Synchronization Part I

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Lecture Schedule (March 2008)

- LLRF Part I (Requirements and Design)
  – March 6, 13:30
- LLRF Part 2 (Maschine Studies at FLASH)
  – March 7: 10:00
- LLRF Part 3 (LLRF for the XFEL)
  – March 11 at 13:30
- **Timing and Sync. Part I (Concepts)**
  – **March 14 at 10:00**
- Timing and Sync. Part II (Design)
  – March 17 at 10:00
- European XFEL (Project Overview)
  – March 26 at 13:30

Outline Synchronization Part I

- Definition of Synchronization
- Synchronization Requirements for ERLs
- Basic concepts
  - Phase noise, phase jitter, timing jitter
  - Phase drift
- Timing/phase measurement
  - RF phase detector
  - Optical detector
- Generation of stable timing
- Stable signal transport
  - RF signal via coaxial cable
  - Fiber link

Outline Synchronization I (C‘tnd)

- Synchronization of systems
  - Phase locked loop (rf/microwave)
  - Synchronization of laser to rf
  - Conversion of Optical pulses to RF
- Beam diagnostics
  - Bunch shape
  - Bunch arrival time
  - Beam energy

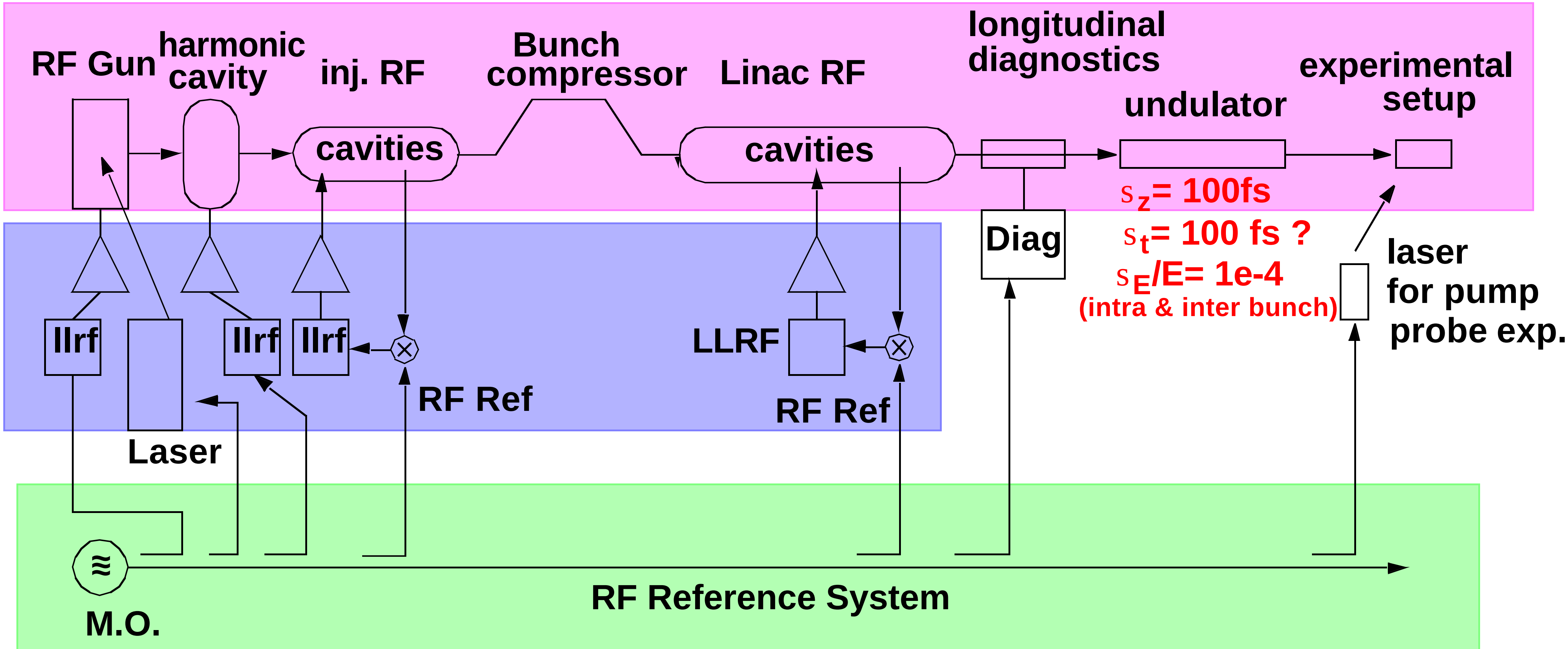
Synchronization

Synchronization

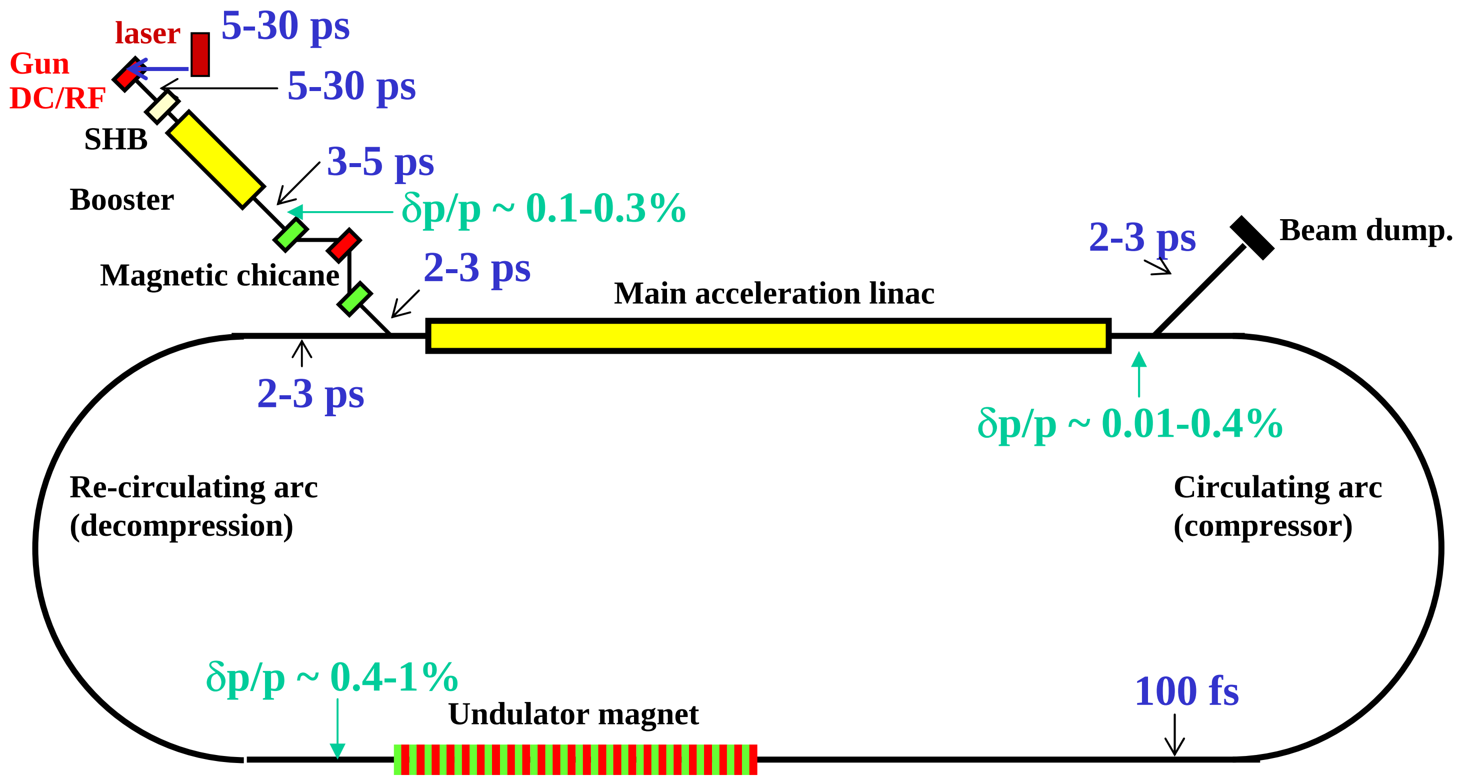
- Definition of Synchronization
  - [1] coordinating by causing to indicate the same time
  - [2] an adjustment that causes something to occur or recur in unison
  - [3] the relation that exists when things occur at the same time
- What is to be synchronized in accelerators:
  - RF reference signals
  - Laser pulses (Photocathode laser, seed laser, pumpe-probe laser, new: master oscillator lasers)
  - Electrical and optical timing signals
  - Charged particle beams (bunch arrival time)

Requirements for ERLs

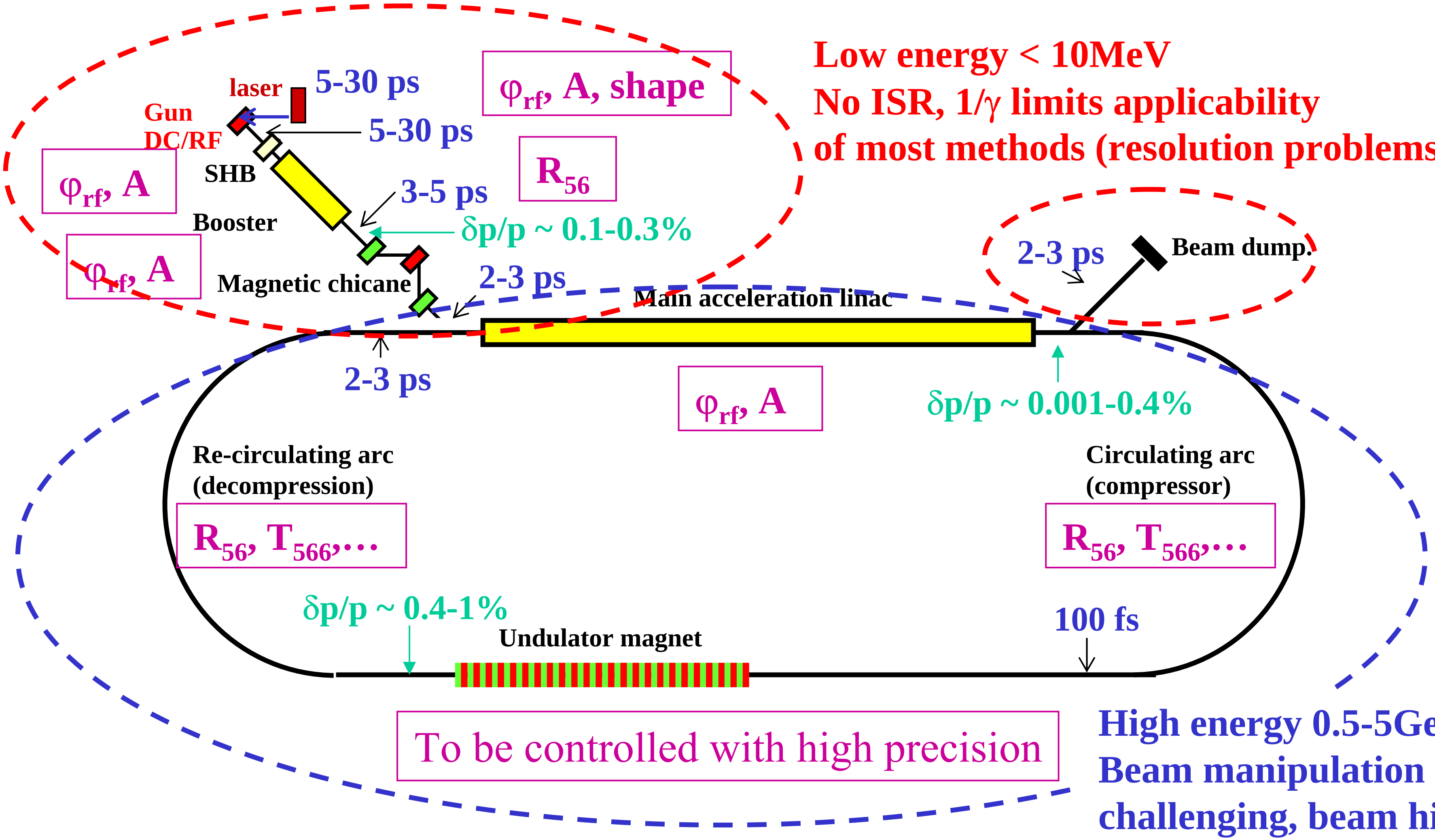
Synchronisation in FELs



Prototype Layout for ERL



Prototype Layout for ERL



Low energy < 10MeV
No ISR, 1/γ limits applicability of most methods (resolution problems)

High energy 0.5-5GeV
Beam manipulation more challenging, beam highly destructive,
10fs resolution desired!

Source of timing jitter
- Caused by RF acceleration prior BC-

Timing jitter Behind BC — Gradient — Phase — Incoming Timing jitter

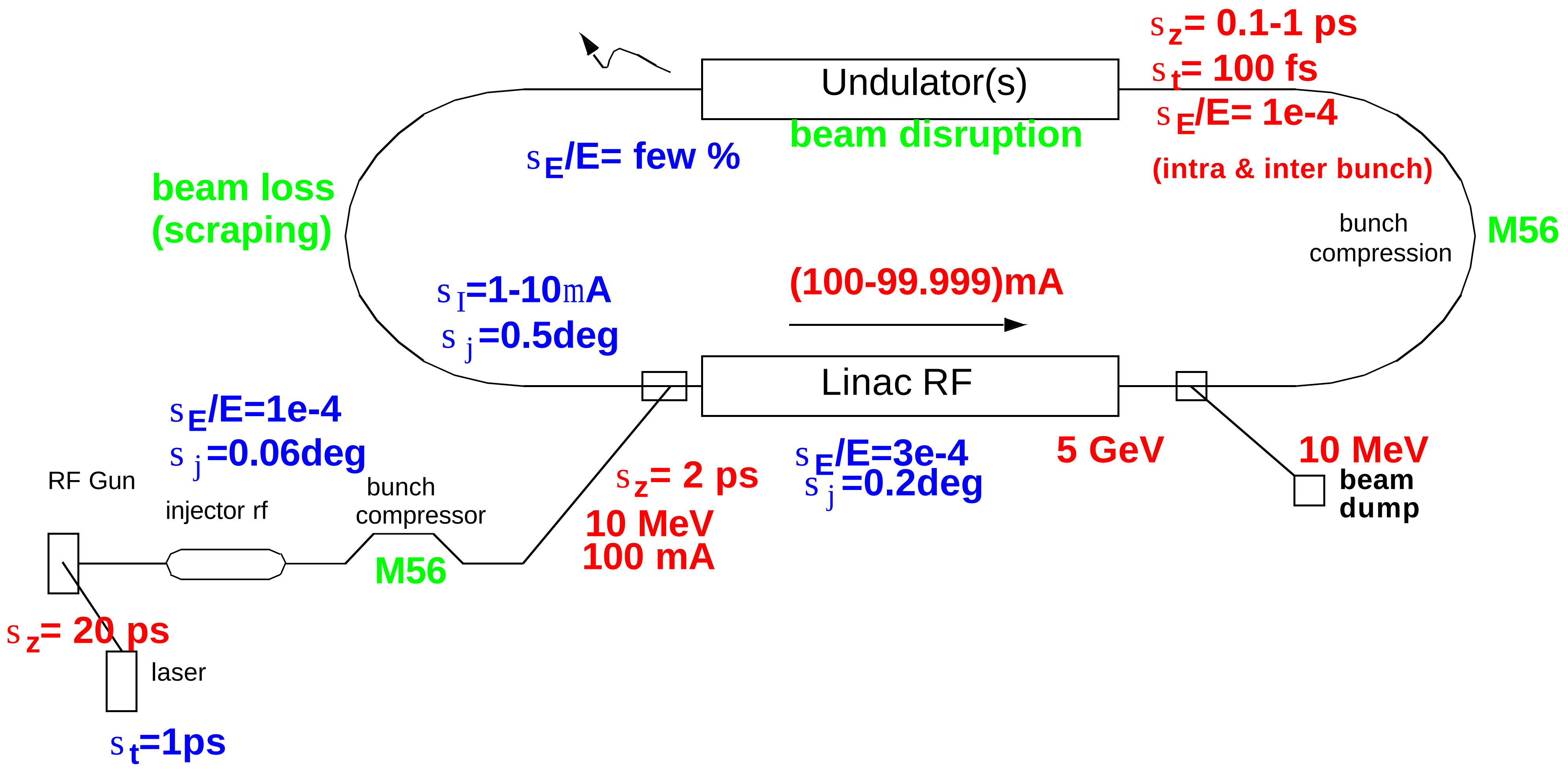
$$\Sigma_t^2 \approx \left(\frac{R_{56}}{c_0}\frac{\sigma_A}{A}\right)^2 + \left(\frac{C-1}{C}\right)^2 \left(\frac{\sigma_\phi}{c_0 k_{rf}}\right)^2 + \left(\frac{1}{C}\right)^2 \Sigma_{i,t}^2$$

6.0 ps/% — **2 ps/deg** — **0.05 ps/ps** (Only if not corrected)

C compression factor (20)
R_{56} ~ 180 mm
k_{rf}: wavenumber RF acceleration (27.2/m)

Vector sum regulation of 8 cavities => 1 deg == 1.8% (statistic 8 cav. helps)
But! Phase changes can be correlated due to local oscillator changes

Synchronisation in ERLs (example)



Requirements

- Derived from beam parameters:
  - Energy Stability and Energy spread
  - Emittance
  - Bunch length
  - Arrival time
- Subsystem Requirements
  - Timing and Synchronization
    - Photocathode Laser, Seed laser, pump probe laser, beam diagnostics (streak camera)
    - RF reference frequencies
  - RF amplitude and phase stability (RF gun, Injector, Linac)

Error sources for timing, bunch length and energy spread in ERLs

- Laser timing jitter (reduced by bunch compressor)
- RF Stability
  - RF Gun
  - harmonic cavity
  - rf section before bunch compressor (off-crest)[1]
  - linac rf[2]
- Stability of magnets (bunch compression, phase for energy recovery)

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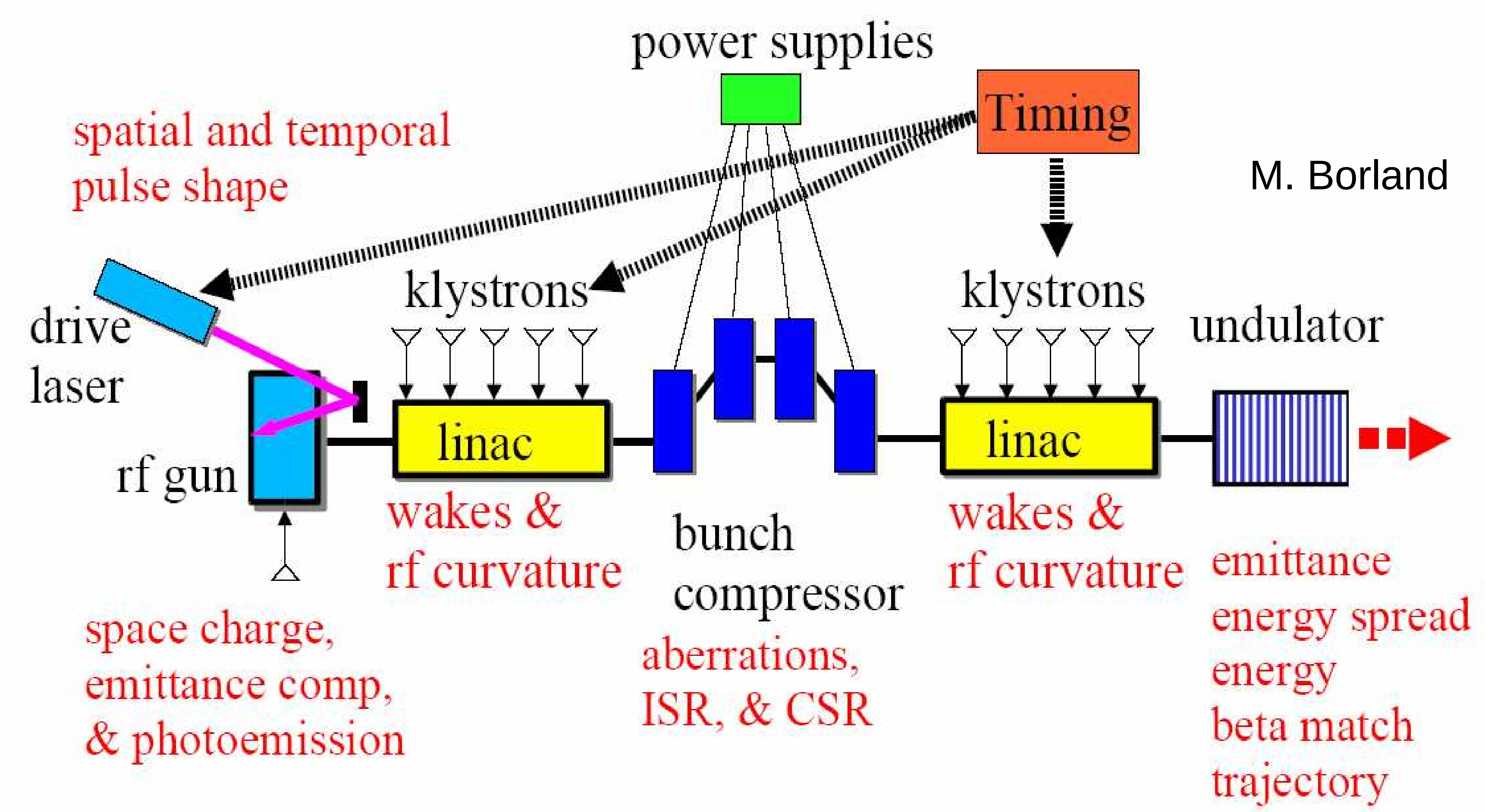
1. Requires up to 1e-4 for ampl. and up to 0.05 deg. in phase
2. Disturbed by beam disruption in beam insertion devices (undulators) and beam instabilities (BBU)

Various factors may affect beam performance



Jitter budgets for LCLS and TESLA

for 0.1% energy spread and 12% current modulation.

(without beam arrival timing requirement)

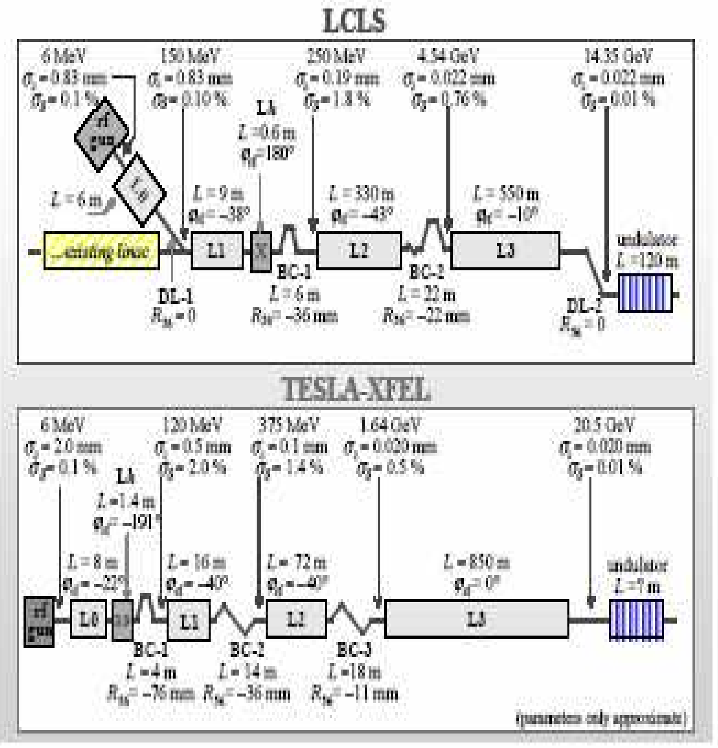
P. Emma, T. Limberg

Set up timing jitter budget, compare LCLS and TESLA XFEL

Table 2. A possible longitudinal jitter tolerance budget for LCLS and TESLA-XFEL.

$|\langle \Delta E/E_0 \rangle| < 0.1\%$ and $|\Delta I/I_0| < 12\%$

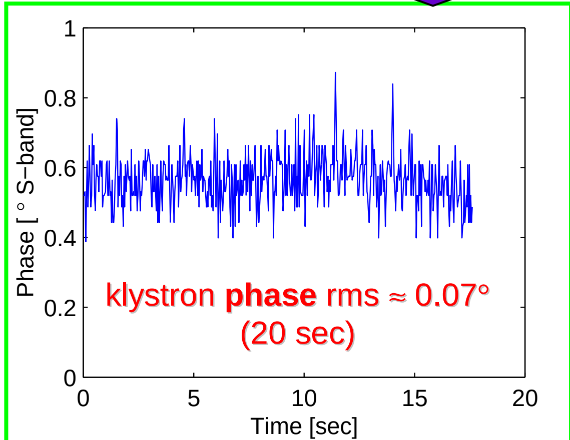
Parameter	Symbol	LCLS	XFEL$_1$	Unit
Gun timing jitter	Δt_0	0.80	1.5	psec
Initial bunch charge	$\Delta Q/Q_0$	2.0	10	%
mean L0 rf phase	φ_0	0.10	0.05	deg
mean L1 rf phase	φ_1	0.10	0.08	deg
mean L*h* rf phase 3.9-GHz & X-band	φ_h	0.50	0.07	*h*-deg
mean L2 rf phase	φ_2	0.07	0.10	deg
mean L3 rf phase	φ_3	0.15	1.0	deg
mean L0 rf voltage	$\Delta V_0/V_0$	0.10	0.08	%
mean L1 rf voltage	$\Delta V_1/V_1$	0.10	0.20	%
mean L*h* rf voltage	$\Delta V_h/V_h$	0.25	0.30	%
mean L2 rf voltage	$\Delta V_2/V_2$	0.10	0.20	%
mean L3 rf voltage	$\Delta V_3/V_3$	0.08	0.09	%

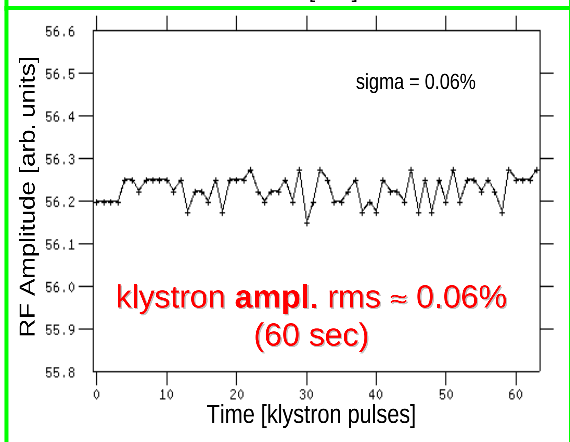


RF phase stability in some existing machines

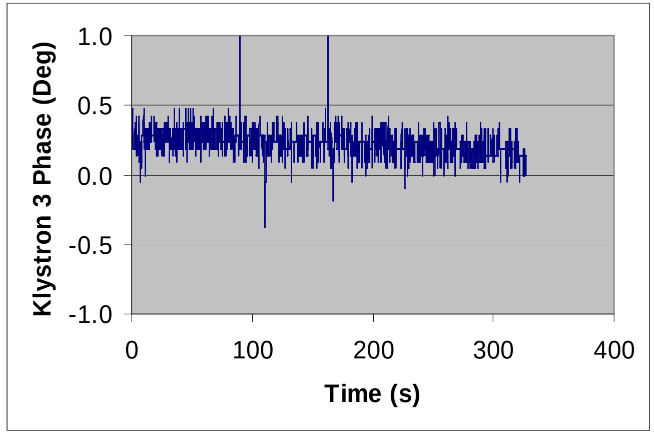
measured RF stability

R. Akre, LCLS





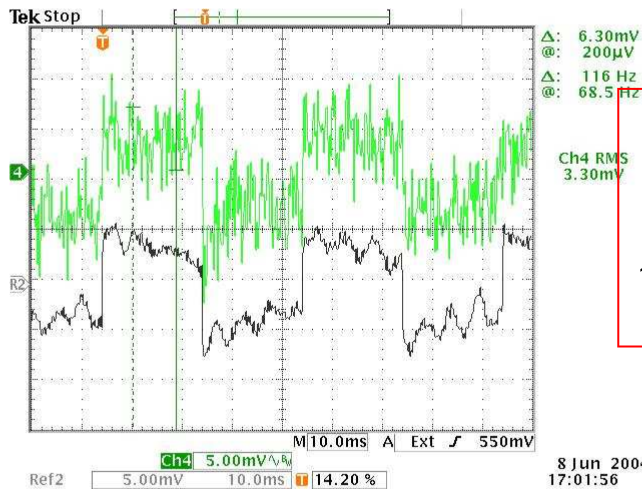
SPPS beam results suggest this RF stability already exists in SLAC linac



MIT Bates Linac RF

Zolfaghari, Cheever, Wang, Zwart

~0.07 degree(rms) level



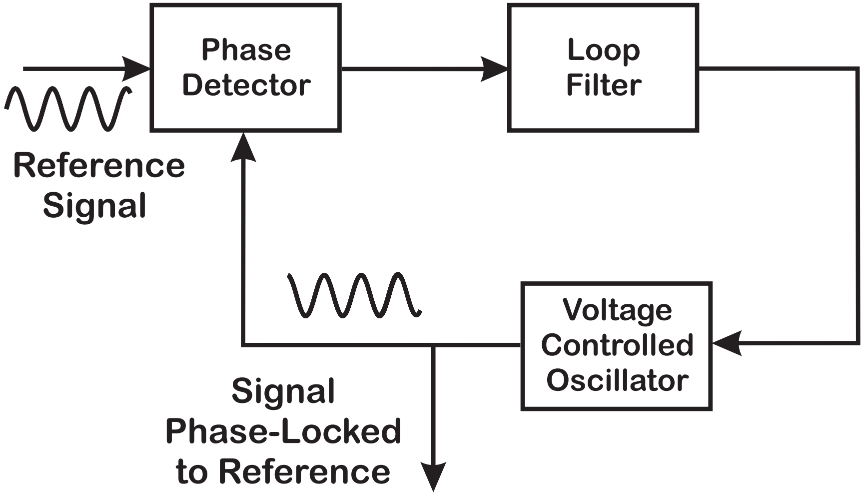
Rossendorf, cw scrf,

Gabriel

~0.02 degree (rms) level

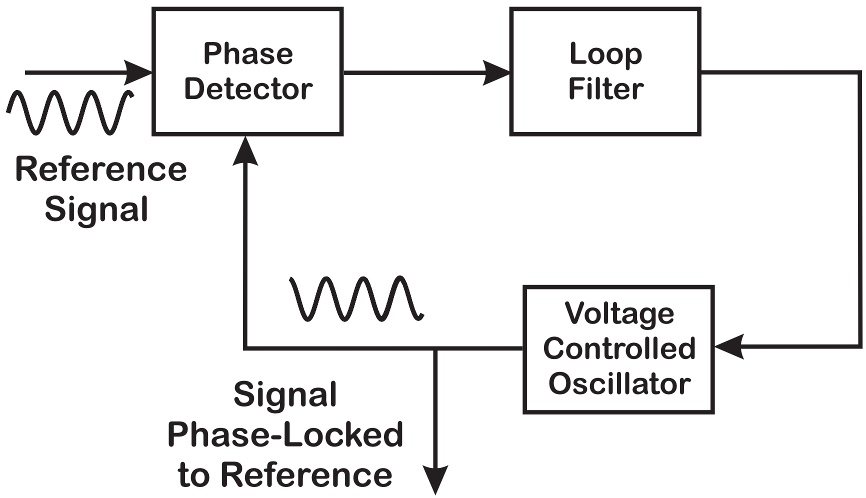
JLAB, cw scrf, ~0.01 degree rms level
0.01% rms amplitude level

PLL Basics



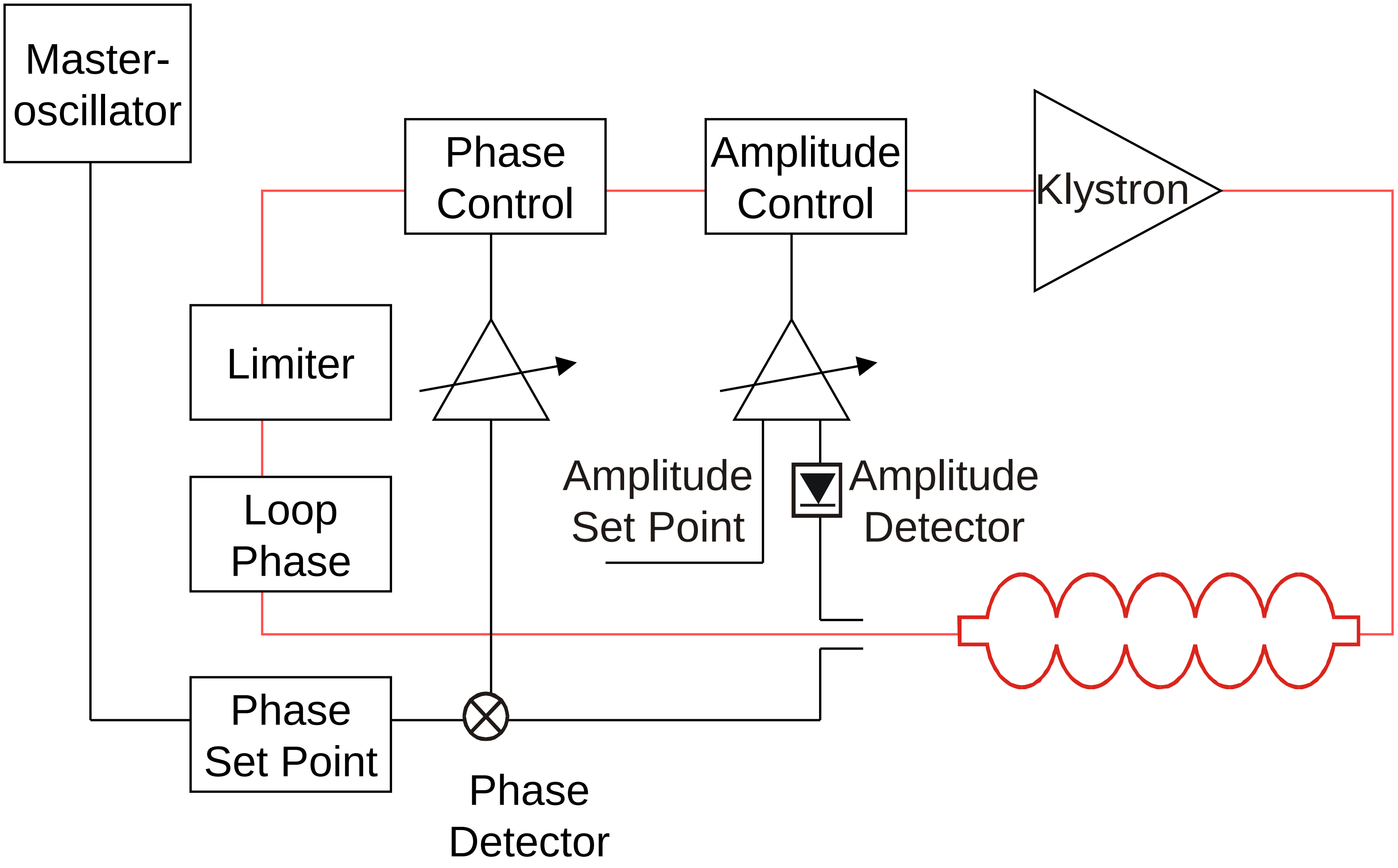
- **Basic idea of a phase-locked loop:**
  - inject sinusoidal signal into the reference input
  - the internal oscillator locks to the reference
  - frequency and phase differences between the reference and internal sinusoid $\Longrightarrow k$ or 0
  - Internal sinusoid then represents a filtered version of the reference sinusoid.
  - For digital signals, Walsh functions replace sinusoids.

General PLL Block Diagram

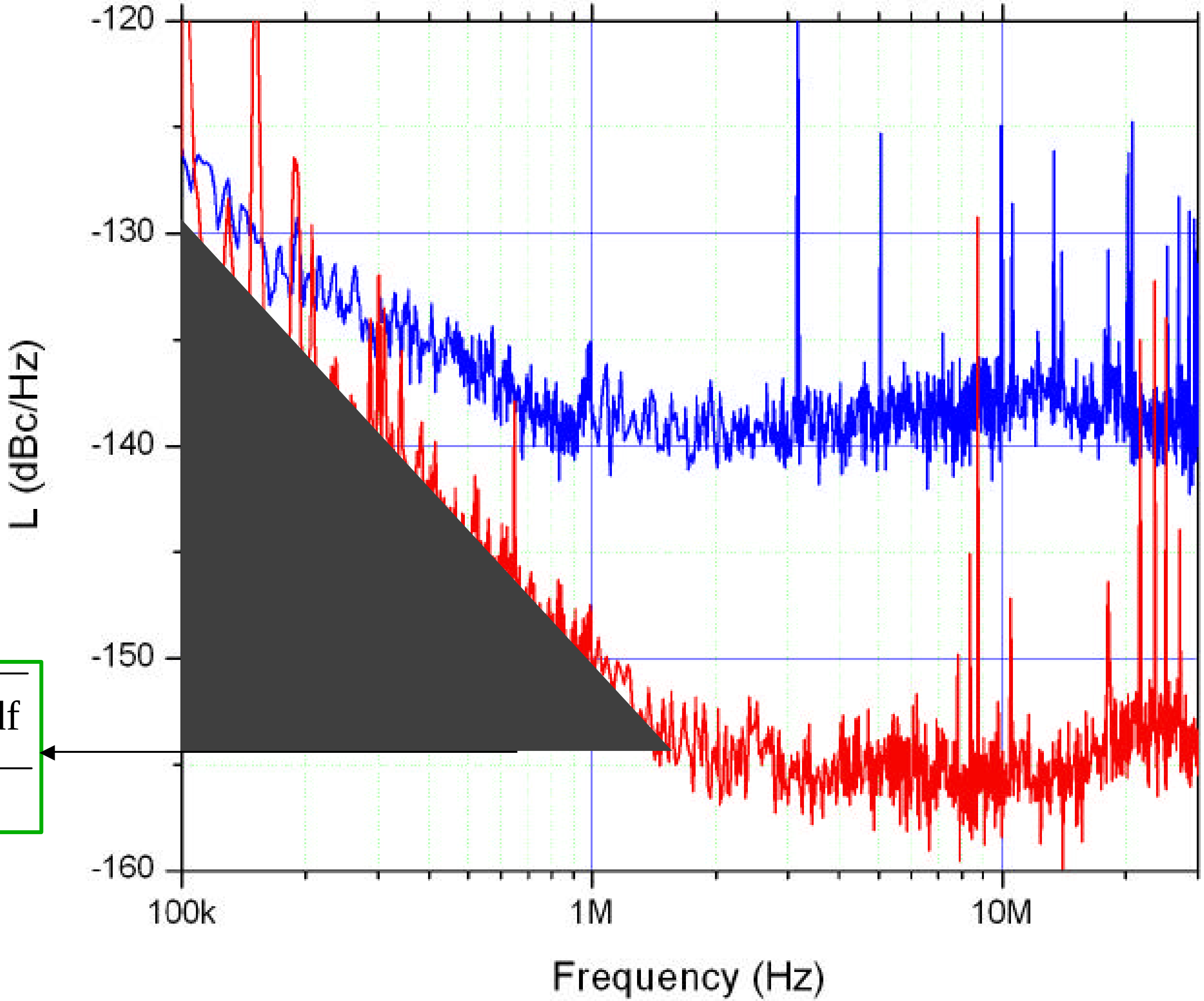


- A phase detector (PD). This is a nonlinear device whose output contains the phase difference between the two oscillating input signals.
- A voltage controlled oscillator (VCO). This is another nonlinear device which produces an oscillation whose frequency is controlled by a lower frequency input voltage.
- A loop filter (LF). While this can be omitted, resulting in what is known as a first order PLL, it is always conceptually there since PLLs depend on some sort of low pass filtering in order to function properly.
- A feedback interconnection. Namely the phase detector takes as its input the reference signal and the output of the VCO. The output of the phase detector, the phase error, is used as the control voltage for the VCO. The phase error may or may not be filtered.

Self Excited Loop

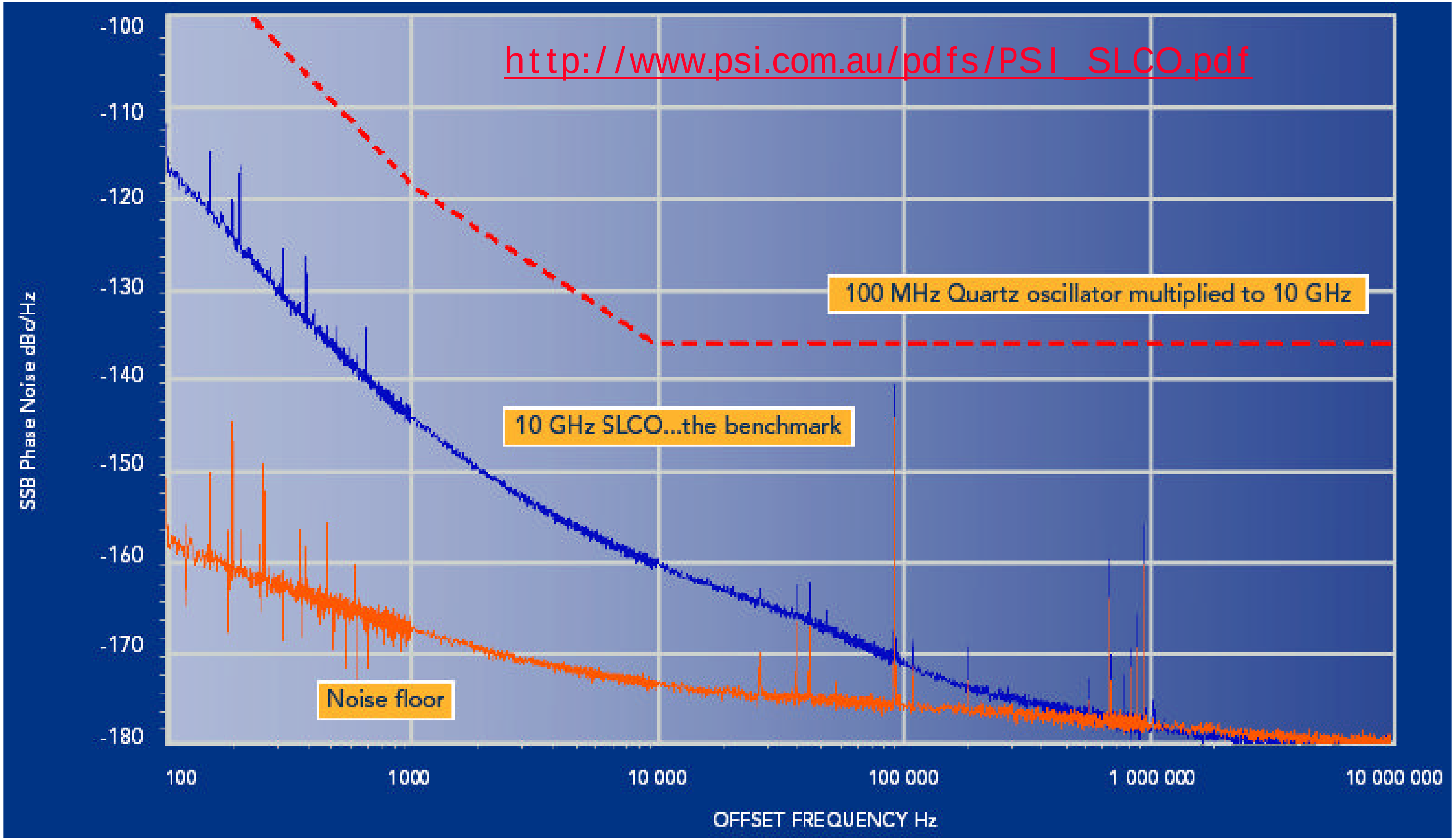


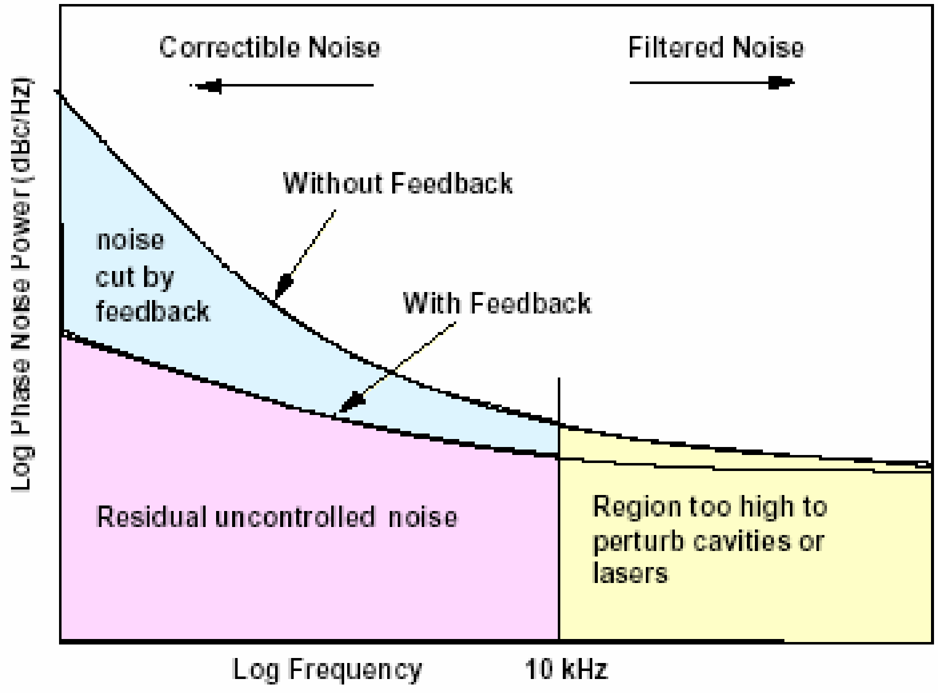
$$\Delta t_{rms} = \frac{\sqrt{2\int_{f_1}^{f_2} L(f)\,df}}{2\pi f_0}$$



Phase Noise (dBc/Hz) reference
Phase Noise (dBc/Hz) free running
Phase Noise (dBc/Hz) laser locked to reference
Phase noise [dBc/Hz^1/2]
Frequency [Hz]
0
-20
-40
-60
-80
-100
-120
-140
-160
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7

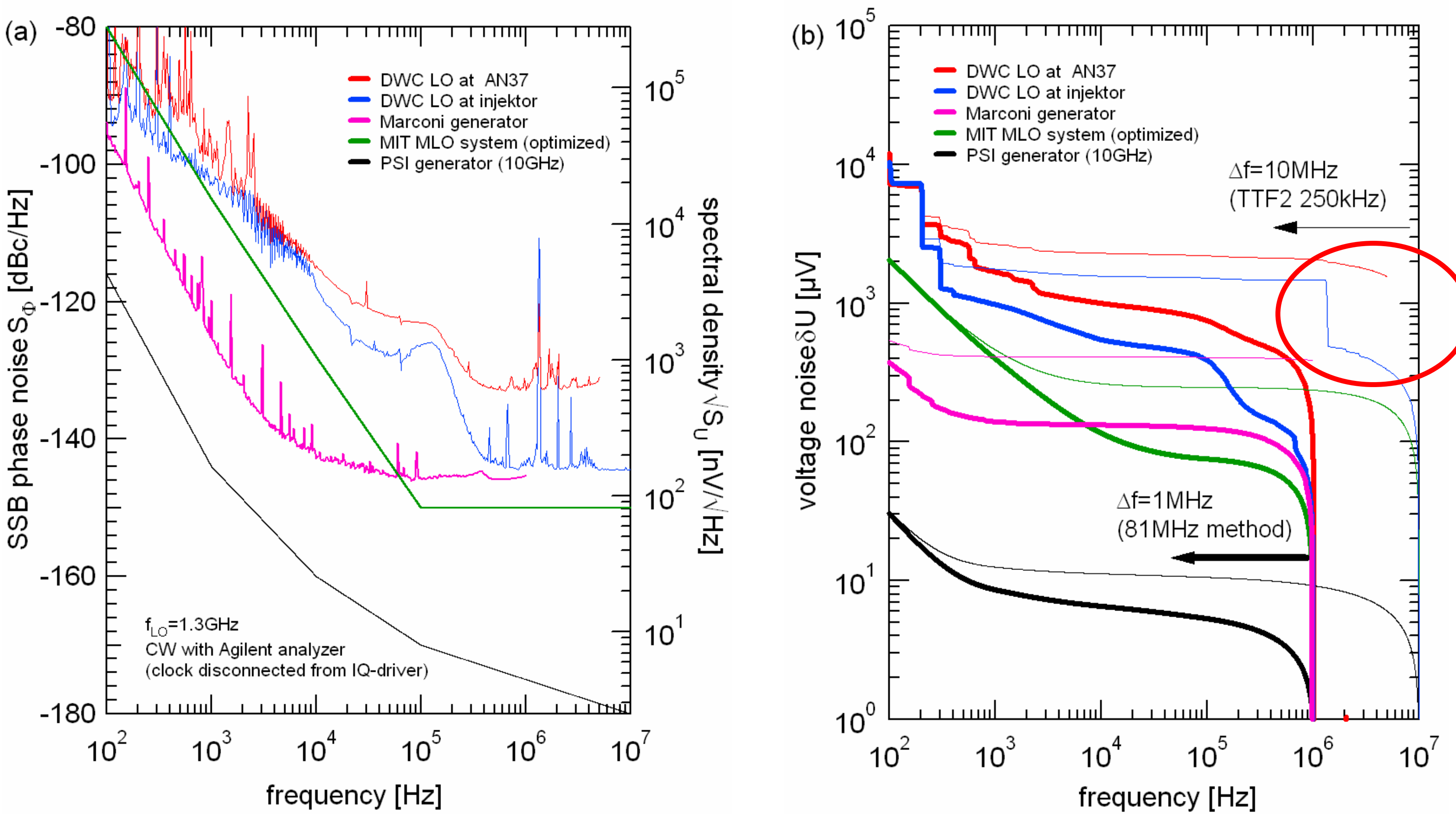
Although there are very good low-noise sapphire loaded cavity oscillators





- **Master oscillator phase noise within bandwidth of feedback systems can be corrected**
- **Residual uncontrolled phase noise plus noise outside feedback systems bandwidth results in timing jitter and synchronization limit**

• **Noise conversion over the LO-Signal at down-converter from master-oszillator :**



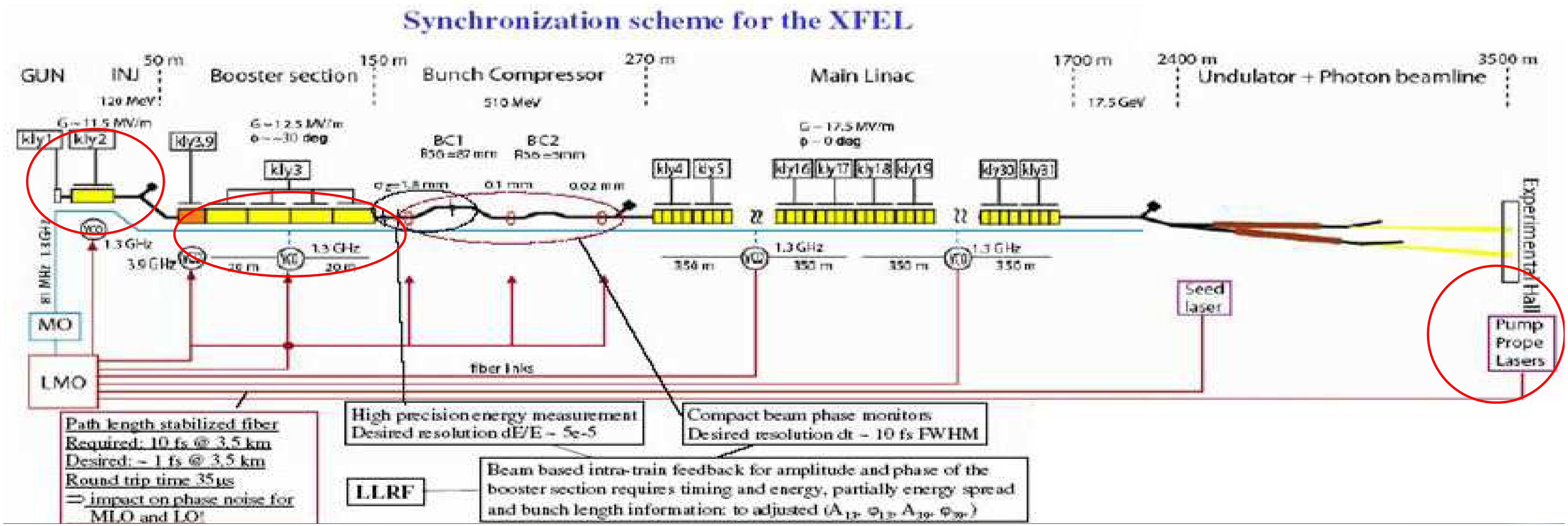
$$dU_{MO} \approx 10 \times dU_{XFEL}$$

Specifications

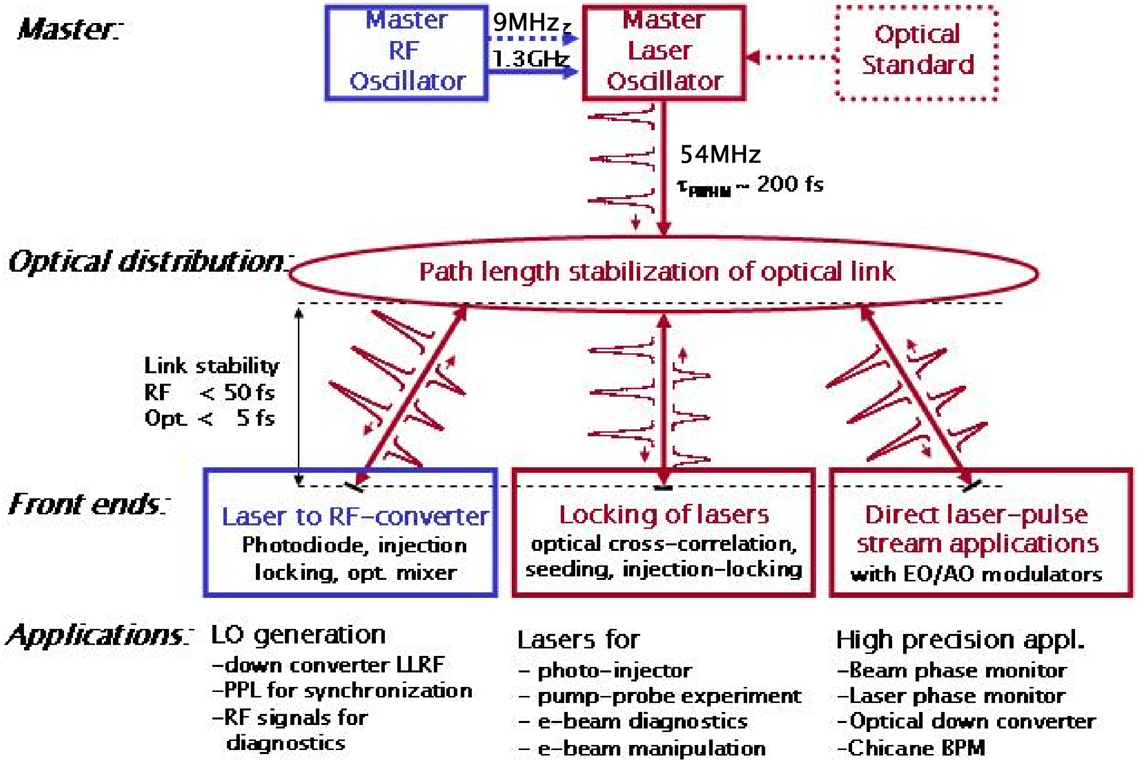
provide FEL pulse with some ten fs arrival time stability:

- amplitude and phase stability of RF in cavities in injector area
- stable reference distributed over 3.5 km to end of linac

Crucial are cavities up to bunch compressor. Jitter in I and Q of RF results in jitter in energy (off crest acceleration). Bunch compressor turns that into arrival time jitter.

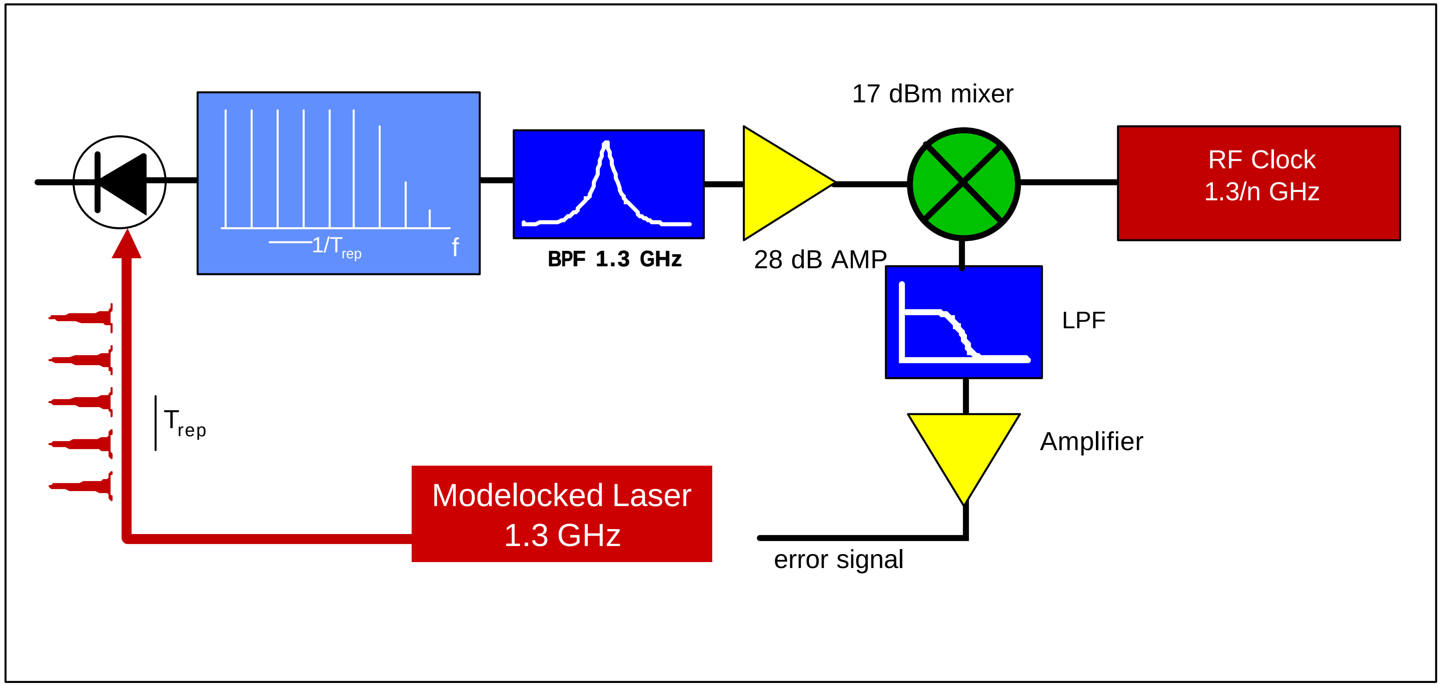


Layout of laser based synchronization



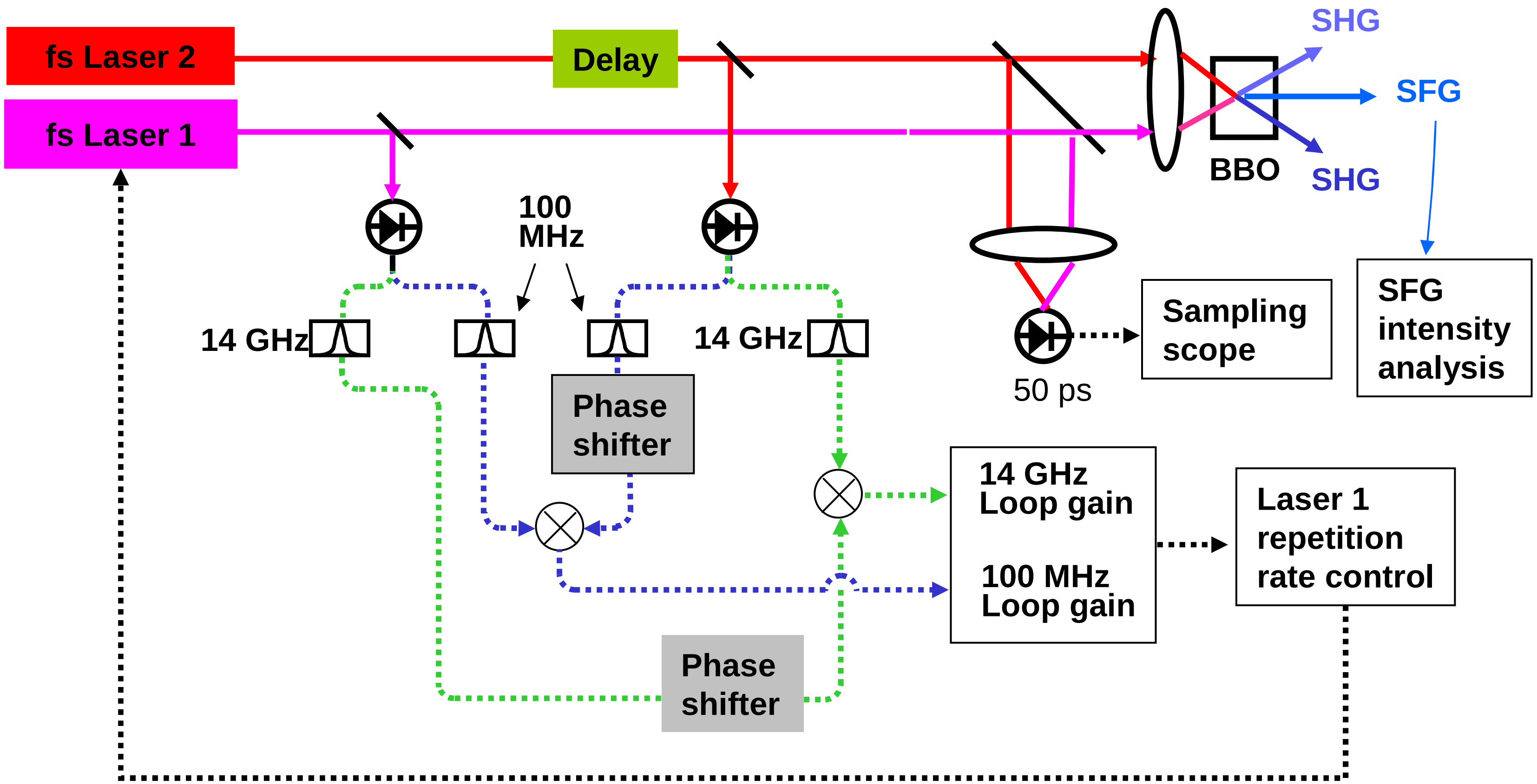
Modelocked fiber laser oscillator rf stabilized

Modelocked Fiber Laser Oscillator – RF Stabilized



- **Phase-lock all lasers to master oscillator**
- **Derive rf signals from laser oscillator**
- **Fast feedback to provide local control of accelerator rf systems**
  - **Synchronization 10's fs**

Experimental Setup for RF Locking

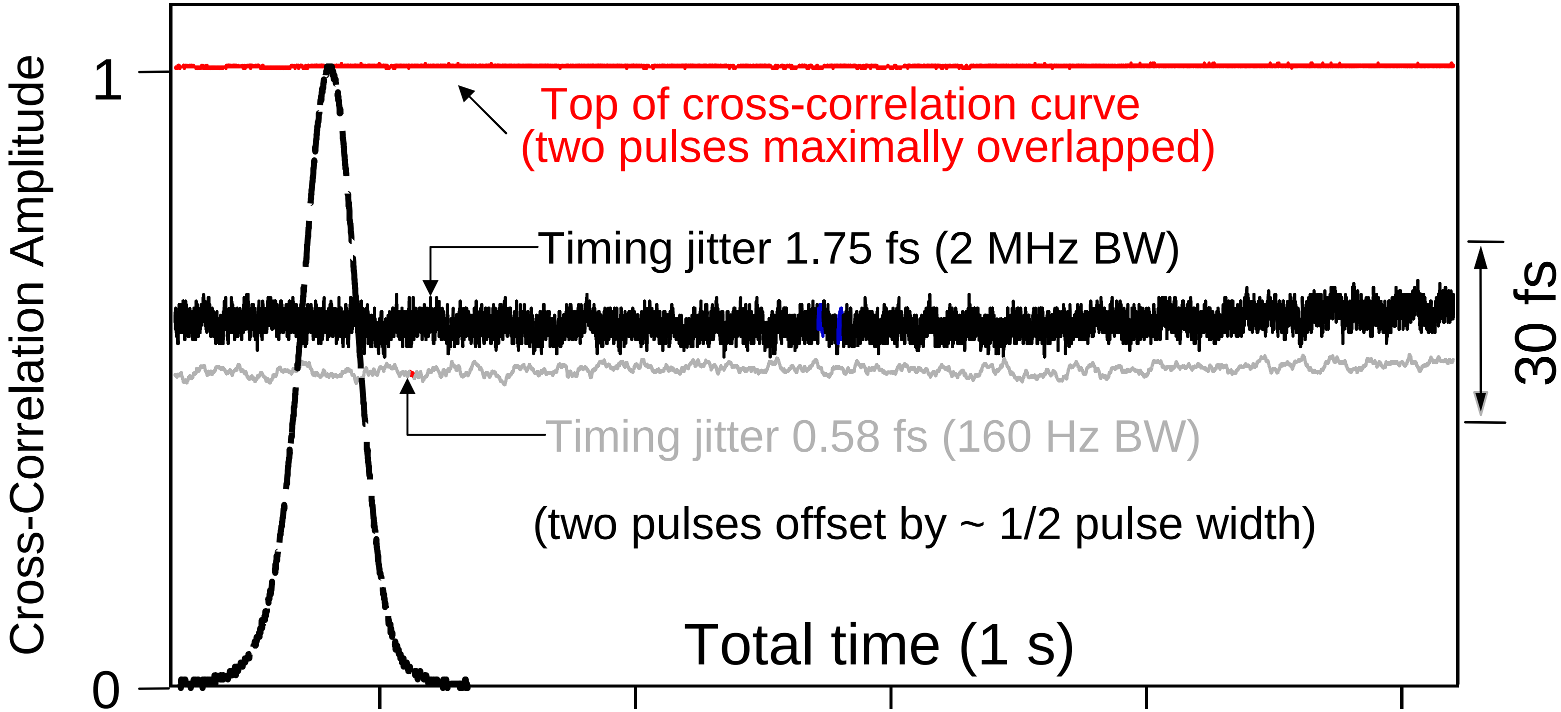


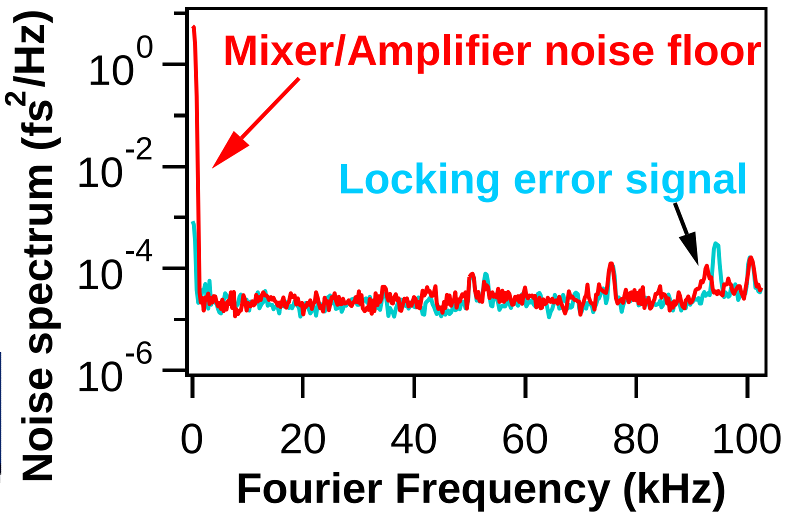
fs lasers share pump source, isolated optical table

RF phase shifter gives electronically addressable timing delay

Jun Ye's lab in collaboration with
Henry Kapteyan and workers

Timing Jitter via Sum Frequency Generation



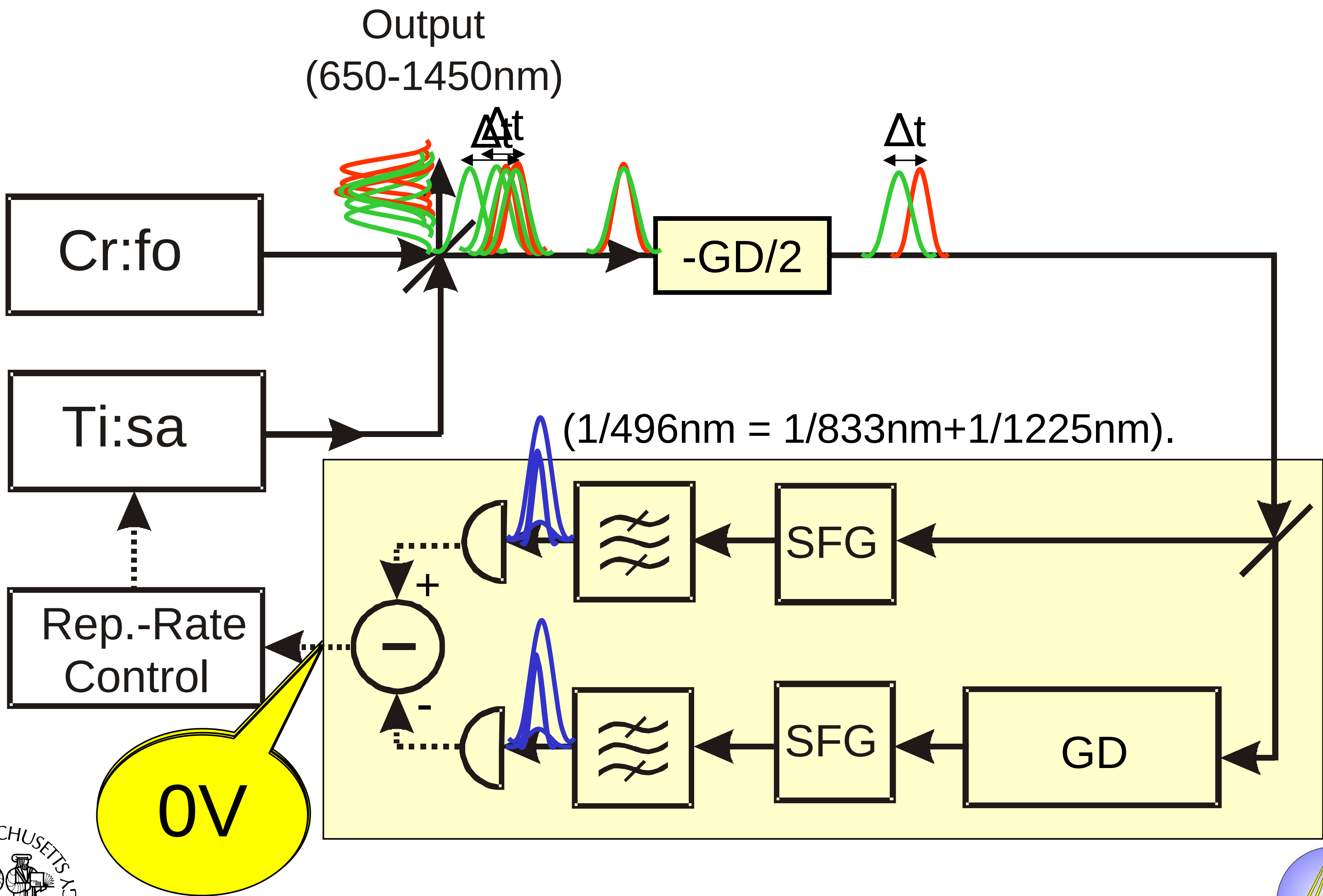


Ma *et al*., Phys. Rev. A **64**, 021802(R) (2001)
Sheldon *et. al*. Opt. Lett **27** 312 (2002) .

UBC

JILA NIST-CU

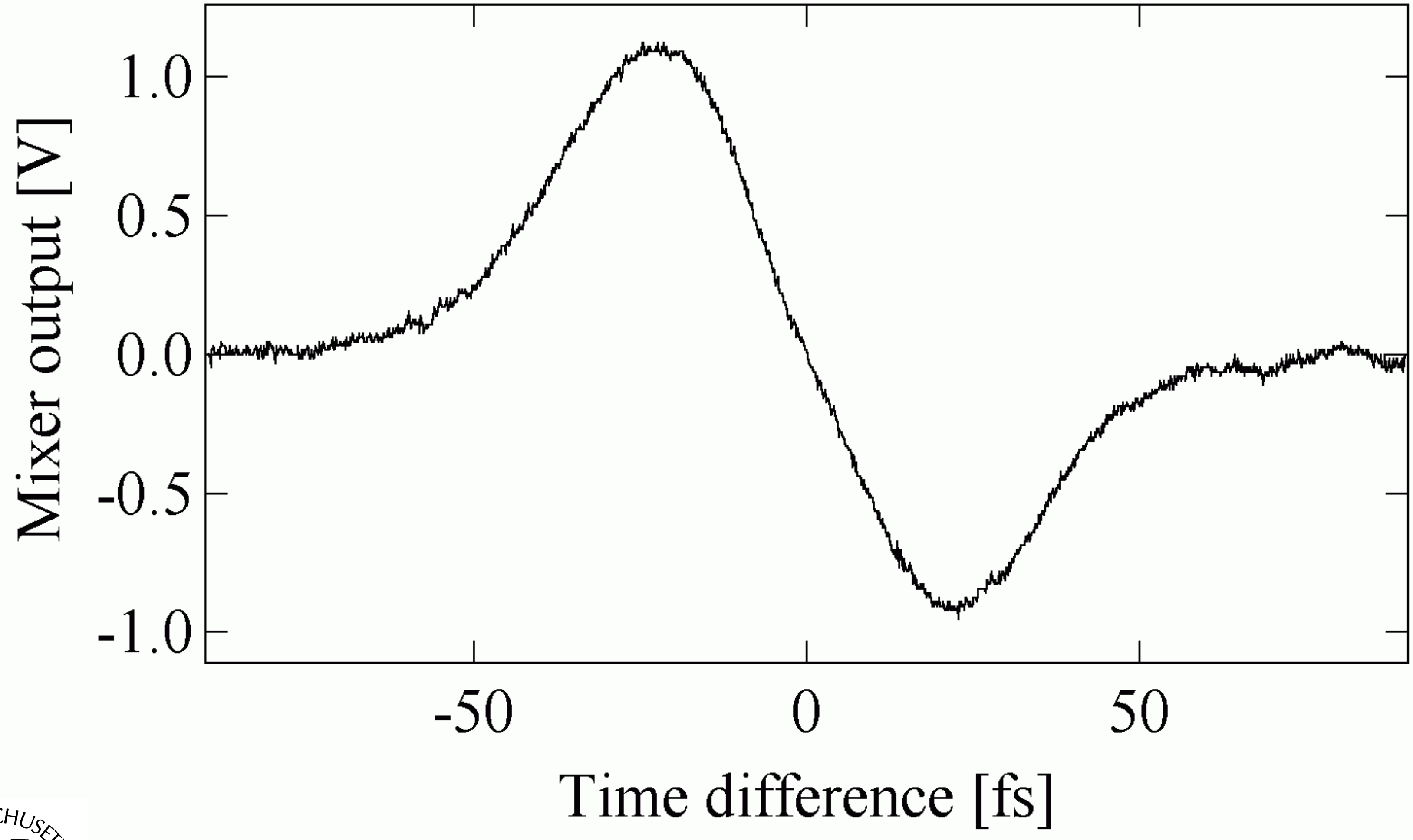
Balanced Cross-Correlator



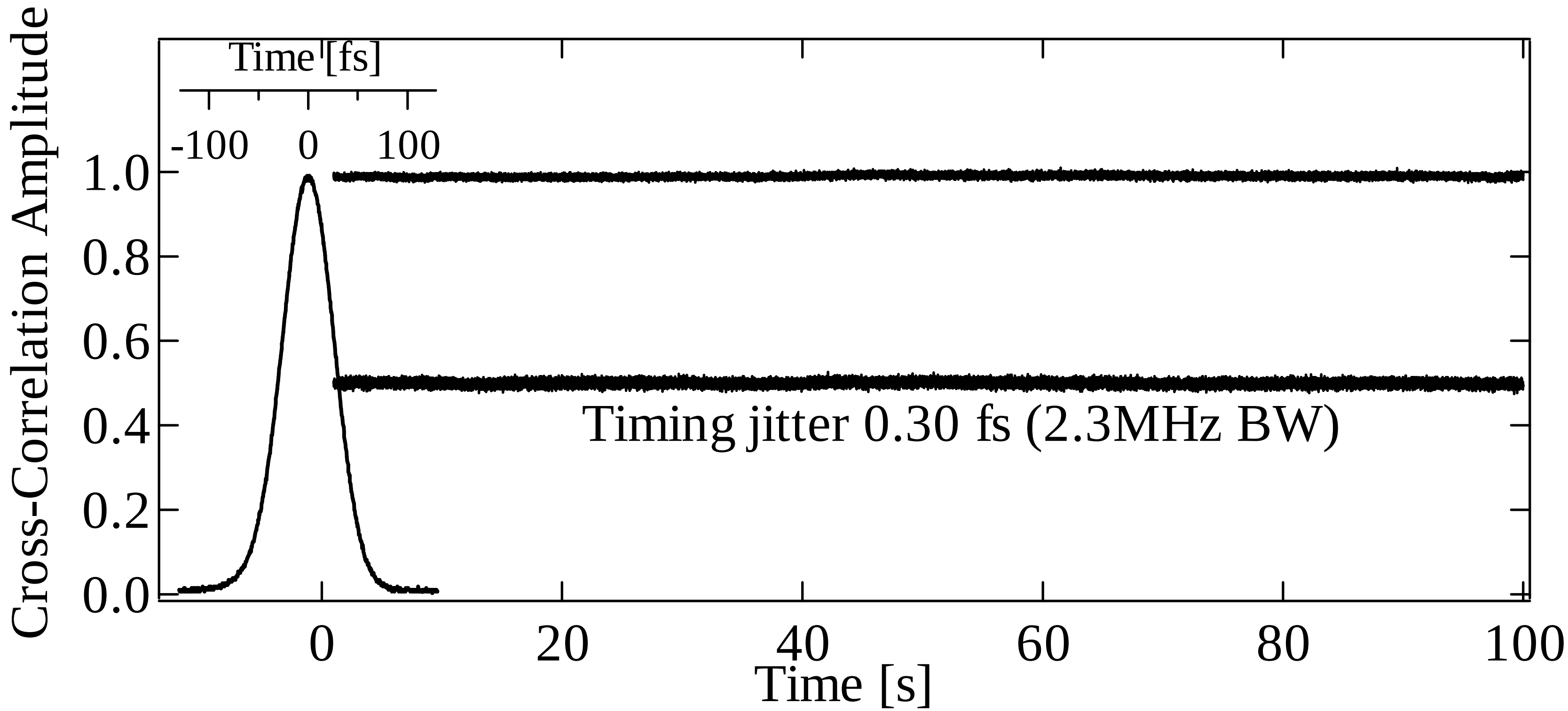
Schibli *et al Opt. Lett*, **28**, 947 (2003)

Balanced Cross-Correlator

Error Signal



Experimental result: Residual timing-jitter



The residual out-of-loop timing-jitter measured from 10mHz to 2.3 MHz is 0.3 fs (a tenth of an optical cycle)

RF Instabilities

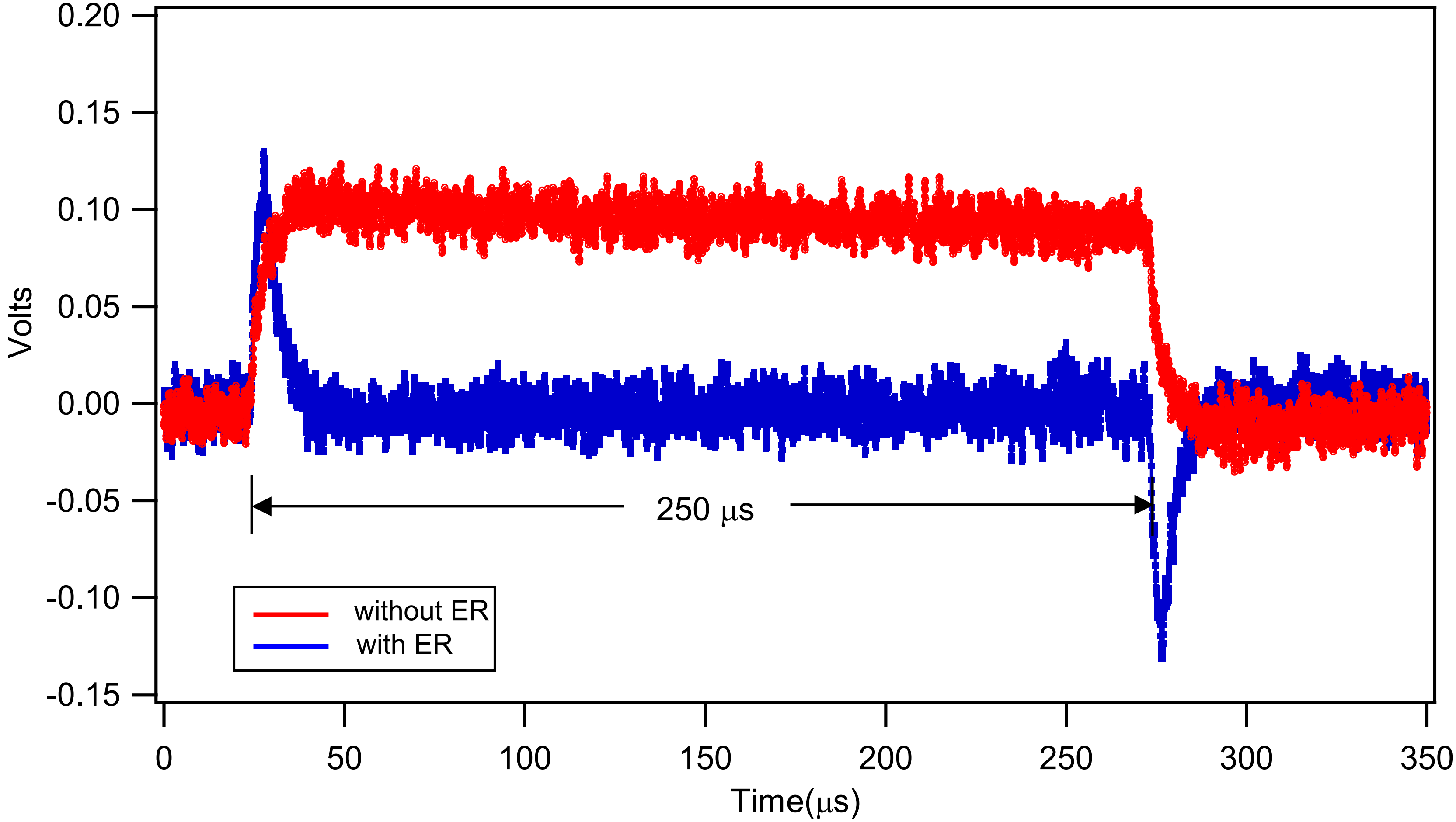
- Instabilities can arise from fluctuations of cavity fields.
- Two effects may trigger unstable behavior:
  - Beam loss which may originate from energy offset which shifts the beam centroid and leads to scraping on apertures.
  - Phase shift which may originate from energy offset coupled to M_{56} in the arc
- Instabilities predicted and observed at LANL, a potential limitation on high power recirculating, energy recovering linacs.

M_{56} is the momentum compaction factor and is defined by:

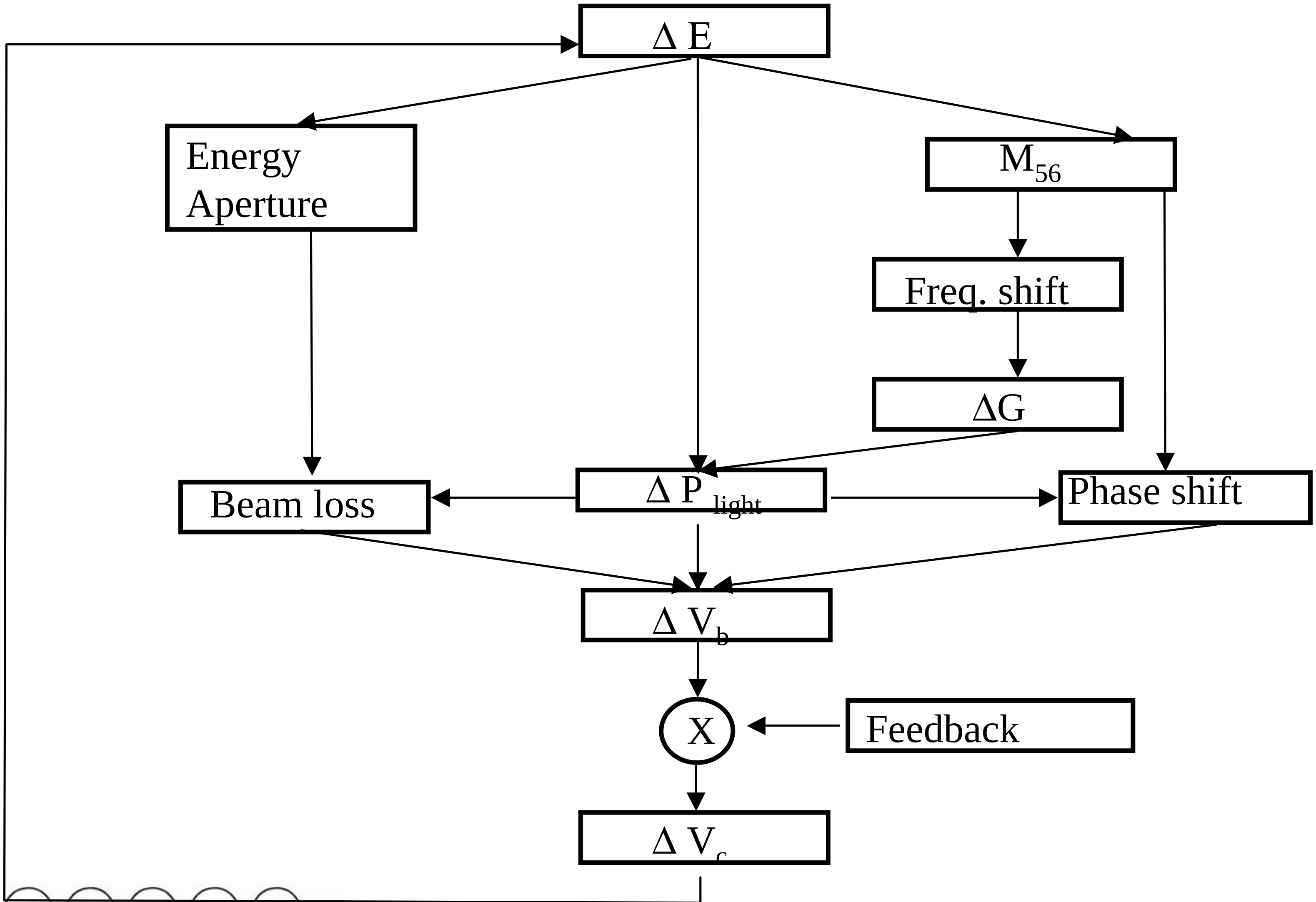
$$\Delta l = M_{56} \frac{\Delta E}{E}$$

RF System Response

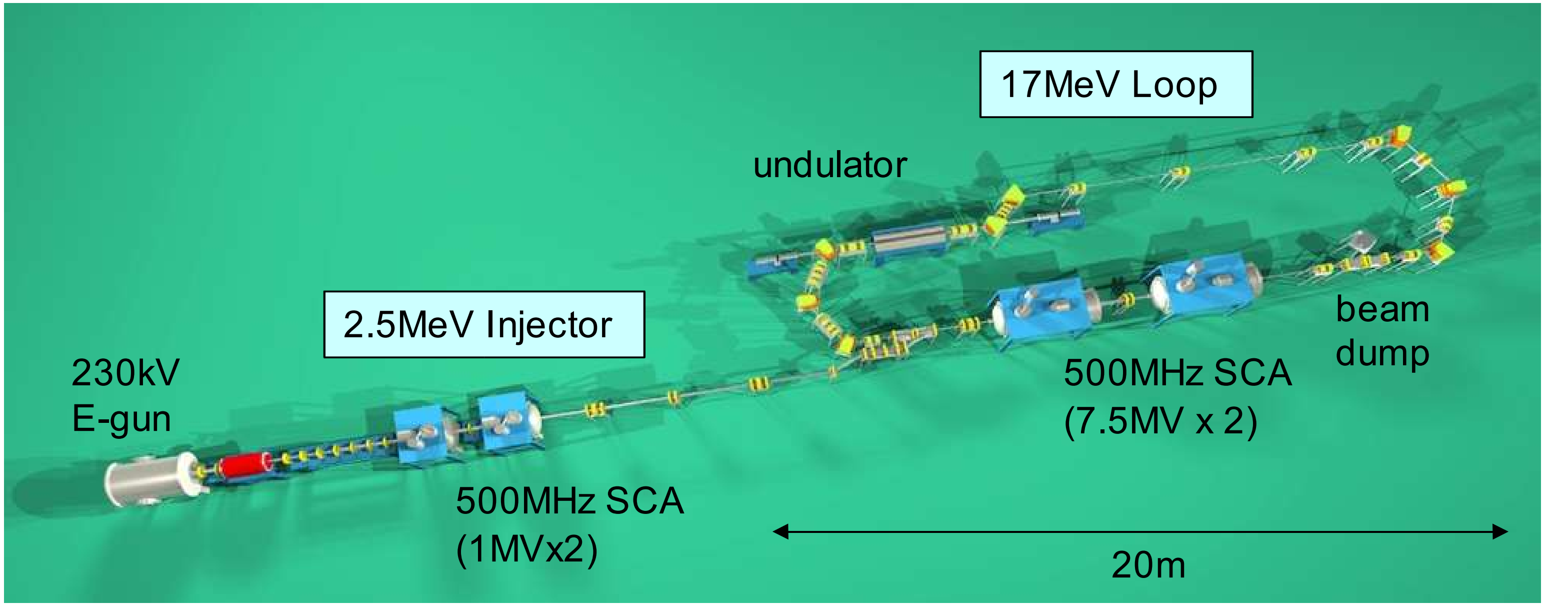
Gradient modulator drive signals **with** and **without** energy recovery in response to 250 μsec beam pulse entering the RF cavity



RF STABILITY FLOW CHART



JAERI Energy-Recovery Linac for 10kW FEL (2002-)



- Natural extension of the original configuration.
- 8 times larger e-beam power.
- Fitting to the concrete boundary.

Energy = 17MeV

FEL : λ = ~22μm

Bunch charge =500pC

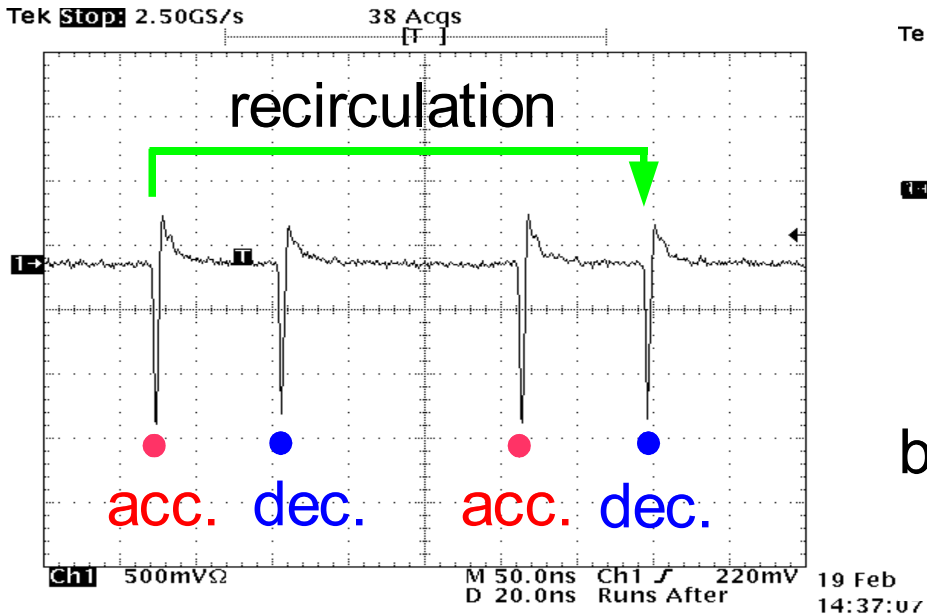
Bunch length = ~15ps (FWHM)

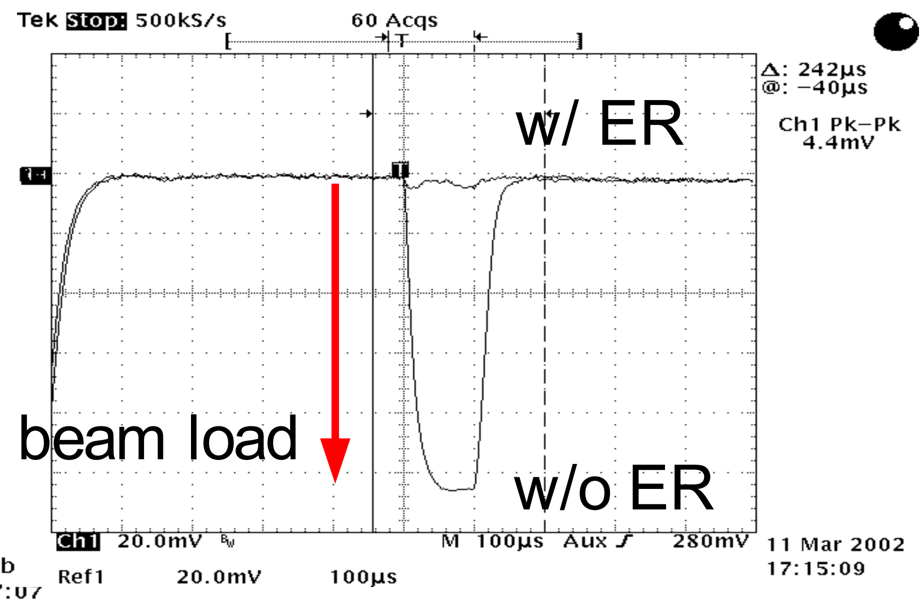
Bunch rep. = 10.4MHz – 83.3MHz

Average current = 5.2mA – 40mA

after injector-upgrade

Demonstration of Energy Recovery





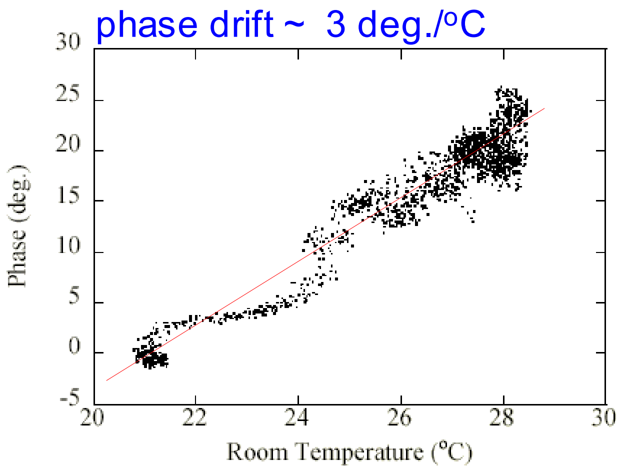
Beam current at the exit of the second main module.

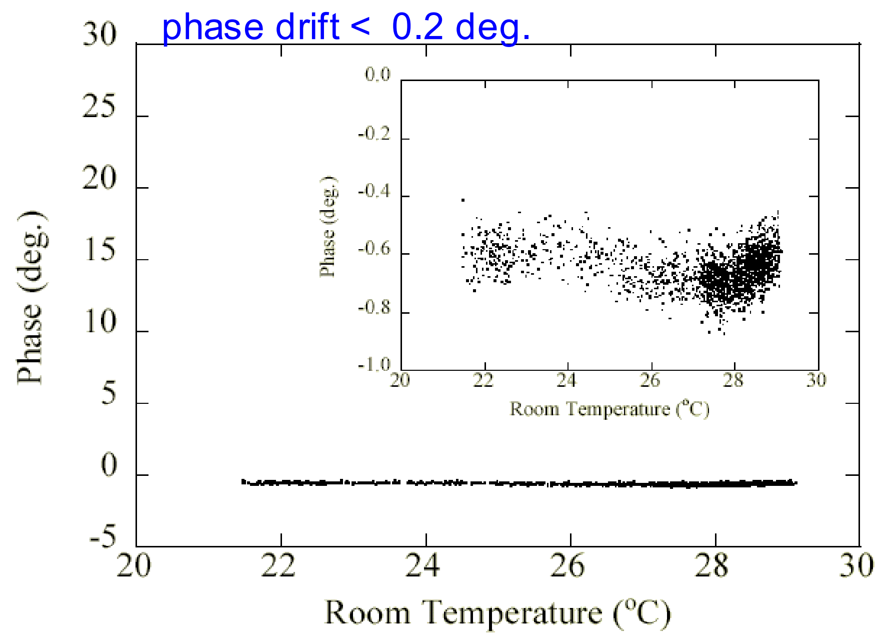
Bunch interval is 96ns, and recirculation time is 133ns.

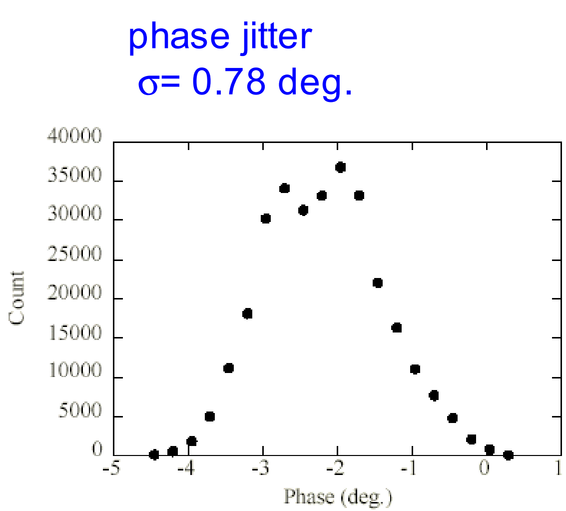
RF amp forward power for the 1st main module.

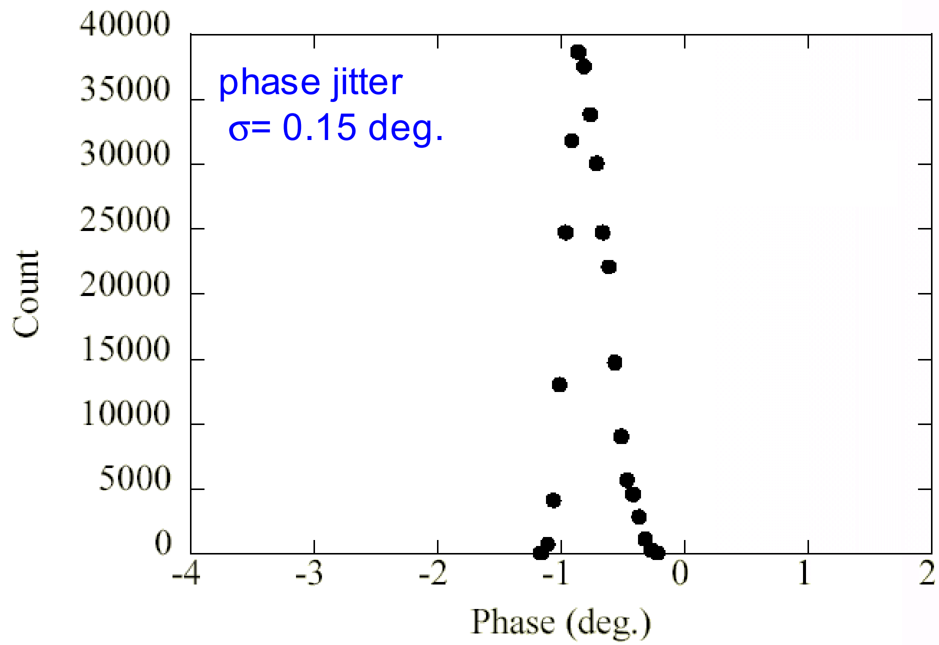
98% energy of e-beam is recovered.

Improvement of RF Stability – new low-level controllers and reference-signal cables

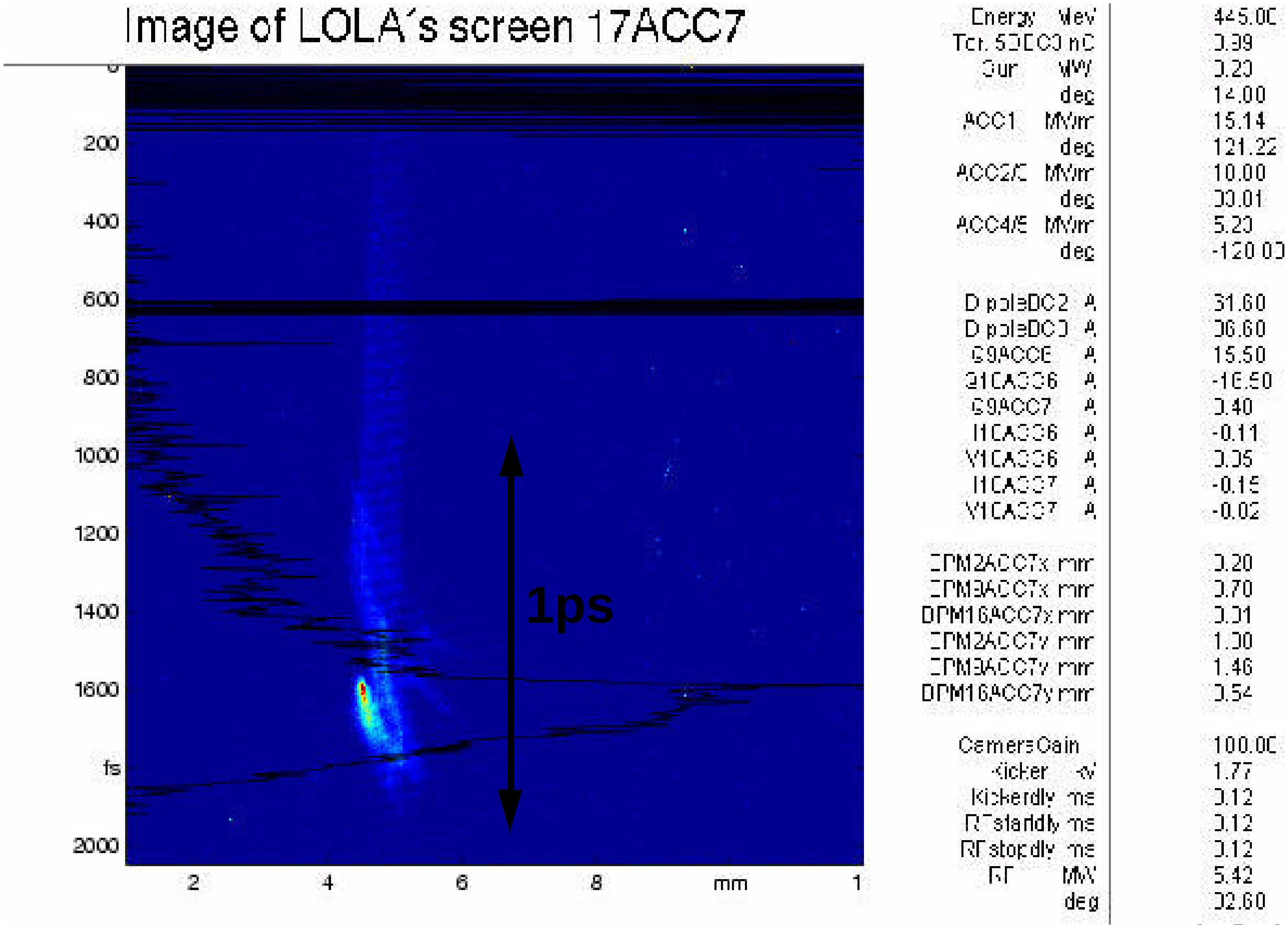




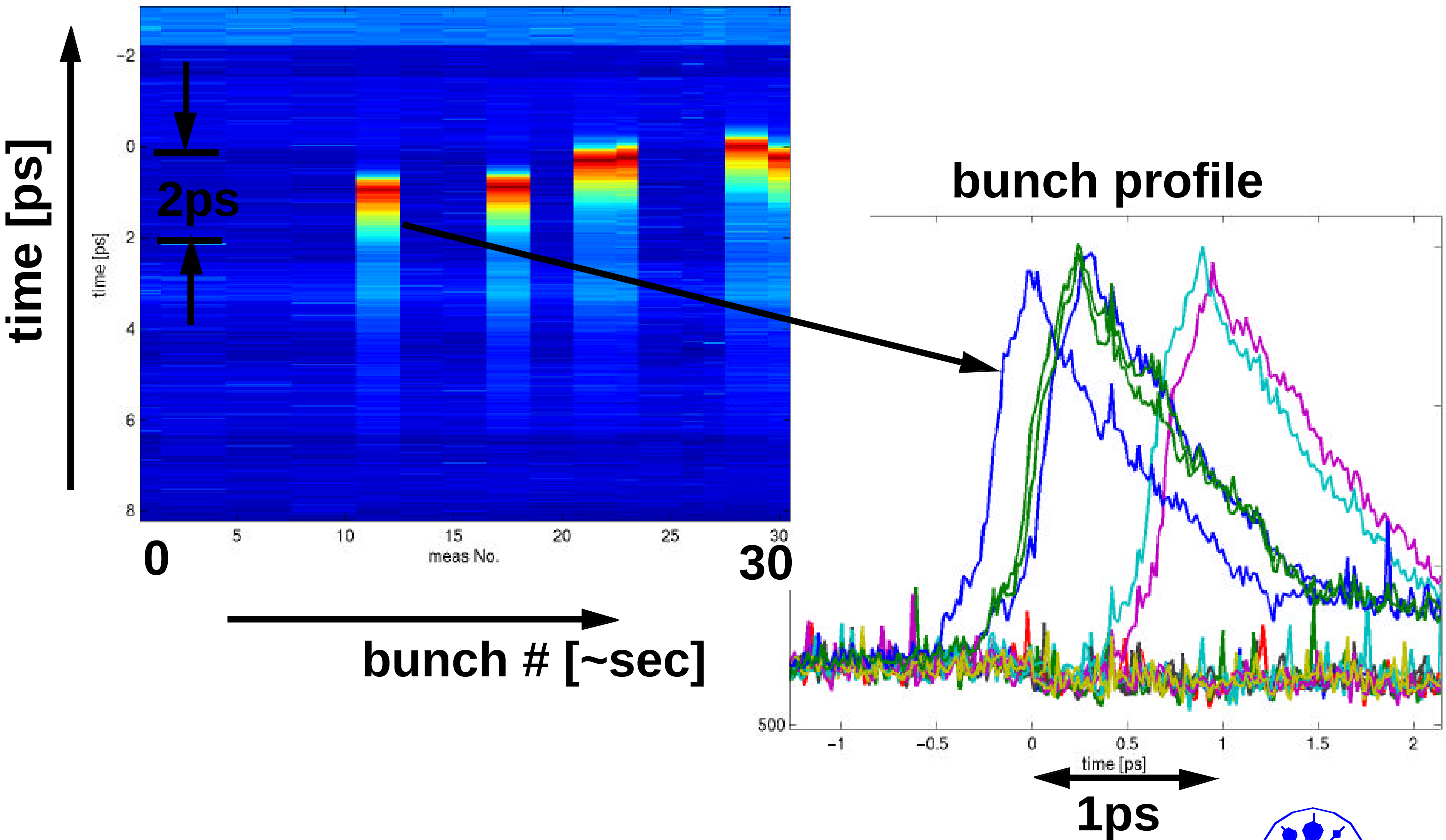




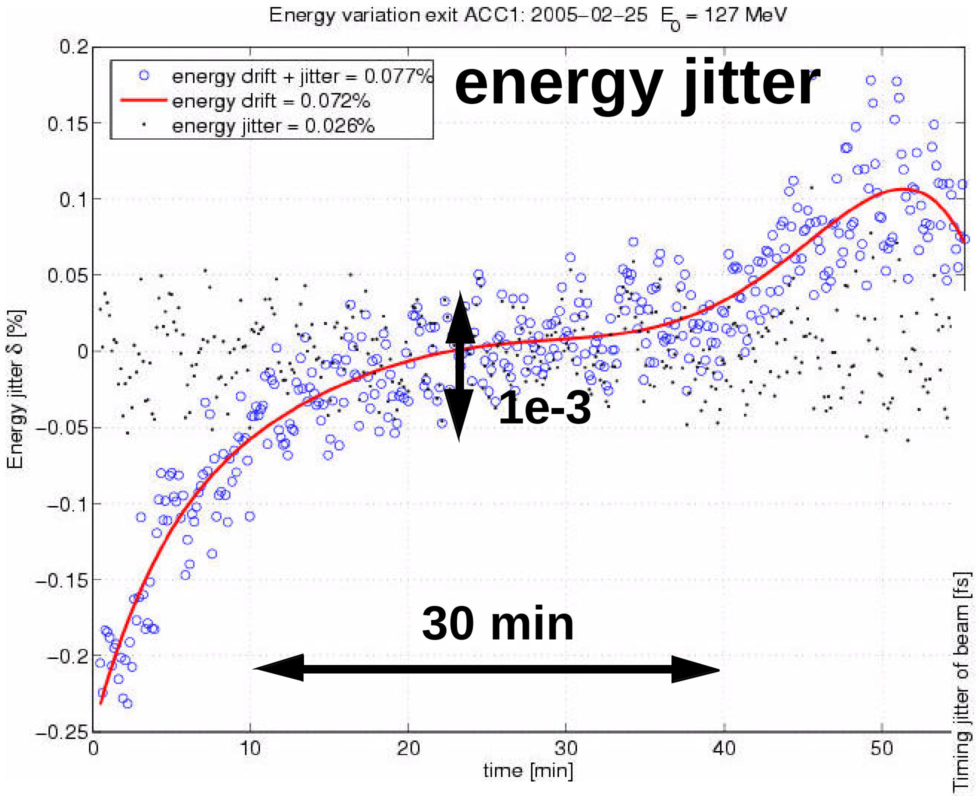
LOLA Bunch Length Measurement

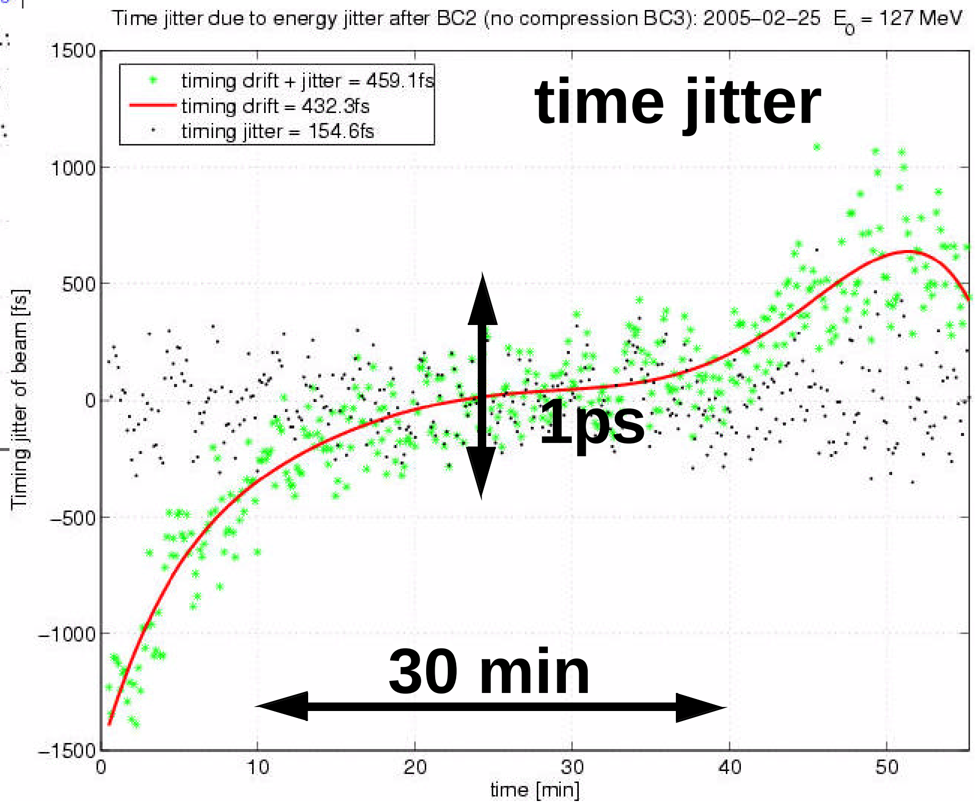


Bunch Profile and Time Jitter



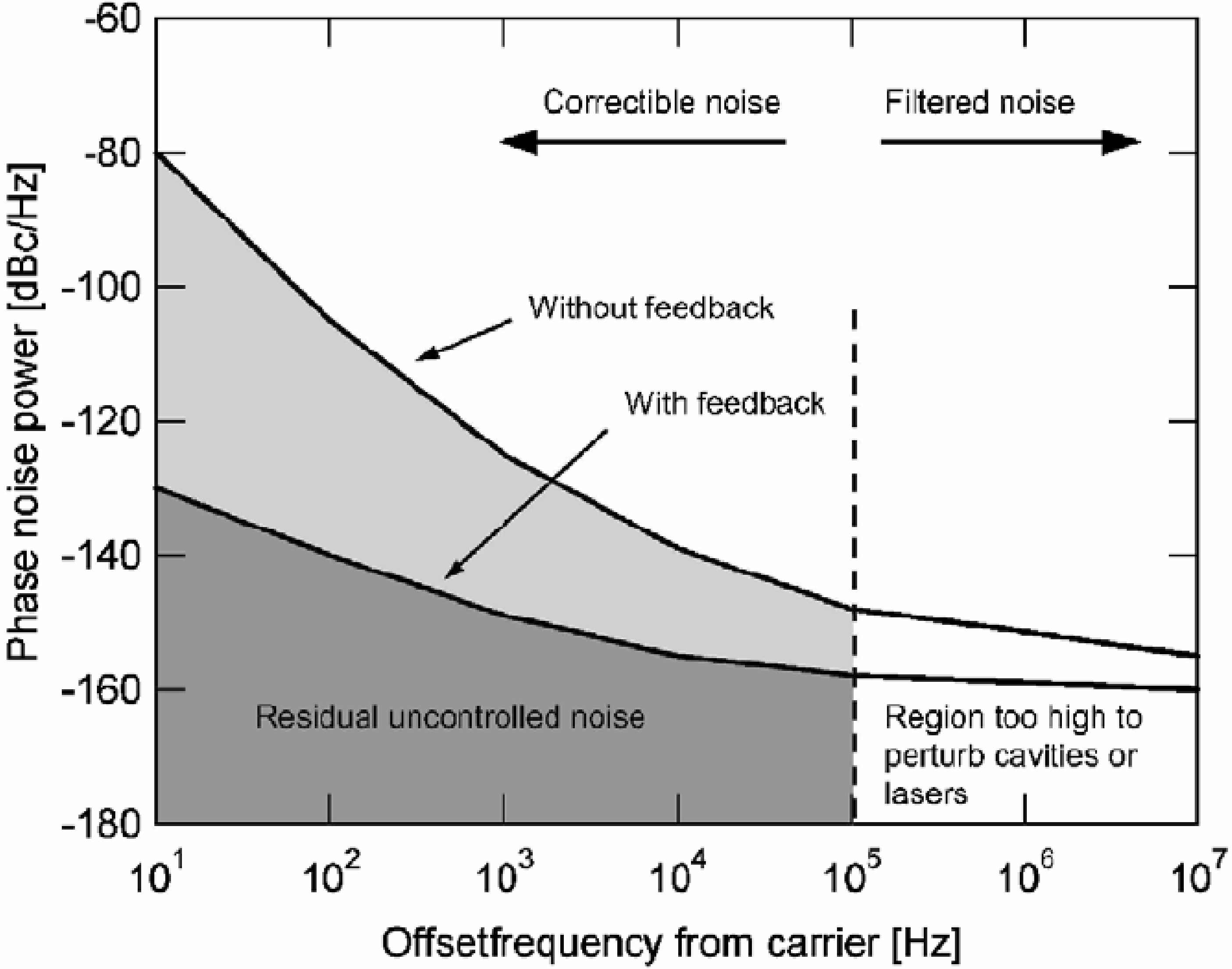
Drift ACC1 (cryomodule before BC) at TTF



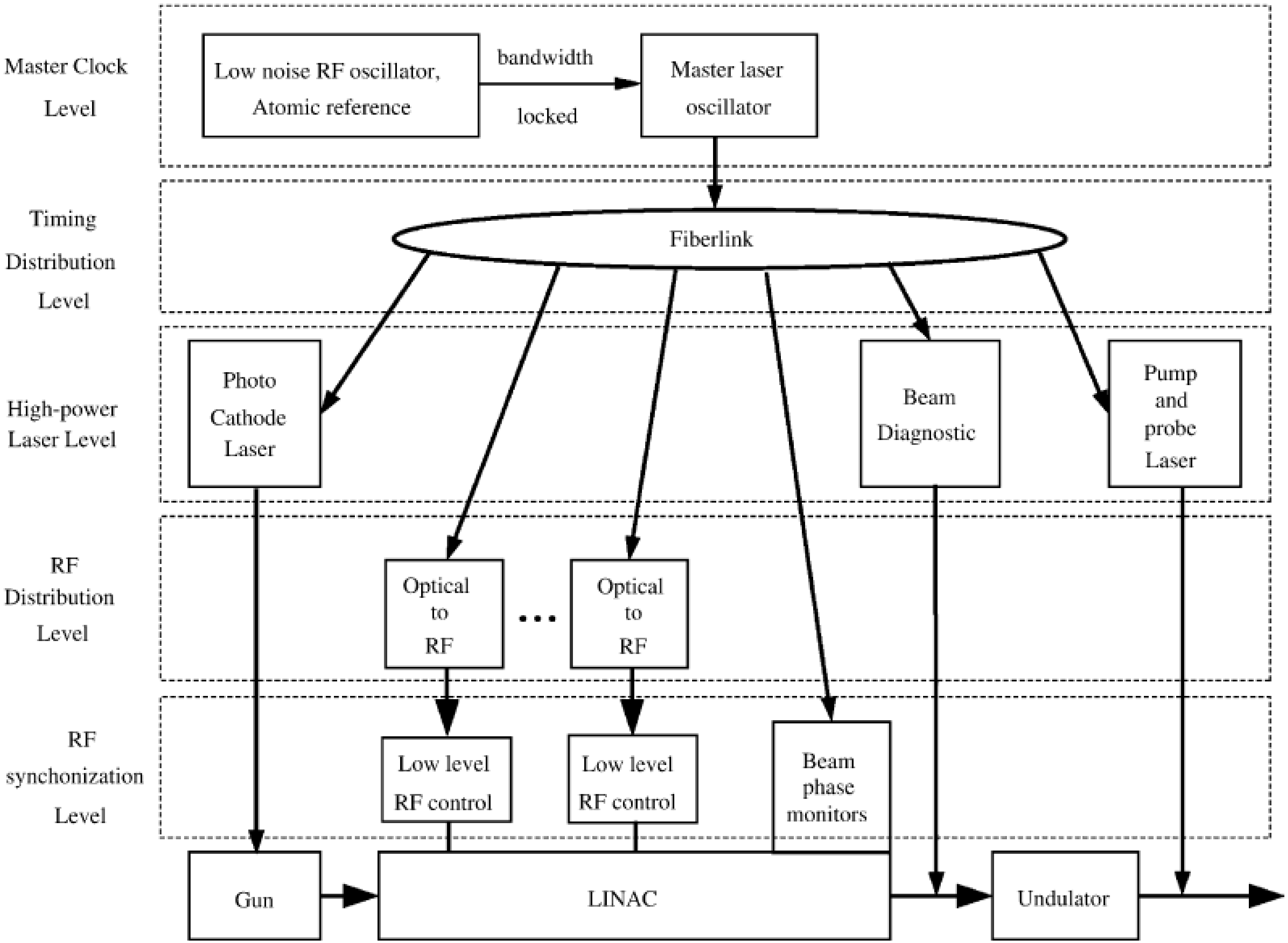


Basic Concepts

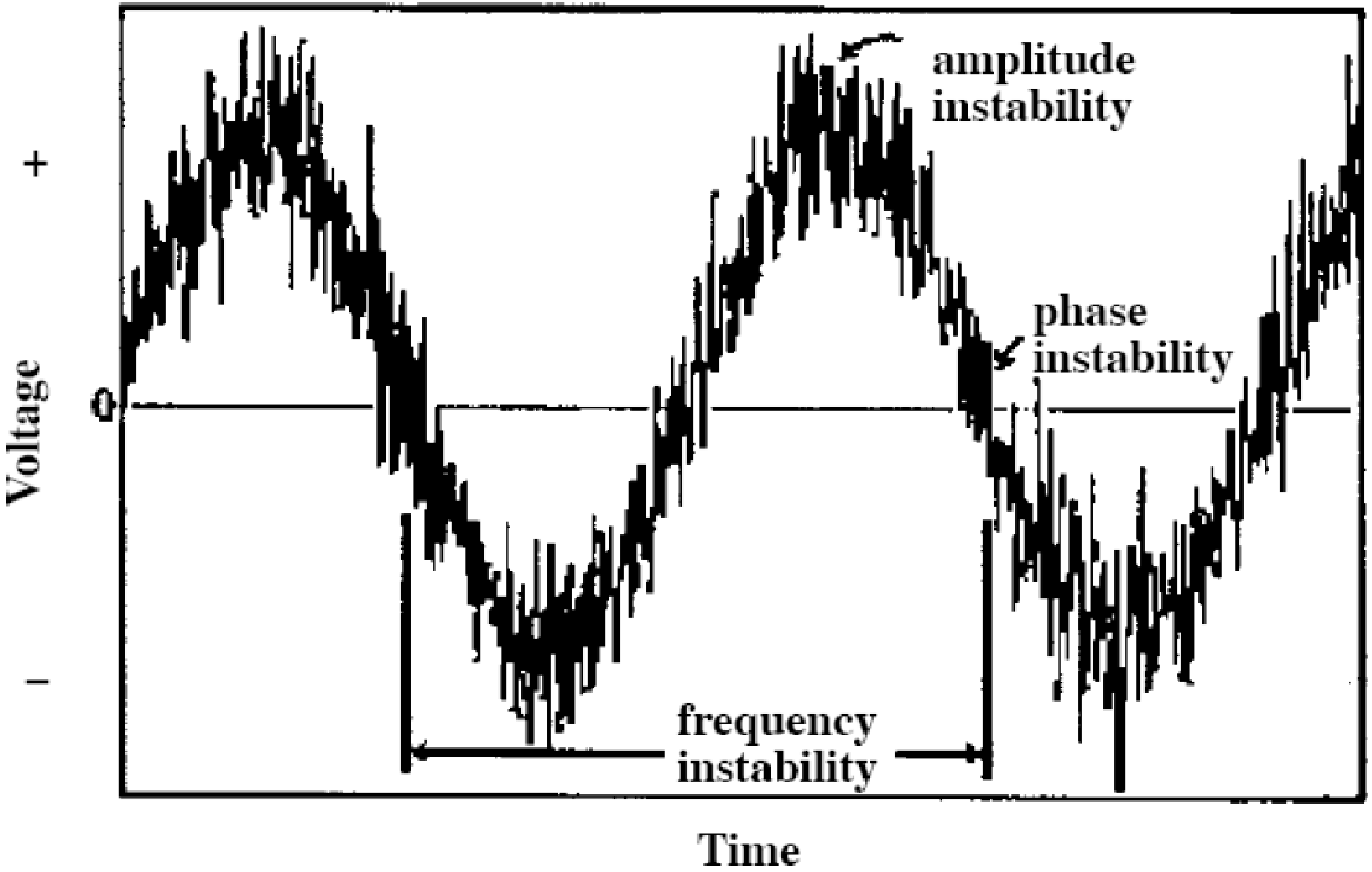
Phase Noise Contributions



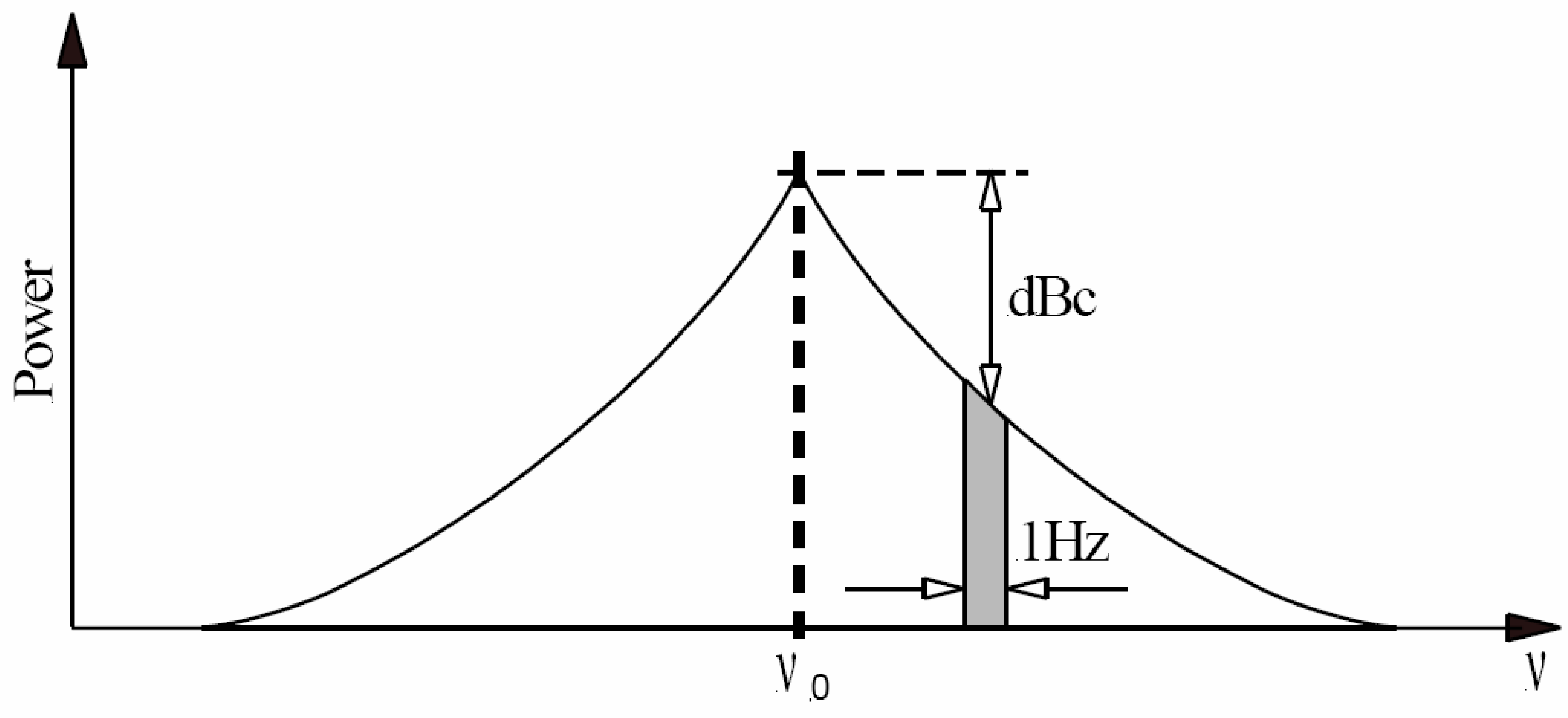
Architecture of Synchronization



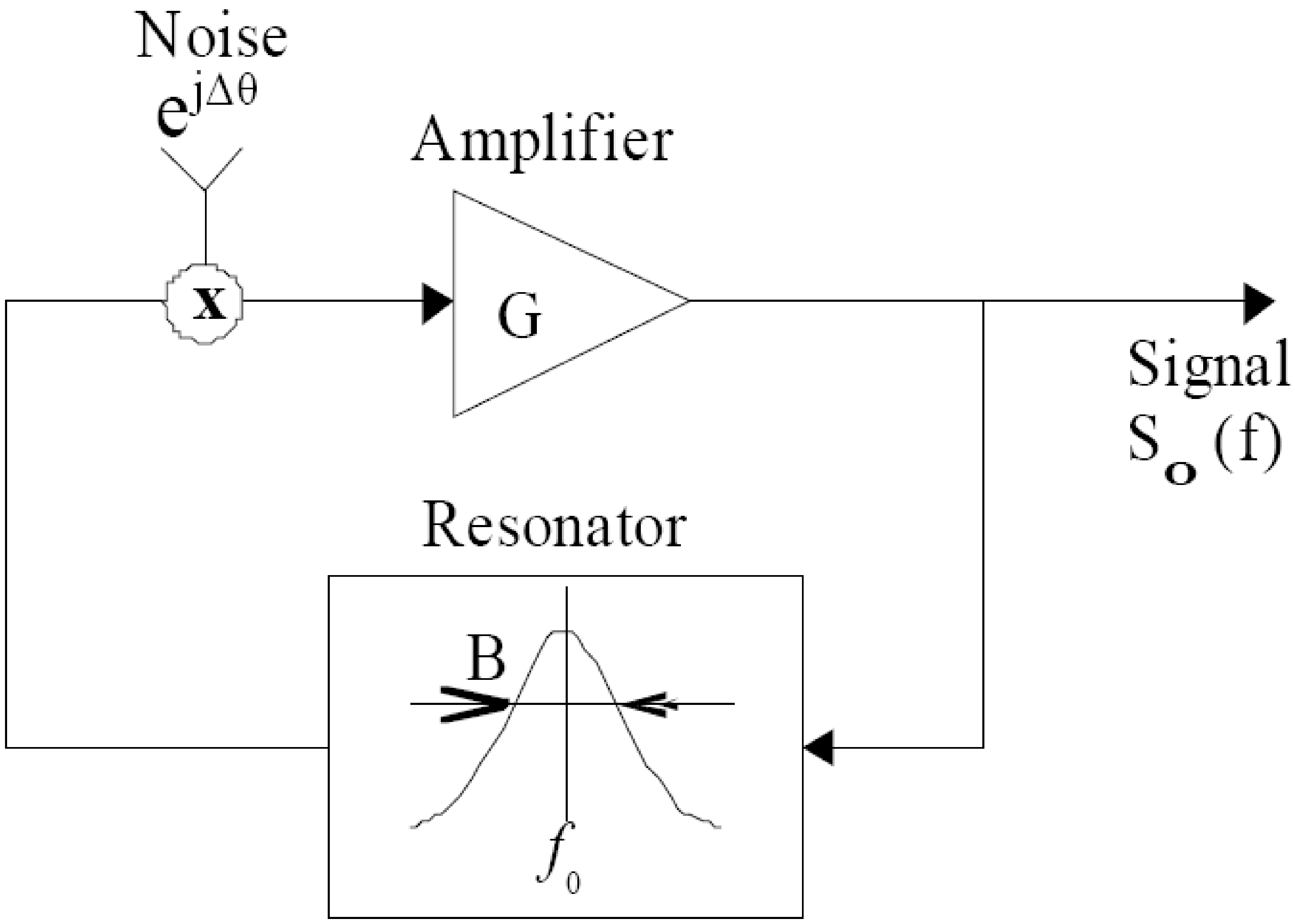
Instantaneous output voltage of an oscillator



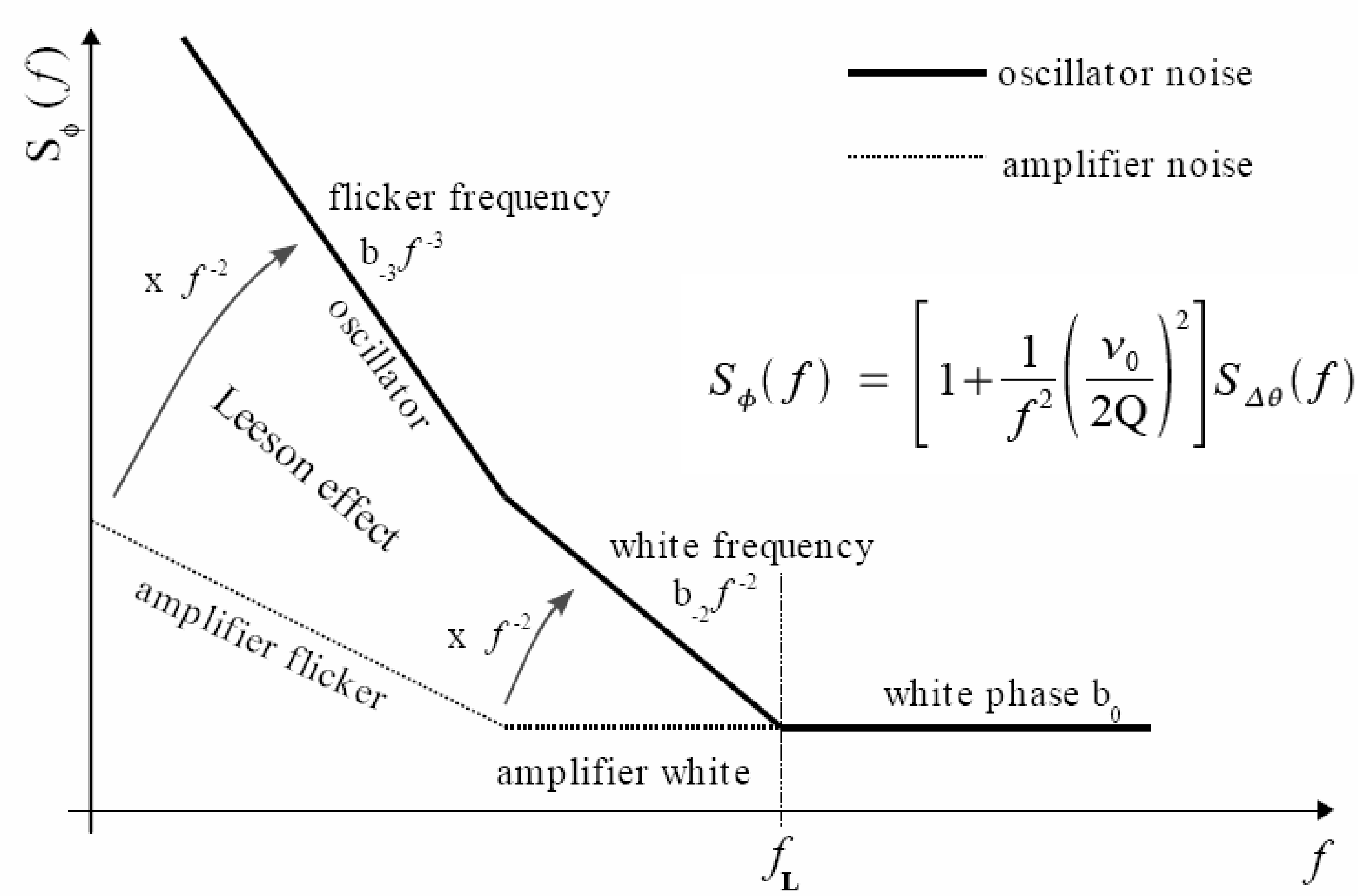
Power spectral density vs frequency



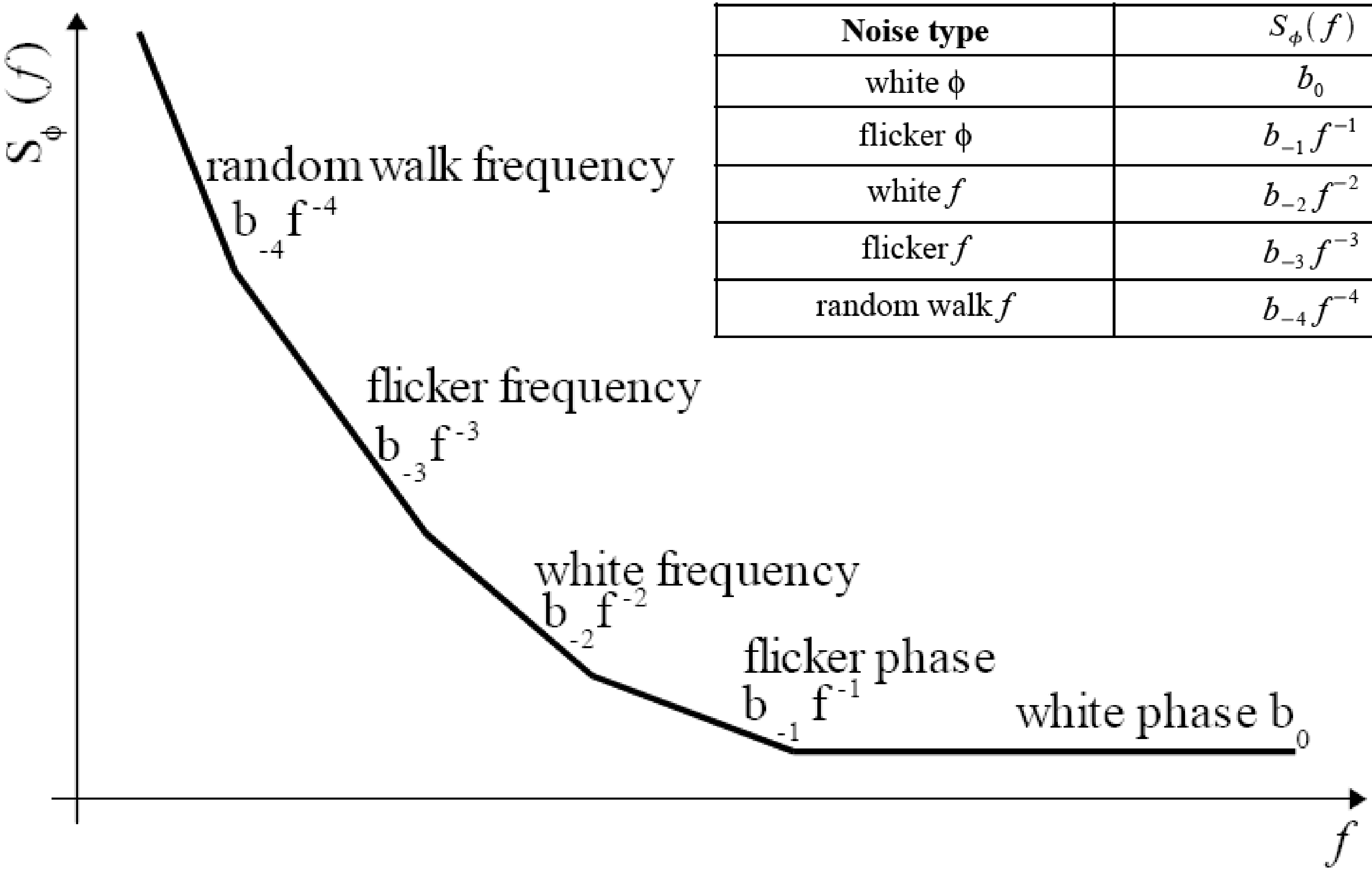
Basic oscillator model



Leeson Effect

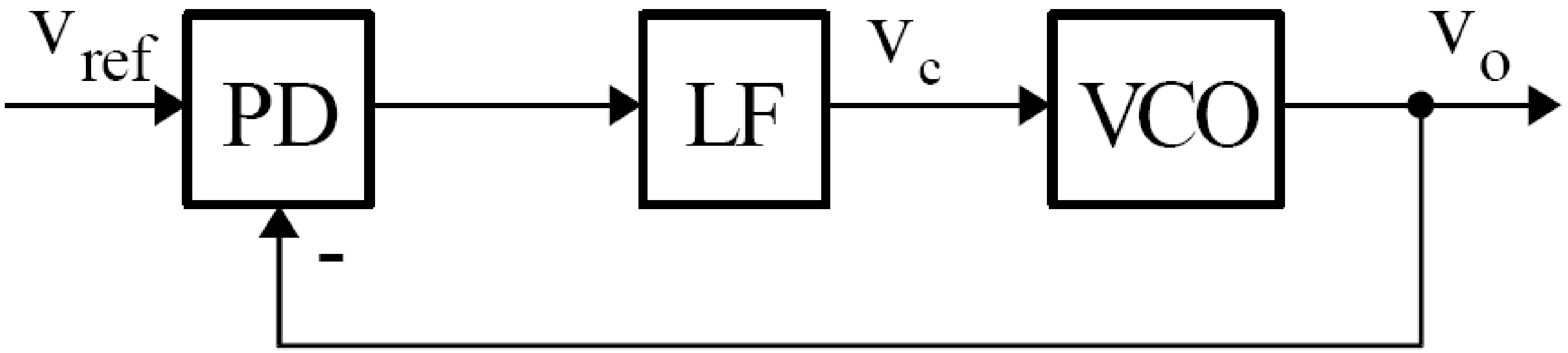


Power law spectra

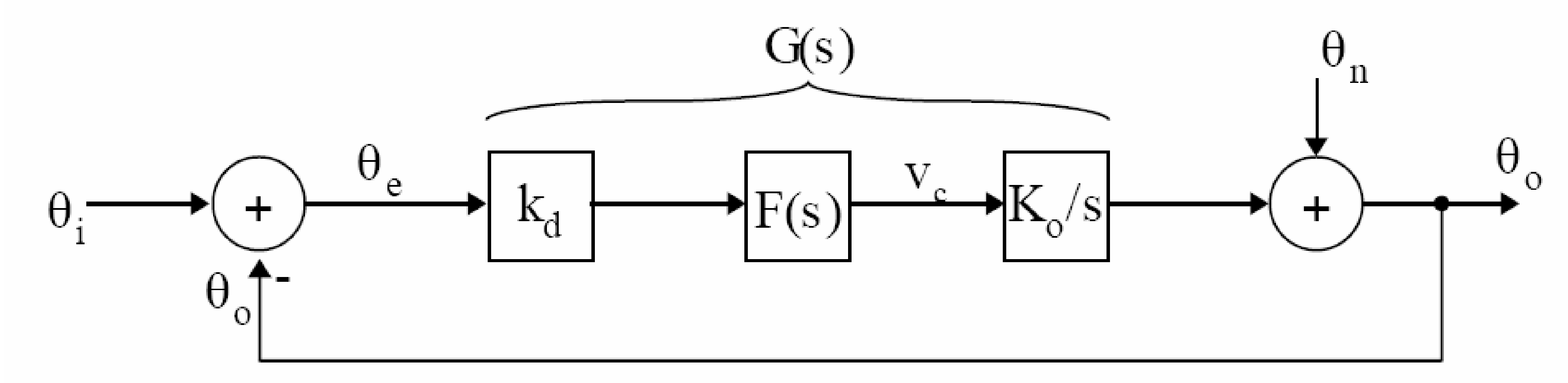


Noise type	$S_\phi(f)$
white ϕ	b_0
flicker ϕ	$b_{-1} f^{-1}$
white f	$b_{-2} f^{-2}$
flicker f	$b_{-3} f^{-3}$
random walk f	$b_{-4} f^{-4}$

Basic diagram of PLL

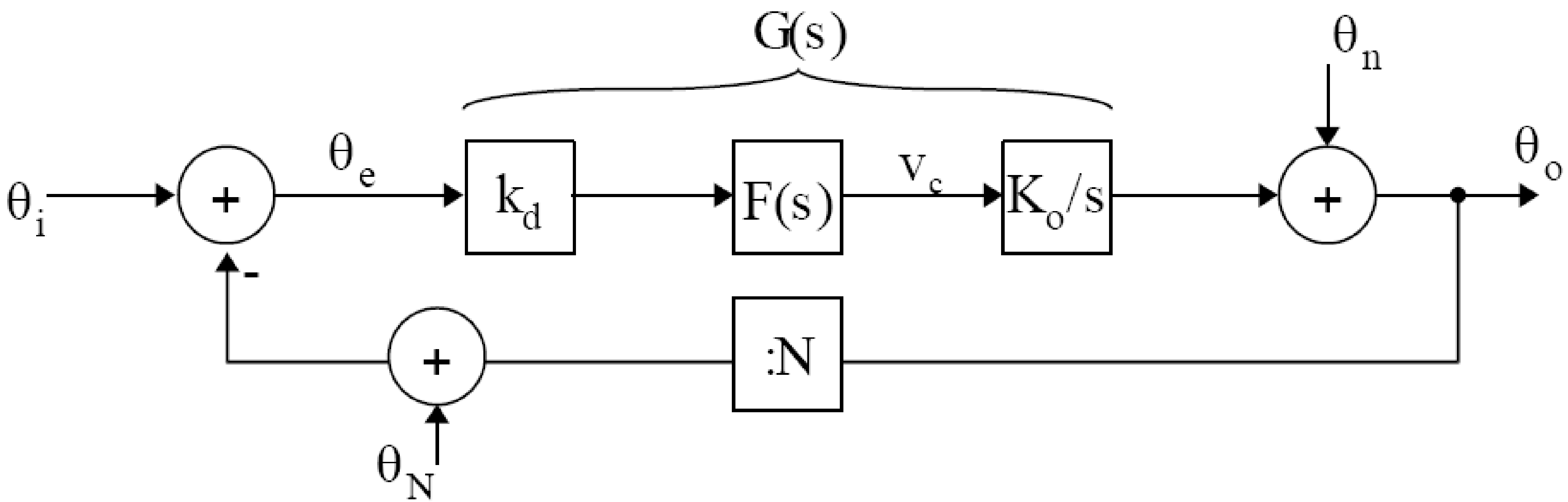


Linear Model for noise transfer function



K_d	- slope of the phase detector voltage to phase characteristic in V/Radian
$F(s)$	- loop filter transfer function
s	- complex frequency in the Laplace domain
K_0	- slope of the voltage controlled oscillator frequency to voltage characteristic in Hz/V
θ_i	- phase of PLL input signal
θ_e	- phase difference (phase error) between input and output signals of the PLL
θ_n	- free running (not in a closed loop) VCO phase noise
θ_o	- phase of PLL output signal

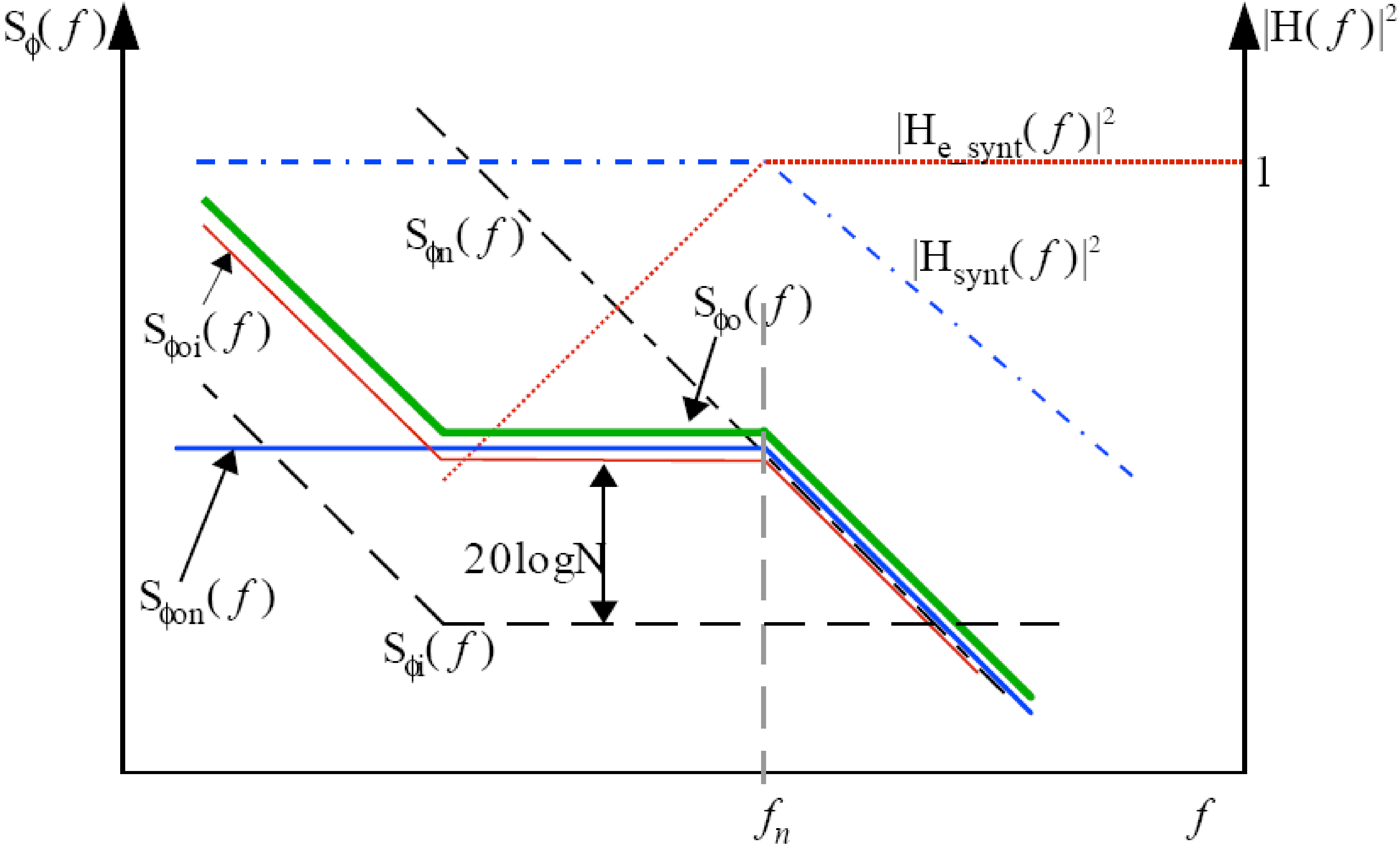
PLL Synthesizer



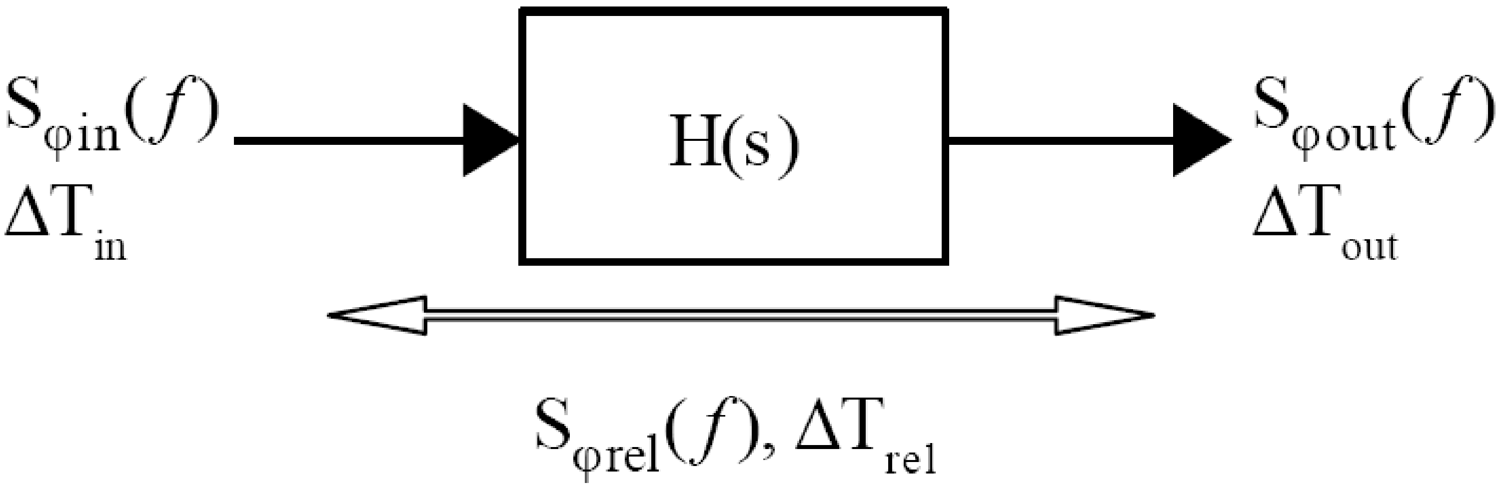
$$S_{\phi o}(f) = S_{\phi oi}(f) + S_{\phi oN}(f) + S_{\phi on}(f)$$

$$S_{\phi o}(f) = [S_{\phi i}(f) + S_{\phi N}(f)]N^2|H_r(f)|^2 + S_{\phi n}(f)|H_{e\_synt}(f)|^2$$

Phase noise at output of synthesizer



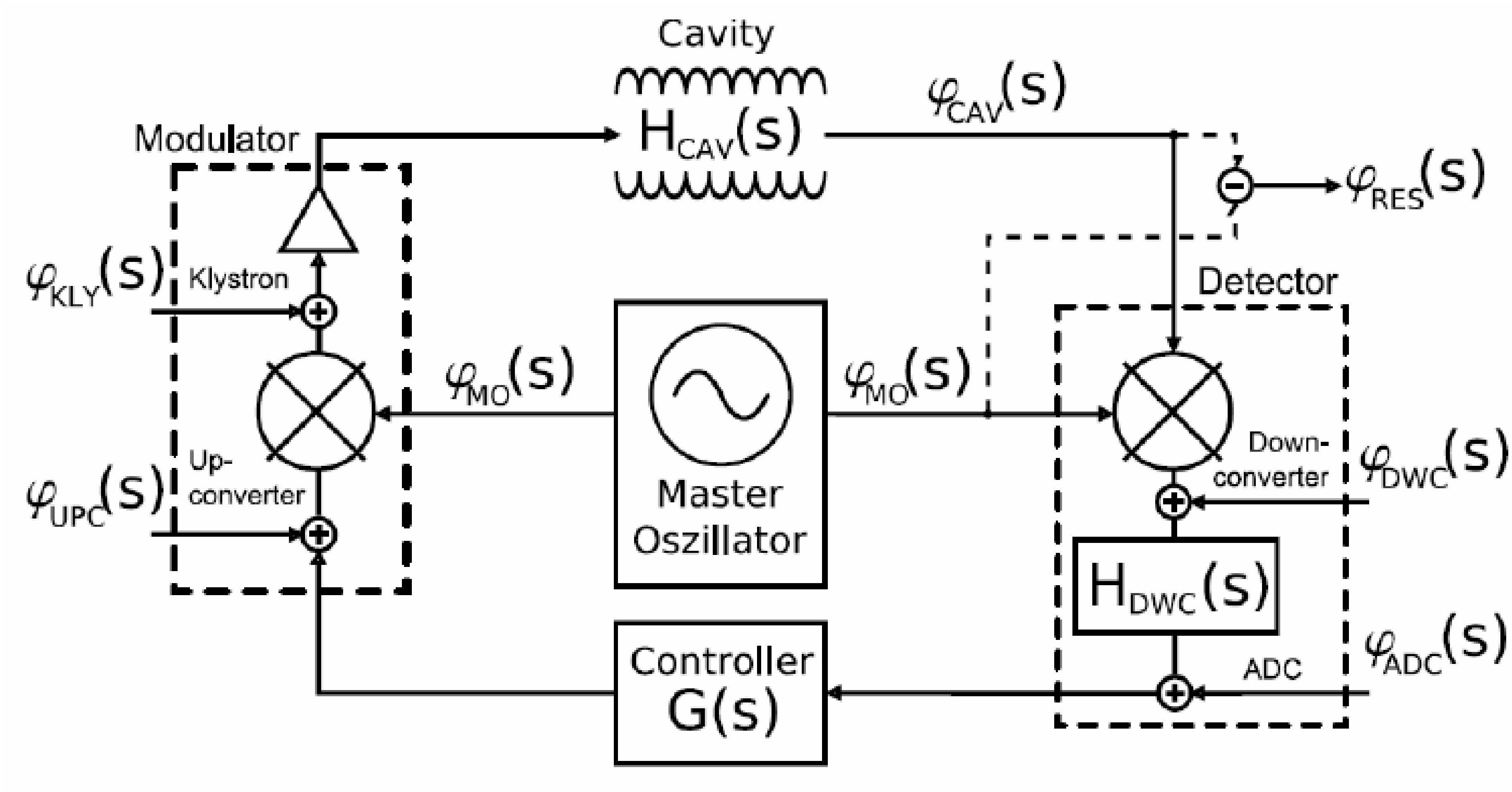
Relative Jitter between Systems



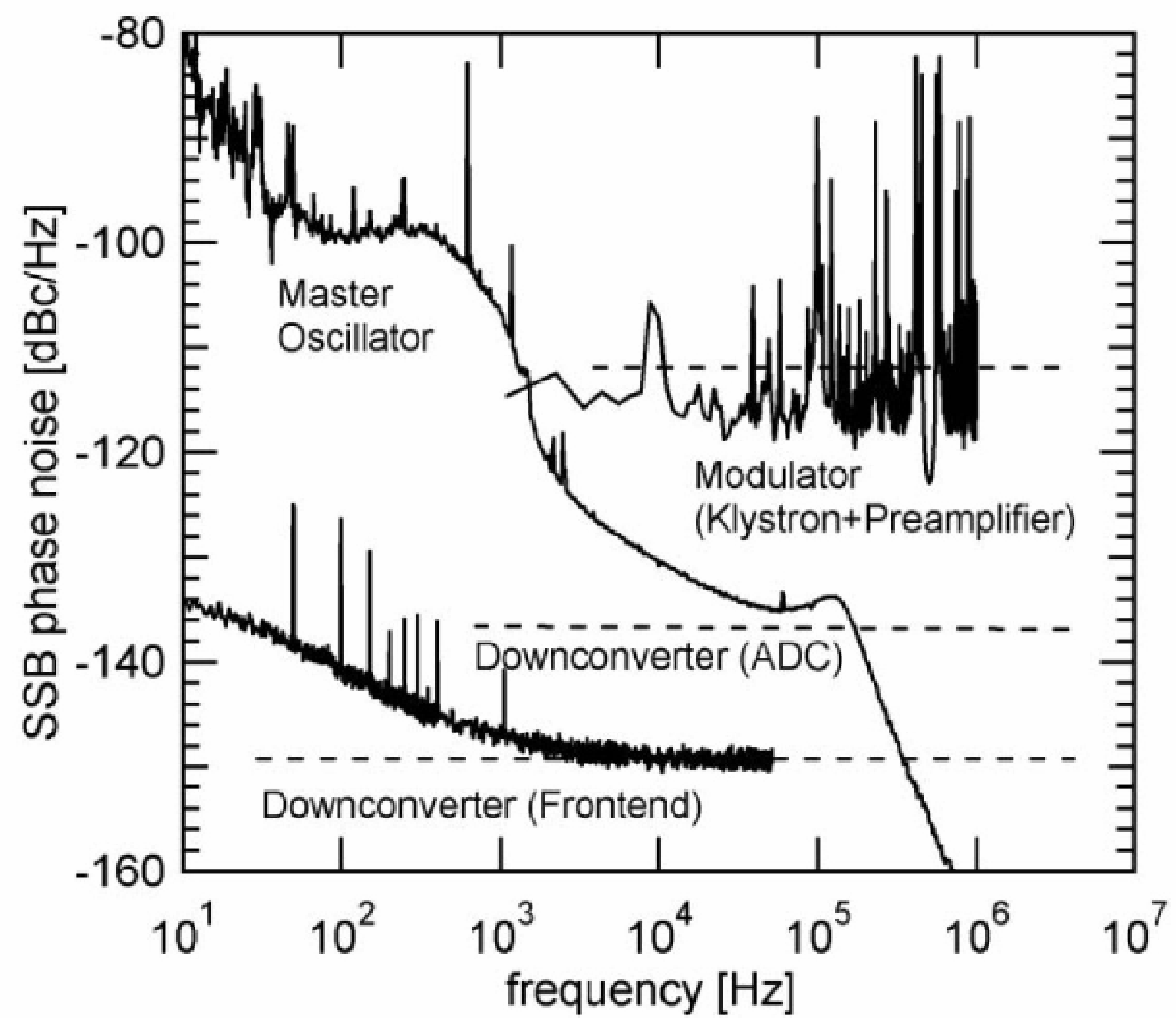
$$\Delta t_{rel} = \left|\Delta t_{out} - \Delta t_{in}\right|$$

$$\Delta t_{rel} = \frac{1}{2\pi\nu_0}\sqrt{\int_{f_1}^{f_2} \left|S_{\phi out}(f) - S_{\phi in}(f)\right| df}$$

Noise model for cavity field



Measured noise sources at FLASH



Various frequencies required for FLASH

Output Frequency [MHz]	Multiple of the Reference	Exact Frequency Value [MHz]	Destination
50 Hz	/180555.5	*	Accelerator timing system. Used for comparison with zero crossings of the mains power supply. TTL output.
1	/9	1.00309	Timing system, TTL output
9	*1	9.027775	Auxiliary frequencies generation (sine) and timing system (TTL)
13.5	*3/2	13.5416625	Laser "new"
27	*3	27.08333	Laser "old"
81	*9	81.24998	Distribution frequency
108	*12	108.3333	Streak Camera
1300	*144	1299.9996	RF system reference frequency
1517	*168	1516.6662	Beam position monitors reference frequency, LINAC Racks
2856 ± 5 kHz	tbd	2856.001105	LOLA – transverse deflecting cavity for bunch monitors

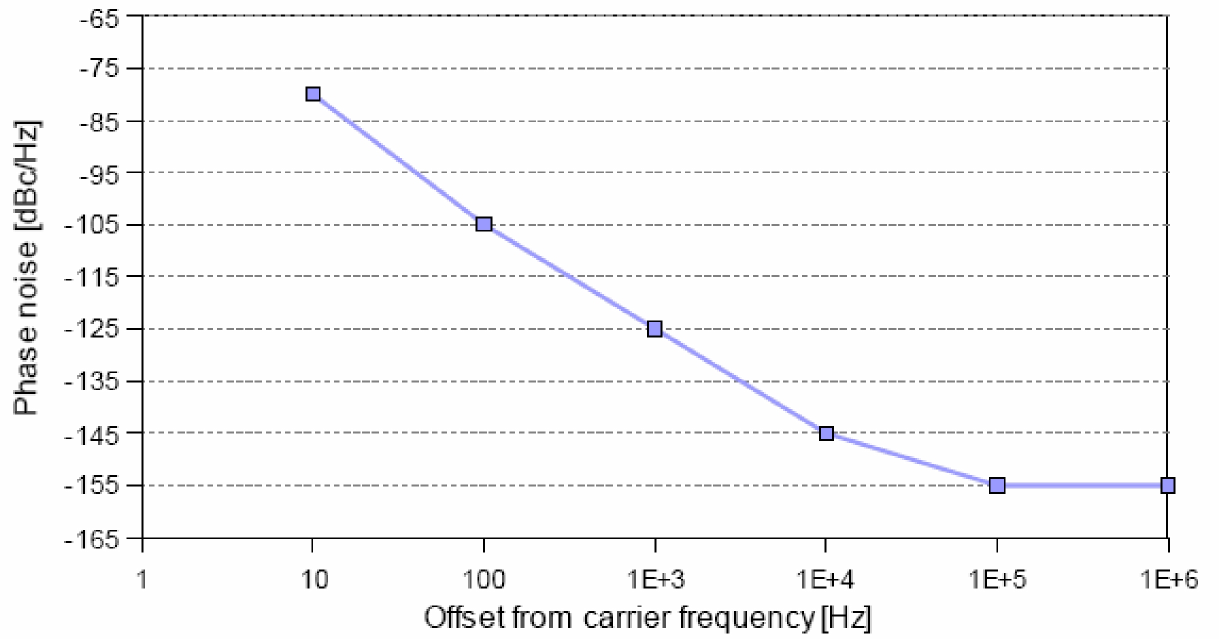
Timing stability requirements for FLASH

	Short term stability [fs]			Long term stability [fs]			
Duration	1 ms	100 ms	1 s	10 s	minute	hour	day
Integration Bandwidth#	1kHz - 1MHz	10 Hz - 1MHz	1Hz - 1MHz	n/a	n/a	n/a	n/a
Requirement before 2006	100	300	1000	1000	1000	2000	10000
Requirements from 2006 on	10	10	10	20	300	750	no data

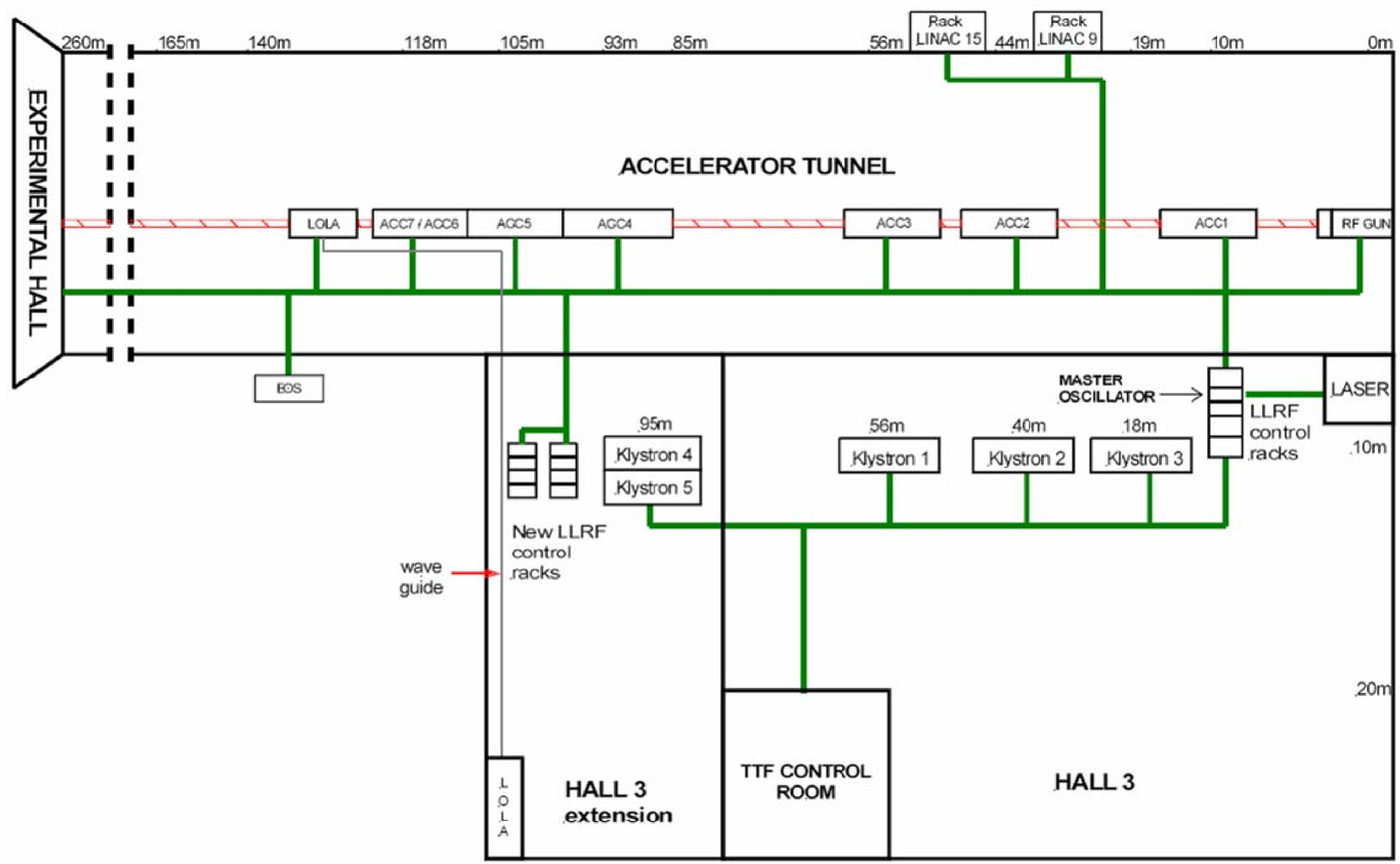
Phase noise integration bandwidth is specified only for short term stability because the equipment available in DESY in the time of writing this thesis, can measure phase noise only in the range of 1 Hz – 10 MHz. The long term stability is measured (where possible) directly by a phase detector.

Phase noise requirements for 1.3 GHz

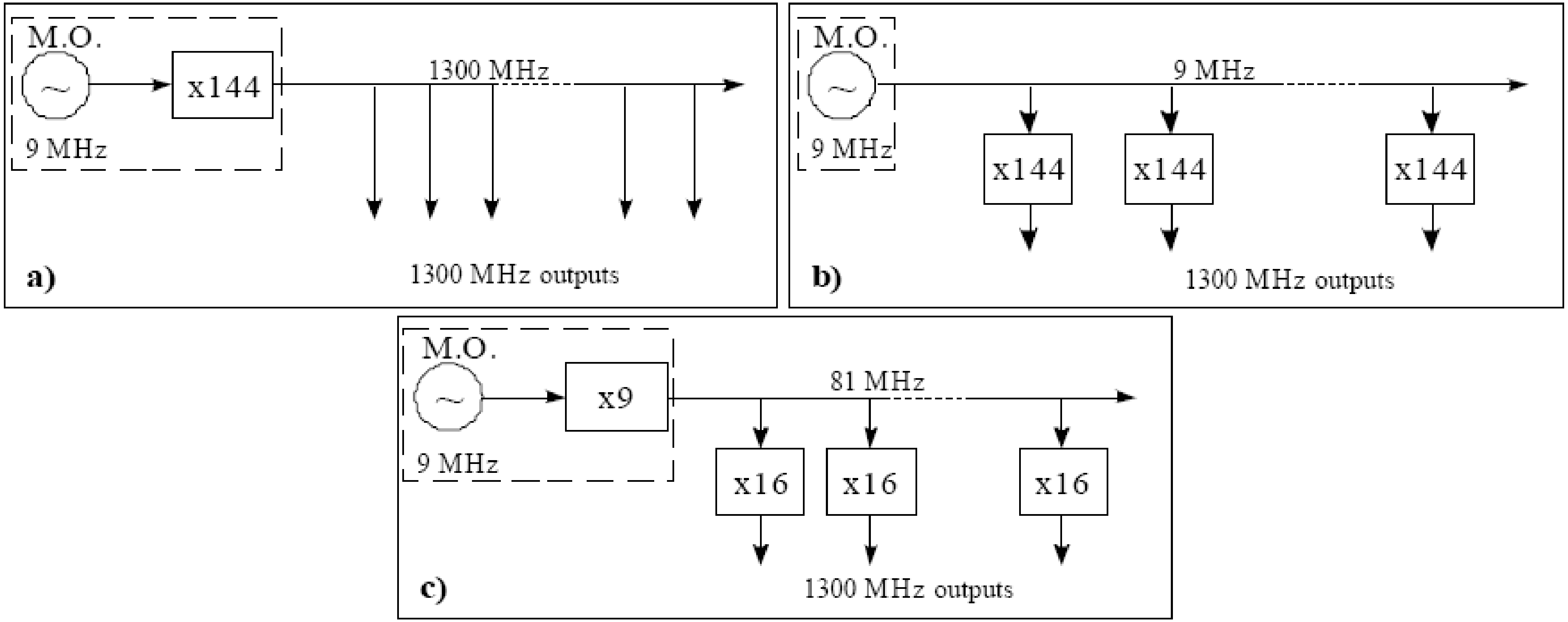
Frequency offset from carrier [Hz]	Phase noise $\mathscr{L}(f)$ Locked condition [dBc/Hz]	Phase noise $\mathscr{L}(f)$ Free running [dBc/Hz]
1	NA	NA
10	< -80	< -60
100	< -105	< -80
1 k	< -125	< -105
10 k	< -145	< - 135
100 k	< -155	< -155
1 M	< - 150 (-155)	< - 150 (-155)



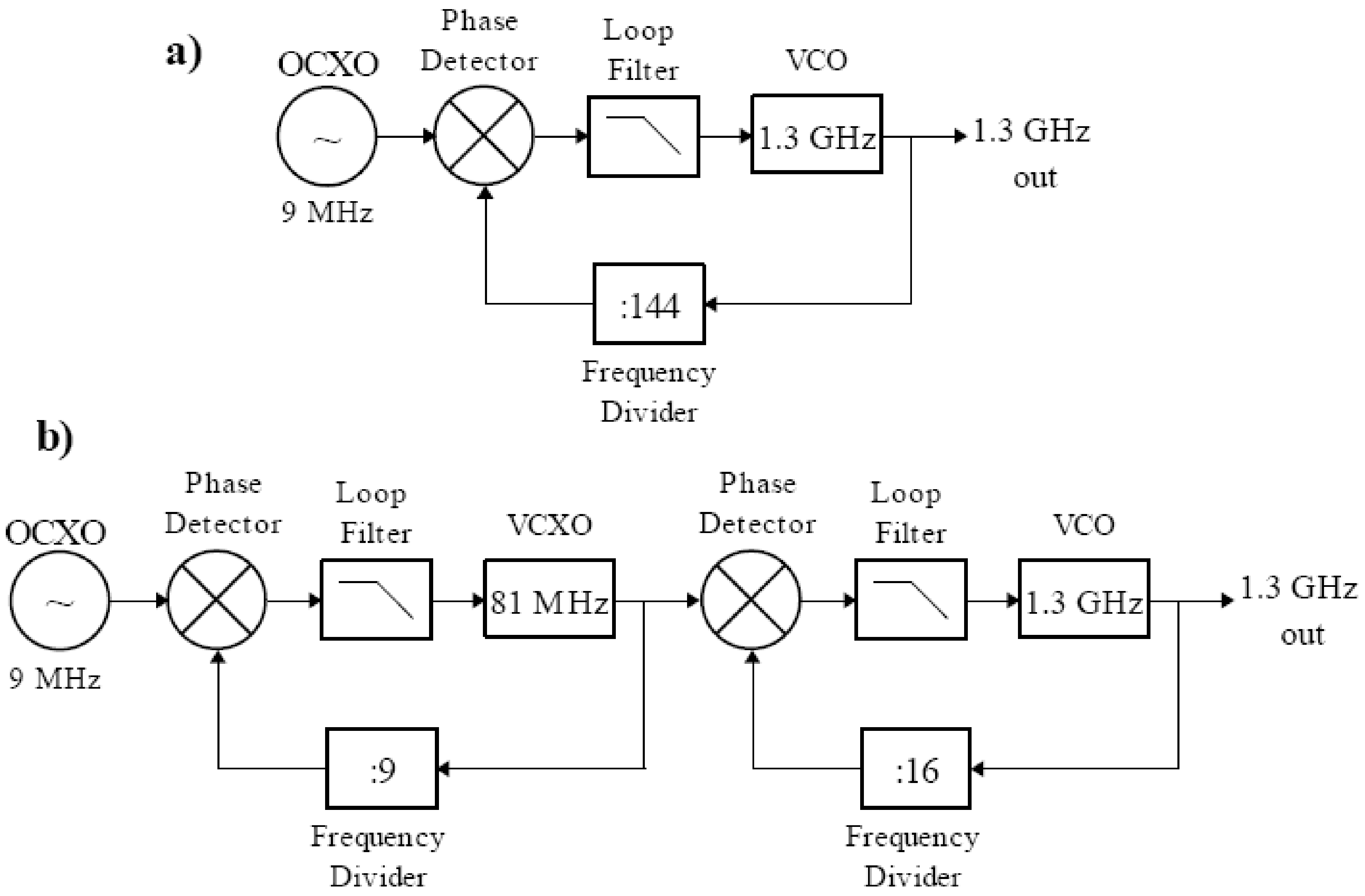
Synchronized system at FLASH



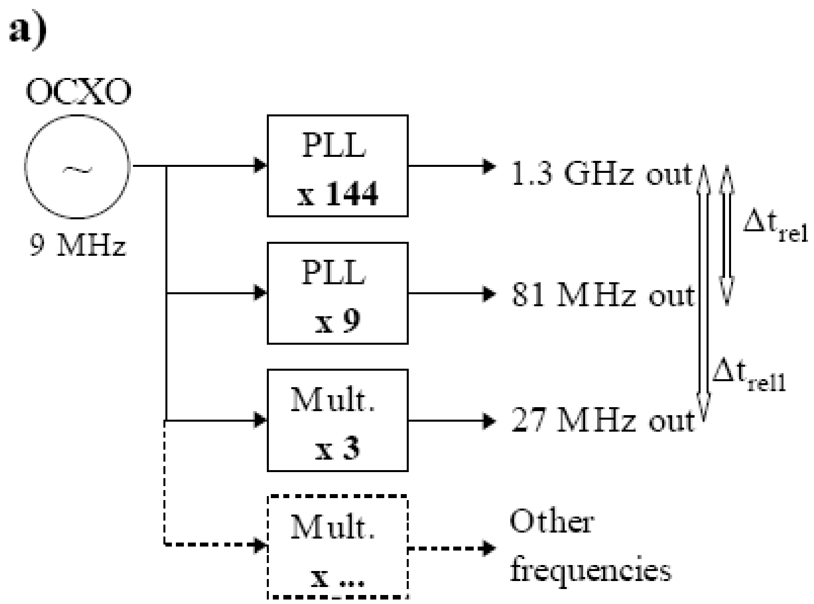
Possible frequency distribution schemes



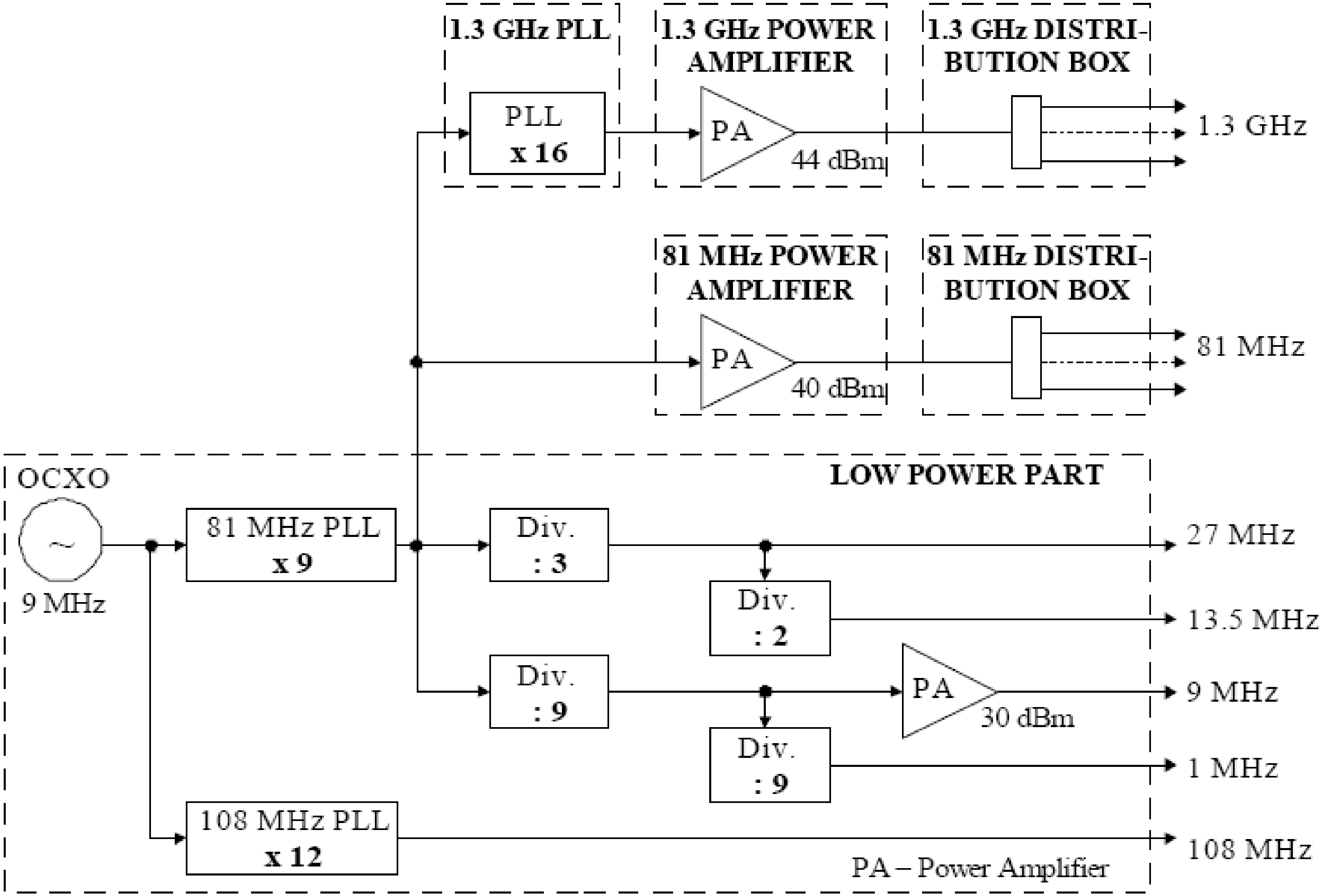
1.3 GHz generation from 9 MHz



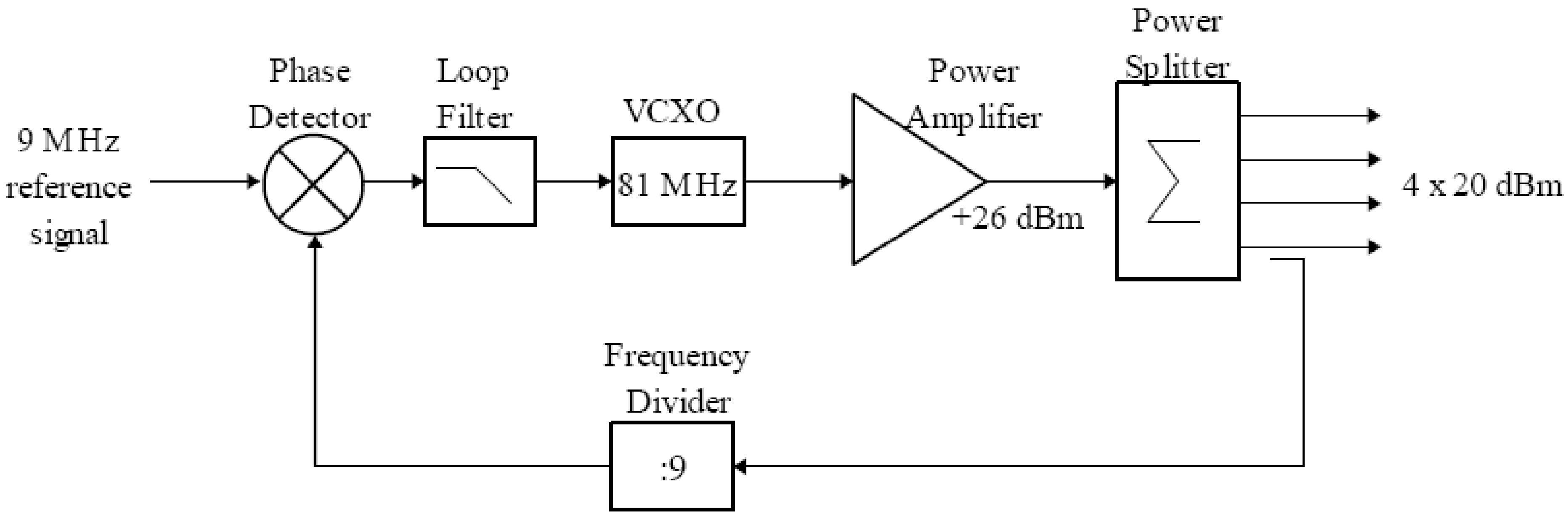
2 possible schemes for MO frequencies



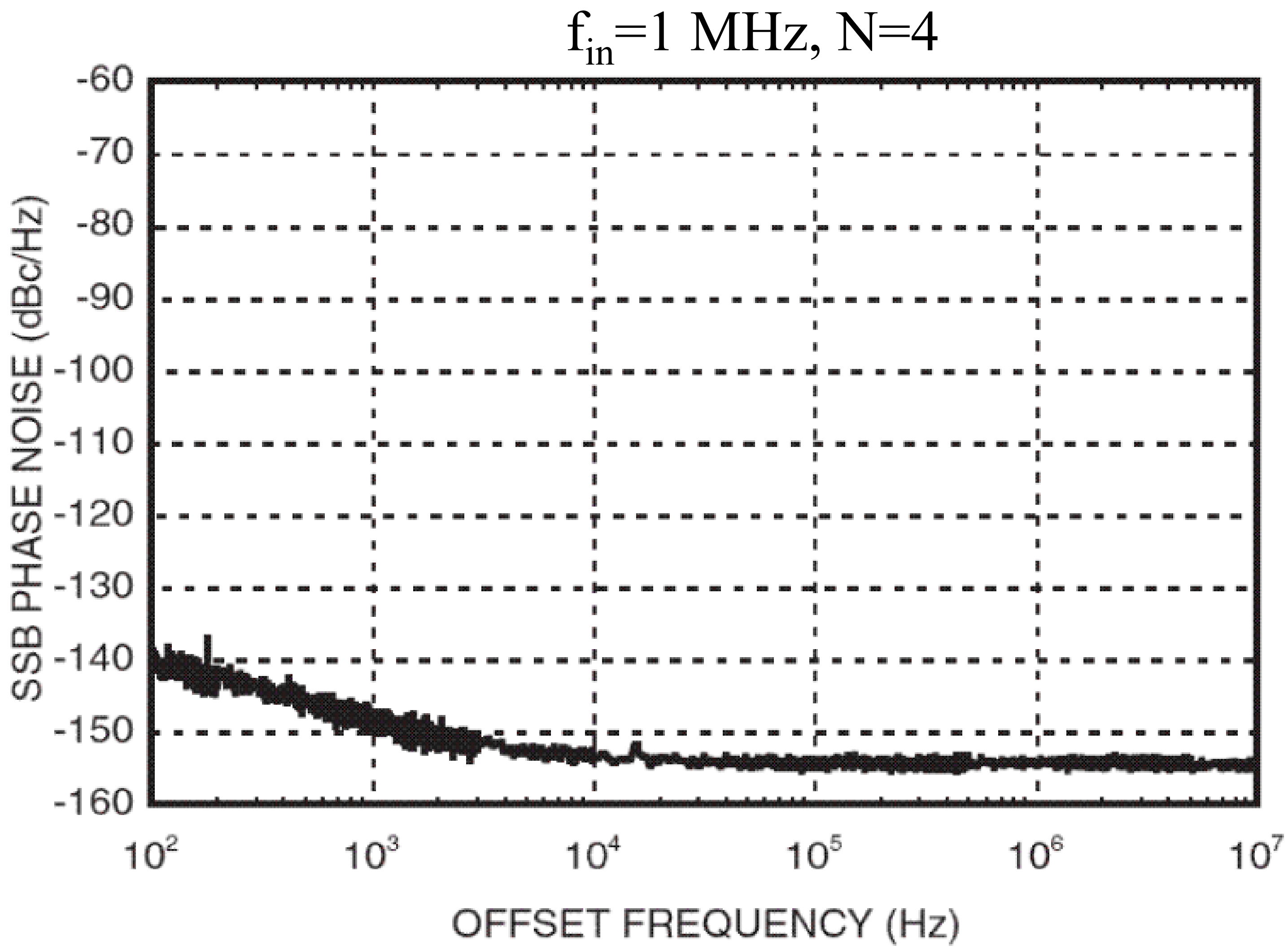
Block diagram of the FLASH MO



81 MHz phase locked loop



HMC 394 frequency divider phase noise



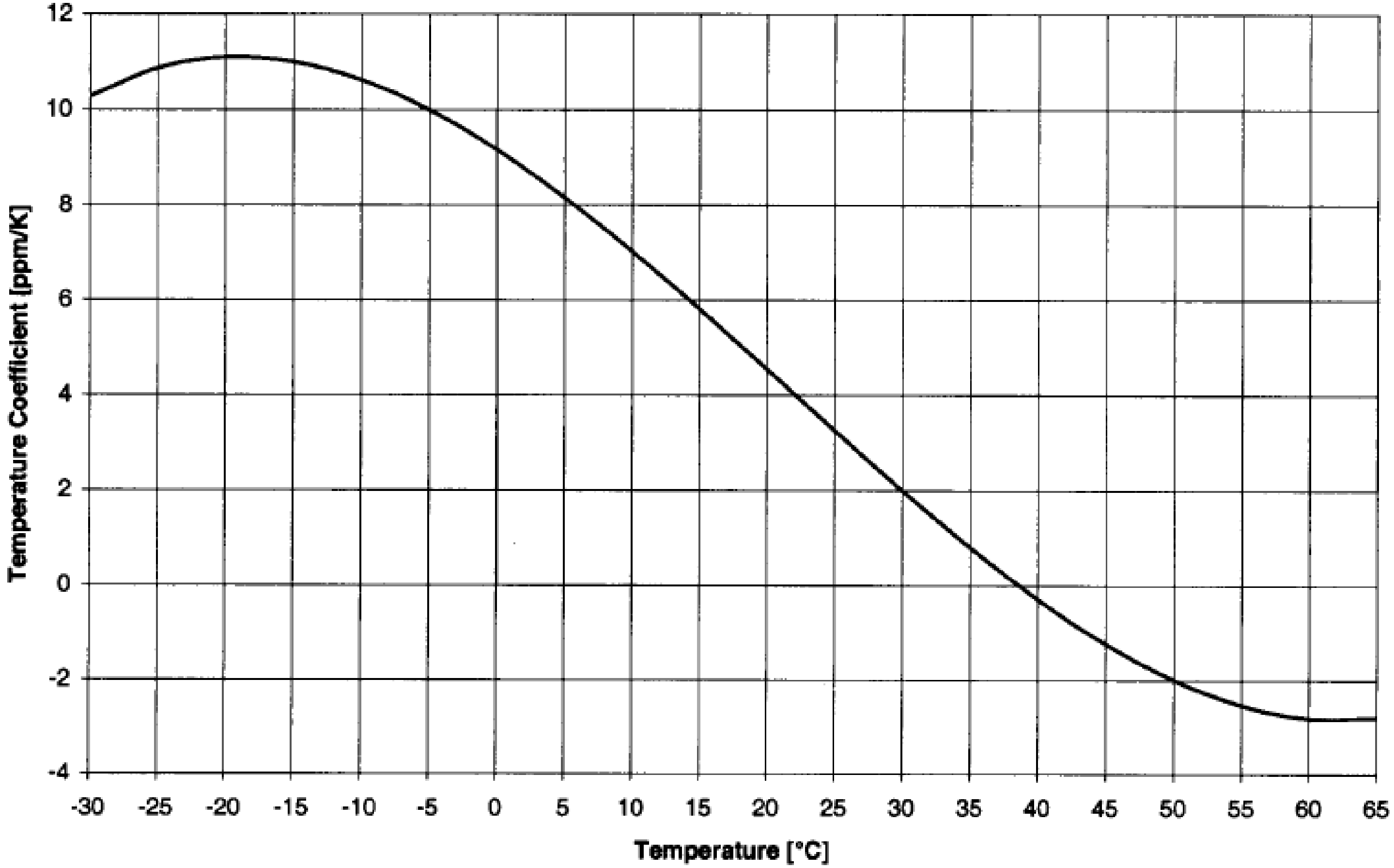
Parameters of coaxial cables

DIAMETER	1/4"	1/2"		7/8"	
CABLE	FSJ1-50A#	LCF12-50J*	FSJ4-50B#	HJ5-50#	LCF78-50J*
Attenuation [dB/100m]					
1 MHz	0.57	0.21	0.32	0.11	0.11
9 MHz	1.75	0.60	0.80	0.35	0.30
81 MHz	5.40	1.90	2.50	0.90	0.90
108 MHz	6.13	2.24	3.55	1.26	1.19
1300 MHz	22.50	8.15	14.00	4.90	4.70
3000 MHz	35.60	13.20	22.40	7.96	7.38
Phase/Temp coefficient -30 to +40°C [ppm/°C]	-7 to +9	+11 to -0.3	-2 to +6	+5 to +11	+9 to -0.5
Signal velocity [% of c_0]	84.0	88.0	81.0	91.6	88.0

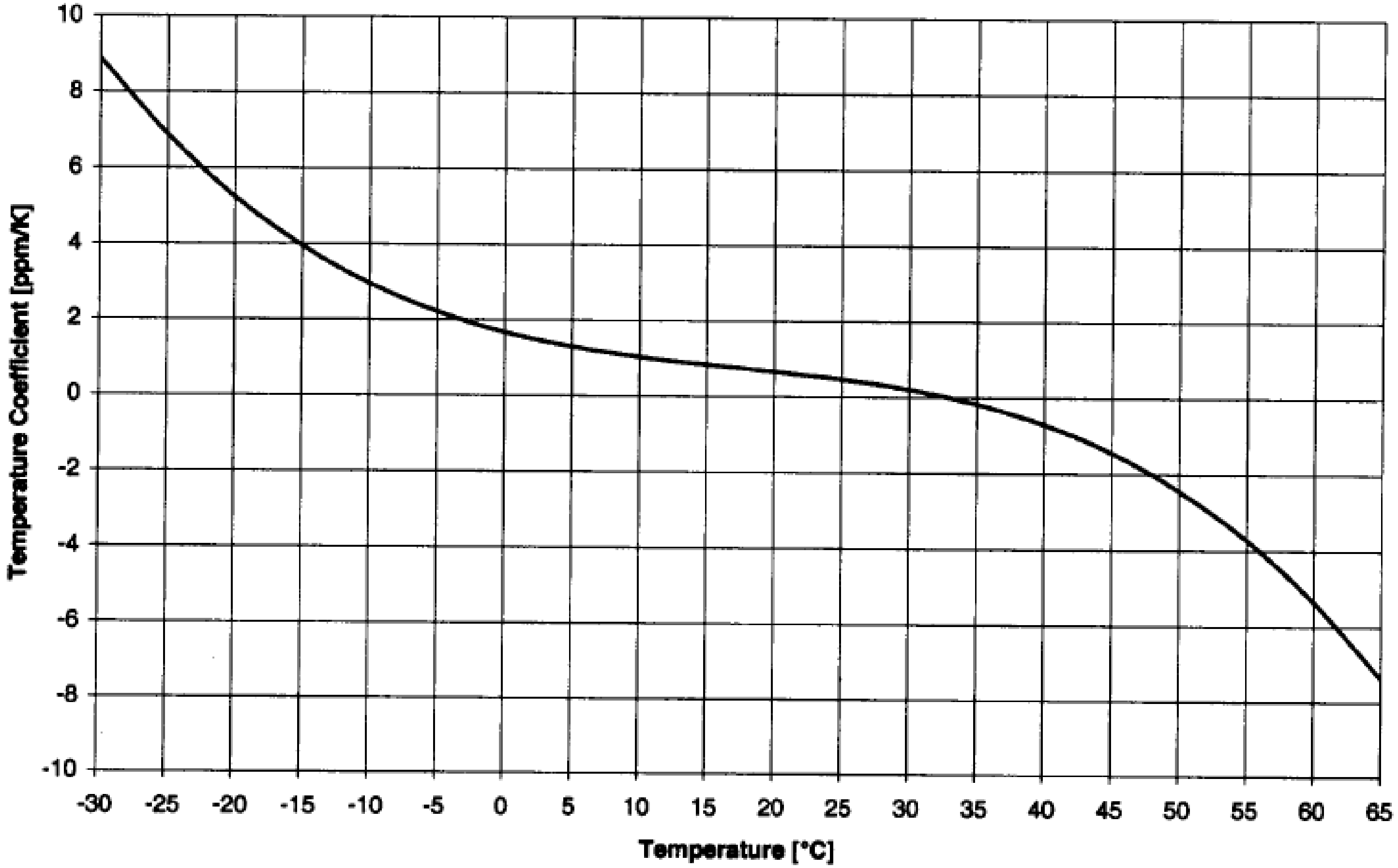
Cable manufactured by the Andrew Corporation

* Cable manufactured by the RFS

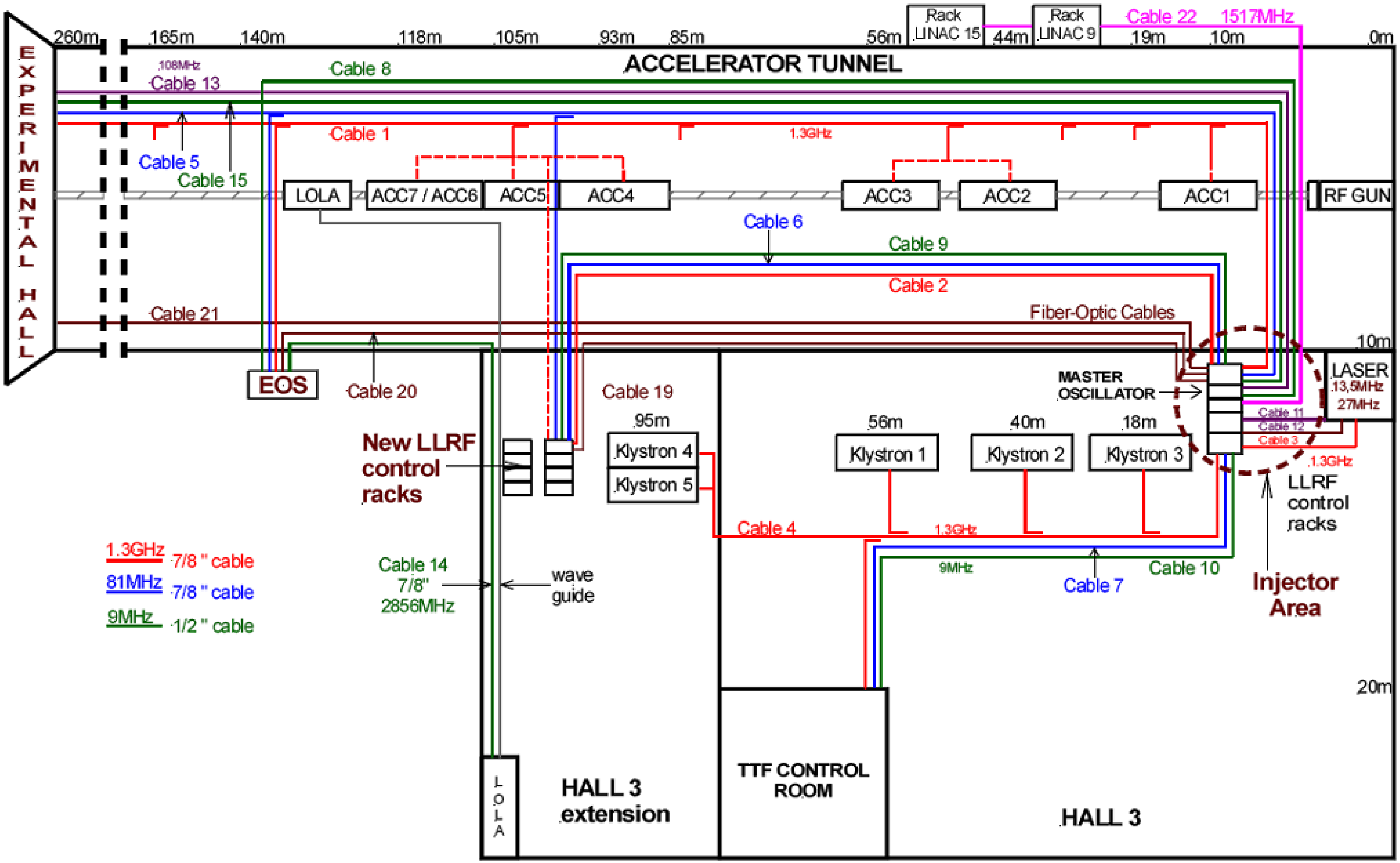
Temp. coeff. of 1/2” cable



Temp. coeff. of 7/8” cable



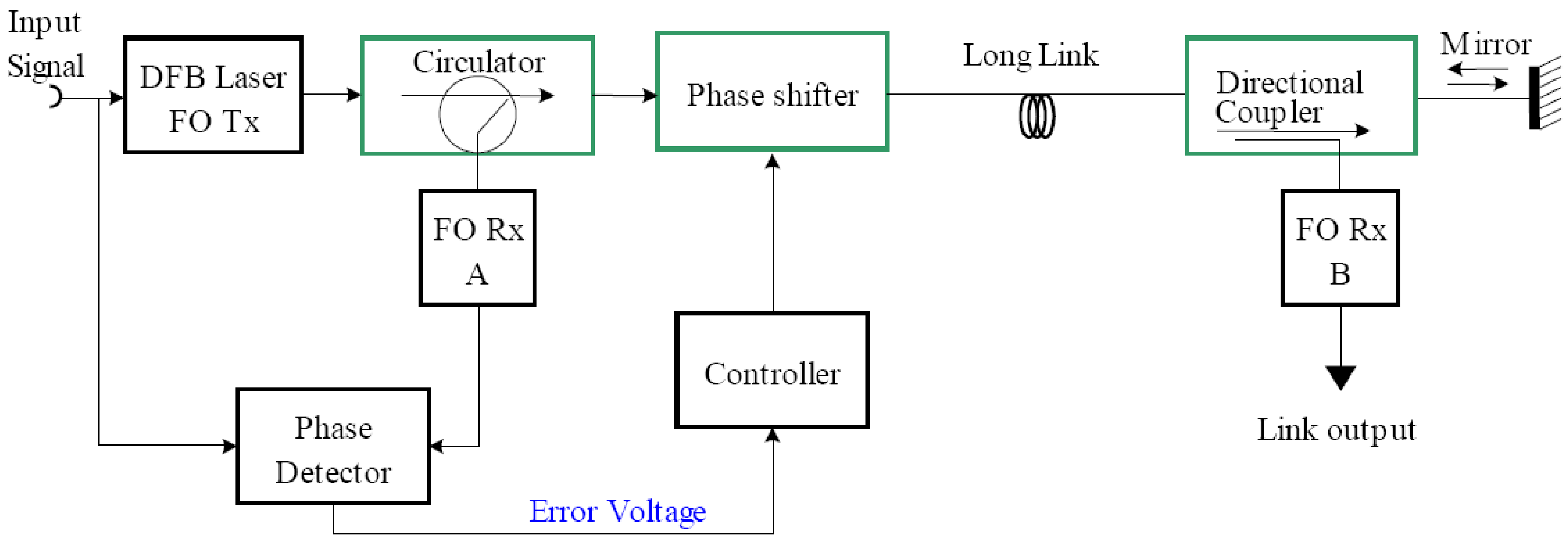
Frequ. Distr. Scheme at FLASH



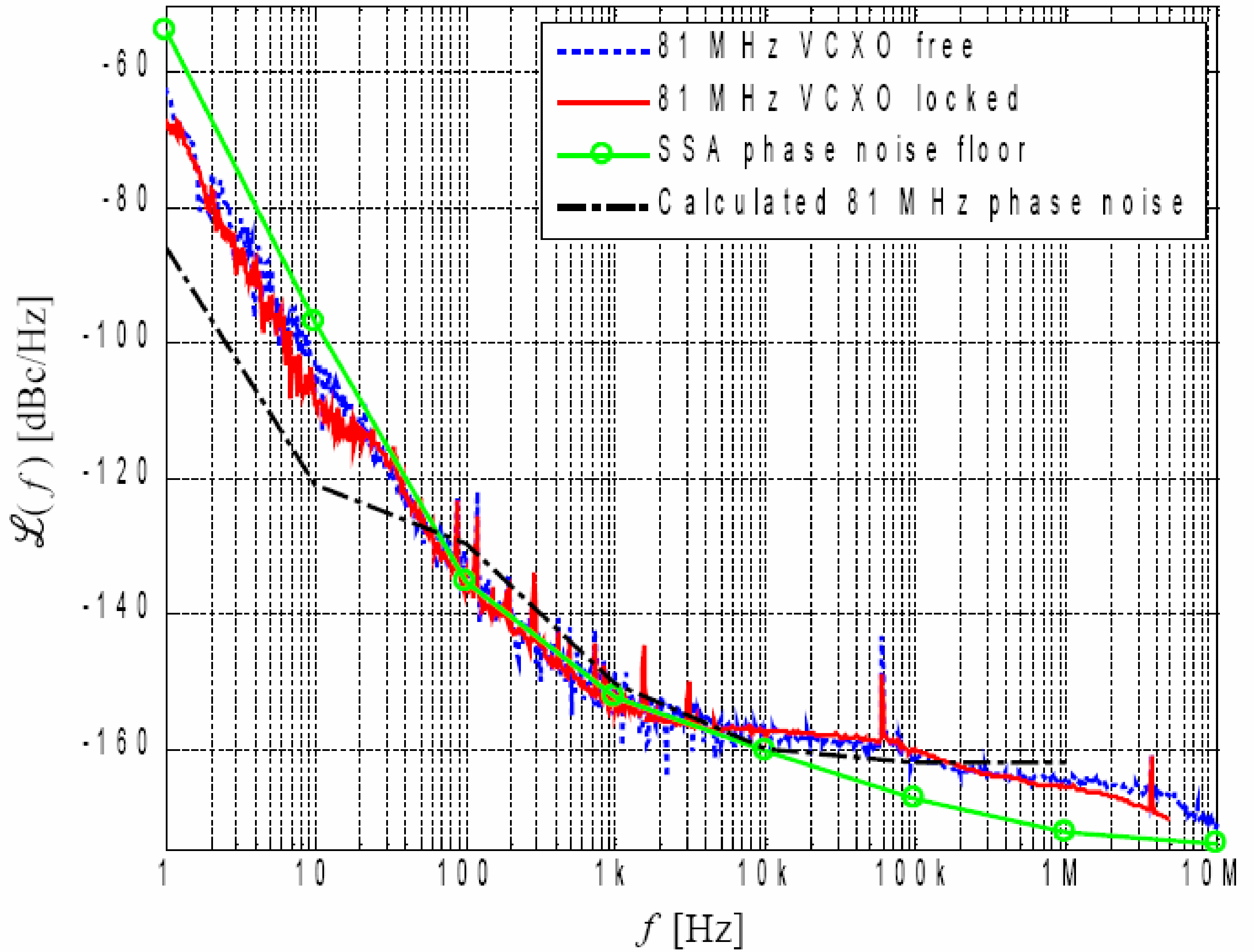
Estimated phase drifts of cables

1	2	3	4	5	6	7
Destination	**Approx. cable length [m]**	**Cable No.**	**Cable Diameter [inch]**	**No cable temp. stabilisation, phase drifts per day for $\Delta T = 5°C$ [ps]**	**No cable temp. stabilisation, phase drifts per hour $\Delta T = 1.5°C$ [ps]**	**Cable temp. stabilised, phase drifts for $\Delta T = \pm 0.5°C$ [ps]**
Experimental Hall	290	1, 5, 13	7/8	5.49	1.65	0.22
		15	1/2	27.46	8.24	1.10
EOS	150	1, 5	7/8	2.84	0.85	0.11
		8	1/2	14.20	4.26	0.57
New LLRF racks	110	2, 6	7/8	2.08	0.63	0.08
		9	1/2	10.42	3.13	0.42
Klystron 4-5, TTF control room	70	4, 7	7/8	1.33	0.40	0.05
		10	1/2	6.63	1.99	0.47

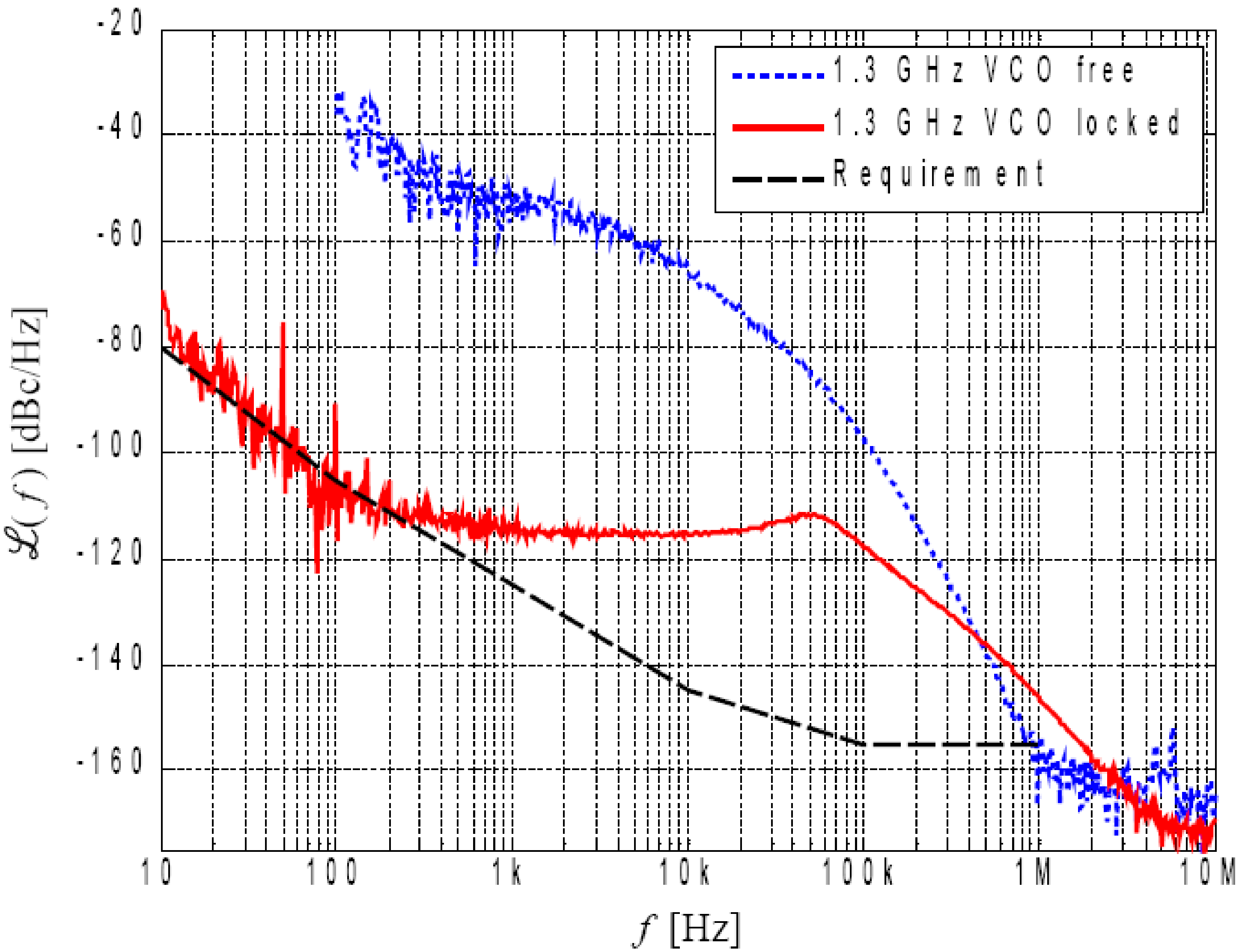
Concept of stabilized fiber link



Measured phase noise at 81 MHz

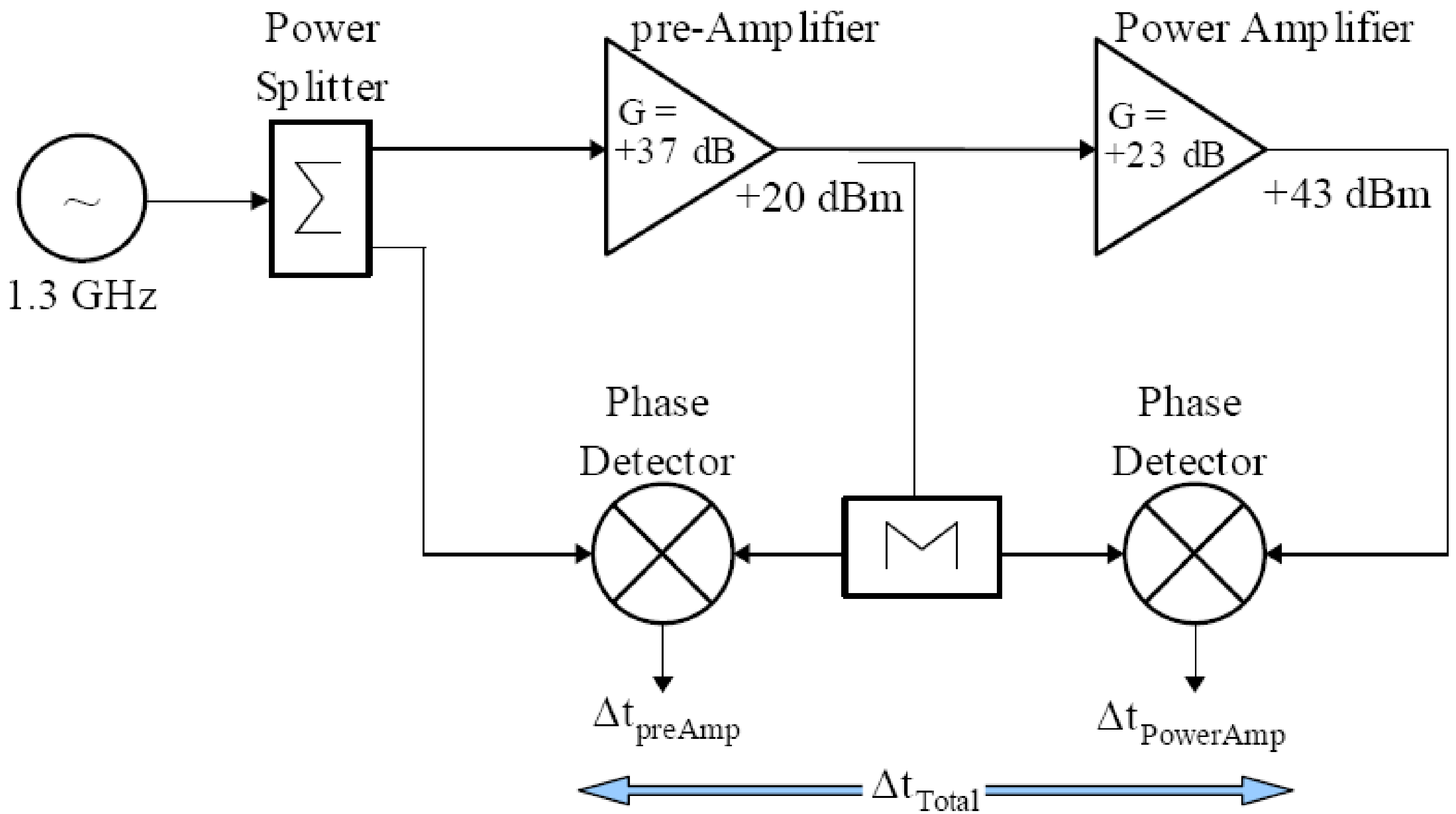


Phase noise at 1.3 GHz

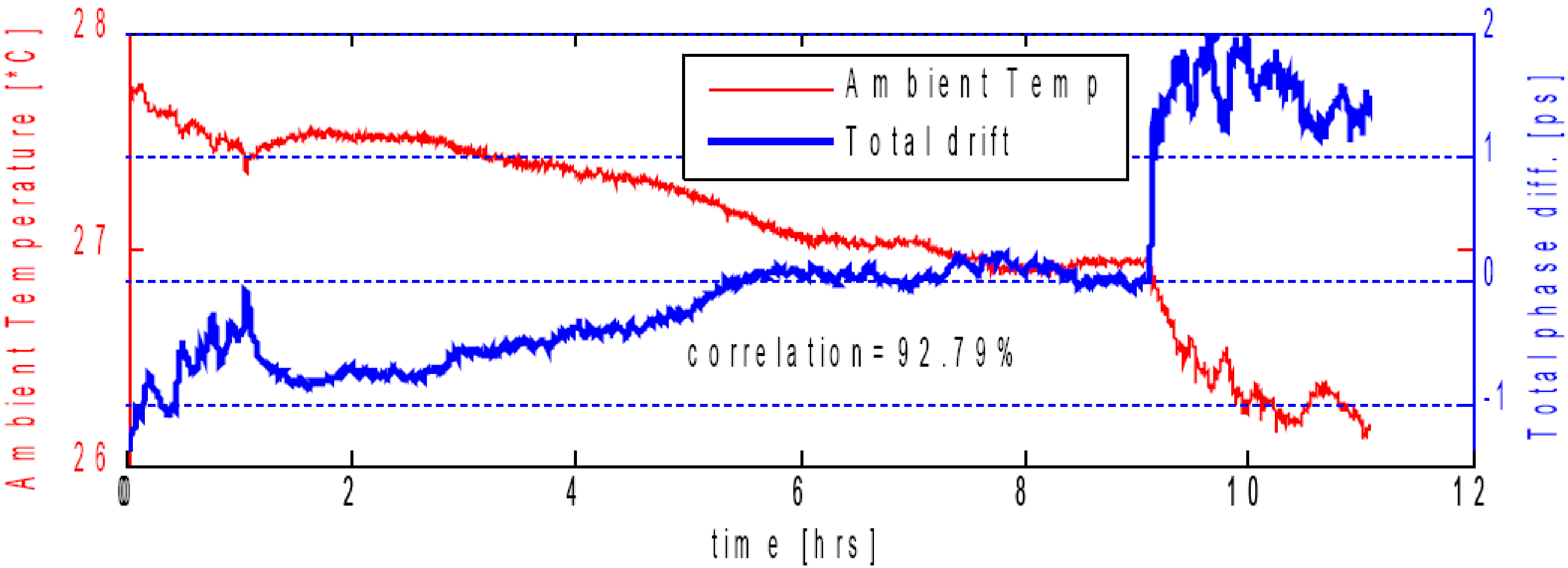


F

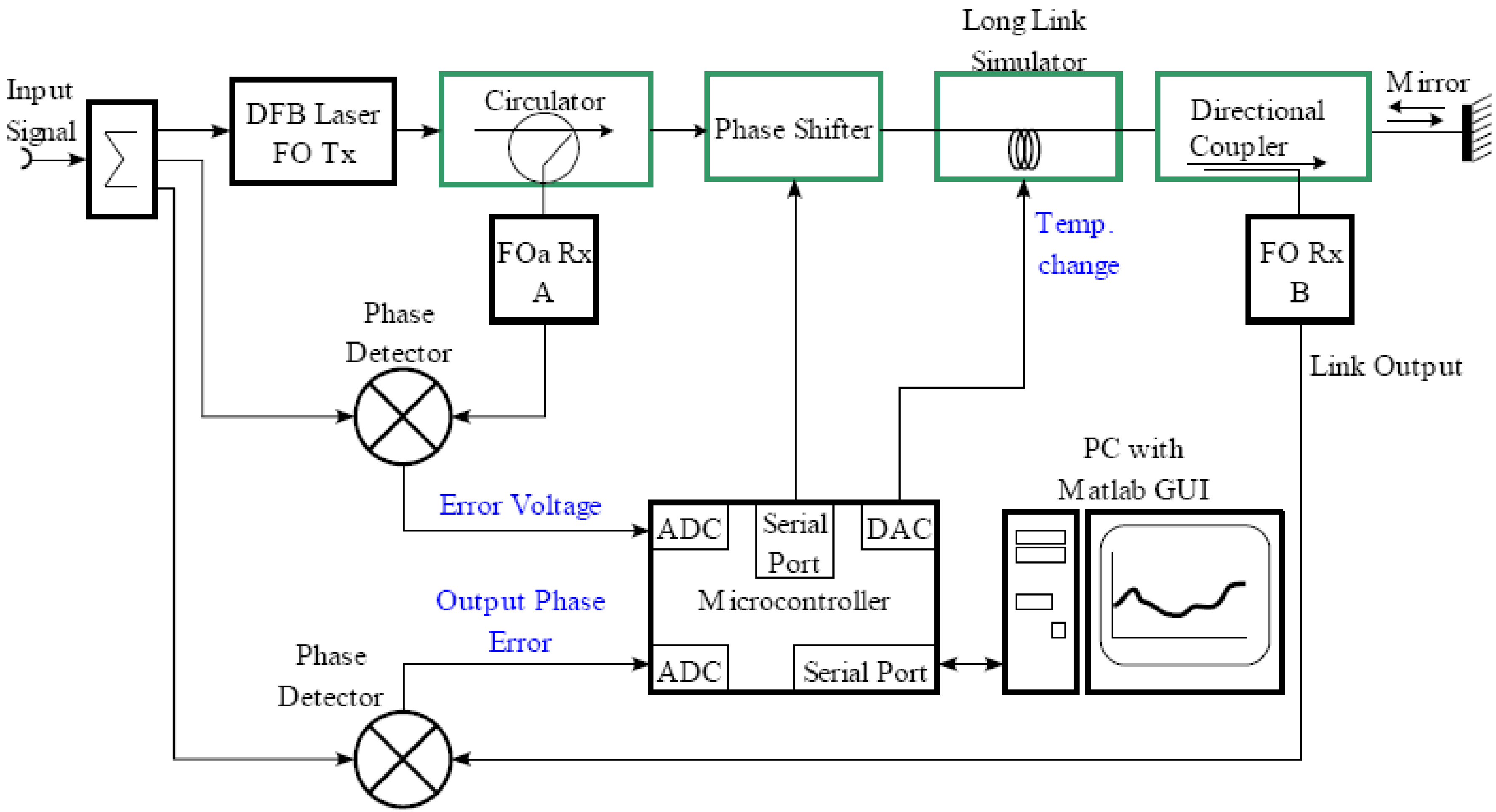
Drift measurement



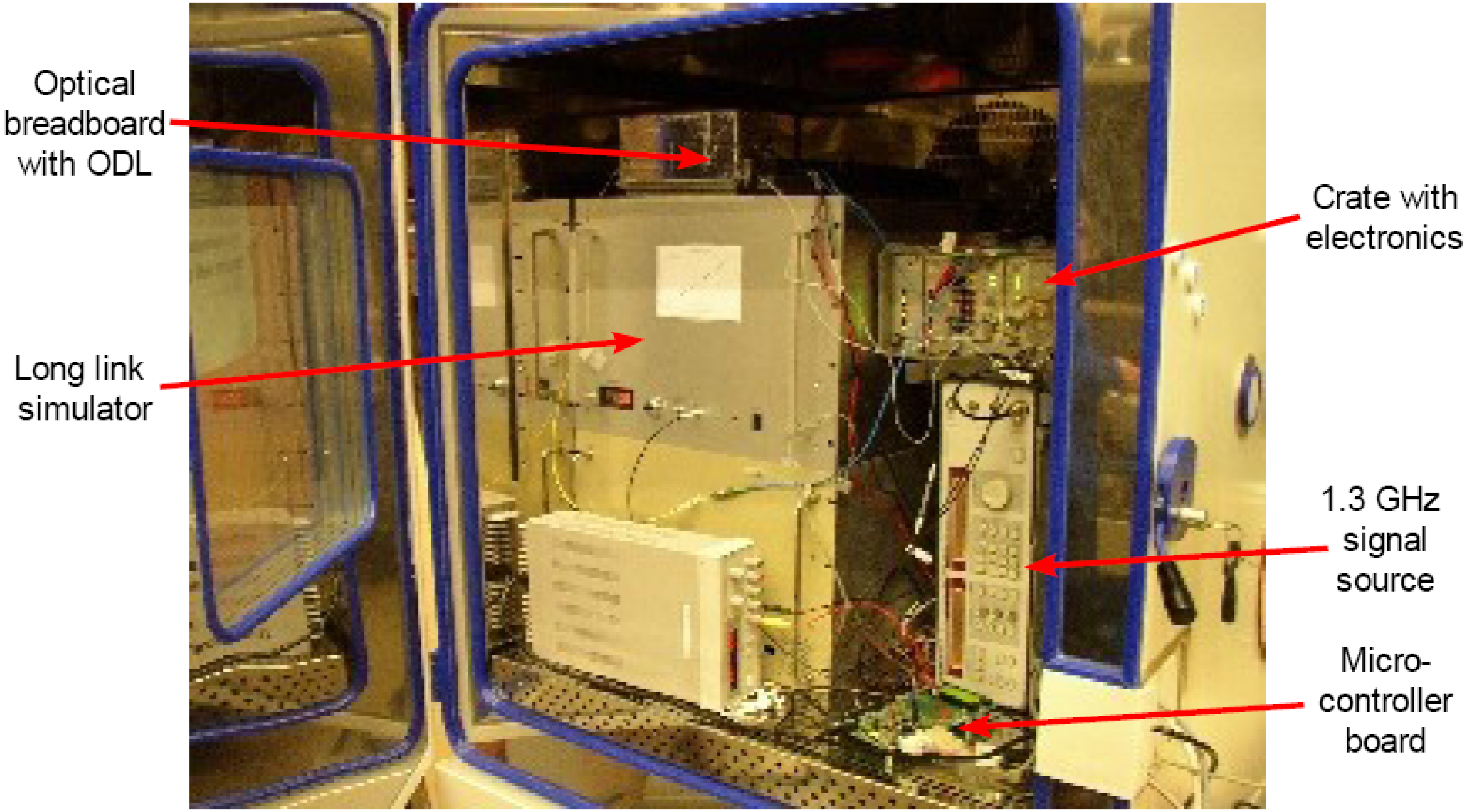
Drift of 1.3 GHz power amplifiers



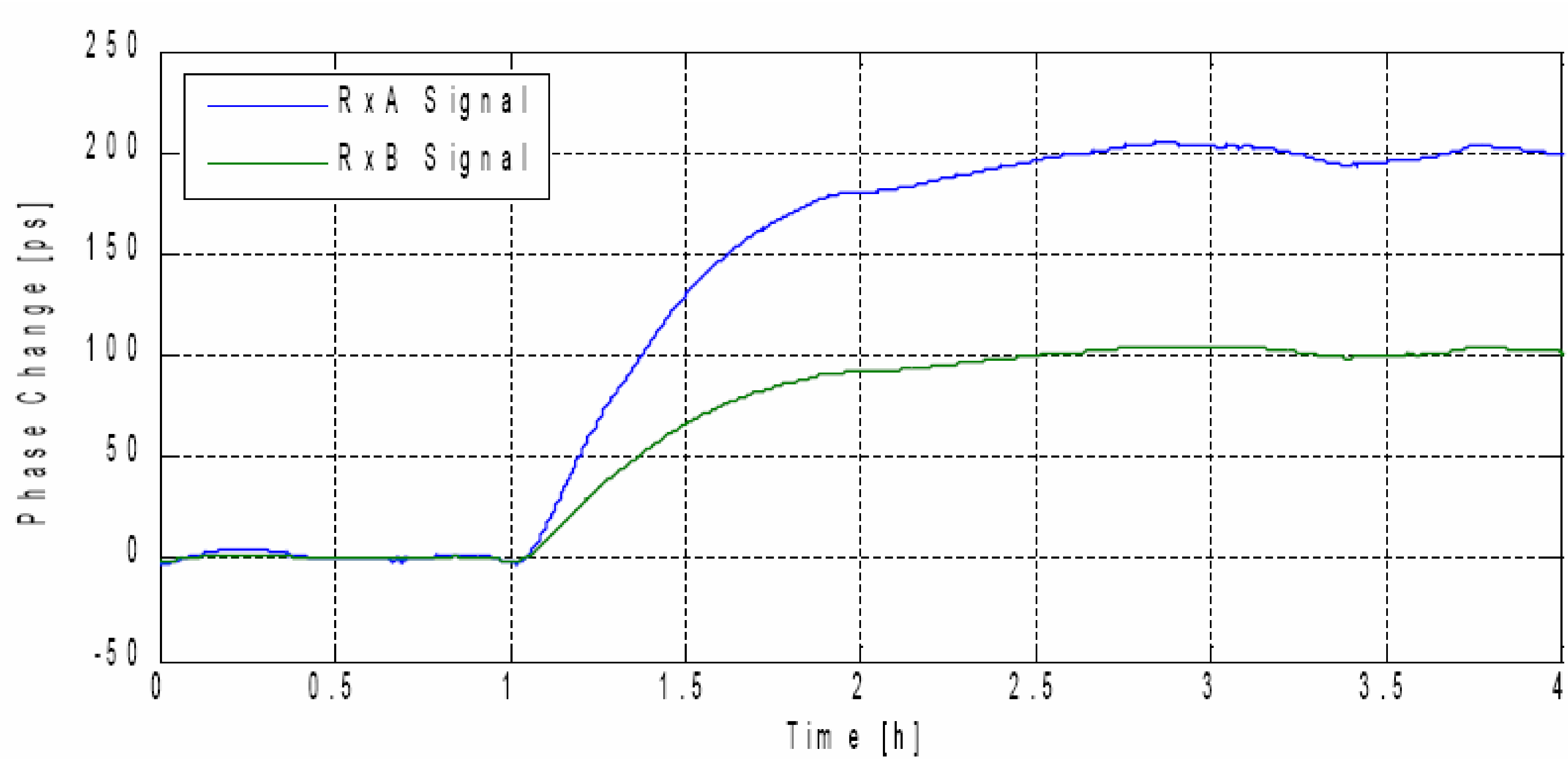
Drift measurement of fiber reference



Setup in climate chamber

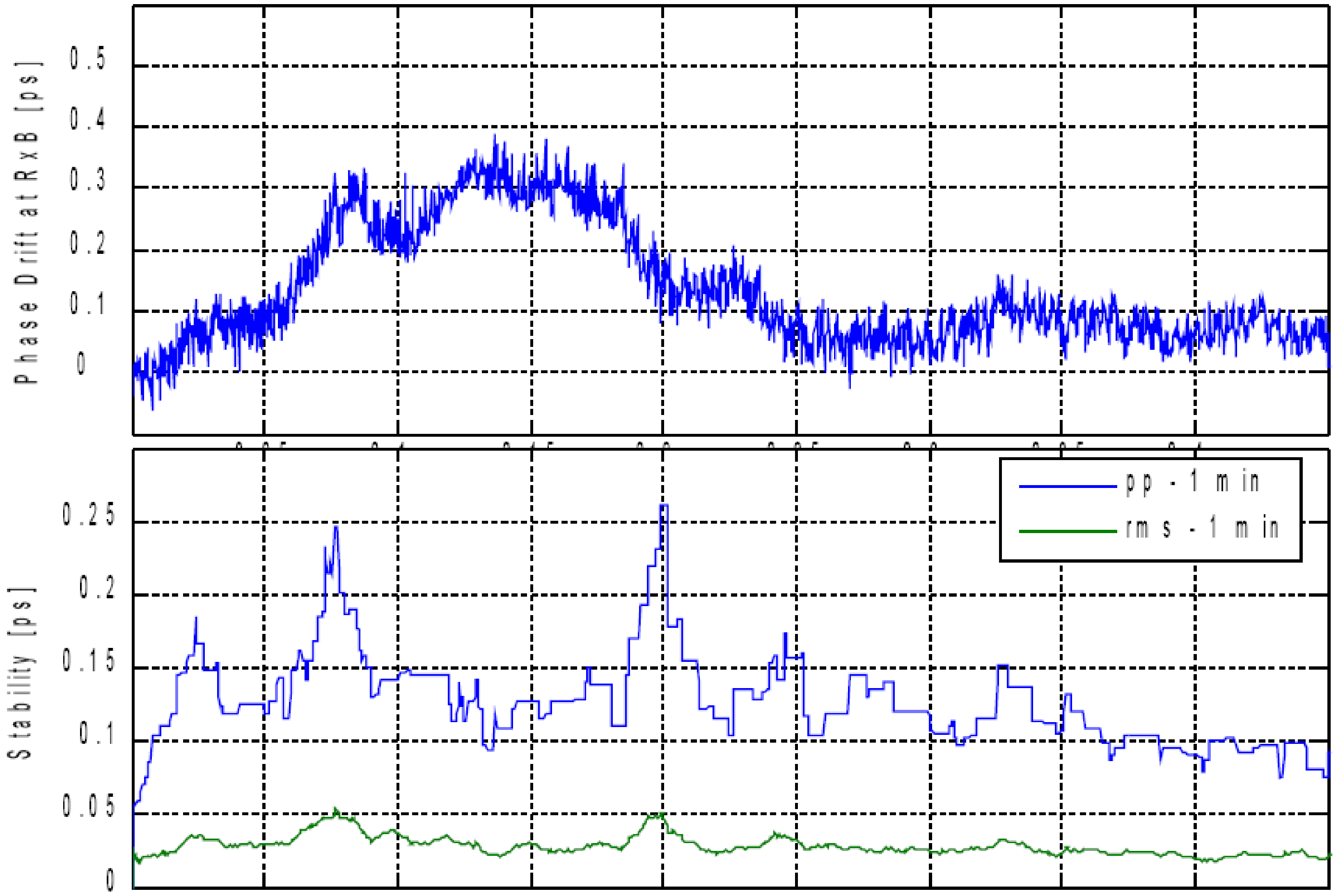


Drift of fiber link

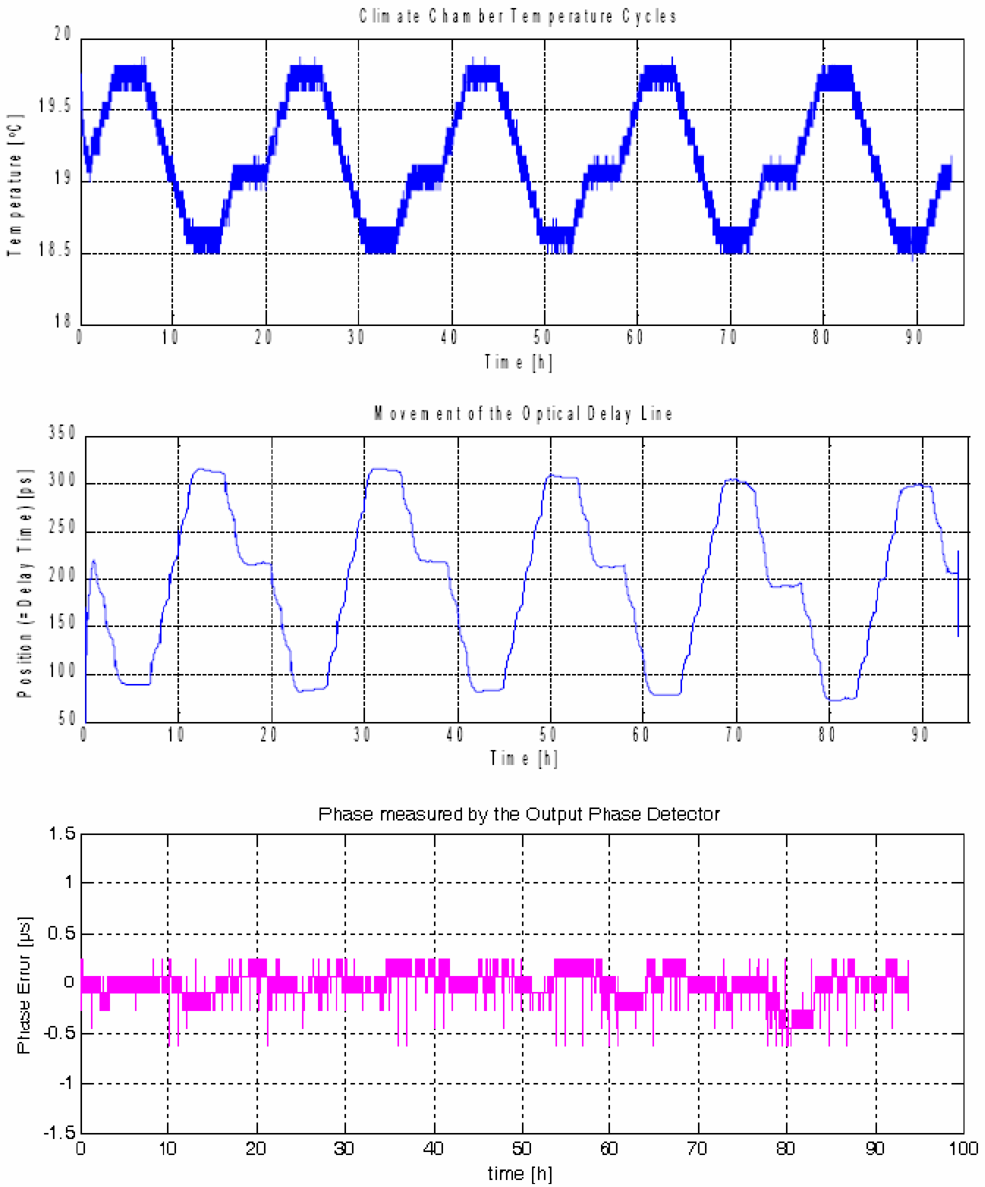


ΔT=0.5 deg.C, 5 km fiber

Drift of stabilized link

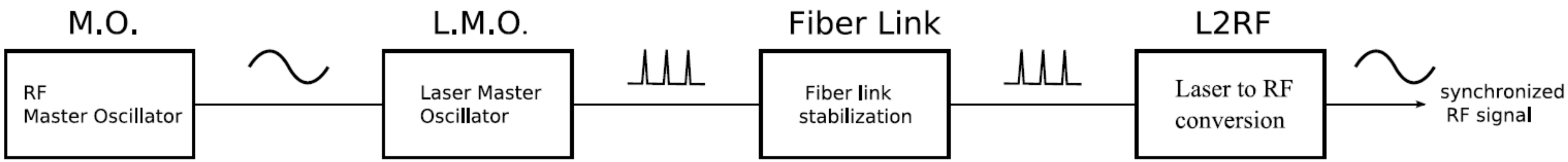


Long term drift measurement

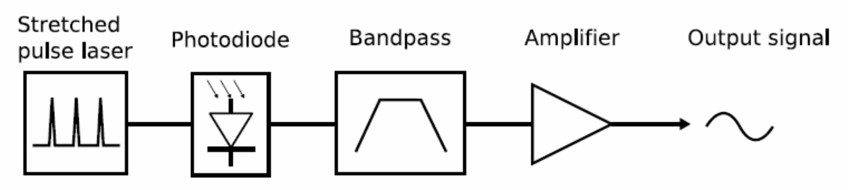


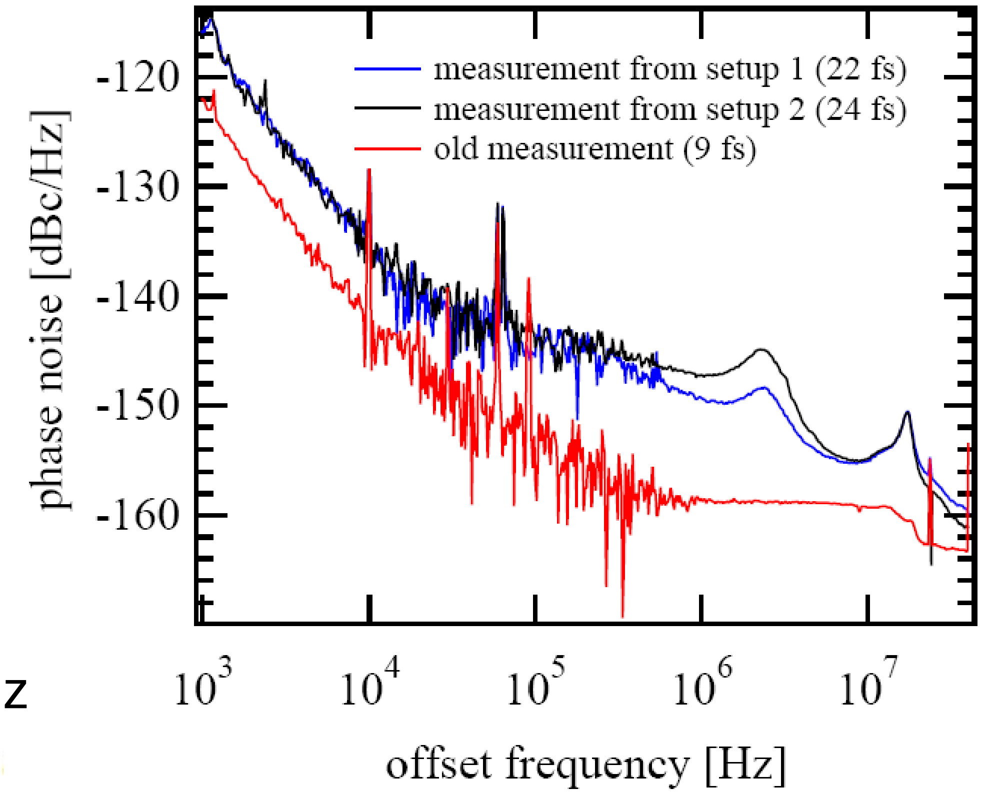
Synchronization of RF Signals

Signal chain



Optical to rf conversion

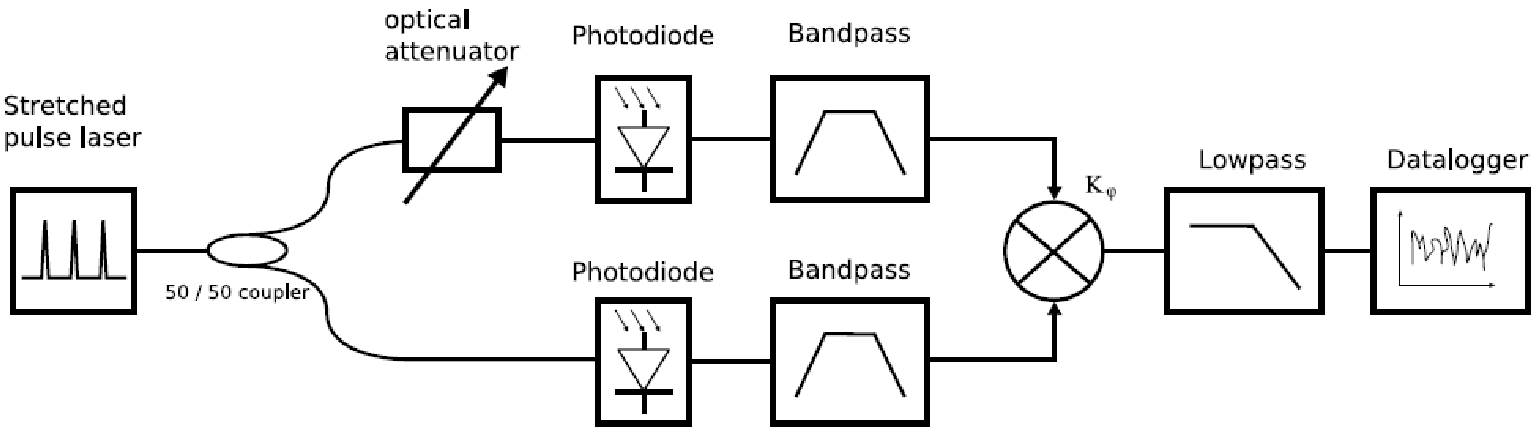




Measured phase noise

(3 diodes, 1kHz-20 MHz

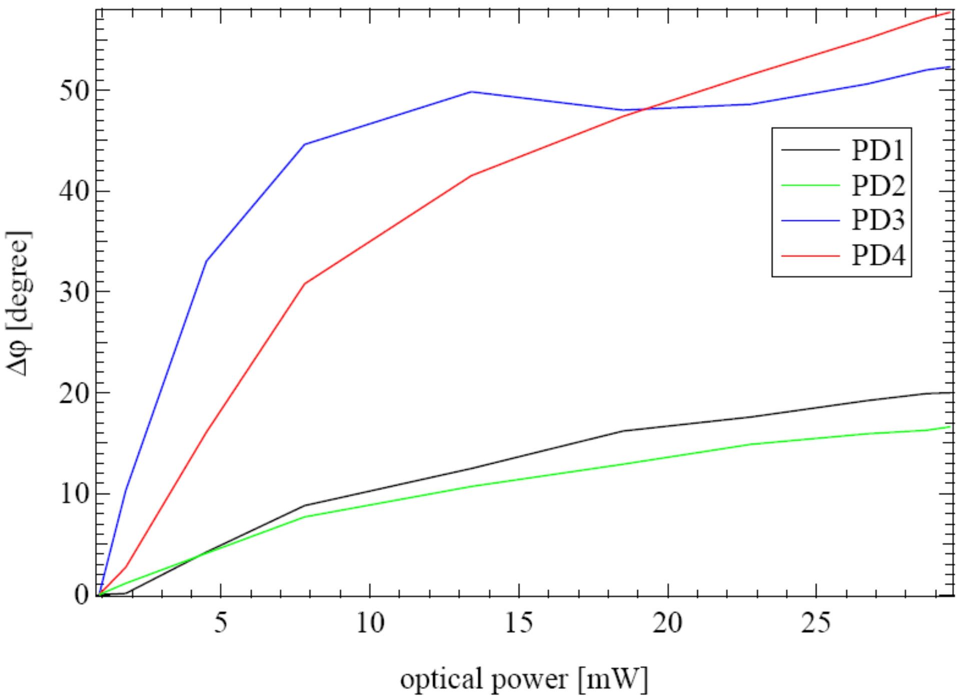
Measurements AM-to-PM Conversion



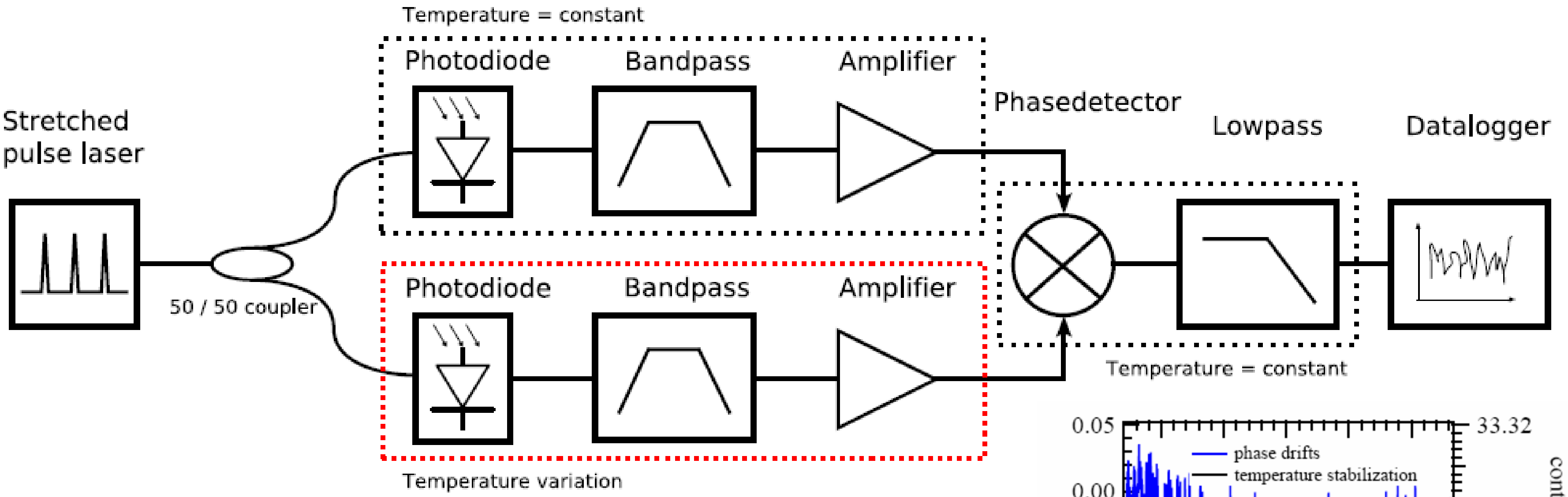
Measurement Setup

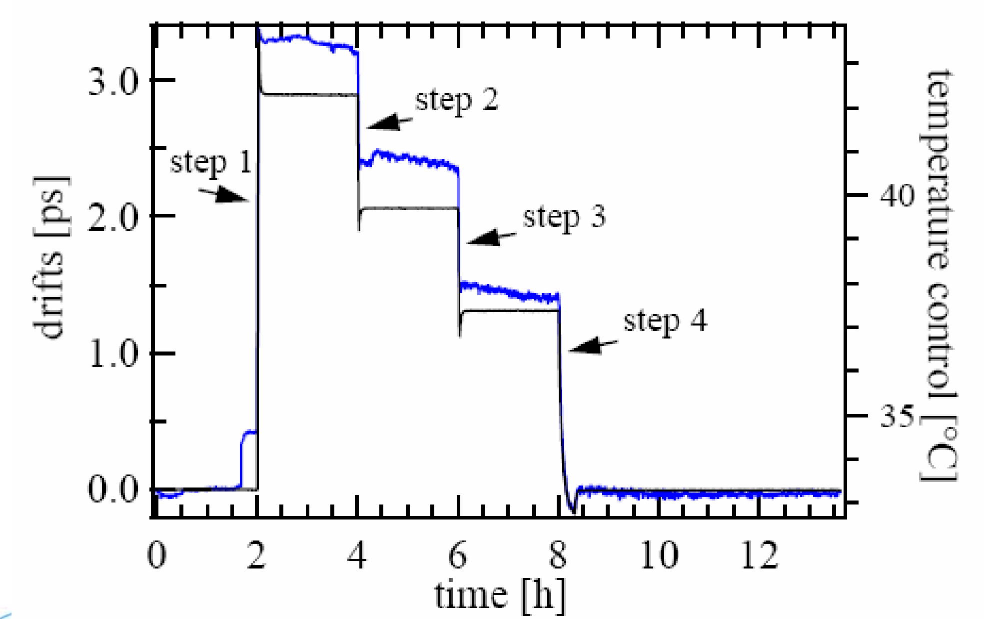
Photodiode	$\frac{\Delta\phi}{\Delta P_{opt}}[\frac{°}{mW}]$	$\frac{\Delta T}{\Delta P_{opt}}[\frac{ps}{mW}]$
PD4	1.6	3.4
PD2	0..0.9	0..1.9
PD1	0.7	1.5
PD3	0.5	1.1

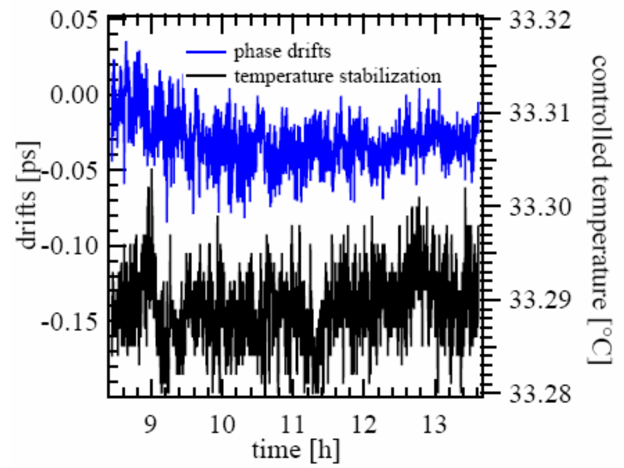
Measurement results
for 4 diodes



Phase drift measurement

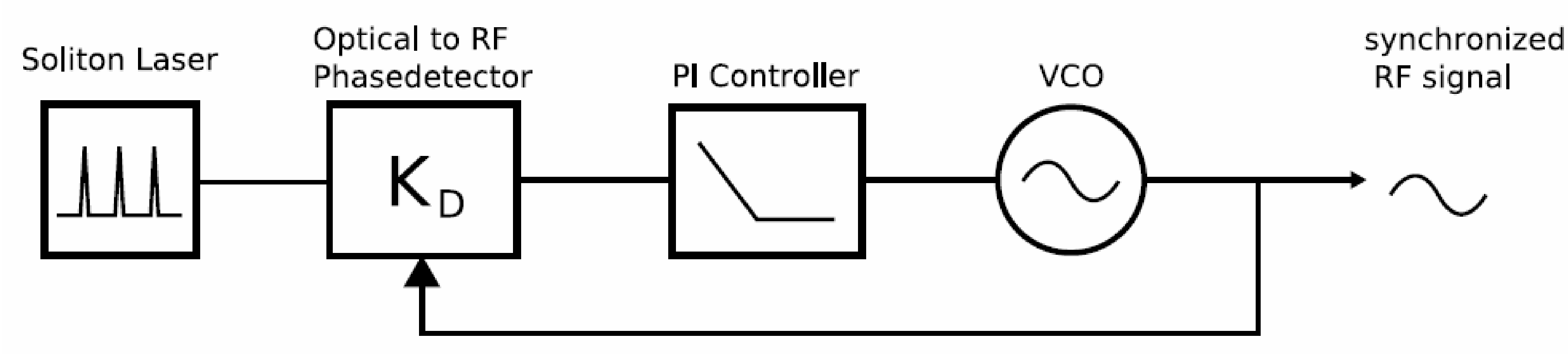


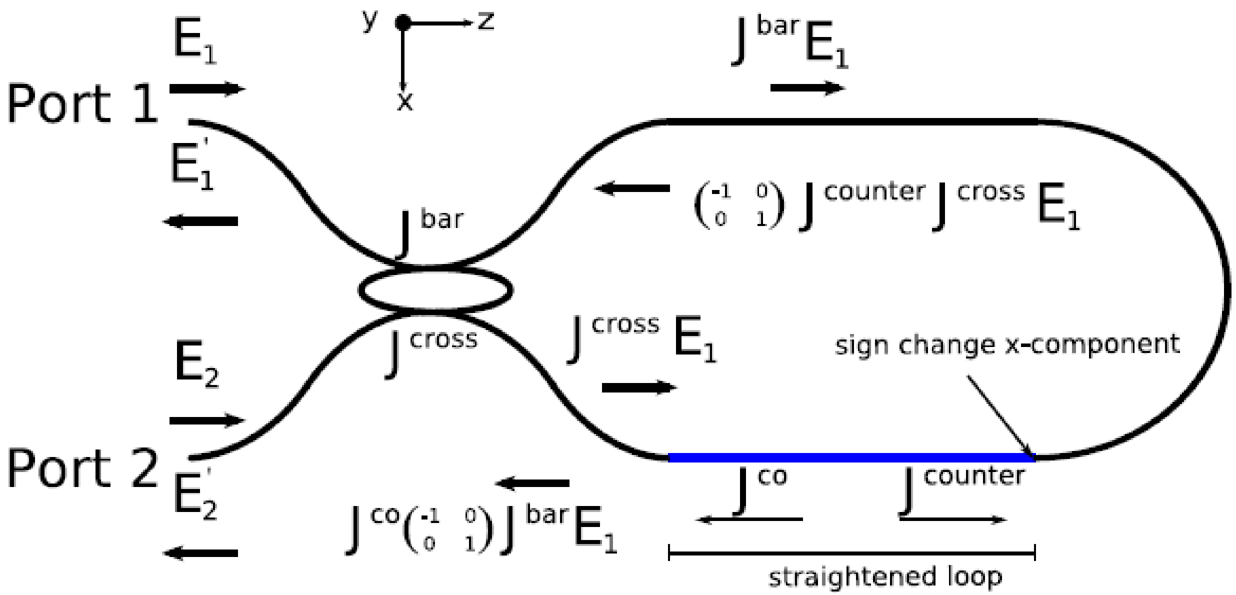




Step number	temperature coefficient [fs/°C]
Step 1	366
Step 2	326
Step 3	359
Step 4	350

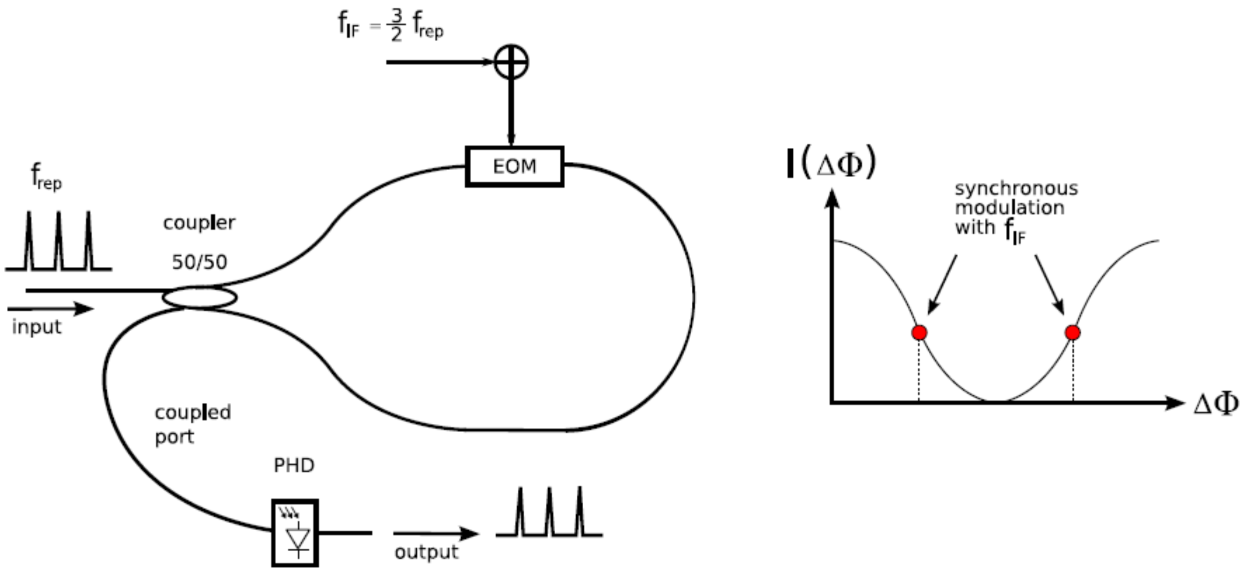
Optical to RF PLL



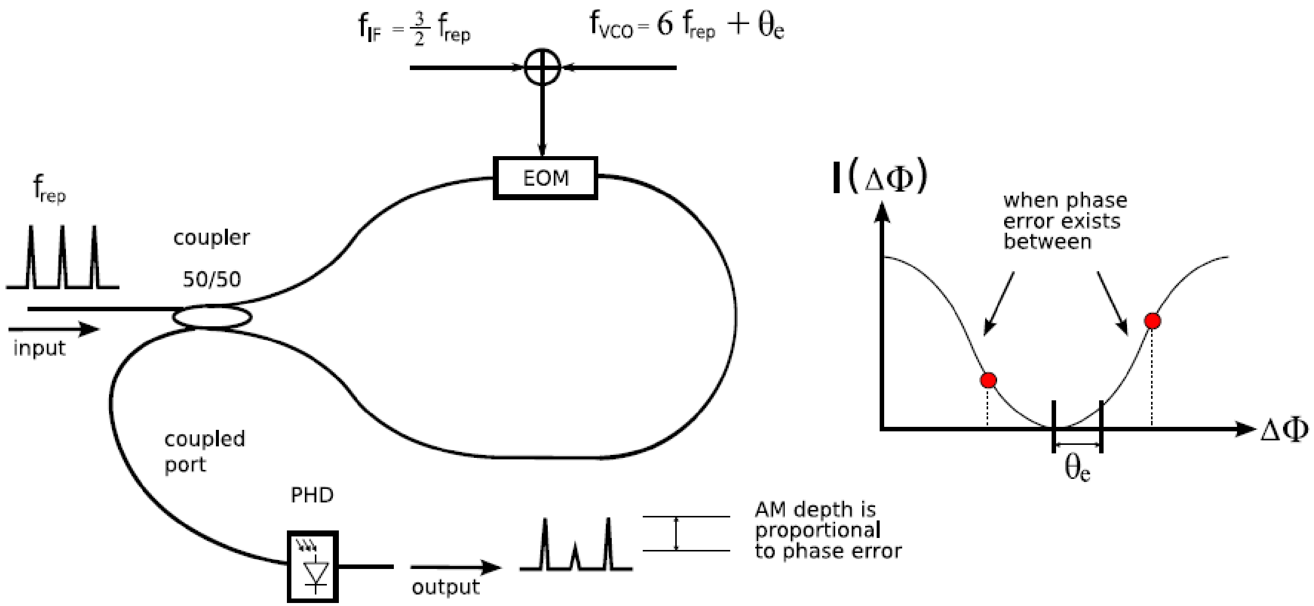


Sagnac Interferometer

Generation of error signal

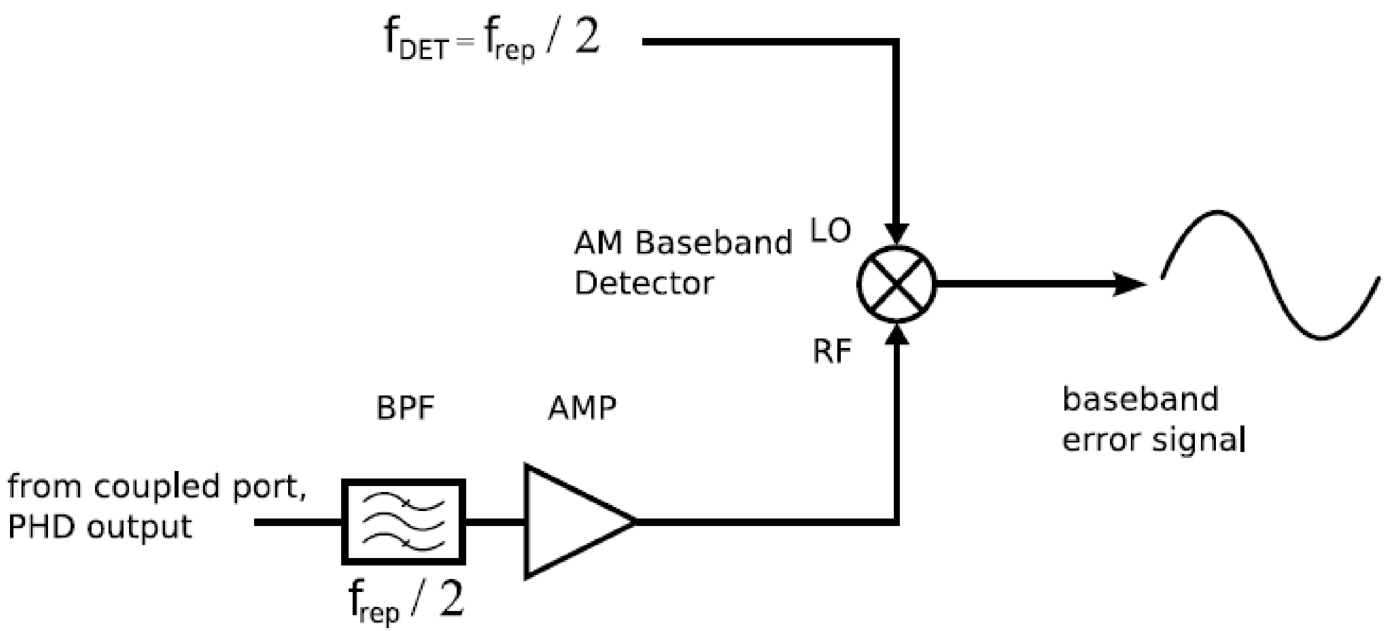


No rf or zero phase error

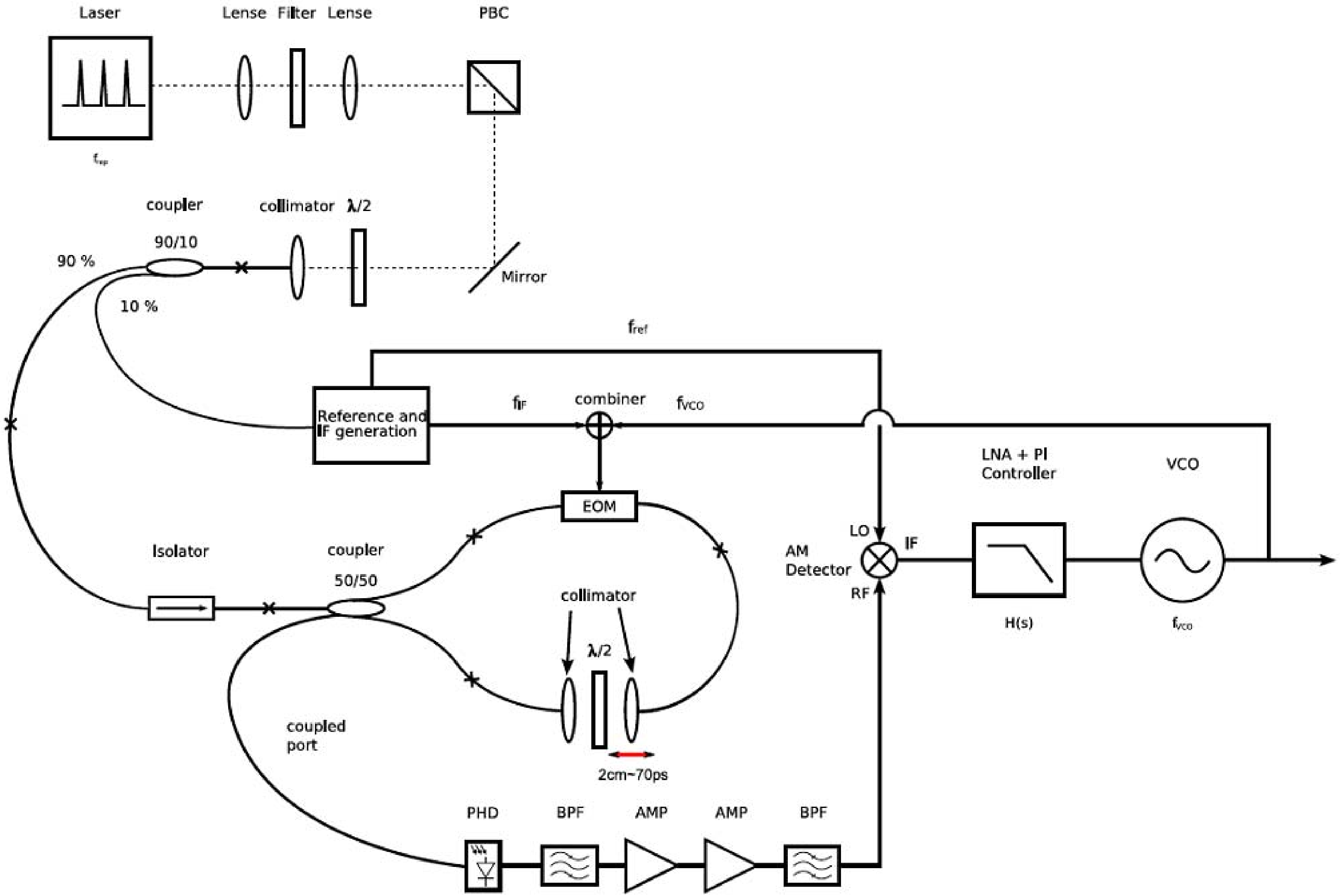


Phase error between VCO and rf

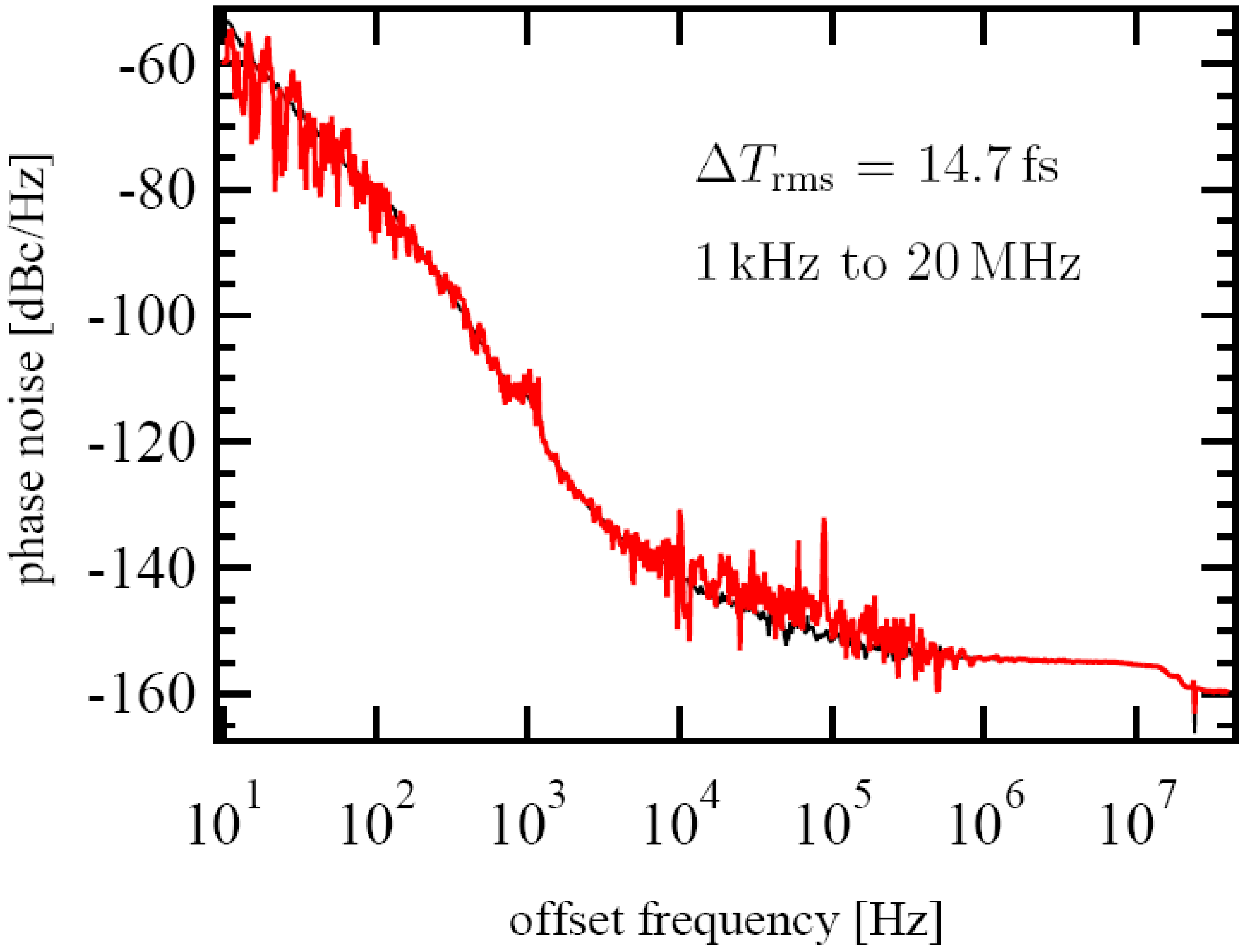
Synchronous demodulation



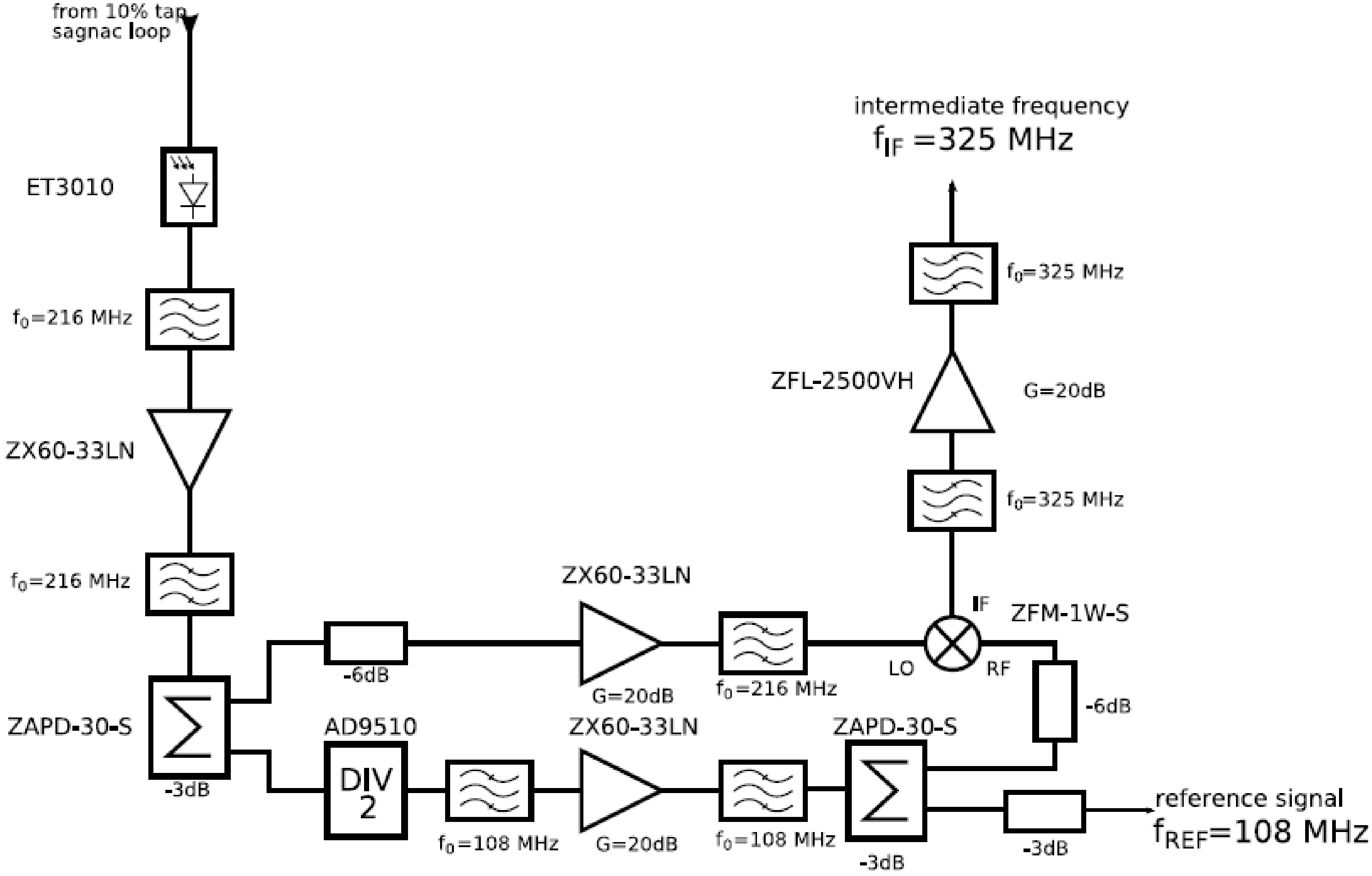
Complete Sagnac Loop



Measured phase noise

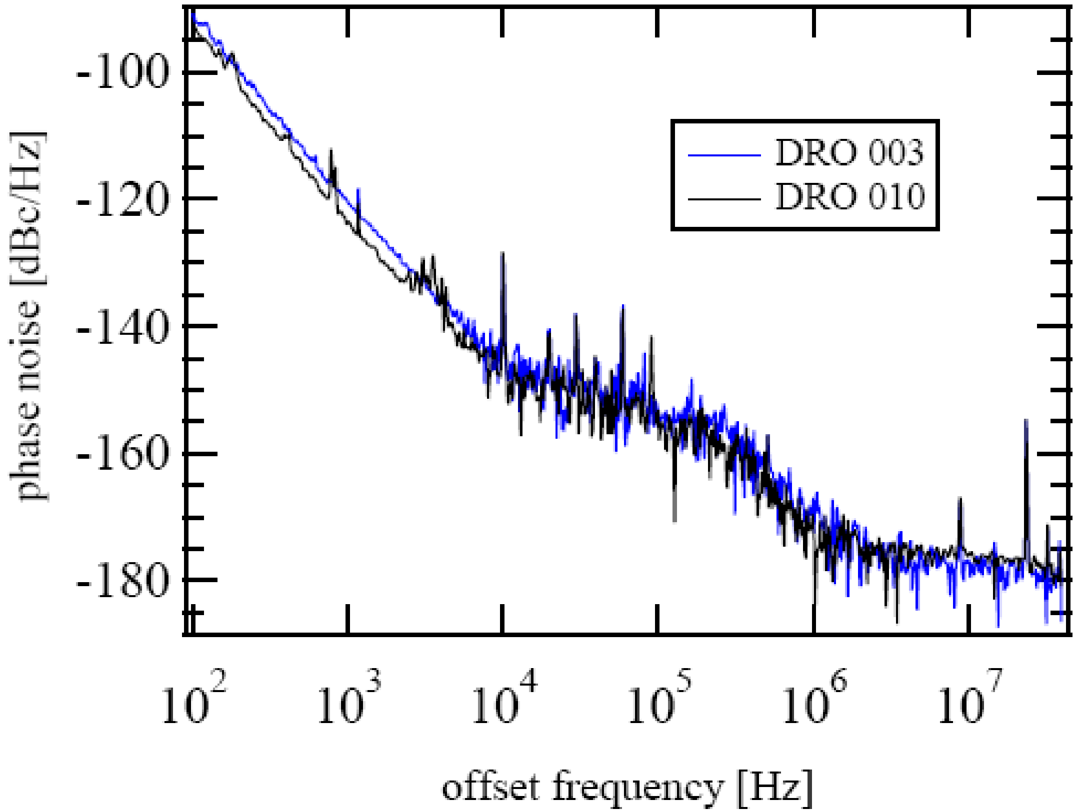


IF and reference generation



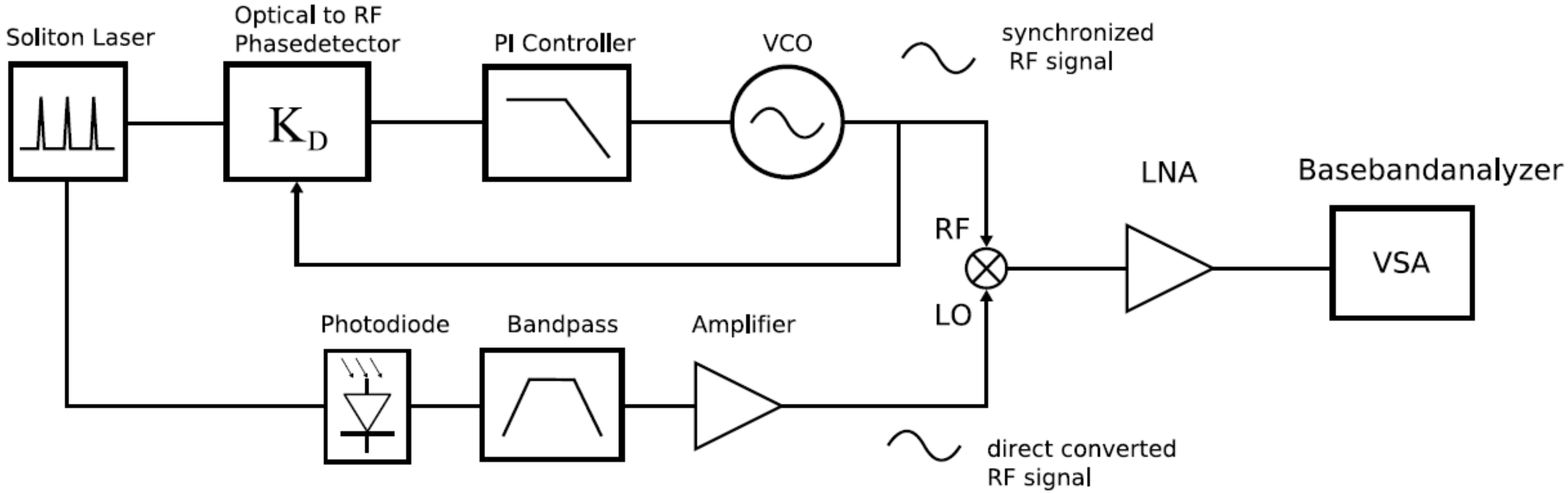
Generation of intermediate and reference frequency from optical pulse train: the power in the generated signals is $P_{\mathrm{IF}} = 5.55\,\mathrm{dBm}$ and $P_{\mathrm{ref}} = 10.71\,\mathrm{dBm}$, integrated timing jitter from $1\,\mathrm{kHz} \ldots 20\,\mathrm{MHz}$ is:$\Delta T_{\mathrm{rms}} = 68.77\,\mathrm{fs}$ for f_{REF} and $\Delta T_{\mathrm{rms}} = 39.2\,\mathrm{fs}$ for f_{IF}

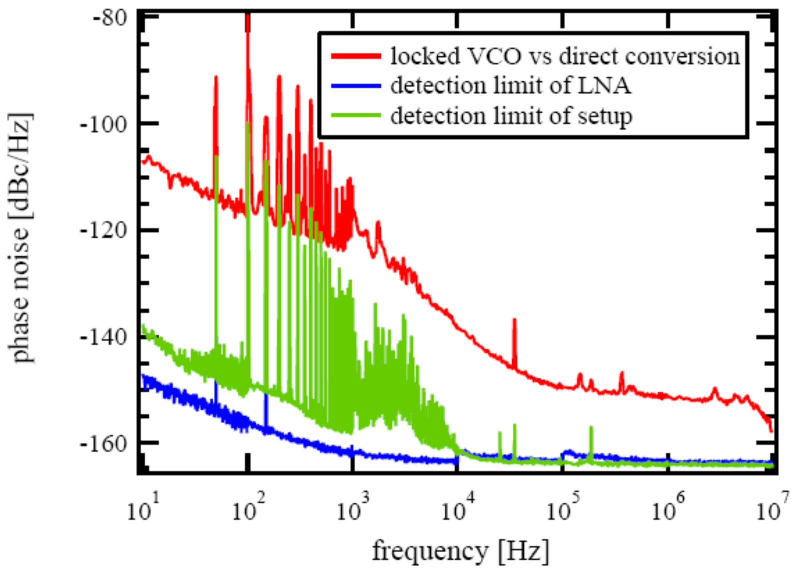
Generation of 1300 MHz

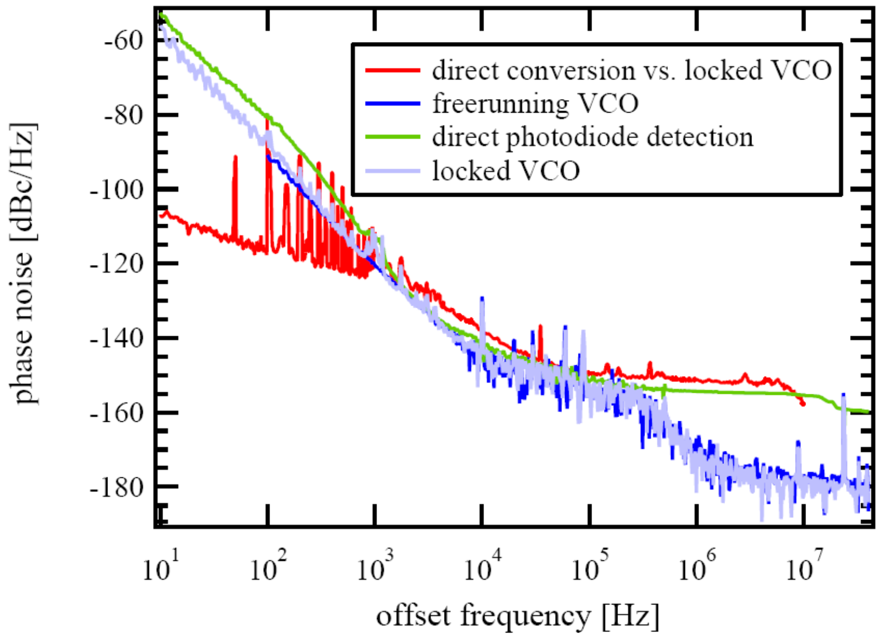


Phase noise characteristics of two DRO's 003 and 010, the integrated timing jitter in a bandwidth from 1 kHz. . . 20 MHz, for DRO 003: $\Delta T_{\text{rms}} = 5.22$ fs and DRO 010: $\Delta T_{\text{rms}} = 4.37$ fs

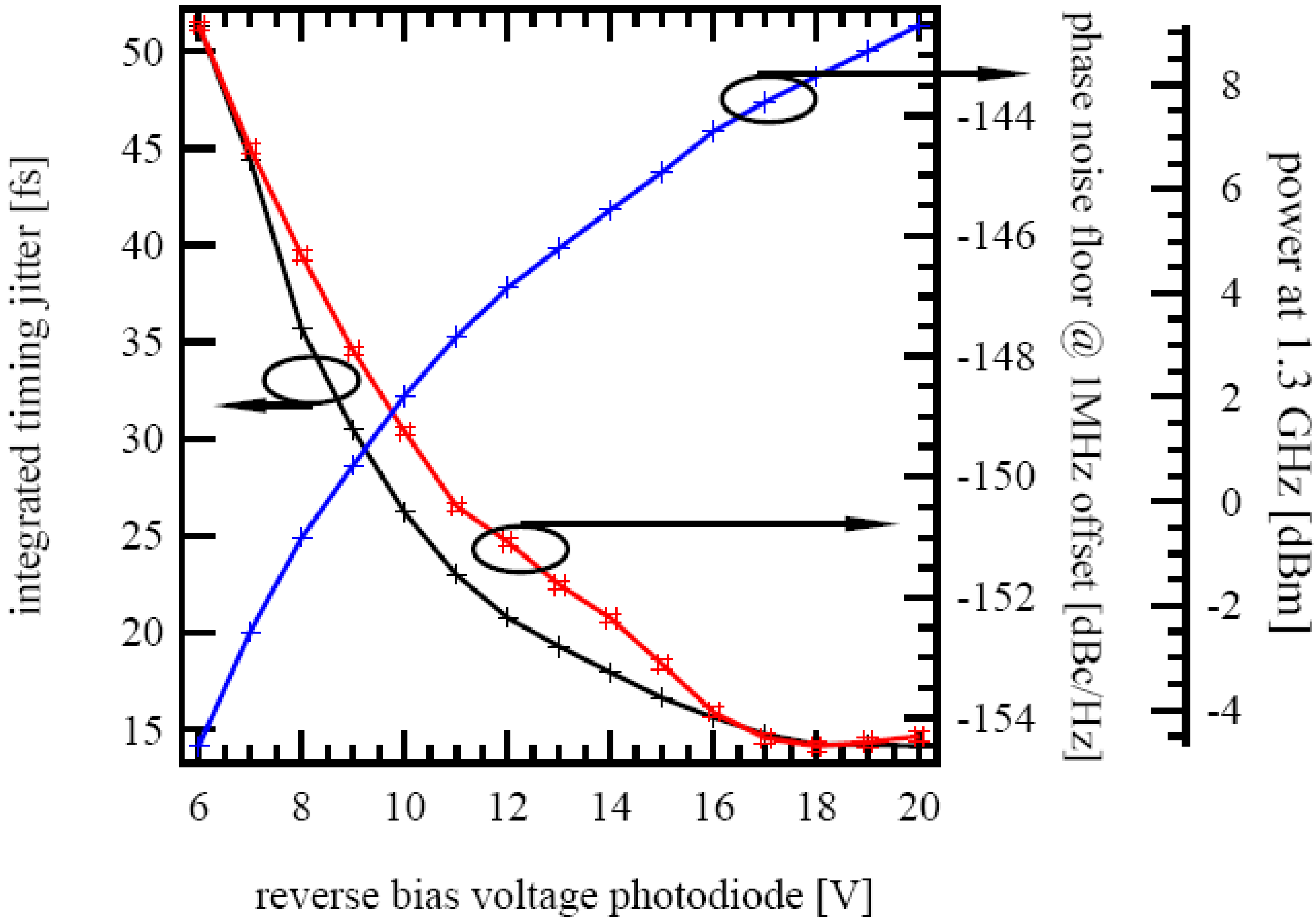
Sagnac Loop vs Diode Conversion







Timing jitter vs bias voltage



Timing/phase Measurements

Signal Generation

Signal Transport

Synchronization of Systems

Longitudinal Beam Diagnostics