Status of LLRF and synchronization for the ELI-NP project

LIBERA WORKSHOP 2016 - GRAD KROMBERK, NOVA GORICA

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Introduction

> ELI-NP project overview

> Machine layout

> Synchronization system – MenloSystems (DE)

> Libera LLRF – Instrumentation Technologies (SI)

ELI-NP overview

WHO

Advanced source of γ-rays delivered by the EuroGammaS consortium (INFN, Rome University "Sapienza", IN2P3/CNRS, Amplitude, Alsyom, ScandiNova, COMEB)

One of the 3 pillars of the ELI (Extreme Light Infrastructure) project, hosted in Magurele site (Romania)

HOW

γ-rays generated by Compton back-scattering between a high quality electron beam and a high power laser

Advantages wrt Bremmstrahlung γ rays: monocromaticity, tunability, higher collimation, full control of polarization

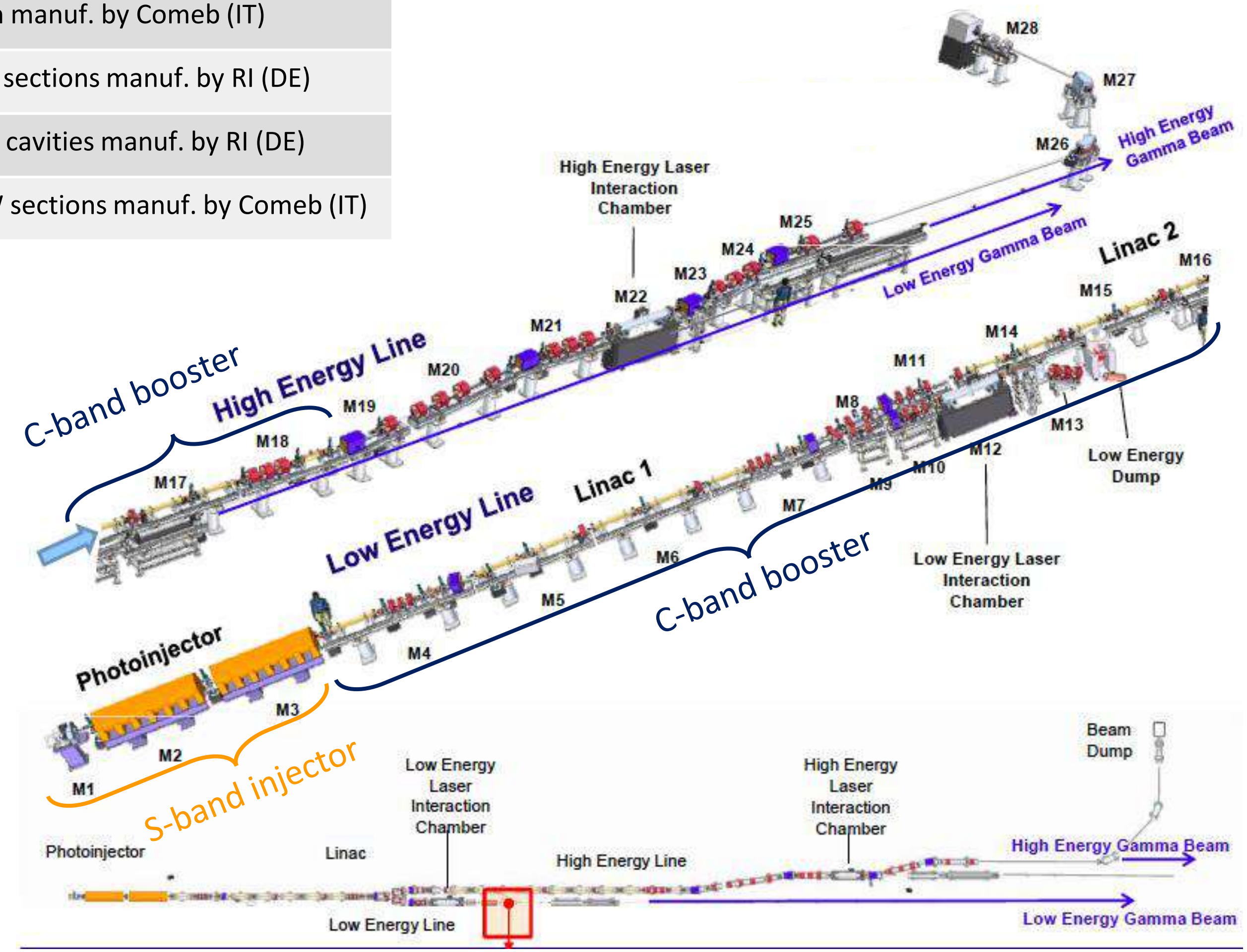
Challenges: alignment, synchronization, phase space density

WHY

Open the era of nuclear photonics and pursue advanced applications in various fields: homeland security, nuclear waste treatment, nuclear medicine, fundamental studies in nuclear physics dealing with nucleus structure and astrophysics

Machine layout

RF System
1 x S-band SW RF-gun manuf. by Comeb (IT)
2 x S-band SLAC-type TW sections manuf. by RI (DE)
2 x S-band SW deflecting cavities manuf. by RI (DE)
12 x C-band HOM damped TW sections manuf. by Comeb (IT)

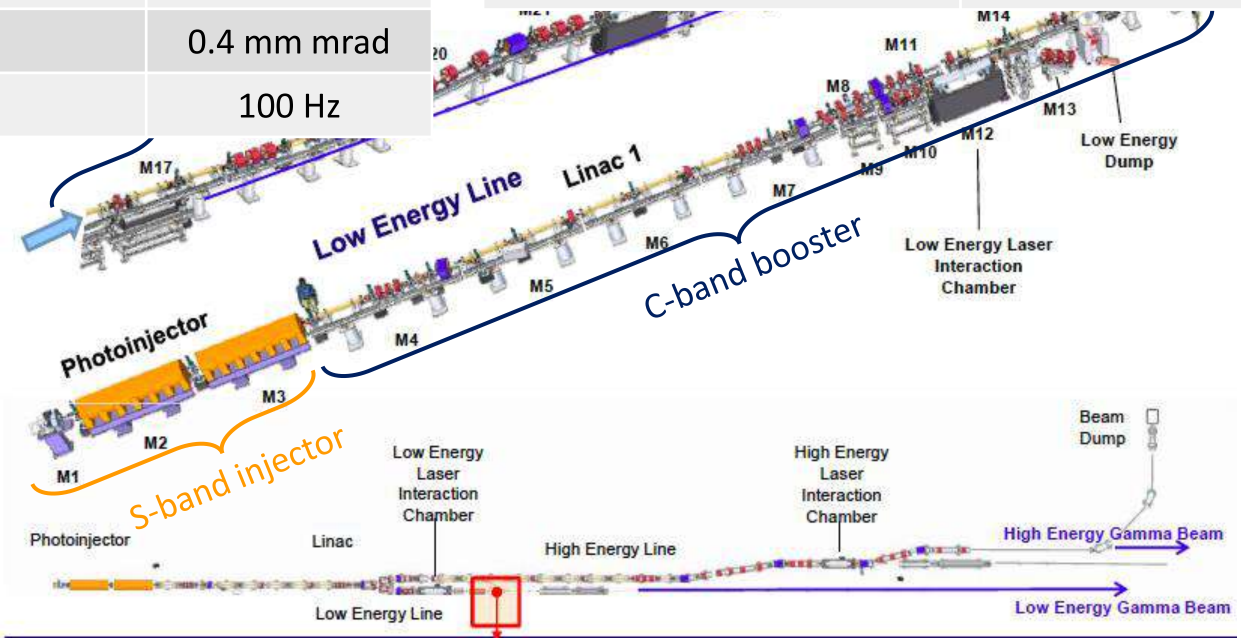


Picture courtesy of N. Bliss - STFC

Machine layout

Electron beam parameters	Value
Bunch charge	250 pC
N. Bunches per RF pulse	32
Bunch separation	16 ns
Bunch length	< 300 µm
Beam energy	300-740 MeV
Energy spread (rms)	< 0.1%
Norm. emittance	0.4 mm mrad
RF rep. rate	100 Hz

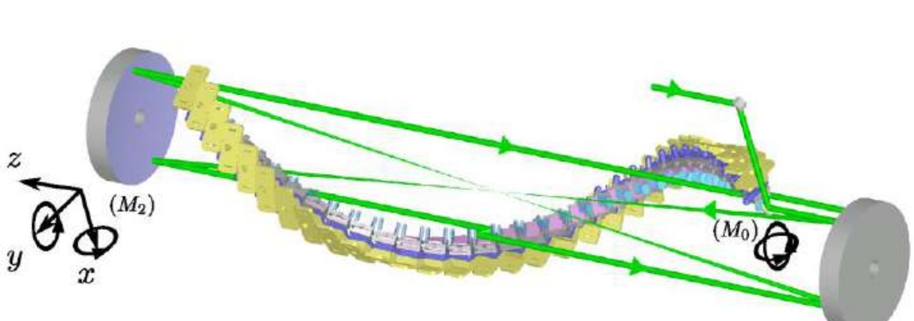
Gamma beam parameters	Value
Energy	Tunable 0.2 - 19.5 MeV
Spectral density	0.8 - 4 × 10^4 ph/s eV
Rms bandwidth	< 0.5%
Peak brilliance	> 10^{20} ph/s mm^2 mrad^2 0.1%
Spot size	< 100 µm
Linear polarization	> 99%



Picture courtesy of N. Bliss - STFC

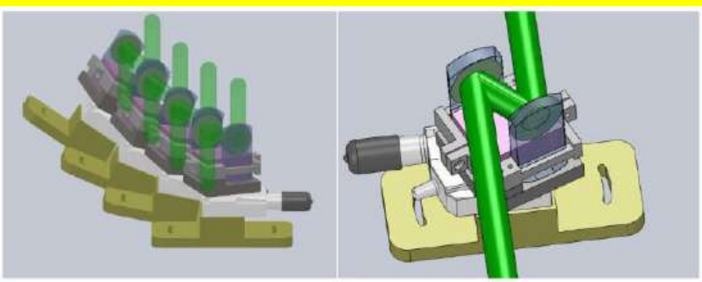
Machine layout

A single laser pulse is recirculated 32 times at the IP by means of the «multipass recirculator»



M1 fixed
M2 5 degrees of freedom
M0 2 tilts for injection

Mirror pairs:
interaction plane rotation
32 pulses synchronization



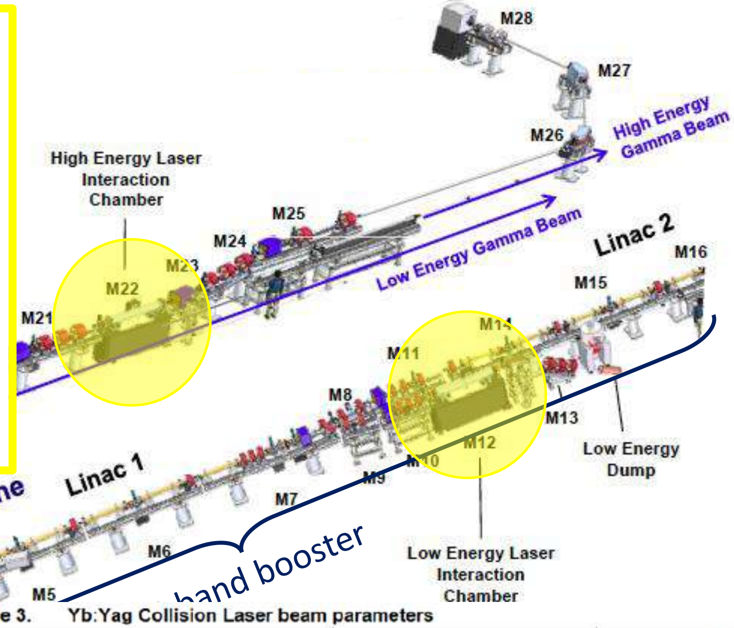


Table 3. Yb:Yag Collision Laser beam parameters

	Low Energy Interaction	High Energy Interaction
Pulse energy (*J*)	0.2	2x0.2
Wavelength (*eV,nm*)	2.3,515	2.3,515
FWHM pulse length (*ps*)	3.5	3.5
Repetition Rate (*Hz*)	100	100
M^2	≤ 1.2	≤ 1.2
Focal spot size w_0 (μm)	> 28	> 28
Bandwidth (*rms*)	0.1 %	0.1 %
Pointing Stability (μrad)	1	1
Synchronization to an ext. clock	< 1 *psec*	< 1 *psec*
Pulse energy stability	1 %	1 %

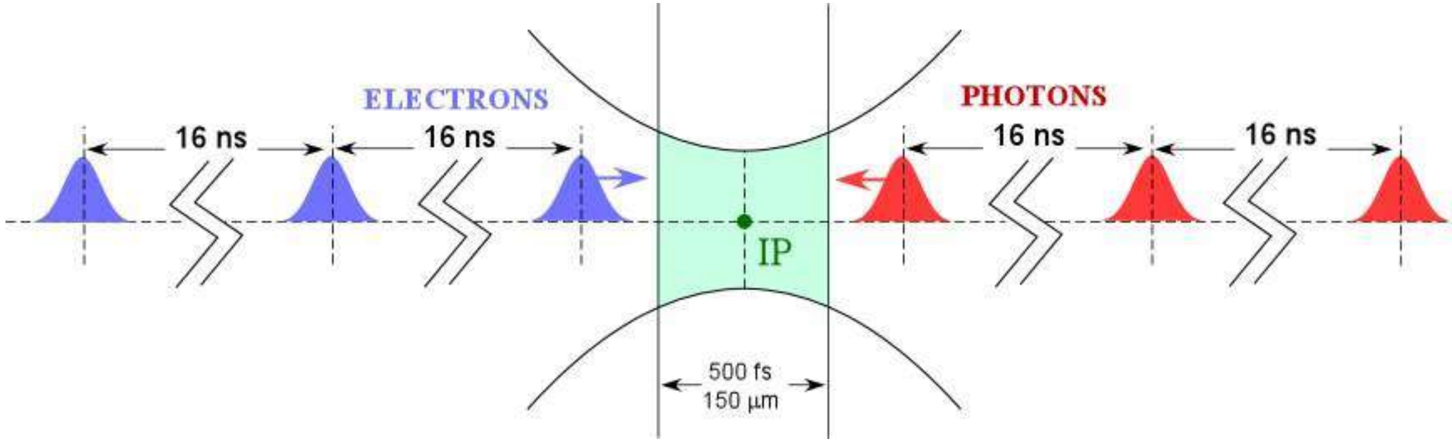
Picture courtesy of N. Bliss - STFC

ELI-NP synchronization SoW

> The general ELI-NP synchronization requirement is that the relative arrival time at the IP of electron bunches and photon pulses is **< 500 fs rms**

$$\langle \Delta t_{el} - \Delta t_{ph} \rangle_{rms} < 500\, fs \;\rightarrow\; \langle \Delta t_{el} \rangle_{rms} \approx \langle \Delta t_{ph} \rangle_{rms} \approx 350\, fs$$

> Collisions have to occur in an area which extends for ≈ 150 µm rms around the IP

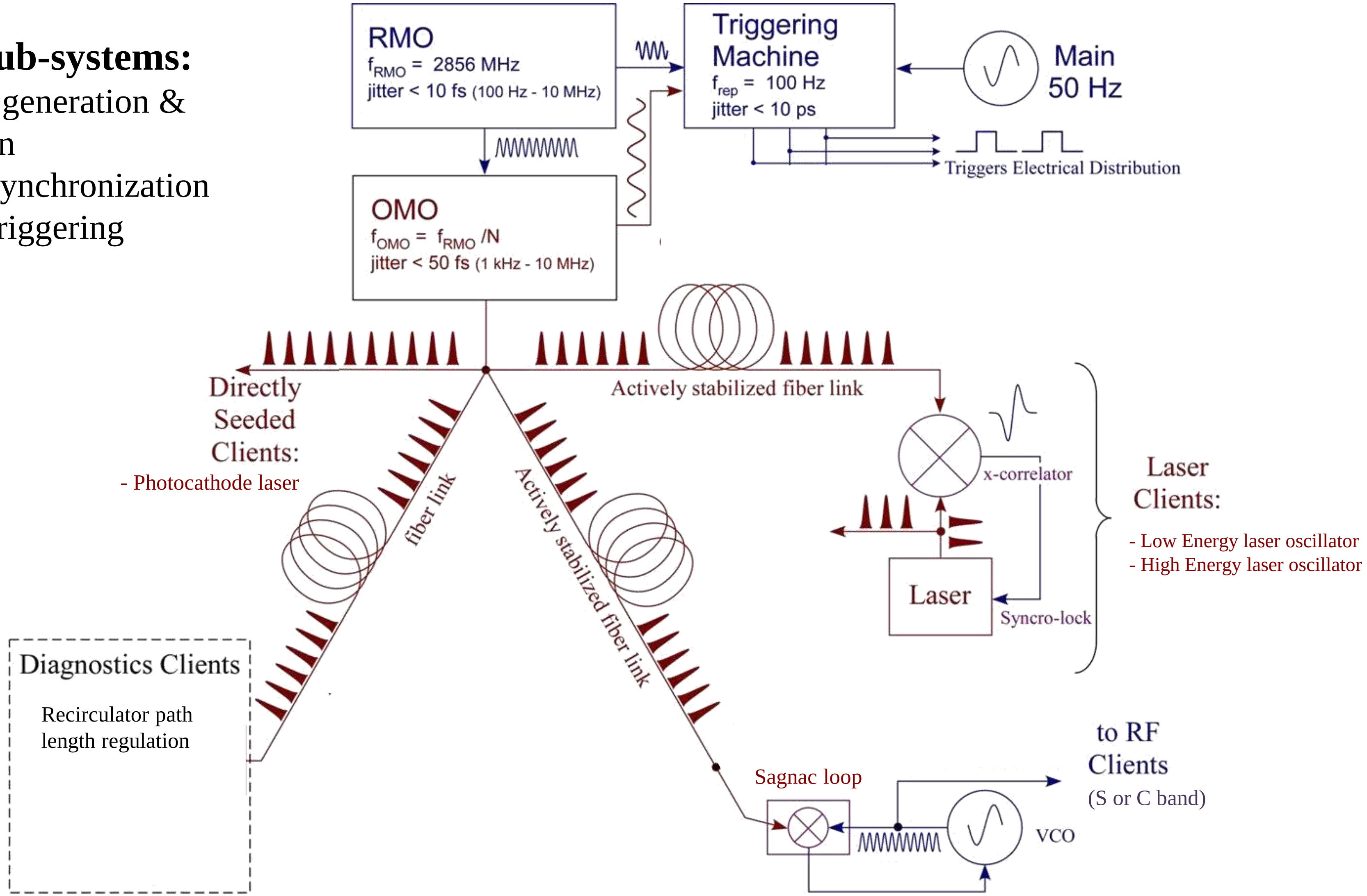


> The ELI-NP synchronization system task is to provide to all clients (laser systems and LLRF) an ultra-stable reference (< 50 fs relative jitter). PC laser is directly seeded from the reference itself, while interaction laser oscillators are directly locked to the reference.

> Mantaining synchronous all pulses along the train is a task involving also:
- Photocathode laser system (pulse train generation) and LLRF – electron side
- Recirculators temporal alignment – photon side

ELI-NP synchronization system

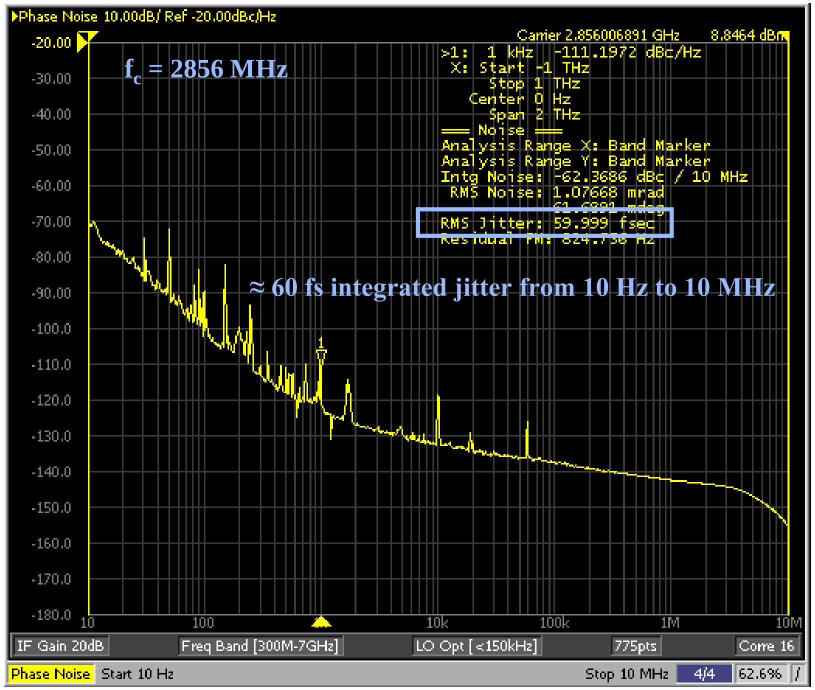
3 main sub-systems:
1) Timing generation & distribution
2) Client synchronization
3) Client triggering



Reference generation (RMO & OMO)

- Reference Master Oscillator: Laurin MO-2856-V3
  - Ultra-low phase noise OCXO: 95.2 MHz (Typ: 802691)
  - Provides a reliable reference tone to an OMO which encodes the reference timing information in the rep. rate of short optical pulses
  - RMO guarantees the long term stability of the OMO and imprints its low frequency noise figure to the whole facility timing network (phase-locking)
  - Output frequencies:
    - $f_{RF1} = f_{OMO} = 62.08$ MHz
    - $f_{RF2} = 46*f_{OMO} = 2856$ MHz (2x on N-connector) >10 dBm
    - $f_{RF3} = 92*f_{OMO} = 5712$ MHz (2x on N-connector) >10 dBm
  - Integrated jitter < 7 fs (1kHz to 10MHz)
  - Integrated jitter < 60 fs (10 Hz to 10 MHz)

Laurin RMO currently in use as RF reference at SPARC_LAB facility (INFN-LNF)



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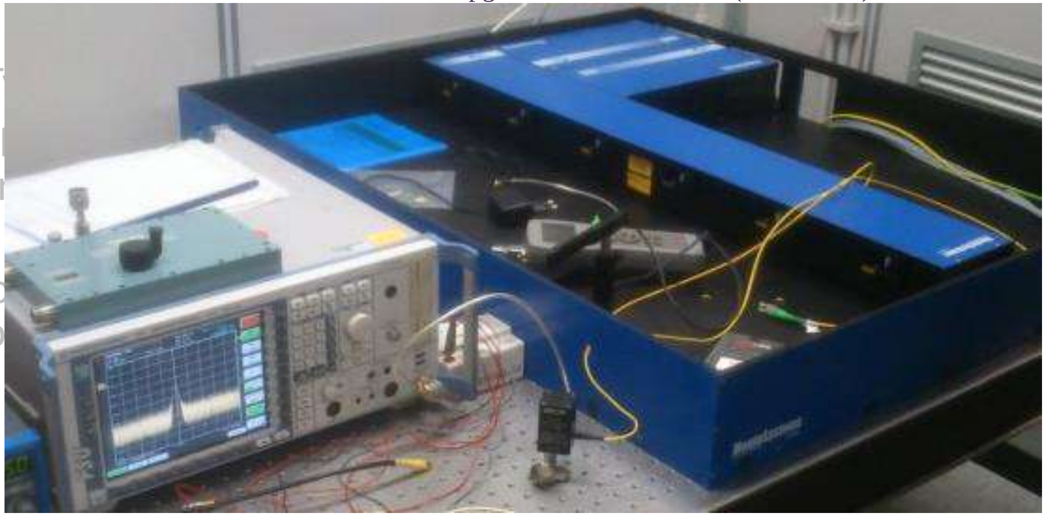
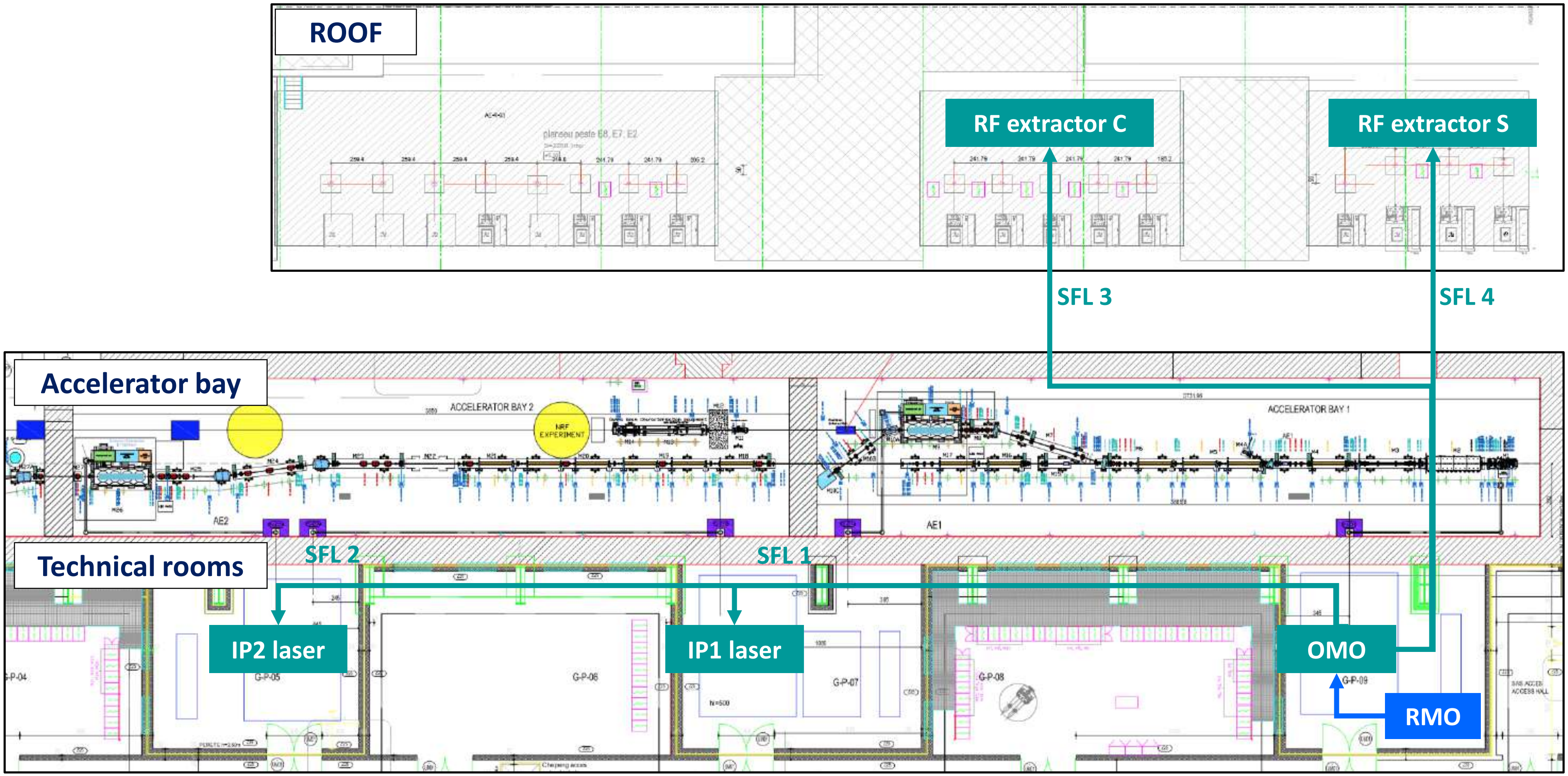
  - Integrated jitter < 7 fs (1kHz to 10MHz)
  - Integrated jitter < 60 fs (10 Hz to 10 MHz)
- Optical Master Oscillator: MenloSystems
  - Mode-locked low noise laser oscillator
  - Er doped fiber at standard telecommunication wavelength (1560 nm)

MenloSystems OMO being installed for the synchronization upgrade at SPARC_LAB (INFN-LNF)



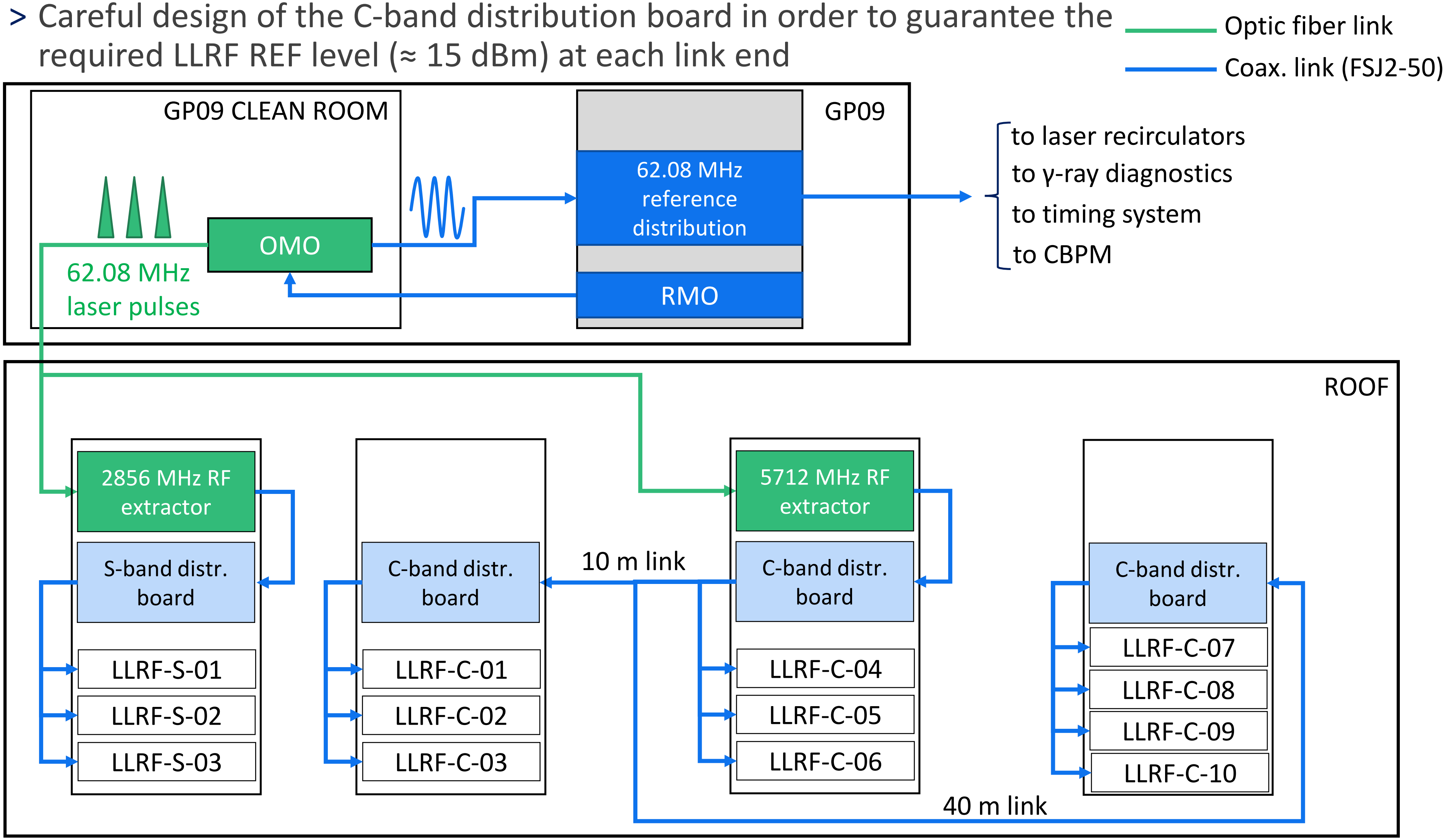
Parameter	Value
Pulse width	t_{pulse}< 200 fs
Wavelength 1	λ_1= 1560 nm
Wavelength 2 (SHG)	λ_2= 780 nm
Pulse rep. rate	2856 MHz/46 = 62.08 MHz
Integrated timing jitter (rms)	Δt < 15 fs (SSB, 1kHz – 10 MHz)
Amplitude stability (rms)	ΔA/A < 0.1%
Synchrolock BW	f_{cutoff} ≈ 1 kHz
Phase jitter rel. to ref. (rms)	Δt_{rel} < 10 fs (dc-1 kHz)

Optical reference distribution

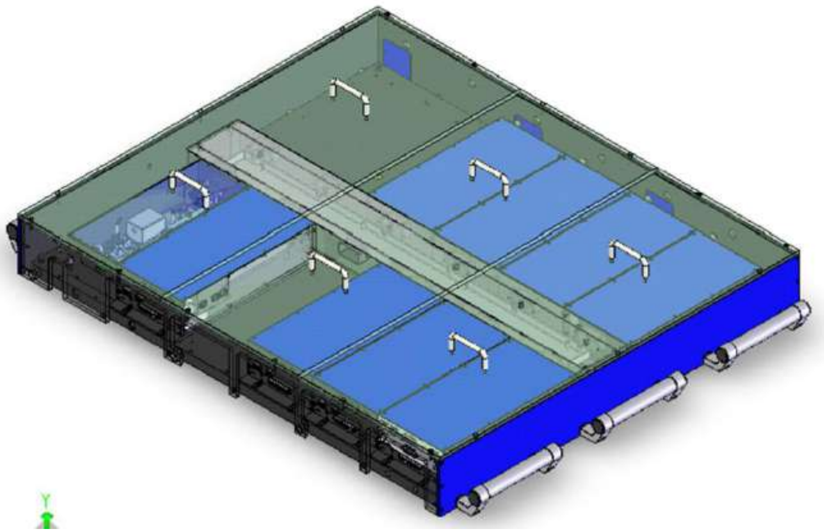


Reference generation & distribution

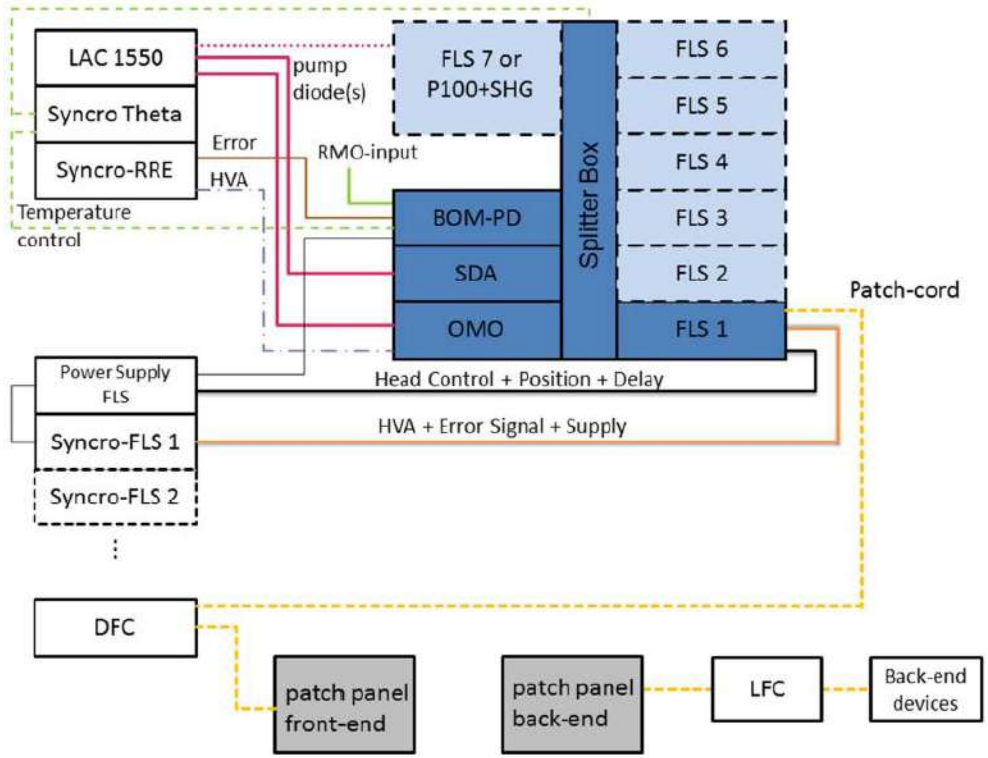
> Careful design of the C-band distribution board in order to guarantee the required LLRF REF level (≈ 15 dBm) at each link end

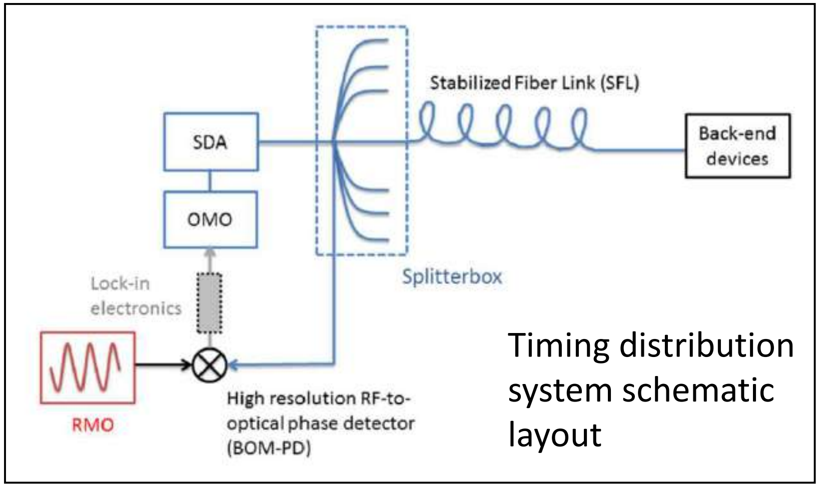


Timing Distr. System central station

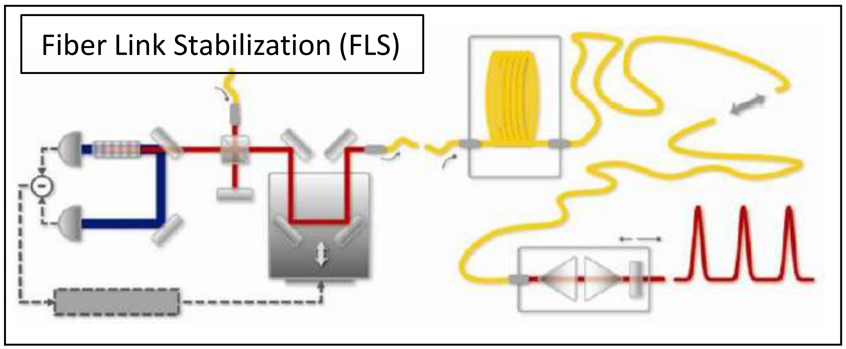


Picture courtesy of MenloSystems Gmbh. (DE)



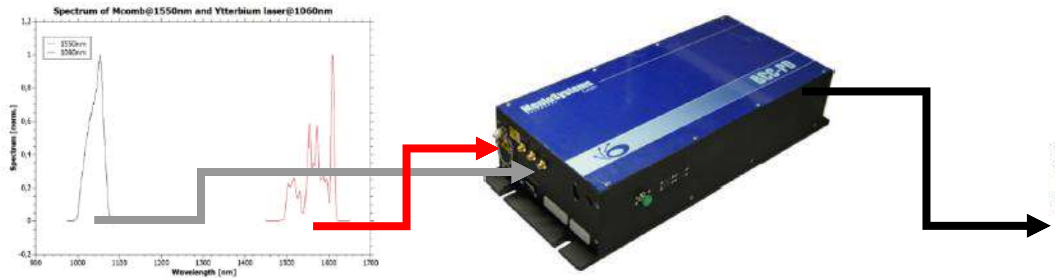


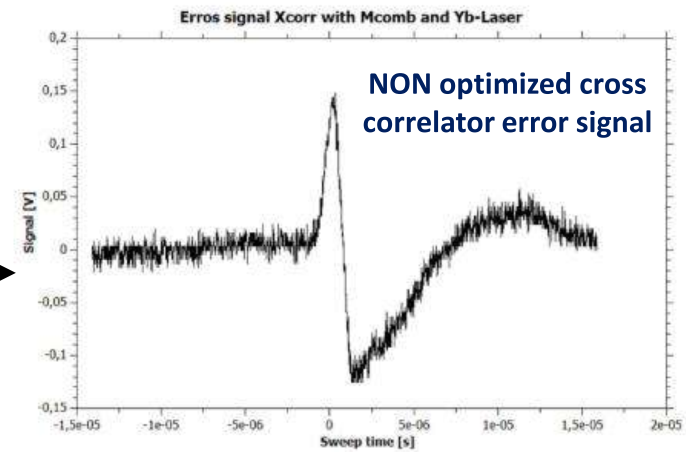
Timing distribution system schematic layout



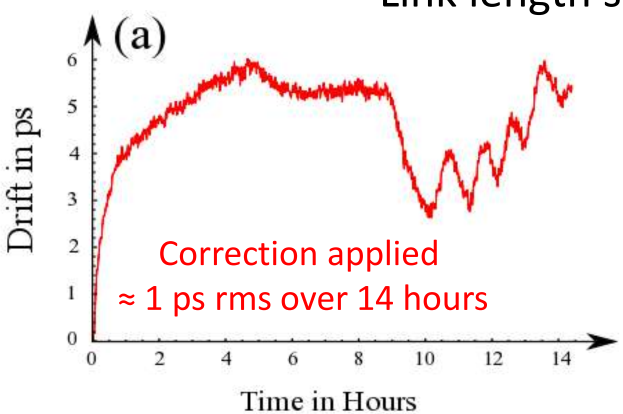
Synchronization system acceptance

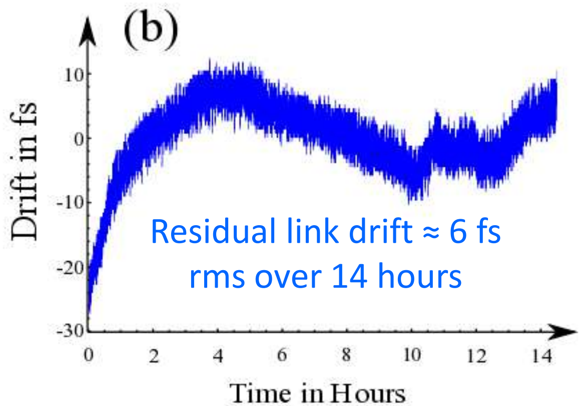
- Between August 2015 and October 2015 all the sub-systems have been accepted in factory with satisfactory results
- A pre-integration of photocathode laser front-end is foreseen at the end of July 2016 at LAL (Orsay)
- All material packed and stored at MENLO, ready to be shipped to LAL for the PC laser system tests scheduled in July





Link length stabilization





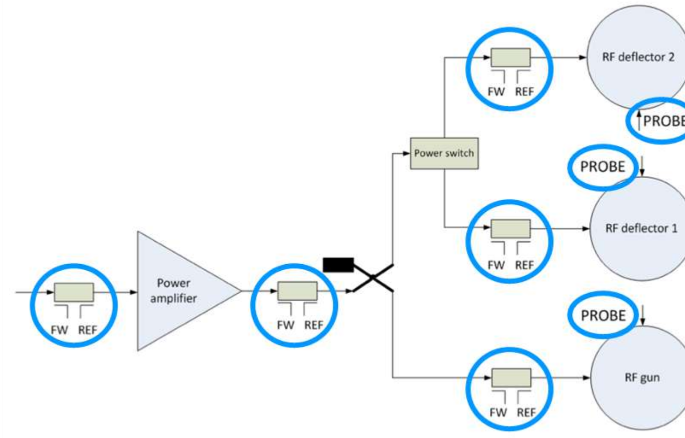
Libera LLRF system

- Input signals:
  - 8 RF inputs per module (max level 20 dBm)
  - RF reference signal
  - External trigger delay
  - 1 Interlock (from machine protection system)
- Output signals:
  - RF output (I/Q, max level 13 dBm)
  - 1 interlock (to machine protection system)
- Pulse shape adjustable during operation (e.g. for beam loading/energy spread compensation)
- Pulse by pulse **A** and Φ independent feedbacks (trim A and Φ waveforms amplitudes, leaving shapes unperturbed)
- Long term stability of RF station: 100 fs
- Resolution:
  - Amplitude 0.1% RMS
  - Phase (added jitter): S-band/C-band < 10 fs

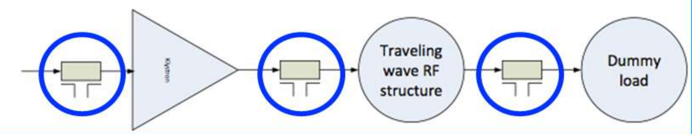
LLRF monitored signals

S-band: 3 Libera LLRF modules

13 RF signals from SW structures (Gun + RFD)

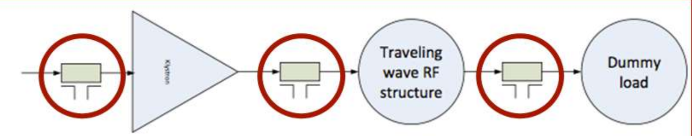


2 x 6 RF signals from TW structures

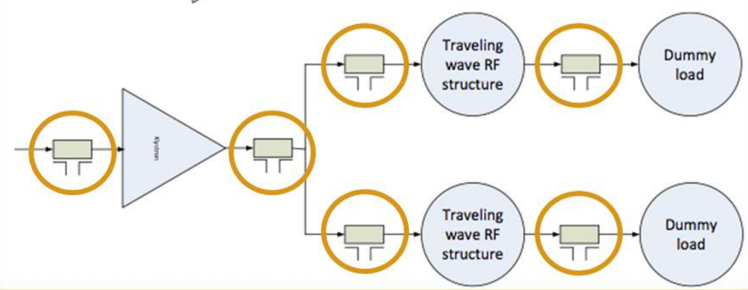


C-band: 8+2 Libera LLRF modules

8 x 6 RF signals from TW structures

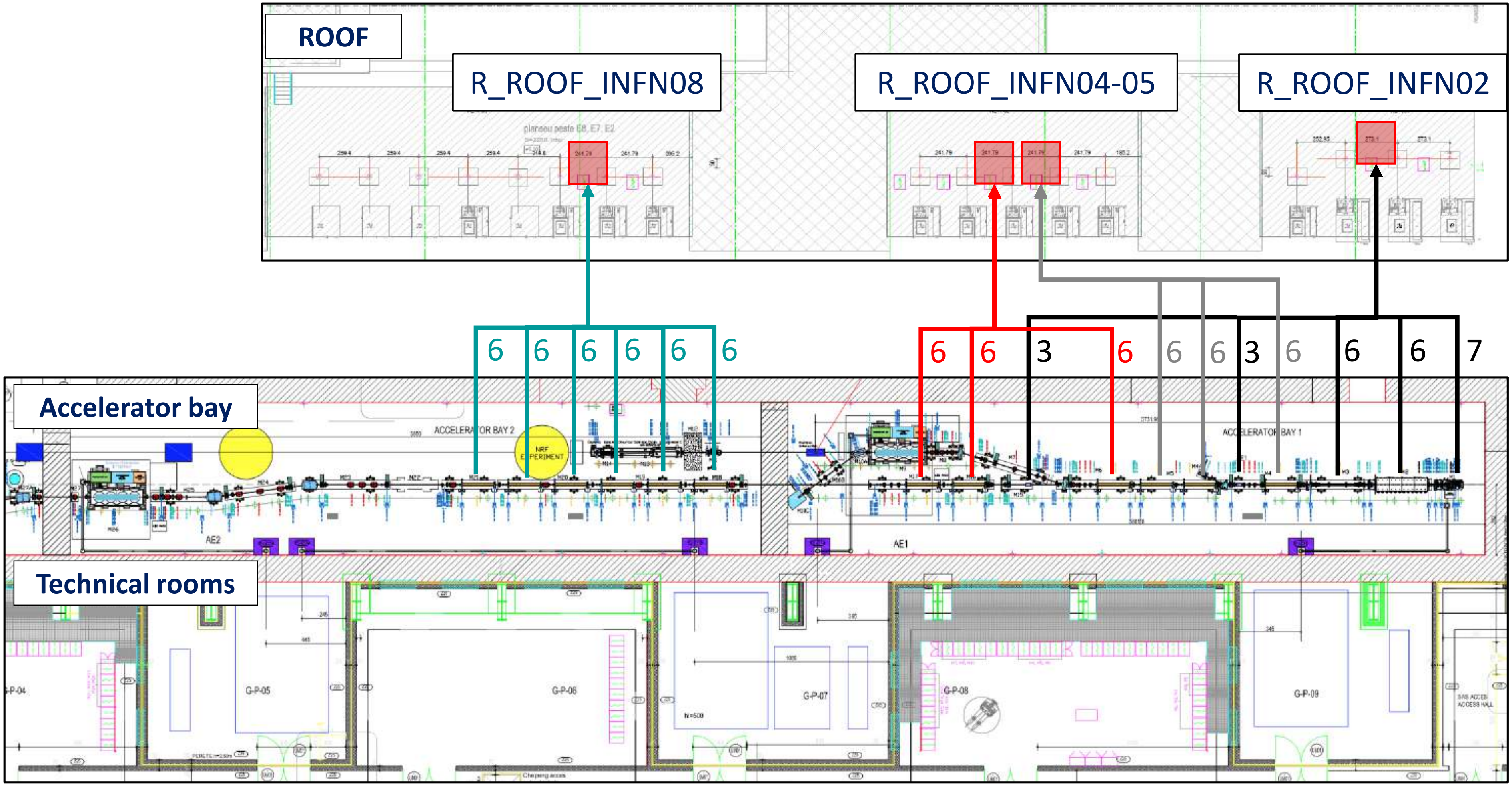


2 x 12 RF signals from the last 4 TW structures



Layout of LLRF signals

- S-band (RF-gun, RFD1, RFD2, M1-M2)
- C-band (M4-M5)
- C-band (M6-M16-M17)
- C-band (M18-M21)



Libera LLRF system

> Input signals:

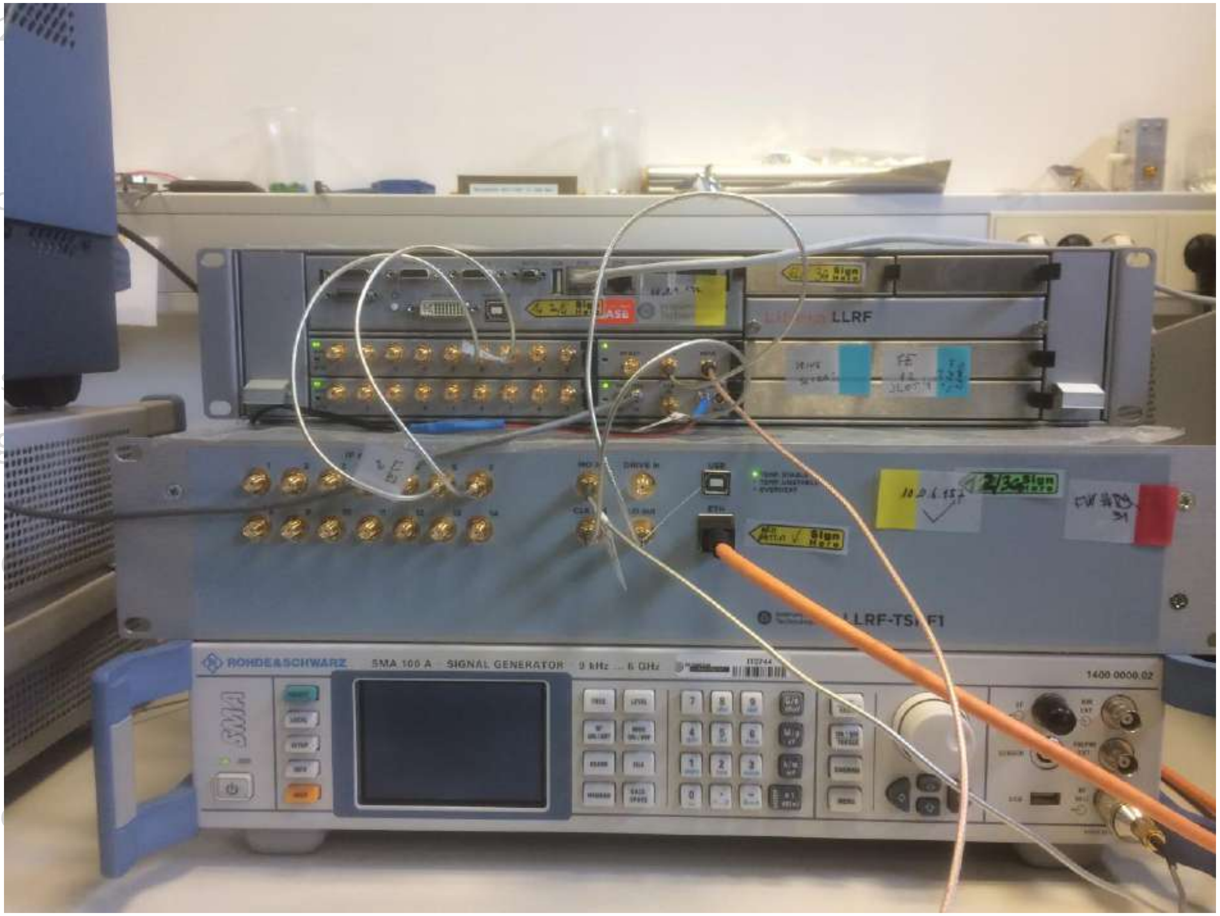
1000 shots, 190 points avg

S-band resolution	Closed Loop	Ext. noise (moving cables)
Drive Amp. (std dev)	0.016%	0.026%
Drive Phi (std dev)	0.01 deg	0.073 deg
LO Amp. (std dev)	0.005%	N/A
LO Phi (std dev)	0.003 deg	N/A

200 shots, 200 points avg

C-band resolution	Closed Loop
Drive Amp. (std dev)	0.013%
Drive Phi (std dev)	0.0095 deg
LO Amp. (std dev)	0.014%
LO Phi (std dev)	0.007 deg

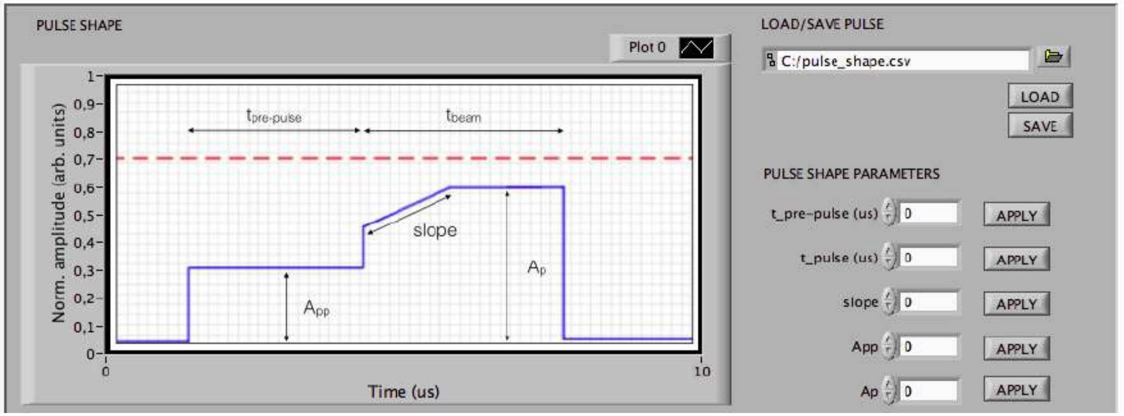
S-band Libera LLRF under test at I.Tech. during INFN-LNF visit 04/05/2016

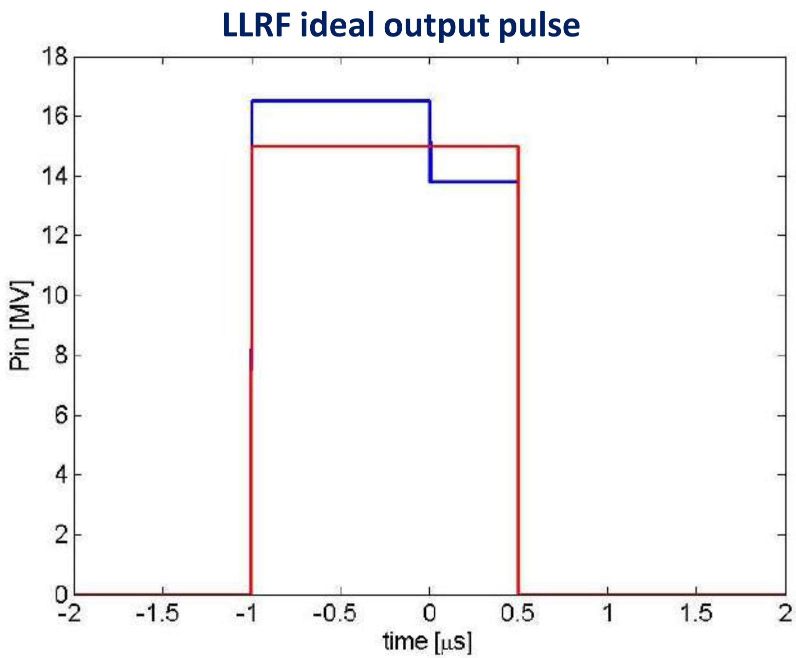


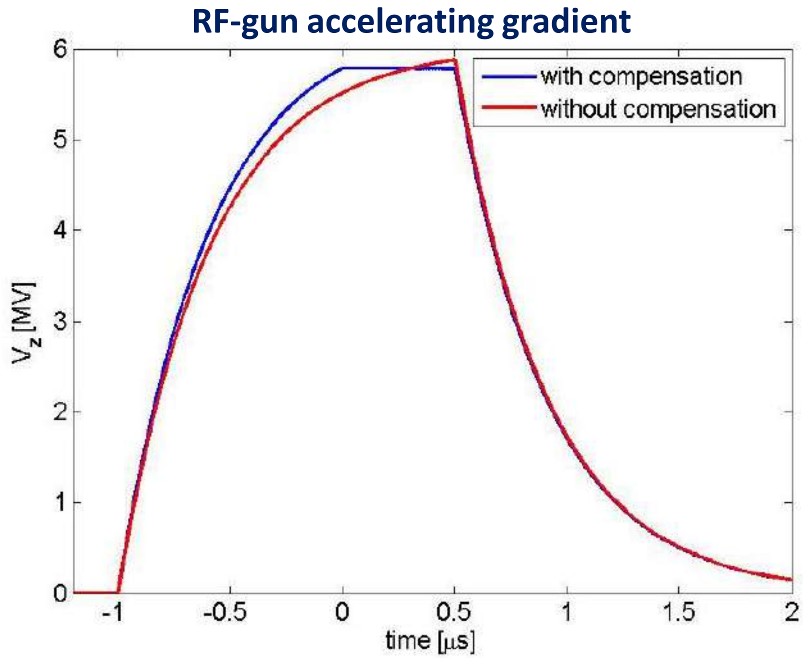
Pulse shaping

> The pulse shape can be updated during operation from control system loading a csv spreadsheet to the LLRF system

> Independent amplitude and phase shaping is allowed







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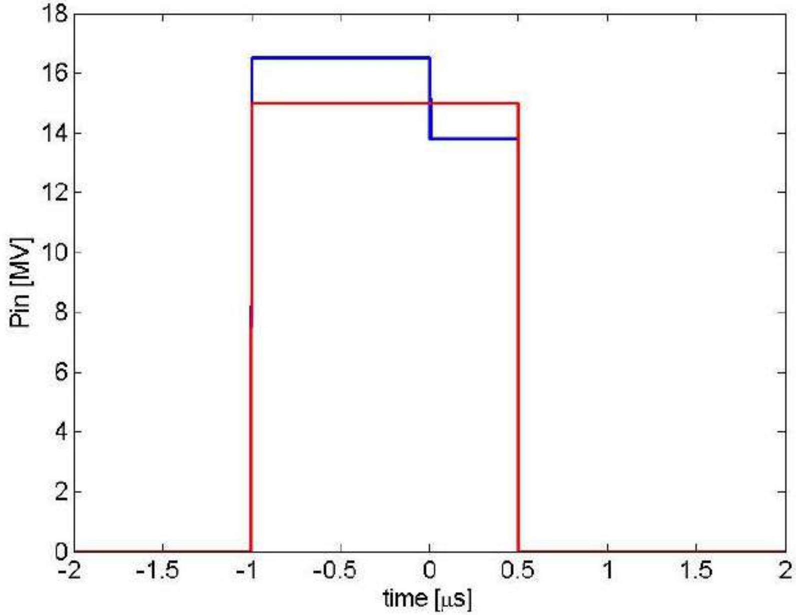
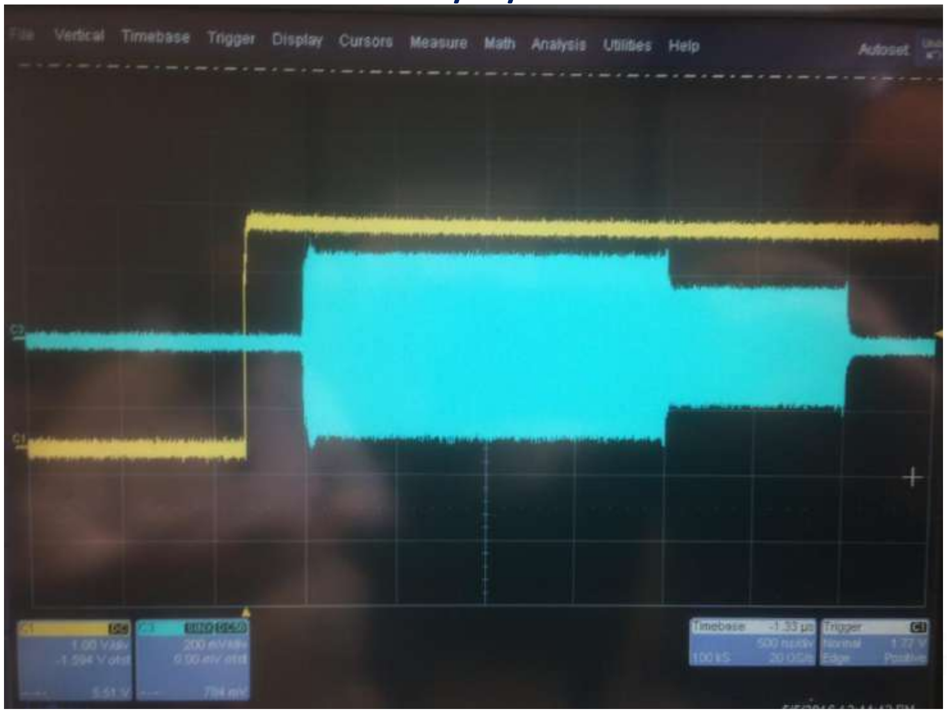
LLRF ideal output pulse



S-band pulse shape measured at I.Tech. during INFN-LNF visit 04/05/2016



Beam loading compensation

GOAL: compensate with LLRF pulse shaping the beam loading induced in the C-band structures

> A first order study of the wakefields induced by the 32 bunches in the C-band structures has been performed

> Each bunch has been considered as a point-like charge

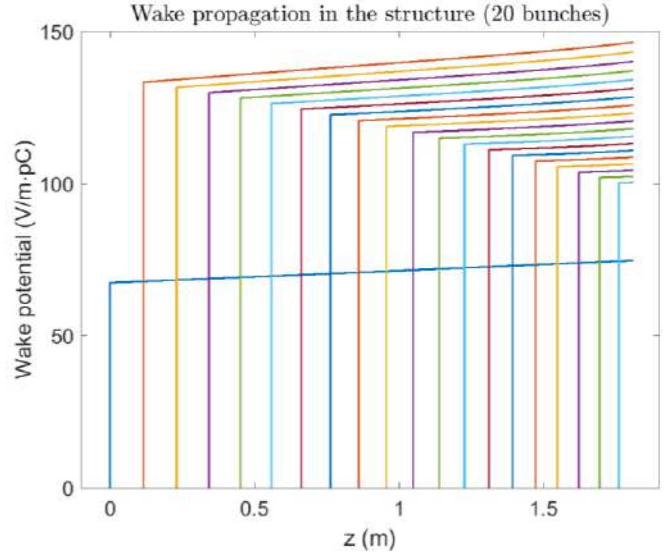
> The wake (normalized to the charge) has been evaluated according to the equation:

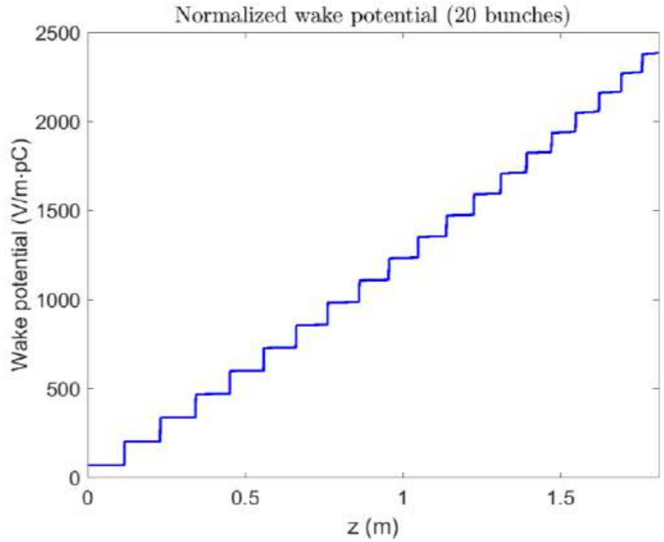
$$W(z) = \frac{1}{2}\omega_{RF}\frac{r}{Q} = \alpha v_g r$$

> Every 16 ns a new bunch traverses the accelerating section -> a new wake is produced and transported within the structure

> After 20 bunches the structure is "fully loaded" (filling time ≈ 314 ns)

> The total wake potential (normalized to the charge) is given by the sum of the 20 "single bunch" wakes





Beam loading compensation

> In order to have a net average accelerating field of 33 MV/m (design value), the structure has to be pre-loaded with a tailored power pulse

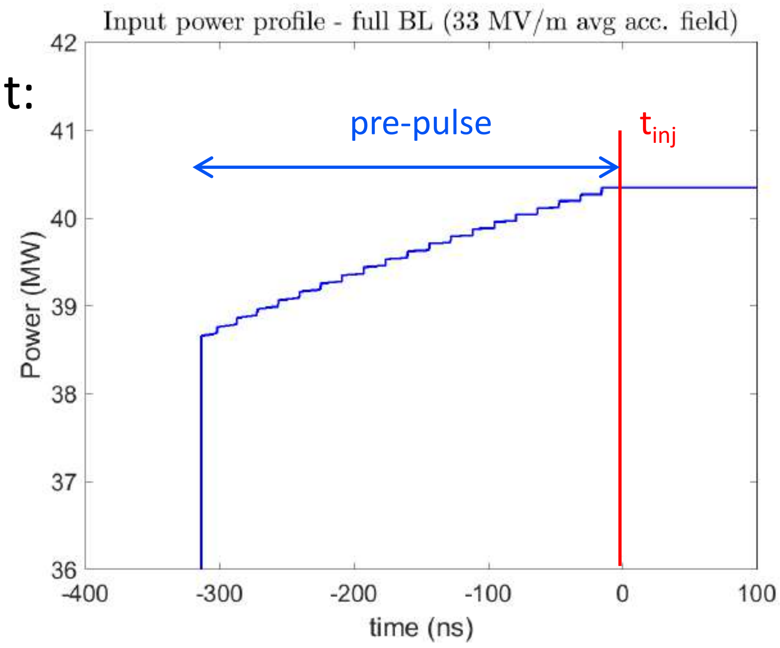
> As the bunch train enters into the perfectly pre-loaded structure, the drive power has to be kept constant for the entire duration of the pulse

Such a waveform can be fed to the LLRF system but:

> Klystron + Modulator BW not known (≈ 10 MHz)

> LLRF backend BW ≈ 15 MHz

An integrated test of Klystron + Modulator + LLRF system could be of great help in order to understand and optimize the pulse shaping capabilities needed for beam loading compensation (e.g. during modulator FAT at ScandiNova)



Thank you for the attention