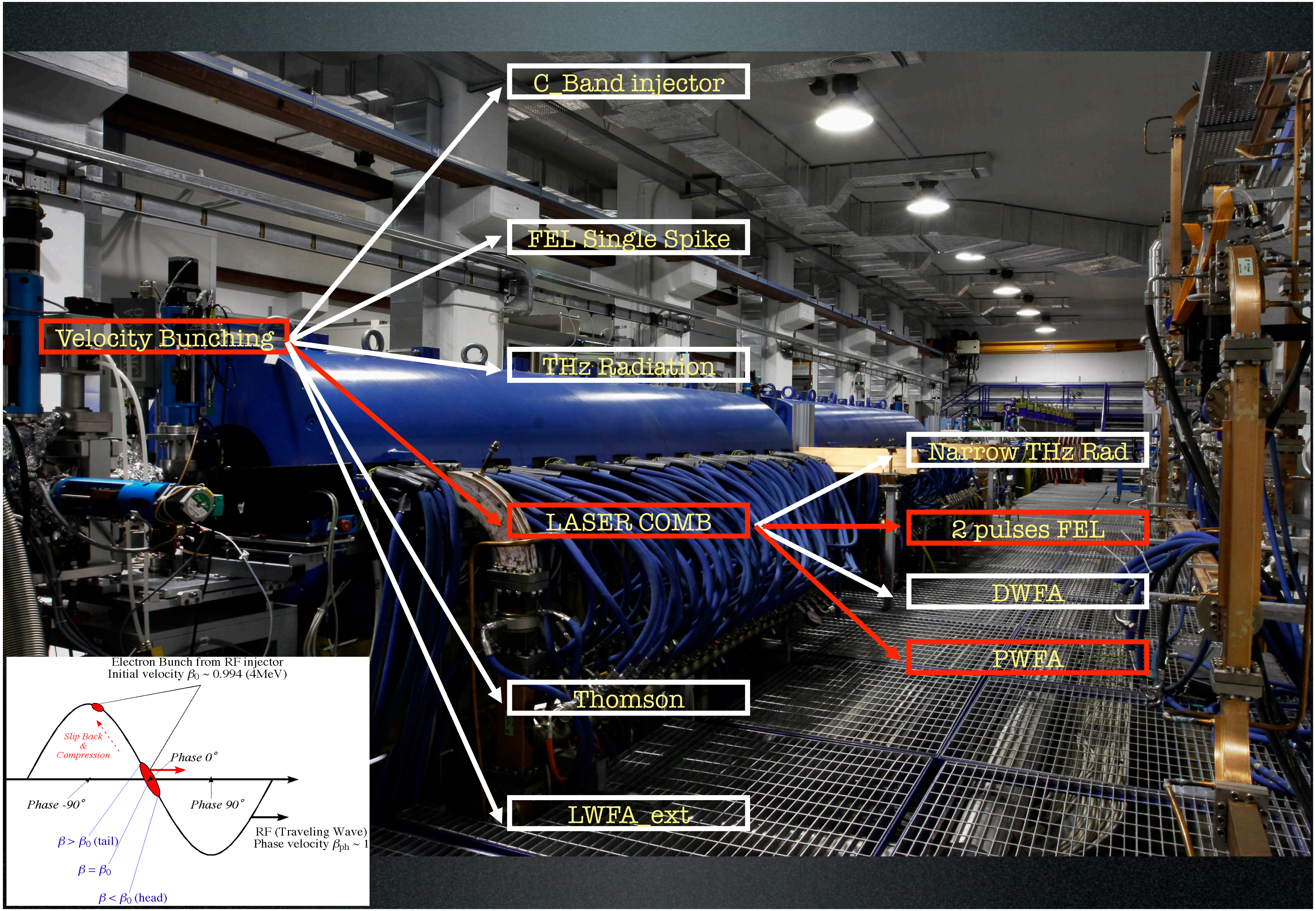
Seeded FEL

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)


C_Band injector
FEL Single Spike
Velocity Bunching
THz Radiation
Narrow THz Rad
LASER COMB
2 pulses FEL
DWFA
PWFA
Thomson
LWFA_ext
Electron Bunch from RF injector
Initial velocity $\beta_0 \sim 0.994$ (4MeV)
Slip Back
&
Compression
Phase 0°
Phase -90°
Phase 90°
RF (Traveling Wave)
Phase velocity $\beta_{ph} \sim 1$
$\beta > \beta_0$ (tail)
$\beta = \beta_0$
$\beta < \beta_0$ (head)

Laser COMB technique

Laser Comb technique: generation of a train of short bunches

(Parmela code)

Charge vs. Time

Energy vs. Time

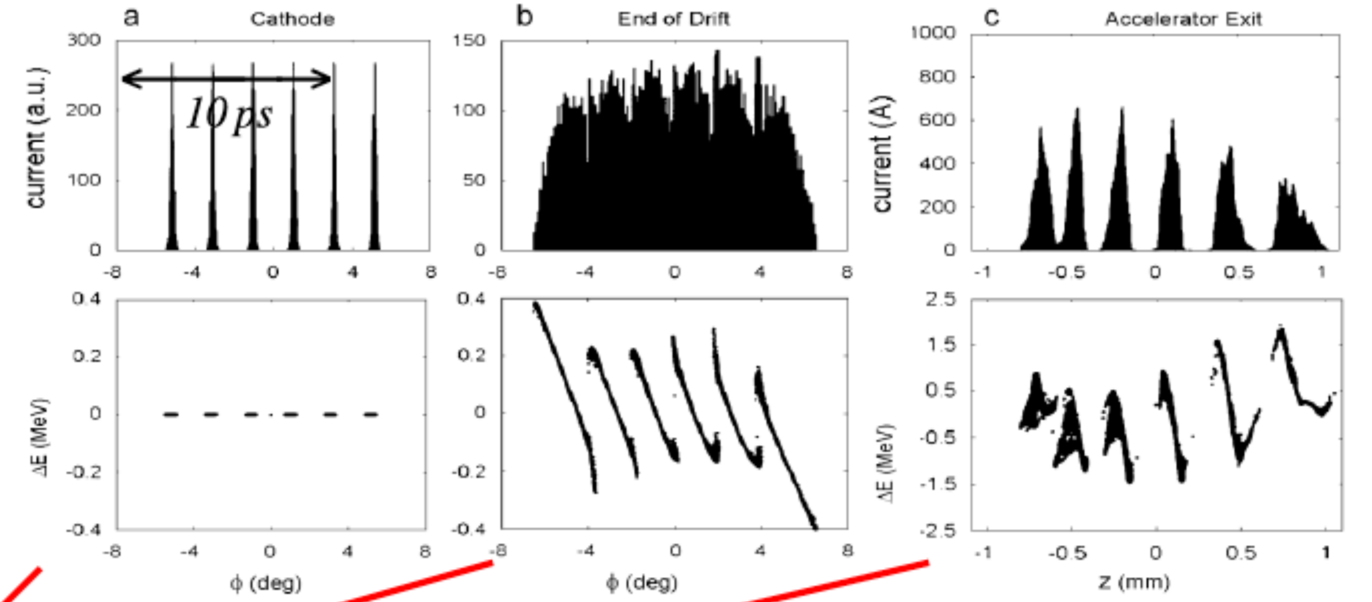
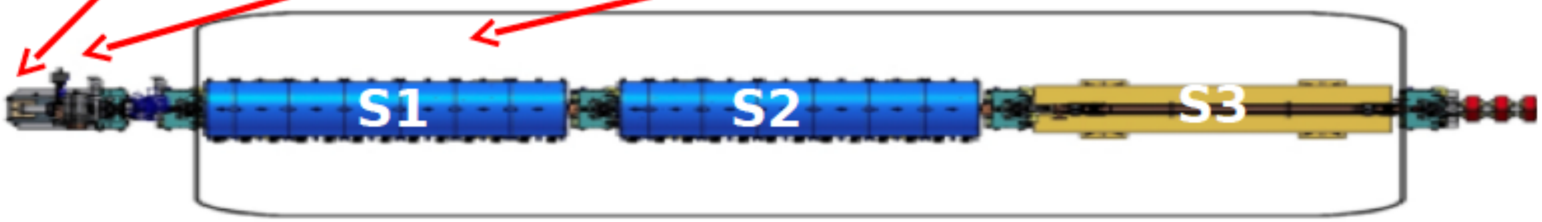
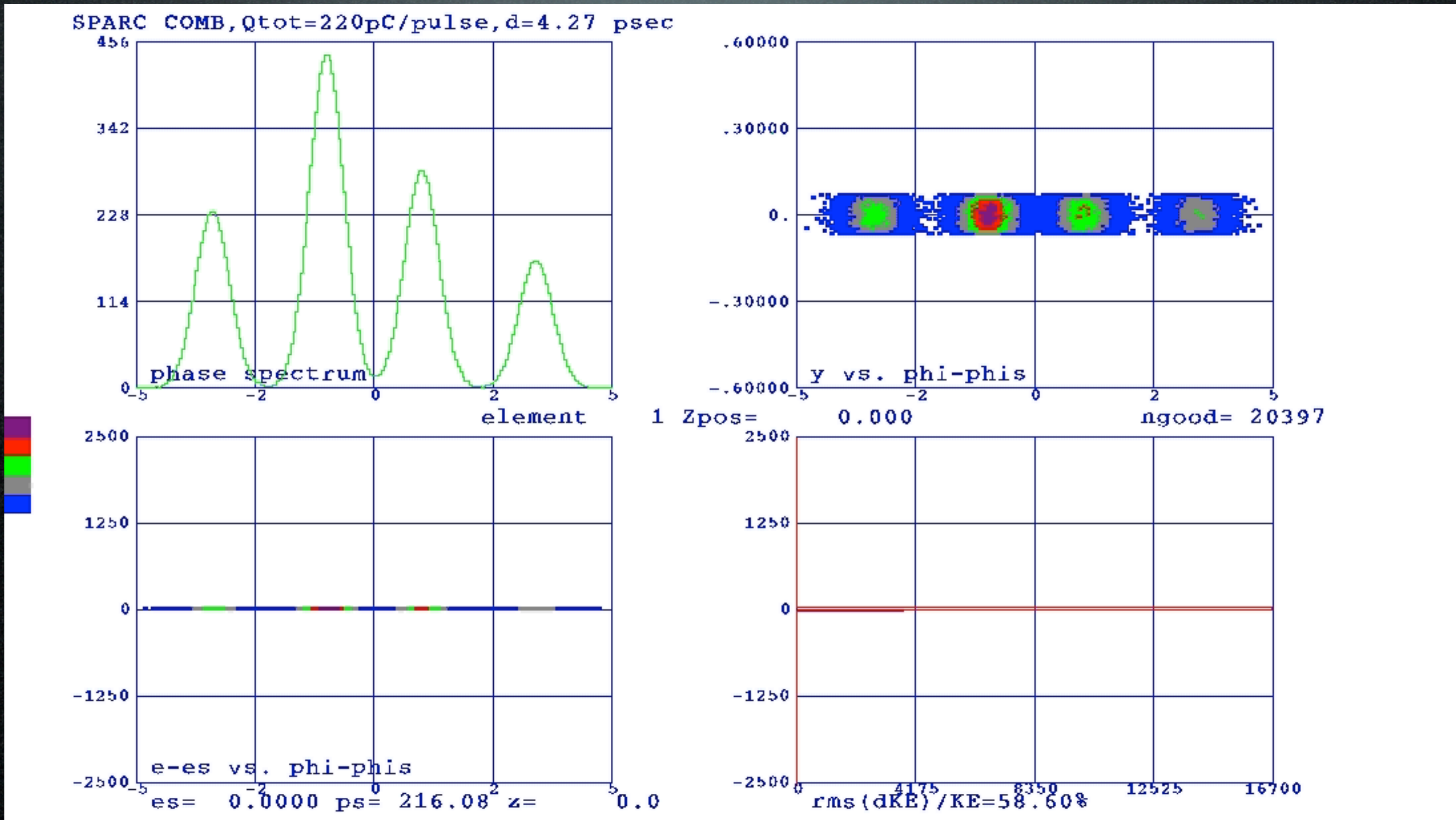


Fig. 1. Evolution of a six bunches electron beam train: the columns from left refer, respectively, to (a) the cathode, (b) the end of the drift at 150 cm and (c) the end of linac at 12 m far from cathode. The rows from top refer, respectively, to longitudinal profile and to energy modulation ΔE (MeV).

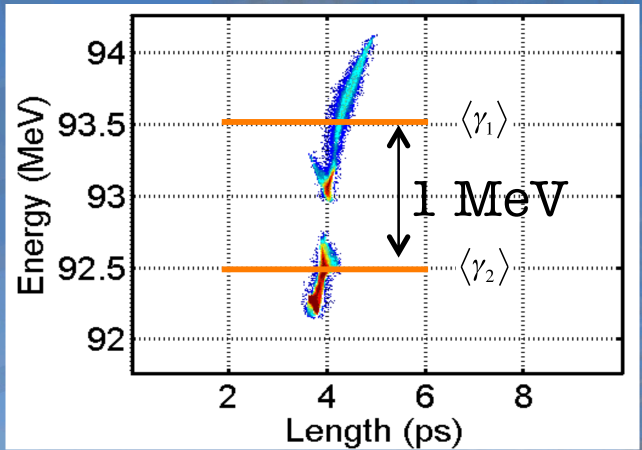


- P.O.Shea et al., Proc. of 2001 IEEE PAC, Chicago, USA (2001) p.704.
- M. Ferrario, M. Boscolo et al., Int. J. of Mod. Phys. B, 2006

Laser COMB: PARMELA simulations



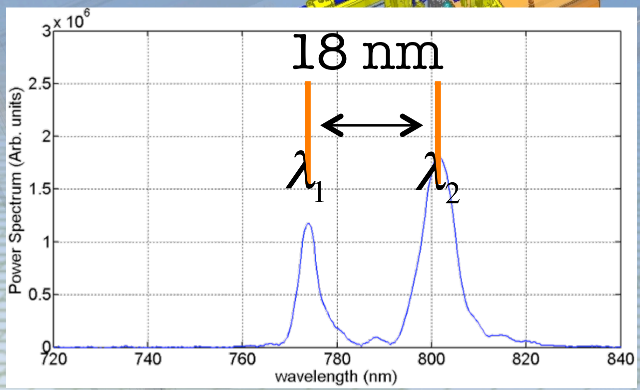
TWO COLORS SASE FEL



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

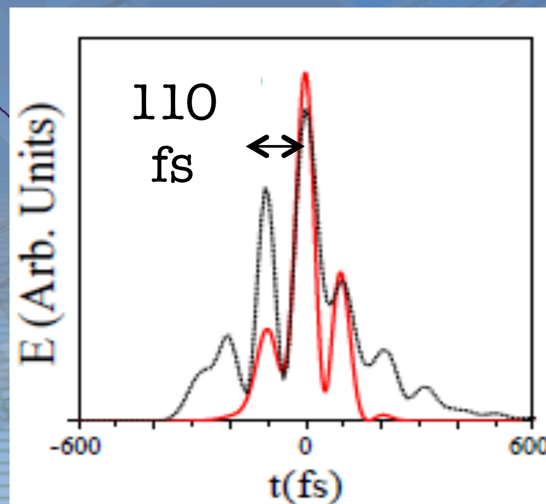
$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1+K_{rms}^2\right)$$

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



produce two wavelength
SASE –FEL radiation
with time modulation

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



PRL 111, 114802 (2013) PHYSICAL REVIEW LETTERS week ending 13 SEPTEMBER 2013

Observation of Time-Domain Modulation of Free-Electron-Laser Pulses by Multipeaked Electron-Energy Spectrum

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

Two Color Free-Electron Laser and Frequency Beating

F. Ciocci[1], G. Dattoli[1]*, S. Pagnutti[2], A. Petralia[1], E. Sabia[1], P. L. Ottaviani[3], M. Ferrario[4], V. Petrillo[5] and F. Villa[4]

Large-bandwidth two-color free-electron laser driven by a comb-like electron beam

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

Physics and Applications of High Brightness Beams Workshop, HBEB 2013

Two Color FEL driven by a Comb-like Electron Beam Distribution

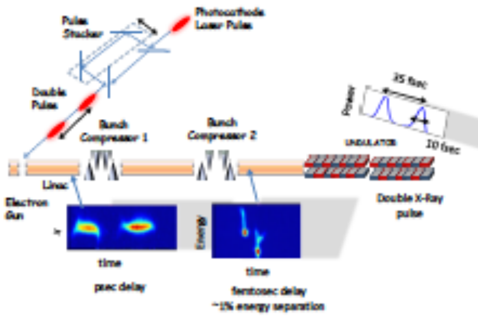
E. Chiadroni[a,*], M. P. Anania[a], M. Artioli[b], A. Bacci[c], M. Bellaveglia[a], A. Cianchi[d], F. Ciocci[b], G. Dattoli[b], D. Di Giovenale[a], G. Di Pirro[a], M. Ferrario[a], G. Gatti[a], L. Giannessi[b], A. Mostacci[e], P. Musumeci[f], L. Palumbo[e], A. Petralia[b], V. Petrillo[c], R. Pompili[a,d], C. Ronsivalle[b], A. R. Rossi[c], C. Vaccarezza[a], F. Villa[a]

Double-Bunch Operation at LCLS

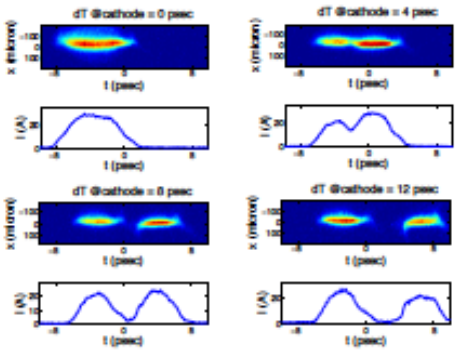
Generate double pulse at cathode and compress.
Similar concept demonstrated at SPARC in the infrared [4]

Double-Bunch Operation at LCLS

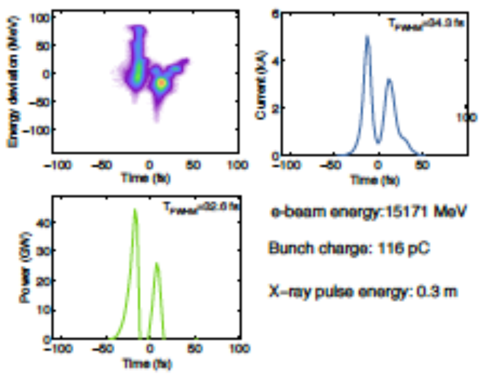
Generate double pulse at cathode and compress.
Similar concept demonstrated at SPARC in the infrared [4]



BEFORE COMPRESSION



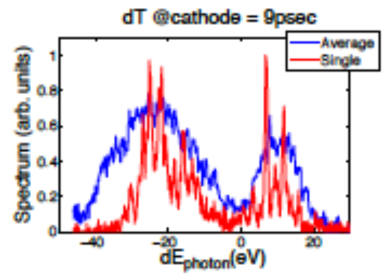
AFTER COMPRESSION (2 STAGE)



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.

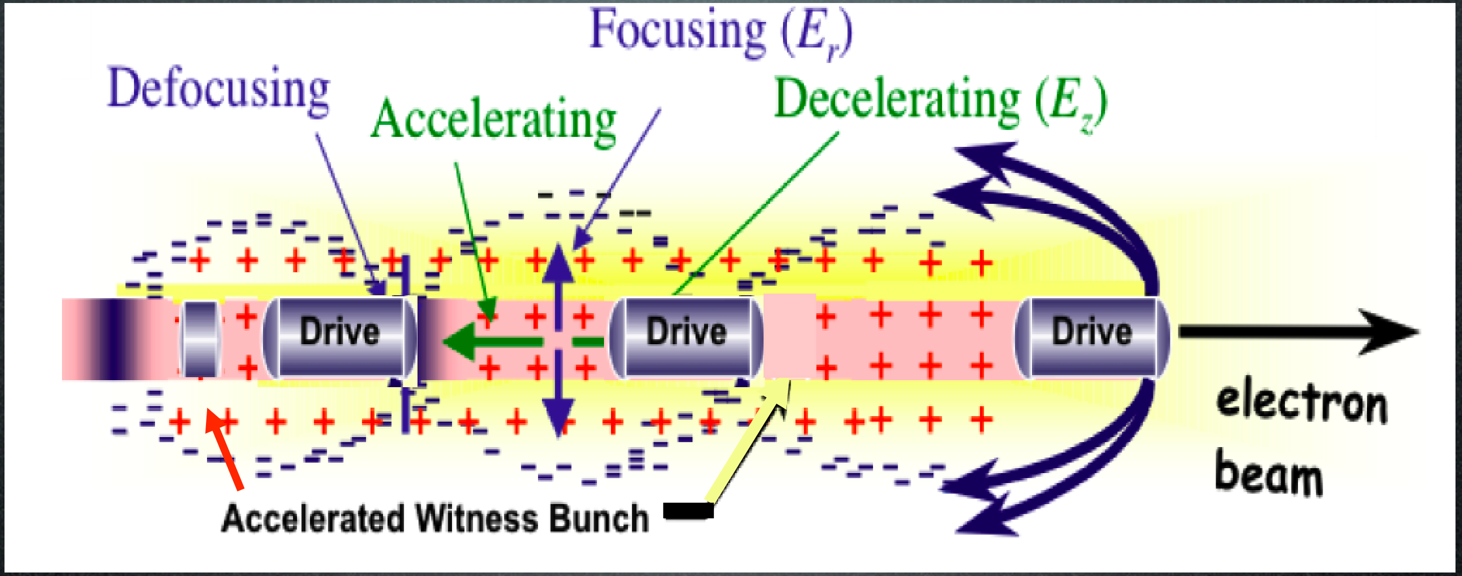
Two-bunch operation is currently under developement. Preliminary experimental results at hard x-rays show the key advantages of this method: full saturation power and possibility to diagnose the x-ray time structure with the x-tcav ona single shot base.

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)

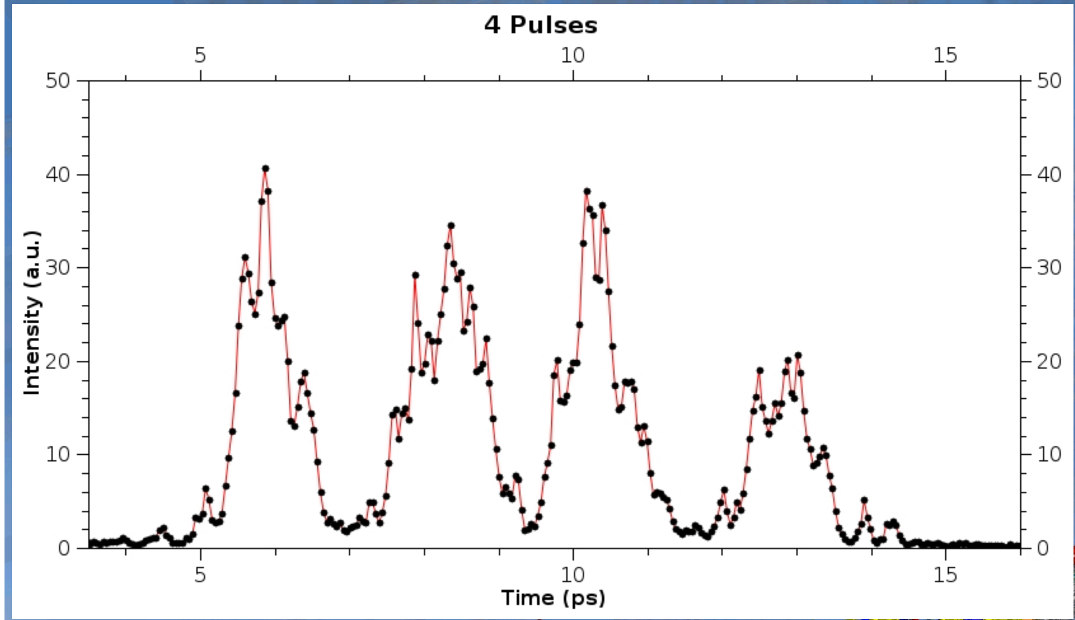
Particle Wake Field Acc.

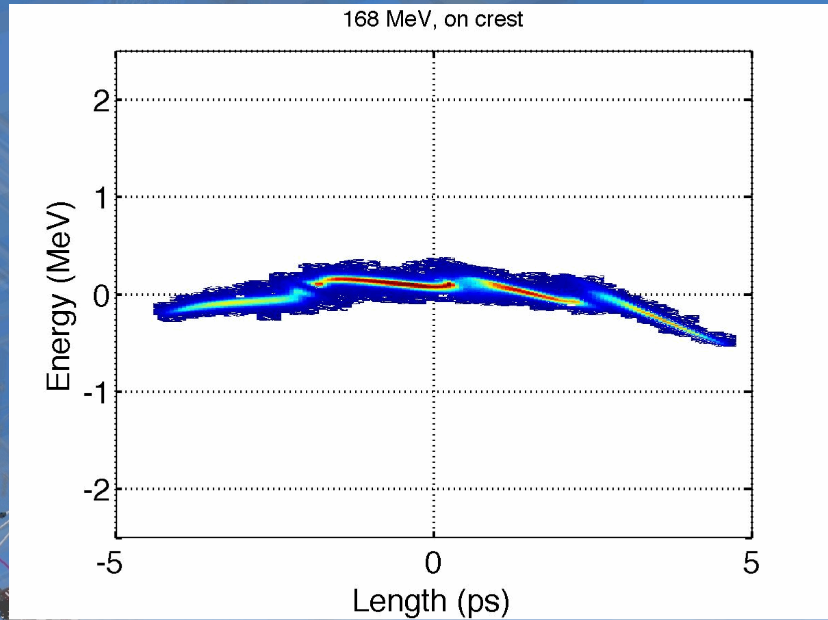
Resonant plasma excitation by a Train of Bunches

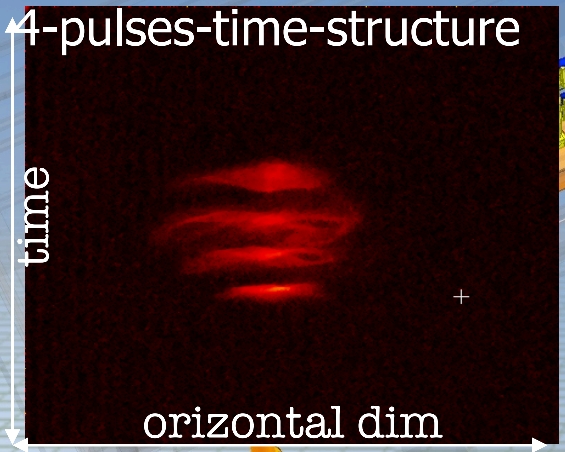


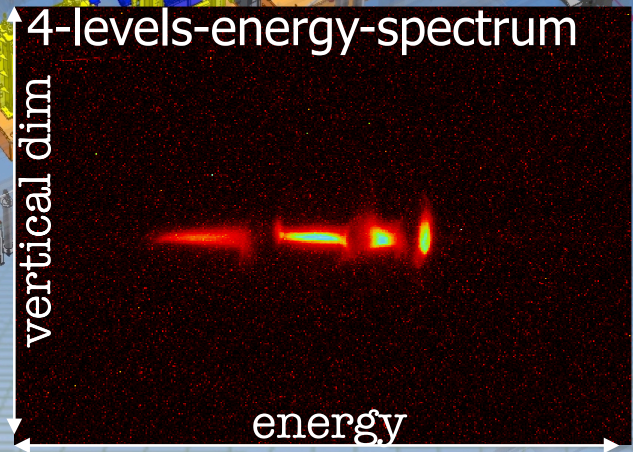
- **Weak blowout regime** with resonant amplification of plasma wave by a train of high Brightness electron bunches produced by **Laser Comb** technique?
- **Ramped bunch train configuration** to enhance tranformer ratio?
- **High quality bunch** preservation during acceleration and transport?

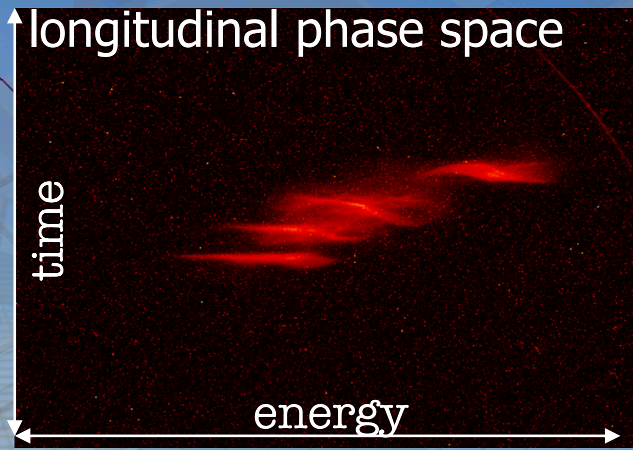
Laser COMB: experimental results











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

A FEL driven by Plasma Accelerator at SPARC_LAB?

I R I D E

Interdisciplinary Research Infrastructure with Dual Electron linacs

Massimo.Ferrario@lnf.infn.it
on behalf of the IRIDE design study group

LUCI DI SINCROTRONE – CNR Roma, 22 Aprile, 2014

Presente e futuro delle grandi sorgenti di raggi X e UV italiane nel contesto europeo

IRIDE aims and potentials

- Science with Free Electron Lasers (FEL) from infrared to X-rays,
- Nuclear photonics with Compton back-scattering g-rays sources,
- Science with THz radiation sources,
- Advanced Neutron sources by photo-production,
- Fundamental physics investigations with low energy linear colliders
- Physics with high power/intensity lasers,

- R&D on advanced accelerator concepts including plasma accelerators and polarized positron sources
- ILC technology implementation
- Detector development for X-ray FEL and Linear Colliders
- R&D in accelerator technology and industrial spin – off

Nuclear Instruments and Methods in Physics Research A 740 (2014) 138–146

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IRIDE: Interdisciplinary research infrastructure based on dual electron linacs and lasers

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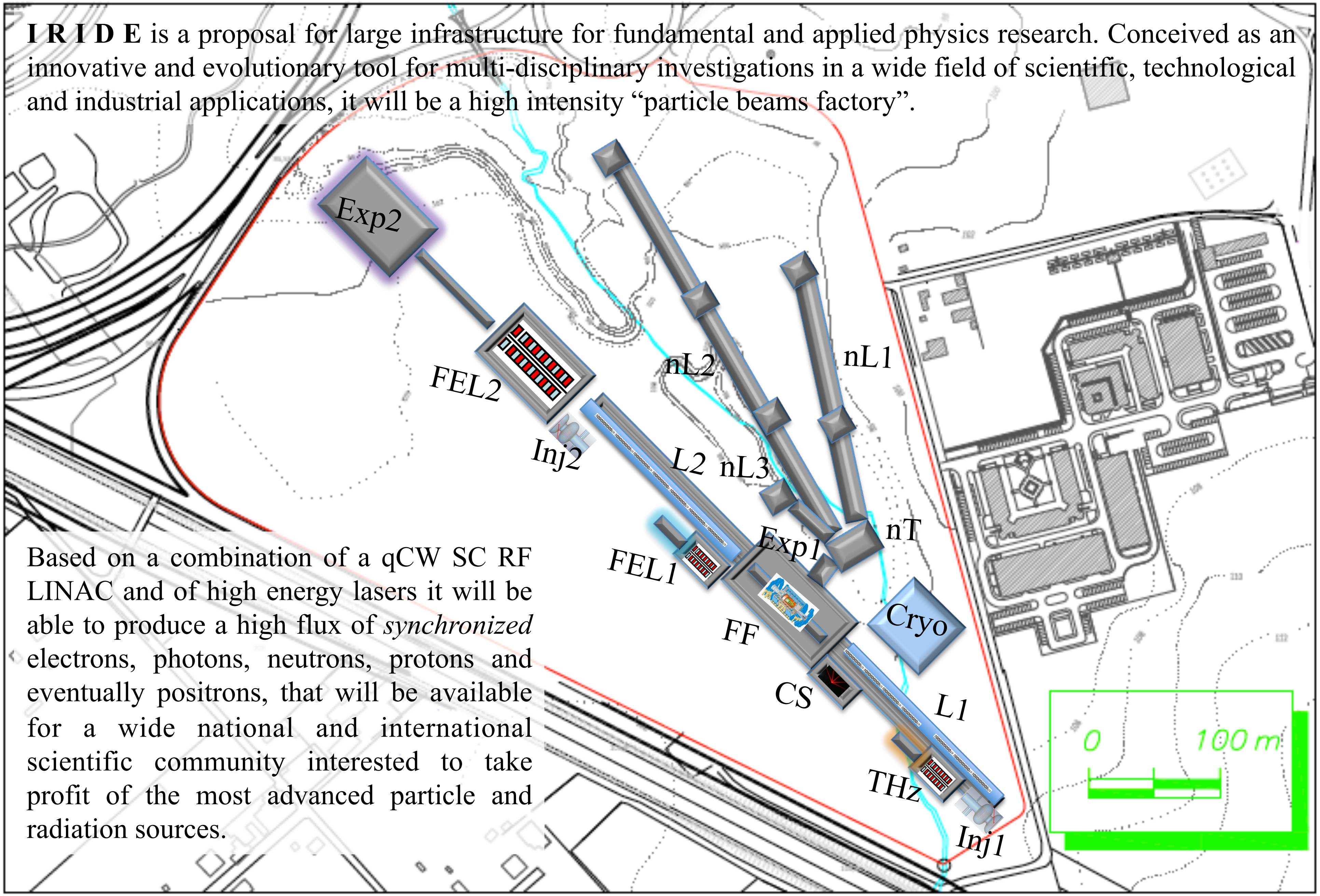
Wide collaboration among Italian and Euopean research institutes !!

Istituzione	# persone	# sezioni
INFN	104	15
CNR	20	6
ENEA	28	2
Altri (Italiani)	40	20
Altri (Stranieri)	43	19

IRIDE White Book delivered on July 17, 2013 available at:

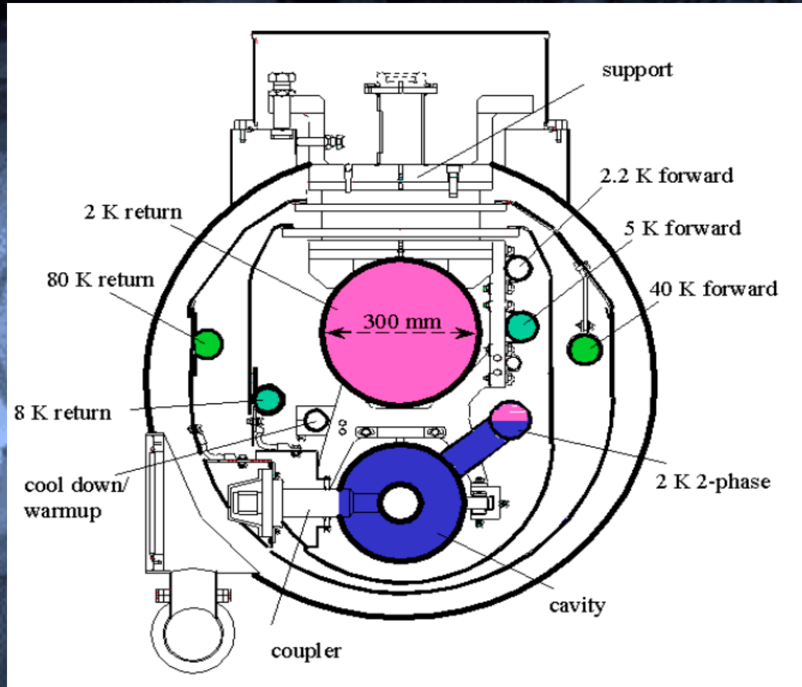
arXiv:1307.7967 [physics.ins-det].

I R I D E is a proposal for large infrastructure for fundamental and applied physics research. Conceived as an innovative and evolutionary tool for multi-disciplinary investigations in a wide field of scientific, technological and industrial applications, it will be a high intensity “particle beams factory”.



Based on a combination of a qCW SC RF LINAC and of high energy lasers it will be able to produce a high flux of *synchronized* electrons, photons, neutrons, protons and eventually positrons, that will be available for a wide national and international scientific community interested to take profit of the most advanced particle and radiation sources.

INFN is in a leading position in the SC RF technology, with knowledge and strong capabilities in the design, engineering and industrial realization of all the main component of a superconducting radiofrequency accelerator.

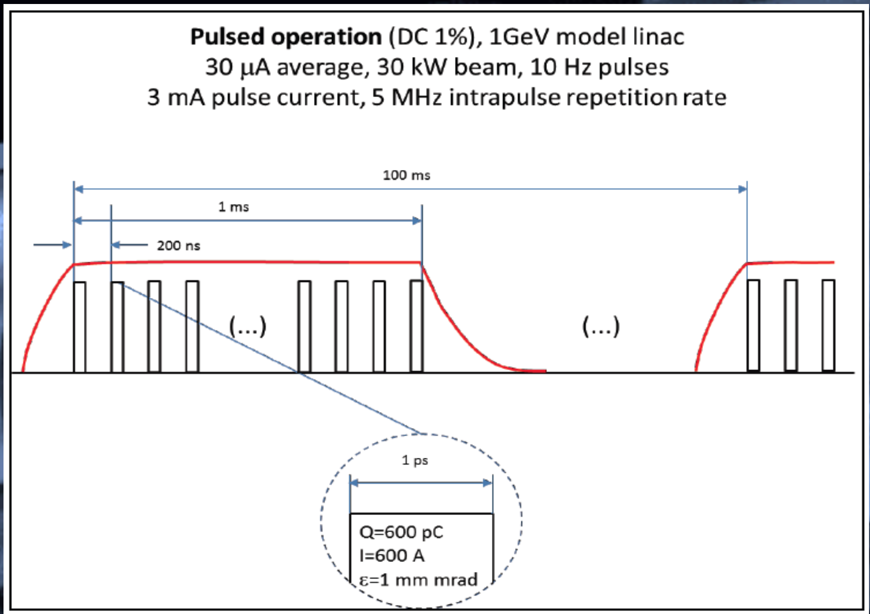


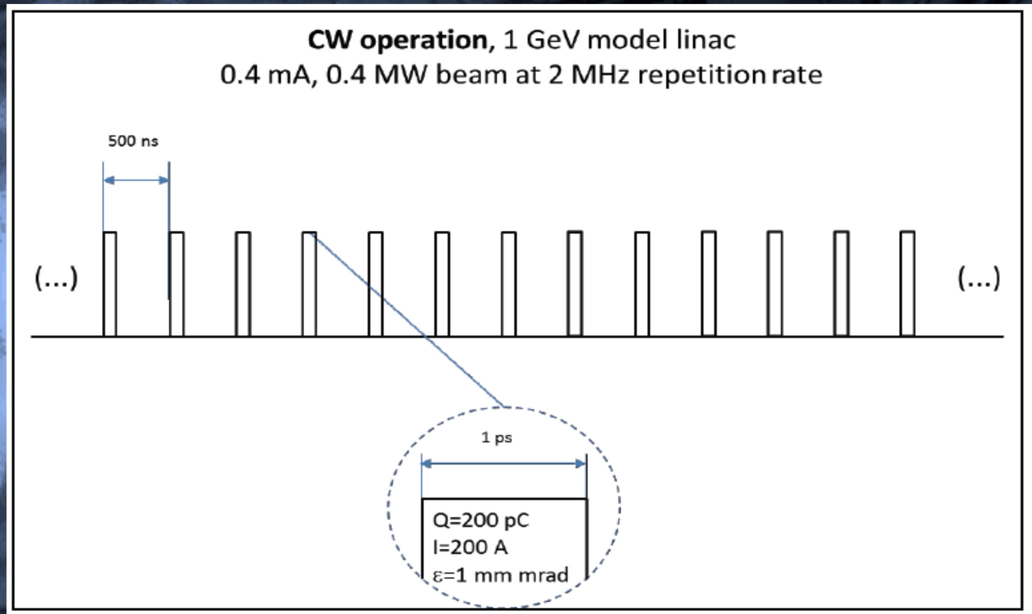
XFEL Italian In-Kind contribution

- 400/800 of the 1.3 GHz cavities
- 45/100 of the cryomodules
- High QE photocathode preparation/transport system
- Cavities/Cryomodule for the 3.9 GHz linearizer

i.e. the main components for a 9 GeV SC linac

The main feature of a SC linac relevant for IRIDE is the possibility to operate the machine in continuous (CW) or quasi-continuous wave (qCW) mode with high average beam power (>1 MW) and high average current (>300 μA).





The CW or qCW choice, combined with a proper bunch distribution scheme, offers the most versatile solution to provide bunches to a number of different experiments, as could be envisaged in a multi-purpose facility.

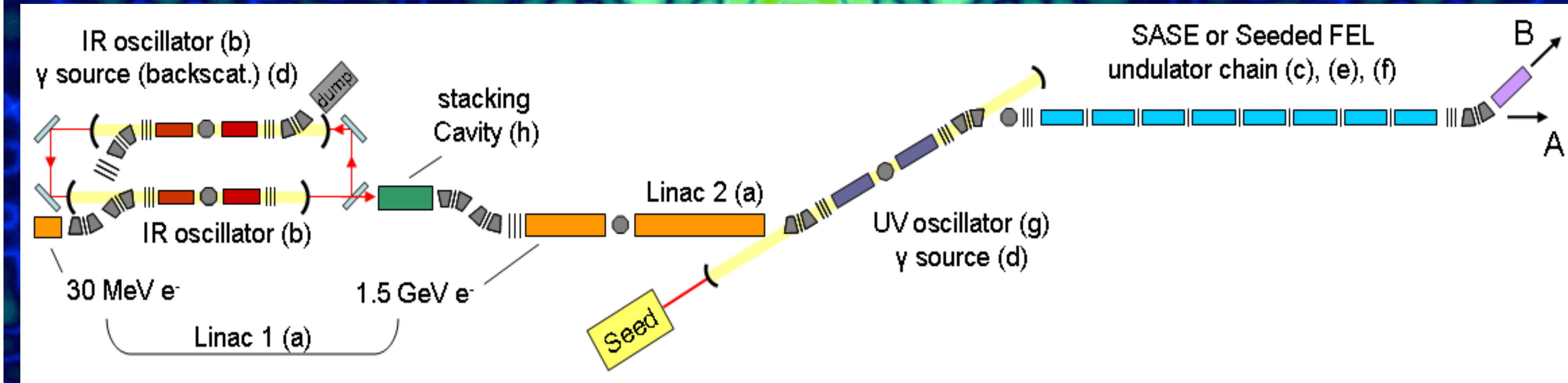
IRIDE linac parameters flexibility (for each linac)

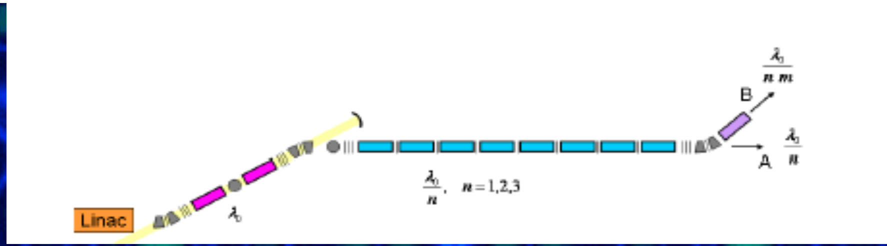
Table 1: Possible SC linac parameters

	Pulsed	qCW	CW
Energy [GeV]	2	2	1.5
I (within pulse) [mA]	2.5	0.26	
I (average) [mA]	0.17	0.16	0.35
RF pulse duration [ms]	1.5	1000	CW
RF Duty cycle [%]	15	60	100
E_{acc} [MV/m]	20	20	15
$Q_0 \times 10^{10} / Q_{ext} \times 10^6$	2/4	2/40	2/40
N. of cavities/N. of modules	96/12	96/12	96/12
Beam average power [kW]	334	309	525

IRIDE Free Electron Lasers

The IRIDE project will provide a new concept of FEL facility by merging the two technologies of FEL oscillators and fourth generation radiation sources by developing a facility providing radiation from IR to EUV to the nm region down to Å level using a mechanism of emission already successfully tested at SPARC.





1.5 Gev electron beam energy

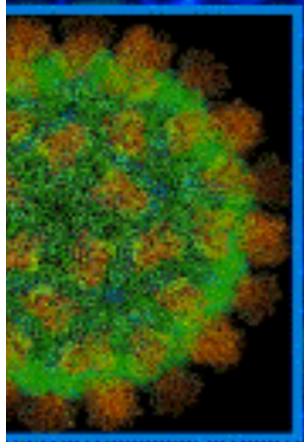
	Fundamental	3° harmonic	5° harmonic
λ(nm/KeV)	4/0.413	1.33/1.23	0.8/2.07
peak flux (n/s/- 0.1%BW)	$2.7*10^{26}$	$2.5*10^{24}$	$1.9*10^{23}$
Peak brilliance	$1.56*10^{30}$	$1.4*10^{28}$	$1.1*10^{27}$
photon/bunch	$5.94*10^{13}$	$5.5*10^{11}$	$4.18*10^{10}$

3.0 Gev electron beam energy

	Fundamental	3° harmonic	5° harmonic
λ(nm/KeV)	1/1.24	0.3/3.72	0.2/6.2
peak flux (n/s/- 0.1%BW)	$4.6*10^{25}$	$4.1*10^{23}$	$3.4*10^{22}$
Peak brilliance	$6.4*10^{31}$	$5.7*10^{29}$	$4.7*10^{28}$
photon/bunch	$1.01*10^{13}$	$9.02*10^{10}$	$7.48*10^{9}$

4.0 Gev electron beam energy

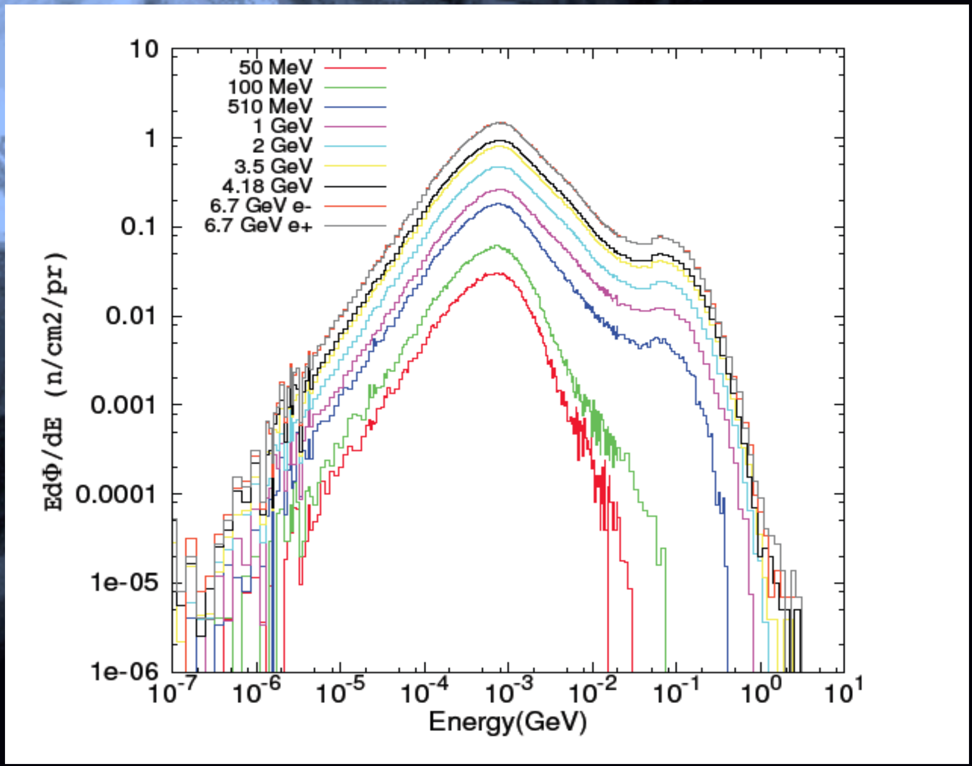
	Fundamental	3° harmonic	5° harmonic
λ(nm/KeV)	0.563/2.2	0.188/6.5	0.113/10.9
peak flux (n/s/- 0.1%BW)	$1.2*10^{25}$	$5.9*10^{22}$	$2.8*10^{21}$
Peak Brilliance	$1.92*10^{31}$	$1.8*10^{29}$	$1.2*10^{28}$
photon/bunch	$2.1*10^{12}$	$1.06*10^{10}$	$5.0*10^{8}$



Neutron Source

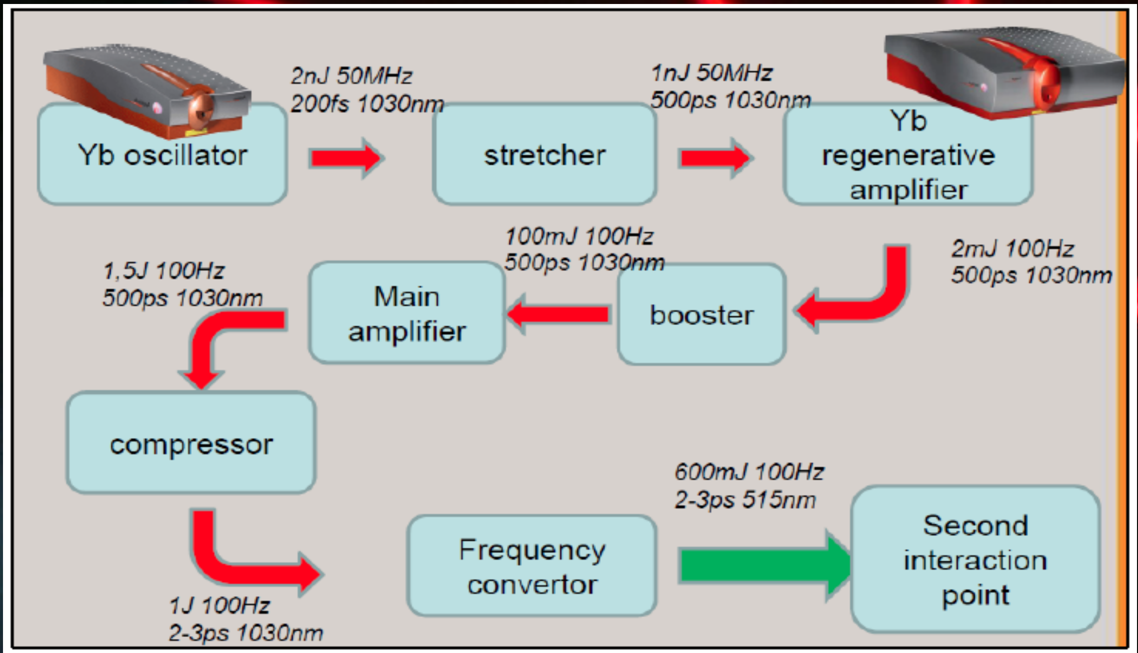
This source may be suitable for multiple applications, ranging from material analysis for industrial and cultural heritages purposes to chip irradiation and metrology. These applications envisage the development of properly designed beam lines with neutron moderation and possibly cold/thermal neutron transport systems. The proposed new facility will represent a great opportunity for research and development of neutron instrumentation (e.g. detectors) as well as training of young scientist in the use and development of neutron techniques.

Deposited Power [kW]	Primary Electron Energy [GeV]	Expected Average Neutron Emission rate [n/s]
30	1	1.3 E+14
250	1	1.0 E+15
400	1	1.7 E+15
30	3	4.3 E+13
250	3	3.3 E+14
400	3	5.6 E+14



Advanced γ-ray Compton Source

The state of the art in producing high brilliance/spectral density mono-chromatic γ-ray beams will be soon enhanced, stepping up from the present performances (γ-ray beams with bandwidth nearly 3% and spectral density of about 100 *photons/s·eV*) up to what is considered the threshold for Nuclear Photonics, *i.e.* a bandwidth of the γ-ray beam lower than 0.3% and a spectral density larger than 10^4 *photons/s·eV*.



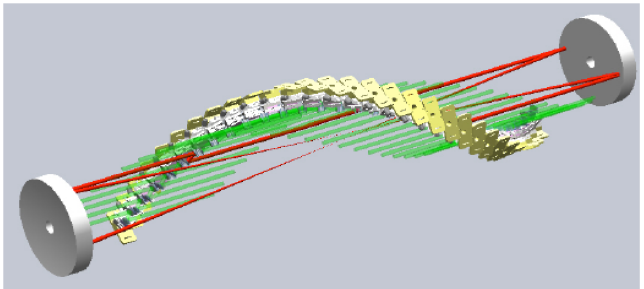


Fig. 133. Schematic view of the re-circulating principle

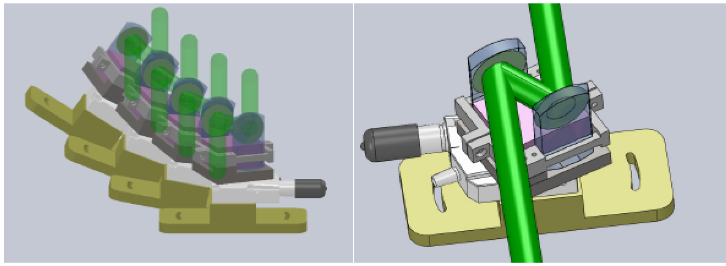


Fig. 134. Schematic view of the motorized mirror pairs used in the re-circulator

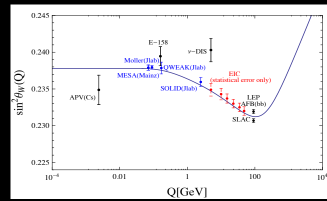
- colliding laser pulses to drive the back-scattering Compton (Yb:YAG, 100 W, 1 J, 0.1% bw)

Particle Physic Opportunities

IRIDE facility can be a precision tool for the SM exploration at low- and medium-energy scales

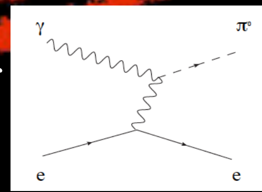
ELECTRONS ON TARGET:

Utilizing the polarized electron beam dumped onto the proton target, one can measure the left-right parity violating asymmetry of electron-proton scattering at the per cent level, and thereby extract precisely the electroweak mixing angle.

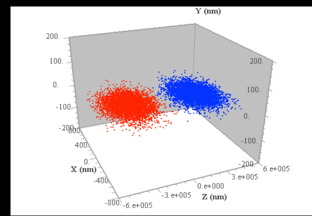


LINEAR COLLIDER CONFIGURATIONS:

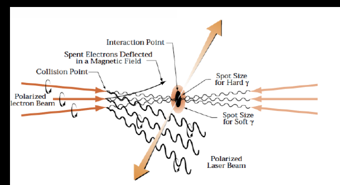
γ-e The precise measurement of the π^0 width through the process $e\gamma \to \pi^0 e$ (*Primakoff effect*), and the search for light dark bosons in the energy region of few to hundreds MeV.



$e^- e^-$, $e^+ e^-$ An electron-positron collider with luminosity of 10^{32} $cm^{-2}s^{-1}$ with center of mass energy ranging from the mass of the φ-resonance 1 GeV up to ~3.0 GeV would allow one to measure the e^+e^- cross section to hadrons with a total fractional accuracy of 1%, with relevant measurements for the the *g*-2 of the muon and the effective fine-structure constant at the M_Z scale.



γ-γ We propose an experiment to observe photon-photon scattering in the range 1 MeV – 2 MeV CM energy, i.e., near the peak of the QED cross-section.

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