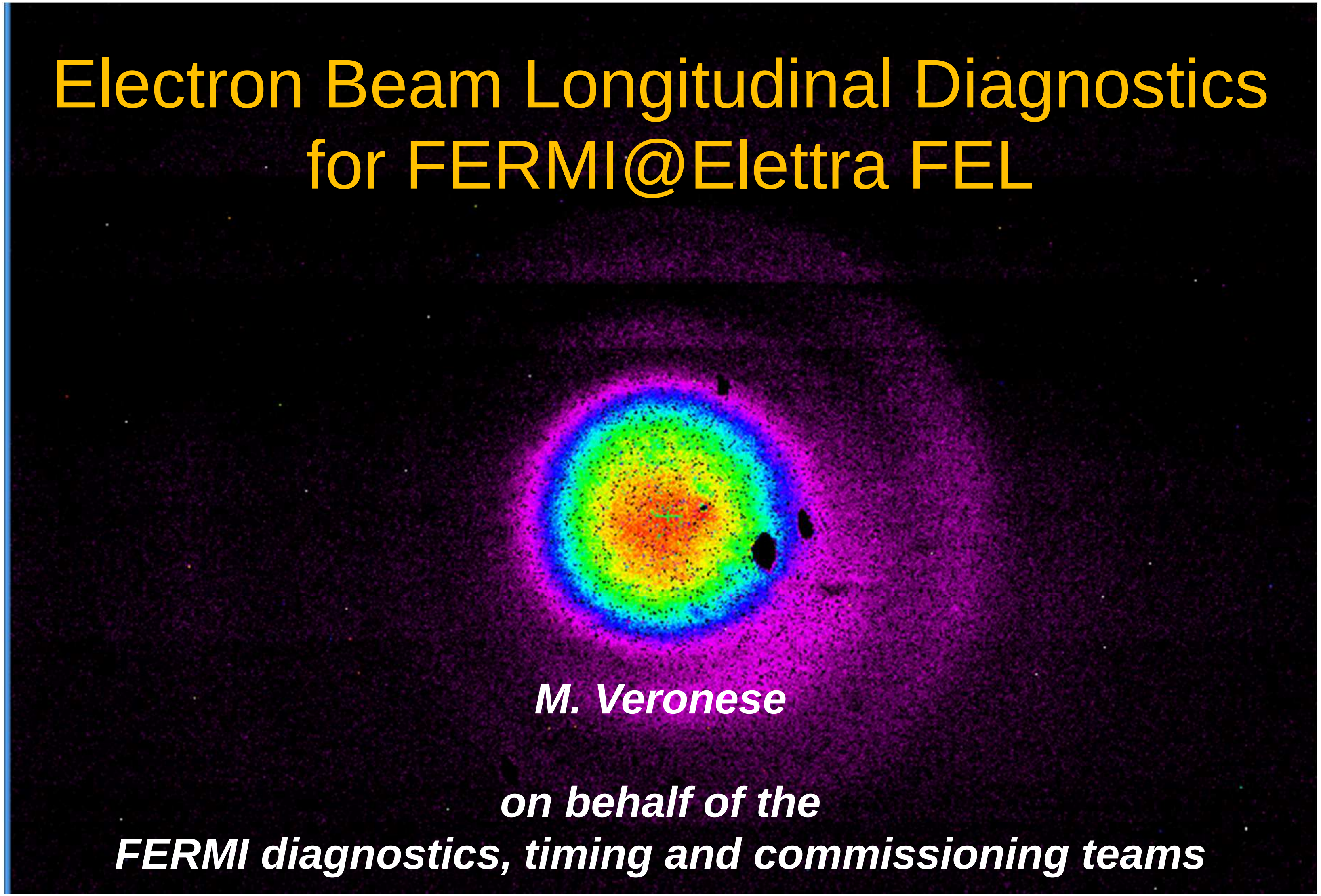
Electron Beam Longitudinal Diagnostics for FERMI@Elettra FEL



M. Veronese

on behalf of the
FERMI diagnostics, timing and commissioning teams

Work partially supported by the Italian Ministry of University and Research under grants FIRB-RBAP045JF2 and FIRB-RBAP06AWK3

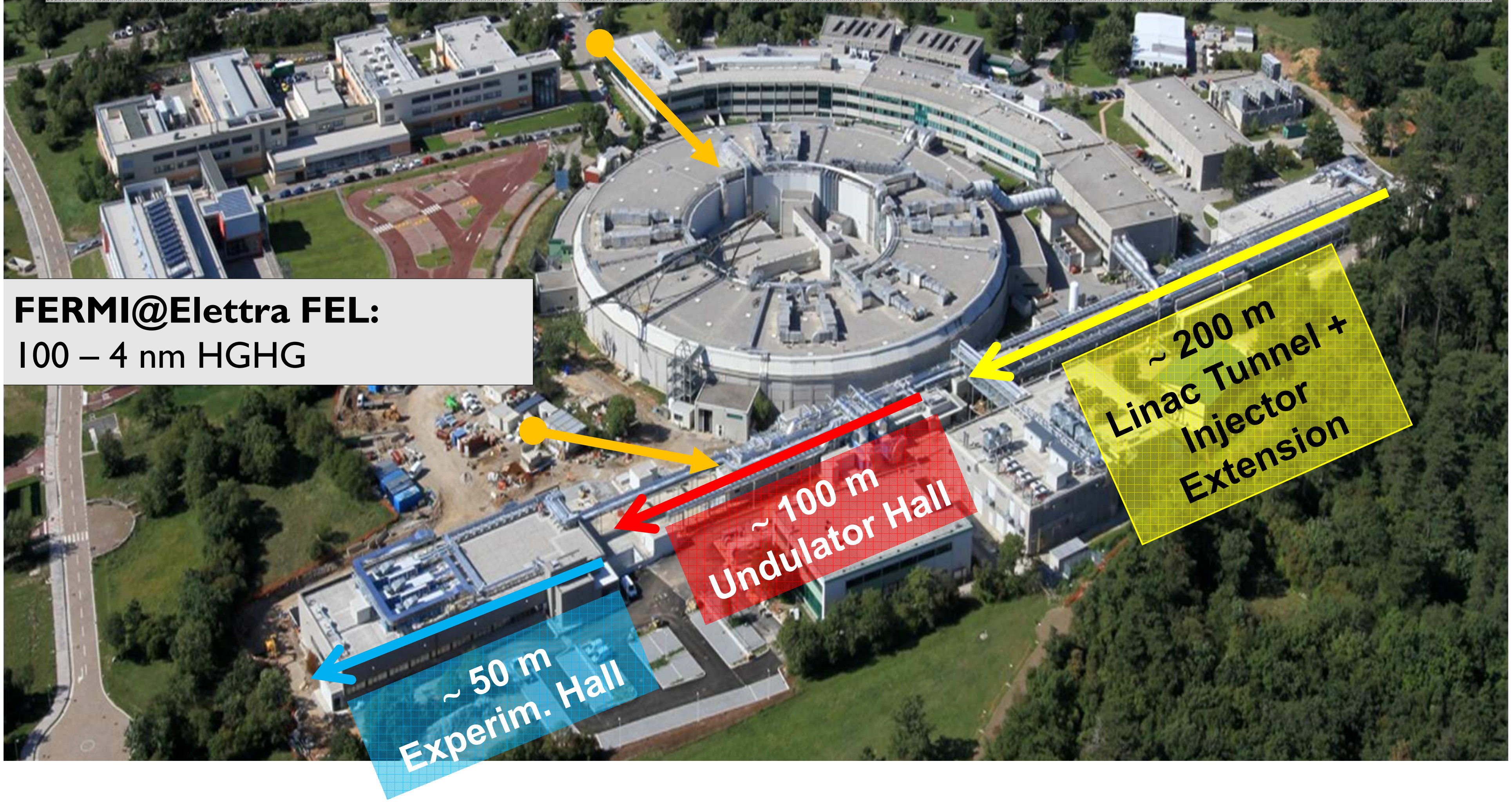
Outline

- FERMI@Elettra FEL project
  - FEL parameters
  - Science goals
- FERMI overview
  - Layout
  - Machine subsections
- Electron beam longitudinal diagnostics
  - Cherenkov + Hamamatsu FESCA200 Streak camera
  - Coherent bunch length monitors (CBLM)
  - Bunch Arrival Monitor (BAM)
  - Low energy RF deflector (LERFD)
  - High Energy RF deflector (HERFD)
  - Electro Optical Sampling stations (EOS)
  - Seed Bunching monitor
- FEL experimental results at FERMI
  - Transverse Coherence, bandwidth properties
  - Energy/pulse, stability, optimization

Sincrotrone Trieste (ST) Facilities

ELETTRA Synchrotron Light Source: up to 2.4 GeV, top-up mode, about 800 proposals per year from 39 countries.

FERMI@Elettra FEL:
100 – 4 nm HGHG



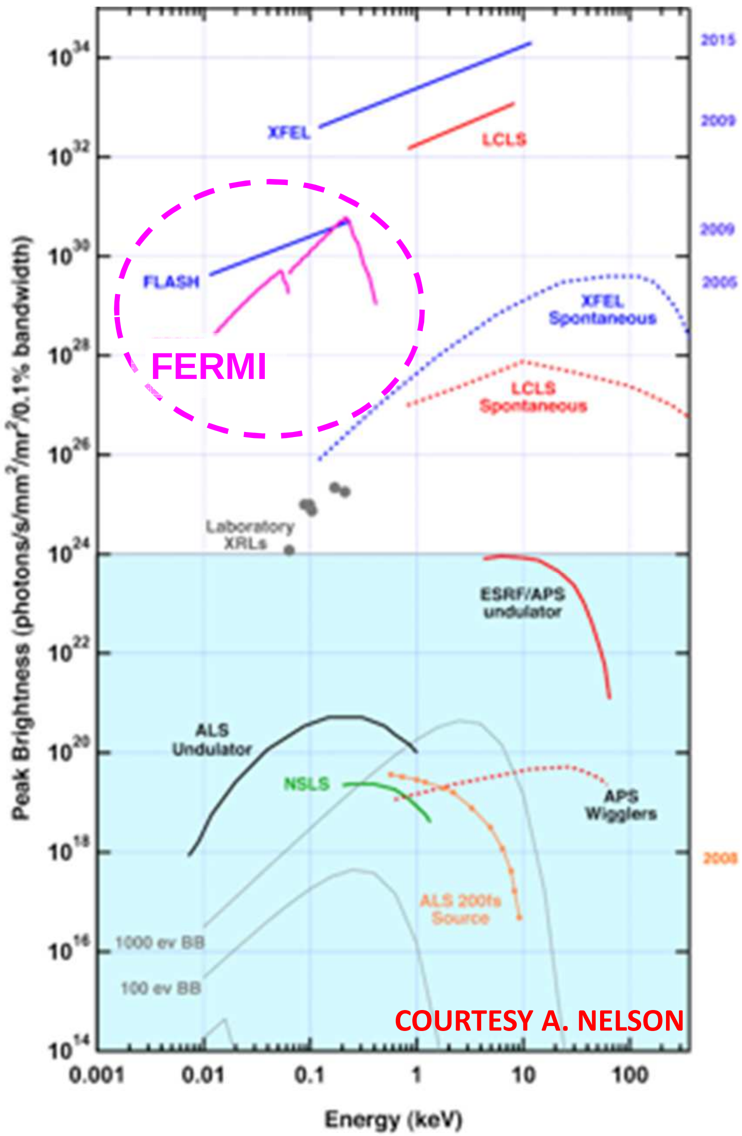
FERMI main features

FERMI@Elettra single-pass FEL user-facility.

Two separate FEL amplifiers will cover the spectral range from 100 nm (12 eV) to 4 nm (310 eV).

The two FEL's will provide users with ~100fs photon pulses with unique characteristics.

❑ high peak power	0.3 – 1 GW's range
❑ short temporal structure	sub-ps to 10 fs time scale
❑ tunable wavelength	APPLE II-type undulators
❑ variable polarization	horizontal/circular/vertical
❑ seeded harmonic cascade	longitud. and transv. coherence



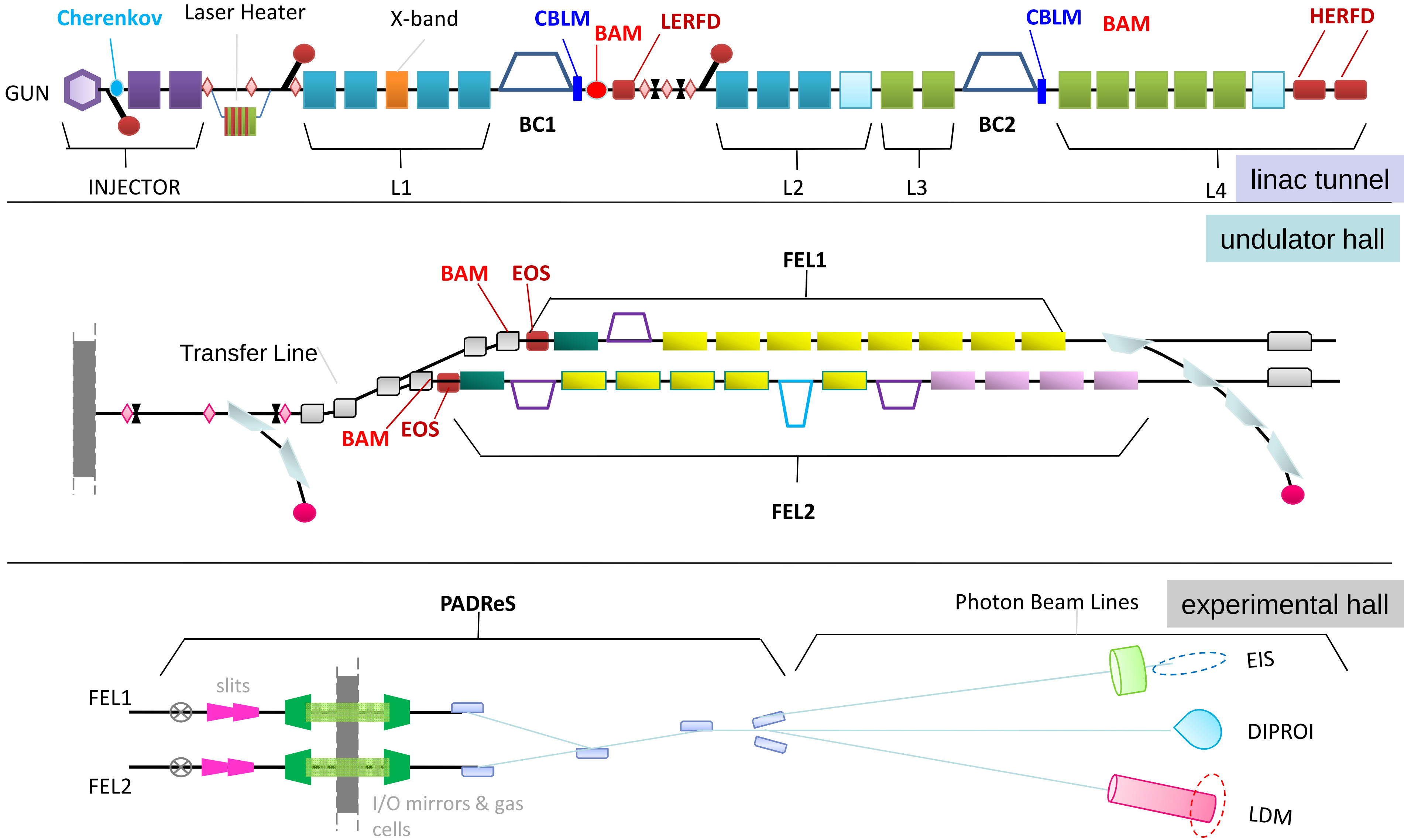
SCIENCE CASE

- **Low Density Matter**
  - 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**
  - Transient Grating Spectroscopy (collective dynamics at the nano-scale) .... *bw Fourier Tansform Limit*
  - Pump & Probe Spectroscopy (meta-stable states of matter) .... *brightness, λ-tunability*

- **Diffraction and Projection Imaging**
- Single-shot & Resonant Transverse Coherent Diffraction Imaging
  - morphology and internal structure at the nm scale
  - chemical and magnetic imaging .... *brightness*

FERMI Layout

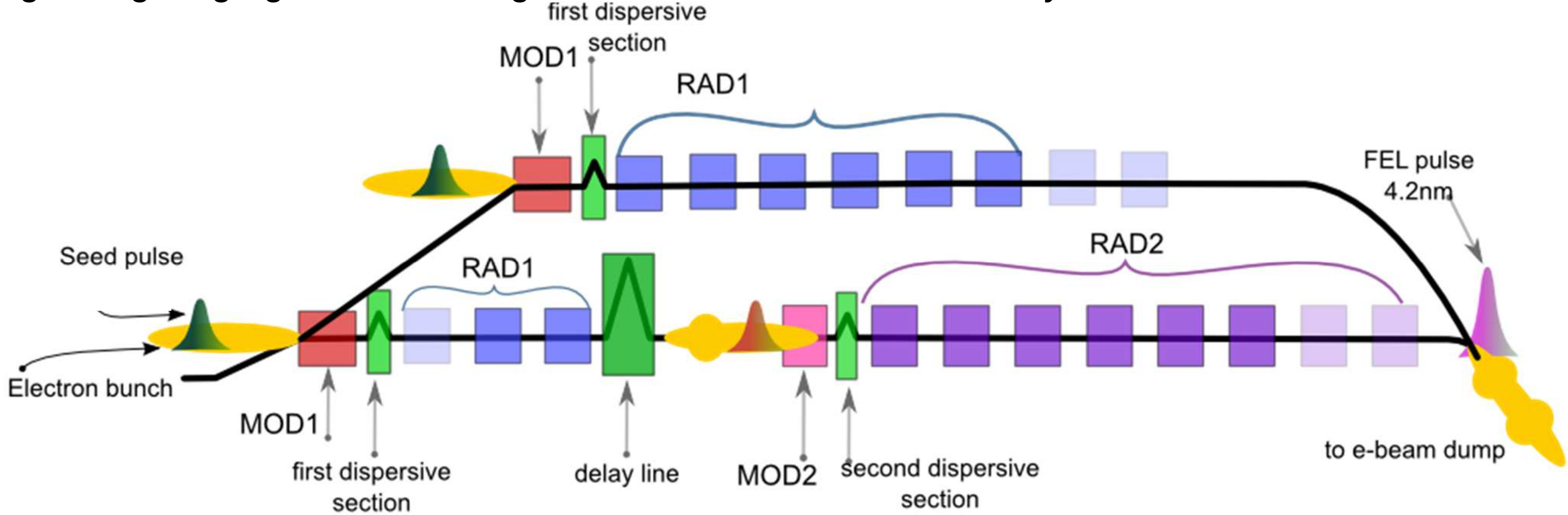


FEL-1 and FEL-2

The two FERMI FELs will cover different spectral regions.

FEL-1: covers the spectral range from ~100 nm down to 20nm.

Single stage high gain harmonic generations scheme initialized by a UV laser.



FEL-2: wavelength range from 20 to ~4 nm.

Starting with seed laser in the UV, will use double cascade high gain harmonic generation. A magnetic electron delay line is installed in order to improve the FEL performance by using the fresh bunch technique. Other FEL configurations are also possible in the future (e.g. EEHG).

PHOTOINJECTOR LASER

Rep rate:	**50 Hz** (initially 10 Hz)
Pulse duration FWHM:	**4-6 ps** and **10 ps range**
Pulse shape:	**flat-top,** ripple **<5% RMS**
Rise-time:	**0.5-1 ps** (10-90%)
Spatial beam profile: flat-top,	~ **1mm (up to 2 mm)** radius (on the cathode)
UV wavelength (third harmonic):	**260-263 nm**
Fundamental Wavelength (for Ti:Sapphire):	**780-790 nm**
Pulse energy in UV (for Cu cathode):	**>0.4mJ**
Timing jitter with respect to the phase reference:	< **0.1 ps RMS**
Energy stability :	**< 4% RMS**
Stability of the beam position on the photocathode :	**< 10% pk-pk**

LINAC

The old S-band Linac structures have been integrated with:

1. RF photo-cathode Gun (SLAC/BNL/UCLA………….ε_n = 0.8 μm **(500pC, 7.5 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 *for phase space linearization*

PC Gun + Injector

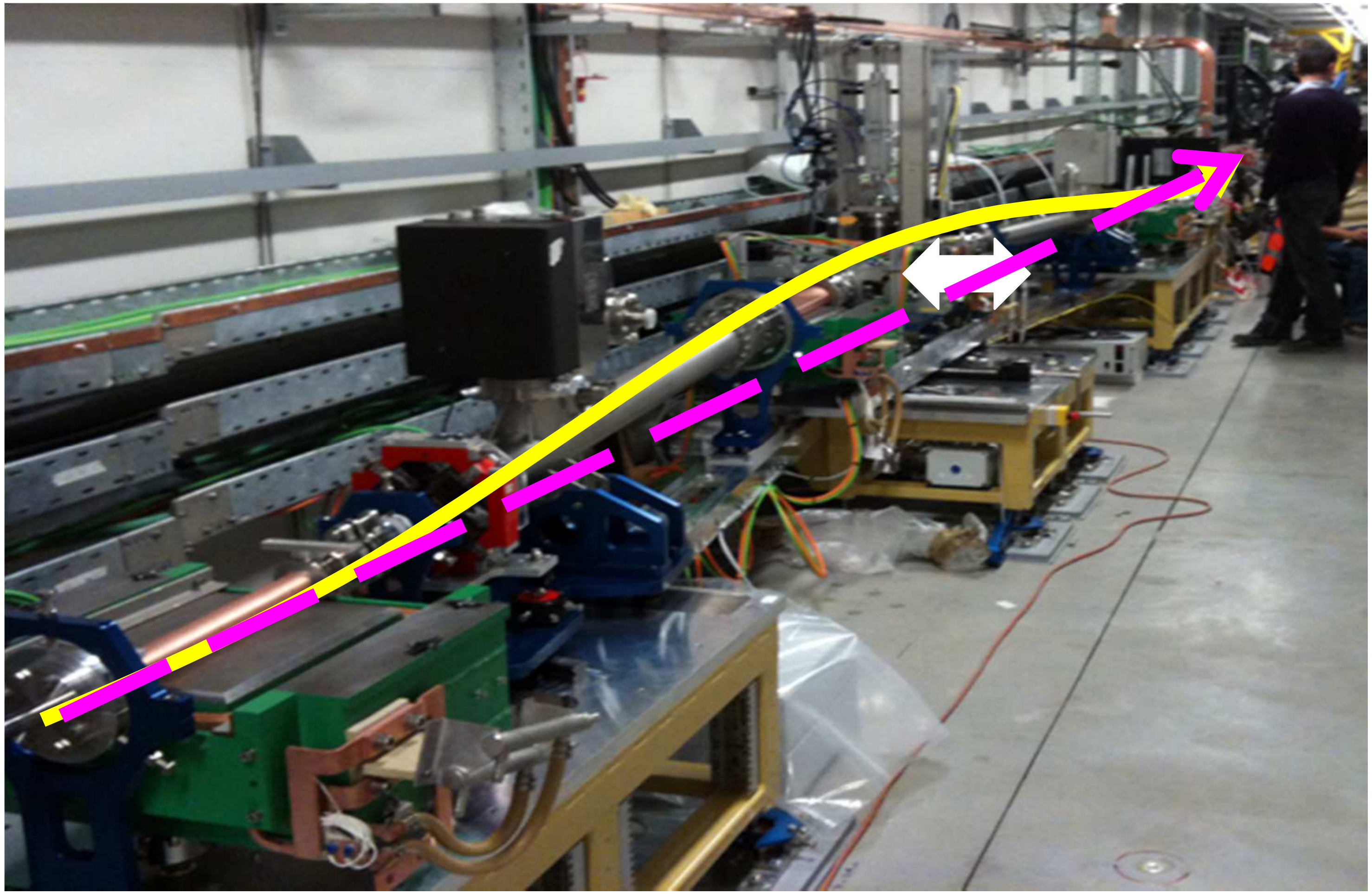
CERN structures

“SLED” structures

M. Danailov (Lasers), M. Trovo’ (Gun), A. Fabris (S-band), P. Craievich, G. Penco

MAGNETIC COMPRESSORs

Two movable magnetic chicanes for one- or two-stage bunch length compression have been developed *in house* on improved LCLS desig **compression factor 5-6 used for FEL**



D. Zangrando, R. Fabris, D. Castronovo, G. Pangon, S. Di Mitri

TRANSFER LINE

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

"Spreader"

Main Beam Dump

E. Karantzoulis S. Ferry, I. Cudin, M. Tudor, S. Di Mitri

FERMI SEED LASER

STATUS:

Fixed wavelength configuration

Wavelength : 260-262 nm (manually tunable)

UV peak power ≥ 400 MW

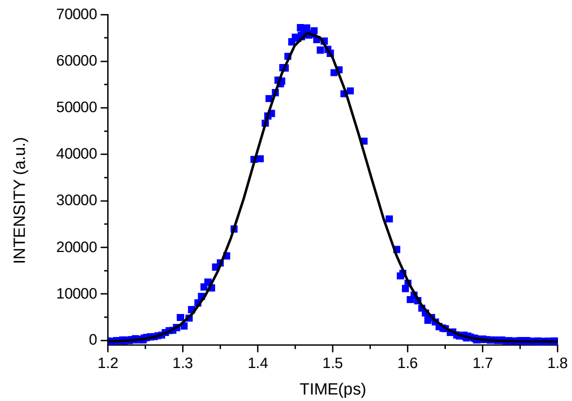
Pulse duration (FWHM): 150-220 fs range

Energy/pulse >80 μJ

Beam dimension (1/e^2 intensity):

0.8 or 1 mm 1/e2 diameter at virtual undulator

Timing jitter with respect to the phase reference: < 100 fs RMS



Tunable wavelength configuration

Wavelength : 235-260 nm

UV peak power ≥ 100 MW (>80 MW at 235 nm)

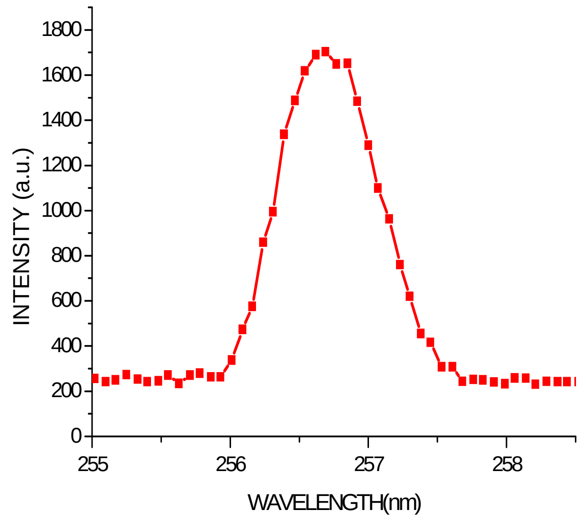
Pulse duration (FWHM): 180-200 fs range

Energy per pulse >20 μJ (>15 μJ at 235 nm)

Beam dimension (1/e^2 intensity):

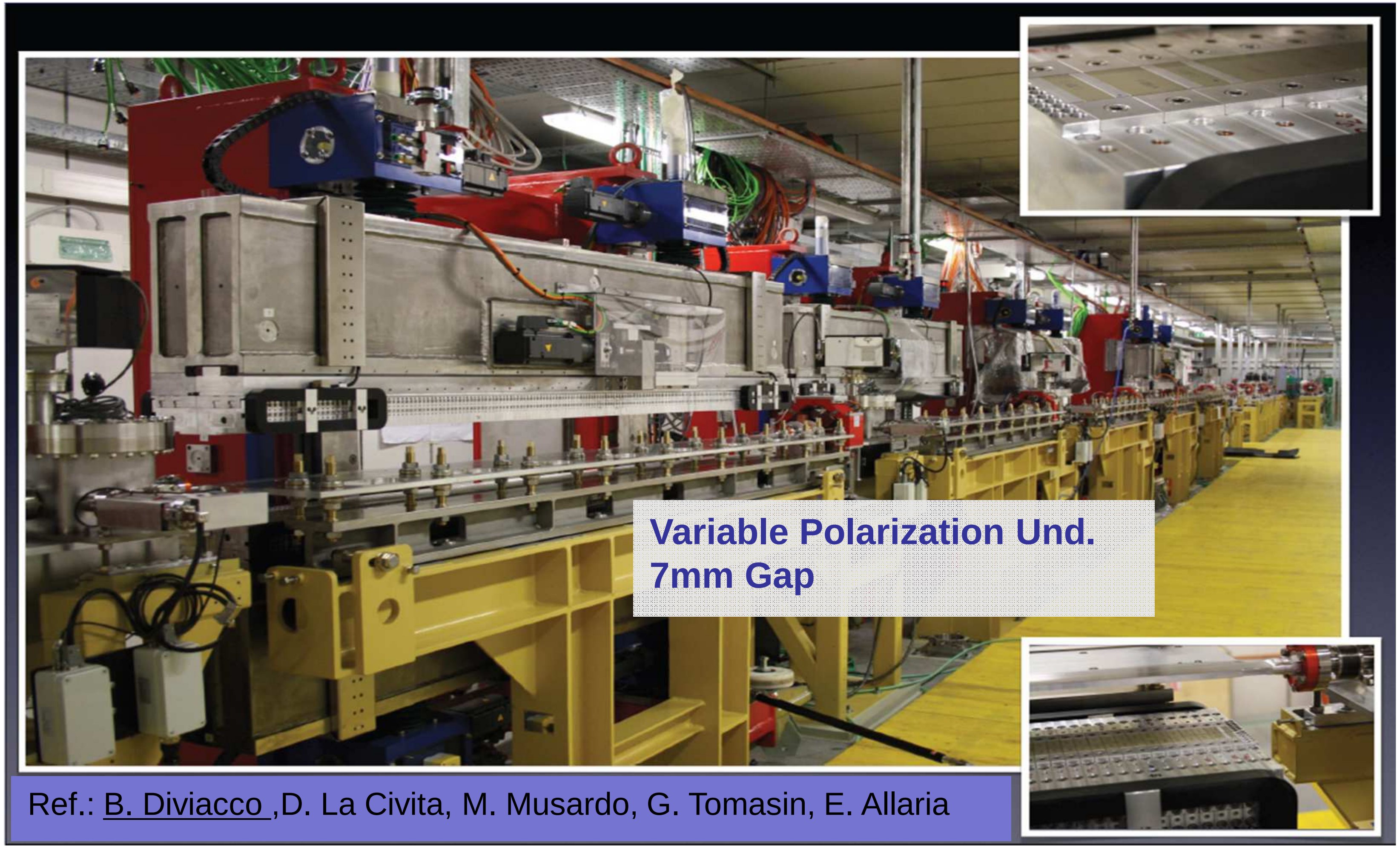
1 mm 1/e^2 diameter at virtual undulator

Timing jitter with respect to the phase reference: <100 fs RMS



UNDULATORS

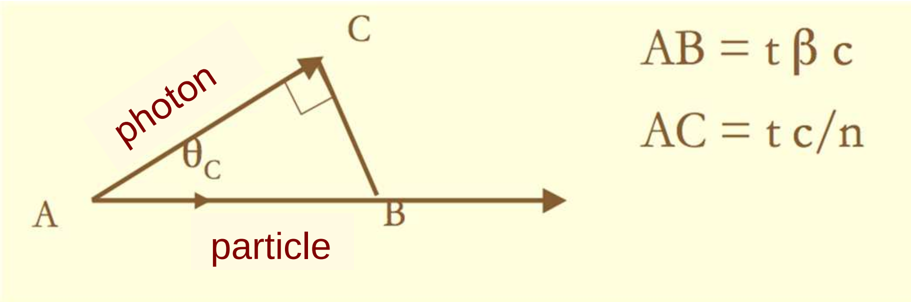
Variable gap, planar and APPLE-II type undulators. In house design, manufacturing by KYMA (ST spin-off)……………………….**variable polarization** & **λ-tuning provided to users**



Ref.: B. Diviacco ,D. La Civita, M. Musardo, G. Tomasin, E. Allaria

Longitudinal Phase Space at low energy → Cherenkov

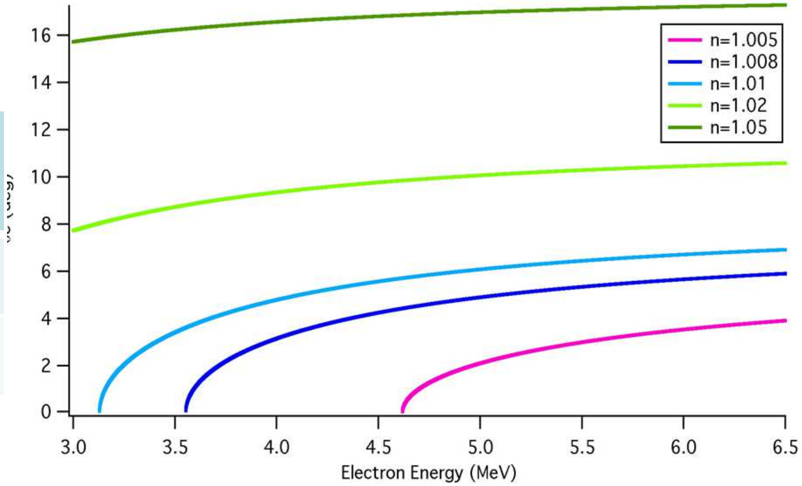
- At low energy (5 MeV) Cherenkov radiation is ~5000 more intense than OTR
- Time resolution is related to the index of refraction (the lower the better)
- Only aerogels can reach refraction index value of n=1.008



Budker Institute of Nuclear Physics, *Novosibirsk*,

→ $\cos(\theta_C) = 1/\beta \cdot n$

100 pC, L= 5 mm.	**Straight Section**	**Dispersive Section**
4 MeV (worst)	$3.6 \cdot 10^{7}$	$3.6 \cdot 10^{6}$
6 MeV (best)	$7.5 \cdot 10^{7}$	$4.6 \cdot 10^{6}$

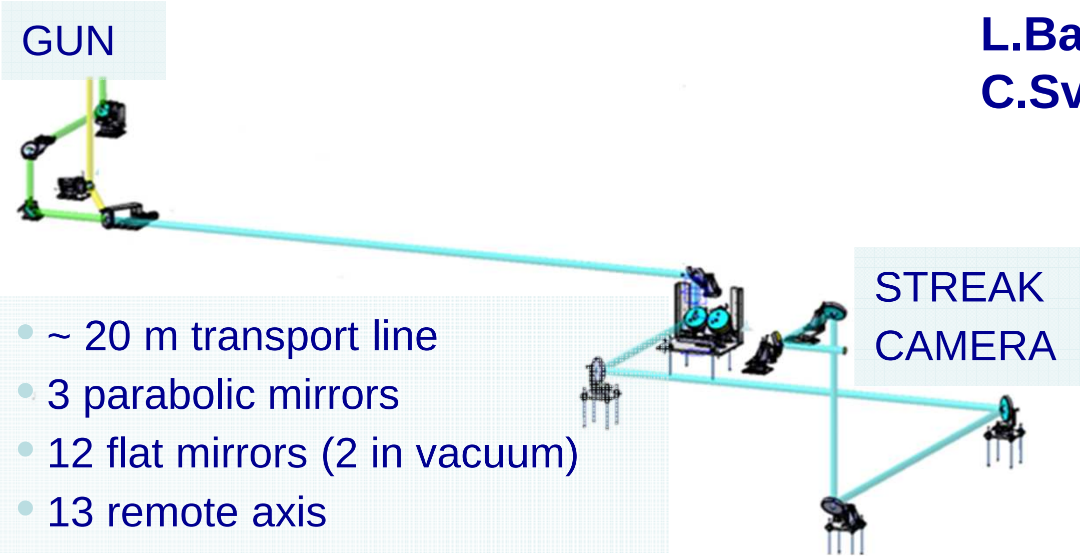


100 pC, L= 5 mm.
Optimized at 400-440 nm for maximum streak camera sensitivity. Limited bandwidth minimize chromatic effects

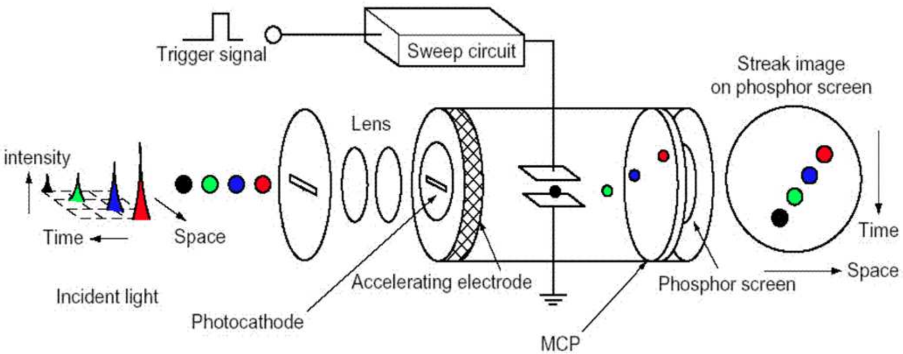
L.Badano

Transport line and Streak Camera

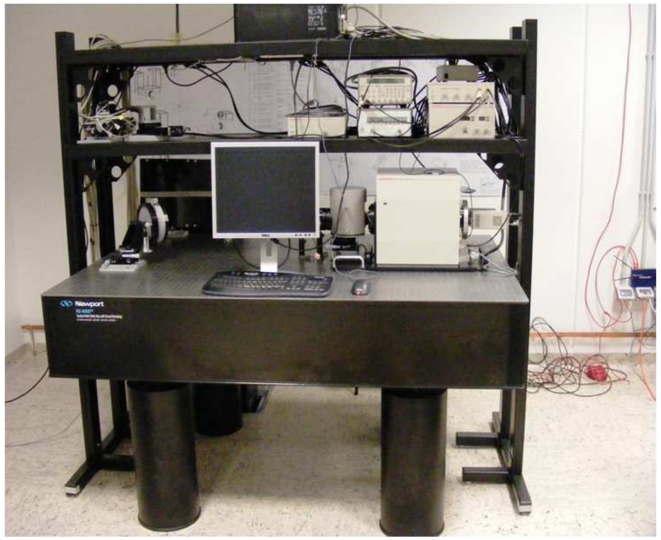
L.Badano, F.Cianciosi, C.Svetina, C.Spezzani



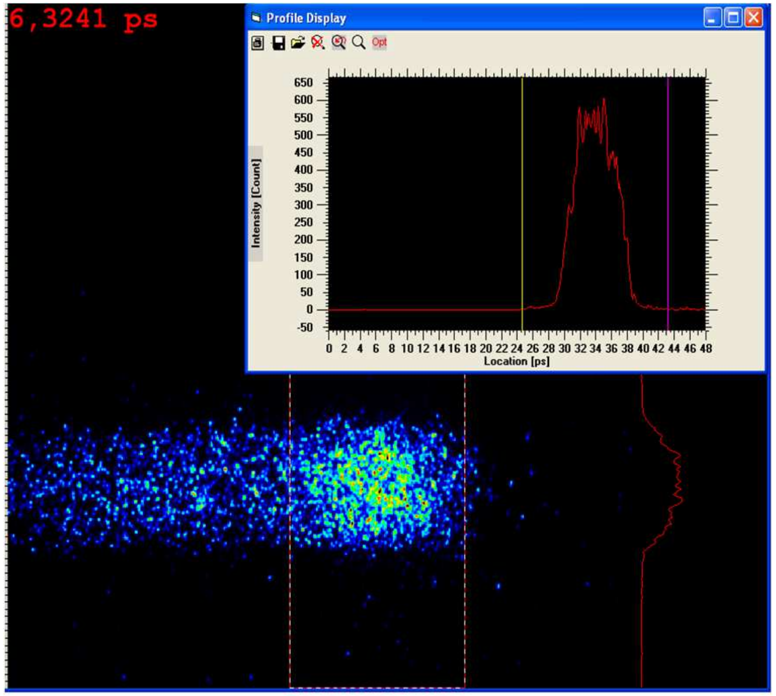
- ~ 20 m transport line
- 3 parabolic mirrors
- 12 flat mirrors (2 in vacuum)
- 13 remote axis



Hamamatsu Fesca200:
time resolution less than 200fs FWHM at single shot operation

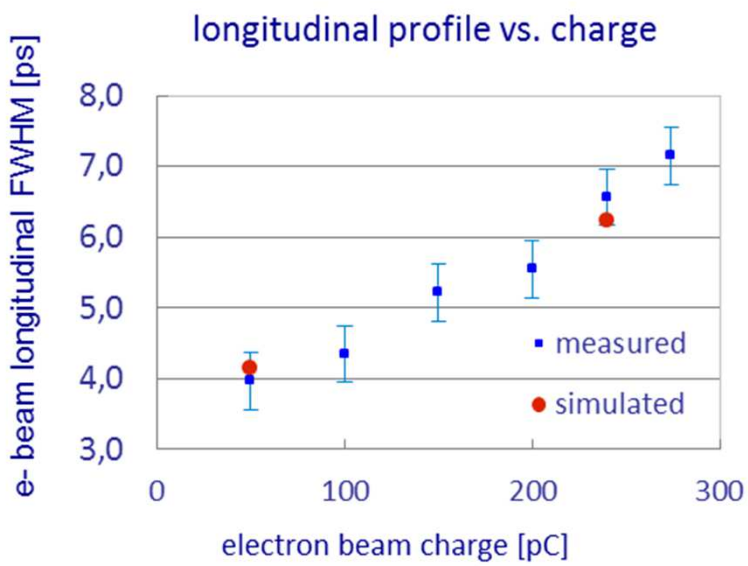


Longitudinal Profile Measurement



single shot acquisition.
4.6 MeV, 240 pC electron beam

Bunch length vs charge at gun exit.



Flat top laser profile, 4 ps FWHM
Good agreement: simulation vs exp. data

L.Badano, M.Trovo'

Coherent Bunch Length Monitor

GOALs: monitor bunch length downstream of Bunch Compressors

- **ONLINE / NON DESTRUCTIVE**
- **USABLE BY FEEDBACKS** → for FEL output intensity stabilization

Coherent radiation: wavelength λ of radiation ~ bunch length

$$\frac{d^2W}{df\,d\Omega} = \left.\frac{d^2W}{df\,d\Omega}\right|_{1e^-} (N + N(N-1)|F(f)|^2)$$

Power measurement: power increases as the bunch gets shorter.

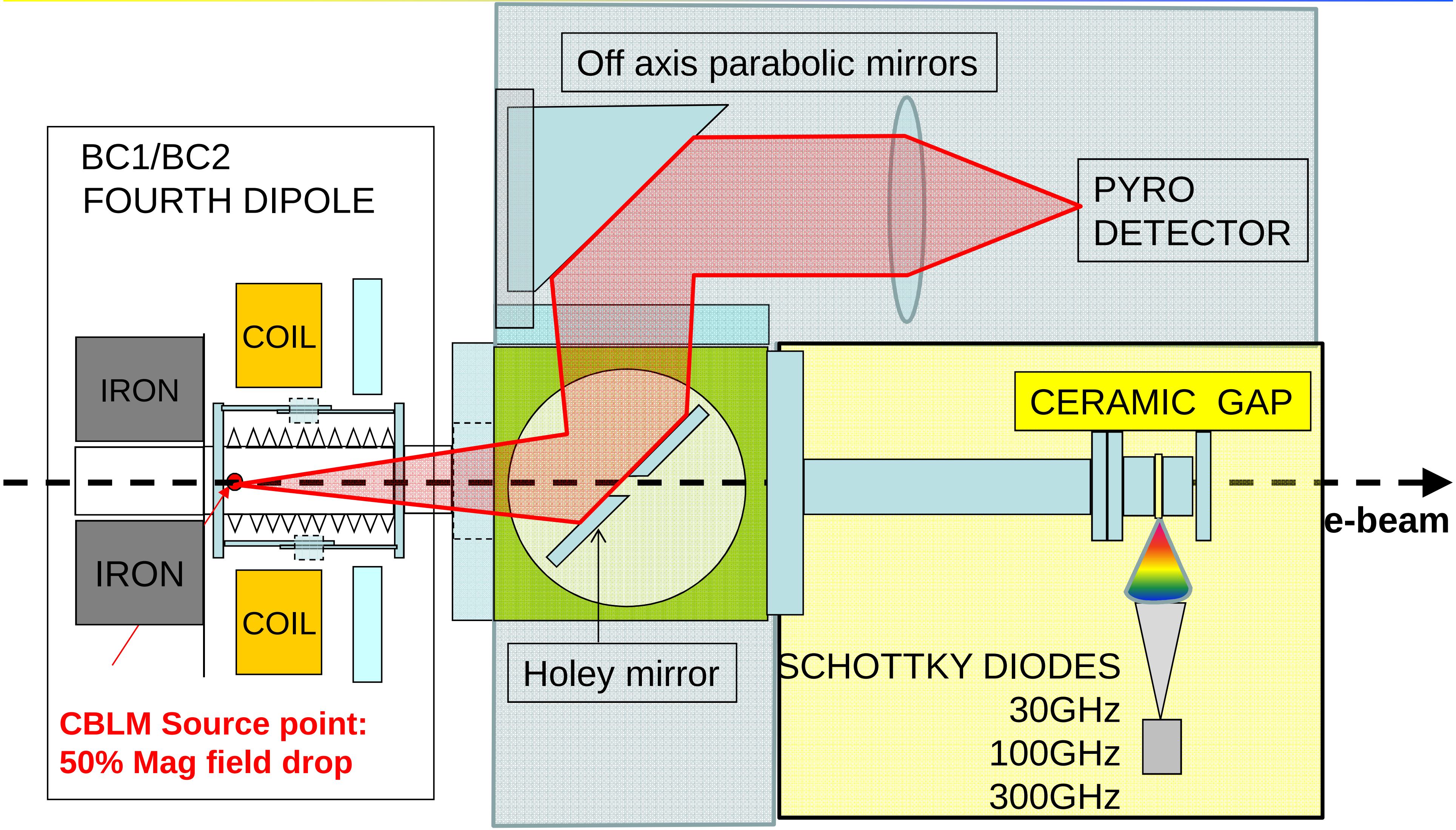
Spectral range: from mm-waves to THz

Bunch Length (FWHM-ps)	Coherent onset freq (THz)
5	**0.11**
0.17	**3.25**

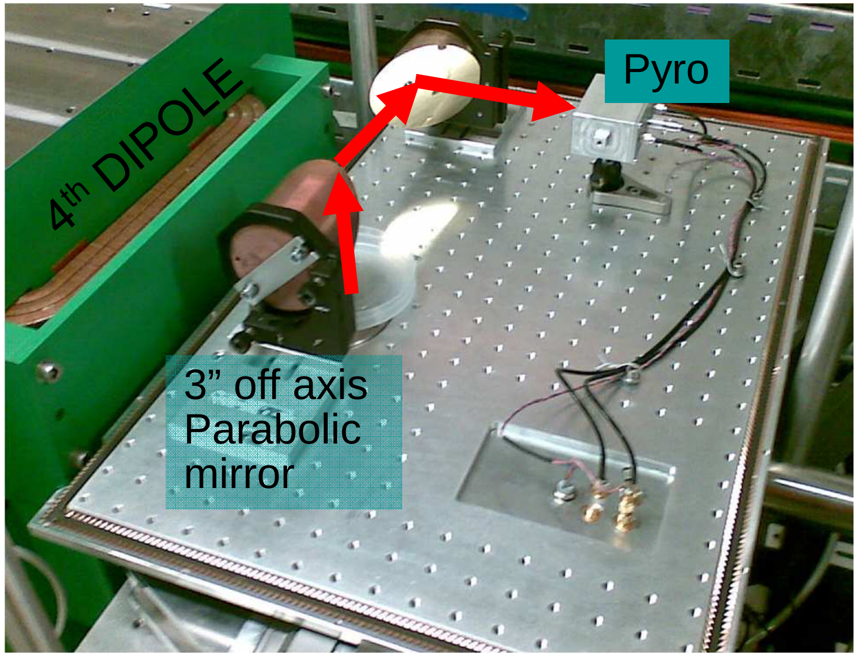
Coherent Radiation Sources for FERMI BLM:

- Coherent Synchrotron/Edge Radiation
- Coherent Diffraction Radiation from a ceramic GAP

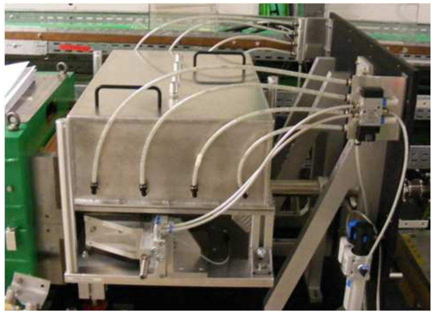
CBLM layout

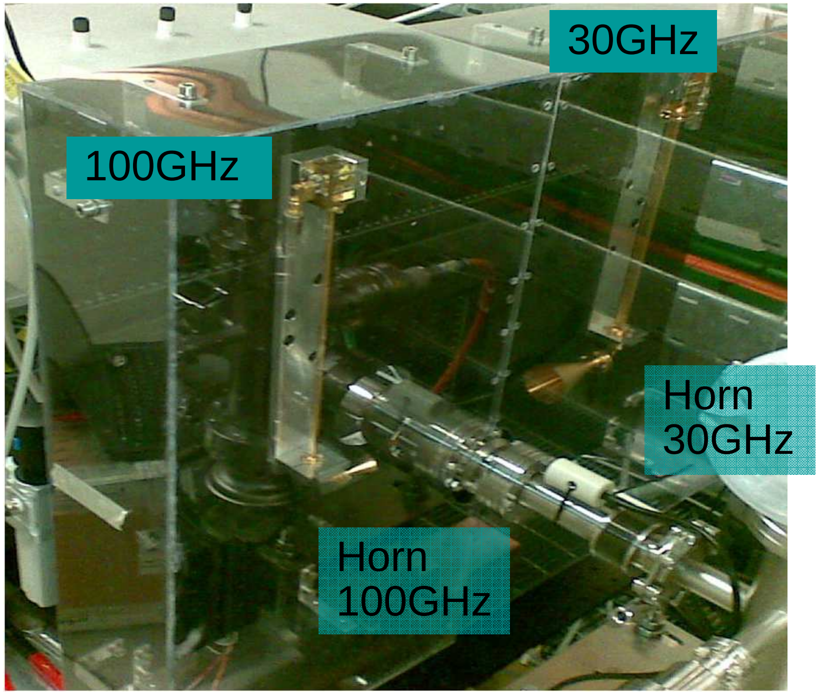

Off axis parabolic mirrors
BC1/BC2
FOURTH DIPOLE
PYRO
DETECTOR
IRON
COIL
IRON
COIL
CERAMIC GAP
e-beam
Holey mirror
SCHOTTKY DIODES
30GHz
100GHz
300GHz
CBLM Source point:
50% Mag field drop

Installed CBLM



Coherent edge radiation





Coherent GAP radiation

Velocity vs accelaration

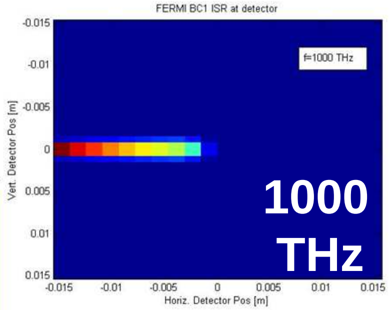
Liénard-Wiechert

$$\mathbf{E}(\mathbf{r},t+\frac{R}{c})=\frac{e}{4\pi\varepsilon_0}\left[\frac{\mathbf{n}-\boldsymbol{\beta}}{\gamma^2(1-\mathbf{n}\boldsymbol{\beta})^3R^2}\right]+\frac{e}{4\pi\varepsilon_0 c}\left[\frac{\mathbf{n}\times((\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}})}{(1-\mathbf{n}\boldsymbol{\beta})^3R}\right]$$

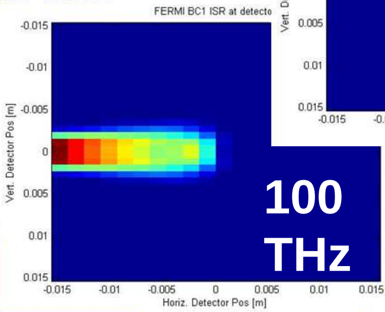
velocity (coulomb) term *acceleration (radiation) term*

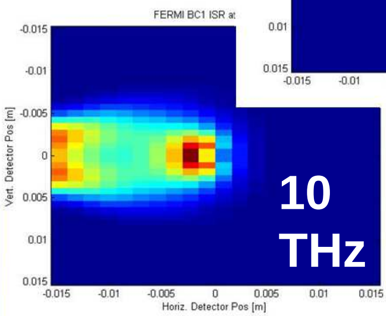
Incoherent radiation source simulations
SynchroSim (O.Grimm -DESY)

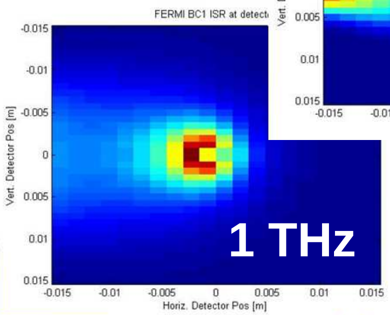
FERMI BC1 4th dipole
250MeV, 30x30mm

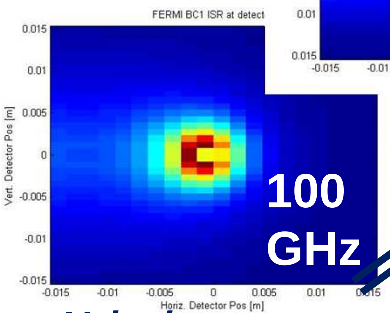


Acceleration term dominates



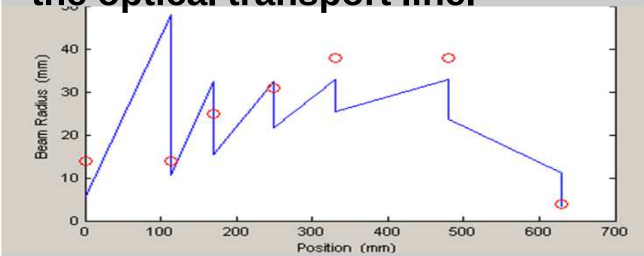




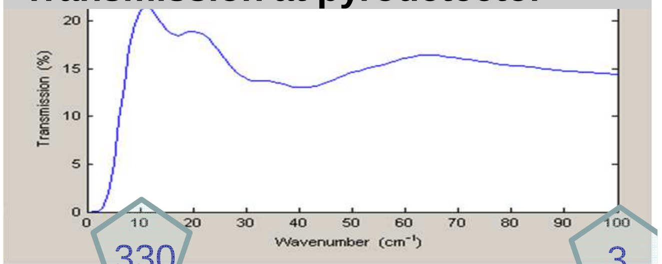


Velocity term dominates

Radiation beam radius along the optical transport line.



Transmission at pyrodetector

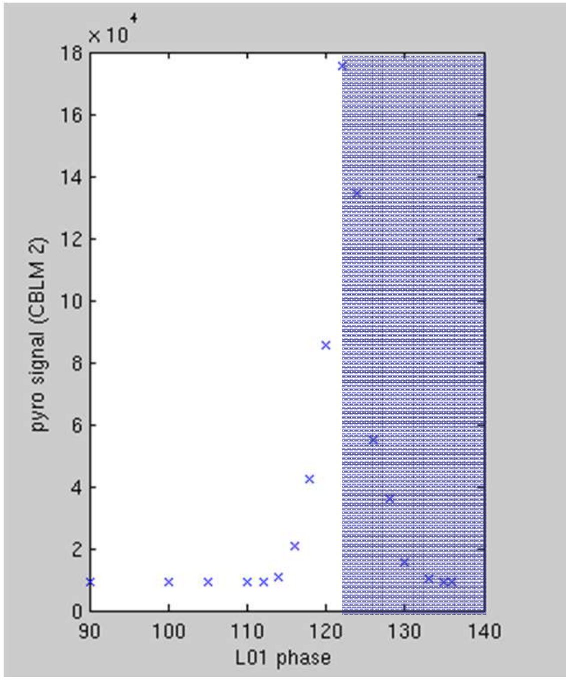


Laguerre Polynomial expansion and matrix optics Matlab code (H.Loos -LCLS)

Rectangular bunch
FW 1.6ps → coher. onset = 330GHz
FW 5ps → coher. onset = 100GHz

Operational experience

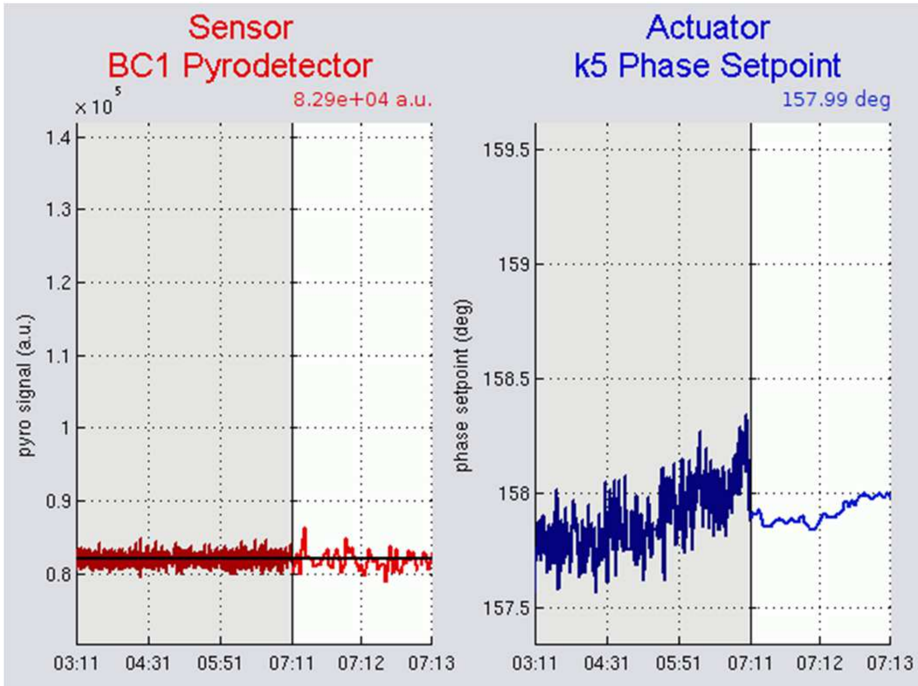
Test of double compression BC1+BC2



Overcompression Phase @ 122deg
in agreement with simulation
90deg on crest condition

Compression feedback

- Pyrodetector used as sensor
- L1 linac phase as actuator



L.Froehlich

Radiation from a GAP

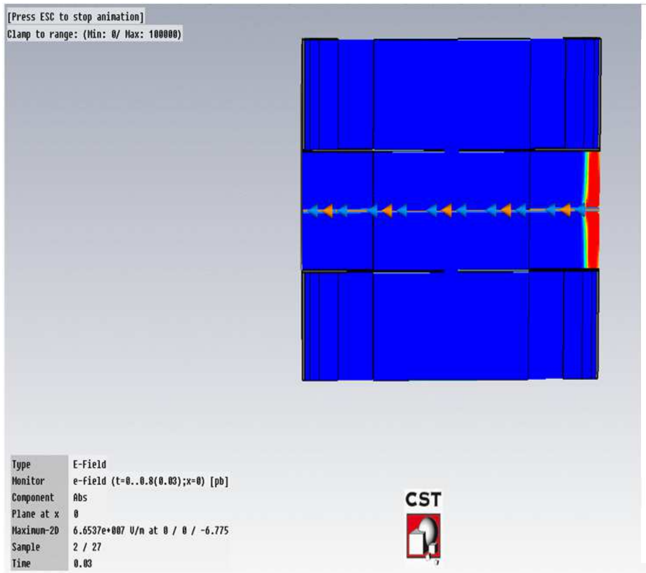
- Maxwell equations
- Bolotowskii and Palumbo approach
- No closed solution of the integrals →
- Proposed high frequency approx.

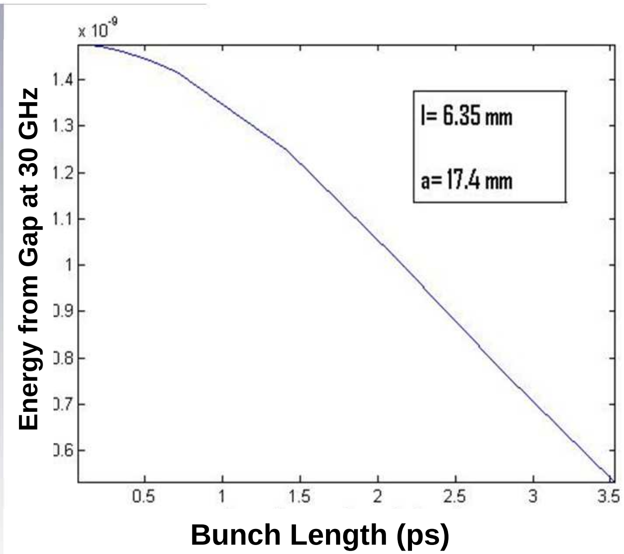
R. Appio, M.Veronese, P. Craievich, G. Penco

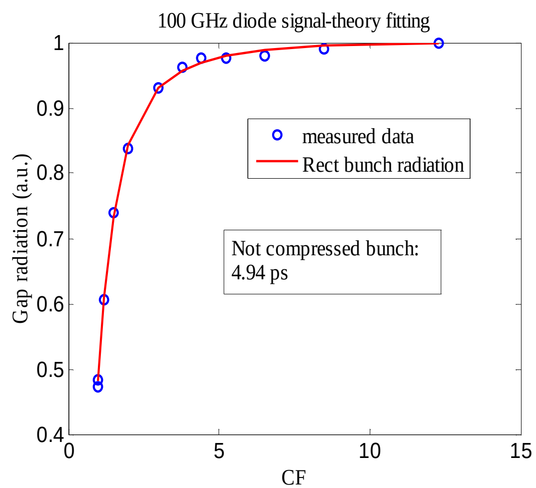
STEP IN term — Negligible for $\beta \to 1$

STEP OUT term — Dominates for $\beta \to 1$

$$\frac{d^2W(\theta)}{d\omega d\Omega} = \beta q^2 \frac{\sin^2\theta J_0^2(ka\sin\theta)}{4\pi^2 c(1-\beta\cos\theta)^2 I_0^2\left(\frac{ka}{\beta\gamma}\right)} \left| \sqrt{\frac{1-\beta}{1-\cos\theta}} e^{jk\ell(1-\beta\cos\theta)/\beta} + j\sqrt{\frac{1+\beta}{1+\cos\theta}} e^{-jk\ell(1-\beta\cos\theta)/\beta} \right|^2$$



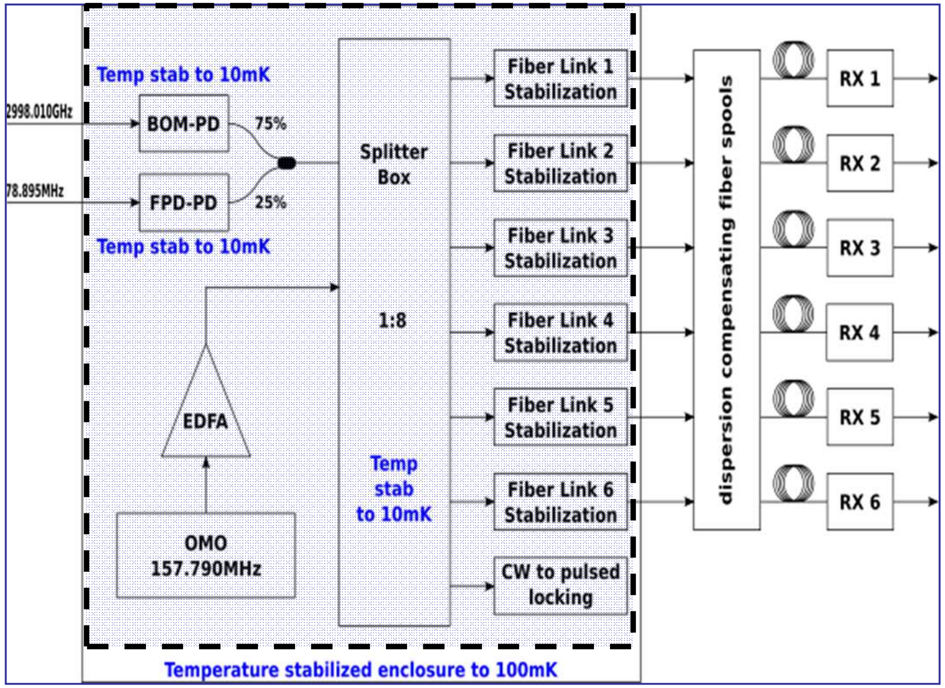




Pulsed optical timing

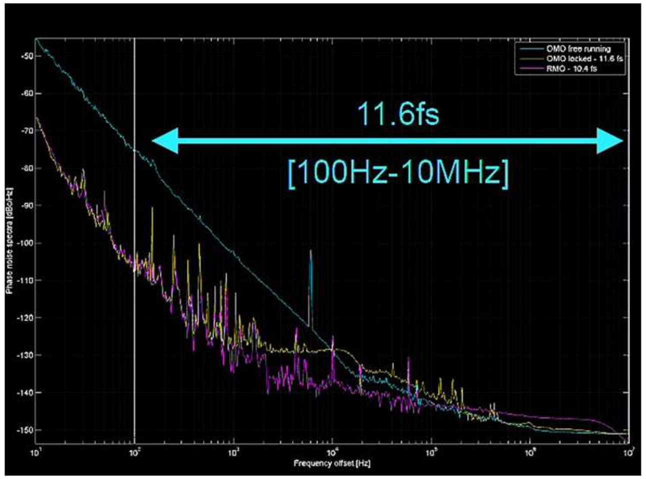
Pulsed optical timing system:

Design and prototyping: collaboration with prof. F. X. Kaertner group (MIT)
Engineering and contstructi0n: MenloSystems, Gmbh.



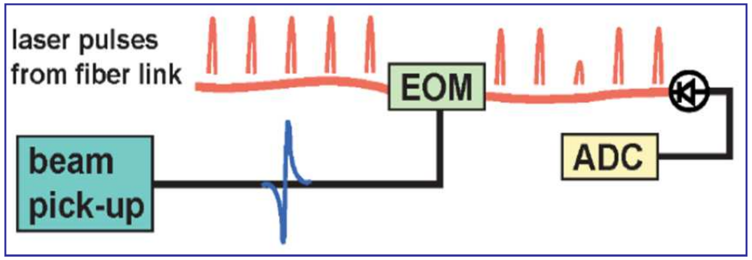
Optical Master Oscillator (OMO)
& 6 Stabilized Links

Phase noise of the locked OMO→
Link drift < 5fsec rms over 10days



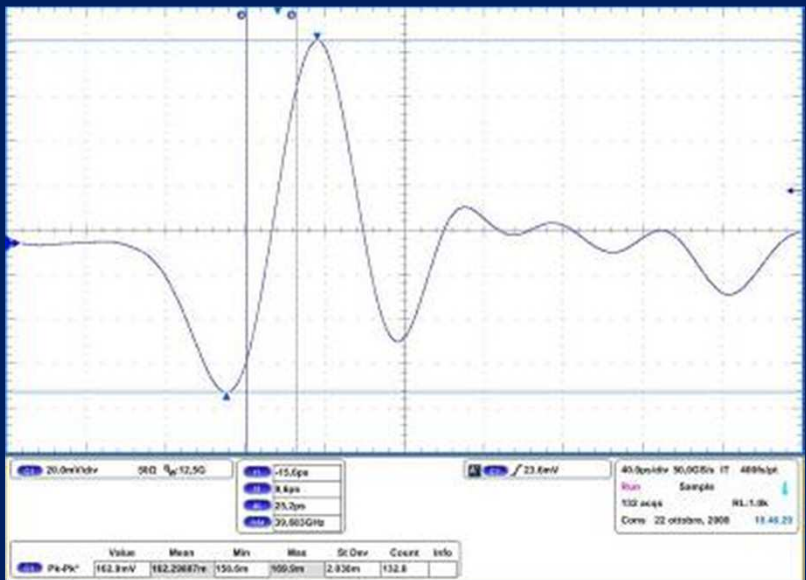
M. Ferianis, F. Rossi, M. Predonzani

FERMI@Elettra BAM

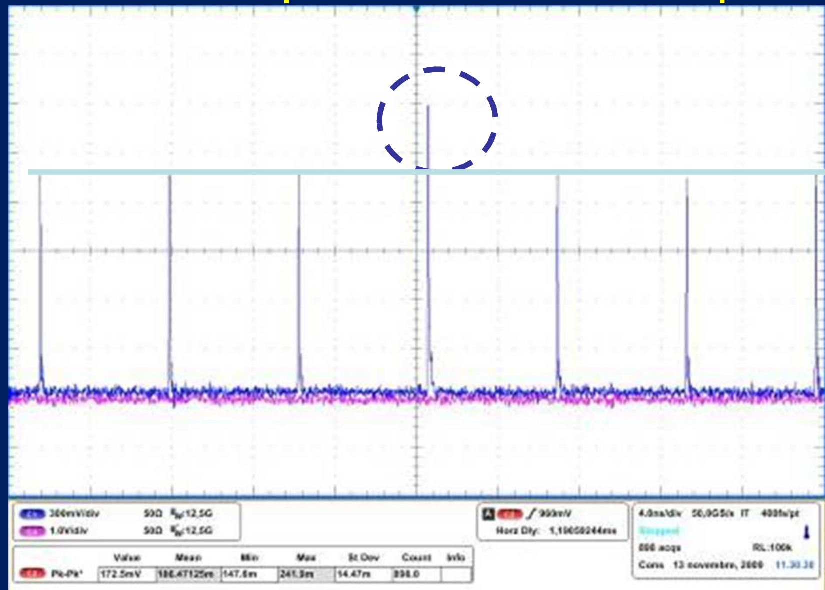


H. Schlarb, DESY;
F. Loehl, PhD Thesis, Uni. Hamburg 2009

BAM pick-up pulse on FERMI

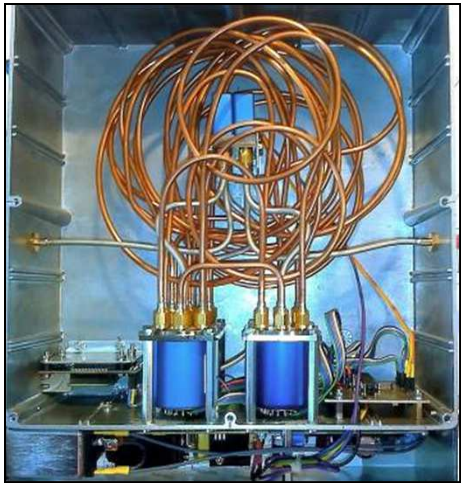


OMO amplitude modulated pulse



M. Ferianis, L. Pavlovic, F. Rossi

BAM alignment & calibration



Coarse alignment *SPAGHETTI BOX!!!*
Remotely controlled, broadband (12GHz) coaxial delay unit; 7.2ns in 600ps steps to cope with the OMO period (f_{OMO}=157MHz)

Fine alignment:
optical delay line housed in the BAM front-end ±300ps

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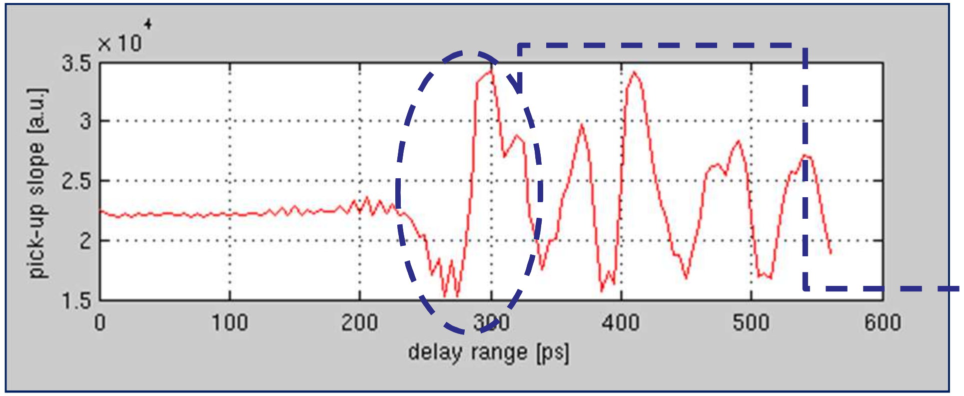
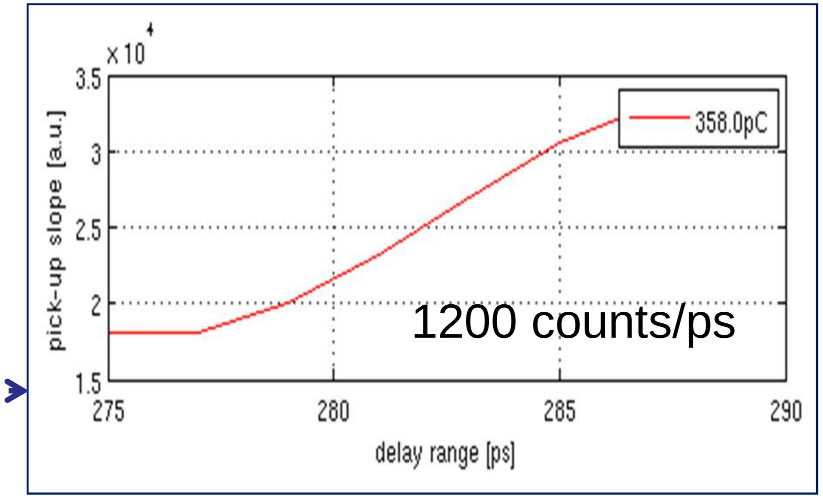
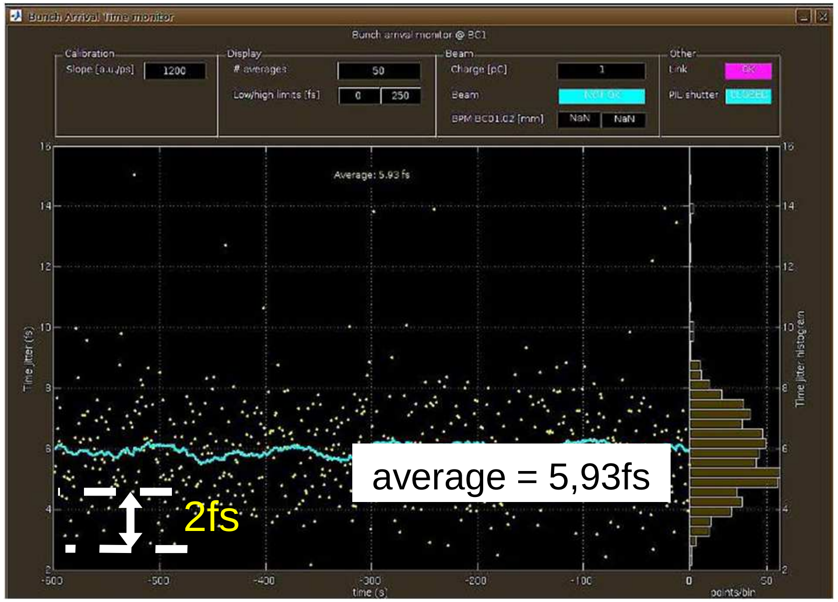
Scan of the OMO pulse vs pick–up signal





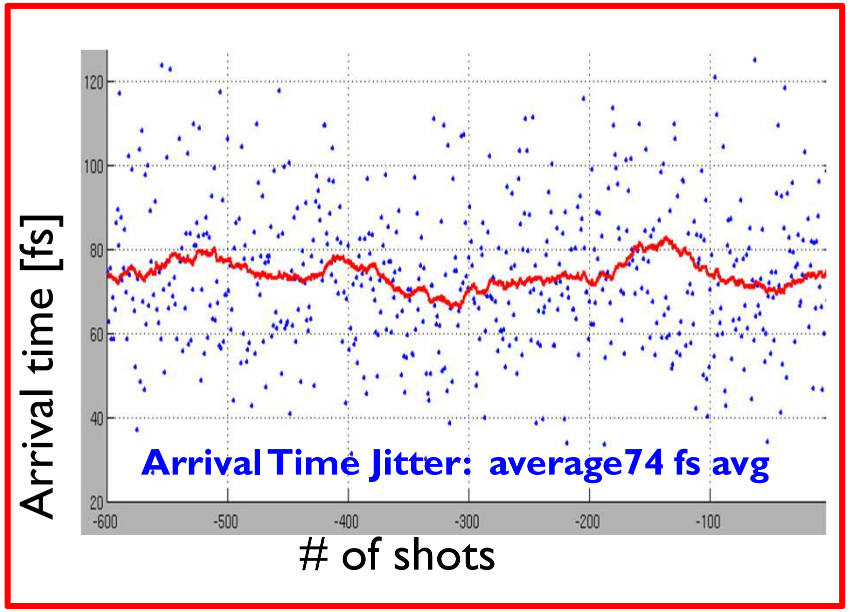
Time jitter measurement

BAM acquisition noise <10fs$_{RMS}$



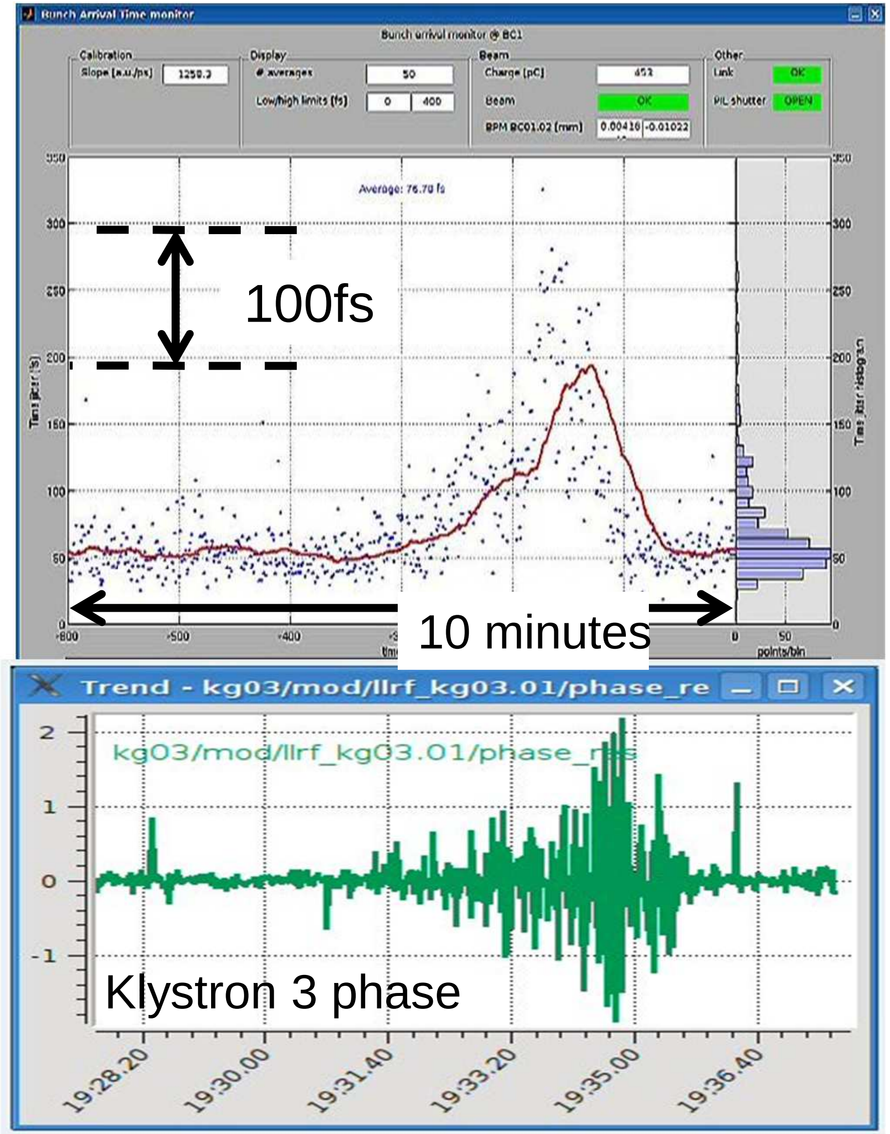
10 minutes

Typical time jitter CF=1 <100fs$_{RMS}$



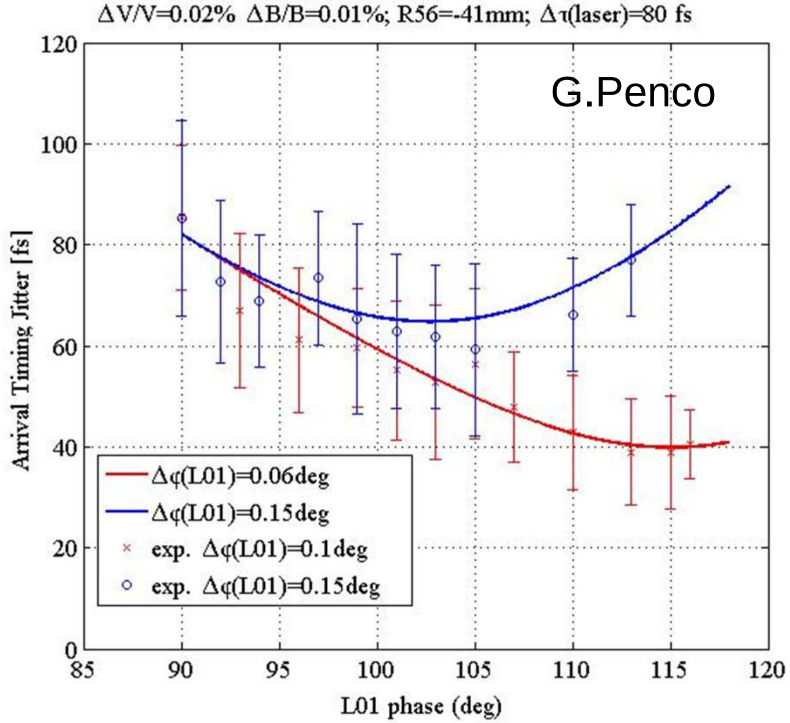
RF and photoinjector laser stability are well in specs!

Machine monitoring and studies



Beam jitter increases due to Klystron3 phase instability

Time jitter compression
Experimental data vs simulation



Low Energy RF Deflector (LERFD)

- collaboration with INFN LNF/Univ. La Sapienza
- scaling to our working frequency of the Alesini's 5-cells RFD

Frequency	2998.010	MHz
Filling time	2.4	µs
Max available RF power	5	MW
Integrated transverse voltage @5MW	4.9	MV
Total length	0.5	m
Beam energy	320	MeV
Natural beam size	200	µm
Temporal resolution	**70**	**fs**

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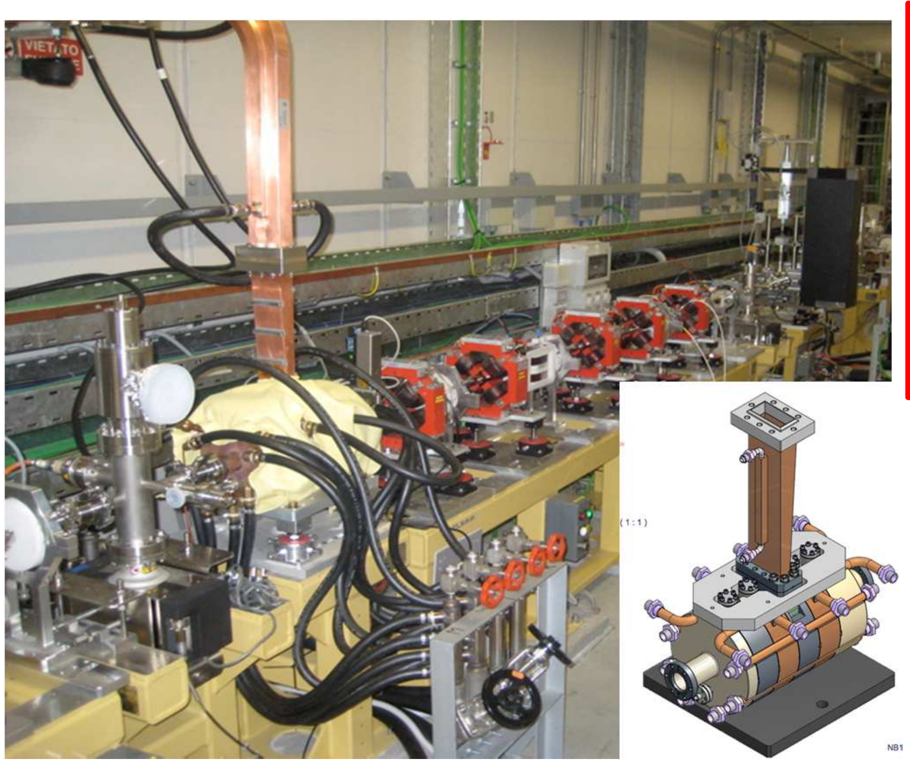
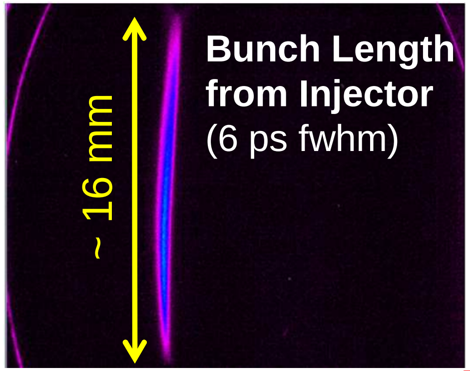
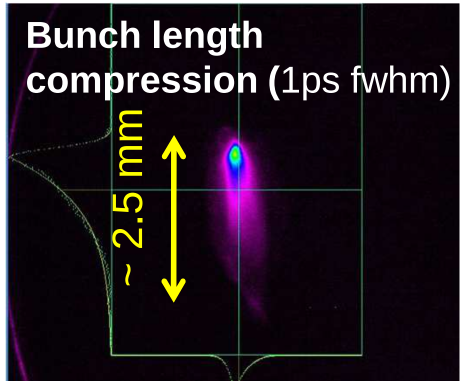
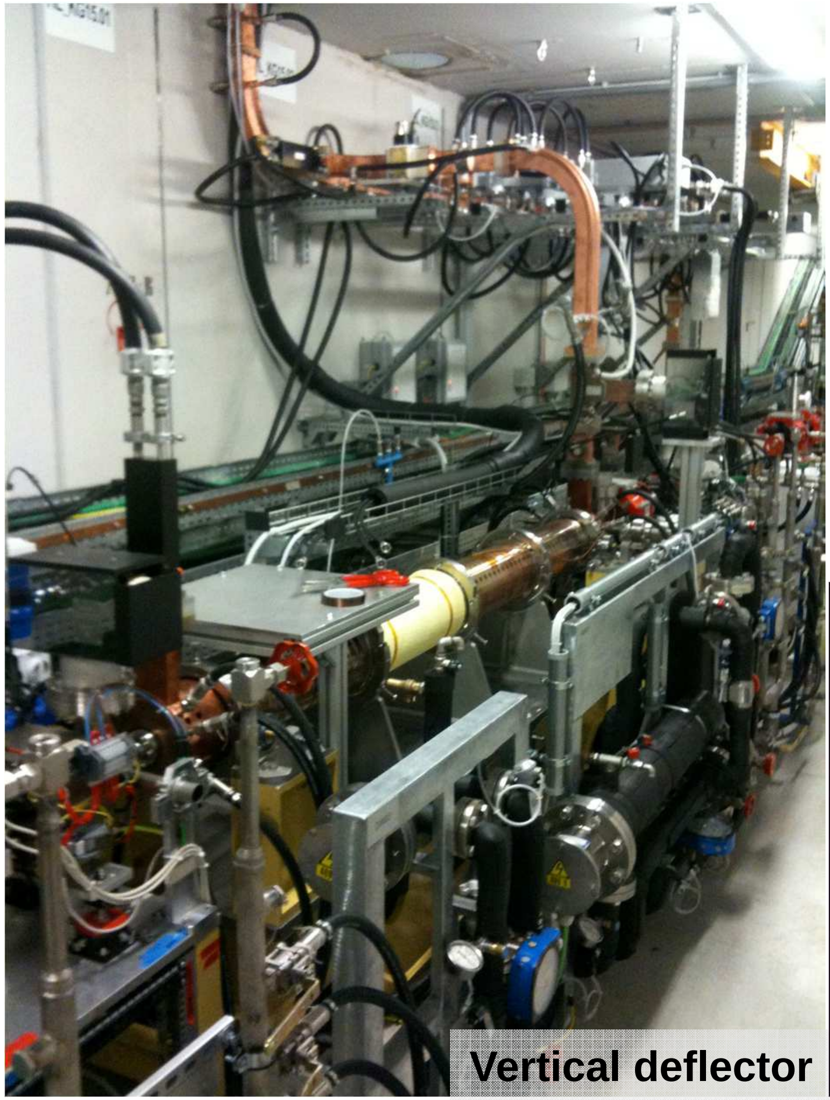




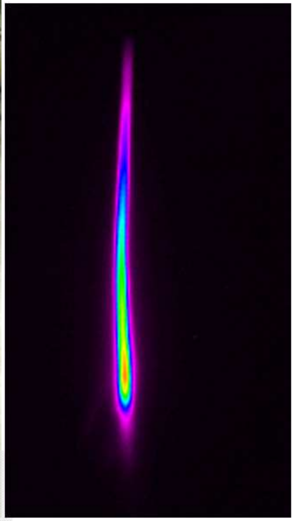


High Energy RF Deflector (HERFD)



Frequency	2998.010	MHz
Filling time	0.5	µs
Max available RF power	15	MW
Integrated transverse voltage @15MW	>20	MV
Total length	2.5	m
Beam energy	1.2	GeV
Natural beam size	70	µm
Temporal resolution	**<20**	**fs**

- deflection on both planes to manage transverse wakes



- vertical deflector in commissioning
- horizontal deflector to be installed during 2012

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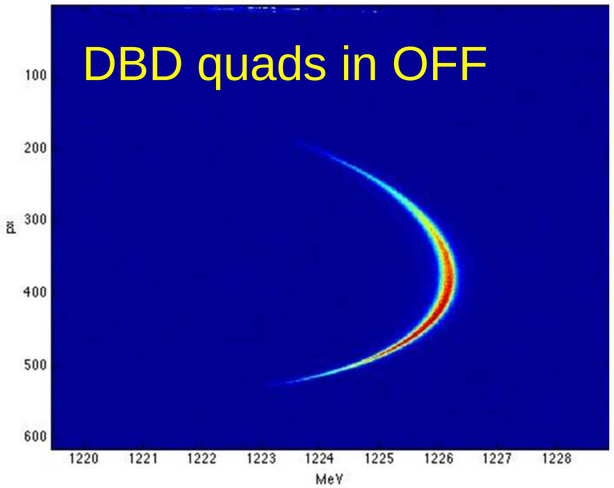
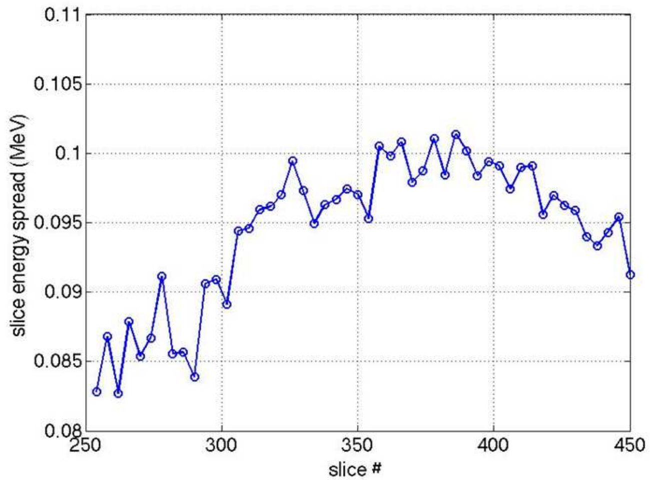
HERFD Slice en. Spread @350pC

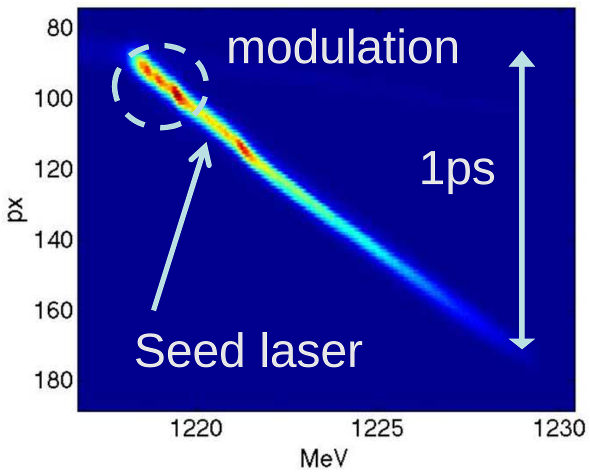


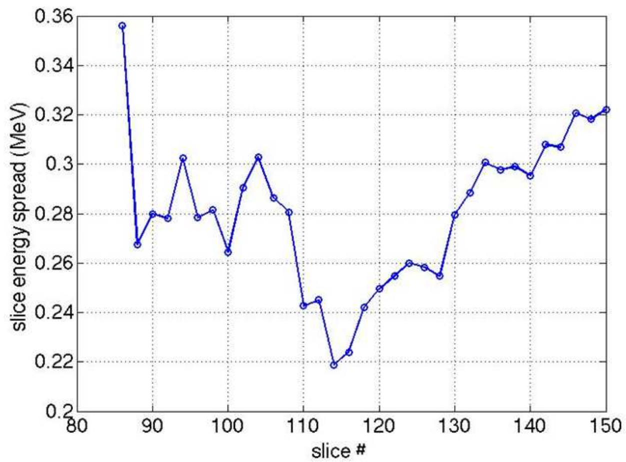


Uncompressed

Slice en. Spread

~100keV (rms)





CF 5

Slice en. Spread

Good region

~220keV (rms)

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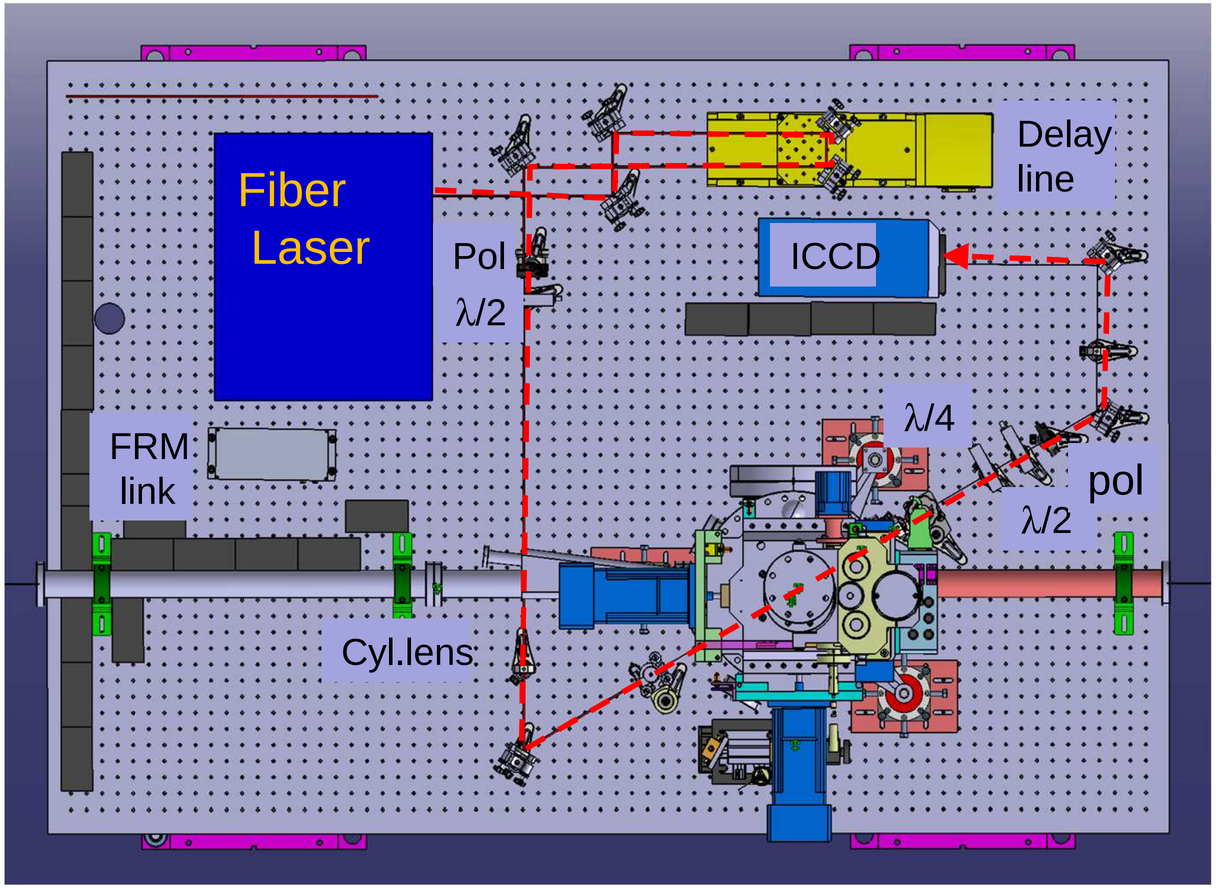
Electro Optical Sampling FEL1

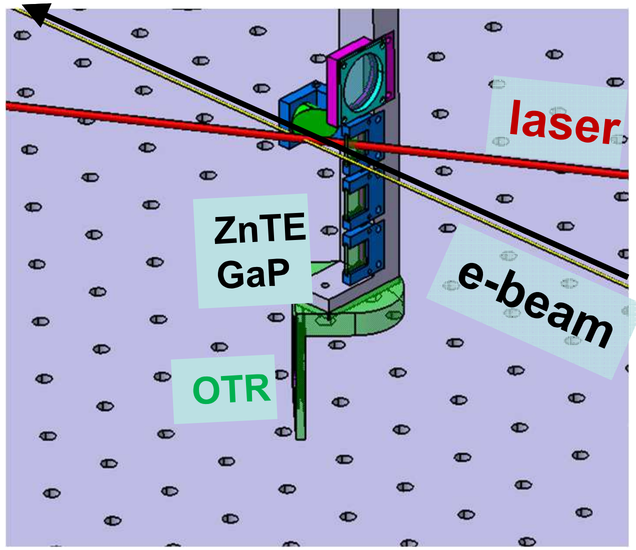


FIRST EOS measurements

Spatial encoding scheme

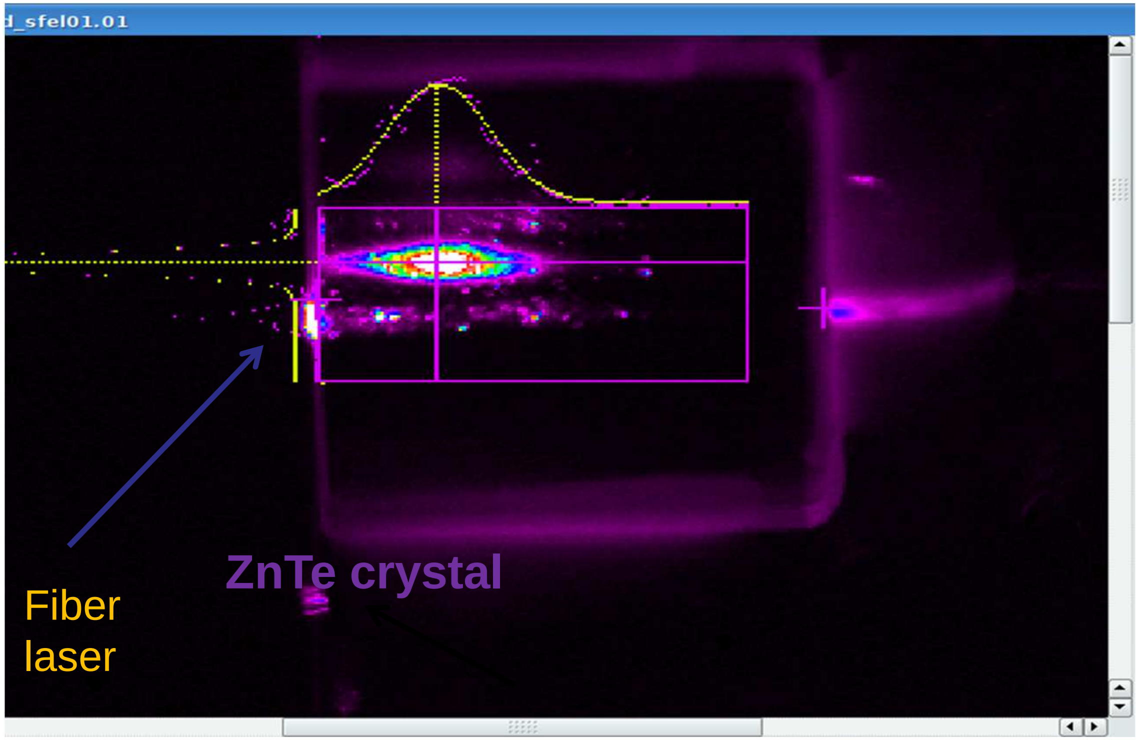
Fiber Laser : 780nm –FW 100fs

ZnTe, GaP, OTR, YAG



Design started from suggestions of D.Fritz (SLAC) and in collaboration with S.Jamison (Alice-STFC). First tests at SPARC (LNF-INFN).

Time scale calibration



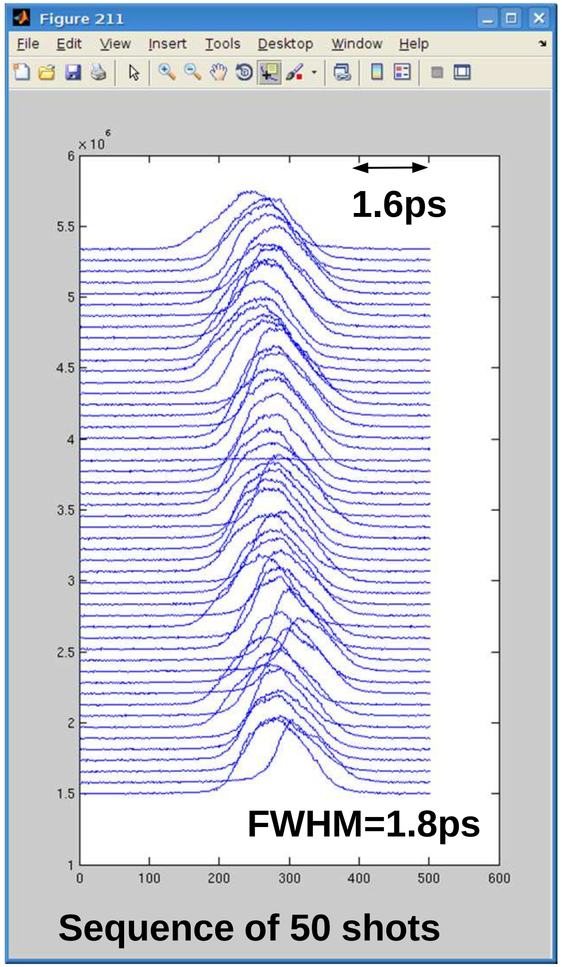
Correlating fiber laser spot size on ZnTe crystal vs ICCD image size.
Taking in account geometrical factor for angle of incidence (30 deg)

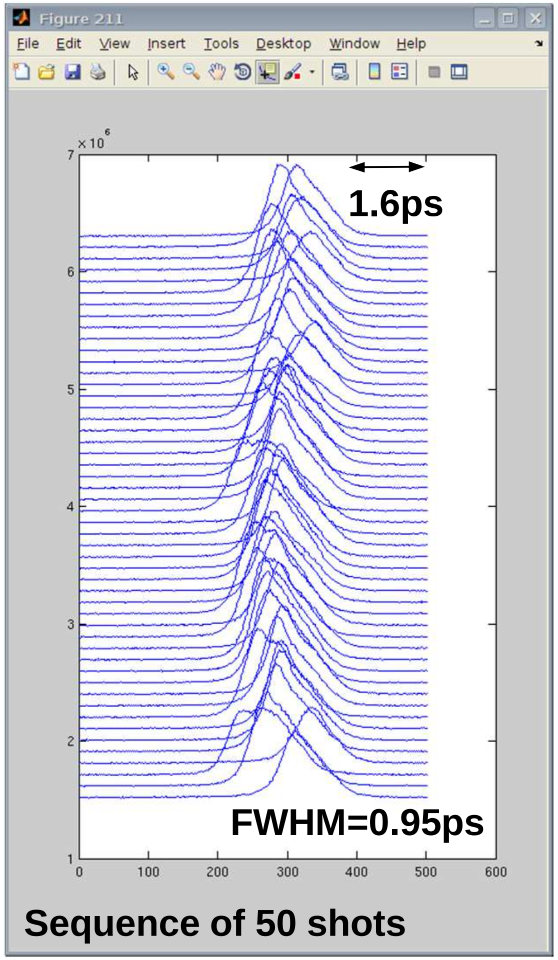
Calibration Coefficient: 16 fs/pixel

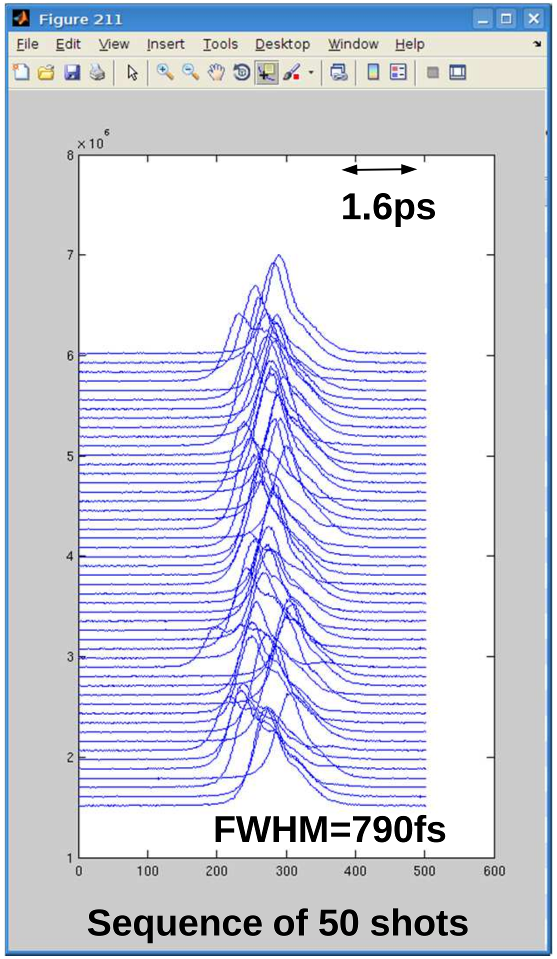
ZnTe 1mm, Horizontal Polarization

M.Veronese, E.Allaria 27/09/11

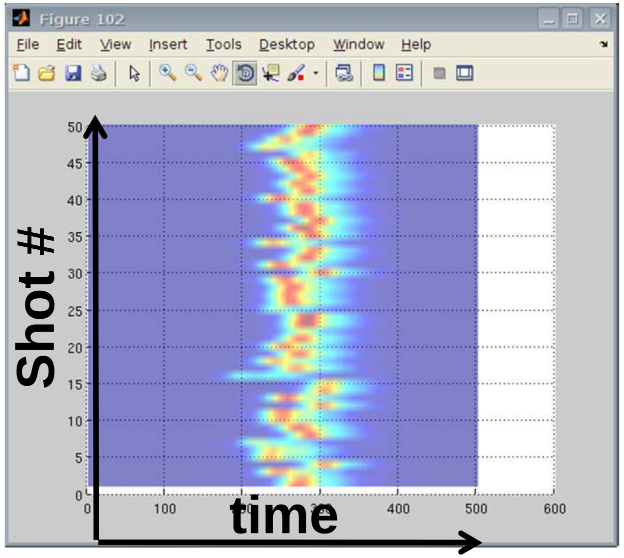
… Increasing compression …

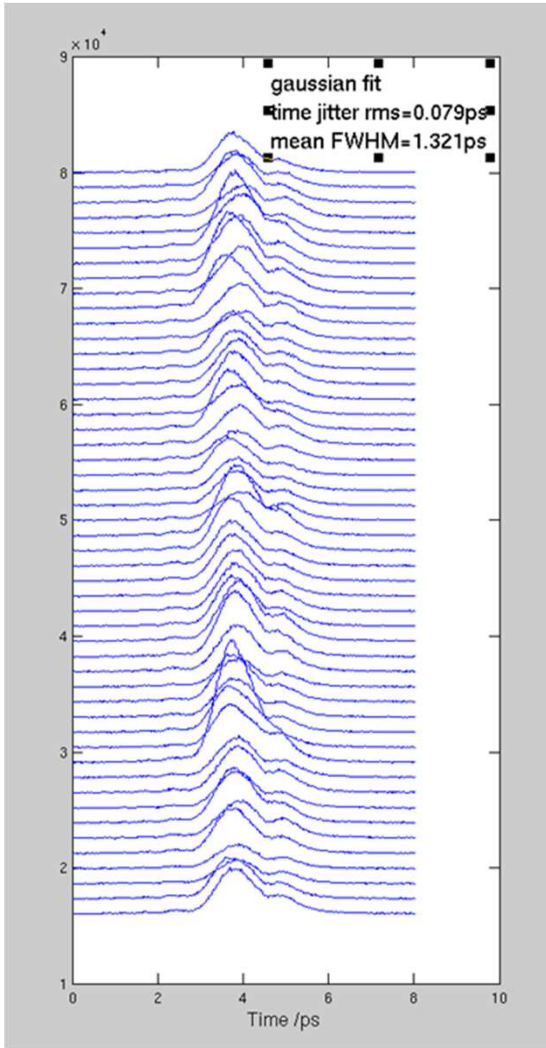






Jitter measurements





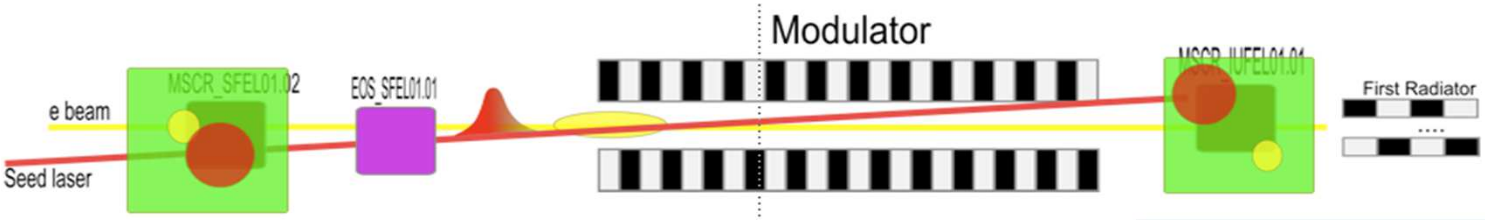
Resolution
ZnTe 1 mm and GaP 0.4 mm chosen for first operation are optimized for signal amplitude

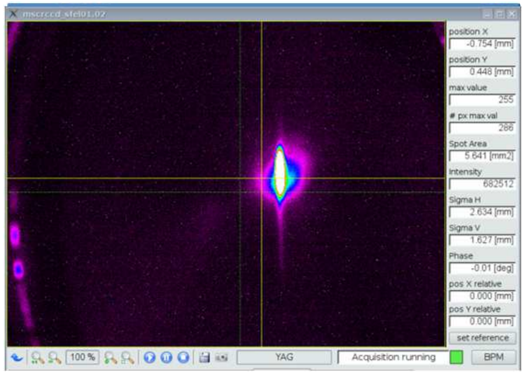
High resolution crystal: GaP 0.1mm
To be be installed in 2012

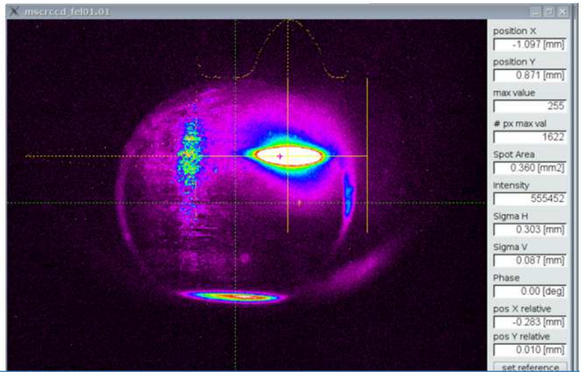
Time jitter/ drift measured ~ 80 fs

SEEDING ALIGNMENT

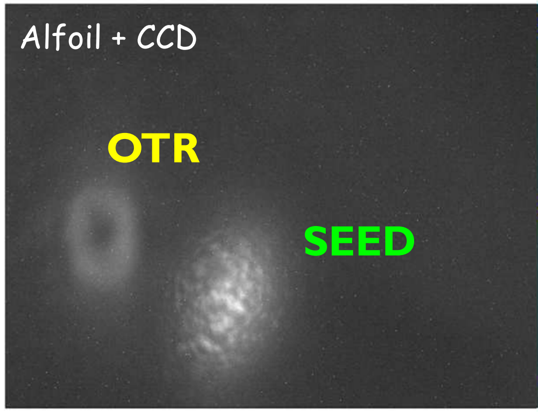
Spatial overlap cross the modulator is carried out with **two YAG screens**.

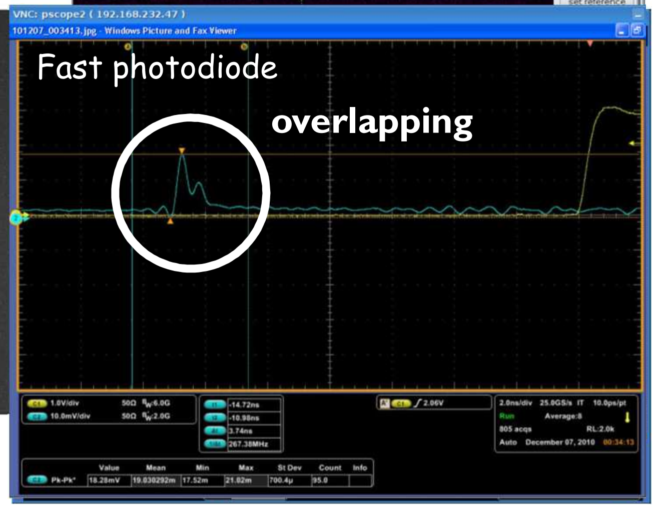






Time Overlap:
An **Al foil** that reflects the laser out of EOS chamber and makes electrons producing OTR. The two signals are detected with a CCD. A fast photodiode on a XY stage allows time alignment within 50ps on 6GHz oscilloscope





M. Veronese, C. Spezzani, M. Danailov, P. Cinquegrana, P. Sigalotti, E. Allaria

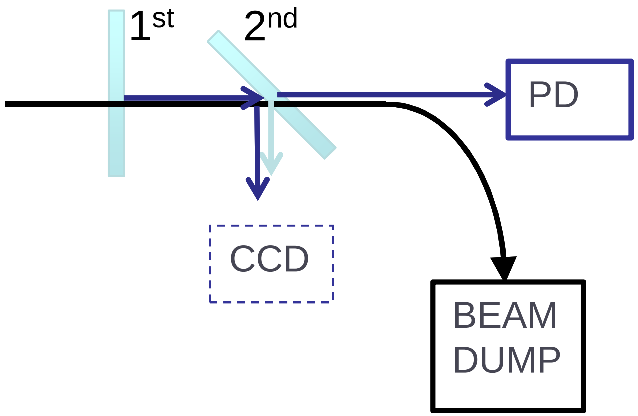
Seed bunching measurement

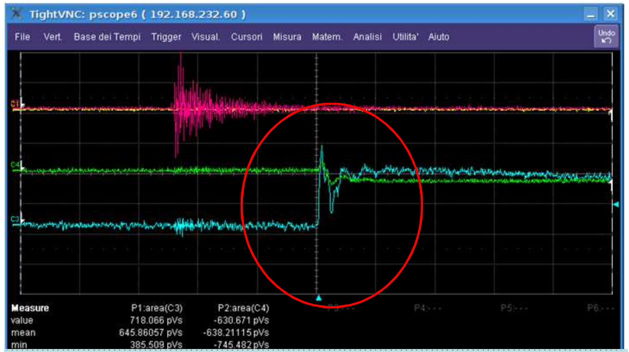
M.Veronese, E.Allaria, M.Trovò

MicroBunching induced by the seed laser at 260nm.

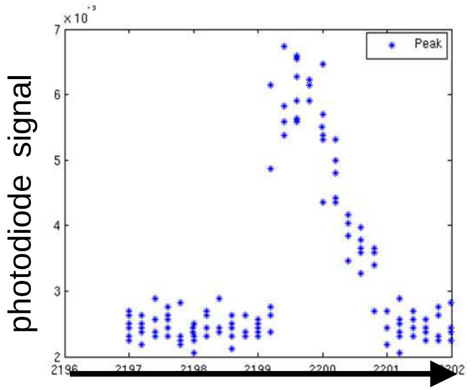
1st foil: Al 1μm
- Stops Seed laser
- Emits Forward CTR

2nd foil: Al 1μm
- Reflects TR from 1st
- Emits Forward CTR

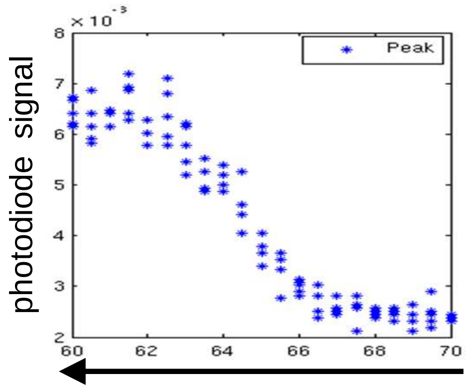




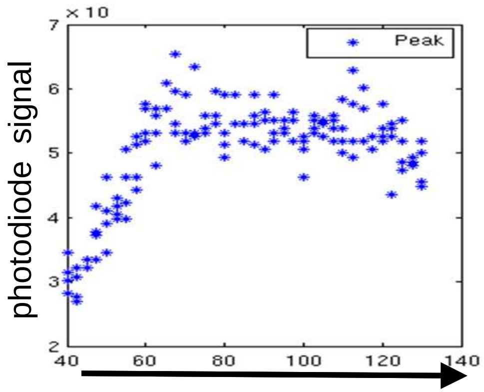
Coherent UV signal on IRD Al coated photodiode downstream 2nd foil



Seed laser Time Delay



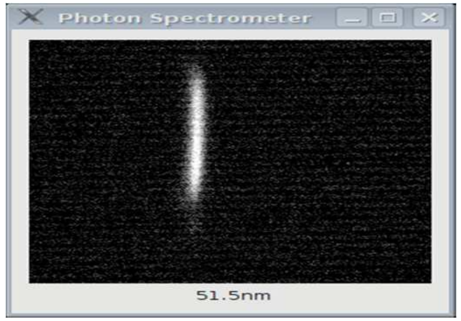
Seed Power

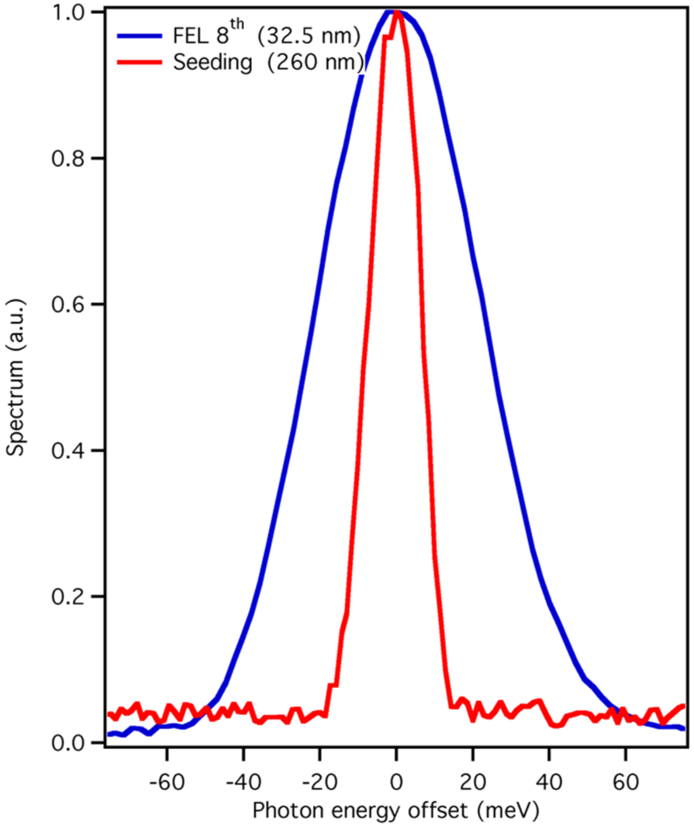


Dispersive chicane Current

FEL bandwidth (eV)

In the frequency (energy) domain the FEL spectrum is larger than the one of the seed laser.





courtesy E.Allaria

We expect the FEL pulse to be shorter than the seed laser. →

Ideal case for the Nth harmonic the relative bandwidth:

$$BW_{FEL} = \sqrt{N}\, BW_{SEED}$$

For the 8th harmonics exp. data fitting this model:

$$BW_{rms}^{FEL} = 49meV \quad BW_{rms}^{seed} = 16.3meV$$

This suggests that longitudinal coherence is preserved.

Transverse coherence

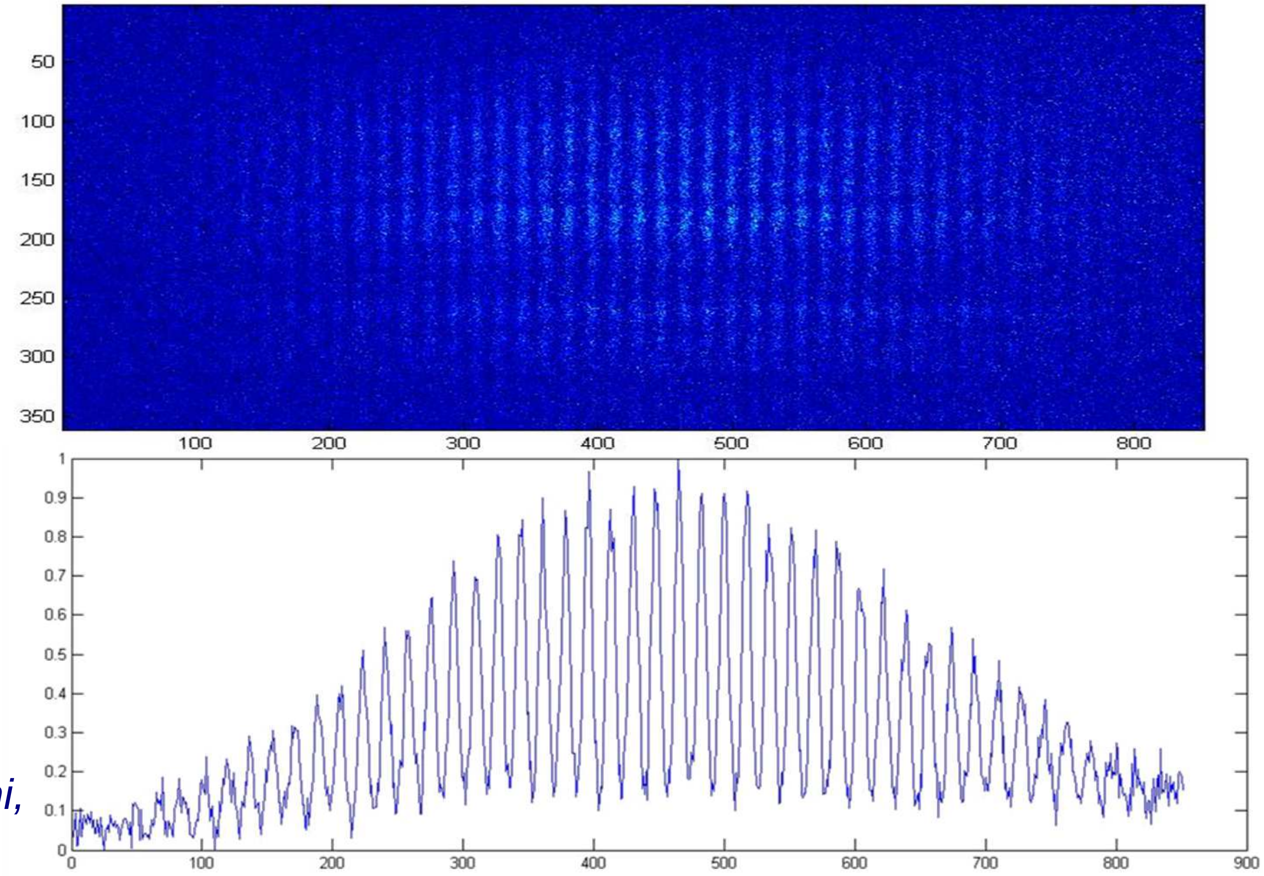
Double slit experiments done at 32.5 nm show very good transverse coherence.

Fringe visibility is very high along the entire FEL pulse indicating a very high degree of transverse coherence.

Quantitative analysis is ongoing.

FEL at 32.5 nm, 6 radiators, 450pC, compression ~3.
Slit separation = 0.8 mm, width = 20 μm

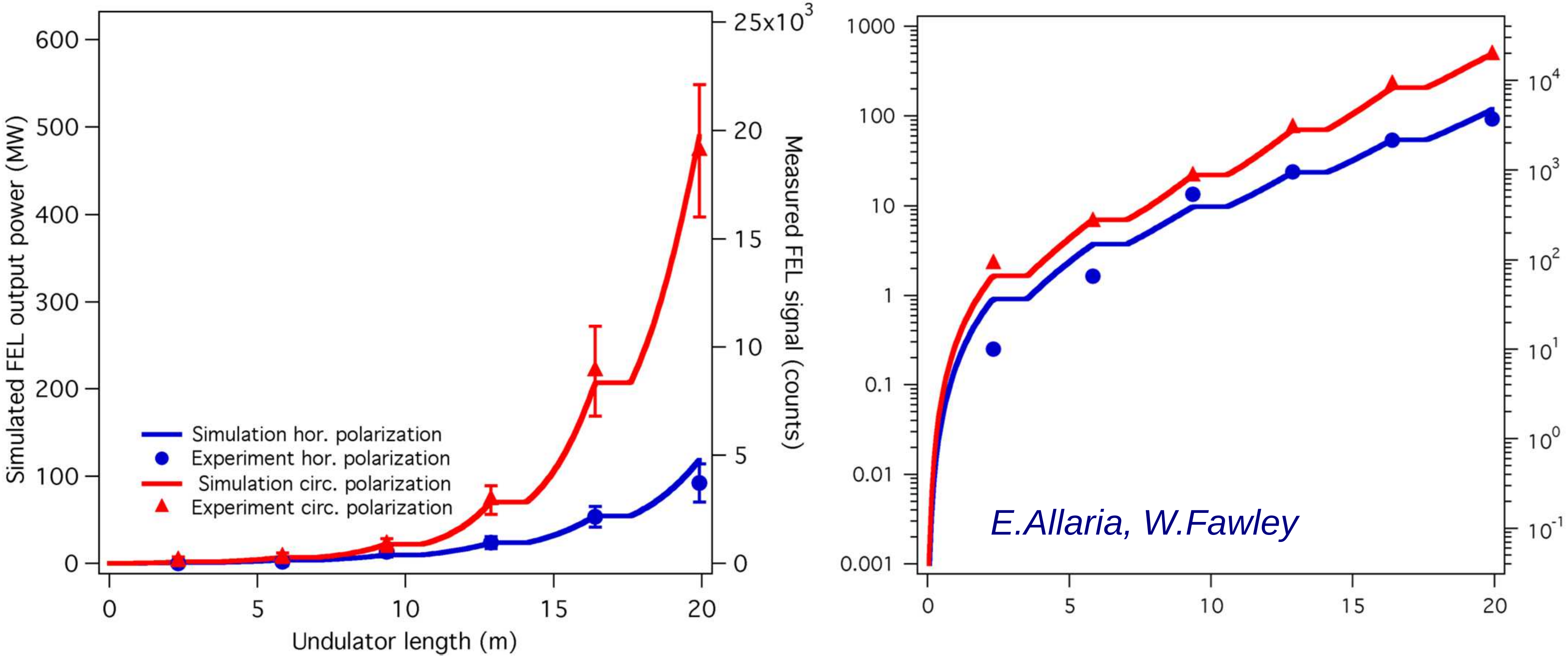
E.Allaria, B.Mahieu, C.Spezzani, G. De Ninno, et al.



23/07/2011

Exponential gain

With the **FEL1 optimized** for **on axis** operation we measured the **exponential gain**.
The FEL1 gain has been measured both for **circular** and **planar polarization** showing the expected behavior (l_g~ 2 and 2.5 m).



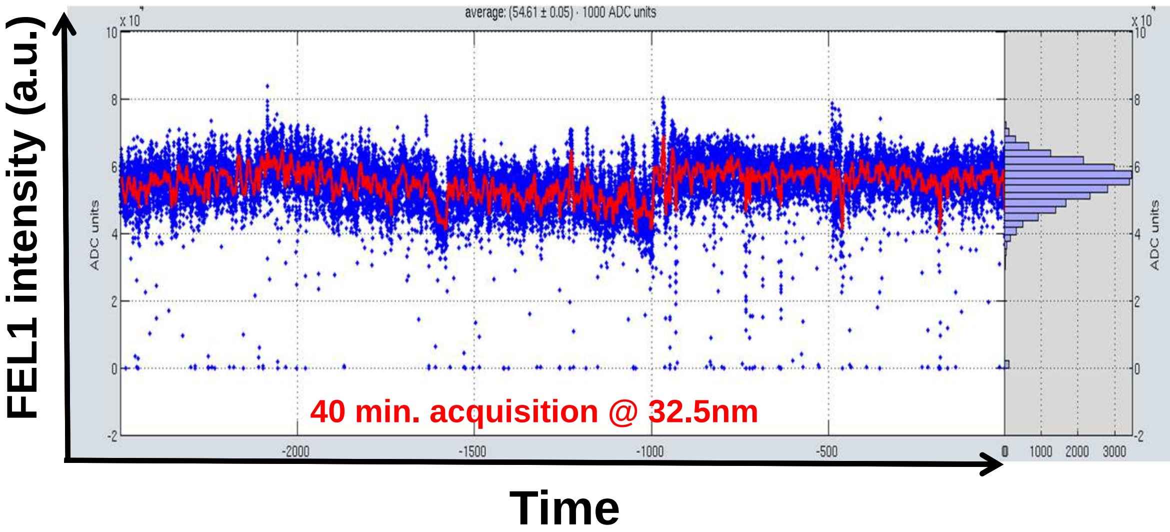
Measured FEL behavior is in good agreement with FEL simulations using the expected electron beam parameters.

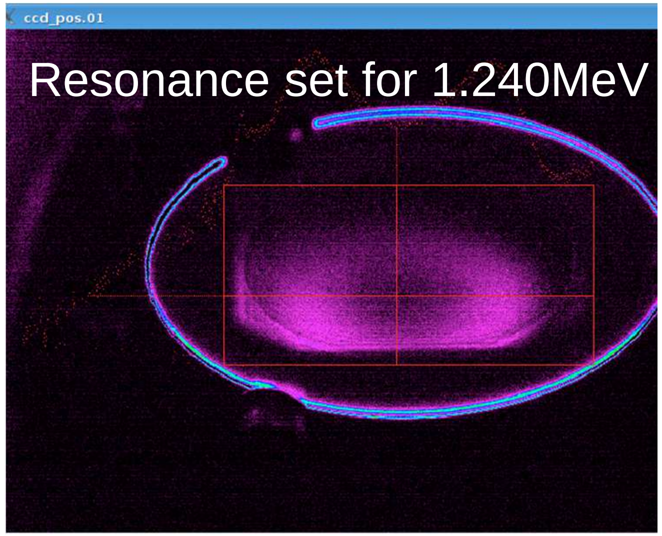
FEL optimization and stability

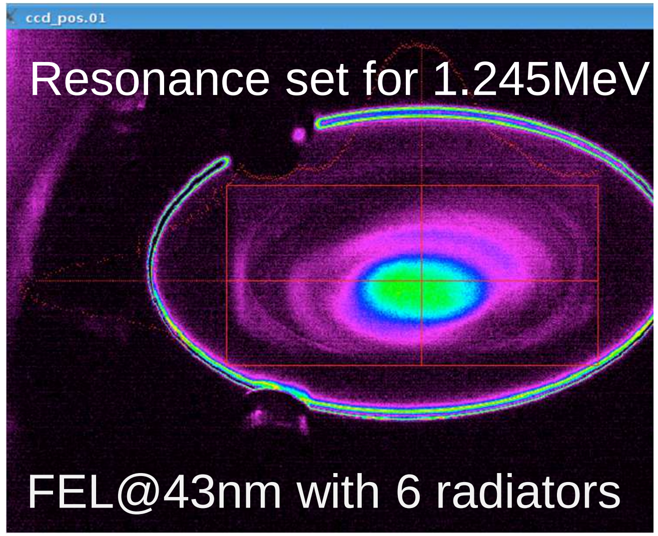
Optimizing the undulator tuning (both in K and electron beam position) is done by examining the far-field FEL spot size.
A small undulator mismatch (of the order of ΔK~0.1%) can produce a "doughnut" transverse mode with resonance moved to the outer portions of e-beam

FEL1 Energy/pulse: Tens of mJ in the range 60→20nm

FEL1 Stability: 10-15% rms







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