Femtosecond Optical Synchronization System for FLASH

Achievements and challenges during the first implementation phase of an engineered version in the accelerator

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for the LbSyn Team

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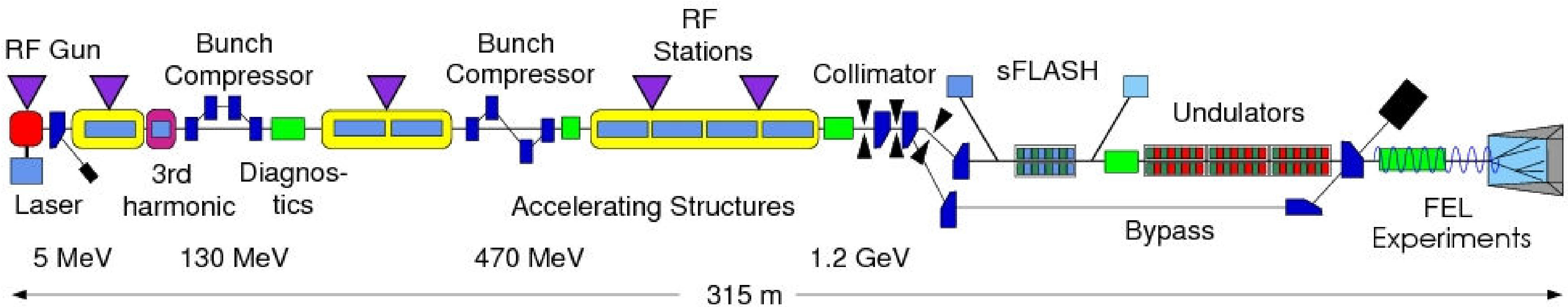
H. Schlarb, B. Schmidt, S. Schulz, A. Winter

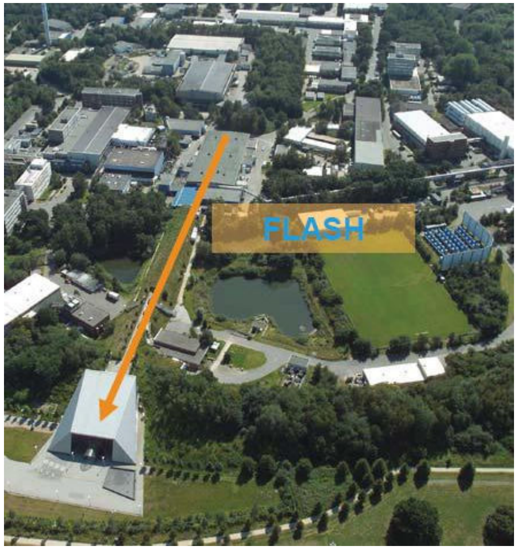
Agenda

- Short Introduction to FLASH
- Synchronization Needs and System Layout
- The Basic Components of the System
- Arrival Time Measurements and Feedback
- RF Generation from Optical Pulse Train
- Closing Remarks

FLASH – Free Electron LASer Hamburg



machine layout after shutdown: March 2010



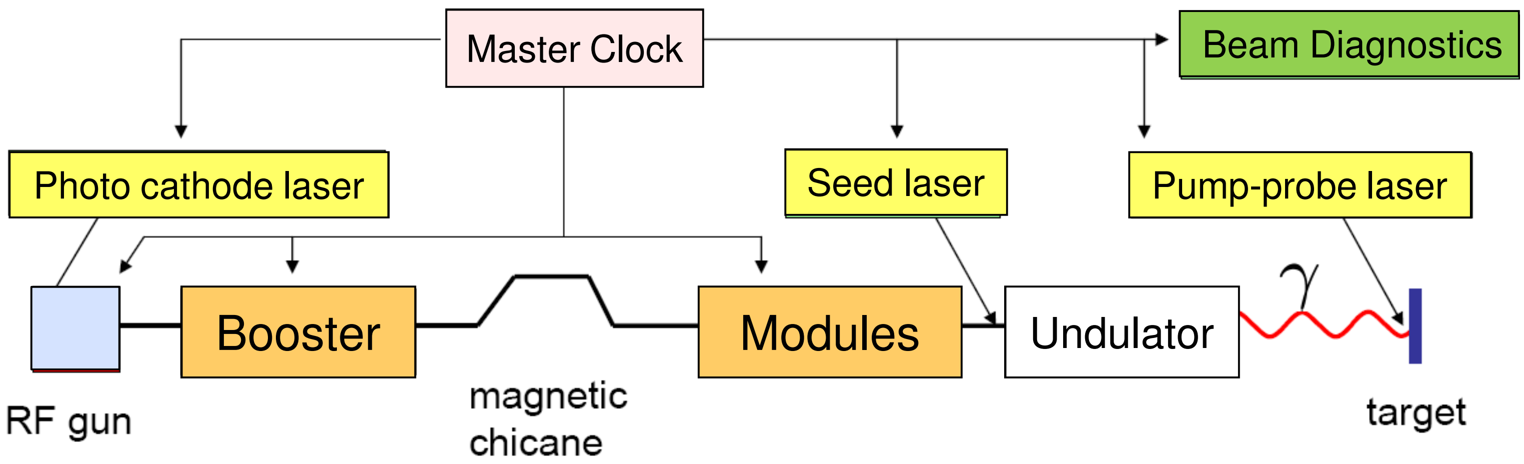
- Started as test facility for the TESLA project
- Superconducting cavities at 1.3 GHz (~25 MV/m)
- 3rd Harmonic Module at 3.9 GHz
- Two dispersive sections for high peak currents
- First user facility for VUV and soft X-ray laser pulses
- Photon pulses have few 10 fs length
- Pump-Probe experiments require synchronization on a 10 fs scale

Synchronization needs in an FEL facility

> Goal

- Measure and stabilize (feedback) timing jitter + drifts
- Lock various lasers (pump-probe, diagnostic, seed, …)
- Provide extremely stable RF reference signals

} on a 10 fs scale



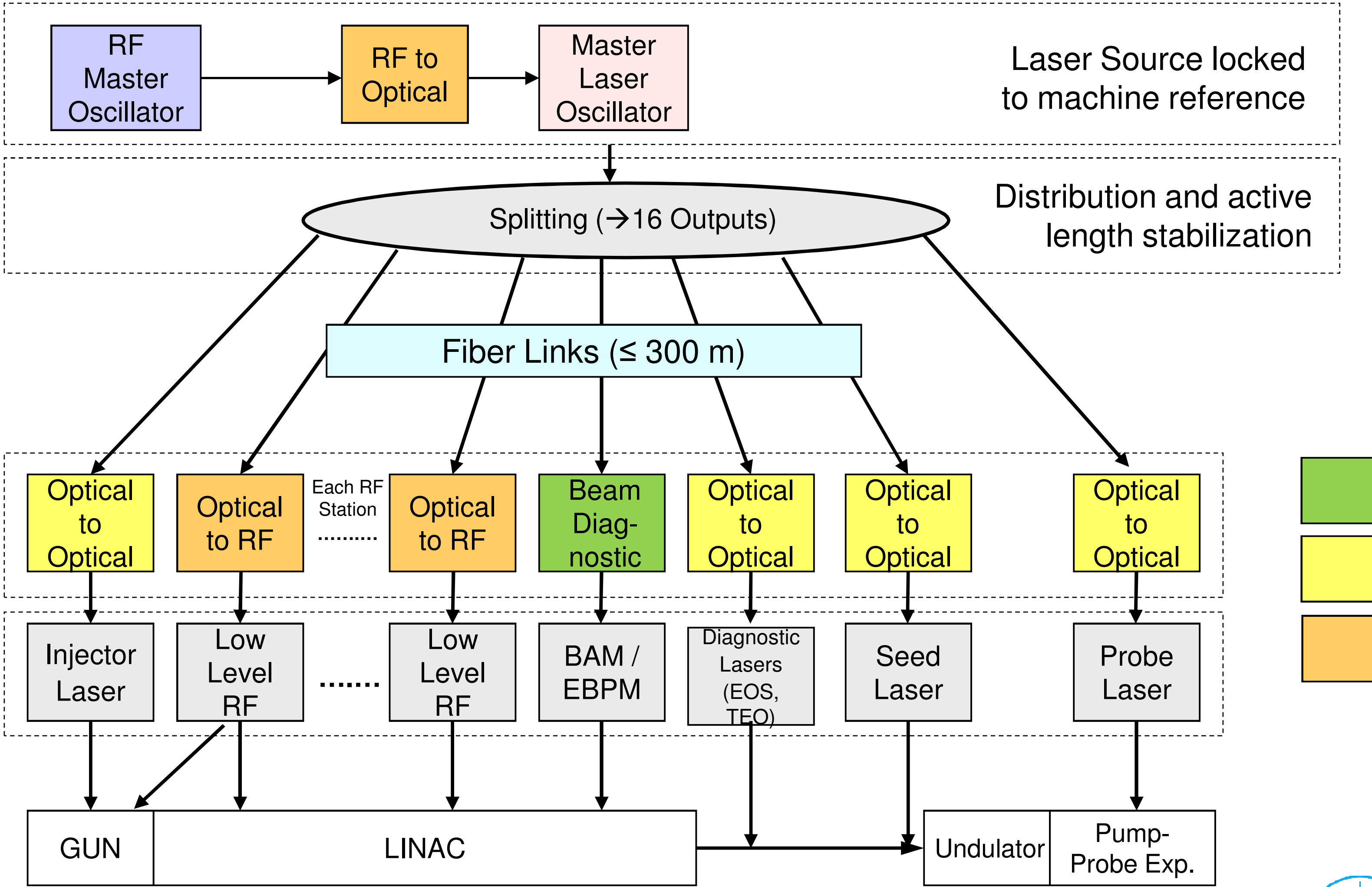
> Main sources for arrival-time changes

- Arrival-time of the photo cathode laser pulses
- Phase of the RF gun
- Amplitude and phase of the booster module(s)

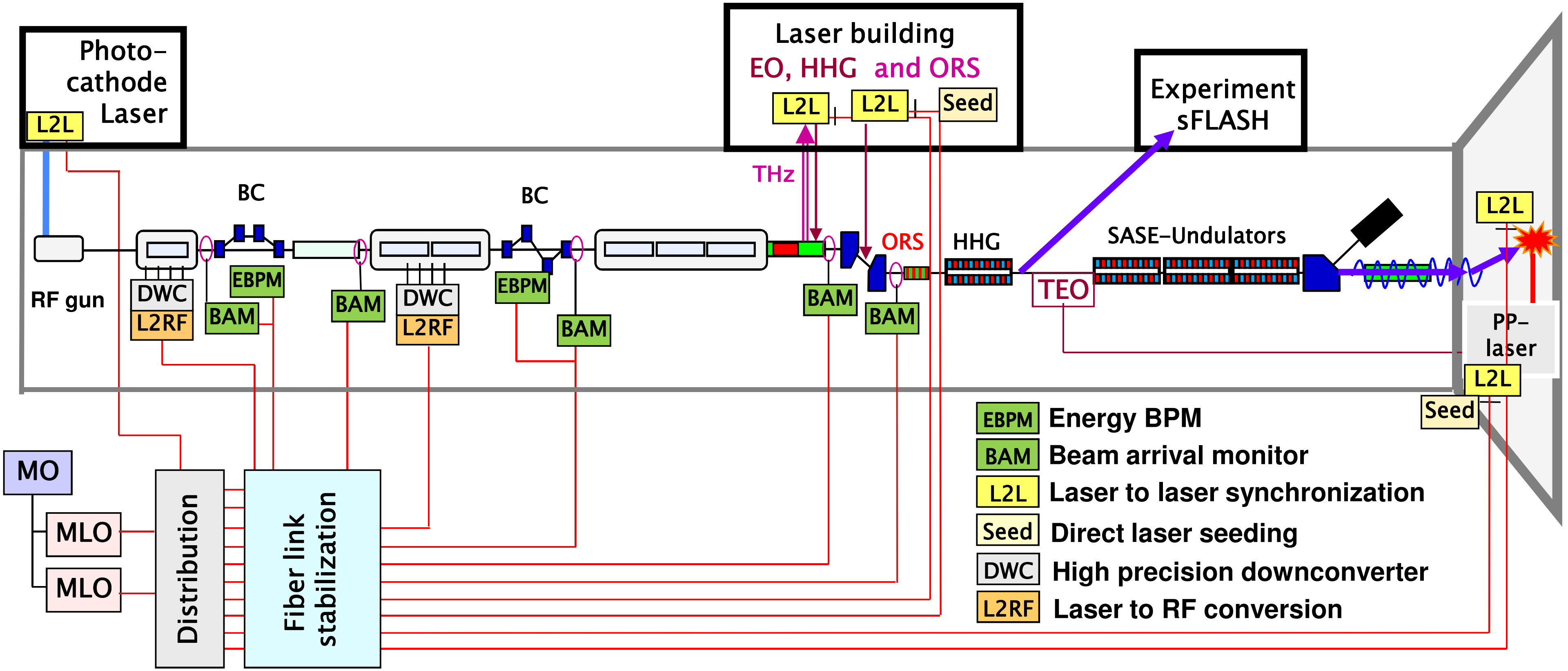
RF requirements for 10 fs arrival stability:
$\Delta\varphi < 0.005°$ @ 1.3 GHz
$\Delta A/A < 1.6*10^{-5}$

Layout of the synchronization system

The reference timing information is encoded in the precise repetition rate of an optical pulse train



Schematic of the optical synchronization system at FLASH



- beam based feedback stabilization of arrival-time
- high precision synchronization of lasers
- synchronization of all timing critical devices (up to 14)

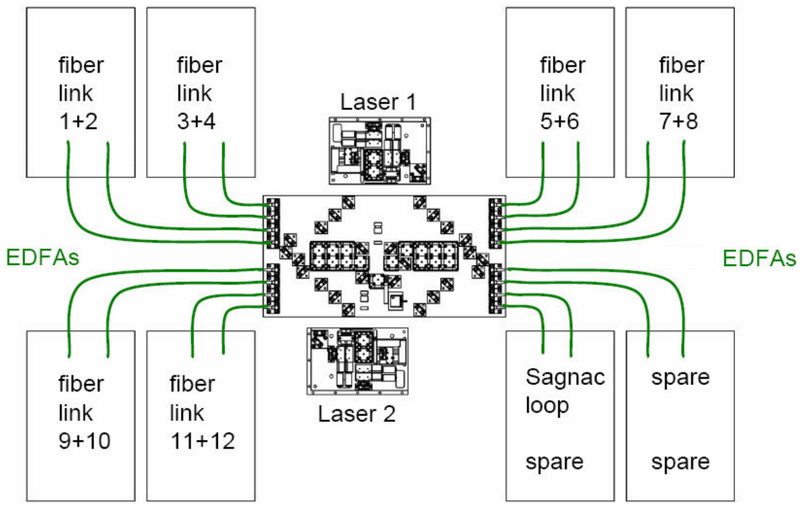
➔ Point-to-point synchronization ~ 10 fs rms (< 30 fs rms to beam)

➔ Permanent operation and long term stability / availability investigation

The synchronization lab at FLASH

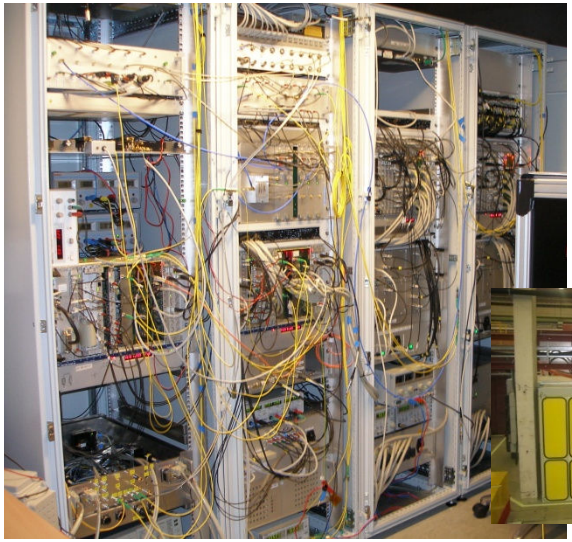
> Optical table (full expansion state)

- two MLOs for redundancy
- free-space distribution
- four fiber (EDFA) distribution units
- up to 14 link stabilization units ('Fiber Links')
- RF-lock unit for MLO
- RF based link stabilization unit

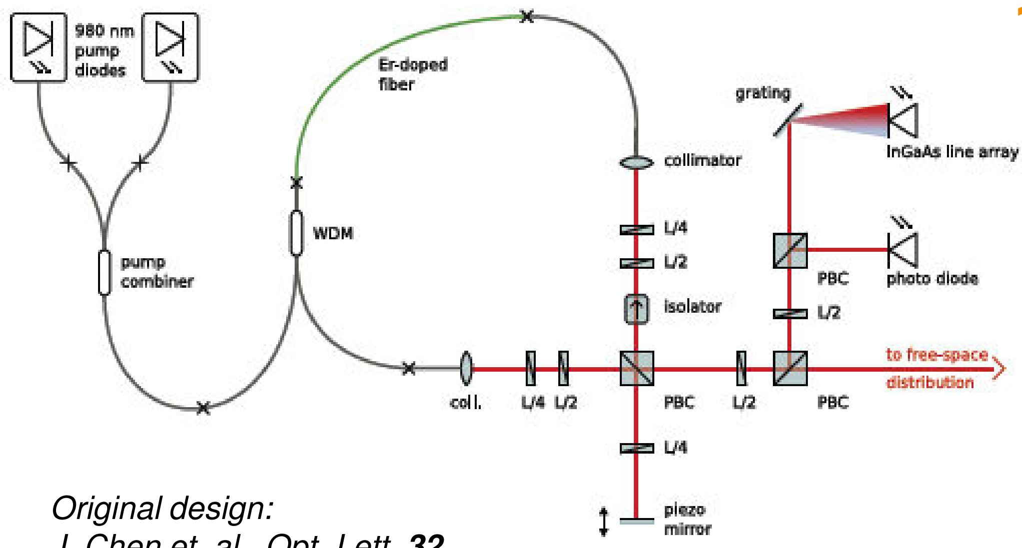


> Four electronic racks

- four VME crates (in future μTCA)
- 18 DSP controls (feedback loops)
- 18 piezo drivers (± 300 V)
- 20 pump laser diode drivers
- 16 stepper motor drivers
- > 40 temperature readouts
- tons of monitor signals
- ~ 300 cables to/from optical table



Master laser oscillator (MLO)

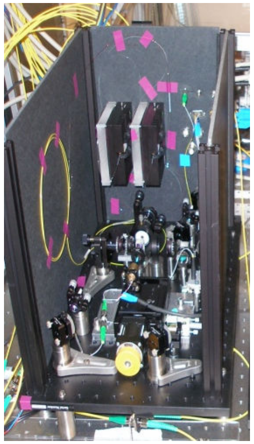


Original design:
J. Chen et. al., Opt. Lett. ***32****,*
1566-1568 (2007)

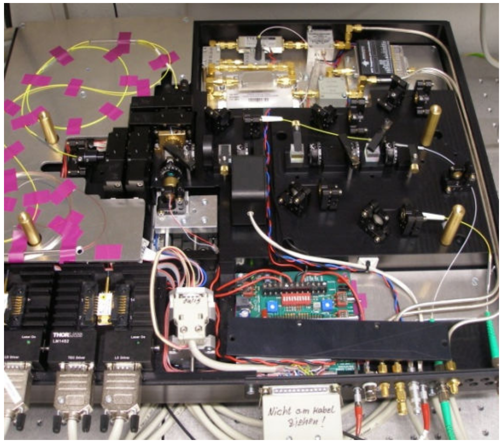
- Properties
  - mode-locked erbium-doped fiber laser
  - 1550nm telecommunication wavelength
  - repetition rate of 216.66 MHz (1.3 GHz /6)
  - average power > 60 mW
  - pulse duration < 100 fs (FWHM)
  - Integr. timing jitter ~15 fs [1 kHz, 10 MHz] (limited by measurement)
  - amplitude noise < $2 \cdot 10^{-4}$ [10 Hz, 40 MHz]

NPR type laser maybe not the best solution?

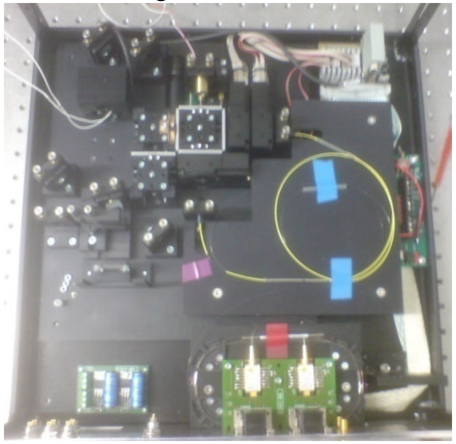
1st generation MLO



2nd generation MLO



3st generation MLO



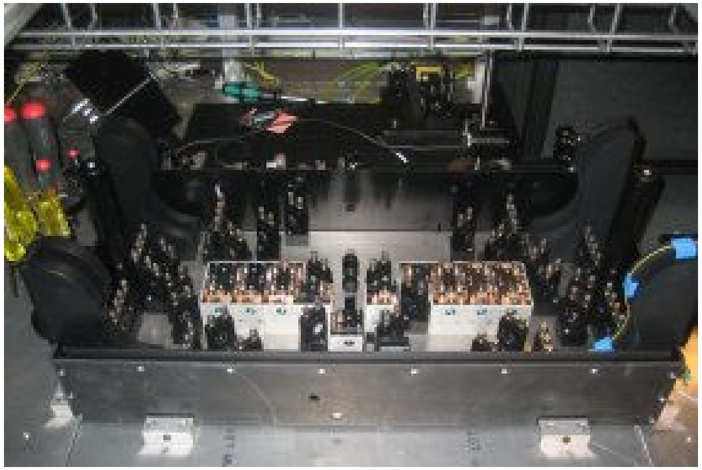
'Plan B' MLO

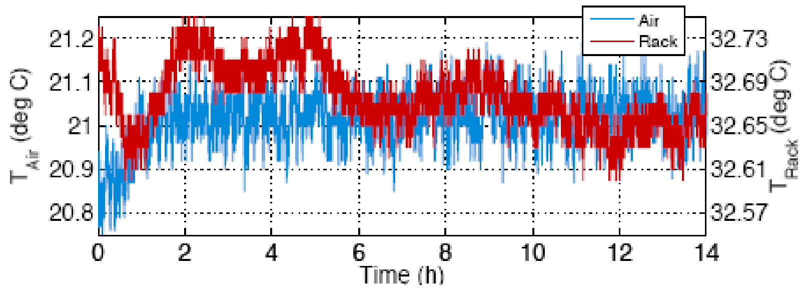
Courtesy F. Loehl, S. Schulz, A. Winter

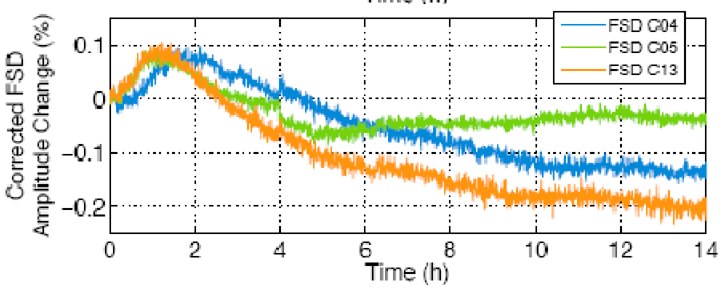
Distribution to up to 16 outputs

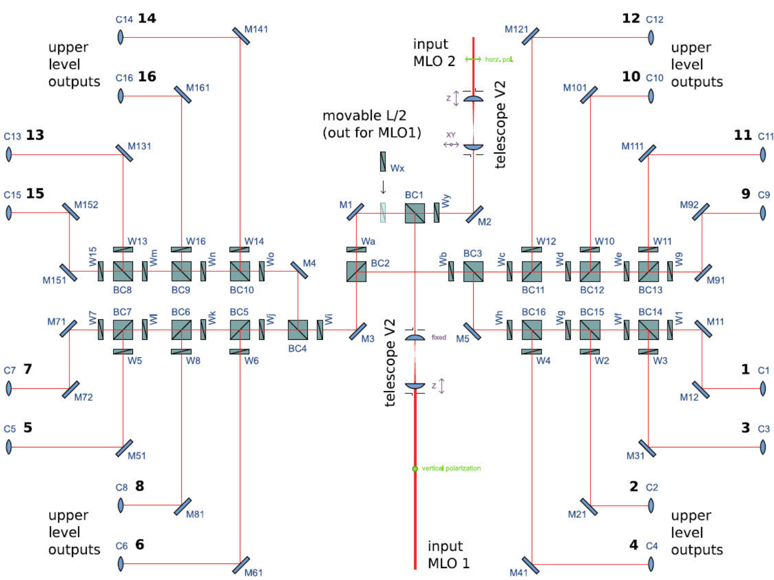
> Properties

- baseplate made of Invar
- two free space inputs, 16 collimator outputs
- same pathlength for each output
- 4-5 mW per output
- ~ 85% incoupling efficiency at all collimators



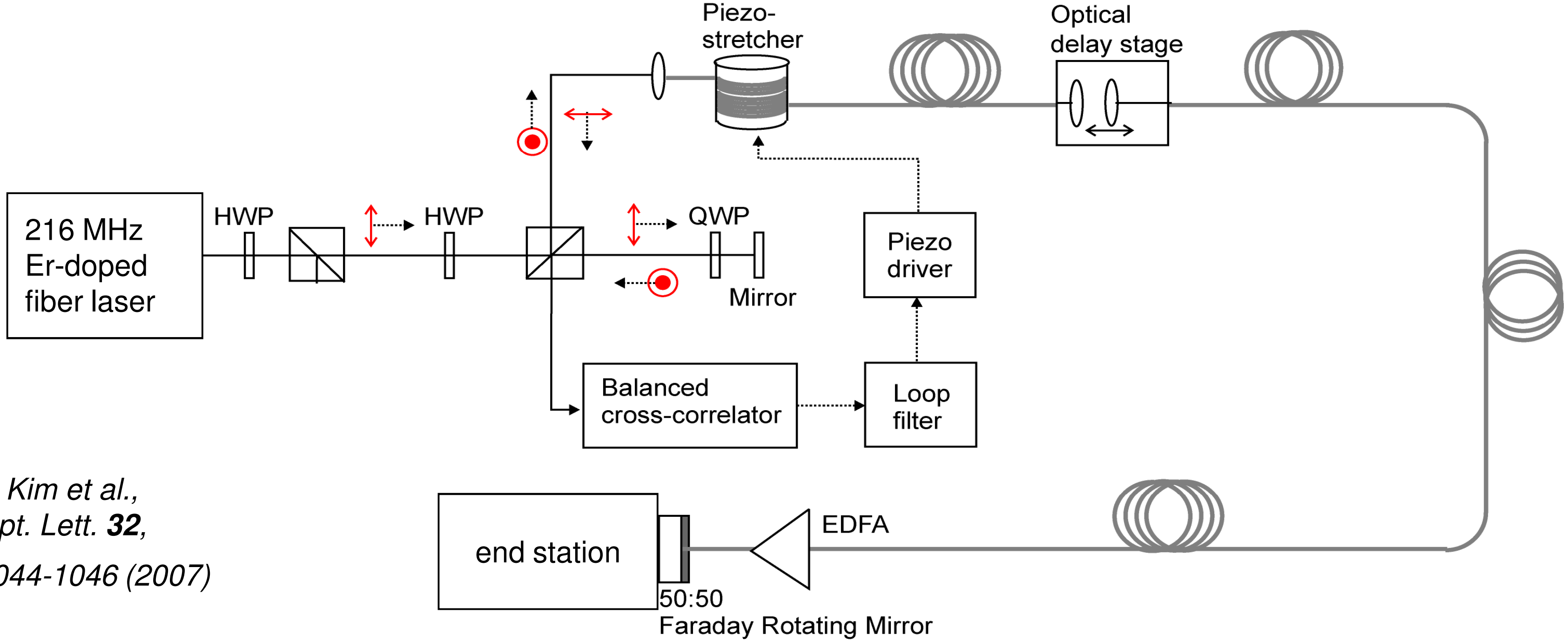




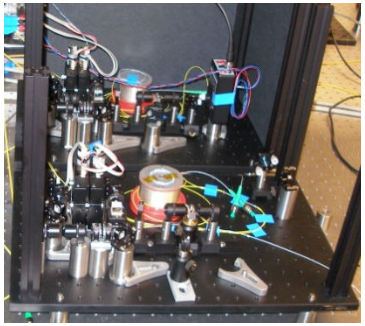


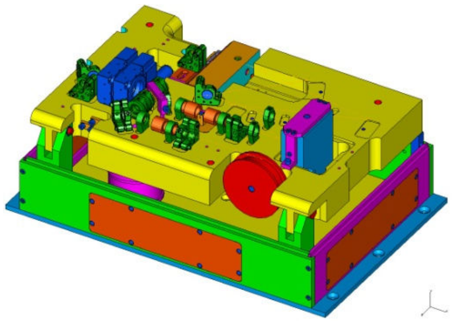
S. Schulz, FEL09, WEPC72

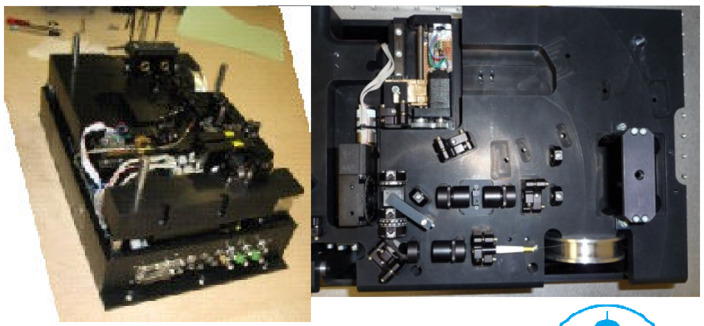
Fiber link stabilization



J. Kim et al.,
Opt. Lett. ***32****,*
1044-1046 (2007)

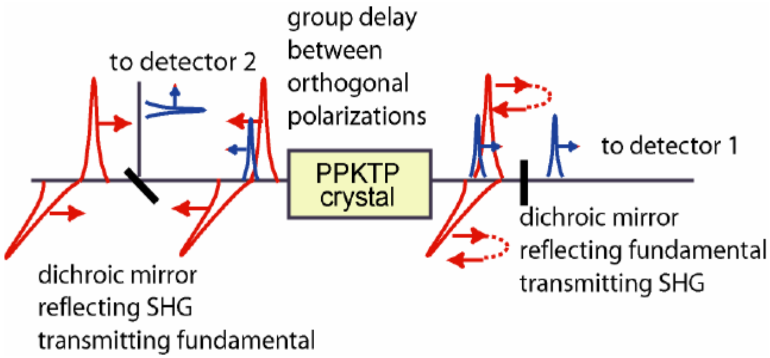




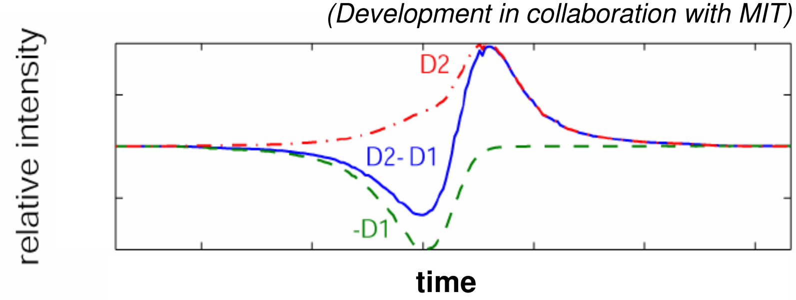


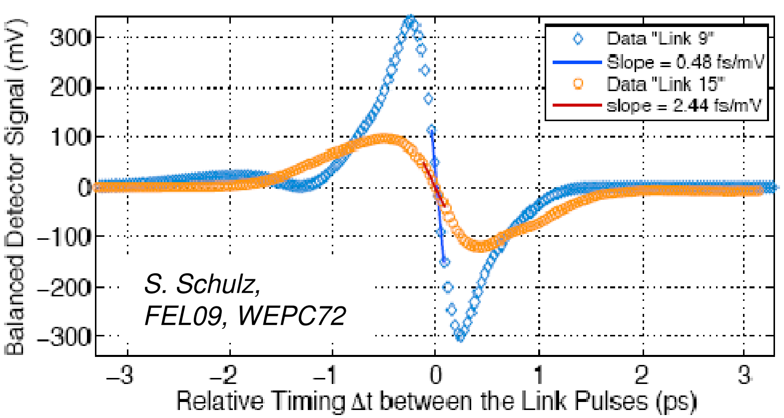
Courtesy F. Loehl

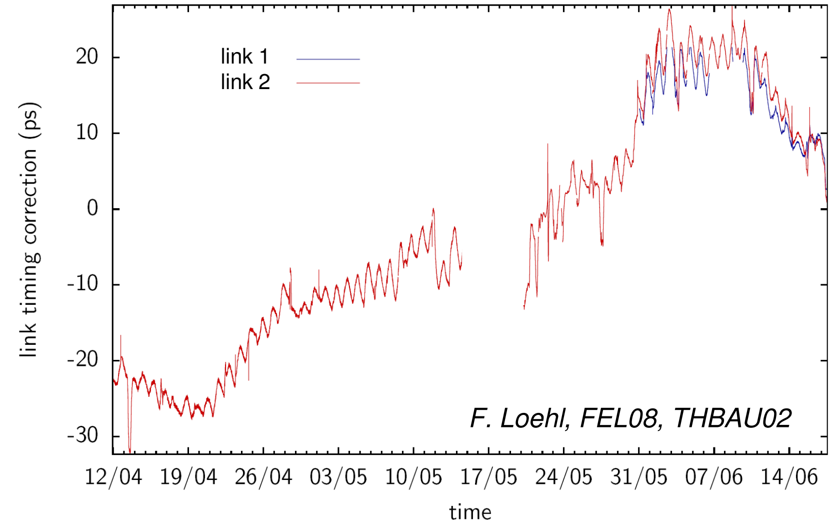
Balanced optical cross-correlator (OCC)

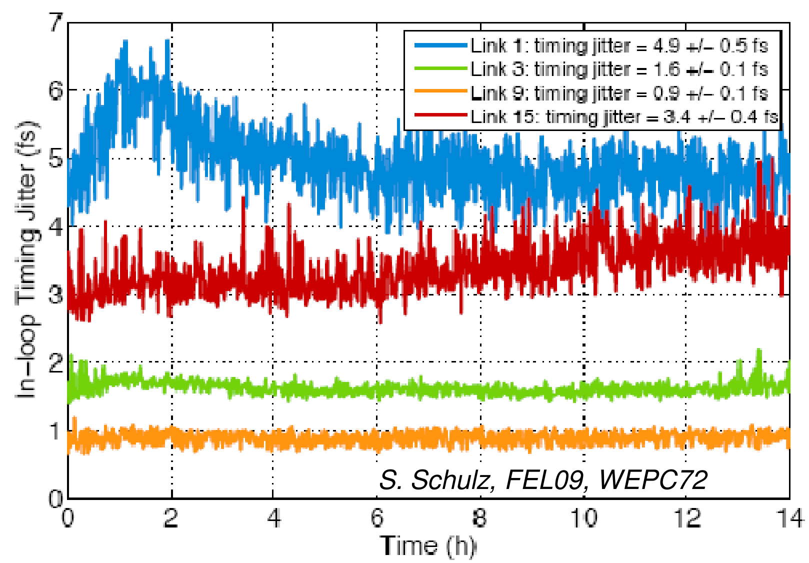


(Development in collaboration with MIT)

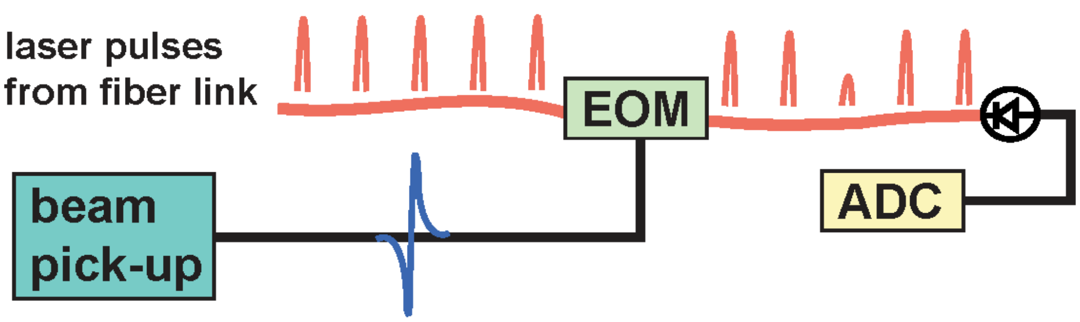


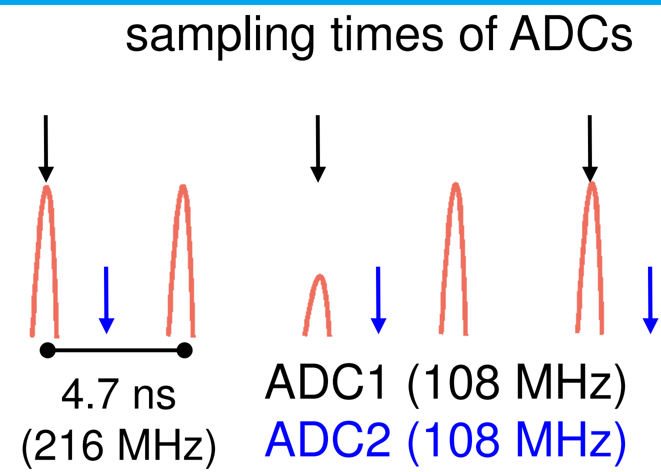


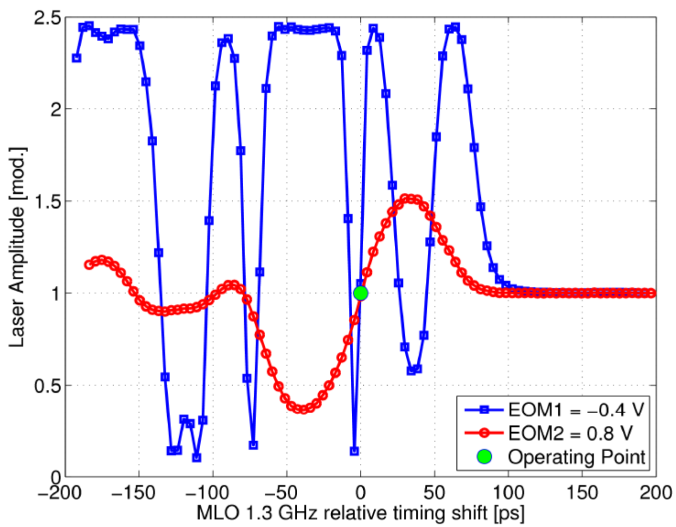


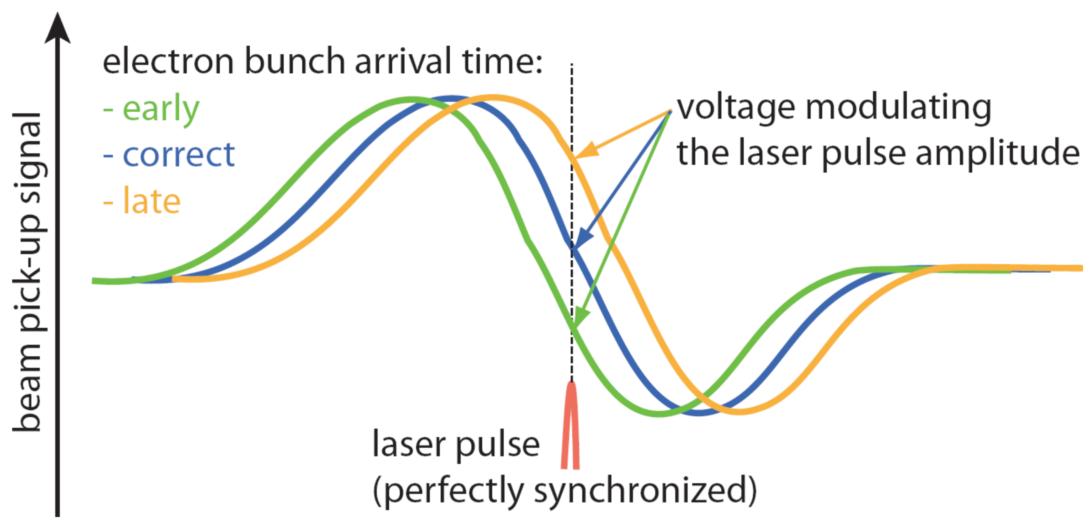


Beam arrival-time monitor (BAM)





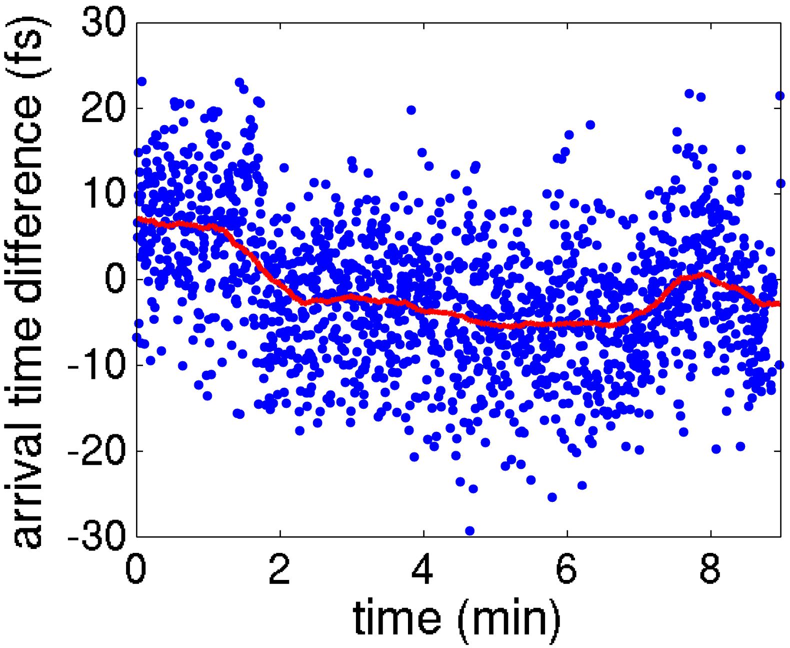


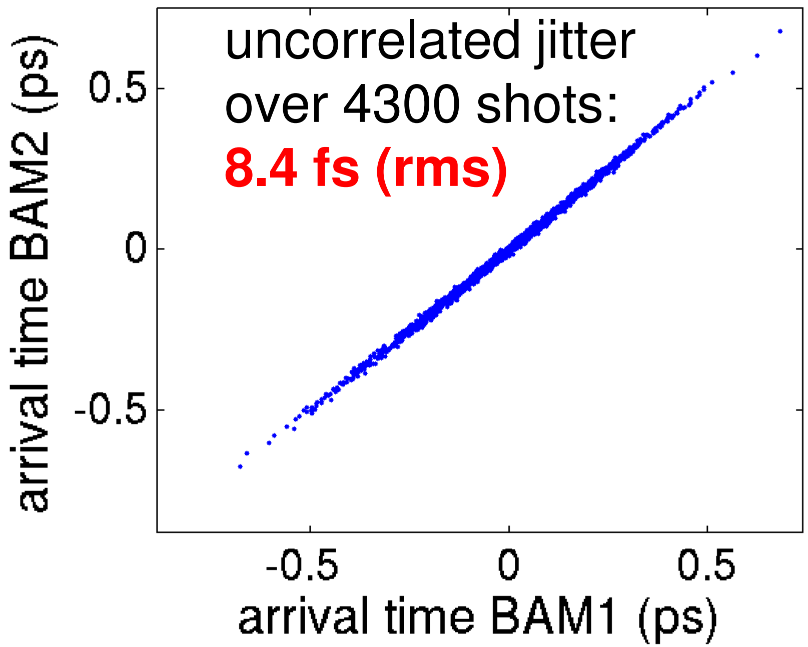


M. Bock, FEL09, WEPC66
F. Loehl, PhD thesis, DESY-THESIS-09-031, 2009

Patented 2006 by DESY

Arrival time correlation between two BAMs





Arrival time difference contains:

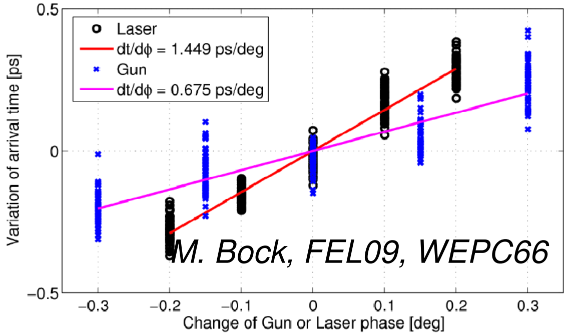
- high frequency laser noise (~3 MHz – 108 MHz)
- stability of two fiber links
- two BAMs

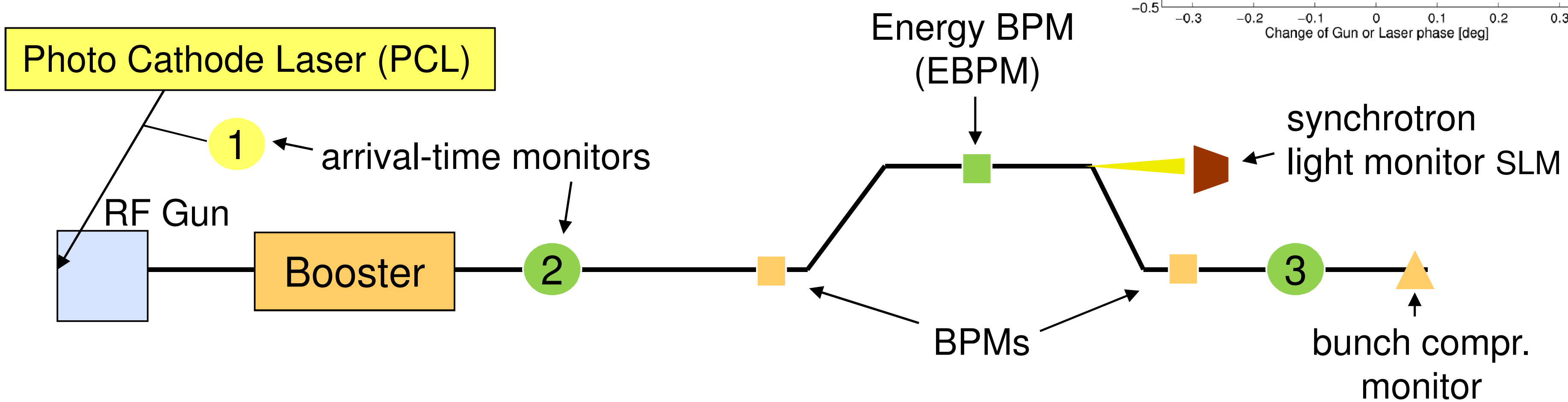
Single bunch resolution of entire measurement chain: **< 6 fs (rms)**

F. Loehl, PhD thesis, DESY-THESIS-09-031, 2009

Beam based injector feedback

- Goal: Achieve stable arrival time, energy and compression
- Need: Many (different) monitor systems and complex regulation algorithms needed

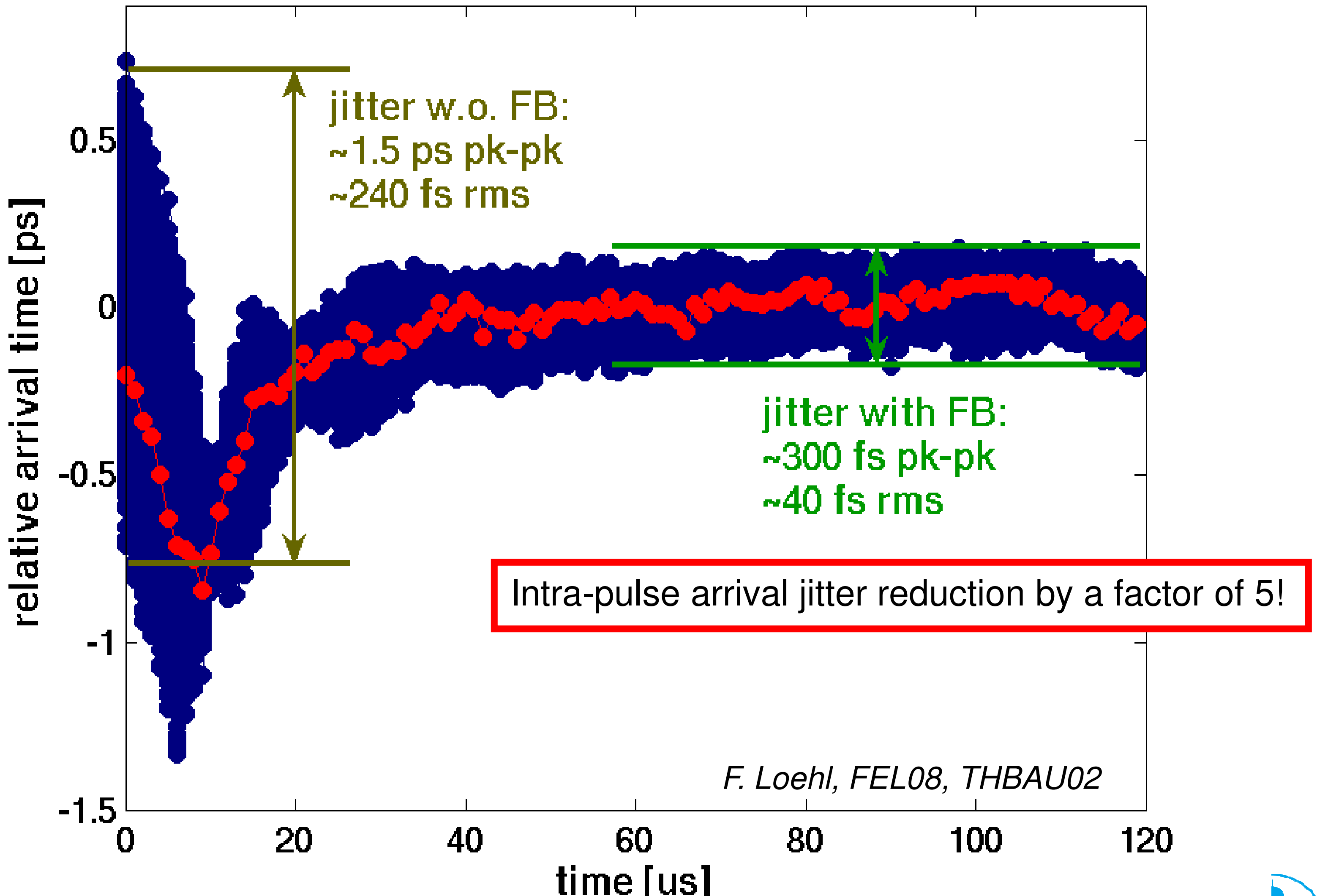




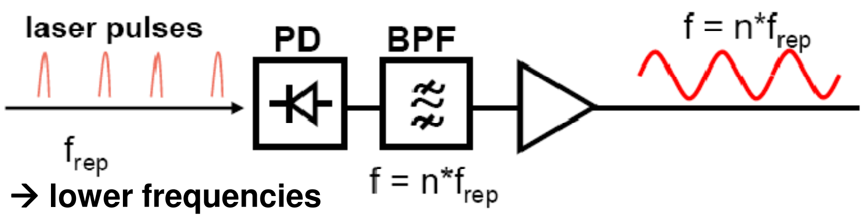
Machine parameter:	*Monitor:*
Arrival-time of PCL	1st arrival time monitor
Phase of RF gun	difference 1st and 2nd arrival-time monitor
Amplitude of booster	EBPM + BPMs / difference 3rd and 2nd arrival-time monitor (/ SLM)
Phase of booster module	(bunch compression monitor / fiber laser + EO)

Intra bunch-train arrival time feedback

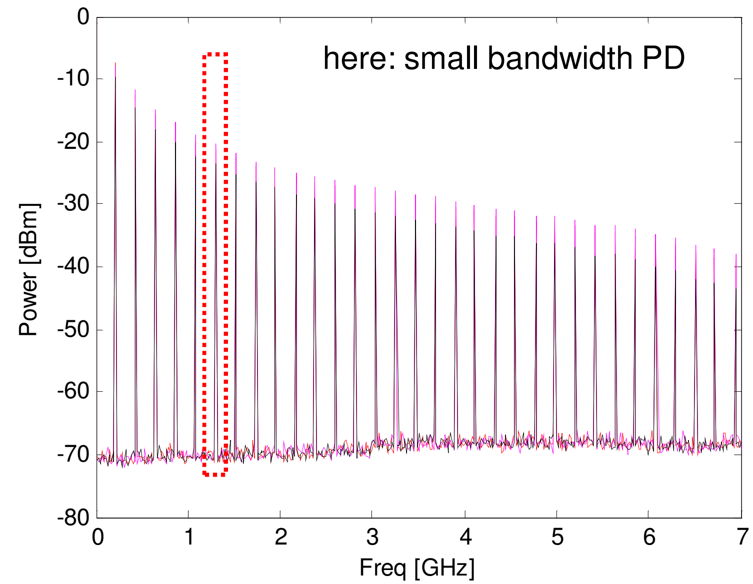
1200 shots:



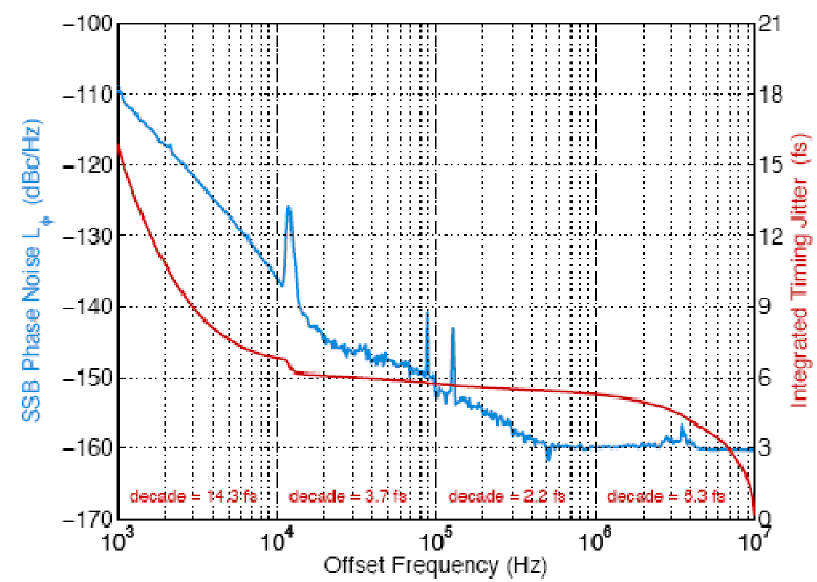
RF generation from optical pulse train



gating → lower frequencies



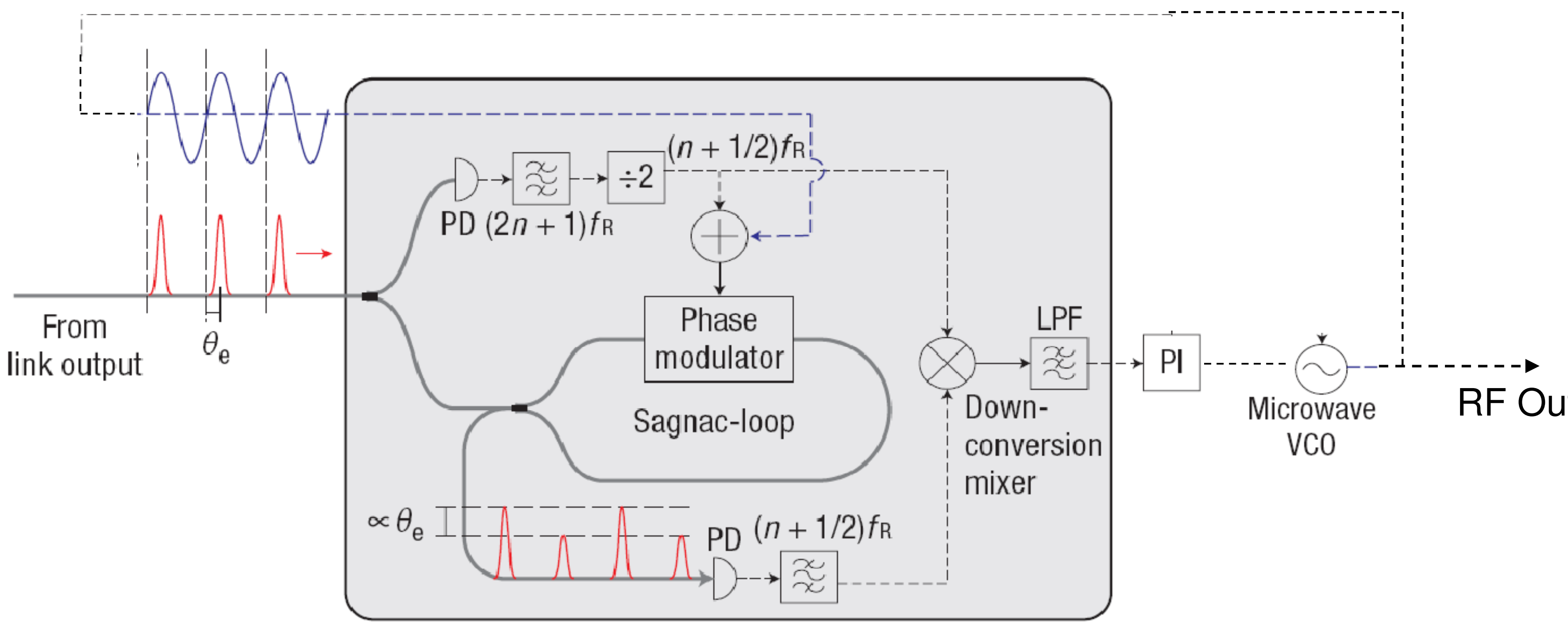
- Direct Conversion
  - \+ Drift: 10.7 fs over >15 h @ 1.3 GHz *(M. Felber, PAC09, TH6REP088)*
  - \+ Jitter: 3.3 fs [1kHz,10MHz] @ 3 GHz *(S. Hunziker, DIPAC09, TUPB43)*
  - \+ small and robust
  - \+ 10 mW P_{opt} sufficient
  - \+ relatively cheap (<2k€)
  - – Small output power vs. amplifier drift
  - – Amplitude to phase conversion: 1-4 ps/mW
  - – Temperature dependency ~350 fs/°C



RF generation from optical pulse train

> Balanced optical-microwave phase detector ➔ PLL feedback loop

- High power output (amplifier can be included in feedback)
- Balanced scheme → potential for ultra-low drift: <7 fs over 7 h (*M. Felber, PAC09, TH6REP088)*

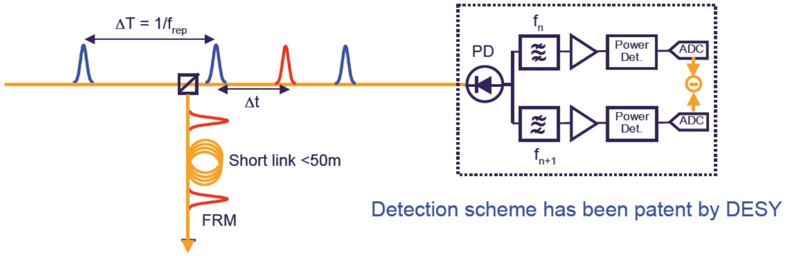


J. Kim et al., Nature Photonics 225: 733-736, 2008

Many more projects at LbSyn…

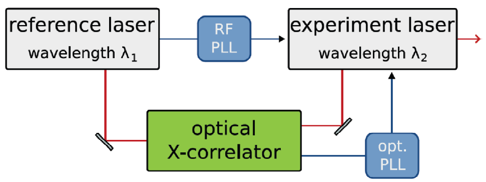
> RF-based fiber (short)link stabilization

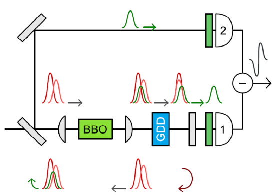
- RF based measurement of link length change <5 fs over 50 h
  (J. Zemella, FEL09, FROA05)



> Two-color optical cross-correlator

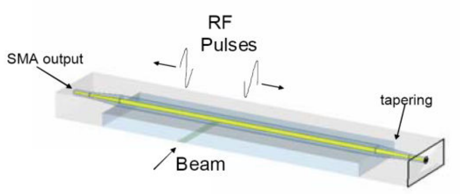
- locking lasers of different wavelength, e.g. Ti:Sa (800 nm)
  (S. Schulz, PAC09, TH6REP091)

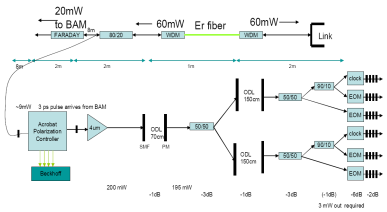




> Energy BPM (EBPM)

- use orbit dependency of pickup signal in chicane + two BAM setups
  (K. Hacker, FEL09, WEPC70)





> …

Requirements for developing a synchronization system

> Infrastructure

- Environment

  Temperature stabilization
  Vibration suppression
  EMI shielding

- Typical laboratory equipment

  Optical spectrum analyzer
  Autocorrelator
  RF Phase- and amplitude noise analyzer
  Baseband analyzer
  Fast scopes (≥8 GHz)
  RF spectrum analyzer (≥26 GHz desired)
  Splicer + PM splicing equipment
  etc…

> Engineering skills

  Optics (Free space- and fiber)
  Electronics (low noise analog / fast digital)
  FPGA programming
  Software (Control system integration / feedback)
  Mechanical (small and precise / big and robust)
  RF

> Time, Money and **Manpower**

Summary & Outlook

- Prototypes for all subsystems have been built and demonstrated <10 fs stability
- Engineered versions of key components have been developed, some with major problems (MLO), some with good performance (Links)
- At FLASH, the system is in the commissioning phase (2 MLOs, 4 Link stabilizations, 3 BAMs, and 1 EBPM in operation)
- Robustness and long-term (>month) reliability tests underway
- Installation of two more BAMs planned, till the end of the current shutdown (March 2010)

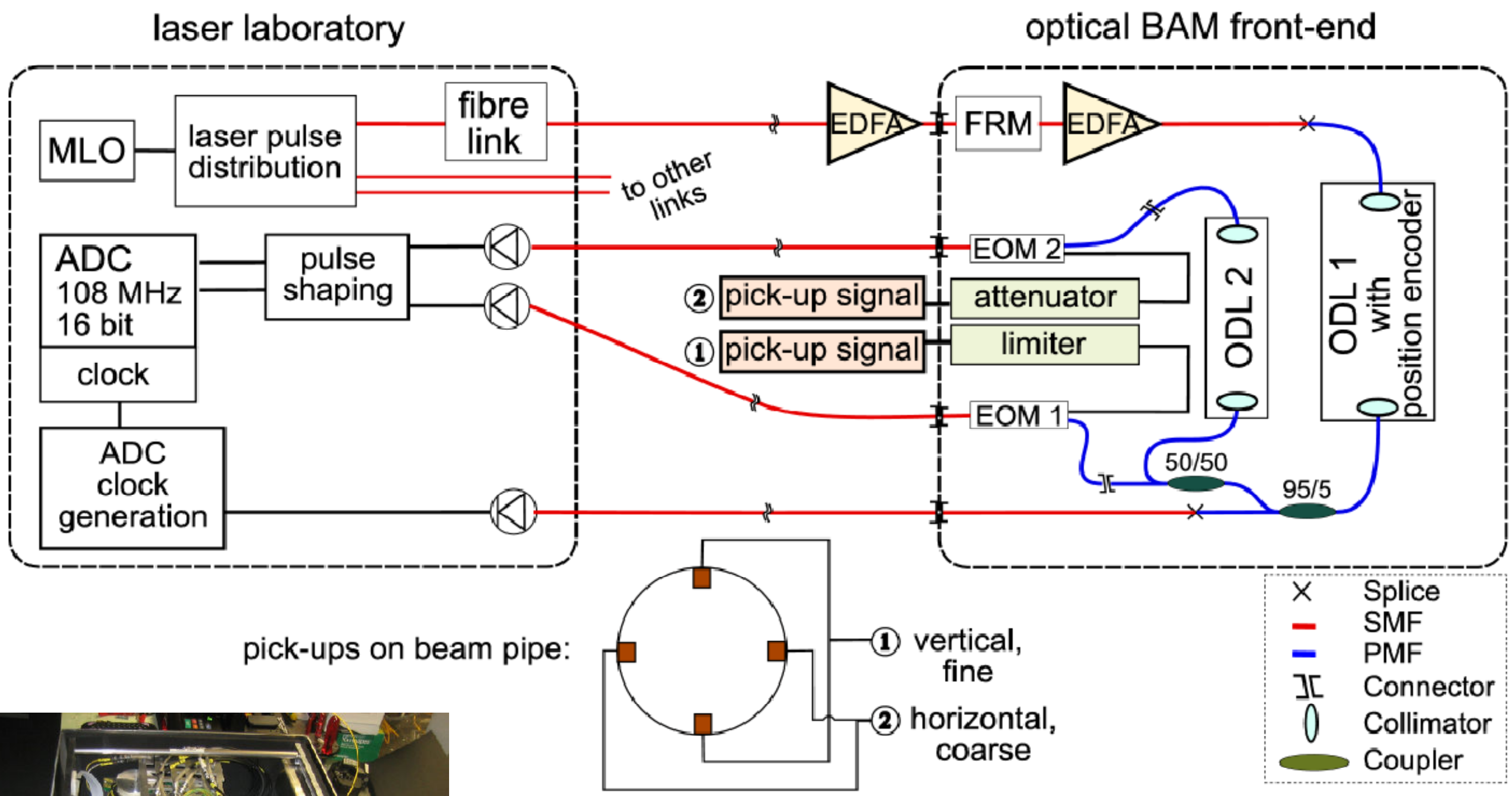
- Still a lot of development to do…

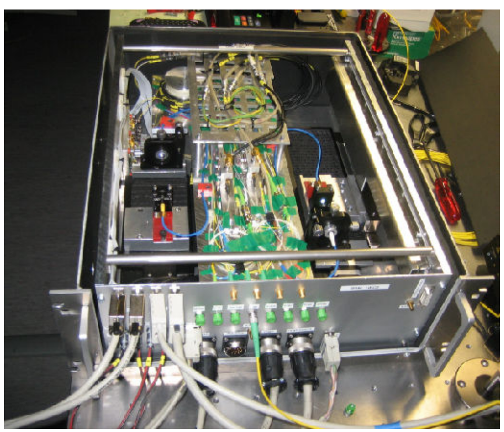
During the past five years many fruitful collaborations contributed to the progress

Thank you for your attention!

Backup

BAM Layout

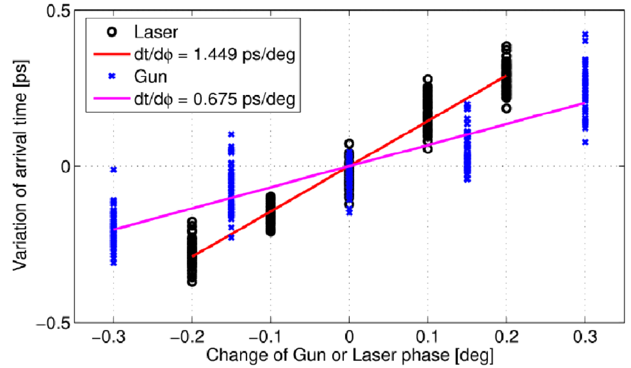




Courtesy M. Bock

BAM measurements – arrival time dependencies

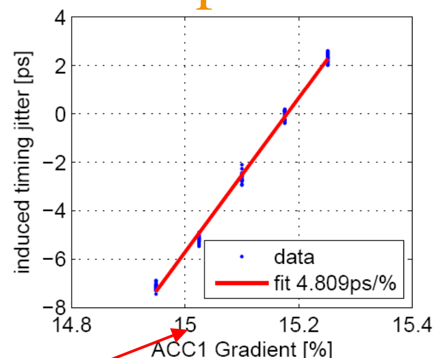
M. Bock et al., FEL09, WEPC66

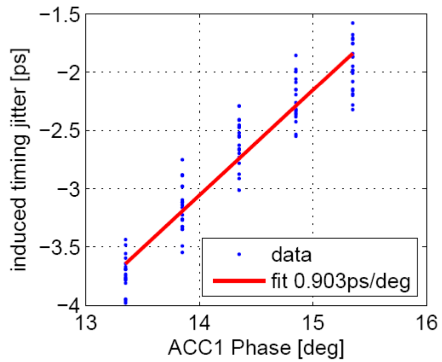


Gun

Amplitude

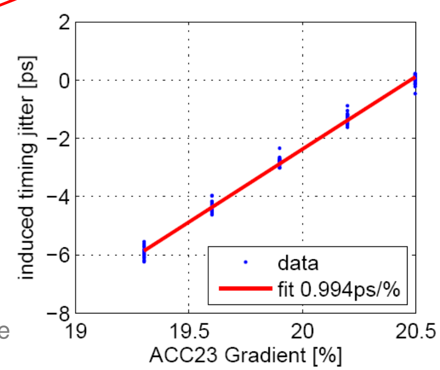
Phase

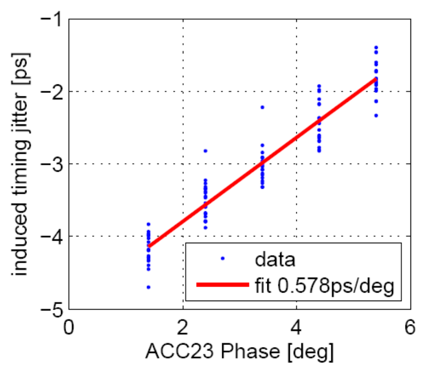




Acc1

Most critical at FLASH 4.8 ps/%

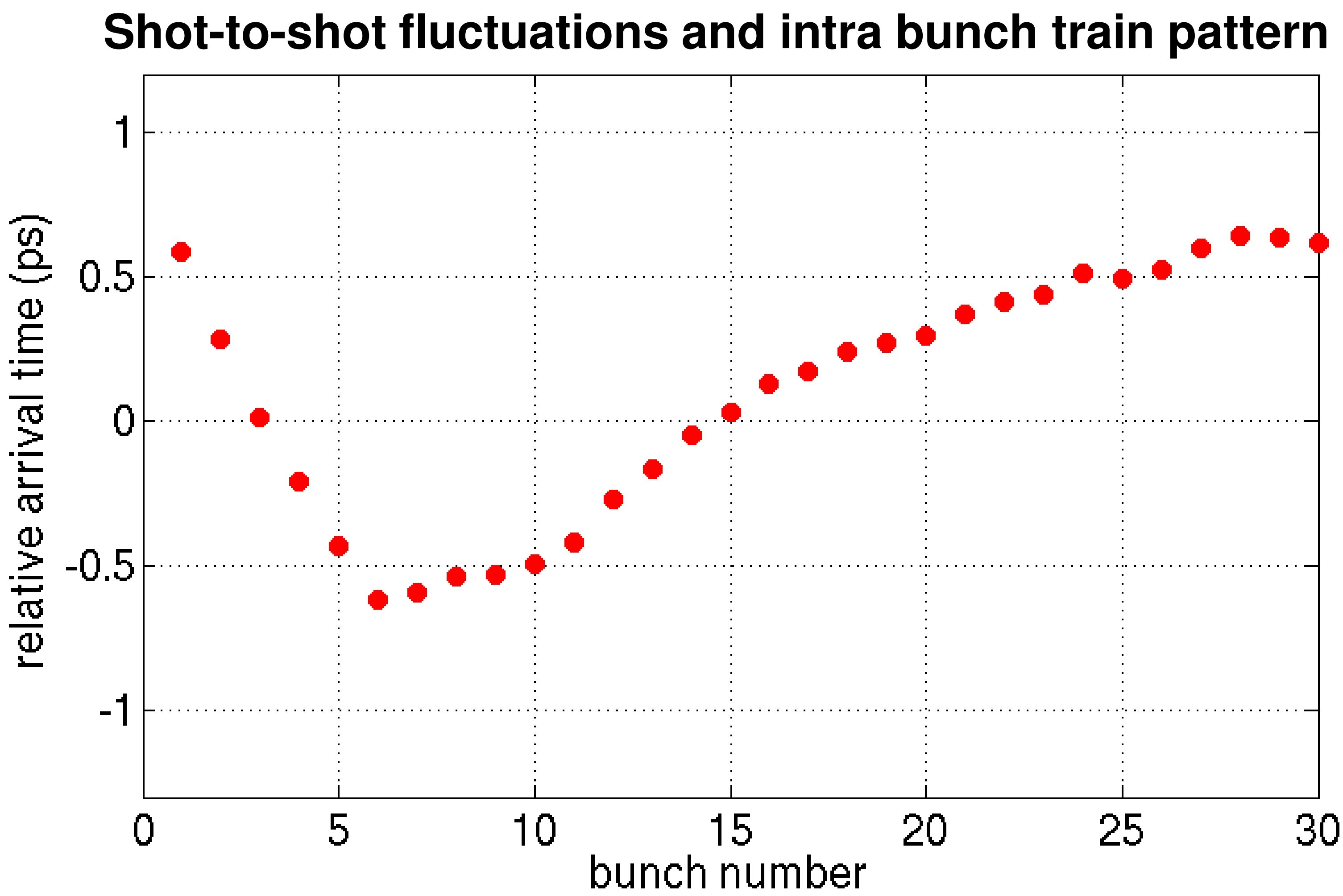




Acc23

Acc456 no effect

BAM bunch train measurement - no arrival time feedback



Courtesy: F. Loehl