Ultra-fast Longitudinal Feedbacks for the European XFEL

H. Schlarb, S. Pfeiffer, Ch. Schmidt,

on behalf of the

DESY LbSyn and LLRF Team

Outline:

- Introduction
- Longitudinal diagnostics
- Feedbacks

Longitudinal jitter sources – Generic FEL Layout –

Long/transverse beam quality & arrival time

- **conventional: for low peak currents ~ 10-50A**

Sources are:

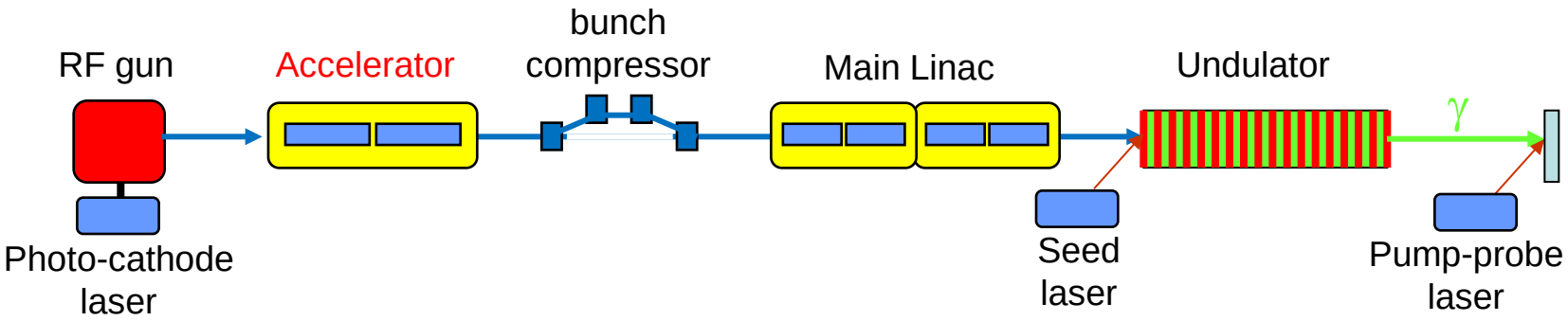
Photo-cathode laser pulse shape	t/λ
Phase of RF gun (non-relativistic electrons)	t
First accelerator cavities (non-relativistic electrons)	t/λ
Seed and Pump-probe laser	t
Charge fluctuation though collective effects	$\lambda/(t)$

t: arrival time λ: longitudinal change distribution

Longitudinal jitter sources – Generic FEL Layout –

Long/transverse beam quality & arrival time

- **conventional: for high peak currents ~ 500 - 20000 A**



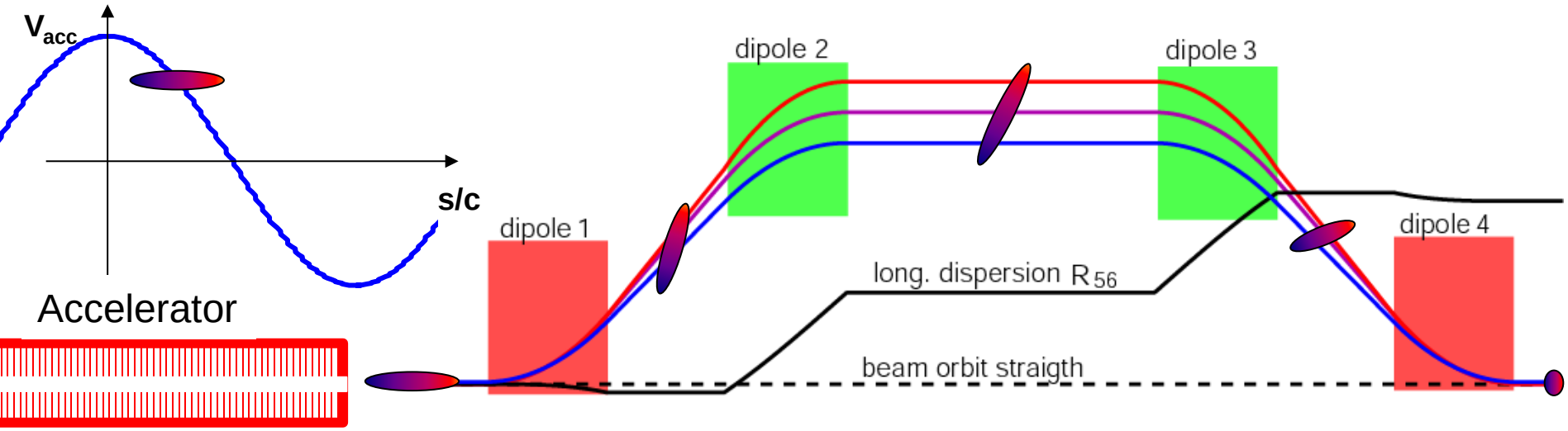
Sources are:

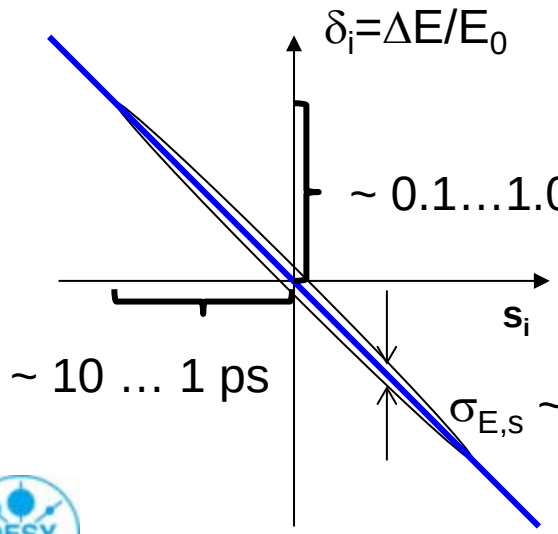
Photo-cathode laser pulse shape	t/λ
Phase of RF gun (non-relativistic electrons)	t
First accelerator cavities (non-relativistic electrons)	t/λ
Seed and Pump-probe laser	t
Accelerator prior to bunch compressor	t/λ
Charge fluctuation though collective effects	λ/(t)

t: arrival time λ: longitudinal change distribution

Tolerances on RF stability: … what will be required?

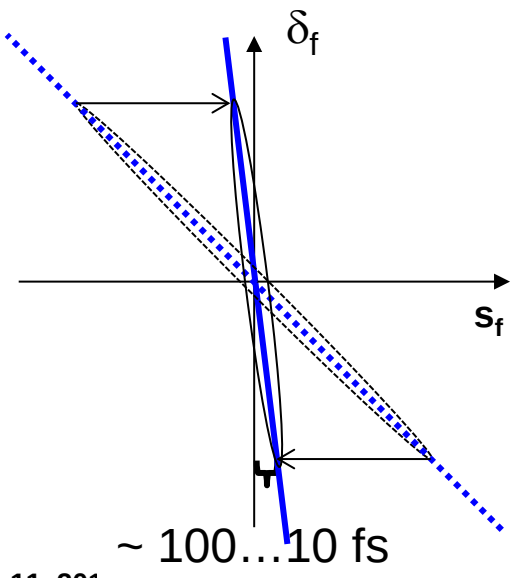
Energy chirp + energy dependent path length





$$\begin{pmatrix} s_f \\ \delta_f \end{pmatrix} = \begin{pmatrix} 1 & -R_{56} \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} s_i \\ \delta_i \end{pmatrix}$$

Sharing process



Tolerances on RF stability: … what will be required?

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If $E_0 << E_1$ and $E_0' << E_1'$

6…3.5 ..4

$$\frac{\delta C}{C_1} = -(C_1 - 1)\left[\left(3\tan(\phi_1) + \frac{1}{\tan(\phi_1)}\right)(\delta\phi_1 - \omega_{RF}\delta t_{ini}) + 4\frac{\delta V_1}{V_1}\right]$$

Tolerance ∝ Compression

Phase & arrival

Amplitude

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Example: C=100, dI/I<10% ⇒ ϕ≈0.014° and dV/V ≈ 2.5e-4

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Tolerance ∝ Compression

Phase & arrival **Amplitude**

Example: C=100, dI/I<10% ⇒ ϕ≈0.014° and dV/V ≈ 2.5e-4

$$\Sigma_{t,f}^2 = \left(\frac{R_{56}}{c_0}\right)^2 \cdot \frac{\sigma_{V_1}^2}{V_1^2} + \left(\frac{C-1}{C}\right)^2 \cdot \frac{\sigma_{\phi_1}^2}{\omega_{rf}^2} + \left(\frac{1}{C}\right)^2 \cdot \Sigma_{t,i}^2$$

Amplitude **Phase** **Arrival**

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Amplitude **Phase** **Arrival**

Example:10fs, C>>1,R_{56}~0.10m ⇒ ϕ≈0.005° L-band and dV/V ≈ 3e-5

Tolerances on RF stability: … what will be required?

- **Impacts the peak current** / longitudinal beam profile

If $E_0 << E_1$ and $E_0' << E_1'$

6…3.5 ..4

$$\frac{\delta C}{C_1} = -(C_1 - 1)\left[\left(3\tan(\phi_1) + \frac{1}{\tan(\phi_1)}\right)(\delta\phi_1 - \omega_{RF}\delta t_{ini}) + 4\frac{\delta V_1}{V_1}\right]$$

Tolerance ∝ Compression | **Phase & arrival** | **Amplitude**

Example: C=100, dI/I<10% ⇒ ϕ≈0.014° and dV/V ≈ 2.5e-4

- **Arrival time jitter:**

$$\Sigma_{t,f}^2 = \left(\frac{R_{56}}{c_0}\right)^2 \cdot \frac{\sigma_{V_1}^2}{V_1^2} + \left(\frac{C-1}{C}\right)^2 \cdot \frac{\sigma_{\phi_1}^2}{\omega_{rf}^2} + \left(\frac{1}{C}\right)^2 \cdot \Sigma_{t,i}^2$$

Amplitude | **Phase** | **Arrival**

Example:10fs, C>>1,R_{56}~0.10m ⇒ ϕ≈0.005° L-band and dV/V ≈ 3e-5

- **Mitigation:** through multi-staged compression, but this adds cost
- **Coupling:** between (Δt_f , C, E) as function of (V, ϕ, Δt_{ini})
- **Significant complexity added:** Harmonic cavity / Laser pulse shaping

Longitudinal Diagnostics

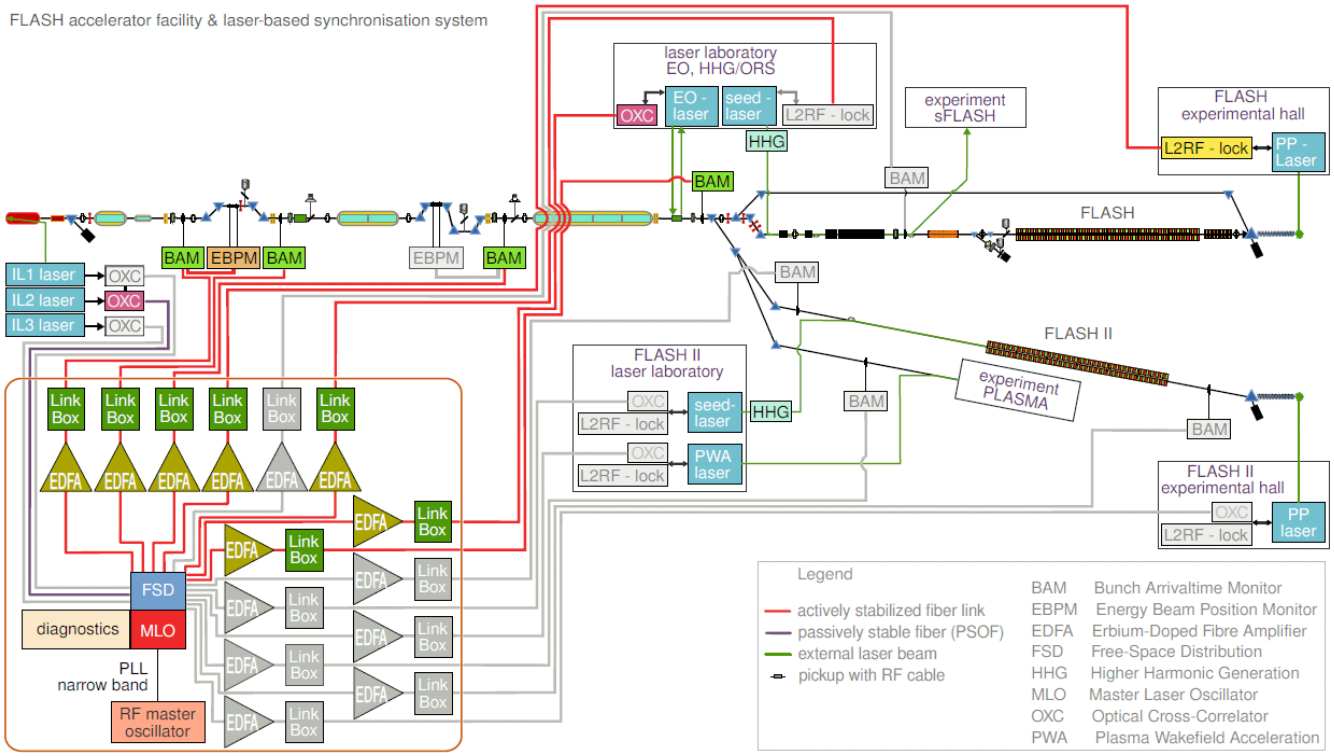
Arrival timing

&

Compression

Synchronization – Pulsed optically, example FLASH

> Optical synchronization system @ FLASH using mode locked laser



Synchronization – Pulsed optically, example FLASH

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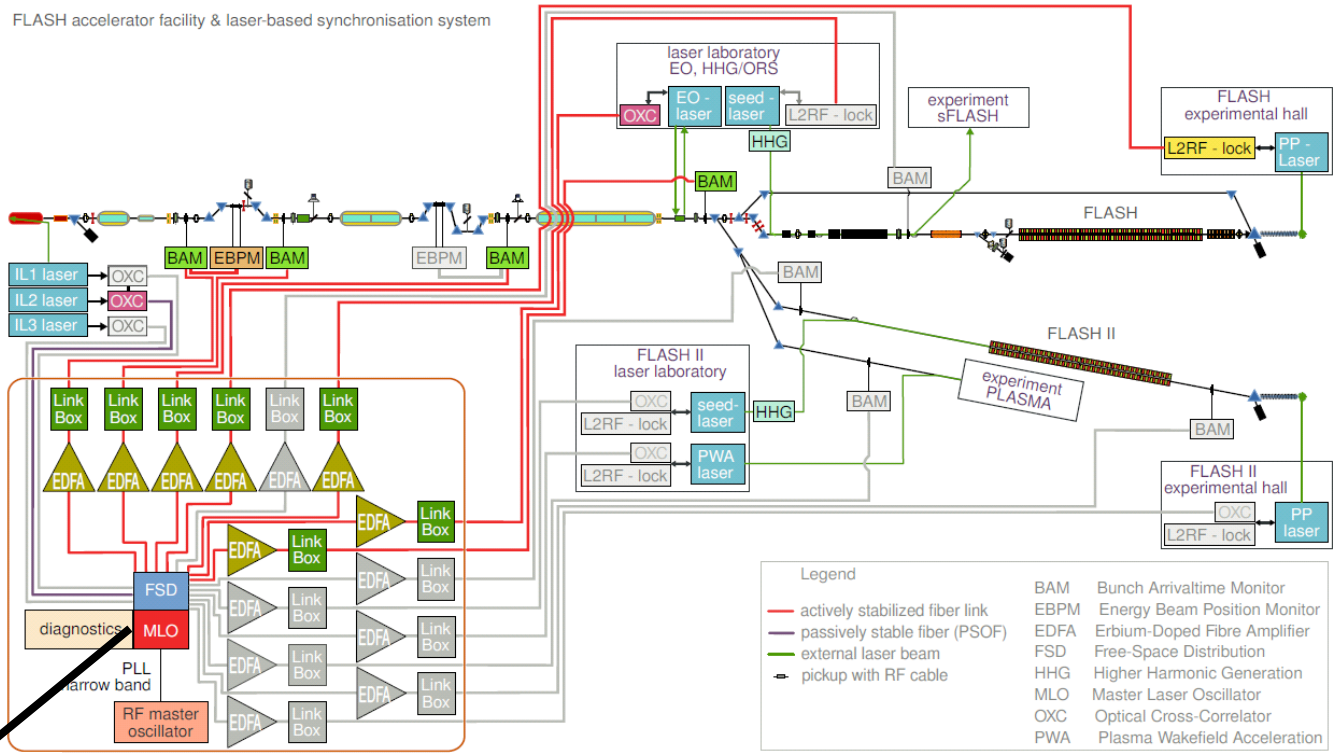
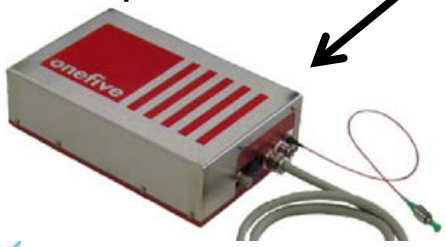


Master Laser
~ 5fs phase noise



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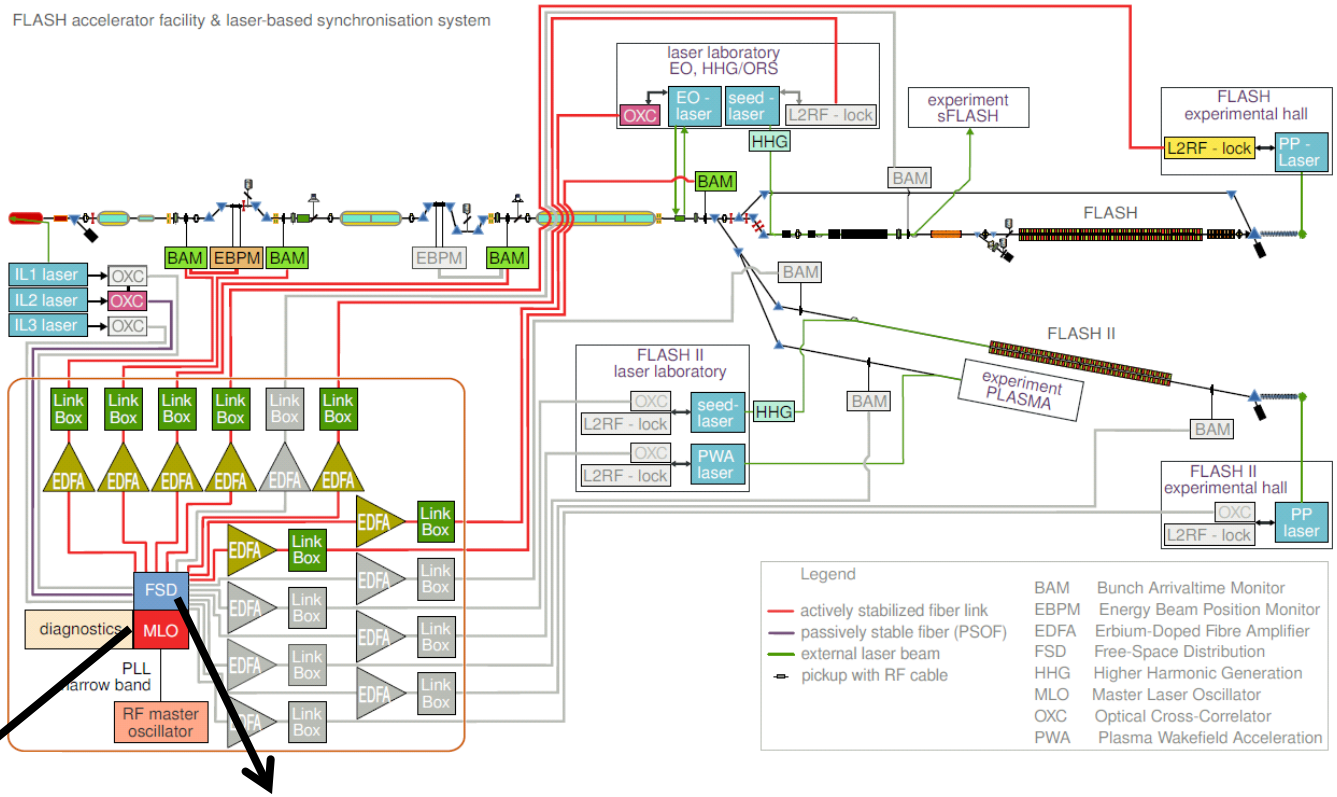

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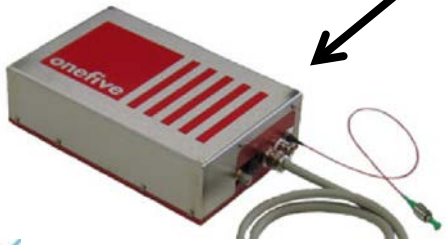

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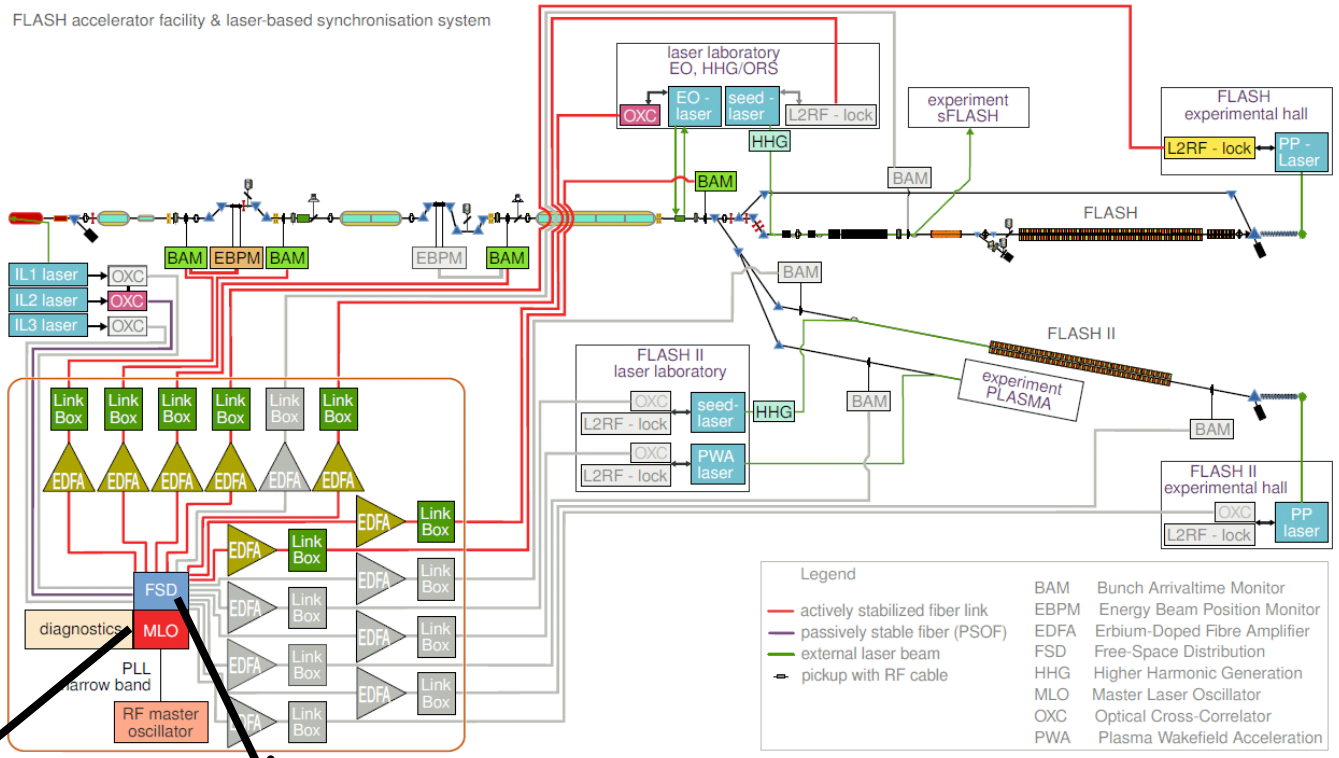

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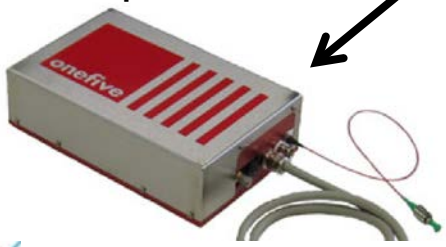

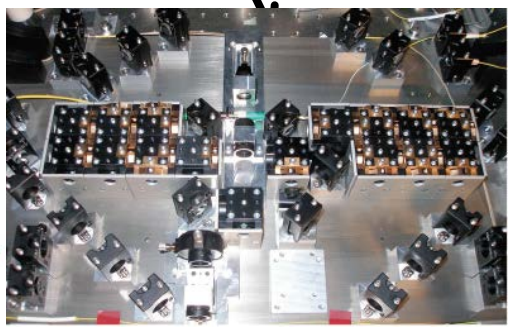

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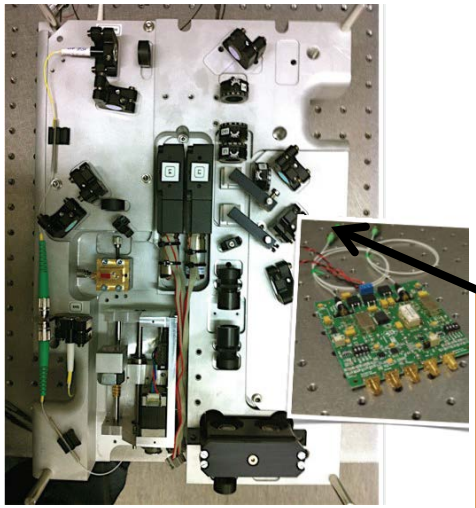
Link stabilization



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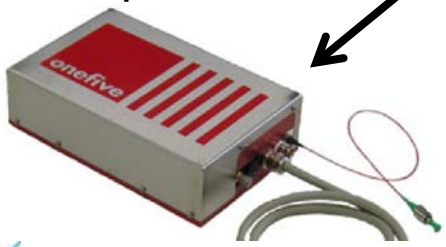

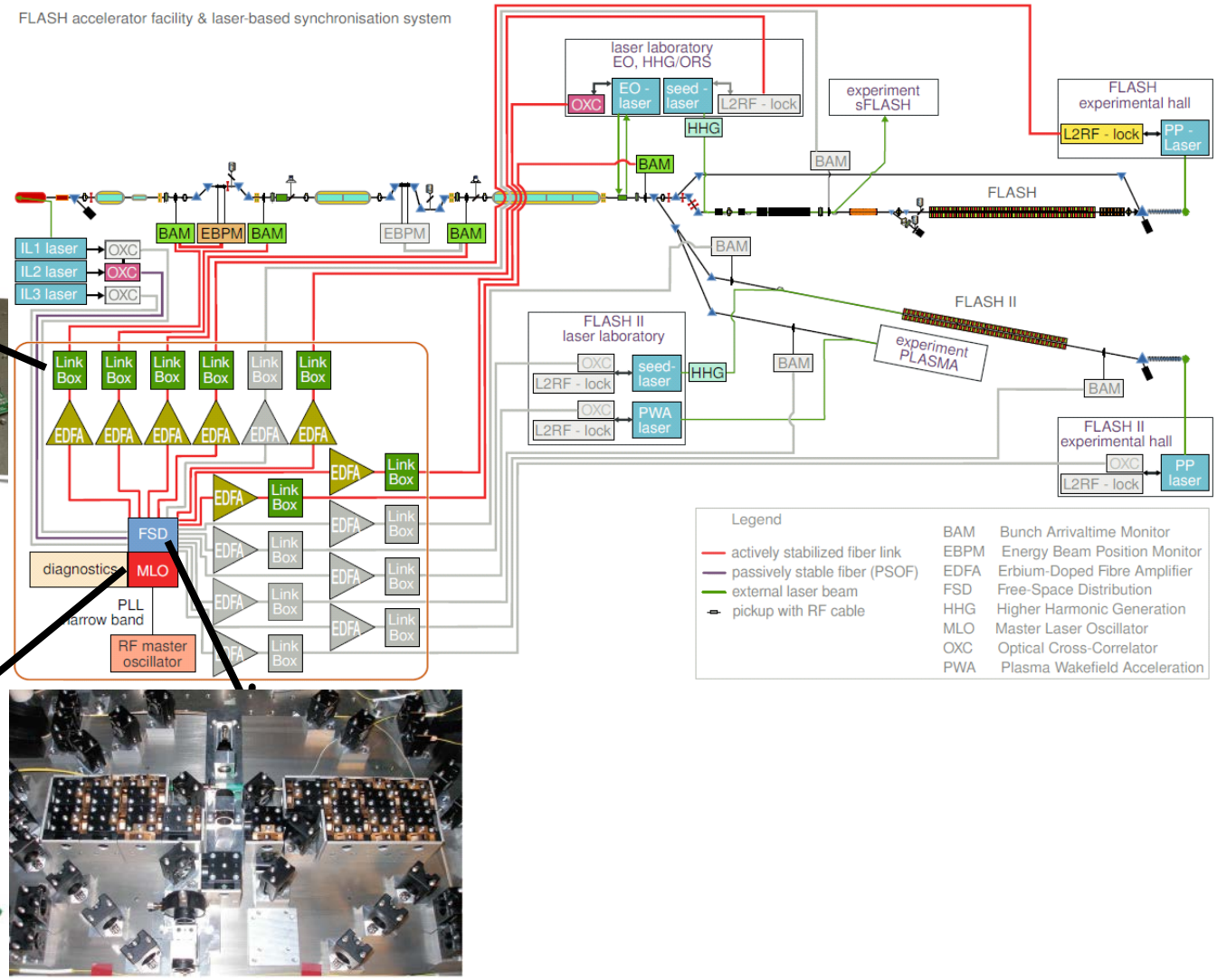

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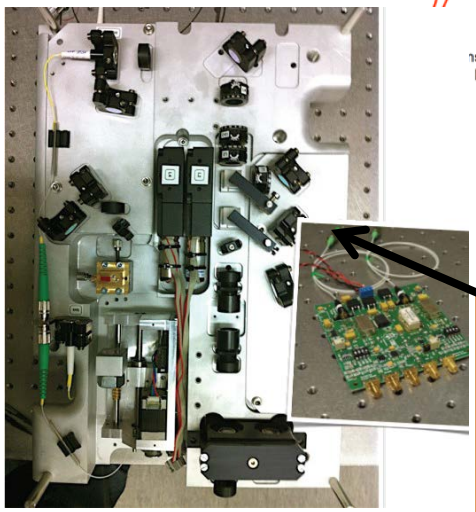

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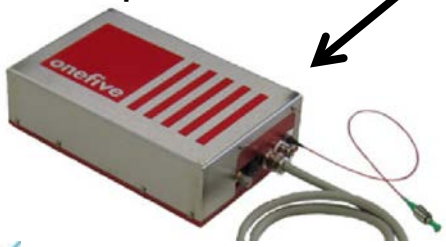

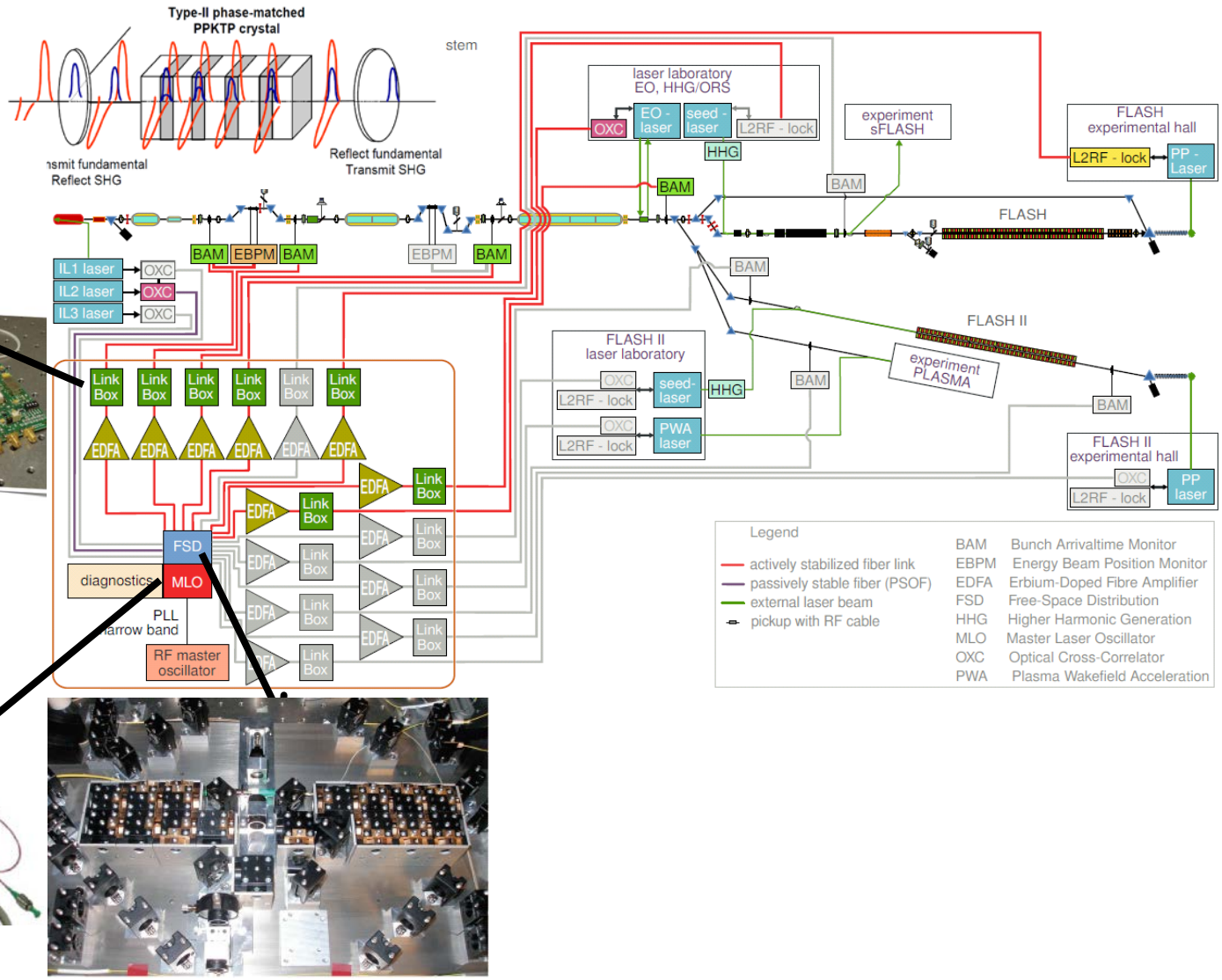

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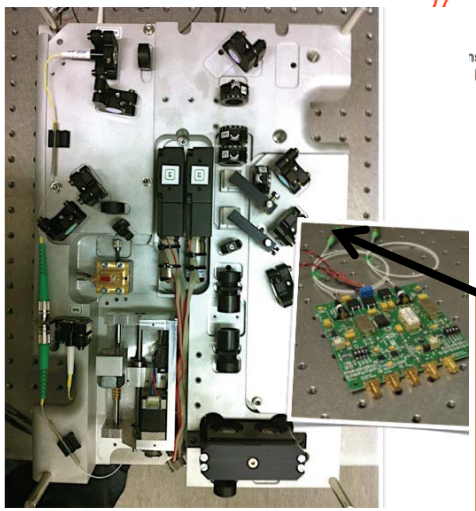

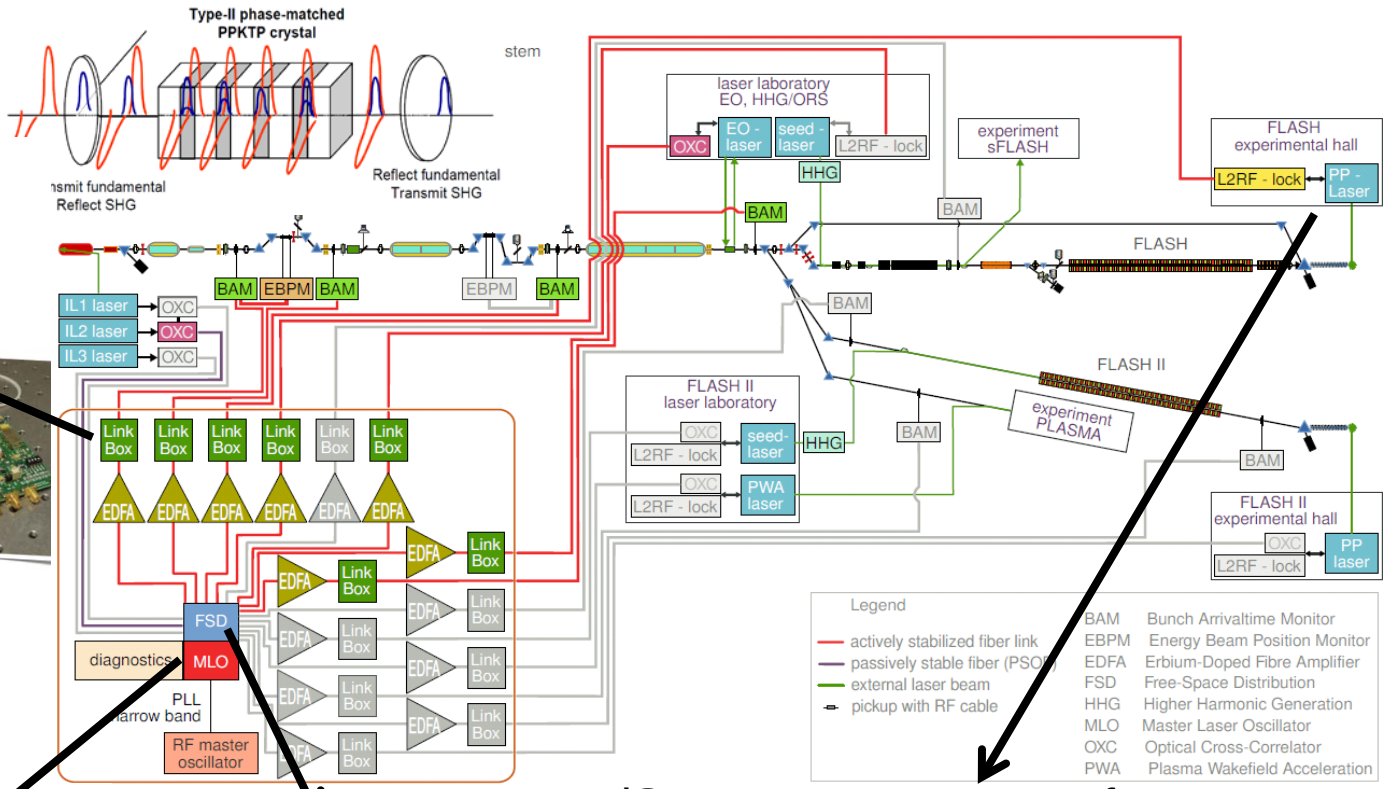

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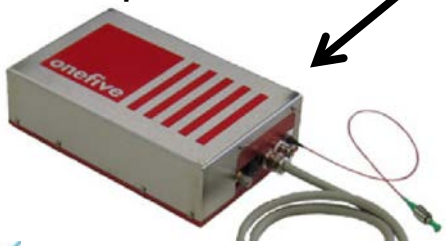
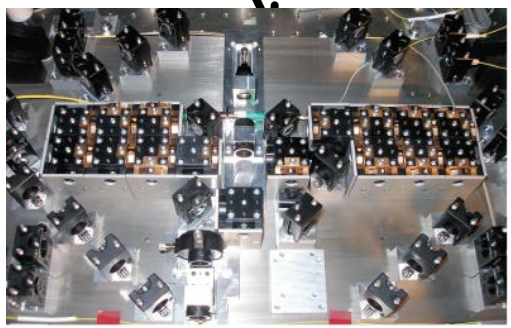
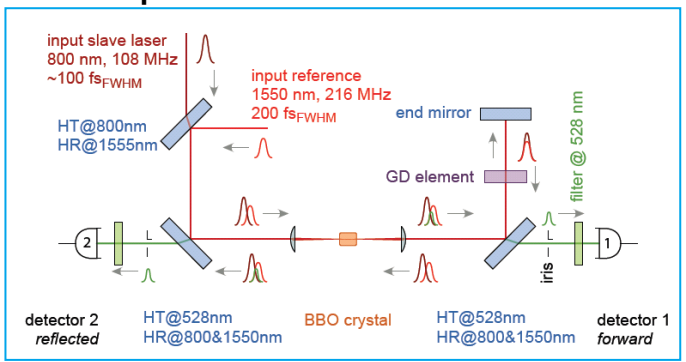




TiSa opt. cross-corr. ~ 5fs rms



Synchronization – Pulsed optically, example FLASH

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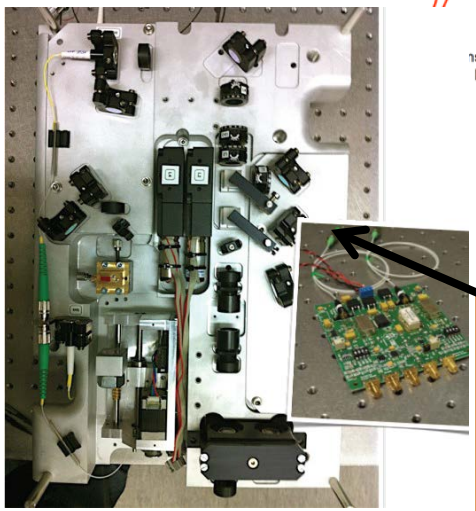

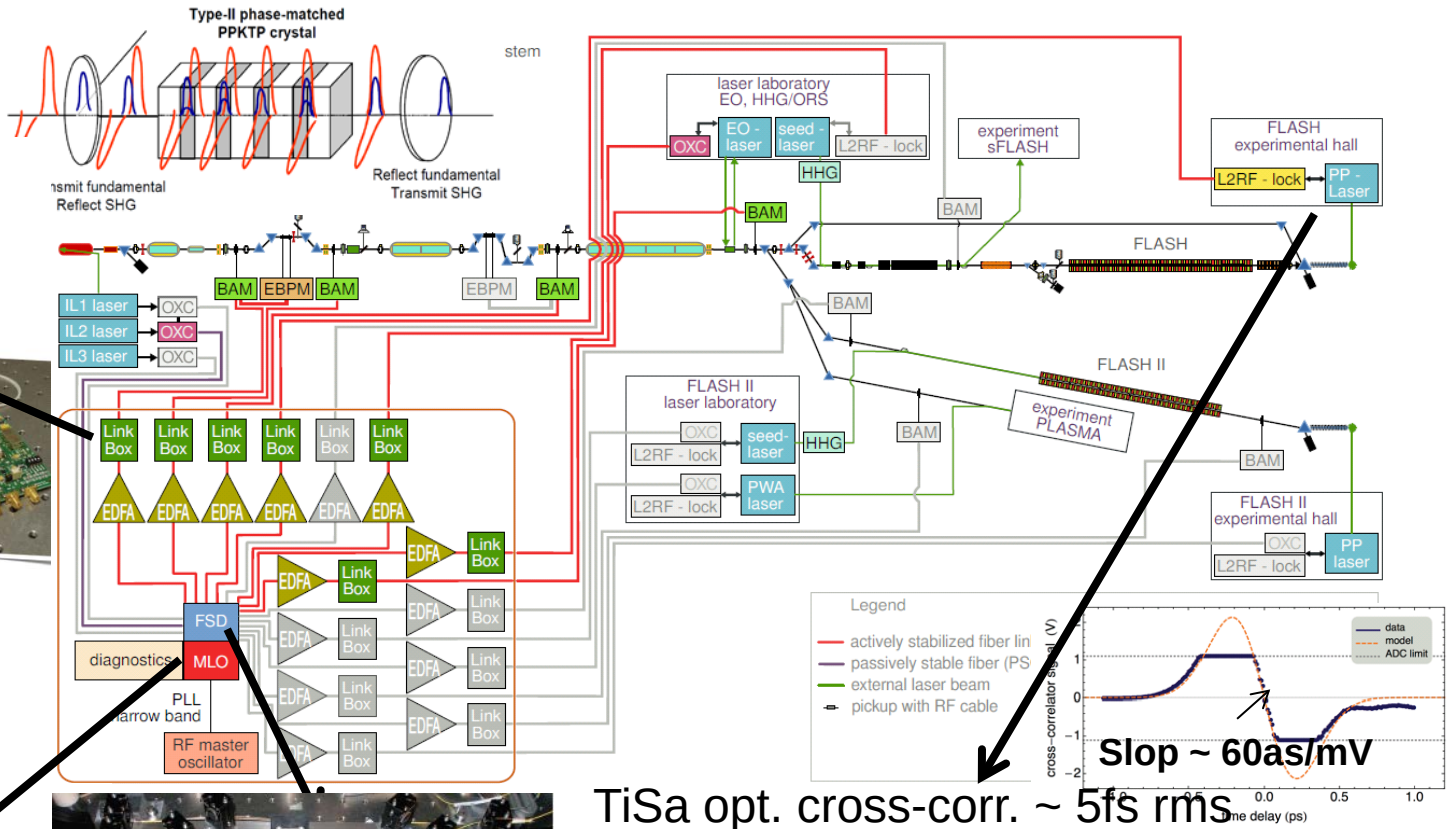

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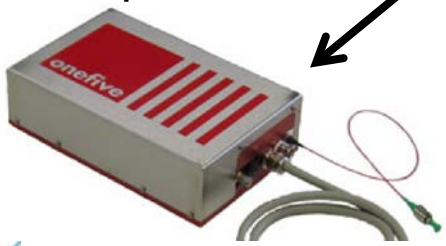

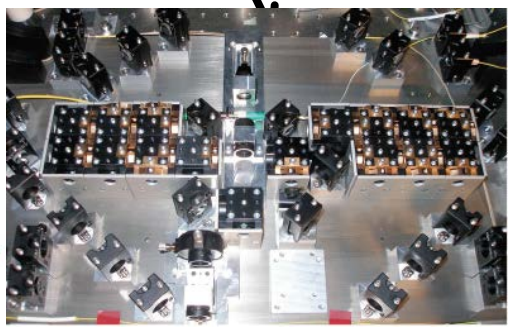

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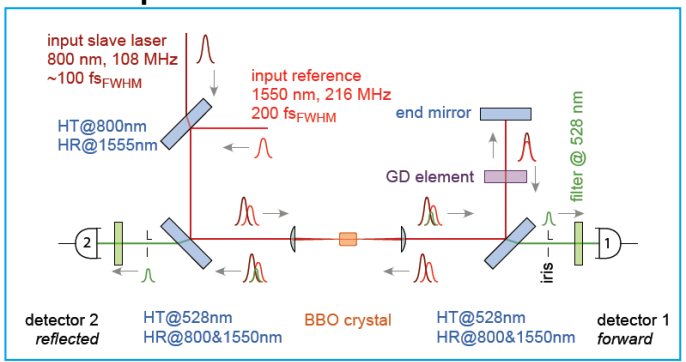


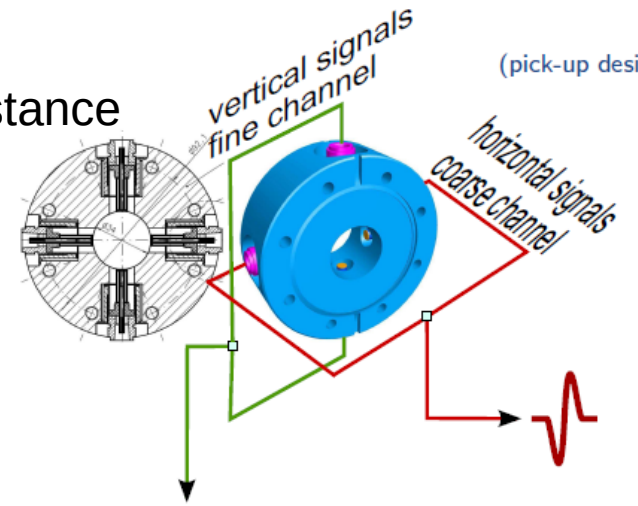
Synchronization – Pulsed optical, arrival monitor

- Uses optical reference laser pulses (single shot)
- Used at FLASH/FERMI/PSI
- Key exp. : two BAMs 60m distance
- Standard diag. at FLASH

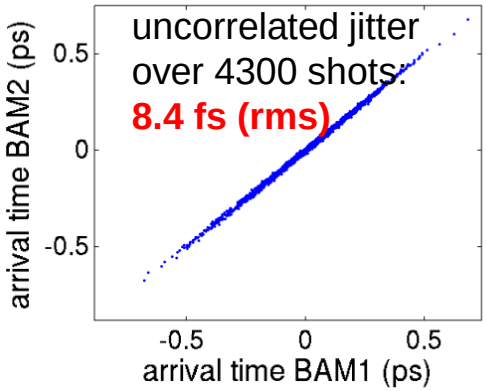
reduced dependency on beam orbit

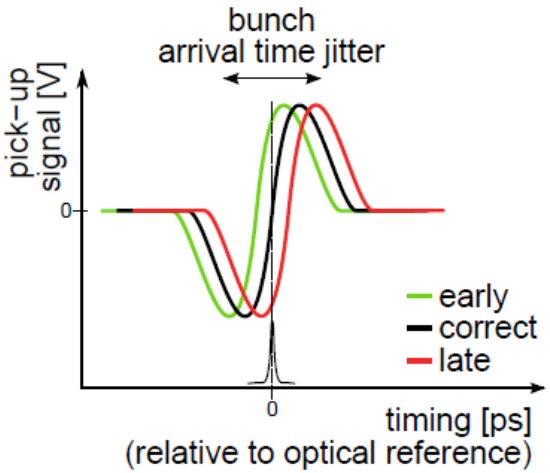
reduced dependency on bunch charge

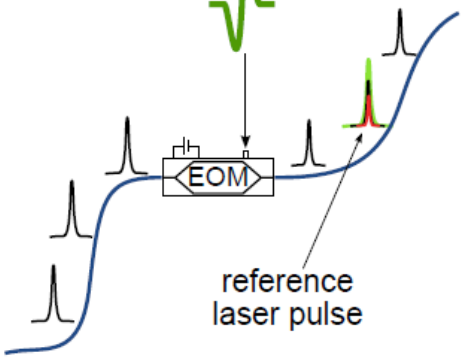
sensitivity in terms of
% modulation per fs timing change



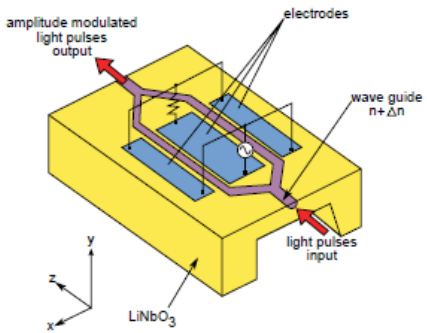
(pick-up design drawing, courtesy: K. Hacker)







electro-optical modulator



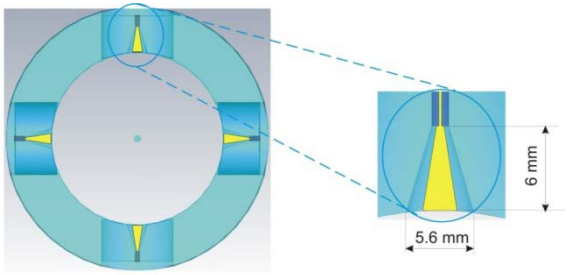
courtesy: K. Hacker, M. K. Czwalinna, F. Löhl, DESY development patented as DE 10 2011 111 114.3

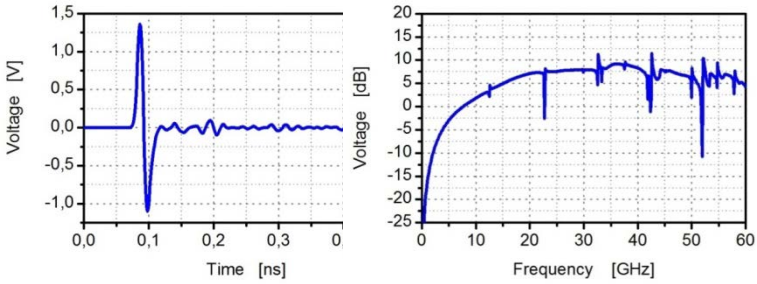
Synchronization – Pulsed optical, arrival monitor

- **Present system:** <10fs resolution @ 250 pC
- **New System:** goal <10fs @ 20pC charge
- → **Increase bandwidth** of monitor to ~ 40 GHz

  + bandwidth increase of front-end (MZI/cables/RF)

- → **Improve readout of electronics** (MTCA.4 based)





General purpose FMC carrier

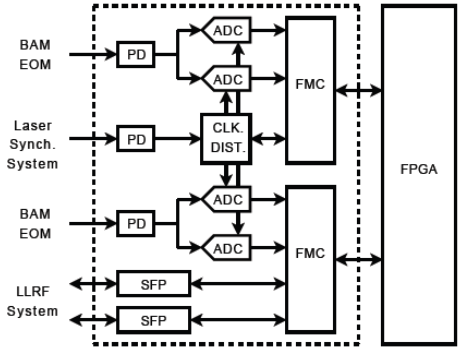
(a) Prototype FMC carrier

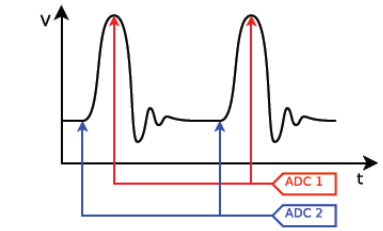
DAMC-FMC25

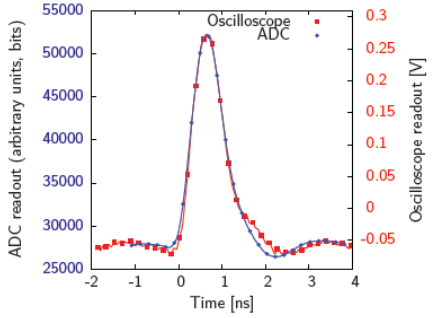
ADC 250MSPS incl. PD/clock circ.

(b) Prototype FMC mezzanine with ADCs

DFMC-BAM







Paper on this conference: THPPC140

H. Schlarb, DESY, ICALEPCS 2013, San Francisco, California, Oct. 11.

Bunch compression monitor (BCM)

- Based on **coherent emission** of Far-IR radiation

Coh. spectral intensity

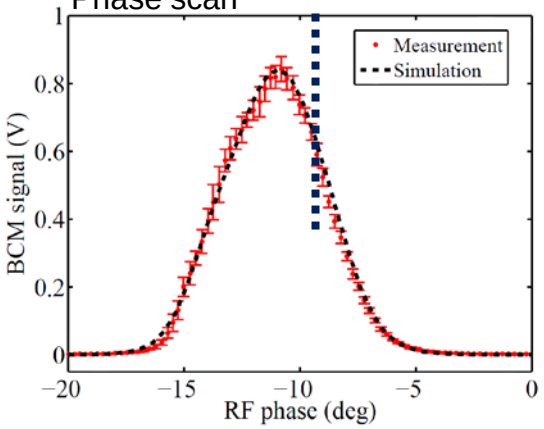
$$\frac{dU_{\mathrm{coh}}}{d\lambda} \approx \frac{dU_1}{d\lambda} N^2 \left|F_l(\lambda)\right|^2$$

Form-factor

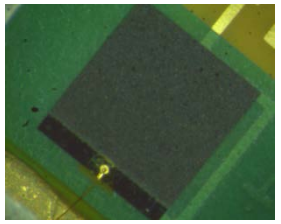
$$F_l(\lambda) = \int_{-\infty}^{\infty} \rho_l(z)\, \mathrm{e}^{-2\pi i z/\lambda}\, dz$$

- **Radiation process:** CSR/CER/CDR/CTR/CGR
- **Detectors**: Pyro / 0.1-1THz Photo-detectors
- **Single detector** arrangement provides estimate on σ_z
- Typically **cross-calibration** with deflecting cav. required!
- **Problem:** pulse shape variation not detected!

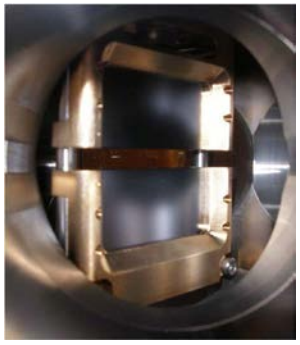
Phase scan



Pyro-element
LiTaO3 (2mm x 2mm x 27 um)

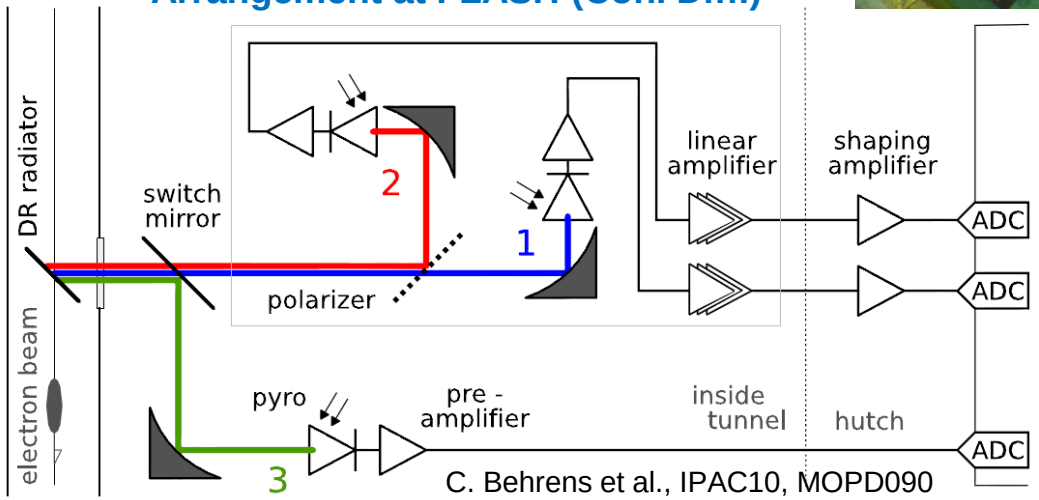


Diff. radiation



INFN / S. Wesch et al.,

Arrangement at FLASH (Coh. Diff.)

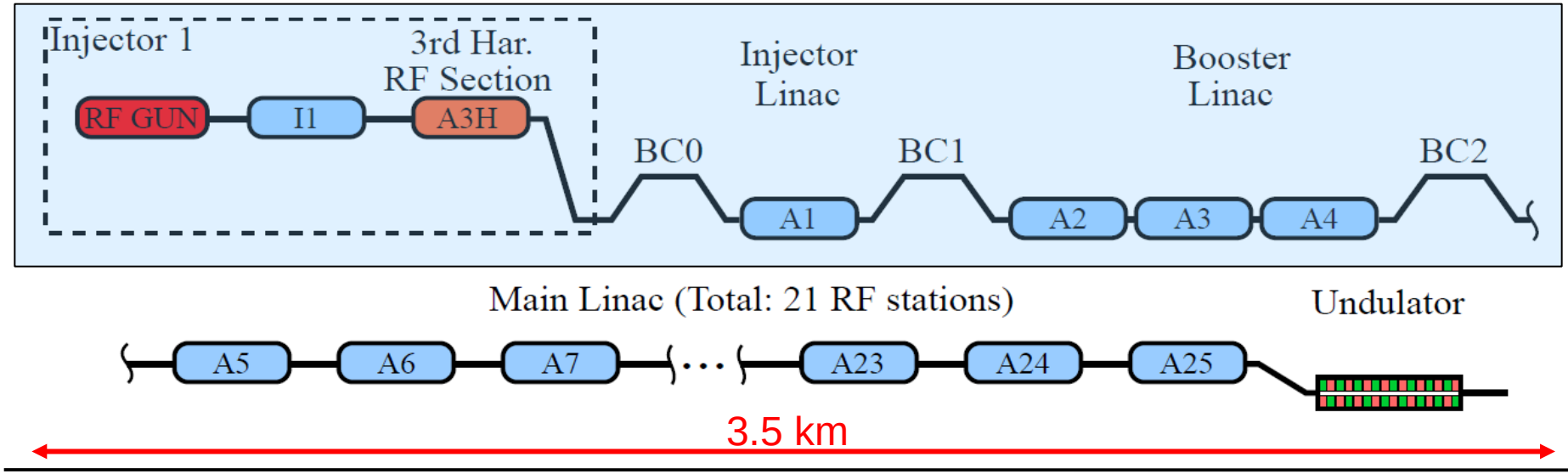


C. Behrens et al., IPAC10, MOPD090

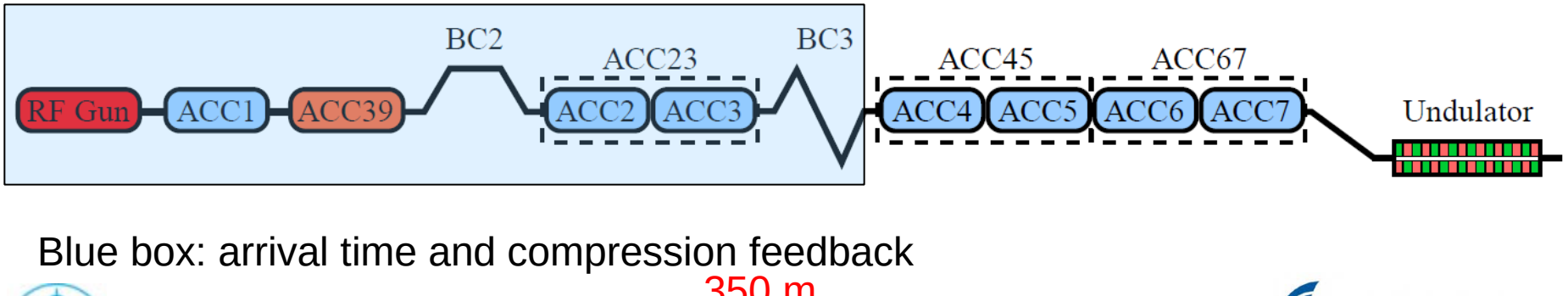
Feedbacks

Linear Accelerators at DESY in Hamburg

European XFEL – currently under construction

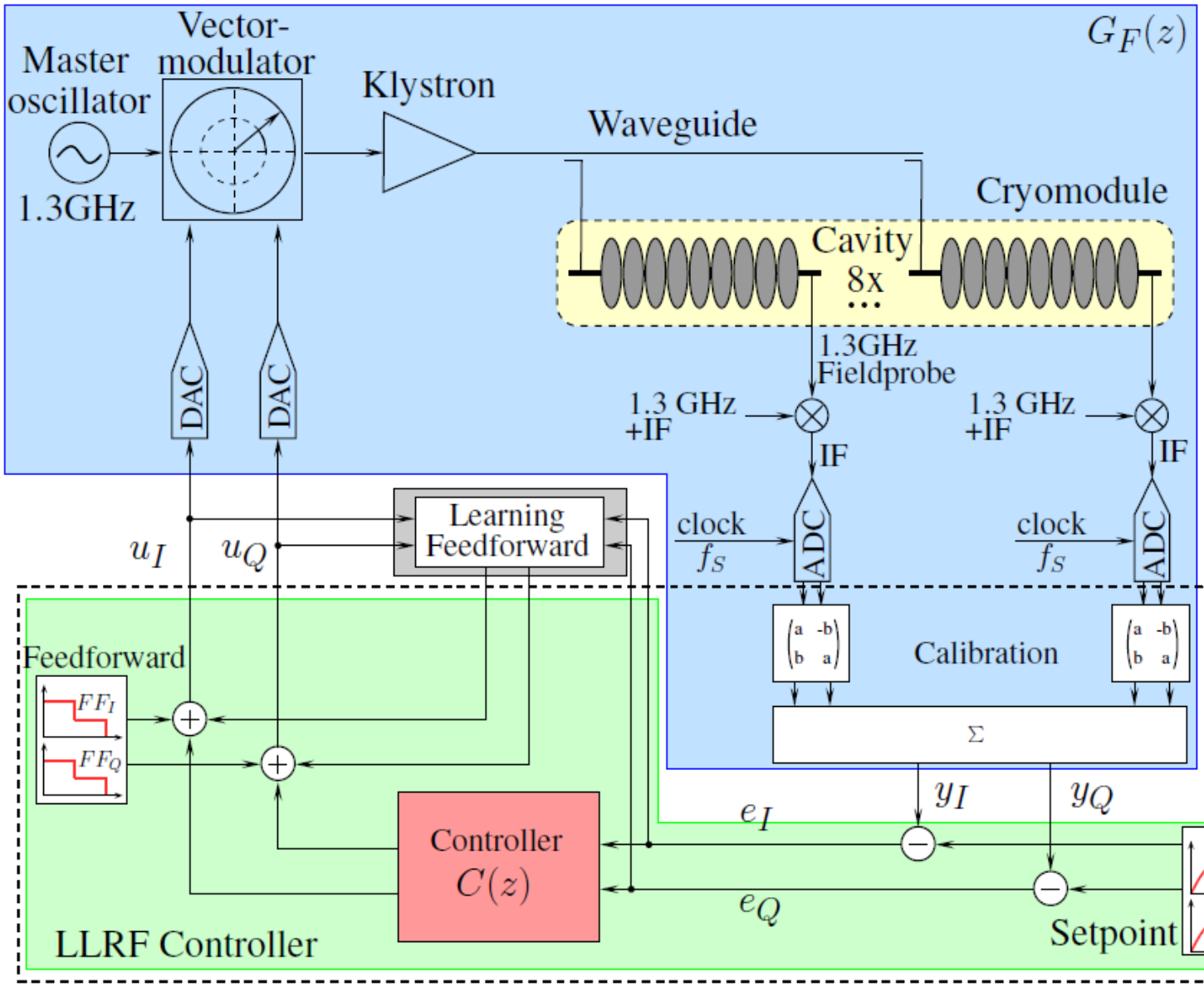


FLASH – in operation (test bench for XFEL)



Blue box: arrival time and compression feedback

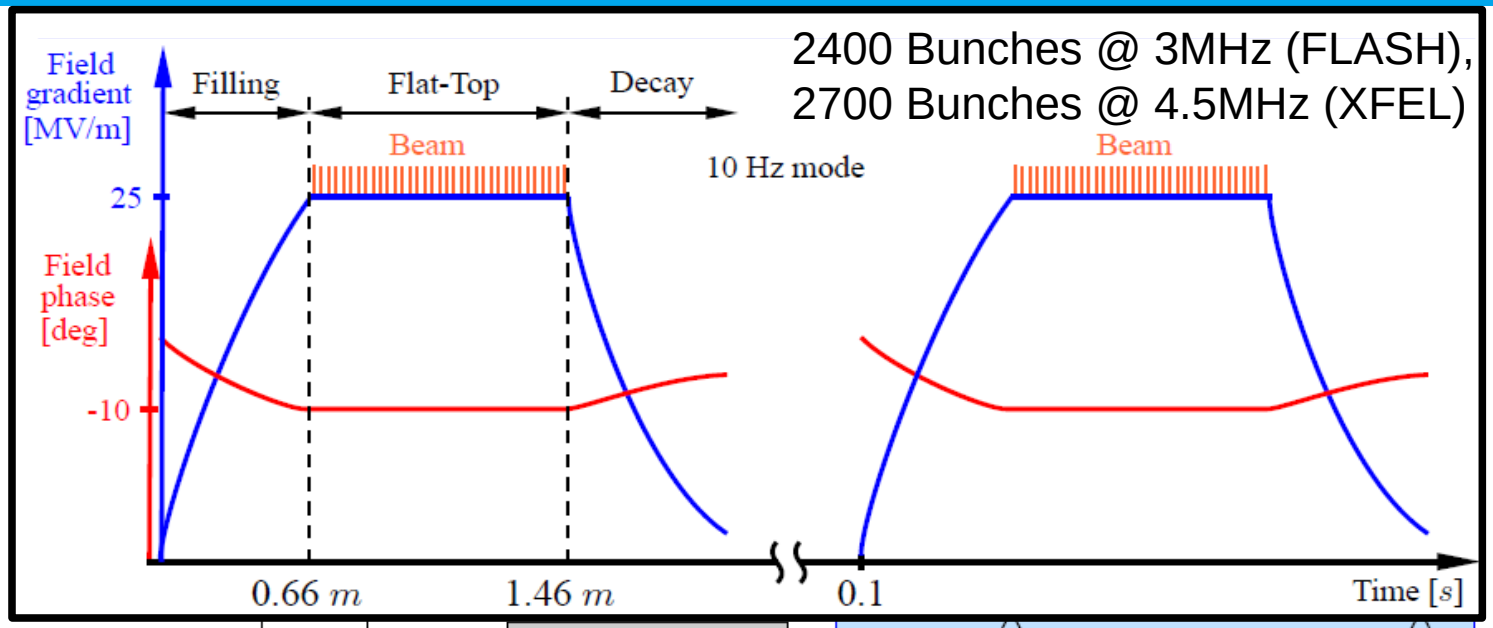
System Overview – FLASH and XFEL



RF Field

I/Q control

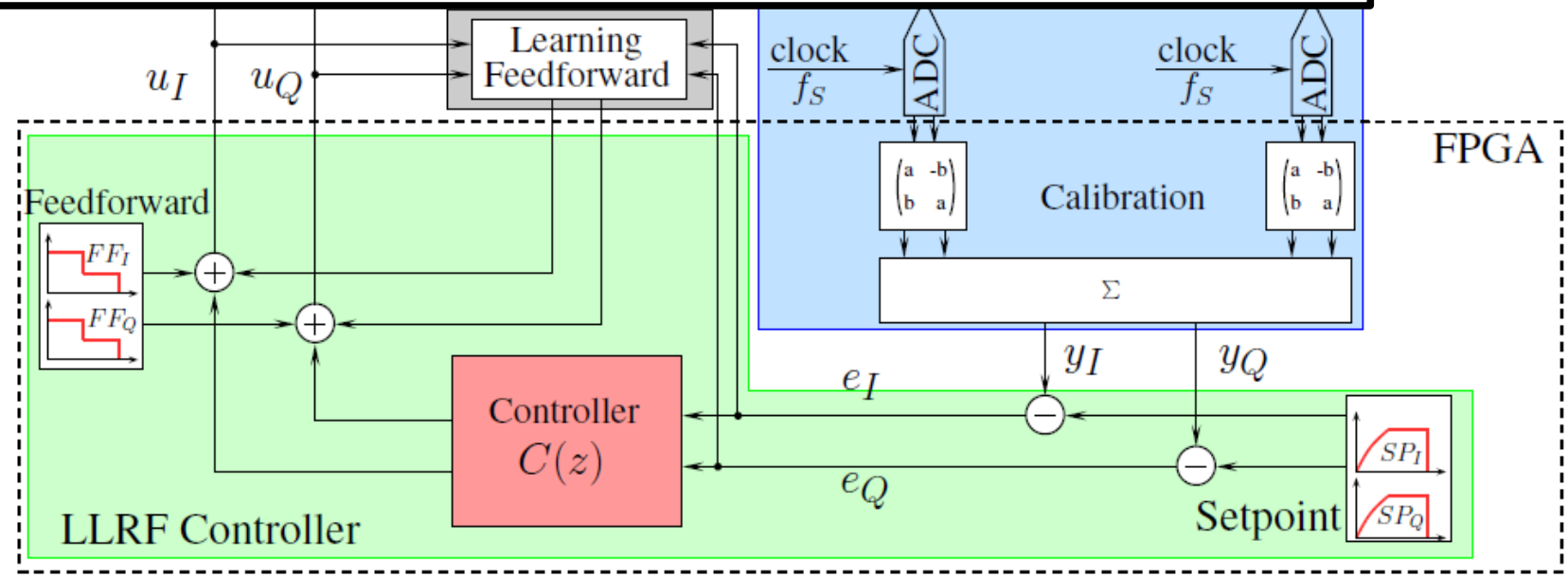
System Overview – FLASH and XFEL



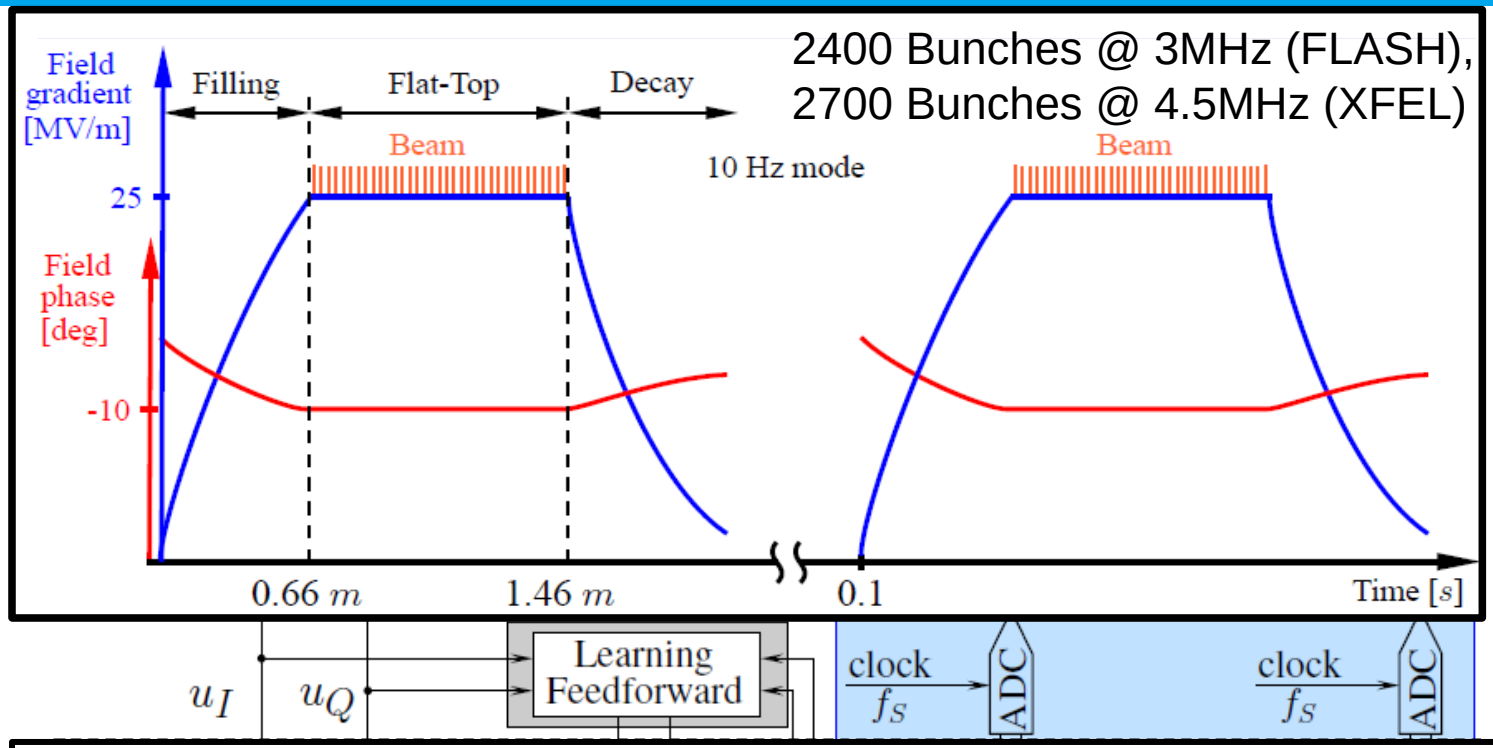
RF Field

I/Q control

Pulsed operation
10 Hz
2ms pulse length
(Filling, Flattop and Decay)



System Overview – FLASH and XFEL



RF Field

I/Q control

Pulsed operation
10 Hz
2ms pulse length
(Filling, Flattop and Decay)

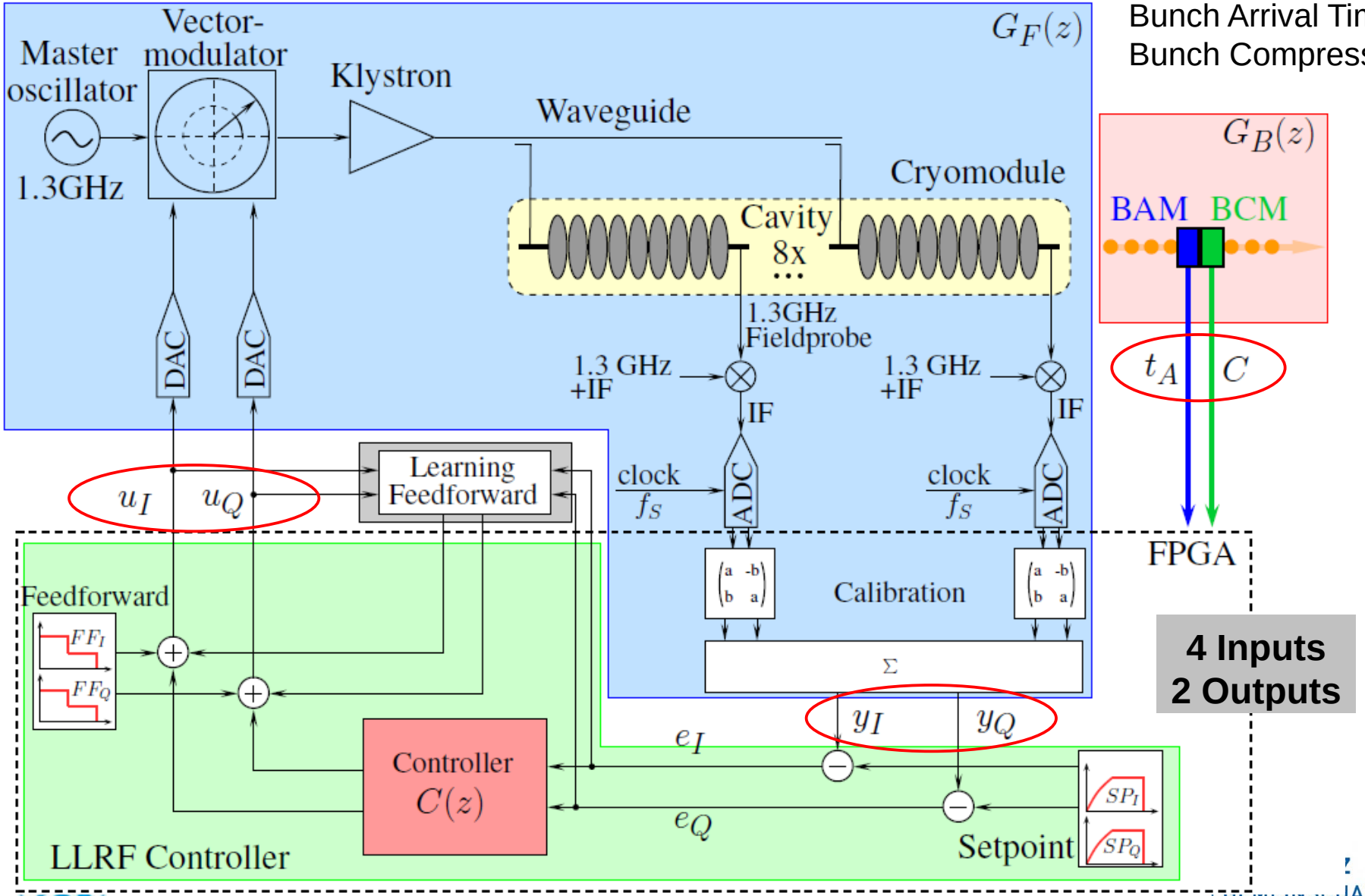
Several feedbacks with different time scales involved:

• Learn feed forwards	~100 mHz	RF meas. → FF drive	Beam → SP shape
• Slow feedback	~ 1 Hz		Beam → SP
• Fast feedback	~ 30kHz/100kHz	RF meas. → RF drive	Beam → RF drive
• Ultra-fast	~ 500 kHz		Beam → NRF drive

+ parameter optimization to keep optimum feedback operation points

Poster on Global FB:

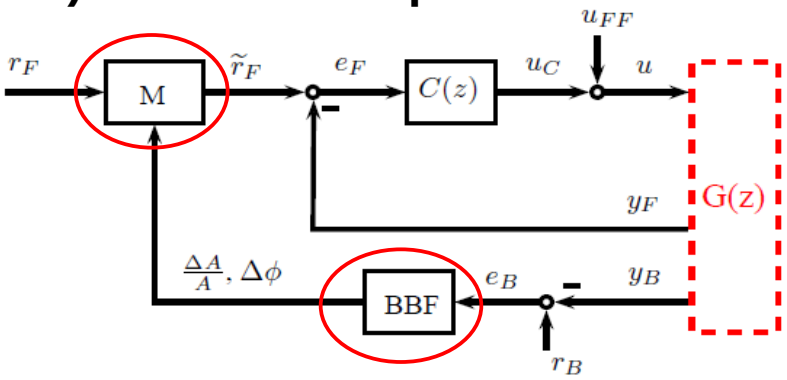
System Overview – FLASH and XFEL



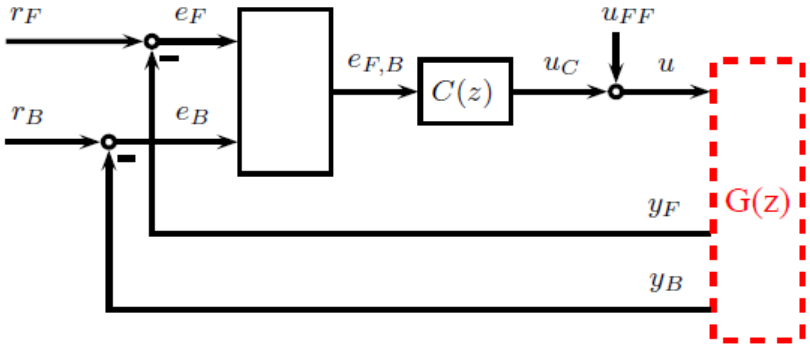
Bunch Arrival Time and Bunch Compression Feedback

Possibilities of beam-based feedback (not complete)

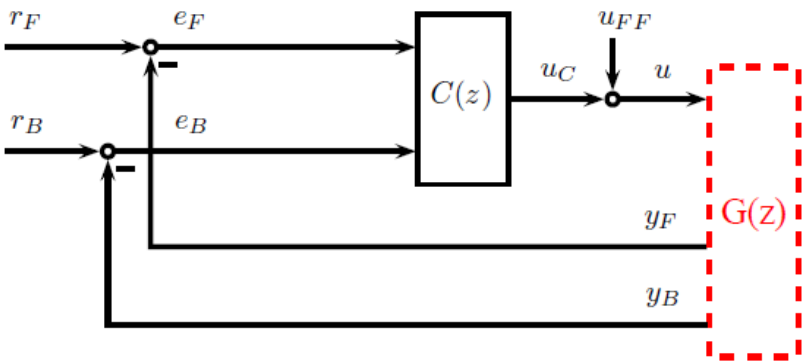
1) Set-Point Adaptation



3) RF field and beam error combination



2) Extended Controller



1) Good if latency of beam-based signals is larger than the latency for RF field signals [M...Modulation, BBF...maps beam errors to RF-field errors]

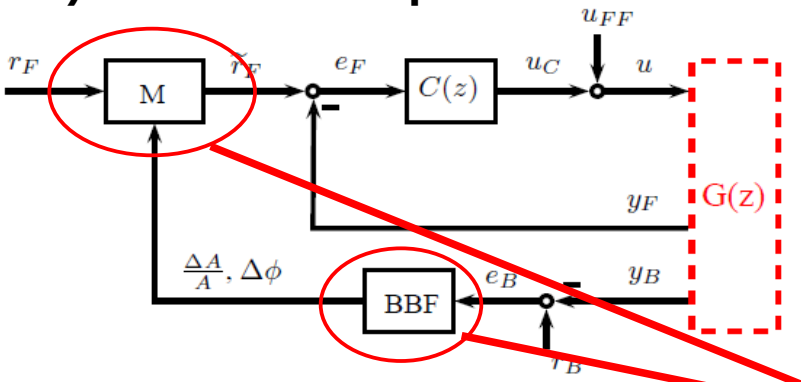
2) Good if the dynamic behavior for the beam-based signals and RF field signals differs

3) Good if the latency of signals are equal

Bunch Arrival Time and Bunch Compression Feedback

Possibilities of beam-based feedback (not complete)

1) Set-Point Adaptation



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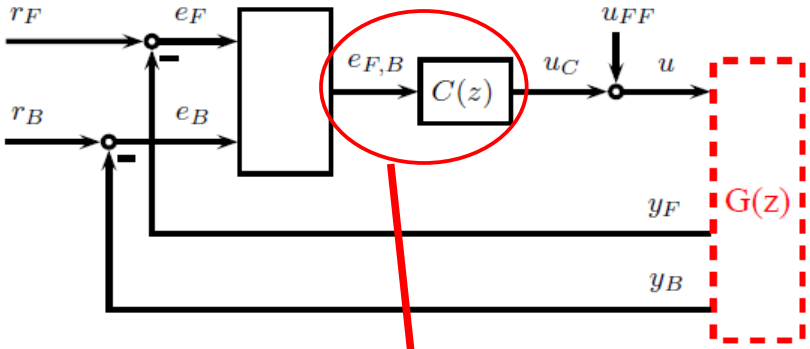

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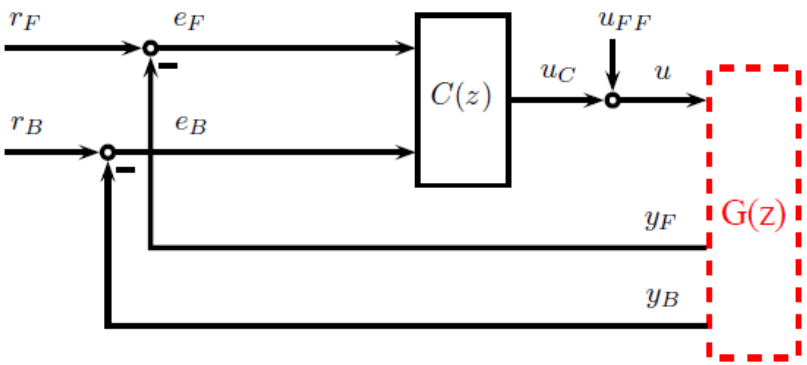
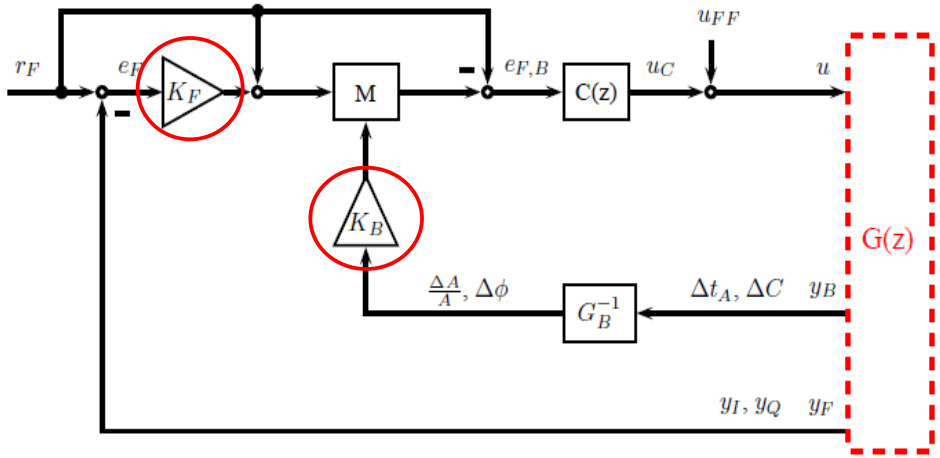
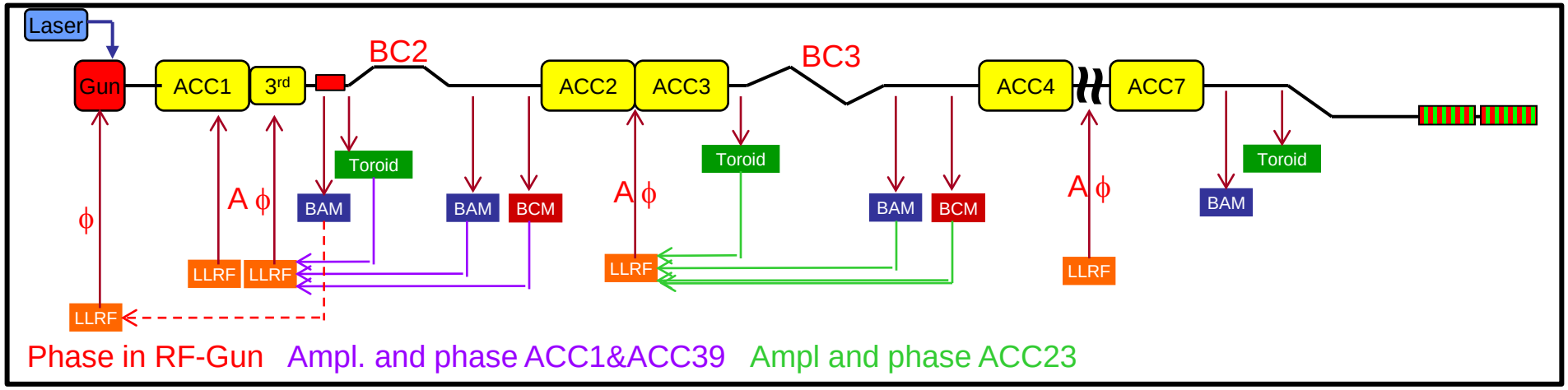


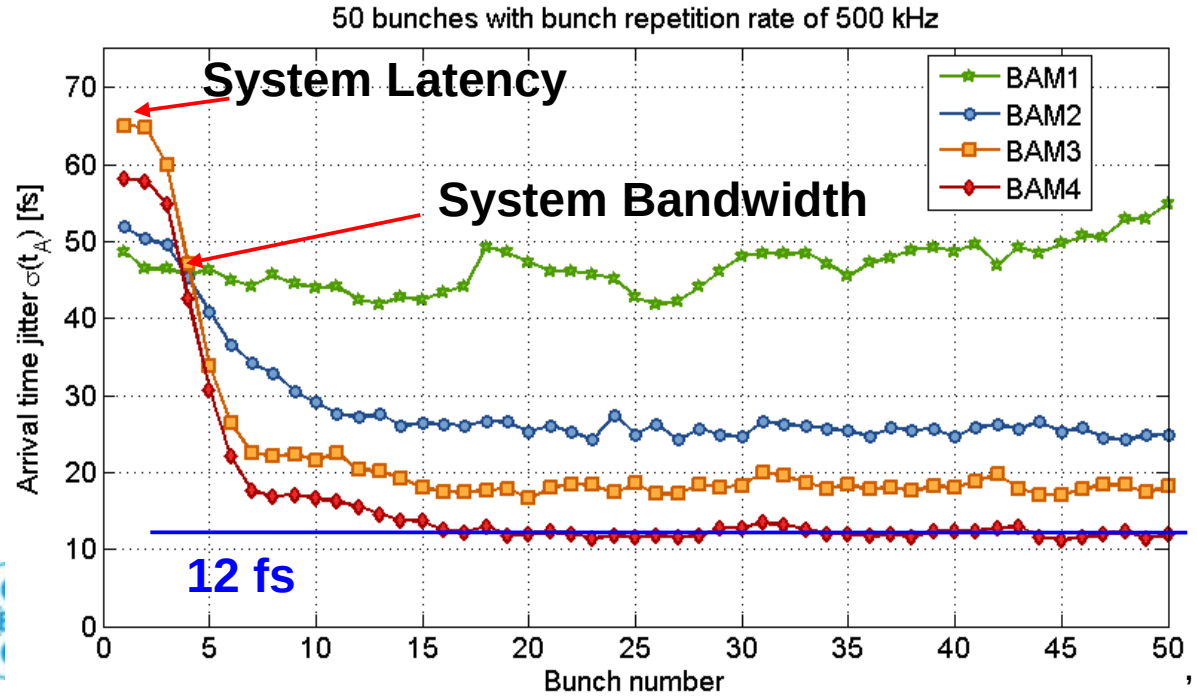
Final implementation at FLASH (simplified)



Ultra-Fast beam based feedbacks

> Large bunch spacing at FLASH (~ us) allow for intra-bunch feedbacks



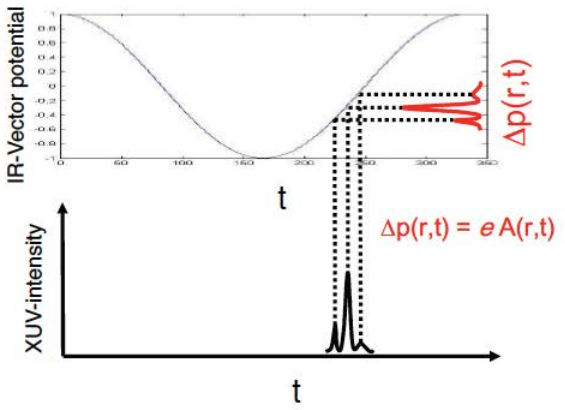


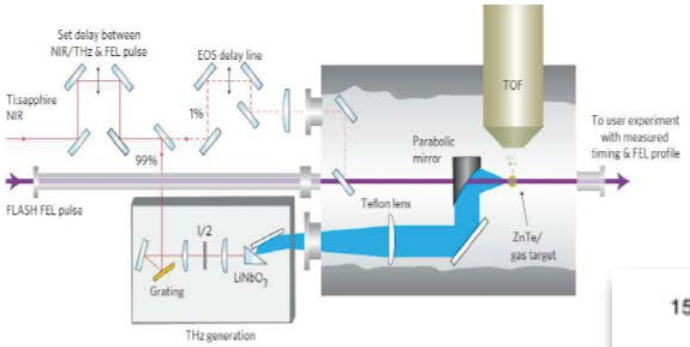
- Bunch rep. Rate: 500kHz, 50 Bunche
- Proposed BBF
- Active on ACC1 and ACC23
- BAM4 is an out-of-loop measurement (highest resolution)

Fast beam based feedbacks & optical lock of TiSa Laser

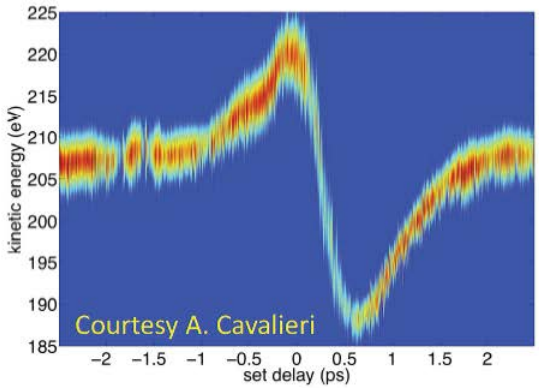
- **Demonstration** of synchronization for FEL users experiment
- **Beam based feedback** using Bunch Arrival Monitor & **optical lock of TiSa laser**
- FEL pulse arrival measured with **laser based THz streaking** (A. Cavalieri)

Measuring the jitter at the experiment





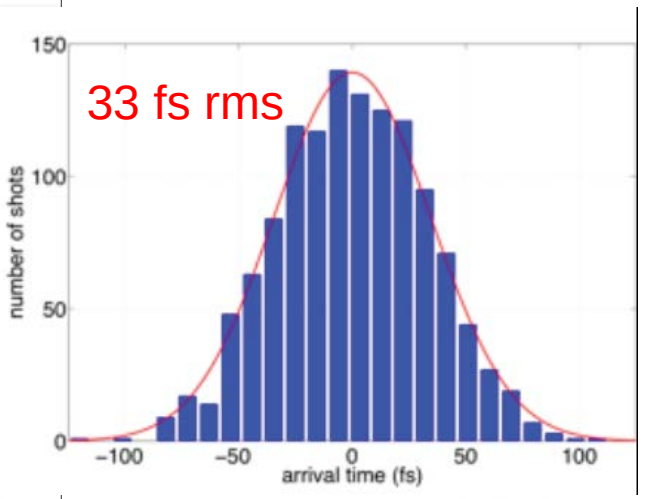
Nature Photonics 6, 852-857 (2012))



Actual jitter between laser and XUV **at** the experiment (fall 2012)

- Standard operation: **80-90 fs rms**
- Optical cross corr

+ BAM feedback : **~ 30 fs rms**

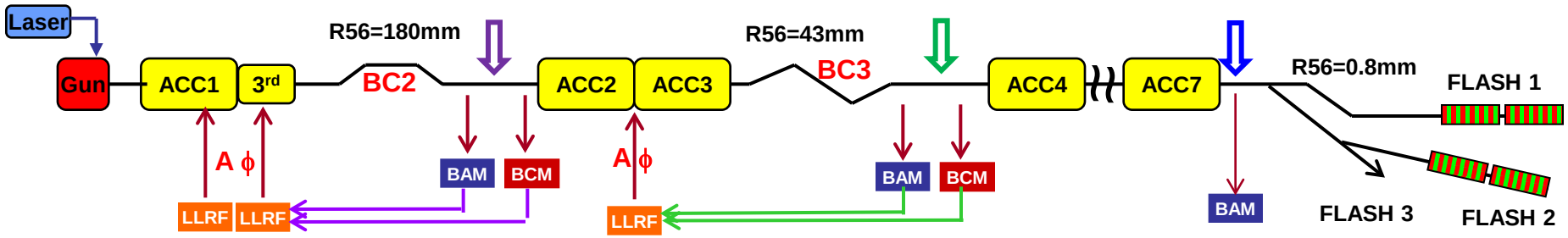


S. Schulz, SPIE13

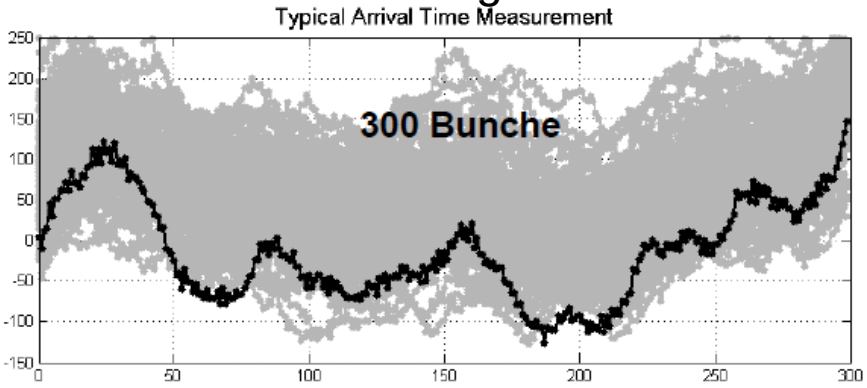
Residual jitter to be investigated (many possible sources!)

Fast beam based feedbacks – next step –

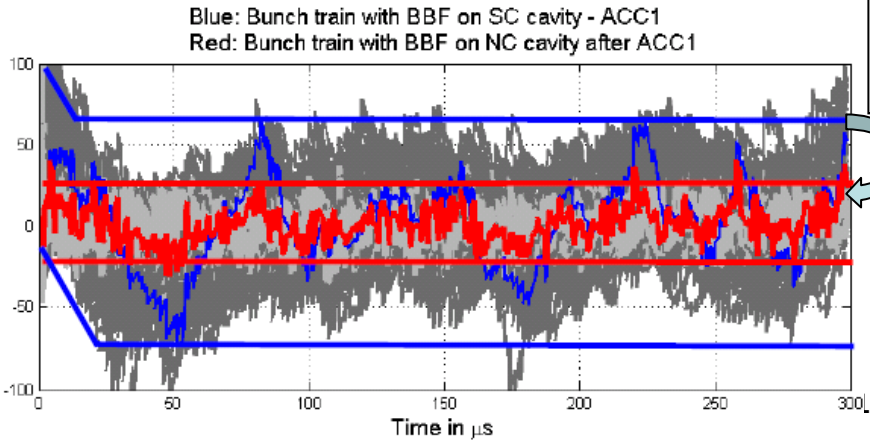
WP13: 2013-2016



FB simulation using measure data



SC:
f_{3dB}=215Hz
t_D = 2us
15-25bunche
25fs rms

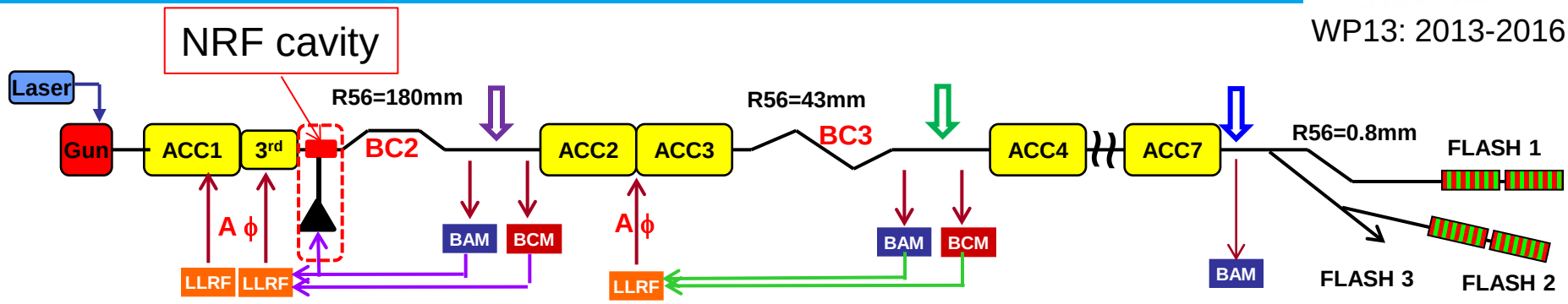


x 2.5

NC:
f_{3dB}=500kHz
t_D = 1us
2-3 bunche
10fs rms

Fast beam based feedbacks – next step –

WP13: 2013-2016



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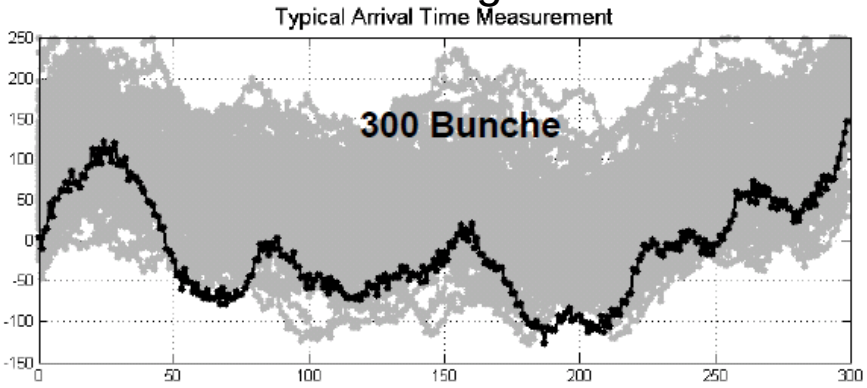

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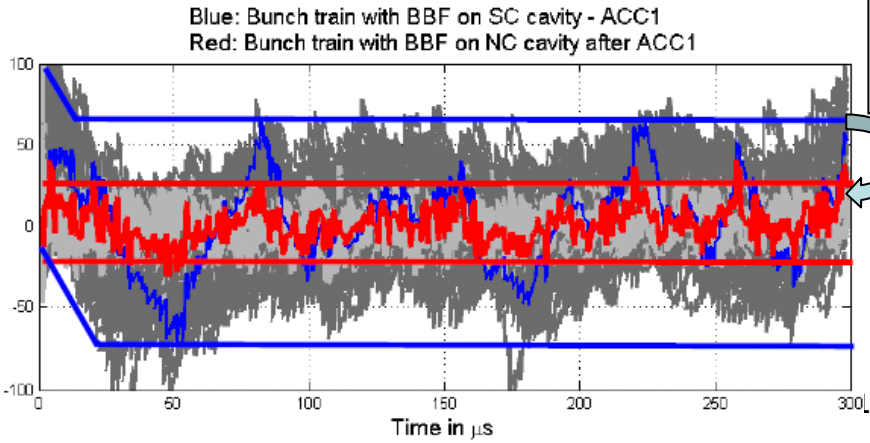

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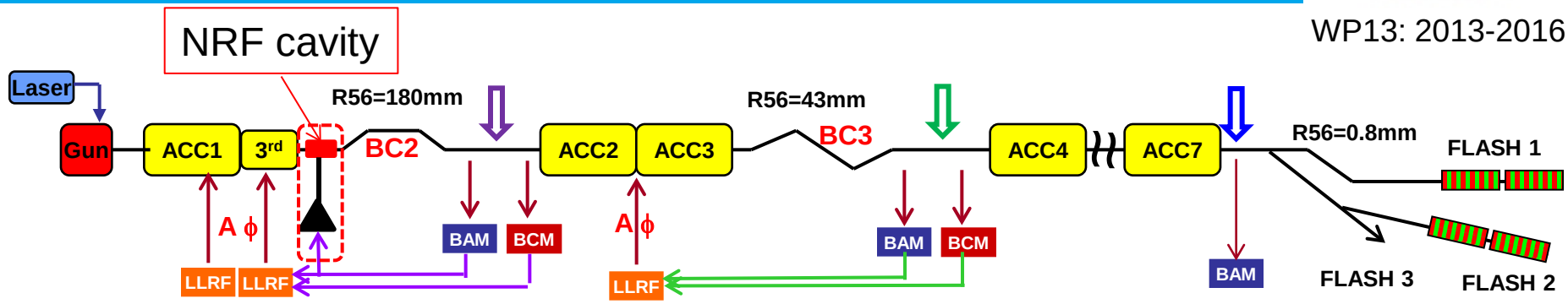
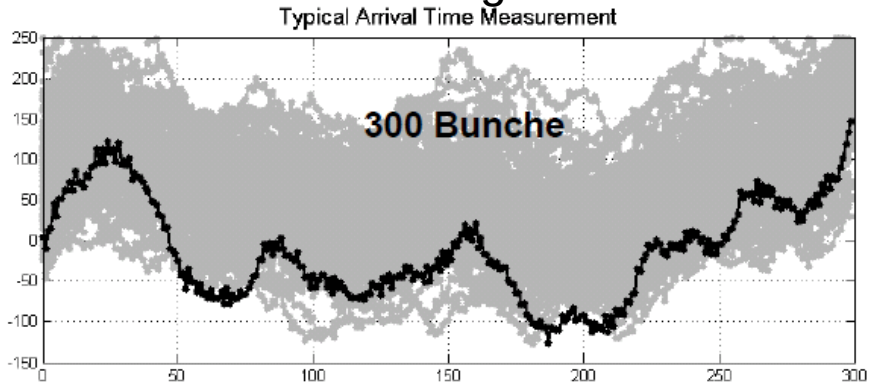
HELMHOLTZ GEMEINSCHAFT

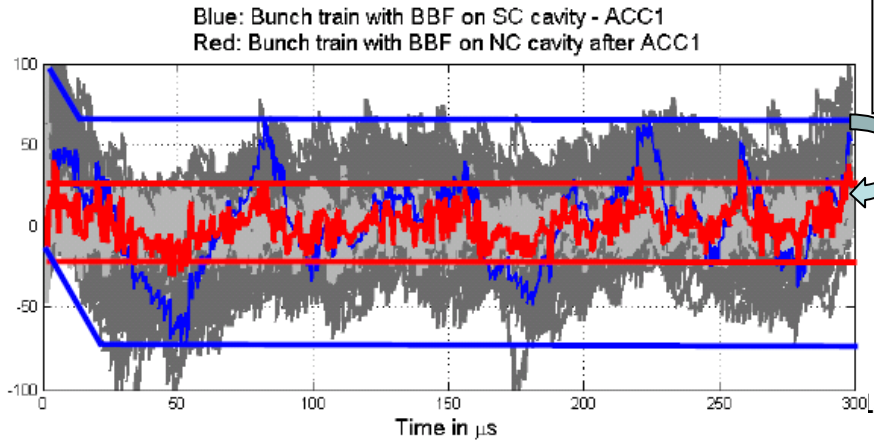
Fast beam based feedbacks – next step –

WP13: 2013-2016

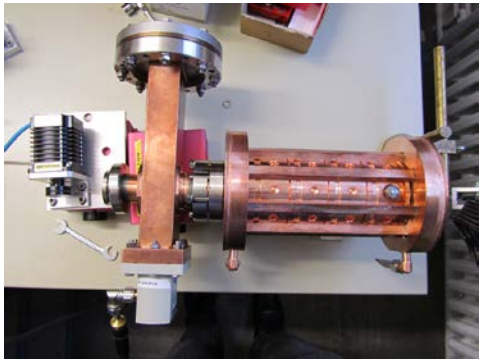


FB simulation using measure data





REGAE buncher



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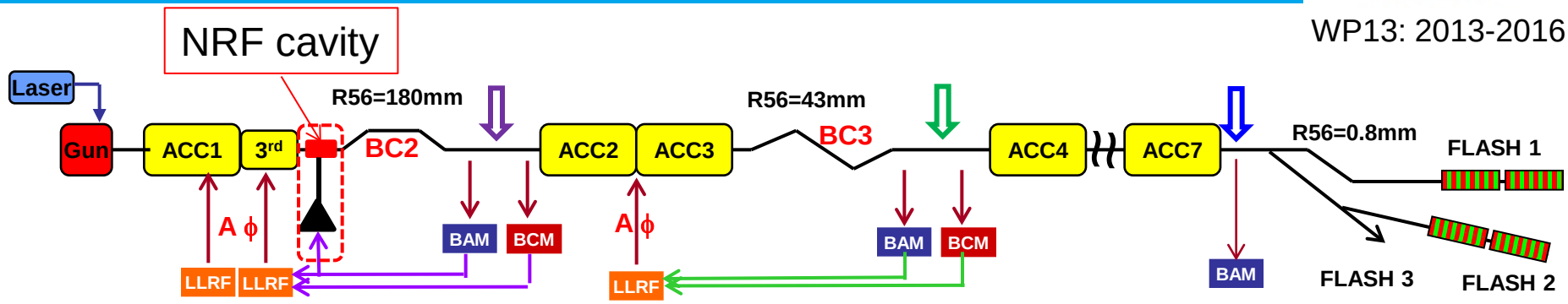
HELMHOLTZ GEMEINSCHAFT

Fast beam based feedbacks – next step –

WP13: 2013-2016



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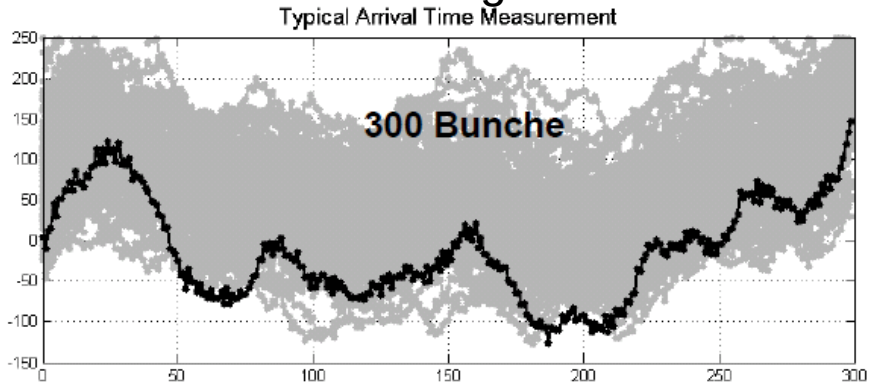

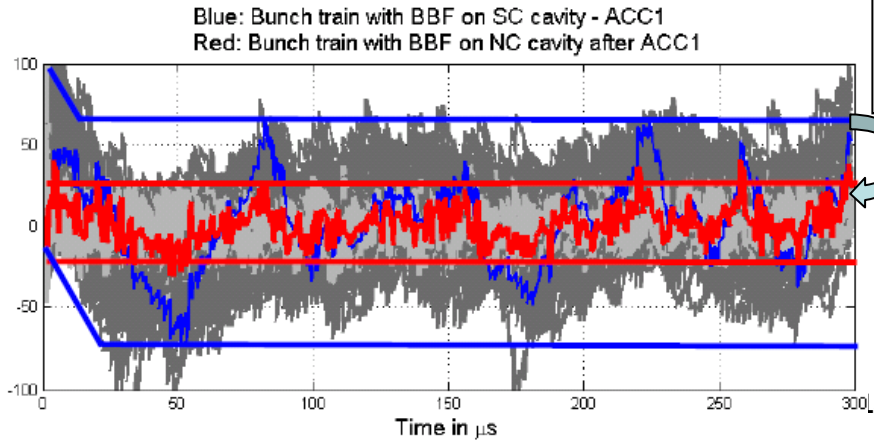

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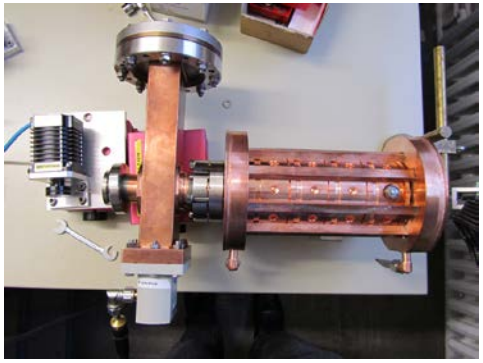
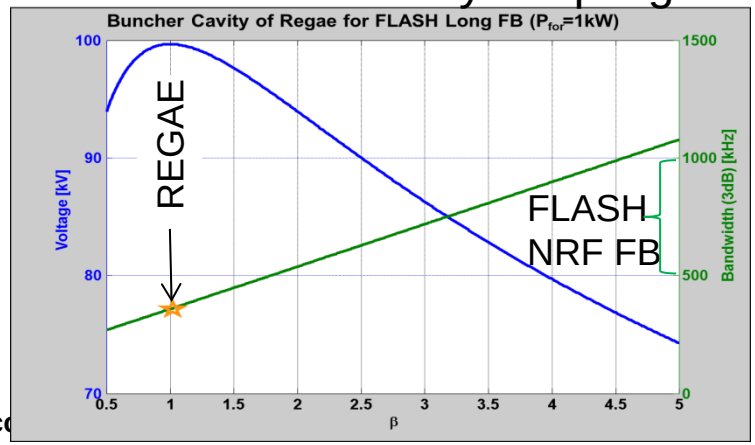
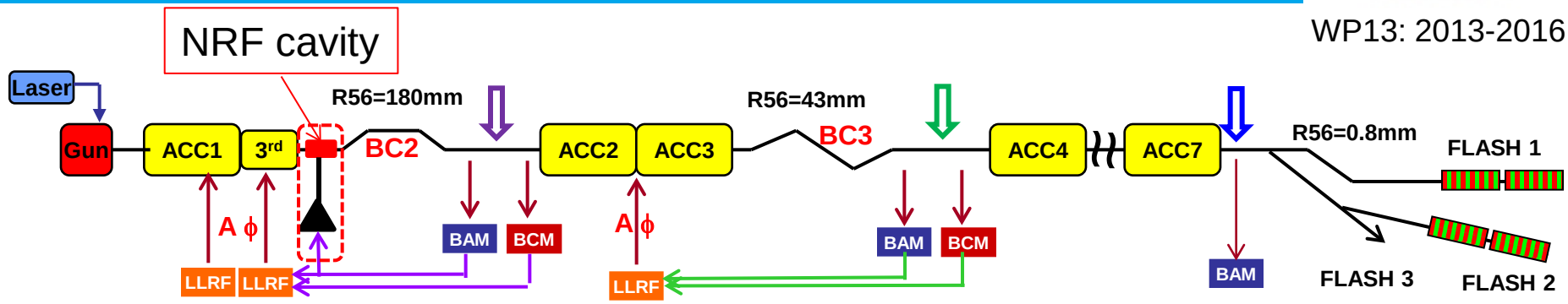


Influence of cavity coupling

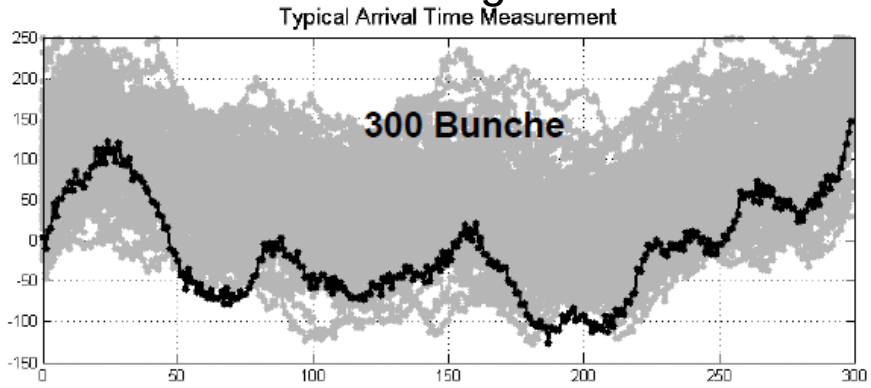


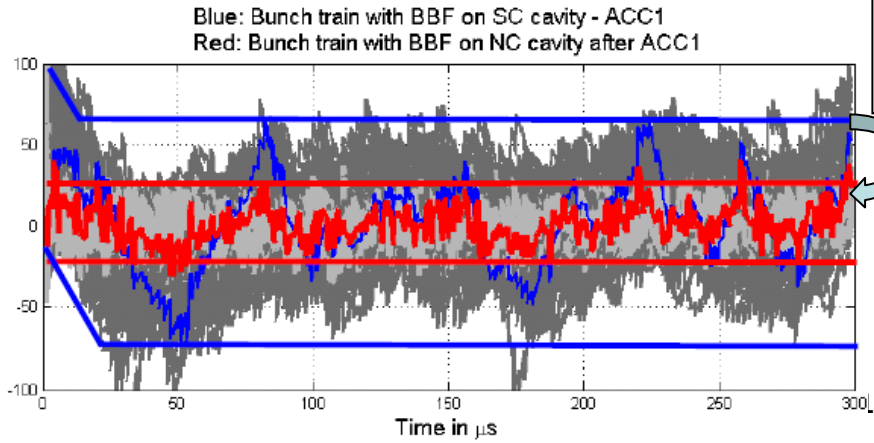
Fast beam based feedbacks – next step –

WP13: 2013-2016



FB simulation using measure data





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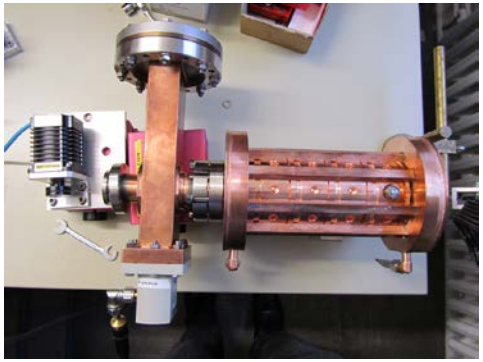
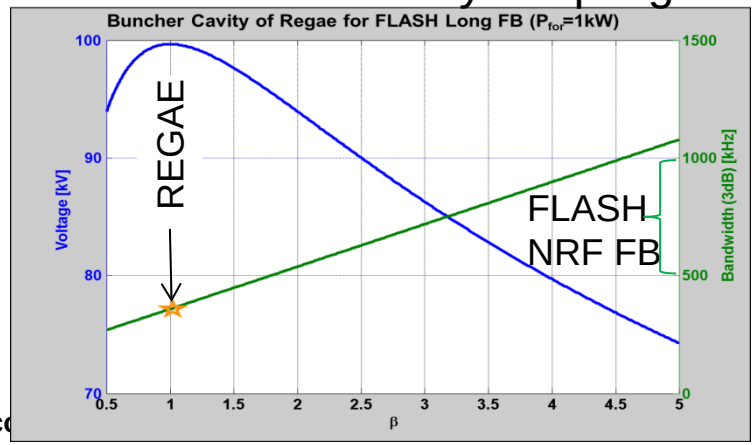
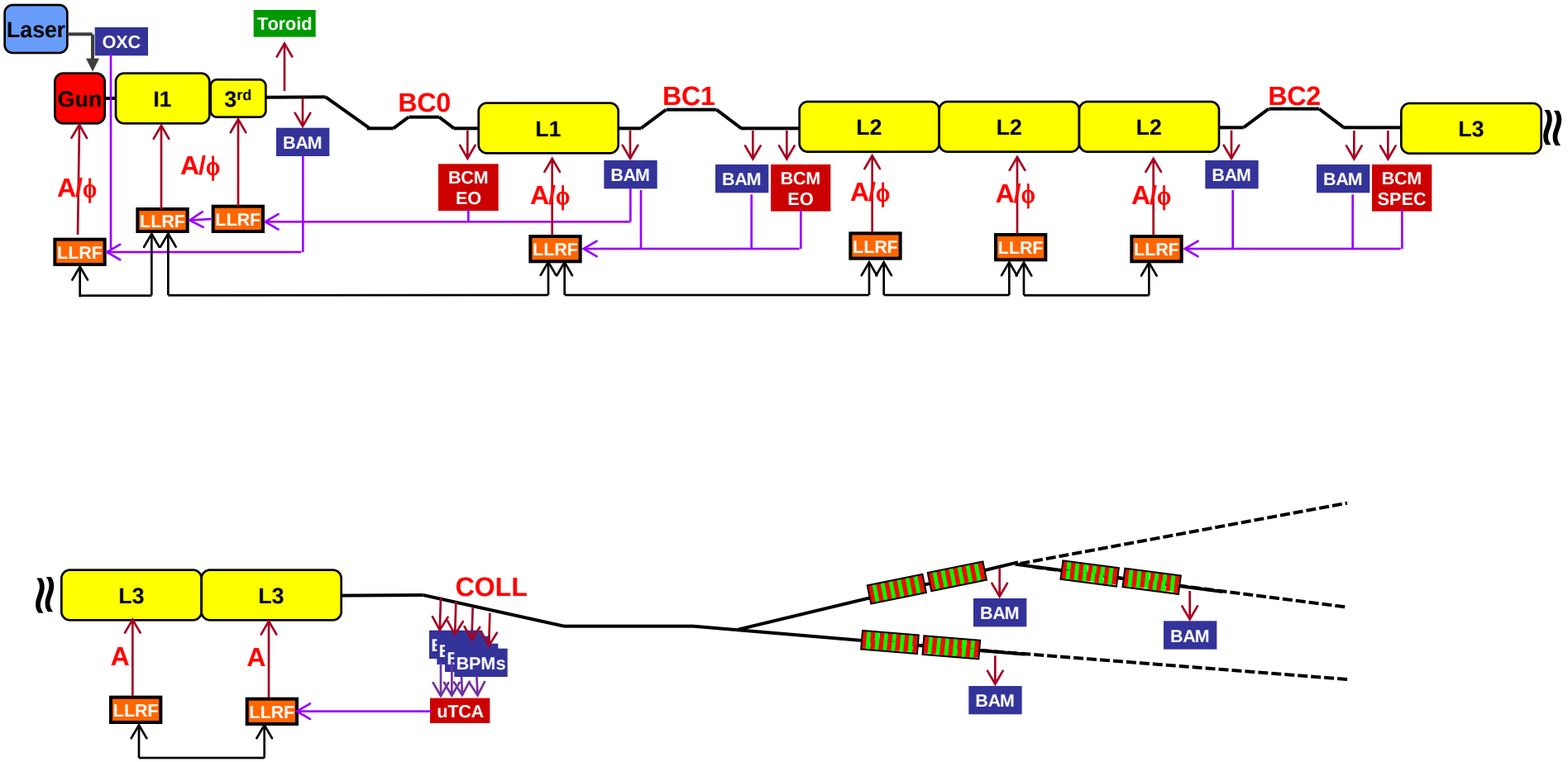


- Latency ~ 0.7us
- Actuator bandwidth: NRF (0.5–1.0MHz)
- Mod. Power (1kW)
- No infl. on orbit
- **Goal: < 5fs rms**

Influence of cavity coupling

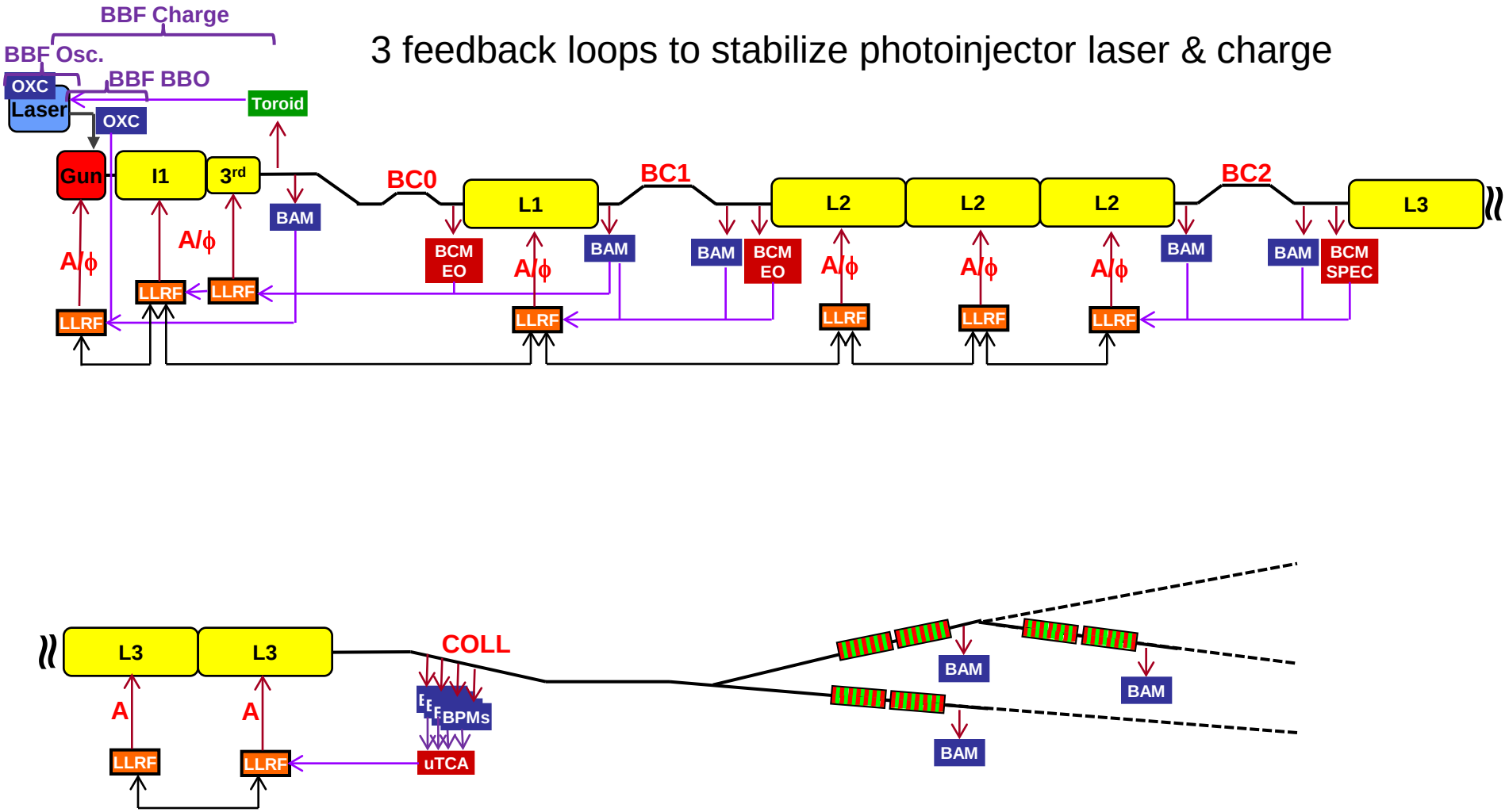


Layout longitudinal FBs for European XFEL



Layout longitudinal FBs for European XFEL

3 feedback loops to stabilize photoinjector laser & charge



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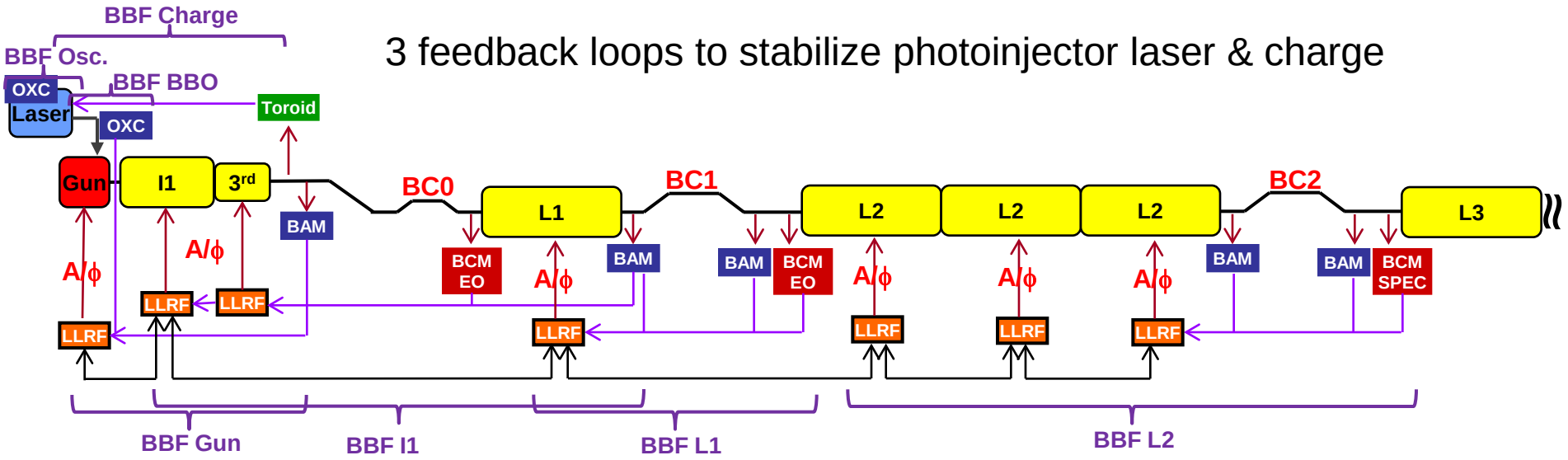
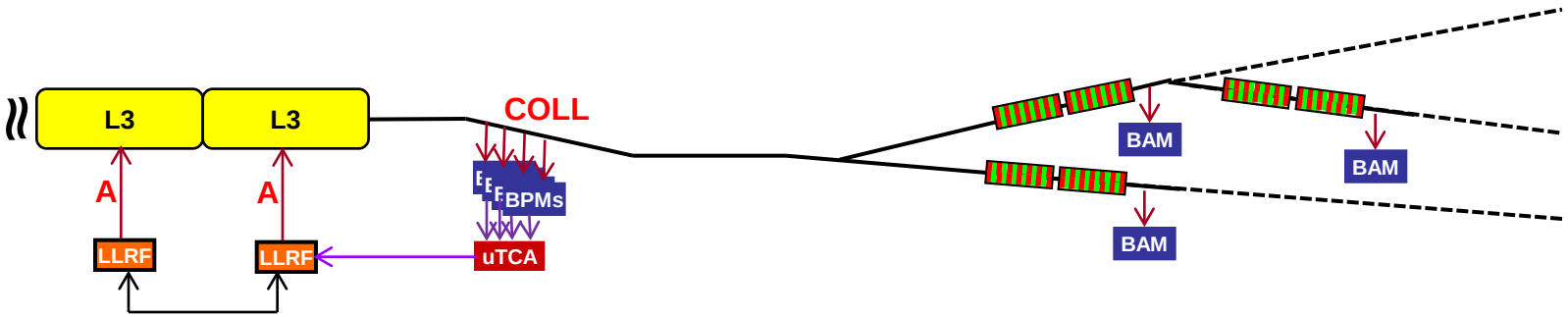


3 feedback loops to stabilize photoinjector laser & charge

4 feedback loops to stabilize arrival times, compression, shape & energy



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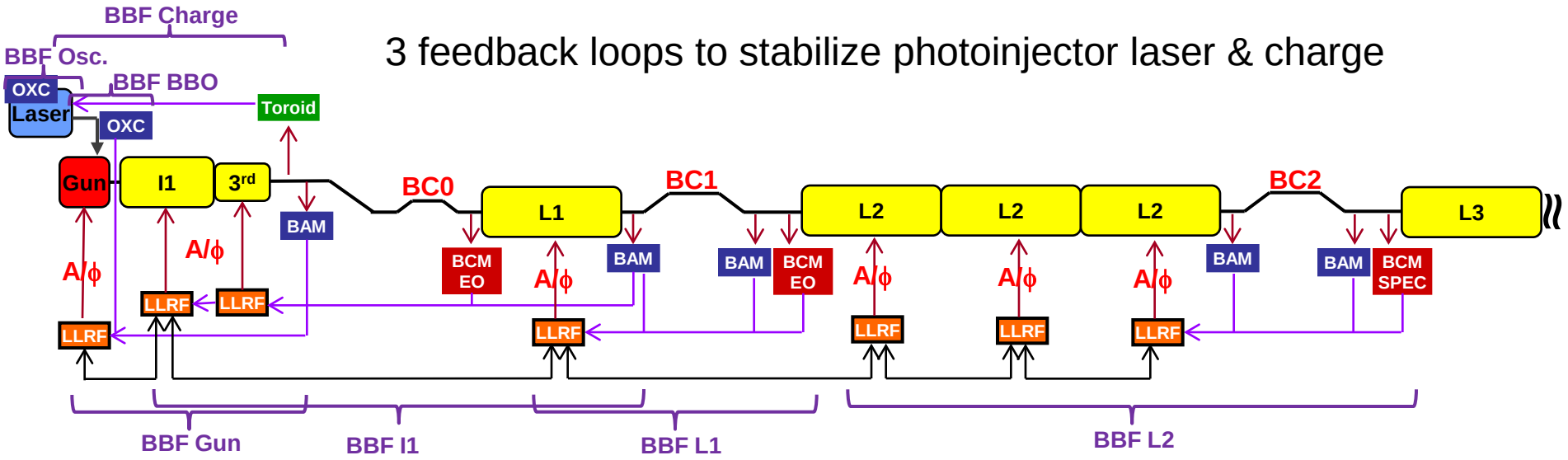

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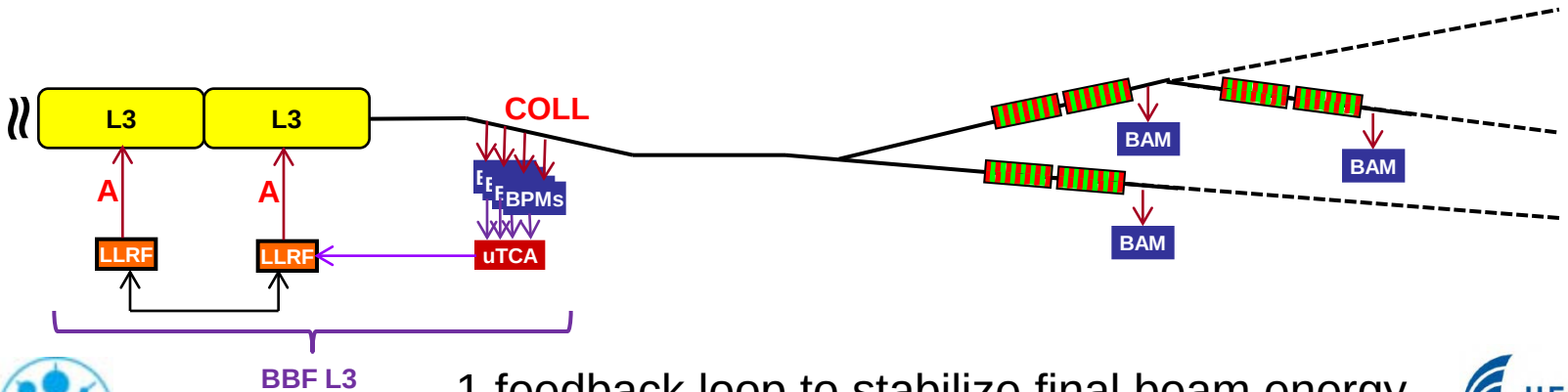
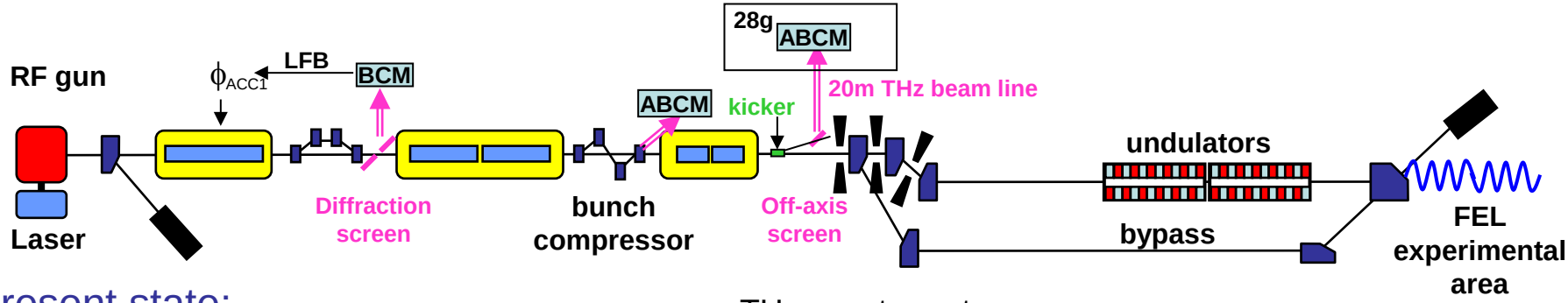


1 feedback loop to stabilize final beam energy

Thanks for attention

Bunch compression monitor CRISP4

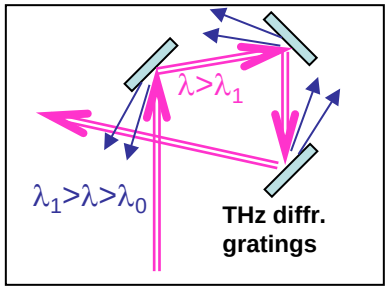
>Coherent radiation: bunch compression monitoring (BCM) and long. FB!

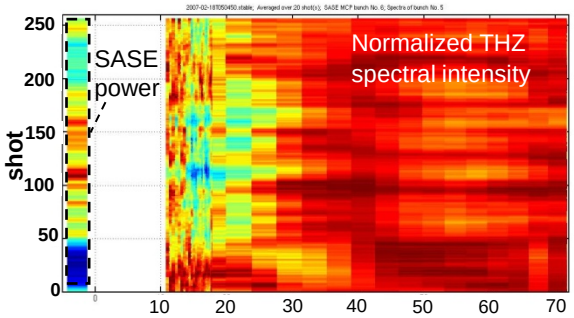


Present state:

- Integrated THz signal (>λ_0) used to stabilize ACC1 phase
- Development of single shot spectrometer (ABCM)
- Reveals importance of spectral information for FEL operation

THz spectrometer

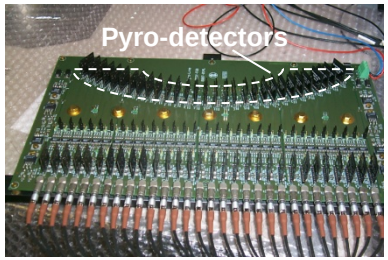


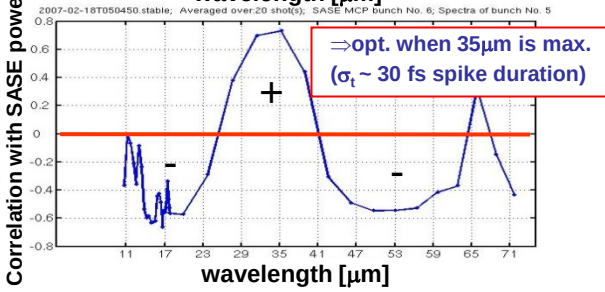


Next steps:

- Investigation of online, suited for macro-pulse operation using CSR
- Compact THz spectrometer (next generation)
- Electronics allowing for readout + processing
  > 1 MHz for long. feedback systems

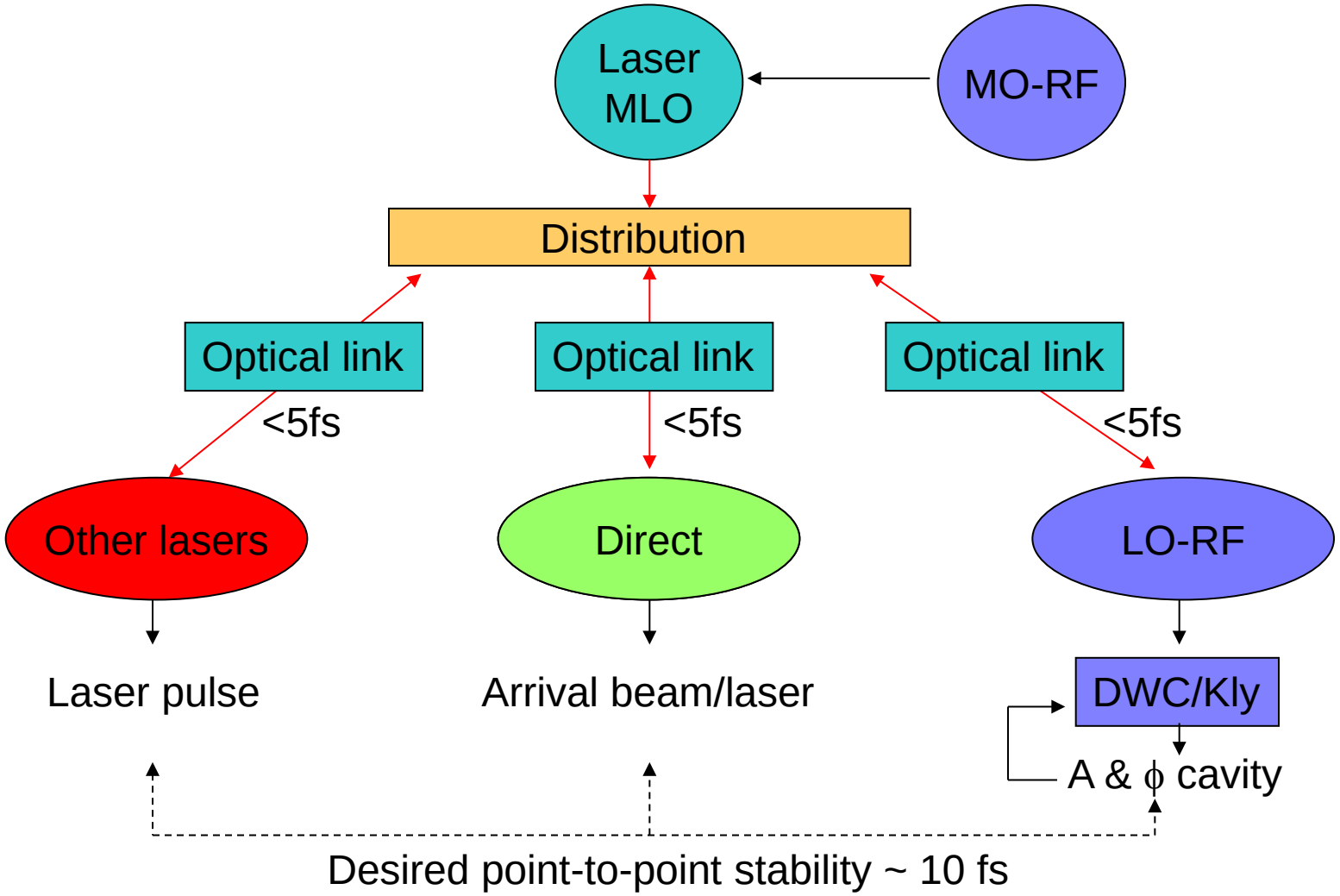
Readout system





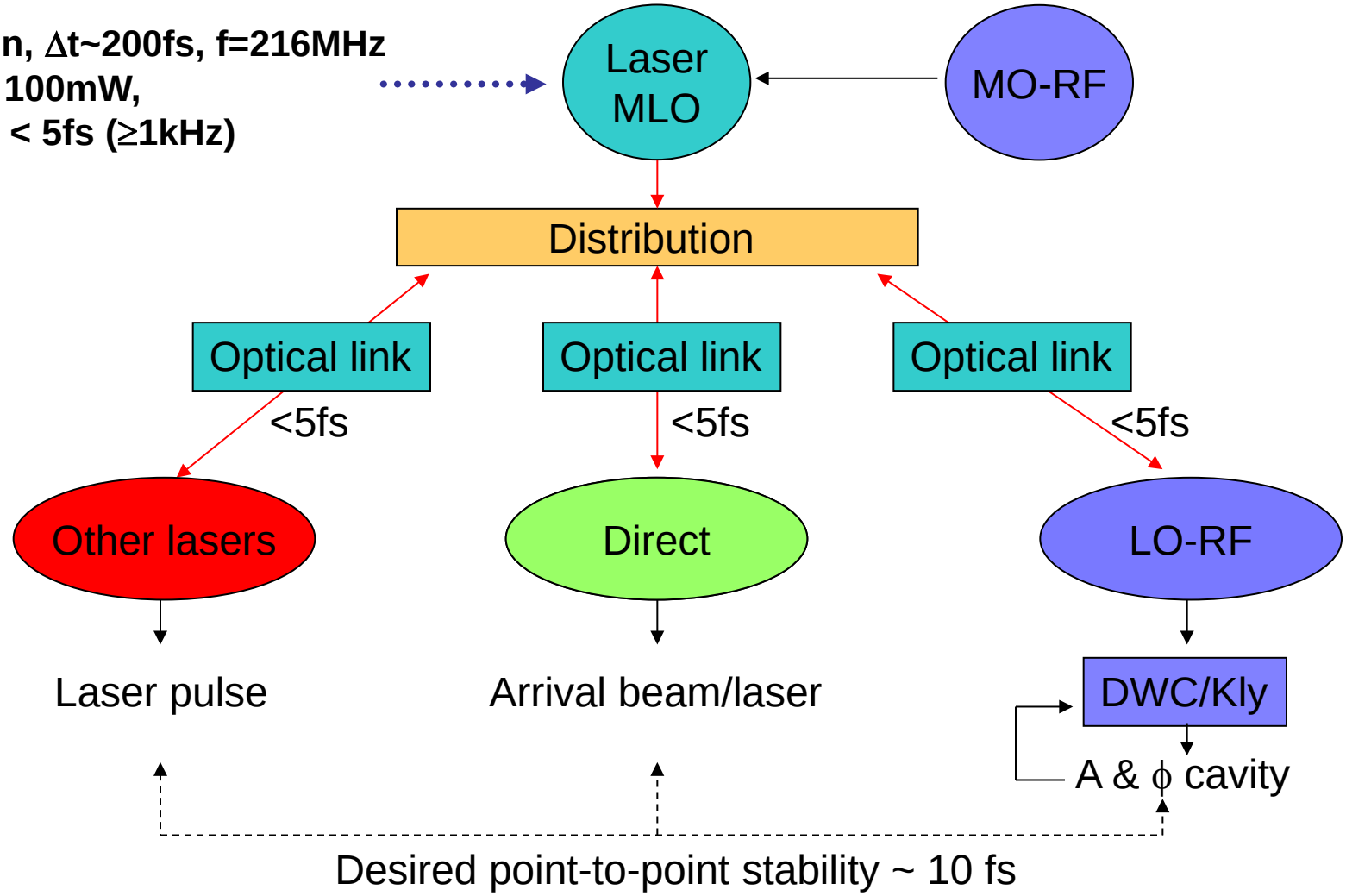
Courtesy: H. Delsim-Hashemi, B. Schmidt

Synchronization reference system using optical pulses

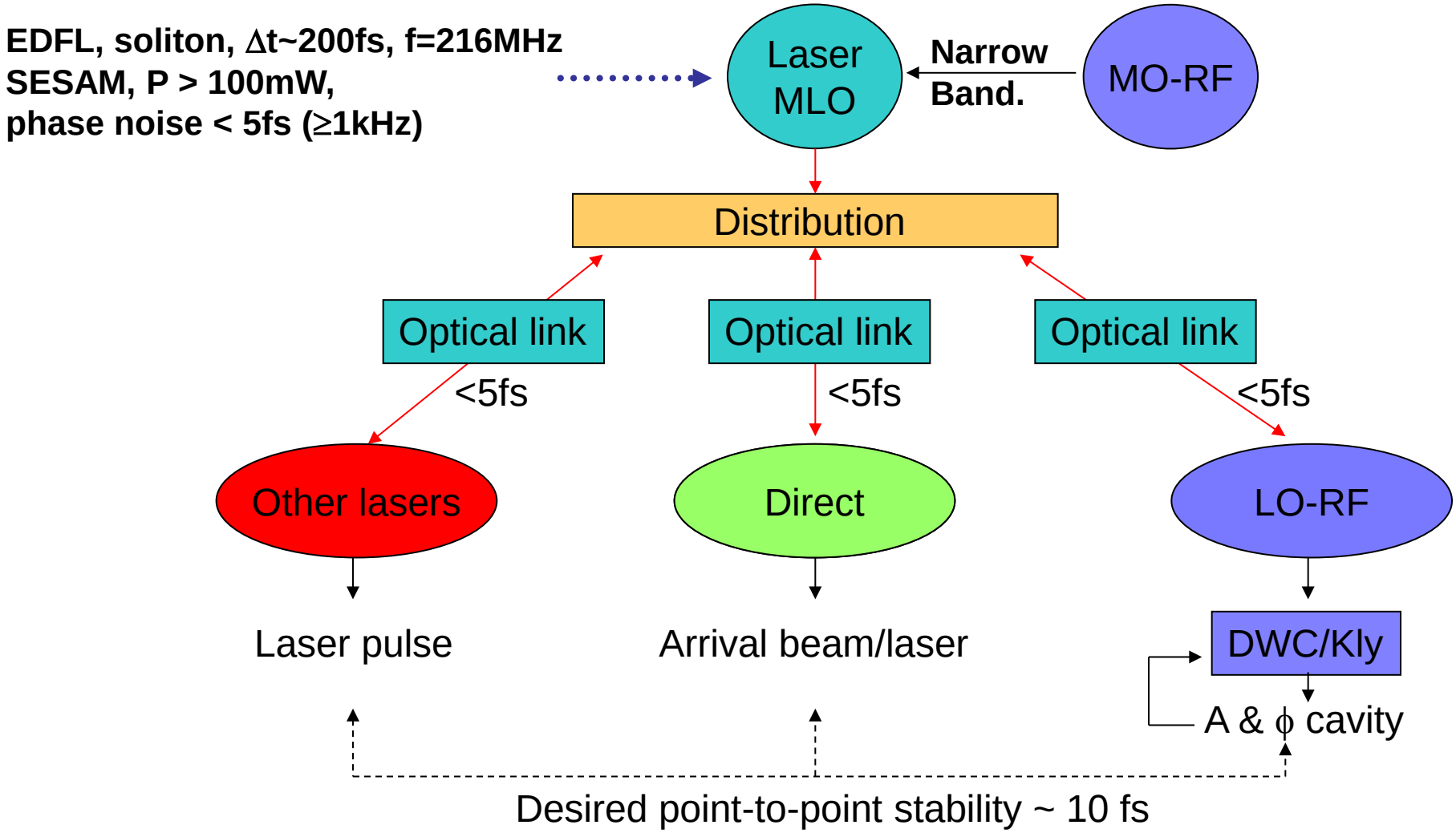


Synchronization reference system using optical pulses

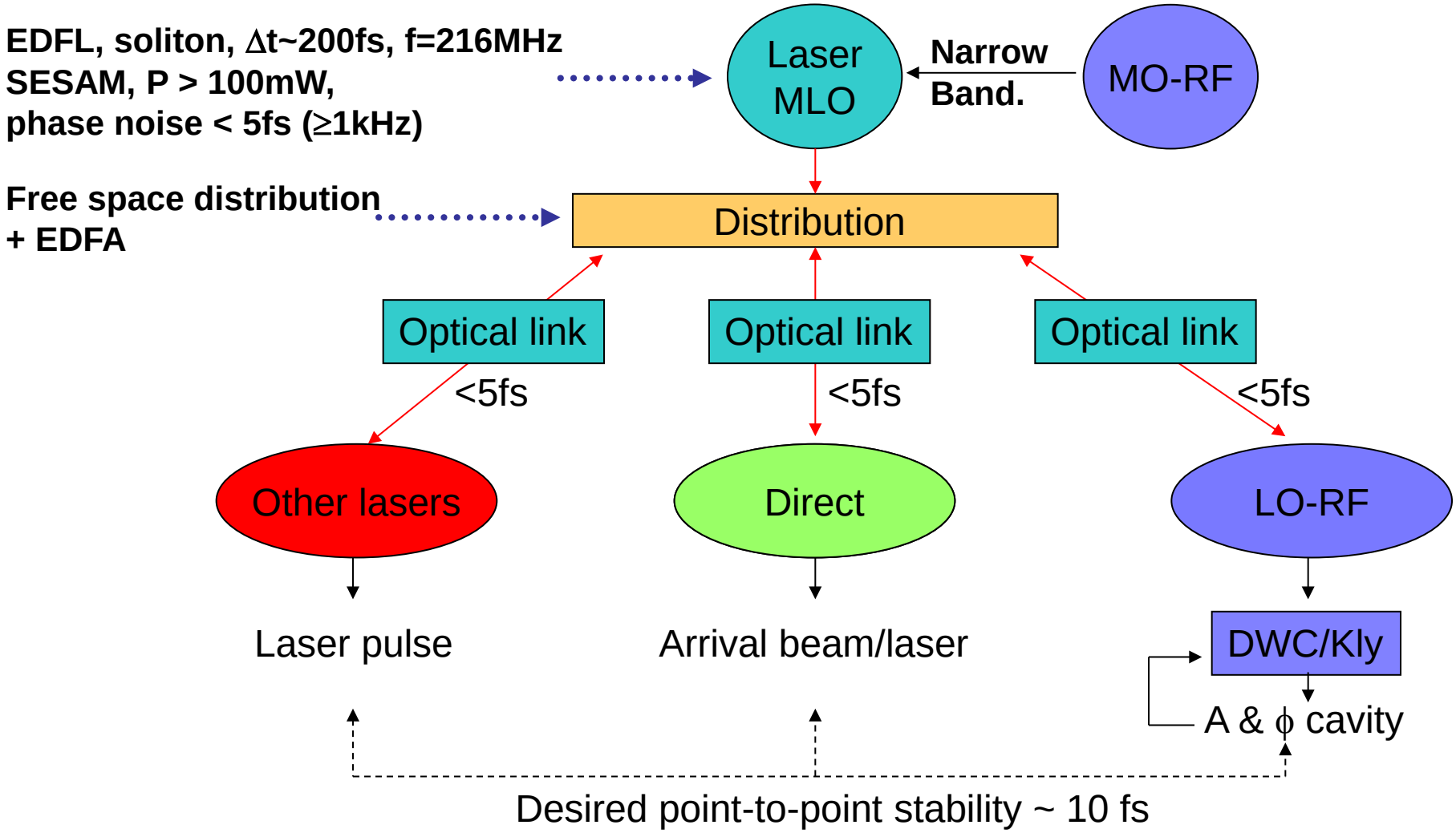
EDFL, soliton, Δt~200fs, f=216MHz
SESAM, P > 100mW,
phase noise < 5fs (≥1kHz)



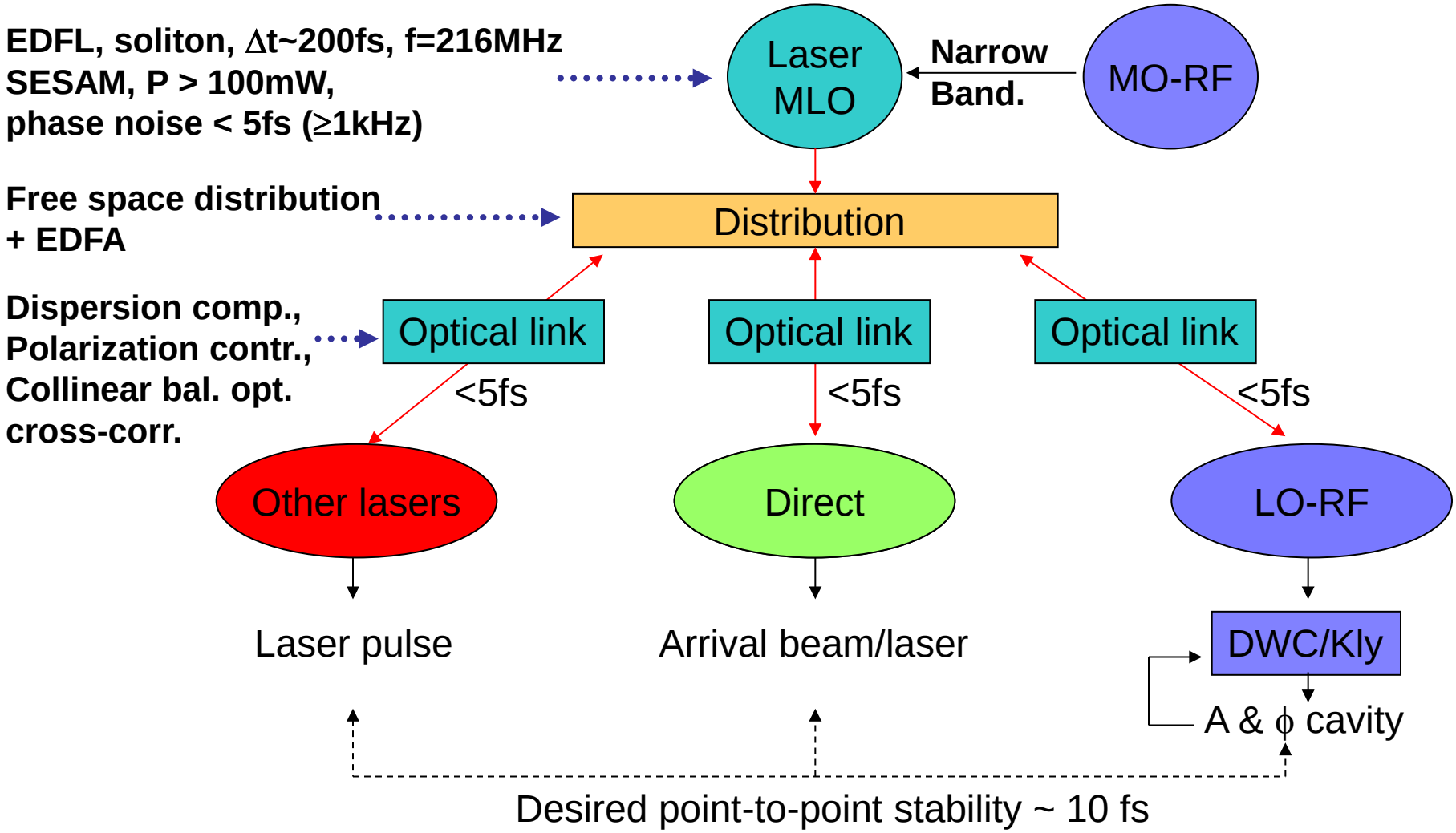
Synchronization reference system using optical pulses



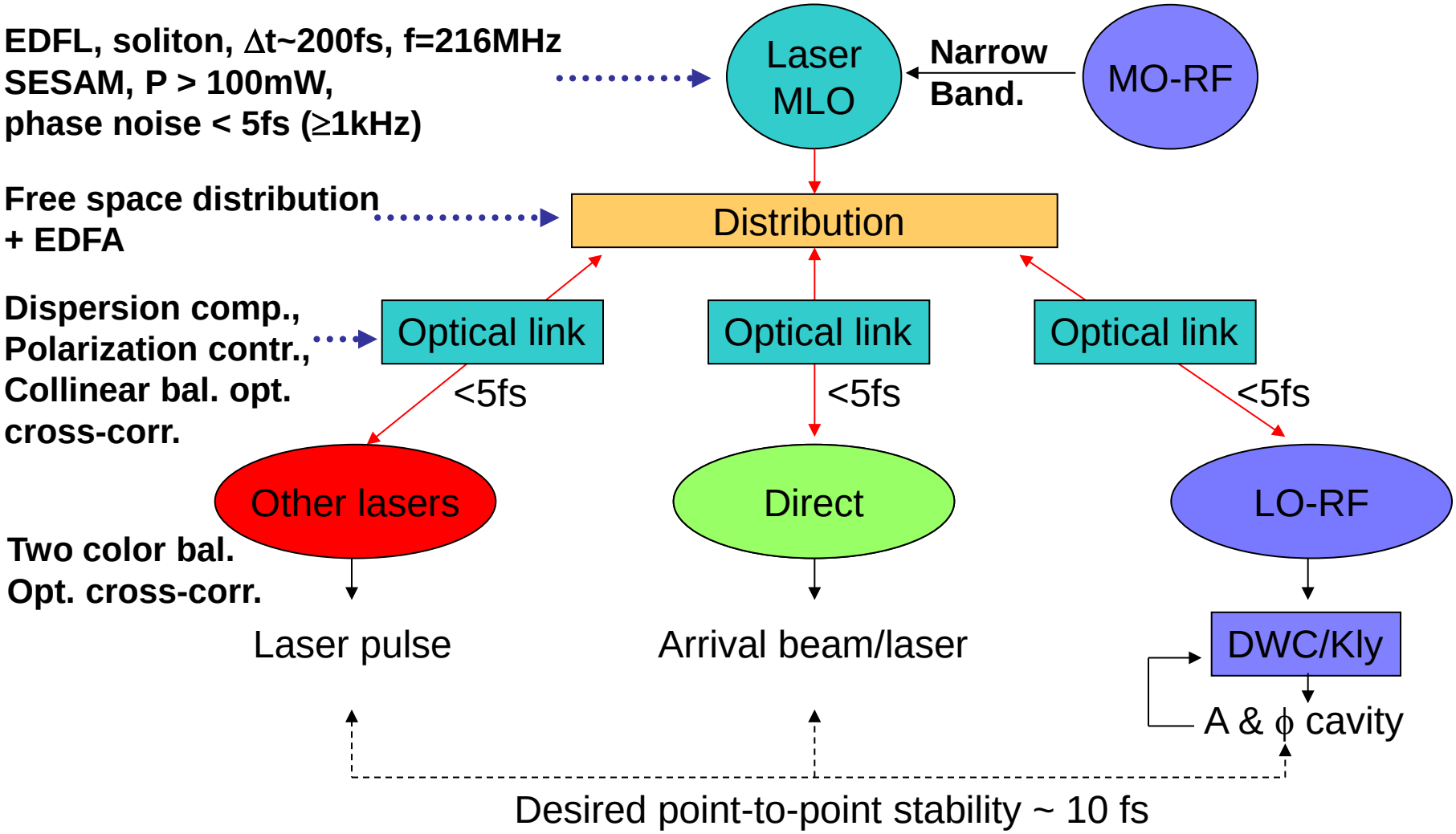
Synchronization reference system using optical pulses



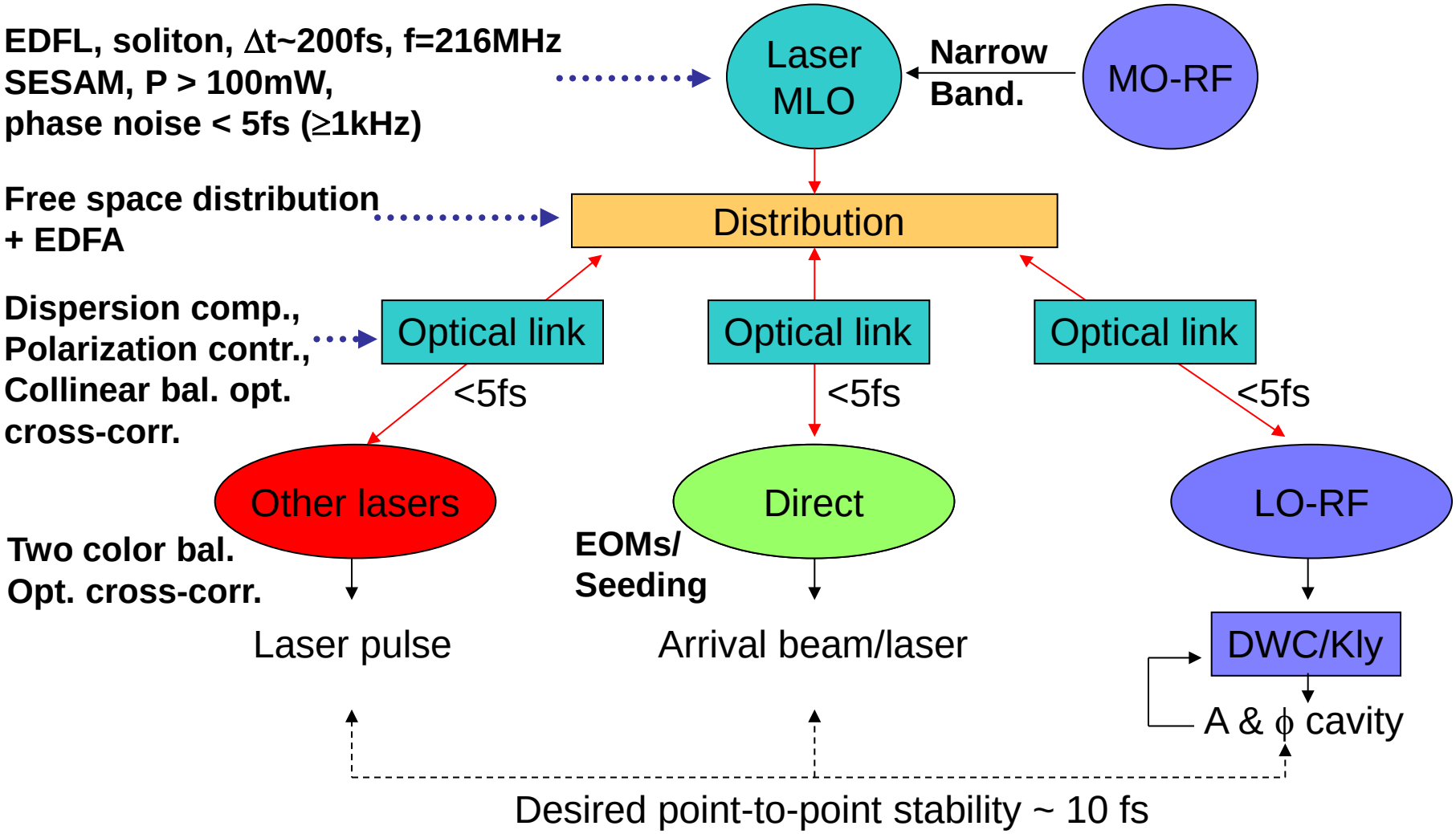
Synchronization reference system using optical pulses



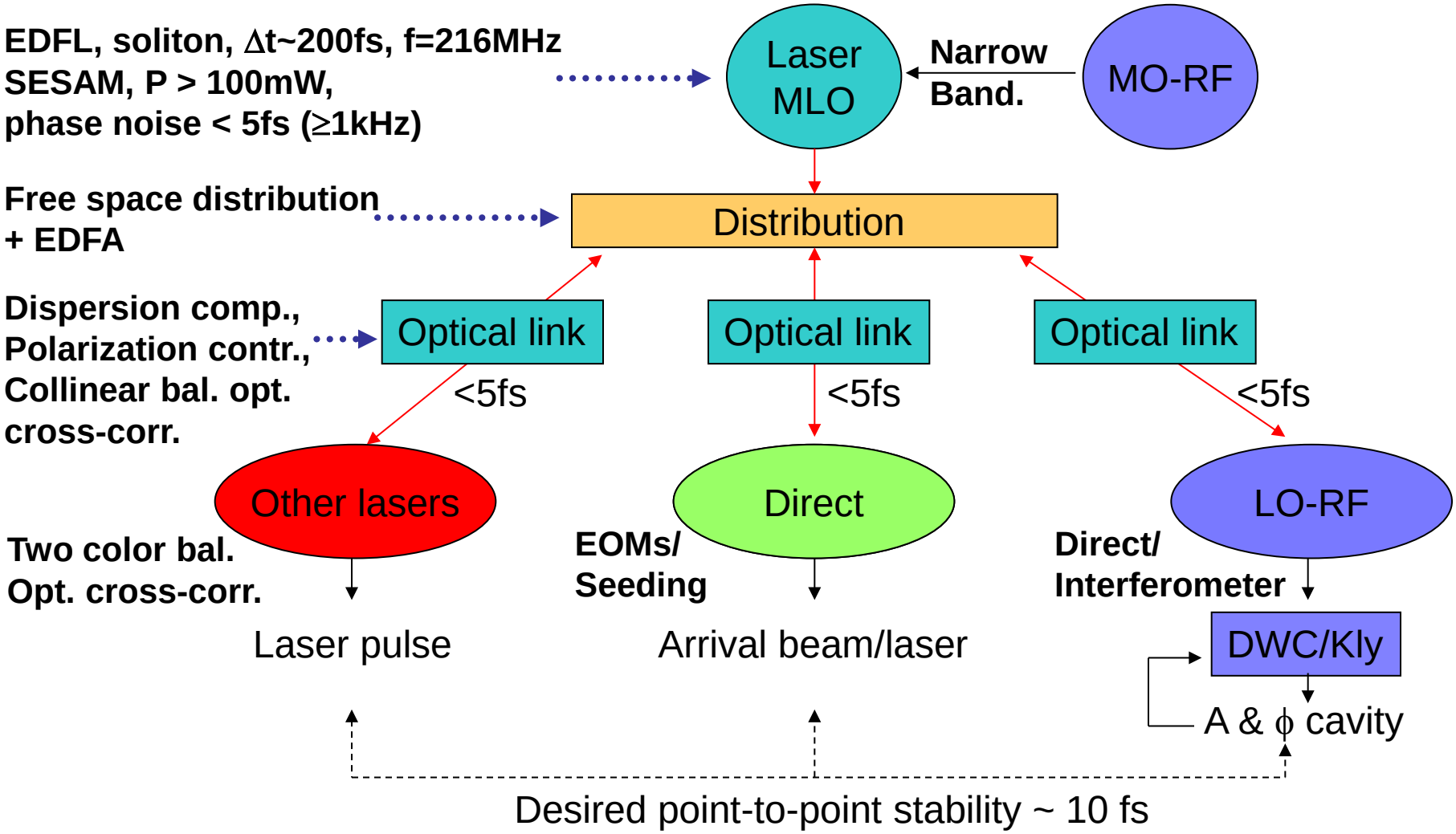
Synchronization reference system using optical pulses



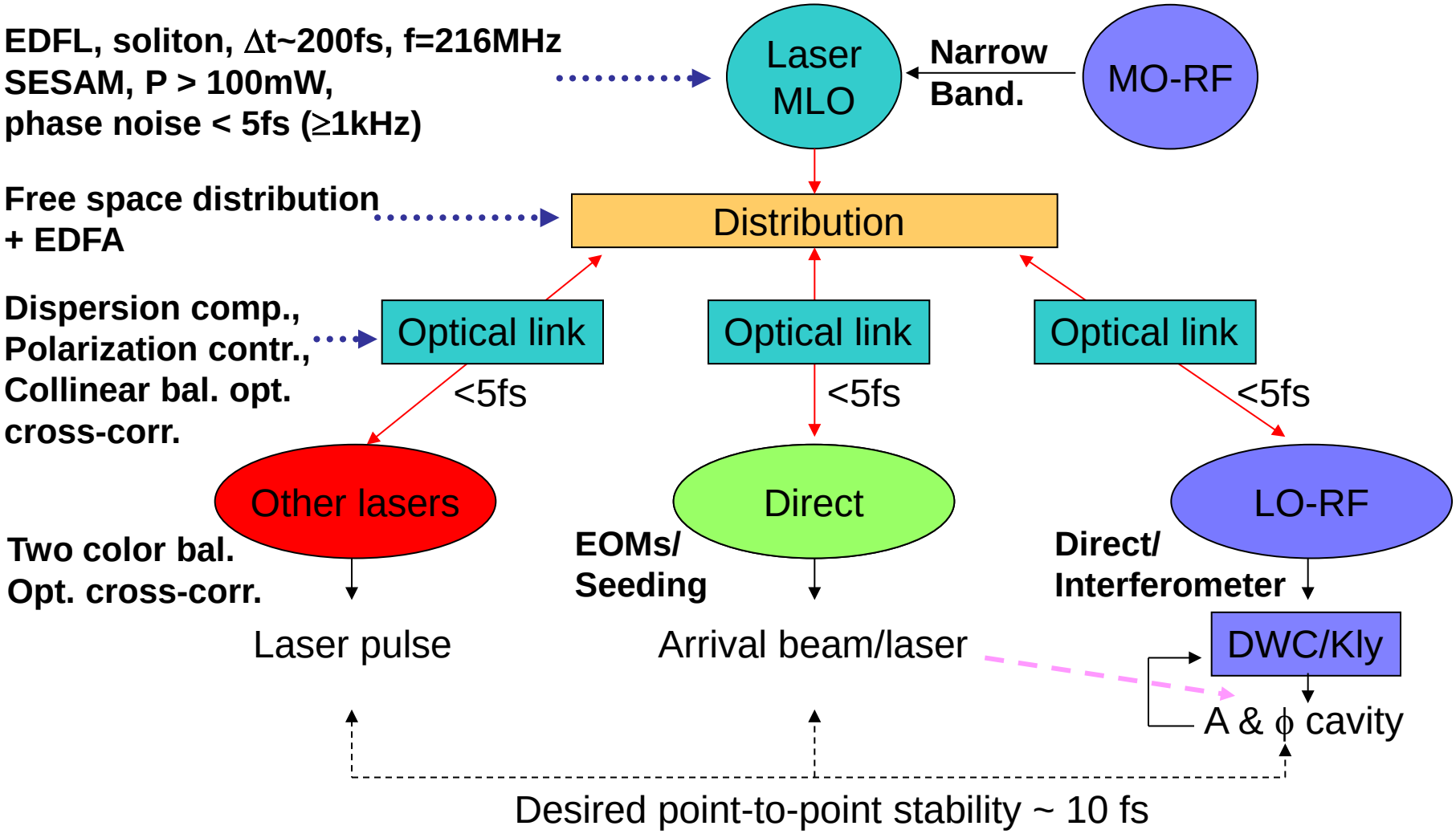
Synchronization reference system using optical pulses



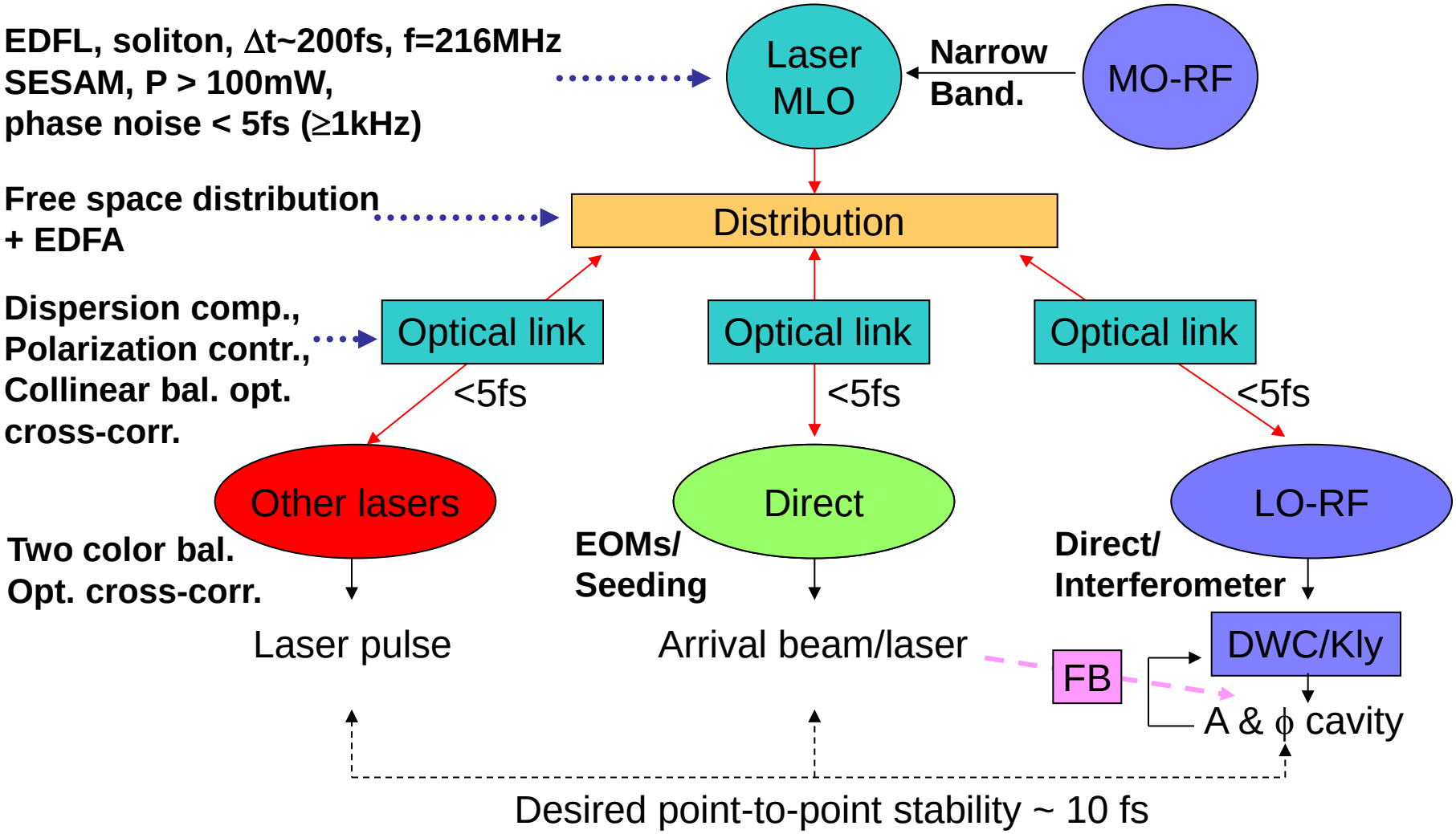
Synchronization reference system using optical pulses



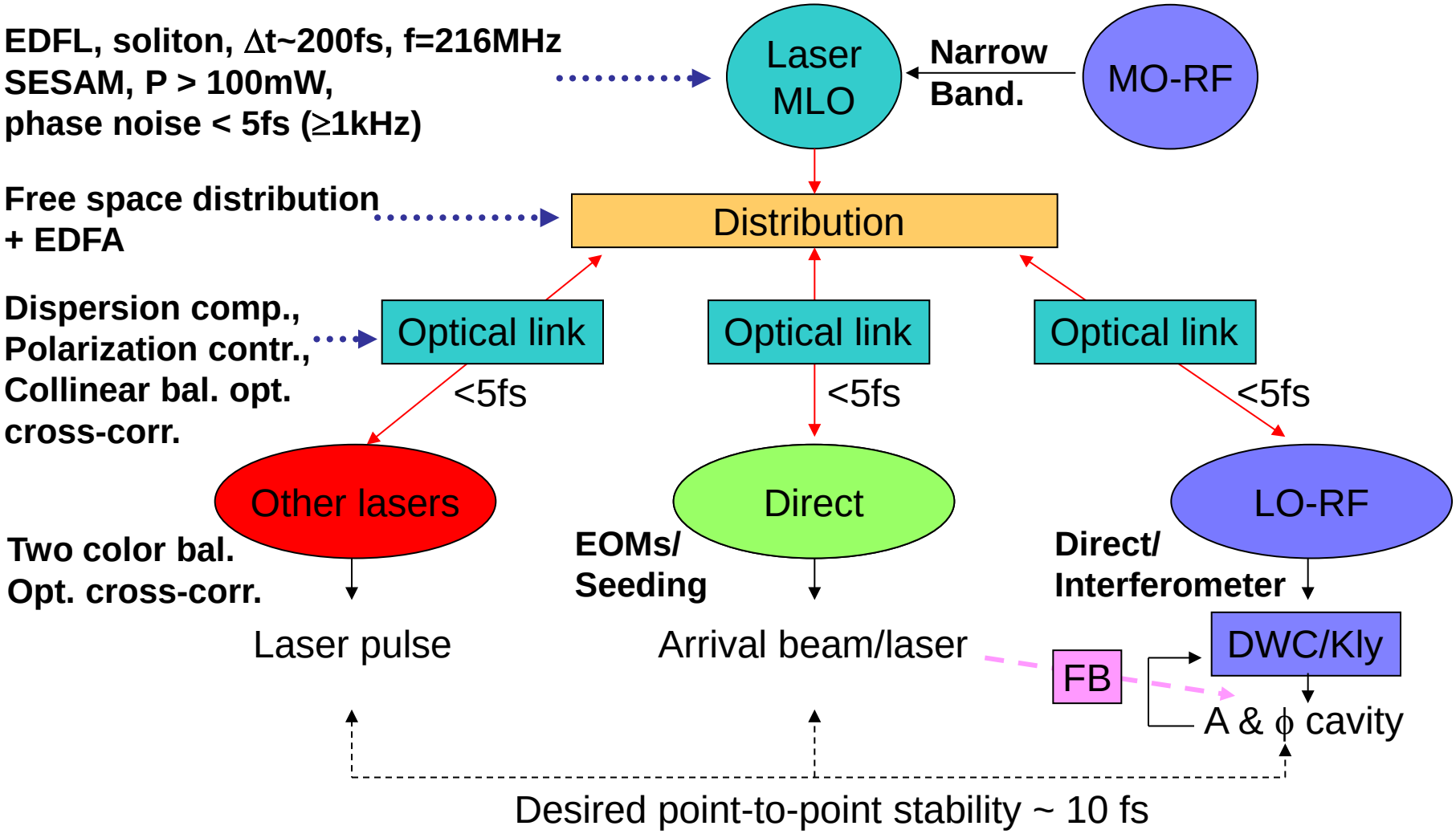
Synchronization reference system using optical pulses



Synchronization reference system using optical pulses



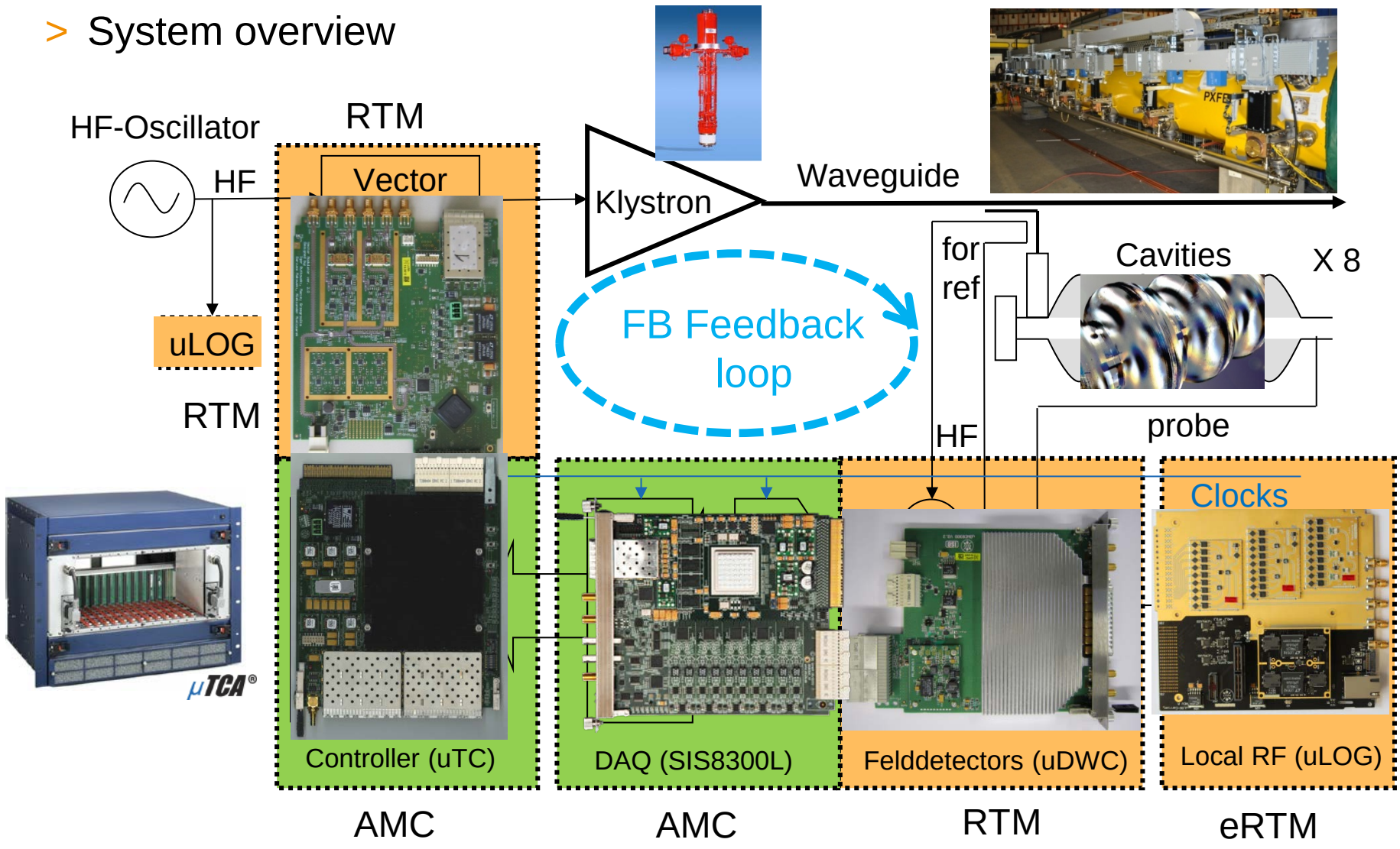
Synchronization reference system using optical pulses



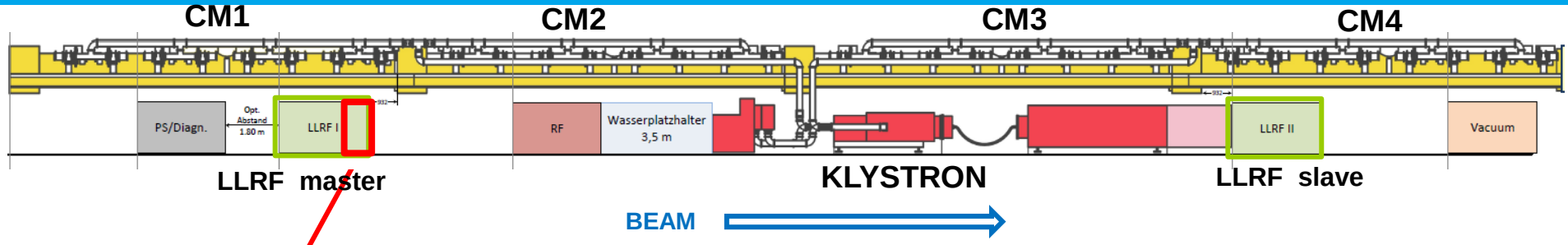
Main issue: robustness, stability and maintainability ⇒ Prototype at FLASH

Work accomplished 2011-2013

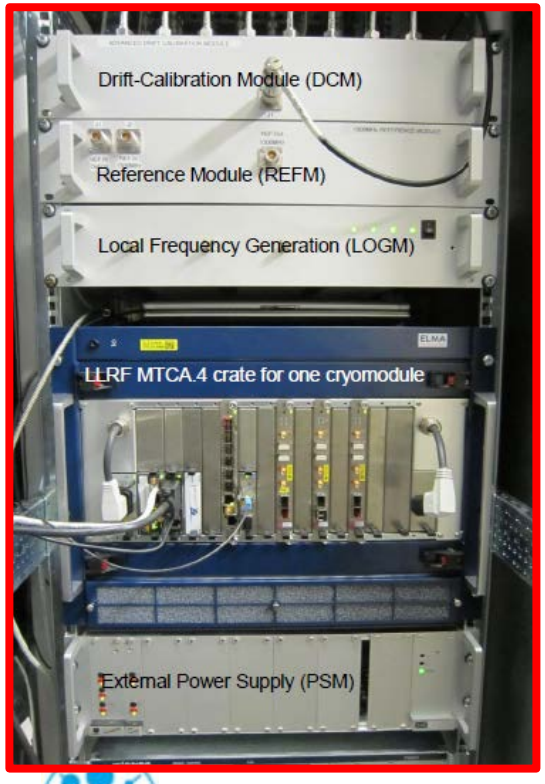
> System overview

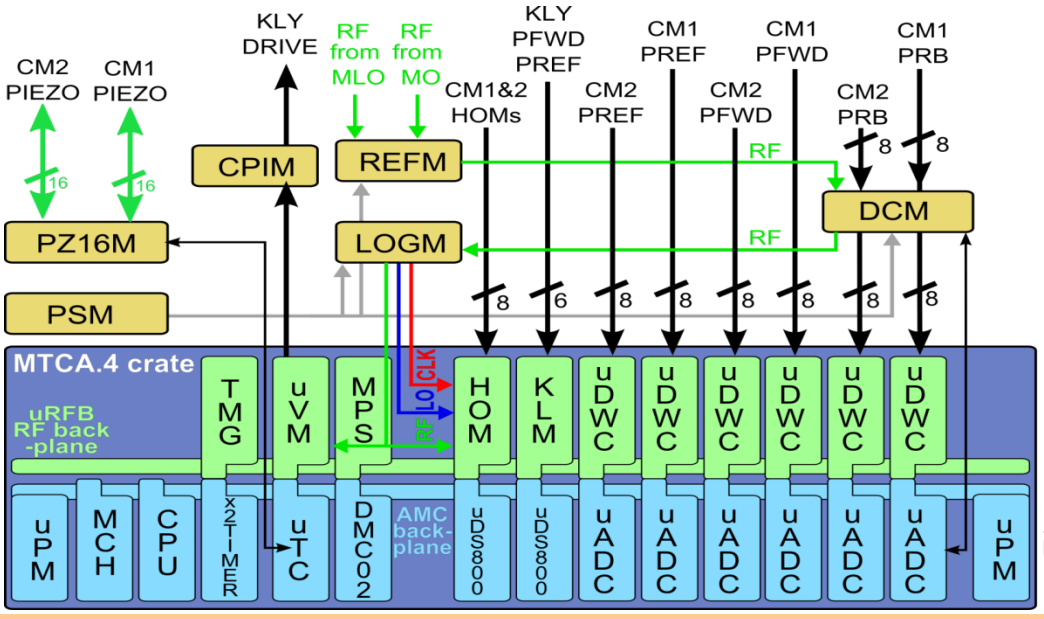


Work accomplished 2011-2013: XFEL LLRF System



< 28U Rack





Talk: J. Branlard

- MTCA.4 incl. complete suite: LLRF/Diag./ Interlocks/HOM

Challenges:

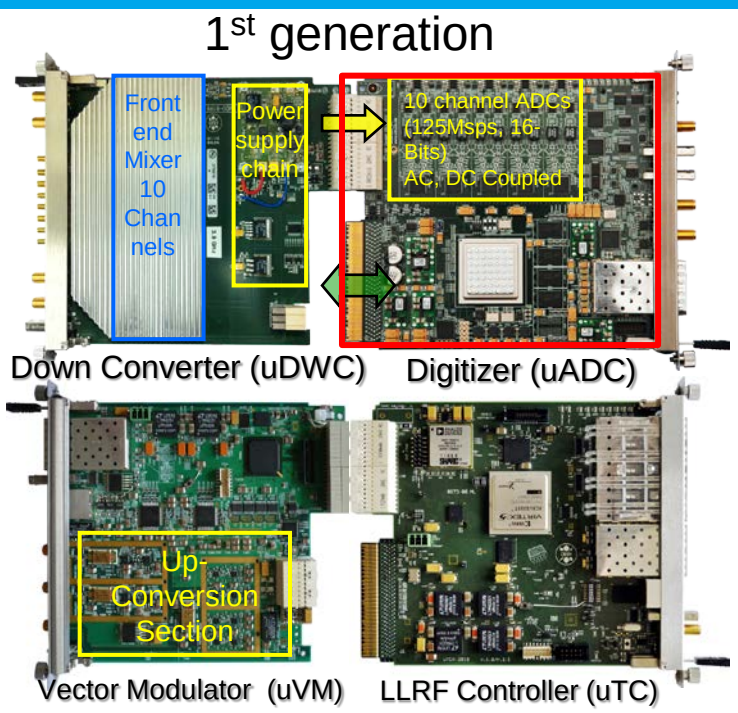
- **Total: 27 RF station / 800 cavities / >3000 RF signals**
- **Stability requirements < 0.01% & 0.01deg**

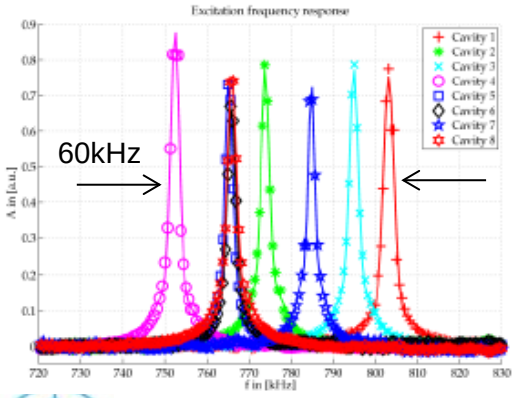
1st to 2nd generation MTCA.4 modules

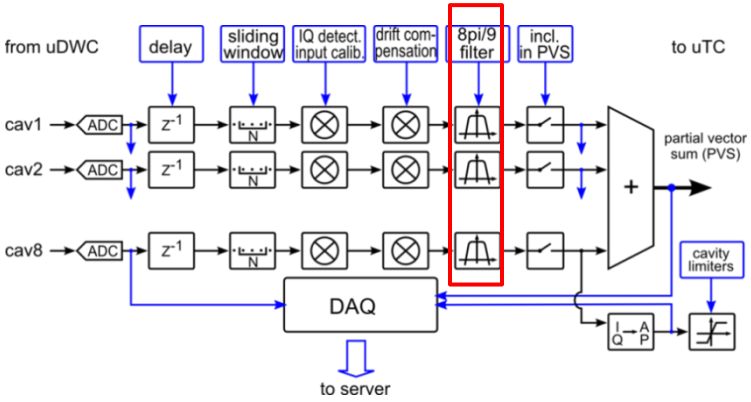
- Core modules:
  - Down converter 1.3GHz → IF=54Mhz
  - SIS8300 10ch, 16bit, 125 MSPS
  - Controller V5 based
  - Vector modulator, 2 channel
- Digitizer ⇒ SIS8300L
  - Resource limitation & communication limitation

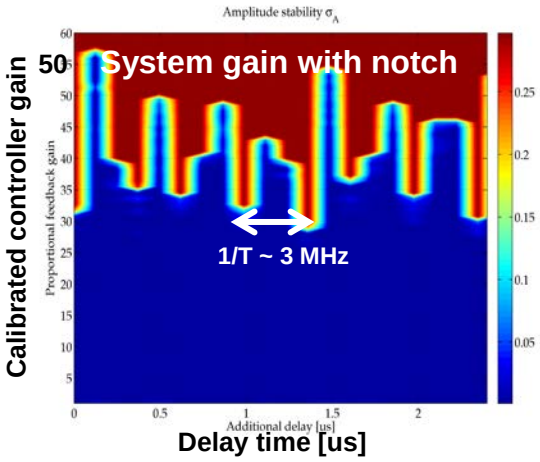
    → XC6VLX130T-2FFG1156C

    → 6.6 Gbps transfer rate to controller



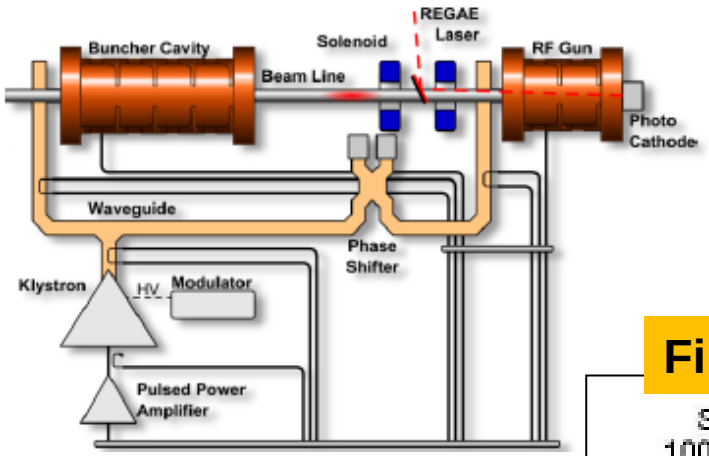


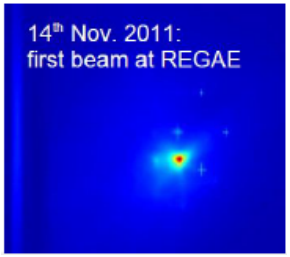




First test of DWC8VM1 at REGAE@3.0GHz:

- **REGAE (Relativistic Electron Gun for Atomic Exploration) :**
  - Electron source for time resolved diffraction experiments

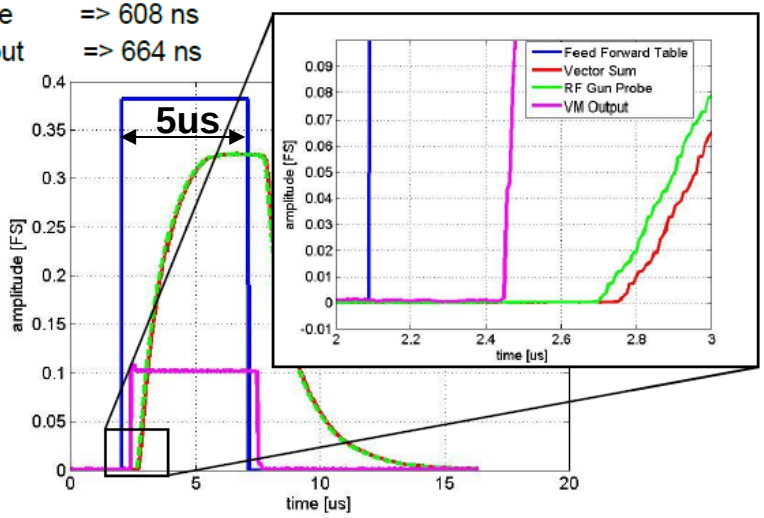




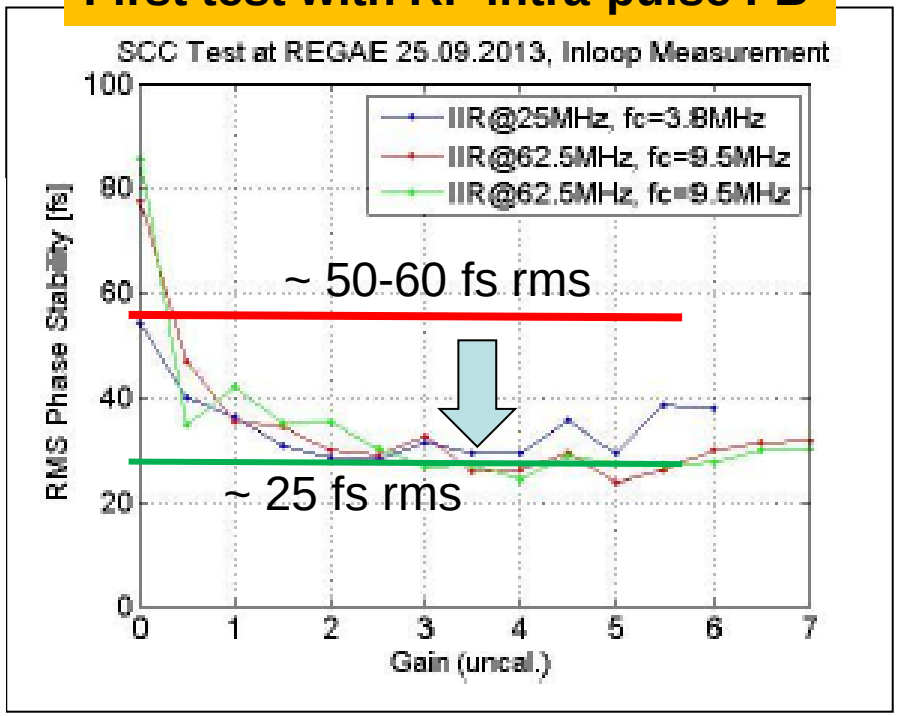
Poster: M. Hoffmann

Delay Budget (new System):

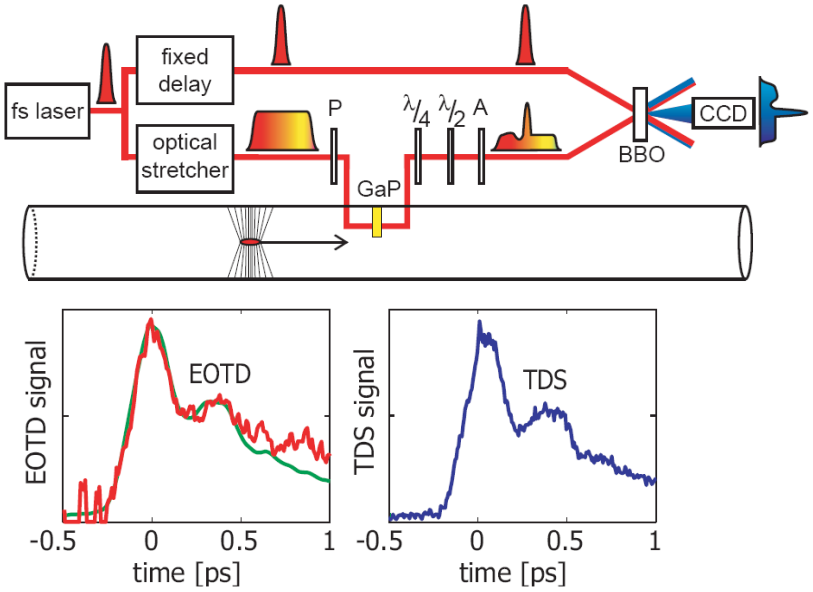
- Vector Mod. Output => 360 ns
- RF Gun Probe => 608 ns
- Controller Input => 664 ns



First test with RF intra-pulse FB



Diagnostics developments – time domain –



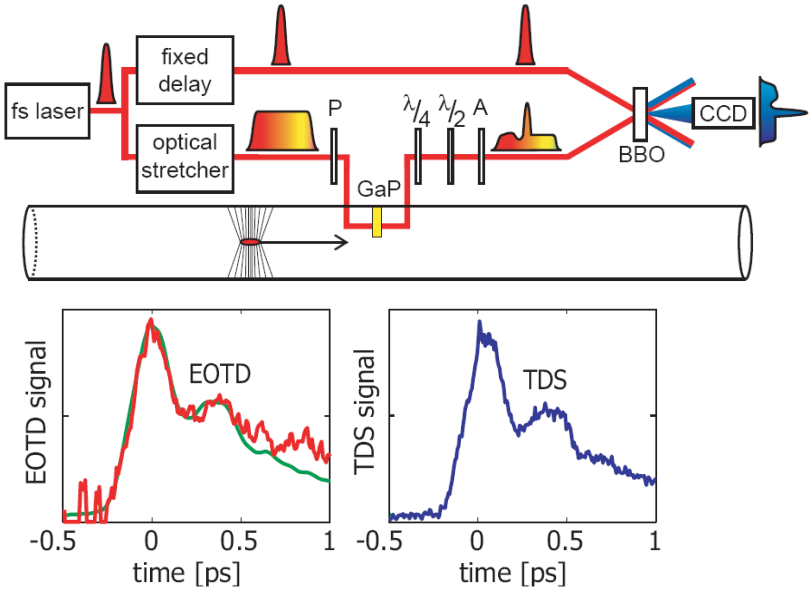
Diagnostics developments – time domain –

>Time domain longitudinal bunch profiling:

- Electro-optical technique (birefringence crystal)
- Time domain approach with stretched laser pulse + cross-correlation in BBO for encoding (EOTD)
- Bench marked with transverse deflecting structure

⇒ Good agreement with expectation

⇒ Resolution 55fs rms (65 μm GaP crystal)



>Collaboration: Abertey & Dundee Uni., Daresbury Lab., FELIX / FOM and DESY (See talk WEBAU04)

>Next development steps:

- Robust source: mode-locked Yb-fiber laser Δt_{FWHM}<100fs (30fs has been achieved)
- Suitable for operation in acc. tunnel
- Packaging of laser: IRUVX-FP7 proposal

> in collaboration with BESSY (T. Quast)

- Fast line camera readout (1030nm, >1MHz)
- Technique: EO spectral or spatial

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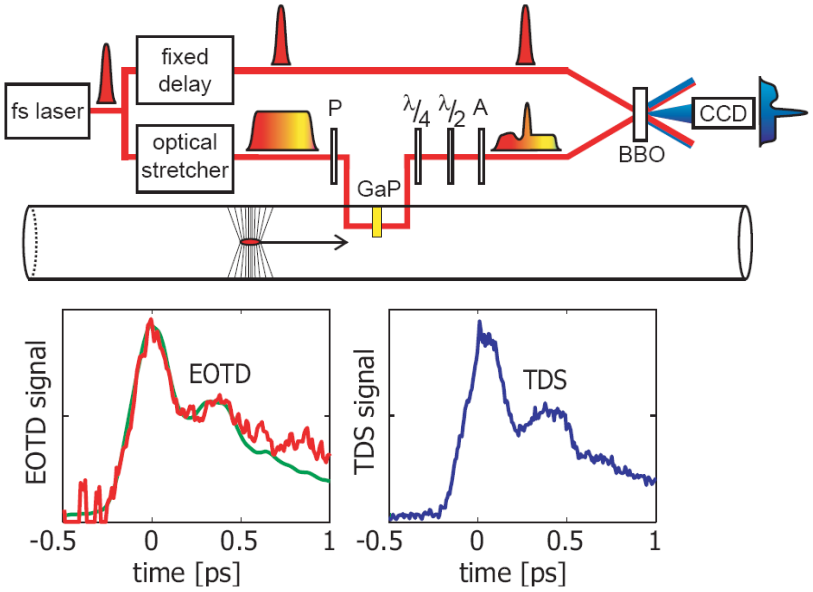

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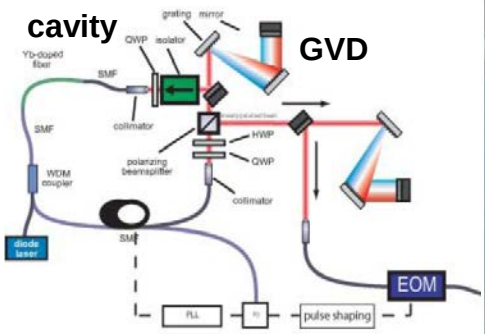
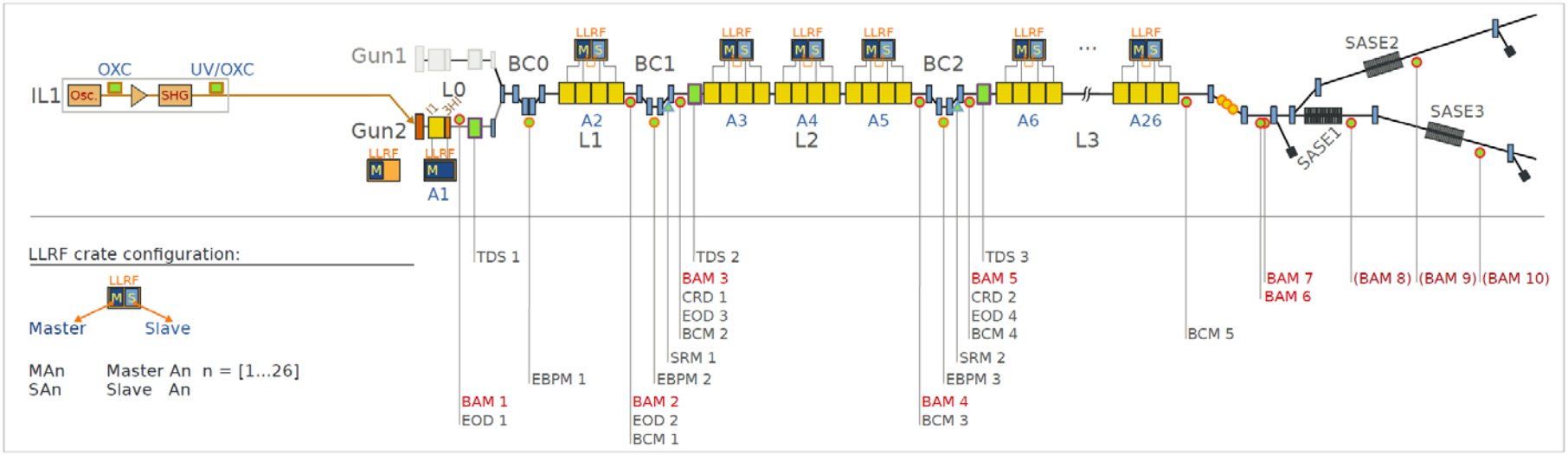


Courtesy: A. Winter, DESY
Ö. Ilday, Bilkent Uni. Ankara
DIPAC07:WEPB03

XFEL Longitudinal FBs – Overview -



- Photo cathode laser:
  - Synchronization
  - Pulse shape
  - Charge feedback
- RF gun phase
- L0 / L1 / L2 compression / arrival / (shape)
- L3 (last RF stations) energy feedback
- L3 (all RF stations) distributed energy gain scheduling feedback