Laser optical clocks and accelerator timing systems

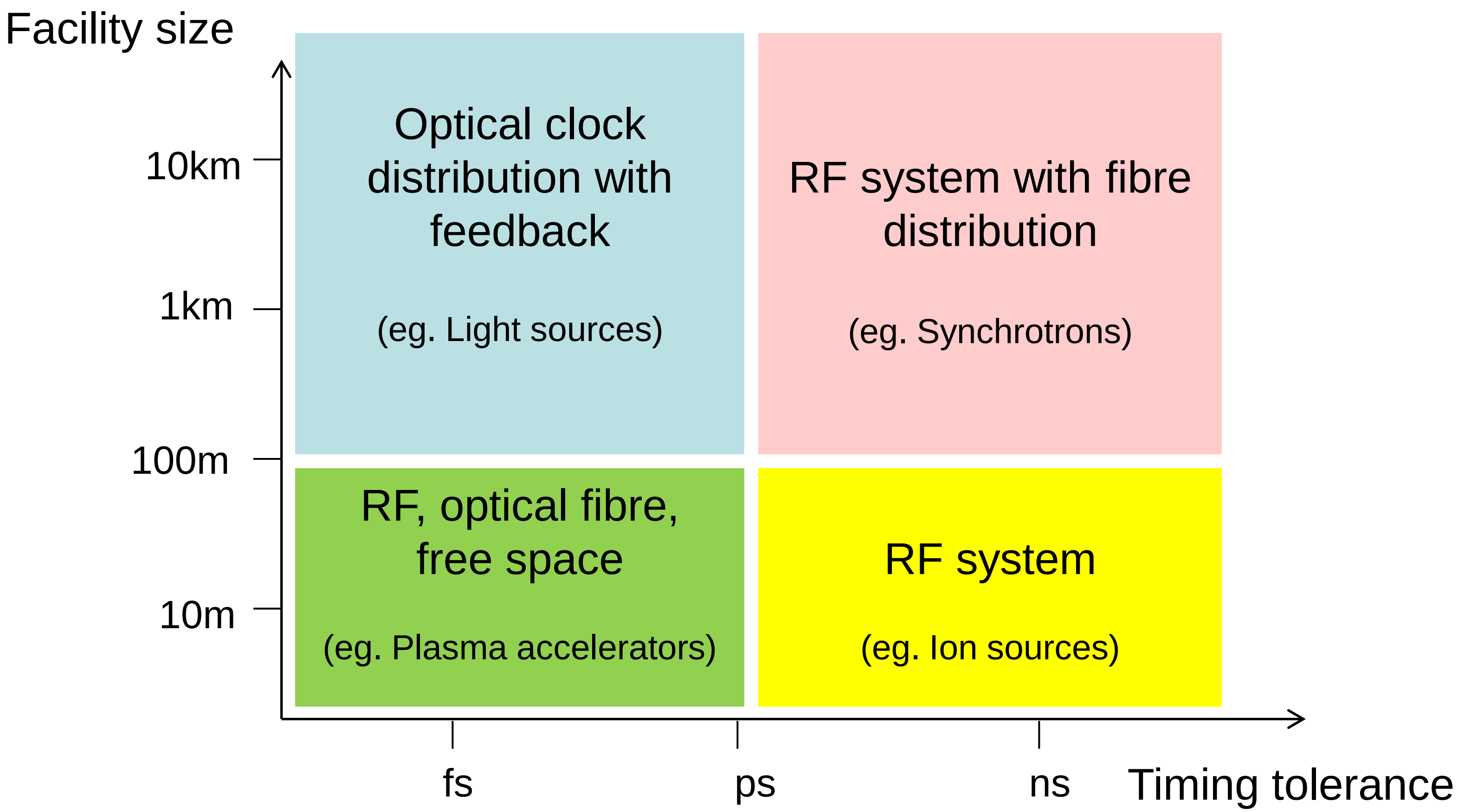
Trina T. Thakker

STFC, Daresbury, UK

Overview

- Timing requirements for accelerators
- ‘Conventional’ RF timing systems
- Going optical
  - The pulsed approach
  - The CW approach
- Challenges for the future...

Timing requirements



Optical clock distribution with feedback

(eg. Light sources)

RF system with fibre distribution

(eg. Synchrotrons)

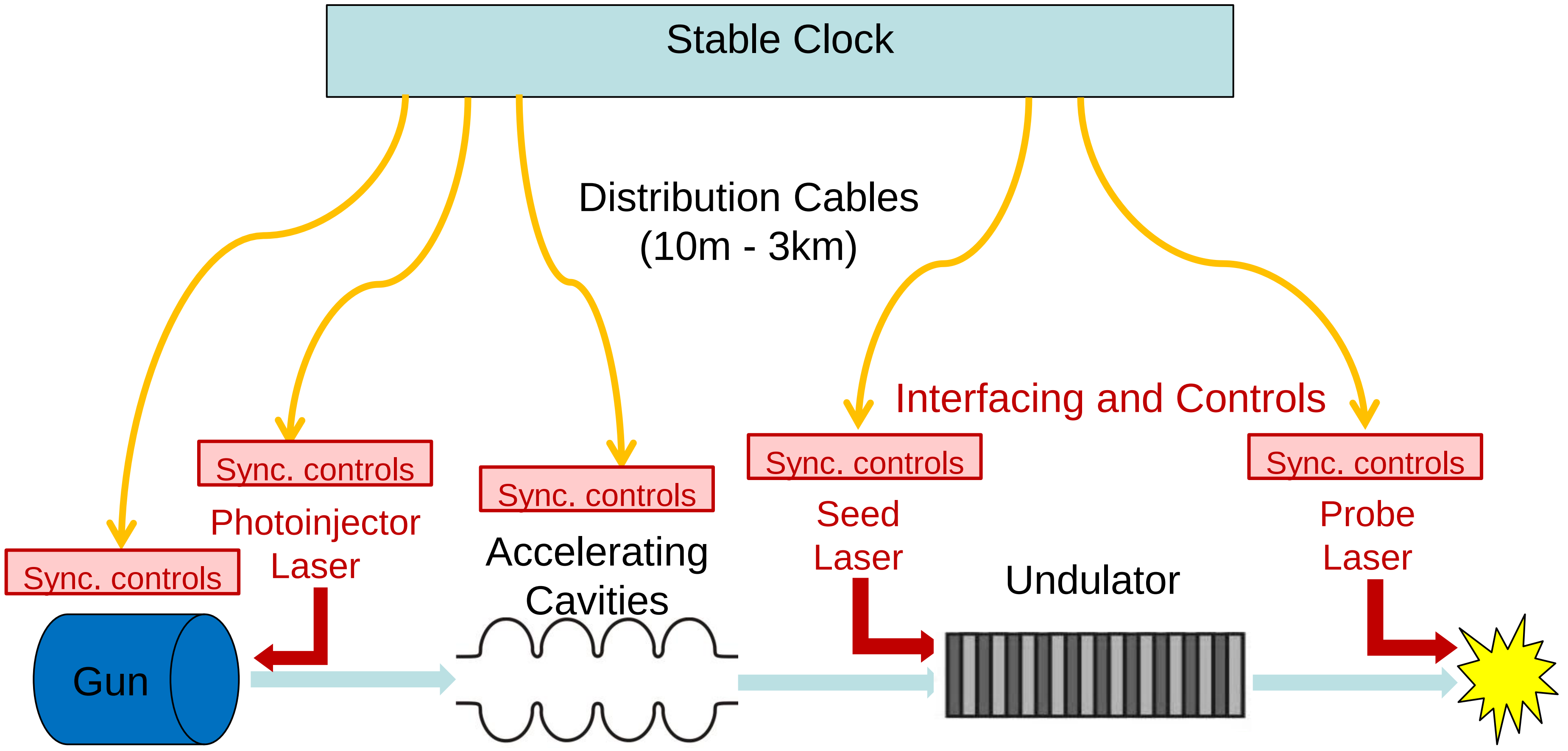
RF, optical fibre, free space

(eg. Plasma accelerators)

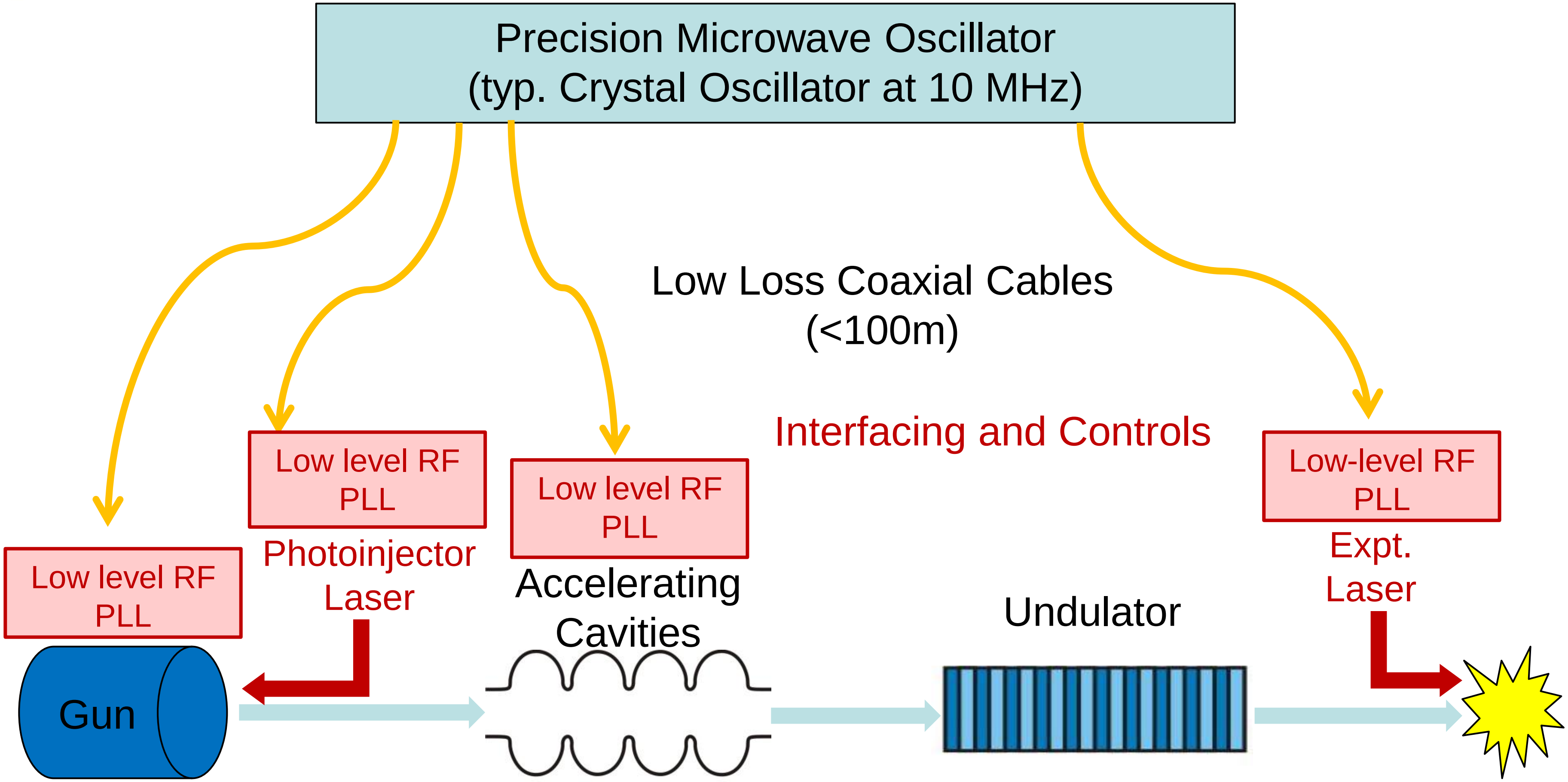
RF system

(eg. Ion sources)

Introduction to timing systems



Basic RF timing (small facility)



Precision Microwave Oscillator
(typ. Crystal Oscillator at 10 MHz)

Low Loss Coaxial Cables
(<100m)

Interfacing and Controls

Low level RF
PLL

Gun

Low level RF
PLL

Photoinjector
Laser

Low level RF
PLL

Accelerating
Cavities

Undulator

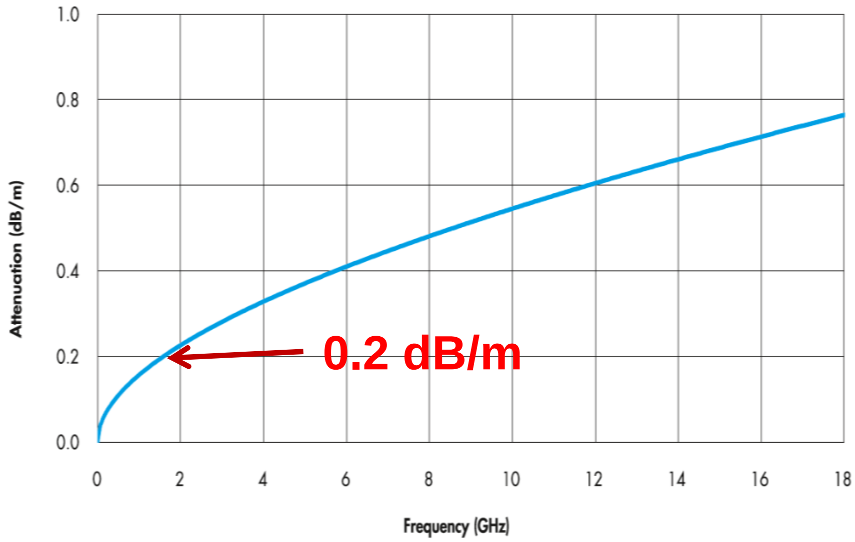
Low-level RF
PLL

Expt.
Laser

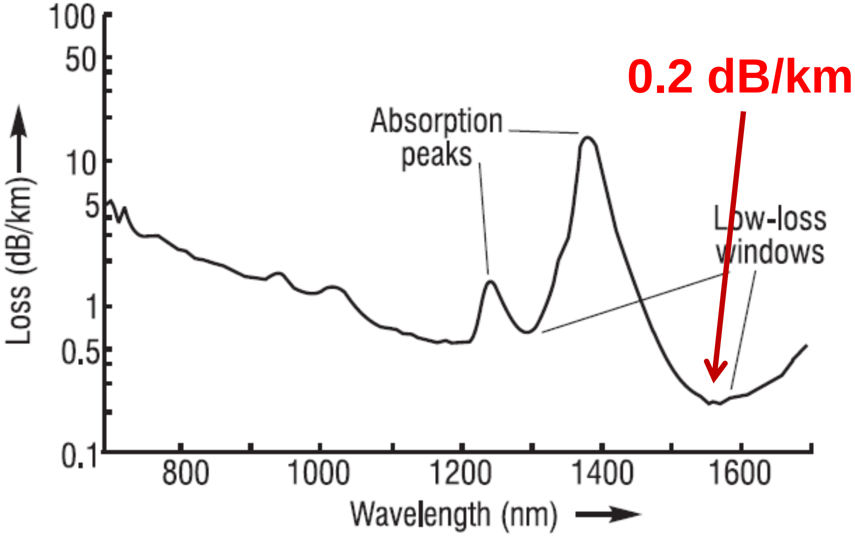
Challenges in RF distribution

- Attenuation over large distances

Coaxial cable attenuation (dB/m)



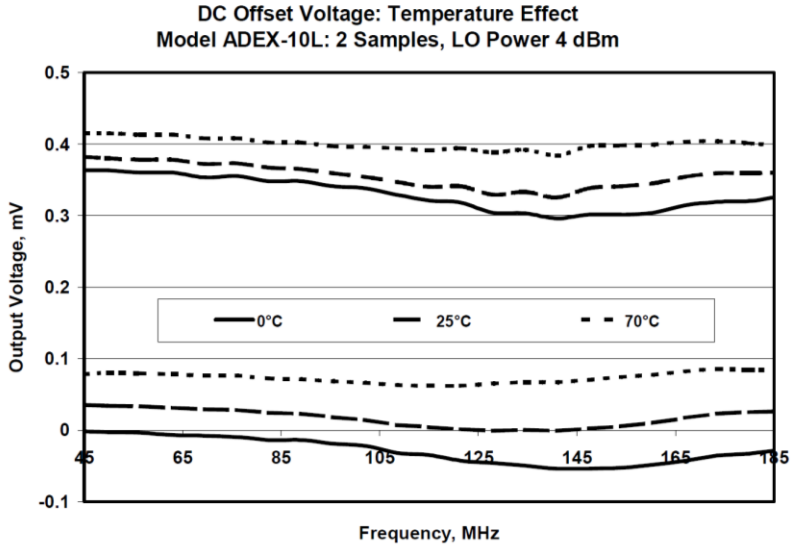
Optical fibre attenuation (dB/m)



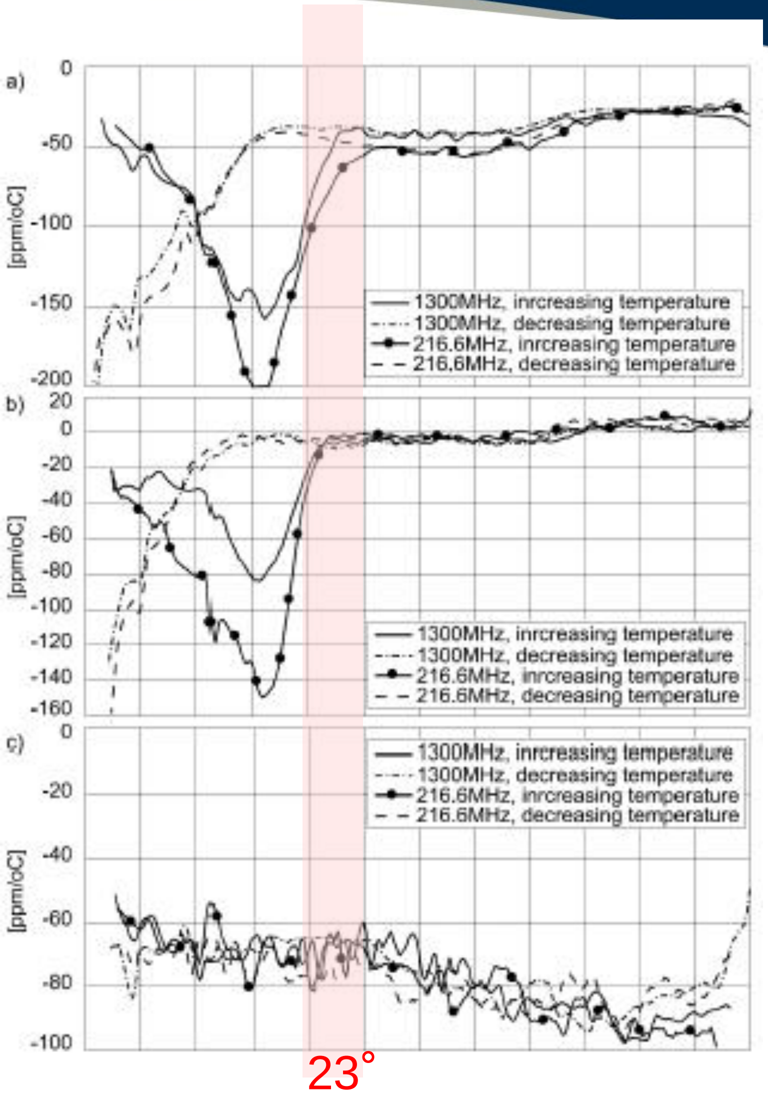
[adapted from Miya, Hasaka, and Miyashita].

Challenges in RF distribution

- Timing jitter
  - Temperature
  - Vibrations
  - Dynamics in oscillators
  - Dynamics in distribution cables

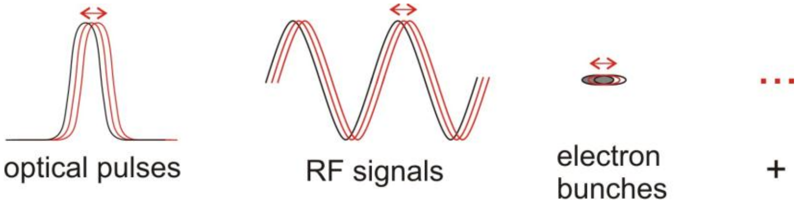


DC Offset Voltage: Temperature Effect
Model ADEX-10L: 2 Samples, LO Power 4 dBm

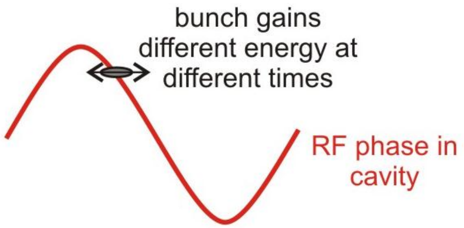


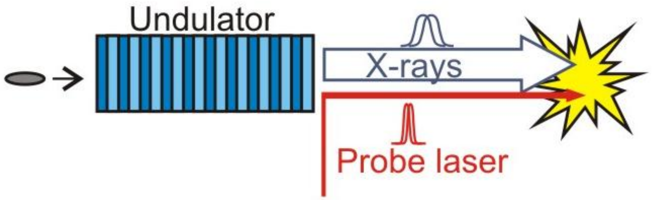
Timing jitter

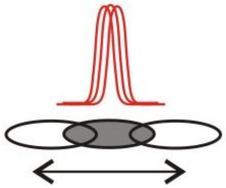
- What is timing jitter?



- Why does it matter?
  - Beam energy spread
  - Pump-probe experiments
  - FEL seeding







Characterizing timing jitter

- How is jitter measured?

Assuming no amplitude noise:

Time domain description

$$v(t) = V_0 \sin(2\pi f_c t + \varphi(t))$$

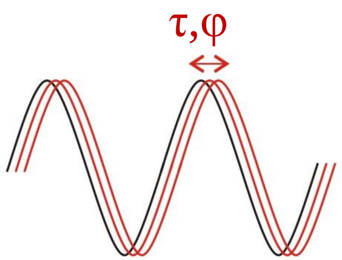
Mean-squared spectrum

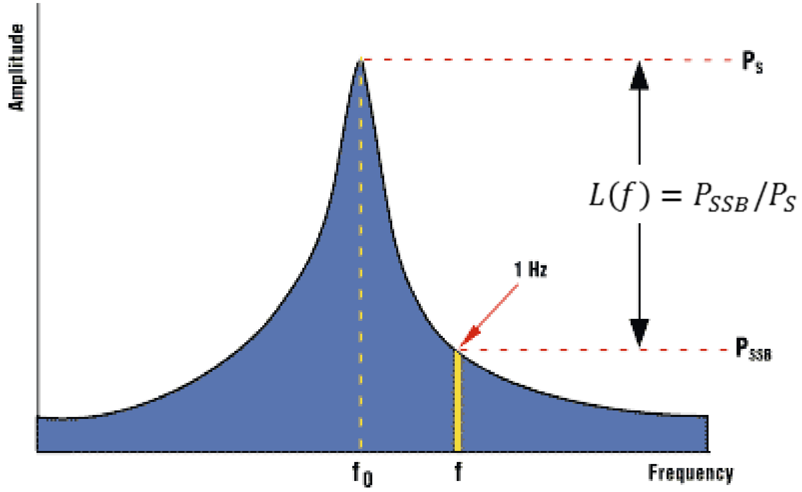
$$\overline{\varphi^2(t)} = \int_{-\infty}^{\infty} S_\varphi(f)\, df$$

For small modulation (<< 1rad.):

$$L(f) \approx S_\varphi(f)/2$$

Conventional form (dBc/Hz)



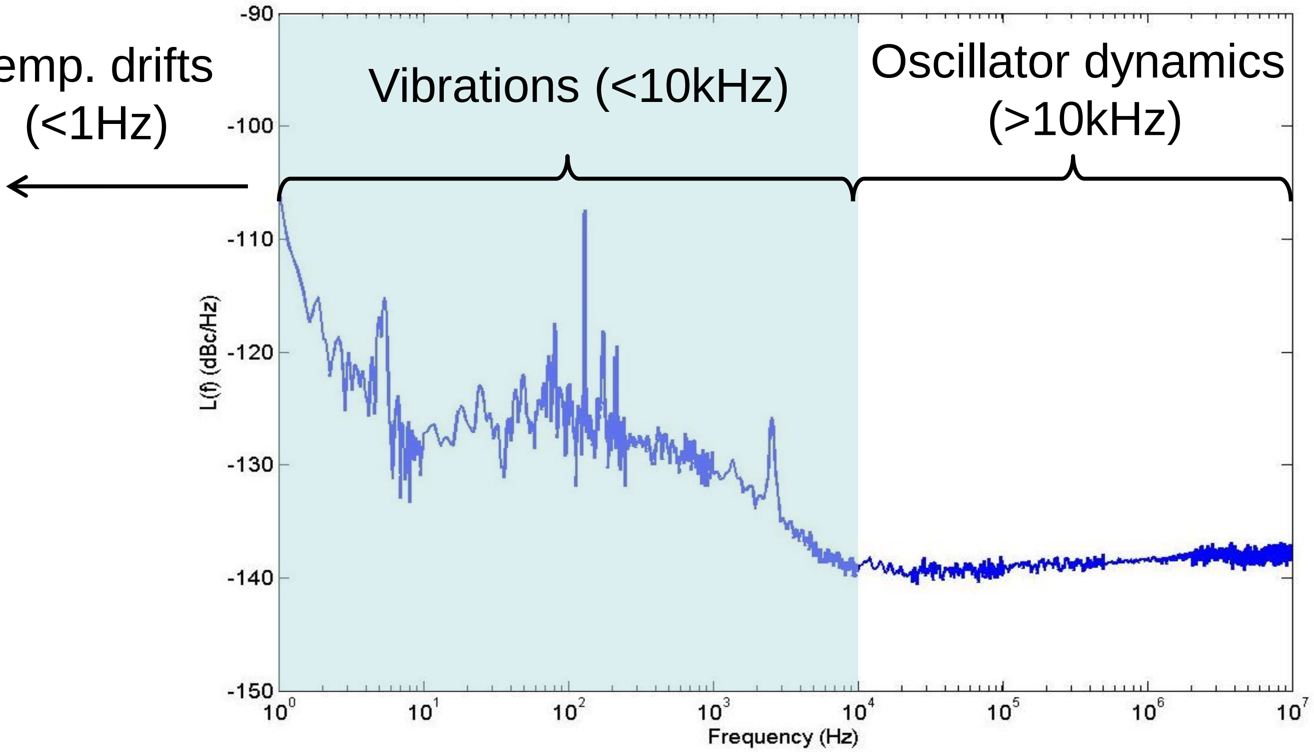


- RMS jitter:

$$\boxed{\tau_{rms}(f_1, f_2) = \frac{1}{2\pi f_c}\sqrt{2\int_{f_1}^{f_2} 10^{L(f)/10}\, df}}$$

Jitter in timing systems

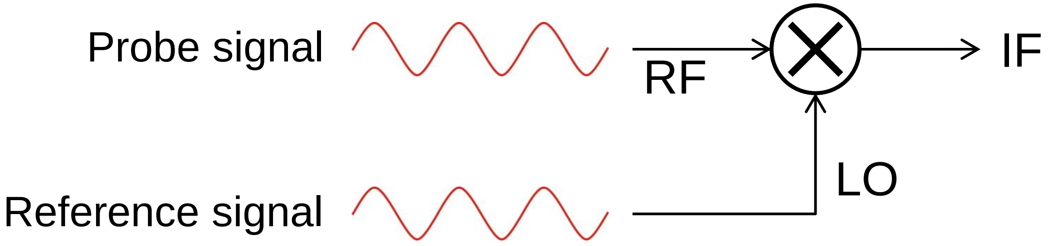
- Sources of jitter



$$\boxed{\tau_{rms}(f_1,f_2) = \frac{1}{2\pi f_c}\sqrt{2\int_{f_1}^{f_2} 10^{L(f)/10}\,df}}$$

RF phase detection and locking

- RF phase detection with a mixer



- Ideal mixer multiplies the probe and reference signals

$$V_{IF}(t) = A_{LO}\cos(\omega_{LO}t) * A_{RF}\cos(\omega_{RF}t + \varphi)$$

$$= \frac{A_{LO}A_{RF}}{2}\{\cos((\omega_{LO}-\omega_{RF})t - \varphi) + cos((\omega_{LO}+\omega_{RF})t + \varphi)\}$$

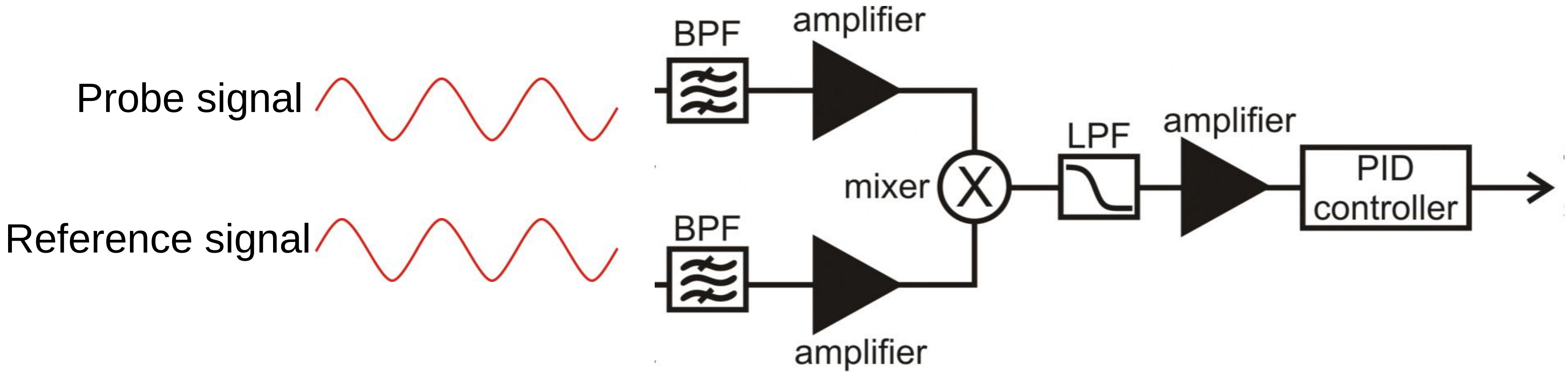
$if\ \omega_{LO} = \omega_{RF}$

$$= \frac{A_{LO}A_{RF}}{2}\{\cos\varphi + cos(2\omega_{LO}t + \varphi)\}$$

DC Voltage
Linear for φ ~ π/2

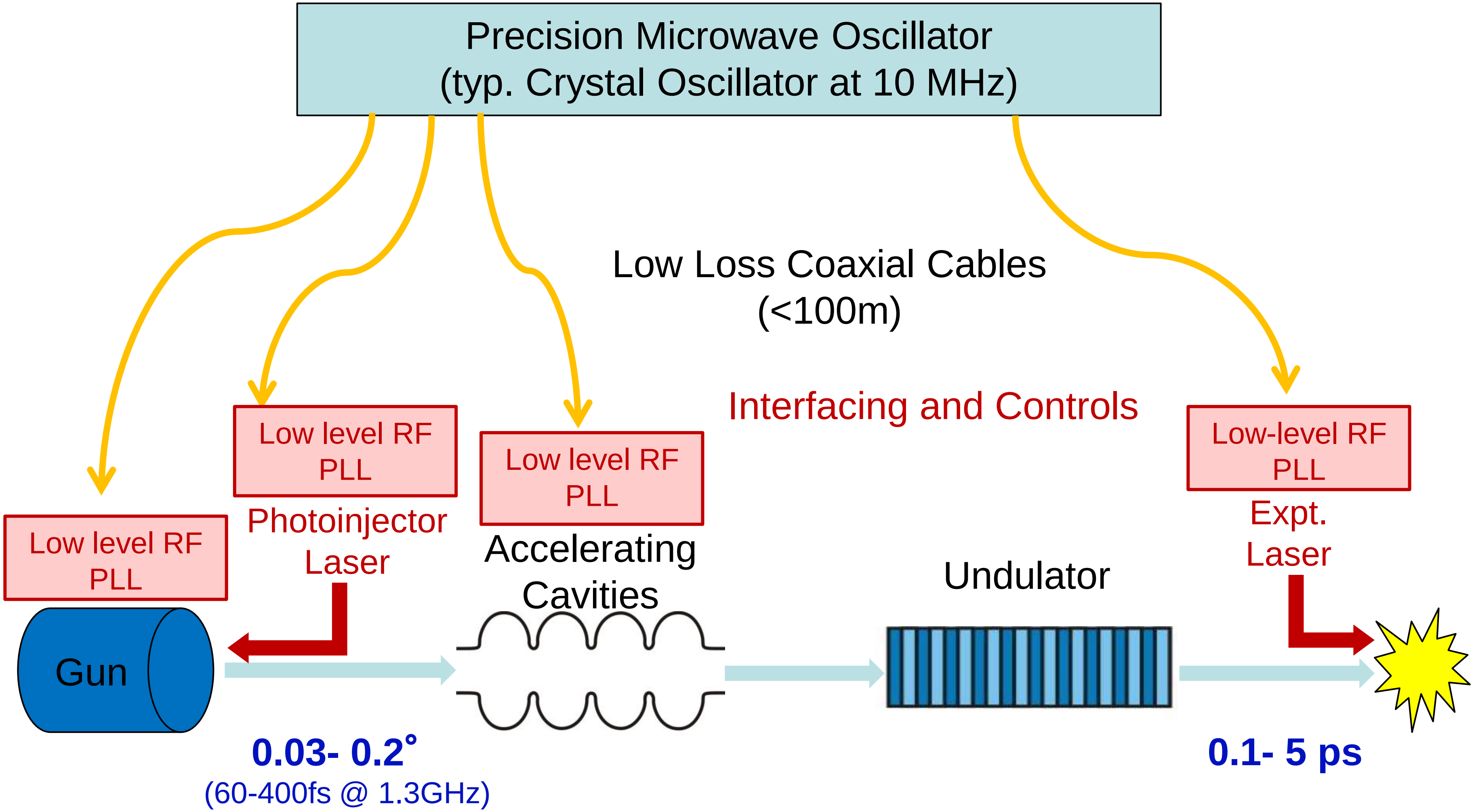
Needs to be filtered out
with a low pass filter

RF phase detection and locking



- Resolution limits of a low noise mixer ~ 0.02°
  - At 1.3 GHz ≈ 42 fs
  - At 3 GHz ≈ 18.5 fs
  - At 10 GHz ≈ 5.5 fs

Basic RF timing (small facility)



Precision Microwave Oscillator
(typ. Crystal Oscillator at 10 MHz)

Low Loss Coaxial Cables
(<100m)

Interfacing and Controls

Low level RF
PLL

Gun

Low level RF
PLL

Photoinjector
Laser

Low level RF
PLL

Accelerating
Cavities

Undulator

Low-level RF
PLL

Expt.
Laser

0.03- 0.2°
(60-400fs @ 1.3GHz)

0.1- 5 ps

Going Optical...

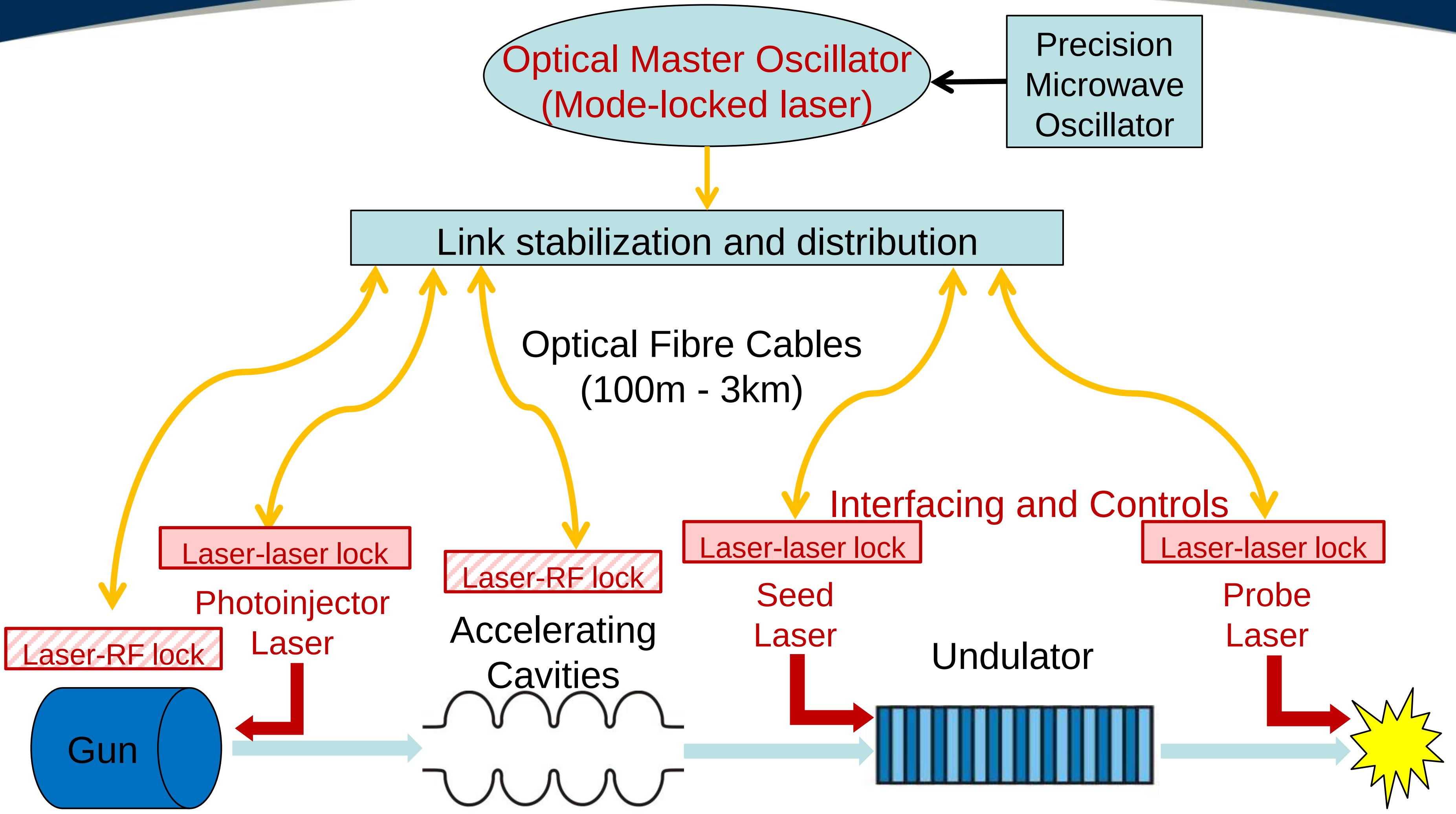
- Advantages of an optical system
  - Quieter clock
  - High bandwidth
  - Low attenuation

- New challenges
  - Phase change with temperature
  - Dispersion compensation
  - Polarisation effects: Polarisation mode dispersion (PMD)
  - Conversion back to RF
  - Reliability ???

Similar to coax
~ 40 fs/° C/m

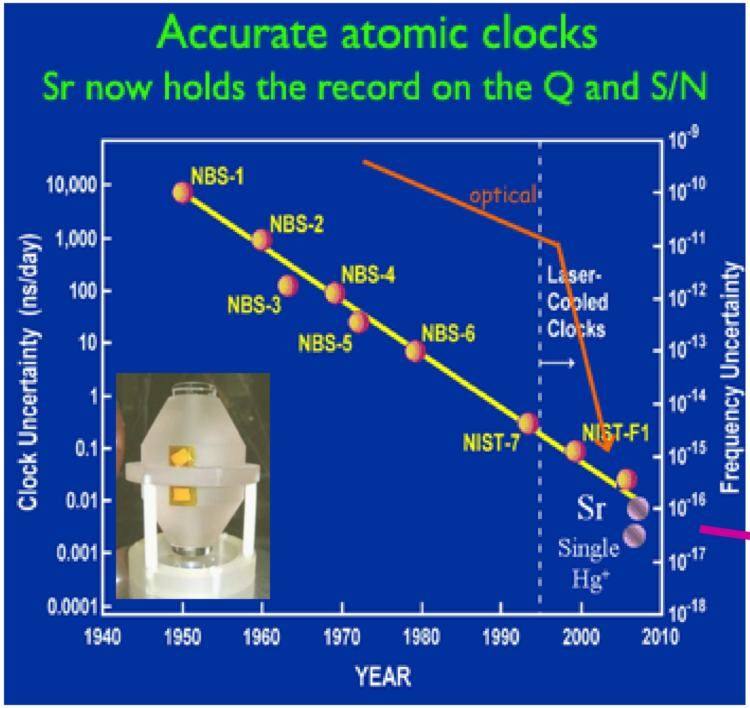
Introduction to timing systems

Science & Technology Facilities Council



Ultrastable clocks

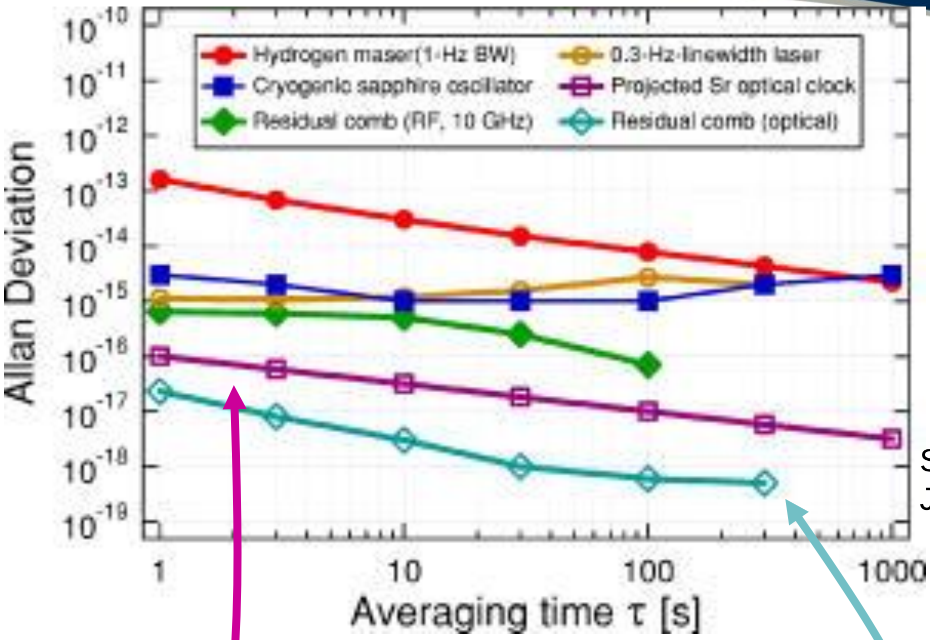
- What isn the most stable clock you can get?



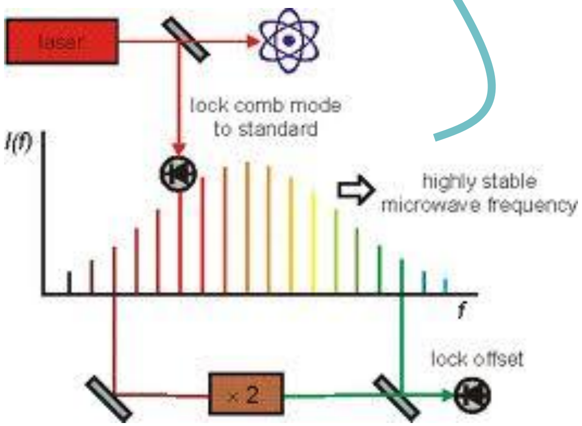
Accurate atomic clocks

Sr now holds the record on the Q and S/N

NIST, USA



S. Foreman, JILA



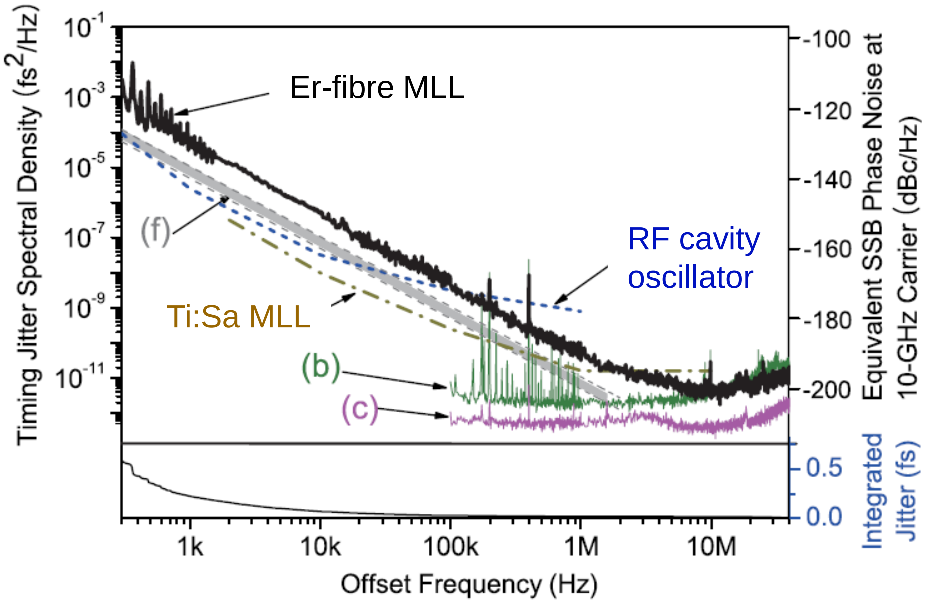
Optical timing systems

2 main approaches

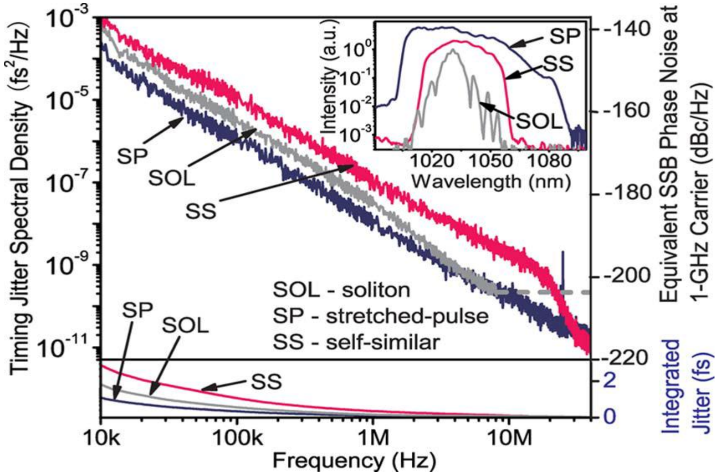
Pulsed Distribution

CW Distribution

Ultrastable clocks



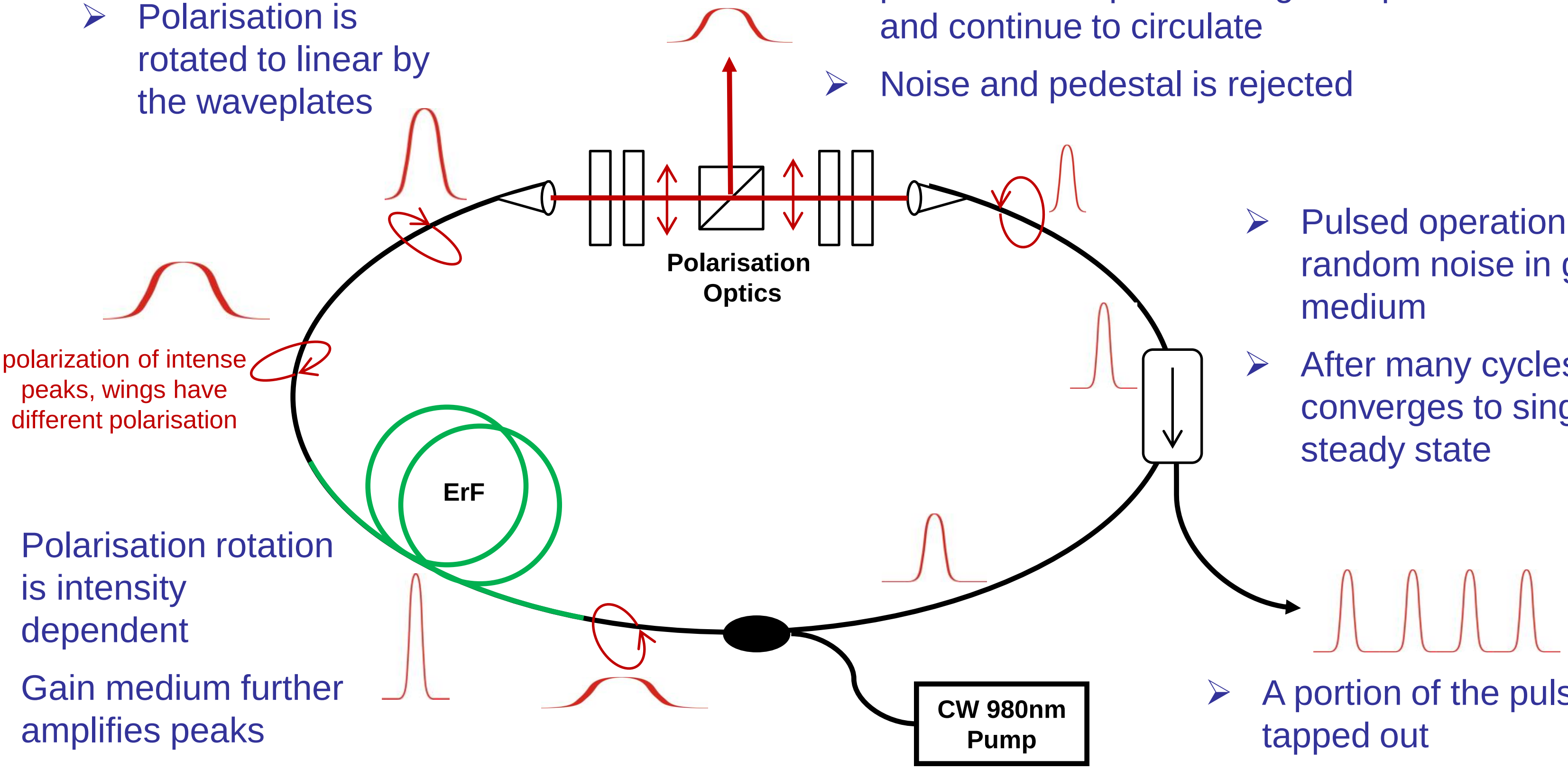
- Some of the most stable microwave and optical clocks
- Passively mode-locked lasers (MLL) are quieter at high frequencies than microwave oscillators
- Ti:Sa oscillators are some of the quietest clocks currently available



- Fibre lasers at telecommunications wavelengths are particularly suitable for distribution
  - Low loss
  - mature components
  - high bandwidth components

Stretched-pulse fibre lasers

- Polarisation is rotated to linear by the waveplates
- Only the intense peaks have the correct polarisation to pass through the polariser and continue to circulate
- Noise and pedestal is rejected
- Pulsed operation starts from random noise in gain medium
- After many cycles laser converges to single pulse steady state

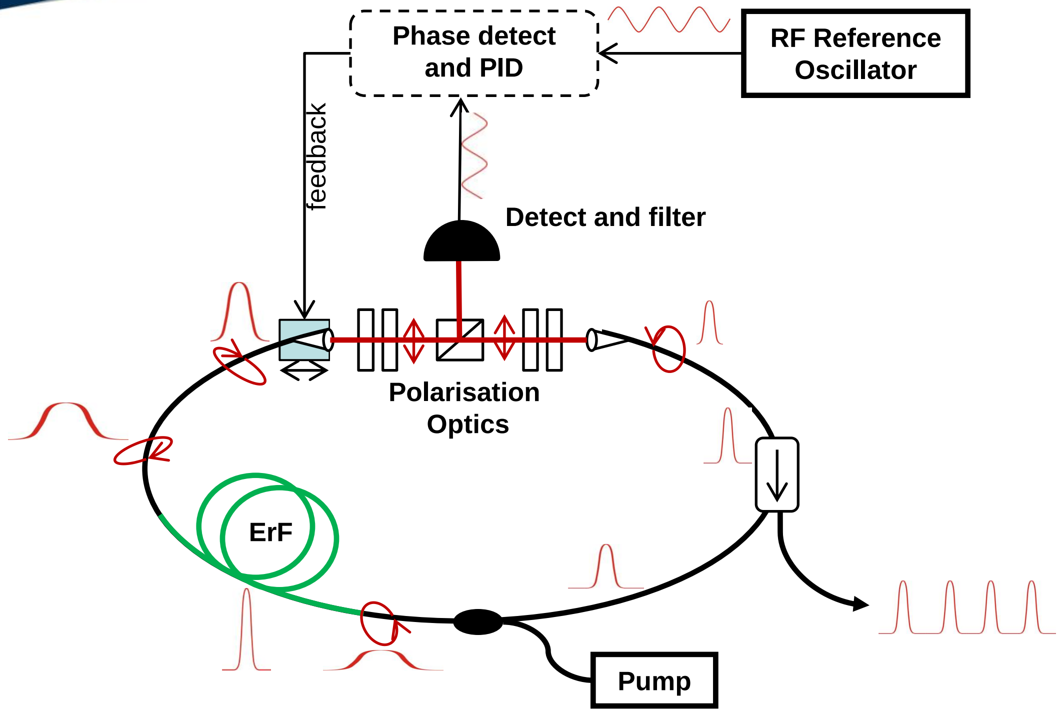


- Polarisation rotation is intensity dependent
- Gain medium further amplifies peaks
- Gain fibre has opposite dispersion to main fibre

$$\Delta\Phi = \Phi_x - \Phi_y = \left[(\beta_x - \beta_y) + \gamma(I_x - I_y) + \frac{2}{3}\gamma(I_y - I_x)\right]2L$$

- A portion of the pulses are tapped out
- Repetition rate is determined by ring transit time

Ultrastable clocks

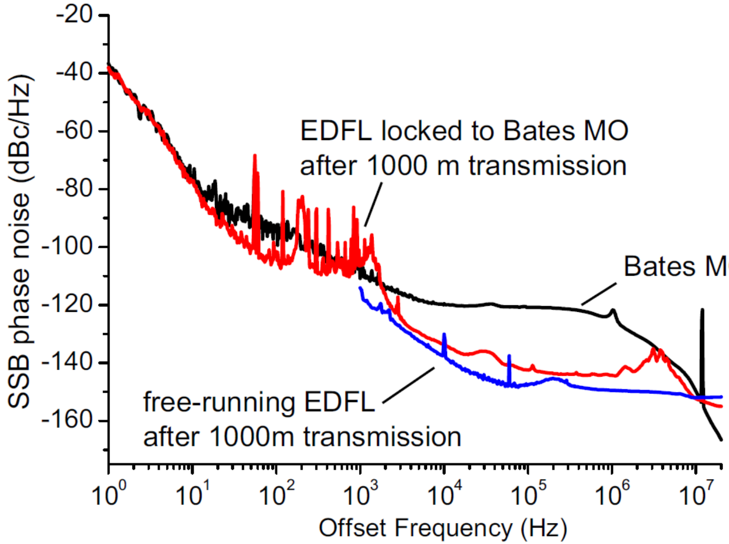


2.637... m cavity length -> 81,250,000 Hz
add **28 nm** -> 81,250,001 Hz

Cavity length susceptible to low frequency noise/drifts...

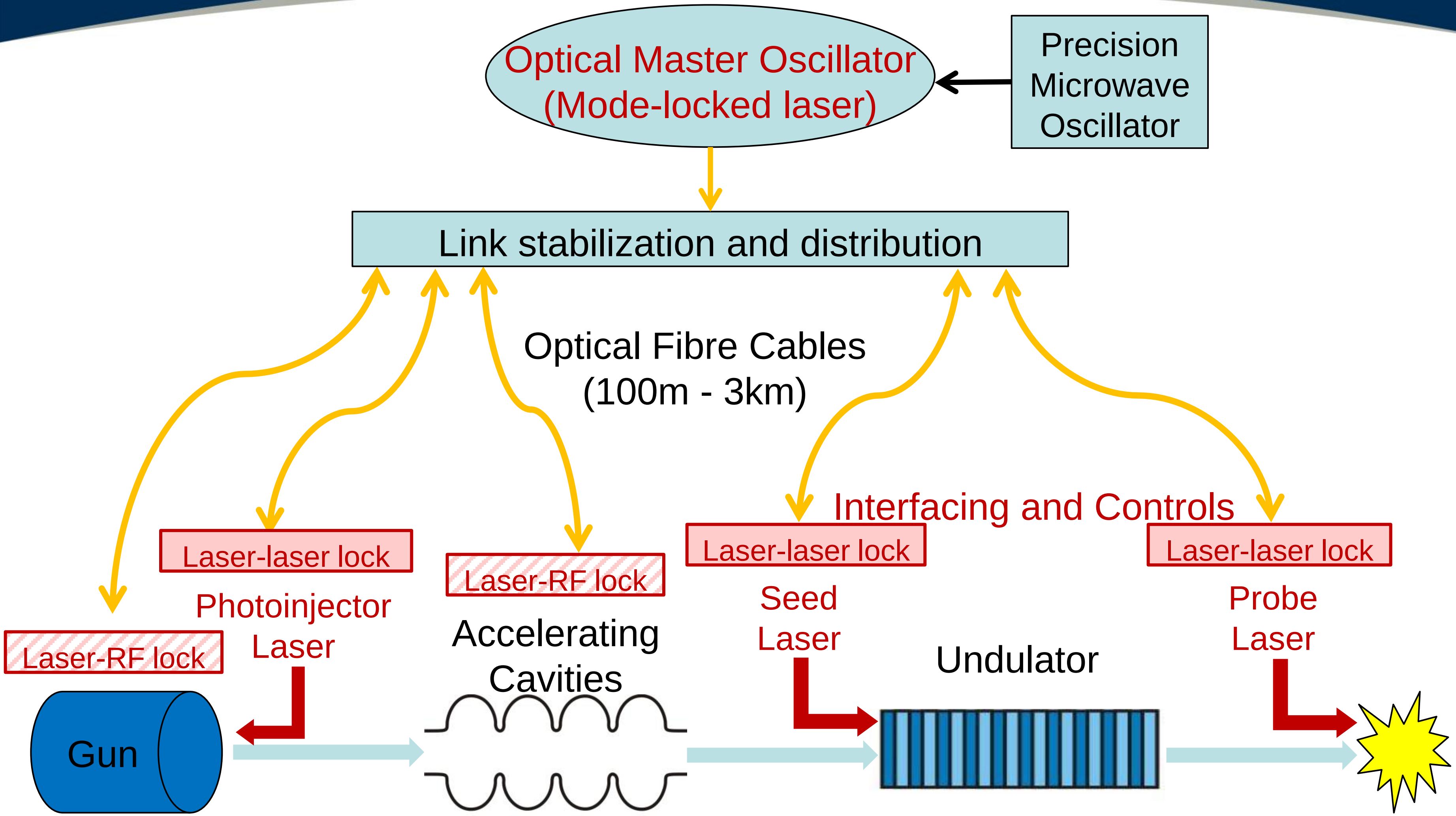
- Fibre length changes are detected through phase comparison to RF
- Feedback signal compensates for changes in path length

but very low noise at high frequencies



(Source: A. Winter, DESY)

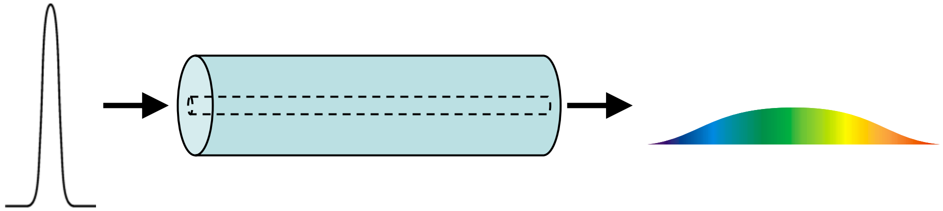
Pulsed timing systems

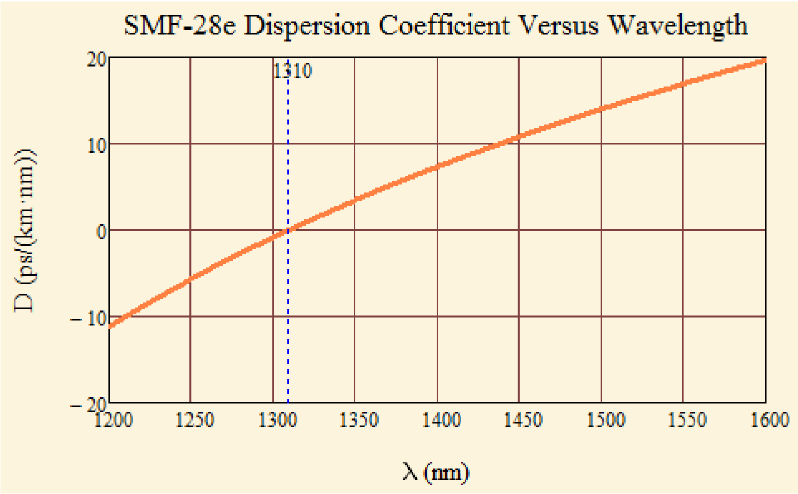


Pulsed distribution

- ‘Undesirable’ effects in fibres:
  - Chromatic dispersion
  - Polarisation mode dispersion
  - Fibre nonlinearities (specifically self-phase modulation)
  - **Temperature sensitivity**
  - **Vibration sensitivity**
  - Radiation darkening

- Dispersion in optical fibres





Dispersion in optical fibres

- Dispersion in optical fibres:
  - In standard fibre (SMF 28e⁺): $\beta_2 \approx 21\ \mathrm{ps^2/km}$

$$L_D = \frac{{T_0}^2}{|\beta_2|} \qquad T_0 = \frac{T_{FWHM}}{2\sqrt{\ln 2}}$$

(1/e-point of Gaussian)

$$T(z) = T(0)\sqrt{1+\left(z/L_D\right)^2}$$

T_{fwhm} = 100 fs; L_D = 17cm

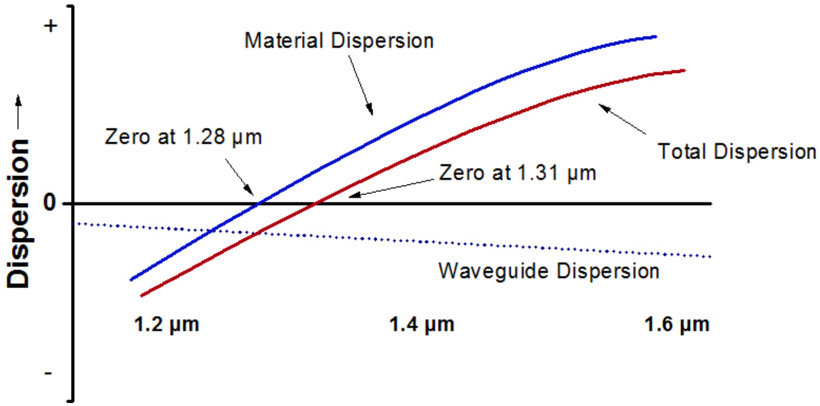
T_{fwhm} = 200 fs; L = 30cm

- Dispersion in waveguides is composed of two parts

$$D = D_m + D_w = -\frac{2\pi c}{\lambda^2}\beta_2$$

Material dispersion Waveguide dispersion

1.31 µm Zero-Dispersion in Step-Index SM Fiber



Dispersion compensation

- Combatting dispersion using Dispersion Compensating Fibre (DCF)

$$D_m = \frac{\lambda}{c}\left(\frac{d^2 n}{d\lambda^2}\right)$$

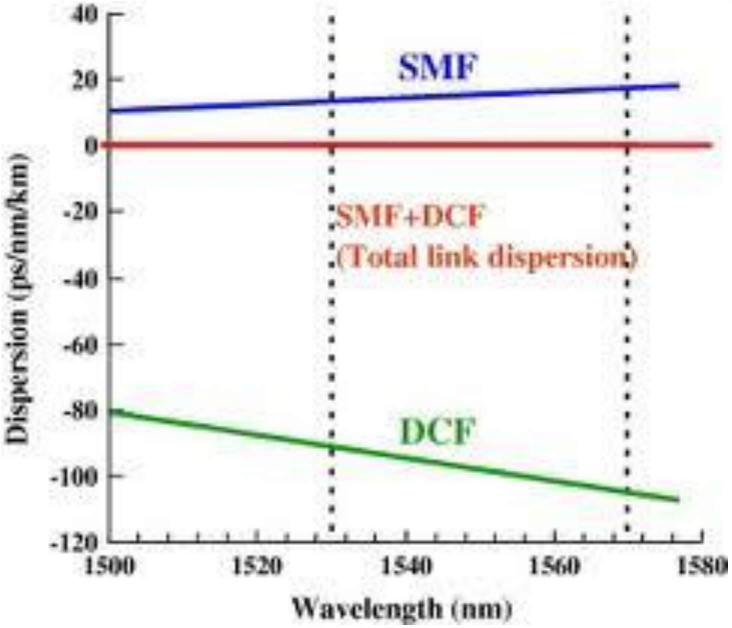
$$D_w = -\frac{n_2(n_1 - n_2)}{c\lambda} V \frac{d^2(Vb)}{dV^2}$$

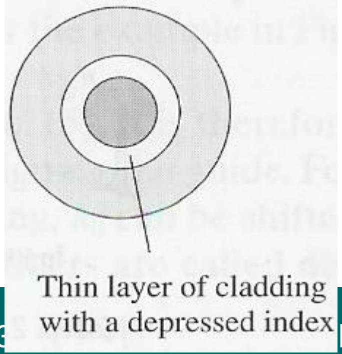
V-number

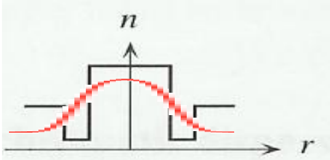
$$V = \frac{2\pi a}{\lambda}(n_1^2 - n_2^2)^{1/2}$$

Normalized propagation constant

$$b = \frac{n_{eff}^2 - n_2^2}{n_1^2 - n_2^2}$$

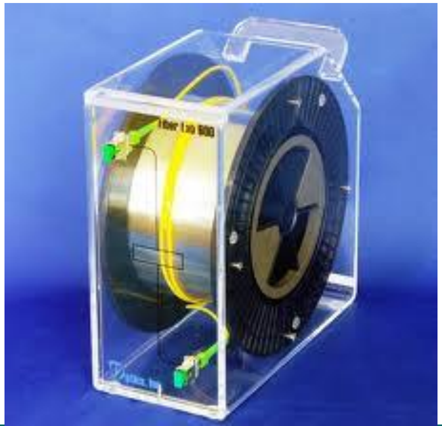






$D_{SMF} \approx 17$ ps/nm/km

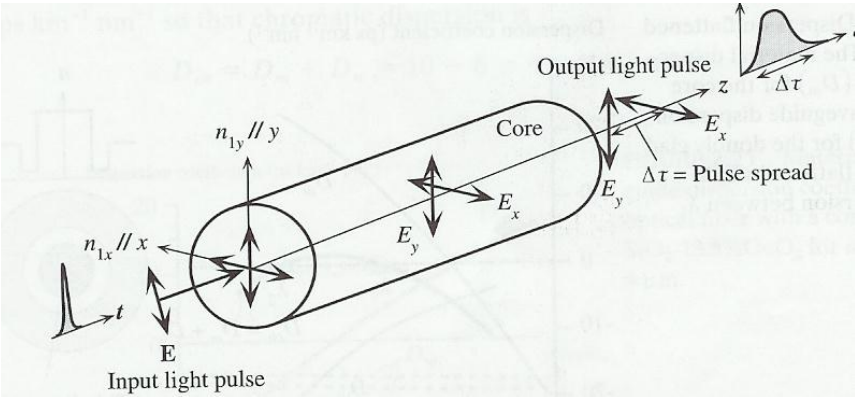
$D_{DCF} \approx -135$ ps/nm/km



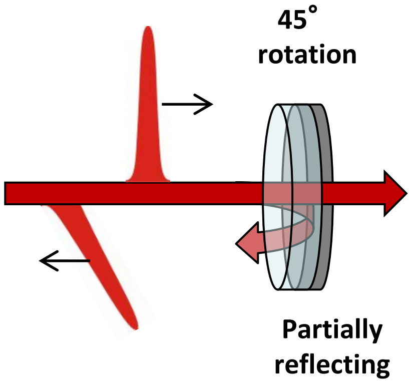
Polarisation mode dispersion

What is PMD?

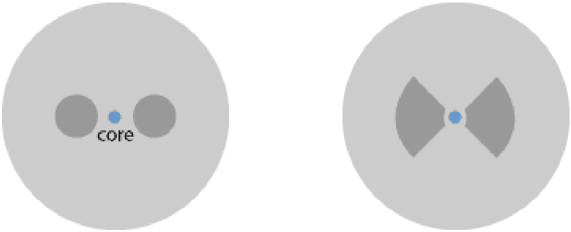
- fiber is not perfectly symmetric, inhomogeneous.
- refractive index is not isotropic
- Polarisations will walk off from each other randomly



Solutions:



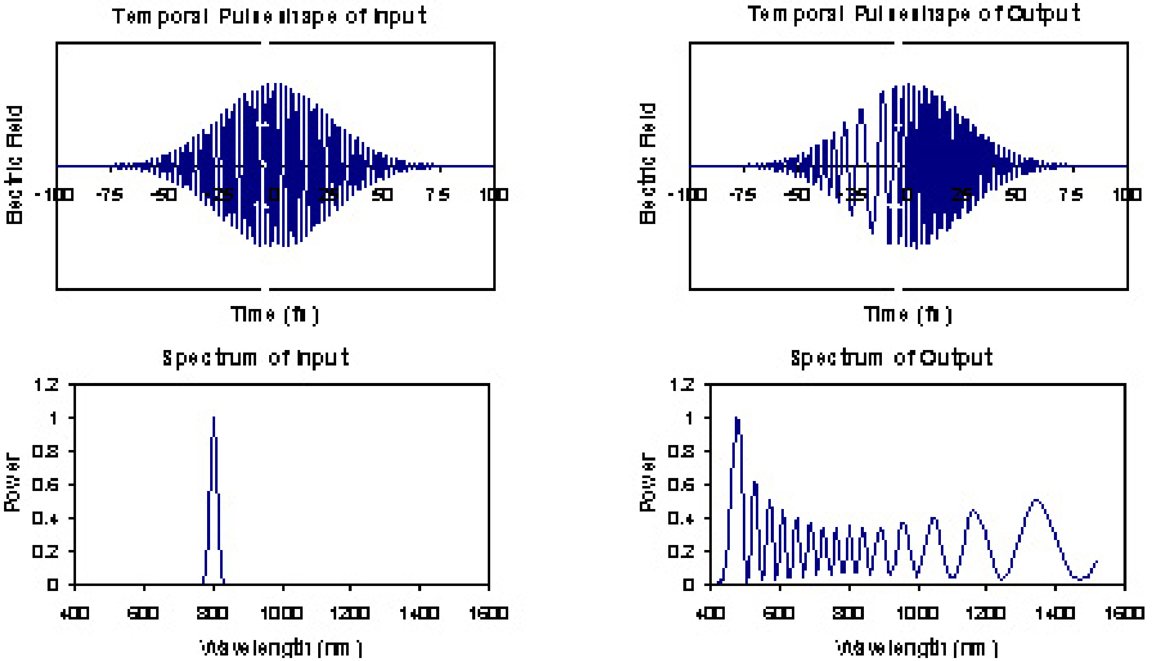
Faraday Rotating mirror



Polarization maintaining fibre

Other effects

- Self-phase modulation
  - Keep your peak powers low!
- Radiation darkening
  - Commercial fibre



- Temperature and vibration sensitivity
  - Difficult to control or predict

→ **Compensate**

Length stabilization

- Estimate how much optical phase change you expect

$$\Delta\phi = \frac{2\pi}{\lambda}\left(\frac{n}{L}\frac{dL}{dT} + \frac{dn}{dT}\right)\Delta T.L$$

$$\frac{dn}{dT} \approx 1.1\times10^{-5}/^\circ C$$

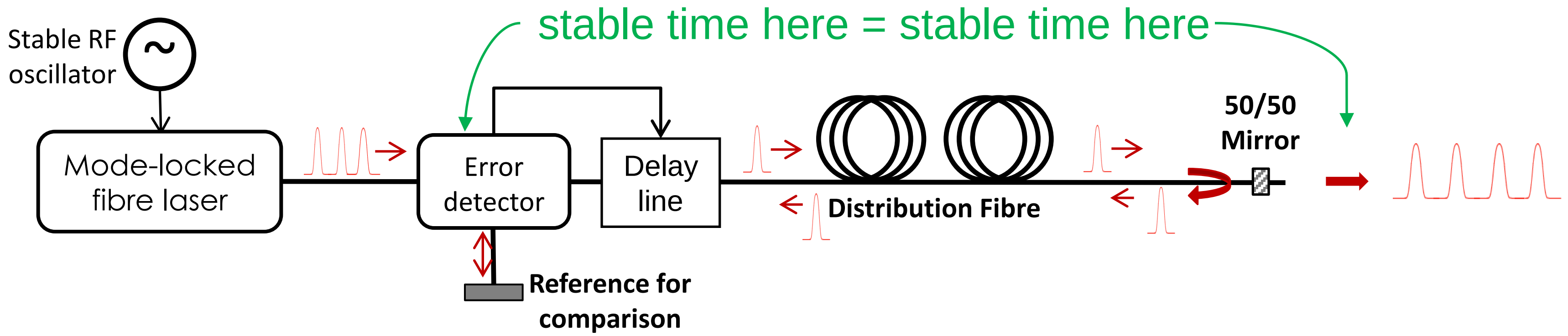
$$\frac{1}{L}\frac{dL}{dT} \approx 5\times10^{-7}/^\circ C$$

$$\approx 47.5\times10^{3} rad/^\circ C$$

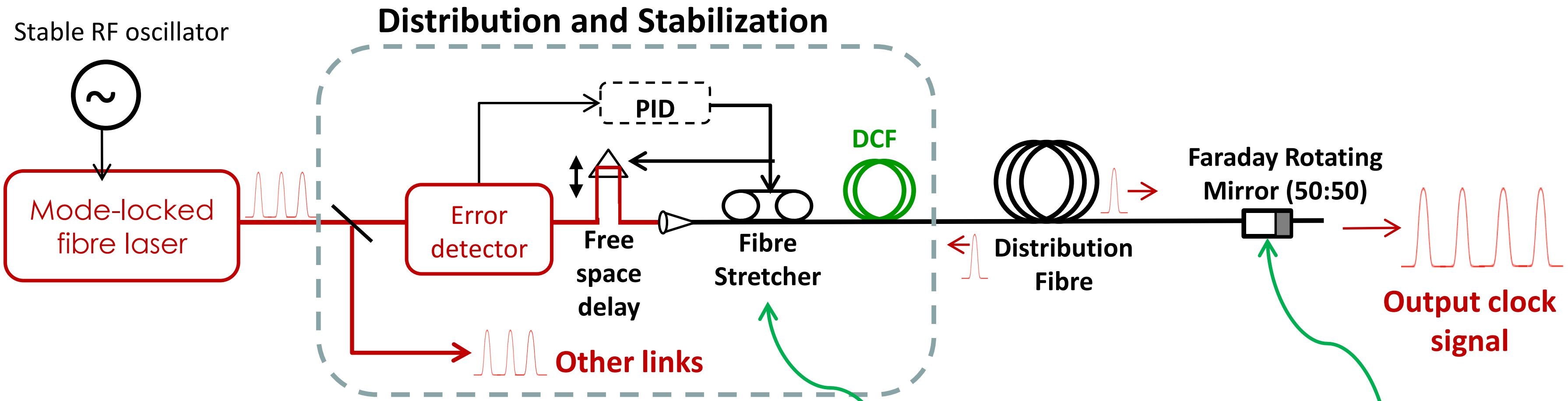
over 1km: $= 11.7 mm/^\circ C$

(Assuming your facility has this stability)

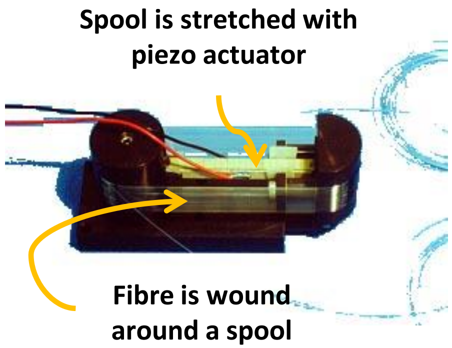
- How to detect and compensate for length changes?
- The ‘same return path’ assumption

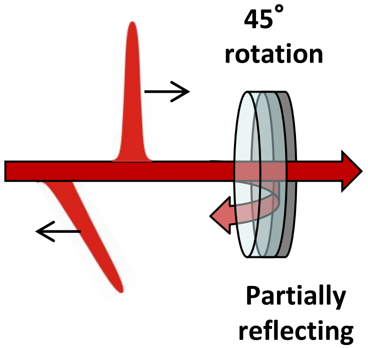


Length stabilization



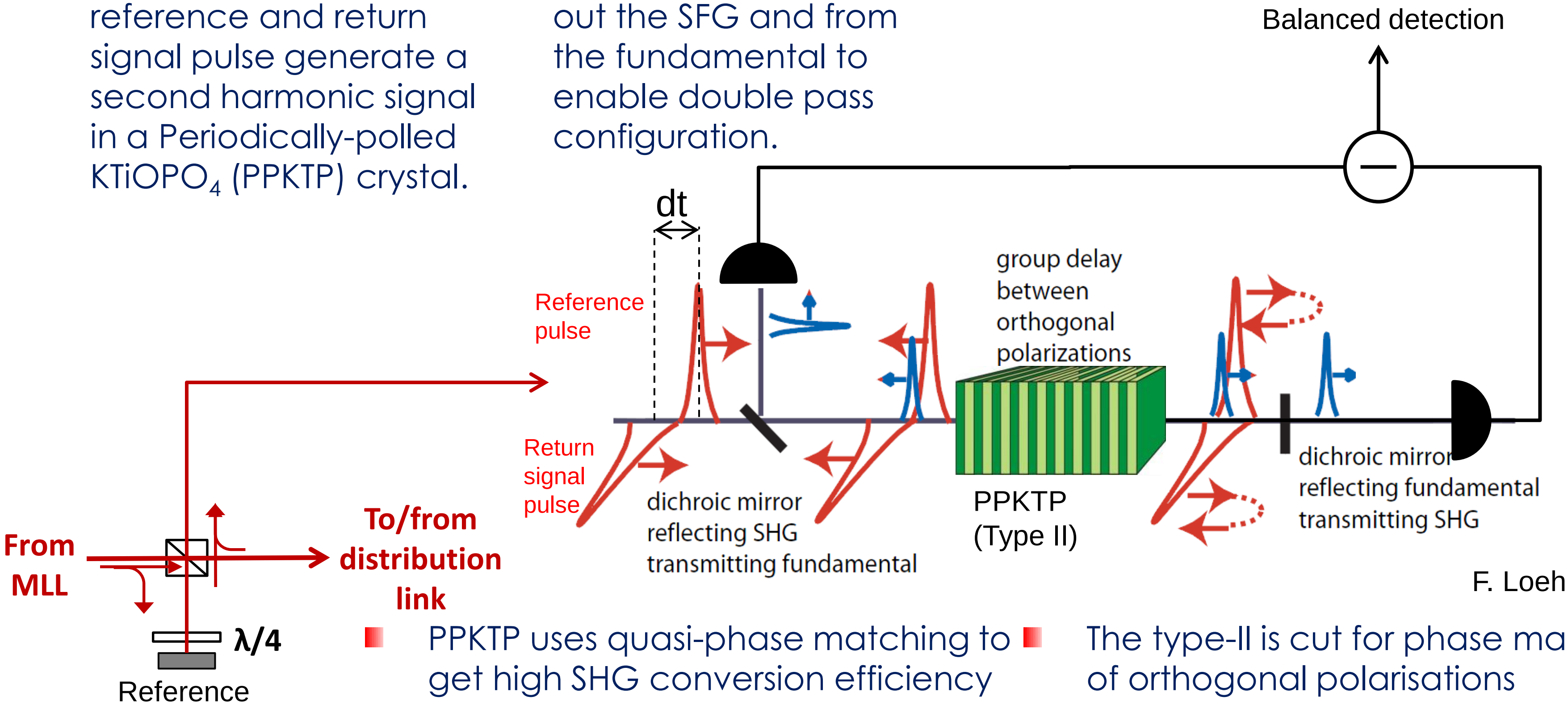
- Coarse delay (free space) provides enough range for max expected drift:
  eg. 390ps for 1km facility with ΔT=5 deg.
- Piezo wafer resonance > locking bandwidth
- 90° rotation at FRM cancels out accumulated PMD in link (within link bandwidth)





Balanced optical cross-correlator

- Overlap between the reference and return signal pulse generate a second harmonic signal in a Periodically-polled $KTiOPO_4$ (PPKTP) crystal.
- Dichroic mirrors select out the SFG and from the fundamental to enable double pass configuration.



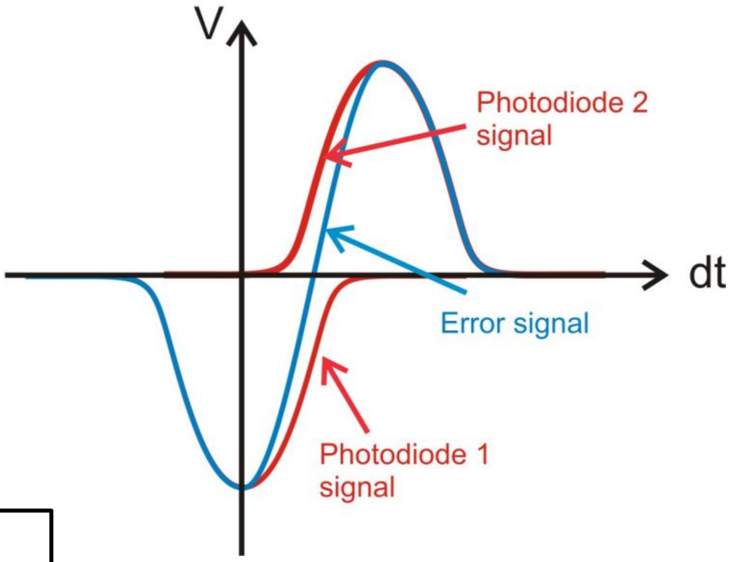
F. Loehl, DESY

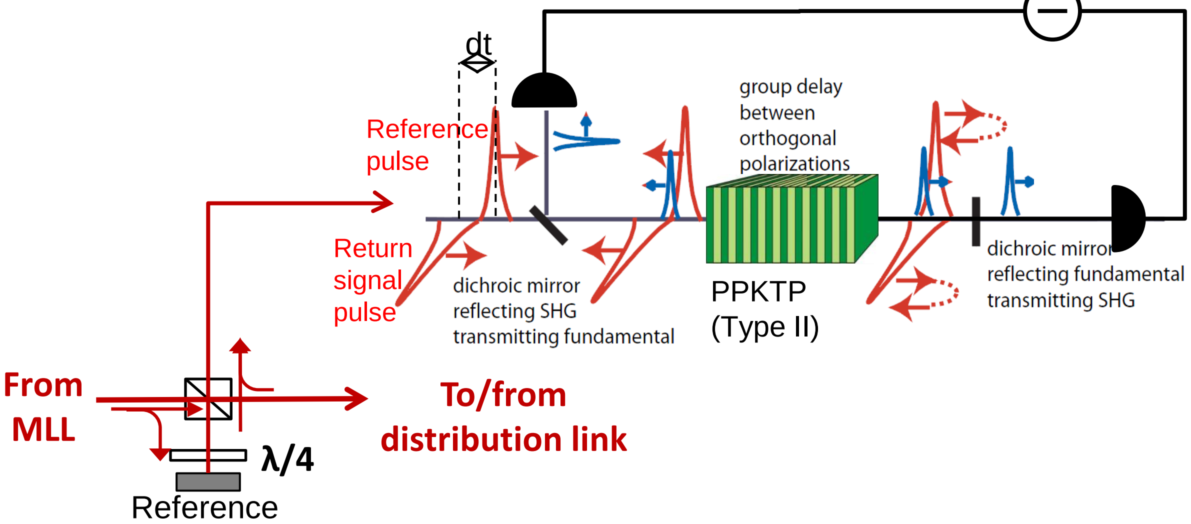
- PPKTP uses quasi-phase matching to get high SHG conversion efficiency
- The KTP is reverse polled when phase mismatch between the pulses walks off to π, to maintain phase matching.

- The type-II is cut for phase matching of orthogonal polarisations
- Using type-II eliminates the background signal associated with each pulse's own SHG and generates only the SFG generated when overlapped

Balanced optical cross-correlator

- The difference signal between the forward and backward SHG detectors give an S-curve error signal with respect to ***dt***
- Balanced configuration increases sensitivity and reduces amplitude dependence of error signal.



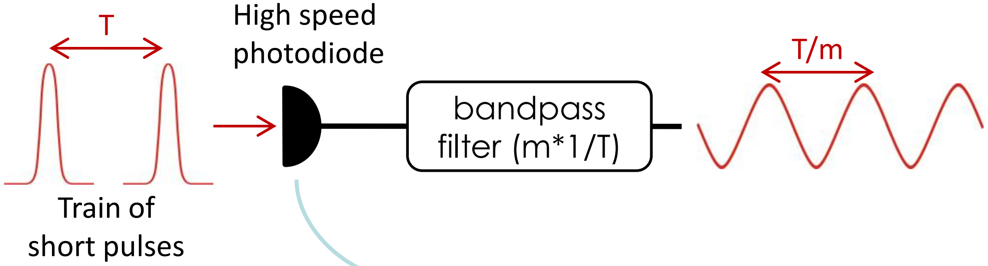


- Error signal will be at zero crossing when the pulses have perfect overlap at the **EXIT** of the PPKTP.

Laser to RF locking

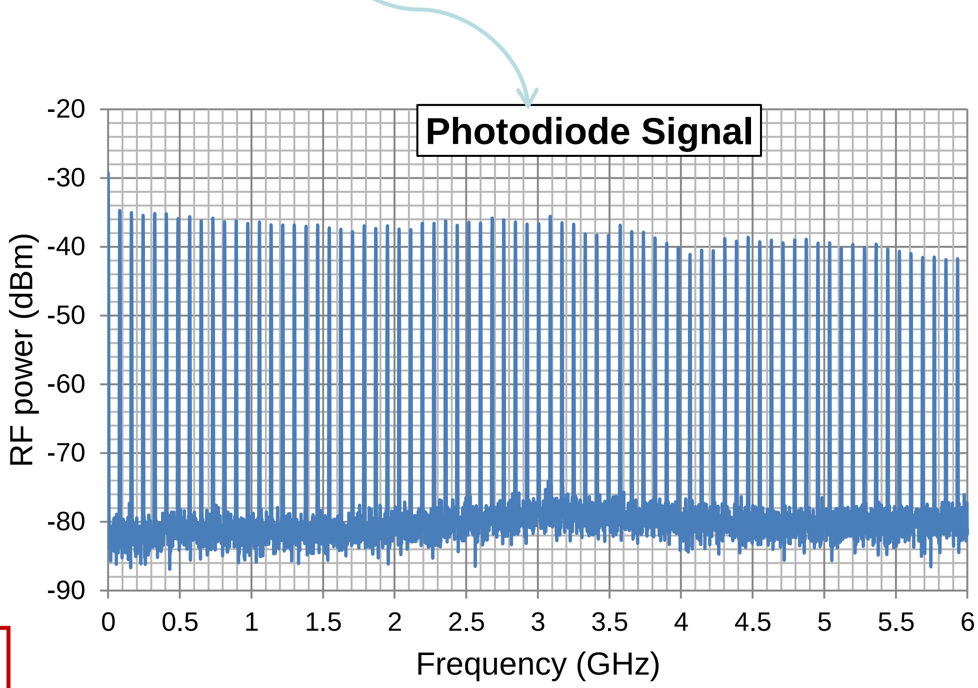
Direct Clock Delivery

- ➢ The clock signal can be directly extracted from the optical signal by detection on a photodiode and filtering.
- ➢ Delivered clocks can be used to lock to RF components with phase detection technique
- ➢ Potential errors in amplitude to phase conversion



Short pulse delivery

- ➢ Generates high harmonics in high speed photodiodes
- ➢ RF filter is used to extract desired harmonic
- ➢ Using higher harmonic improves locking resolution

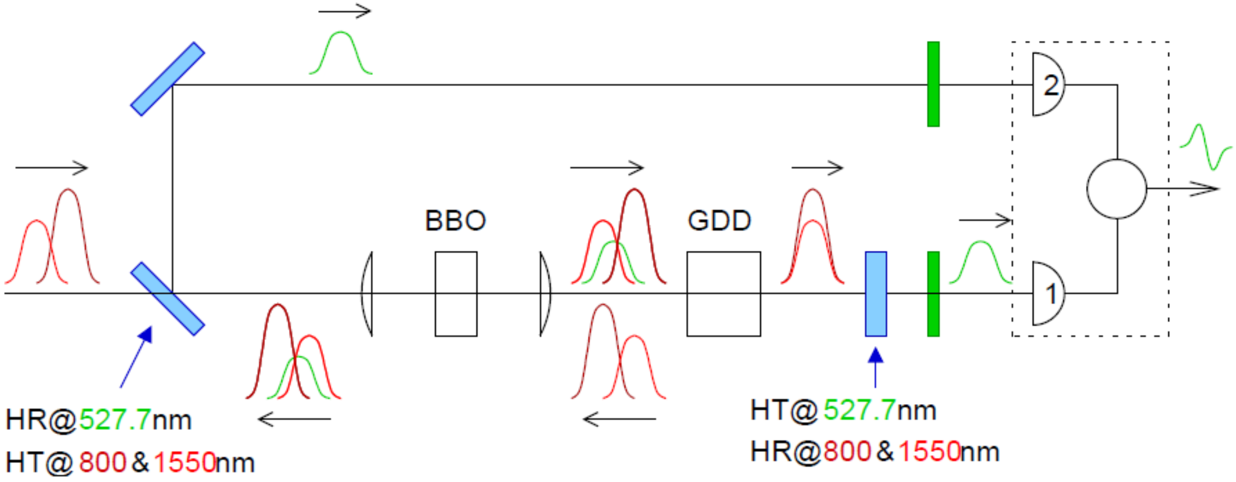


Stable clocks signals can be delivered at harmonics far above the laser repetition rate

Locking to other lasers

- Can modify balanced cross-correlator to lock 2 lasers at different wavelengths
- SFG signal gives the overalp between the pulses

Eg. Locking Ti:Sa (800nm) to optical clock (1550nm) -> SFG at 527nm



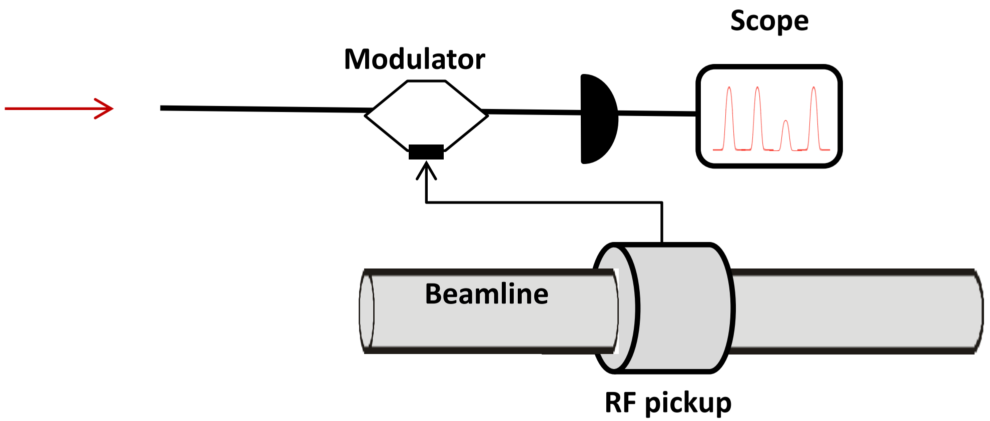
- Since BBO is not birefringent, the delay between the two pulses is generated with a dispersive block.

Timing Monitoring

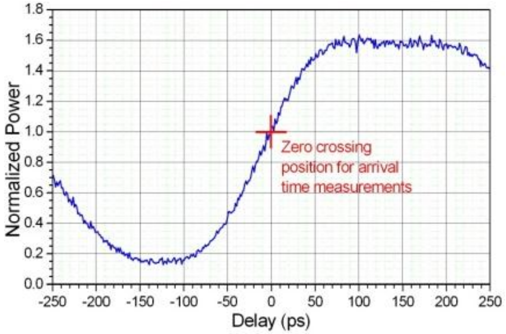
Science & Technology Facilities Council

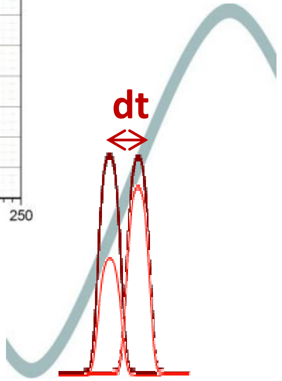
➢ Beam Arrival Monitor

From stabilized link



Pickup characteristic

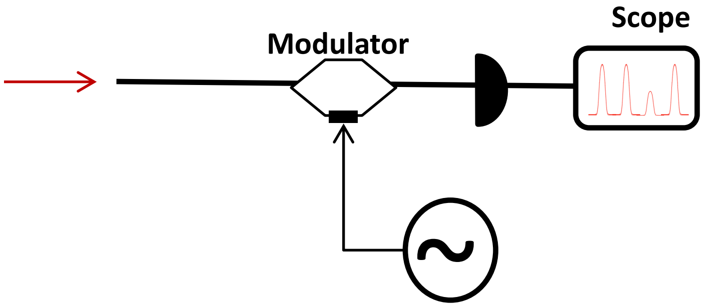


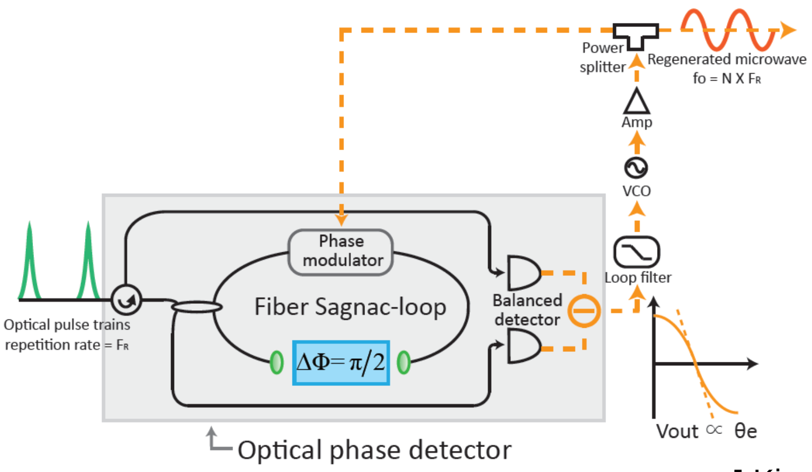


RF signal

➢ RF phase monitoring

From stabilized link





Optical phase detector

J.Kim, FLS12

LA3NET ASTeC

Optical timing systems

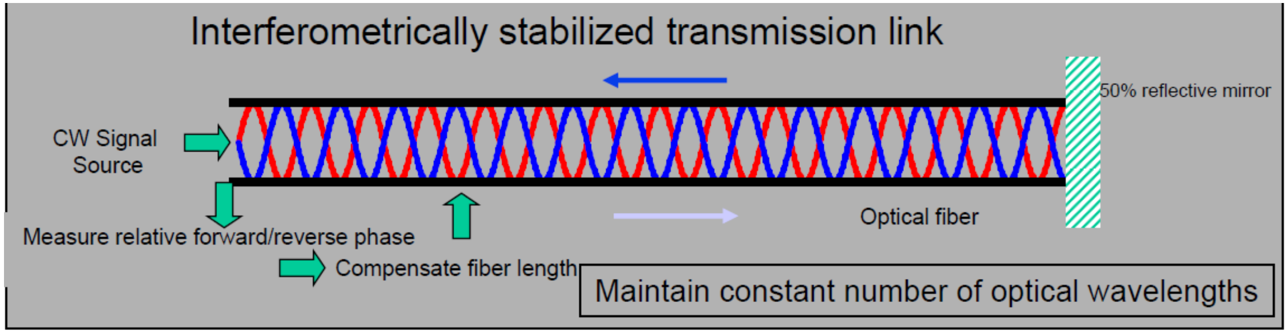
2 main approaches

Pulsed Distribution

CW Distribution

CW timing systems

- Transmit CW laser instead of pulsed



Interferometrically stabilized transmission link

50% reflective mirror

CW Signal Source

Measure relative forward/reverse phase

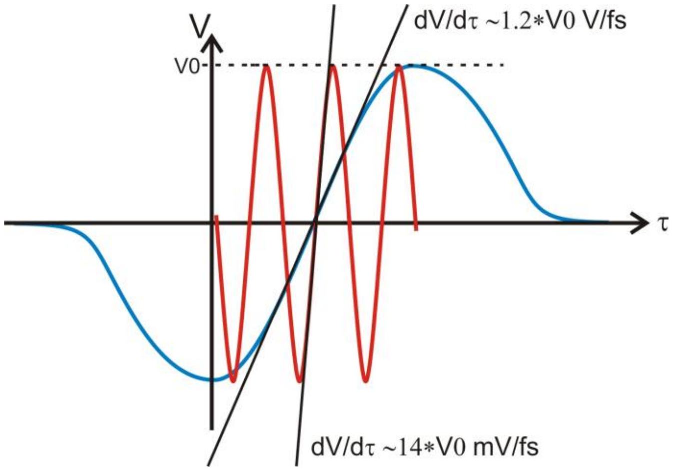
Optical fiber

Compensate fiber length

Maintain constant number of optical wavelengths

- Detect delay in phase shift of optical **carrier** rather than pulse

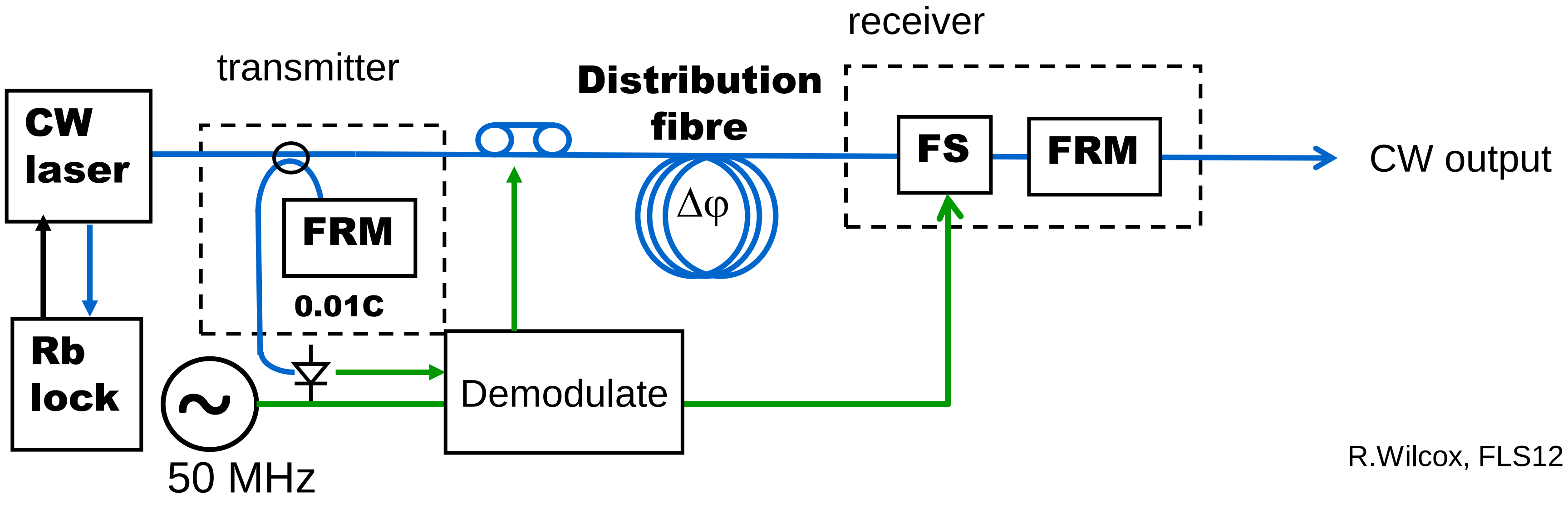
- Much higher sensitivity can be achieved:
  - S-curve from cross-correlator has max sensitivity **14.1 mV/fs** for 100fs pulse
  - Zero crossing of inteference fringes has max sensitivity **1.21 V/fs** at 1550nm



- Problems avoided – PMD, dispersion, SPM

CW timing systems

- Timing stability = Frequency stability
- Lock to a frequency standard.

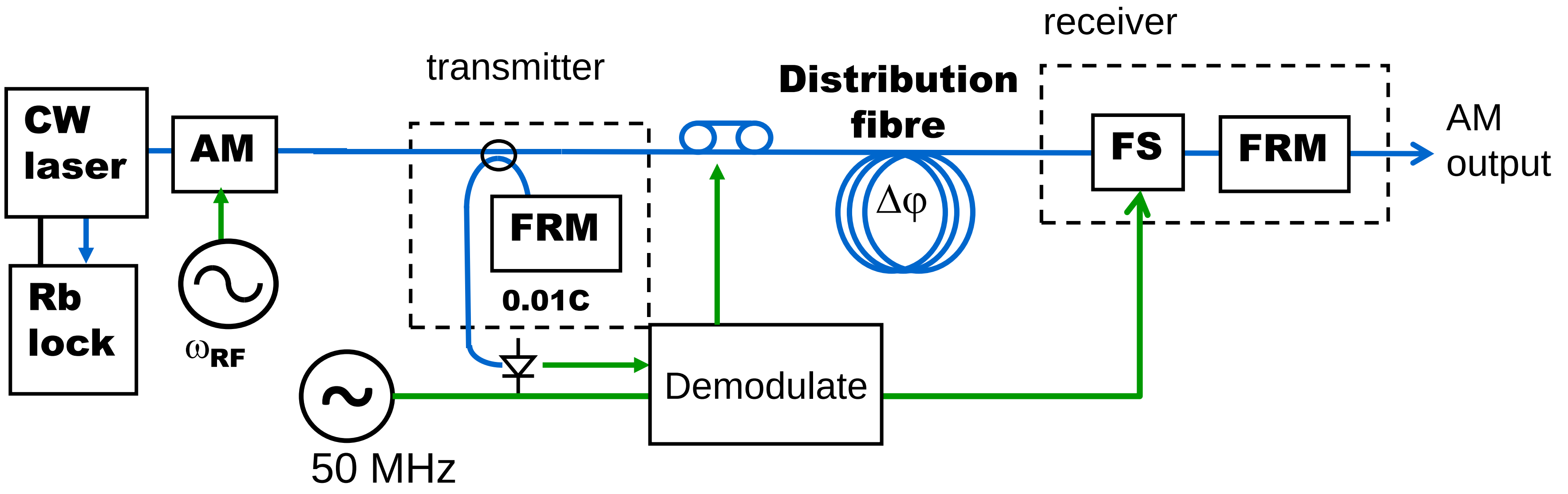


R.Wilcox, FLS12

- New Challenge – Fringe counting, Fringe jumps!
- Divide down to lower frequency (but we're optical, so have lots of headroom to do this)
- Down-convert the phase information to a lower band

CW timing systems

- Optical frequencies much too high for accelerators to operate on. Need clocking information in the RF range.
- Once fibre is stabilized, amplitude modulation required to transmit clock frequency

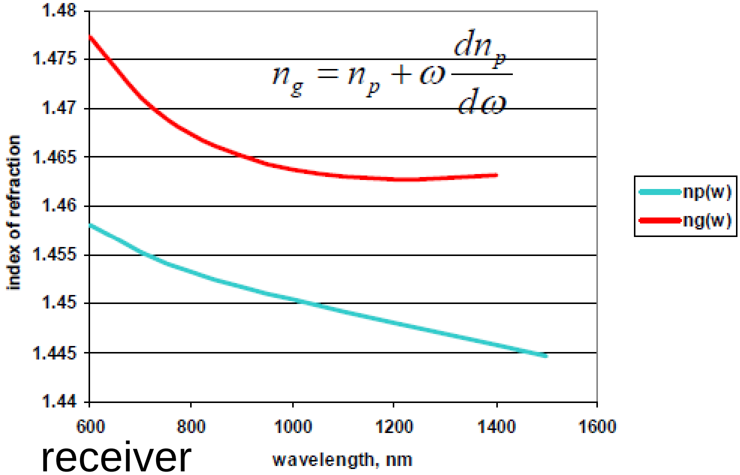


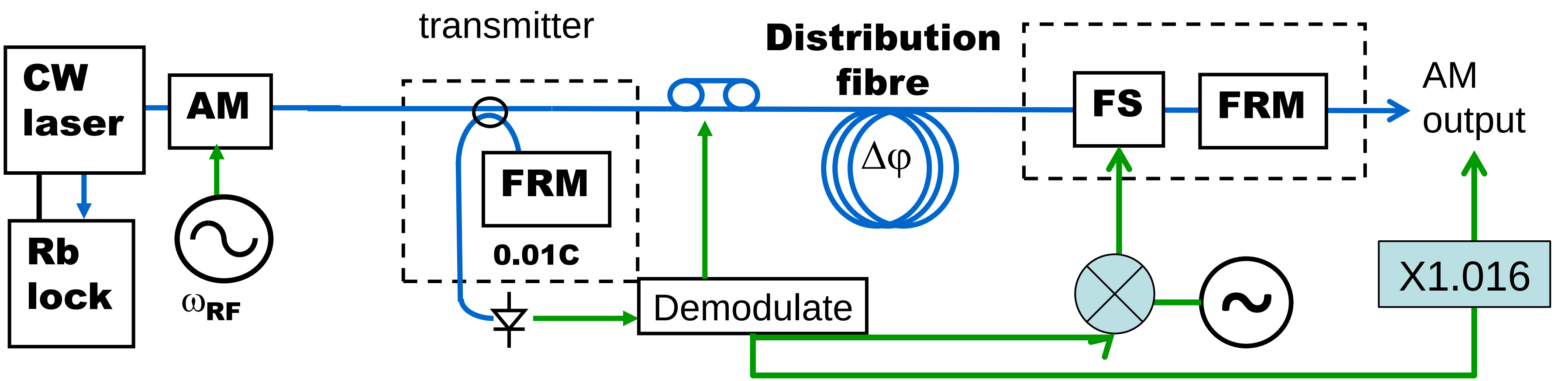
R.Wilcox, FLS12

We will stabilize group delay while measuring phase delay

BUT.... phase delay ≠ group delay

- Difference has been measured to be 1.6%
- Add this to the 'feed forward'



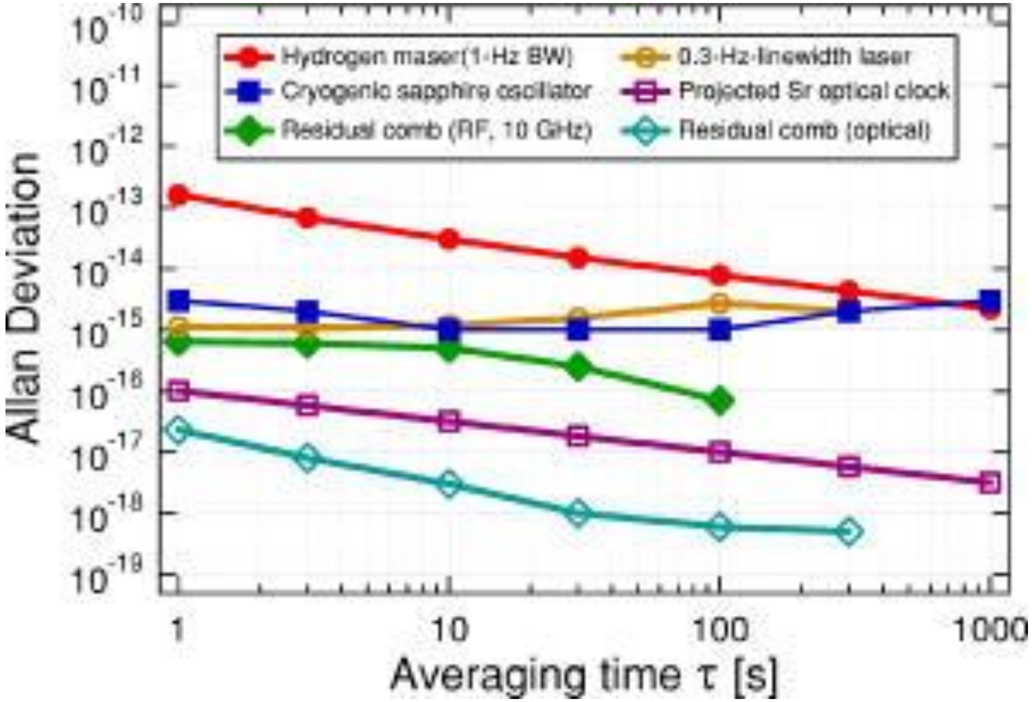


R.Wilcox, FLS12

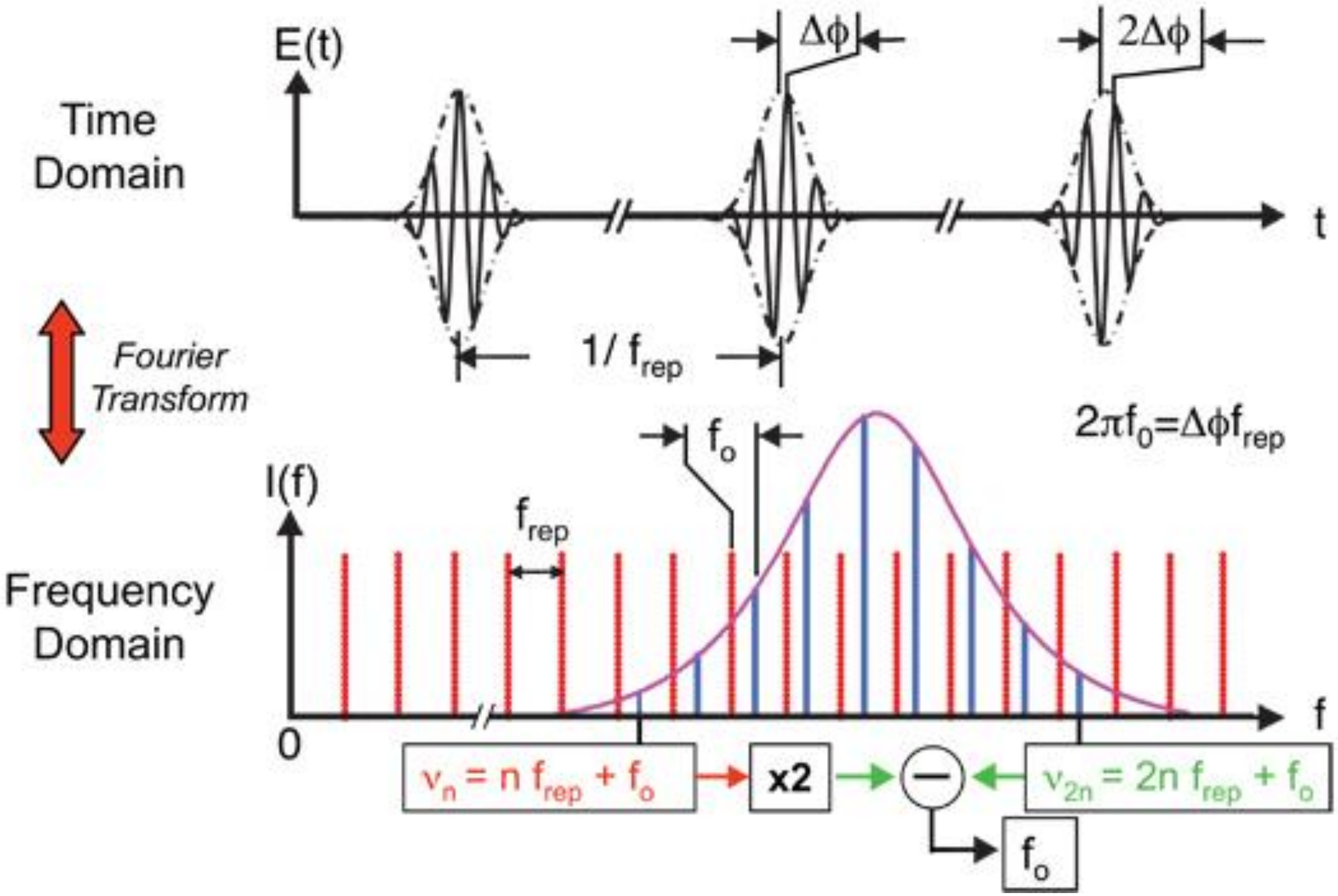
Laser-to-Laser locking

- Required for:
  - Photoinjector laser
  - Seed lasers
  - Pump-probe lasers
  - Diagnostics

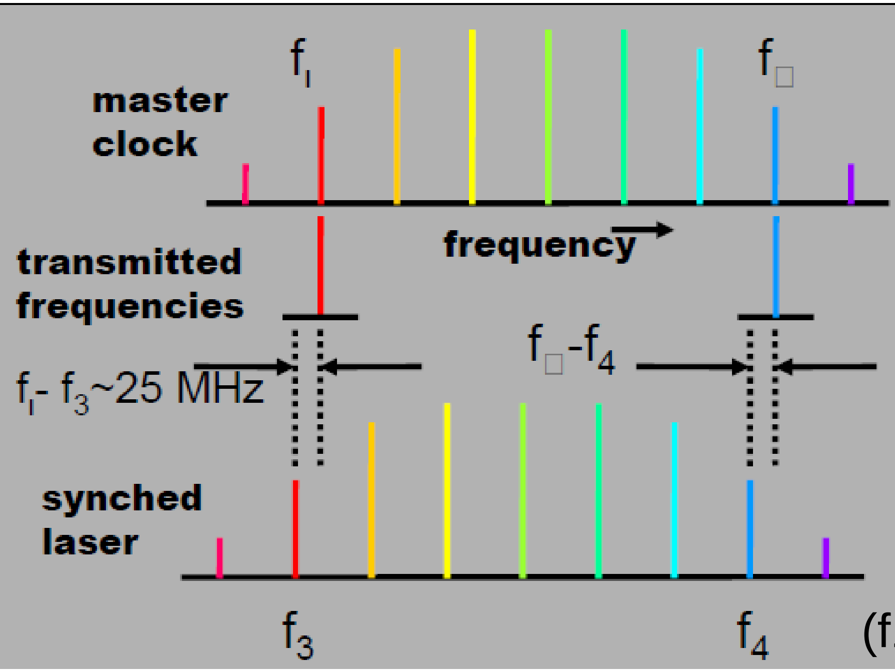
- Can we take advantage of the very best clocks?



Optical frequency combs



Laser-to-laser locking



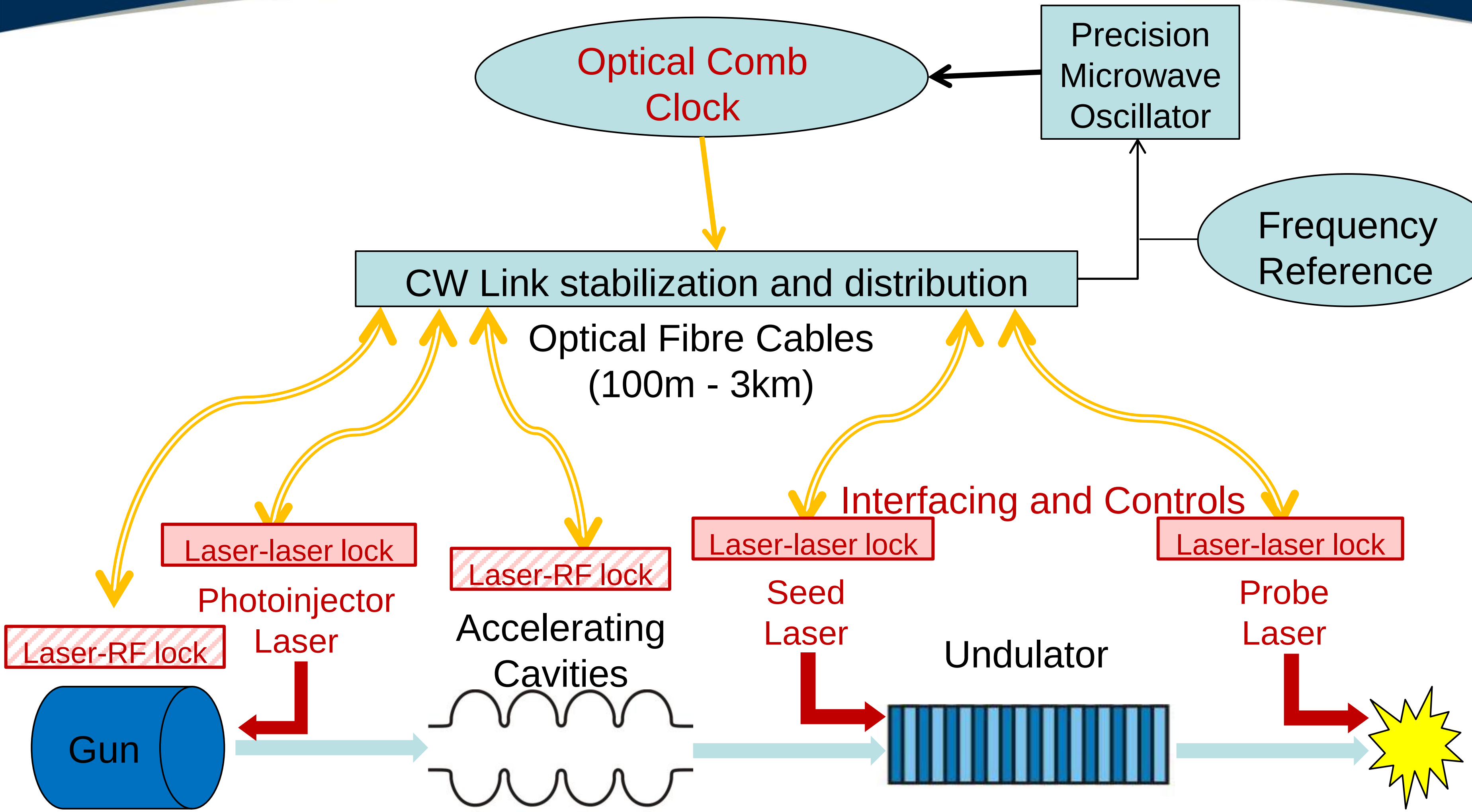
Lock two frequencies within the frequency comb separated by 5 THz.

For a 1**degree** error in phase detection, temporal error is <0.6 fsec

(f1–f3) –(f2–f4) = error signal

<u>Neither laser needs to be CEP stabilized</u>

CW timing systems



Optical Comb Clock

Precision Microwave Oscillator

Frequency Reference

CW Link stabilization and distribution

Optical Fibre Cables (100m - 3km)

Interfacing and Controls

Laser-RF lock

Laser-laser lock

Photoinjector Laser

Laser-RF lock

Accelerating Cavities

Laser-laser lock

Seed Laser

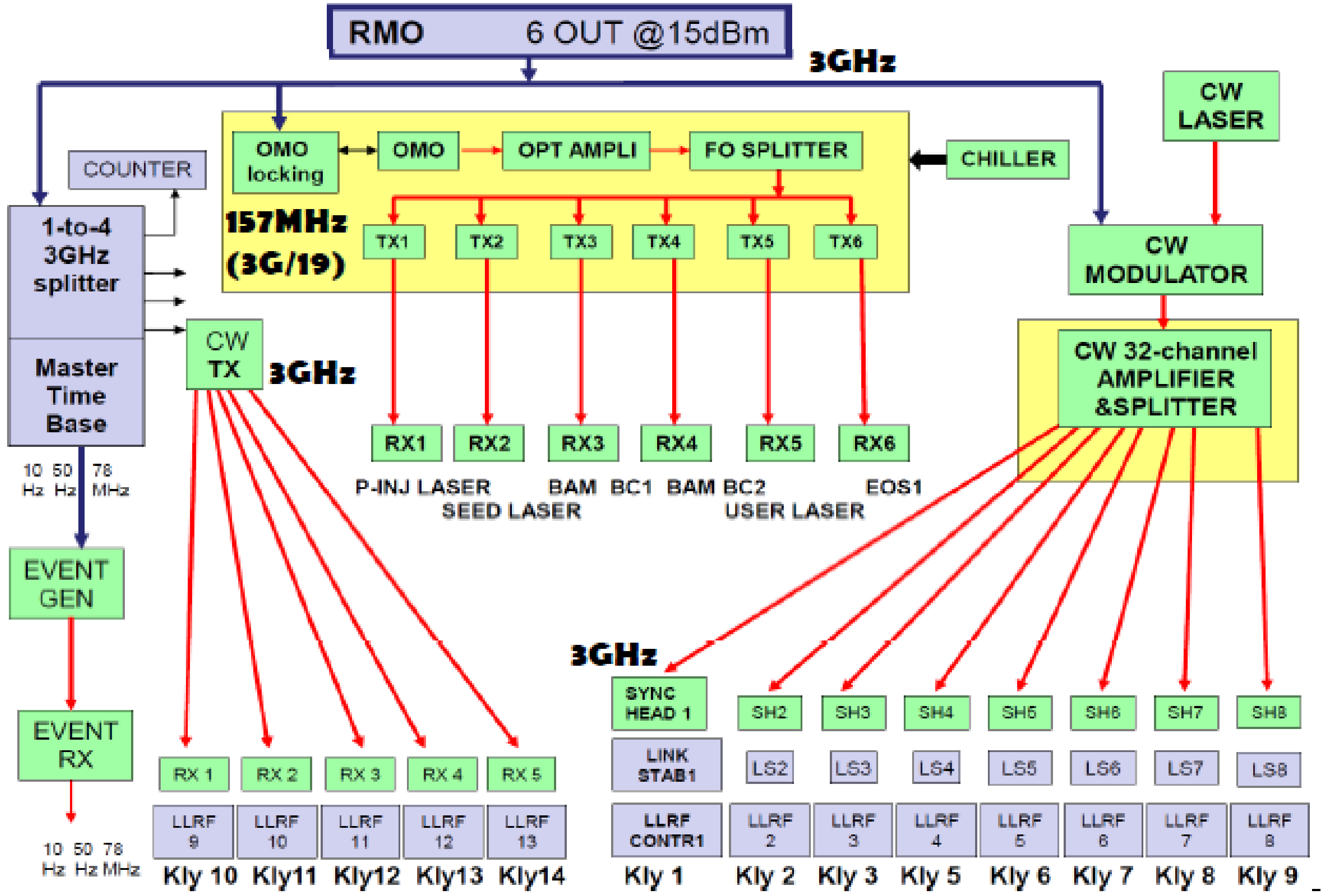
Laser-laser lock

Probe Laser

Gun

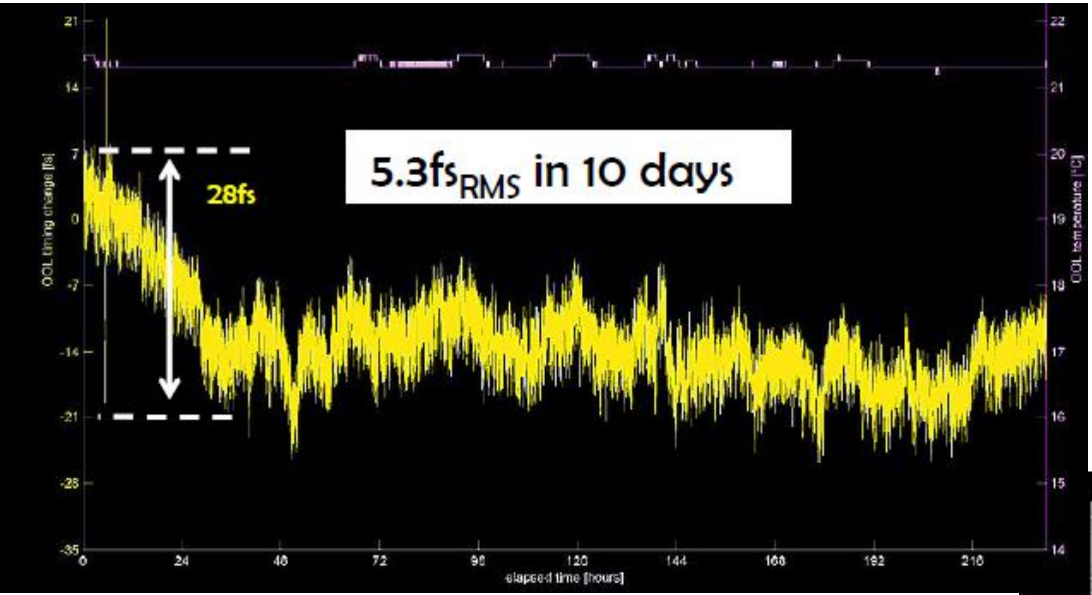
Undulator

Hybrid system at Fermi



Mario. Ferianis, FEL 2011

Hybrid system at Fermi



5.3fs$_{RMS}$ in 10 days

Arrival Time Jitter: 74 fs avg

RF and PIL stability are in specs!

Mario. Ferianis, FEL 2011

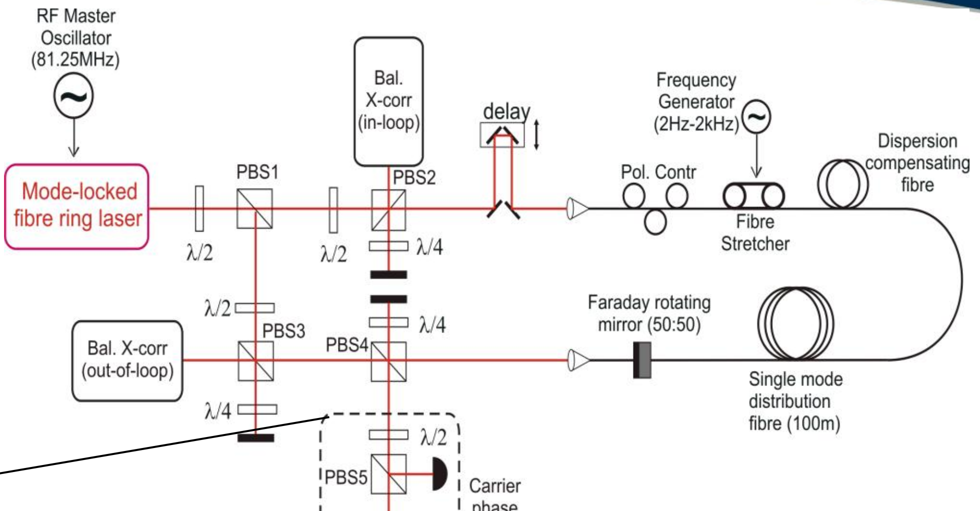
All-optical femtosecond timing system for the Fermi@Elettra FEL

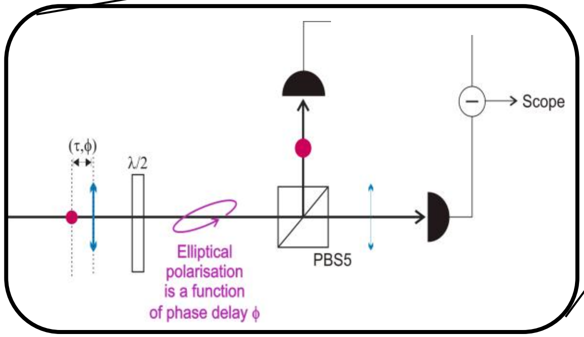
Summary

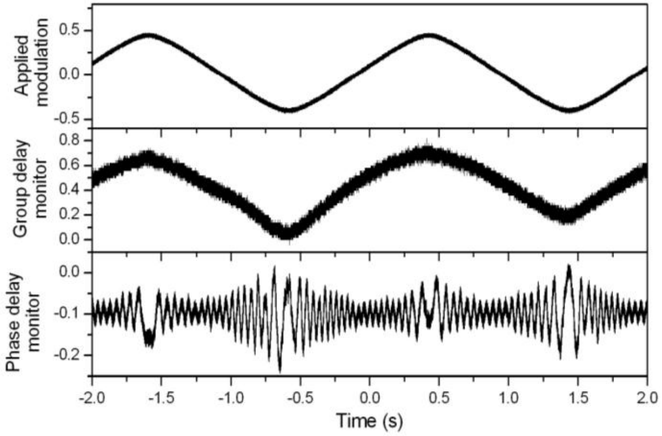
- RF timing schemes:
  - Simple distribution, cost effective for small facilities
  - Low resolution, very expensive for large facilities
- Pulsed timing schemes:
  - >5fs resolution, easy to integrate, high bandwidth output, commercially available
  - >5fs resolution, scalability?
- CW timing schemes:
  - Attosecond distribution, long distances
  - Complex, costly, difficult to integrate

Future R&D

- Higher resolution with pulsed inteferometric system
- Integration with electro-optic techniques







- What lengths do we need to reach

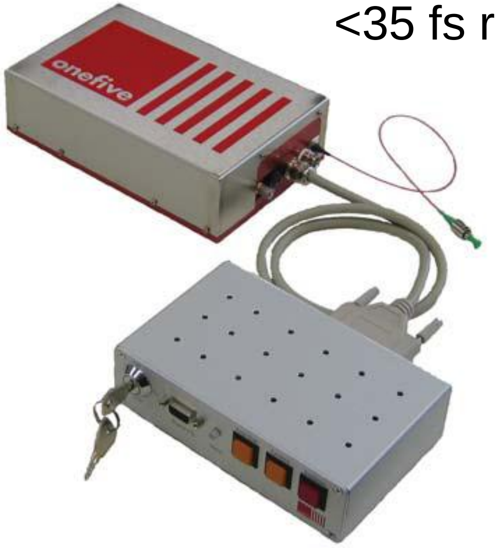
(Recall 'same return path' assumption)

Thanks for your attention!

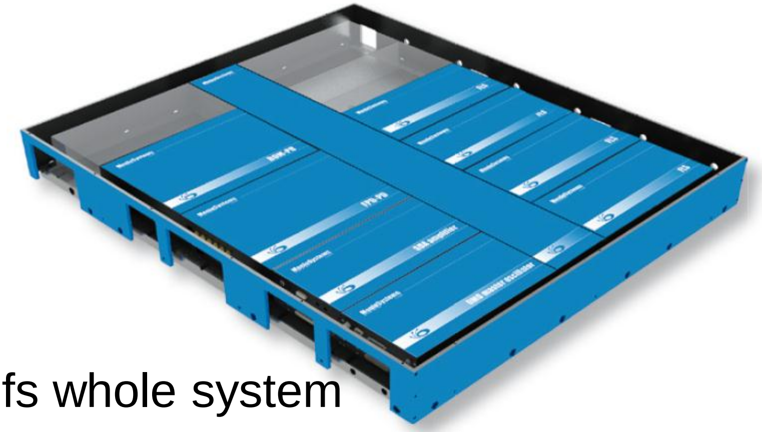
Commercial Systems

5×10^{-13} stability

<35 fs rms jitter



40fs distribution



5.3fs whole system