ESFRI XFEL Workshop, DESY, Oct 31, 2003

Photon Beam Diagnostics for the XFEL

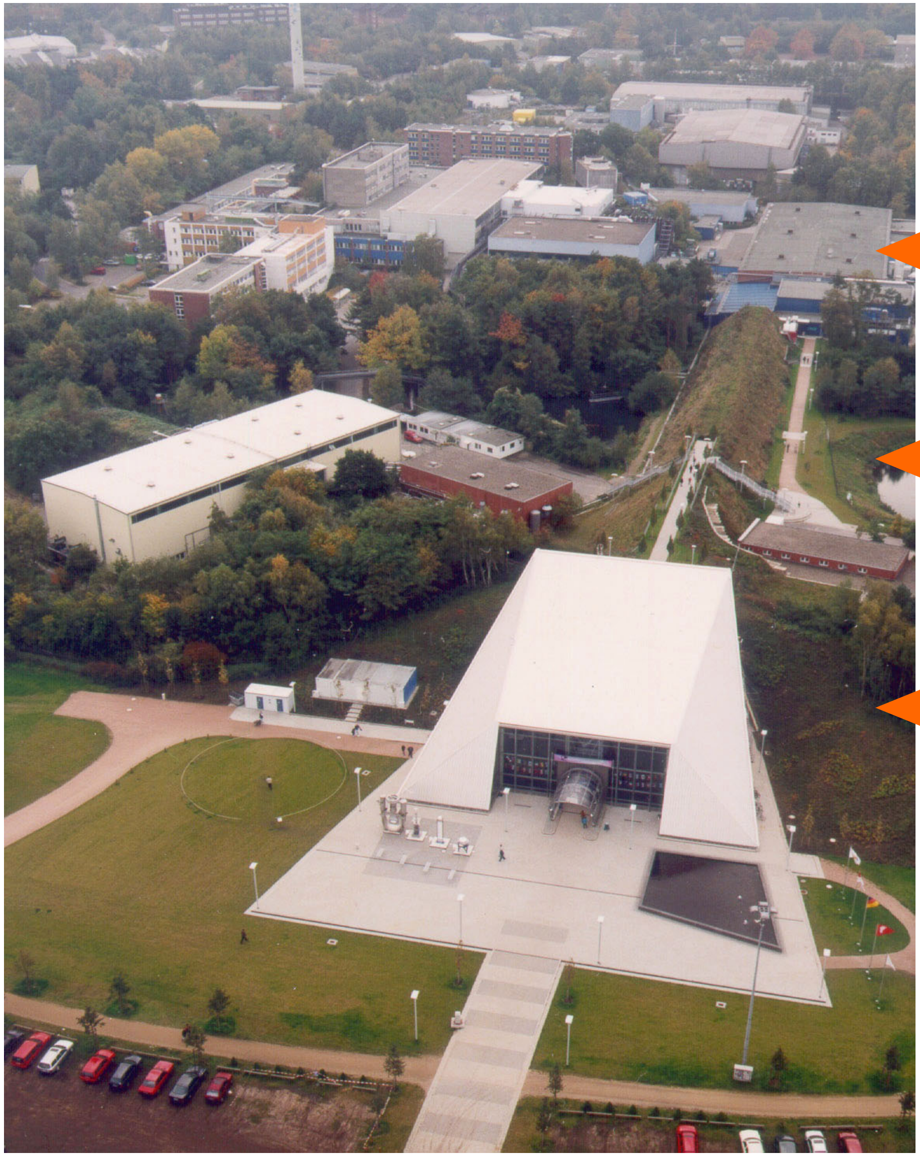
Josef Feldhaus, DESY

Introduction

- **Photon diagnostics measures FEL beam parameters**
  - pulse energy and statistical properties
  - angular distribution, spatial coherence
  - wavelength and spectral distribution
  - arrival time, pulse duration, temporal structure
- **Photon diagnostics – what for?**
  - tuning the FEL
  - characterizing and understanding the FEL
  - supplying user experiments with basic beam parameters
- **What is new?**
  - new source with different properties
  - single pulses with very high intensity

- ***develop pulse-resolved diagnostics based on well-known techniques***
- ***learn from VUV FEL***

VUV FEL User Facility at DESY



TESLA Test Facility (TTF 1, 1995-2002)

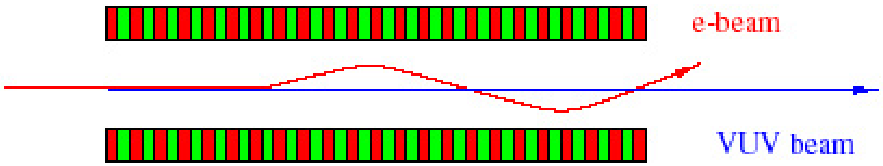
TTF 2

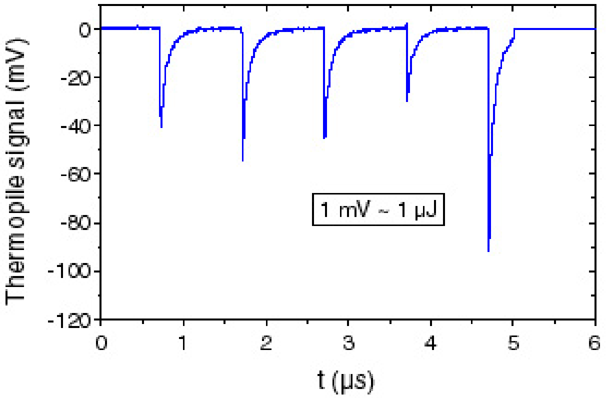
experimental hall

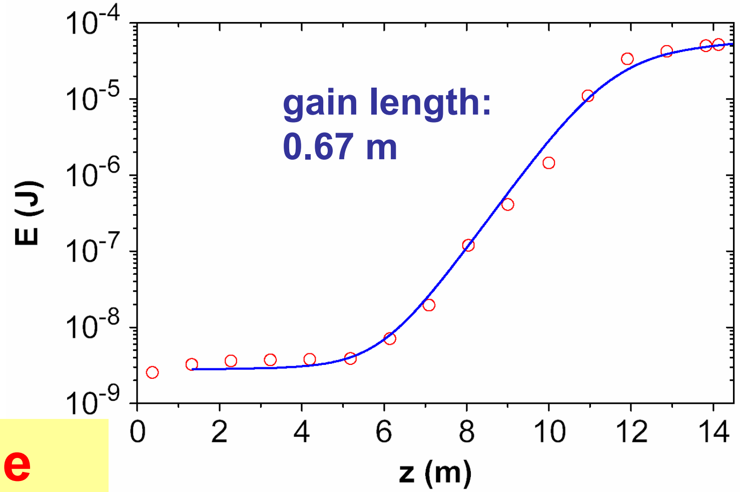
start of operation in 2004

FEL pulse energy

TTF1 results

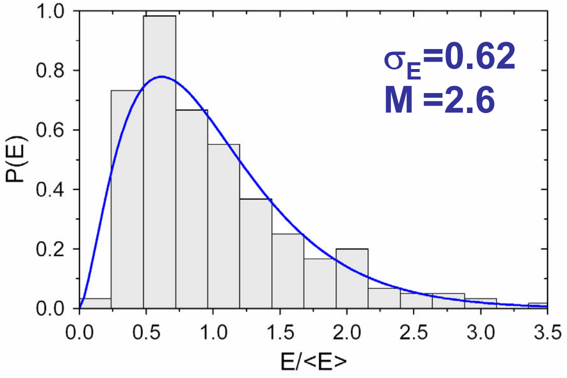




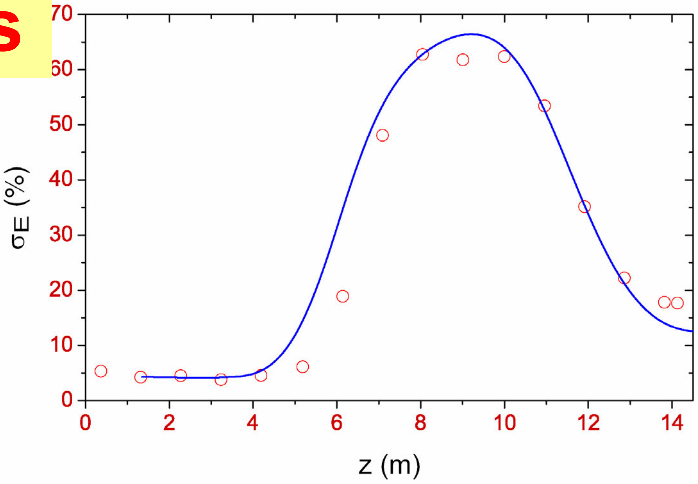


pulse duration
~ 50 fs

FEL saturation at 95 nm

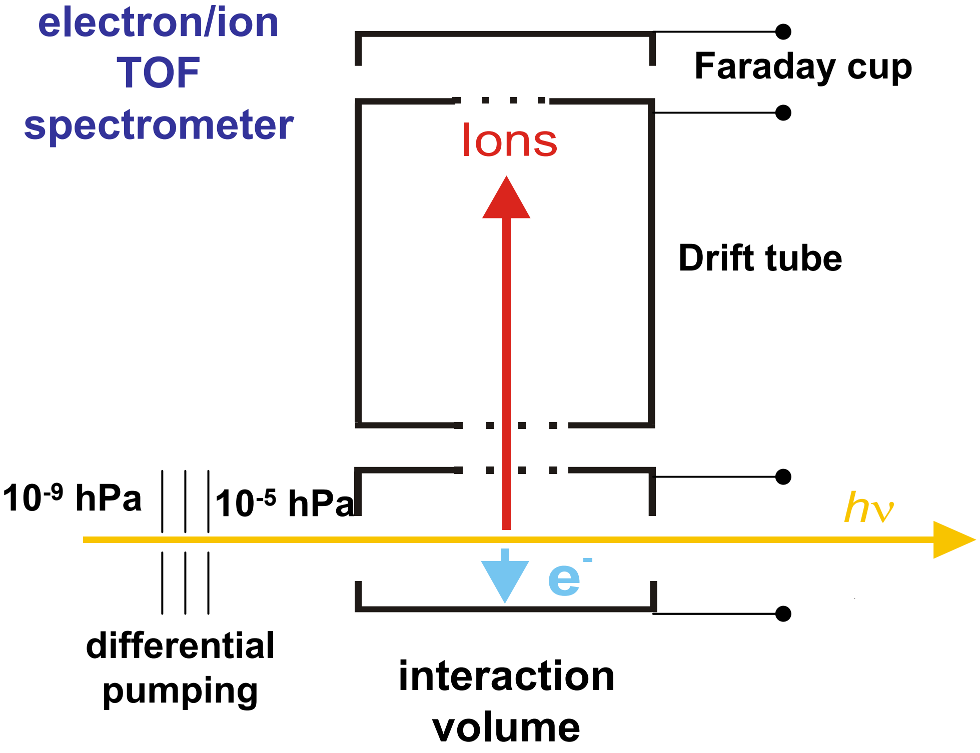


Intensity distribution at z = 9 m



Online monitor of FEL pulse energy

Gas ionisation detector



+ transparent
+ wide dynamic range (spont. to sat.)
+ independent of beam position
+ can measure beam position
+ no saturation effects
+ $\lambda < 93$ nm
+ absolute calibration (~10%)

- **successfully tested at TTF1**
- **needs some more work:**
  - **- saturation limit**
  - **- beam position**
  - **- photon energy**

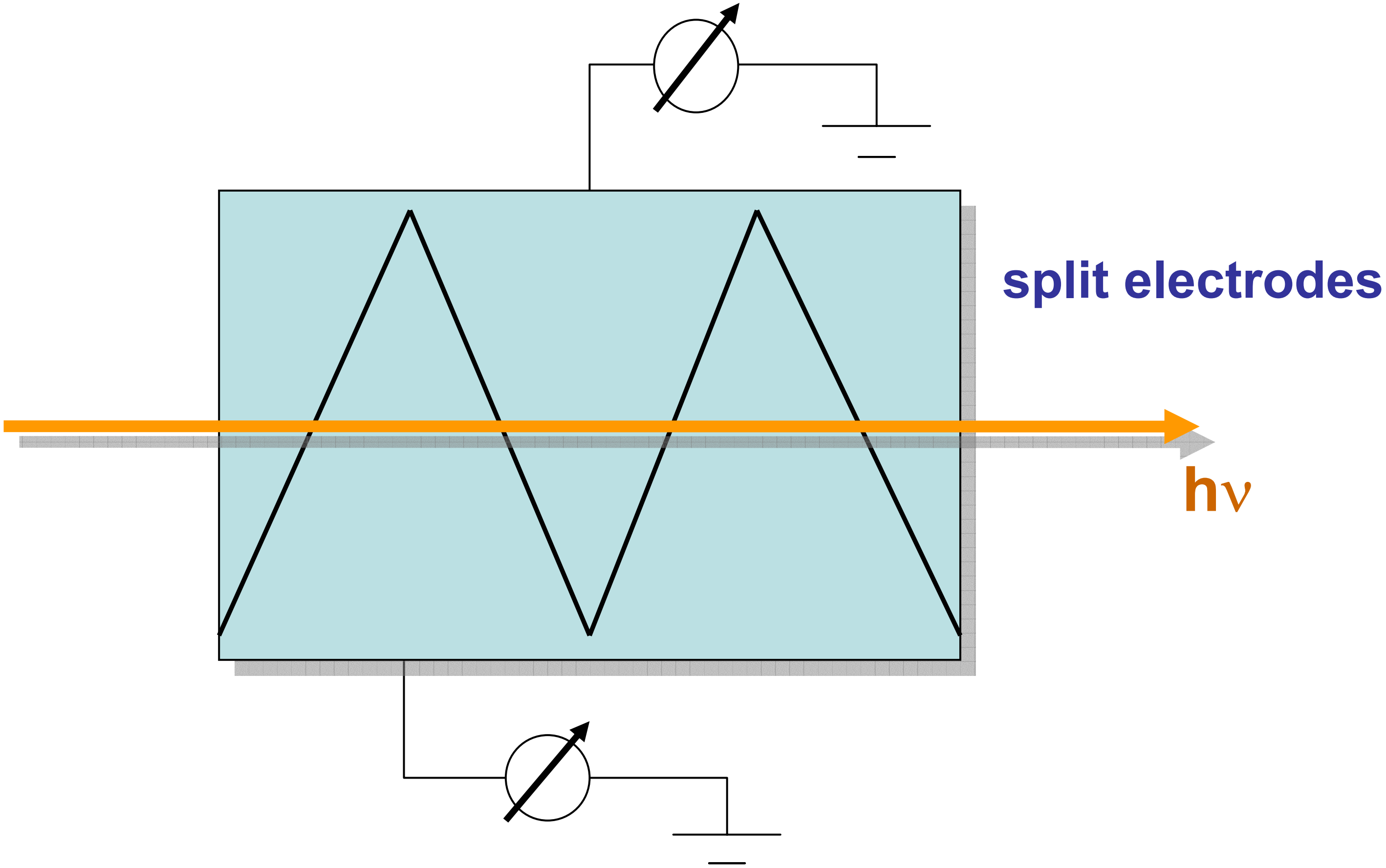
Single photoionisation:

$$N = N_{ph} \times n \times s \times l$$

N = number of electrons or ions
N_{ph} = number of photons
n = target density
s = photoionisation cross section
l = length of interaction volume

Collaboration with PTB, Berlin, and Ioffe Institute, St. Petersburg

Gas ionisation detector as beam position monitor



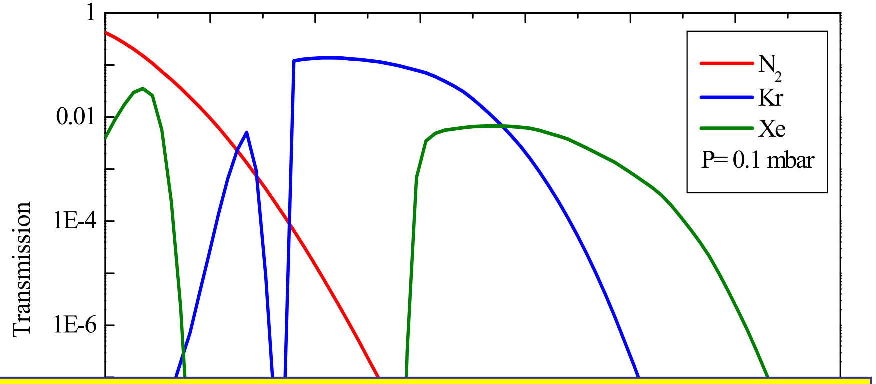
Gas ionisation detector

- can be extended to sub-nm wavelengths, but needs special design due to low cross sections
- plenty of experience with ionisation chambers for X-rays

Gas absorber to control the intensity

- Controlled attenuation of FEL beam for 6-120 nm
- Attenuation of 10^{-6} (depends on gas)
- Preserves beam attributes (coherence, statistics, spectrum, etc.)

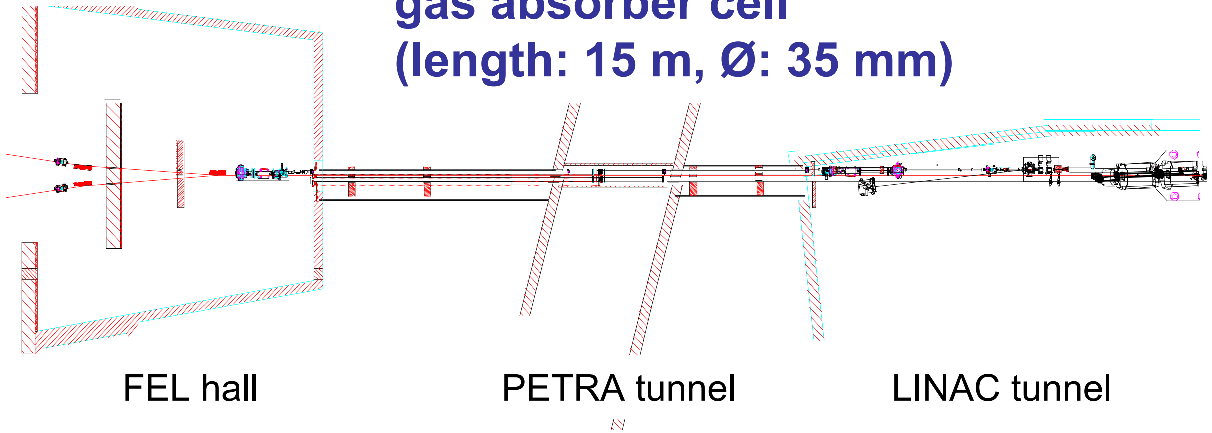
calc. transmission of gas absorber



X-rays need higher pressure and more space

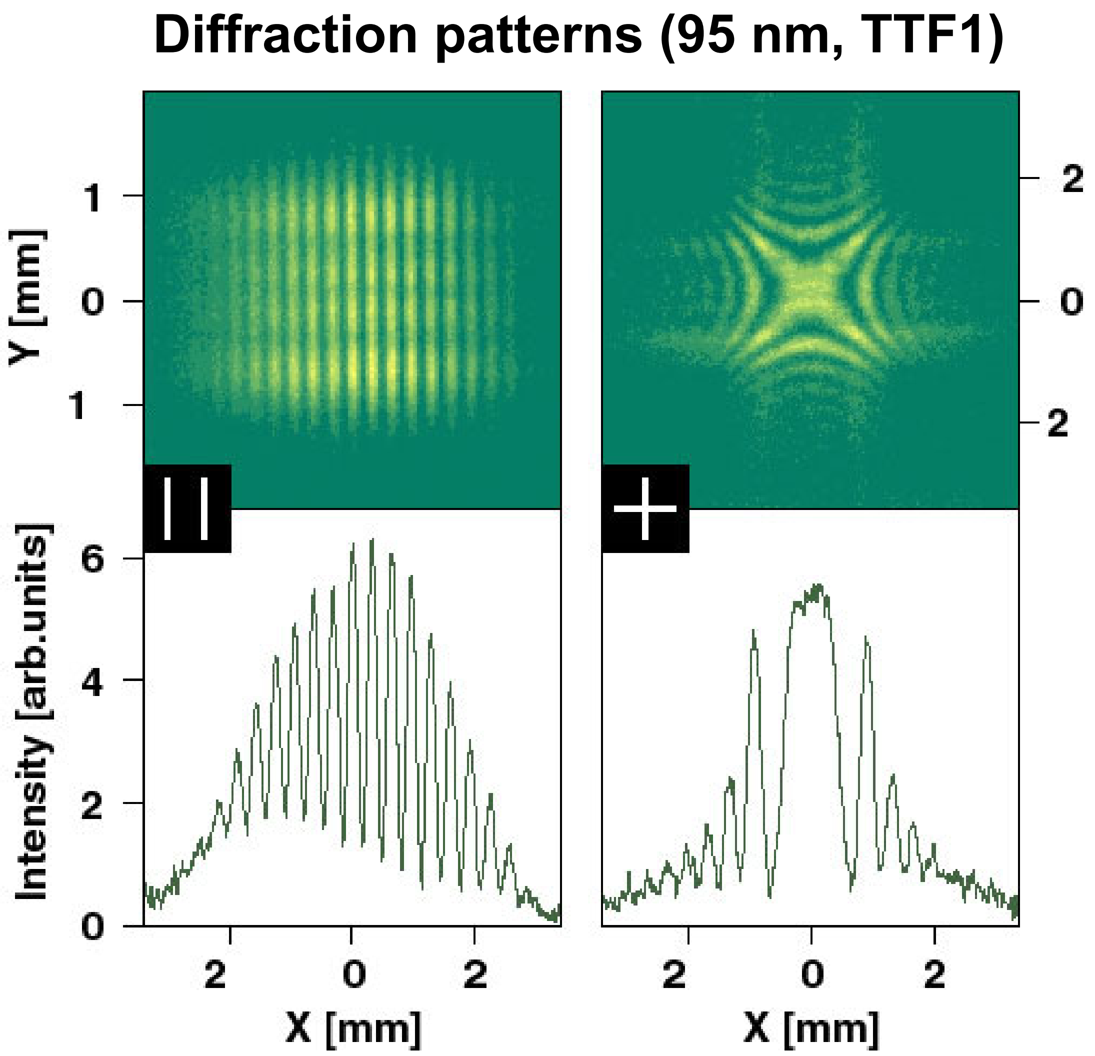
Design has been worked out for LCLS
(D. Ryutov, A. Toor, LCLS-TN-00-10)

gas absorber cell
(length: 15 m, Ø: 35 mm)



TTF1 results

Spatial coherence

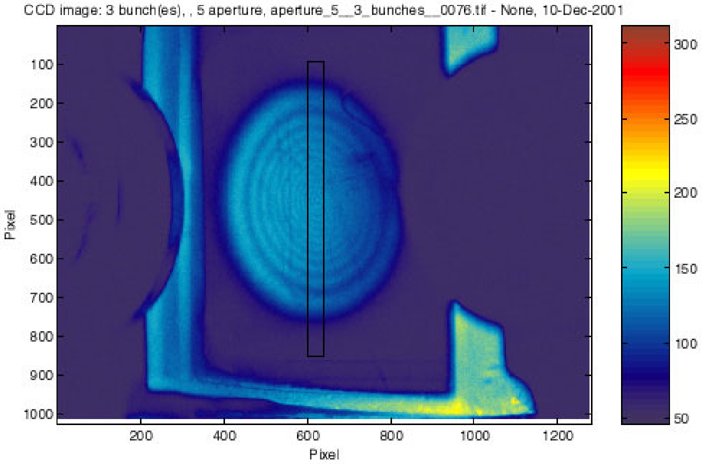


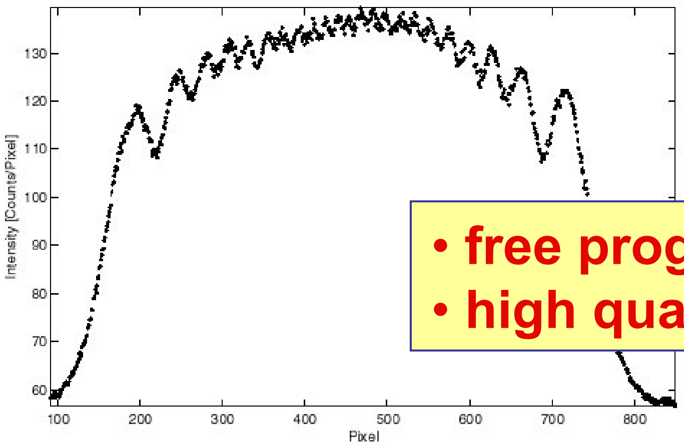
95 nm FEL radiation,
parallel slits: 200 µm wide,
2mm long, 1 mm apart,
crossed slits: 100 µm wide,
4 mm long,
FEL-slit distance ~12 m,
Ce:YAG crystal at 3 m
behind the slits

TTF1 results

Coherence

Diffraction from a 5 mm aperture

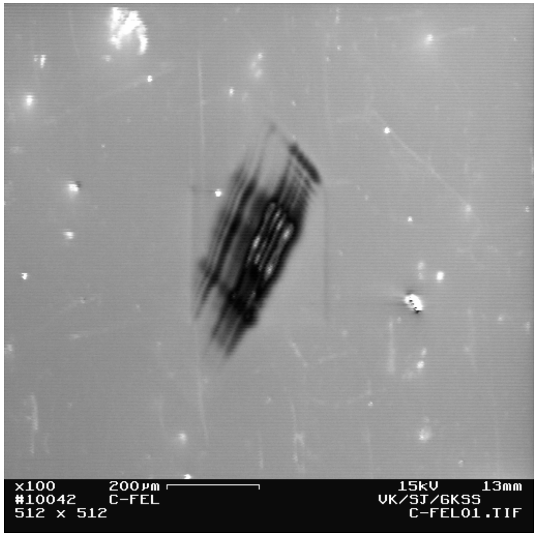




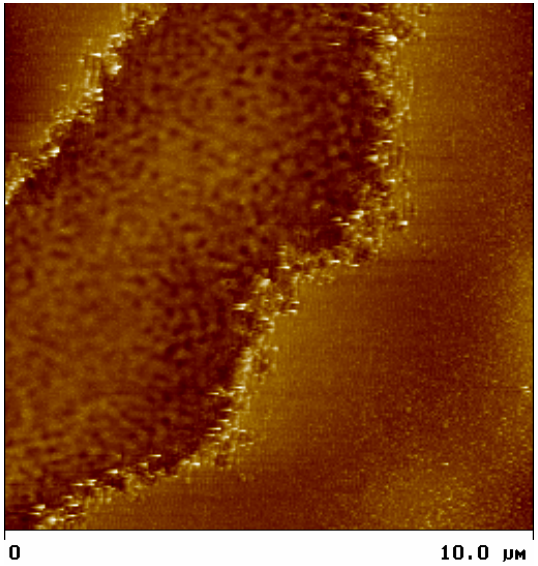
- **free progagation**
- **high quality optics**

Damage of C coatings

R. Sobierajski et al., IFPAN, DESY, GKSS



SEM



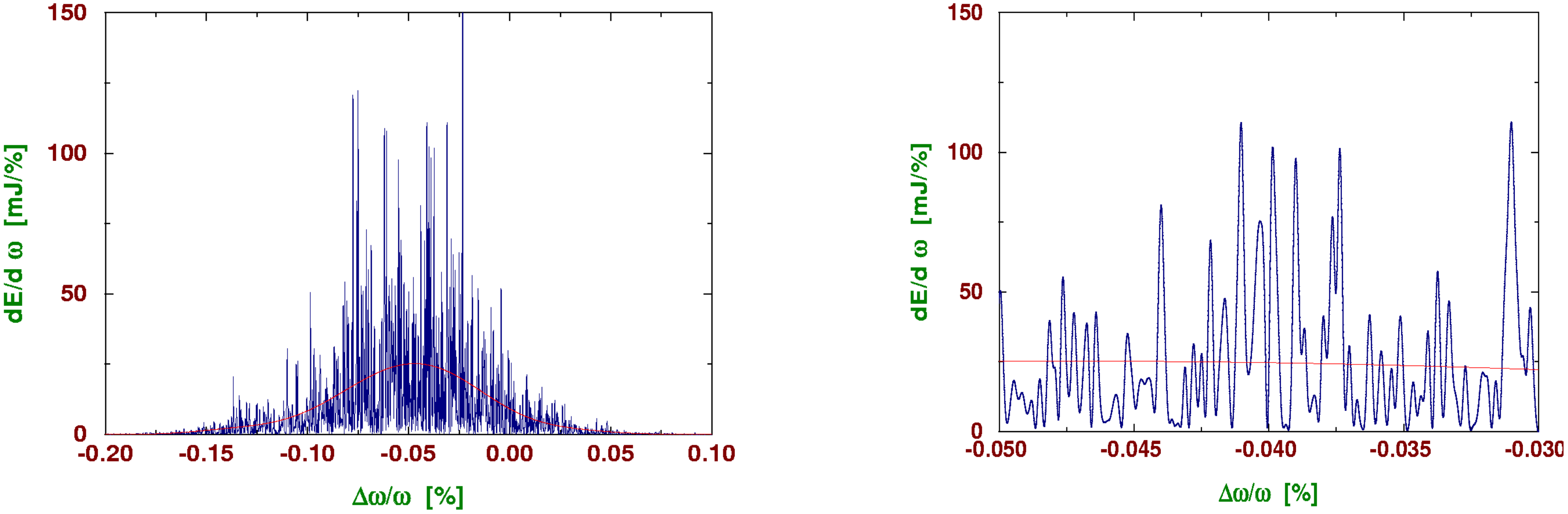
AFM

Sub-micrometer focusing: Wavefront measurements on VUV FEL

- wavefront measurement using a Shack-Hartmann sensor
- try to use adaptive optics to correct wavefront

Collaboration with LIXAM (France) and ELETTRA (Italy), funding by FP6 expected

Spectroscopy of X-ray FEL pulses



Spectral structure of 1 Å SASE FEL radiation pulse

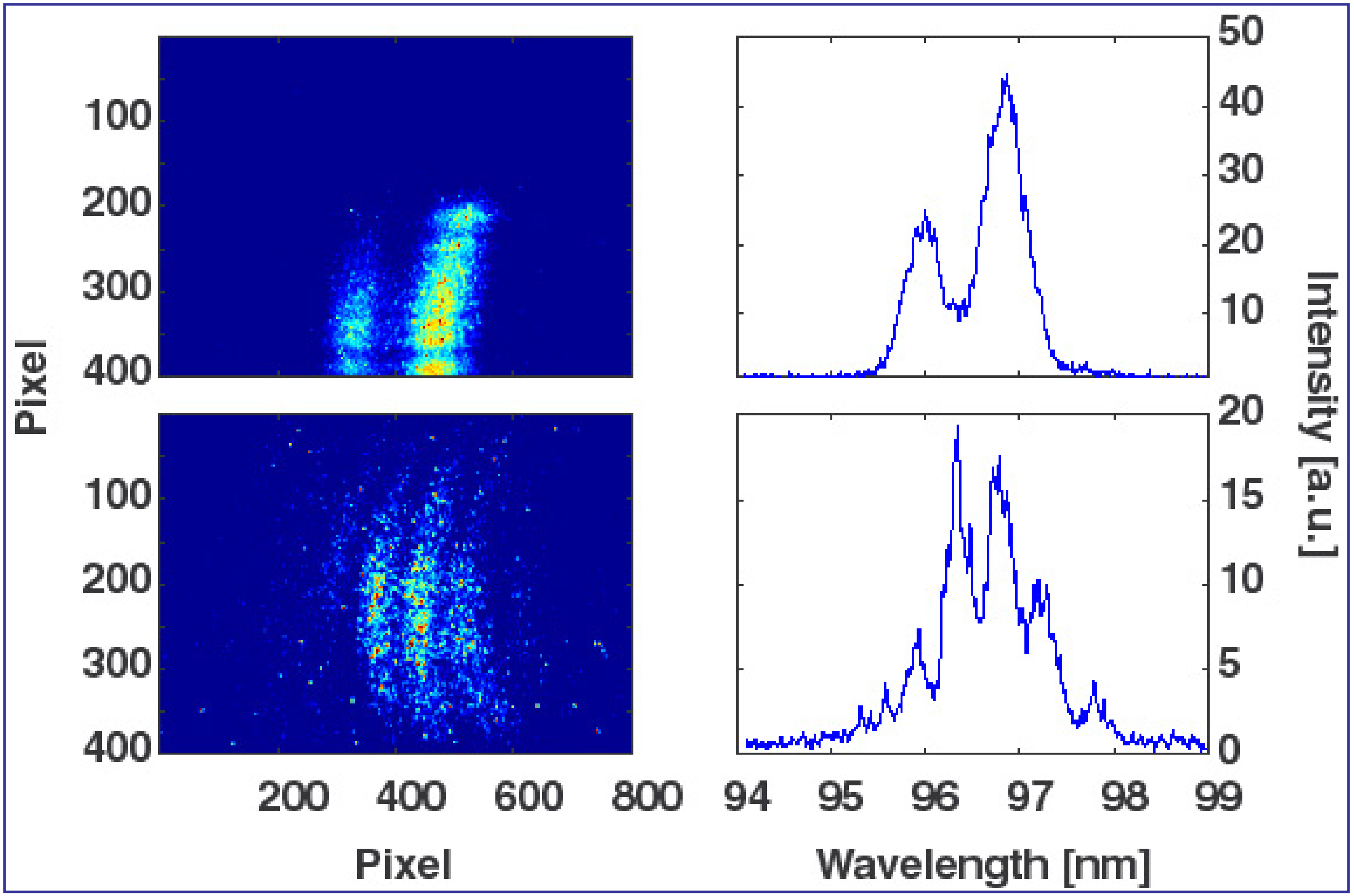
1. **Wavelength calibration and bandwidth**
   - crystal (or photoelectron) spectrometer
2. **Online spectrometer for single pulses is probably not necessary since there are too many lines**
3. **Seeding schemes can avoid fine structure, development and test on VUV FEL** (*see poster*)

TTF1 results

Spectra of single FEL pulses

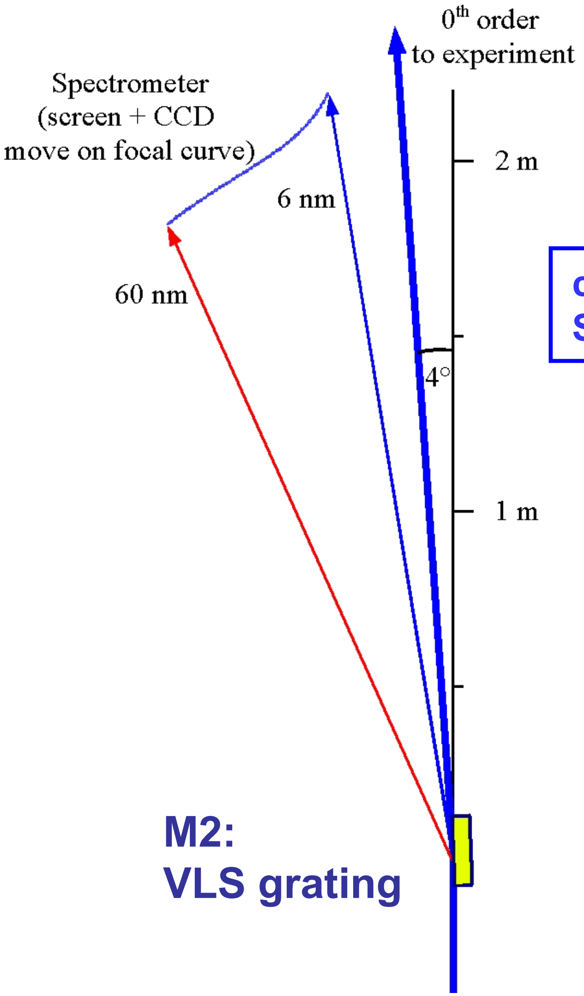
Short pulse (~50 fs)

Long pulse (~200 fs)



each pulse is different → **need online spectrometer with single shot resolution**

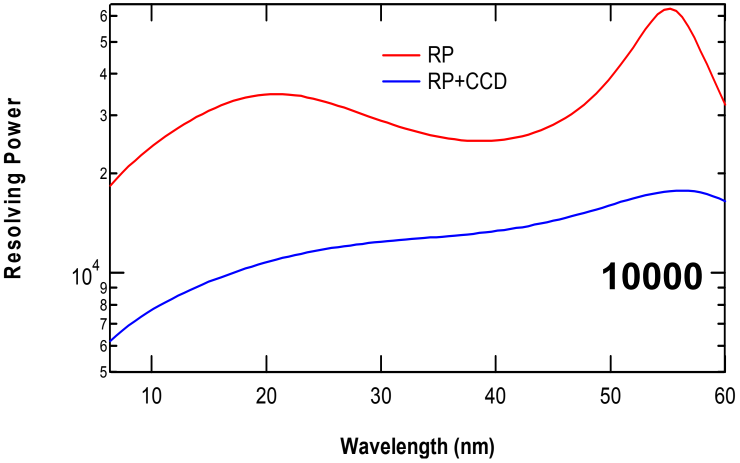
Online spectrometer for single pulses *for the VUV FEL*



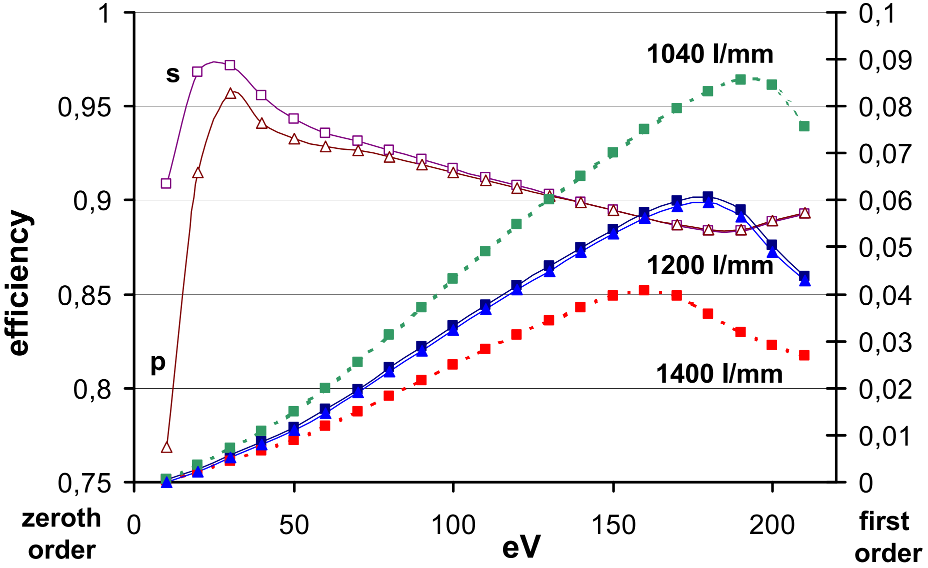
**M2:
VLS grating**

**collaboration with
SAS and CLRC**

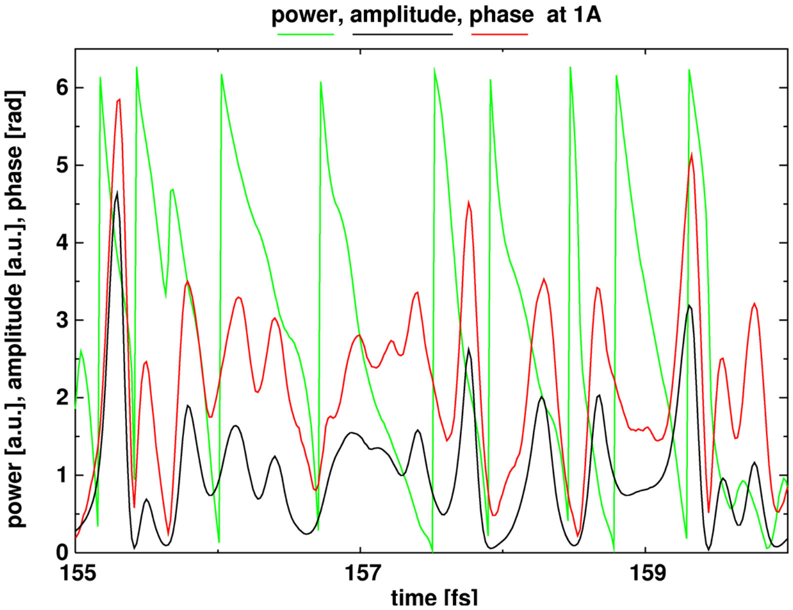
resolving power 1200 lines/mm



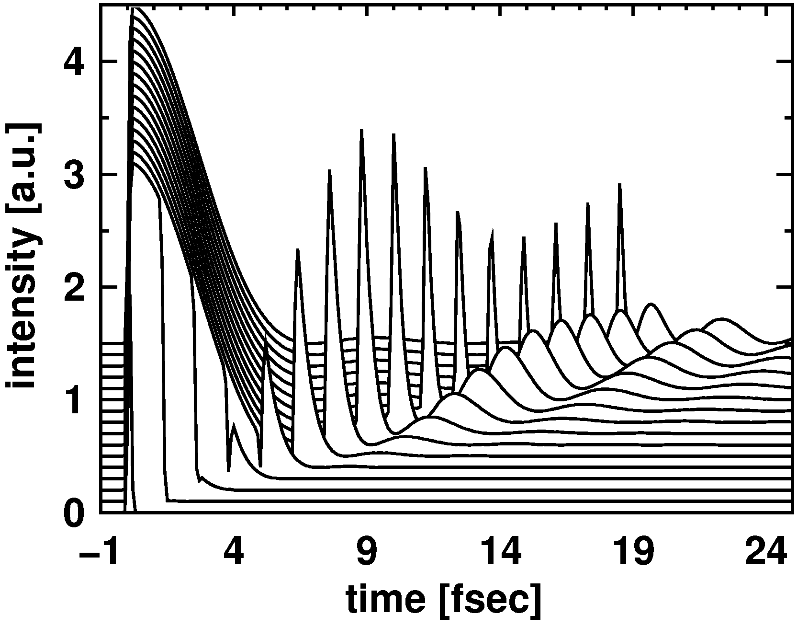
grating efficiency



Diffraction of X-ray FEL pulses



Temporal structure of a 1Å FEL pulse: pulse duration 100 fs, coherence time 0.1fs



X-ray delta-pulse reflected from diamond (111) for different crystal thickness (from 0.1µm to 11.3µm)

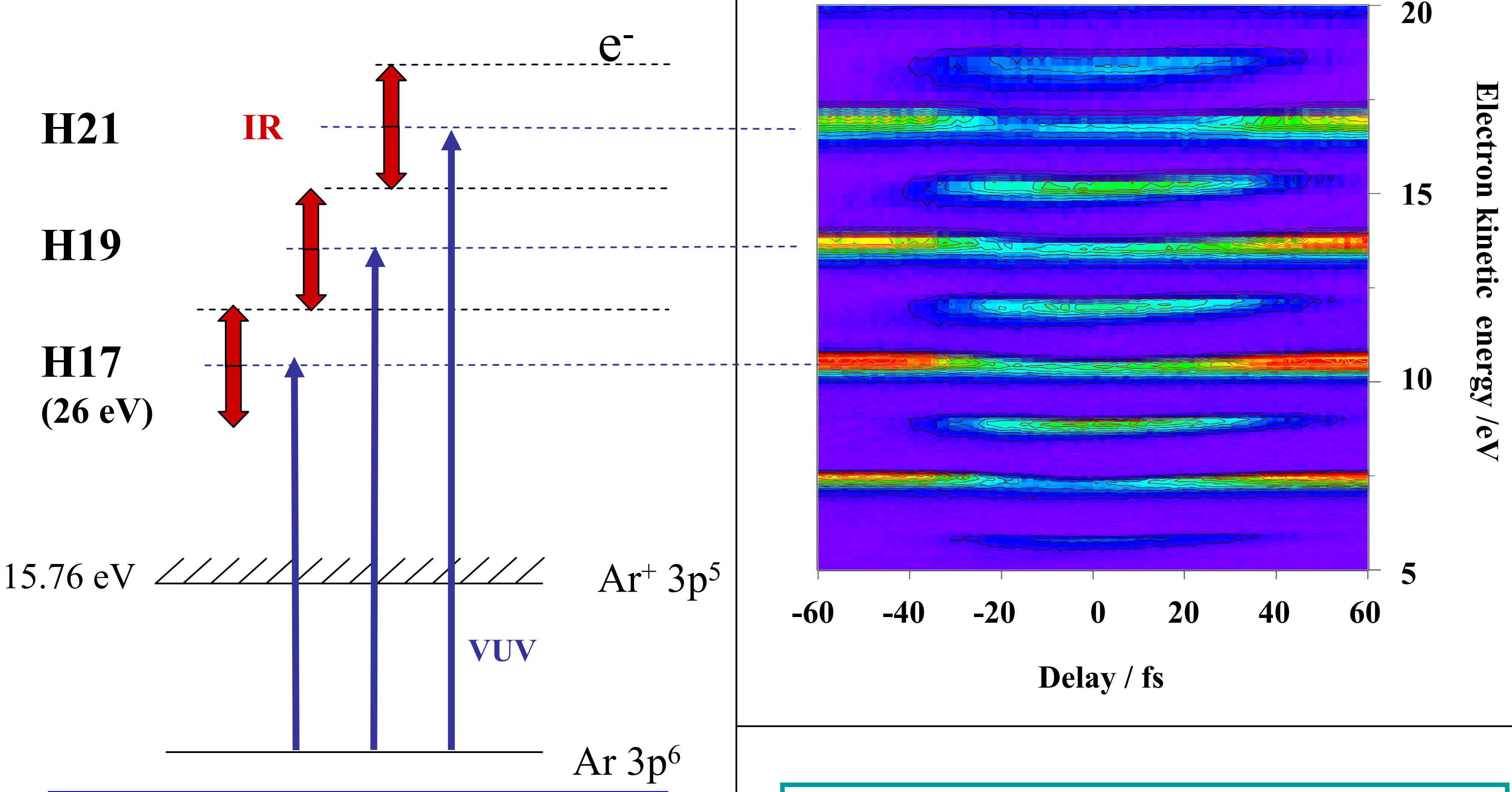
Principle problem:
The coherence length is much shorter than the extinction length of the Bragg crystal

→

measure statistical properties for different bandwidths

Pulse duration

VUV-IR cross-correlation experiments on atomic Ar at Lund



Instrumentation under construction for the VUV FEL

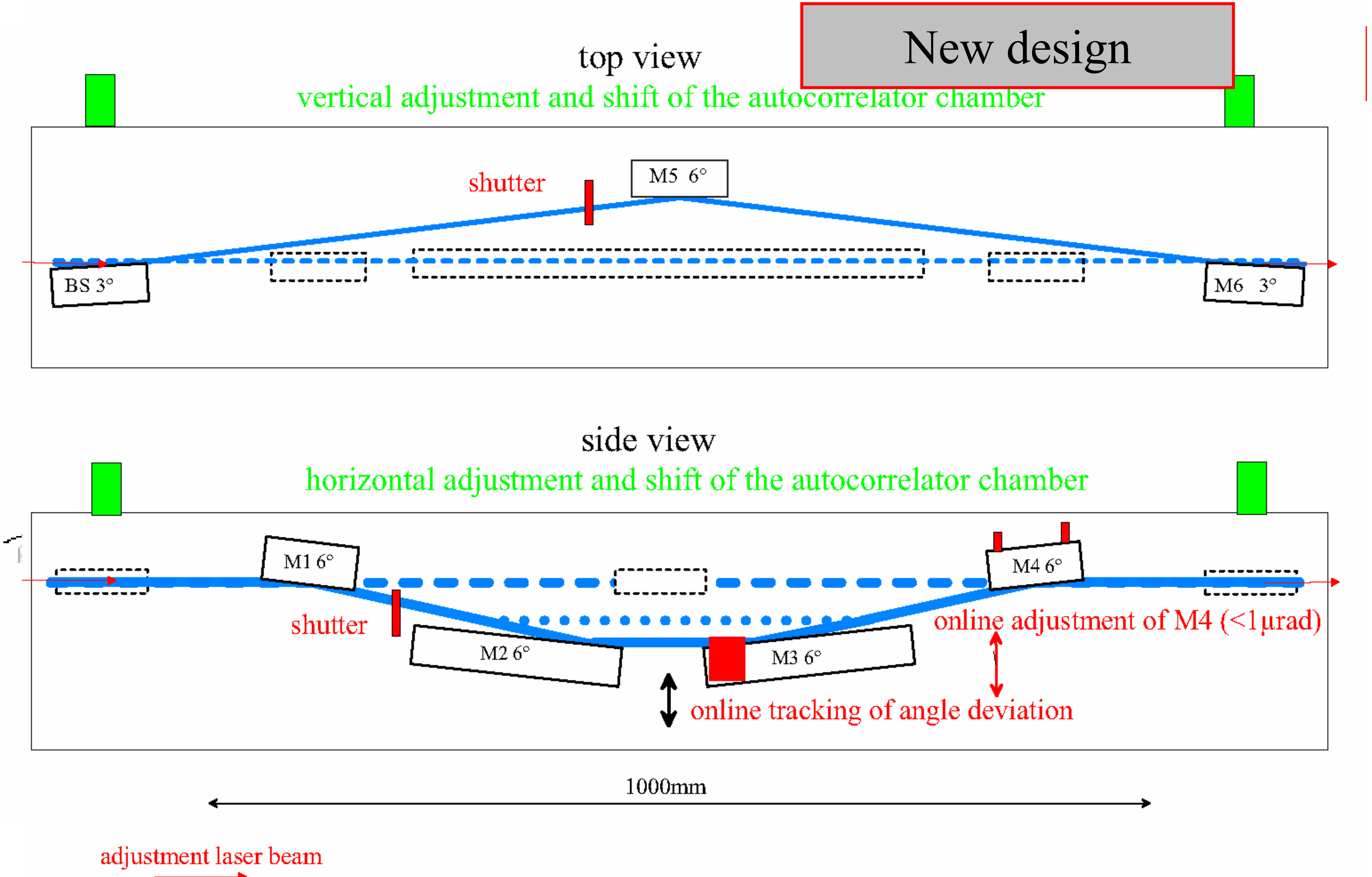
Low field regime: $I(IR) \approx 10^{11}$ W/cm^2

$\Gamma(\text{sideband})^2 = \Gamma(\text{IR})^2 + \Gamma(\text{VUV})^2$

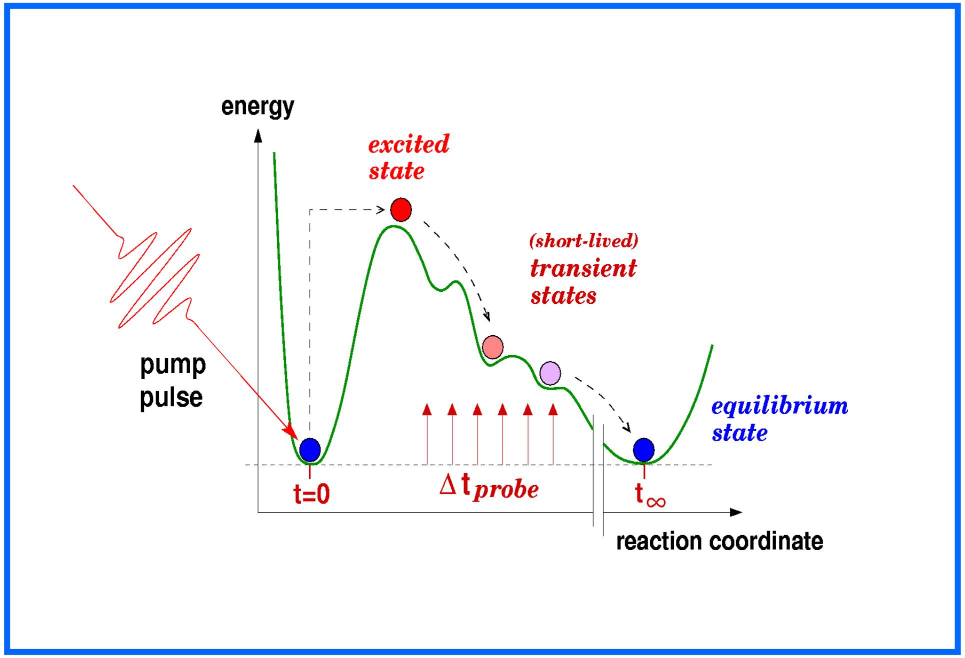
XUV beamsplitter/autocorrelator

design by BESSY, in progress

New design



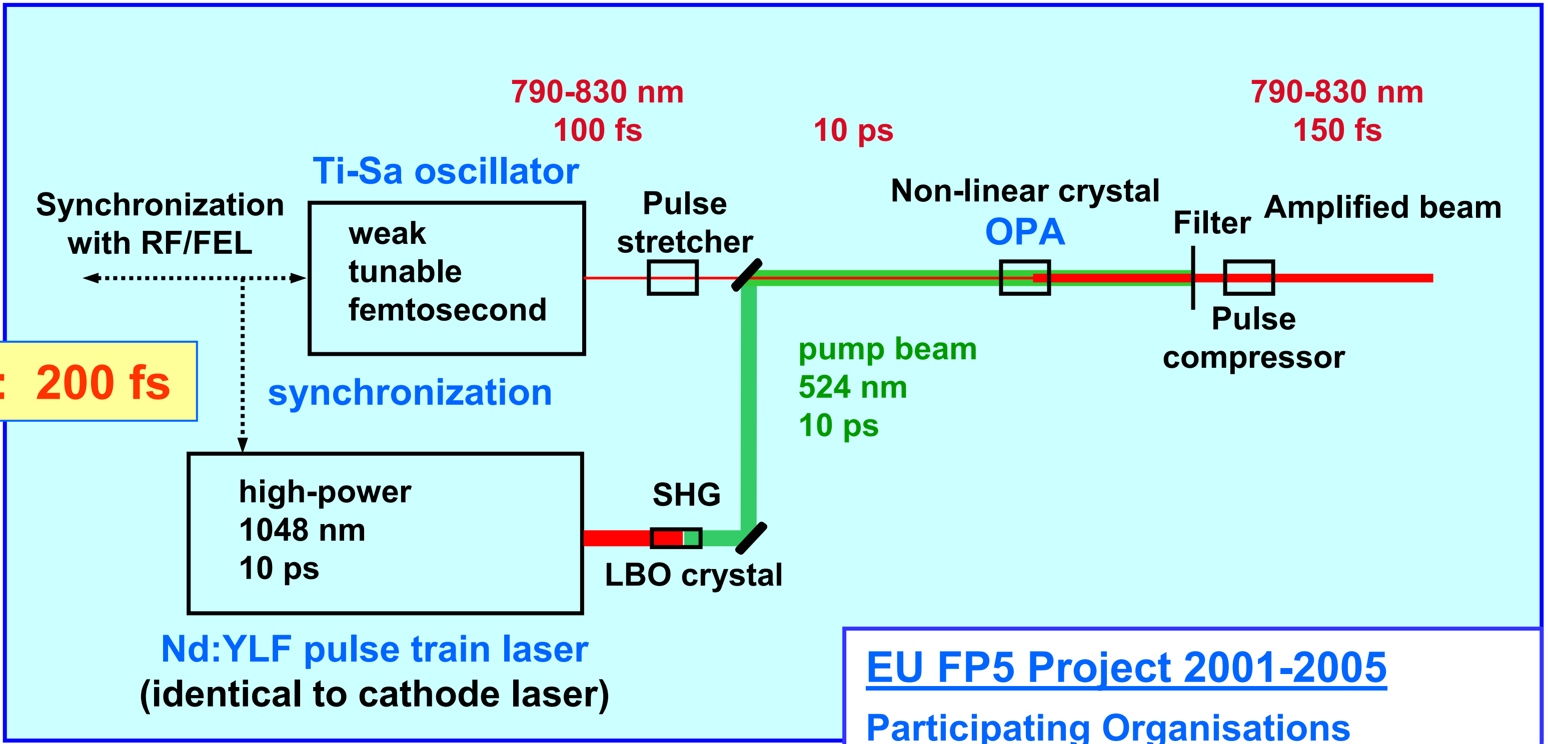
Time-resolved experiments



Schematic presentation of transition states in a chemical reaction

- **Pump-probe experiments need fs laser system synchronised with the FEL**
- **need accurate time delay between laser and FEL**
- **need information on pulse duration** ***(see poster)***

Two- color pump-probe facility combining a FEL and a high-power optical laser



Goal: 200 fs

Laser system developed by MBI
Transport to DESY early 2004

EU FP5 Project 2001-2005

Participating Organisations
HASYLAB at DESY, Germany (coord.)
BESSY GmbH, Germany
Max-Born-Institut Berlin, Germany
Dublin City University, Ireland
MAX-Lab, Lund Laser Centre, Sweden
CNRS/LURE Orsay, France

The synchronisation challenge

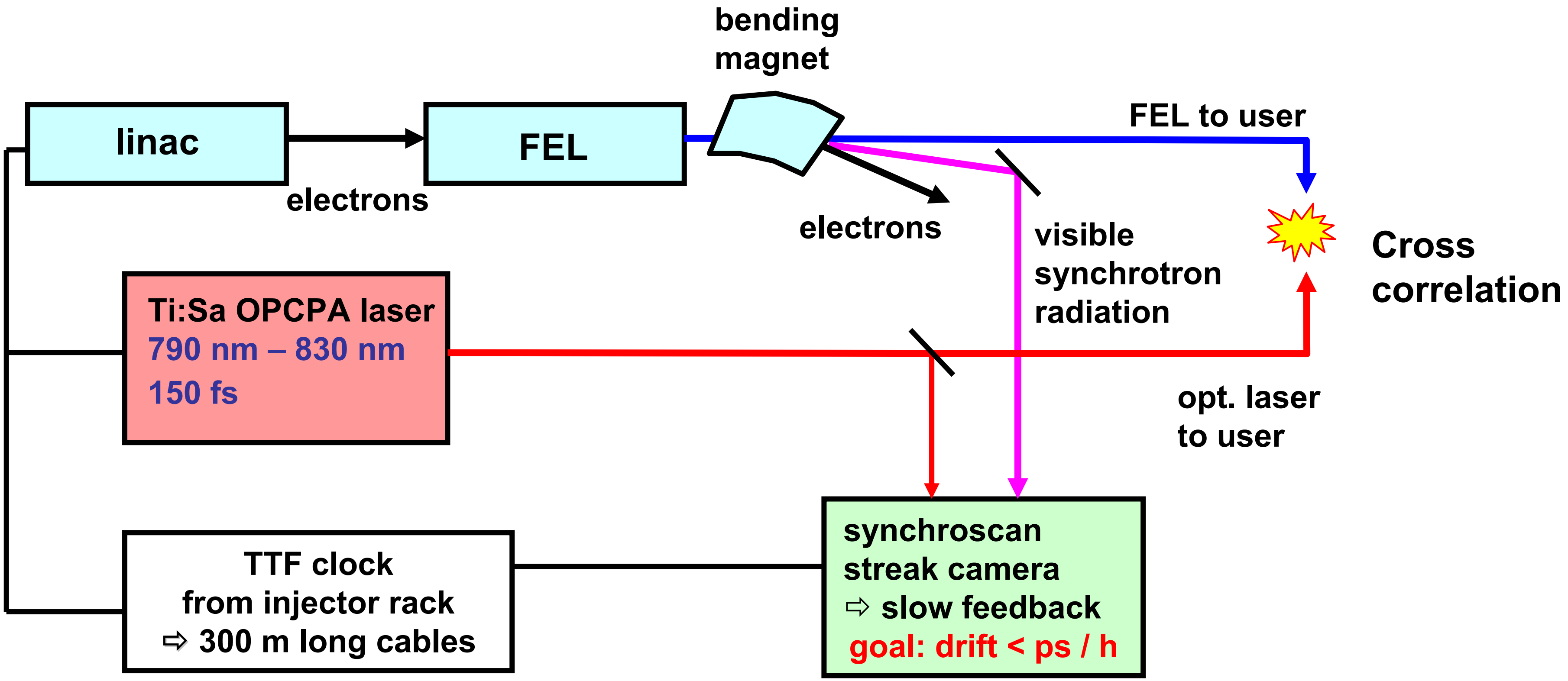
- **Two independent lasers can be synchronised with <fs precision *, but:**
- **Photocathode laser, pump-probe laser and accelerator RF independently synchronised with master oscillator and far apart**
- **Thermal drifts**
- **Accuracy of the electronic synchronisation? Initially a few 100 fs.**
- **Phase jitter of the accelerator RF pulses causes ~0.1% energy jitter of the electron bunches → several 100 fs time jitter**

Measurement of exact timing - Feedback

- Streak camera (vis. synchrotron radiation – opt. laser, slow)
- Cross correlation (single shot)
  - Visible synchrotron radiation – optical laser
  - Electron bunch – optical laser (EOS)
  - FEL – optical laser → **should be done close to experiment**

* R. Shelton et al., Opt. Lett. 27, 312 (2002)

Synchronisation with the FEL



Ti:Sa OPCPA laser
790 nm – 830 nm
150 fs

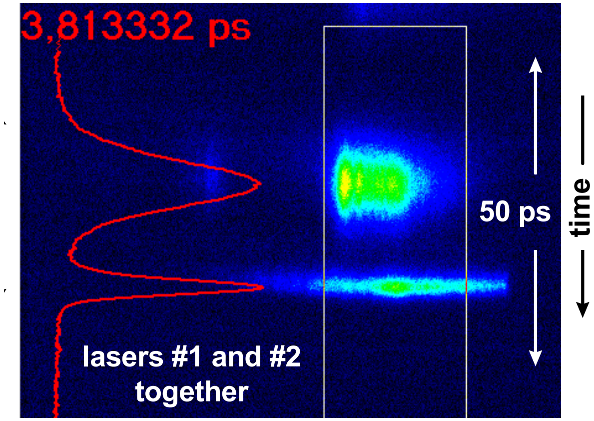
TTF clock
from injector rack
⇨ 300 m long cables

synchroscan
streak camera
⇨ slow feedback
goal: drift < ps / h

Current developments
(funding expected from FP6)
Cross correlation techniques,
electro-optical sampling
⇨ Fast feedback

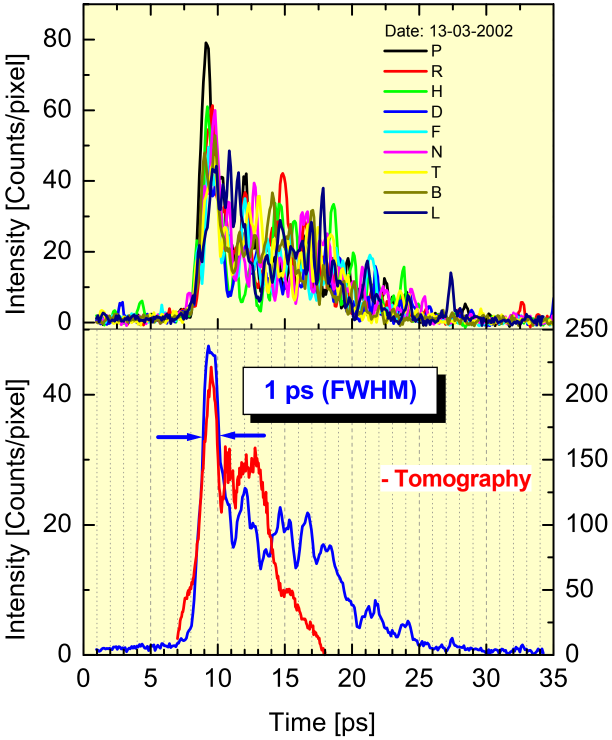
Phase detection, test experiments

Streak camera



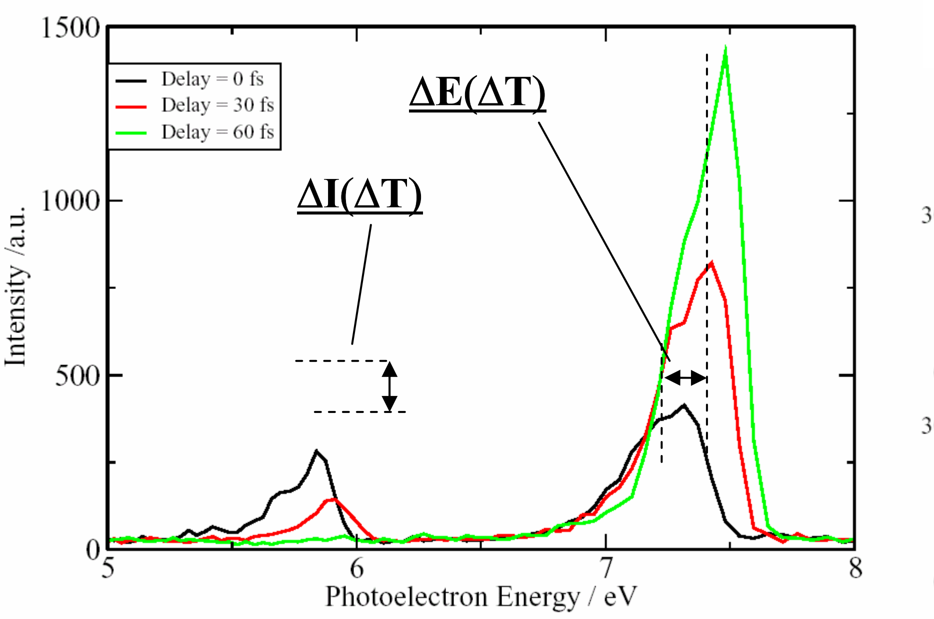
two independent laser beams (MBI)

TTF1 result

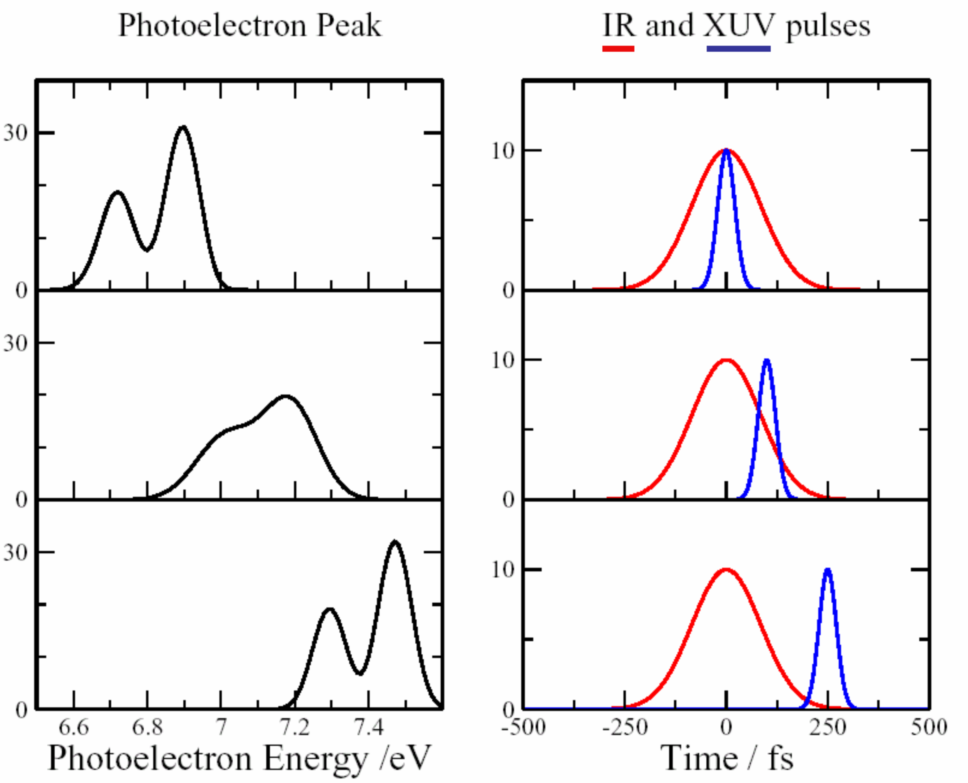


FESCA 200 at TTF1 green dipole radiation

VUV-IR cross-correlation experiments on atomic Ar at Lund



Simulation



High field regime: I (IR) ≈ 10^{13} W/cm^2

$$E_{kin} = \omega_{XUV} - IP - U_p$$

$$U_p\ [eV] = \alpha\ I\ [W/cm^2]$$

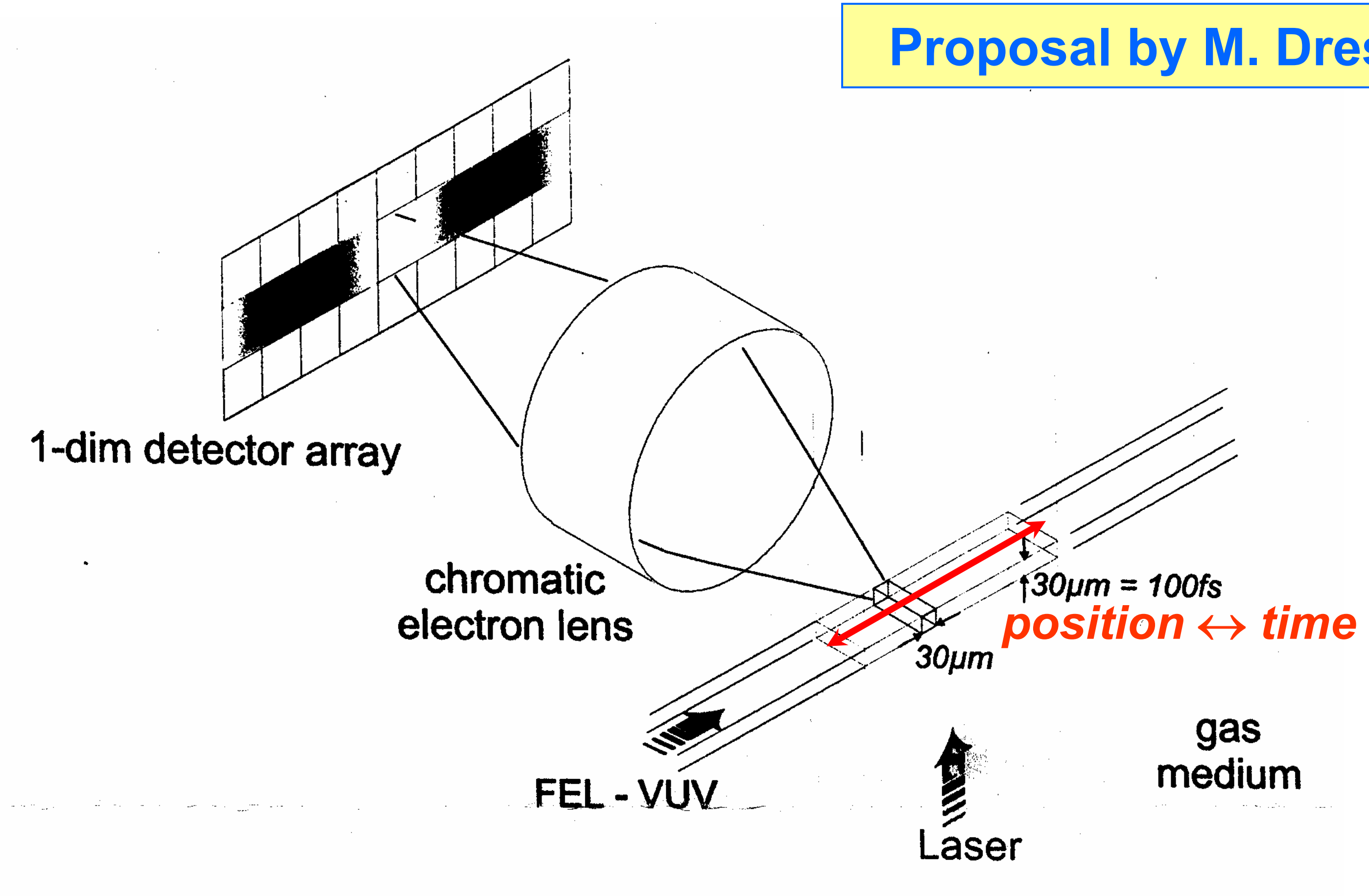
$$\alpha = 9.33 \times 10^{-14}\ \lambda^2\ [\mu m^2]$$

→ *timing information*

Single-shot cross correlator

for the VUV FEL

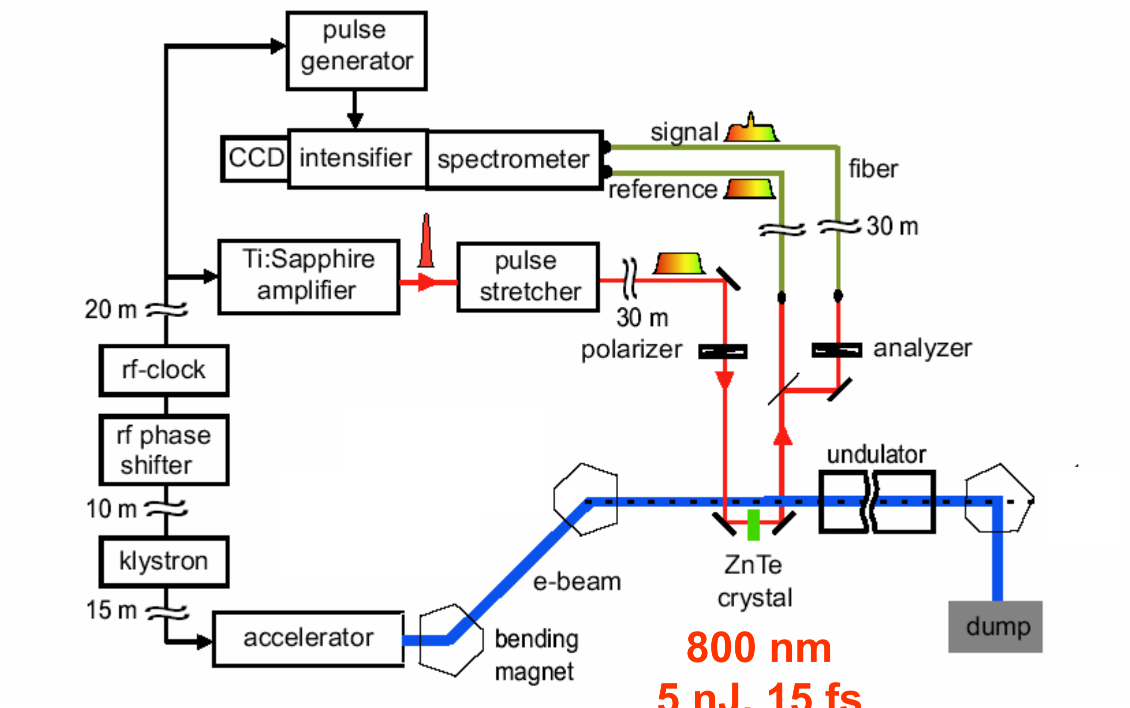
Proposal by M. Drescher



Concept:

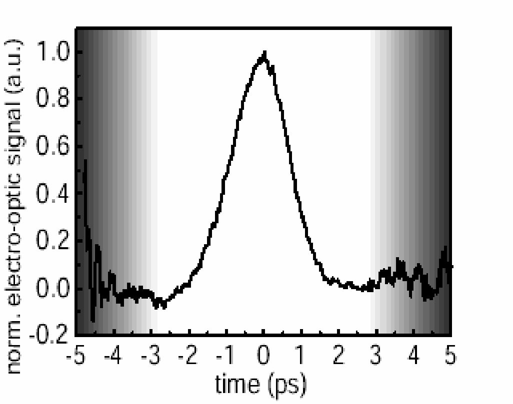
measure exact timing online for every pulse and sort the data

Electro-optical sampling (EOS)



800 nm
5 nJ, 15 fs

Single-shot chirped pulse spectrometer



Single- shot measurement of the electric field of an individual electron bunch at FELIX, pulse length ~ 1.7 ps FWHM)

G. Berden et al., Proceedings DIPAC 2003, GSI, Mainz, Germany

A similar system

- **is currently commissioned at SPPS (Stanford) using optical fibre**
- **will be installed at the VUV FEL (collaboration with SLAC, U. Mich.)**

Current developments

for the VUV FEL

1. Test of different correlation techniques
2. Installation of EOS using light from the pump-probe Ti:Sa oscillator transported by optical fibre to EOS crystal
3. Use separate laser for EOS, synchronise all lasers and accelerator RF to <10 fs using laser master oscillator and fibre network
4. Investigate and improve accelerator induced time jitter

→ Prerequisite to seeding with fs harmonics

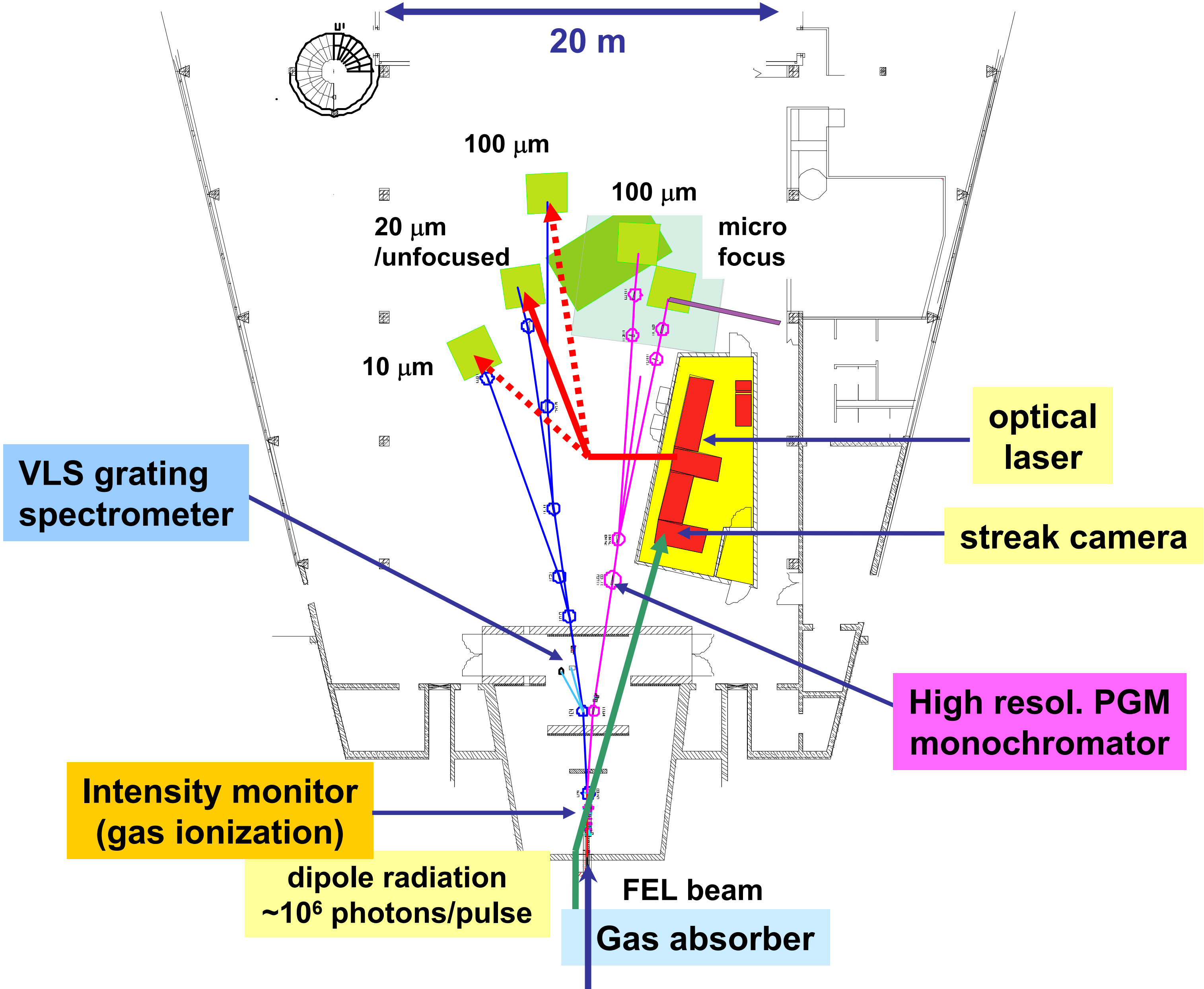
Avoiding the synchronisation problem

- Produce the optical pulse by the same electron bunch in a second, long-wavelength undulator
- Combine fractions of the same pulse (autocorrelation) or combine with higher FEL harmonic

Challenges

- Beam transport with tunable delay
- Beam splitting

Layout of VUV FEL user facility



optical laser

streak camera

VLS grating spectrometer

High resol. PGM monochromator

Intensity monitor (gas ionization)

dipole radiation ~10^6 photons/pulse

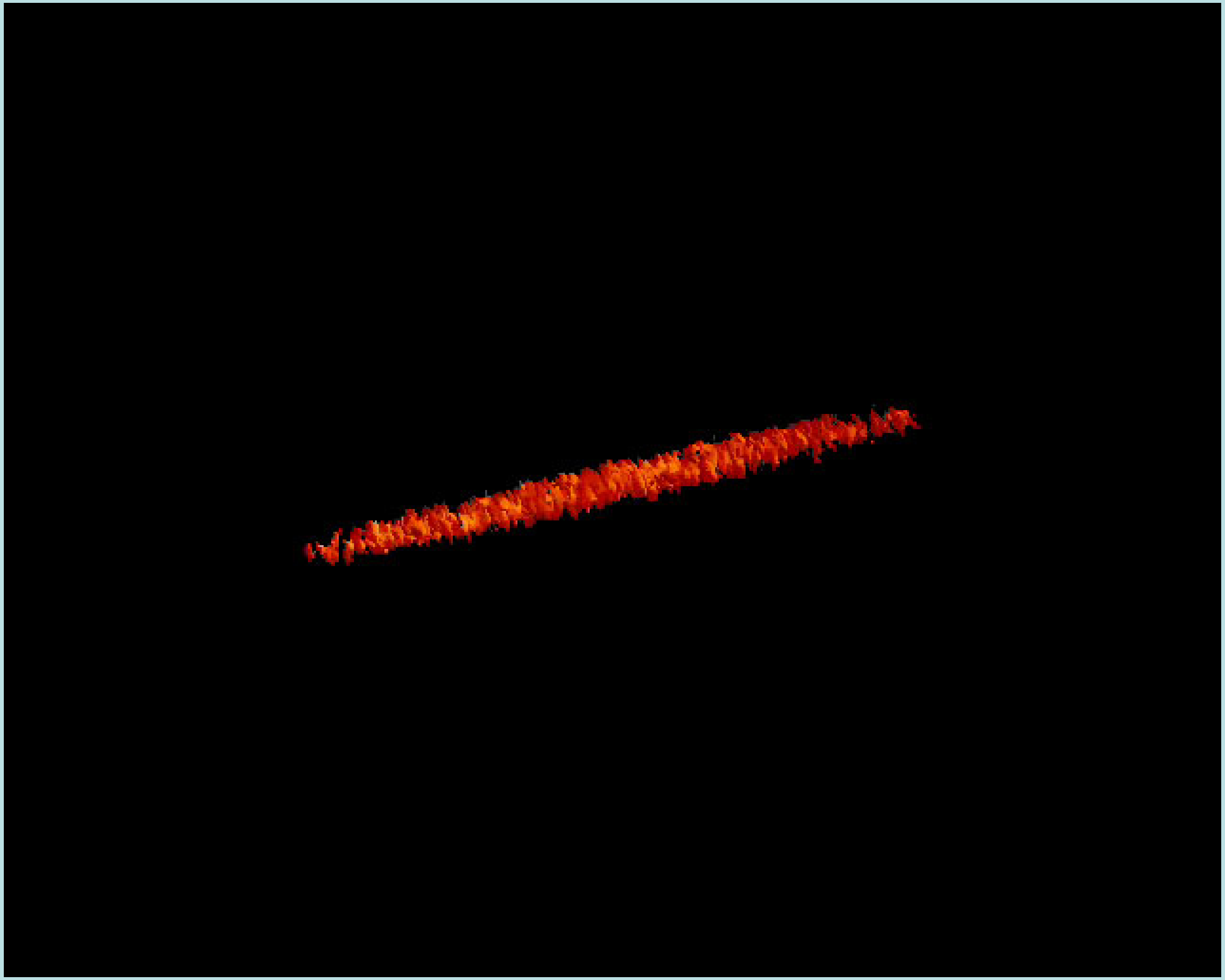
FEL beam

Gas absorber

Conclusions

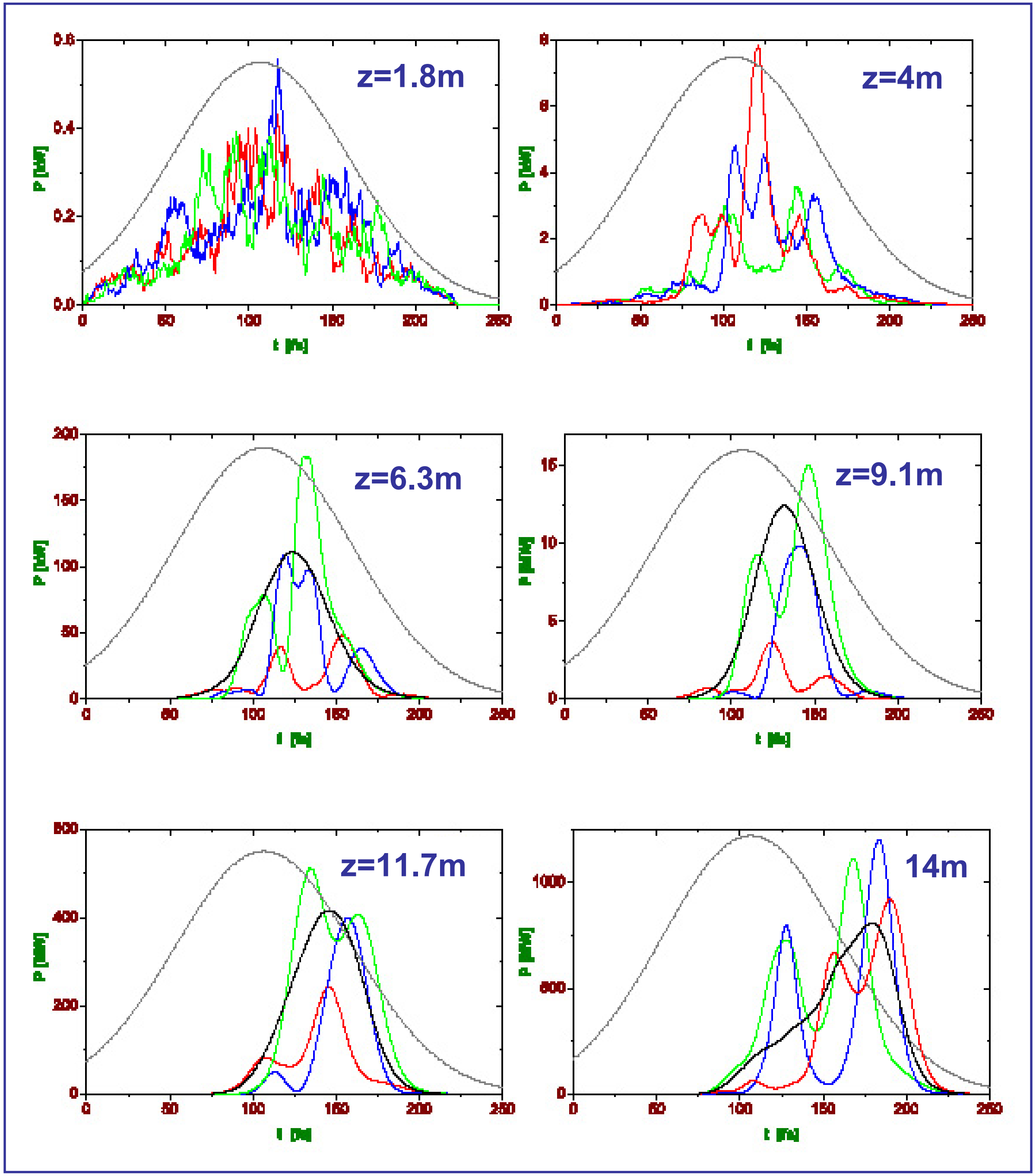
- **Basic techniques for XFEL beam diagnostics are available**
- **Much will be learned from current R&D for the VUV FEL and SPPS**
  - **pulse-resolved online diagnostics**
  - **synchronisation of optical lasers, measurement of exact timing and temporal pulse structure**
  - **seeding schemes to improve beam properties**
  - **hardware and software integration of all systems**

SASE FEL simulation



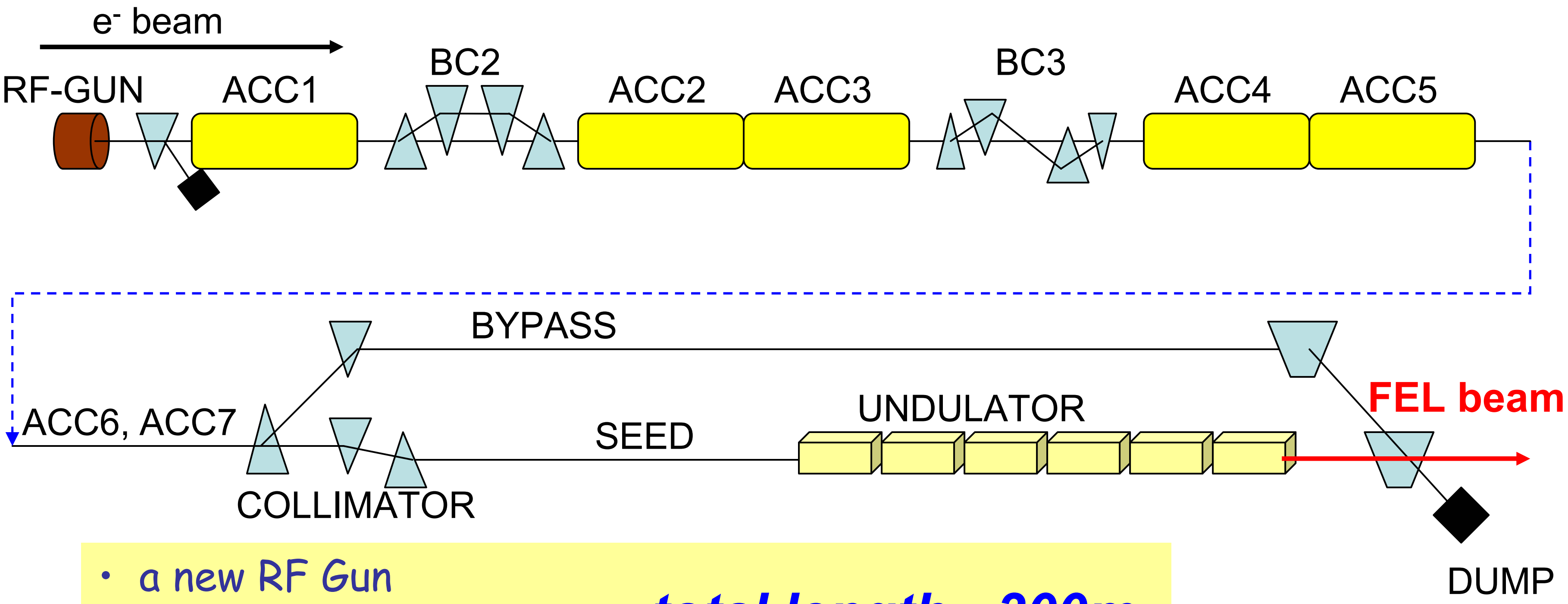
λ = 12 µm, GENESIS, S. Reiche

TTF1, short pulse
FAST, M. Yurkov



VUV FEL user facility

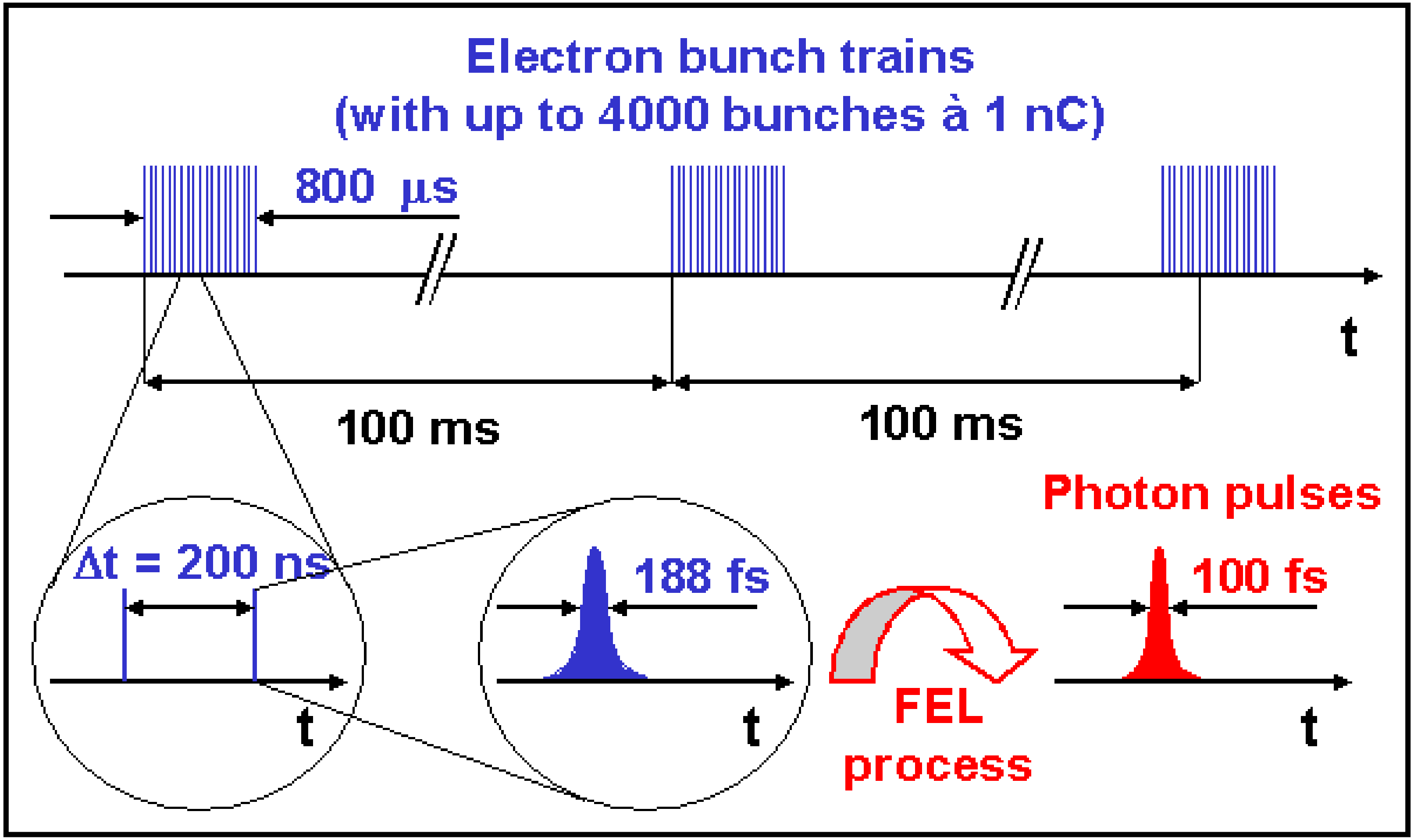
The layout of TTF2



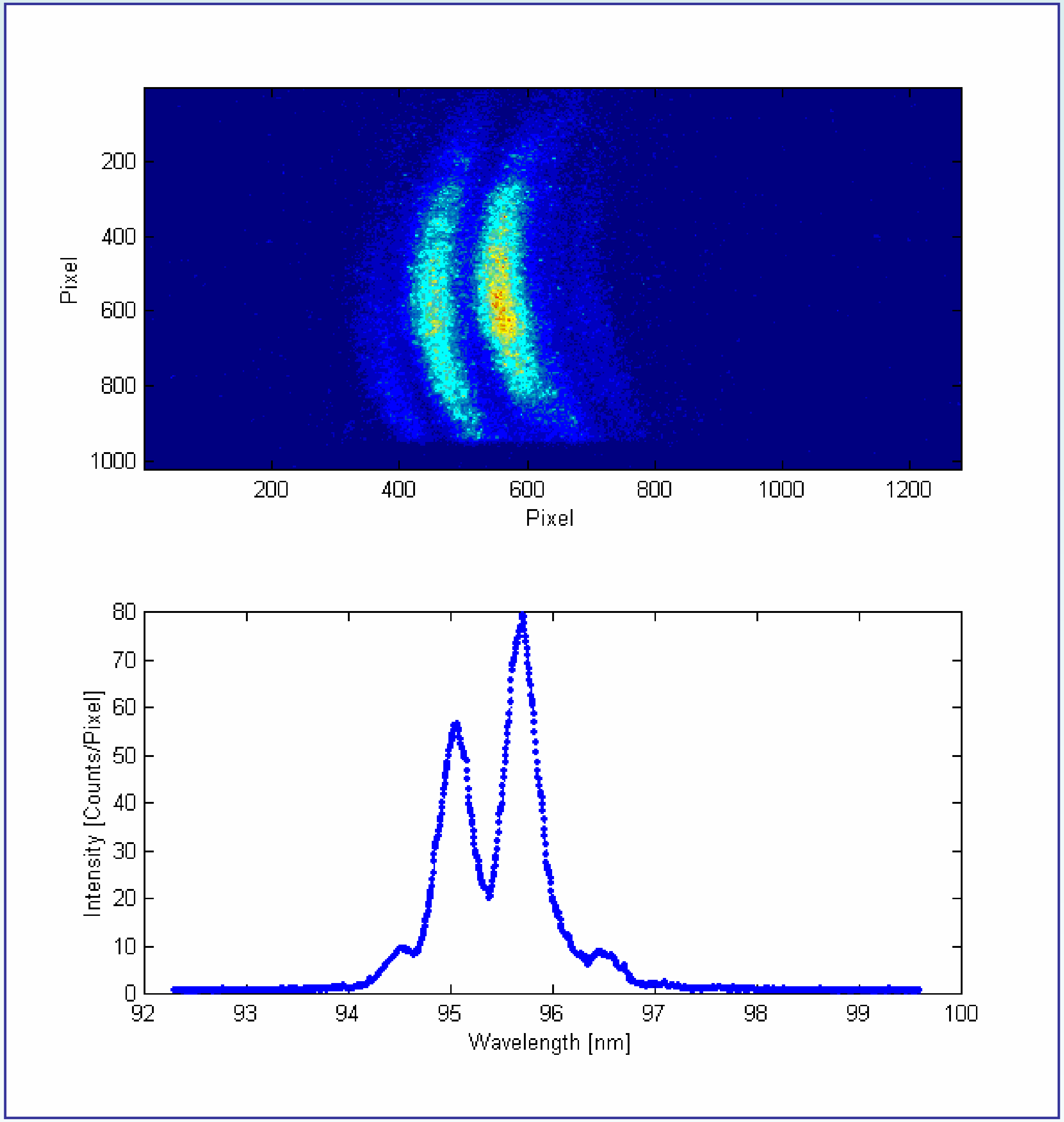
- a new RF Gun
- a new injector concept
- 5 new accelerator modules (later 6 or 7)
- another bunch compressor
- new beamlines (more than 150 m)
- a new collimator concept (transv. and energy collim.)
- a 30 m long undulator (6 modules plus quads.)
- a long bypass and a spectrometer line

total length ~300m

Pulse distribution of the XFEL



TTF1 results

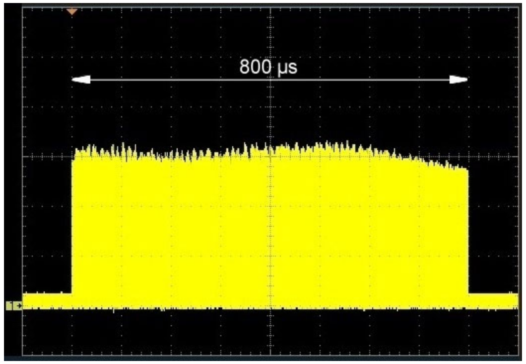


Ti:Sapphire OPCPA laser – actual parameters

complete OPCPA system works and is implemented in DOOCS

pump laser

- drift < 1 ps/h without active synchronization
- thermal lensing corrected by deformable mirror
- pulse length: 10 ps
- energy per pulse: 150 µJ (green)



OPCPA output

- tunability: 790 nm – 830 nm
- pulse length: 150 fs (8 ps)
- energy per pulse: ~ 5 µJ
- pulse rate: 1 pulse/ 1µs (for 800 µs pulse train)
- fluctuations: < 10 % RMS

Edge diffraction

Simulation