



Femto-second synchronization for plasma acceleration with external injection at SPARC_LAB

Valentina Martinelli 16/10/2017

Supervisor: Massimo Ferrario



Co-supervisor: Alessandro Gallo

Outline



- Purpose: Femto-second timing jitter
- Two ways to improve Synchronization:
 - Residual time jitter reduction to the fs level.
 - Beam dynamics studies



 Measurements of a pulse train phase monitor to be used for ELI-NP PC-laser system synchronization diagnostics

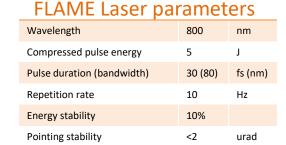
Purpose: Femto-second timing jitter

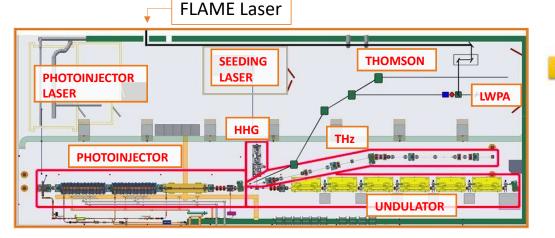
- Increasing the accelerating gradients much beyond the limits of the conventional RF structures is one of the most recognized goals of the contemporary particle accelerator physics.
- Plasma wake-field acceleration is a very promising technique providing accelerating fields in the range of many GV/m
 - High gradient acceleration has been already proven in a large number of experiments BUT specifications on beam quality for the most demanding applications still have to be met.
- The use of external injection in plasma accelerators is attractive since, according to theoretical and numerical studies, it could provide a beam quality comparable to that obtained with modern RF accelerators

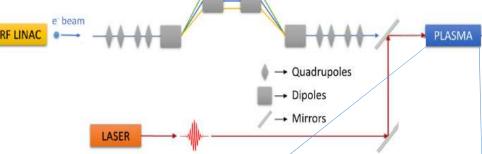
External injection at SPARC_LAB

SPARC

- 1. <u>Laser Driver</u>: Super intense and ultra-short laser pulses interact with hydrogen filled capillary or a gas-jet exciting a plasma wave with large electric fields. The driver displace electrons while propagating in the plasma. Displaced electrons oscillate generating the plasma accelerating field (up to GV/m gradient).
- 2. <u>e⁻ beam witness</u>: the high brightness electron beam is injected inside the plasma bucket where, if it is at the right phase feels the high accelerating gradient.





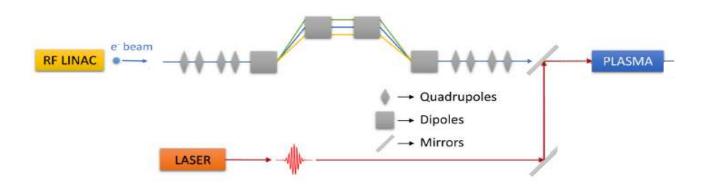


Due to the **small size of the accelerating plasma buckets** (typically on the order of $10 - 100 \mu m$) and the steep field gradients in them, fs long beams with fs synchronization accuracy are required.

Operating a plasma accelerator with external injection requires an extremely low timing jitter between the beam and driver laser.

drive beam electron bubble wakefield

Different contributions to the reduction of the arrival time jitter respect to PC-laser



In order to obtain the low timing jitter between the beam witness and the drive laser pulse we need to proceed along 2 different directions in parallel:

- Reducing the residual jitter of the clients respect the reference master oscillator of the facility (RMO).
- 2. Studying photo-injector working point and beam line in order to reduce the bunch length and the arrival time jitter respect to the PC laser by means of a hybrid compression scheme.

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 Measurements of a pulse train phase monitor to be used for ELI-NP PC-laser system synchronization diagnostics



Reference generation and distribution:

• The Reference Master Oscillator (RMO) is a custom low noise RF source at the S-band frequency (2.856 GHz).

Lock of FLAME interaction laser:

- locked by means of a mechanical-electro-optical PLL.
- Piezo actuator, driven by the loop error signal, moves a mirror to regulate the length of the optical oscillator cavity

Lock of the photocathode laser:

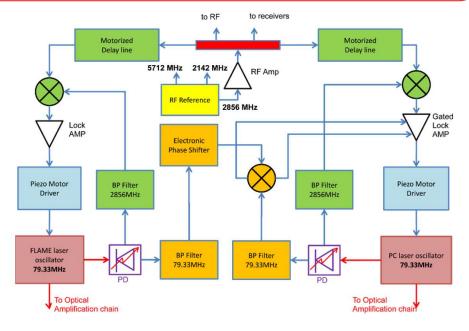
- Custom locking system based on an electro-optical PLL using an optimized active loop
- Last upgrade result: Residual jitter respect to RMO < 20 fs.

Flame and PC laser:

 their relative delay can change every time they are locked since the synchronization is made at the 36th harmonic (2856/79.33=36), they can lock to the reference at 36 different position.

The synchronization system aim:

- transport a stable and precise reference clock, taken from a Reference Master Oscillator (RMO),
- lock all the "clients" to the RMO by high precision phase locked loops (PLLs)





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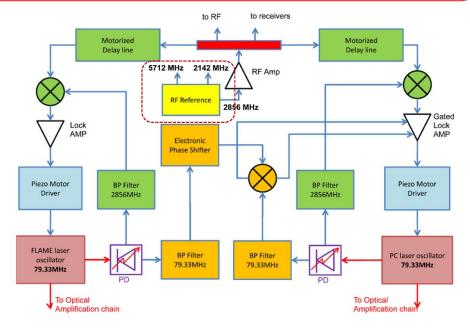
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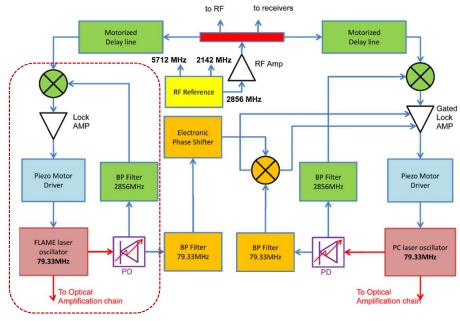
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10

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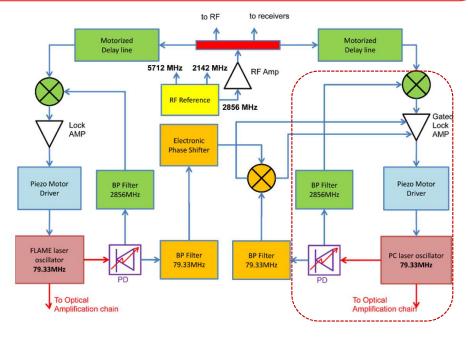
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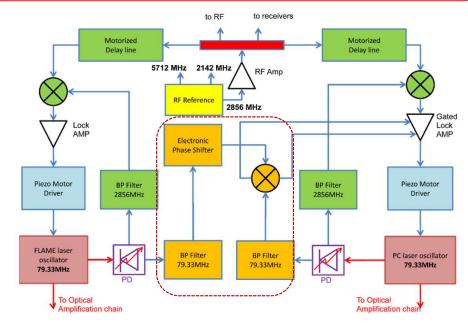
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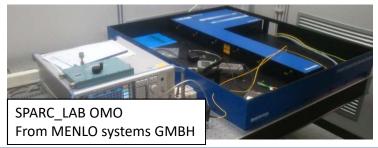
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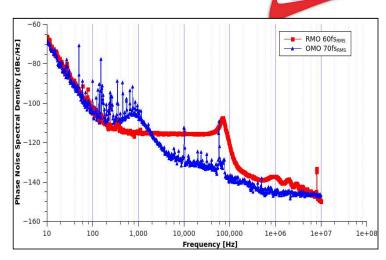


Synchronization system upgrade

• Reference generation and distribution:

- To obtain a reference stability below 10 fs RMS on a large scale facility, the choice of an optical architecture based synchronization system is preferable.
- A 1550nm telecom-like fiber pulsed laser is used as OMO and the reference signal is distributed through a length-stabilized fiber network
- The Optical Master Oscillator (OMO) is locked to the RMO to avoid slow drifts of the repetition rate
- Lock of the RF accelerating fields:
 - To avoid amplitude to phase modulation (AM-to-PM) conversion in the RF extraction performed by a photo-detector, it is important to use a balanced optical-microwave phase detector (BOMPD) that gives an added in-loop jitter of ~3 fs (integrated from 1Hz to 10MHz)
- Lock of Flame interaction laser and PC laser to OMO:
 - By means of a balanced optical cross correlator we are able to lock the two laser clients to the OMO with a resolution well below 10 fs





SPARC LAB OMO laser specs

Pulse width	tpulse	< 200 fs
Wavelength 1	λ1	1560 nm
Wavelength2 (optional)	λ2	780 nm
Pulse rep rate	f_rep	2856/N MHz
Pulse energy	E_pulse	> 2 nJ (~ 180 mW)
Phase jitter	Δt	< 10 fs rms (SSB Df > 1 kHz)
Amplitude jitter	(ΔA/A)rms	< 0.05 % rms
Synchrolock BW	<i>f_cutoff</i>	> 5 kHz
Phase jitter relative to reference	Δt_{rel}	< 10 fs rms (dc – 1 kHz)

Outline

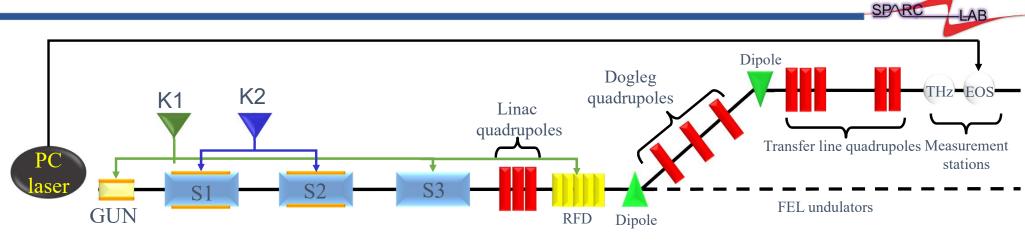


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Beam dynamics studies to reduce arrival time jitter and bunch length



- Using General Particle Tracer (GPT), a pic code used to simulate beam dynamics and space charge effects.
 Optimization of the photo injector working point is now under study in order to meet the bunch length and synchronization requirements.
- We investigated and exploited the difference between the intra-bunch energy chirp, which depends also on space charge, and the multi-shot time-energy distribution of bunch centroids.
- The space charge effect gives a different energy chirp to the beam in the LPS. This link the beam to the launch time (PClaser) and this permit us to reduce the ATJ respect to the PC-laser by choosing the magnetic parameters of the dogleg.

PC Laser Parameters	Experimental value	simulation
X(Y) spot (rms)	(230± 5) um	230 fs
Pulse duration (rms)	(450 ± 50) fs	450 fs
Beam parameters	Experimental value	simulation
Charge	(50 ± 2) pC	50 pC
Energy	(81.2±0.1) MeV	81 MeV
Energy spread	(400±10) keV	410 keV
Duration	(68±18) fs	65 fs
Normalized emittance	(1.7±0.2) um	1.8um



Longitudinal positon

$$z_f \approx z_0 + R_{56}\delta_0 + T_{566}\delta_0^2$$
 $\delta_0 = \sigma_E/E_0$ $\sigma_E = E - E_0$

while its normalized energy error can be expressed according

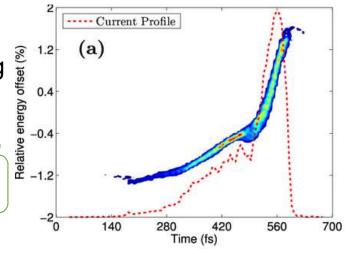
to:

$$\delta_0(z_0) = \delta_u + h_1 z_0 + h_2 z_0^2 \dots$$

Compressed bunch length

$$\sigma_{z,f}^2 = R_{56}^2 \sigma_{\delta u}^2 + (1 + h_1 R_{56})^2 \sigma_{z,i}^2 + 3(h_2 R_{56} + T_{566} h_1^2)^2 \sigma_{z,i}^4$$

to minimize the bunch length: $h_1 = -\frac{1}{R_{56}}$, $h_2 = -\frac{T_{566}}{R_{56}}h_1^2 = -\frac{T_{566}}{R_{56}^3}$



• For an energy of 81.2 Mev the matrix term result R_{56} <0:

$$R_{56} = -4.5 \text{ mm}, T_{566} = -83.6 \text{ cm}.$$

Therefore the beam is injected in off-crest (-88 Deg from the crest phase), toward negative RF phases, with a positive energy chirp so that the electron on the tail are faster then electron in bunch head.

$$h_2 = 1.5 \times 10^7 \text{ m}^{-2}$$

δ_{..}=60 keV



$$\sigma_{z_f}$$
= 90 fs



Reference particle and particle energy

Time (fs)

---- Current Profile

(a)

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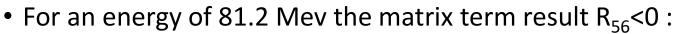
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 $\sigma_{z_f} = 90 \text{ fs}$

560

700



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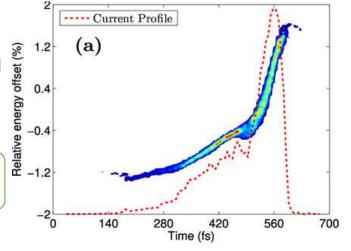
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Uncorrelated energy offset

Compressed bunch length

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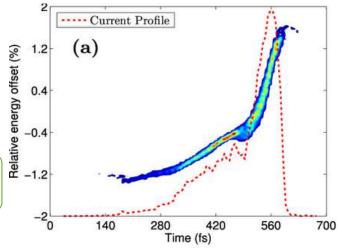
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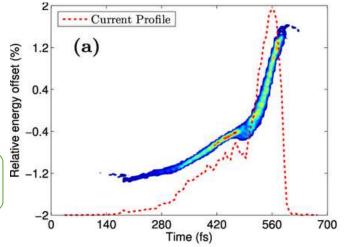
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h₁= 204.1 m⁻¹

 $h_2 = 1.5 \times 10^7 \text{ m}^{-2}$

δ_{..}=60 keV

 $\sigma_{z_f} = 90 \text{ fs}$



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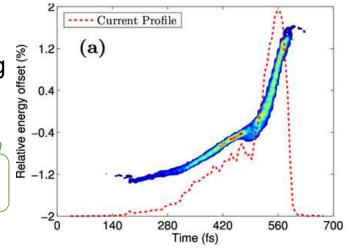
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 $h_2 = 1.5 \times 10^7 \text{ m}^{-2}$

δ..=60 keV



 $\sigma_{z_f} = 90 \text{ fs}$

Arrival time jitter analytic model and benchmarks



- Arrival time jitter is a shot-to-shot time fluctuation of the time of arrive of bunch centroid at a given position. It is produced by fluctuation of the PC laser launch time, of the accelerating fields RF phases and also of the magnetic fields fluctuation of dispersive elements. In the SPARC_LAB facility the sources are:
- [1] the PC Laser, [2] Gun & S3 (klystron 1) and [3] S1 & S2 (klystron 2).

$$\frac{\Delta E_0}{E_0} \approx c \sum_{i=1}^3 h_{1i} \Delta t_i \qquad \Delta t_{linac} \approx \sum_{i=1}^3 c_i \Delta t_i$$

Coefficient condition

$$\sum_{i=1}^{3} h_{1,i} = 0 \qquad \sum_{i=1}^{3} c_i = 1$$

$$\sum_{i=1}^{3} h_{1,i} = 0 \quad \sum_{i=1}^{3} c_i = 1 \quad \Delta t_{dogleg} \approx \sum_{i=1}^{3} (c_i + h_{1,i} R_{56}) \Delta t_i \quad \sigma_{t_{dogleg}}^2 = \sum_{i=1}^{3} (c_i + h_{1i} R_{56})^2 \sigma_{t_i}^2$$

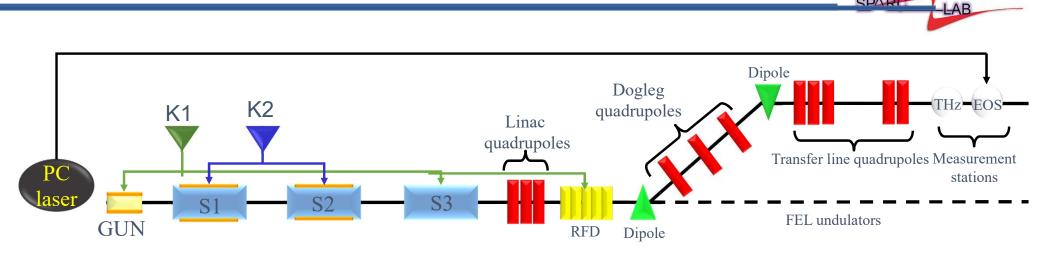
Expected absolute ATJ (wrt RMO)

$$\sigma_{t_{linac}}^{2} = \sum_{i=1}^{3} c_{i}^{2} \sigma_{t_{i}}^{2}$$

$$\sigma_{t_{dogleg}}^{2} = \sum_{i=1}^{3} (c_{i} + h_{1i} R_{56})^{2} \sigma_{t_{i}}^{2}$$

$$\sigma_{t_{dogleg}}^{2} = \sum_{i=1}^{\infty} (c_{i} + h_{1i} R_{56})^{2} \sigma_{t_{i}}^{2}$$

Longitudinal phase spase diagnostic



In the SPARC_LAB facility we have the possibility to compare simulation results with experimental data measuring:

<u>@DOGLEG EXIT:</u> bunch length and ATJ relative to the PC-Laser with the Electro Optical Modulator (EOS)

<u>@LINAC EXIT:</u> bunch length and ATJ relative with a Radio Frequency Deflector

Numerical simulation and GPT results



ATJ measured with RFD at linac exit:

$$\sigma_{t_{\text{linac}}}^2 \approx c_1^2 \sigma_{t_{\text{L}}}^2 + (c_2 - 1)^2 \sigma_{t_{\text{K}1}}^2 + c_3^2 \sigma_{t_{\text{K}2}}^2.$$
 $\approx 34 \text{ fs}$

From our model: $\sigma_{t_{K1}} \approx \sigma_{t_{K2}} = 22$ fs and $\sigma_{t_L} = 48$ fs

coefficients	On crest	Velocity bunching	
C ₁	0.7 ± 0.2 (0.66)	-0.1 ± 0.4 (-0.14)	
C ₂	0.3 ± 0.1 (0.34)	-0.2 ± 0.5 (-0.07)	
c ₃	0.1 ± 0.9 (0.01)	1.2 ± 0.5 (1.18)	
h _{1,1}	-1.8 ± 1.2 (-0.8)	-93 ± 22 (-90)	
h _{1,2}	-0.6 ±1.2 (-0.4)	41 ± 23 (38)	
h _{1,3}	2.8 ± 2.5 (1.2)	42 ±35 (52)	

Expected ATJ with respect to PC laser at linac exit:

$$\sigma_{t_{\mathrm{linac}}}^2 pprox (c_{\mathrm{l}}-1)^2 \sigma_{t_{\mathrm{L}}}^2 + c_{\mathrm{2}}^2 \sigma_{t_{\mathrm{K1}}}^2 + c_{\mathrm{3}}^2 \sigma_{t_{\mathrm{K2}}}^2, \qquad \Longrightarrow \qquad \sigma_{t_{\mathrm{linac}}} = 60 \, \mathrm{fs}$$

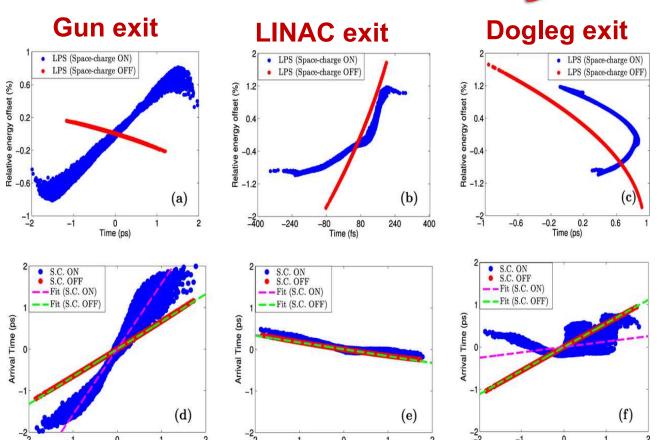
ATJ after hybrid compression measured with (EOS):

$$\sigma_{t_{\text{dogleg}}}^2 \approx (c_1 + h_{1,1}R_{56} - 1)^2 \sigma_{t_L}^2 + (c_2 + h_{1,2}R_{56})^2 \sigma_{t_{\text{K}1}}^2 + (c_3 + h_{1,3}R_{56})^2 \sigma_{t_{\text{K}2}}^2. \implies \sigma_{t_{\text{dogleg}}} = 26 \text{ fs}$$

ATJ respect PC laser reduction with the hybrid scheme



- Space charge forces strongly affects intra-bunch dynamics. Multi-shot dynamics of bunch centroids it is almost unaffected.
- The space charge effect gives a different energy chirp to the beam in the LPS. This link the beam to the launch time (PC-laser).

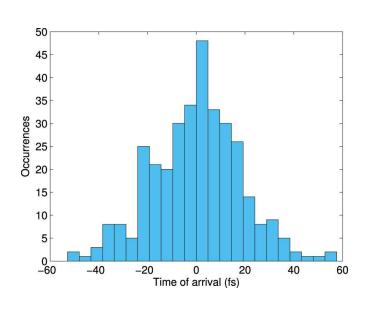


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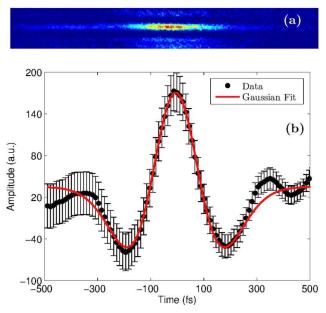
Launch Time (ps)

Results at SPARC LAB





Relative ATJ	Value (fs)	
Theoretical model	26	
GPT simulation	25	
EOS	19 ± 5	



Bunch duration	Value (fs)	
Theoretical model	90	
GPT simulation	92	
Experimental data	90 ± 7	

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 - Beam dynamics studies



 Measurements of a pulse train phase monitor to be used for ELI-NP PC-laser system synchronization diagnostics

Proposal for a pulse train phase monitor for synchronization diagnostic:



- The ELI-NP-GBS (Extreme Light Infrastructure Nuclear Physics Gamma Beam Source) project foresee the realization of a gamma ray source in Magurele (Bucharest, Romania) for nuclear physics research by the European association "EuroGammas".
- The gamma photons will be generated by Compton backscattering in the collision between a high quality electron beam and a high power laser. The accelerator is expected to achieve an energy of the gamma photons tunable between 1 and 20 MeV with a narrow bandwidth (0.3%) and a high spectral density (104 photons/sec/eV).
- The repetition rate of the machine is 100 Hz and up to 32 electron bunches will be accelerated, each one carrying 250 pC of charge, separated by 16 ns
- The phase error of the 32 pulses along the bunch train must be limited to 100 fs in order to fulfil the efficiency requirements for gamma ray production

My work is consisted in some preliminary measurements of a pulse train phase monitor to be used for ELI-NP PC laser system synchronization diagnostics

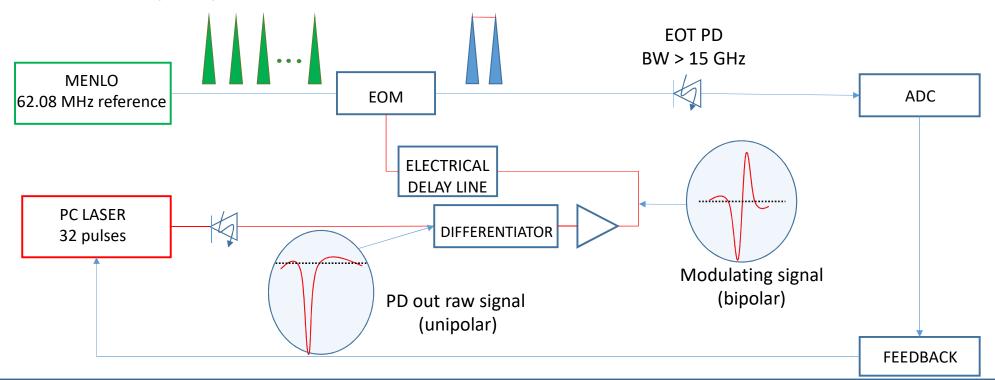


Proposal for a pulse train phase monitor for synchronization diagnostics



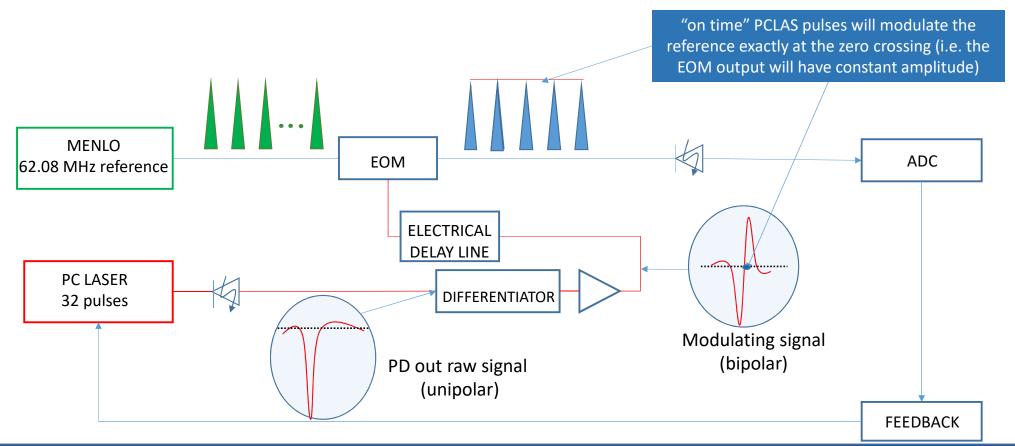
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The Optical reference given by MENLO is modulated in amplitude by a electro-optical modulator (Mach-Zehnder interferometer) driven by a RF signal extracted by the Photo cathode Laser: "On time" pulses will be modulated with the same signal level, while "early or late" pulses will be modulated differently the reference optical pulses.

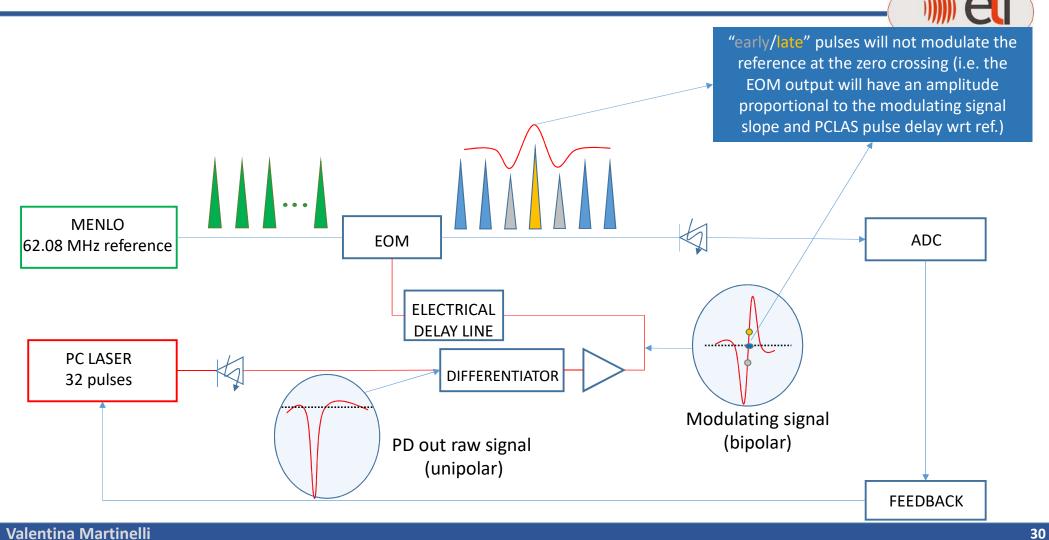


Proposal for a pulse train phase monitor for synchronization diagnostics





Proposal for a pulse train phase monitor for synchronization diagnostics



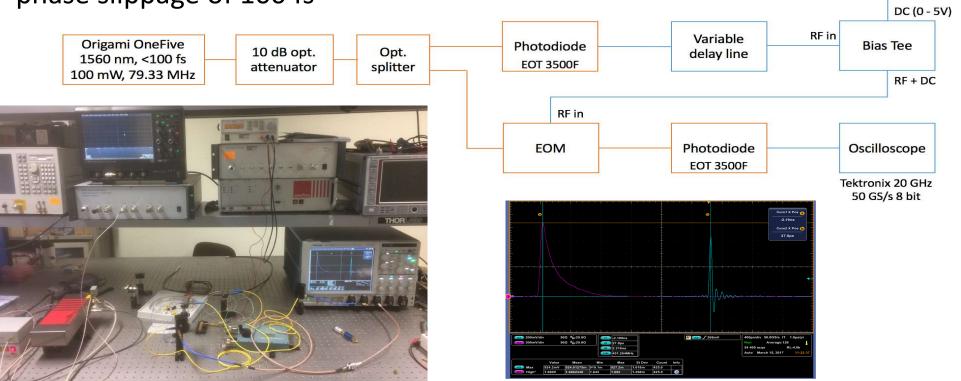
Preliminary measurements of a pulse train phase monitor for synchronization

Nuclear Physic

LV power supply

diagnostics

 Preliminary measurements based on EOM have been performed in order to understand if we could detect a phase slippage of 100 fs

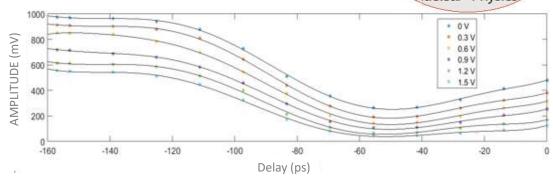


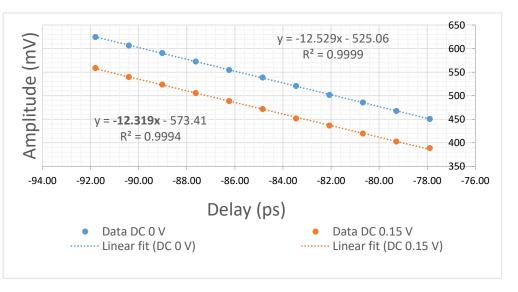
Electro optical modulator characterization

Nuclear Physics

Laser pulse is modulated with a RF signal, extracted by the photodiode, in order find the **deepest response region** we performed this measurements:

- 1. We calibrate in DC the EOM, varying the DC bias from 0 to 5V
- 2. We modulate with an RF signal extracted by a photodiode varying the delay for different bias voltages.
- 3. Fitting the results with a polynomial and plotting the derivatives we find the best DC bias voltage
- 4. We obtain the best sensitivity by varying the delay around the maximum of the derivative (at the zero crossing) for a DC bias level of 0 V and 1.5V





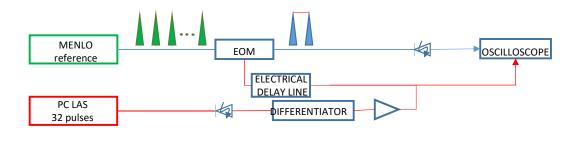
Eli-NP preliminary measurements results



- The sensitivity obtained is around S=12.5 mV/ps
- The amplitude modulated pulse jitter has been measured with a 8 bit oscilloscope by averaging the signal 128 times and measure the peak statistic on 100 consecutives shots: Resolution= St.Dev./S

Peak min [mV]	Peak max [mV]	St.Dev.[mV]	St.Dev./mean	Resolution [fs]
496.4	500.6	0.41	8.2e-4	35

- In order to prove the preliminary results we test it on the 32 pulses of ELI-PC laser, placed temporarily in Paris at the Laboratoire de l'accélérateur linéaire (LaL)
- The results are not satisfying as we expected.
 The reason is due to the high different in amplitude of the 32 pulses that cause, converting optical pulse train with photodiode, an amplitude-to-phase (AM-to-PM) conversion error.



Conclusion and next steps



- The results of the laboratory measurements demonstrate that this technique can discriminate phase jitter well below the 100 fs required
- BUT this setup can't be used for signal with a non-uniform amplitude
- However we are planning to improve the system to quantify the AM-to-PM modulation in order to reduce the contribute.

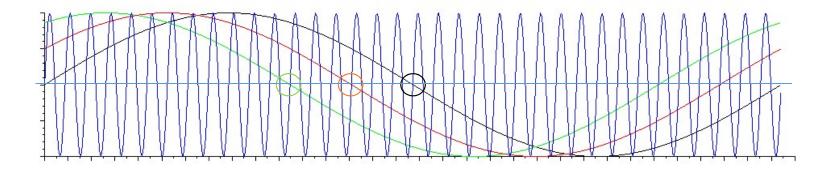


- The new Synchronization system has been already purchased and installed .
- The hybrid compression scheme can provide bunch durations below 90 fs and ATJ relative to the photo cathode laser below 20 fs rms.
- Numerical studies to optimize the photoinjector working point in order to further improve these performances are in progress.

References:

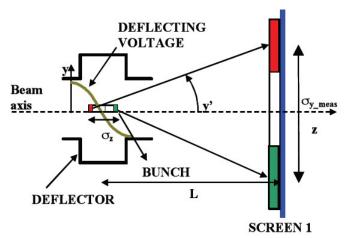
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Client locking - Lasers



- Blue curve: locking frequency (f_{REF} =2856 MHz), typically the RF frequency Nth harmonic of laser repetition rate to increase the phase detection sensitivity
- Other colors: laser oscillator frequency $\binom{f_{REF}}{N} = 79.33MHz$
- N possible time delays between different lasers locked at f_{REF}
- Locking methods must take it into account

Diagnostics – RF deflector

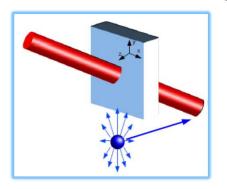


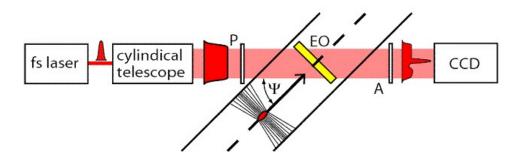


The beam is **streaked** by a **transverse RF cavity** on a **screen**. The image is captured by a camera. Longitudinal charge distribution and centroid position can be measured.

- ✓ Works typically on single bunch. Bunch trains can be eventually resolved with fast gated cameras;
- ✓ Destructive (needs a screen ...)
- ✓ Measure bunch wrt to RF (relative measurement)

Diagnostics – Electro-optic sampling





An *electro-optic crystal* is placed near the beam trajectory. In correspondence to the beam passage the crystal is illuminated with a *short reference laser pulse* transversally enlarged and *linearly polarized*. The bunch electric field induces *bi-rifrengence* in the crystal, so that while propagating the laser gains *elliptical polarization*. A polarized output filter delivers a signal proportional to the *polarization rotation*, i.e. to the *beam longitudinal charge distribution*.

- ✓ Single shot, non-intercepting;
- ✓ Provides charge distribution and centroid position;
- Resolution $\approx 50 \ fs$ for the bunch duration, higher for centroid arrival time (1 pixel $\approx 10 \ fs$).

