Commissioning and Initial Operation of FERMI@Elettra FEL

S. Di Mitri, on behalf of the **FERMI Commissioning Team**

Project Dir.: **M. Svandrlik** (2011–to date), **S. V. Milton** (2007–2010)

Outline

- Project Overview and Achievements
  - Science Beamlines
  - Design Goals and Achievements
  - Status Report & First Coherent Emission
- Machine Status
  - Layout & Components
  - Electron Beam Preparation & Seeding
- FEL Commissioning
  - FEL Experience
  - Outlook

FERMI Project Overview & Achievements

Science, Design and Achievements

FERMI at the ELETTRA LABORATORY

SINCROTRONE TRIESTE is a nonprofit shareholder company of Italian national interest, established in 1987 to construct and manage synchrotron light sources as international facilities.

ELETTRA Synchrotron Light Source:
up to 2.4 GeV, top-up mode,
768 proposals from 39 countries in 2010

Ref.: M. Svandrlik, M. Giannini, S. Noe', D. Zangrando

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FERMI@Elettra FEL:
100 – 4 nm, fully funded

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  Italian Minister of University and Research (MIUR)
  Regione Auton. Friuli Venezia Giulia
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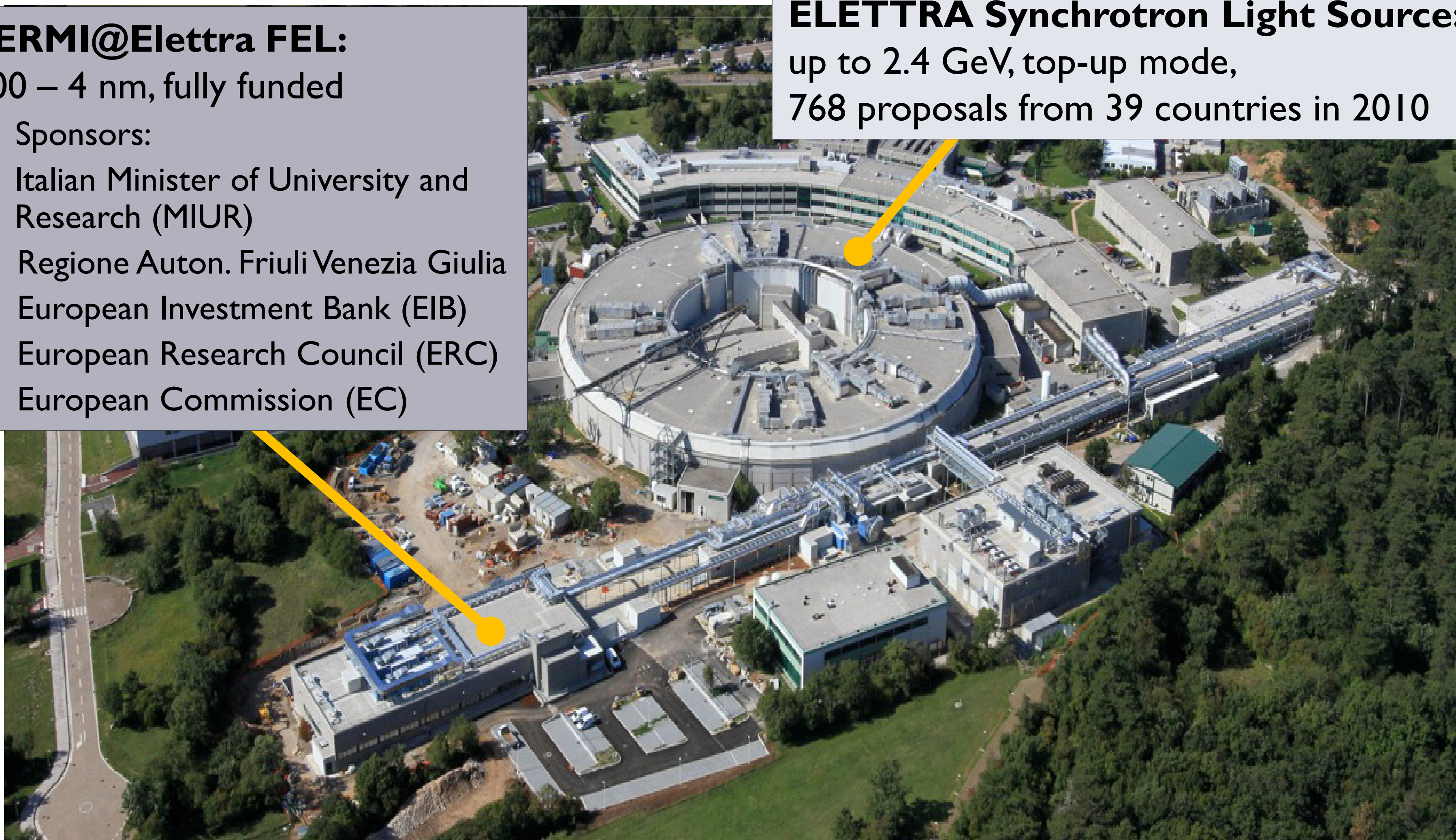

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  - European Research Council (ERC)
  - European Commission (EC)
- Collaborations:
- and many others…

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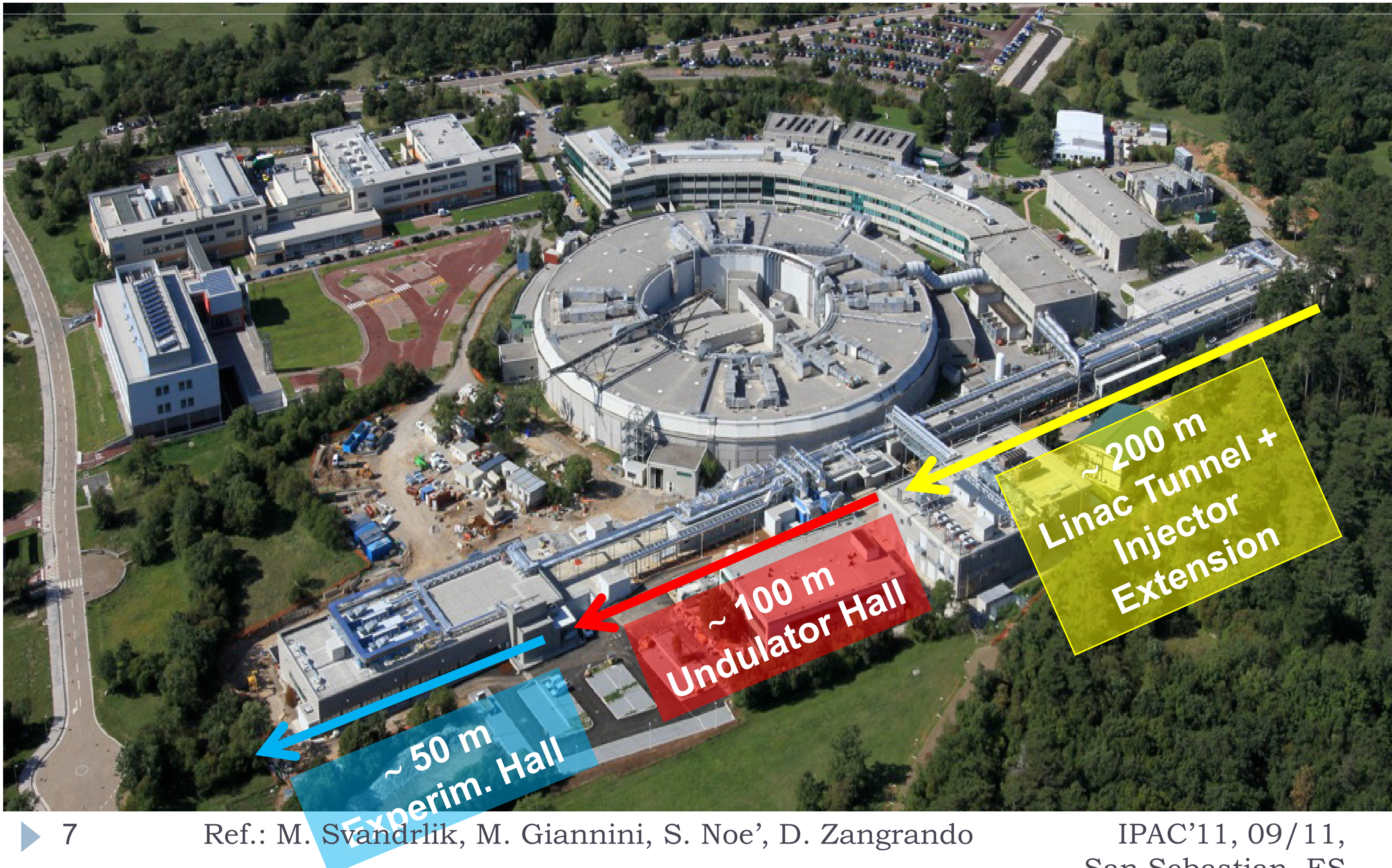


SCIENCE BEAMLINES

- **Low Density Matter** (*coord. C. Callegari*):
  (Partners: F.Stienkemeier (Un.Freiburg), T. Moller (TU Berlin), K. Prince (ST), S. Stranges (Un. Rome-Sapienza), P. Piseri (Un. Milan) et al.)
  - Structure of nano-clusters ....brightness
  - High resolution spectroscopy..............................narrow bw, λ-tunability
  - Magnetism in nano-particles...................................circular polarization
  - Catalysis in nano-materials......................................fs pulse and stability

- **Elastic and Inelastic Scattering** (*coord. C. Masciovecchio*):
  (Partners: A. Dicicco et al. (Univ. Camerino), A. Filipponi et al. (Univ. L'Aquila))
  - Transient Grating Spectr. (collective dynamics at the nano-scale) ....transform-limited bandwidth
  - Pump & Probe Spectr. (meta-stable states of matter)......brightness, λ-tunab.

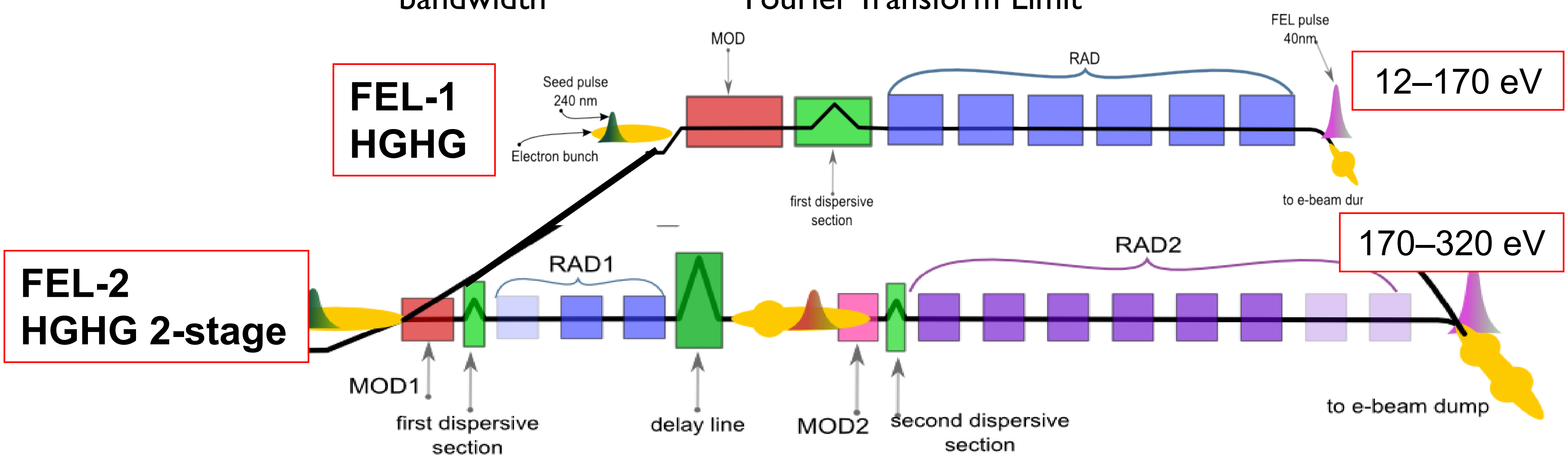
- **Diffraction and Projection Imaging** (*coord. M. Kiskinova*):
  (Partners: H.Chapman et al.(CFEL-DESY), J.Hajdu et al.(Uppsala), M.Bogan et al.(SLAC), M.Pivovaroff, A.J.Nelson et al.(LLNL))
  - Single-shot CDI (bio&solid state struct. with diffr.-limited resol.)......brightness
  - Resonant CDI ('element selectivity' and 'magnetic' imag.).......λ-tunab., circ. pol.
  - Time-resolved CDI (transient nano-scale dynamics)..................λ-tunab., circ. pol.

OUR VISION

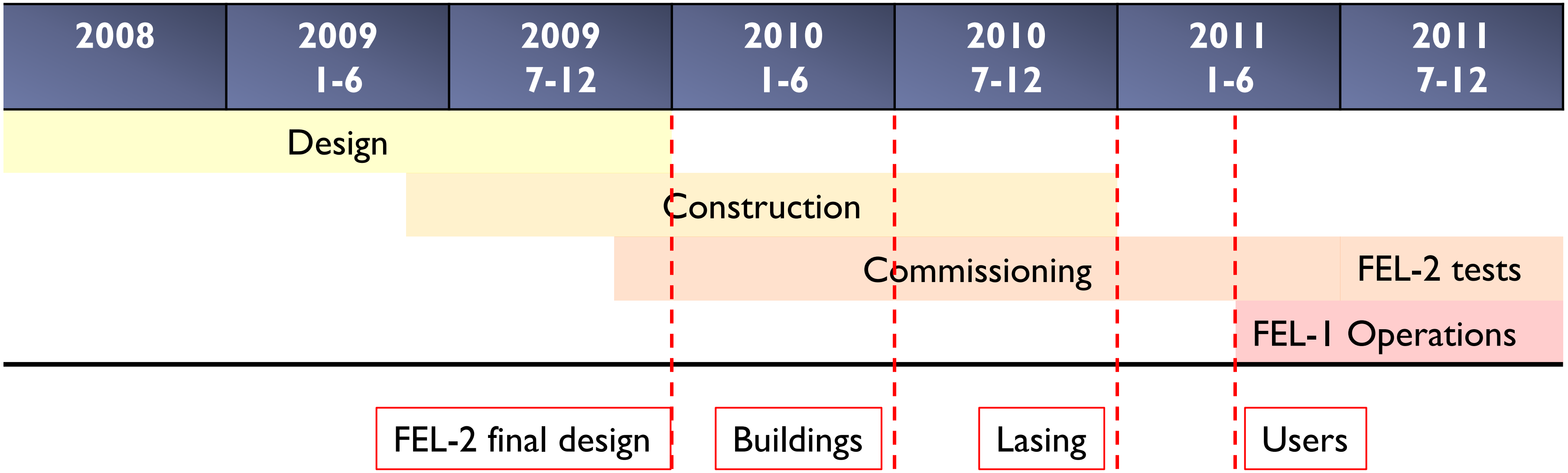
FERMI is a **single-pass, 50 Hz, externally seeded FEL facility** producing **soft X-rays**:

- ❑ high peak power — 0.3 to GW's range
- ❑ short temporal structure — sub-ps to 10 fs time scale
- ❑ tunable wavelength — APPLE II-type undulators
- ❑ variable polarization — horizontal/circular/vertical

peak brilliance	$10^{30} – 10^{31}$	ph/sec/mm^2/mrad^2/0.1%bw
flux	$10^{12} – 10^{14}$	ph/pulse
bandwidth	~ Fourier Transform Limit	



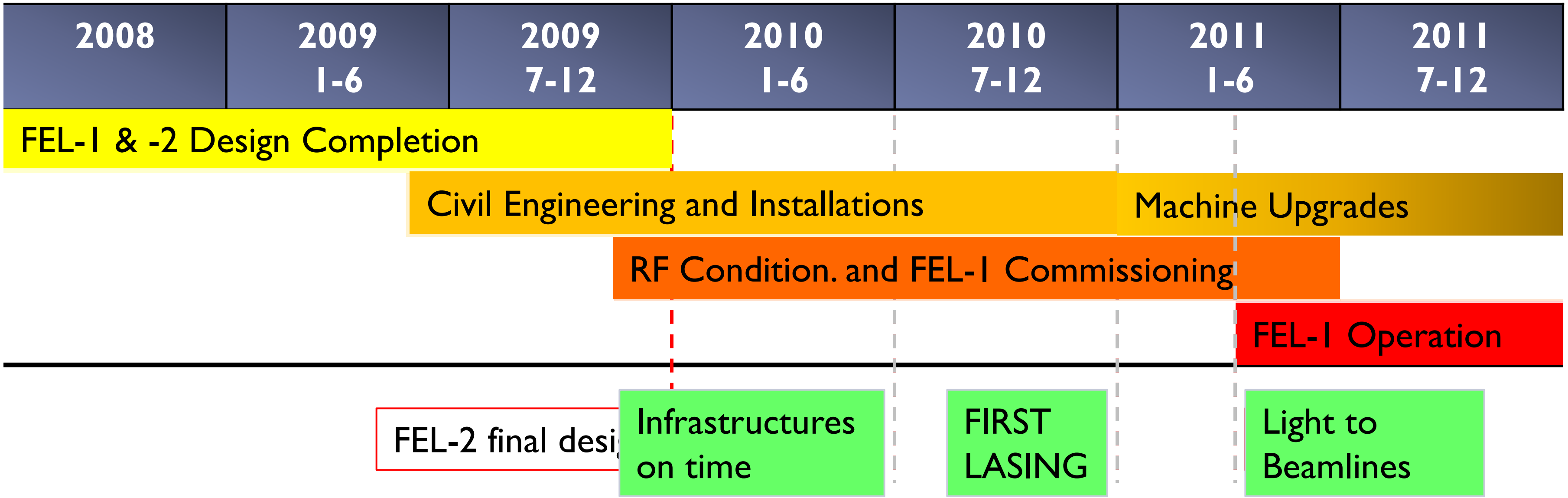
DESIGN GOALS & ACHIEVEMENTS



	Parameter	FEL-1	FEL-2	Units
γ	Output Wavelength (fund.)	100 – 40	40 – 10	nm
	Peak Power	~1 – 5	> 0.3	GW
	Repetition Rate	10	50	Hz
e	Energy	1.2	1.5	GeV
	Peak Current (core)	200 – 800	800	A
	Bunch Length (fhwm)	0.7 – 1.2	0.7	ps
	Slice Norm. Emittance	1.5 – 3.0	1.0	mm mrad
	Slice Energy Spread	0.20	0.15	MeV

CDR

DESIGN GOALS & ACHIEVEMENTS



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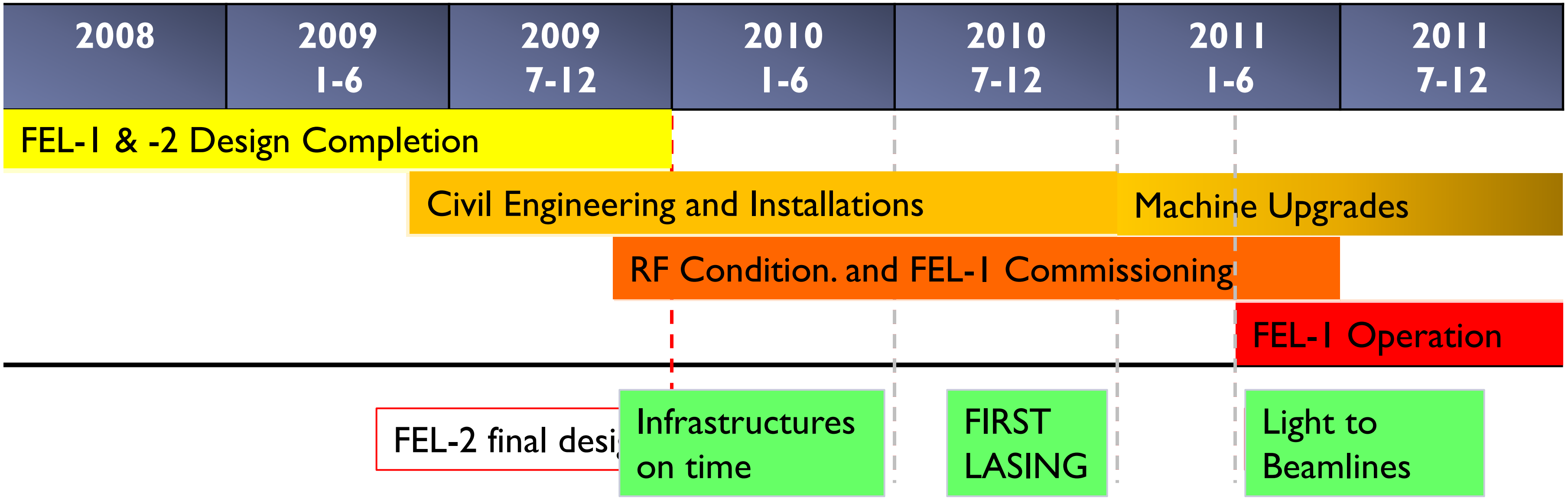

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	Slice Norm. Emittance	**1.5** – 3.0	1.0	mm mrad
	Slice Energy Spread	0.20	0.15	MeV

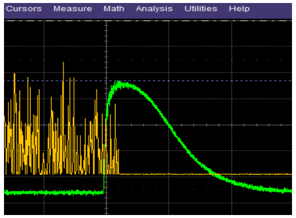
* achieved

Commissioning Status Report

- PI Laser, Gun & Injector: 2009 **– 2.5 months.**

  (2008, first Gun tests at MAX-lab.)

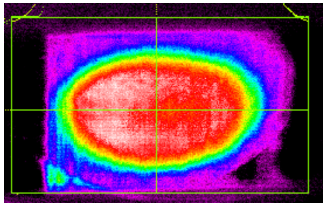
- Linac & First Bunch Length Compressor: 2010 **– 3.5 months.**



- Transfer Line to Main Beam Dump: 2010 **– 1.5 month.**

- 1st Coherent Emission at 43 nm: 2010 **– 1.5 months.** (13 Dec. 2010)

Coherent X-rays within 9 months after warm-up



- X-ray Transport & Diagnostics: 2011 **– 2 months.**

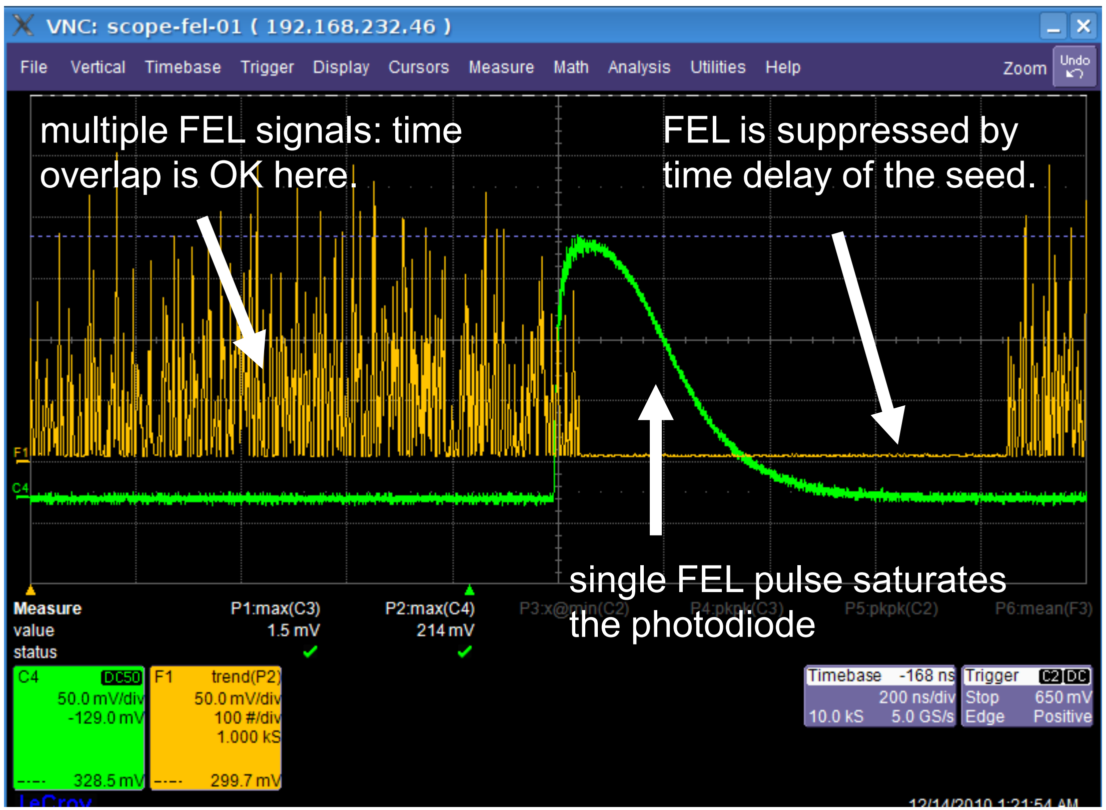
- FEL Exponential Gain, Polarization & Tunability: 2011 **– 1.5 months.**

- 65 – 32.5 nm to *LDM*, *TIMEX* & *DIPROI* Lines: 2011 **– 1.5 months.**

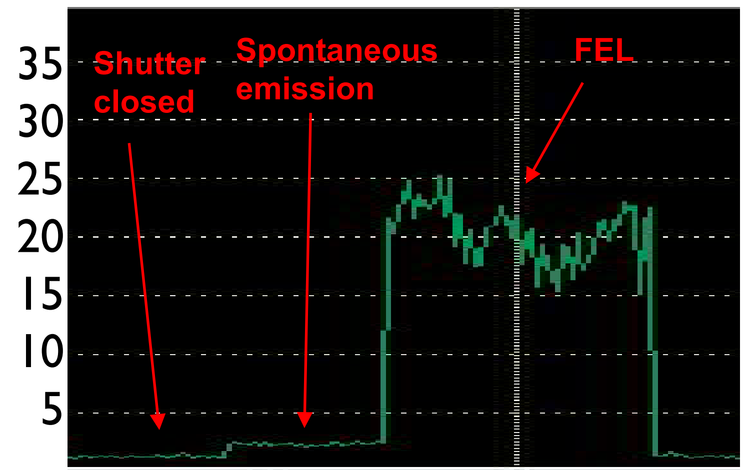
First users tests 5 months after 1st coherent output

First Attempt at Seeded Emission: CHG at 43 nm

- The 1st **seeded FEL coherent output** was observed at **43 nm, 13 December 2010.**
- **6 radiators** tuned in K via calibration tables. e-beam compressed softly, **~100A**.
- After spatial and temporal overlap of the seed laser (260nm, 160fs, 100 MW) with the e-beam, we saw the **coherent emission exceeding spontaneous emission** by several orders of magnitude at a diagnostic photodiode, ~40 m far from the undulator exit.



Shot-to-shot signal [a.u.] from atomic photo-ionization of Nitrogen at 10^{-5} mbar.



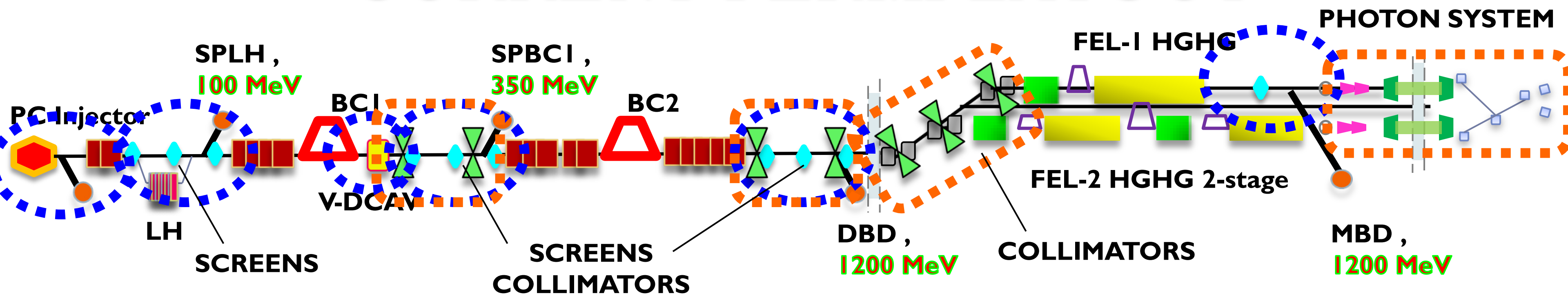
see G. Penco's talk at FEL Conf. 2011

 These data collected by: C. Spezzani, M. Veronese, S. Spezzani, G. De Ninno, P. Sigalotti, I. Nikolov et al.

Machine Status

Installations, e-Beam Gymnastics and Seeding

CURRENT *FERMI* LAYOUT

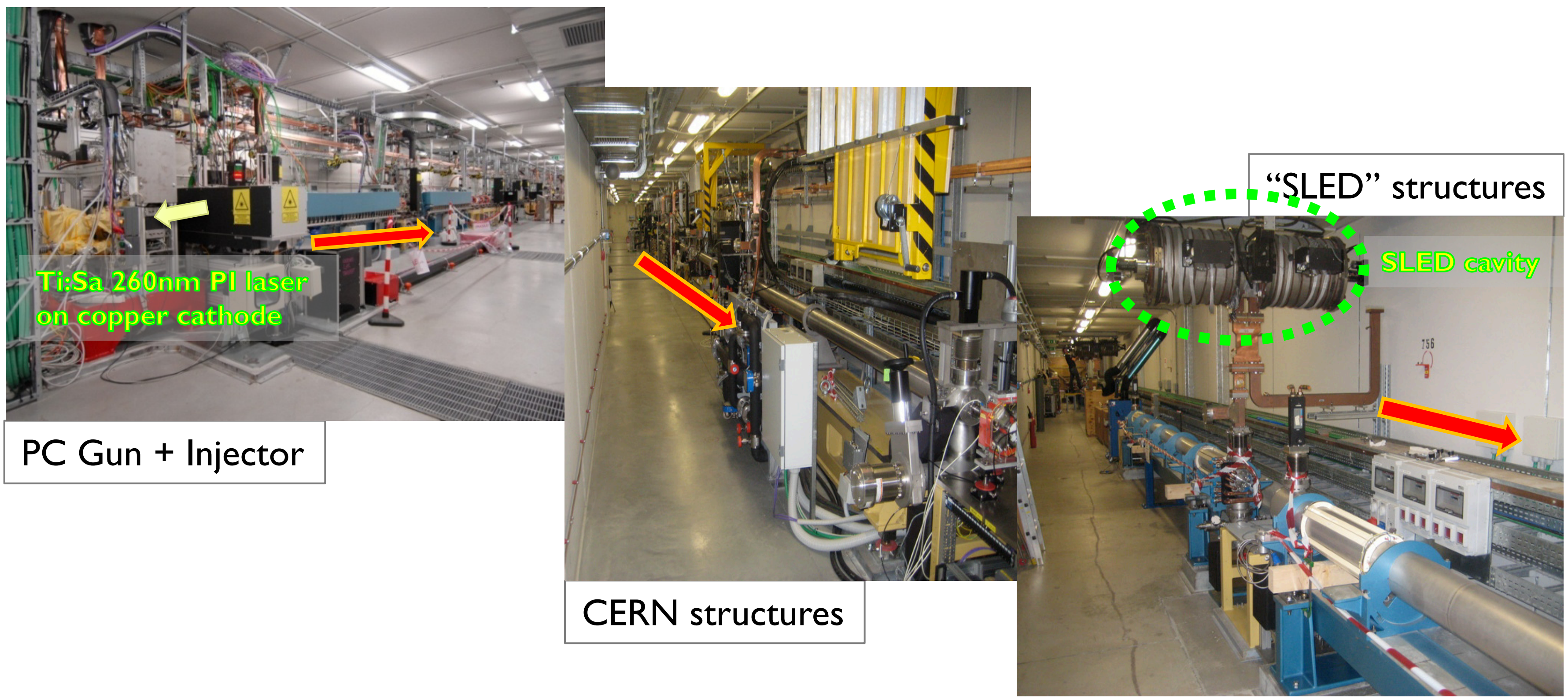


- RF Photo-cathode Gun and Injector + up to1.35 GeV Linac
- 2 Magnetic Bunch Length Compressors + 2 Bunch Length Monitors
- RF Vertical Deflector for time-resolved measurements
- 4 optics Diagnostic Stations + 5 Spectrometers
- 3 Collimation sections
- Planar and APPLE-II type Undulators + RF BPMs + γ/e- Screens + Quad-movers
- Photon Diagnostics Hutch + X-ray Transport + 3 Beamlines

LINAC

The previously existing 9-structures S-band Linac has been upgraded with:

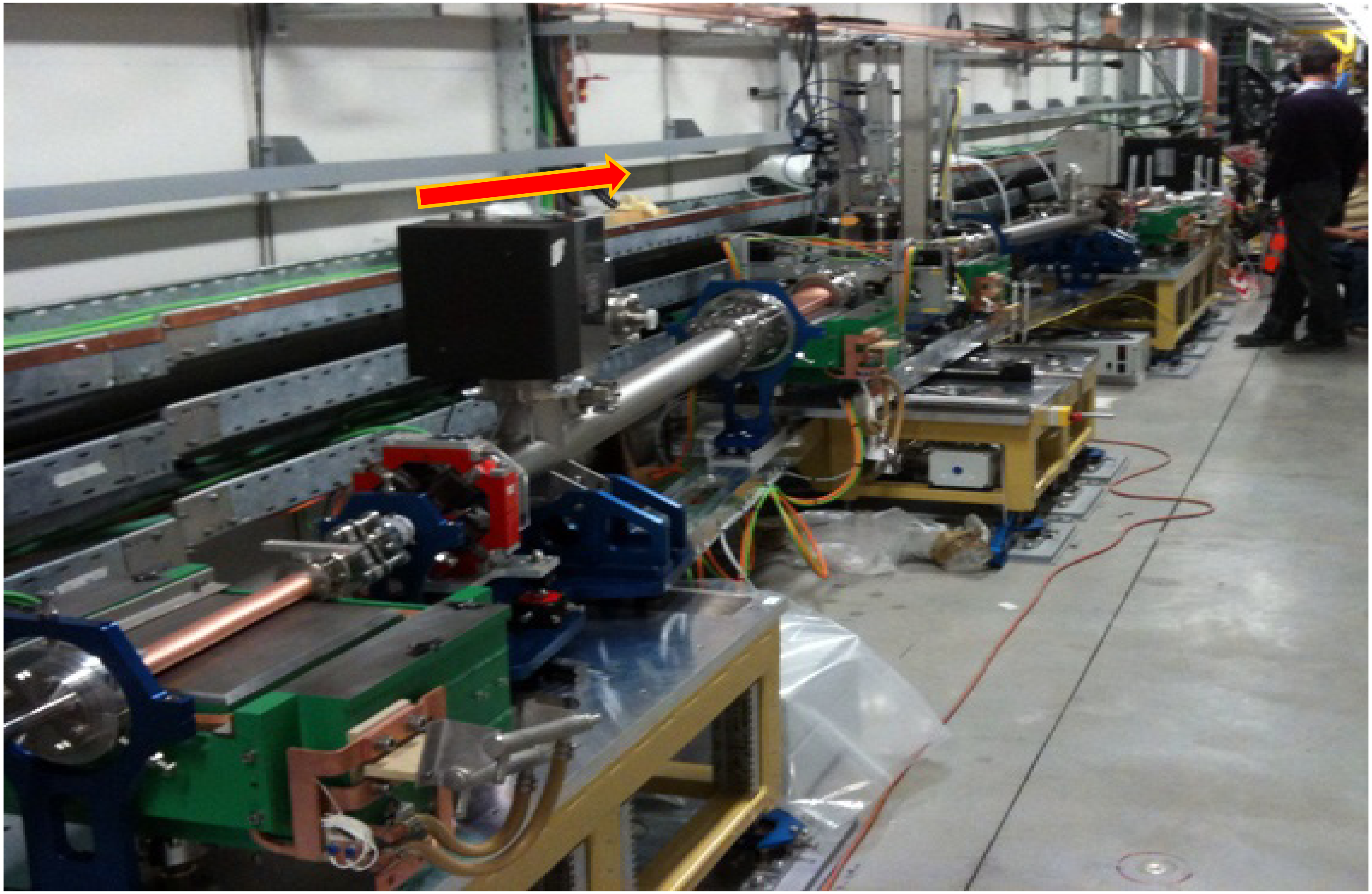
1. RF photo-cathode Gun (SLAC/BNL/UCLA)............$\varepsilon_n = 1\ \mu m$ **(450pC, 6 ps,100 MeV)**
2. 7 more CERN/LIL structures...**1.35 GeV reached**
3. SLED optimization and phase-modulation..........**27 MV/m promising 1.5 GeV (FEL-2)**
4. X-band TW structure *to be installed for linear time-compression*



 Ref.: M. Danailov (Lasers Area Leader), M. Trovo' (Gun Area Leader), A. Fabris (S-band Area Leader), P. Craievich, G. Penco

MAGNETIC COMPRESSOR

Two movable magnetic chicanes for one- or two-stage bunch length compression have been developed *in house* on improved LCLS design……… **compression factor ≤ 6 used for FEL**



Ref.: D. Zangrando (Area Leader), D. La Civita, R. Fabris, D. Castronovo, G. Pangon, T. Borden, S. Di Mitri

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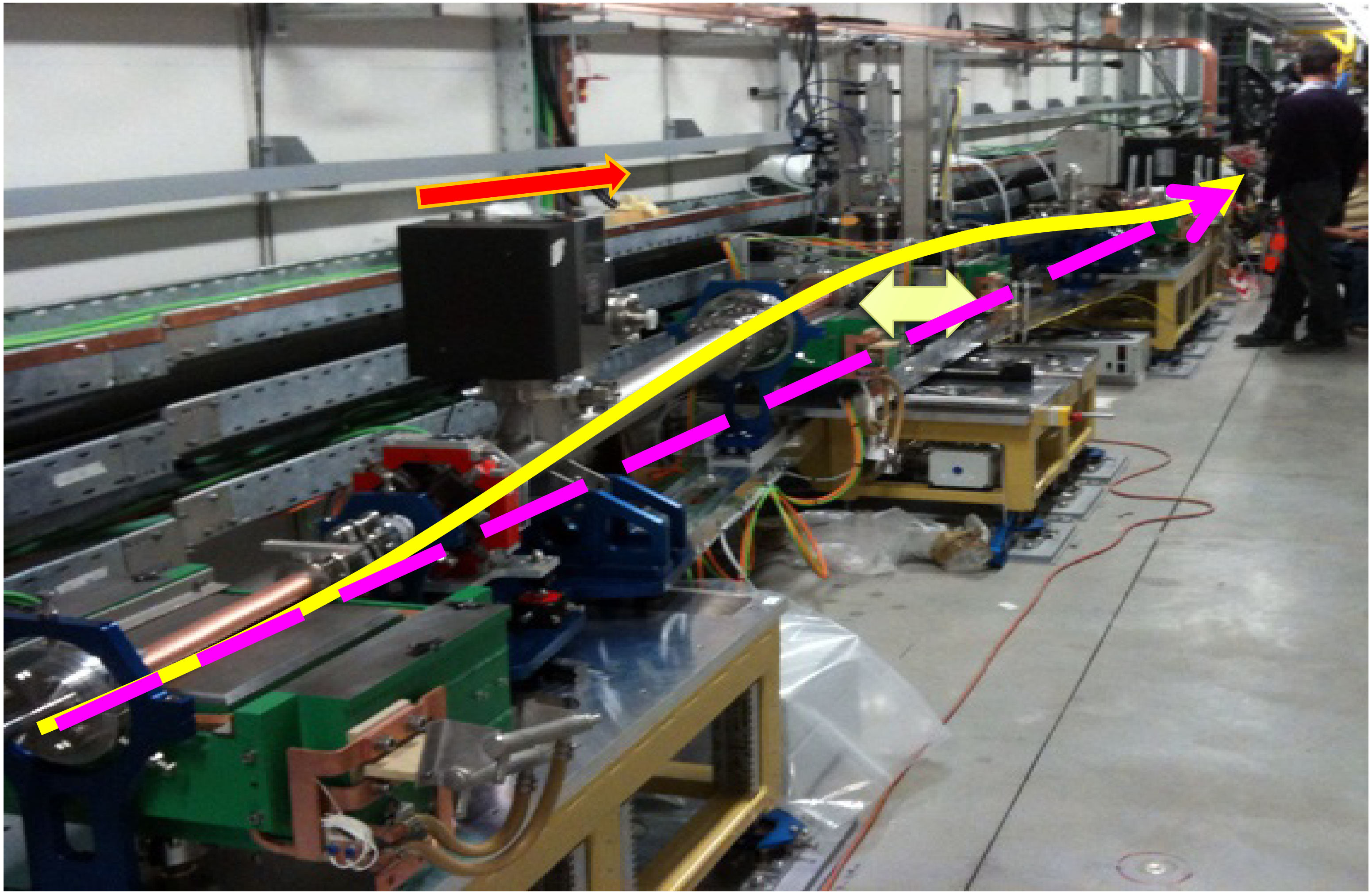

TRANSFER LINE

Compact (~30 m) **FEL-1/FEL-2 Spreader line;** e-beam **diagnostics** and **collimation** included. Followed by the undulators (~30 m) and the **Main Beam Dump** line (~40 m).

"Spreader"

Main Beam Dump

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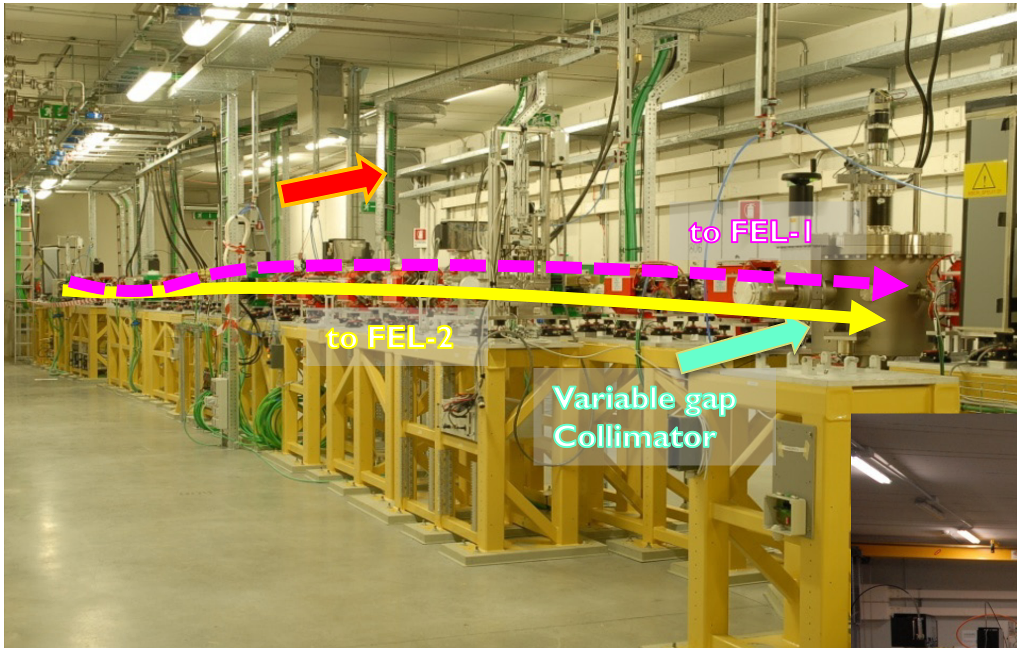
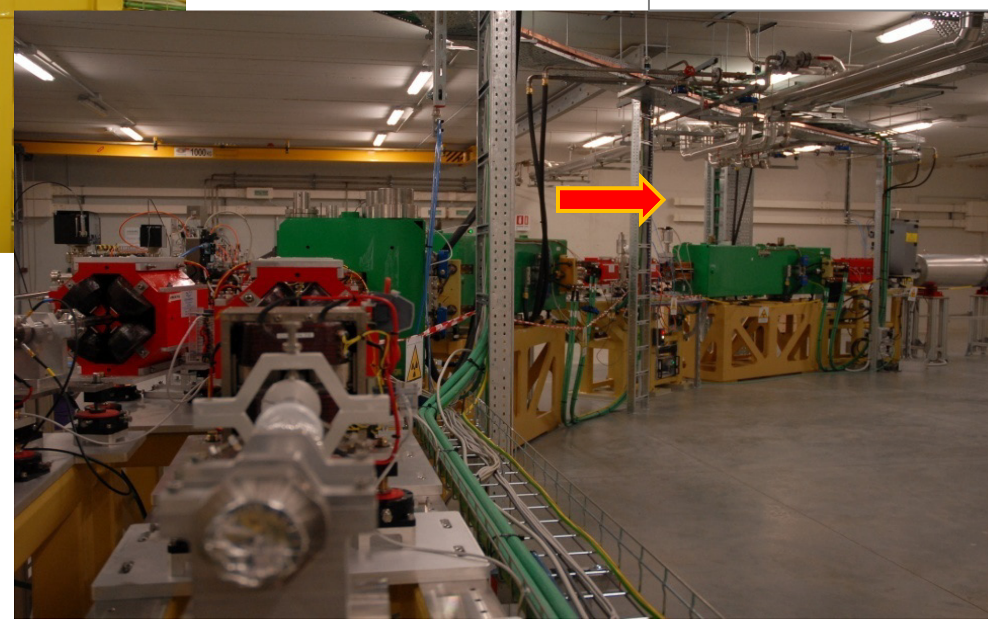


"Spreader"

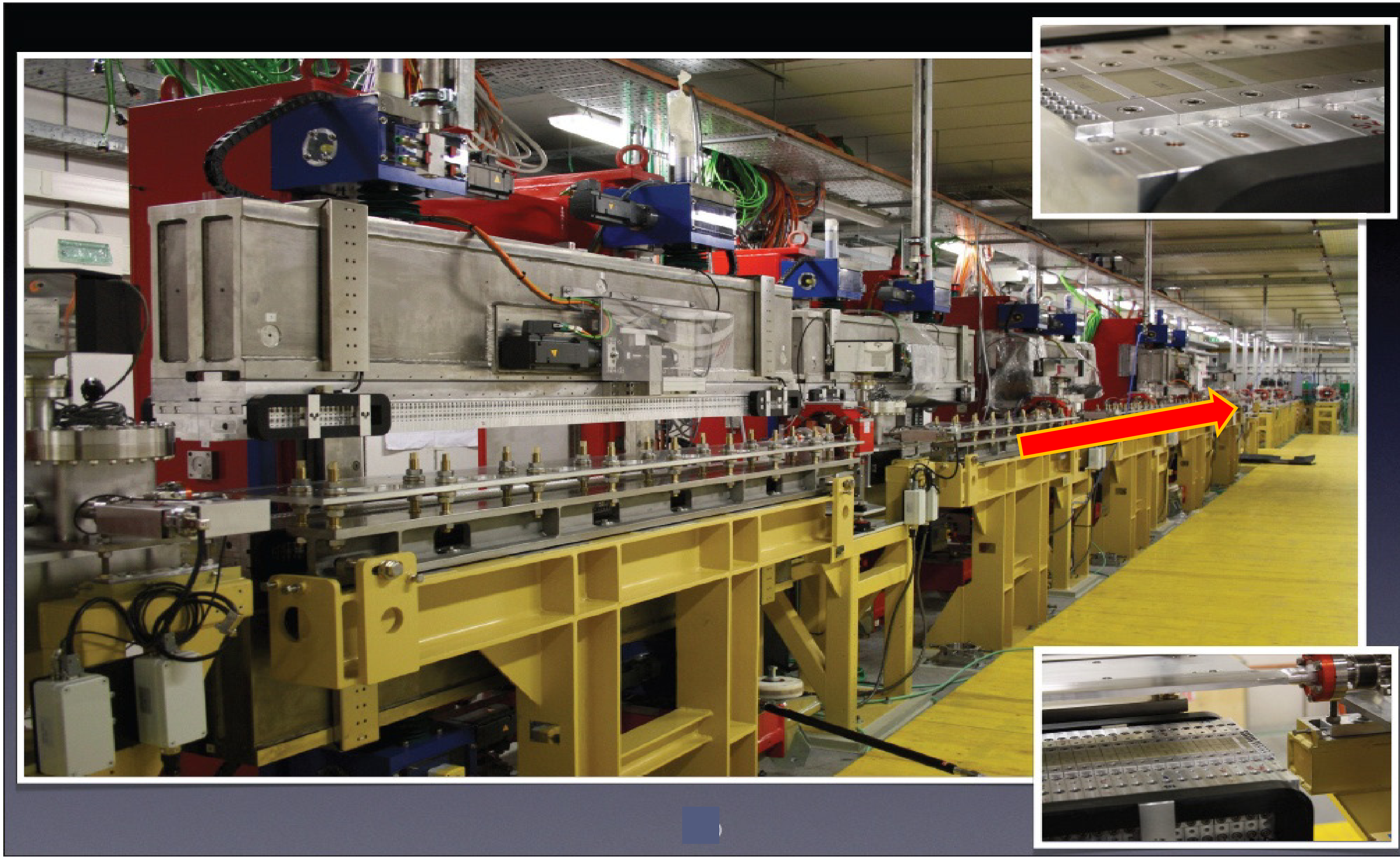
Main Beam Dump



 Ref.: E. Karantzoulis (Area Leader), S. Ferry, I. Cudin, M. Tudor, S. Di Mitri et al.

UNDULATOR

Variable gap, planar and APPLE-II type undulators. In house design, manufacturing by KYMA (ST spin-off)............................**variable polarization** **&** **λ-tuning** **provided to users**



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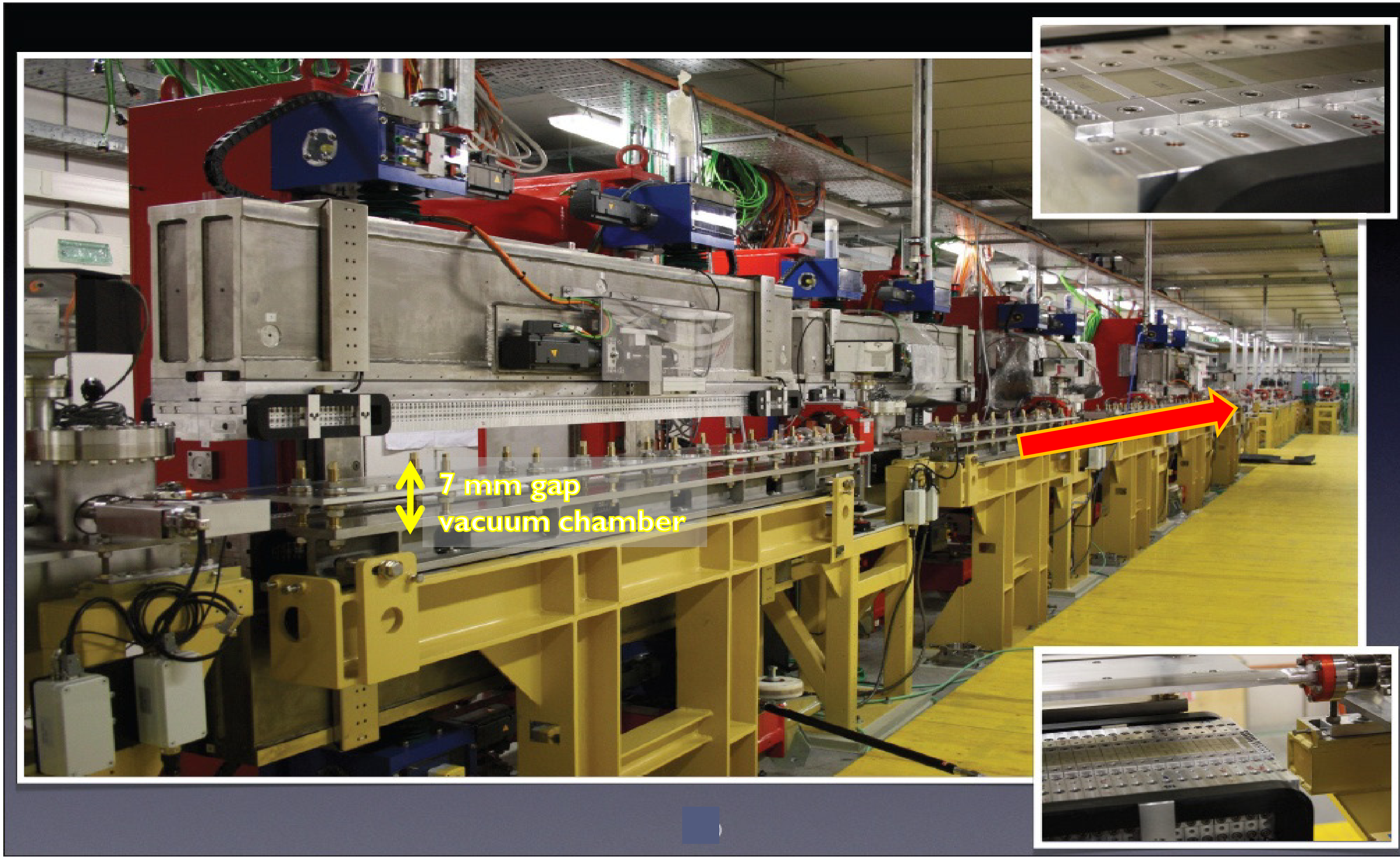

Ref.: B. Diviacco (Area Leader), D. La Civita, M. Musardo, G. Tomasin, E. Allaria

PHOTON TRANSPORT & DIAGNOSTICS

On-line and off-line X-ray diagnostics. Active mirrors. KB mirrors for $5\mu m \times 5\mu m$ focusing on the sample. 3-way switching system for transport to the beamlines.

Ref.: D. Cocco, M. Zangrando, C. Svetina, F. Parmigiani

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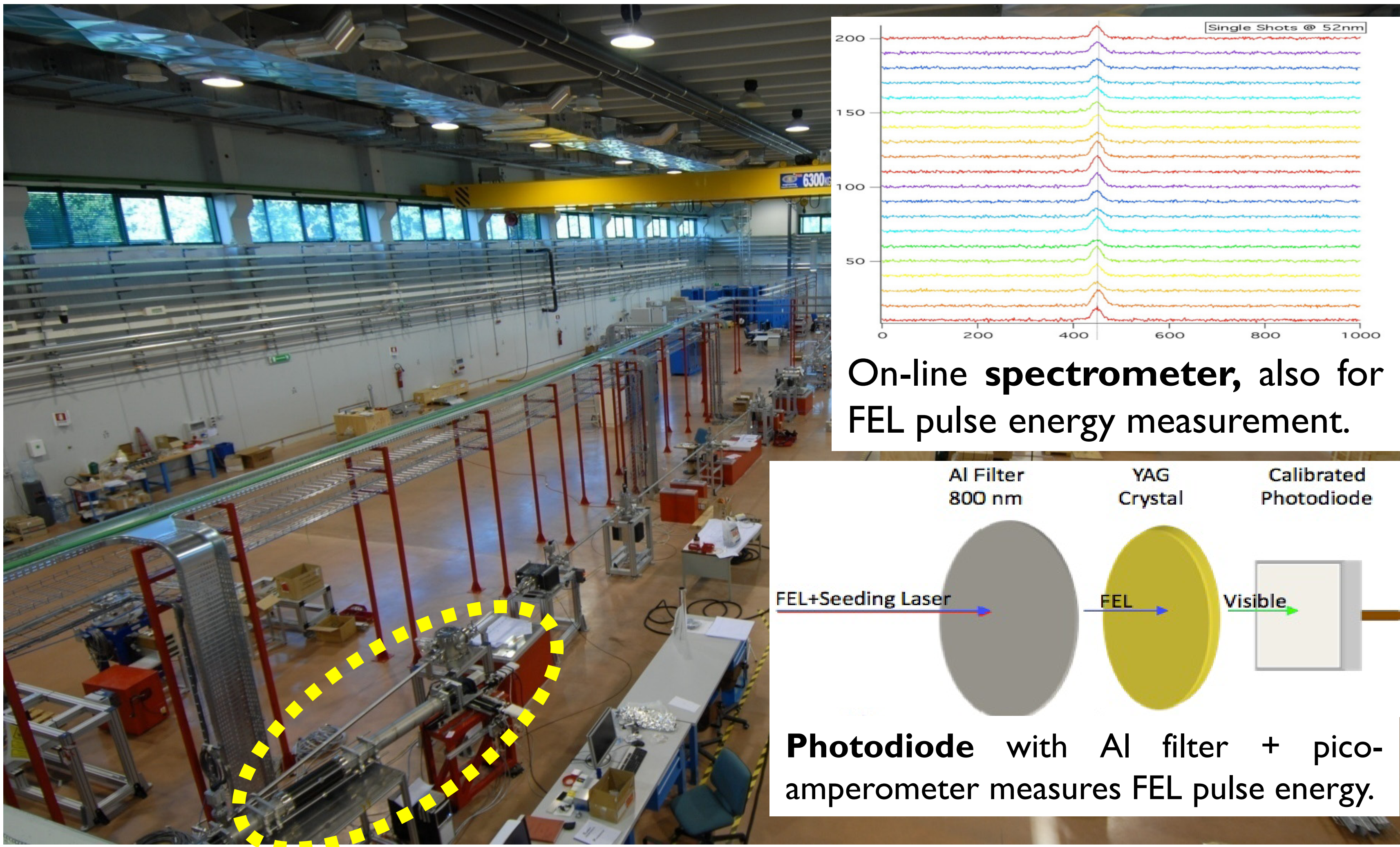
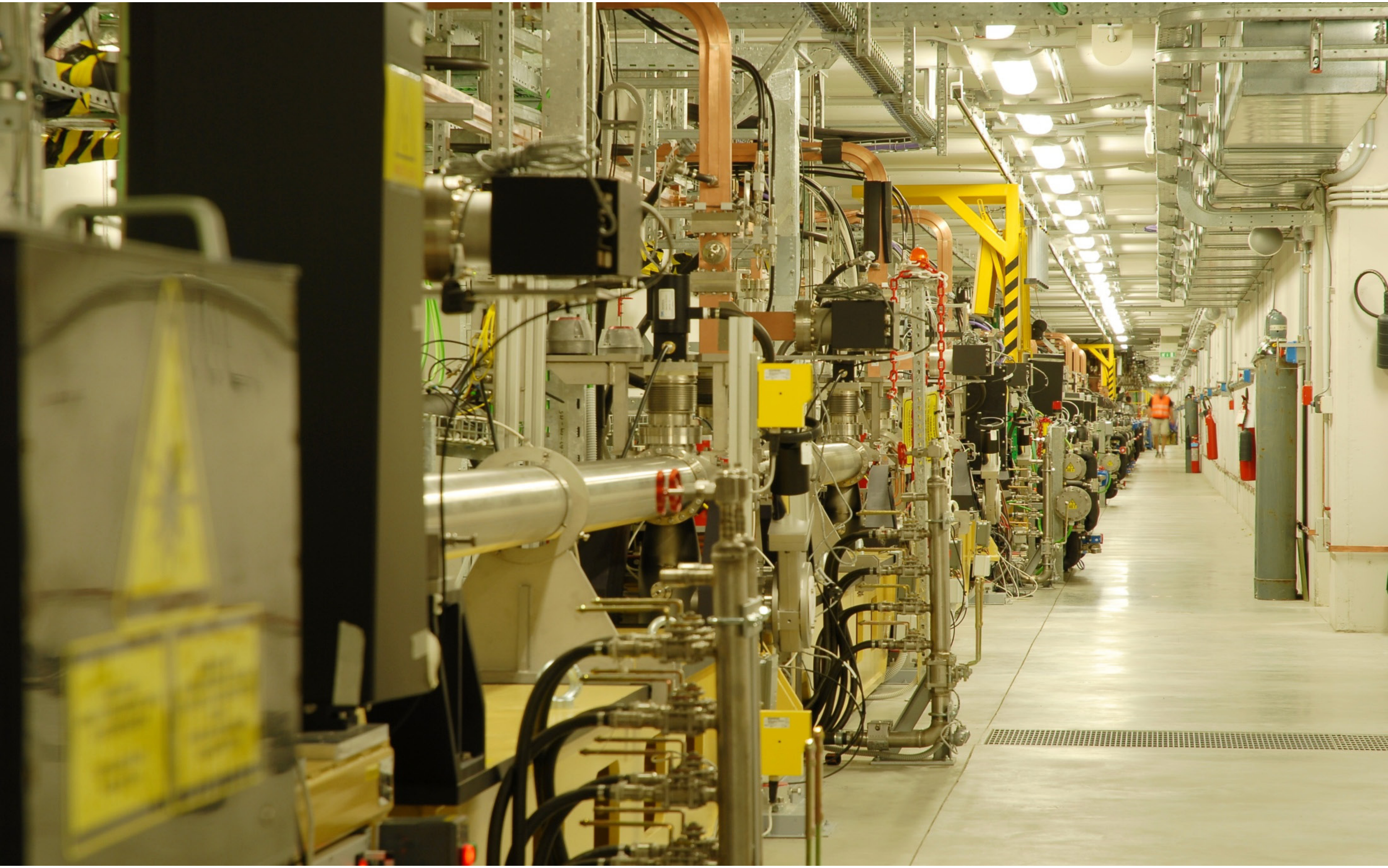


On-line **spectrometer,** also for FEL pulse energy measurement.

Photodiode with Al filter + pico-amperometer measures FEL pulse energy.

 Ref.: D. Cocco, M. Zangrando, C. Svetina, F. Parmigiani

OTHER MACHINE SYSTEMS…



 M. Lonza, C. Scafuri, G. Gaio, M. Ferianis, M. Veronese, R. De Monte, L. Badano, F. Rossi, M. Predonzani, L. Froehlich, M. Danailov, et al.

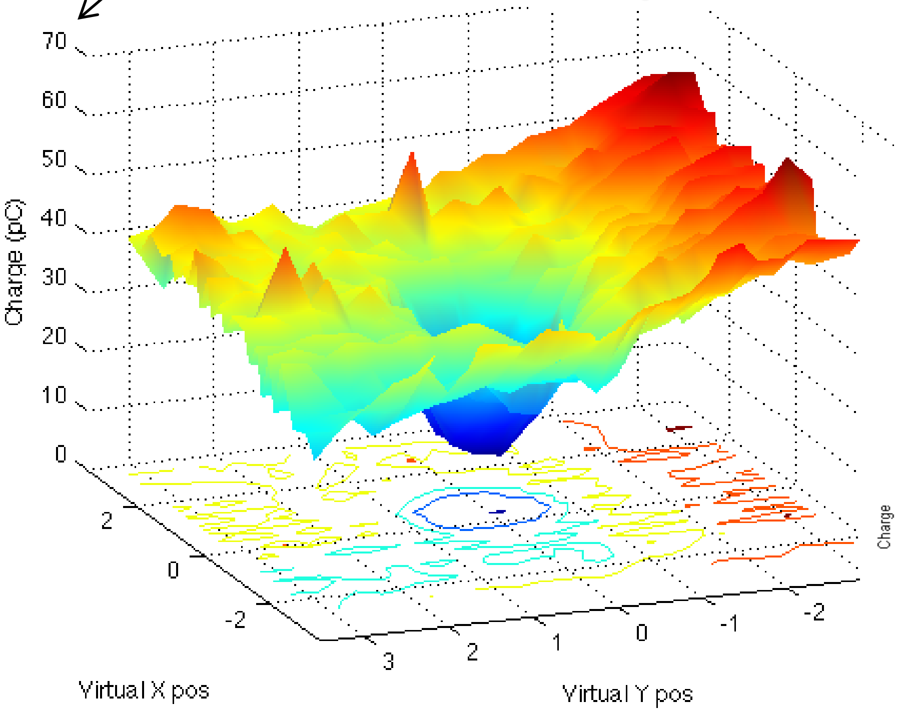
OTHER MACHINE SYSTEMS…

- **Controls** (news in M. Lonza's, G. Gaio's and L. Pivetta's talk at ICALEPCS 2011)
  - *Tango*-based
  - Real-time framework
  - `elegant`-based on-line optics control
  - MATLAB for Mach. Phys. Applications
  - Scientific Data Management
- **Diagnostics** (see R. De Monte's talk and "Elettra" contributions at DIPAC 2011)
  - Electro-Optical Sampling
  - Bunch Length Monitor
  - Bunch Arrival Monitor
  - 2μm-res. RF Cavity BPMs
  - Intra-Undulator Screens
- **Timing & Synchronization** (see M. Ferianis' talk at FEL Conf. 2011)
  - All-optical timing system
  - Synchronization with femtosecond precision
- **Machine Protection System** (see L. Froehlich's talk at DIPAC 2011)
  - Cerenkov fiber beam loss posit. monitor
  - On-line dosimeter with MOSFETs
  - Ionization chamber beam loss monitor
- **Lasers** (see M. Danailov's talk at FEL Conf. 2011)

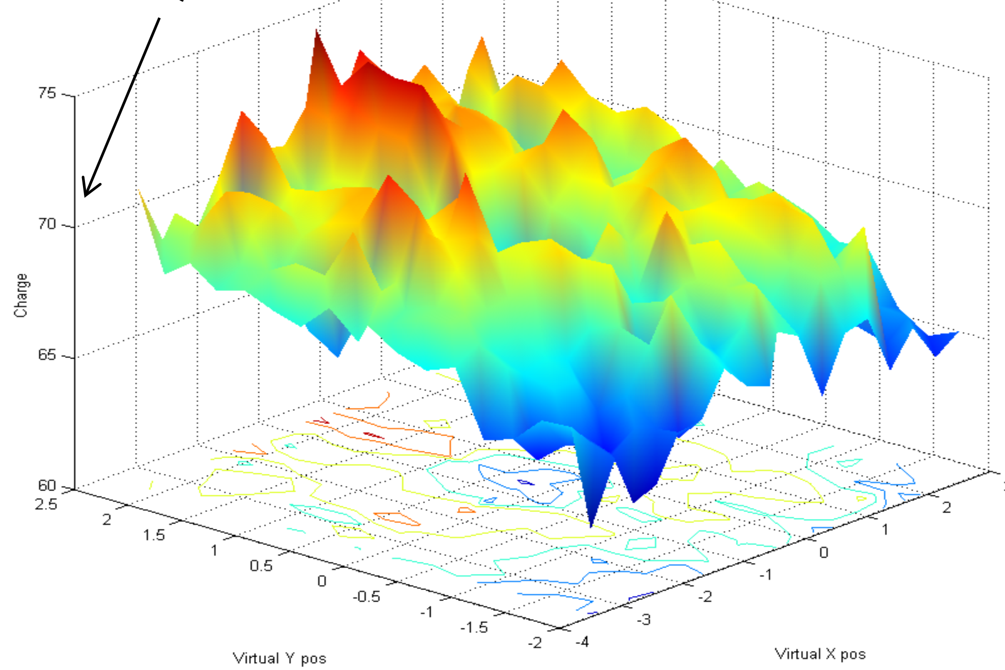
ELECTRON SOURCE

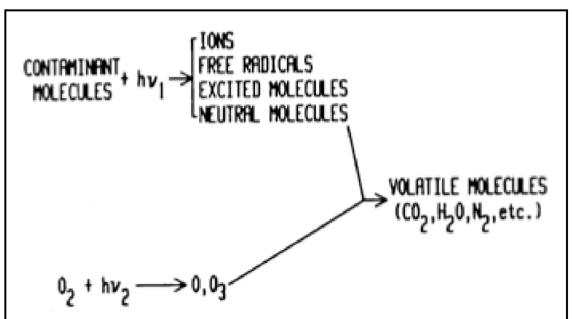
After 2 months operation:
QE depletion

QE=2.5×10^{-5}



After UV/Ozone cleaning* routinely implemented at machine start-up:
QE restored.

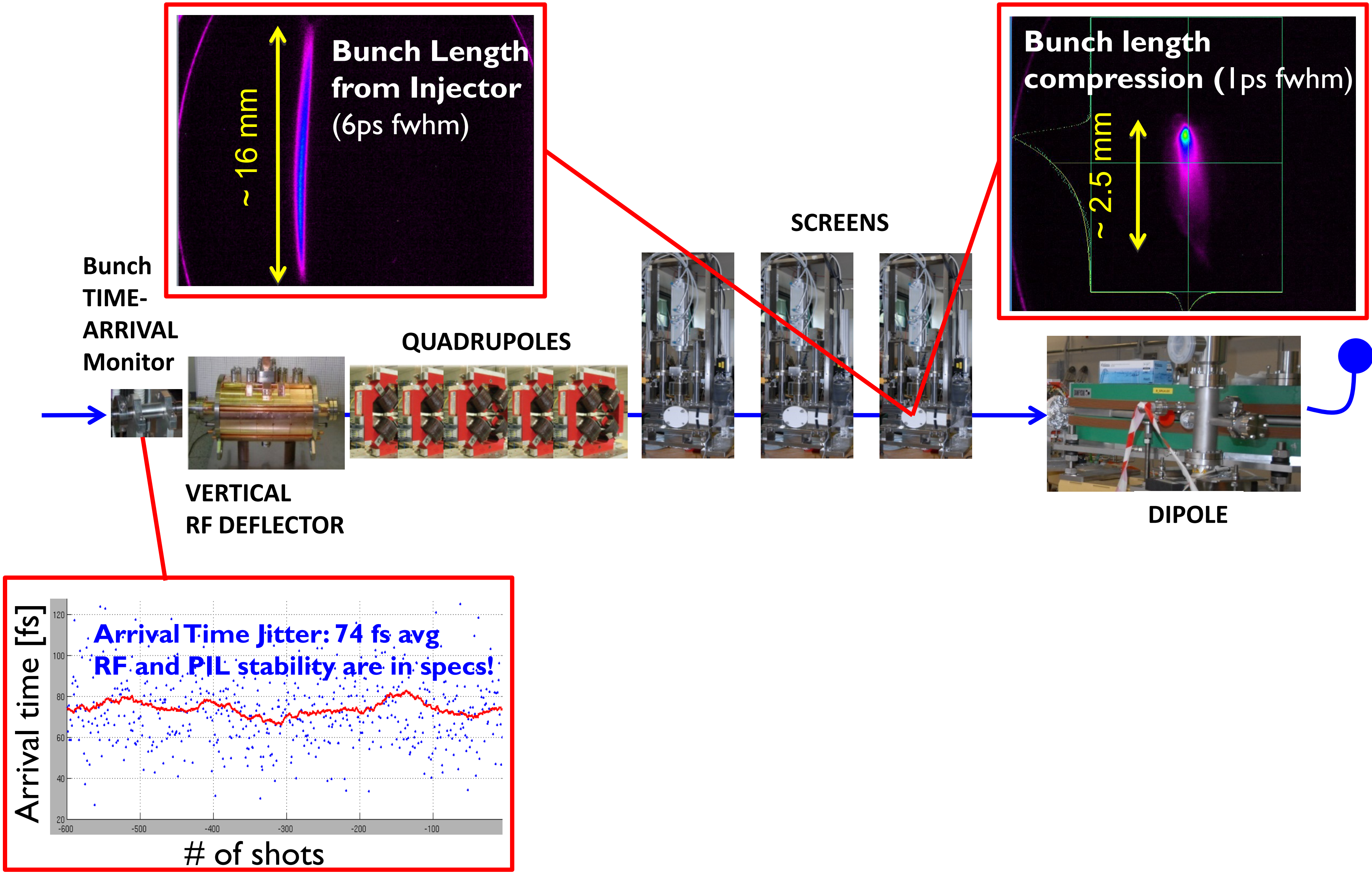




*W. Kern, Handbook of Semiconductor Wafer Cleaning Technology, W. Andrew Publishing/Noyes (1993) .

These pictures: the Cu cathode surface is sampled by a 200 μm laser spot and 10 μJ.

ELECTRON BEAM DIAGNOSTICS



 These data collected by: G. Penco, P. Craievich, M. Petronio, A. Lutman, F. Rossi, M. Predonzani, S. Spampinati

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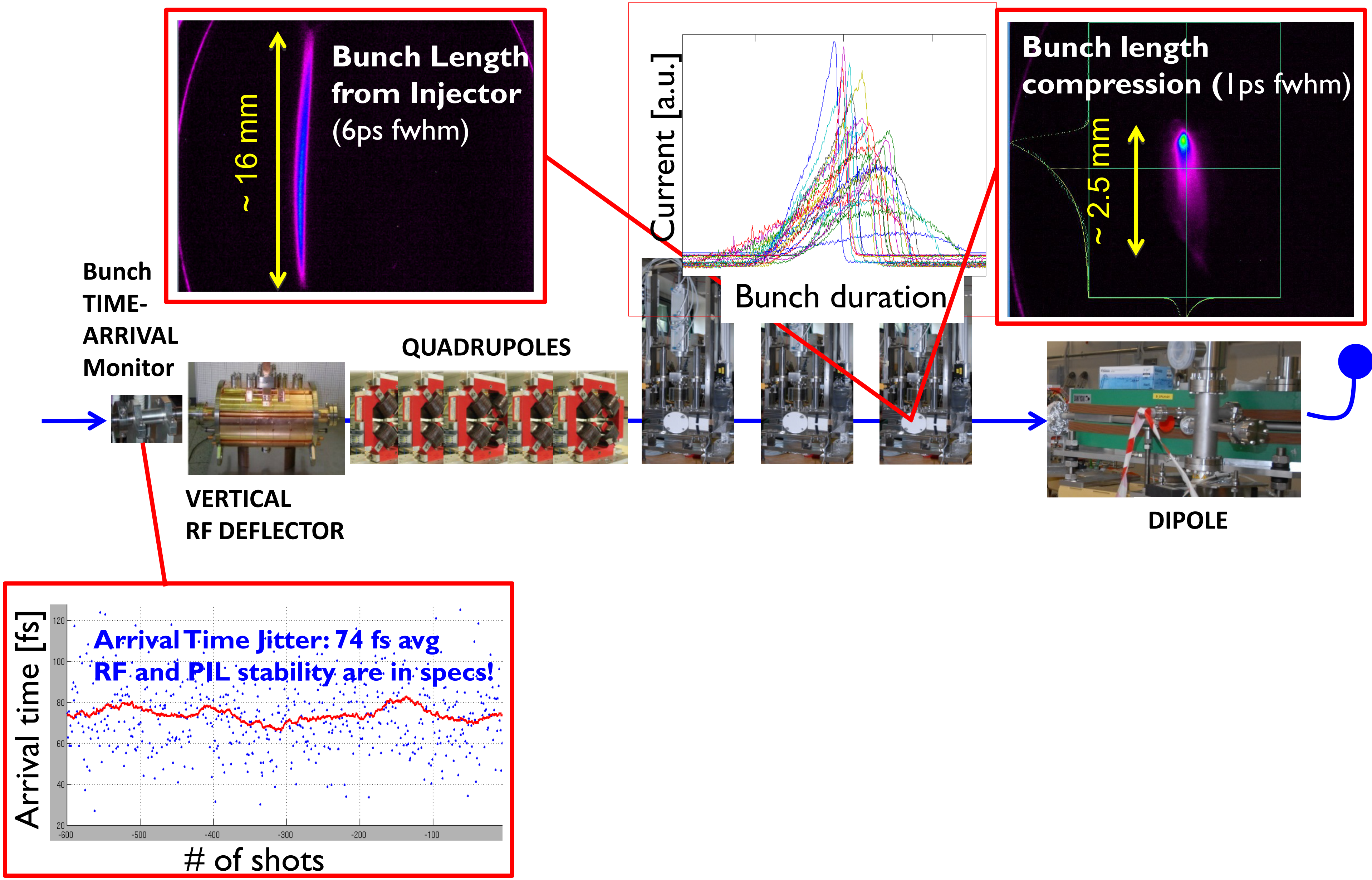

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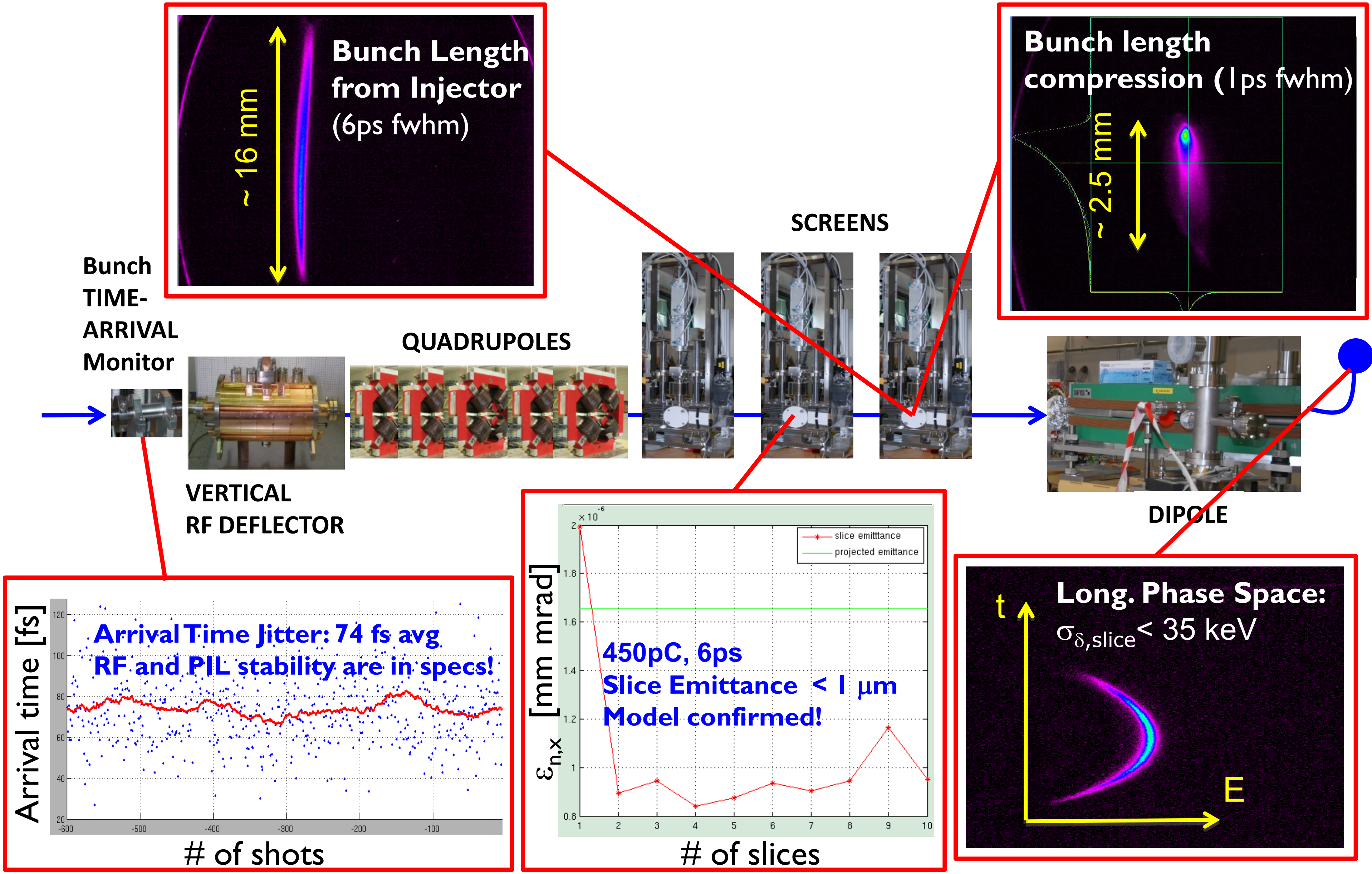

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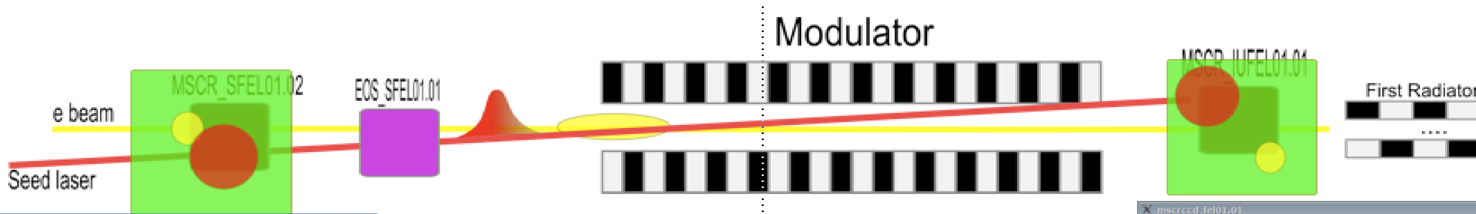
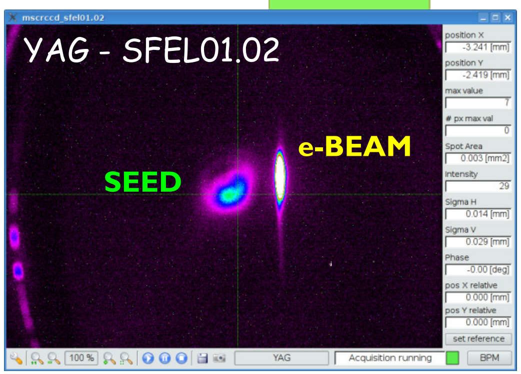
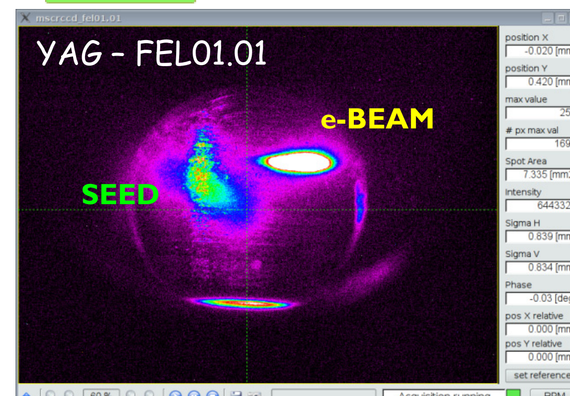
SEEDING

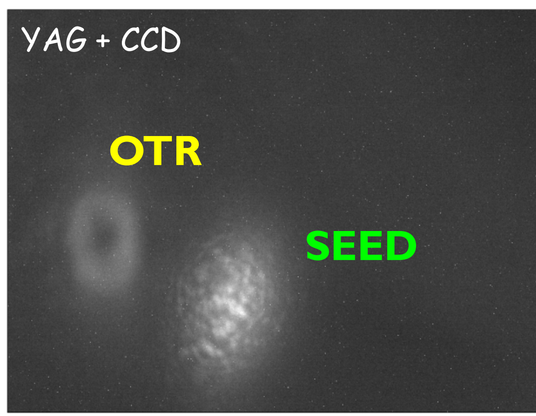
Spatial overlap across the modulator is carried out with **two YAG screens**. The e-beam is aligned with **μm resolution** RF cavity BPMS. Seed laser movement done with remotely controlled mirrors.

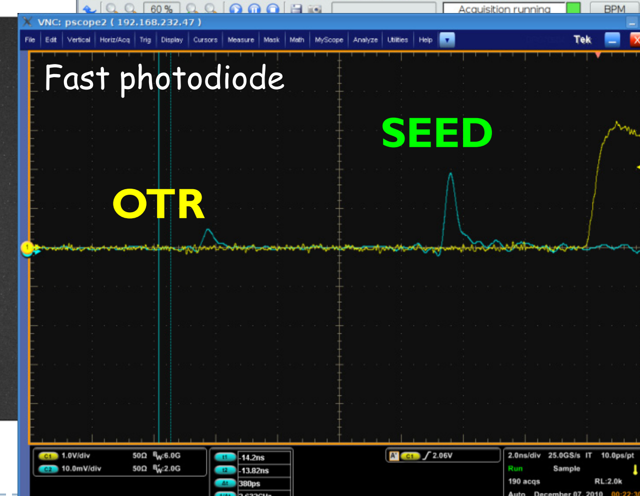






Time overlap at the modulator entrance is carried out with an **Al foil** that reflects the laser out of the chamber and makes electrons producing OTR. The two signals are detected with a CCD and a **fast photodiode**. A **delay line** is used for **sub-ps tuning**.





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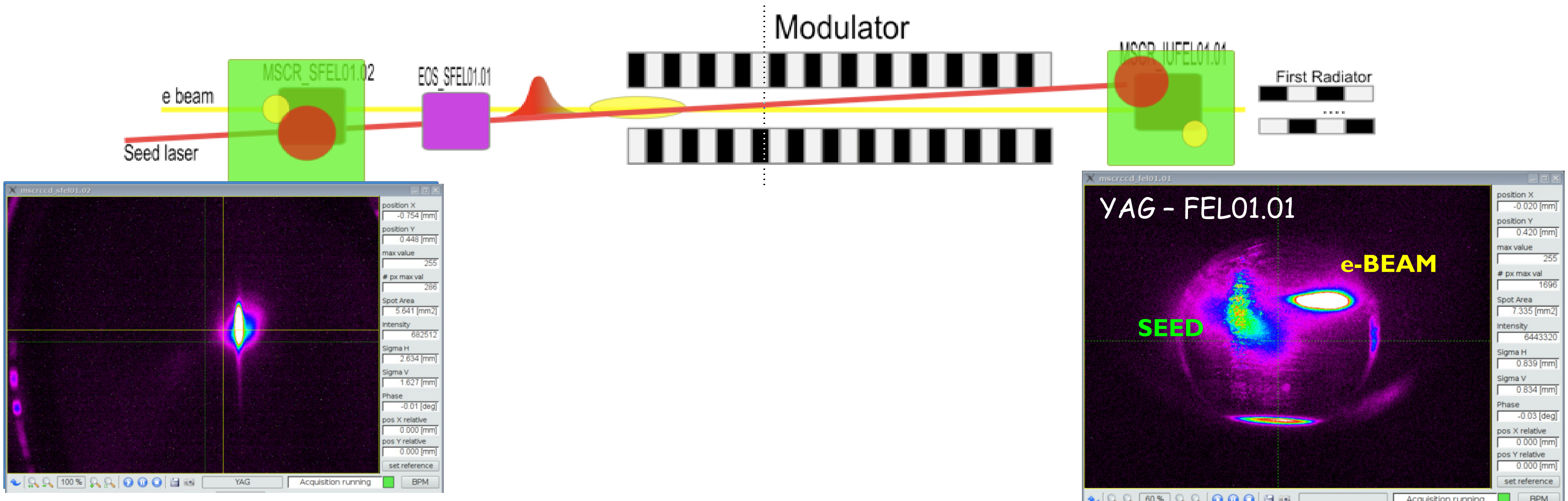

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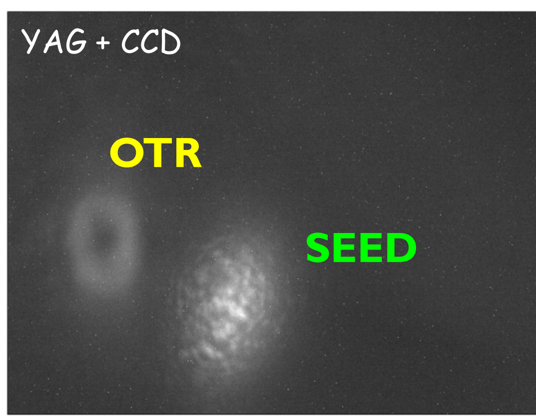

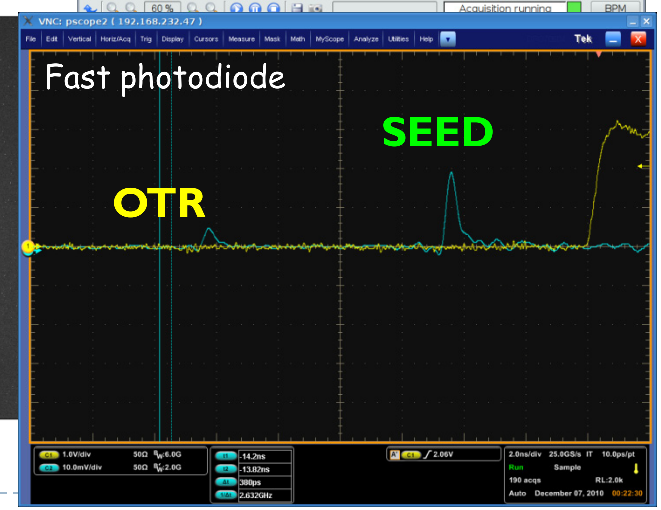

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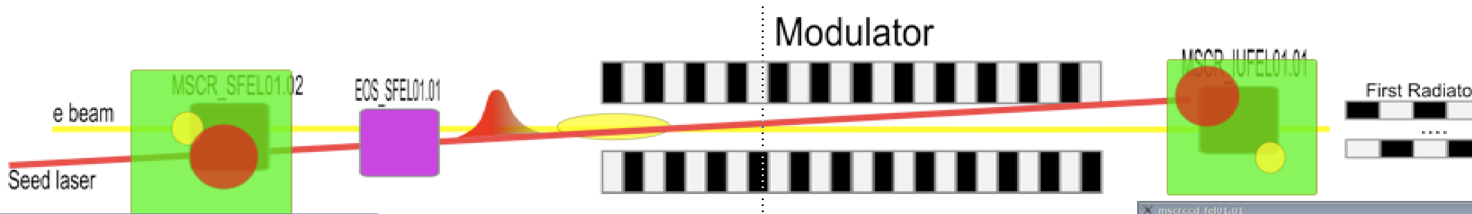
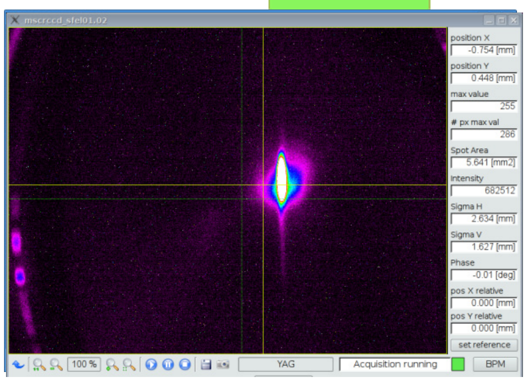
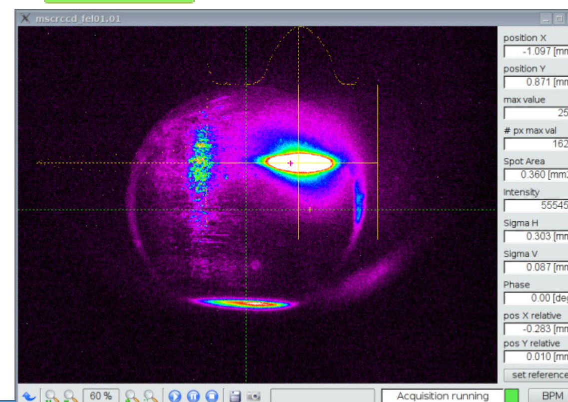
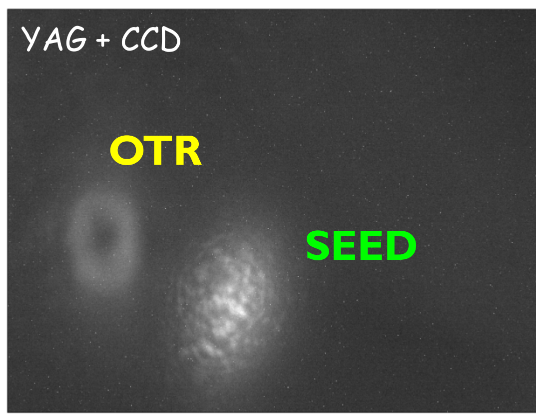
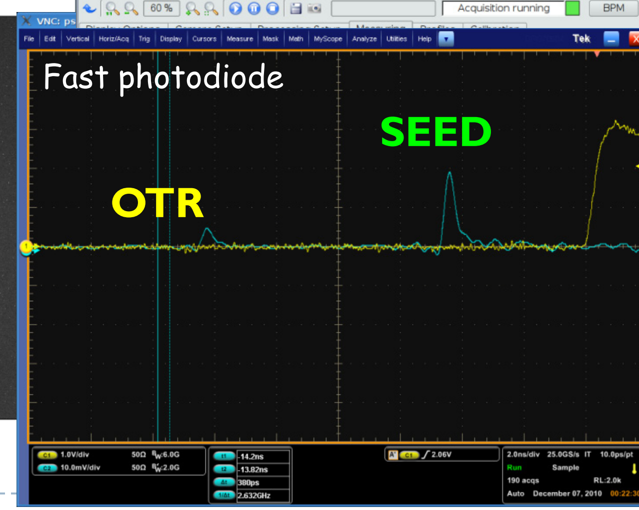






Time overlap at the modulator entrance is carried out with an **Al foil** that reflects the laser out of the chamber and makes electrons producing OTR. The two signals are detected with a CCD and a **fast photodiode**. A **delay line** is used for **sub-ps tuning**.

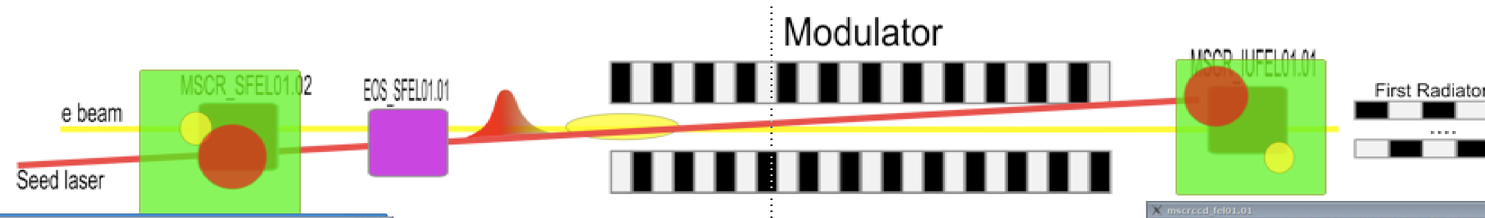


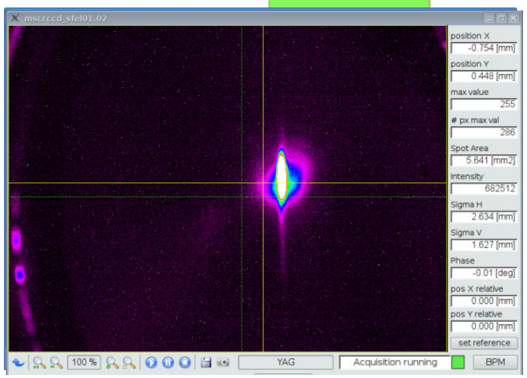


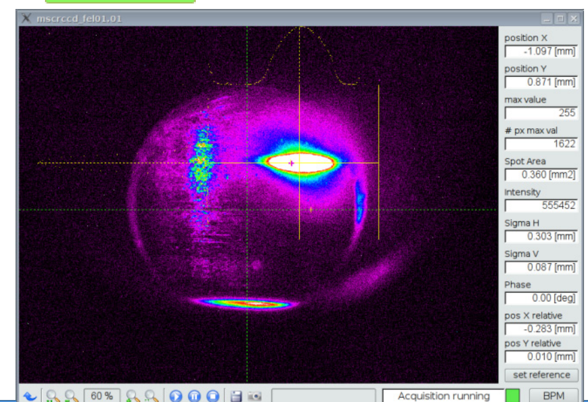
 These data collected by: F. Rossi, M. Veronese, C. Spezzani, M. Danailov, P. Cinquegrana, P. Sigalotti, E. Allaria

SEEDING

Spatial overlap across the modulator is carried out with **two YAG screens**. The e-beam is aligned with **μm resolution** RF cavity BPMS. Seed laser movement done with remotely controlled mirrors.







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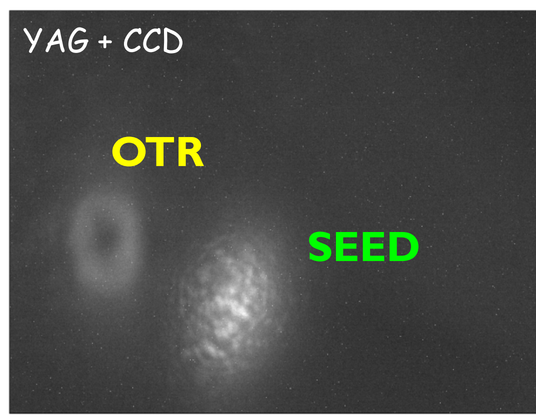
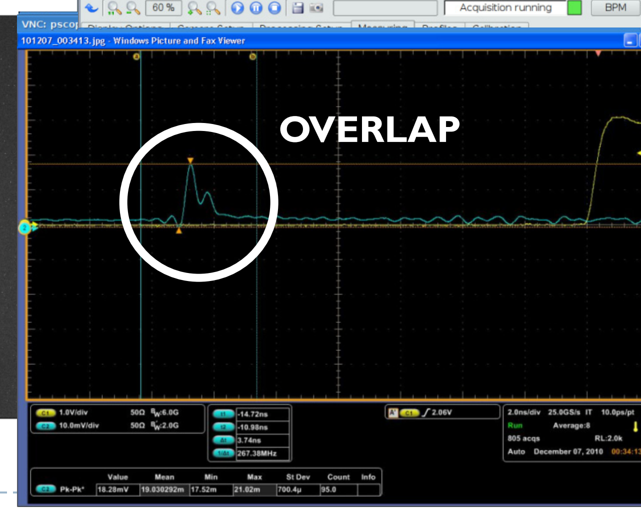




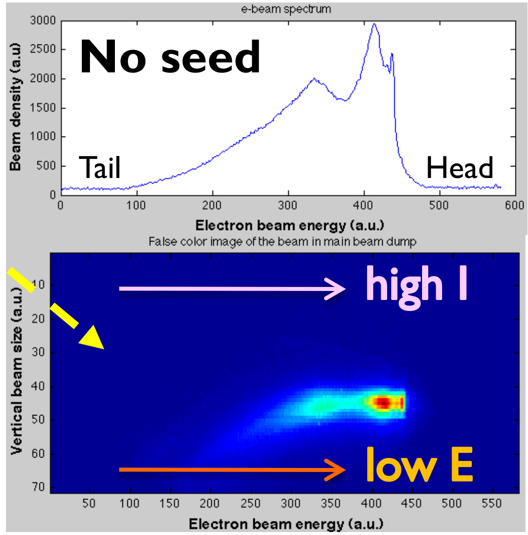
These data collected by: F. Rossi, M. Veronese, C. Spezzani, M. Danailov, P. Cinquegrana, P. Sigalotti, E. Allaria

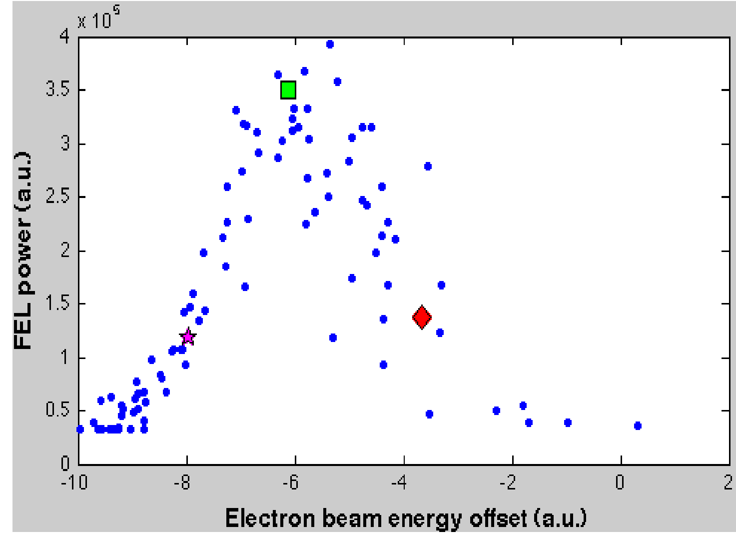
FEL-1 Experience & Outlook

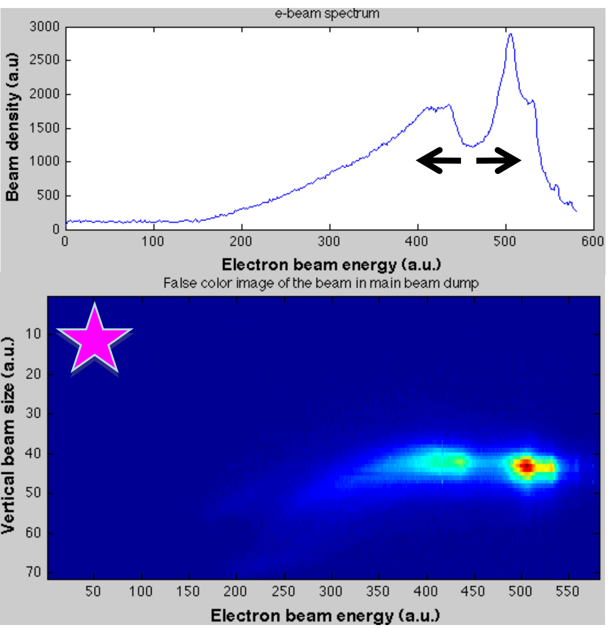
HGHG FEL Commissioning Results, Beamlines, Outlook

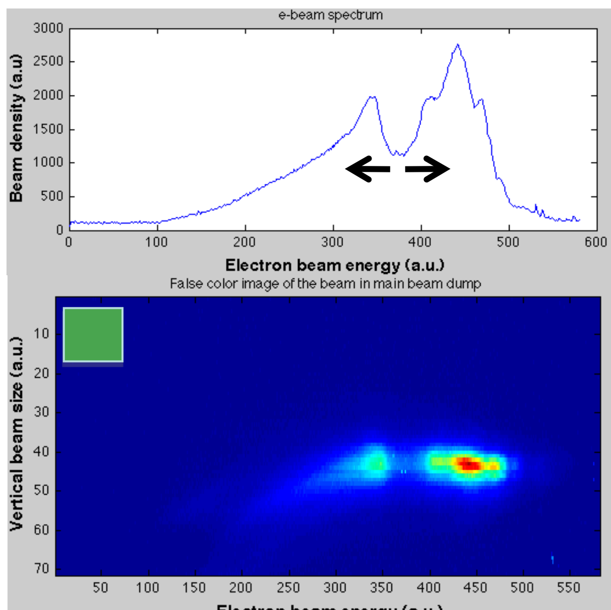
e-Beam Seeding Optimization

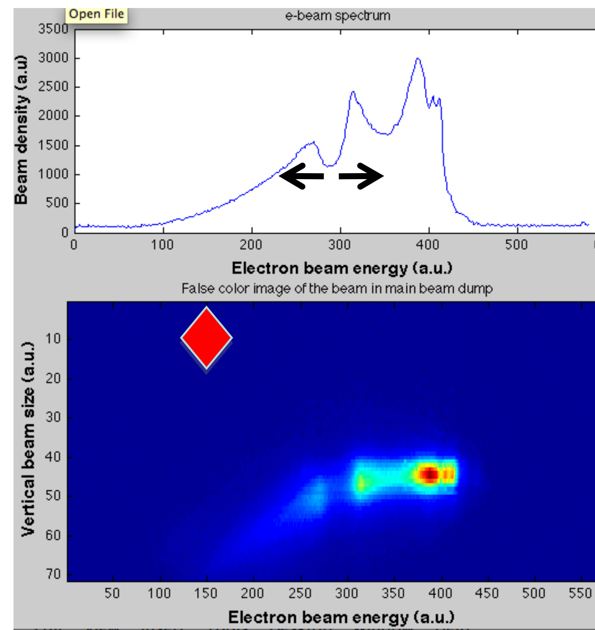
300 pC, CF~4, 6 radiators at 65nm





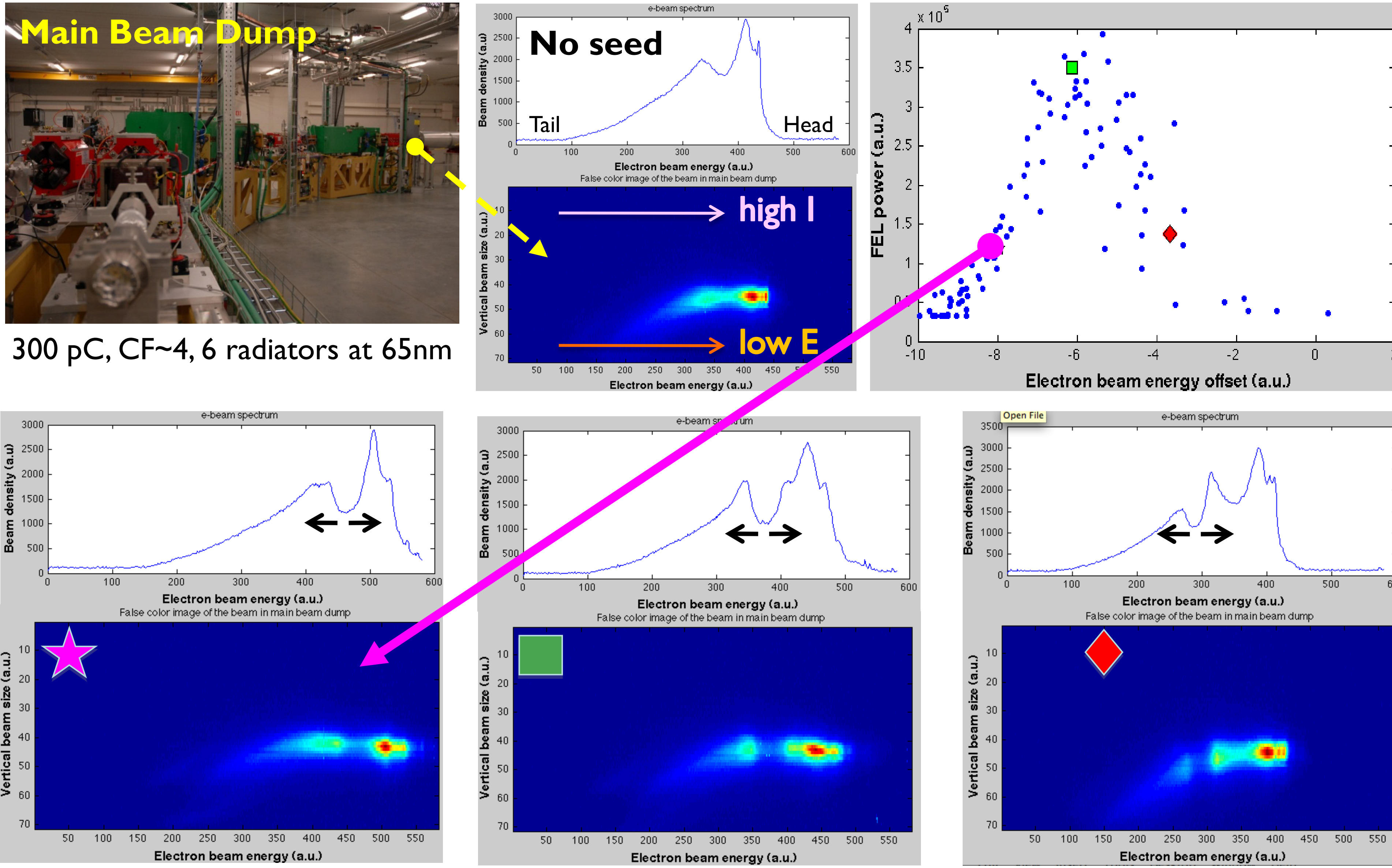






These data collected by: E. Allaria, S. Spampinati

e-Beam Seeding Optimization



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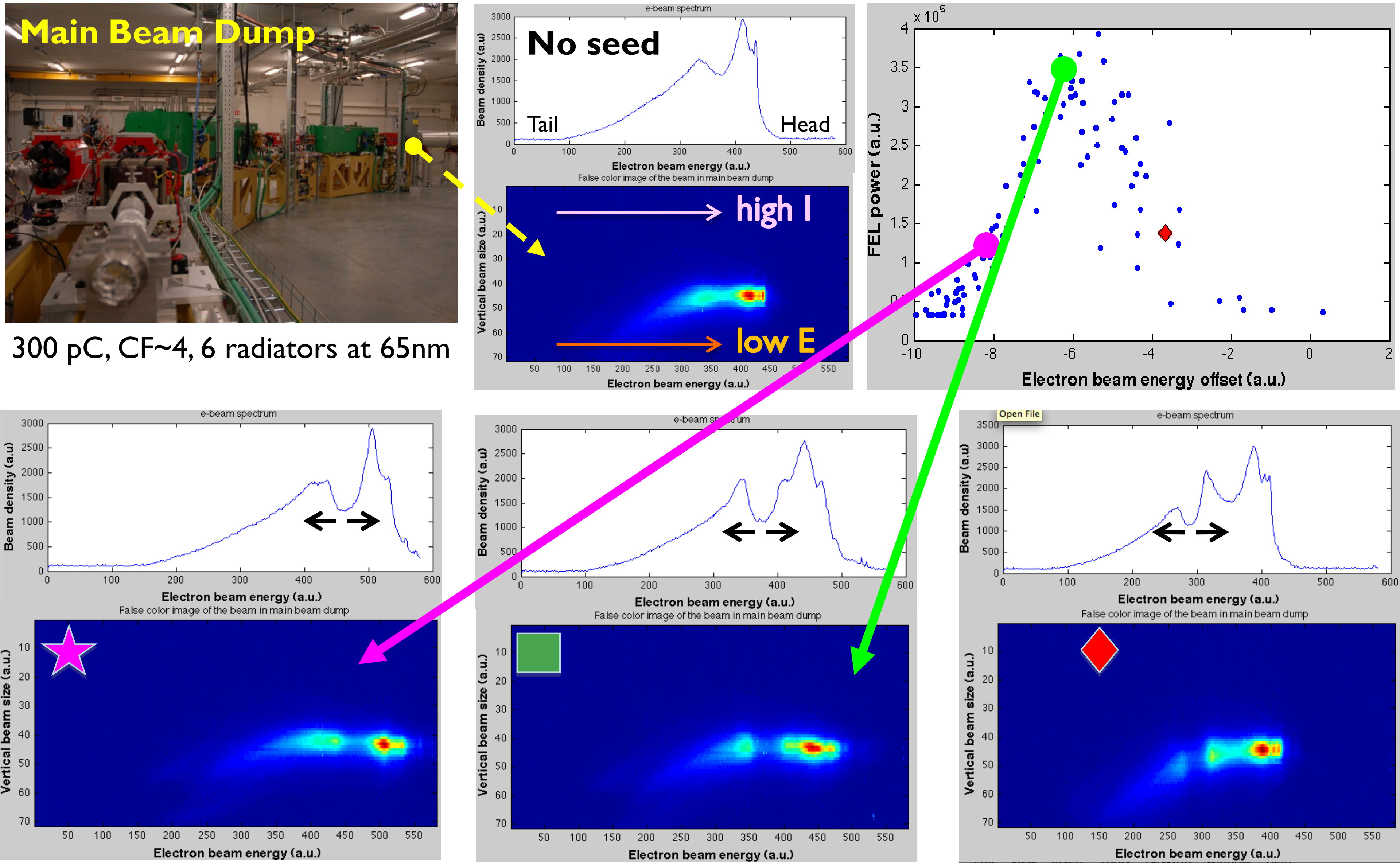
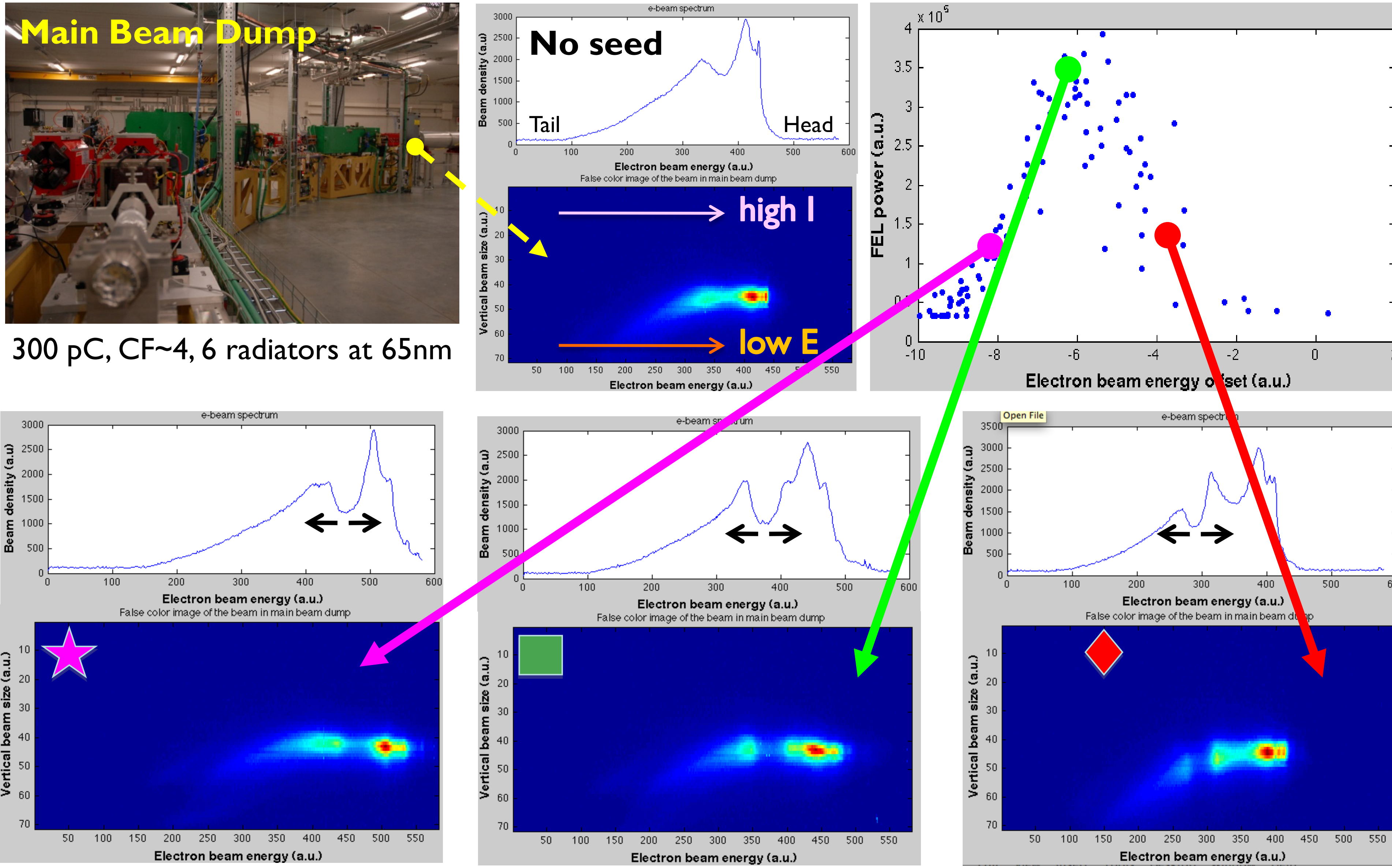
e-Beam Seeding Optimization



300 pC, CF~4, 6 radiators at 65nm

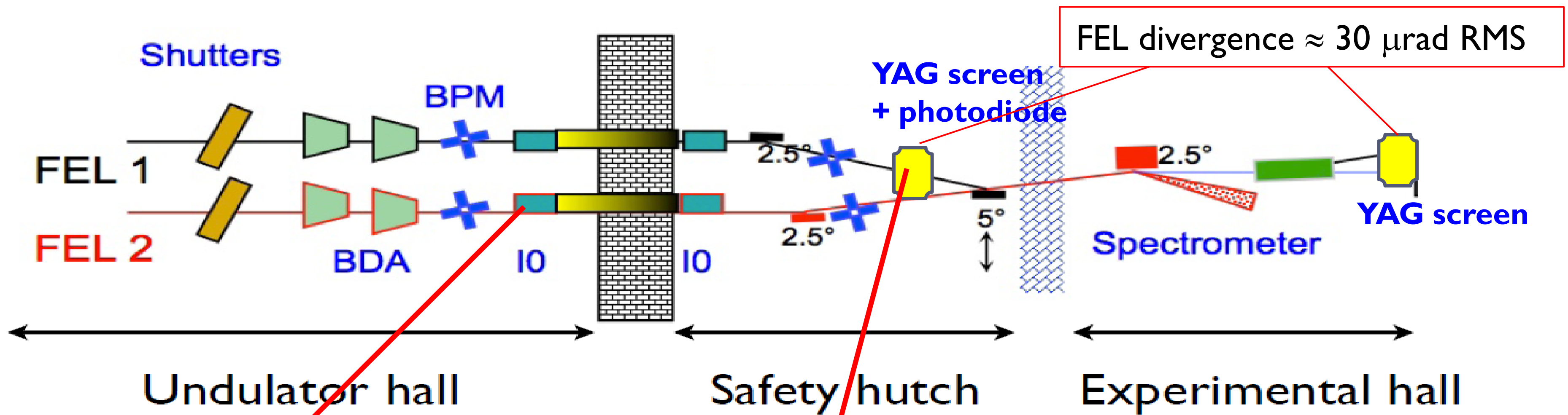
e-Beam Seeding Optimization

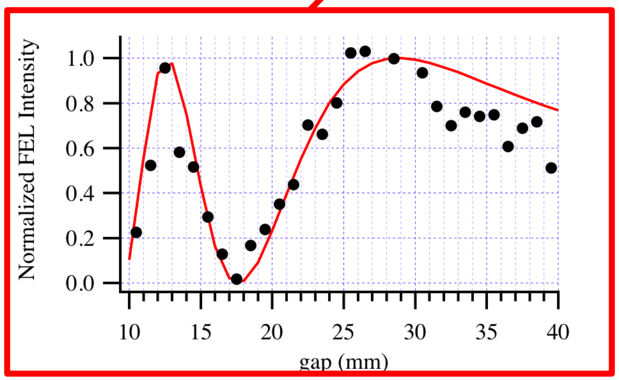


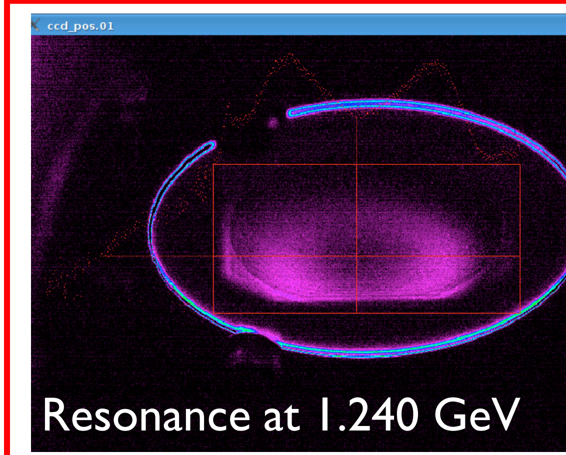
300 pC, CF~4, 6 radiators at 65nm

These data collected by: E. Allaria, S. Spampinati

FEL DIAGNOSTICS



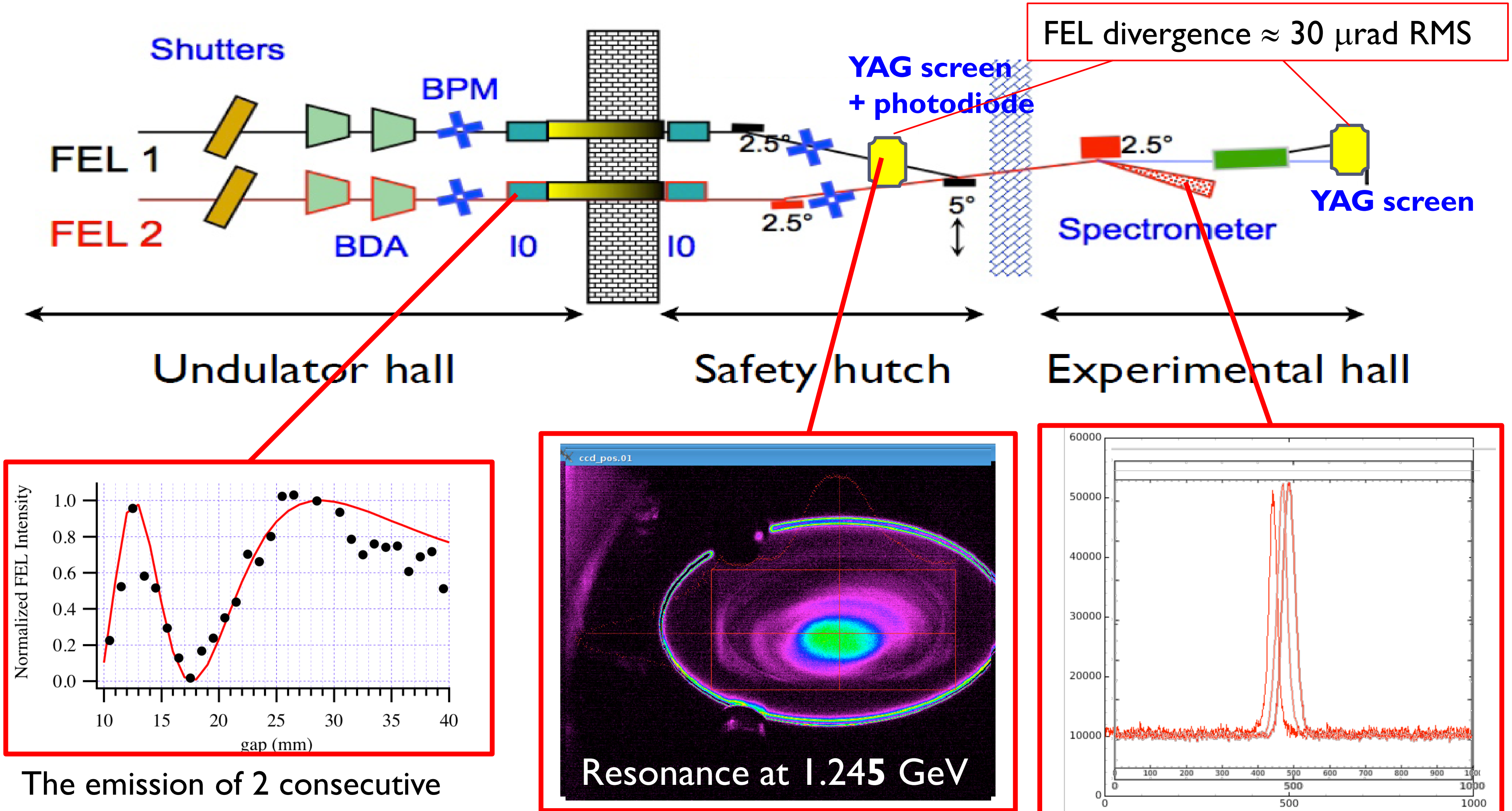




The emission of 2 consecutive radiators tuned at 52 nm *sums coherently* for a proper gap of the phase shifter. PS calibration and model are confirmed.

 These data collected by: E. Allaria, B. Mahieu, W. Fawley, B. Diviacco, M. Musardo, L. Froehlich, C. Svetina, C. Spezzani, M. Danailov, S. Demidovich, C. Callegari, M. Zangrando

FEL DIAGNOSTICS



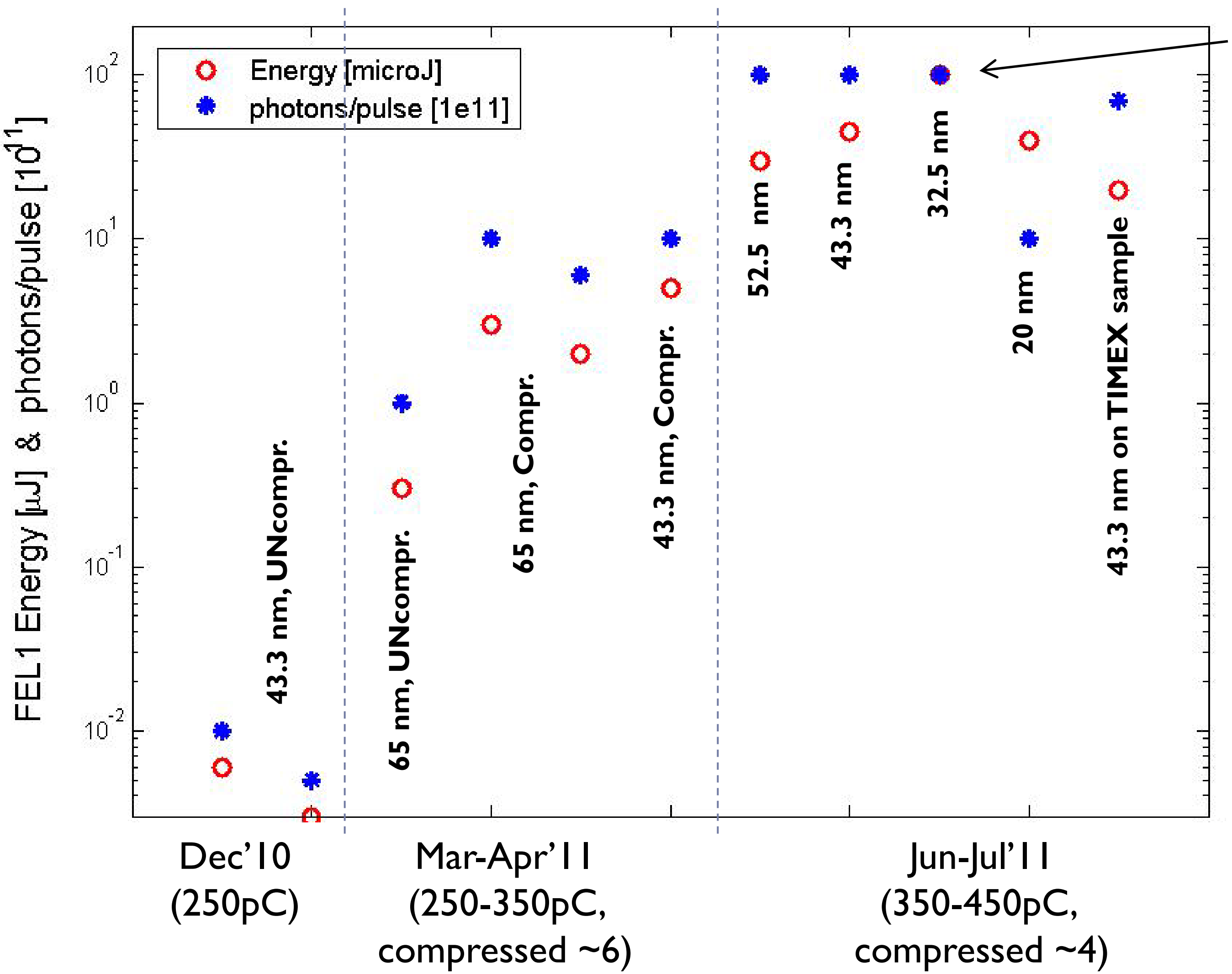
The emission of 2 consecutive radiators tuned at 52 nm *sums coherently* for a proper gap of the phase shifter. PS calibration and model are confirmed.

$\Delta E/E \sim \rho_{FEL} \sim 0.1\%$ does *not* suppress the FEL but *affects the lasing mode* (here 43 nm). Look for the TEM00 mode!

$\Delta\lambda_{seed}/\lambda_{seed}$ =0.4%, undulators gap tuning around 52 nm
→ **on-line tunable λ_{FEL}**

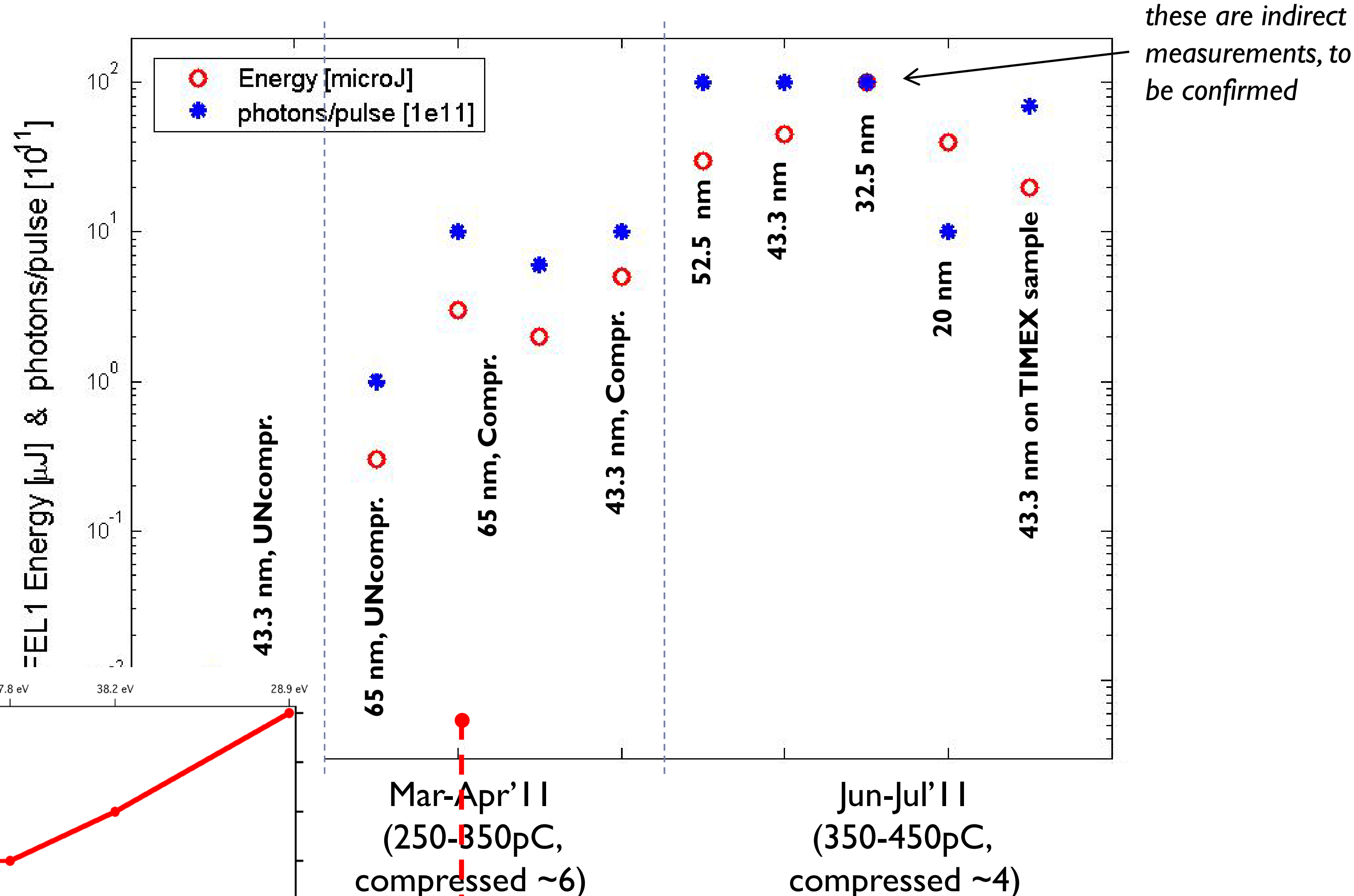
 These data collected by: E. Allaria, B. Mahieu, W. Fawley, B. Diviacco, M. Musardo, L. Froehlich, C. Svetina, C. Spezzani, M. Danailov, S. Demidovich, C. Callegari, M. Zangrando

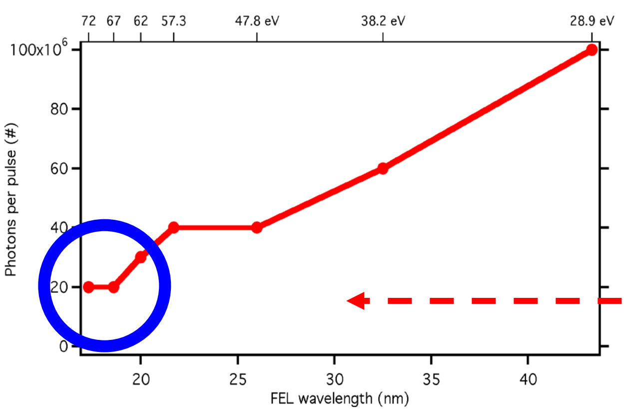
PHOTON FLUX Measurements



these are indirect measurements, to be confirmed

PHOTON FLUX Measurements

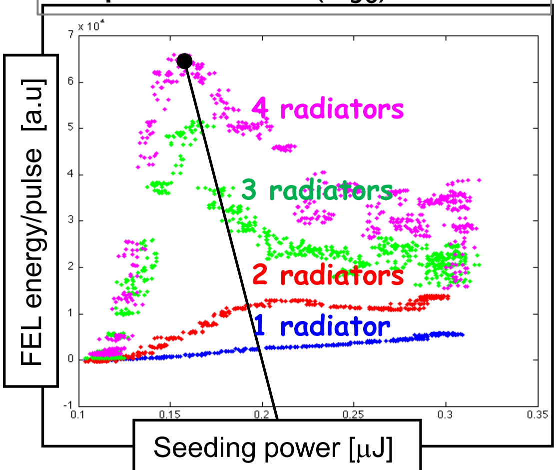


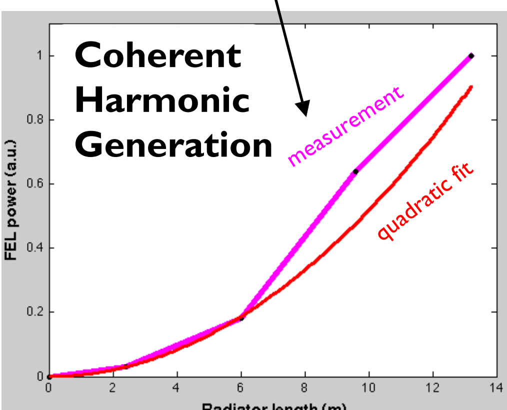


17.3 nm detected at very low intensity (early March'11)

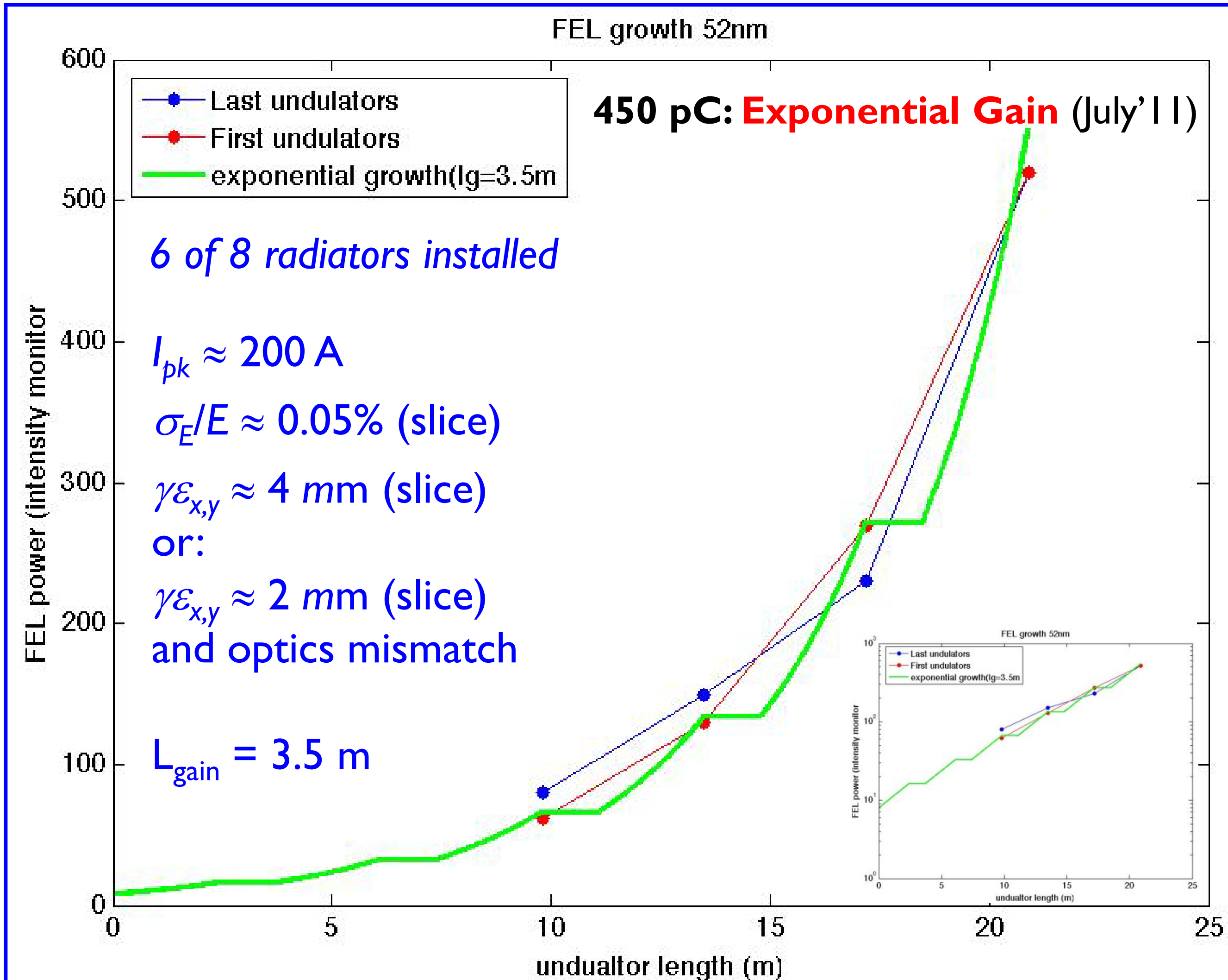
FEL GAIN Measurements

The gain depends on current, seeding power and dispersive line (R_{56})





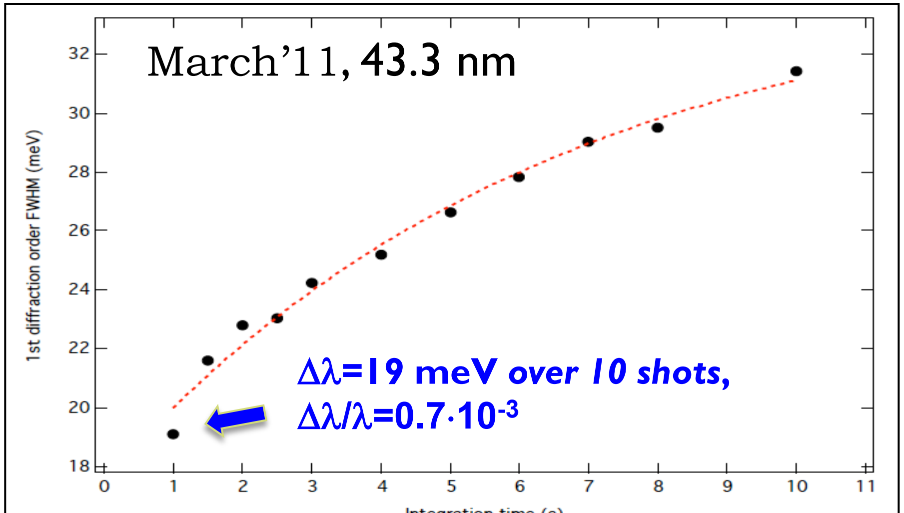
250 pC, no yet beam self-interaction (Dec.'10)

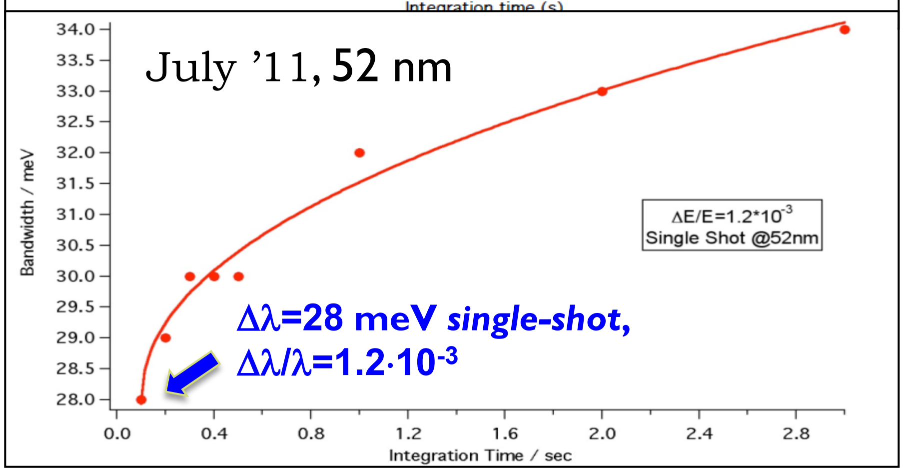


see E. Allaria's talk at FEL Conf. 2011

COHERENCE Measurements

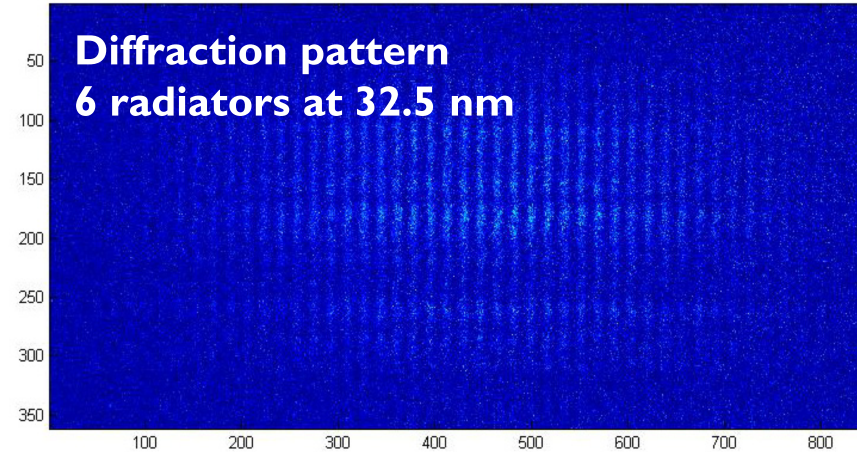
Spectral Bandwidth: ***~1.7 FTL***

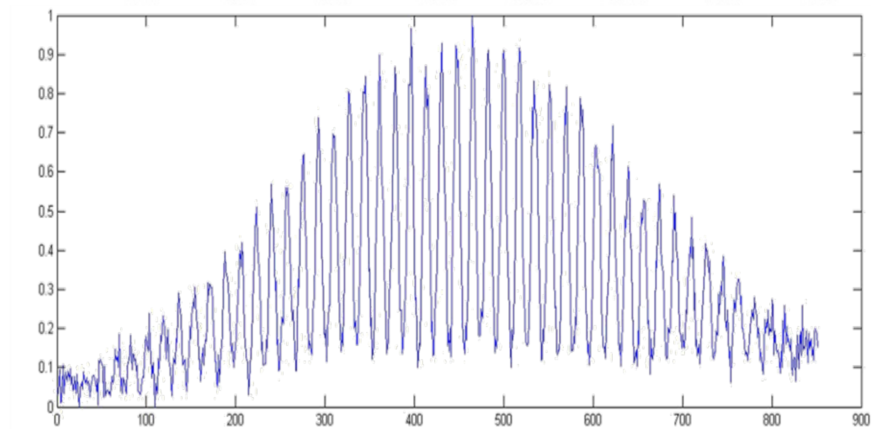




Due to CCD issue, the bw depends on the expos. time. Seed laser: $\Delta\lambda/\lambda$=0.3%, ~150fs, *~1.2 FTL,*

Transverse Coherence: 2-slits experiment



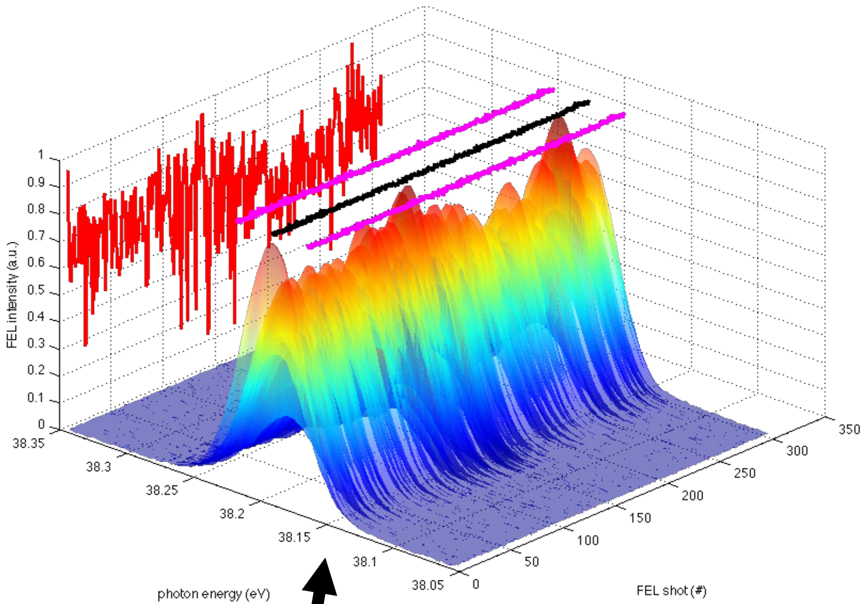


Preliminary analysis indicates good spatial coherence. Further quantitative analysis ongoing…

These data collected by: D. Cocco, M. Zangrando, C. Svetina, F. Parmigiani, S. Spampinati, E. Allaria, E. Ferrari, G. De Ninno, M. Trovo', D. Castronovo, S. Di Mitri

STABILITY

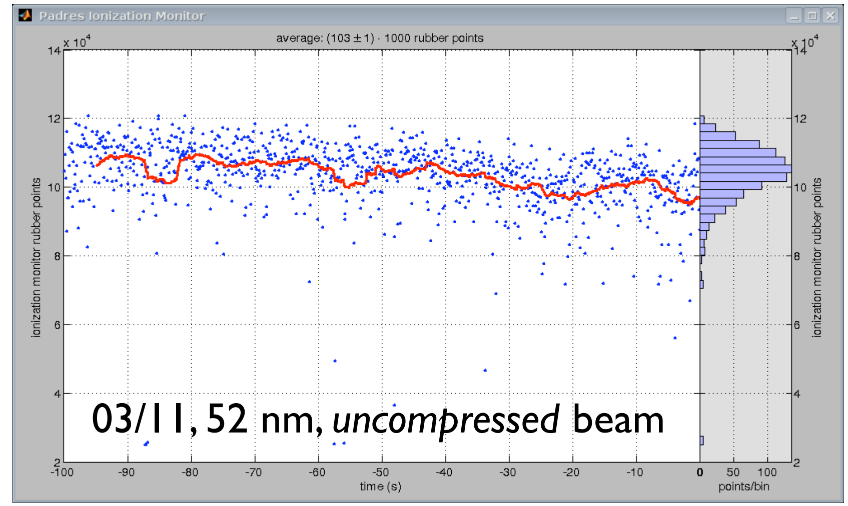
Central Wavelength Stability: **≤ 10^{-4} (RMS)**
Spectral BW Stability: **≤ 3% (RMS)**

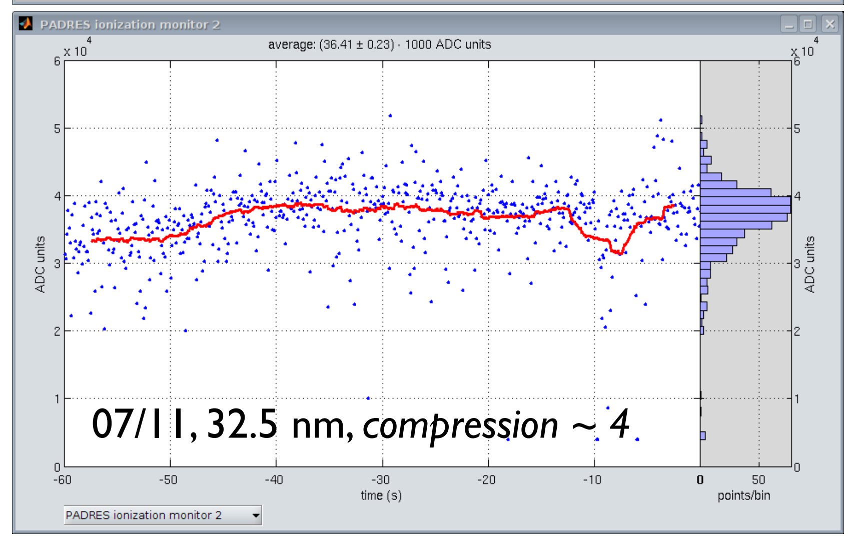


FEL continuously on supplying exp. stations.
The spectral stability remains at *~10^{-4} level for hours.*

After linac improvements, we achieved *10% flux stability* with off-crest acceleration.

Peak Intensity Stability: **≤ 10% (RMS)**





EXP. BEAMLINE Commissioning

- All 3 Beamlines aligned and receiving FEL. Issues remain concerning focusing mirrors.

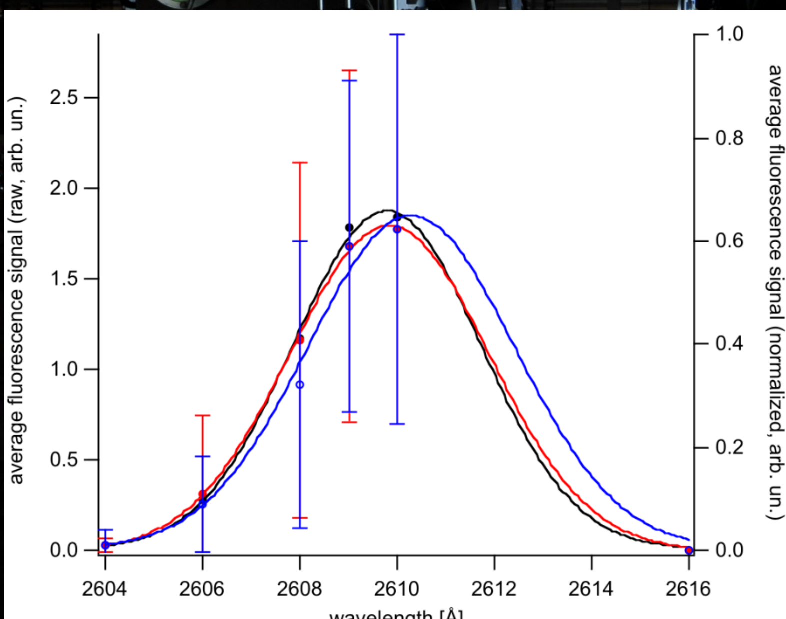
Pictures courtesy of: C. Callegari, C. Spezzani, W. Fawley, P. Craievich, M. Danailov, S. Demidovich, F. Capotondi, E. Pedersoli, R. H. Menk, M. Kiskinova, S. Spampinati, S. Bassanese, E. Allaria

EXP. BEAMLINE Commissioning

- All 3 Beamlines aligned and receiving FEL. Issues remain concerning focusing mirrors.

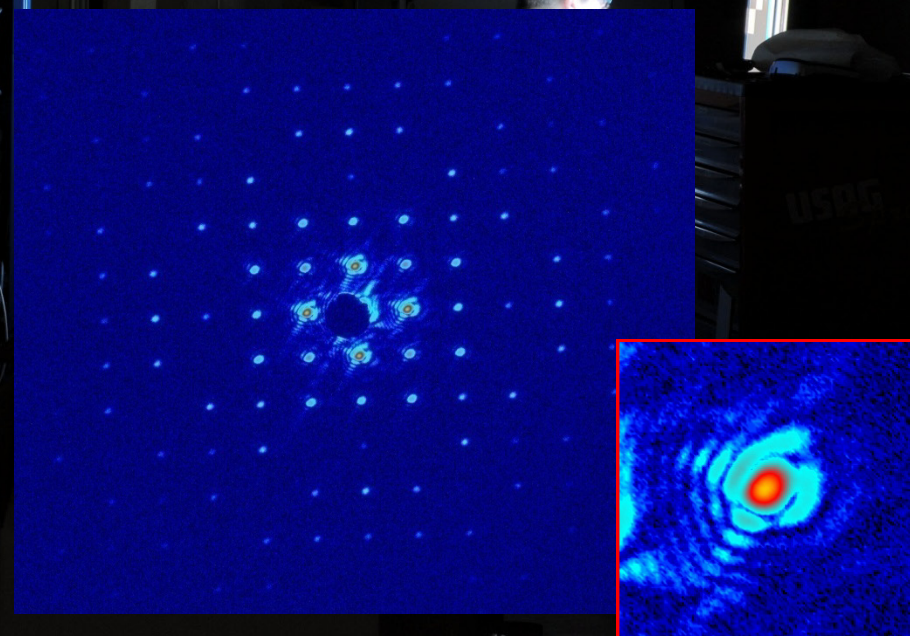
***Low Density Matter* Exp. Station**

λ_{FEL}-tunability to scan resonant absorption line (He 1s-4p transition around 52 nm). The experiment measures the dependence of the fluorescence signal on λ_{FEL}.



***DiProI* Exp. Station**

Coh. diffraction test with a periodic array. Beam passes through a 20 μm pin-hole, attenuated with Al filters. 6 diffraction orders demonstrate good FEL coherence. Interference fringes due to a finite dimension of the sample illuminated area are also visible.



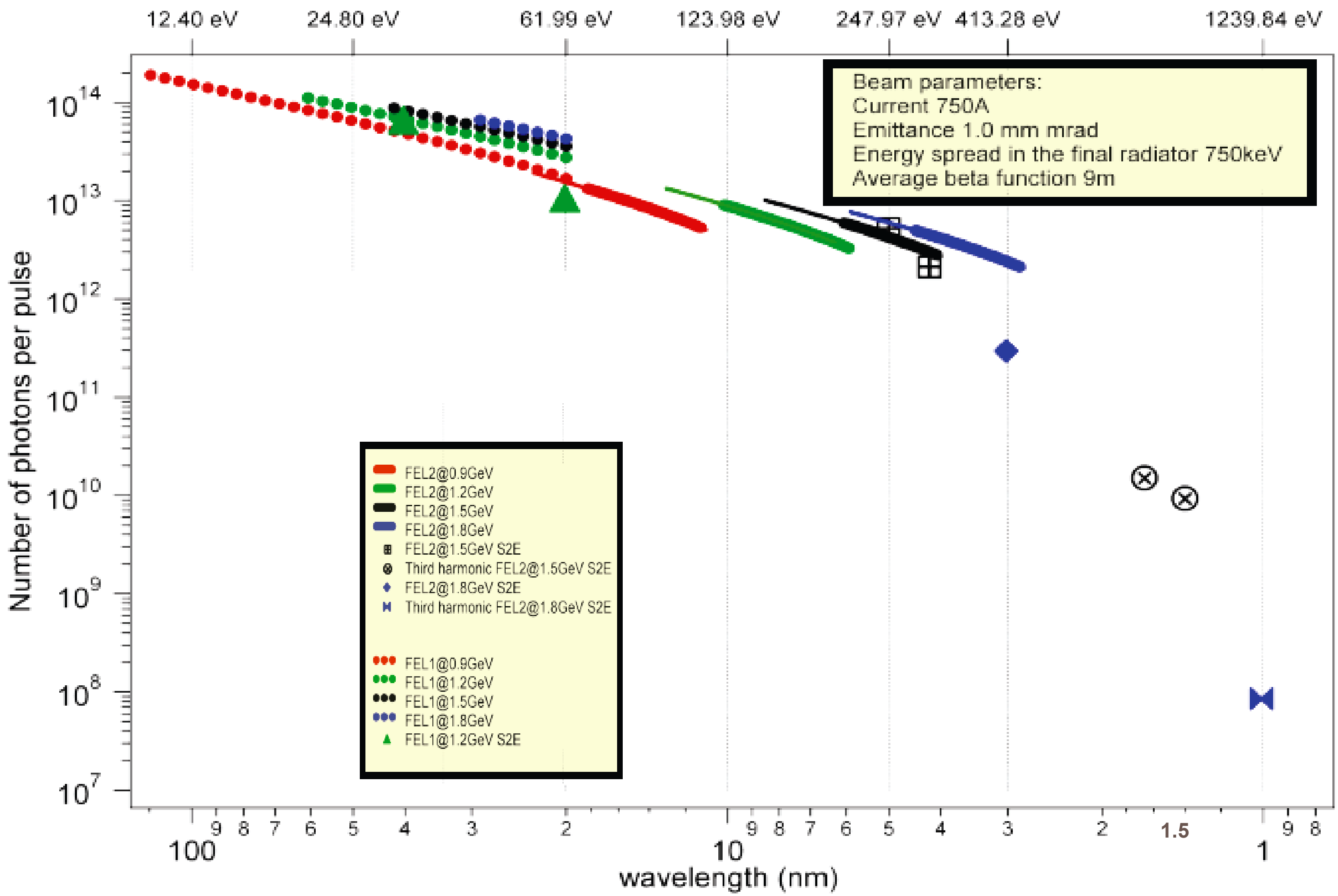
Pictures courtesy of: C. Callegari, C. Spezzani, W. Fawley, P. Craievich, M. Danailov, S. Demidovich, F. Capotondi, E. Pedersoli, R. H. Menk, M. Kiskinova, S. Spampinati, S. Bassanese, E. Allaria

Issues & Lessons Learned

- X-ray spot size too large on the samples (focusing mirrors to be optimized)
- BC2, X-band, Laser Heater, FEL-2, 50 Hz oper. …still require much work
- Many smaller issues require attention (and time):
  - Feedback systems
  - Transverse wake field-induced emittance growth
  - E-beam optics matching into FEL undulators

- Seeded FEL starts up quickly after linac maintenance; stays on for hours
  - *No need to use SASE mode for HGHG optimization.*
- We face a machine still under active development
  - *Commissioning involves compromise between sub-systems testing, FEL optimization and set-in-operation for users.*
- Exponential FEL gain with 40% charge increase and minor machine changes
  - *Linac shows a large acceptance in "beam parameter space".*

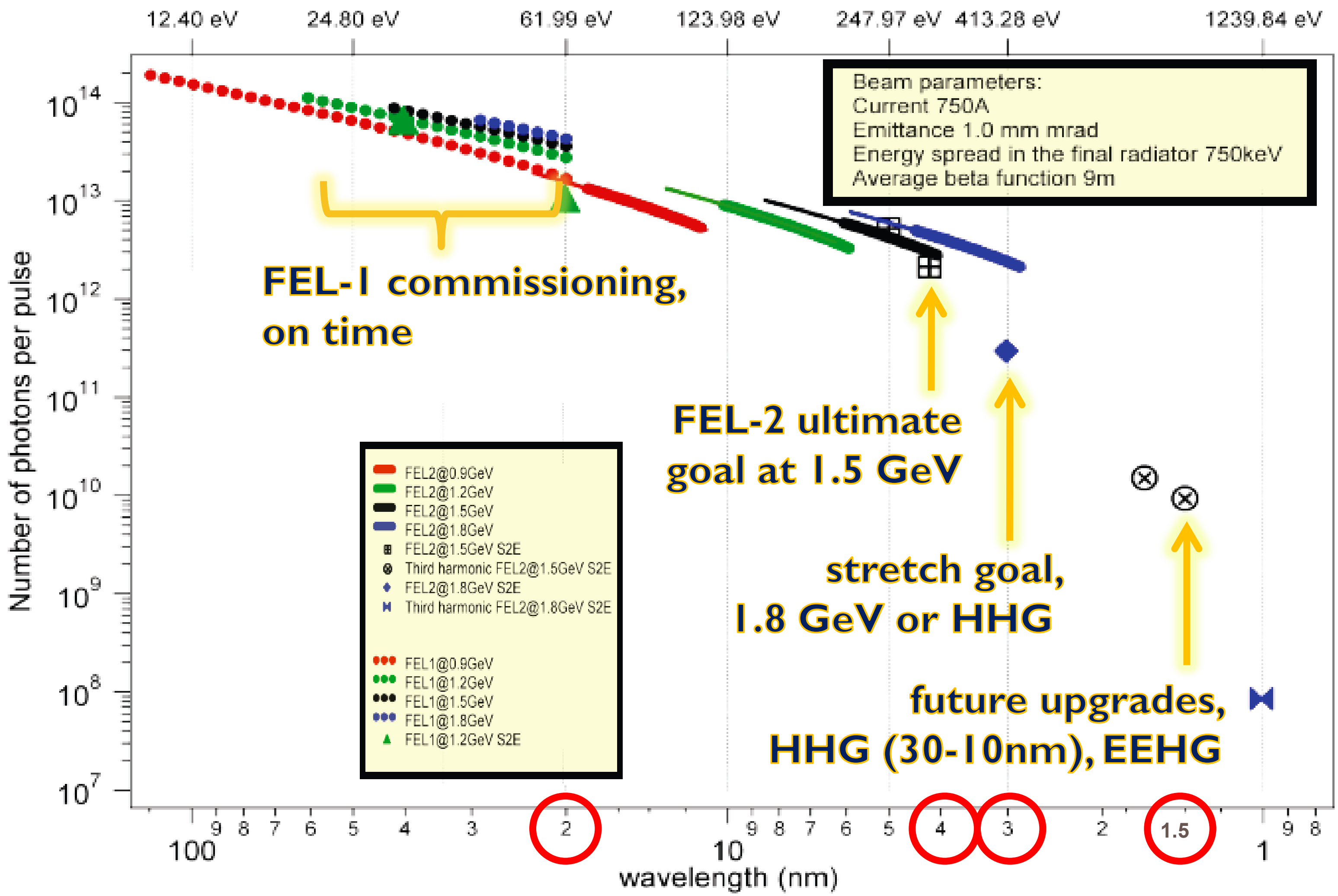
Towards Shorter Wavelengths



Lines predicted using M.Xie formulae for expected FERMI parameters assuming 40fs pulse length
Points Ginger and Genesis simulations for S2E files

Picture courtesy of: S. Milton, E. Allaria, W. Fawley

Towards Shorter Wavelengths



Lines predicted using M.Xie formulae for expected FERMI parameters assuming 40fs pulse length
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ACKNOWLEDGEMENTS

The ***FERMI TEAM*** includes dozens of people who designed, installed, tested and commissioned hundred's of machine systems. They made FERMI being just "short of a miracle", transforming raw **ground...**

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Let me specifically mention and thank here all colleagues who participated in the commissioning shifts and, in particular, that bunch of people that in the last 2 years contributed to the success of FERMI working on most of the shifts:

E. Allaria, R. Appio, L. Badano, R. Bartolini, S. Bassanese, A. Borga, K. Casarin, D. Castronovo, D. Cocco, M. Cornacchia, P. Craievich, M. Dal Forno, R. De Monte, G. De Ninno, P. Delgiusto, S. Di Mitri, B. Diviacco, W. Fawley, E. Ferrari, L. Froehlich, R. Fabris, S. Ferry, G. Gaio, F. Gelmetti, L. Giannessi, E. Karantzoulis, M. Lonza, A. Lutman, B. Mahieu, M. Milloch, M. Musardo, L. Pavlovic, G. Penco, M. Petronio, M. Predonzani, E. Quai, F. Rossi, C. Scafuri, C. Serpico, M. Sjostrom, S. Spampinati, C. Spezzani, C. Svetina, M. Trovo', M. Veronese, A. Vascotto, R. Visintini, M. Zangrando, D. Wang.

Thank you for your attention

Questions are more than welcome!