Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Technology developments for ELI-NP Gamma Beam System

L. Piersanti (INFN-LNF) on behalf of the EuroGammaS collaboration

Outline

- ELI-NP project overview
- ELI-NP Gamma Beam System (GBS)
  - EuroGammas consortium
  - Machine layout and main parameters
- Main technology developments:

  Electron linac
  - The new 1.6 cell SW RF-gun manufactured without copper brazing
  - C-band HOM damped accelerating structures
  - LLRF and synchronization systems

  Laser
  - The IP laser recirculation system

ELI-NP overview

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

Pursue advanced applications in various fields:

- nuclear medicine
- nuclear physics
- astrophysics
- homeland security
- nuclear waste treatment

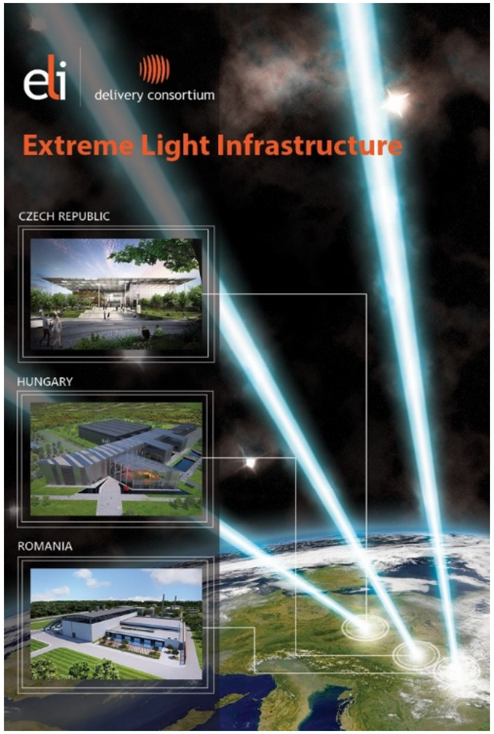
Based on two advanced light sources:

- Laser source (delivered by Thales):

  Two 10 PW APOLLON-type lasers, output energy > 200 J, pulse length 20-30 fs, intensity > 10^{23} W/cm^2

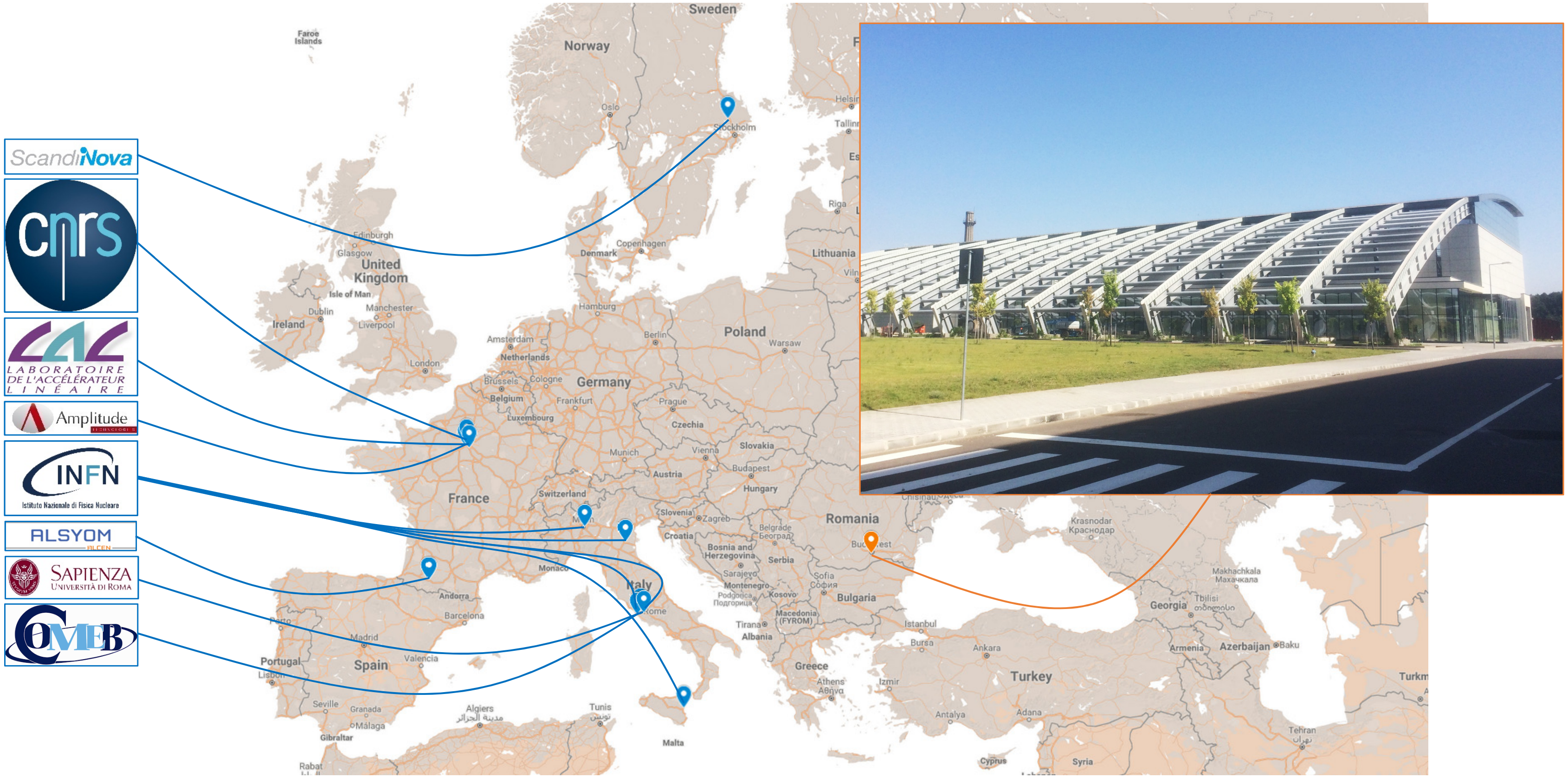
- Gamma source (delivered by EuroGammaS consortium):

  Inverse Compton scattering machine with tunable energy of gamma photons between 0.2 and 19.5 MeV, narrow bandwidth (0.5%), high spectral density (10^4 photons/sec/eV).



ELI-NP Gamma Beam System

EuroGammaS a European consortium to deliver the ELI-NP-Gamma Beam System: 8 partners



ELI-NP Gamma Beam System

INFN
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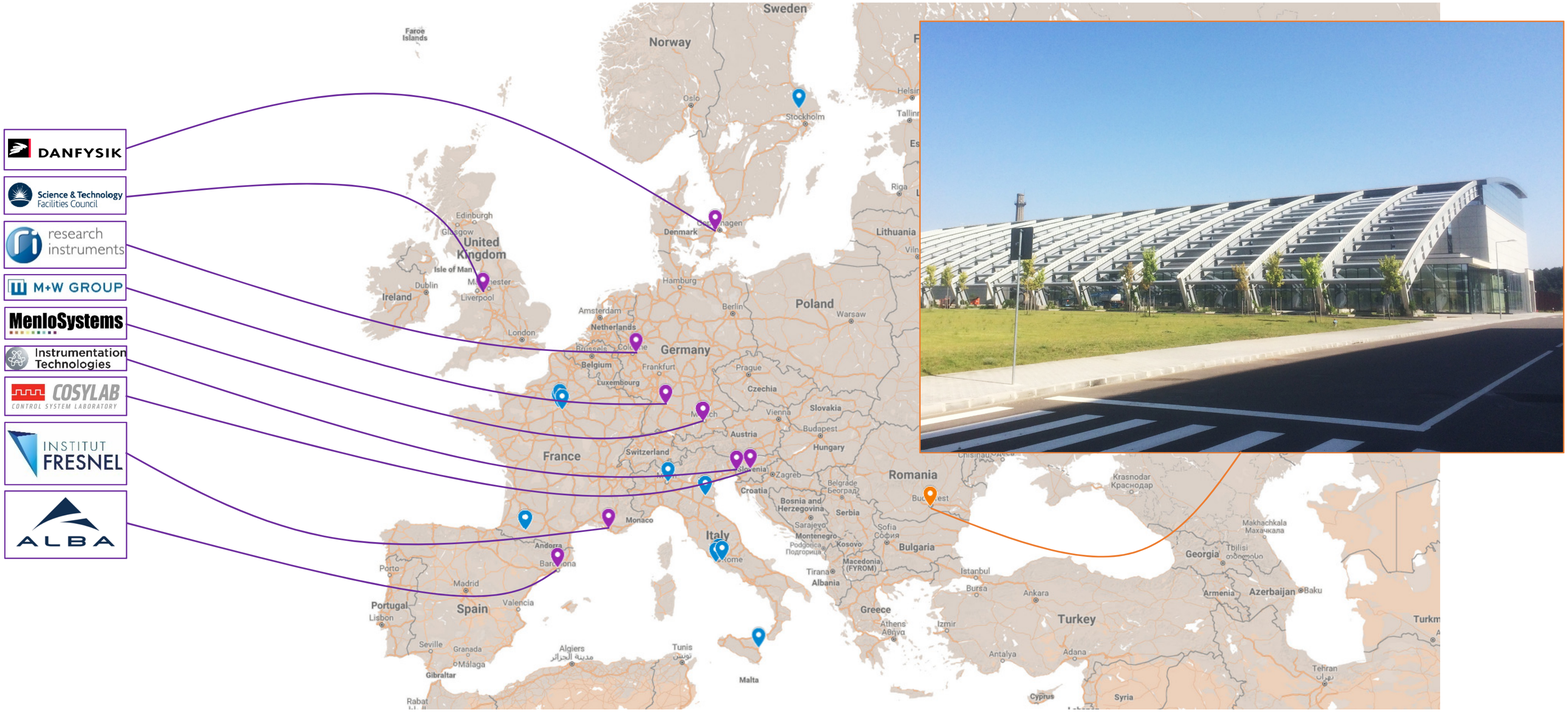
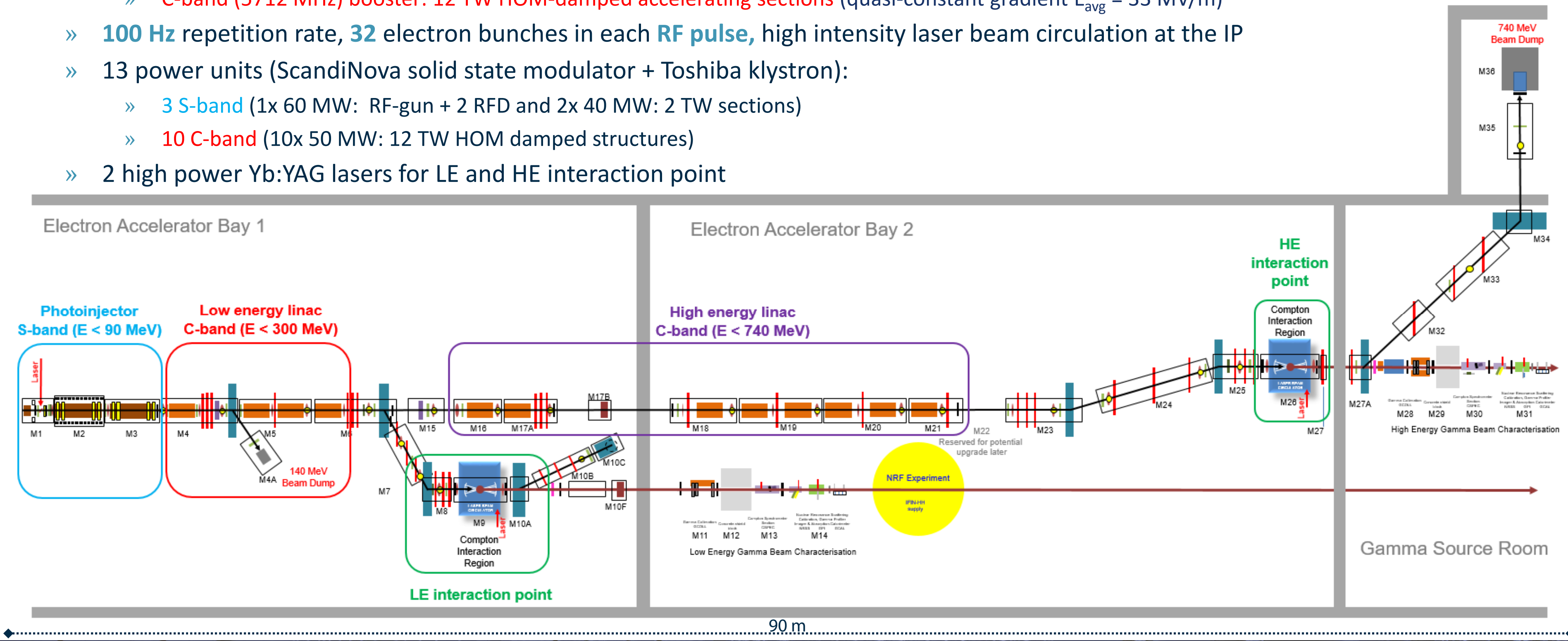
EuroGammaS a European consortium to deliver the ELI-NP-Gamma Beam System: 8 partners + 9 sub-contractors



Machine layout & main parameters

GBS linac:

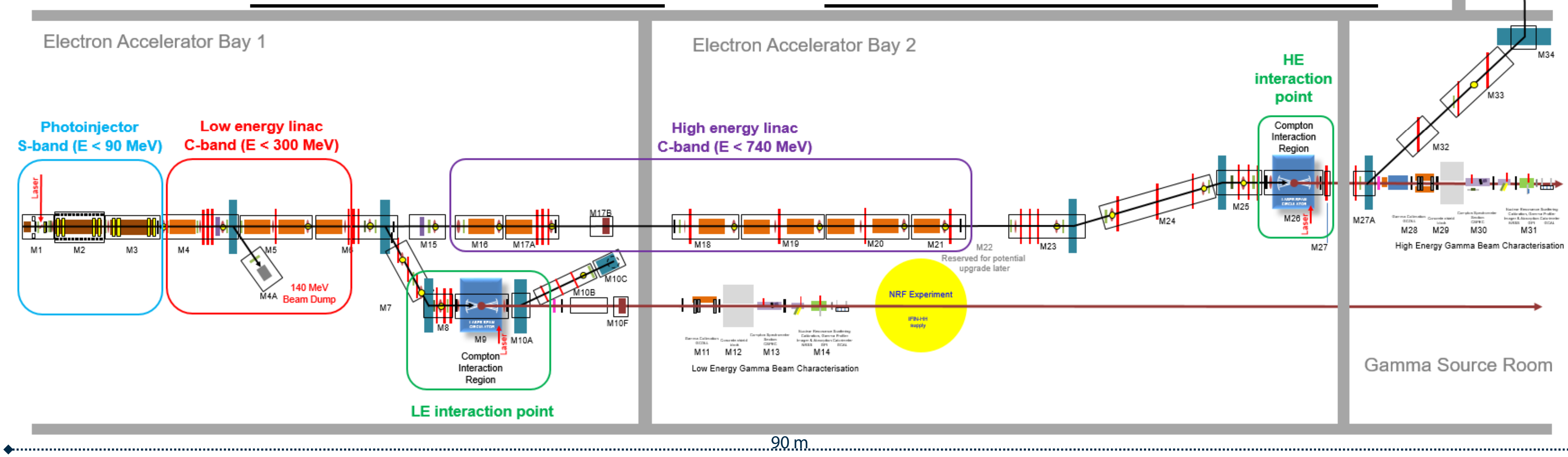
- 90 m room temperature hybrid linac:
  - S-band (2856 MHz) high brightness photoinjector: SW RF-gun + 2 TW SLAC-type accelerating sections (constant gradient E_{avg} = 23.5 MV/m)
  - C-band (5712 MHz) booster: 12 TW HOM-damped accelerating sections (quasi-constant gradient E_{avg} = 33 MV/m)
- **100 Hz** repetition rate, **32** electron bunches in each **RF pulse,** high intensity laser beam circulation at the IP
- 13 power units (ScandiNova solid state modulator + Toshiba klystron):
  - 3 S-band (1x 60 MW: RF-gun + 2 RFD and 2x 40 MW: 2 TW sections)
  - 10 C-band (10x 50 MW: 12 TW HOM damped structures)
- 2 high power Yb:YAG lasers for LE and HE interaction point



Machine layout & main parameters

Electron beam parameters	Value
Bunch charge	250 pC
N. Bunches / pulse	32
Bunch distance	16.1 ns
Bunch length	< 300 µm
Beam final 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)
Bandwidth (rms)	< 0.5 %
Peak brilliance	> 10^{20} ph/(s · mm² · mrad² · 0.1 %)
Source size (rms)	10 - 30 µm
Source divergence (rms)	25 – 250 µrad
Linear polarization	> 95 %
Pulse length (rms)	0.7 – 1.5 ps

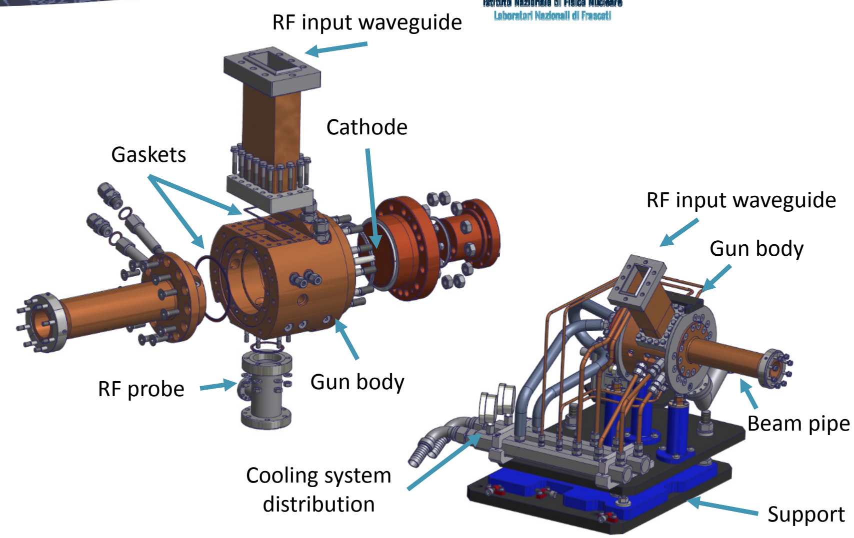


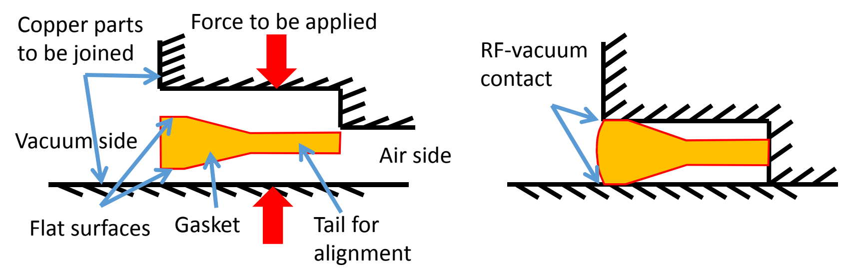
S-band RF gun with new clamping technology

Optimization of S-band (2.856 GHz) BNL/SLAC/UCLA SW 1.6 cell RF-gun

- **Manufactured without brazing** (with special gaskets developed at INFN-LNF[1],[2])
- Elliptical irises with large aperture (lower surface peak fields, faster pumping speed)
- Tunability by deformation of the full cell
- Overcoupled (**β=3**) to reduce peak input power, avg. dissipated power, pulse length and thus BDR probability
- Rounded coupling hole to reduce pulsed heating
- **Cooled cathode** (peak field 120 MV/m) + 5 cooling channels
  - at 100 Hz full power: 1.3 kW dissipation-> 100 kHz detuning (2-3 °C compensation needed)

Parameter	Unit	Value
Repetition frequency	Hz	100
Working mode		π
Max RF input power	MW	16 (shaped)
RF peak field at the cathode	MV/m	120
Total RF pulse length	μsec	**1.5**
Unloaded Q factor (Q_0)		14500
Average dissipated power	kW	**1.3**
Working temperature	°C	32
Coupling coefficient (β)		3
Filling time	ns	**420**
Shunt impedance	MΩ	1.64
Cathode quantum efficiency @ 266 nm		$5 \cdot 10^{-5}$





[1] D. Alesini et al. International patent application PCT/IB2016/051464
[2] D. Alesini et al. Phys. Rev. ST Accel. Beams, vol. 18, no. 9, 2015

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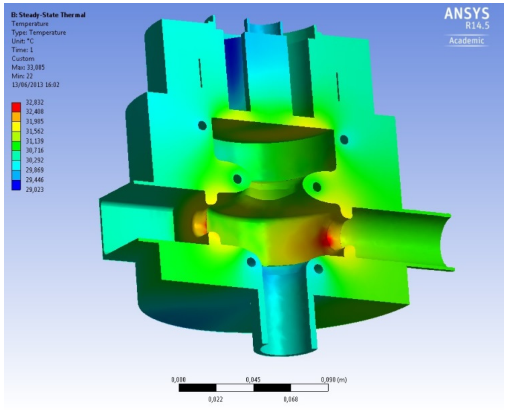

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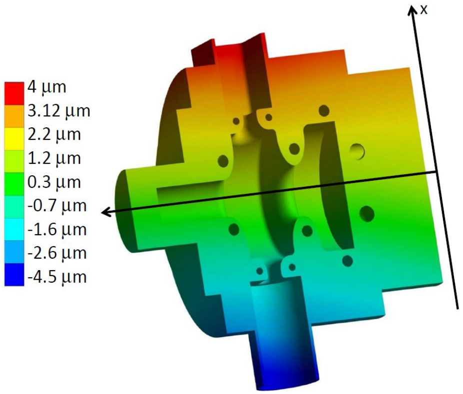
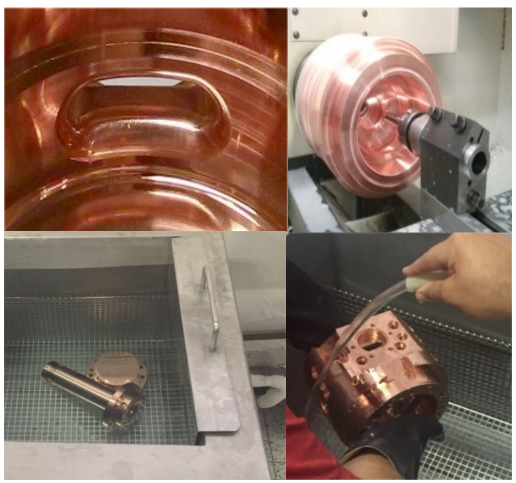
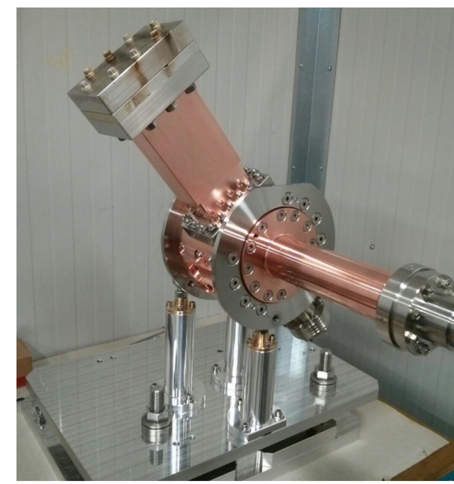


V. Pettinacci et al, Proceedings of IPAC2014, THPRI043 p. 3860
V. Pettinacci et al. Thermal Analysis of a Radiofrequency Gun, ANSYS user group meeting Italy, 2013

RF gun machining & assembly

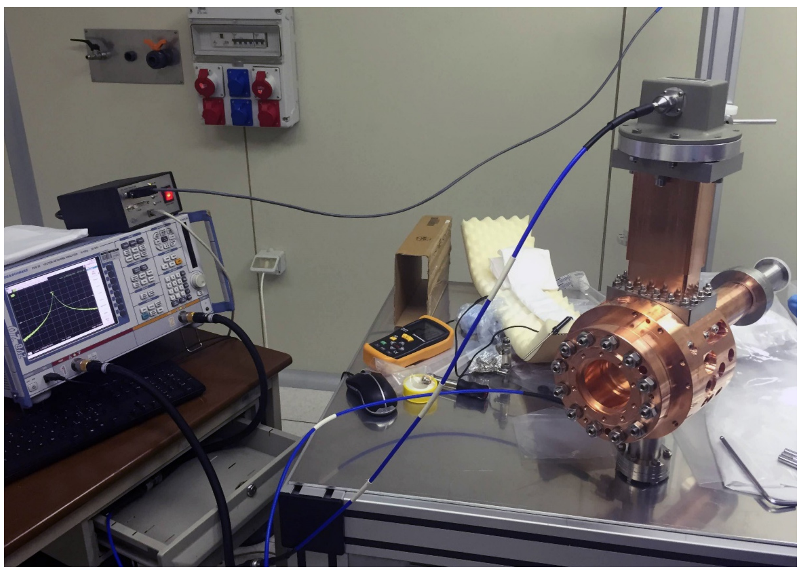
- All parts fabricated by **COMEB** (EuroGammaS partner) with a **precision of ±10 μm** and surface **roughness <150 nm**. Rounded coupling hole machined with a 5 axis milling machine
- All parts **cleaned** with detergent, followed by a ultra-sound bath of citric acid in distilled water, dried with N_2 flux
- Assembly in **clean room**
- **Vacuum leak** inspection
- **Low power RF characterization and tuning** (acting on deformation tuners, see next slide)
- Final assembly of **cooling system and support**

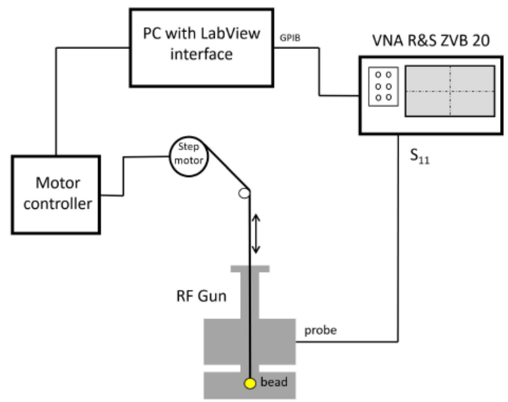




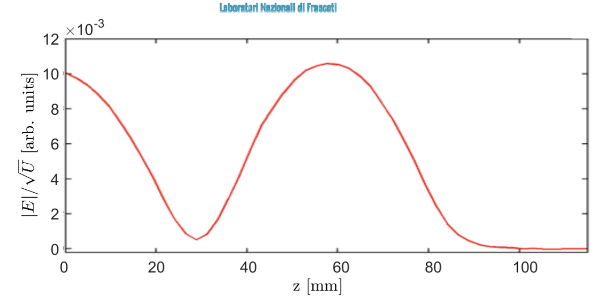
RF gun low power meas. @ INFN-LNF

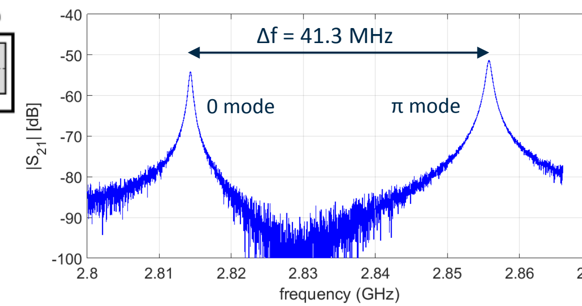
- After its assembly the RF gun has been tuned acting on the 2 deformation tuners of the full cell
- Low power measurements and gun tuning have been performed at INFN-LNF with **bead drop technique** (Slater theorem)
- All the parameters are in very good agreement with simulations, coupling coefficient is slightly lower than designed **β = 2.64**

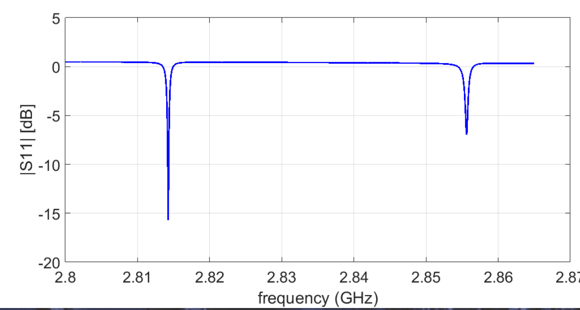




Parameter	Meas. value	Sim. value
Resonant frequency at 32 °C	2.856 02 GHz	2.856 GHz
Unloaded quality factor (Q_0)	14 990	14 600
Coupling coefficient (β)	2.643	3
$0/\pi$ mode separation	41.3 MHz	40 MHz







D. Alesini et al. "Design, realization and high power test of high gradient, high repetition rate brazing-free S-band photo-gun" Submitted for publication to Phys. Rev. ST Accel. Beams 2018

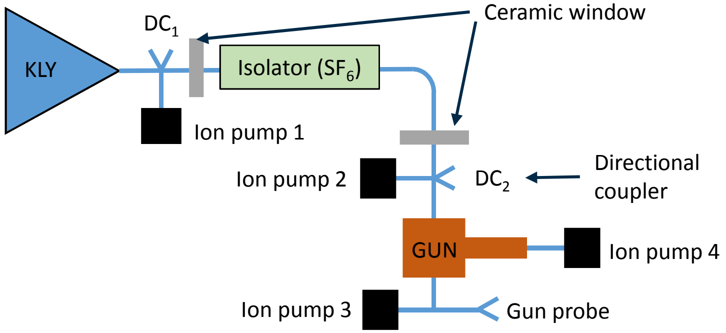
S-band RF gun high power test at Bonn Uni.

» High power RF tests have been performed at the Bonn University under Research Instruments responsibility

» ELI-NP power unit: Scandinova solid state modulator (k2-3) + Toshiba 60 MW klystron

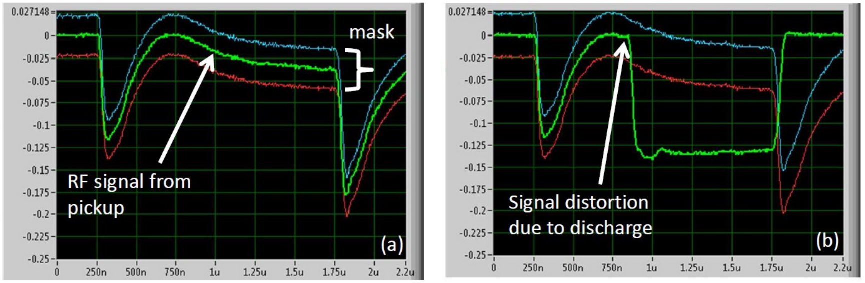
» RF signals monitored by means of 2 directional couplers with peak detectors

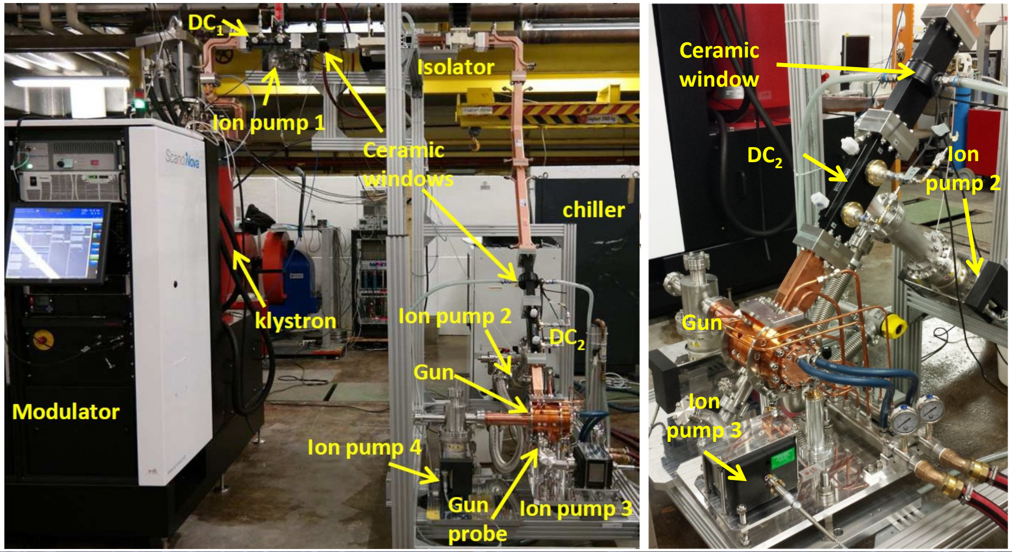
» 3 sources of interlock:
  » Vacuum pressure exceeding 1x10^{-8} mbar
  » VSWR at the klystron input exceeding 1.2
  » Fast cRIO pulse-by-pulse **waveform mask** on RF gun reflected power



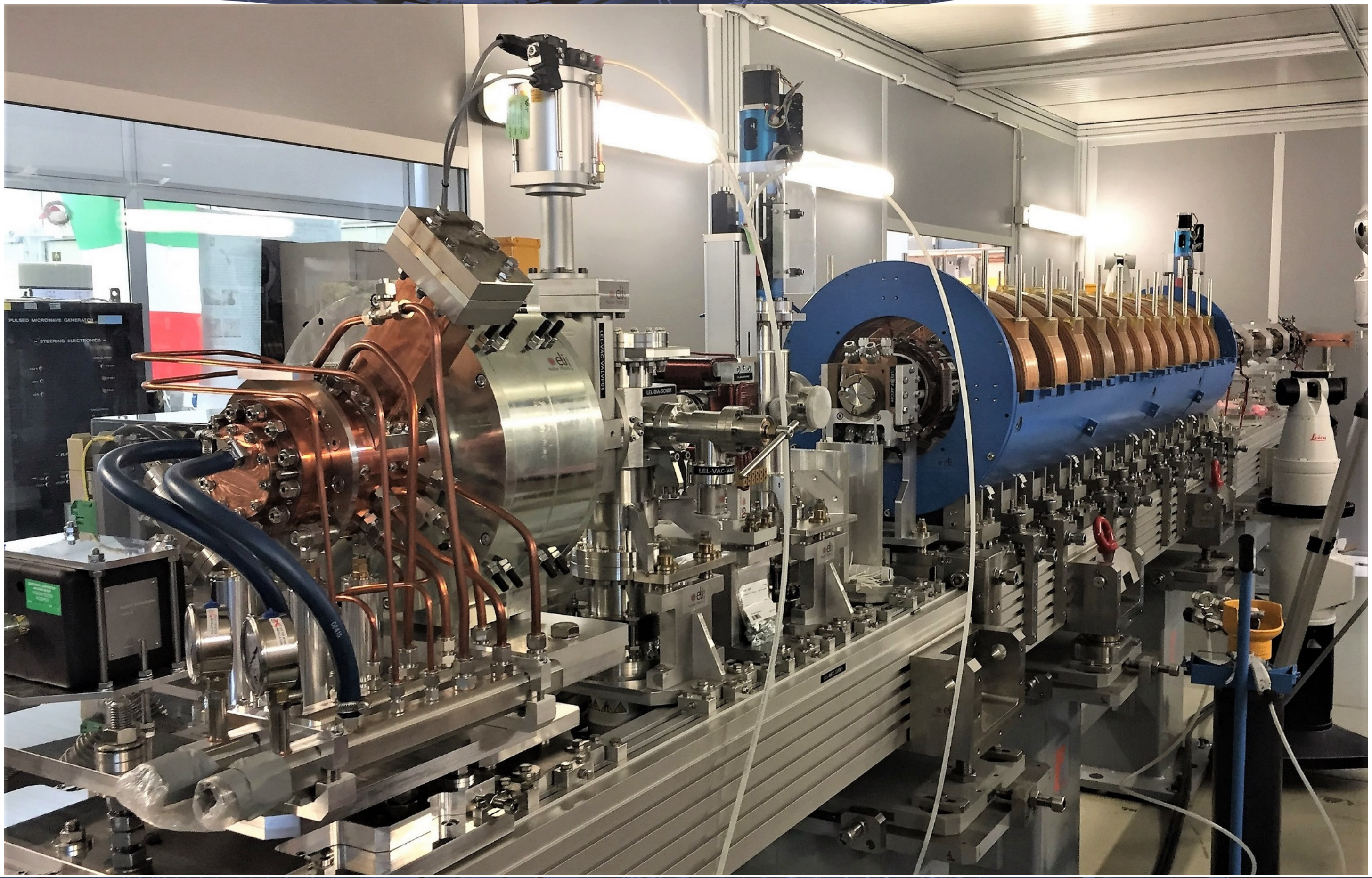
» The RF conditioning lasted ≈160 h and the gun reached the nominal parameters (14 MW input power, 100 Hz rep. rate, 1.5 µs pulse length) with a BDR of ≈ $2\cdot10^{-5}$ bpp

» At the end of conditioning and without RF power the vacuum pressure in the gun was < 5x10^{-10} mbar





S-band photoinjector integration @ INFN-LNF

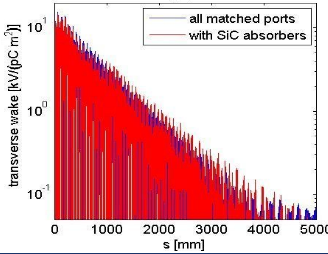


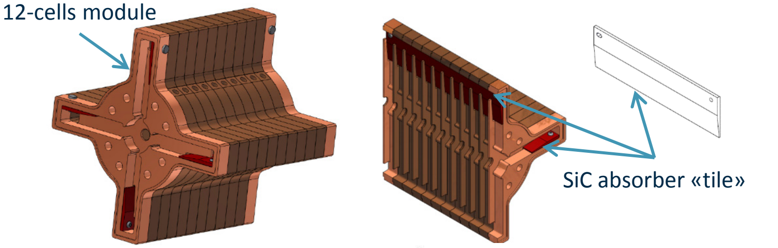
C-band TW HOM damped structures

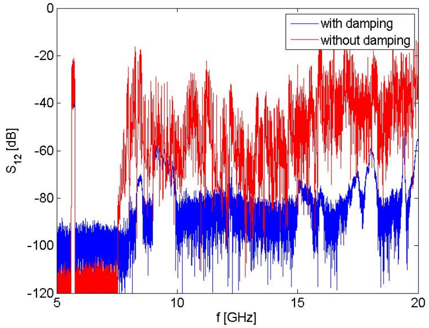
- The ELI-NP-GBS booster comprises 12 TW **1.8 m** long **quasi-constant gradient** C-band structures, **2π/3** field phase advance per cell, **33 MV/m** average accelerating field
- **Multi-bunch operation** imposes an effective **damping of the dipole HOM** to avoid Beam Break Up instabilities
- Our solution foresees a **waveguide damping system** (simplified respect to CLIC structures). **4 waveguides/cell** that allow HOMs to propagate and dissipate into silicon-carbide (SiC) RF loads
- The **SiC tiles, the cells and waveguide coupling apertures** have been optimized with HFSS, GdFidL and CST Microwave Studio
- Low power RF tests have been performed at INFN-LNF on a **single 12-cells module** with and without the SiC absorbers showing the effectiveness
- Ultra-precise manufacturing of irises and cells with lathe (precision ±5 µm and roughness ≤ 50 nm)
- The structure has been brazed in several steps:
  - **Modules of 12 cells** (8 for each structure) and input/output couplers have been brazed and vacuum/mechanically checked after brazing
  - **SiC absorbers assemby** in the module
  - Brazing of two sub-assemblies (6 modules + out. coupler & 2 modules + in. coupler)
  - Final brazing of the whole structure. The last two steps have been performed in the INFN-LNL oven in Legnaro

Simulated transverse wake potential (CST)

- Bunch separation ≈ 4.8 m
- Transverse beam size $\sigma_{x,y}$ = 3 mm
- Beam displacement from axis = 2 mm
- Q dipole modes < 100







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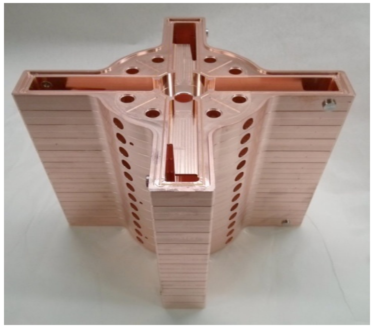
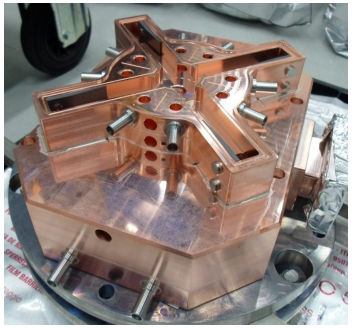
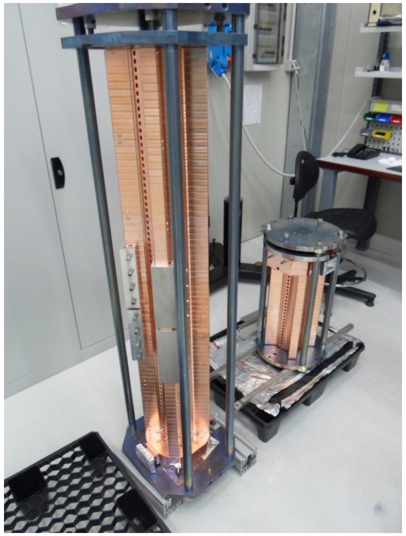
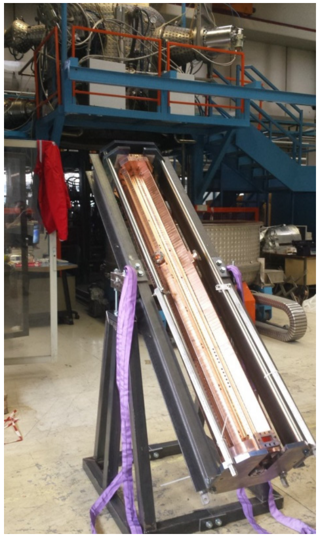
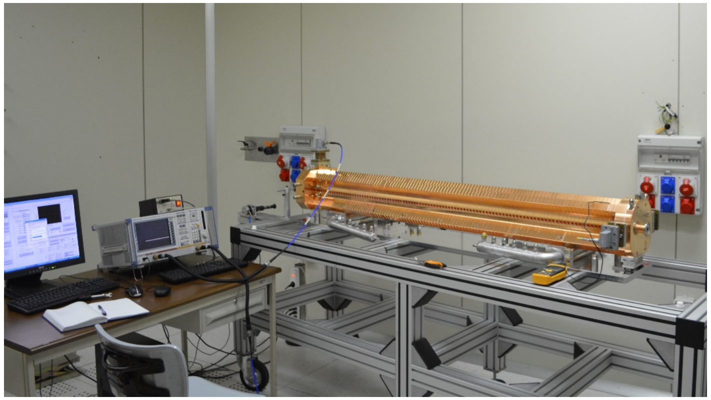
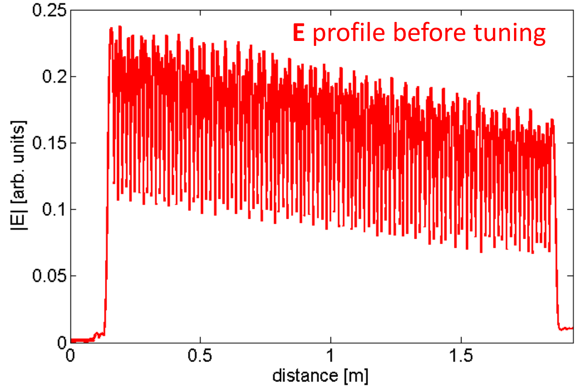
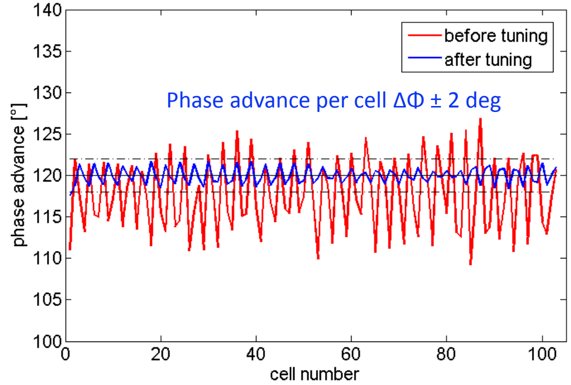
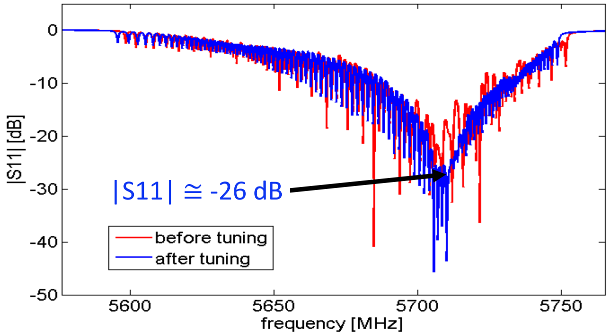





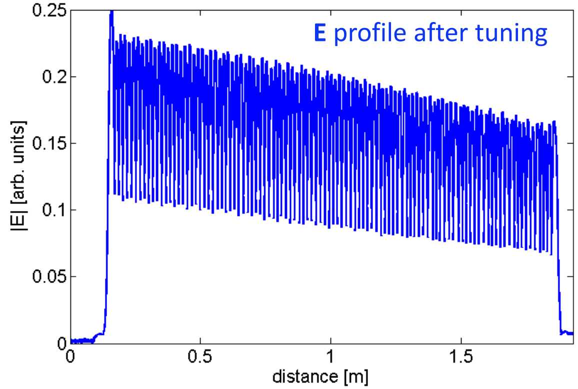
- Electric field into the structures has been measured at INFN-LNF using the **bead pull technique** and the **structures have been tuned** using the local reflection coefficient technique[1],[2]

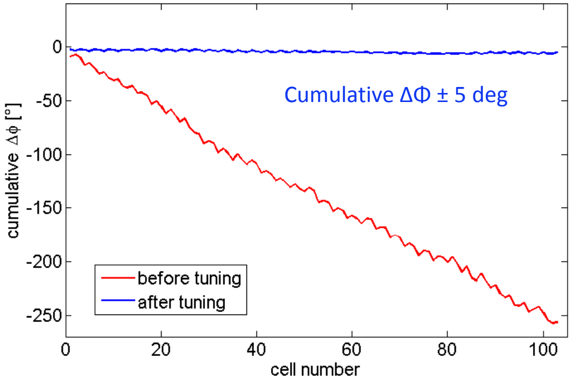










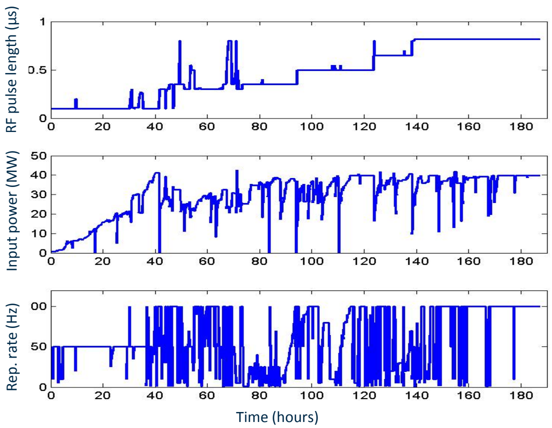


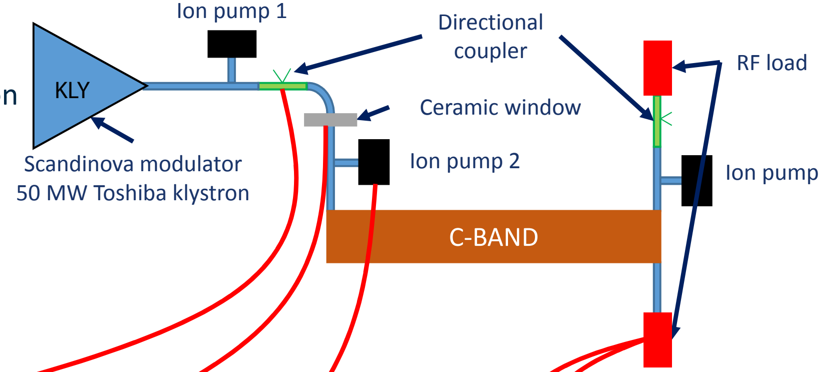
[1] J. Shi et al., Proc. of LINAC 2010, Tsukuba, Japan 2010

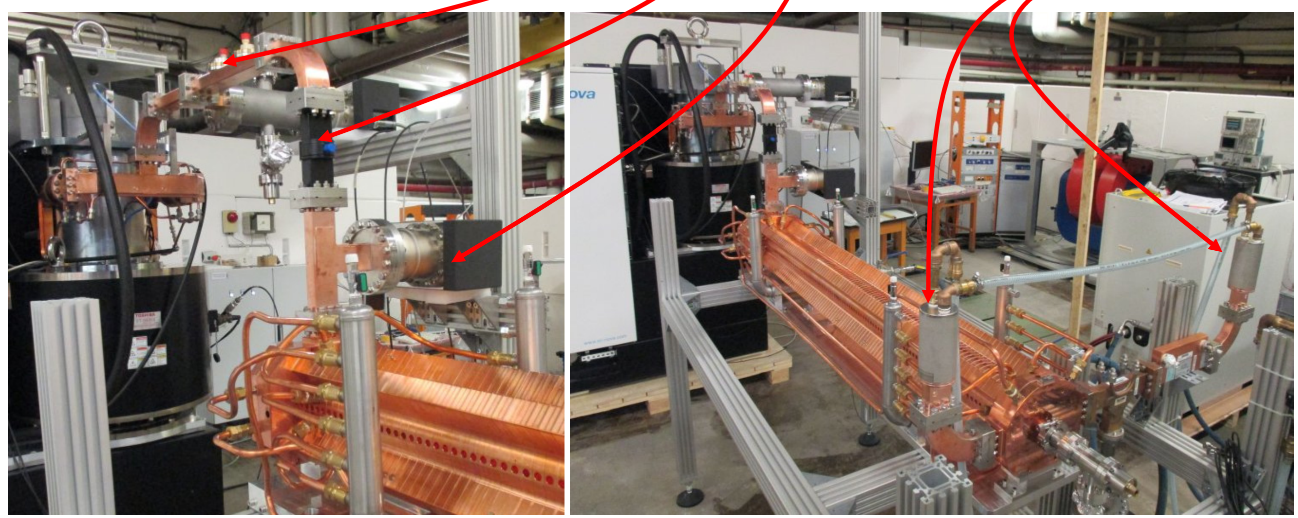
[2] D. Alesini et al., JINST 8 P10010 2013

C-band structures: high power tests at Bonn Uni.

- High power RF tests have been performed at the Bonn University under Research Instruments responsibility
- The RF power unit was the ELI-NP one: Scandinova modulator + 50 MW klystron
- The **forward/reflected power signals** at the input coupler and output coupler were measured using peak detectors acquired by an oscilloscope
- The structure took about **190 hours to reach** the target parameters: **40 MW** input power at **100 Hz** repetition rate and **820 ns** pulse width
- The HV interlock conditions were:
  - ion pumps pressure >1x10^{-7} mbar
  - VSWR at the klystron input exceeding 1.2







ELI-NP-GBS LLRF system

» “Libera LLRF” developed and manufactured by Instrumentation Technologies

» 13 modules (3 S-band, 10 C-band), each power unit independently driven by a single LLRF system

» **Temperature stabilized front-end** (long-term drifts compensation, **<100 fs** in normal operating conditions (24 ± 2) °C

» Pulse by pulse amplitude and phase feedback with arbitrary pulse shaping (e.g. to compensate beam loading in C-band structures)

» Required resolutions: amplitude **< 0.1% rms**, phase added jitter **< 10 fs (S-band < 0.01 deg; C-band < 0.02 deg)**

FRONT-END

- 8 RF input per module
- 8x16 bit ADCs (119 MS/s)
- VIRTEX5 FPGA
- BW: 5 MHz

BACK-END

- 1 RF output
- BW: 16 MHz
- VIRTEX5 FPGA

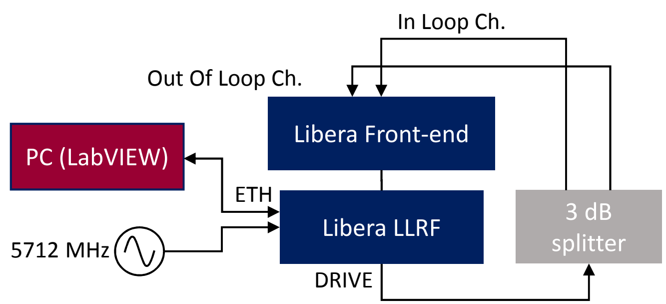
TIMING BOARD

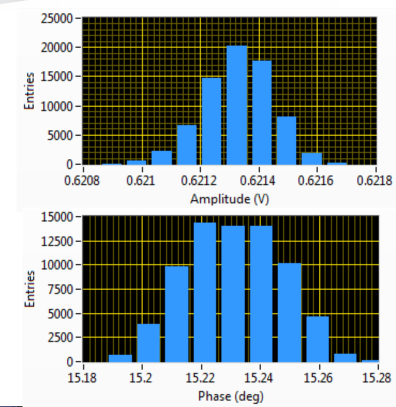
- Sampling clock: 119 MHz, 16 bit
- IF freq: RF/64 or RF/128 = 44.625 MHz
- Low jitter LO gen. @ RF + 44.625 MHz
- Interlock IN/OUT

Performance tests at INFN-LNF:

2 hours of continuous data acquisition **(>70000 shots)** without thermal conditioning on a C-band module, out of loop amplitude and phase resolution have been measured:

- Amplitude rms = **0.019%**
- Phase rms = **0.013 deg** (**< 8 fs** added jitter @ 5712 MHz)



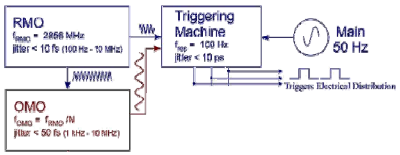


Piersanti et al. “The RF system of the ELI-NP gamma beam source”, in Proc. IPAC16 MOPMW006
Piersanti et al. “Review of the ELI-NP-GBS LLRF and synchronization systems”, in Proc. IPAC18 WEPAL010

ELI-NP-GBS synchronization system

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Synchronization system requirement: relative arrival time jitter at the IP between e⁻ bunches and laser **< 500 fs**



RF reference generation

- Reference Master Oscillator (RMO) **Laurin A. G.** : µ-wave crystal oscillator with ultra-low phase noise

(2856 MHz integrated jitter <60 fs 10 Hz - 10 MHz)

- Optical Master Oscillator (OMO) **Menlo Systems**: mode-locked low noise laser oscillator

(Er-doped fiber at standard telecommunication wavelength 1560 nm)

RF reference distribution **(Menlo Systems)**

- Directly seeded clients: Photocathode laser (free space second harmonic of OMO - 780 nm)
- Length stabilized links: 2 IP laser oscillators + 2 RF extractors
- Non-stabilized links: 2 recirculator path length regulation (LBC synchronization system)

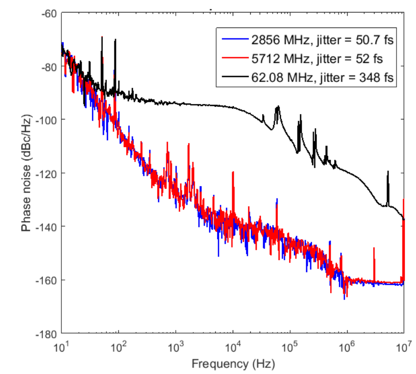
Client locking **(Menlo Systems)**

- Fully optical: optical cross correlators
- Electro-optical: RF extractors (BOM-PD)

Synchro system main specifications

Parameter	Spec. Value
Pulse width at link end	< 200 fs
Fiber laser wavelength	1560 nm
Free space wavelength (SHG output)	780 nm
Pulse rep. rate (RF/46)	62.08 MHz
Integrated timing jitter (1 kHz-10 MHz)	< 5 fs
Amplitude stability (rms)	< 0.1 %
Phase jitter rel. to ref. (rms 0.1 Hz-1 kHz)	< 10 fs

ELI-NP-GBS RMO phase noise measurement at INFN-LNF



Piersanti et al. “Review of the ELI-NP-GBS LLRF and synchronization systems”, in Proc. IPAC18 WEPAL010

ELI-NP-GBS synchronization system

Synchronization system requirement: relative arrival time jitter at the IP between e⁻ bunches and laser **< 500 fs**

RF reference generation

» Reference Master Oscillator (RMO) **Laurin A. G.** : µ-wave crystal oscillator with ultra-low phase noise (2856 MHz integrated jitter <60 fs 10 Hz - 10 MHz)

» Optical Master Oscillator (OMO) **Menlo Systems**: mode-locked low noise laser oscillator (Er-doped fiber at standard telecommunication wavelength 1560 nm)

RF reference distribution **(Menlo Systems)**

» Directly seeded clients: Photocathode laser (free space second harmonic of OMO - 780 nm)

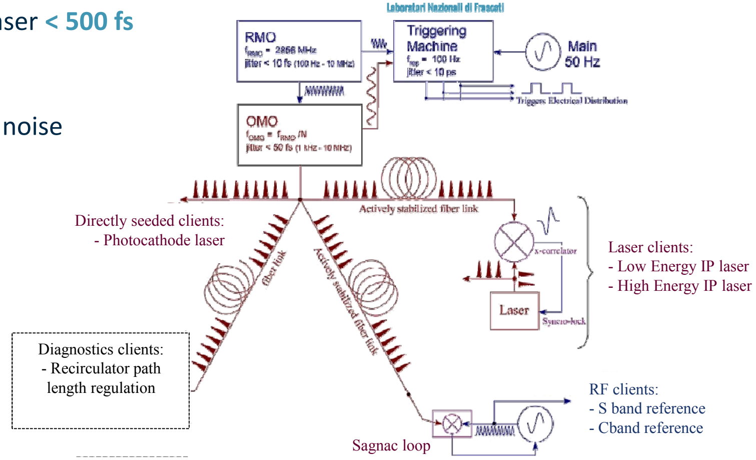
» Active length stabilization: 2 IP laser oscillators + 2 RF extractors

» Non-stabilized links: 2 recirculator path length regulation (LBC synchronization system)

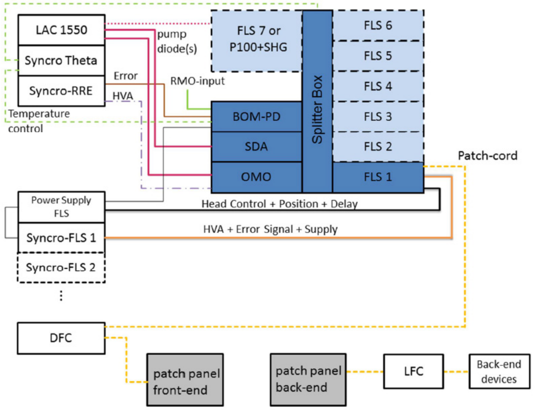
Client locking **(Menlo Systems)**

» Fully optical: optical cross correlators

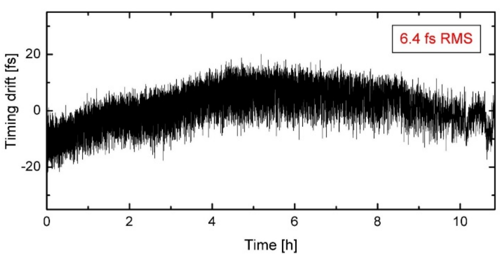
» Electro-optical: RF extractors (BOM-PD + VCO)



Menlo Timing Distribution System



Long term timing drift of 200 m fiber link



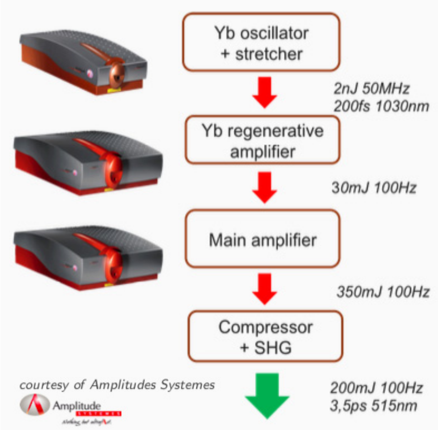
Piersanti et al. "Review of the ELI-NP-GBS LLRF and synchronization systems", in Proc. IPAC18 WEPAL010

Laser Beam Circulator (LBC) overview

- The IP laser is a high power pico-second laser (Amplitude) based on the **Chirped Pulse Amplification** (CPA) scheme: **E = 200 mJ (400 mJ at HE IP), rep. rate = 100 Hz, t = 3.5 ps, λ = 515 nm**
- Since we have 32 electron bunches in each pulse, to enhance the average power of the laser beam at the IP, a passive multi-pass optical device has been designed: **Laser Beam Circulator**

LBC must fulfill the following constraints:

- Temporal:
  - laser pulse **round-trip period** must be tightly matched to the **bunch repetition frequency** (62.08 MHz, 16.1 ns)
  - adjustable round-trip length to individually synchronize the laser pulse to the electron bunches
- Spatial:
  - stable and small enough (**< 30 μm**) laser beam waist to optimize the gamma ray flux
- Gamma Beam:
  - **fixed collision angle ϕ** between electron beam and photons to preserve gamma ray spectral width
  - polarization transport



LBC nominal parameters

Parameters	values
ω_0 [μm]	28.3
ϕ [$^\circ$]	8
F_{max} [J/cm^2]	0.4
ν_{RF} [MHz]	2856
D_{MPS} [mm]	40.41
θ [$^\circ$]	23.78
N_{pass}	32
L_{RF}	$46 \times c/\nu_{RF}$
D [mm]	2377.31
R_C [mm]	166.24
w_1 [mm]	8.25
Φ_M [mm]	29.7

"Dragon shaped" Laser Beam Circulator

» Designed by LAL/CNRS[1], industrial collaboration with ALSYOM (opto-mechanical company) for manufacturing

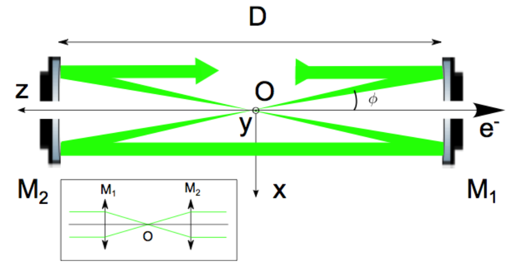
» Two high-quality parabolic mirrors (M1, M2) arranged in confocal geometry

» **Crossing angle ϕ must be kept constant**, the laser-electron beam interaction plane must rotate if more than 2 recirculations are foreseen: **mirror pair system (MPS)**

» MPS only changes the interaction plane, **laser direction is conserved**

» Laser injected from mirror M0 (2 degrees of freedom), M1 fixed, M2 has 5 degrees of freedom

» Laser path length can be adjusted (**electron-photon synchronization**) rotating the MPS arount its axis (Γ_i)



Full tolerance study of the LBC has been realized[1] (e.g. mirror pair optical surfaces alignment, parabola focal length, optical surfaces error, positioning and motorization, input laser beam parameters, temperature etc.)

[1] K. Dupraz et al. Phys. Rev. ST Accel. Beams 17, 033501, 2014

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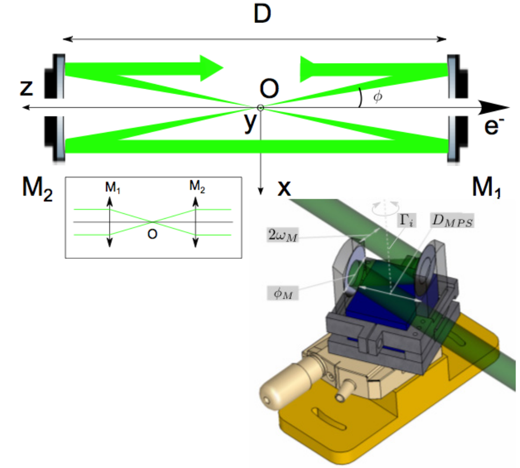

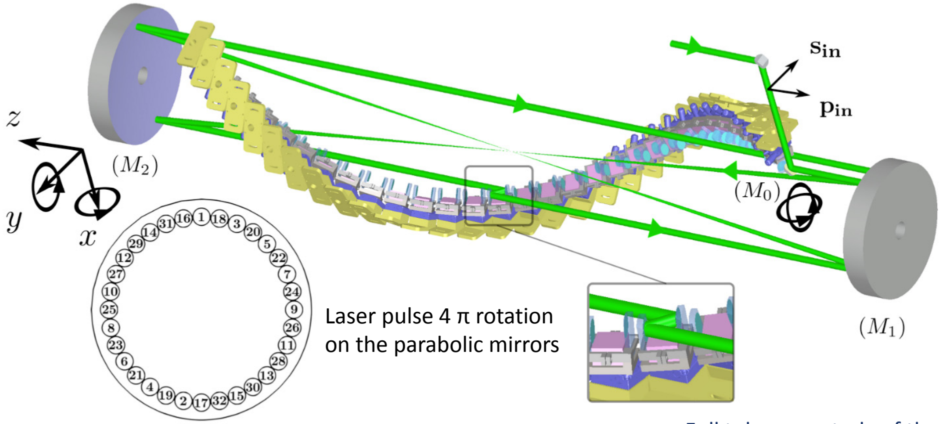

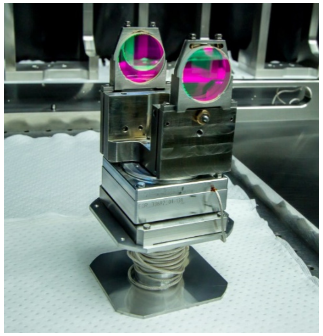

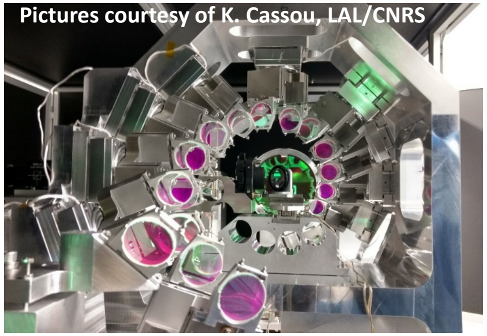

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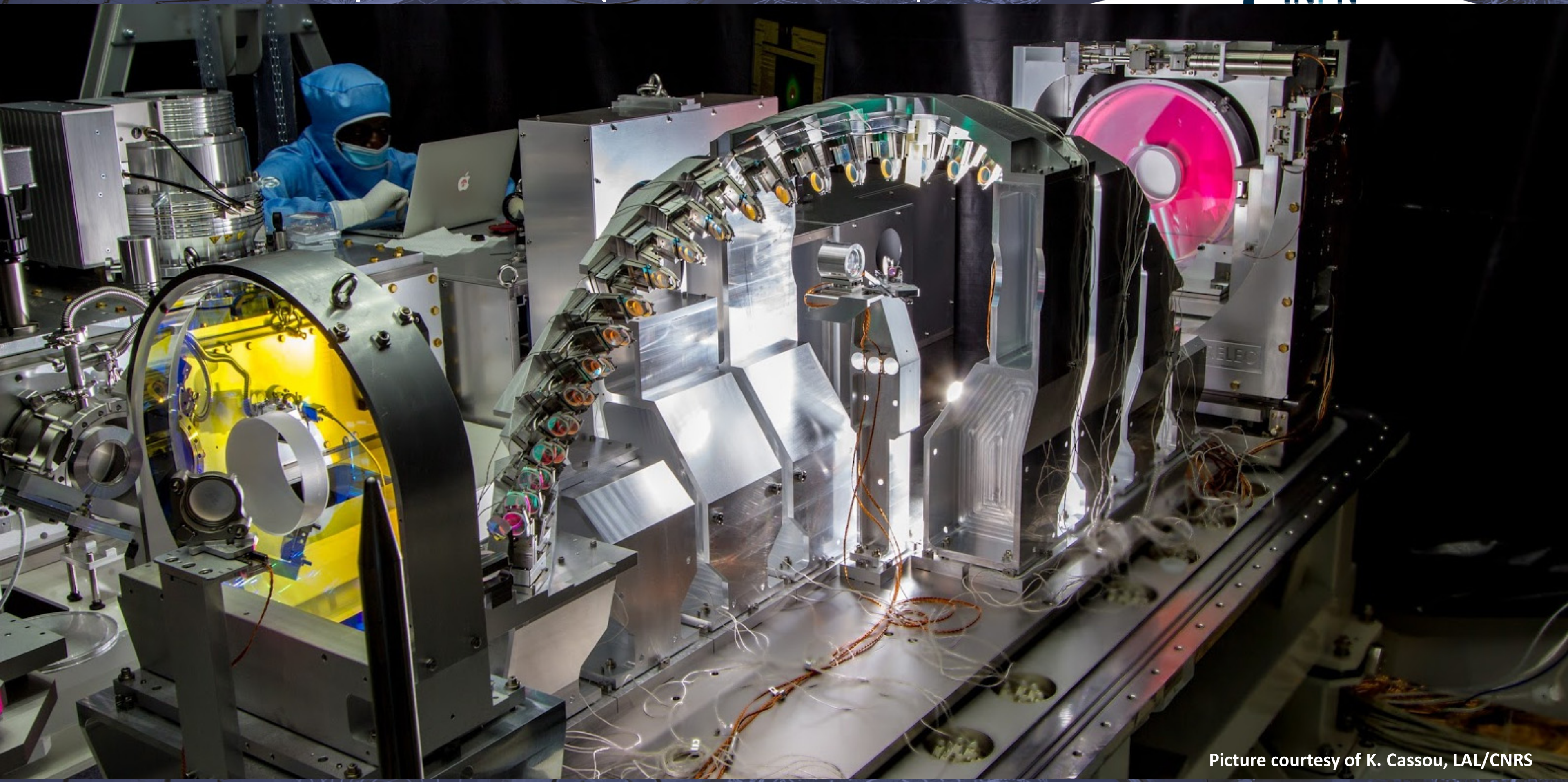
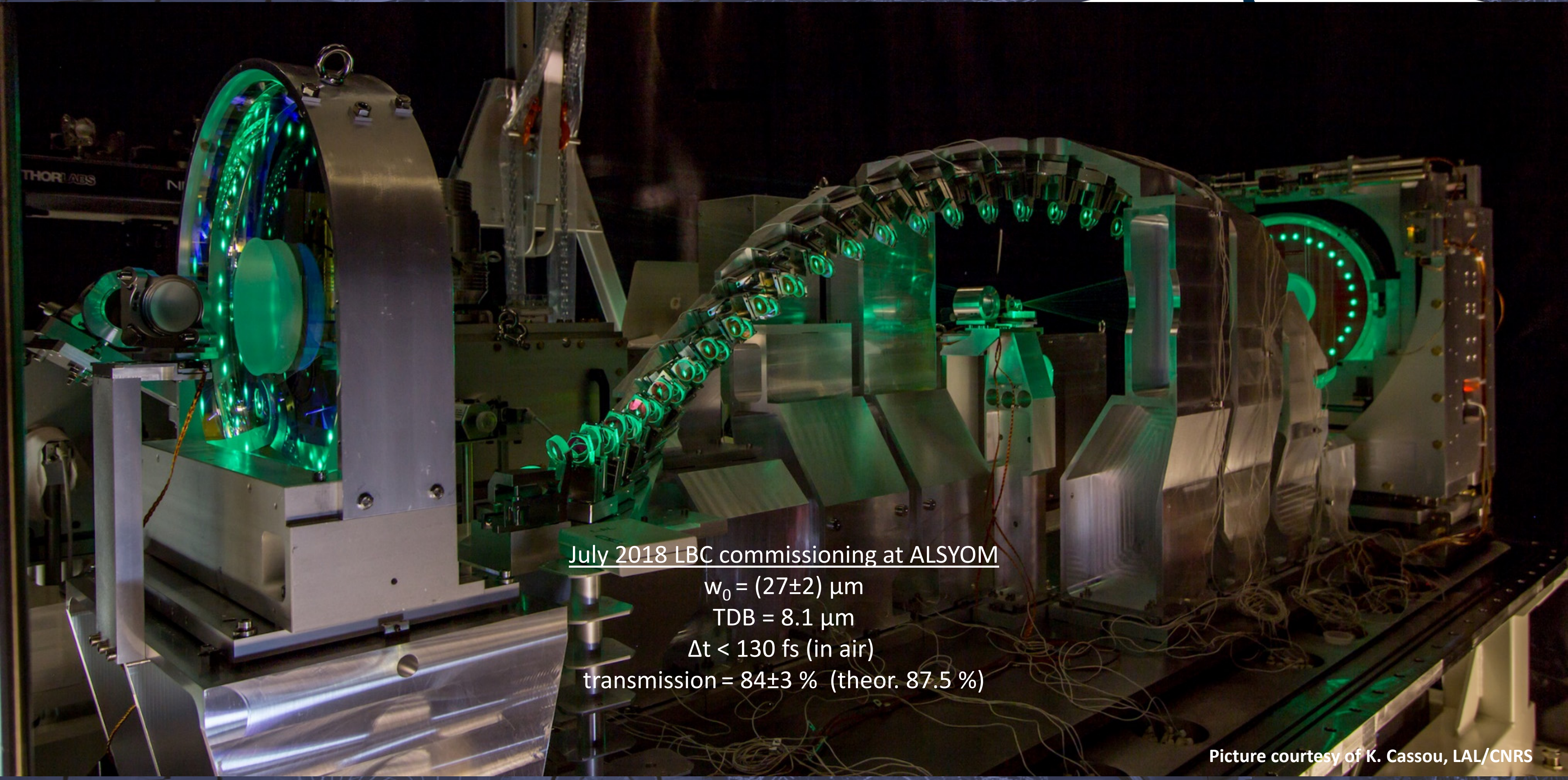
LBC assembly at ALSYOM (ISO 5 cleanroom)



Picture courtesy of K. Cassou, LAL/CNRS

LBC spatial alignment test at ALSYOM



<u>July 2018 LBC commissioning at ALSYOM</u>

w_0 = (27±2) μm

TDB = 8.1 μm

Δt < 130 fs (in air)

transmission = 84±3 % (theor. 87.5 %)

Picture courtesy of K. Cassou, LAL/CNRS

Picture courtesy of K. Cassou, LAL/CNRS

Thank you for your attention

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