NOVEL FEMTOSECOND LEVEL SYNCHRONIZATION OF TITANIUM SAPPHIRE LASER AND RELATIVISTIC ELECTRON BEAMS

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Abstract

Laser driven plasma accelerators are offering high gradient (~10-100 GV/m), high quality (low emittance, short bunch length) electron beams, which can be suitable for future compact, bright and tunable light sources. In the framework of the Laboratory for Laser-and beam-driven plasma Acceleration (LAOLA) collaboration at Deutsches Elektronen-Synchrotron (DESY) the external injection experiment for injecting electron bunches from a conventional RF accelerator into the linear plasma wave is in progress. External injection experiments at REGAE (Relativistic Electron gun for Atomic Exploration) require sub-20fs precision synchronization of laser and electron beams in order to perform a beam scan into the plasma wave by varying the delay between electron beam and laser pulses. In this paper we present a novel optical to microwave synchronization scheme, based on a balanced single output integrated Mach-Zehnder Modulator (MZM). The scheme offers a highly sensitive phase detector between a pulsed 800 nm Ti:Sa. laser and a 3 GHz microwave reference source. It is virtually independent of input laser power fluctuations and it offers femtosecond long-term precision. Together with the principal of operation of this setup, we will present promising preliminary experimental measurements of the new detector stability.

INTRODUCTION

Preparations for external injection experiments at REGAE facility for mapping the plasma wakefield are currently ongoing. At REGAE, electron bunches are generated by impinging commercial ultrafast (25 fs pulse duration) Ti:Sa. laser on a photo-cathode. Generated electrons are accelerated by S-band (resonance frequency f_{RF} = 2.9979 GHz) RF structure. Accelerated electrons reach maximum energy of ~ 5 MeV. Subsequently, electrons are longitudinally compressed down to 10 fs rms by S-band RF buncher using so called "ballistic bunching" technique, more details about REGAE can be found everywhere [1].

In order to deliver ultrashort electron bunches with femtosecond level accuracy for external injection purposes in a linear plasma wave, it is crucial to precisely synchronize photo-injector 83 MHz repetition rate 800 nm center wavelength Ti:Sa. laser oscillator to 2.9979 GHz RF source from Master Oscillator (MO).

Different approaches can be considered for synchronizing femtosecond laser pulses to RF reference signals: One could employ a so called direct conversion scheme which involves a fast photo-diode followed by an RF band-pass filter, used to extract a desired microwave signal from the laser pulse train. The phase difference between the RF reference and the microwave signal generated from the laser can be used to synchronize the latter. Currently, the direct conversion based down converter scheme is in daily operation at REGAE. General layout of the REGAE is shown in Fig. 1. It is clear form the block diagram that our reference source is RF Master Oscillator. Signals from MO are distributed to different sub-systems of the accelerator as well as to photo-injector laser for synchronization purposes.

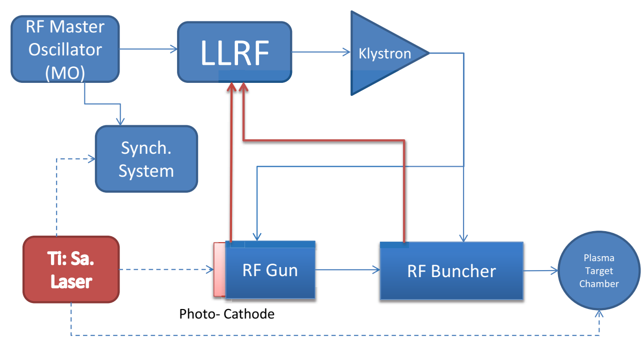

Figure 1: Layout of the RF and laser systems of REGAE.

In general, earlier mentioned direct conversion scheme suffers from AM/PM (amplitude modulation to phase modulation) effects in the photodiode, which can be as high as 1-3 ps/mW [2]. Another Laser to RF locking setup, which is highly accurate and very sensitive, uses an single output integrated electro-optical amplitude modulator (EOM, practically a Mach-Zehnder Intensity Modulator). The phase error between the laser pulse train and the RF reference causes an amplitude modulation of the laser pulse train, which can be detected with a photodiode much more accurately. The original idea of the new synchronization setup based on MZM was first published in 2011 [3] for RF stabilization purposes when the reference was laser itself. The scheme was realized for 1.3 GHz RF and 216 MHz repetition rate (FLASH and European XFEL frequencies) 1550 nm wavelength laser pulses and it showed very promising results ~ 15 fs peak-to-peak drift over 40 hours, the results were improved in 2013 where the experiment showed 3.6 fs peak-to-peak stability over 24 hours [4]. At REGAE, our reference is a 2.9979 GHz RF signal coming from RF Master Oscillator. Therefore, we

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want to precisely synchronize/lock the Ti:Sa. laser oscillator to our reference.

There is a conceptual difference between the setup what is presented in this paper and the one which was tested for FLASH and European XFEL [3, 4]. For FLASH and European XFEL setups, MZMs are available with dual outputs. The dual output configuration gives flexibility to overcome several significant challenges of the setup, such as splitting ratio mismatch between two pulse trains and DC bias drift of the MZM. Additionally, in dual output MZM one could quadruple the repetition rate of the pulse train by adding an extra delay to one of the outputs of the MZM which increases the sensitivity of the detector.

PRINCIPLE OF OPERATION

The idea is, to take the incoming laser pulse train and split it into two beams. After splitting, a time delay is introduced to one of the pulse trains. Both pulse trains (delayed and non-delay) are then recombined and guided into an integrated MZM. The time delay between laser pulses is chosen such that when 3 GHz reference is applied to the MZM, the pulses arrive on zero crossings with positive and negative slopes of the microwave reference signal. Ideally, when there is no timing jitter between two sources, laser pulses do not get any amplitude modulation. If there is a phase mismatch between the laser pulse train and the RF reference, the laser pulse arriving on the positive slope will see a positive voltage from the RF reference, while the laser pulse arriving on the negative slope will experience a negative voltage from the RF reference or vice versa, depending on the direction of the phase change. This will lead to an amplitude modulation of the optical pulse train. The modulated optical pulses can be represented as following:

$$P_{mod} = P_{in}\frac{\alpha}{2}\left(1 + \cos\left(\frac{\pi(V_{in} - V_0)}{V_\pi}\right)\right) \tag{1}$$

Where, P_{in} is an average power of input radiation to the MZM from the laser, V_0 and V_{in} are offset and input voltages respectively. V_π is a value of V_{in} needed to introduce a π phase shift, resulting full transmission to no transmission of the input optical power at the output of the MZM. α is an insertion loss of the MZM. Fig. 2 summarizes the idea of the new synchronization system.

In Fig. 2, upper sketch shows 3GHz RF signal from Master Oscillator (MO) is sampled by two pulse trains of 83 MHz repetition rate laser with a time delay T. The laser pulses are aligned with respect to RF signal such that they arrive on zero crossings as well as opposite slopes of the signal. Since, relative phase shift between two sources is zero, we do not observe any amplitude modulation.

On the other hand, lower sketch of Fig. 2 depicts the case when there is a timing jitter between microwave signal and a laser and it is converted into amplitude modulation of the laser pulses via MZM. Once the amplitude modulation is detected, it is possible to use this information to lock the laser to the 3 GHz RF reference.

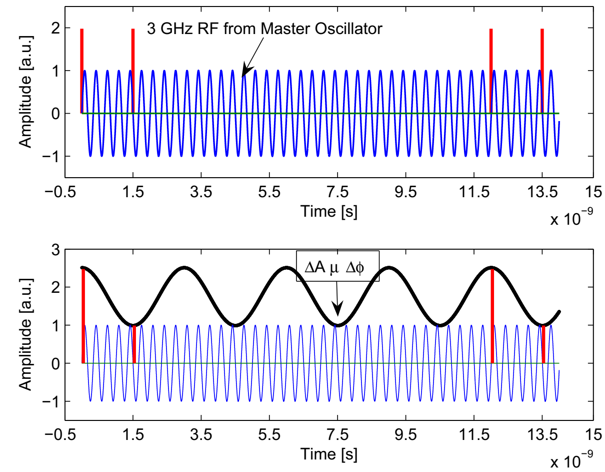

Figure 2: Conceptual representation of the modulated vs. non modulated laser pulses.

How to choose a Delay between Laser Pulse Trains and what is a Modulation Frequency?

It is crucial to define a correct time delay between two pulse trains of the Ti:Sa. after splitting. As we mentioned earlier there are several conditions which needs to be satisfied when choosing a time delay T. The separation of 83 MHz laser pulses cover 36 full periods of 3 GHz RF signal.

- Laser pulses should arrive opposite slopes of the RF.
- Product of harmonic of the laser N, and sub-harmonic of RF M should result 36.
- M has to be odd sub-harmonic of 3 GHz signal so laser pulses can experience opposite slopes of the RF.

For REGAE frequencies these conditions can be satisfied only by the following three combinations:

Table 1: Possible Combinations of Laser and RF Harmonics

Laser harmonic	RF sub-harmonic	Freq. f_{mod}
4	9	~ 333 MHz
12	3	~ 1000 MHz
36	1	~ 3000 MHz

From the table above, it is obvious that the best combination due to practical reasons is the first combination which results the modulation frequency of ~333 MHz. Since, $\mathrm{T} = \frac{1}{2}\mathrm{T}_{mod} = \frac{1}{2f_{mod}}$ the time delay between laser pulses should be ~ 1.5 ns.

REALIZATION OF THE EXPERIMENTAL SETUP

A new synchronization setup is based on free space optics as well as fiber optics since we use integrated MZM which has polarization maintaining fiber input and output. The detailed sketch of the setup is shown in Fig. 3.

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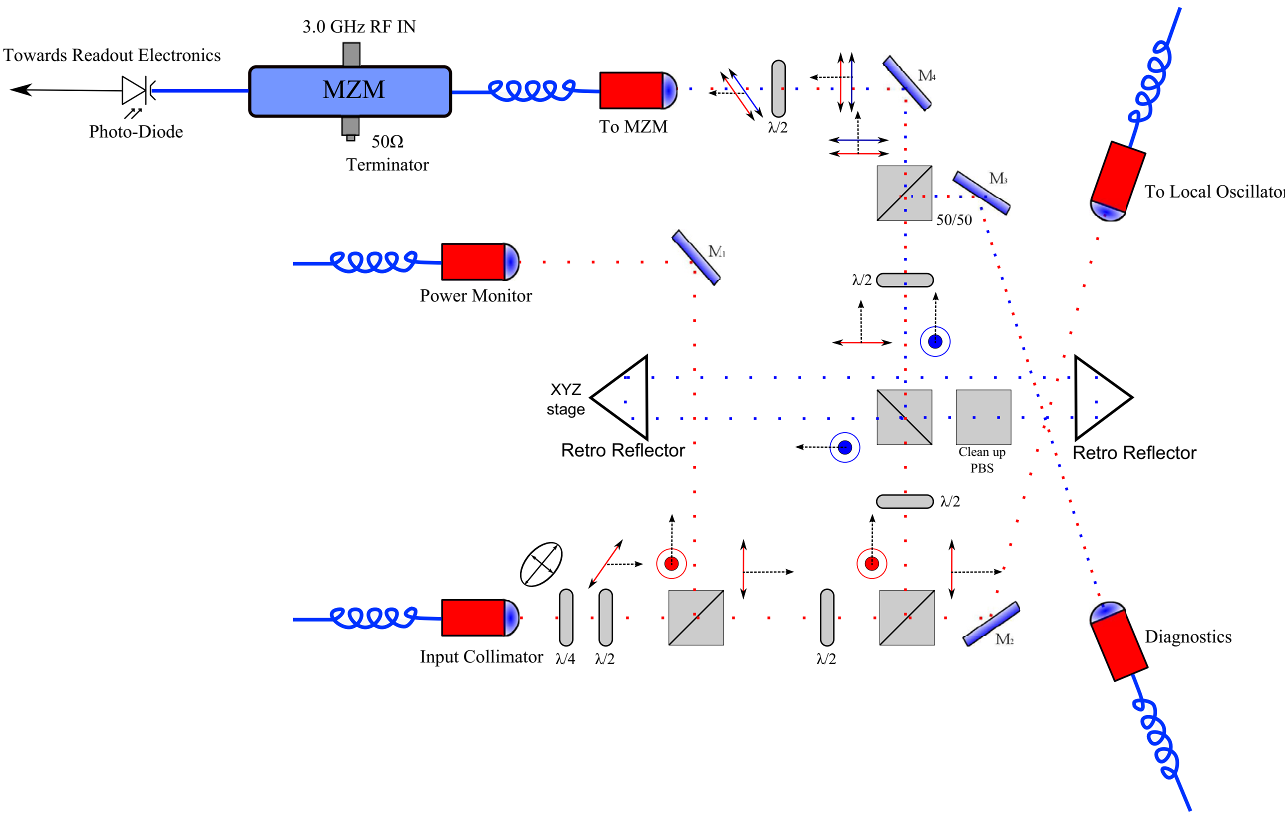

Figure 3: Optics part for novel laser to RF synchronization system.

The reader may observe that in Fig. 3 pigtailed fiber collimators are used throughout the setup. The major advantages of using them is that collimators output defined spot size of the laser beam, they are less sensitive to laser beam pointing and collimator to collimator incoupling efficiency can be more than 80% over distances up to 0.5 m. In Fig. 3, after the first collimator we have $\frac{\lambda}{4}$ waveplate to make sure that the input light after the collimator is linearly polarized. It is followed by two pairs of $\frac{\lambda}{2}$ waveplates and polarizing beam cubes (PBC) to tap off some light for diagnostics purposes. The third pair of wavepalate and PBC is the most important in this setup because it adjusts the splitting ratio of the delayed vs. non-delay pulse trains. The delayed pulse train passes through a pair of retro-reflectors and a PBC which is used for "clean up" purposes to remove the undesired polarization state which might be generated after the retro-reflectors. Afterwards both delayed and non-delayed pulse trains get combined using the same PBC which was used for splitting. After recombining the pulses the polarization states are orthogonal to each other and in order to make them collinear we need to rotate polarization states of both pulse trains by 45^{o} using a $\frac{\lambda}{2}$ waveplate. This will result 50% optical power loss after the PBC. The pigtailed fiber collimator which is used for guiding both pulse trains into the MZM has a polarization maintaining fibre (PMF). MZM is build in a way that, it requires input light polarization state to be aligned to the slow axis of the PMF fibre. We do not know the orientation of the pigtailed fibre collimator in terms of its polarization axis (slow axis). Therefore, additional $\frac{\lambda}{2}$ waveplate is used to align the polarization state of the light to the slow axis of the PMF fibre. We can crosscheck it by measuring the maximum optical power at the output of the MZM. Both pulse trains passing the MZM undergo the insertion loss of the modulator which varies depending on the manufacturer of the modulator. In our case MZM was designed and manufactured by Jenoptik AG and the insertion loss of the modulator amounts to 6 dB of the input optical power. One can roughly estimate what fraction of the initial optical power do we obtain at the output of the MZM, taking into account all the losses we mention earlier in this discussion and it turns out to be ~ 10% of the total input power. The modulated pulses after the MZM are sent to fast photo-diode to convert the optical pulses into electric signals for further signal processing and ultimately detecting the amplitude modulation of it. Therefore, the desired input average optical power of the novel laser to RF synchronization setup should be around 10 mW. Fig. 4 below shows the commissioning process of the new synchronization setup.

In Fig. 4, red line shows the propagation of the optical pulse train from input collimator to output collimator including optical delay line made by a pair of retro-reflectors. An engineered baseplate [4, 5] is used for mounting the opto-mechanics. It is actively temperature stabilized using two Peltier elements connected to analog temperature controller from Team Wavelength. Additionally, special isolation is

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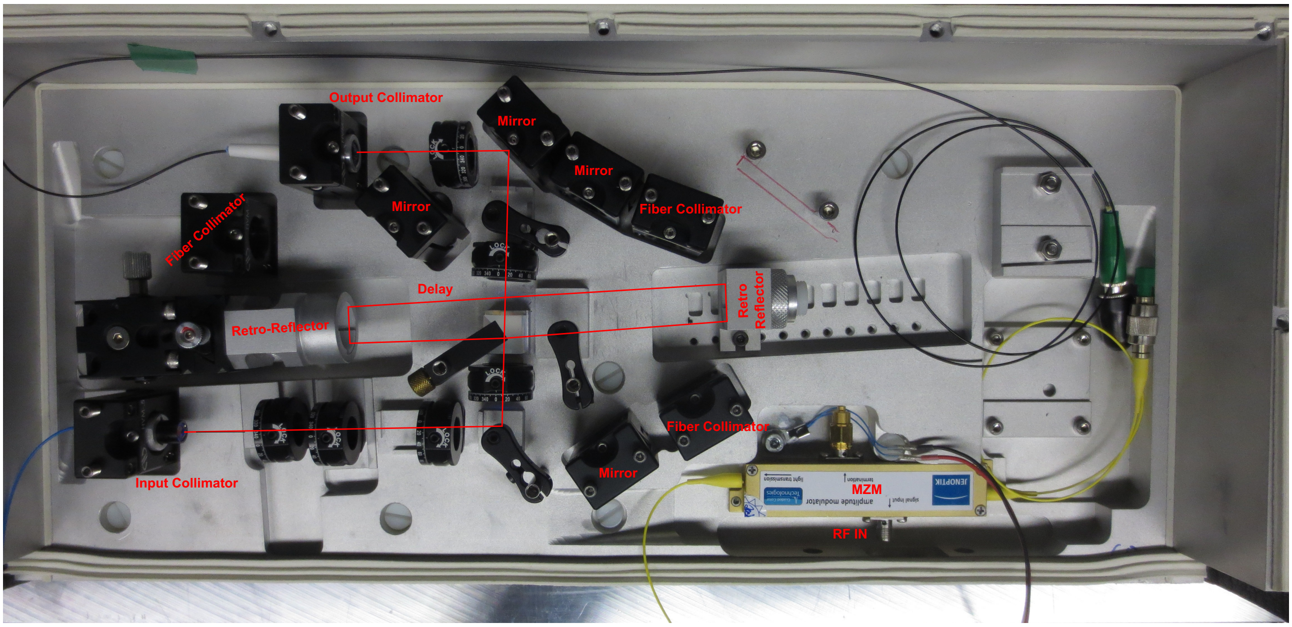

Figure 4: Commission process of the opto-mechanical setup for the novel synchronization system.

used to minimize the influence of the ambient temperature variations inside the box.

Fig. 5 shows the temperature stability of the two different positions of the baseplate measured over approximately 6 days. The measurement shows ambient temperature variation peak-to-peak more that 0.6 K, while the temperature changes near the MZM and across the baseplate are peak-to-peak 11 mK and 63 mK, resulting suppression factors of ~ 56 and ~ 10 respectively.

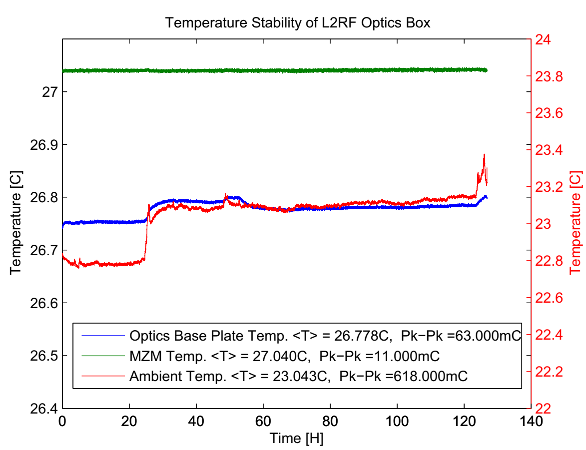

Figure 5: Temperature stability of the engineered baseplate.

ELECTRONICS SETUP FOR AMPLITUDE DETECTION

Once optical pulses are converted to electric signals via photo-diode, we need to filter out desired frequency line from the RF comb. As it was discussed earlier, the modulation frequency of the optical pulses is ~ 333 MHz for REGAE frequencies. Therefore we employed 333 MHz RF bandpass filter and further amplified signal using low noise RF amplifiers. We decided to use an RF mixer for detecting the amplitude of the 333 MHz signal by mixing the signal to 333 MHz local oscillator (LO) which is also derived from the same laser oscillator pulse train. LO power should be high enough to saturate the mixer so small power fluctuations from the laser oscillator which will convert to amplitude variations of the LO signal can be neglected. Additionally, an electric phase shifter should be used to drive mixer as an amplitude detector. The schematics of the electronics setup for amplitude detection of 333 MHz signal is shown in Fig. 6. The diagram also shows how we plan to stabilize DC bias drift of the MZM and how to keep the working point of the modulator in a so called "quadrature bias point" or half transmission point.

Performance Measurements

The performance of the synchronization scheme will be limited by noise floor of the photo-diodes and read-out electronics. For that reason, we carried out baseband voltage noise measurements. For the measurement we used 1550 nm central wavelength Menlo Laser, InGaAs photo-diodes and minicircuits RF components (Filters, Amplifiers). Optical power levels were set to ~ 1 mW for both diodes. Agilent Signal Source Analyzer (SSA) was used to measure baseband voltage noise of the read-out electronics setup. Calibration constants K_φ were obtained by applying 1.3 GHz RF signal to the MZM. K_φ is used to convert integrated voltage noise to timing jitter (femtoseconds). Figure 7 shows the voltage noise and integrated timing jitter over the frequency range of 1 kHz to 10 MHz of the amplitude modulation read-out electronics for two different cases.

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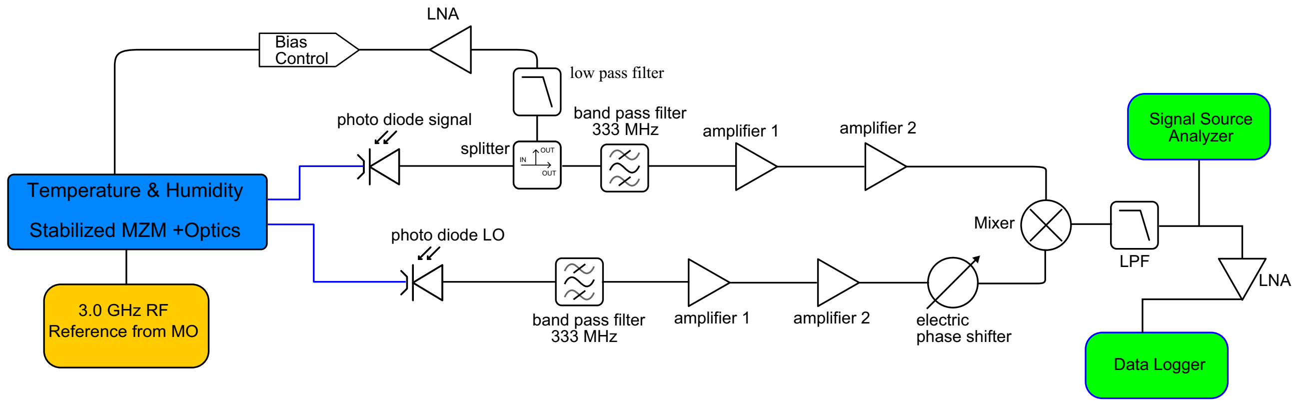

Figure 6: Schematics for amplitude modulation read-out electronics.

First we had two low noise RF amplifiers connected in series for signal amplification coming from the photo-diode which was getting signal from the MZM output. The calibration factor in this case was $K_\varphi = 0.3\frac{\text{V}}{\text{ps}}$, which results integrated timing jitter of $\Delta T_1 = 15.5$ fs. Adding one more low noise amplifier, definitely increases the noise floor of the signal, but on the other hand it also increases the calibration factor up to $K_\varphi = 6.2\frac{\text{V}}{\text{ps}}$ which compensates the higher noise floor and results almost factor of 2 smaller timing jitter $\Delta T_2 = 8.86$ fs.

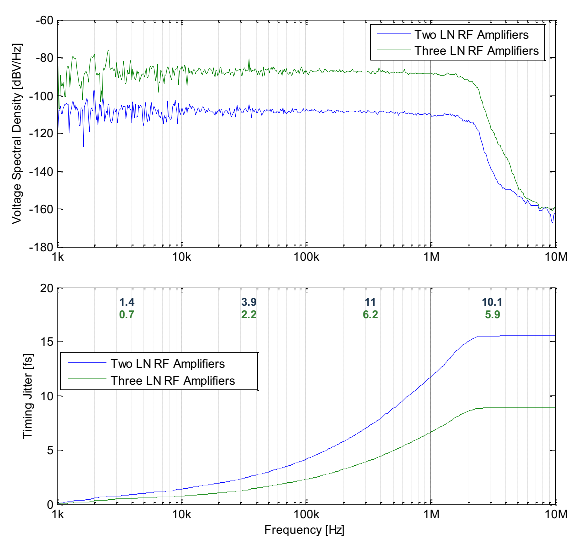

Figure 7: Baseband voltage noise (top) and Integrated timing jitter (bottom).

CONCLUSION AND FUTURE WORK

We presented novel synchronization system for locking Titanium Sapphire laser and 2.997 GHz RF reference with fs level of precision. The setup was discussed in great details and pointed out some of the technical challenges. Noise floor measurements of the read-out electronics show promising results. Next step is to test the single output MZM based setup in a real accelerator environment and lock the Ti:Sa. oscillator to the RF reference.

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