Laser to RF synchronisation

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Miniworkshop on XFEL Short Bunch Measurement and Timing

Overview

- Requirements
- Synchronisation scheme used at SLS for EOS measurements
    - general remarks/simulation
    - experimental setup
- Stability measurements
- Limits of electronic synchronisation
- Outlook

Requirements

- Requirements for EOS at the SLS:
  - Synchronise the laser repetition rate (81 MHz) to linac RF of SLS (500 MHz)
  - Short term stability of laser repetition rate to linac RF <100 fs
  - Long term drifts <500 fs
- feasible solution: using single loop PLL with temperature stabilized controller.

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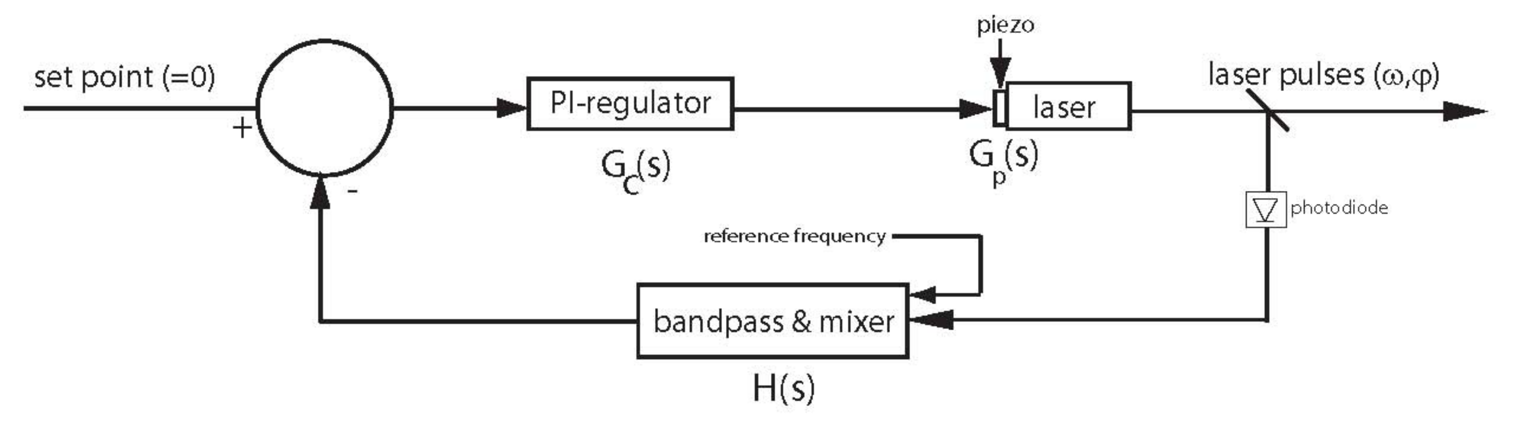
Concept of Synchronisation



- Single loop PLL with set point zero
- Sensor measures timing error by mixing higher harmonic of laser repetition rate with a reference frequency. Amplified and filtered error signal drives piezo actuator for frequency control

- Transfer function (Mason‘s Gain Formula) $$T(s) = \frac{G(s)}{G(s) + H(s)}$$

with $G(s) = G_C(s) + G_p(s)$

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Transfer Functions

- piezo actuator acts as integrator for phase. $\phi = \int dw dt$
- applied voltage leads to frequency difference to the reference, so phase difference adds up. For a frequency difference of 1Hz, 360 degrees are accumulated per second.

$$G_P(s) = \frac{k_{piezo}}{s} \cdot \frac{\omega_{res}^2}{s^2 + \gamma\omega_{res} \cdot s + \omega_{res}^2}$$

- PI-controller:

$$G_{PI}(s) = \left(k_p + \frac{k_I}{s}\right) \cdot \frac{1}{(1 + \omega_{LP} \cdot s)^2}$$

- mixer:

$$H(s) = 5.81 \cdot 10^{-3} \frac{V}{\deg}$$

Aim: optimize parameters to achieve a maximum loop gain

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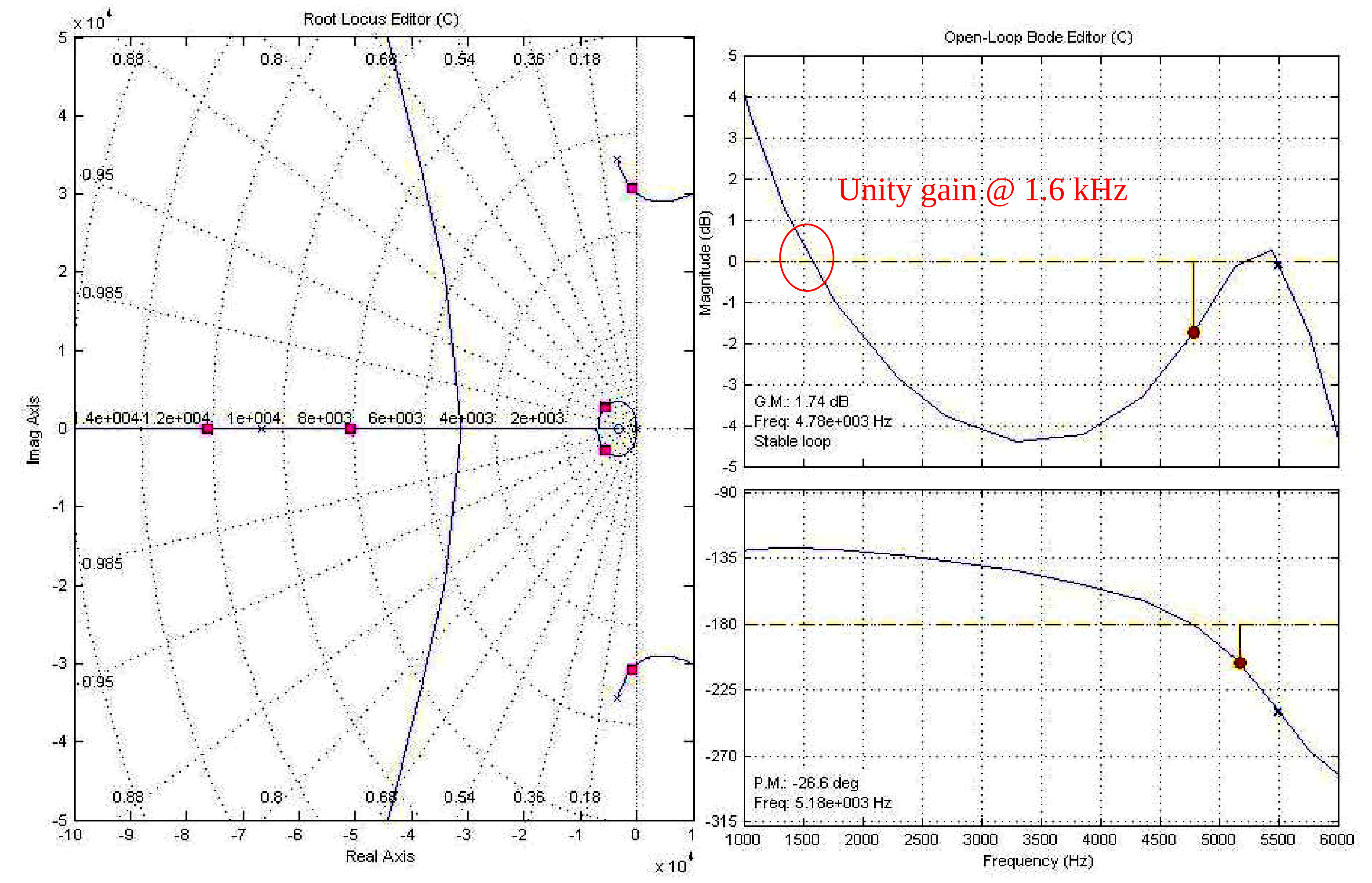
Stability simulation



Unity gain @ 1.6 kHz

- Root locus analysis shows the poles of transfer function as the loop gain is varied
- Bode plot shows the open loop transfer function (top:amplitude bottom: phase) vs. frecuency

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Experimental Setup

$f_{laser} = 81$ MHz

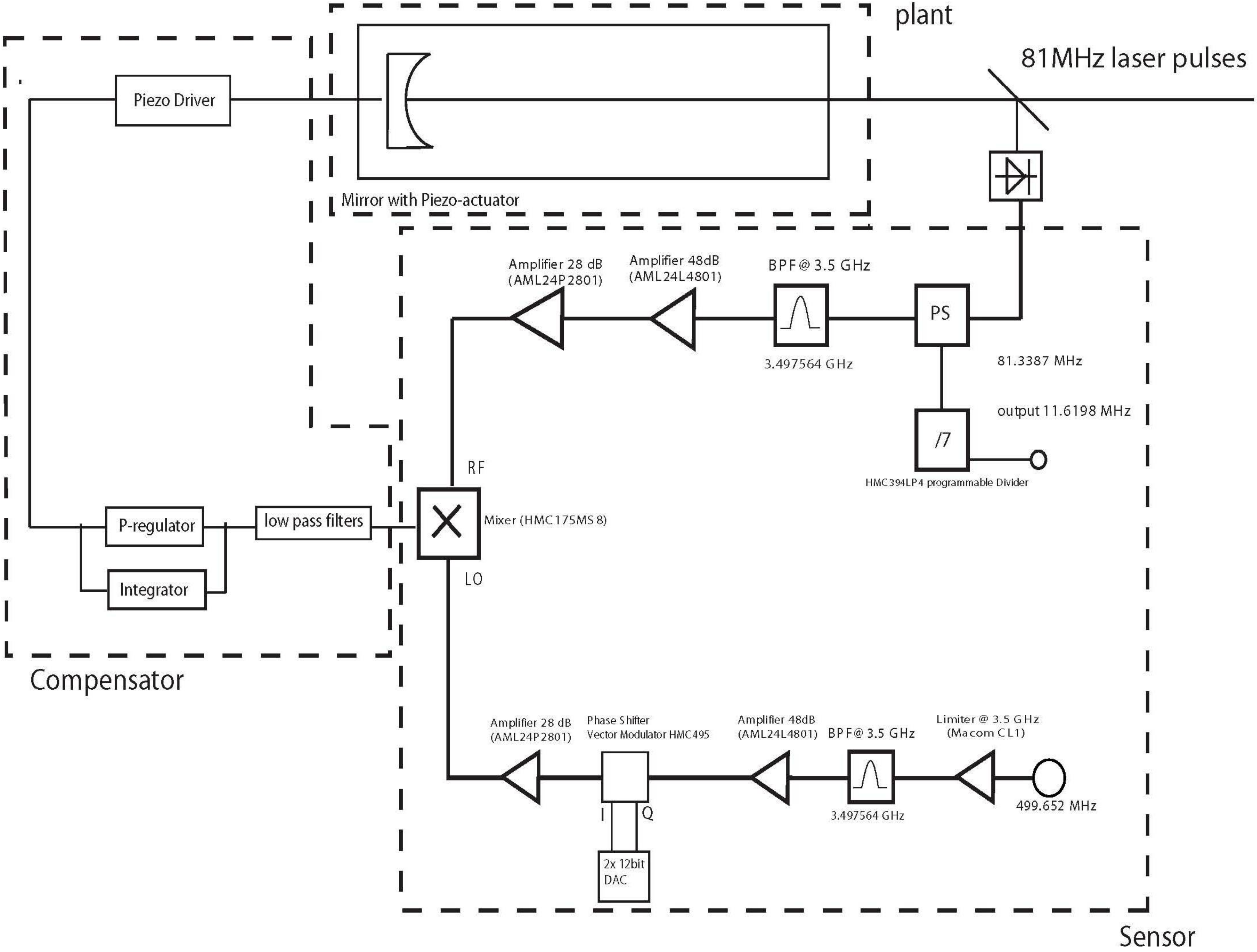
$f_{RF} = 500$ MHz

$f_{mix} = 3.5 \text{ GHz} = 7 * f_{RF} = 43 * f_{laser}$

- 7th harmonic of linac RF generated using an overdriven amplifier as nonlinear device
- 43rd harmonic of laser repetition rate selected using narrow bandpass

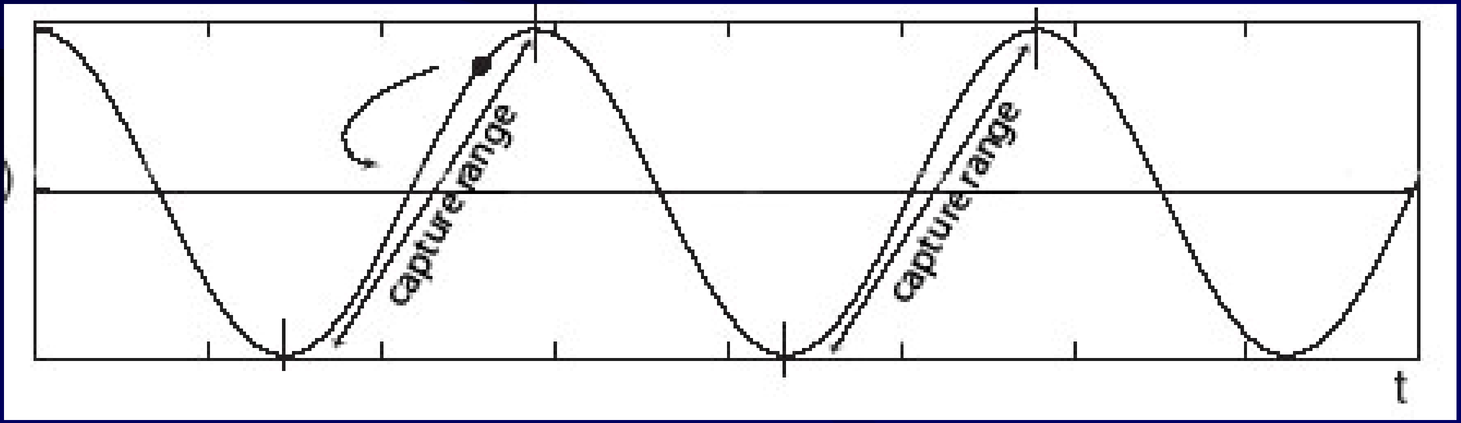
- only every 7th laser pulse is at the same spot relative to the linac RF (every 43rd RF cycle)
- problem: linac trigger must be synchronized to laser

- solution: downconverting of 81MHz to 11.65MHz (=81MHz/7) and synchronising that to the 3.125 Hz Linac trigger


plant
81MHz laser pulses
Piezo Driver
Mirror with Piezo-actuator
Amplifier 28 dB
(AML24P2801)
Amplifier 48dB
(AML24L4801)
BPF@ 3.5 GHz
PS
3.497564 GHz
81.3387 MHz
output 11.6198 MHz
/7
HMC394LP4 programmable Divider
RF
Mixer (HMC175MS 8)
LO
P-regulator
Integrator
low pass filters
Compensator
Amplifier 28 dB
(AML24P2801)
Phase Shifter
Vector Modulator HMC495
Amplifier 48dB
(AML24L4801)
BPF@ 3.5 GHz
Limiter @ 3.5 GHz
(Macom CL1)
I
Q
2x 12bit
DAC
3.497564 GHz
499.652 MHz
Sensor

Locking the Laser

- Laser can be locked on one slope of the IF mixer signal only (pos. feedback on other slope)
- Method:
  - Use DC-voltage applied to piezo to achieve low difference frequency between laser rep rate and RF
  - Close loop using only proportional controller (short integral part)
  - Turn on integrator



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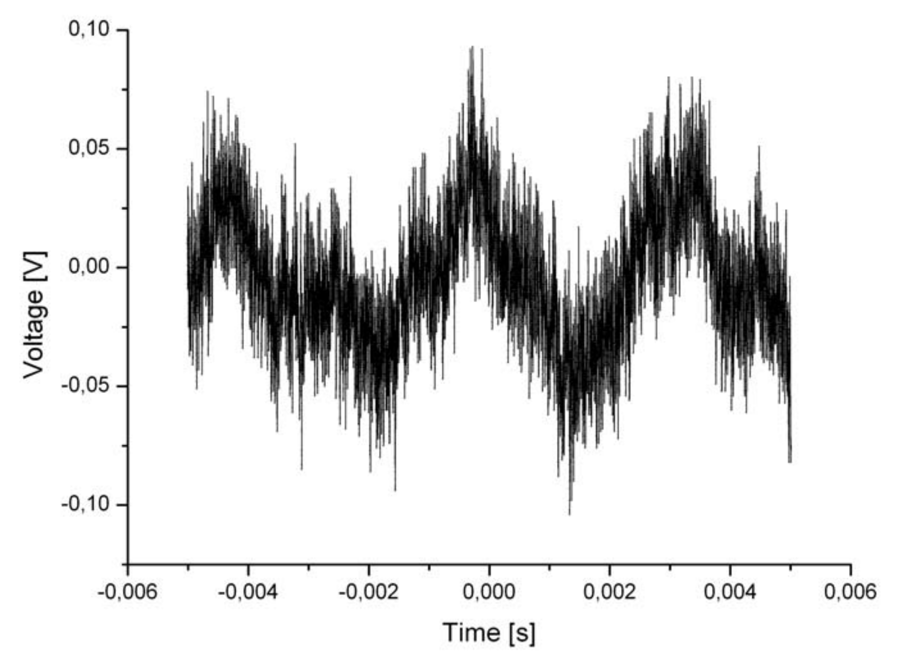
Synchronisation Stability

- open loop: 5.85 mV per degree phase shift

at 3.5 GHz: 1°~793 fs, so 1 mV per 135 fs jitter



measured rms value: 260 µV

short term

stability of 37 fs (rms)

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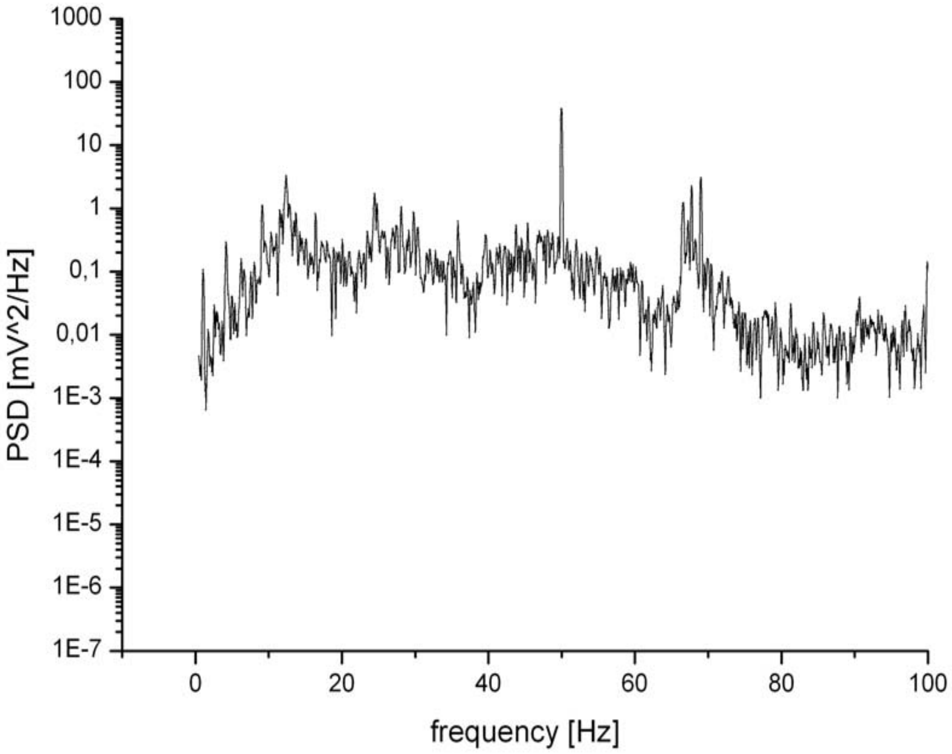
Synchronisation Stability



- Spectrum shows dominant peaks at 50Hz, 375Hz, 19 kHz and 30 kHz.

$$1\frac{\mathrm{mV}^2}{\mathrm{Hz}} = 2.4\frac{\mathrm{fs}^2}{\mathrm{Hz}}$$

stability of 37 fs

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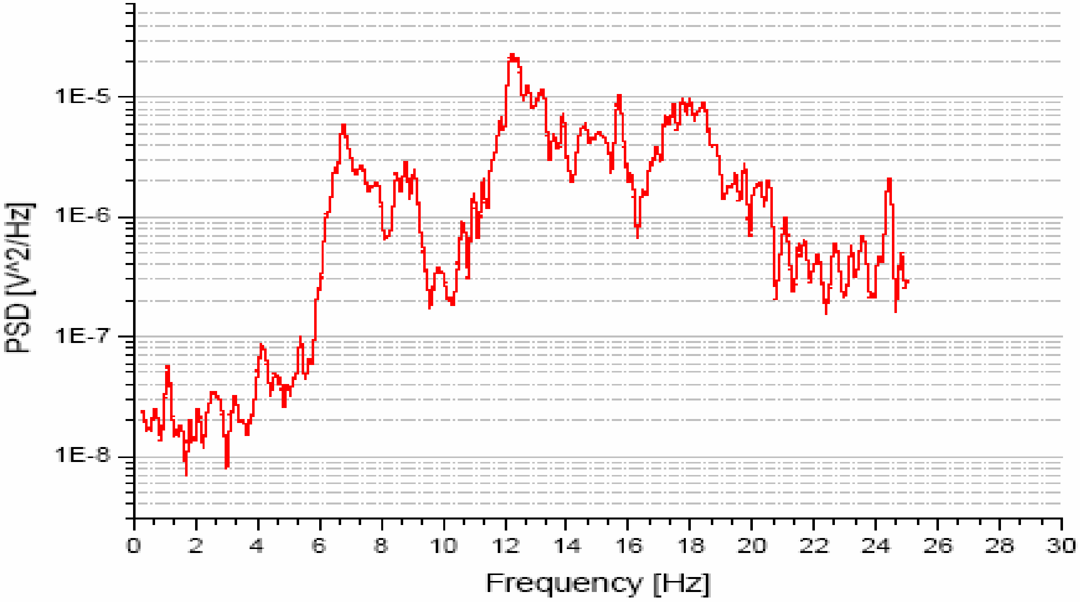
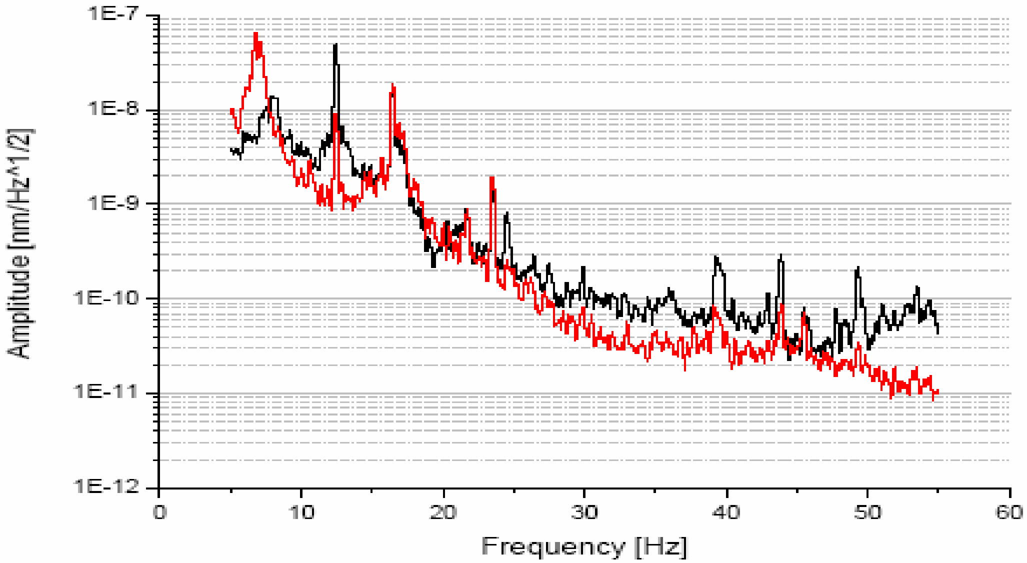
Vibrational Noise





- Displacement in m/Hz$^{1/2}$ vs. frequency
- Improvement of almost 2 orders of magnitude at higher frequencies
- to pay: increase of amplitude at 6 Hz due to resonance of the dampers

Peaks from seismic pectrum can be found on error signal, but are suppressed by integrator

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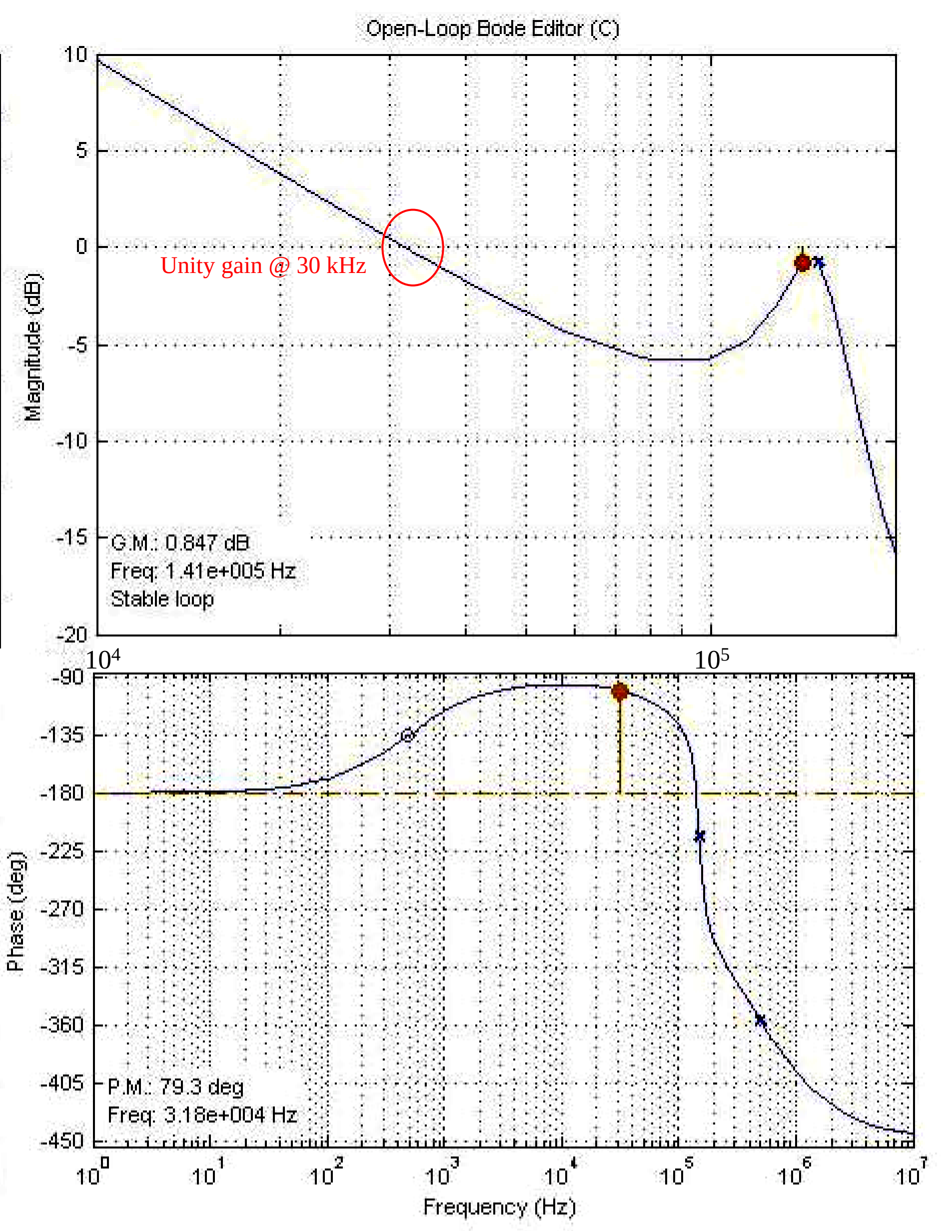
Stability Limit



- main problem: piezo resonance at a low fequency caused by heavy mirror.
  - solution: exchange mirror to achieve resonance frequency close to intrinsic resonance of piezo crystal (200 kHz feasible) or use digital regulation

- Loop gain can be increased by a factor of 20, so gain is high enough to suppress pertubations to µV level.

Loop stability does not limit accuracy anymore

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Noise Limit

- Resolution of phase detector is limited (e.g. for 1.3 GHz 2V p-p for 360°). stabilization of 50µV in regulation seems feasible (limit of around 20 fs)
  - Solution: use multiplying scheme to compare at higher frequencies
    - problem: additional noise through multipliers on linac RF side
    - Signal to noise of higher laser rep rate harmonic

- Remaining offset of balanced mixers (amplitude stability of laser matters!!)
  - For long term stability: drift of offset (1 mV per °C)
  - solution: use compensated digital phase detector (exists only for 1.3 GHz)

- Added noise through amplifiers in system (~5 $nV/Hz^{1/2}$) means for 100 kHz bandwidth time jitter (@ 1.3 GHz) of ~2 fs

Digital Regulation

- Using FPGA board allows using flexible transfer function (e.g. compensate piezo resonance, use fexible filters)
- Very small latency of some hundred ns achievable.
- To minimize rms fluctuations: program self-learning controller

- Problem: additional noise through ADCs and DACs of FPGA board.

Outlook and Conclusion

- Sub 40 fs regulation possible using analog controller in temperature stabilized area.
- Limited by piezo resonance at 5 kHz, which can be overcome, so the new circuit is noise limited.

- @ 1.3 GHz synchronisation to 20 fs is feasible using digital regulation or new piezo.