Technological Challenges Towards Short-Wavelength FELs

Jörg Rossbach
University of Hamburg & DESY

Past,

Presence,

Future, …

Basic FEL requirements

No good mirrors at short wavelengths → FELs must operate in high-gain mode

power gain length (1D): $L_G = \frac{1}{\sqrt{3}} \left(\frac{I_A \gamma^3 \sigma_r^2 \lambda_u}{4\pi \cdot \hat{I} \cdot K^2} \right)^{1/3} \propto \frac{\gamma_{res}}{(n_e)^{\frac{1}{3}}}$

BUT:
talk by K.J. Kim TUBAU05

3D charge density

Particles with large betatron-amplitude fall out of FEL resonance.

→ Need small electron beam emittance and kA-peak current.

Focal length due to linear part of space charge forces:

$$f \approx \frac{ec}{r_e} \frac{\bar{\beta} \varepsilon_{norm}}{z} \frac{\gamma^2}{\hat{I}} \approx 10 \text{ m within few meters of drift } z$$

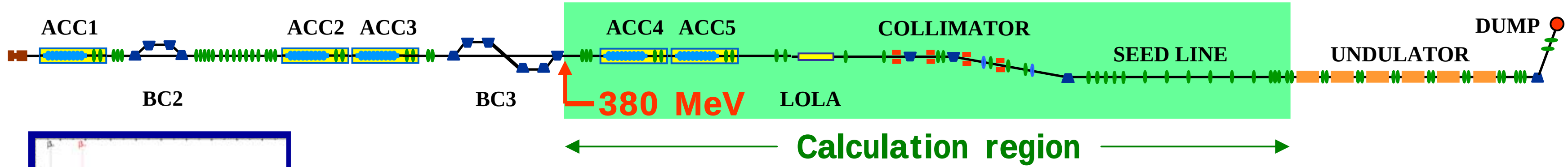
$$(\text{for } \gamma \approx 200,\ \bar{\beta} \approx 10\text{m},\ \varepsilon_{norm} \approx 2 \times 10^{-6}\text{m},\ \hat{I} \approx 1\text{kA})$$

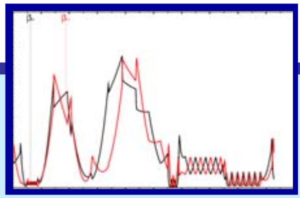
Electron beam carries its own focusing system, difficult to control!

Also: strong longitudinal forces if bunches are short, see later…

talk by G.Stupakov MOCAU05

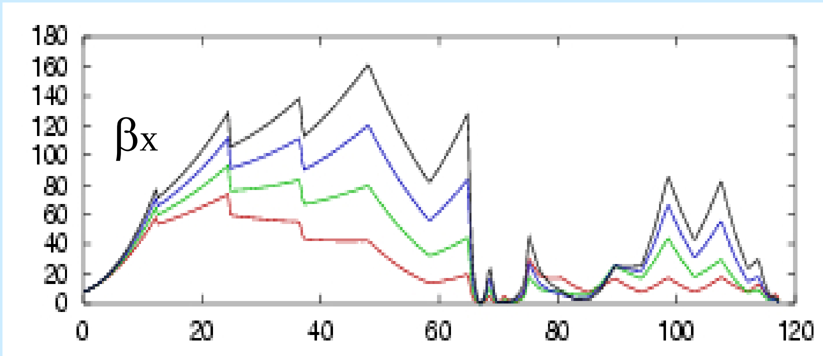
Transverse space charge effect on optics at FLASH

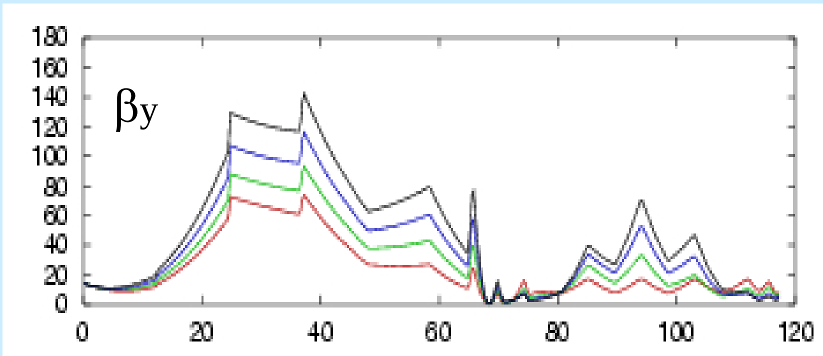




$\varepsilon_{n,\ initial}$ = 2 mm mrad.

I = 0, 1, 2, 3 kA





$$\beta_x = \frac{\langle x^2 \rangle}{\sqrt{\langle x^2 \rangle \langle p_x^2 \rangle - \langle x\, p_x \rangle^2}}$$

courtesy
N. Golubeva,
V. Balandin

How to produce electron beam?

cf. paper of M.- Ferrario on EPAC06

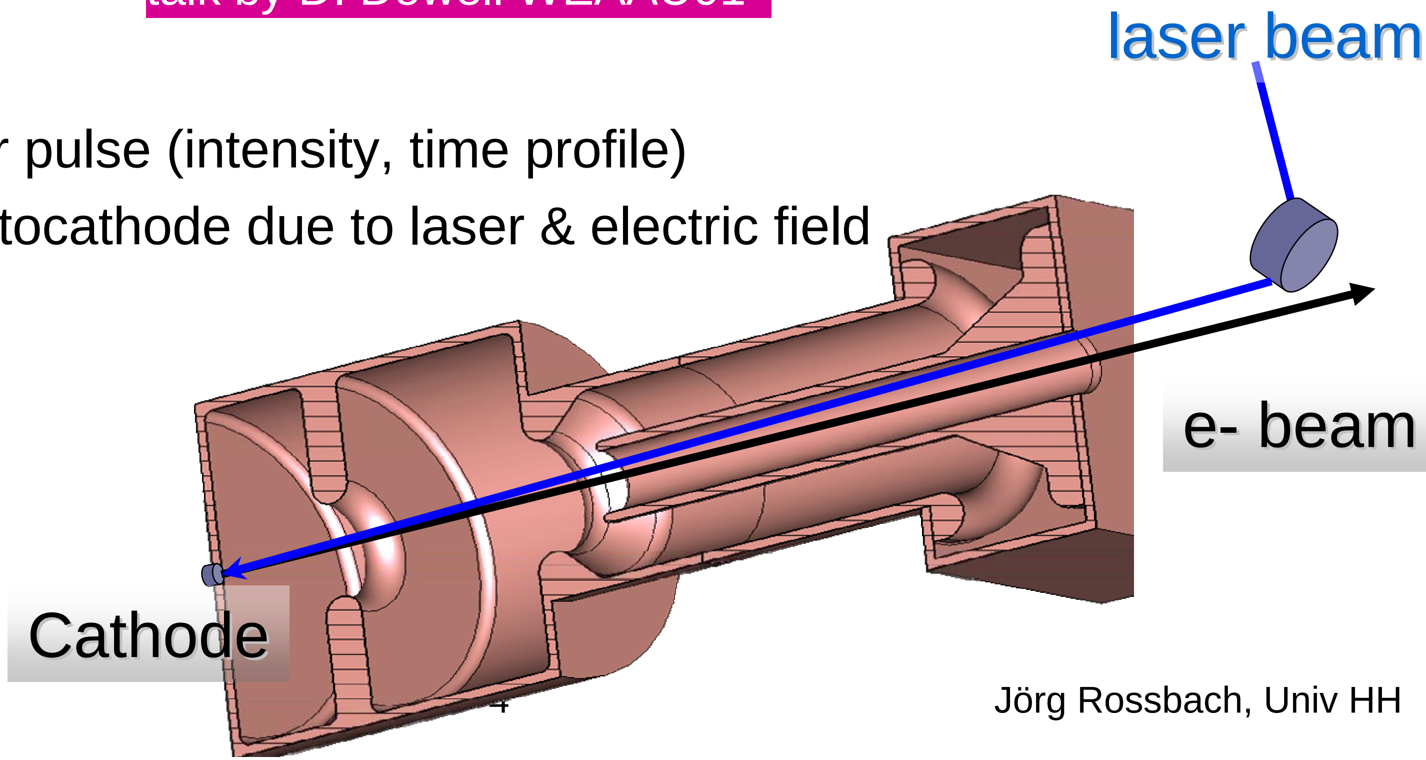
A) Photoinjector (R. Sheffield/LANL)

Results:

- PITZ/DESY: Normalized emittance ~ 1.5 mrad mm @ 1nC (long pulse trains) talk by F. Stephan WEBAU02
- LCLS/SLAC: Normalized emittance ~ 0.8 mrad mm @ 1nC (single bunch) talk by D. Dowell WEAAU01

Issues:

- Stability of laser pulse (intensity, time profile)
- Damage of photocathode due to laser & electric field



How to produce electron beam?

B) Thermionic (Shintake/SPring8)

talk by T. Shintake TUBAU02

Single CeB6 crystal, 500 kV dc acceleleration

Results:

- Normalized emittance ~ 0.7 mrad mm @ 1 A dc current
- Excellent stability, very small momentum spread

Issues:

- Complex bunching and compression system

C) Field emitter arrays (PSI)

talk by A. Oppelt TUBAU05

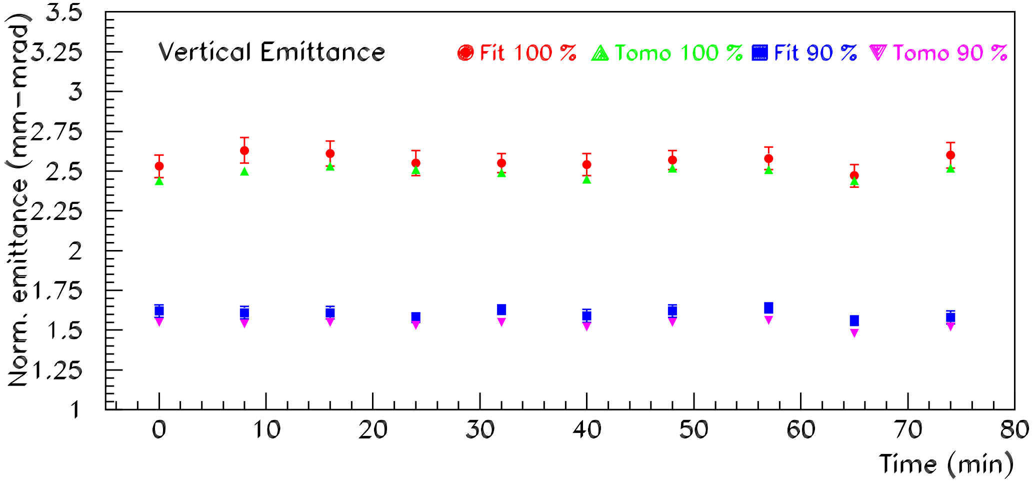
Combine array of µm size field emitters with up to 1 MV dc acceleration and subsequent rf cavity.

D) Plasma-based sources (Leemans et al.)

Use high long. E-field generated in the wake of laser-generated plasma shock wave.

Issues: Momentum spread, stability, space charge forces

Emittance during 1.5 hours



- Jitter 2 - 3 % (rms)

Fitting method, 100% emittance

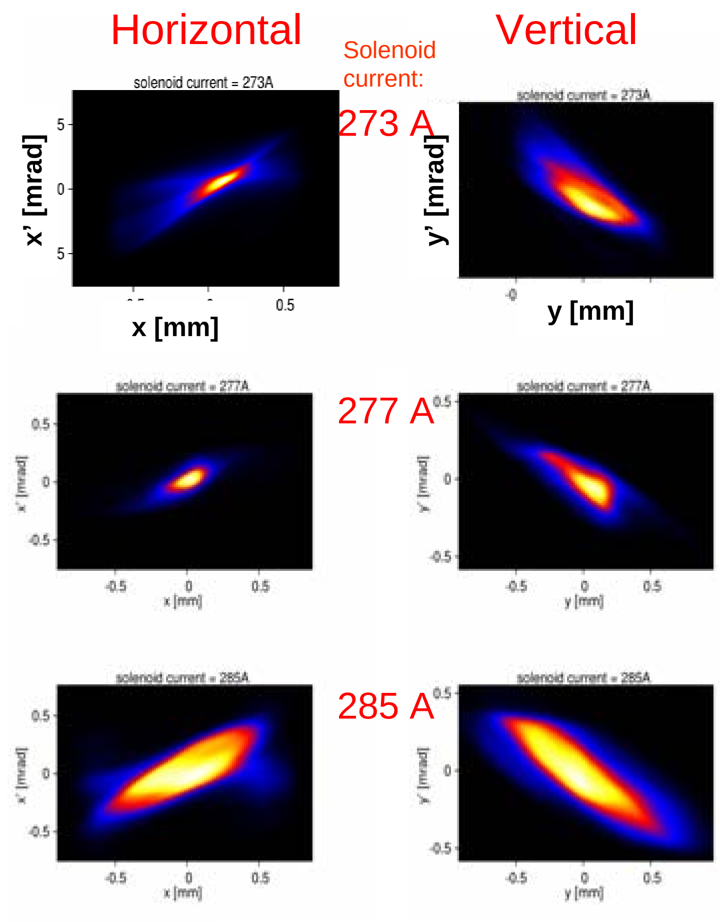
Tomography, 100% emittance

Fitting method, 90% emittance

Tomography, 90% emittance

Needs beam observ. screens with
<10μm resolution
+ large dynamical range & linearity

Transverse phase space, reconstructed by tomography

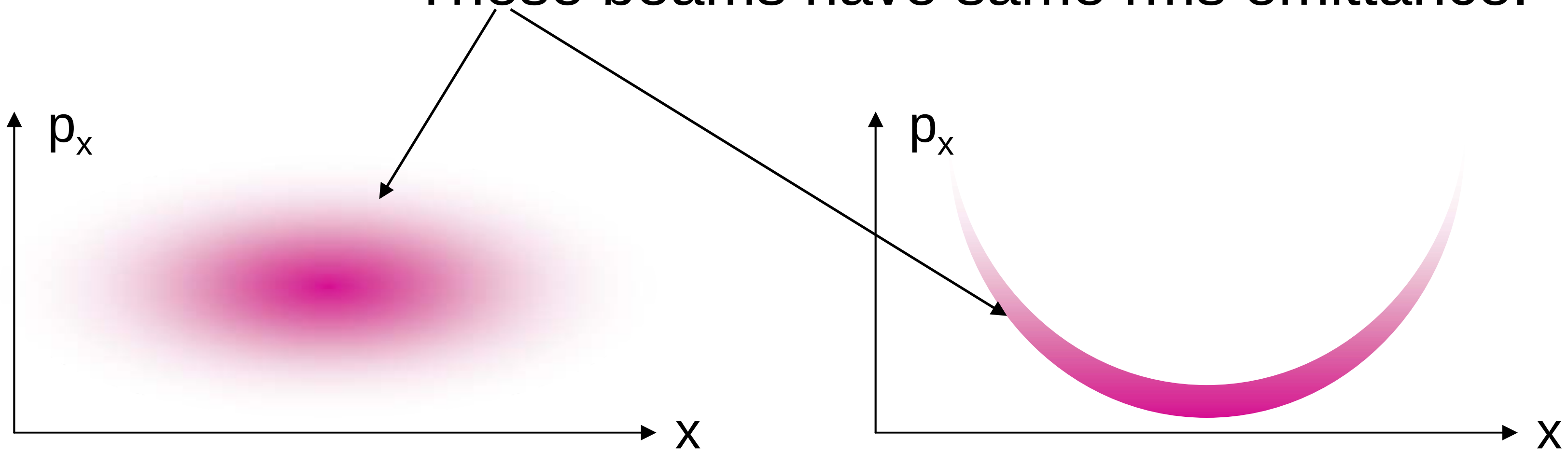


1 nC, 125 MeV

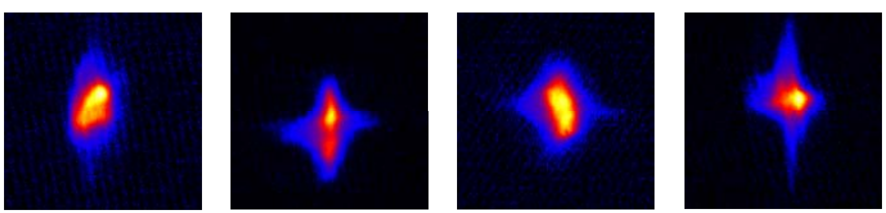
Transverse emittance

Question:

These beams have same rms emittance.



Are they really equvalent?



Is rms emittance the adequate & sufficient way of description?

If not: Need adequate parametrization and optics treatment

Short bunch issues

A) Up to ~100 MeV:

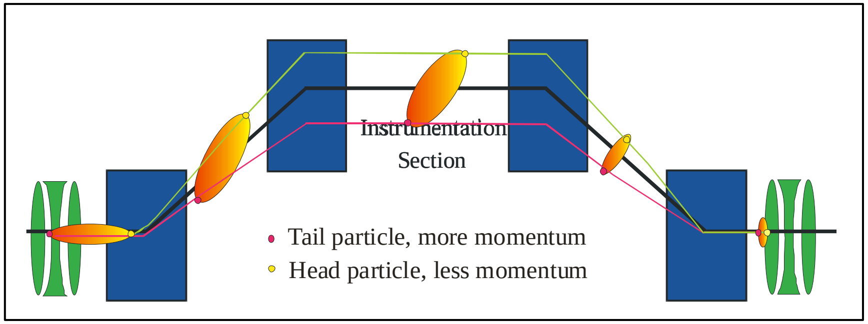
Space charge absolutely disastrous for $\hat{I} \approx 1\text{kA}$

→ $\hat{I} < 50\text{A}$ at injector →must compress longitudinally at γ >>1

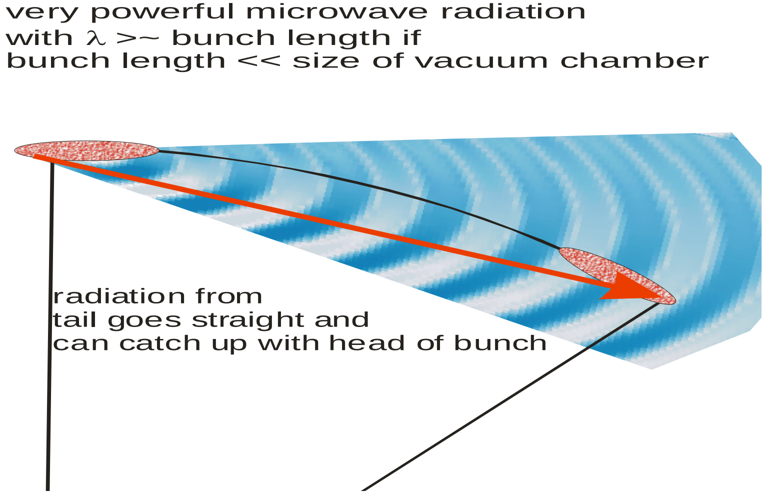
Velocity bunch limited for v ≈ c particles

→ magnetic chicane → coherent synchrotron radiation

Derbenev, Saldin, et al.



Magnetic bunch compression



Short bunch issues

Rf error (phase & amplitude)

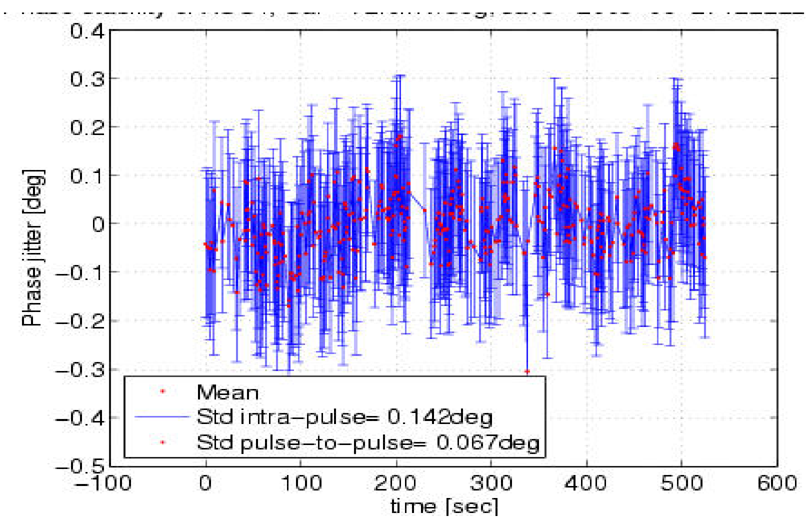
→ errors on momentum, bunch length, bunch arrival time

→ **Stability**!! Build feedback for rf phase, using

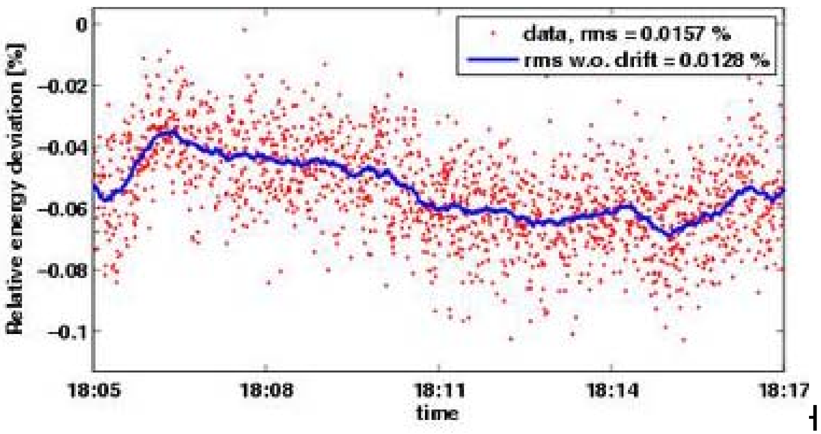
- rf probes
- pyrodetectors to measure coherent synchrotron radiation
- synchrotron radiation monitor in dispersive section

Result after first compression stage at 125 MeV:

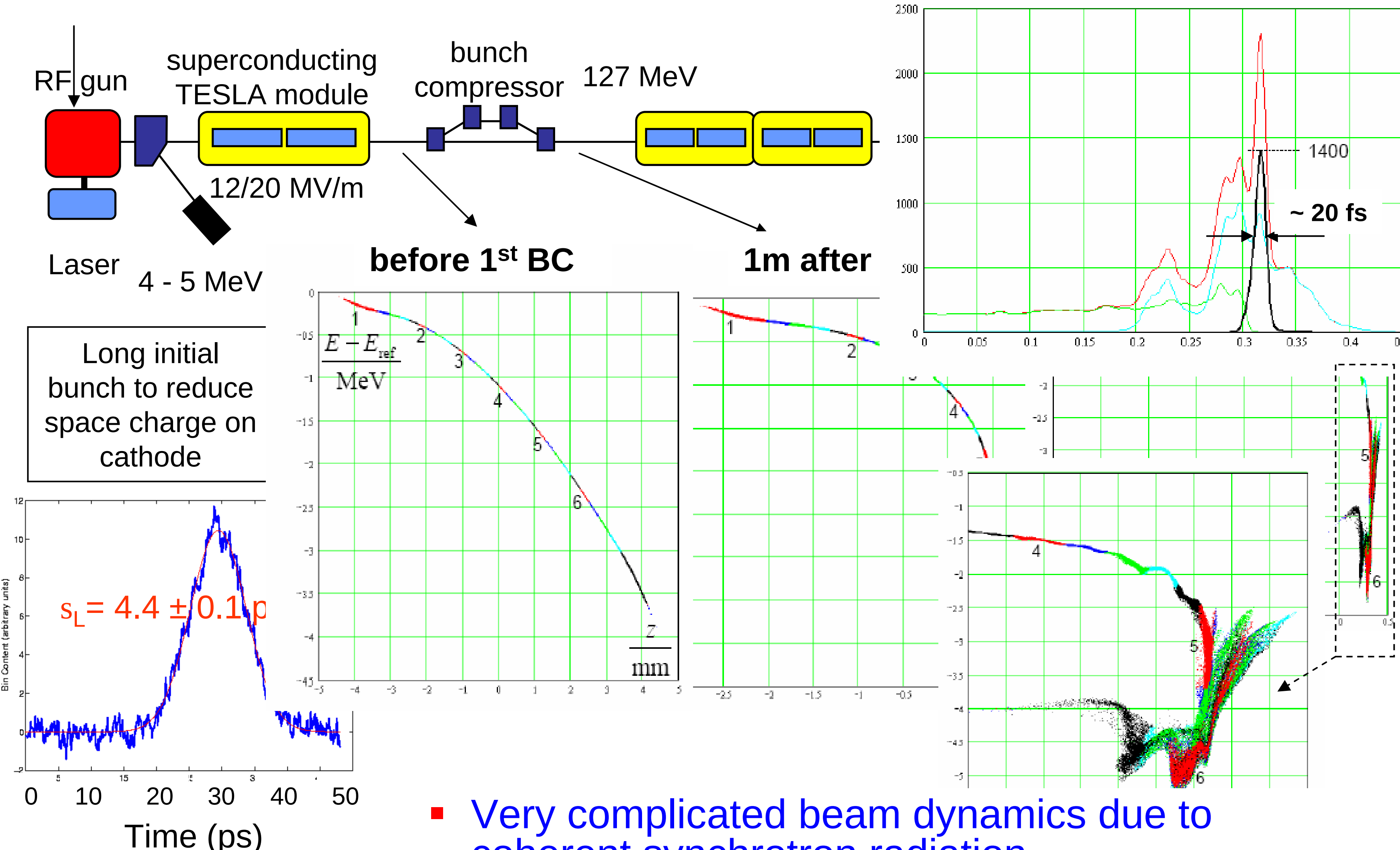
Rms phase jitter: 0.07 deg



Rms momentum jitter: 1.3×10^{-4}

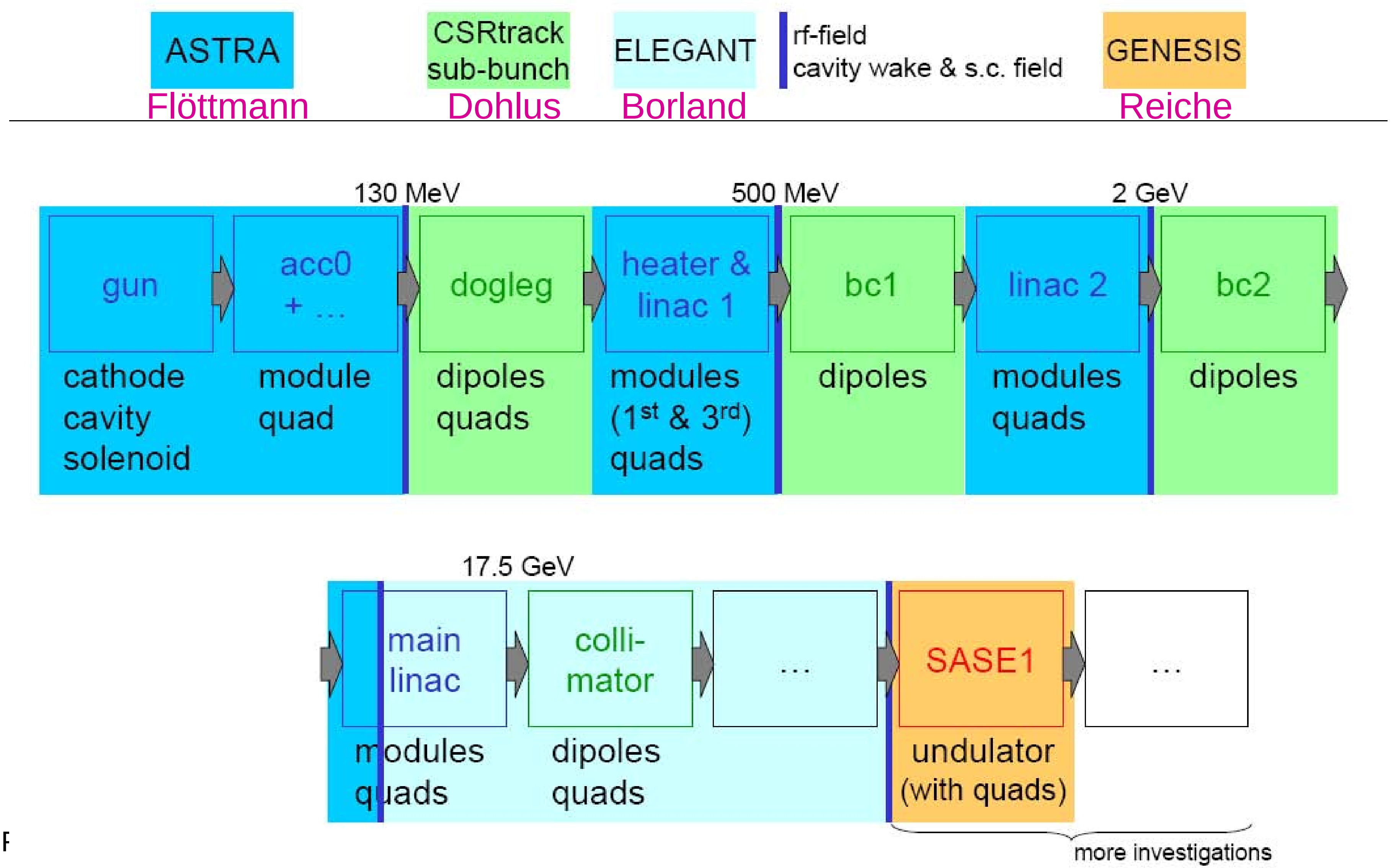


Short bunch issues: Beam dynamics

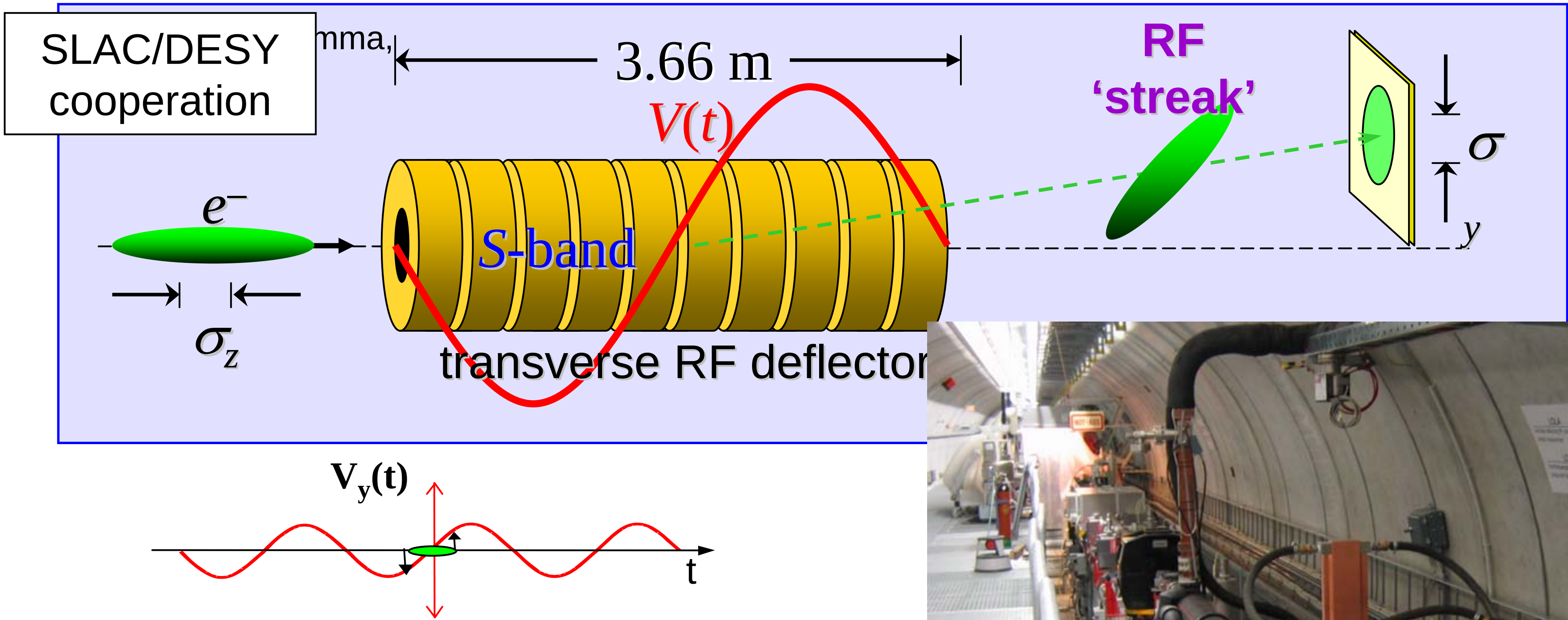


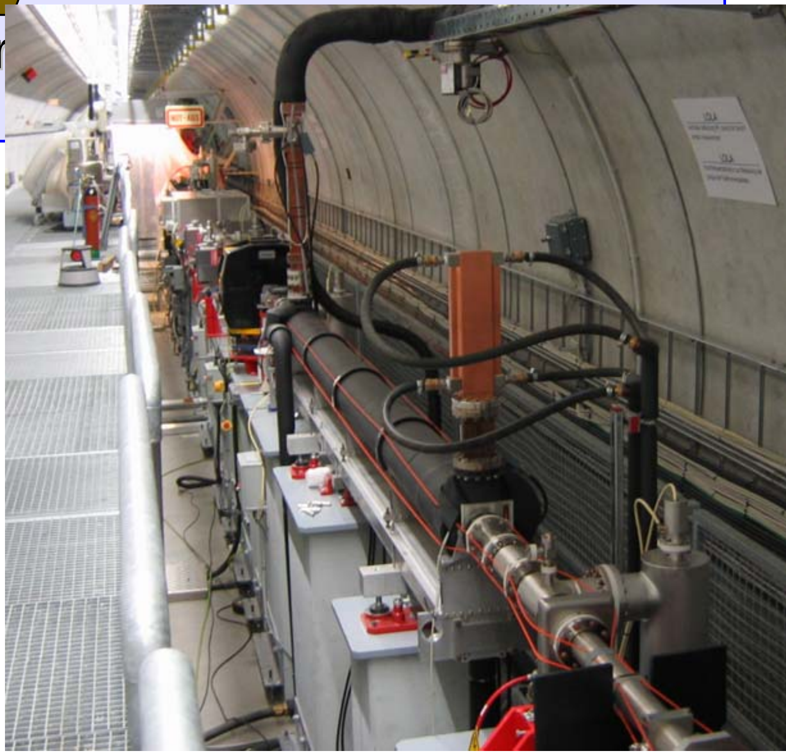
- Very complicated beam dynamics due to coherent synchrotron radiation
- Difficult access to relevant parameters
- Ultra-short photon pulses created ~20fs FWHM

Beam dynamics simulation tools



Bunch Length Measurement: 1. LOLA

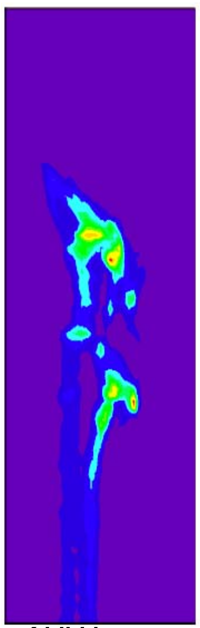




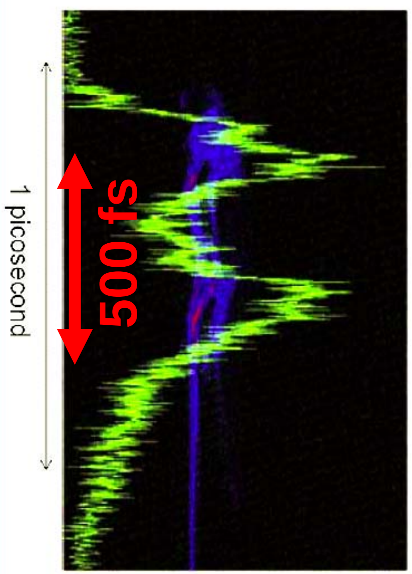
- Deflecting RF structure (S-band) from SLAC is used as a 'streak camera'
- Resolution ~ 10 µm

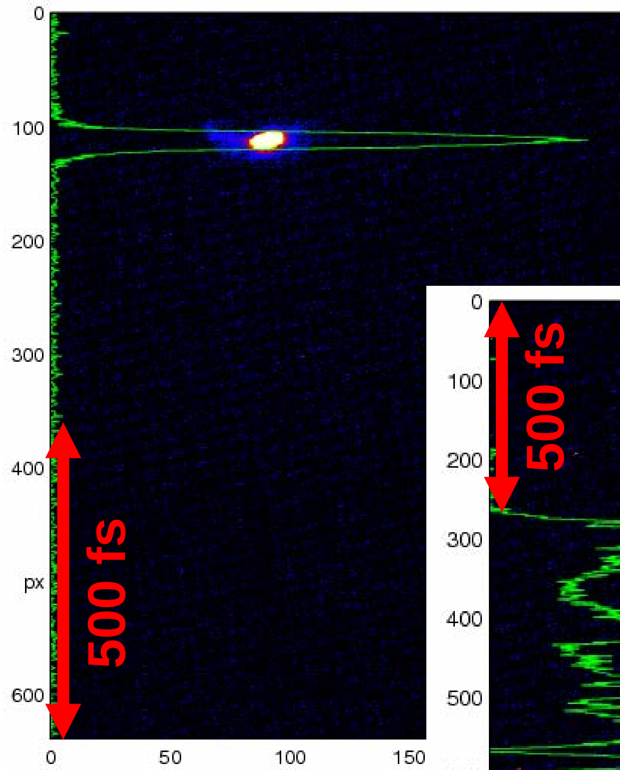
Pictures from LOLA

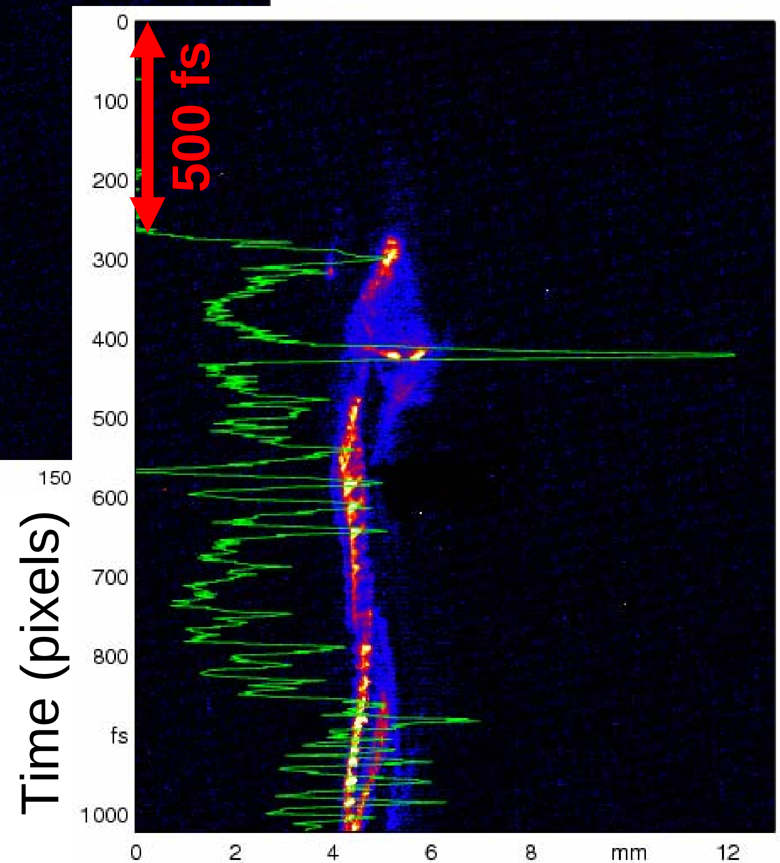
- Three examples for different compressor settings:
  they demonstrate the power of the instrument in resolving bunch structures
- Preliminary calibration 1.8 fs/pixel



simulation



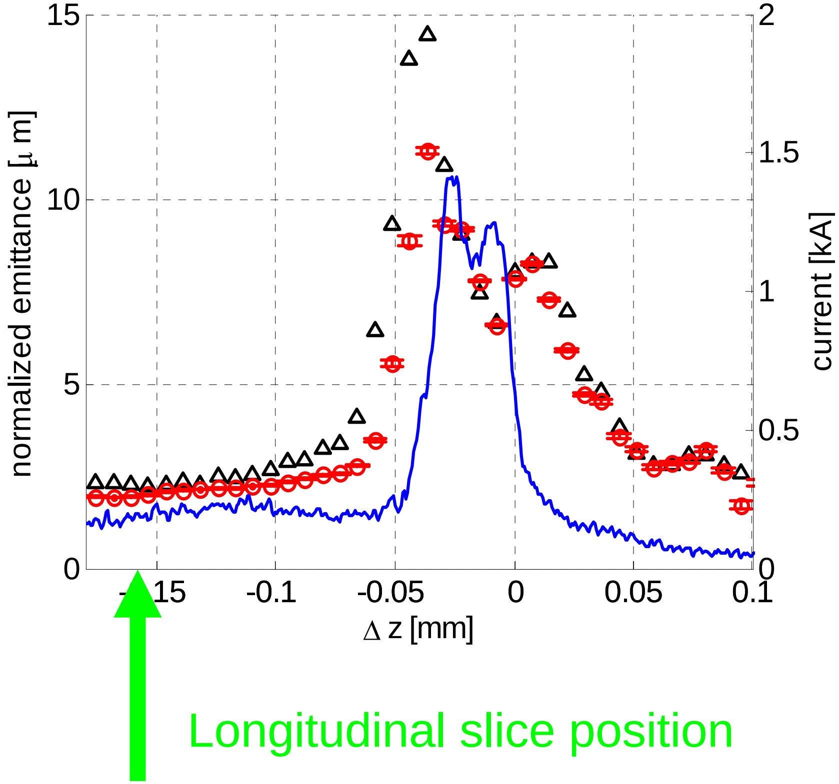




poster by B. Beutner MOPPH004

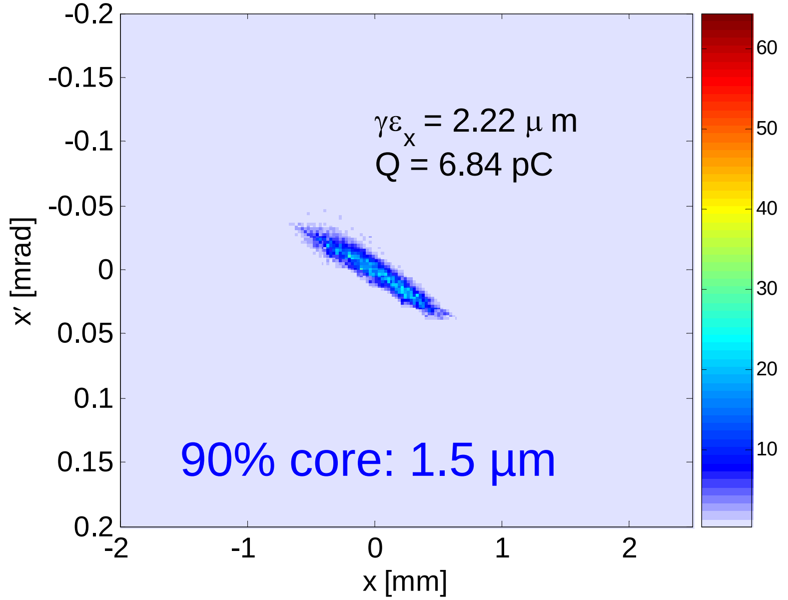
Horizontal phase space slice resolved

Slice emittance and current:



Longitudinal slice position

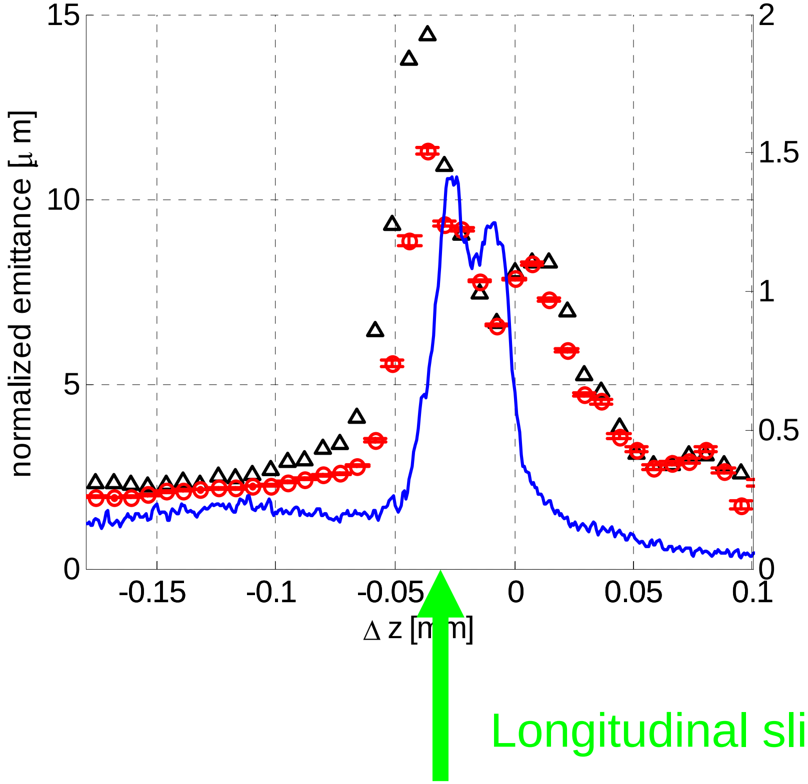
Horizontal phase space
(selected slice) :



courtesy M. Roehrs

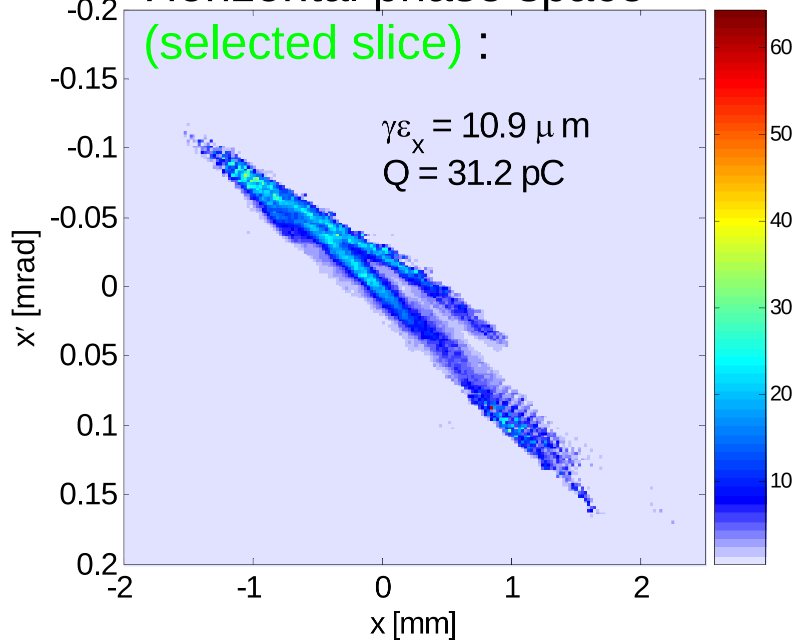
Horizontal phase space slice resolved

Slice emittance and current:

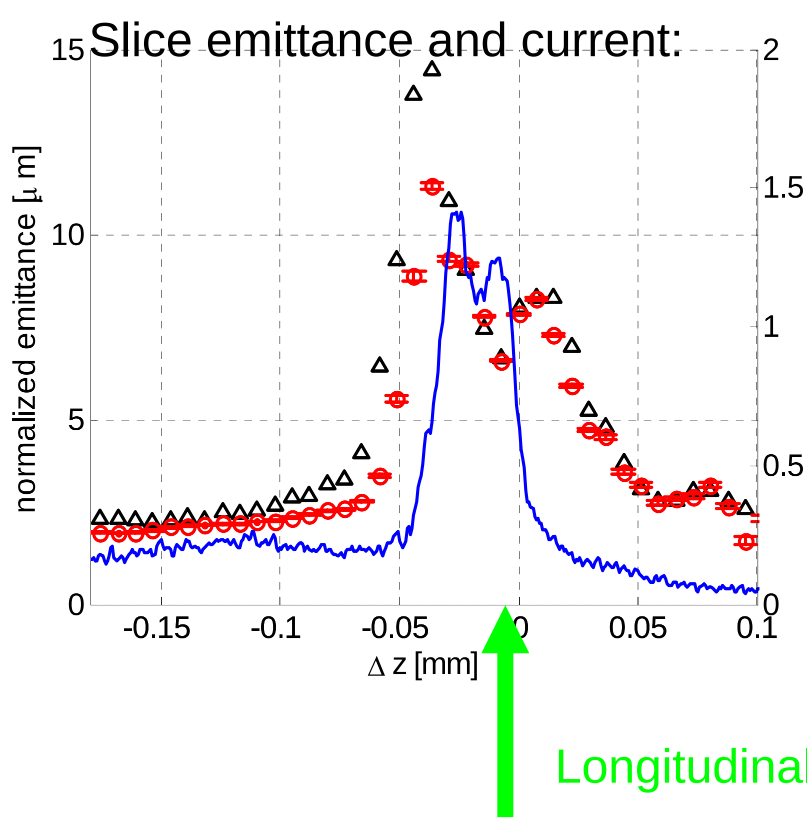


Longitudinal slice position

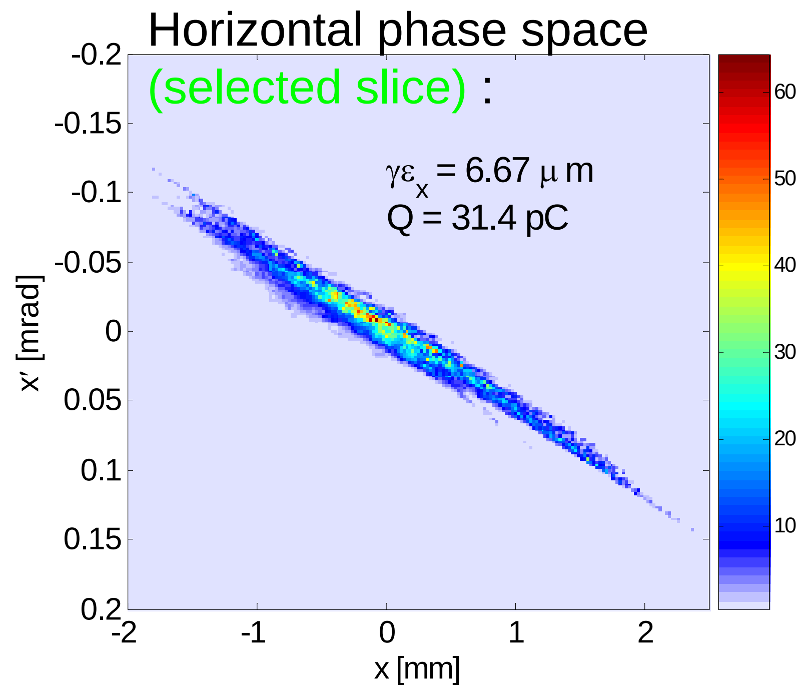
Horizontal phase space (selected slice) :



Horizontal phase space slice resolved



Longitudinal slice position



Short bunch issues B) From user point of view

1) Make pulse as short as possible:

small momentum spread helps at compression

coherence length (“single mode”)

FLASH at 13 nm: $\tau_{\mathrm{coh}} \approx 1.3\mu\mathrm{m}$

$\tau_{\mathrm{pulse}} \approx 3\mu\mathrm{m}$ not bad !

Electron diagnostics should be capable to resolve $t < \tau_{\mathrm{coh}}$

Angstrom FEL: $\tau_{\mathrm{coh}} \approx 0.03\mu\mathrm{m}$

-- Diagnostics more and more demanding

+ Possibility to produce attosecond pulses

(Saldin et al, Zholents)

Optical Replica Syntesizer (ORS)

E.L. Saldin et al. Instr. Methods A 539, 499 (2005)

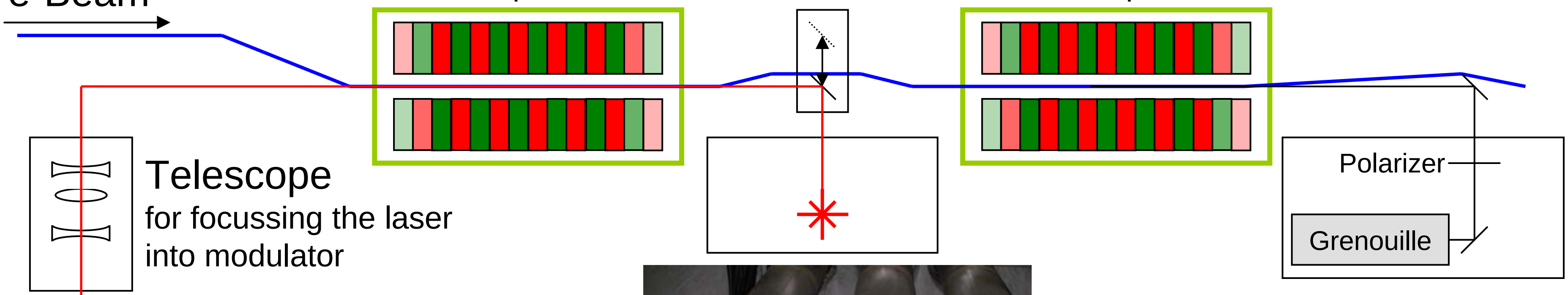
collaboration U Stockholm, U Uppsala, U Hamburg & DESY

Modulator vertical polarized

Chicane with mirror or OTR

Radiator horizontal polarized

e-Beam



SEED Laser System

-Erbium-doped Fiber Laser
 (775 nm output freqenz doubled)
-Clark CPA2001 amplifier
-For ORS:
 - 2ps pulse width
 - 0,8mJ pulse energy
 - 5-10 Hz rep. Rate
 - vertical polarized (s. Modulator)

Optical Station II

Analyse optical replica with Grenouille (FROG)

courtesy J. Boedewadt

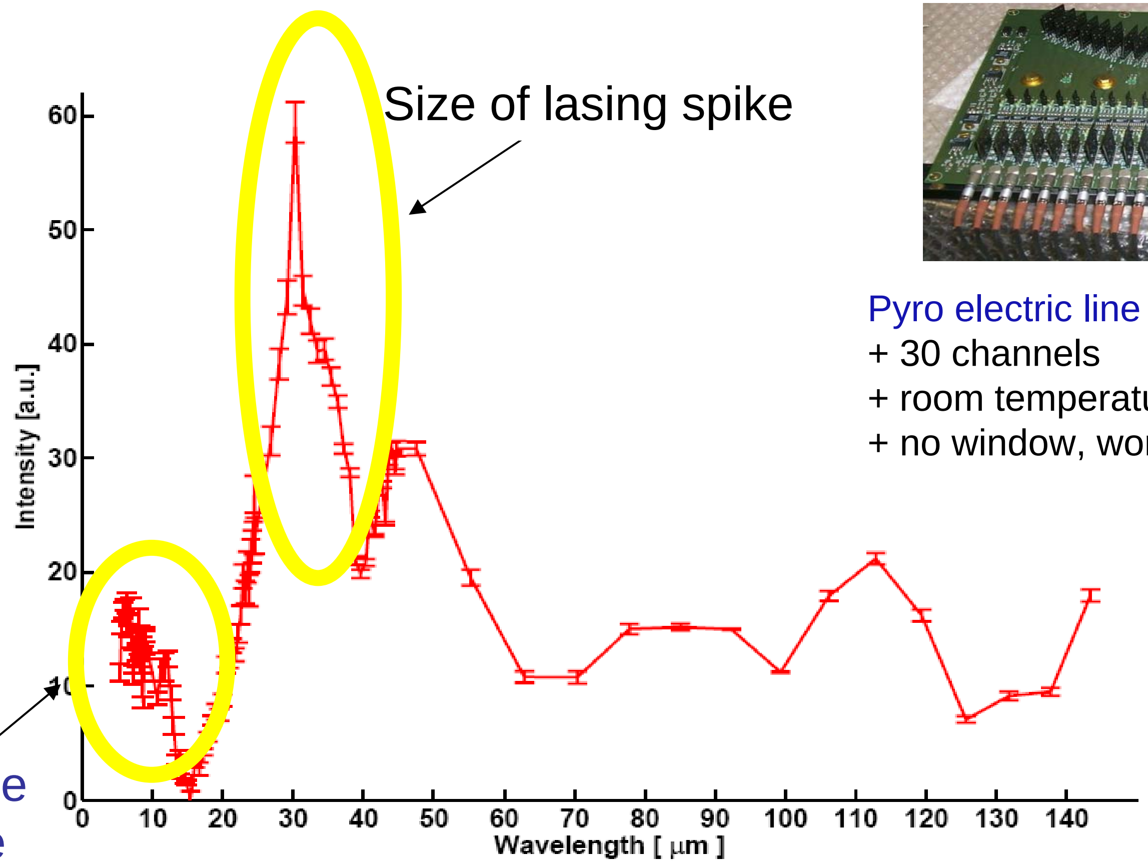
fs diagnostics with THz radiation

Single shot spectrum of coherent infrared radiation exhibits structure in the longitudinal density modulation < 5 µm

Need <u>single shot</u> spectrometer for wide IR bandwidth

Recent development at DESY

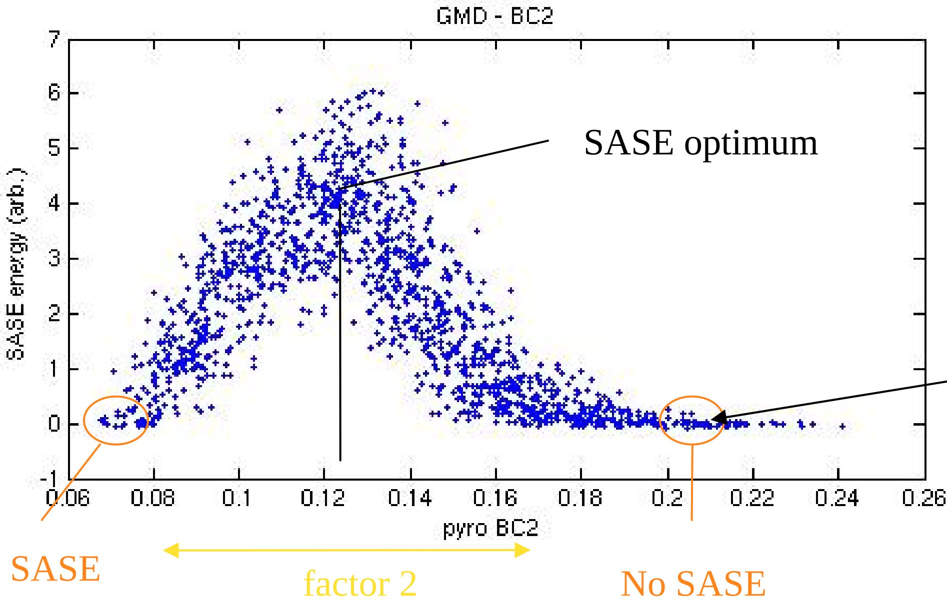
Pyro electric line detector from individual pyros
+ 30 channels
+ room temperature
+ no window, works in vacuum



Substructure inside spike

courtesy
H. Delsim-Hashemi

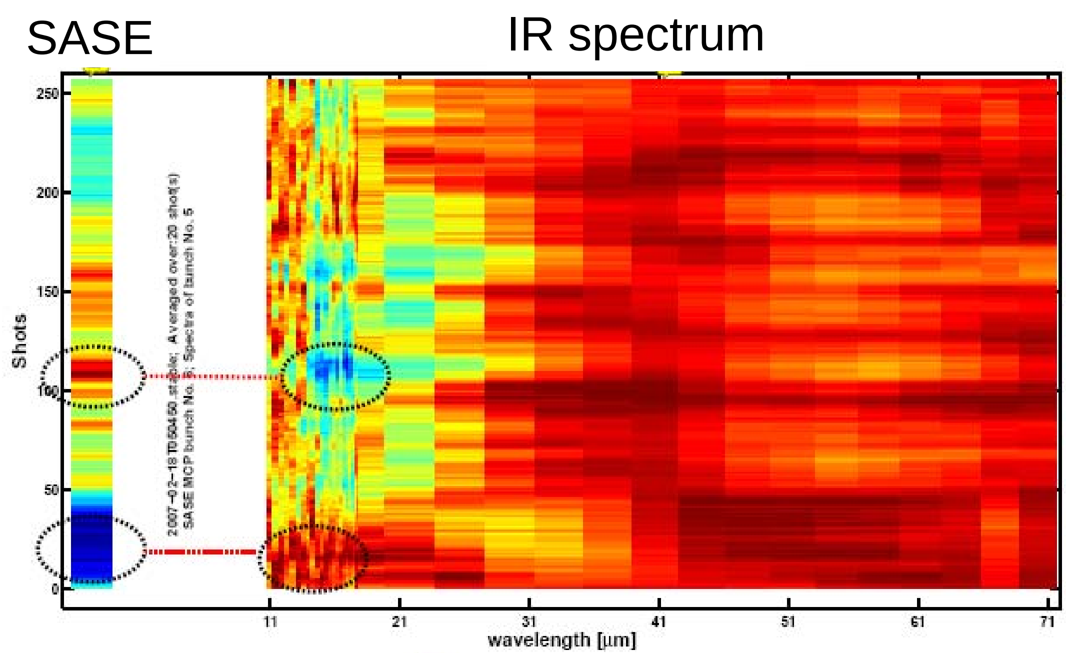
Correlations SASE – IR power (pyro)



Maximum IR power does NOT correspond to max. SASE!

(rather to over-compression)

Spectral resolved correlation shows max. SASE (red) whenever there is LITTLE signal (blue) at 10-20 nm



FEL 2007

Short bunch issues: Timing + Synchronisation

Rf phase jitter translates into arrival time jitter of beam:

expect: $\Delta\varphi \geq 0.07\,\mathrm{deg} \quad \Leftrightarrow \quad \Delta t \geq 150\ \mathrm{fs}$

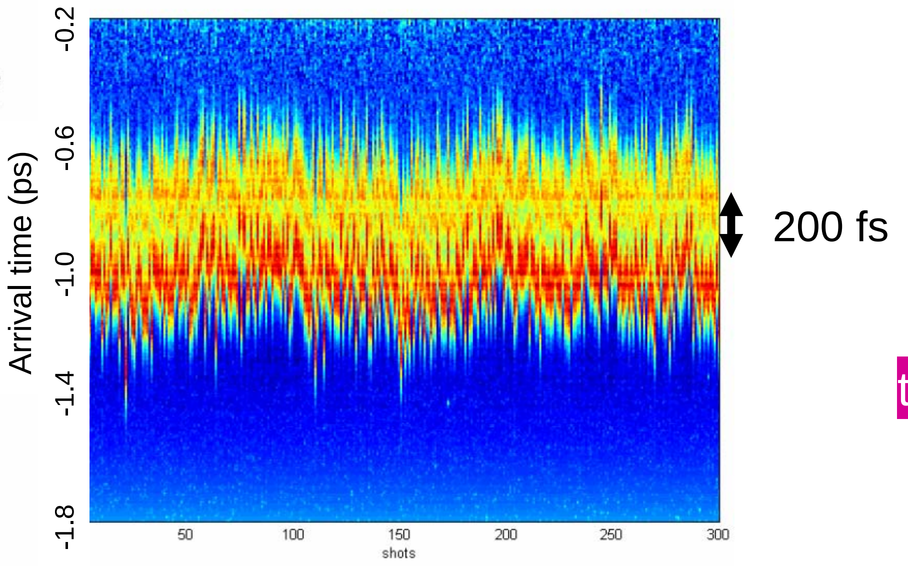
measured with electro-optic sampling:

rms timing fluctuations 200 fs

300 consecutive bunches on June 5th,

off crest,

1 nC

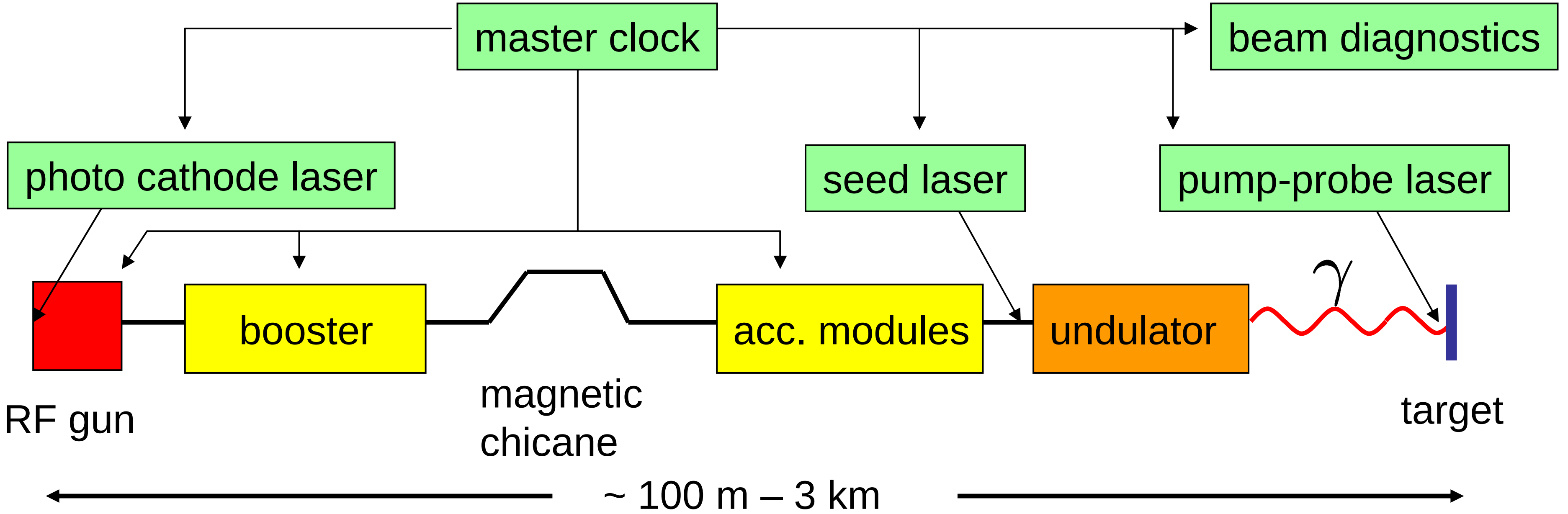


talk by B. Steffen WEBAU04

Task: Measure bunch arrival at ~10 fs precision

-- and distribute time stamp over several 100 m!!

Synchronization needed in a FEL facility



Main sources for arrival-time changes of the FEL radiation

- arrival-time of the photo cathode laser pulses
- phase of the RF gun
- amplitude and phase of booster module
- arrival-time of potential seed lasers

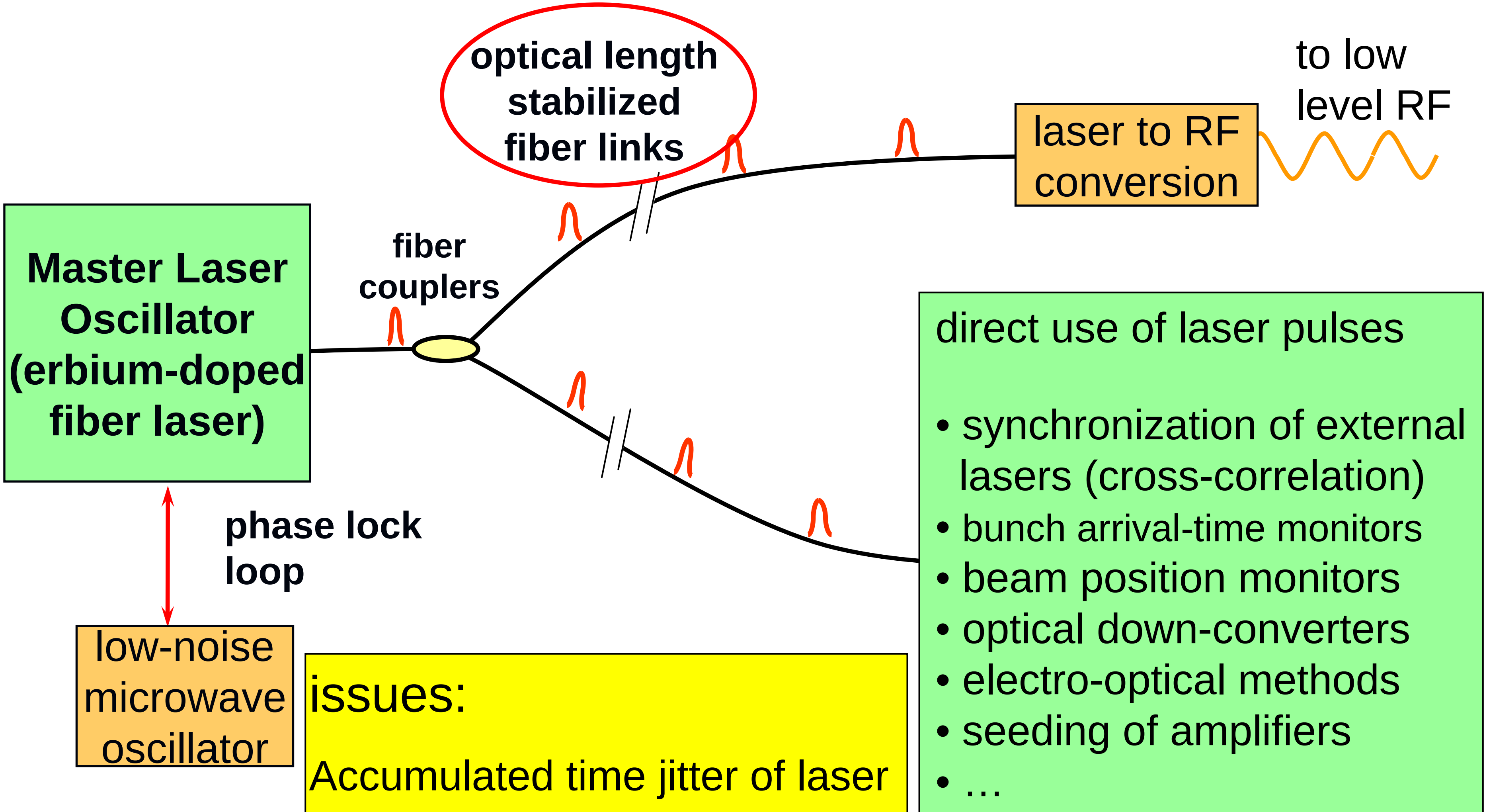
Key Problem:

rf microwave oscillator is excellent master clock, but long-distance distribution of rf signals with cables is impossible at fs stability !

An all-optical synchronization system

Berkeley, DESY, ELETTRA, MIT

talk by H. Schlarb TUBAU01



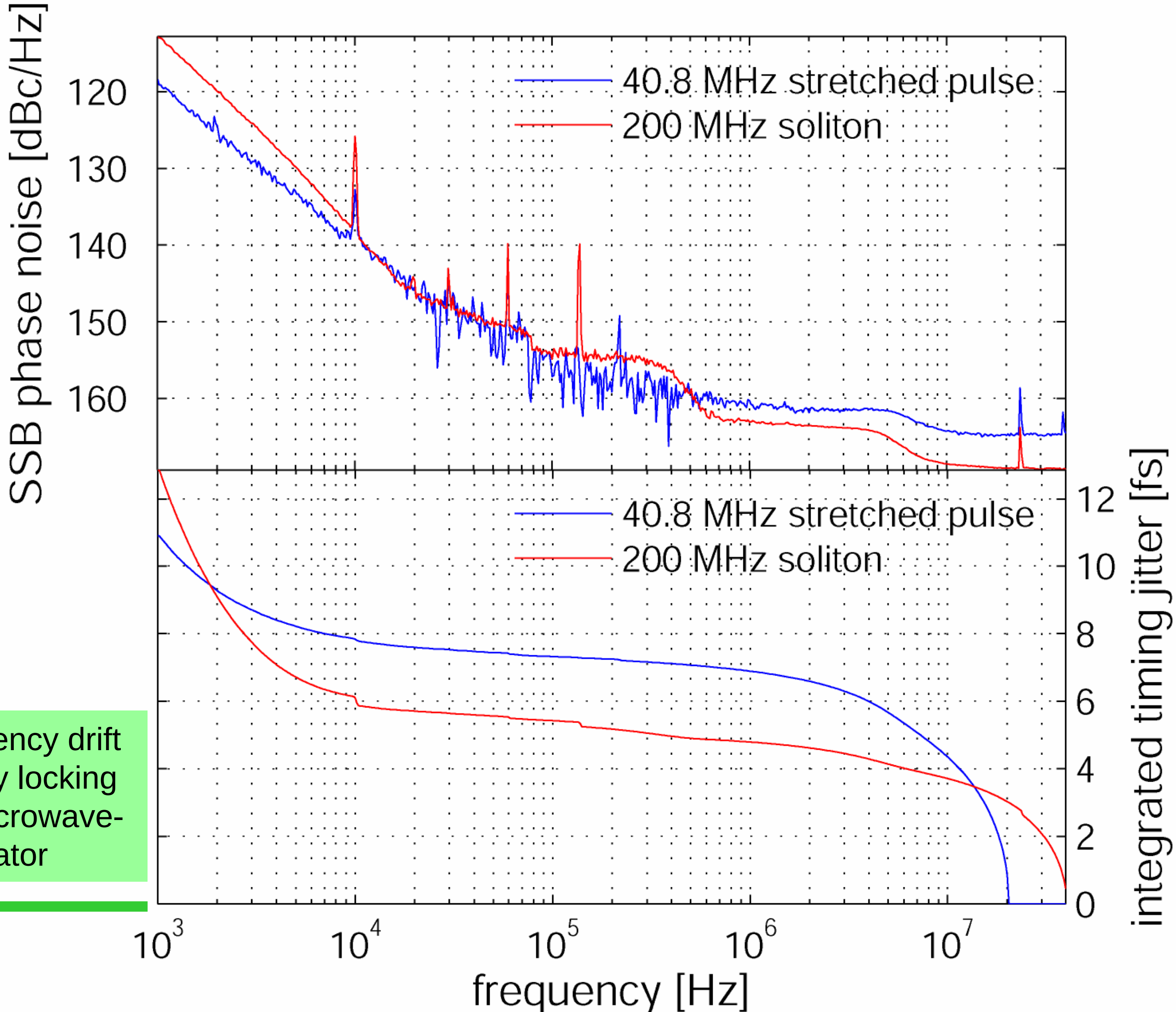
issues:

Accumulated time jitter of laser

Stability of fiber length

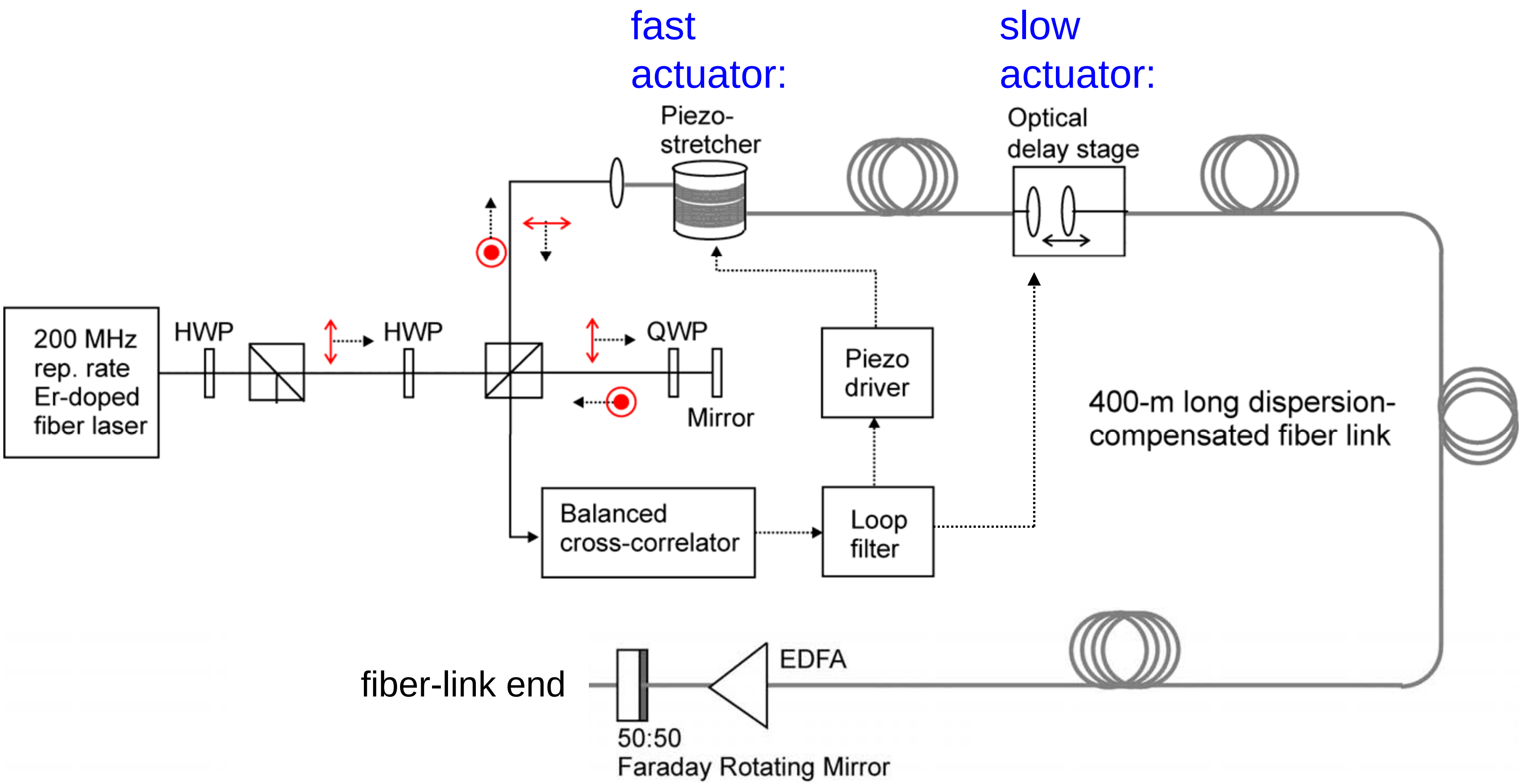
Noise of laser → rf converter

Phase noise measurement of 200 MHz soliton laser



Low-frequency drift covered by locking laser to microwave-oscillator

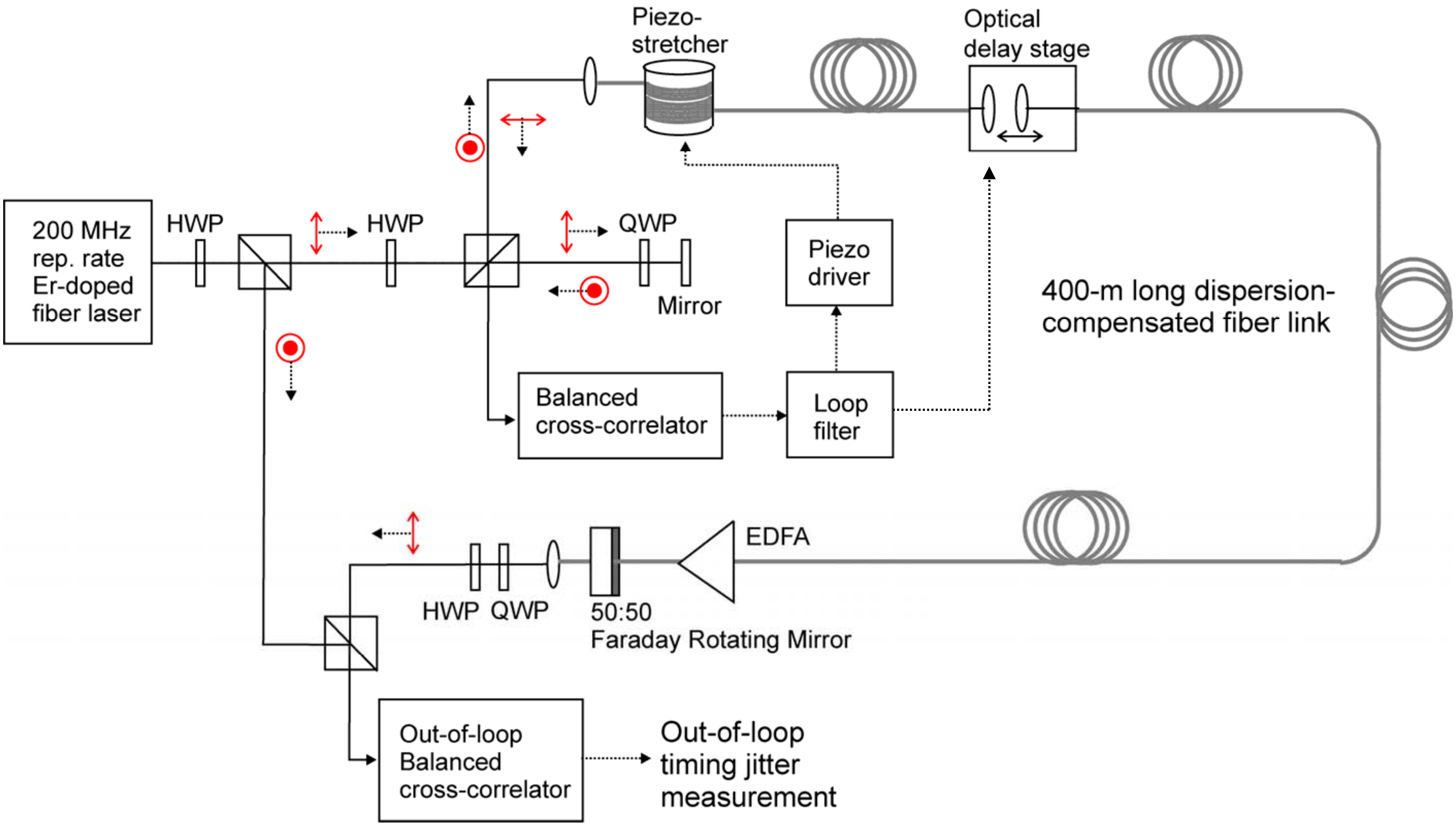
Schematic setup of the fiber-link stabilization



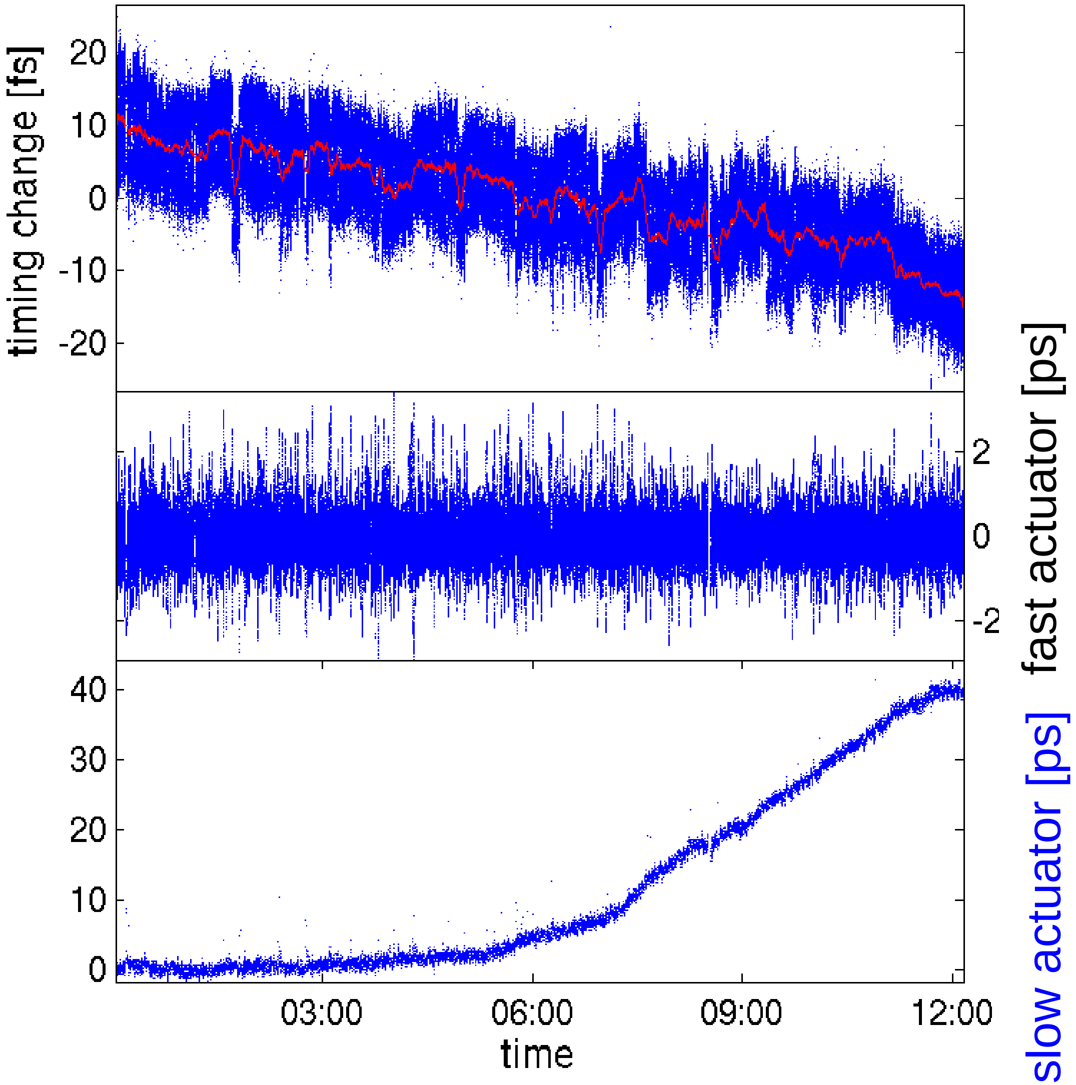
FEL 2007

courtesy
F. Loehl/DESY

Verification of fiber-link stabilization



Fiber link stabilization



- **400 meter stabilized test link in Hall 1 at DESY**
- **Jitter 7.5 fs rms during 12 hours**
- **Additional 25 fs rms drift during that time**

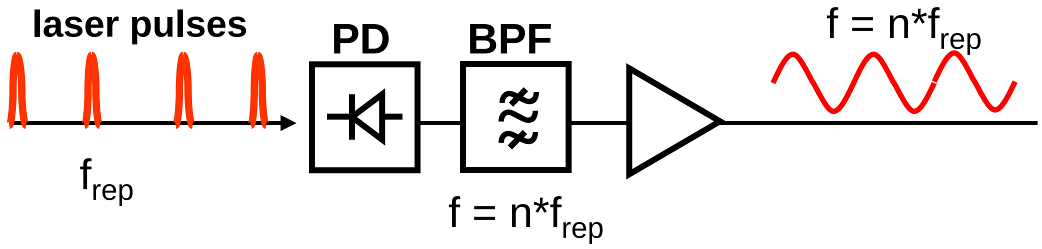
courtesy F. Loehl/DESY

Laser → rf converter

Several options, e.g.

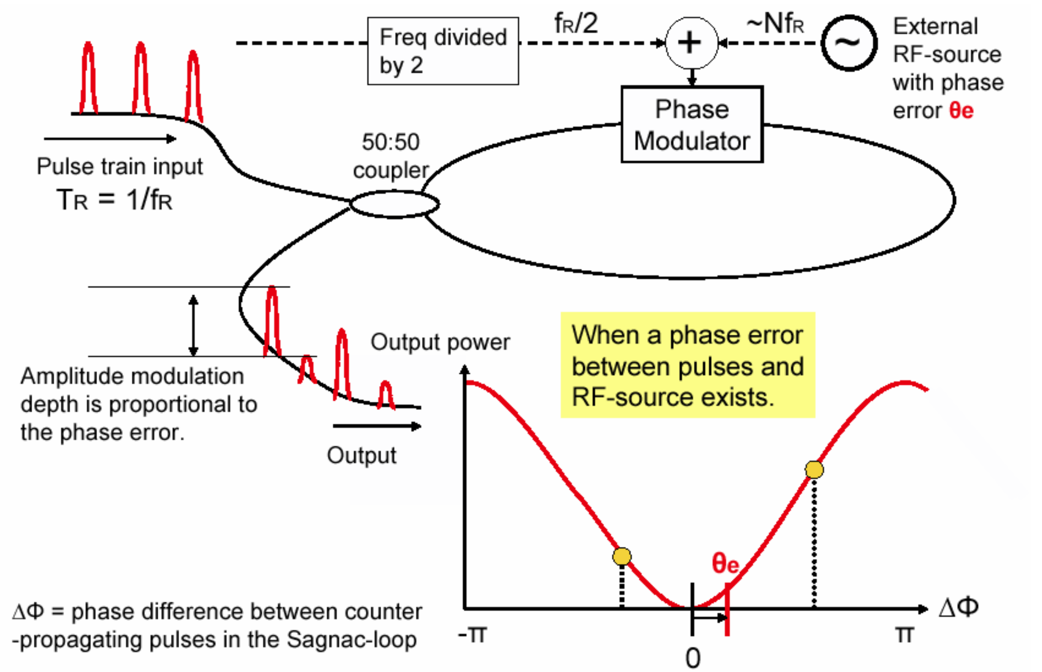
Direct conversion with PD
– temperature drifts
– AM to PM conversion*
– noise limitation due to low power in spectral line of PD output
– still 10 fs high frequency jitter can be obtained

(*) typical AM to PM conversion: 1-10ps/mW



better:

Sagnac loop
– complex system
– expensive
+ virtually drift free
+ balanced detection, so AM/PM no issue

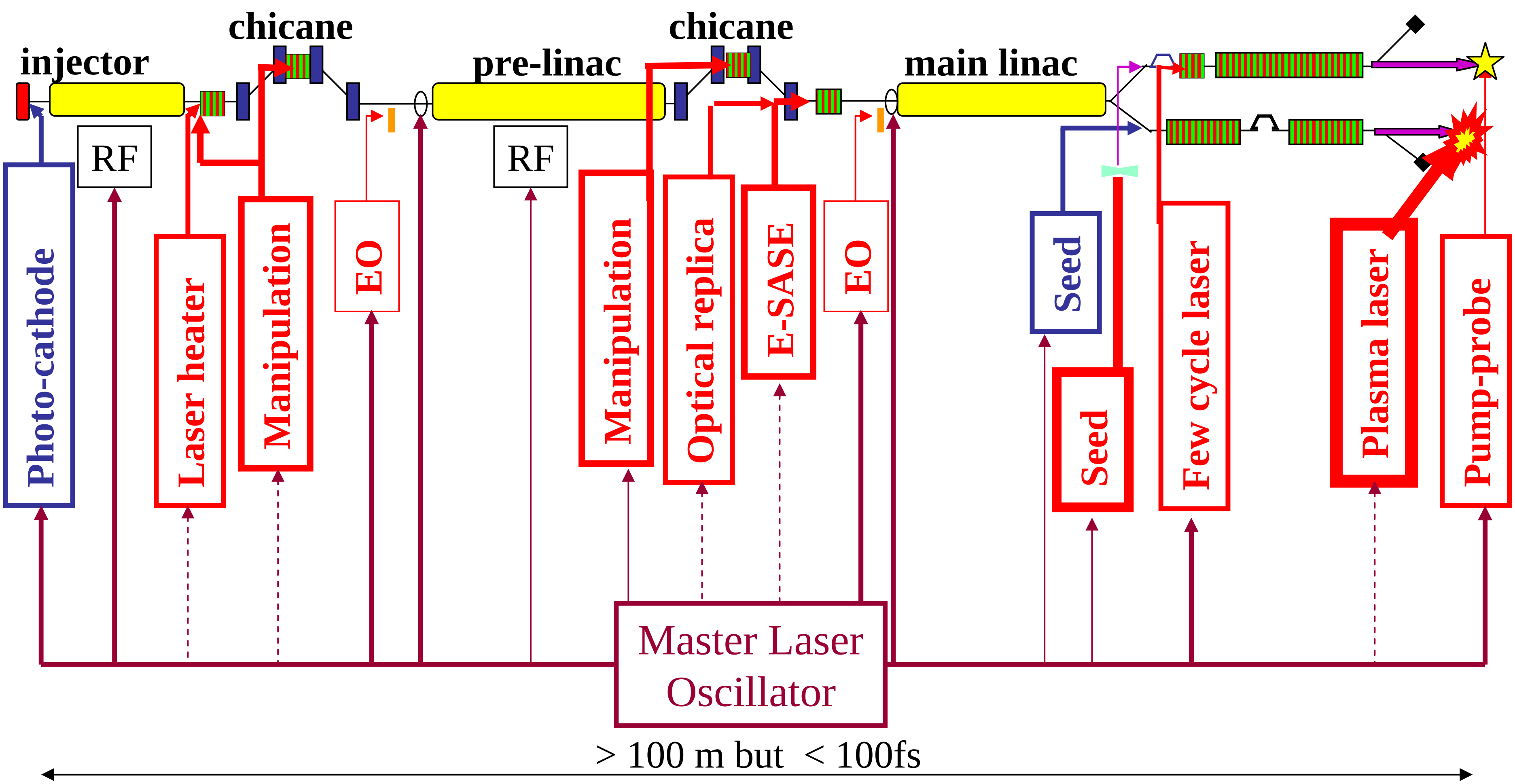


FEL 2007

Lasers for FELs

talk by H. Schlarb TUBAU01

Generic layout of single pass FELs



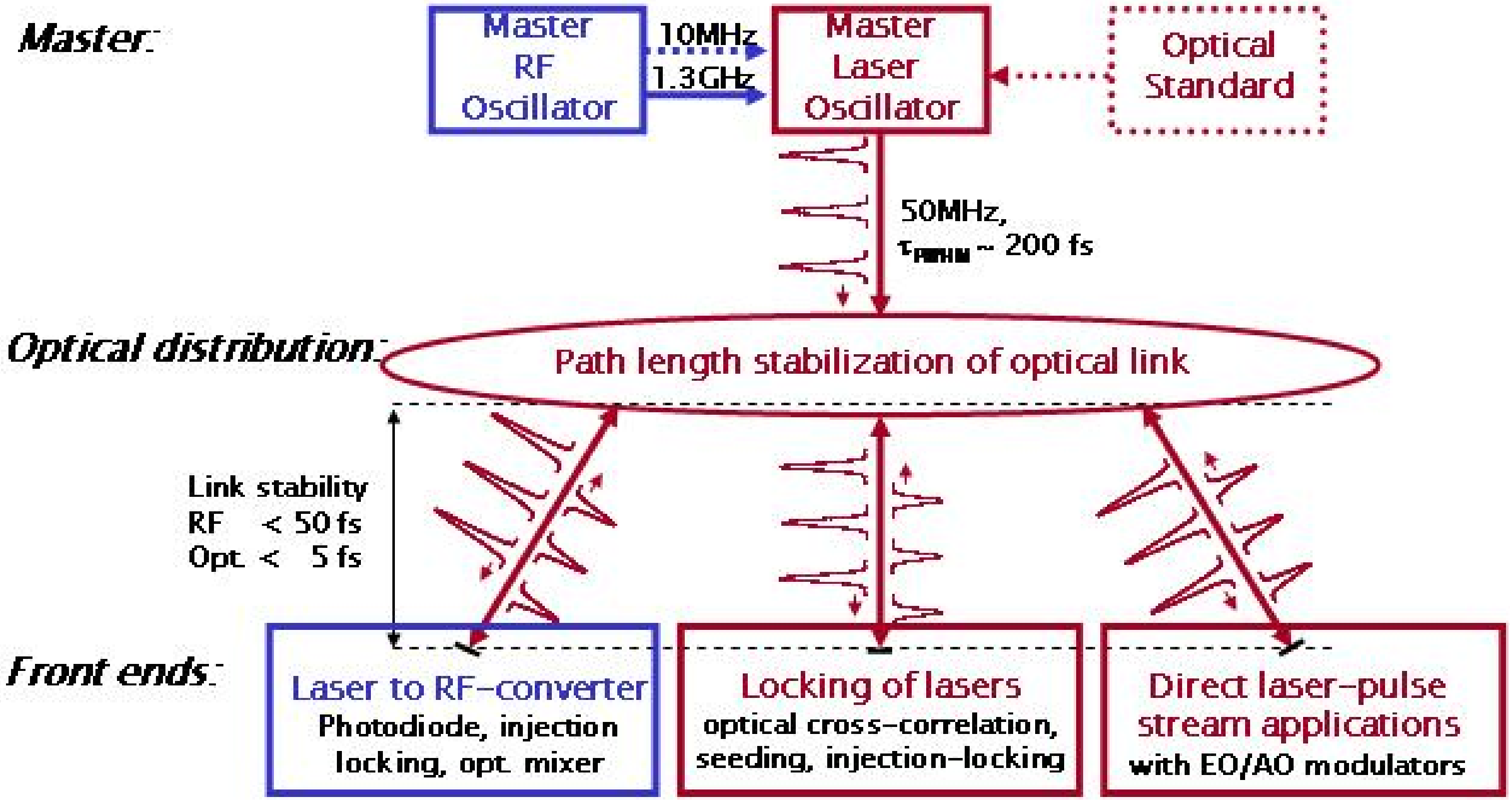
CONCLUSIONS

- Many important issues skipped:
  orbit precision, undulator issues, tapering, ERLs, seeding techniques, reliability of components, size and costs, …
- Similar challenges on photon diagnostics side

- X-ray FELs evolved into a major technology driver for accelerator R&D.
- There is still a long way to go to fully exploit the possiblities of FELs for short wavelengths.

Thanks to all my colleagues at FLASH and to the entire community!

Layout of laser based synchronization



Applications:

LO generation
- down converter LLRF
- PPL for synchronization
- RF signals for diagnostics

Lasers for
- photo-injector
- pump-probe experiment
- e-beam diagnostics
- e-beam manipulation

High precision appl.
- Beam phase monitor
- Laser phase monitor
- Optical down converter
- Chicane BPM

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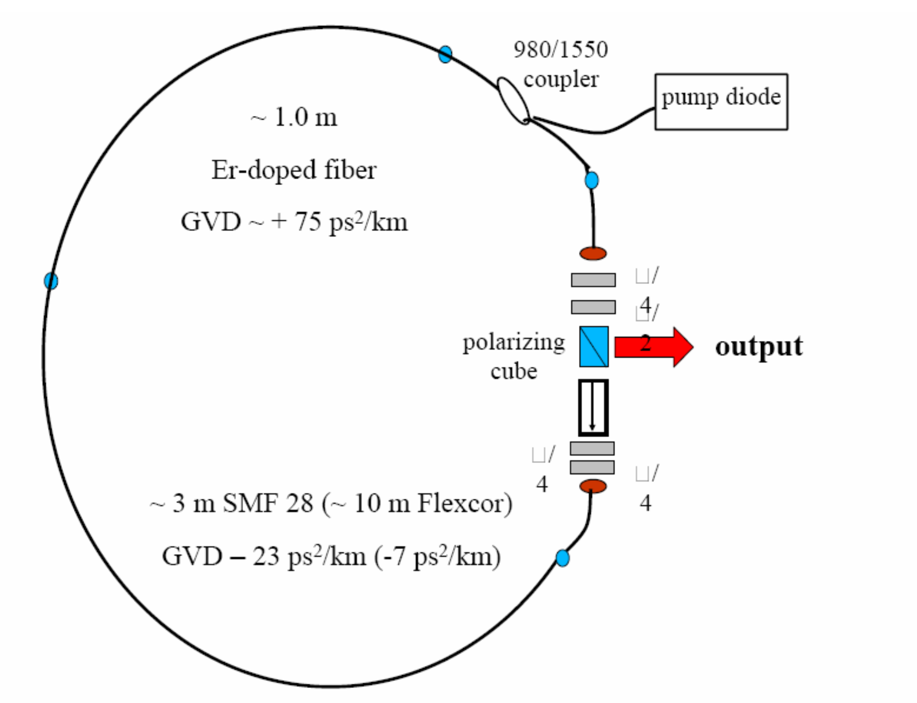
See also: A. Winter TUPCH028/TUPCH029, talks: Kim THOPA03, F.Löhl THOBFI01

Synchronization laser

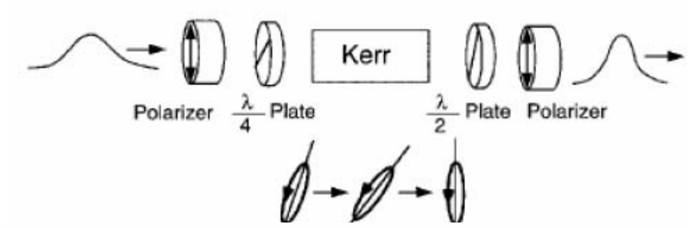
Dispersion managed soliton fiber-laser with artificial saturable absorber

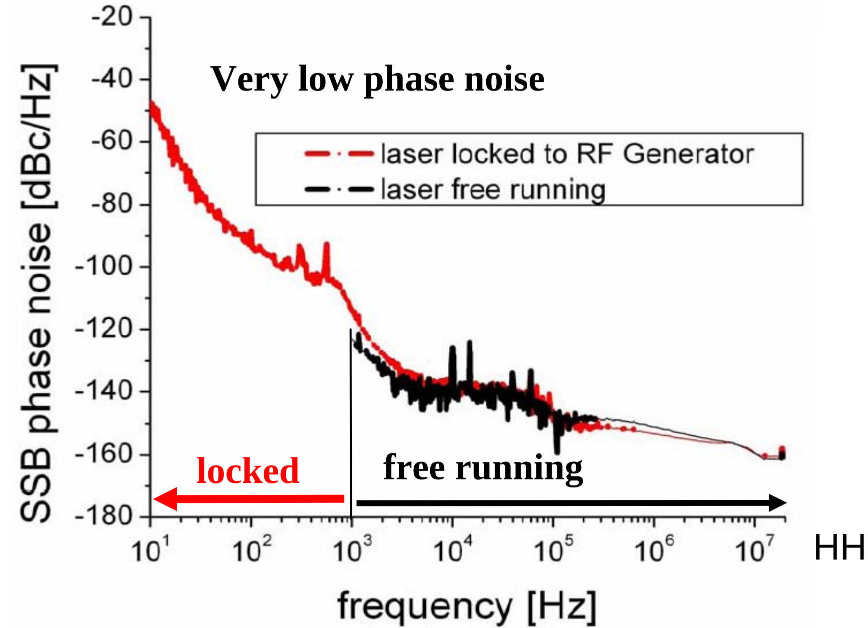
- Fiber stretcher for passive mode locking to RF generator
- Gain medium Erbium, 1550 nm wavelength
- High output power up to ~ 1 nJ (50 mW average)
- Pulse duration ~ 100 fs FWHM
- Repetition rate ~ 50 MHz

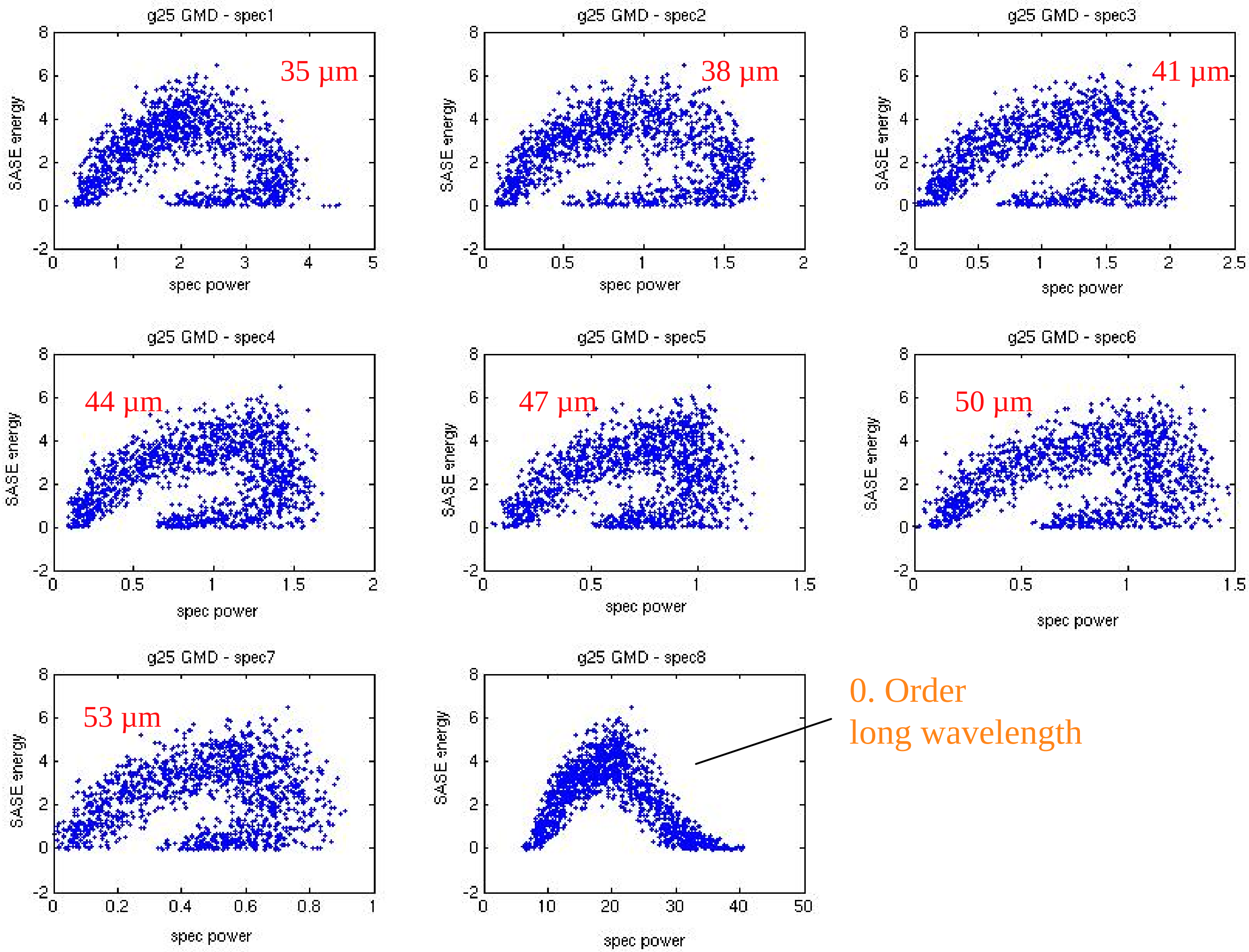


www.bilkent.edu.tr/~ilday

Polarization control for mode locking






g25 GMD - spec1
35 µm
g25 GMD - spec2
38 µm
g25 GMD - spec3
41 µm
g25 GMD - spec4
44 µm
g25 GMD - spec5
47 µm
g25 GMD - spec6
50 µm
g25 GMD - spec7
53 µm
g25 GMD - spec8
SASE energy
spec power
0. Order
long wavelength

First spectra

- single transmission grating
- during SASE conditions (5.10.06)

See poster by
Hossein Delsim-Hashemi
during this workshop

- single reflective grating
- during SASE conditions (20.8.06)