Upgraded Bunch-Arrival-Time Monitors for the European XFEL Reaching Below 3fs Time Resolution

First Results Evaluating the BAM Performance and Jitter Behaviour of the Electron Bunches.

Marie K. Czwalinna, (DESY)
On behalf of the Special Diagnostics team, and many others.

IBIC 2019, Malmoe, Sweden

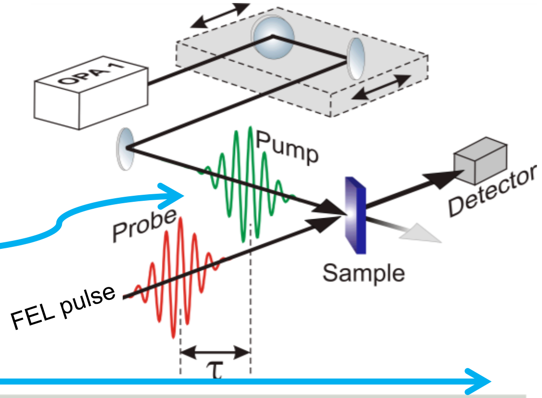
Facility & Infrastructure

- Optical Synchronisation System
- Locations of Arrival Monitors

Optical Synchronisation System at EuXFEL

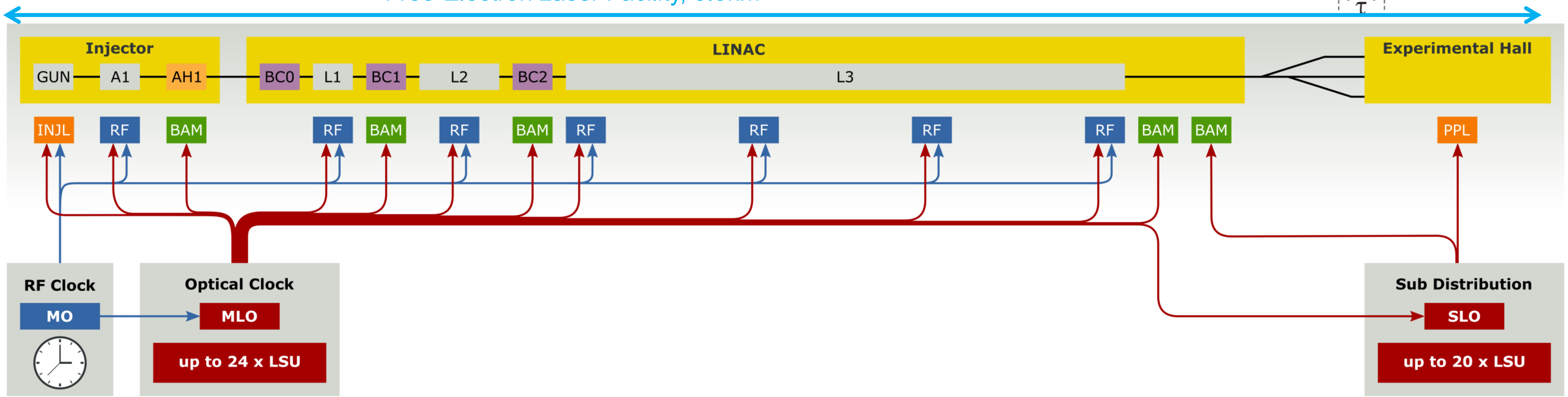
World-wide Unique Large-Scale 24/7 Operation

Few femtosecond Timing Precision
Between FEL & Optical Lasers



https://dariopolli.wordpress.com/spectroscopy/

Free-Electron Laser Facility, 3.5km



RF Master Oscillator

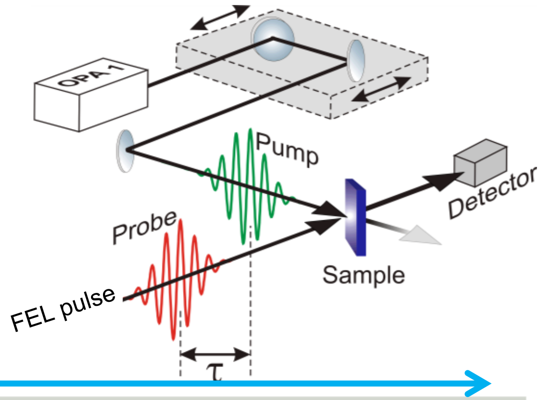
Optical Master Laser Oscillator

Pump-Probe Laser

By courtesy of Jost Mueller, representing the Laser-based Synchronisation team, DESY MSK.

Optical Synchronisation System at EuXFEL

World-wide Unique Large-Scale 24/7 Operation



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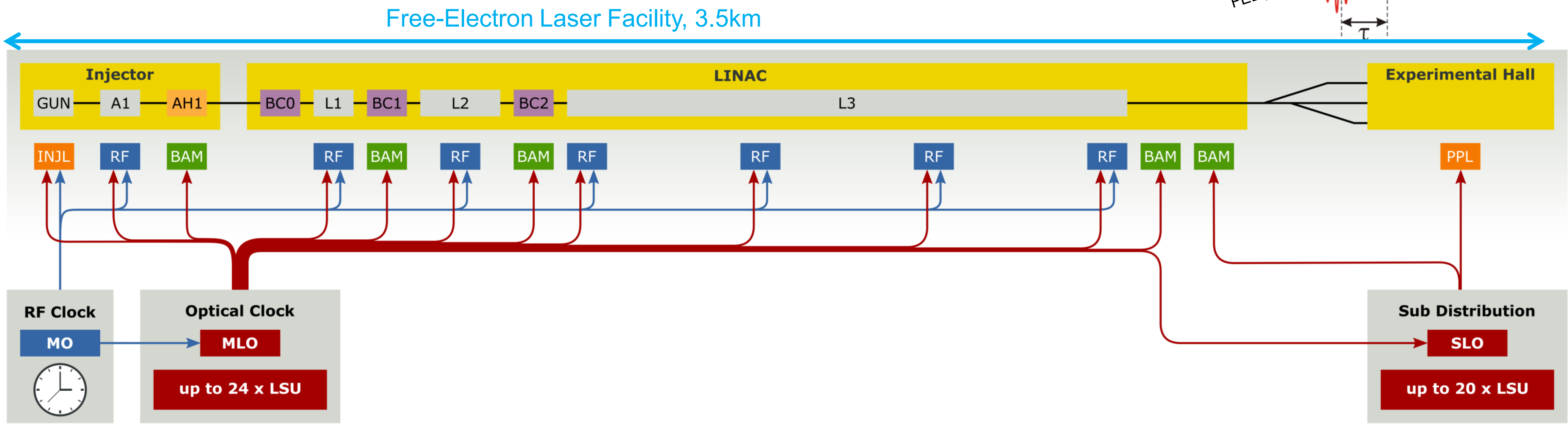


optical reference **distributed via length-stabilized optical fiber links** and used for

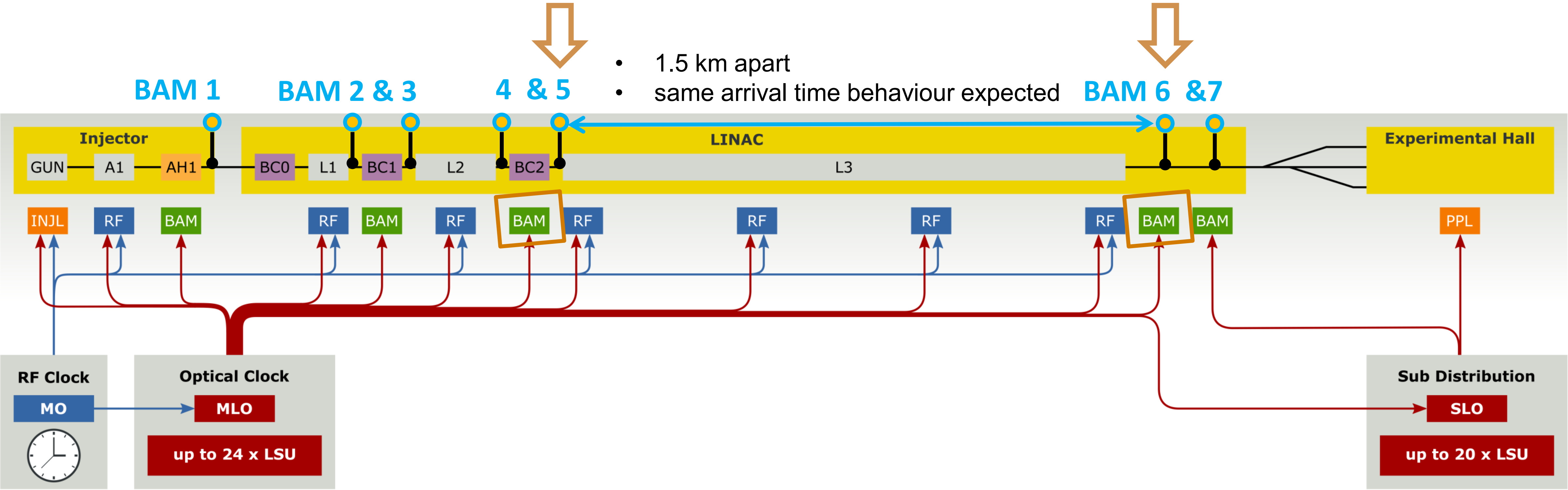
- ❑ **laser locking** (injector, pump-probe, …)
- ❑ RF re-synchronization (**REFM-OPT**)
- ❑ bunch arrival time diagnostics (**BAM**)

By courtesy of Jost Mueller, representing the Laser-based Synchronisation team, DESY MSK.

Optical Synchronisation System at EuXFEL

Point-to-Point Stability MO → Pump-Probe Laser

- 1.5 km apart
- same arrival time behaviour expected



- MLO: **3 fs (rms)**
- optical link (3.5 km): **0.5 fs (rms)**
- SLO synchronization: **1.3 fs (rms)**
- optical link (100 m): **0.3 fs (rms)**
- PPL oscillator: **5 fs (rms)**

6 fs (rms)

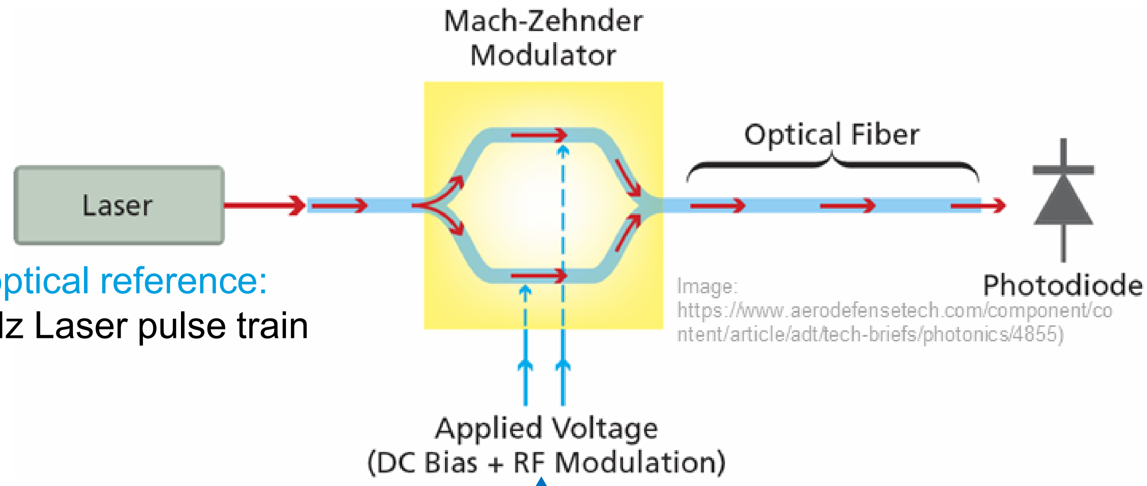
By courtesy of Jost Mueller, representing the Laser-based Synchronisation team, DESY MSK.

Technical Concept

- Improvements

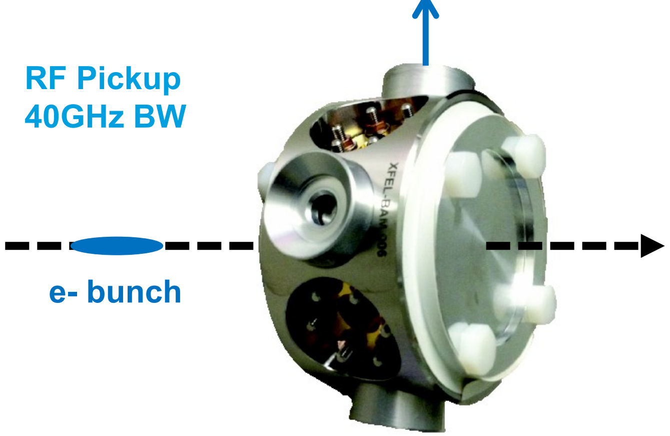
Bunch Arrival Monitor (BAM)

BAM Operation Principle



From optical reference:
216MHz Laser pulse train

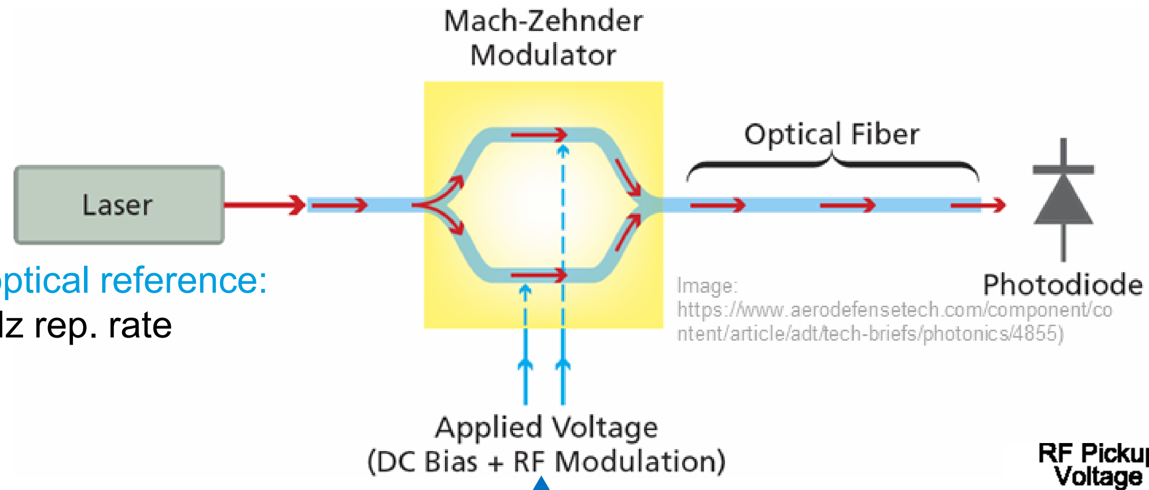
RF Pickup
40GHz BW



e- bunch

Bunch Arrival Monitor (BAM)

BAM Operation Principle

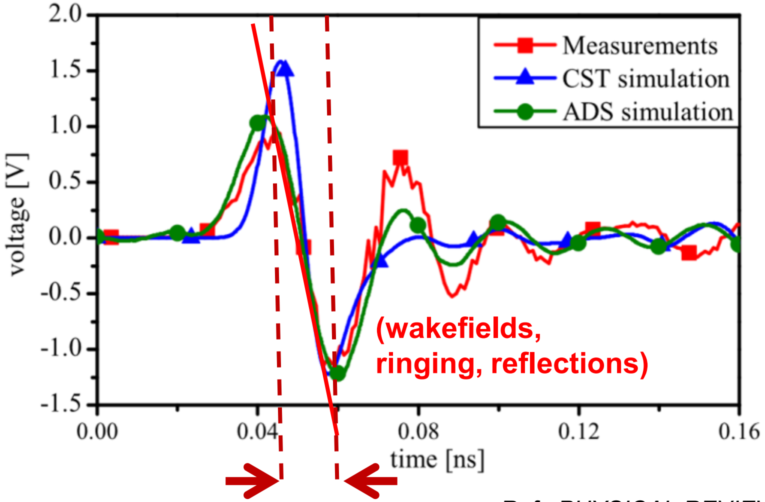


From optical reference:
216MHz rep. rate

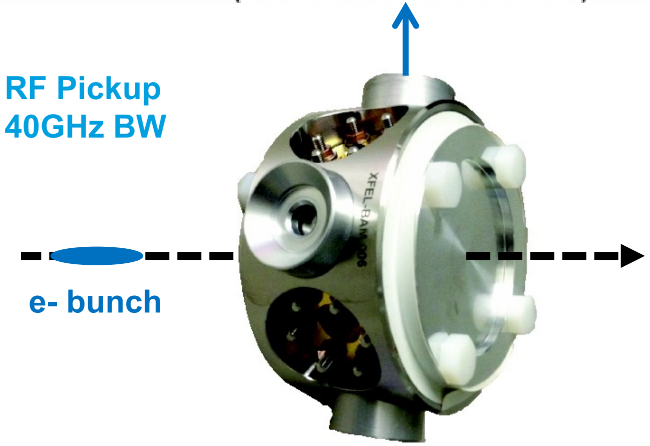
Image: https://www.aerodefensetech.com/component/content/article/adt/tech-briefs/photonics/4855)

RF Signal of 1 bunch

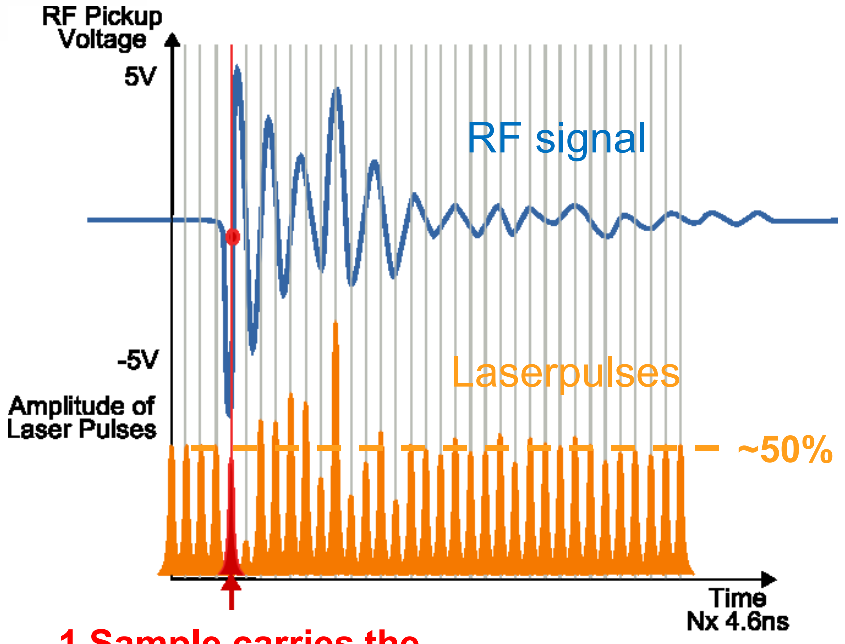
Slope: @20pC > 0.3 mV/fs



RF Pickup
40GHz BW



Encode $t_{arrival}$ → A_{laser}



1 Sample carries the Arrival time information.

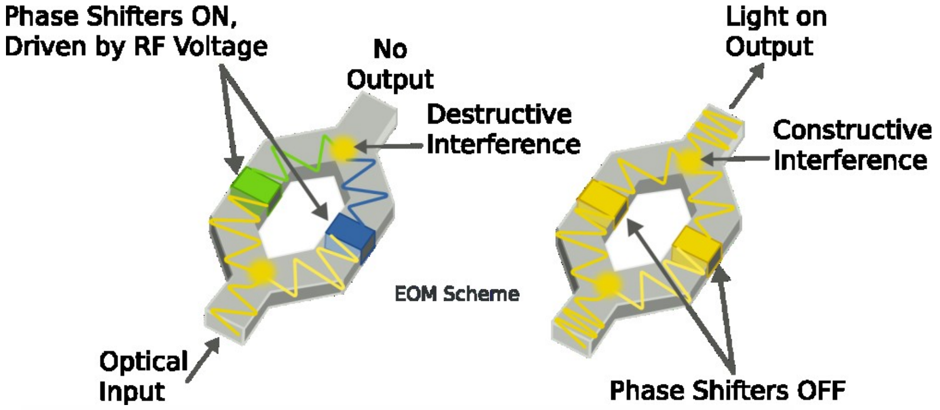
Ref.: PHYSICAL REVIEW STAB, 18, 012801 (2015) A.Angelovski, M.Kuntzsch, M.K.Czwalinna, et al.

BAM: Critical Components

Electro-Optical Modulator

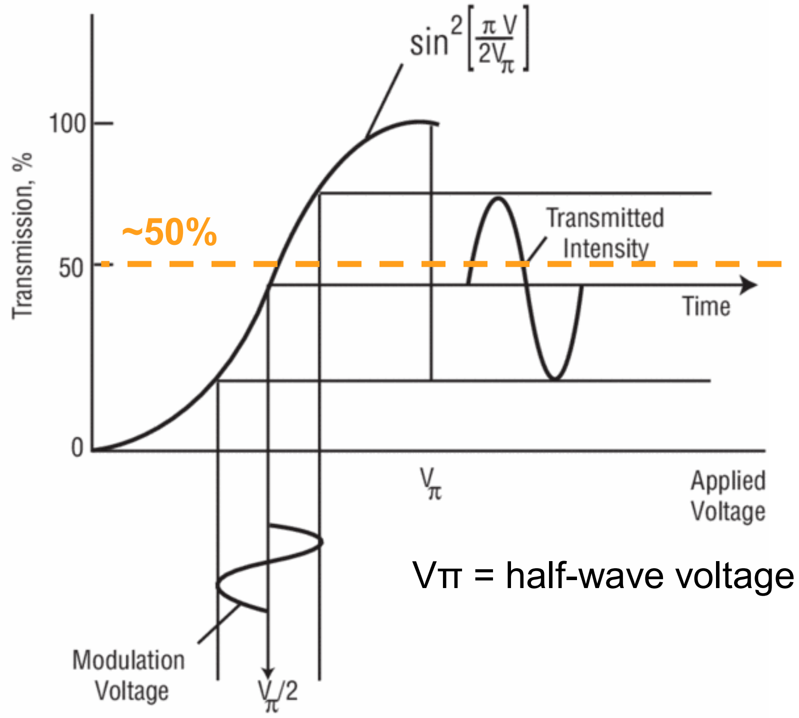
Choice of Electro-Optical Modulator:

Compromise between
RF bandwidth, Vπ & optical properties



Electro-Optic Modulator (commercial) - 33GHz bandwidth
Vπ typically 3.8V to 4.3V

Transfers RF phase changes into amplitude changes of a laser signal.



Vπ = half-wave voltage of EOM

BAM: Critical Components

Electro-Optical Modulator

Choice of Electro-Optical Modulator:

Compromise between
RF bandwidth, Vπ & optical properties

LiNbO3

Good

+/- Vπ 3.8V to 4.5V, typically

+ uniform E/O coefficients in laser bandwidth

+ high damage voltage damage threshold

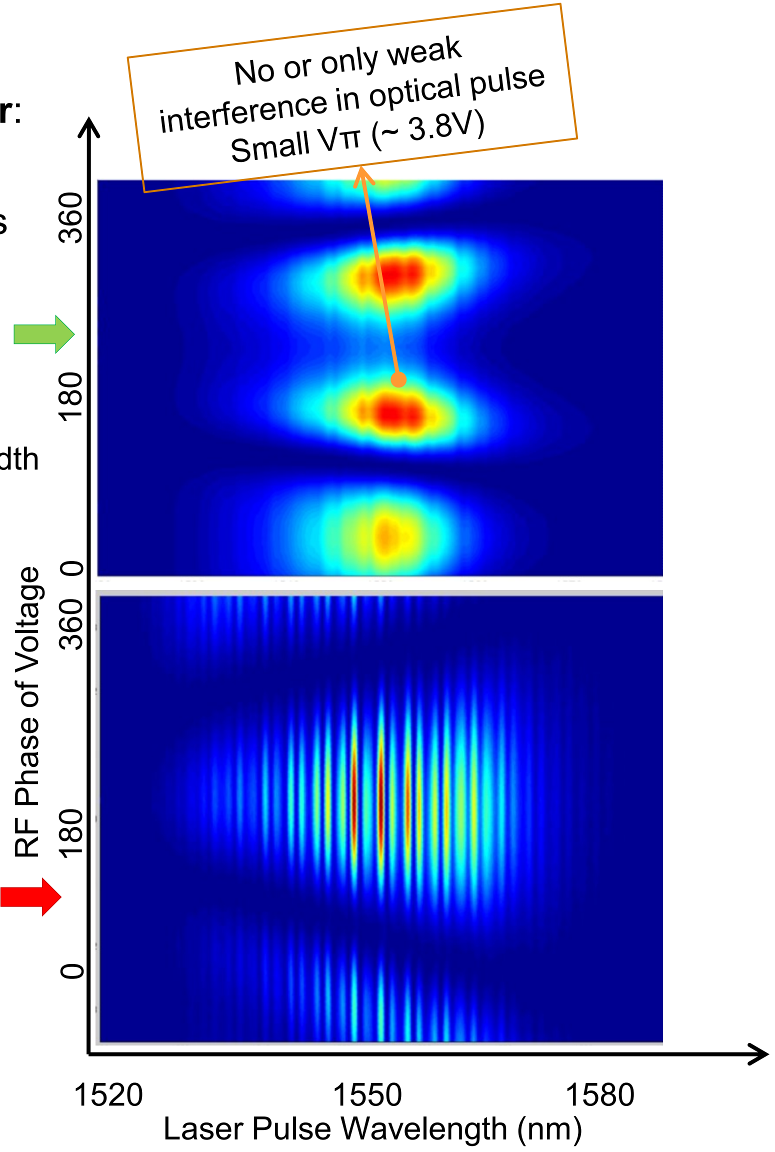
Semiconductors

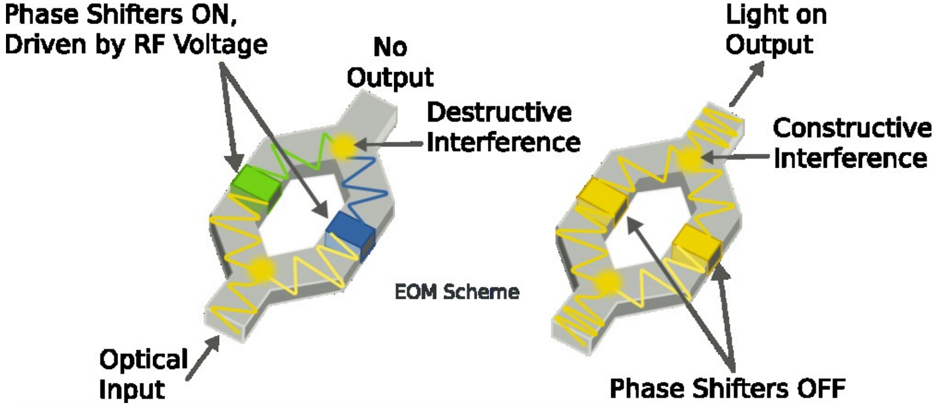
+ Small Vπ

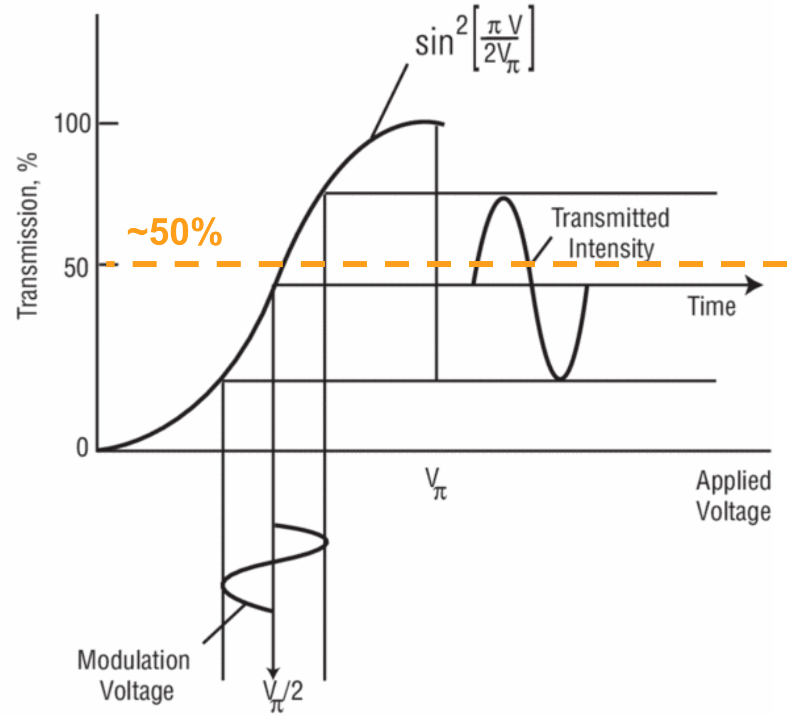
Bad

- Large wavelength dependence of E/O coefficients

- Large wavelength dependence of Vπ

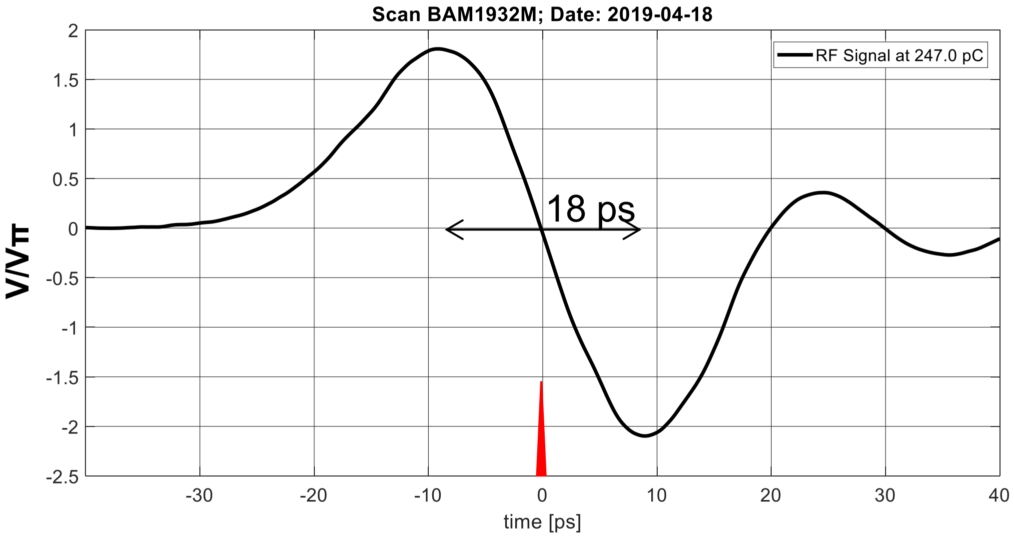


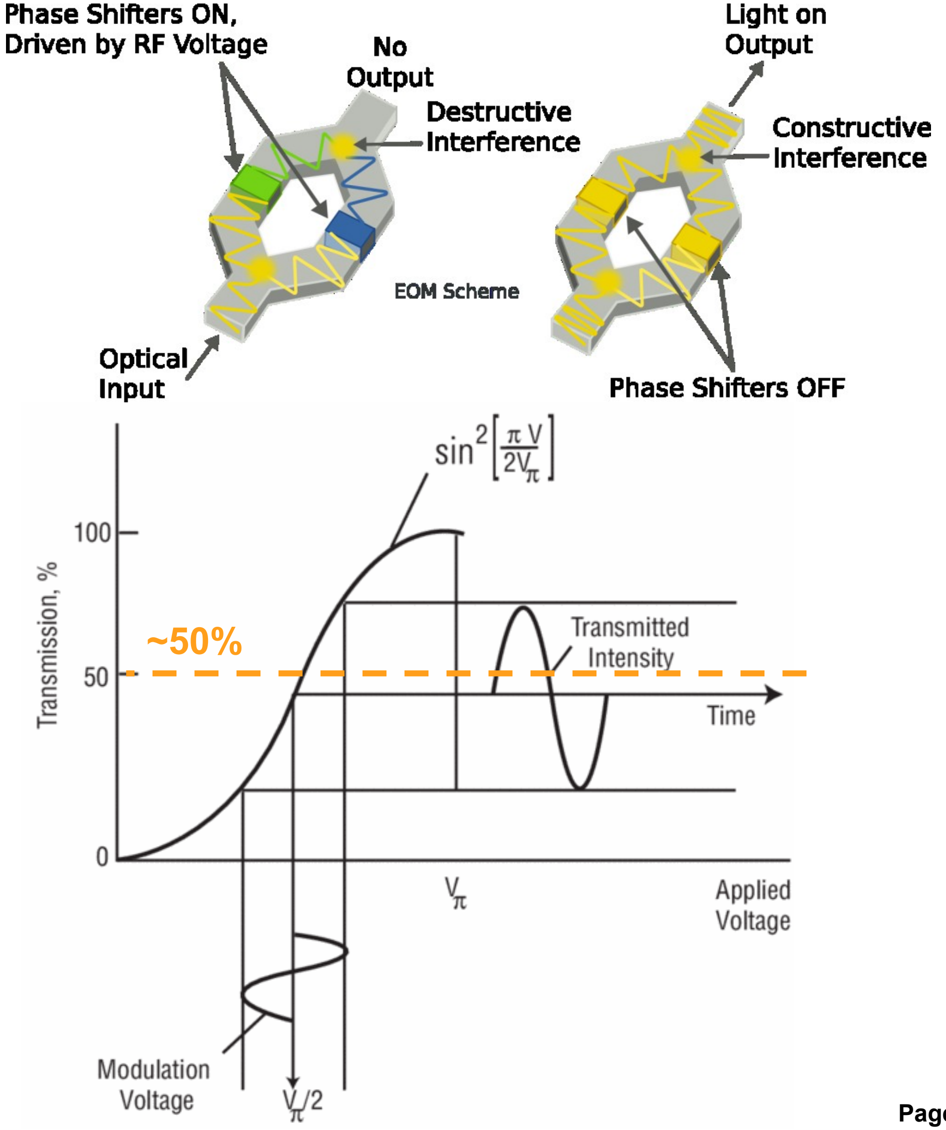




BAM: Critical Components

Electro-Optical Modulation with BAM Signal



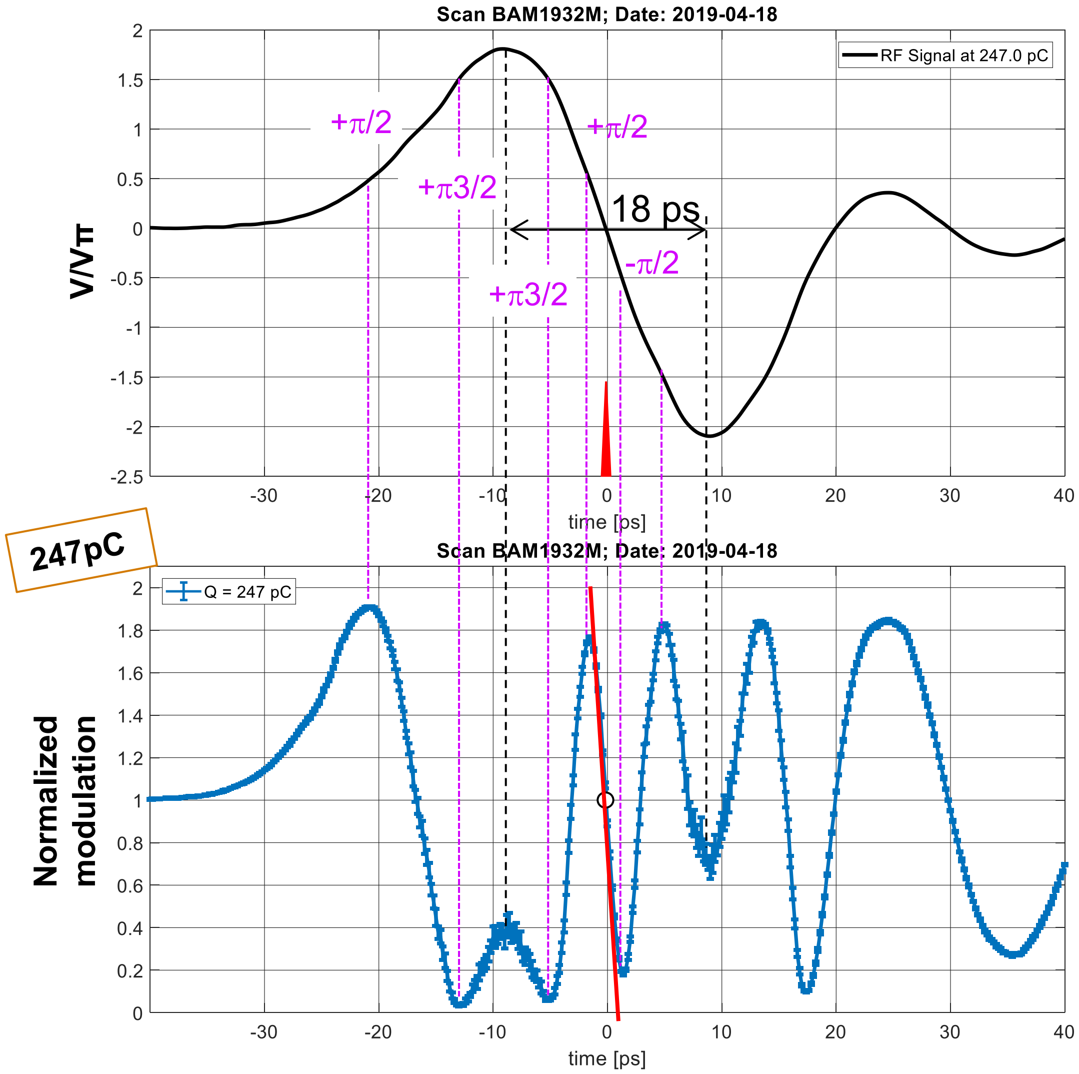


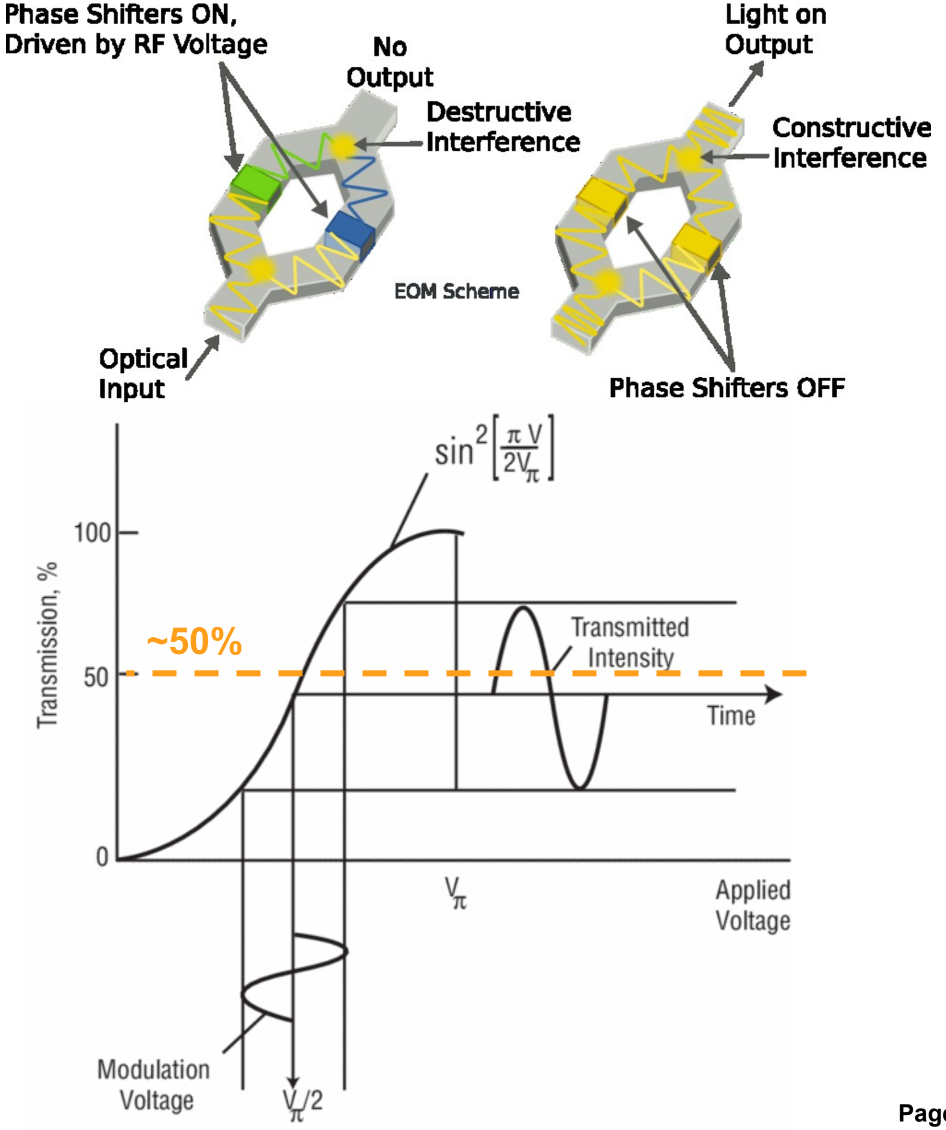
Voltage signal @ 250pC

- Calculated from a small signal response (deconvolution)
- Measurement of modulation @ 6pC depicts actual voltage signal

BAM: Critical Components

Electro-Optical Modulation with BAM Signal

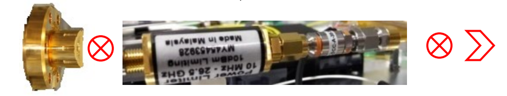


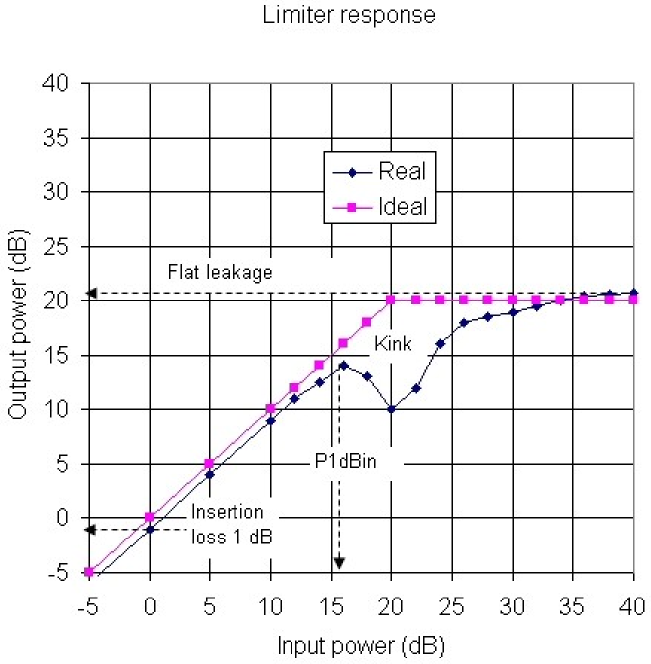


BAM: Critical Components

Nonlinearities in the RF Chain

Pickup 40GHz | **RF Limiter 26GHz, 25dBm** | EOM, 35GHz





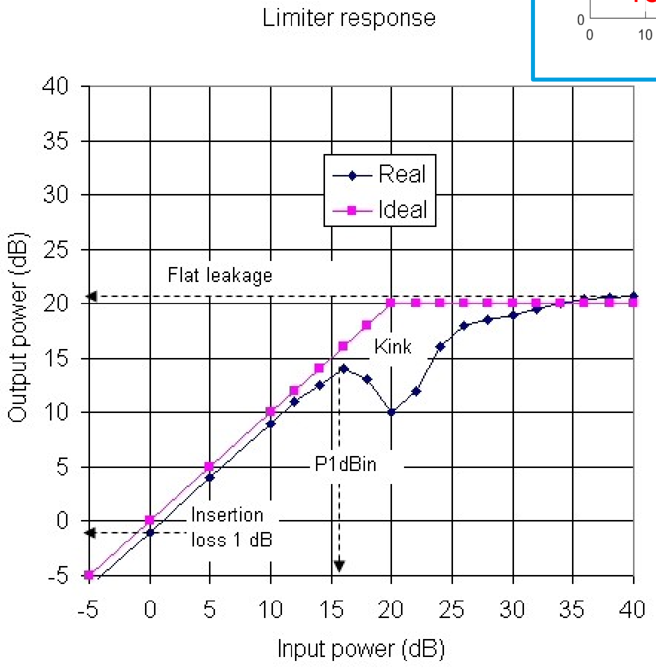
https://www.everythingrf.com/community/what-is-an-rf-limiter

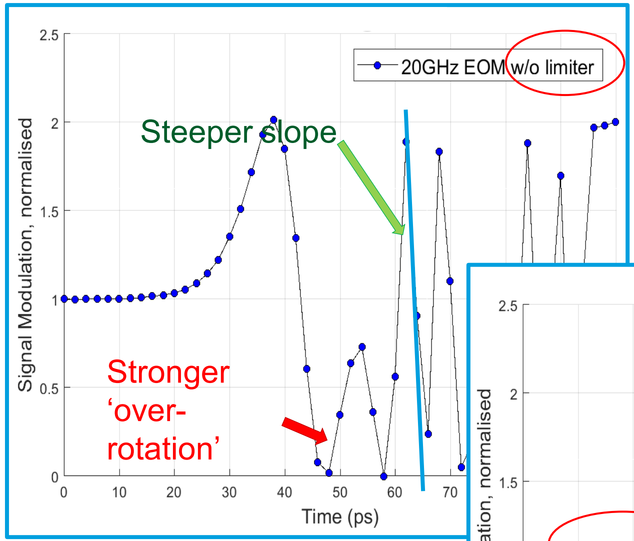
RF Limiter (PIN diode), drawbacks

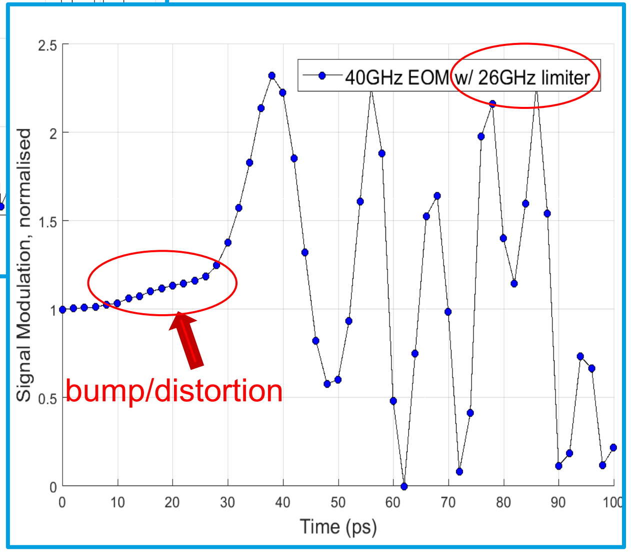
- Semiconductor with AM-to-PM effect (→ falsely detected timing change)
- Signal distortion due to limited response time of EOM
- & Non-Linearity from non-ideal transmission curve

BAM: Critical Components

Nonlinearities in the RF Chain







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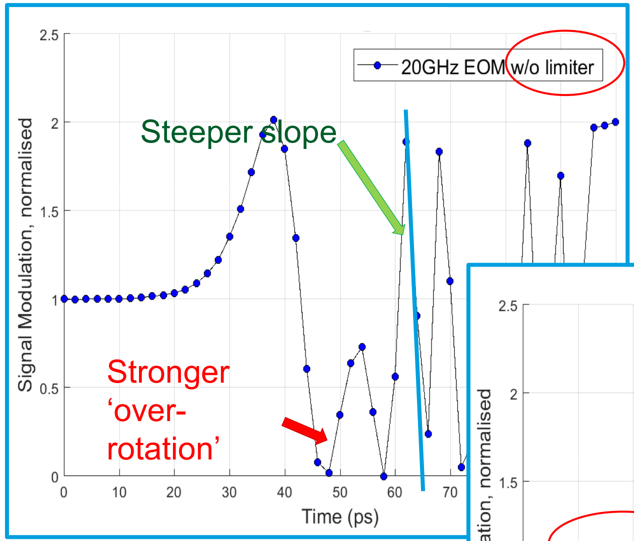
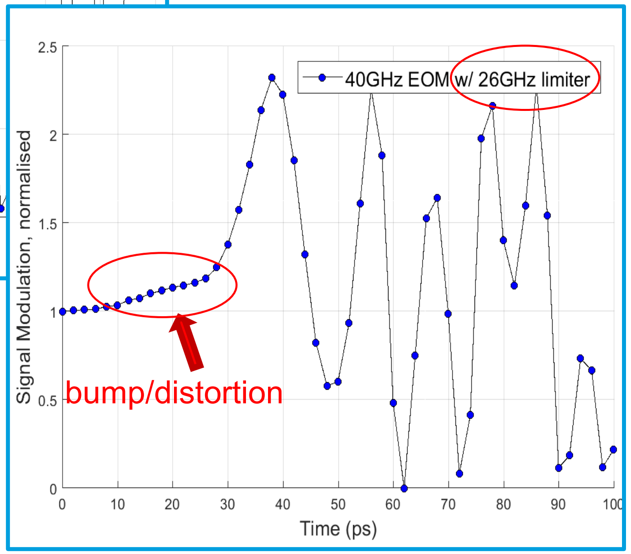
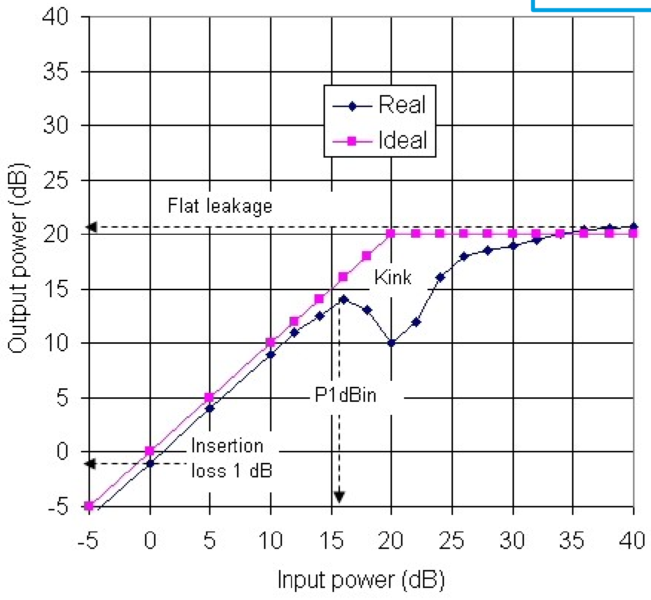
BAM: Critical Components

Nonlinearities in the RF Chain





Limiter response



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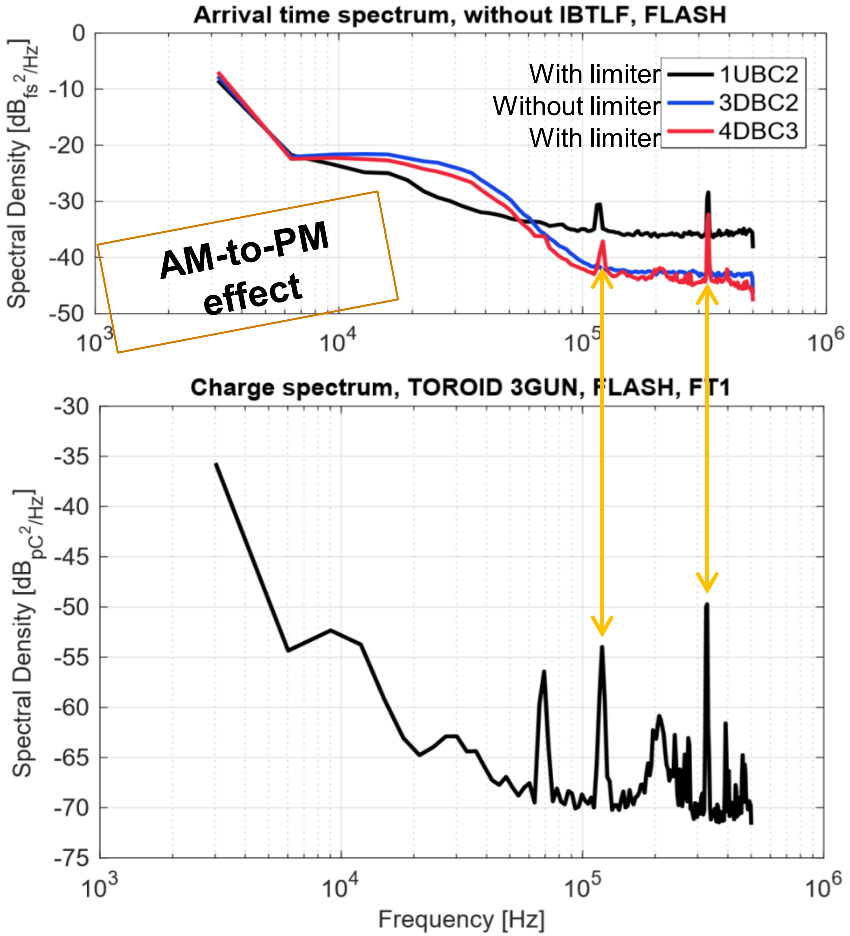
Measurements at FLASH,
With bunch charge noise spectrum



RF Limiter (PIN diode), drawbacks

- Semiconductor with AM-to-PM effect (→ falsely detected timing change)
- Signal distortion due to limited response time of EOM
- & Non-Linearity from non-ideal transmission curve

BAM: Signal Scan

RF & EO part optimised

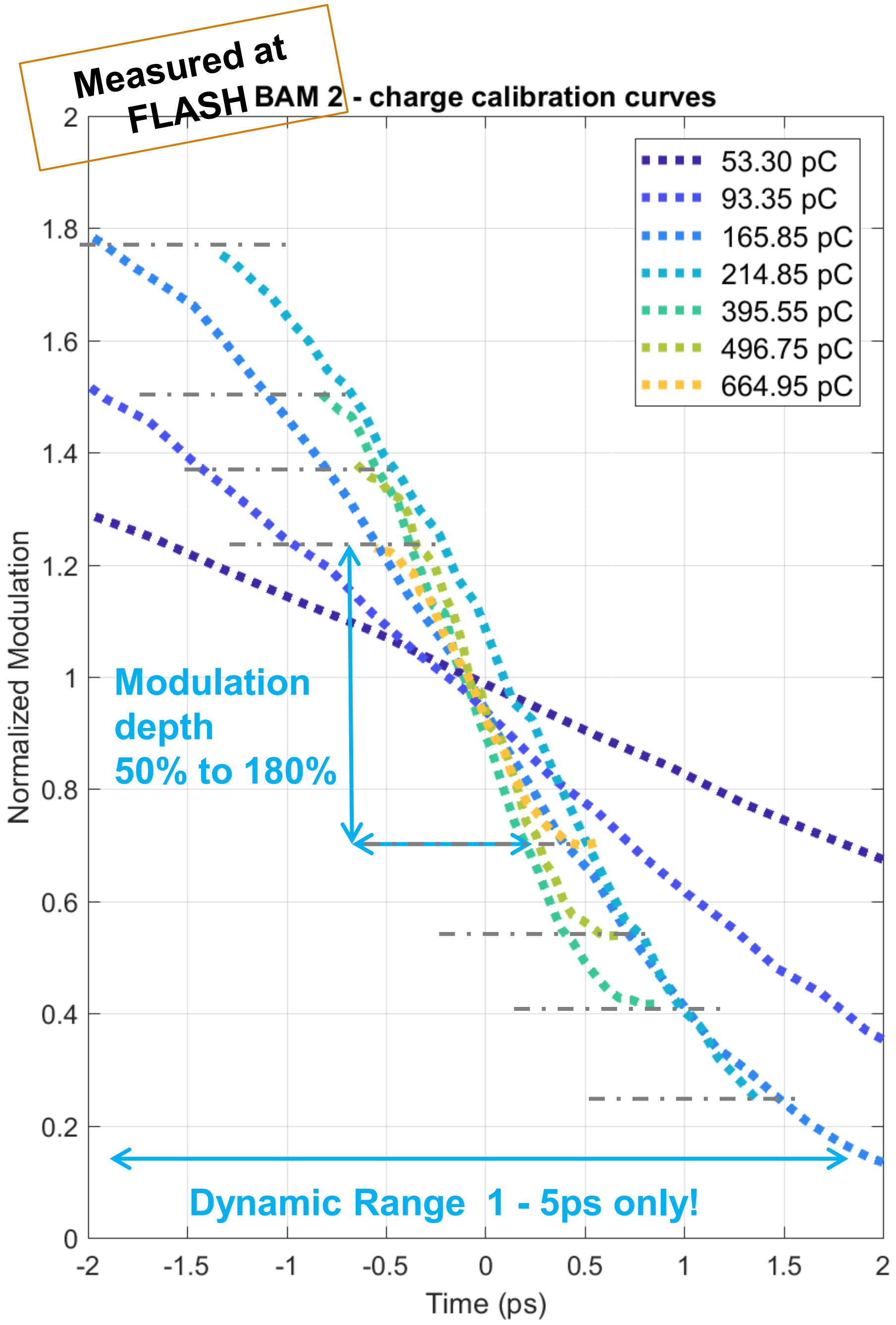
✓ **RF Limiter removed**

✓ No distortions in modulation signal anymore

✓ With larger the voltage increasing slope steepness

But, with larger voltage,

- Decreasing dynamic range
- Decreasing modulation depth:
  - ❑ Finite laser pulse width (1.5s to 2ps)
  - ❑ Phase slippage between RF and laser group velocity

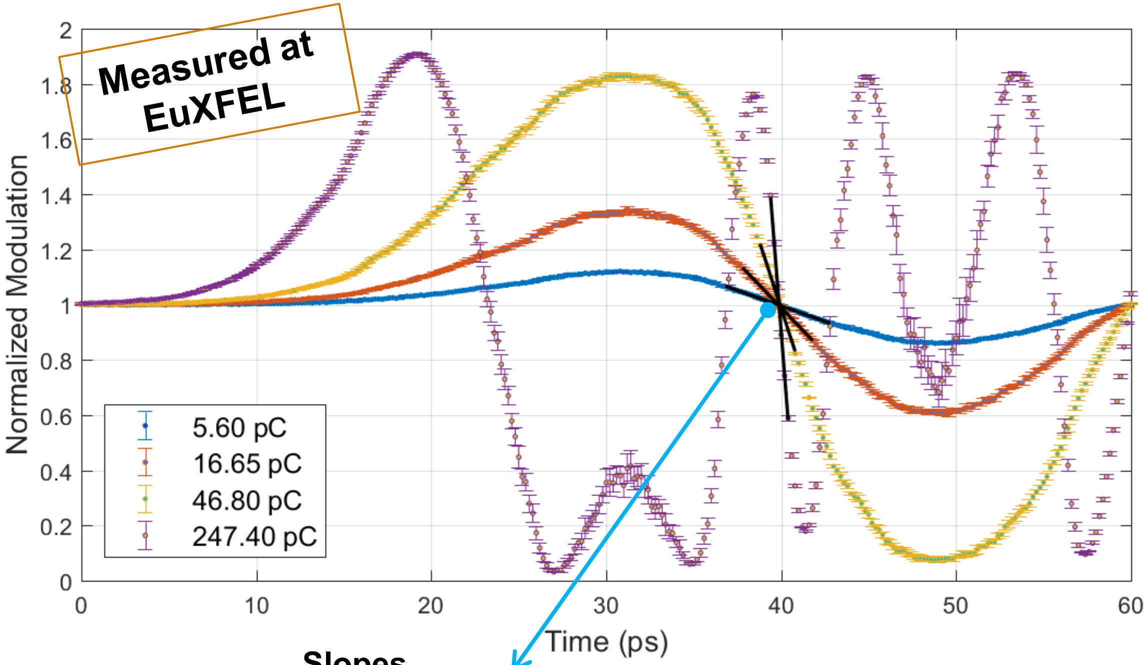


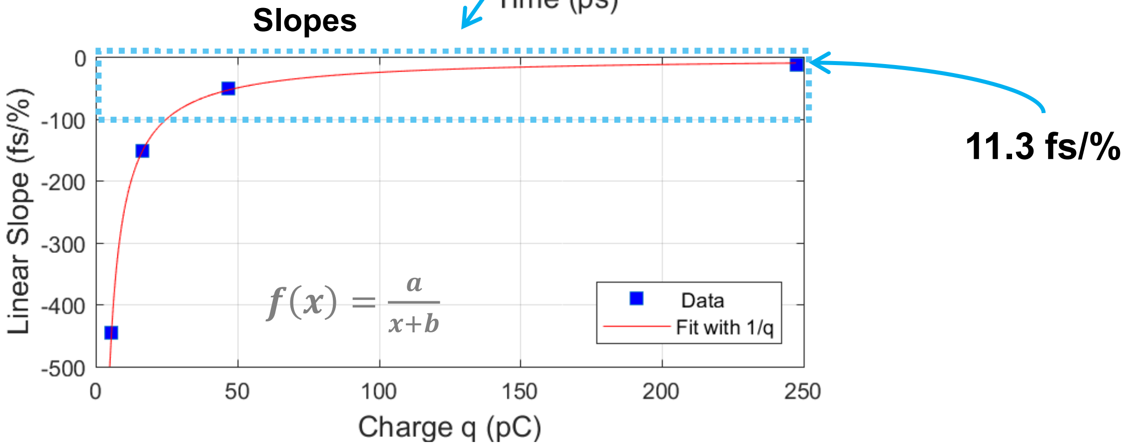
Technical Concept

- **Performance Evaluation**

BAM: Signal Scan

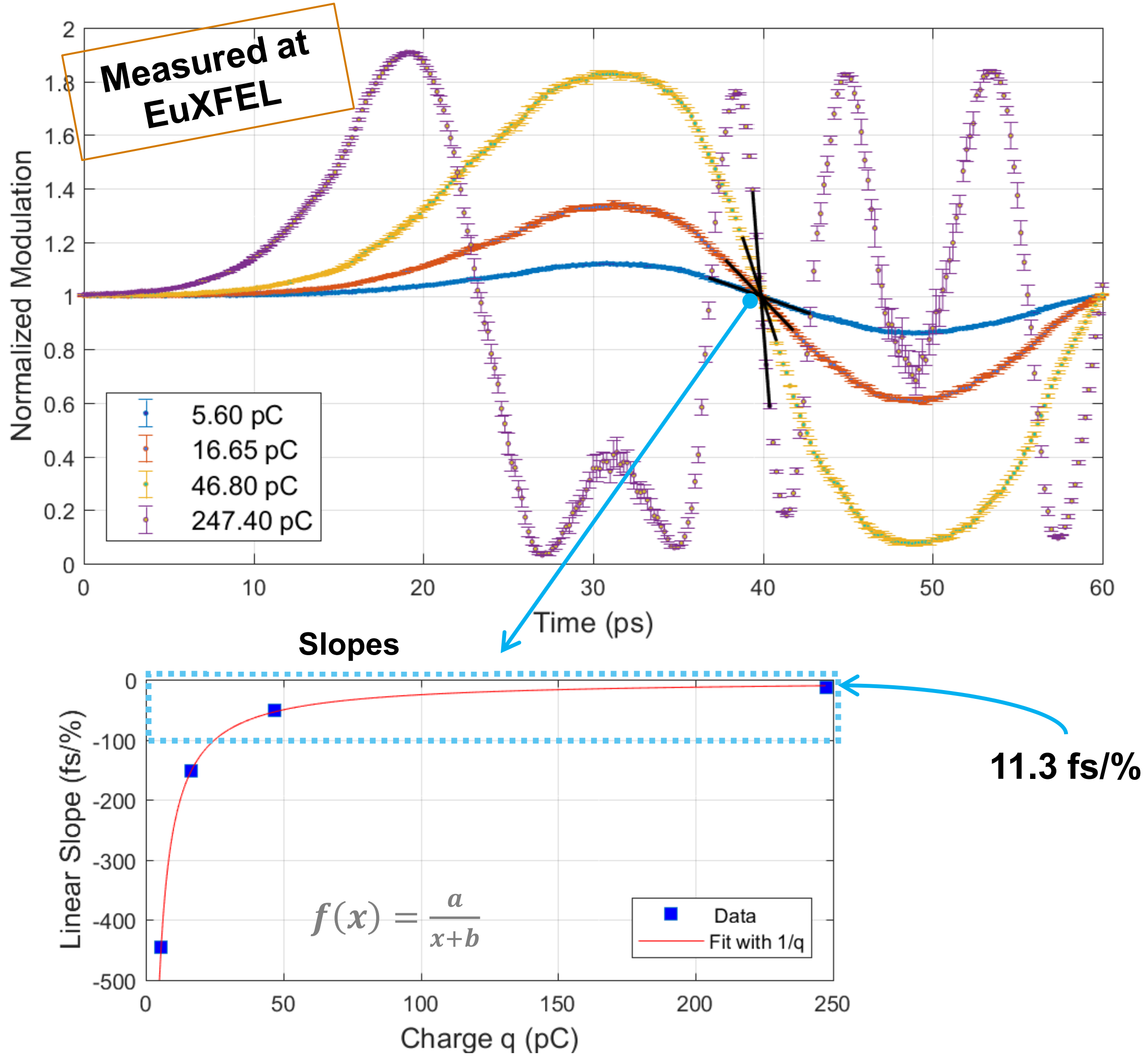
Sensitivity of arrival time detection & its charge calibration



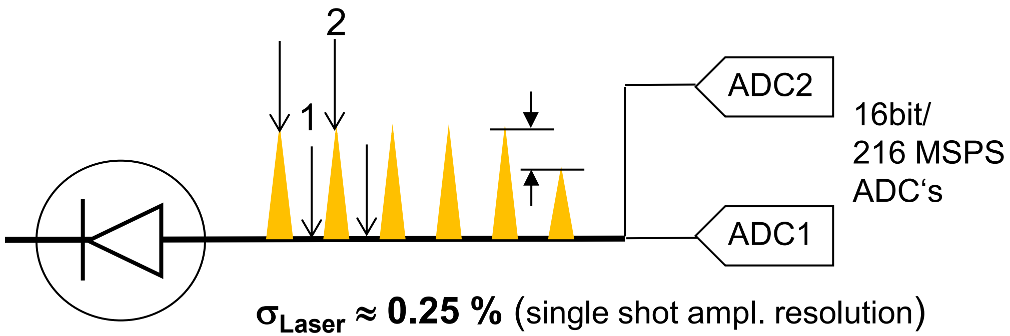


BAM: Signal Scan

Sensitivity of arrival time detection & its charge calibration



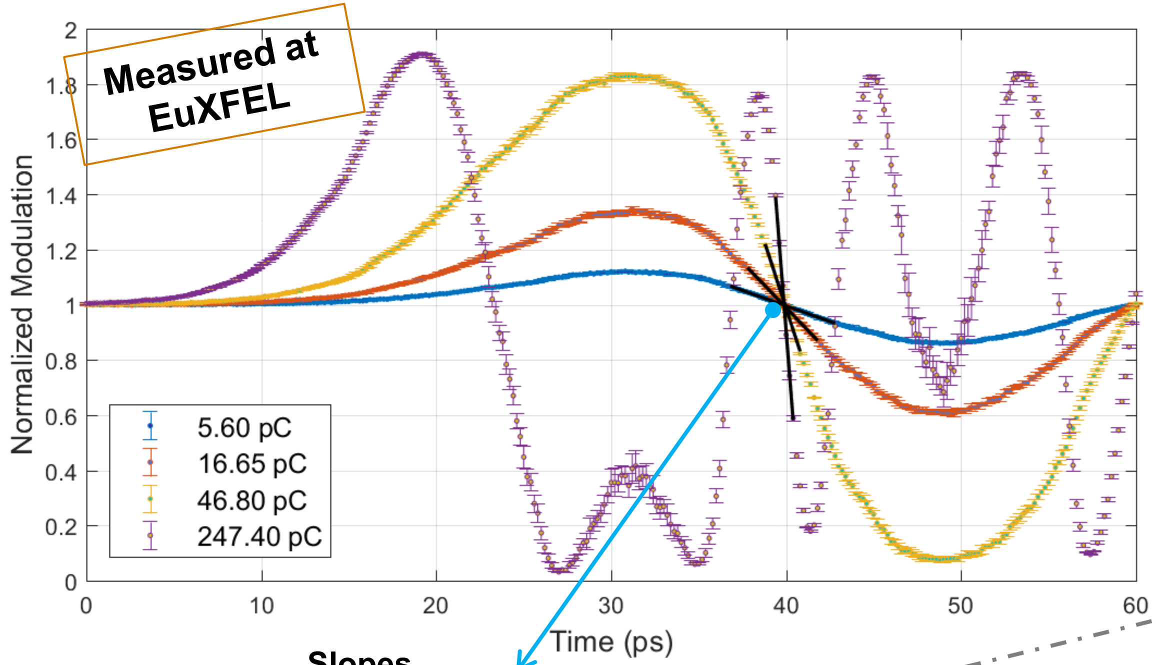
Laser pulse train readout & procession in FPGA (high-pass filter scheme).

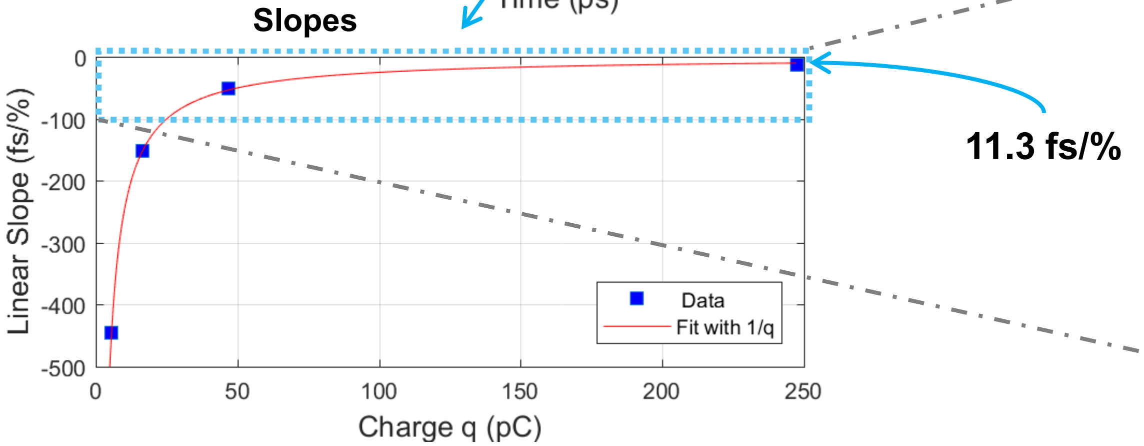


$\sigma_{Laser} \approx$ **0.25 %** (single shot ampl. resolution)

BAM: Signal Scan

Sensitivity of arrival time detection & its charge calibration





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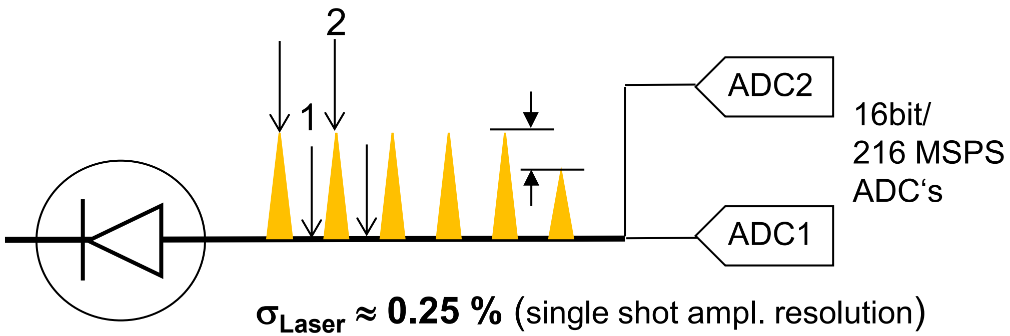
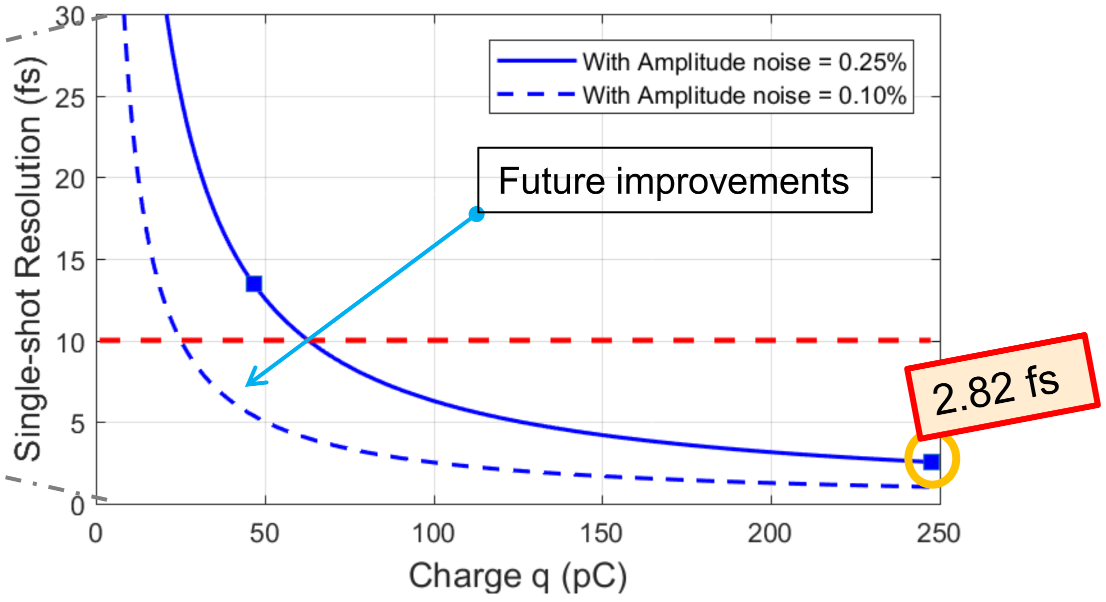


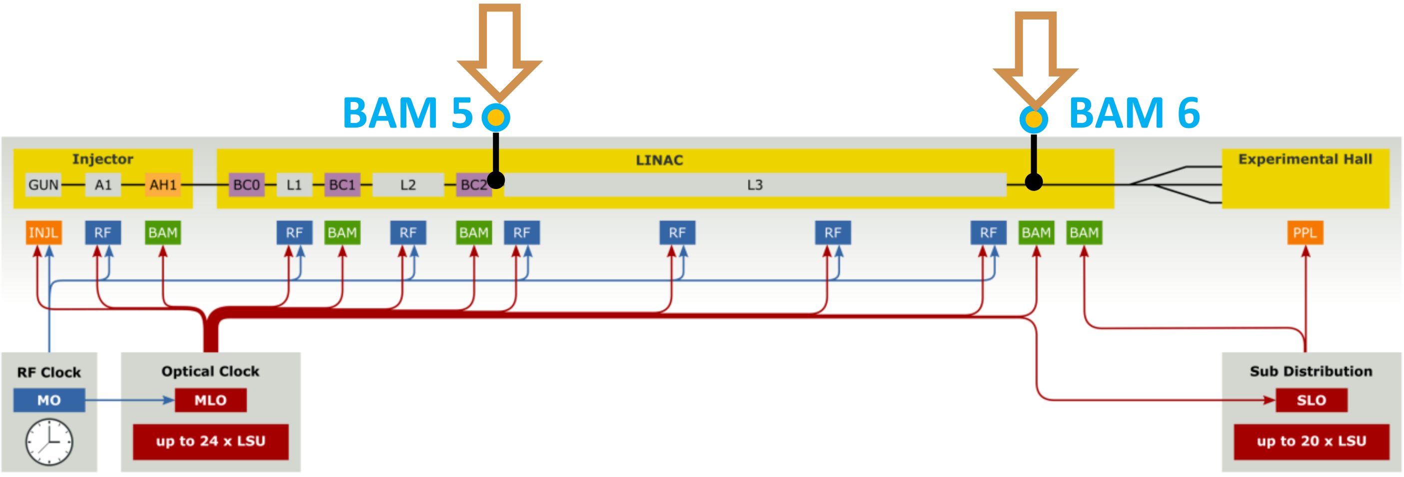
$\sigma_{Laser} \approx$ **0.25 %** (single shot ampl. resolution)

Resolution: σ_t = slope · $\sigma_{Laser} \approx$ 2.82 fs



BAM: Signal Scan

Sensitivity of arrival time detection & its charge calibration



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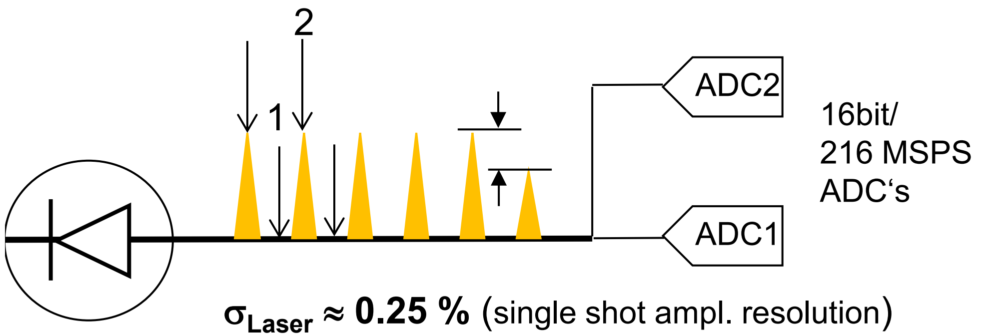

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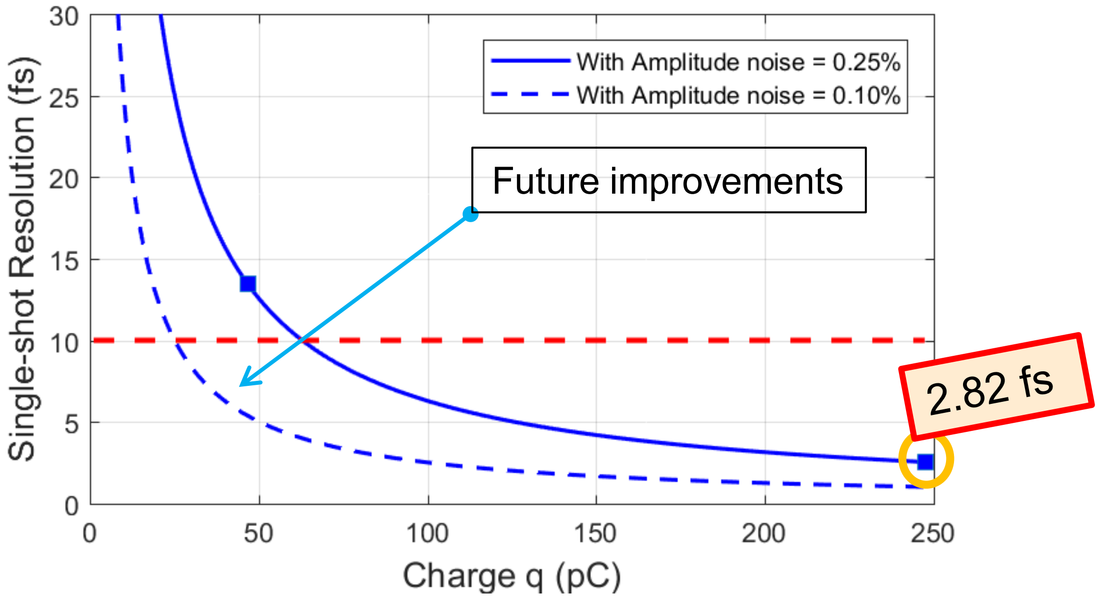

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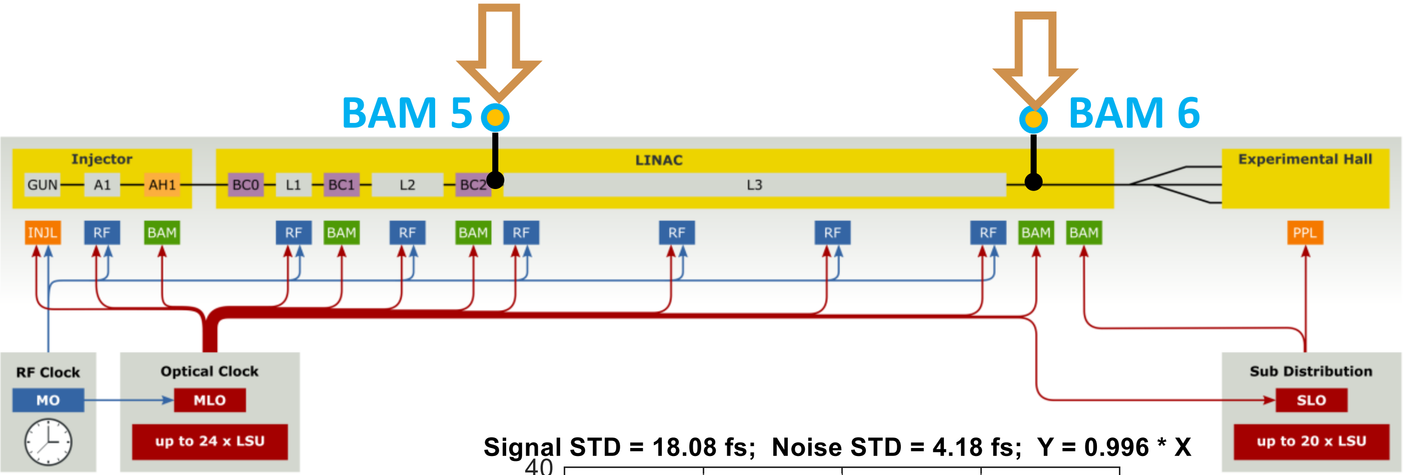
Sensitivity of arrival time detection & its charge calibration



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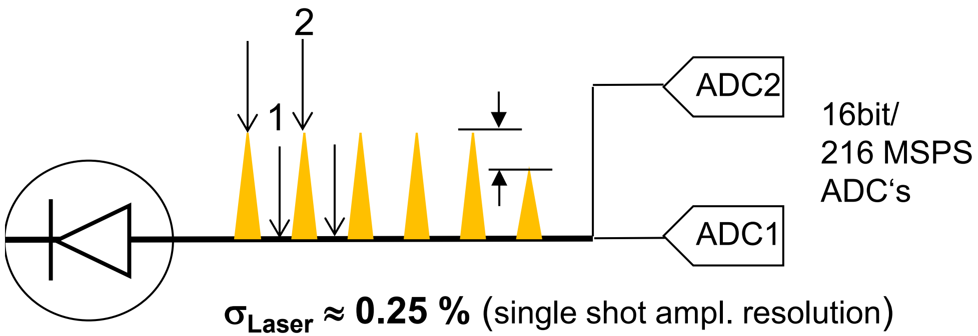

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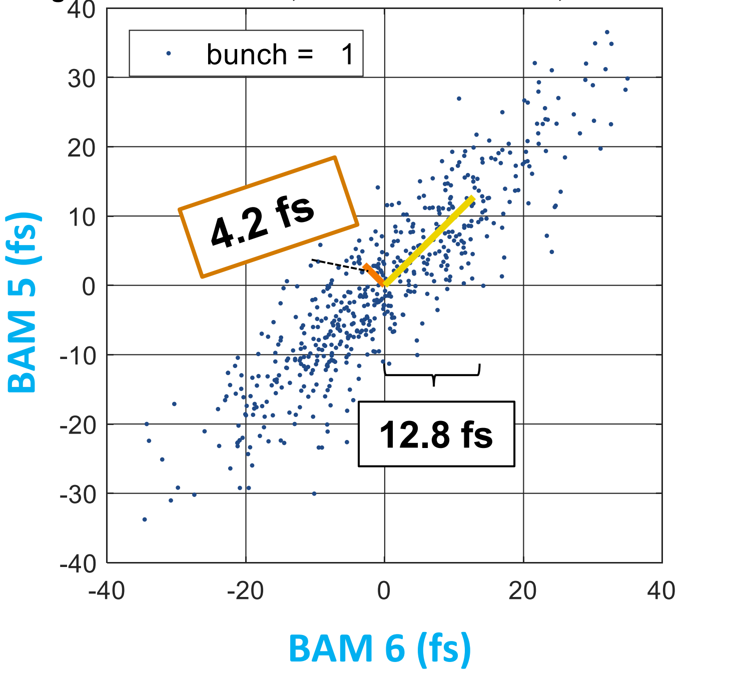
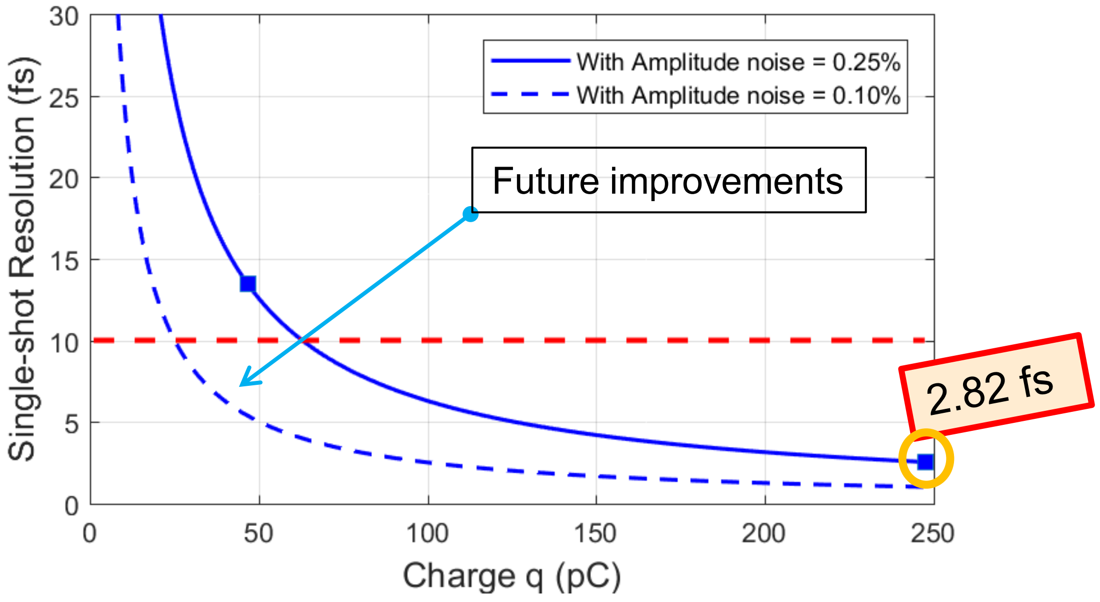
Resolution: σ_t = slope · $\sigma_{Laser} \approx 2.82$ fs

Single-bunch Correlation

600 pulses (1min.)





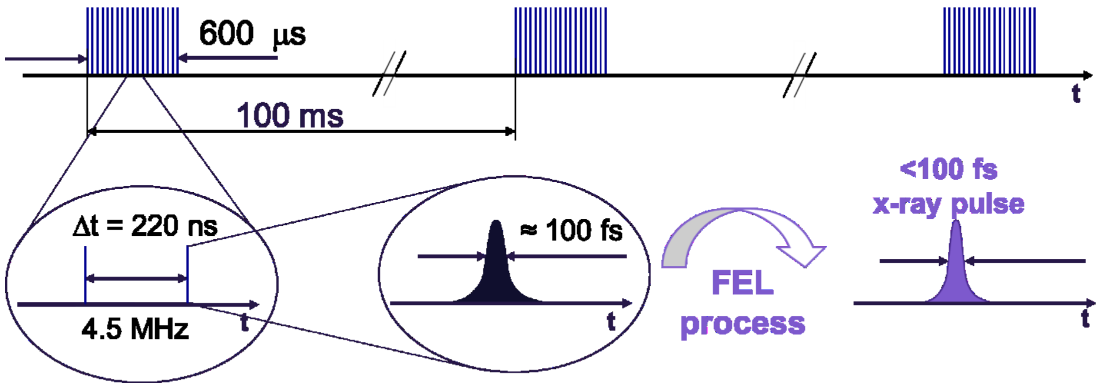
$\frac{1}{\sqrt{2}} \cdot \sigma_t \approx 2.9$ fs

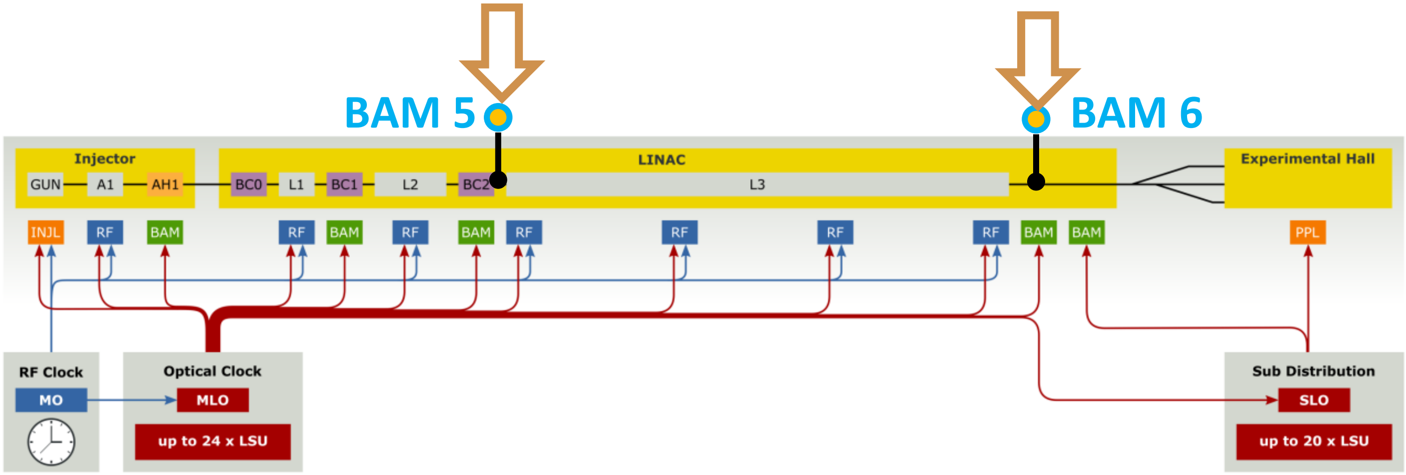
First Results

- Accuracy of Arrival Time Measurements

BAM: Measurement Accuracy

Whole detection chain from Optical Synchronisation to BAM system



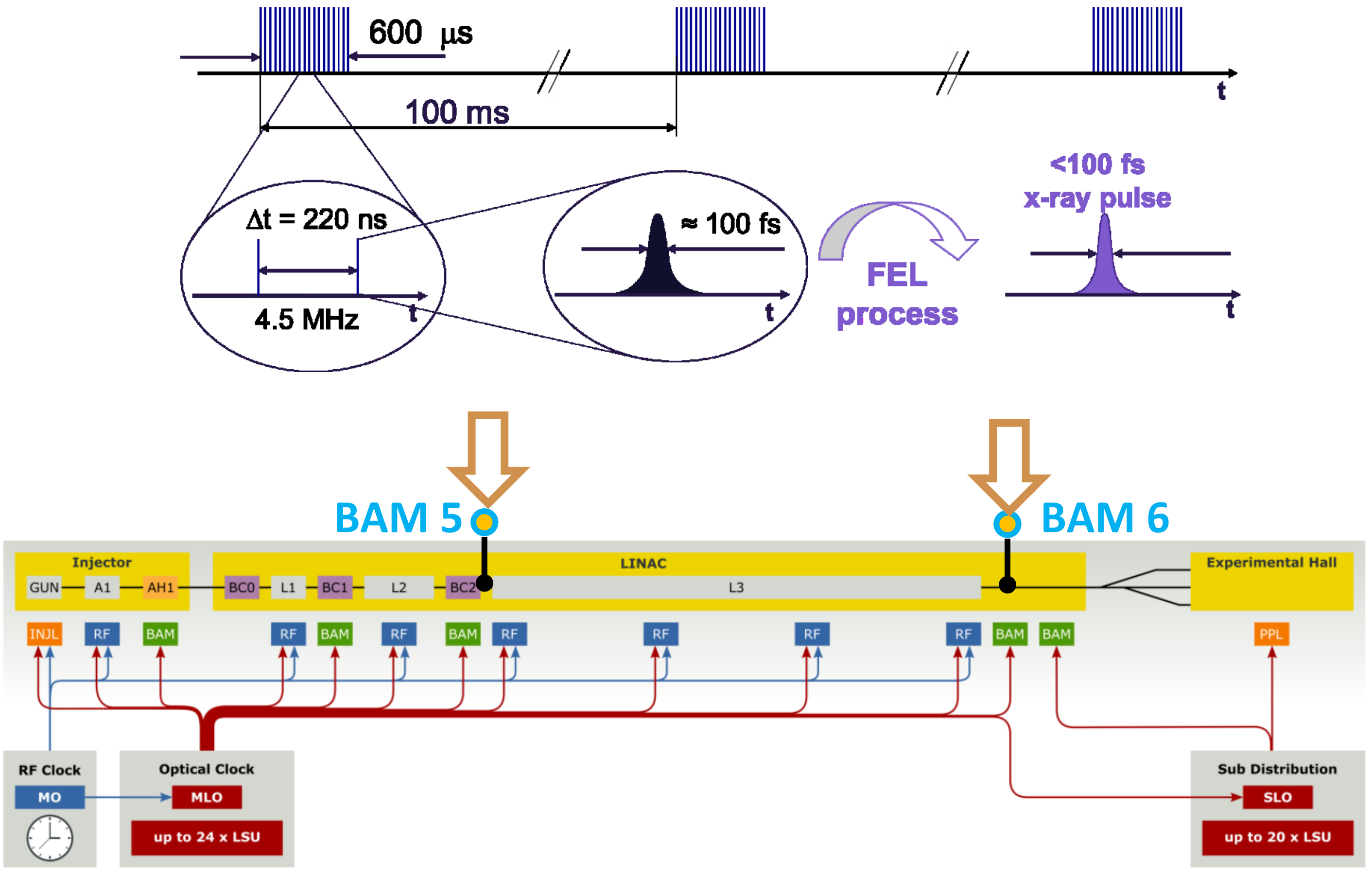


Pulsed operation (RF ~ 1ms, 10Hz)

- 27000 / sec
- e- bunches 220ns spaced
- 100ms separation

BAM: Measurement Accuracy

Whole detection chain from Optical Synchronisation to BAM system

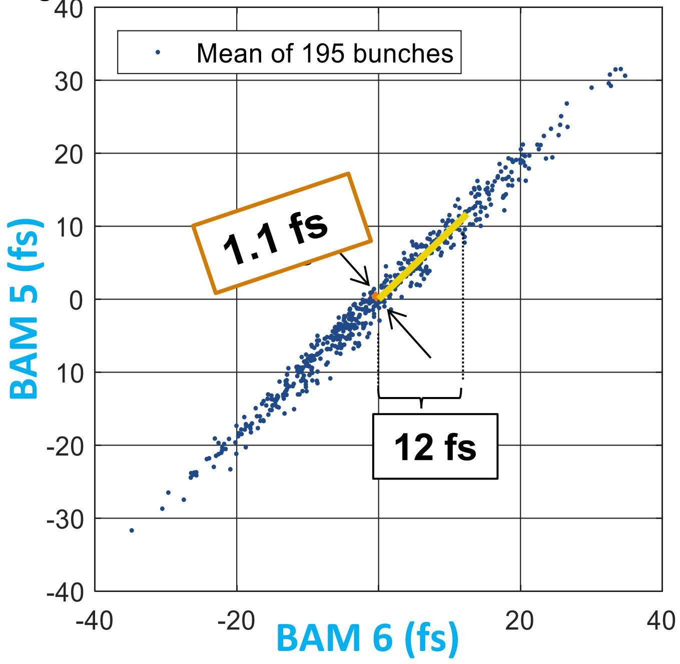


➔ **Chain:** MLO → Distr → Link → BAM $< \frac{1}{\sqrt{2}} \cdot \sigma_t \approx$ **0.8 fs**

Pulsed operation (RF ~ 1ms, 10Hz)

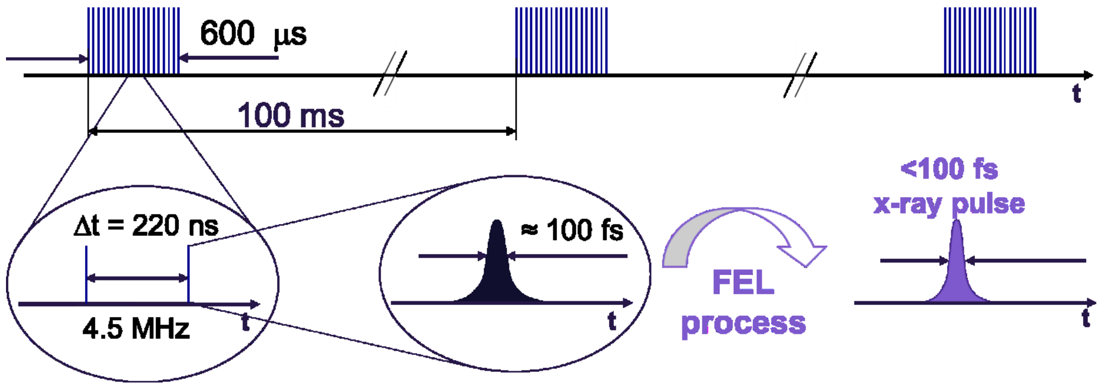
- ❑ 27000 / sec
- ❑ e- bunches 220ns spaced
- ❑ 100ms separation

Mean value over 200 bunches per train, 600 trains (1min.)

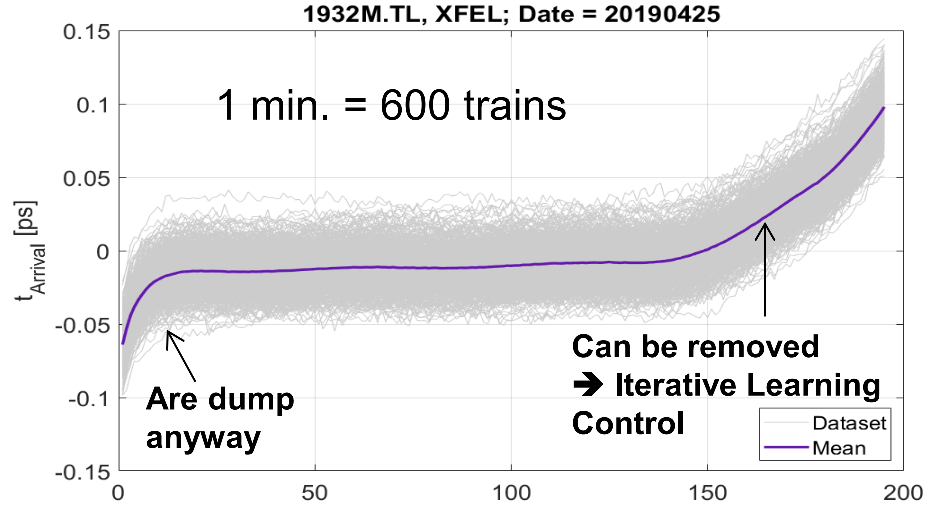


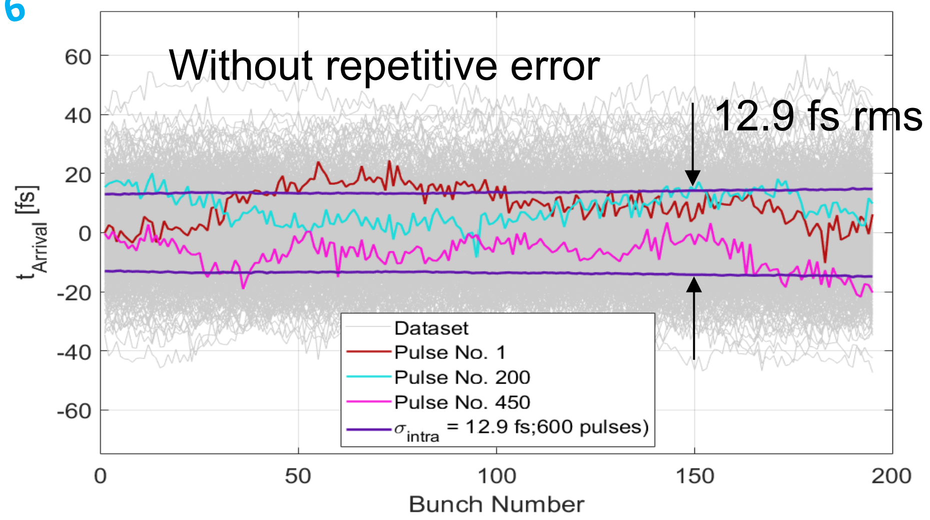
Residual arrival time jitter

… the road to a fast feedback correction



@BAM 6





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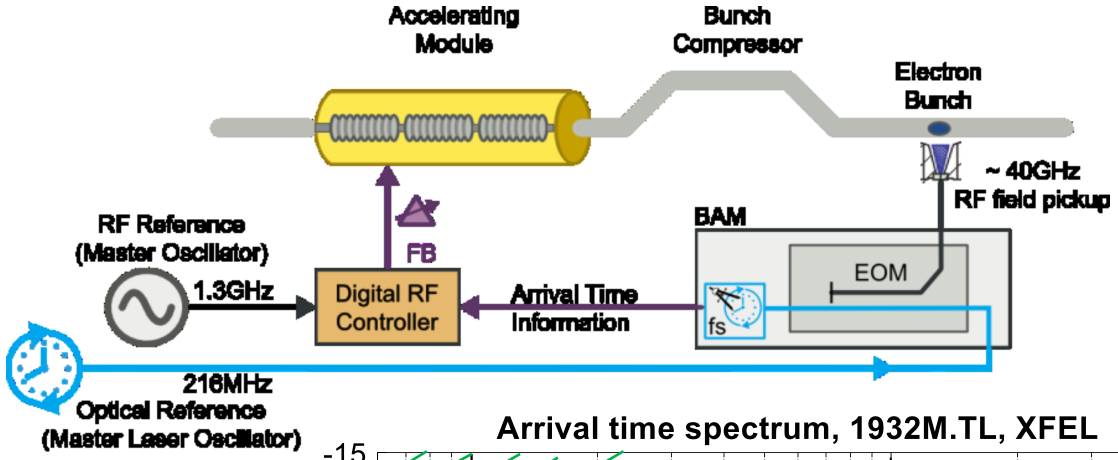

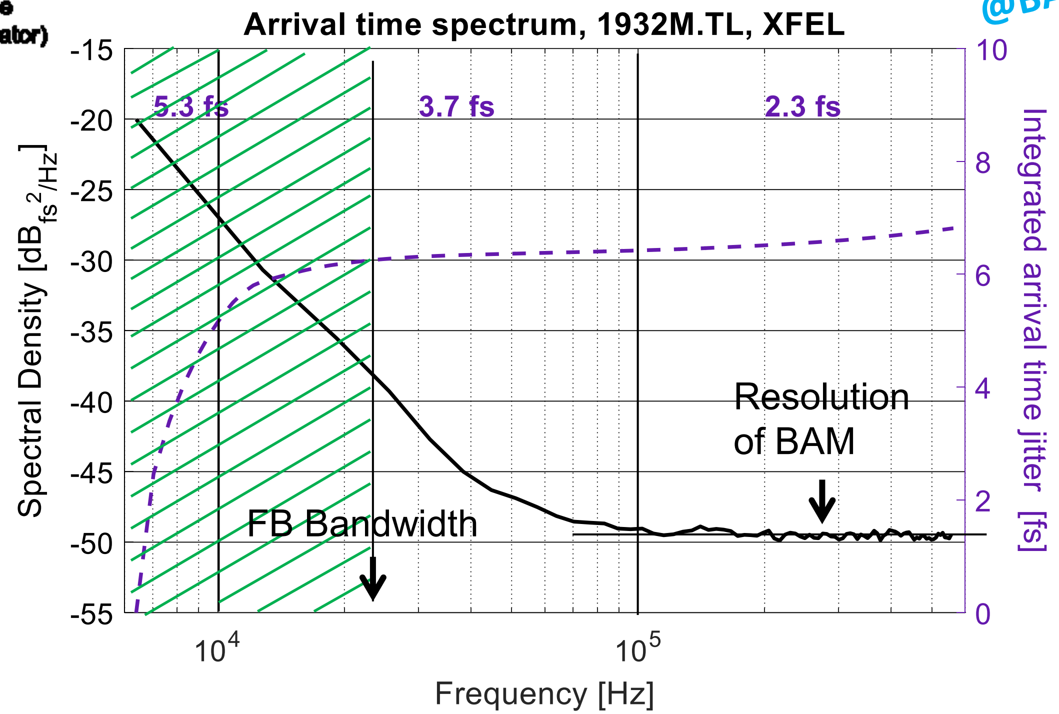

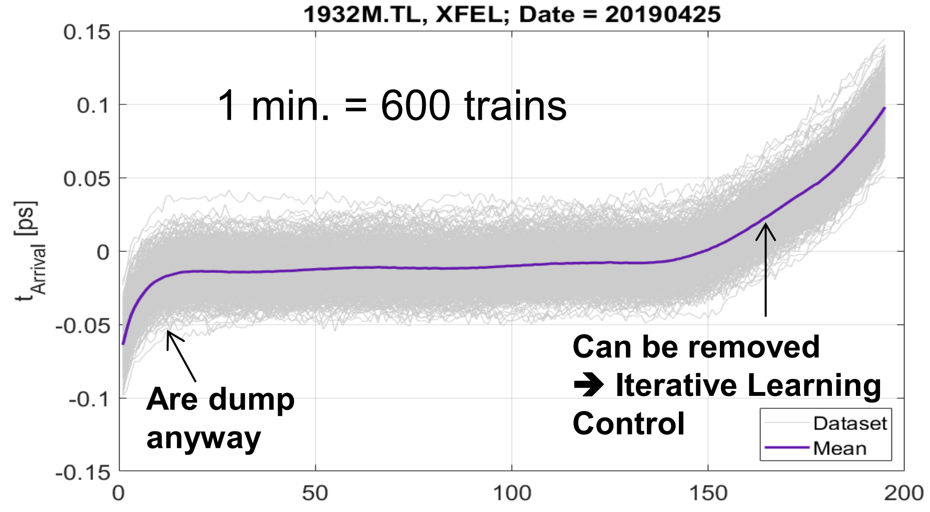

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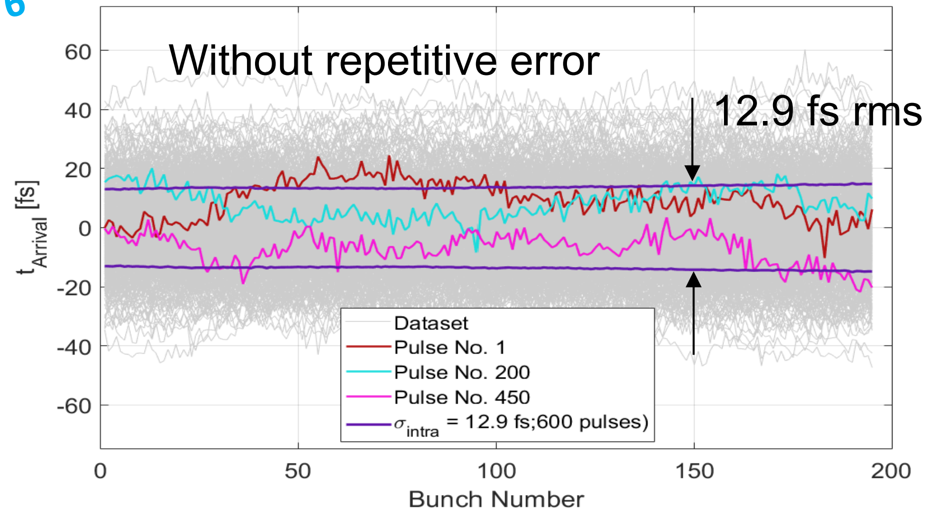


Dominated by low frequency perturbations

➔ Can be removed by fast intra-train feedback

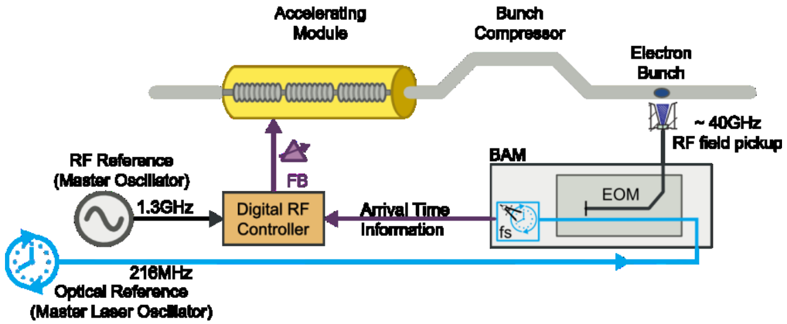
➔ σ_t < 4 fs rms seems to be feasible

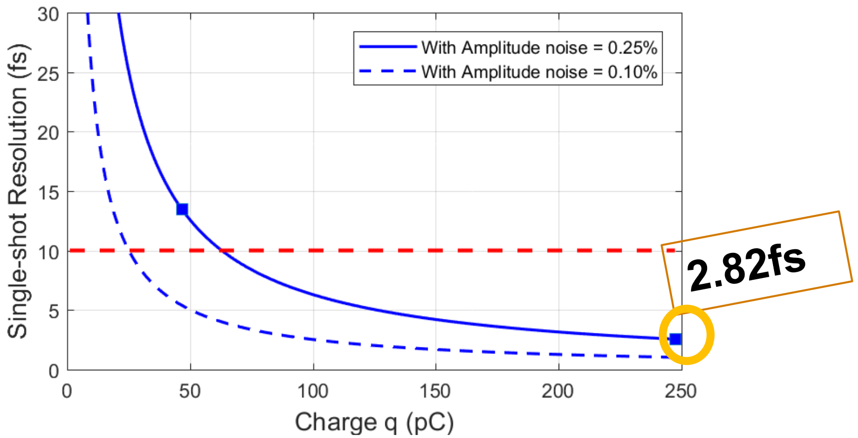
Summary & Outlook

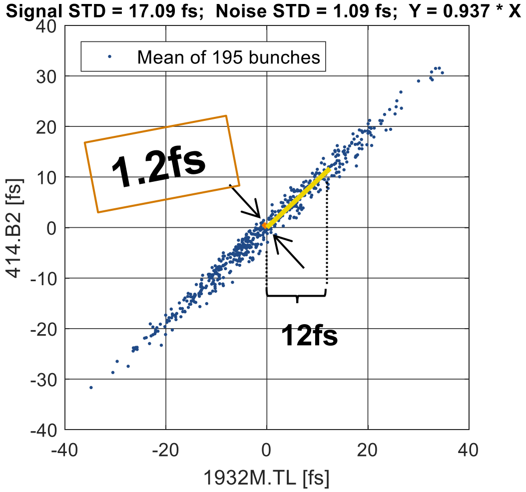
Summary & Outlook

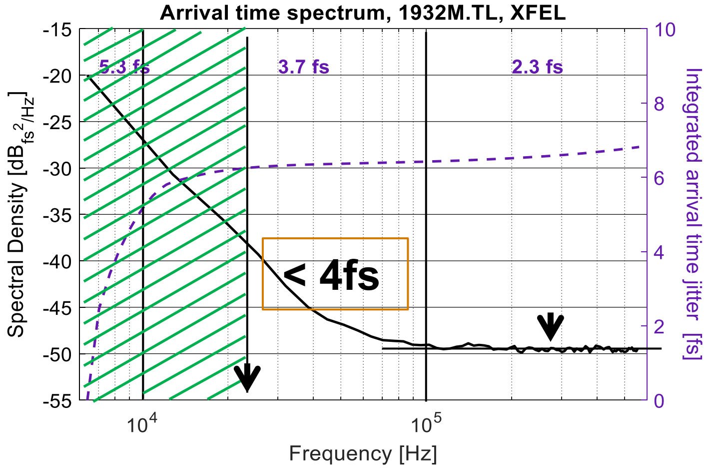
High Precision Arrival Time Measurement → Longitudinal Intra-Train Feedback as Perspective

- BAMs with single shot resolution of <3fs @250pC
- Correlation between equivalent BAMs → Synchronisation level ≈ 1.2fs rms
- Suppressing low frequency noise up to 25kHz from pulse to pulse jitter using an intra-train beam-based FB to reach 4fs rms stability is within realms of possibility









Summary

Thank you for your attention !

Involved people :

(without any claim to completeness)

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