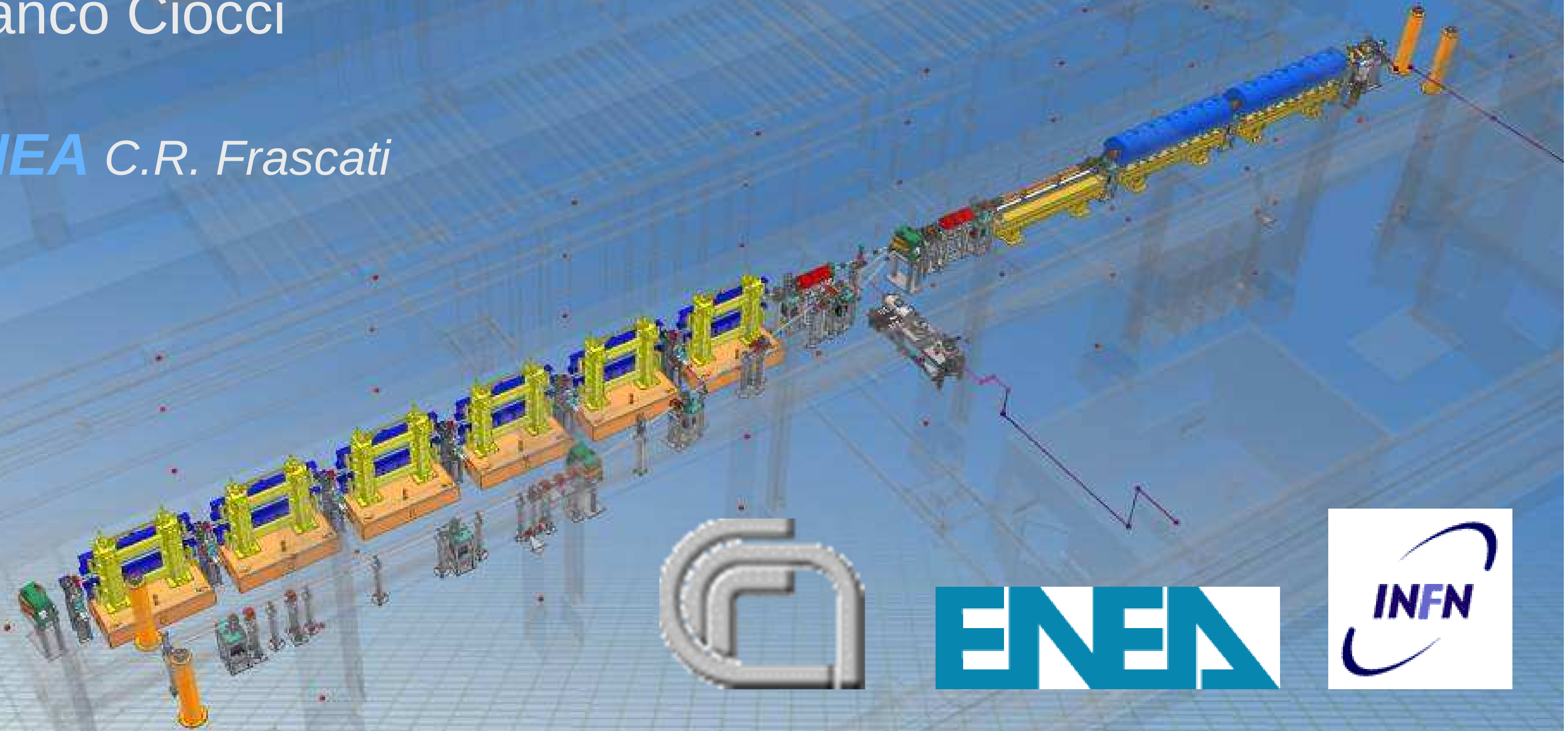
FEL experiments at SPARC

Franco Ciocci

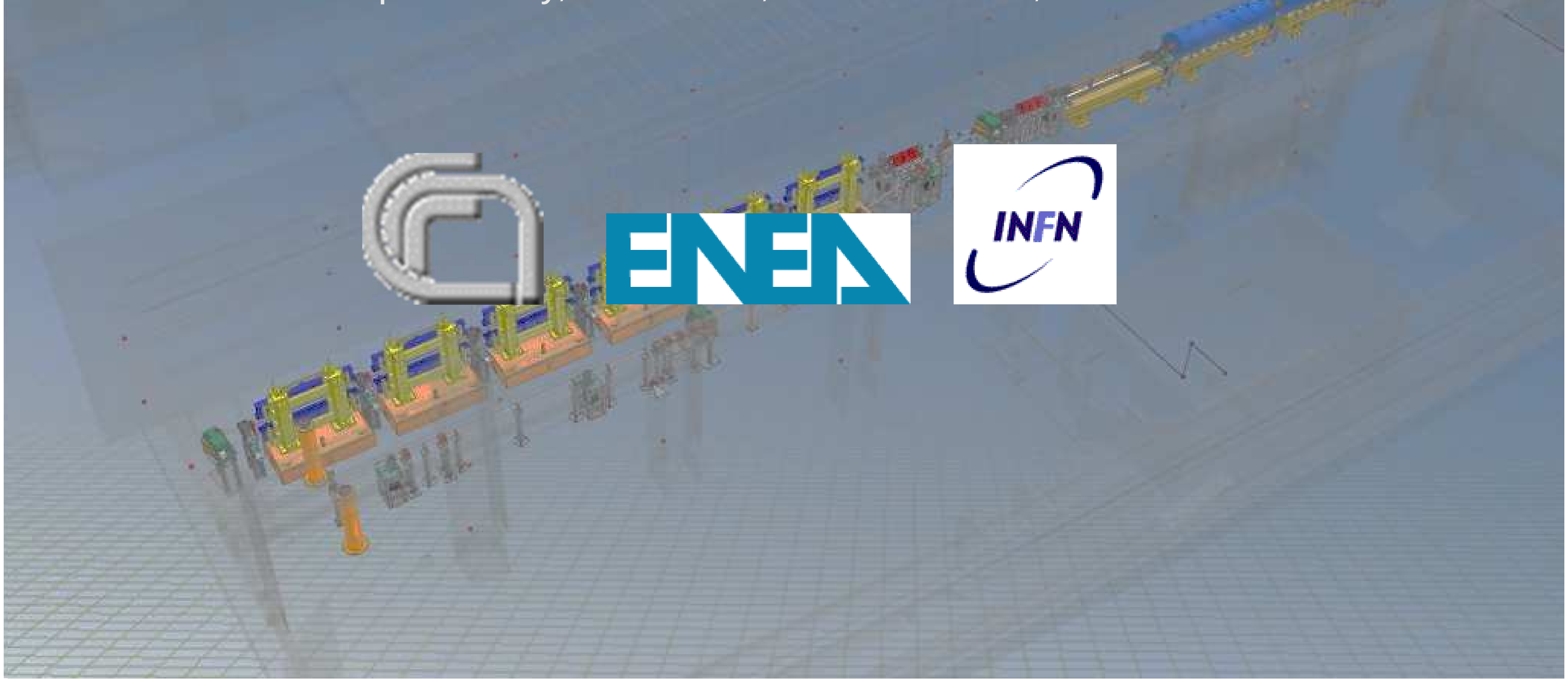
ENEA C.R. Frascati



Seeding and Self Seeding at New FEL sources 10 December 2012

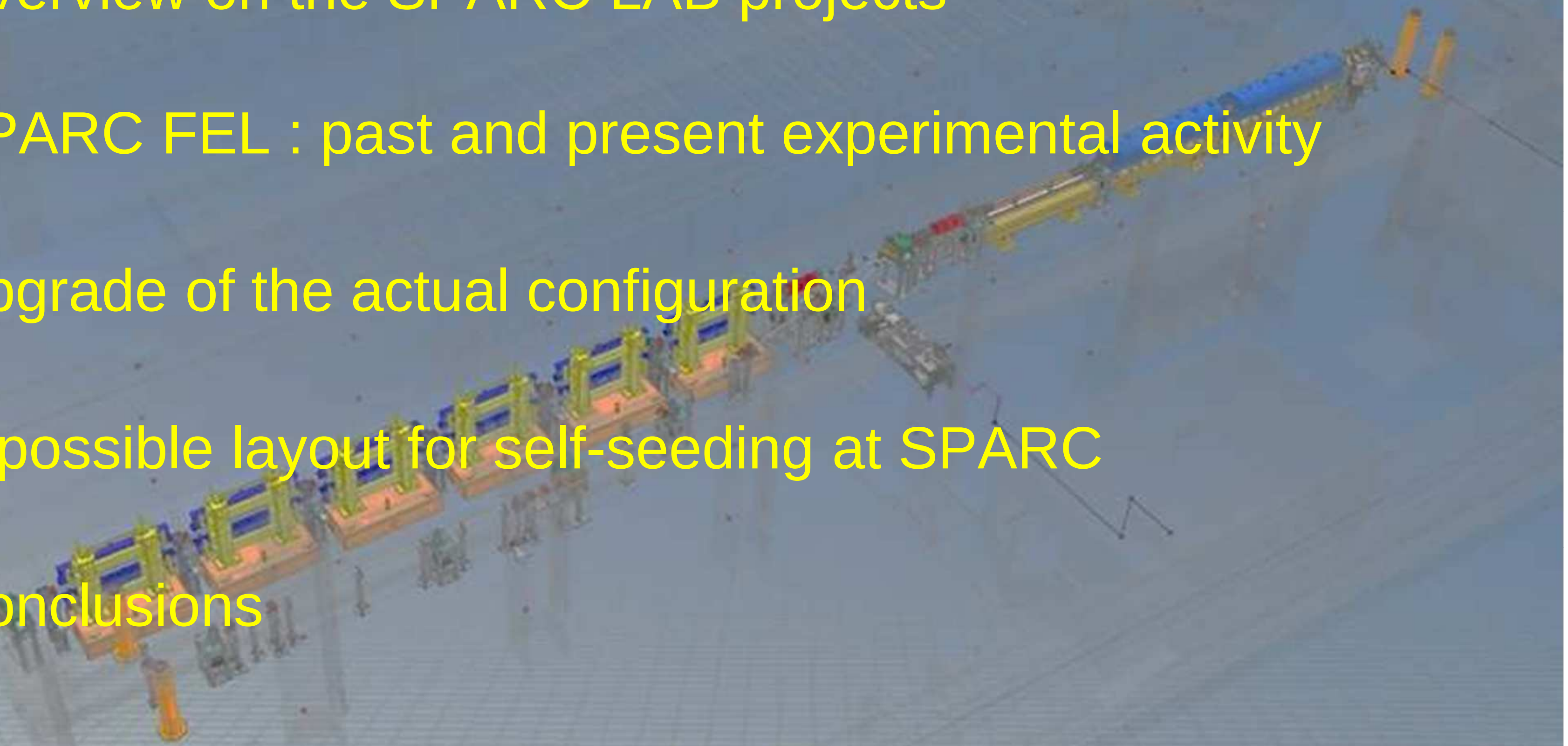
The SPARC FEL scientific staff

D. Alesini, M. Anania, A. Bacci, M. Bellaveglia, E. Di Palma, M. Castellano, E. Chiadroni, A. Cianchi, F. Ciocci, G. Dattoli, M. Del Franco, D. Di Giovenale, G. Di Pirro, A. Drago, M. Ferrario, A. Gallo, G. Gatti, L. Giannessi, A. Mostacci, E. Pace, A. Petralia, V. Petrillo, R. Pompili, M. Quattromini, J.V. Rau, C. Ronsivalle, A. R. Rossi, E. Sabia, I. Spassovsky, V. Surrenti, C. Vaccarezza, F. Villa



Outline

- SPARC FEL device
- Overview on the SPARC LAB projects
- SPARC FEL : past and present experimental activity
- Upgrade of the actual configuration
- A possible layout for self-seeding at SPARC
- Conclusions



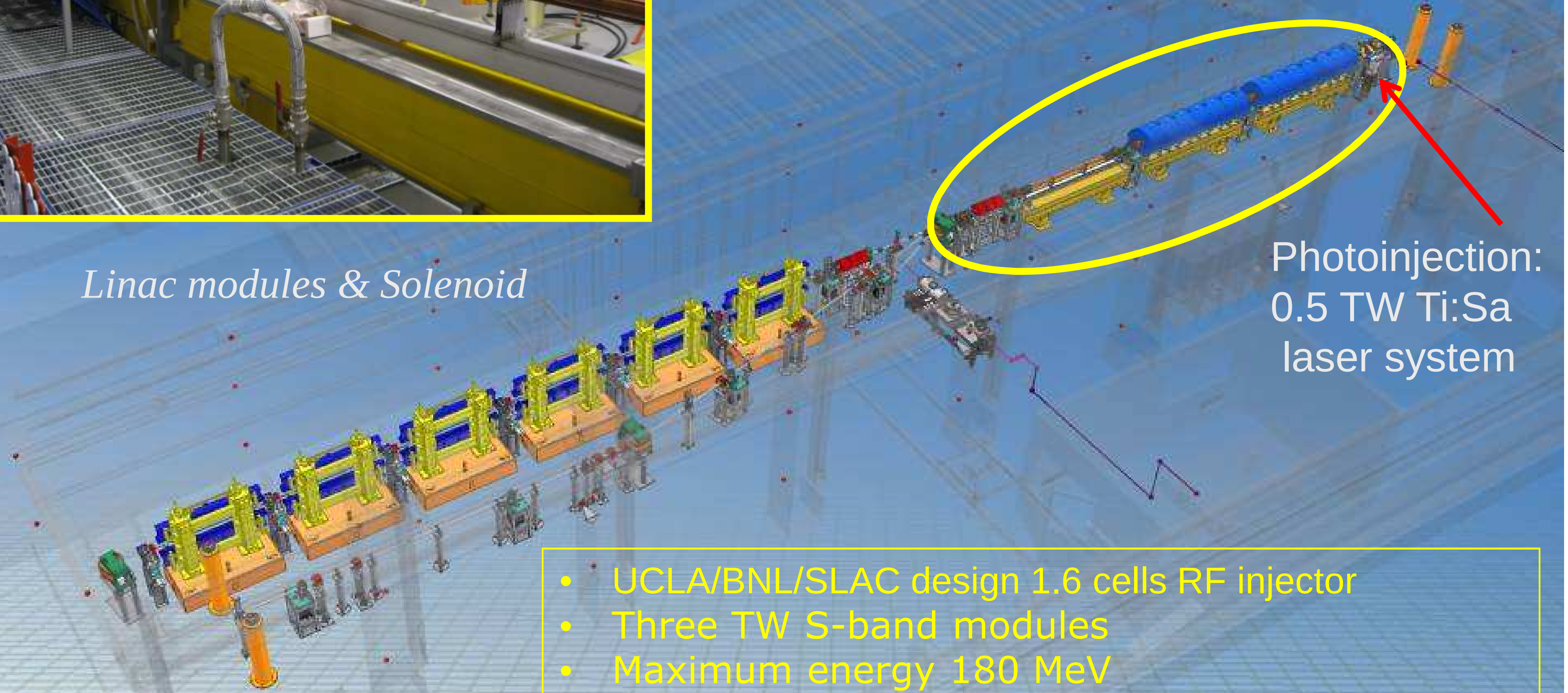
Linac modules & Solenoid

RF Gun & Solenoid

Solenoid ~3 kG

Input Power 14 MW

Max Acc. Field @ cathode ~ 130 MV/m

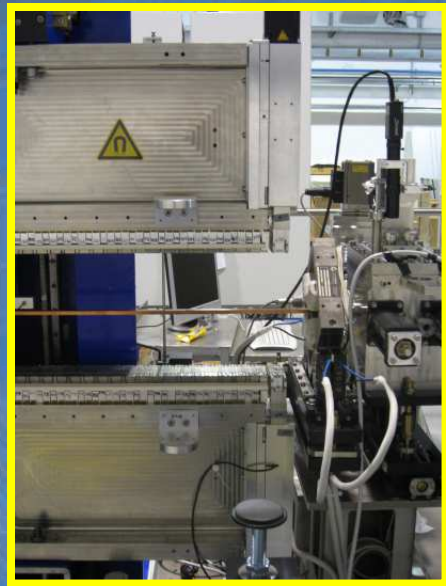


Photoinjection: 0.5 TW Ti:Sa laser system

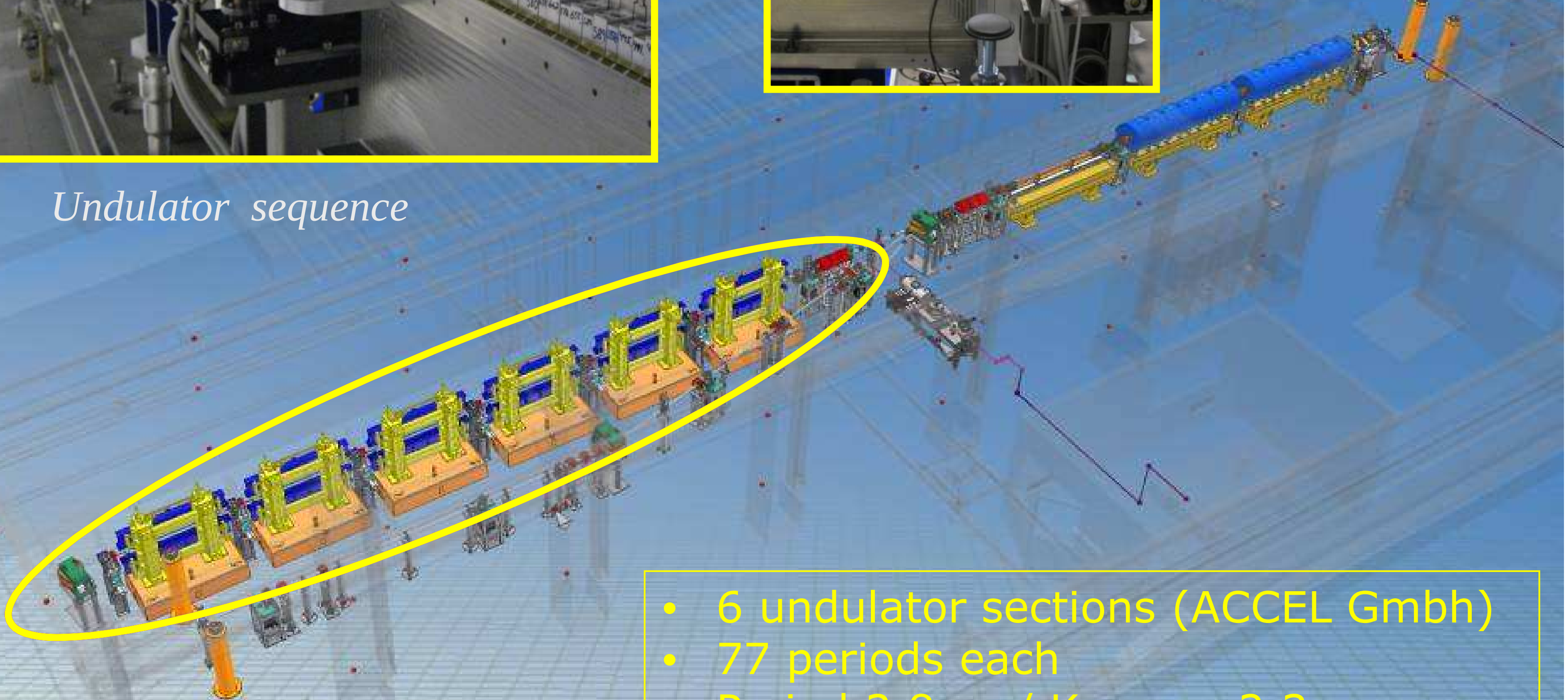
- UCLA/BNL/SLAC design 1.6 cells RF injector
- Three TW S-band modules
- Maximum energy 180 MeV
- Focusing solenoids on the first two modules (longitudinal compression via velocity bunching)

SPARC

Undulator sequence

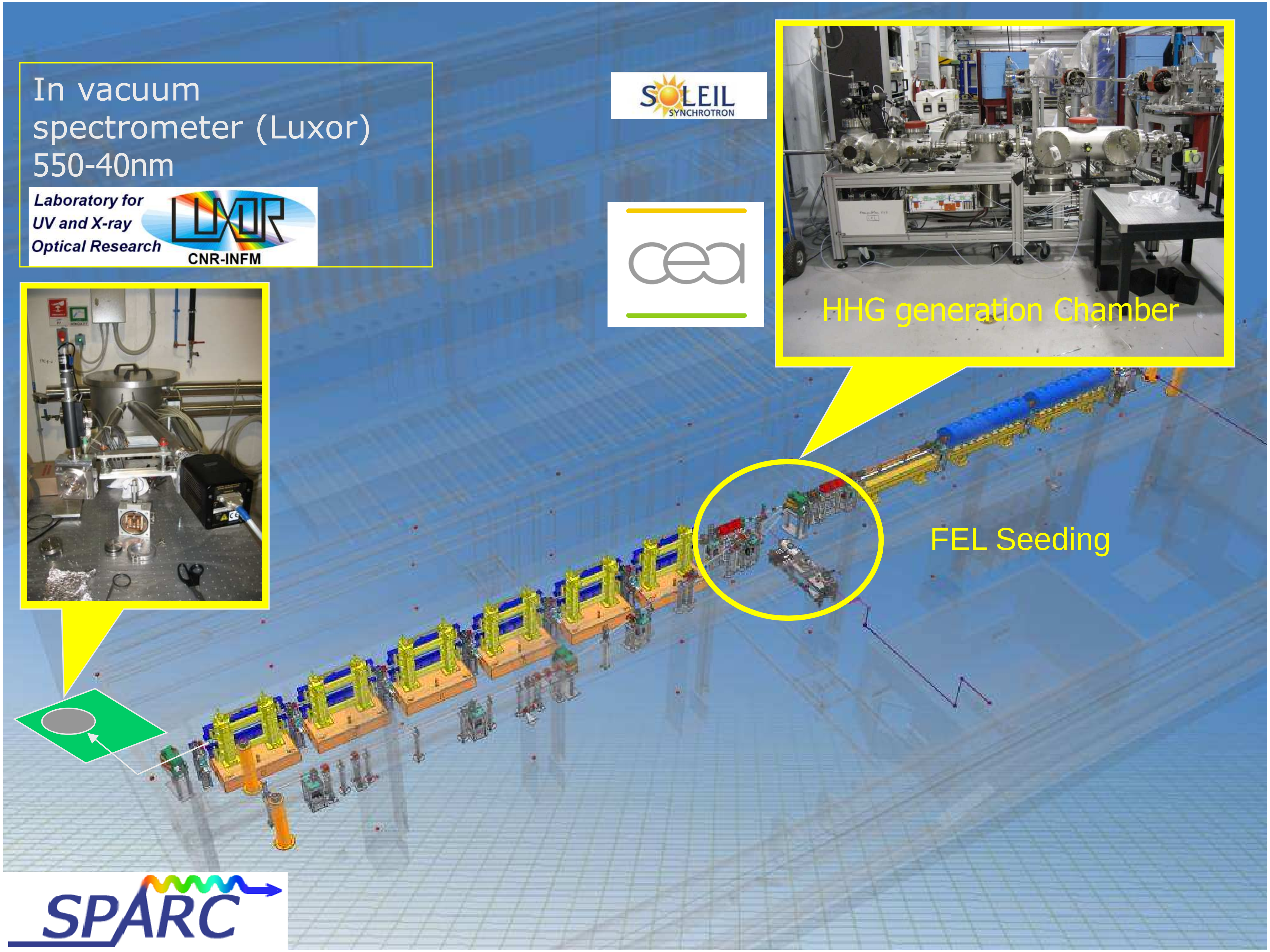


Undulator termination with phase shifter



- 6 undulator sections (ACCEL Gmbh)
- 77 periods each
- Period 2.8cm / K max ~2.3
- Phase shifters between the modules

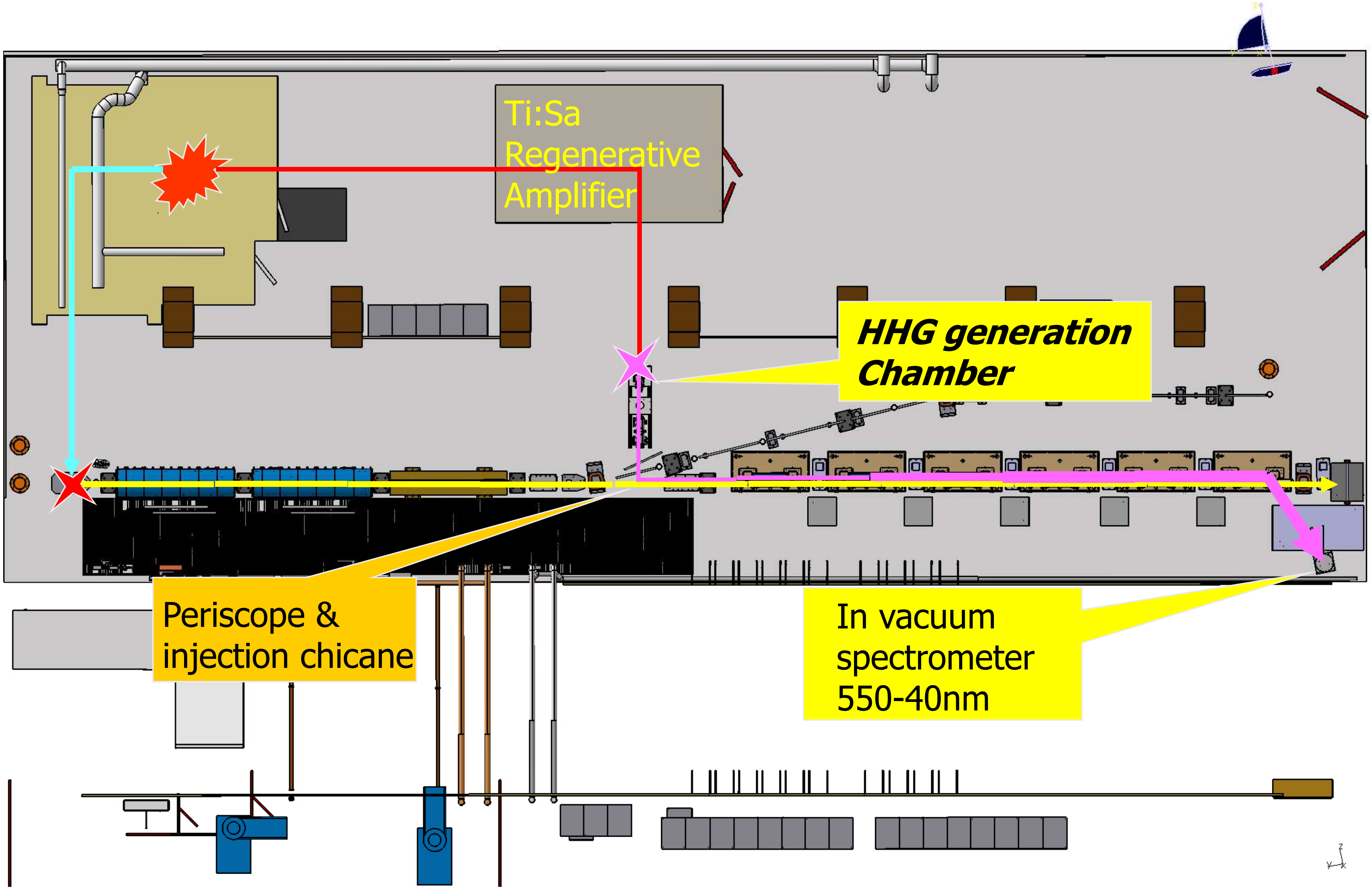
SPARC



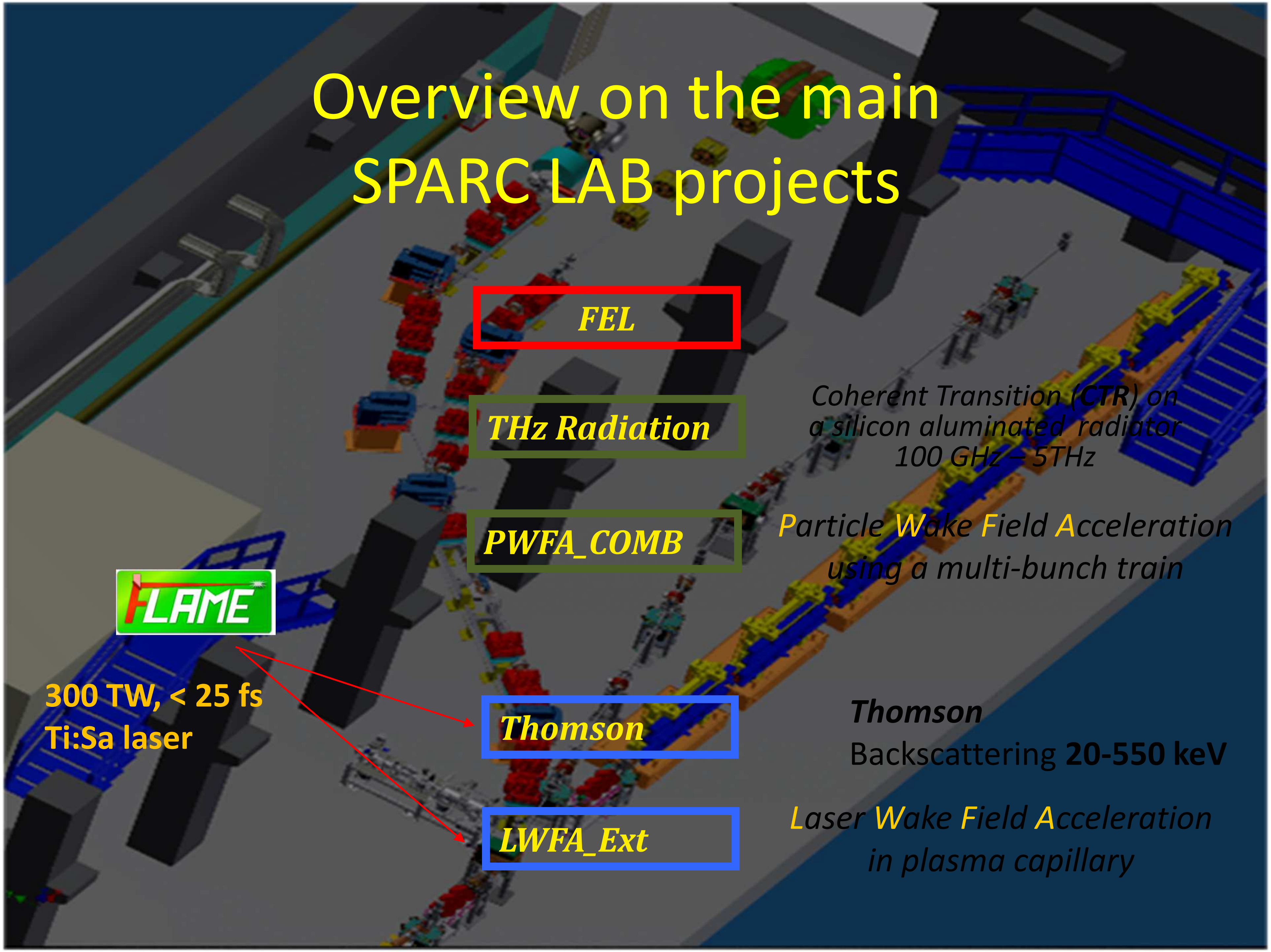
In vacuum
spectrometer (Luxor)
550-40nm
Laboratory for
UV and X-ray
Optical Research
CNR-INFM
SOLEIL
SYNCHROTRON
cea
HHG generation Chamber
FEL Seeding
SPARC

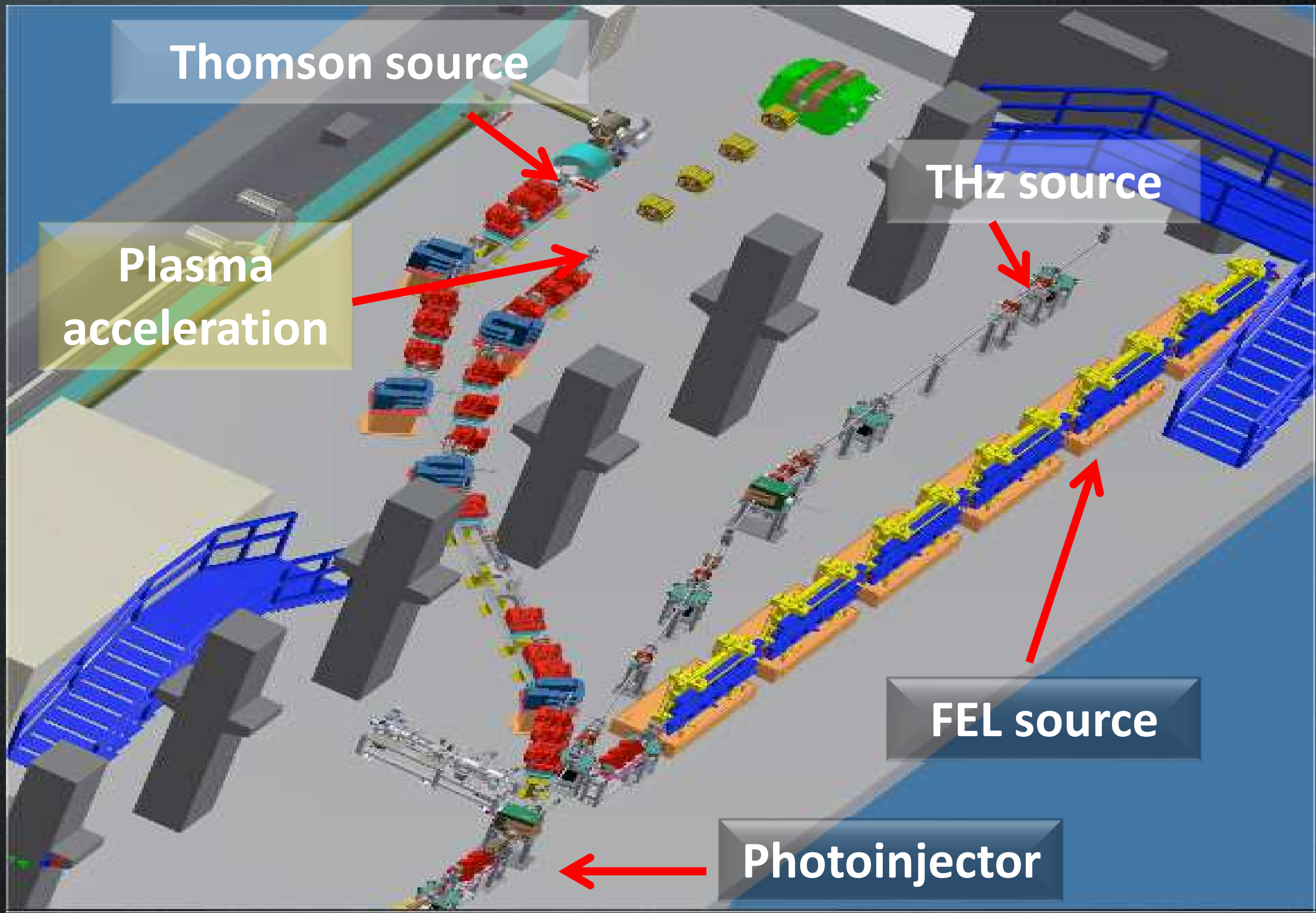
Seeded SPARC Layout

EURO FEL + MUR



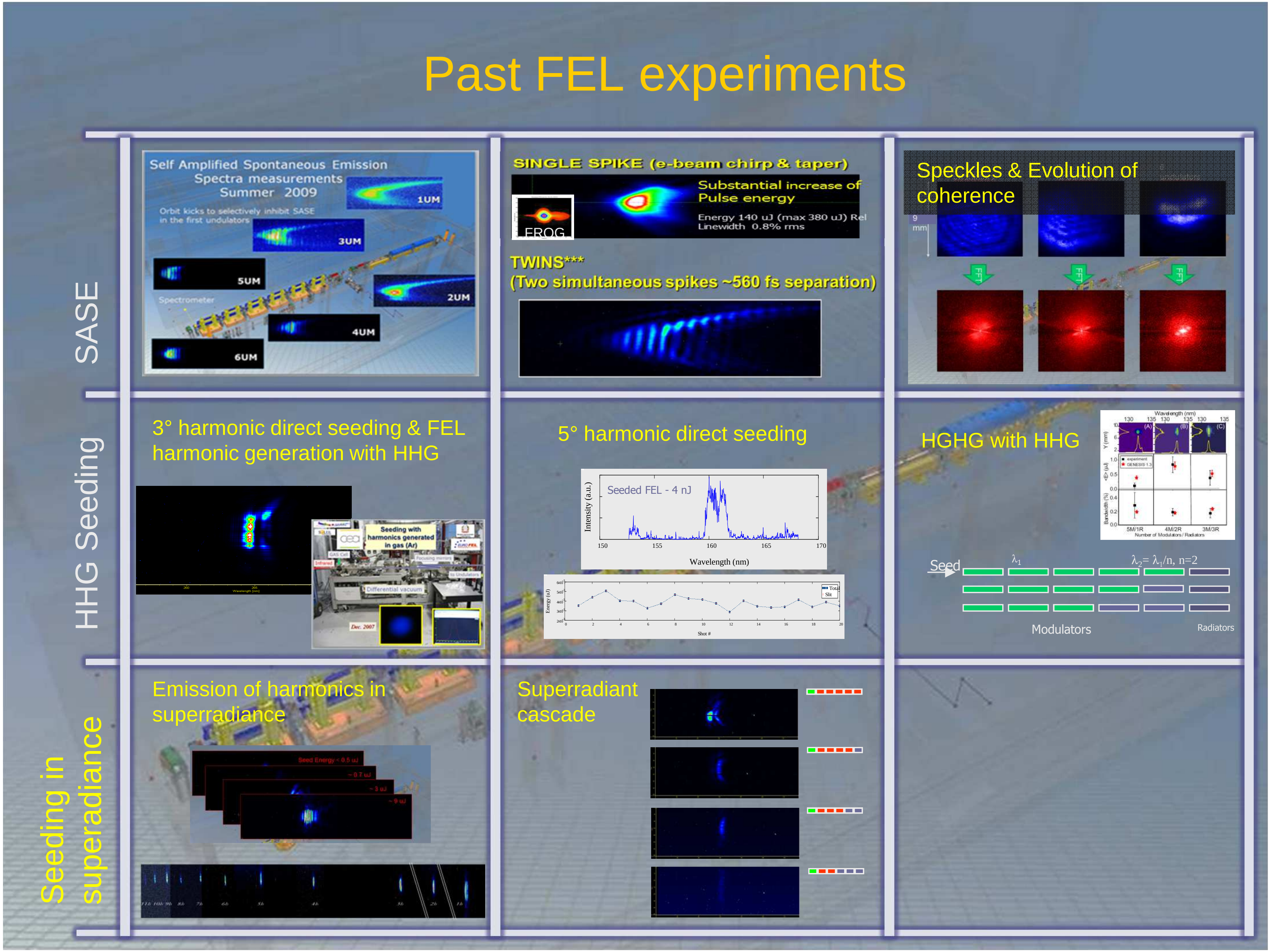
Overview on the main SPARC LAB projects



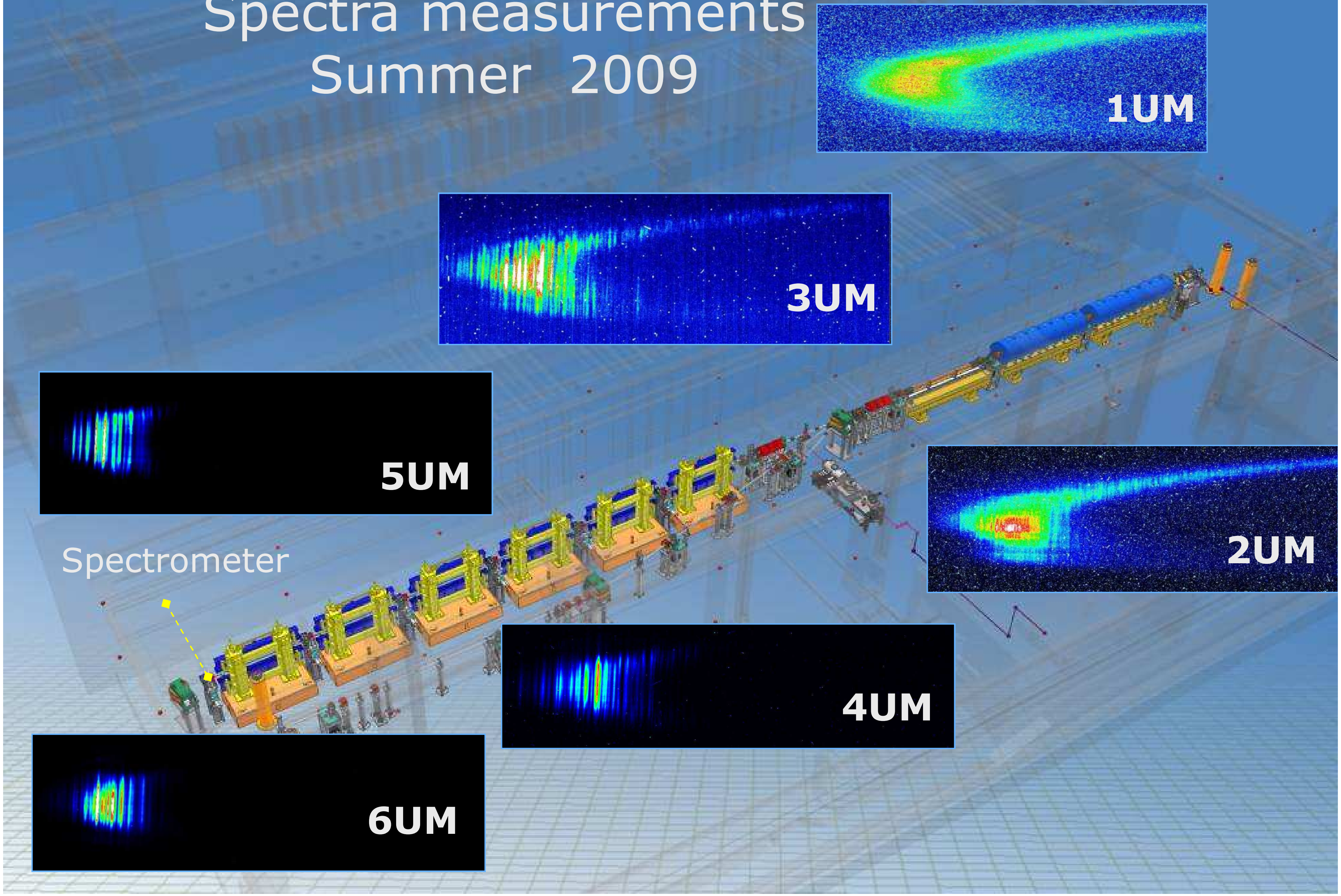


Courtesy of M. Ferrario

SPARC FEL :
past and present experimental activity


Past FEL experiments
SASE
HHG Seeding
Seeding in superradiance
Self Amplified Spontaneous Emission
Spectra measurements
Summer 2009
Orbit kicks to selectively inhibit SASE in the first undulators
1UM
3UM
5UM
2UM
4UM
6UM
Spectrometer
SINGLE SPIKE (e-beam chirp & taper)
Substantial increase of Pulse energy
Energy 140 uJ (max 380 uJ) Rel Linewidth 0.8% rms
FROG
TWINS***
(Two simultaneous spikes ~560 fs separation)
Speckles & Evolution of coherence
FF
3° harmonic direct seeding & FEL harmonic generation with HHG
Seeding with harmonics generated in gas (Ar)
Differential vacuum
Dec. 2007
5° harmonic direct seeding
Seeded FEL - 4 nJ
Intensity (a.u.)
Wavelength (nm)
Shot #
HGHG with HHG
Seed
λ1
λ2= λ1/n, n=2
Modulators
Radiators
Emission of harmonics in superradiance
Seed Energy < 0.5 uJ
~ 0.7 uJ
~ 3 uJ
~ 9 uJ
Superradiant cascade

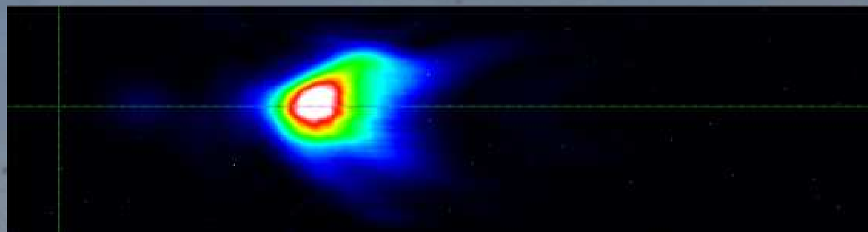
Self Amplified Spontaneous Emission Spectra measurements Summer 2009



SASE experiments in 2010 …

SASE*

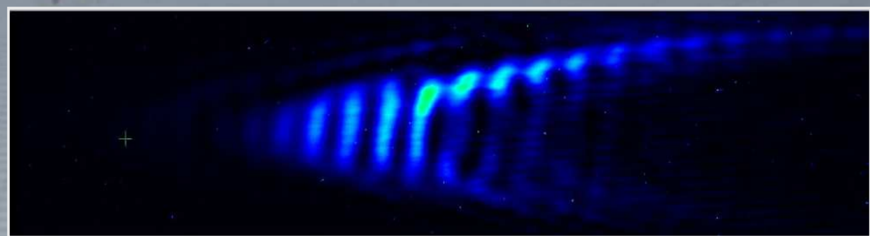
SINGLE SPIKE**
(Combination of e-beam chirp & taper)



Substantial increase of
Pulse energy

Energy 140 uJ (max 380 uJ)
Rel Linewidth 0.8% rms

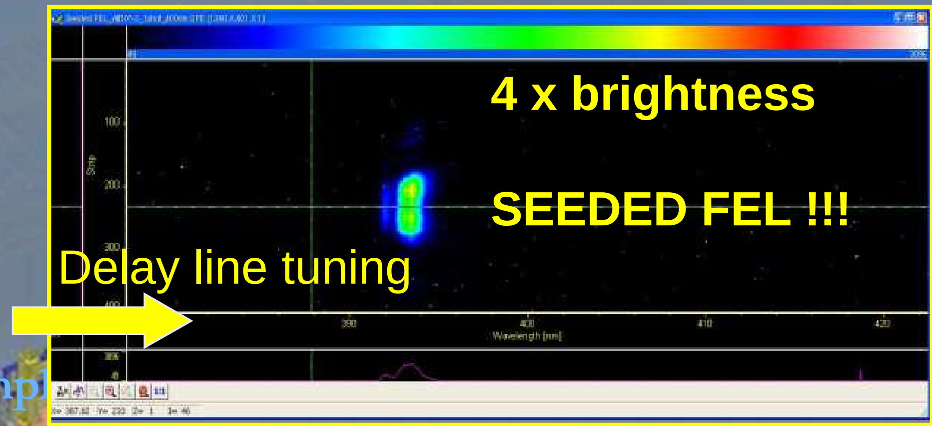
TWINS***
(Two simultaneous spikes ~560 fs separation)



* *L.Giannessi et al.Phys. Rev. ST Accel. Beams 14, 060712 (2011)*
** *L.G. et al. PRL 106 144801 (2011)*
G. Marcus et al. APL . 101, 134102 (2012);
*** *work in progress*

SPARC Seeded Operation (2010)

- Seed modes:
  - Low pulse energy seeding: 266 nm & 160 nm generated in gas
  - High pulse energy seeding: 400 nm in BBO crystal



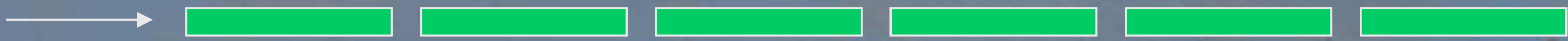
Low intensity seeding

Beam parameters (3-4/6/2010)
Transverse emittances ~ 2 mm mrad
Peak current 45 A

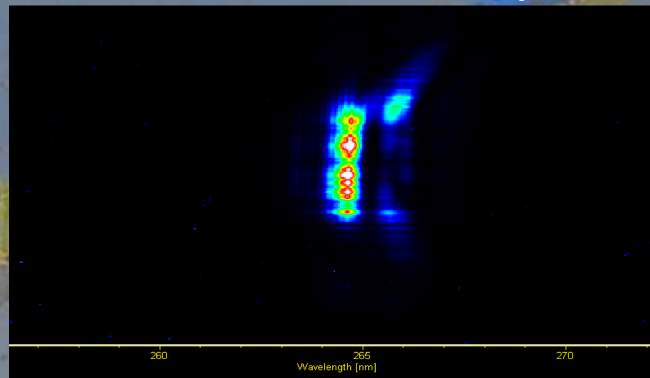
FEL Amplifier

Seed

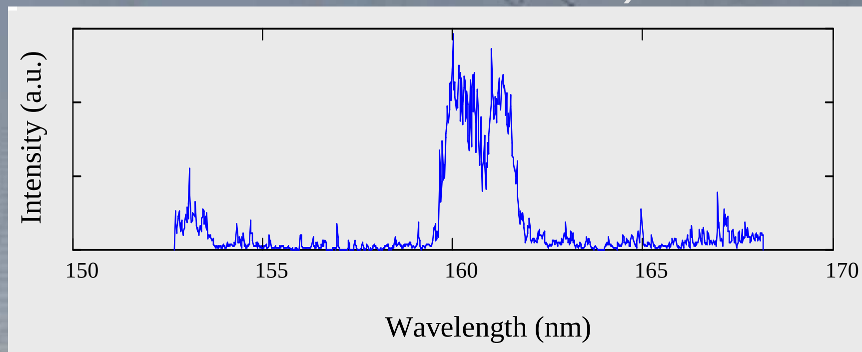
λ



Wavelength 266 nm (3° harmonic of Ti:Sa in Ar, E~50 nJ (±20nJ)

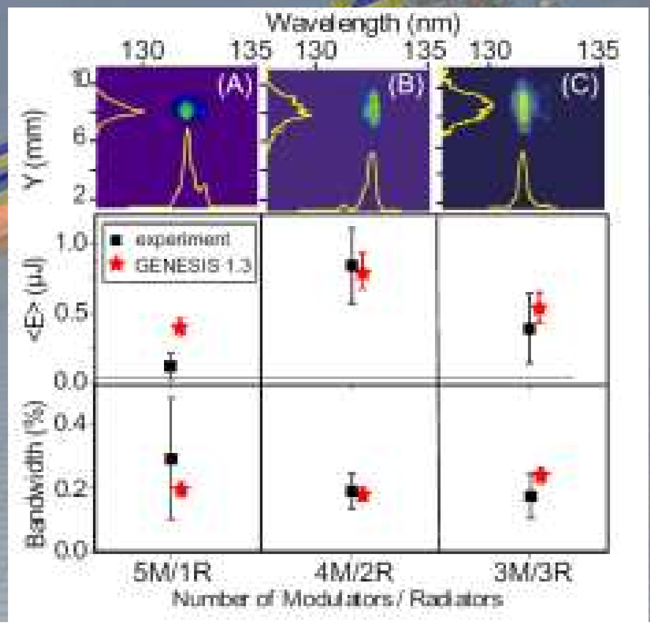


Wavelength 160nm (5° harmonic of Ti:Sa in Ar,, E<< 1nJ)



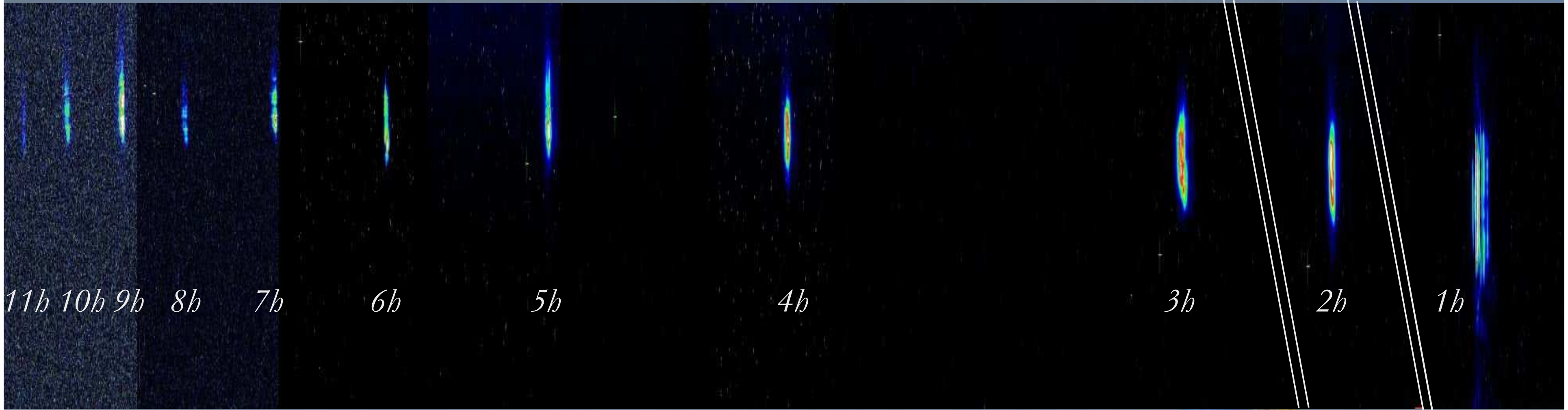
Cascaded FEL seeded with harmonics generated in gas

- Seed @ 266 nm / ~50 nJ
- 5-4-3 UM tuned @ 266 nm / 1-2-3 UM tuned @133 nm

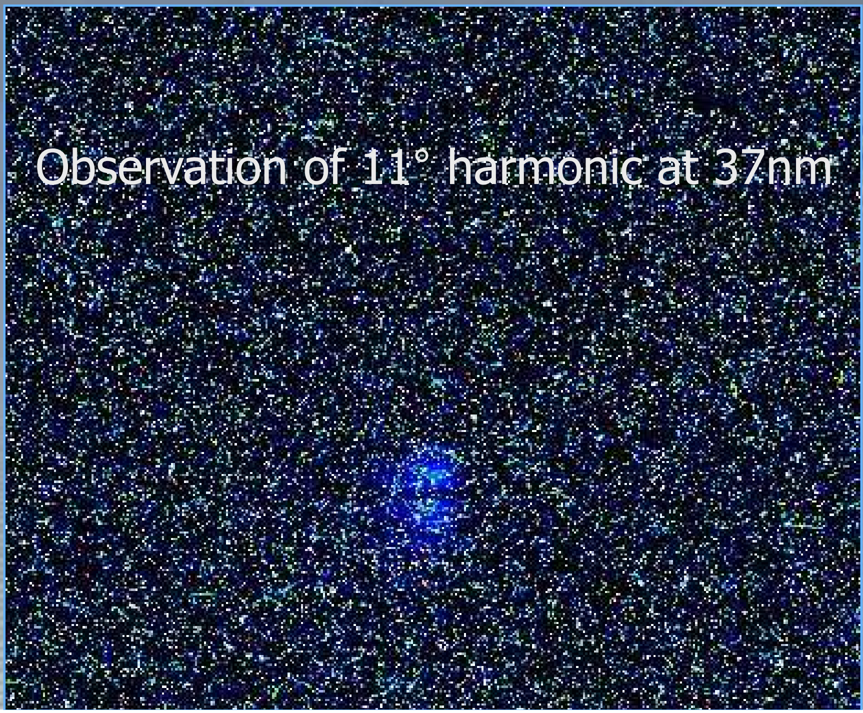


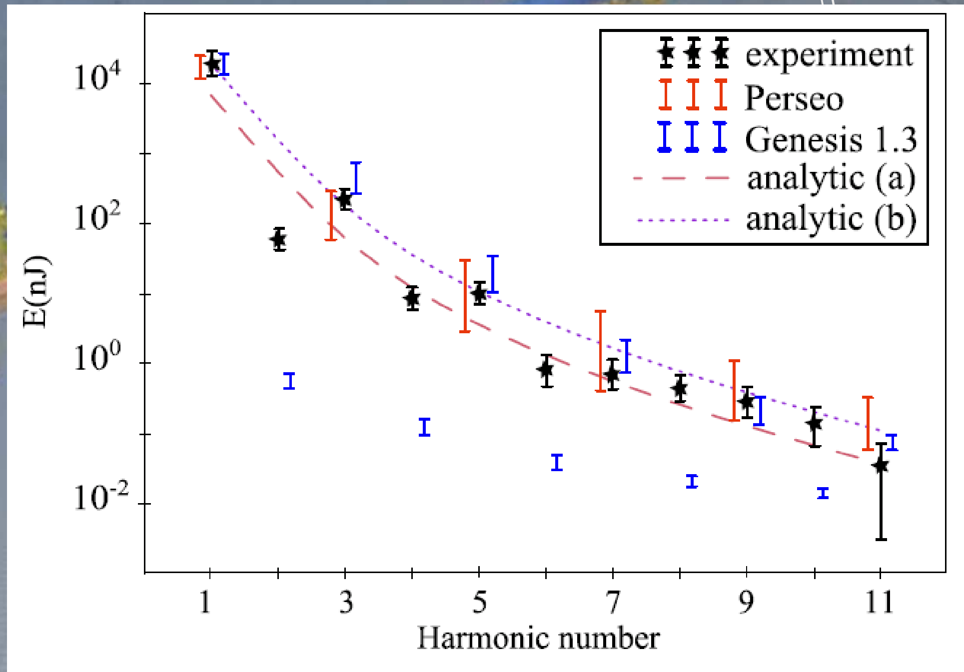
PRL 107, 224801 (2011)

Emission of harmonics in superradiance



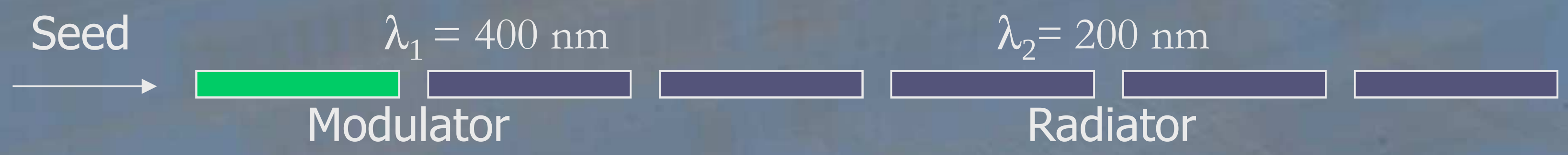
PRL 108, 164801 (2012)

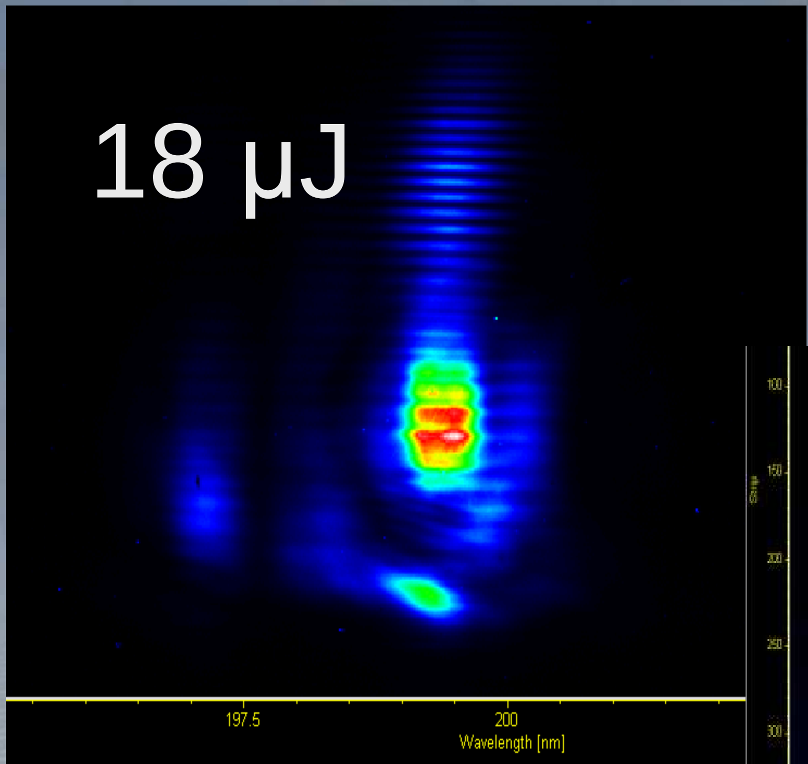


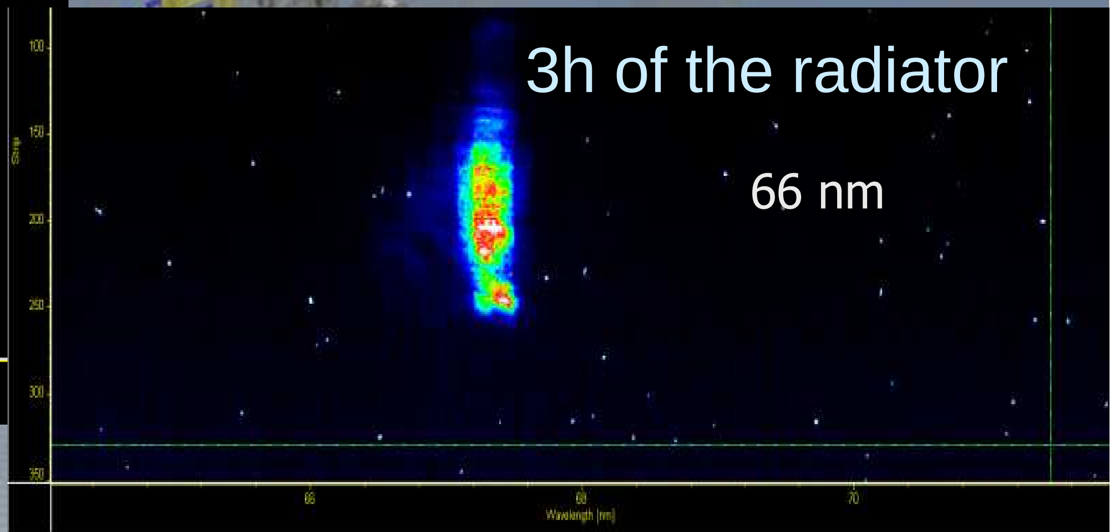


Analytical model: G. Dattoli and P. L. Ottaviani, J. Appl. Phys. 86, (1999) (4/6/2010) Seed @ 400 nm

2 uJ - 1 UM tuned at 400 nm – 5 UM tuned @ 200nm







Seeded SPARC spectral range

Harmonics

Fel generated harmonics

1	2	3	4	5	6	7	8	9
400	200	133.3	100	80	66.7	57.1	50	44.4
266.7	133.3	88.9	66.7	53.3	44.4	38.1	33.3	29.6
160	80	53.3	40	32	26.7	22.9	20	17.8
114.3	57.1	38.1	28.6	22.9	19	16.3	14.3	12.7

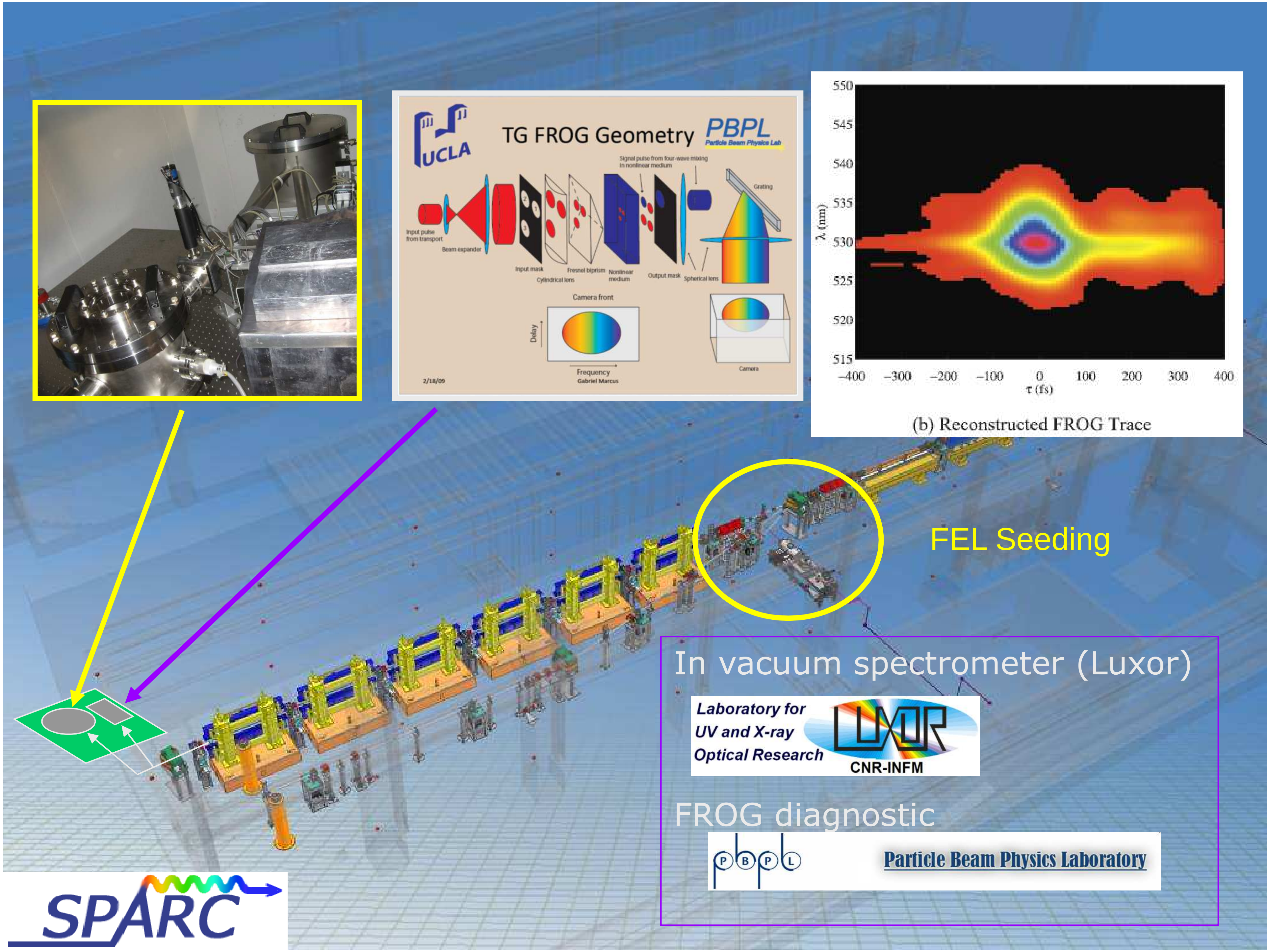
Seed/Fundamental

10	11
40	36.4

Pulse energy vs. wavelength (~ 50-60A / 178MeV)

Mode of operation	SASE	Seeded		
Wavelength	500 nm	200nm	133 nm	66nm*
Energy/pulse (~ 100 fs)	~100 μJ	~10 μJ	~1 μJ	~100 nJ
# photons	2.5×10^{14}	1×10^{13}	6×10^{11}	3×10^{10}

SPARC MAX ENERGY 178 MeV

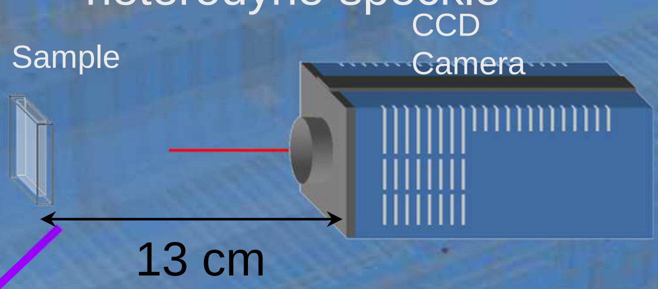


TG FROG Geometry
UCLA
PBPL
Particle Beam Physics Lab
Input pulse from transport
Beam expander
Input mask
Cylindrical lens
Fresnel biprism
Nonlinear medium
Signal pulse from four-wave mixing in nonlinear medium
Output mask
Spherical lens
Grating
Camera front
Delay
Frequency
Camera
2/18/09
Gabriel Marcus
λ (nm)
τ (fs)
(b) Reconstructed FROG Trace
FEL Seeding
In vacuum spectrometer (Luxor)
Laboratory for UV and X-ray Optical Research
LUXOR
CNR-INFM
FROG diagnostic
pbpl
Particle Beam Physics Laboratory
SPARC

Laboratory for UV and X-ray Optical Research

LUXOR CNR-INFM

Coherence measurement: heterodyne speckle approach

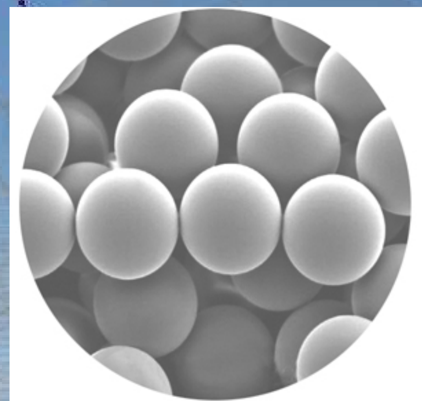


Università di Milano

- Matteo D. Alaimo
- Marzio Giglio
- Michele Manfredda
- Marco A.C. Potenza
- Daniele Redoglio

Testing coherence with small spheres

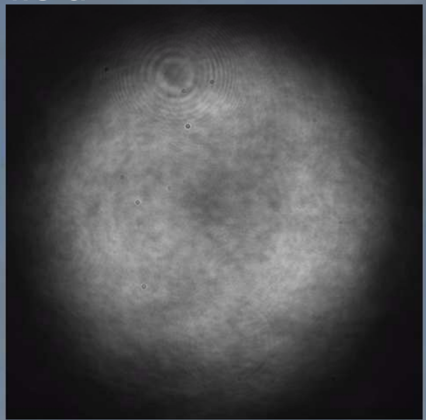
Sample:
- Colloidal particles in water suspension
- Polystyrene (n=1,59)
- d= 2,1μm



SPARC

Coherence measurement at SPARC SASE (λ=400nm)

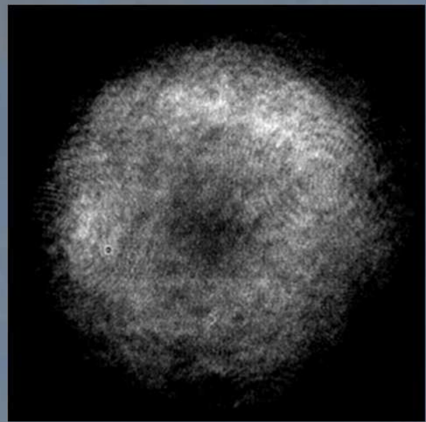
Beam + weak scattered field



6 mm

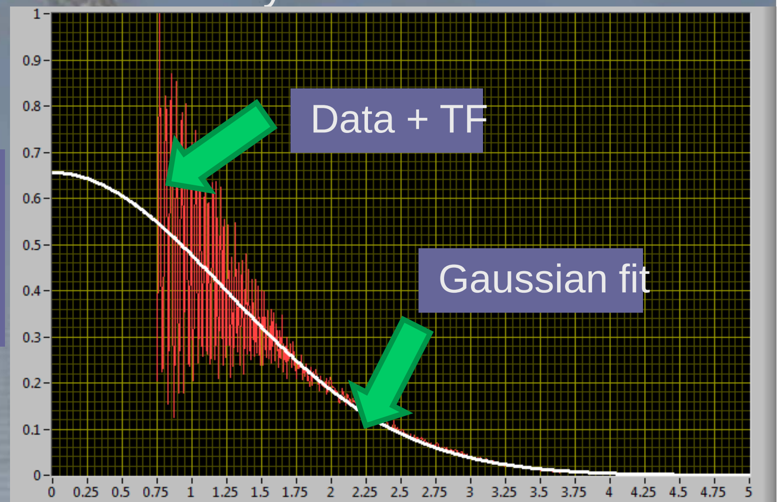
Background subtraction

Heterodyne speckles



Radiation at the end of the undulator

Fourier analysis



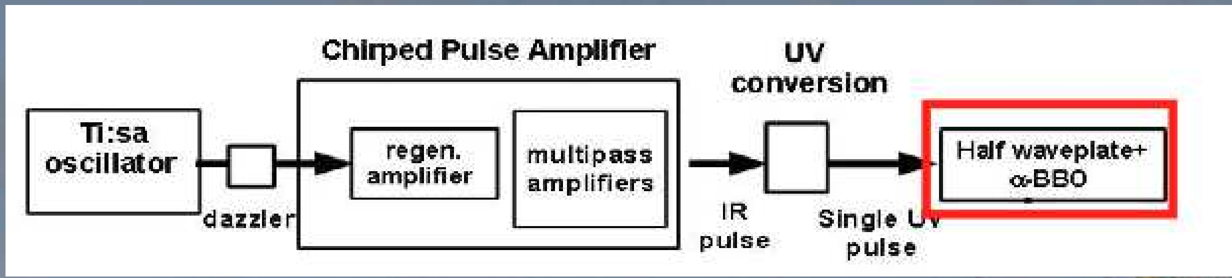
Coherence length:
FWHM = 4 mm

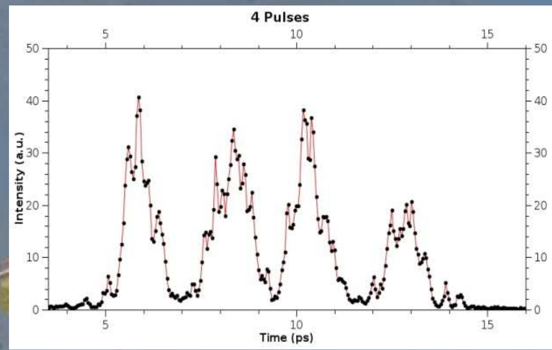
	4 UM	5 UM	6 UM
Energy exp.	5.4±2.8 nJ	-	2.4±1.9μ J
Energy sim.	11 nJ	156 nJ	2.2 μJ
TC exp.	0.7	0.8	0.82
TC sim.	0.61-0.73	0.68	0.8-0.92-0.8
TC spectrometer	0.88	0.96	0.96

Comb FEL

Laser COMB technique

A train of laser pulses at the cathode by birefringent crystal





The technique used for this purpose relies on a **birefringent crystal**, where the input pulse is **decomposed** in **two orthogonally polarized pulses** (ordinary, extraordinary) with a time separation proportional to the crystal length.

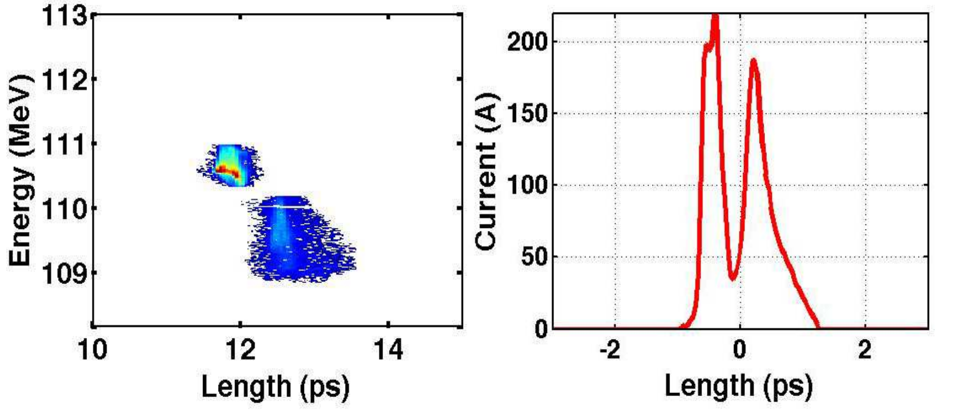
Different crystal thickness are available (10.353 mm in this case).

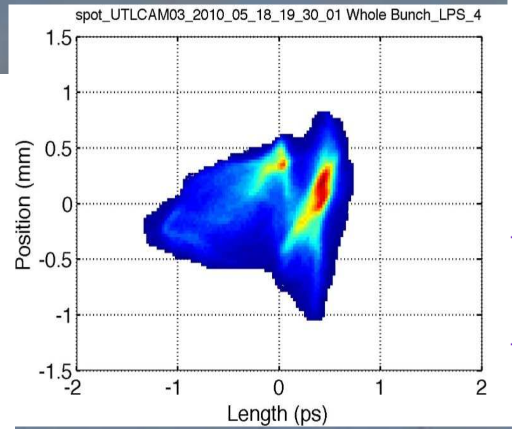
Putting more crystals, one can generate **bunch trains** (e.g. 4 bunches).

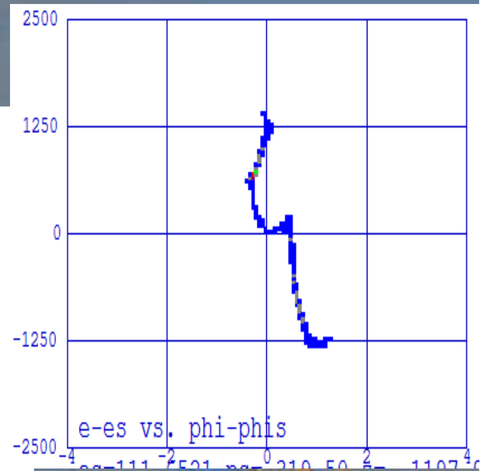
The intensity along the pulse train can be modulated

$$\Delta\tau = (1/v_{go} - 1/v_{ge})L_1$$

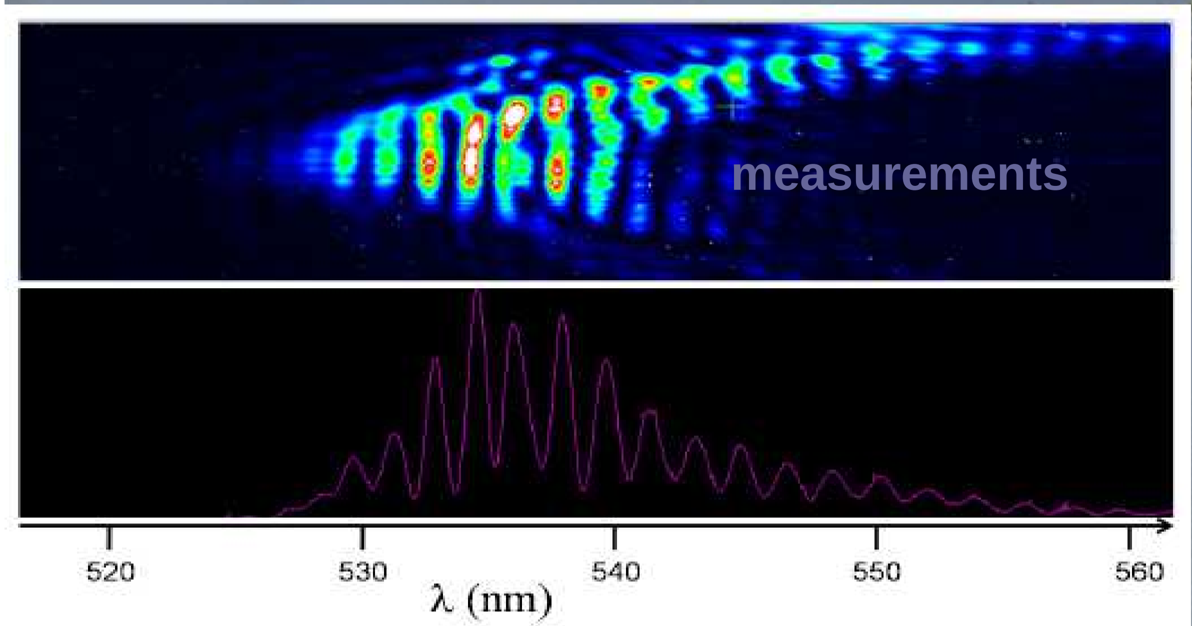
Comb FEL







Simulation Tstep
by C.Ronsivalle



simulations

σt I =140 fs, σt II =270 fs

$T_{separation}$≈0.8 ps

$\varepsilon_{x,y}$(100%) = 6.2,4.4 mm-rad

$\varepsilon_{x,y}$ (90%) = 5.8,4.0 mm-rad

E_{spread} 0.16% and 0.4%

Energy separation ≈ 1.2 MeV

Comb FEL now

Interesting operation points:

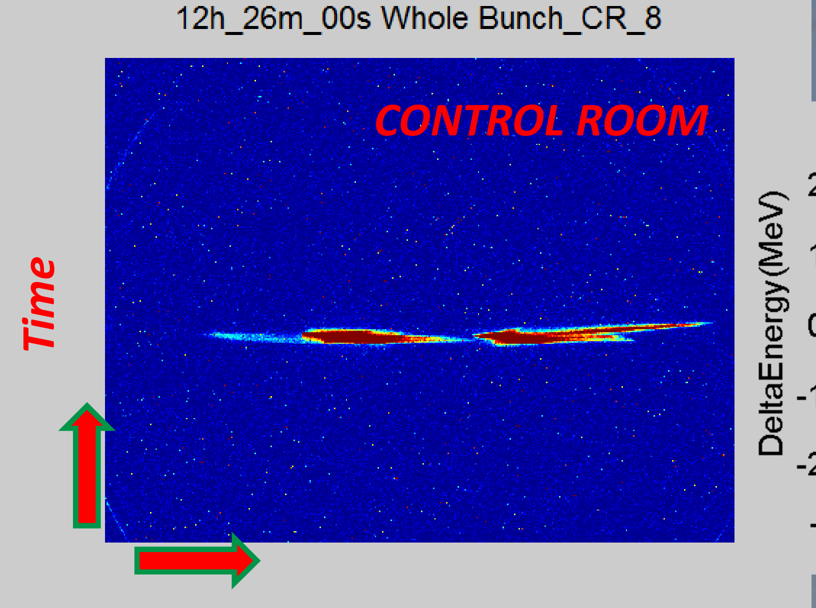
1- MAX COMPRESSION REGION*: two pulses spatially superimposed,*
separated in energy

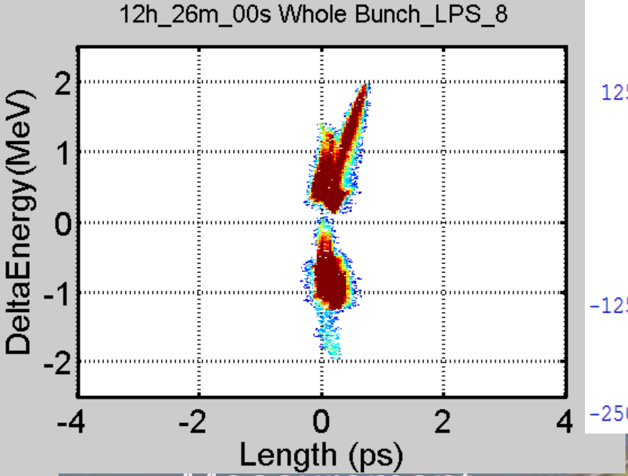
Charge: 160-180 pC (i.e. 80-90 pC/bunch)
Energy distance:1.2-1.5MeV (well separated,that means low energy spread in the single bunches)
Energy: 85 MeV
Almost equal current

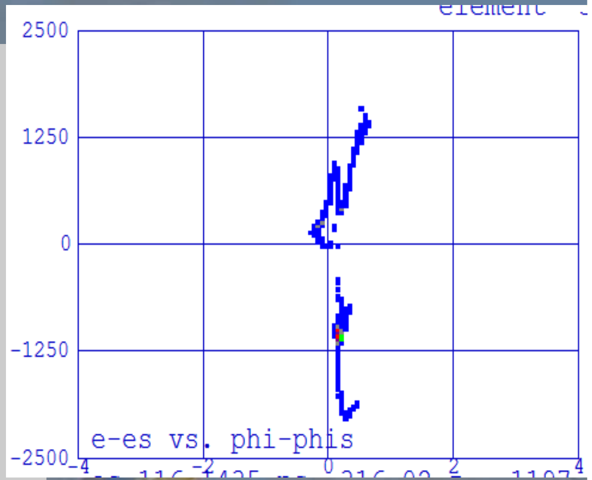
2- OVER COMPRESSION REGION: *two pulses with the same energy*
separated in space

Charge: 160-180 pC (i.e. 80-90 pC/bunch)
Same Energy
Temporal separation: to be explore
Energy: 85 MeV
Almost equal current

18 MAY: MAX. COMPRESSION-Q=180pC.Measurements

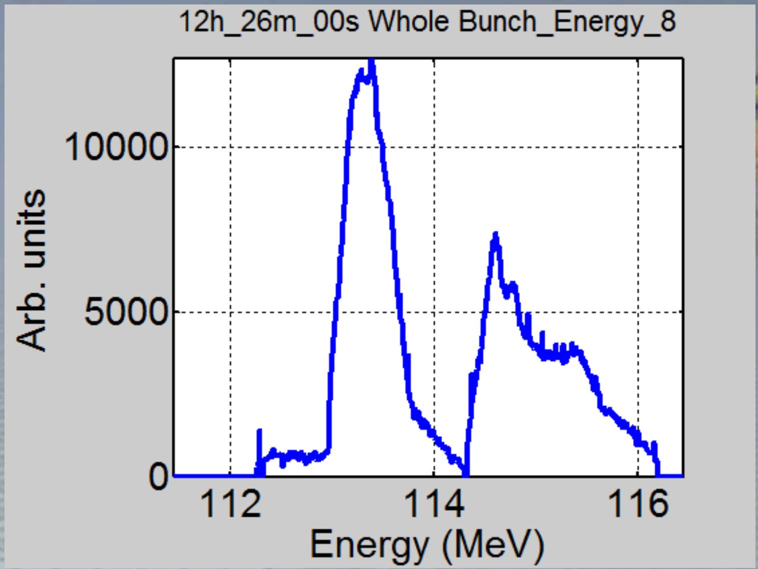


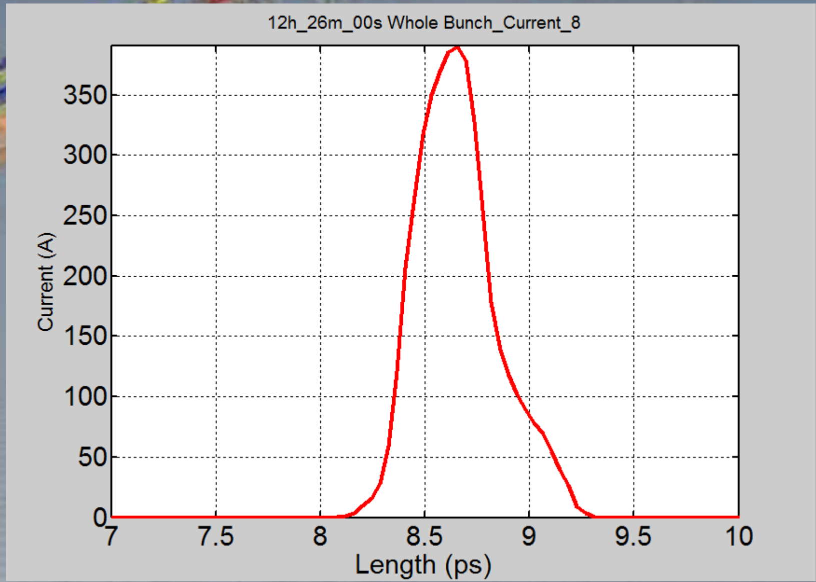


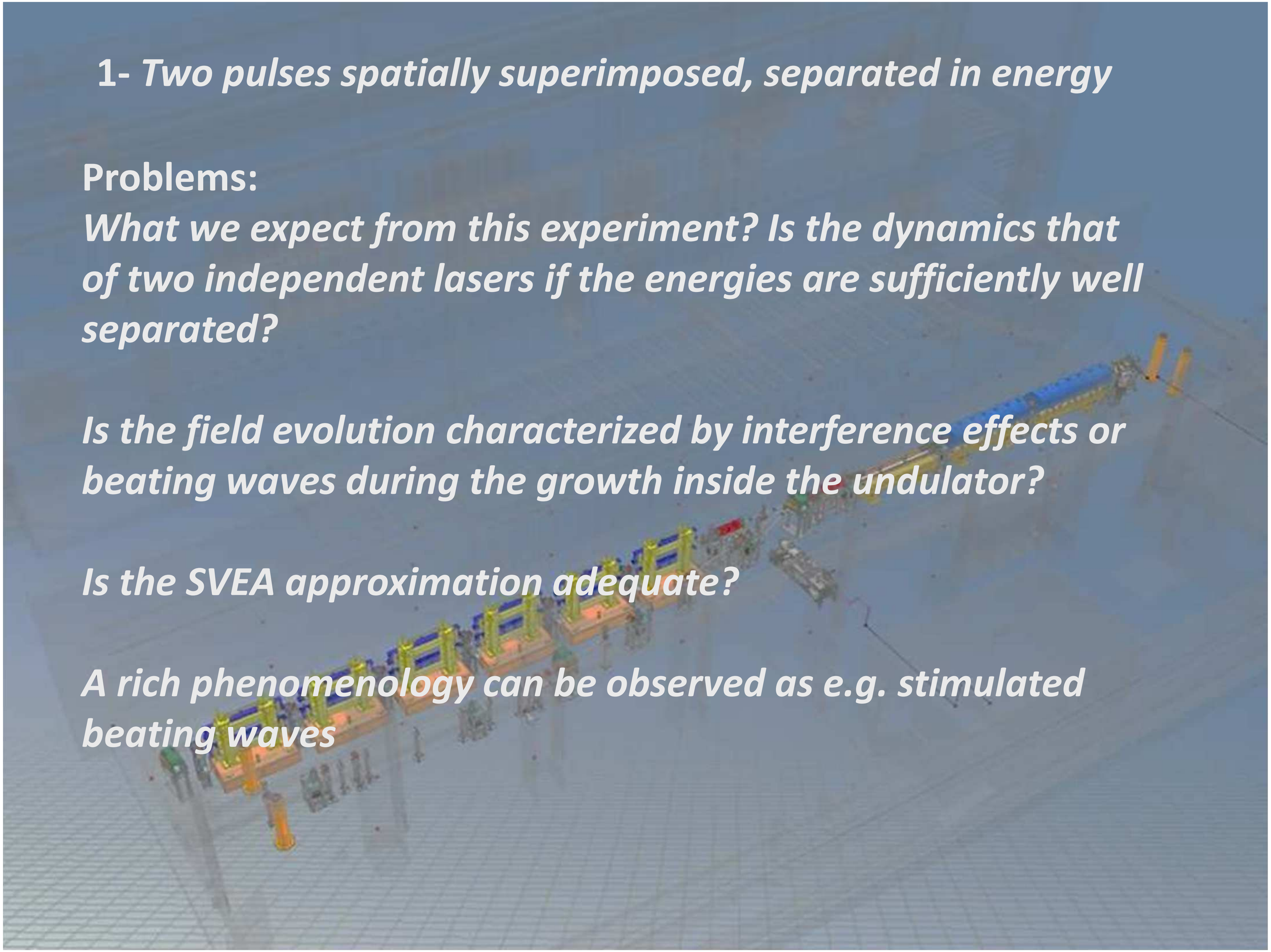


Measurement

Simulation Tstep
by C.Ronsivalle







1- *Two pulses spatially superimposed, separated in energy*

Problems:

What we expect from this experiment? Is the dynamics that of two independent lasers if the energies are sufficiently well separated?

Is the field evolution characterized by interference effects or beating waves during the growth inside the undulator?

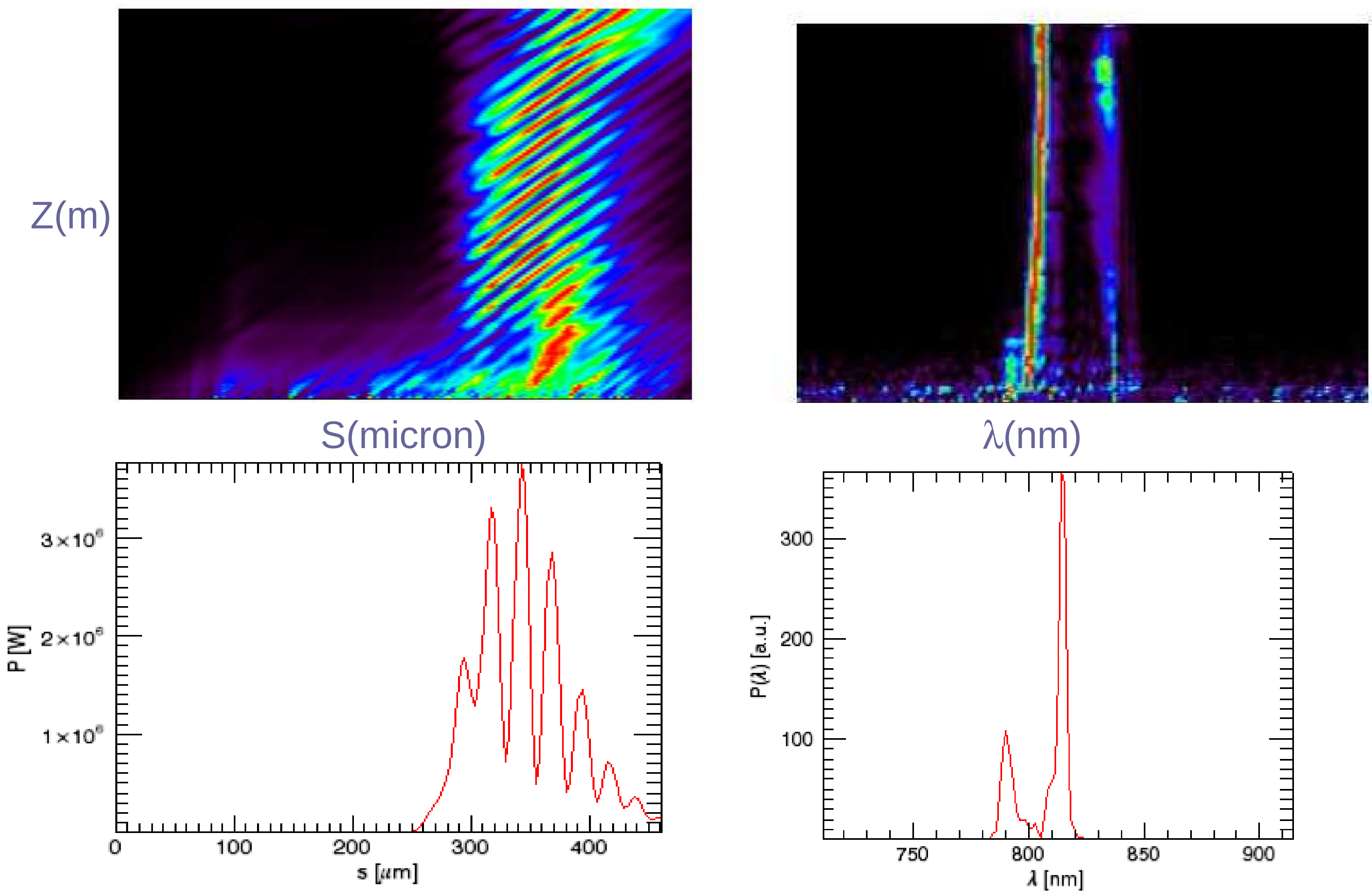
Is the SVEA approximation adequate?

A rich phenomenology can be observed as e.g. stimulated beating waves

Electron beam

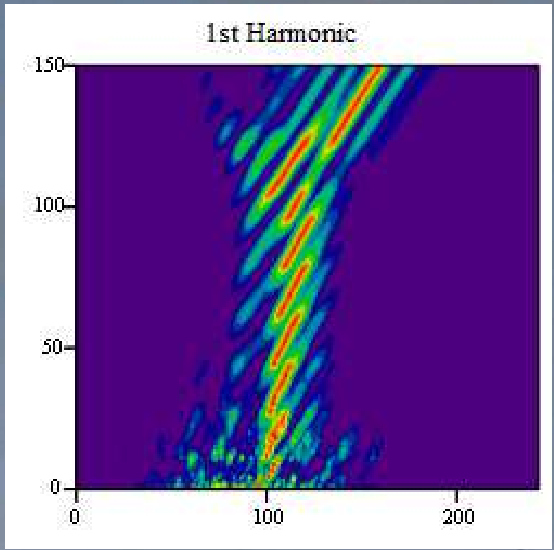
Parameter	Last Experimental beam (7/12/2012)	Simulated beam
Charge	160 pC	160 pC
Beam energy (total)	MeV	86.1 MeV
Beam 1 energy Beam 2 energy		85.1 MeV 86.9 MeV
Emittance_x	mm mrad	1.5 mm mrad
Emittance_y	mm mrad	1.5 mm mrad
Energy spread beam1 beam2		 6.5e-4 4.3e-4
Length separation	ps	0
Total length	ps (?)	0.5 ps
Energy separation		1.4

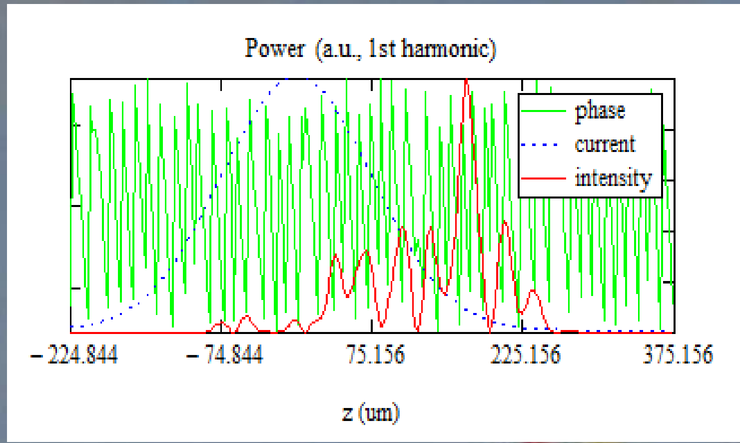
Simulations with Genesis

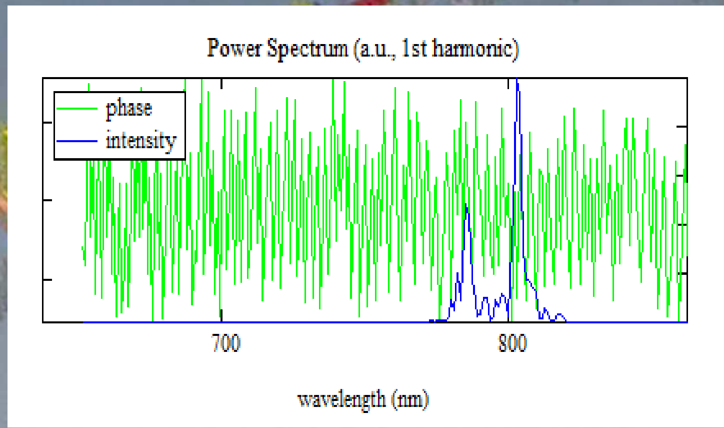


Courtesy of Vittoria Petrillo

Simulations with Perseo

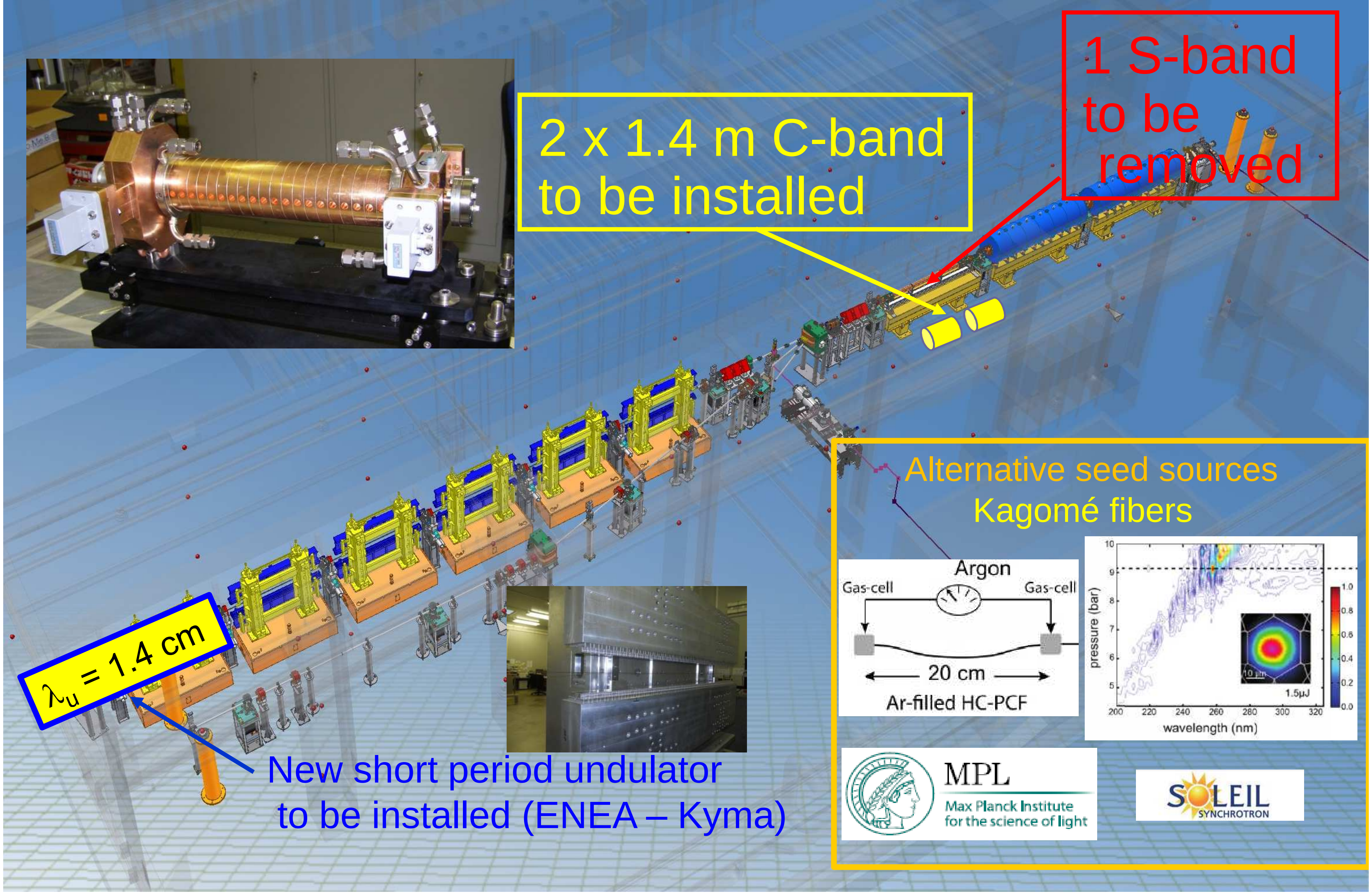






Perseo

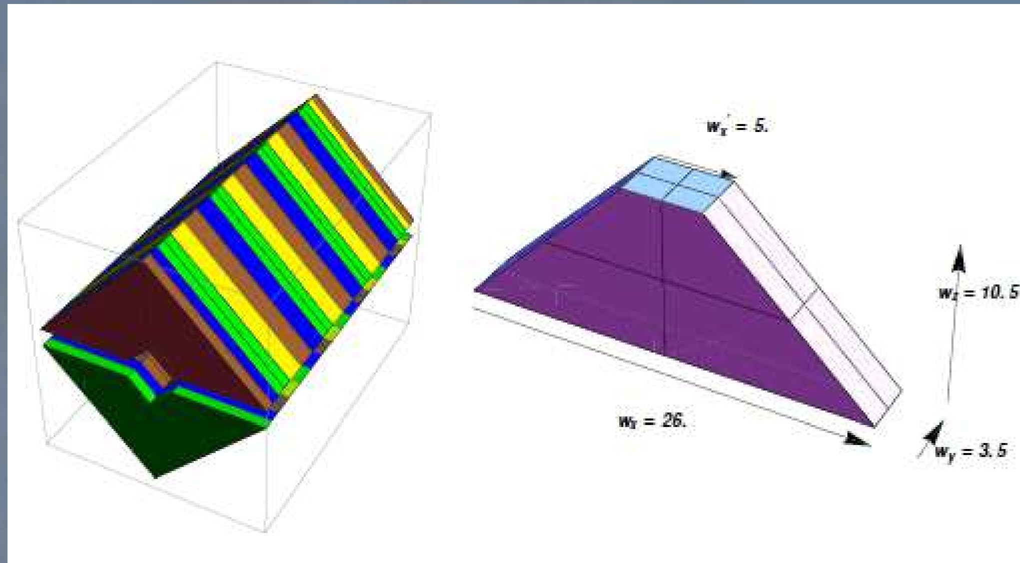
Upgrade of the actual configuration



SPARC-FEL: future developments

- DELTA like undulator
  (Under measurement at ENEA)

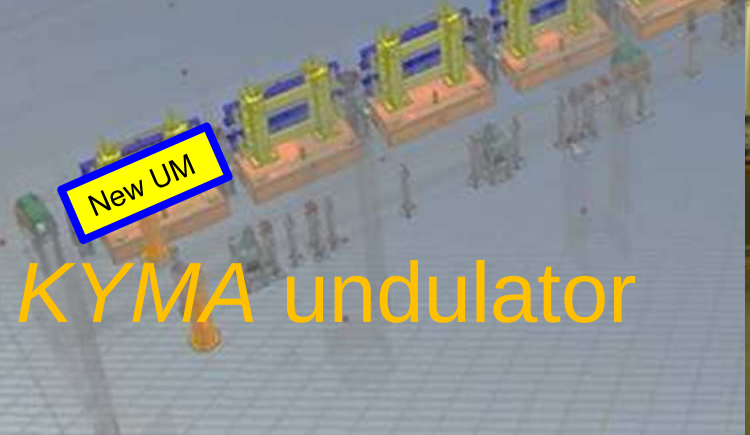
  λu = 14.0mm, gap g = 5mm, Br = 1.22T.



Undulator test in two possible configuration with the actual accelerator:

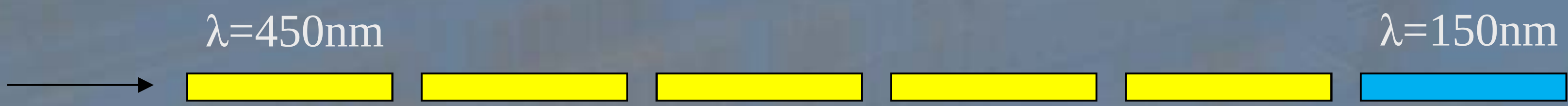
1)Two stage SASE-FEL cascade:
450nm to 150 nm

2)Three stage seeded FEL cascade:
400nm – 200nm – 100nm

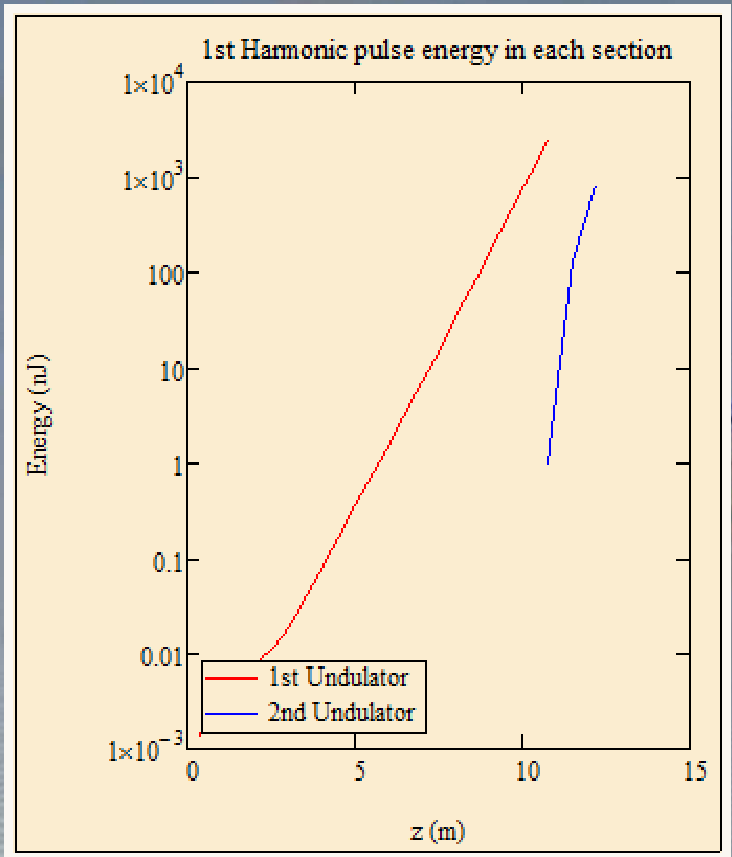


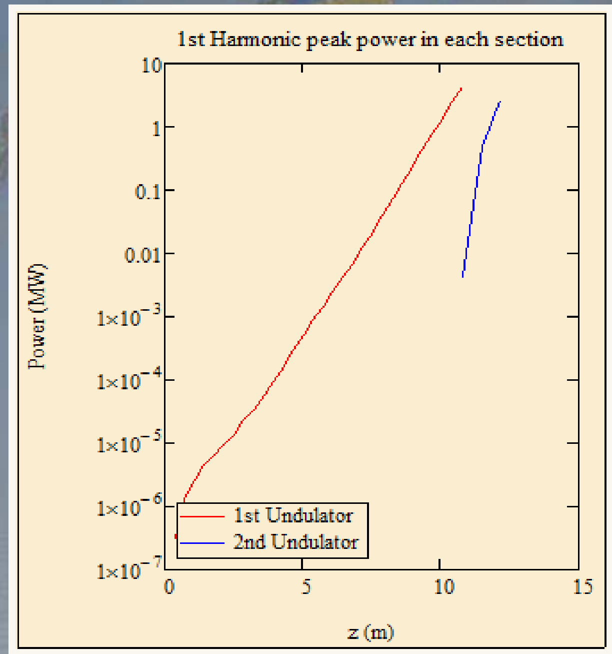
KYMA undulator

Two stages SASE-FEL cascade: 450nm - 150nm



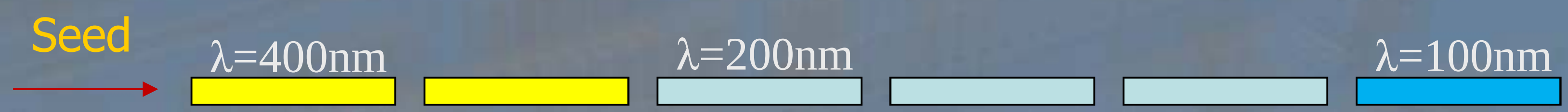
Beam energy	140 MeV
Current	60 A
N. emitt.	2 mm mrad
En. Spread (s)	2 x 10^{-4}

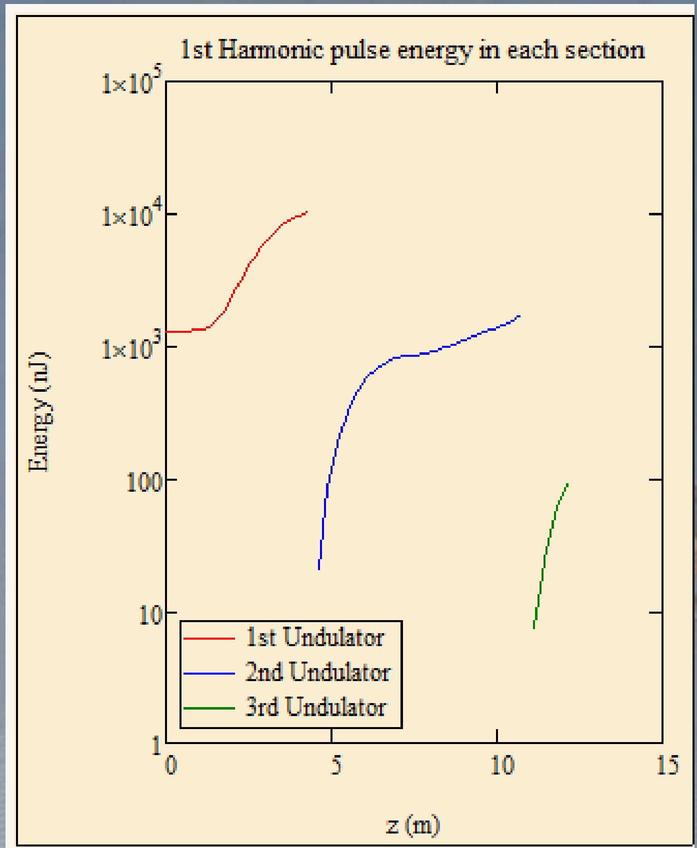




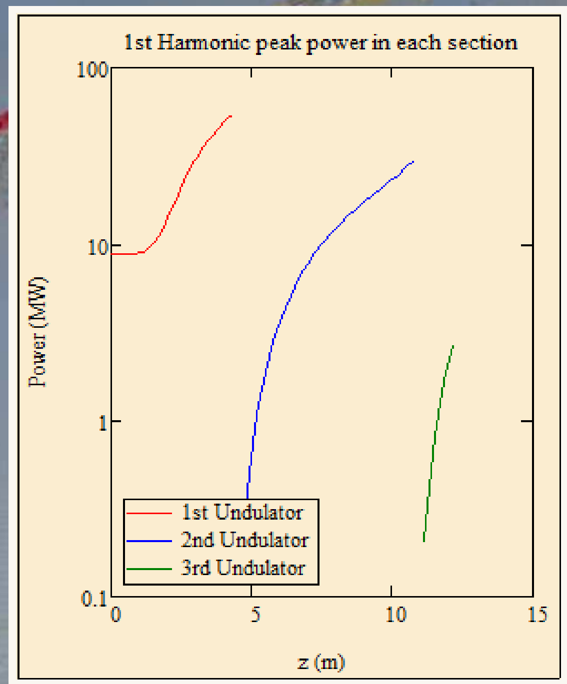
Perseo

Three stages cascade – seed at 400nm – final λ=100nm





Beam energy	165 MeV
Current	60 A
N. emitt.	2 mm mrad
En. Spread	4 x 10^{-4}

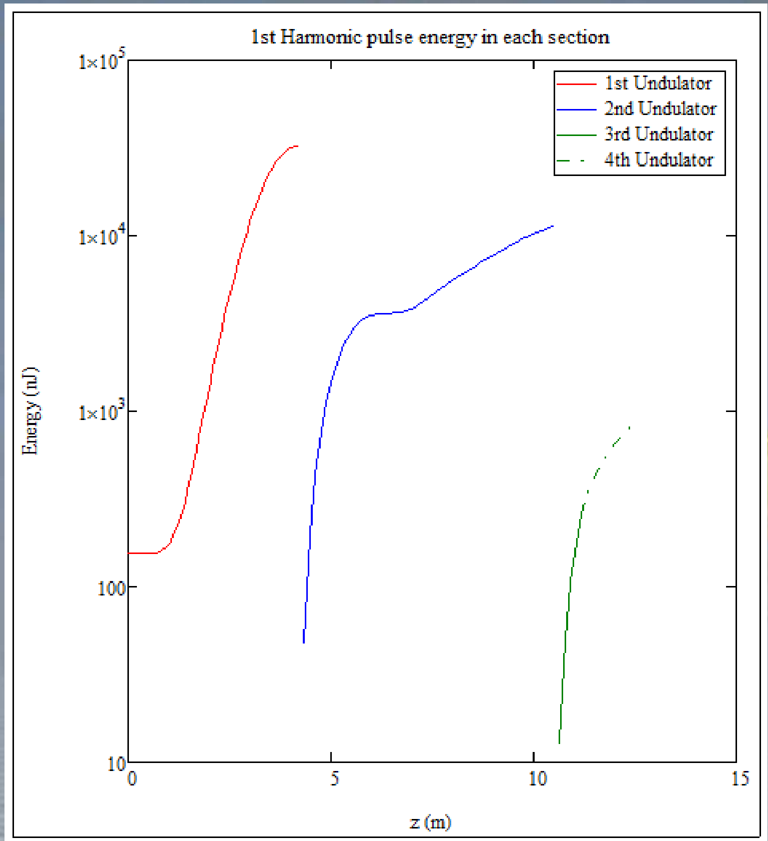


Perseo

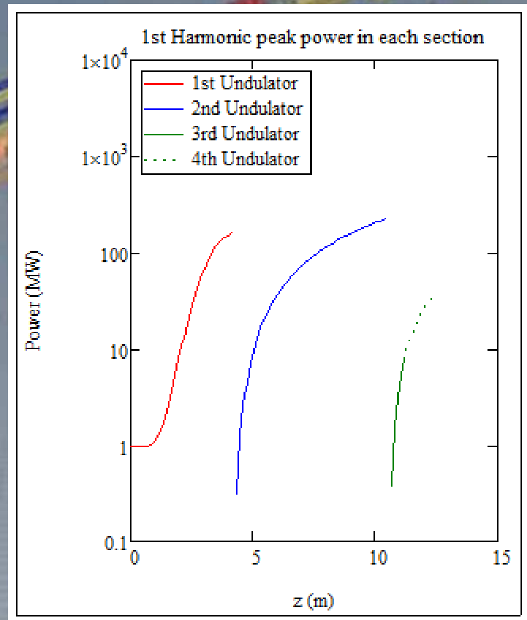
Operation with C-band accelerating section

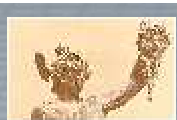
Three stages cascade: seed at 266nm – final λ=66nm

Seed → λ=266nm λ=133nm λ=66nm



Beam energy	200 MeV
Current	150 A
N. emitt.	1.5 mm mrad
En. Spread	4×10^{-4}





Perseo

Simulation by L.Giannessi

Proceedings of FEL2011, Shanghai, China

NEW TUNABLE DUV LIGHT SOURCE FOR SEEDING FREE-ELECTRON LASERS

N.Y. Joly[2,1], P. Hölzer[1], J. Nold[1], W. Chang[1], J. C. Travers[1], M. Labat[3], M-E. Couprie[3] and P. St.J. Russell[1,2]

Photonic crystal fibre (HC-PCF) filled with argon is able to generate an diffraction-limited DUV pulse of 50 nJ and fs duration, continously tunable from 150 to 320 nm. This source is considered to be very attractive to seed SPARC-FEL.

Table 1: parameters used for Genesis simulation in the case of seeding of SPARC-FEL

E-beam		
Energy	170 MeV	
Current	50 A	
Emittance	1.5 π.mm.rad	
Energy spread	2×10^{-4}	
Undulator		
Period	28 mm	
Nb. periods/section	77	
Nb. of sections	6	
Deflexion parameter	K = 0 to 3.4	
Seeding pulse		
Wavelength	150 nm	300 nm
Energy/pulse	<10 nJ	<80 nJ
Pulse duration	10 fs	15 fs
Peak Power	1 MW	5 MW

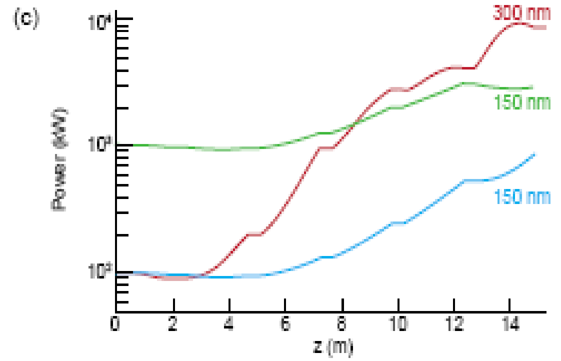
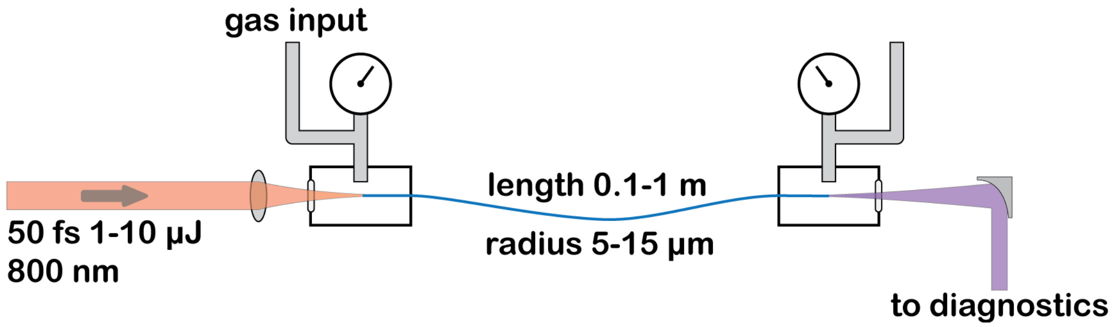
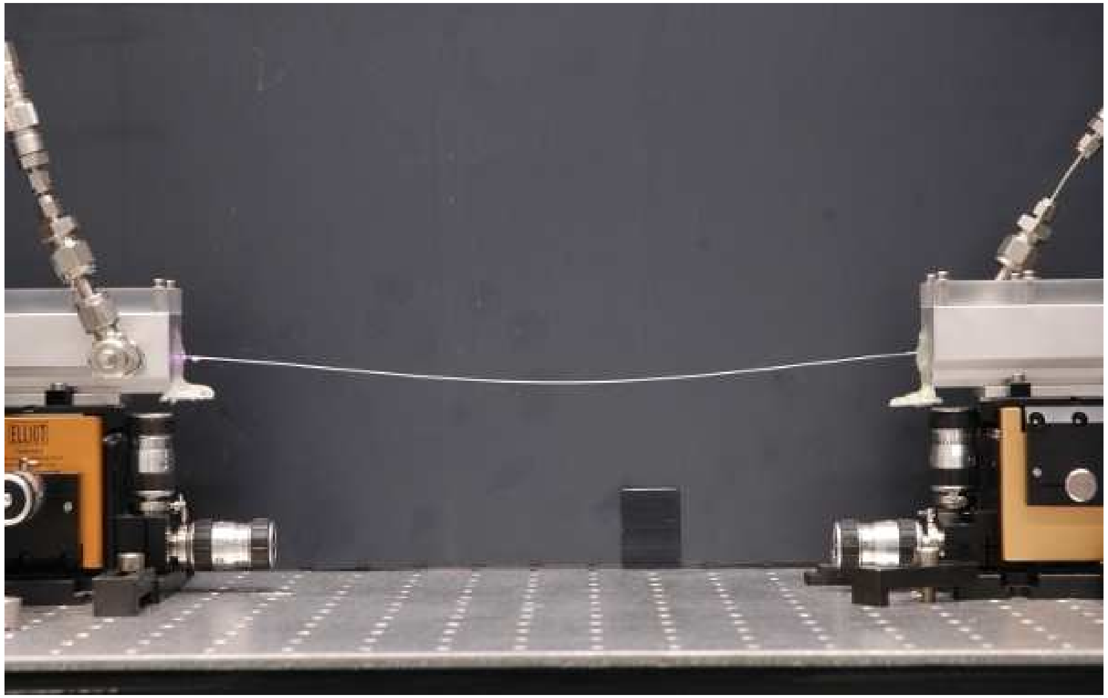


Figure 5: Simulations using the Genesis code with parameters given in Table 1.

Hollow Core Photonic Crystal (Kagome') Fiber





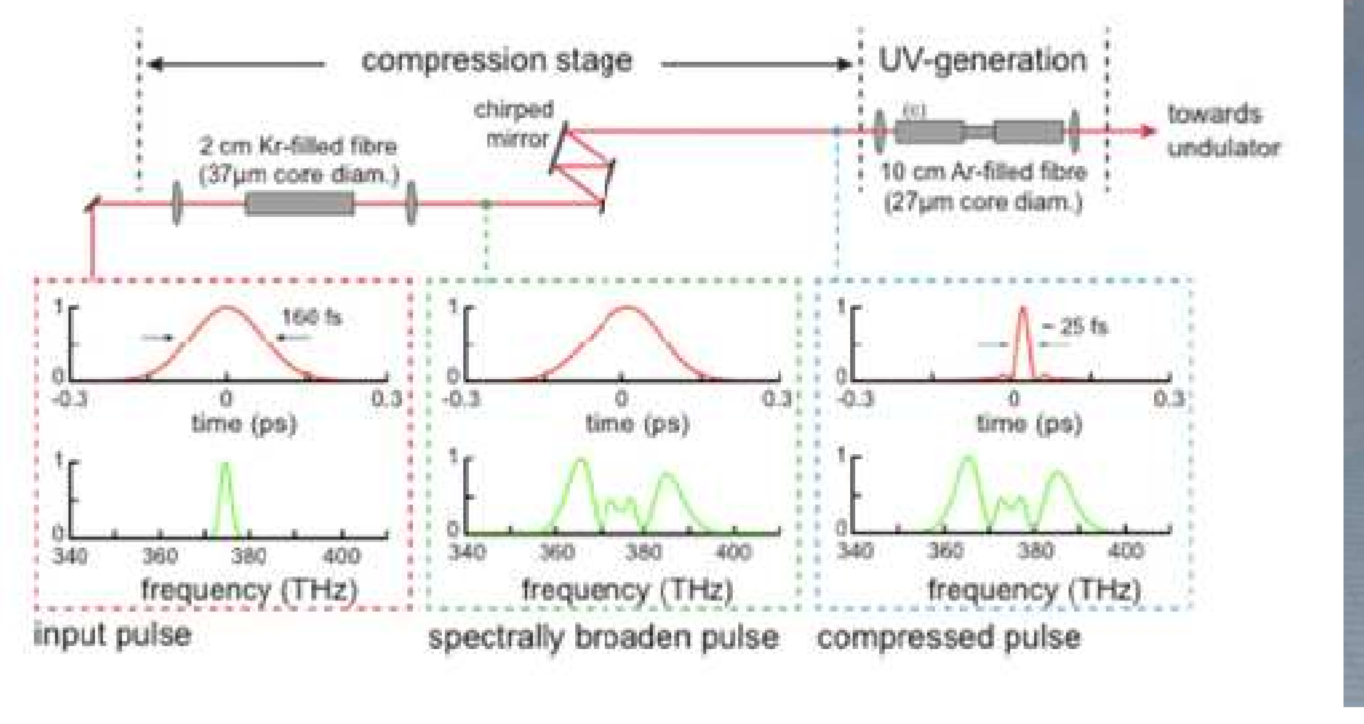
- Propagation of self compressed Solitons
- Emission of resonant dispersive wave at phase matched wavelength in the UV
- Tunable emission with Ar pressure 150-320 nm

MPL
Max Planck Institute for the science of light

2013 FEL Conference

SEEDING OF SPARC-FEL WITH A TUNABLE FIBRE-BASED SOURCE

Nicolas Yann Joly (University of Erlangen-Nuremberg, Erlangen-Nuremberg), Giovanni De Ninno, Benoît Mahieu (ELETTRA, Basovizza), Franco Ciocci, Luca Giannessi, Alberto Petralia, Marcello Quattromini (ENEA C.R. Frascati, Frascati (Roma)), Giancarlo Gatti (INFN/LNF, Frascati (Roma)), Julietta V. Rau (ISM-CNR, Rome), Vittoria Petrillo (Istituto Nazionale di Fisica Nucleare, Milano), Wonkeun Chang, Philipp Hölzer, KaFai Mak, Philip Russell, Francesco Tani, John Colin Travers (Max Planck Institute for the Science of Light, Erlangen), Serge Bielawski (PhLAM/CERCLA, Villeneuve d'Ascq Cedex), Marie- Emmanuelle Couprie, Marie Labat, Takanori Tanikawa (SOLEIL, Gif-sur-Yvette)



SELF SEEDING CONFIGURATION AT SPARC

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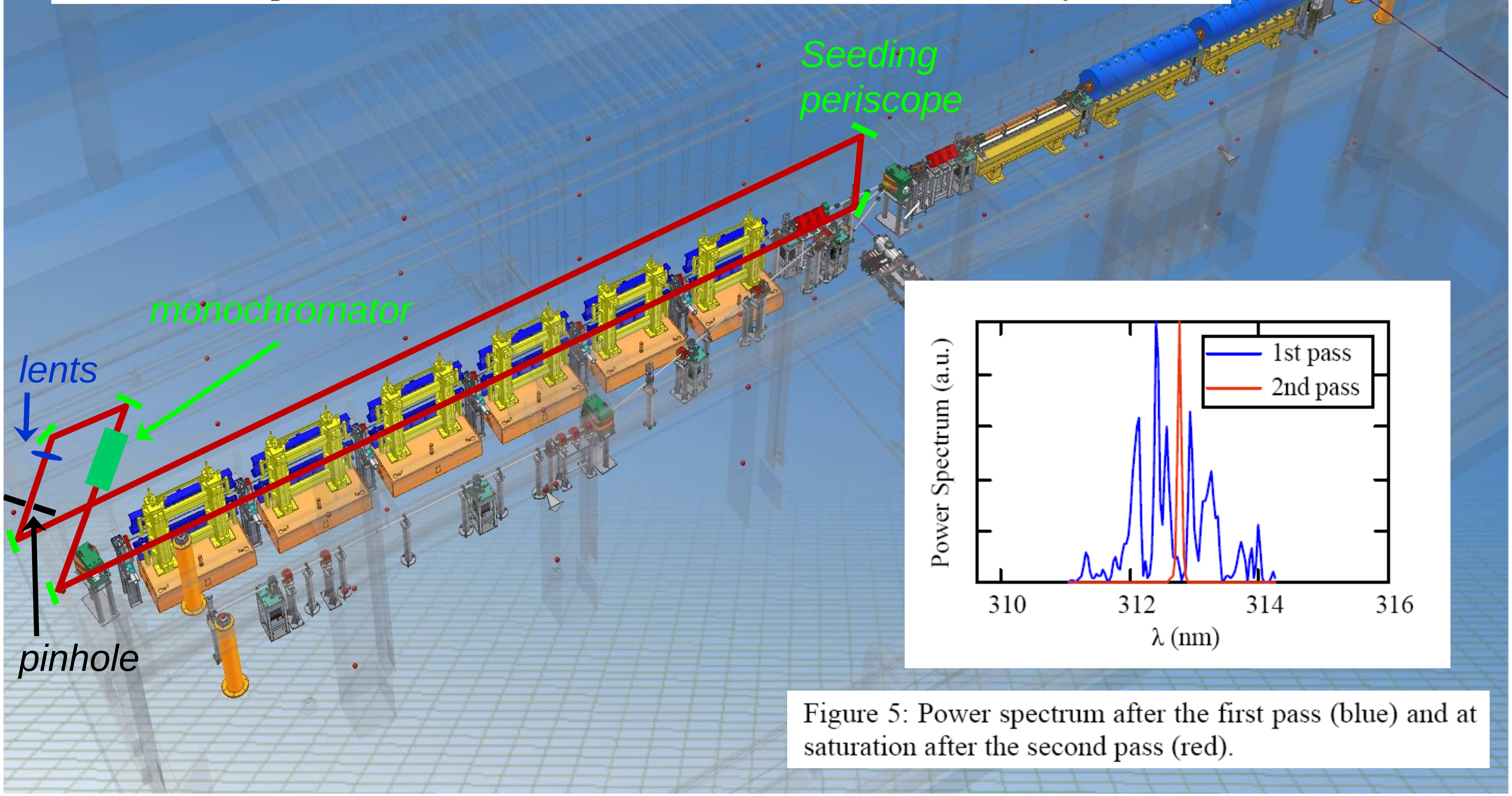

Figure 5: Power spectrum after the first pass (blue) and at saturation after the second pass (red).

Conclusions

- Future developments: ENERGY Upgrade to 220 – 245 MeV
  - Compressed beam operation with a reduced energy chirp
  - Seeding at higher frequencies
  - Harmonic cascade and spectral range extended to the EUV

+ FEL physics experiments:

- Wavefront characterization of the FEL beam (Seeded/SASE)
- Developments on short undulators
- Seeding with «alternative» sources in the UV/VUV range
- FEL dynamics – pulse length characterization – gain & index of refraction

- SPARC is a FEL-FACILITY within a different framework, it is indeed operating as a tool for the development of FEL physics and possible new schemes ,open to scientific collaboration to enhance the performance and the perspectives of the present FEL devices as well as to test diagnostics and physical effects on e-beam and FEL source.