EUROPEAN UNION

GOVERNMENT OF ROMANIA

Structural Instruments
2007-2013

Sectoral Operational Programme
„Increase of Economic Competitiveness”
“Investments for Your Future”

eli Nuclear Physics

Extreme Light Infrastructure – Nuclear Physics (ELI–NP)

IFIN-HH

Project co–financed by the European Regional Development Fund

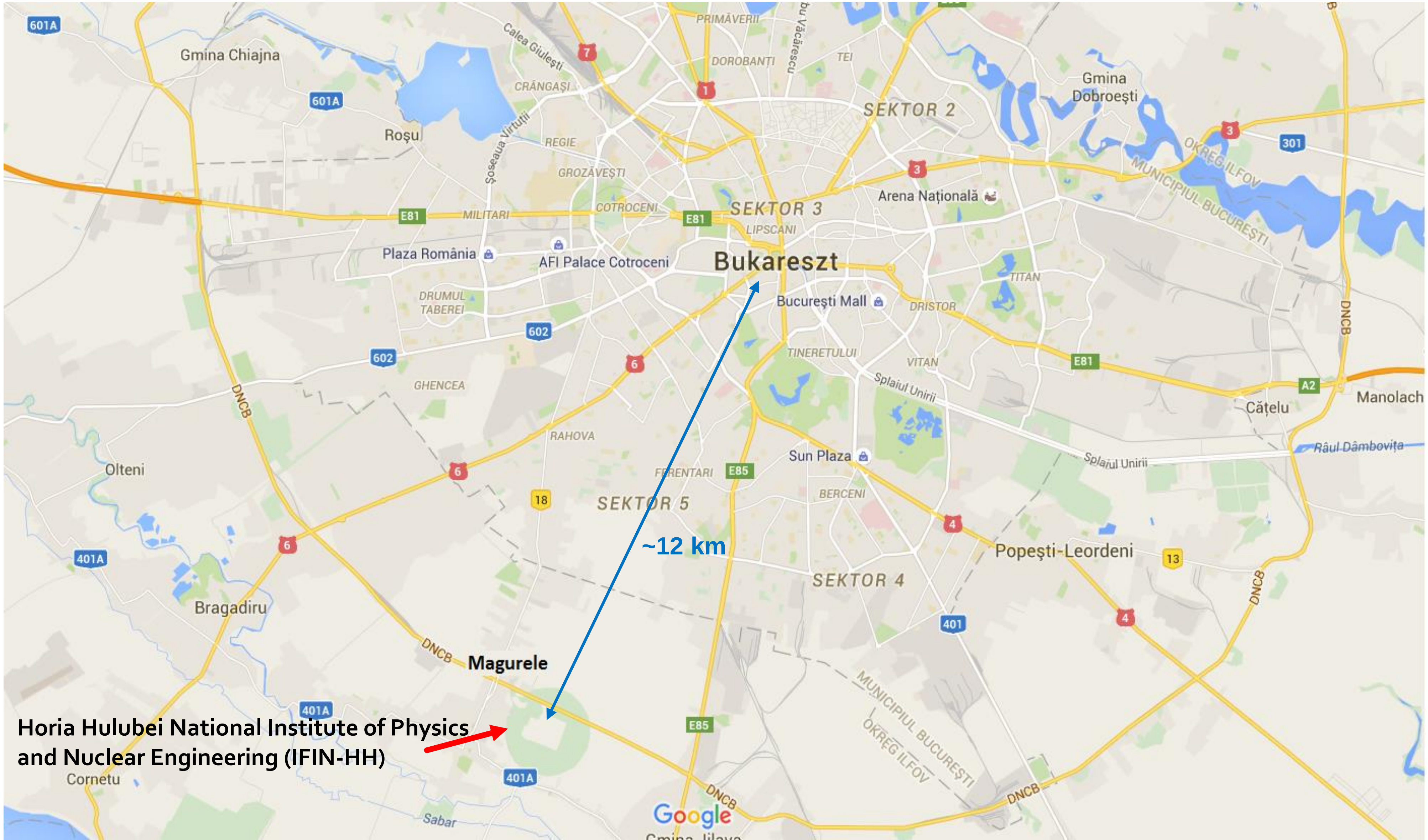
ELI-NP GAMMA BEAM SYSTEM:

NEW FACILITY FOR NUCLEAR PHYSICS RESEARCH

PIOTR TRACZ
FOR THE ELI-NP TEAM

19th ESLS-RF Workshop
October 1st , 2015 Lund, Sweden

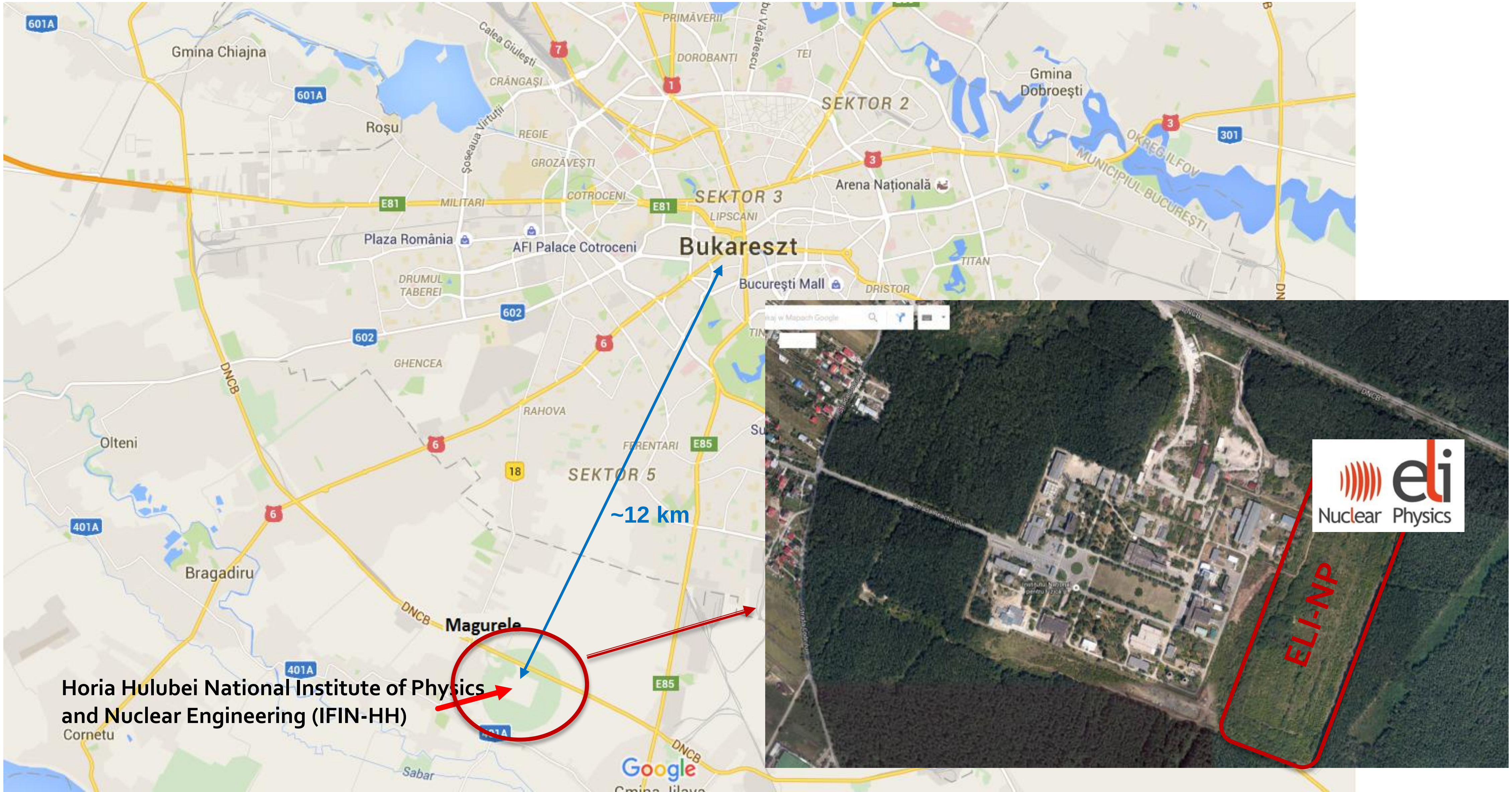
ELI–NP project


~12 km

Magurele

Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH)

ELI–NP project

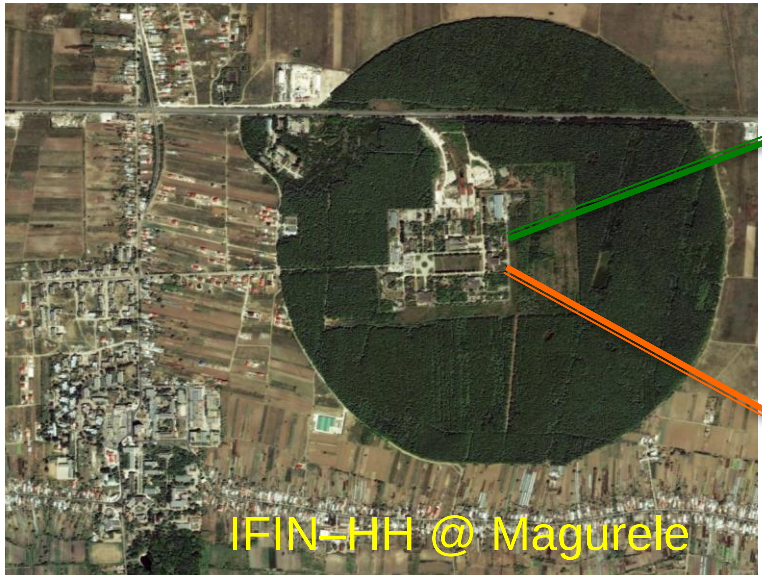


~12 km

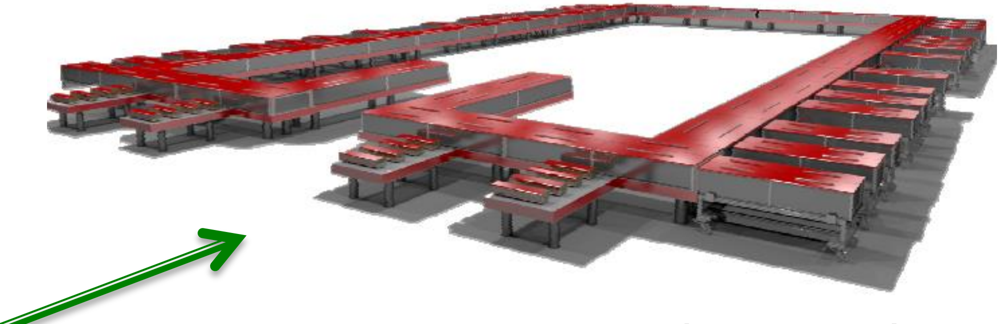
Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH)

ELI–NP project

Two major systems



High Power Laser System

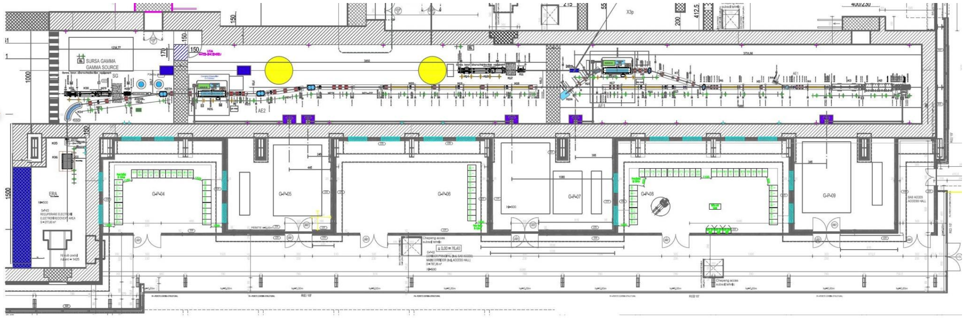


Thales Optronique

6 output lines 820nm :

- 2 x **0.1 PW**
- 2 x **1 PW**
- 2 x **10 PW**

High Brilliance Gamma Beam System



EuroGammaS

Gamma Beam System at ELI–NP

Advance Source of Gamma-ray photons

γ photons with E_γ up to 18 MeV with a narrow bandwidth (≤0.5%) and high spectral density (10^4 ph/sec/eV).

Provider – EuroGammaS Association

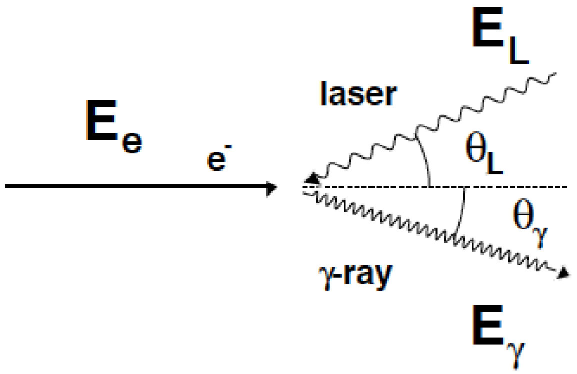
Academic Institutions
INFN (Italy), Sapienza University (Italy), CNRS (France)
Industrial Partners
ACP Systems (France), ALSYOM (France),
COMEB (Italy), ScandiNova Systems (Sweden)

and several Sub-Contractors:
Alba (Spain), STFC (UK)
Amplitude Systems (France), Amplitude Technology (France), iTech (Slovenia), Cosylab (Slovenia), Danfysik (Denmark), M&W Group (Italy), Menlo Systems (Germany), RI (Germany),


19/03/2014

Gamma Beam System – Basic Concept

Compton backscattering involves the collision of a low-energy (eV) photons with high-energy (hundreds of MeV) – ultra relativistic ($\gamma \gg 1$) – electrons.



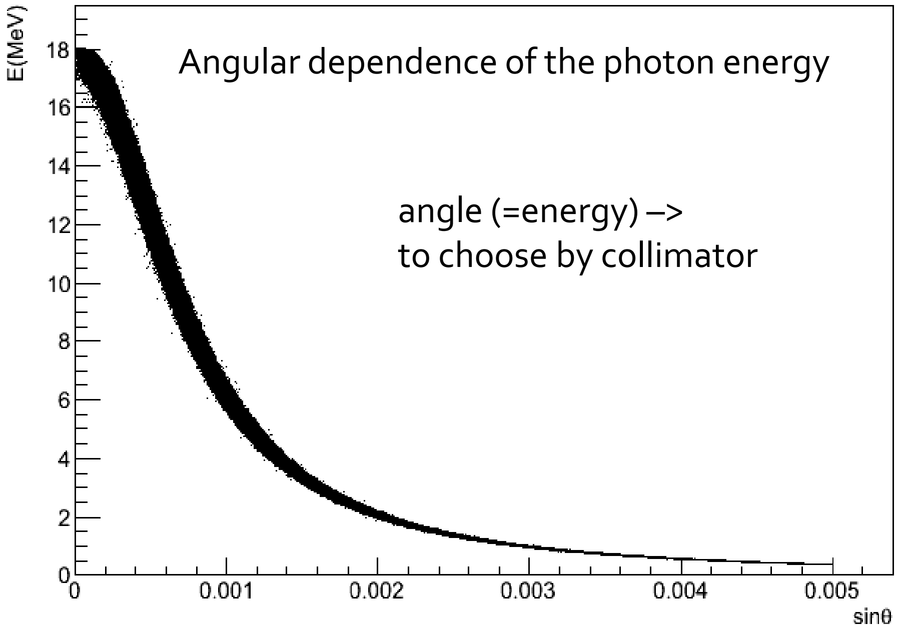
- $E_L \sim 2.4eV$ (515nm - green)
  - $E_e \sim 300MeV$ ⇒ $E_\gamma < 3.5\ MeV$ (Low Energy Branch)
  - $E_e \sim 720\ MeV$ ⇒ $E_\gamma \leq 18\ MeV$ (High Energy Branch)

Low cross section (~ 10^{-25} cm²)

→ need of high density of electron and photon beams

ELI-NP-GBS solution: Compton back scattering of laser pulses on relativistic electron bunches

- high intensity, small emittance, small energy spread, high e⁻ beam charge
- very brilliant high rep. rate intense laser
- small collision volume

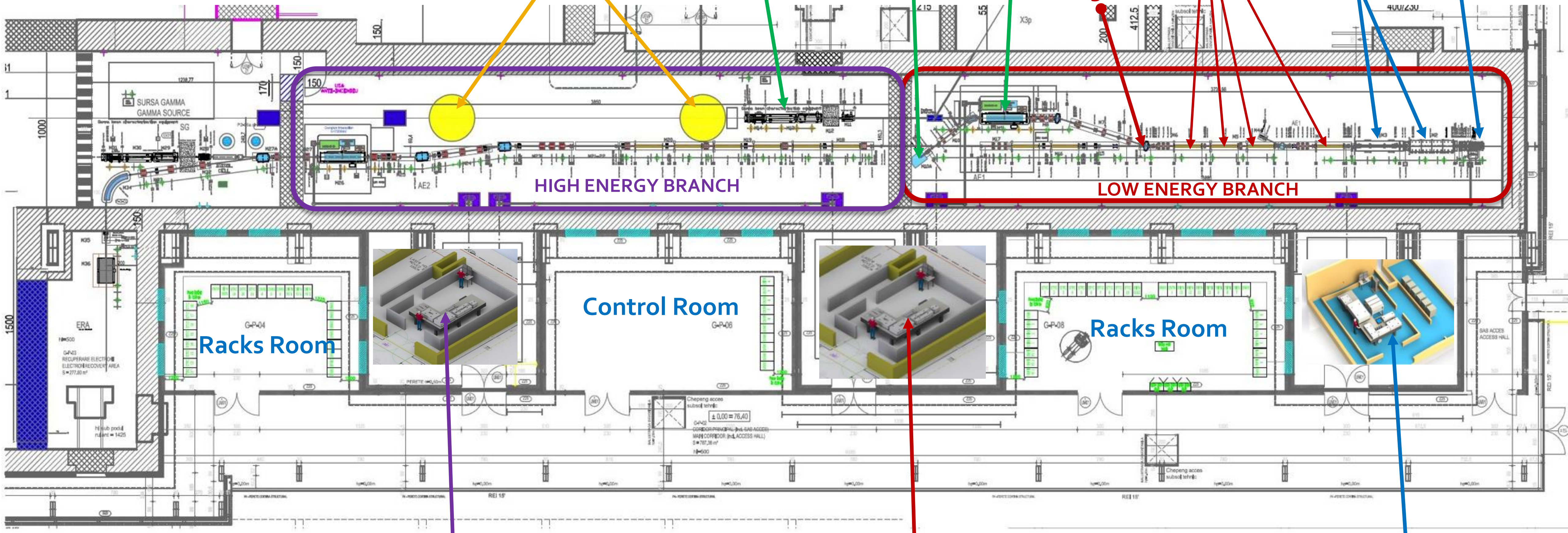


Angular dependence of the photon energy

angle (=energy) –>
to choose by collimator

Low Energy Linac

$(E_e \approx 300MeV \rightarrow E_\gamma \approx 3.5MeV)$



end stations experiments

γ beam Collimator & Diagnostics

Interaction Point Low Energy

e^- beam dump

Dipole magnet

e^- RF linac 4x C-band TW structures

2x S-band TW structures

Photo-cathode RF Gun

Interaction Laser High Energy

Interaction Laser Low Energy

Photo-cathode Laser

High Energy Linac
$(E_e \approx 720MeV \rightarrow E_\gamma \approx 18MeV)$

γ beam
Collimator & Diagnostics

e$^-$ beam dump

Interaction Point
High Energy

e$^-$ RF linac
8 + 4 x C-band TW structure

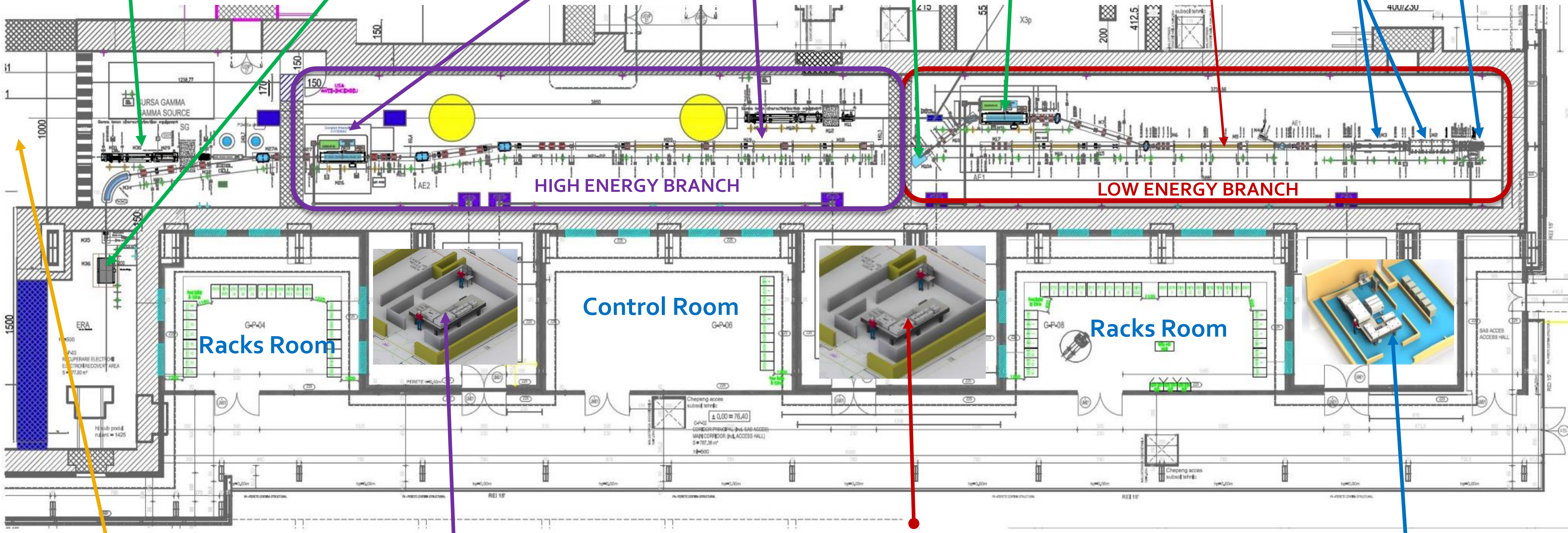
Interaction Point
Low Energy

e$^-$ beam dump

e$^-$ RF linac
4x C-band TW structures

2x S-band
TW structures

Photo-cathode RF Gun



end stations
experiments

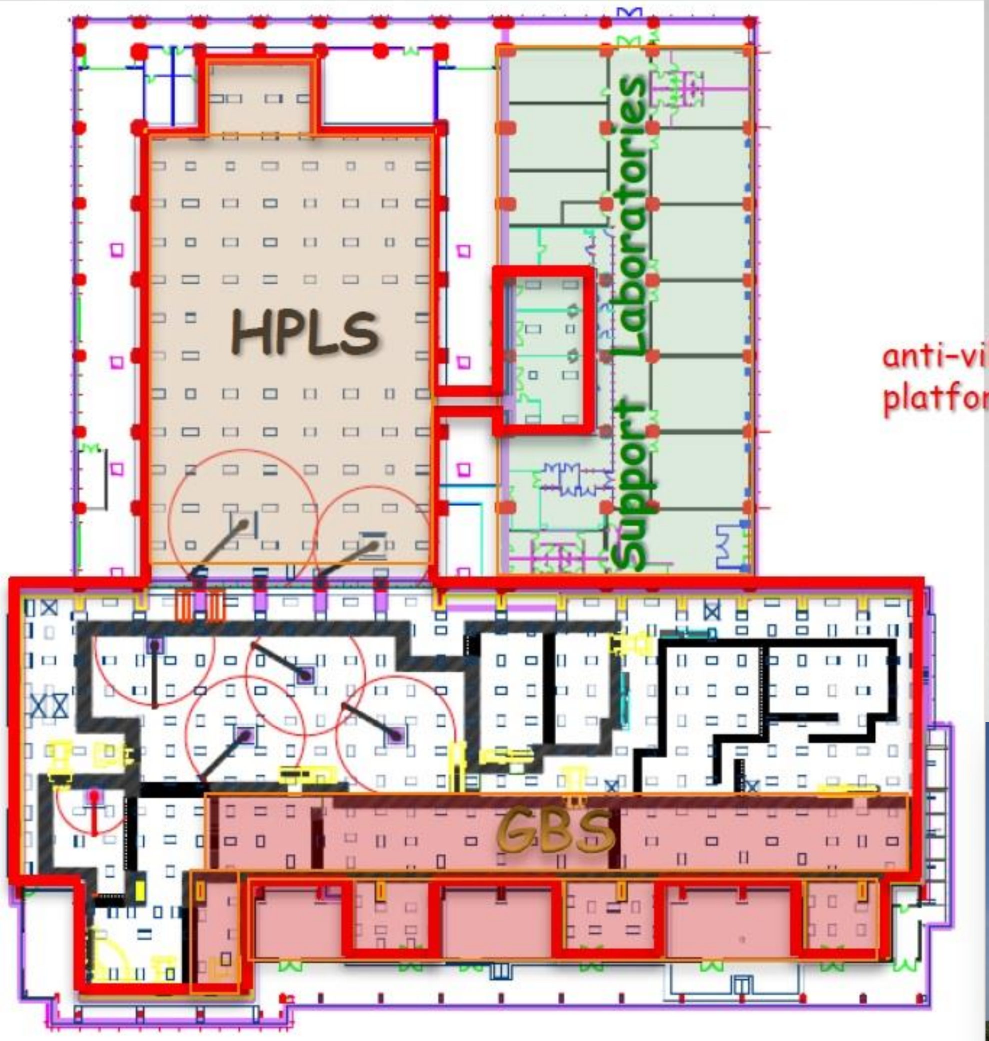
Interaction Laser
High Energy

Interaction Laser
Low Energy

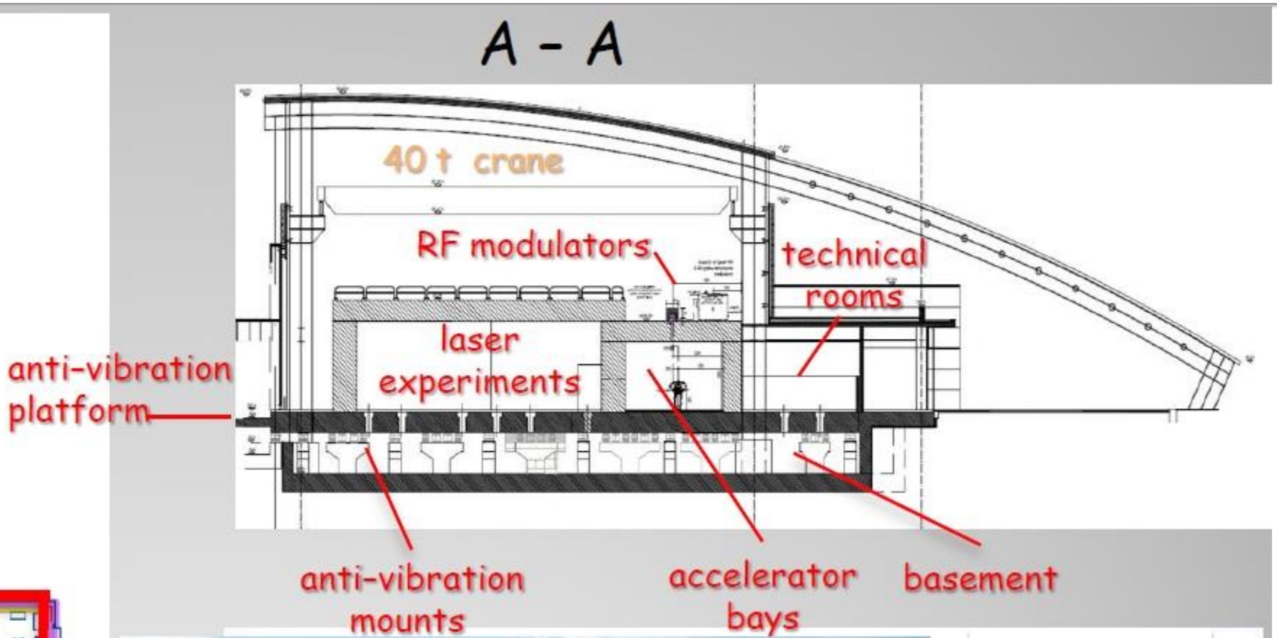
Photo-cathode Laser

Master Clock synchronization @ < 1ps

ELI–NP Facility Concept



ELI -NP Main Experimental Building ~ 15,000 m^2



±1μm @ < 10 Hz

July 2015

ELI-NP Gamma Beam System

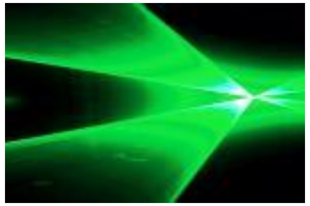
The Gamma Beam System is based on **warm RF linac** operated at **C-band with S-band photo-injector**.

GBS - γ beam specification

Photon Energy	up to 18 MeV
Spectral Density	10^4 ph/sec/eV
Bandwidth (rms)	≤ 0.5%
# photons / shot within FWHM bdw.	$\leq 2.6 \cdot 10^5$
# photons/sec within FWHM bdw.	$\leq 8.3 \cdot 10^8$
Source rms size	10 ÷ 30 μm
Source rms divergence	25 ÷ 200 μrad
Peak brilliance (N_{ph}/sec mm² mrad² 0.1%)	$10^{20} \div 10^{23}$
Pulse length (rms)	0.7 ÷ 1.5 ps
Linear polarization	> 95%
Repetition Rate	100 Hz
Source position transverse jitter	< 5 μm
Energy jitter pulse-to-pulse	< 0.2 %

Electron beam parameters at Interaction Points

Energy [MeV]	up to 720
Bunch charge	250 pC
Bunch length	1 ps
Norm. transverse emittance	0.4 mm·mrad
Bunch energy spread	0.04 ÷ 0.1 %
Focal spot size	~ 20 μm
Number of bunches	32
Bunch-to-bunch distance	16 ns
Energy variation along macro-bunch	0.1%
Energy jitter shot to shot	0.1%
Time arrival jitter	< 0.5 ps
Pointing jitter	1 μm
Bunch rep rate	100 Hz



Ti:sapphire laser for photocathode RF gun with ~10 ps pulse duration in UV range, 100Hz.

Yb:YAG lasers for Interaction Points with 3.5 ps pulse duration at 515 nm, 100Hz.

GBS Linac

High quality gamma beam -> requires high quality electron beam

- Low emittance, low energy spread, and high beam charge
- To increase the gamma flux we need to increase the number of collision per second.

100 Hz repetition rate

Multi bunch

- Dumping of HOM dipole modes in RF structures to avoid BBU (beam break-up) instabilities
- Compensation of beam loading effects
- Accurate thermal design (high average dissipate power)

-> Waveguide dumping system with silicon-carbide (SiC) RF loads

-> amplitude modulation of the input RF power along the e^- beam train to reduce the energy spread

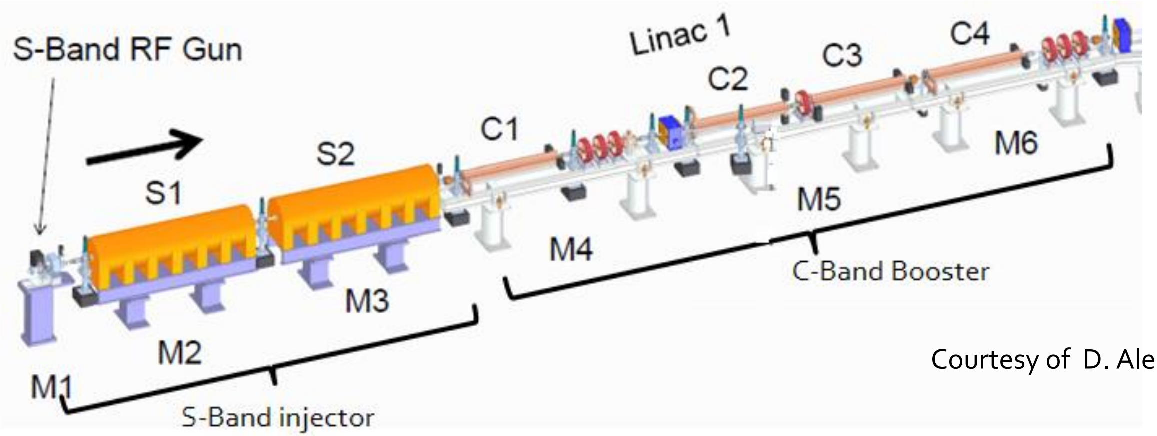
-> each structure has 14 water cooling channels for temperature stabilization; water flow of 66 litre /mi

Multi-bunch mode -> **wakefields** (both longitudinal and transverse components) -> affect the longitudinal and transverse beam dynamics.

Longitudinal components -> **beam loading effects ->** increase of energy spread and decrease of accelerating field gradient in the structure.

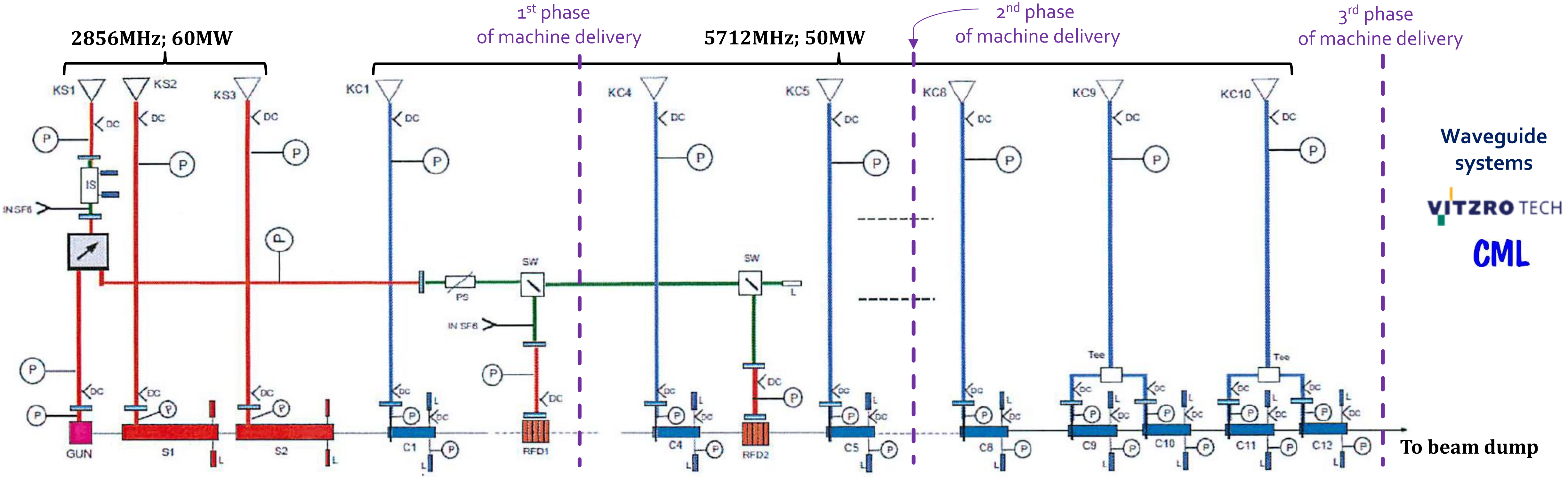
Transverse components -> drive instability along the train generating the **HOM dipole modes**.

compact system -> **High gradient** -> **C-band linac combined with S-band Injector**



Courtesy of D. Alesini

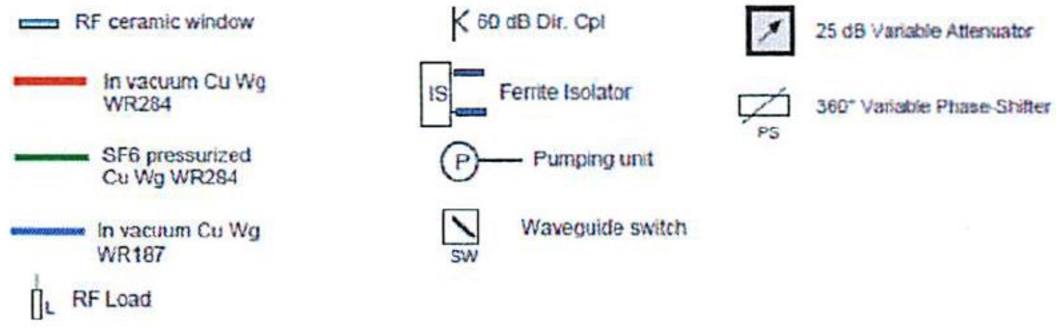
RF power distribution



Waveguide systems

VITZRO TECH

CML



KLYSTRON MODULATORS	Electron Gun	Injector	Booster
Frequency [GHz]	2.856	2.856	5.712
Output Peak Power [MW]	45	60	50
Pulse length [µs]	5	1,5	0,5
Rep. Rate [Hz]	100	100	100

ScandiNova

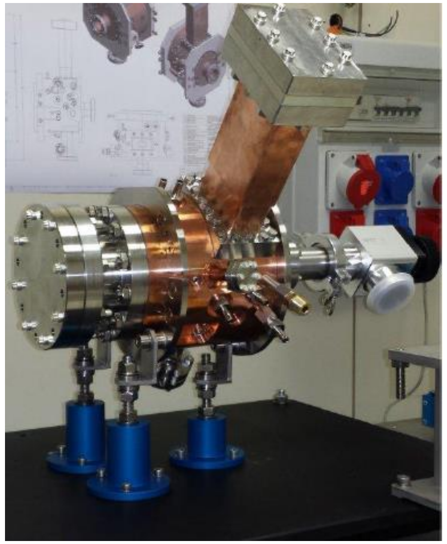
TOSHIBA
Leading Innovation

Electron Gun

Gun sector – module 1

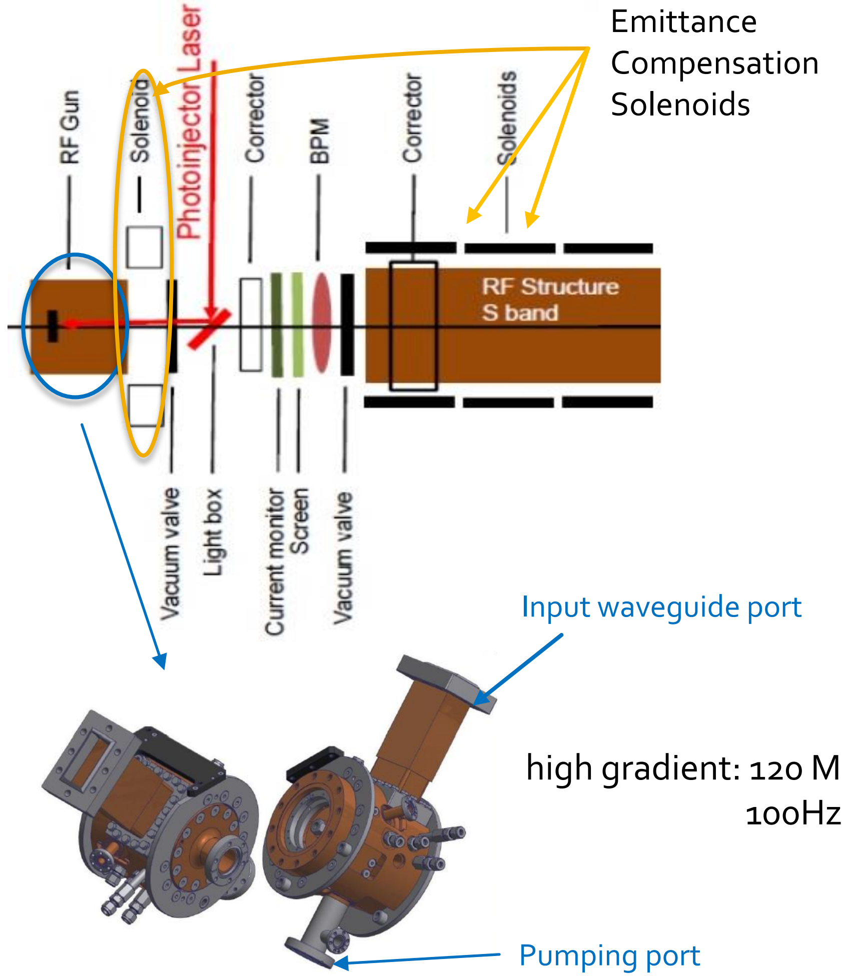
Laser-driven photocathode
1.6-cell standing-wave RF cavity, working in S-band at 2.856 GHz.

Photocathode – (oxygen-free high thermal conductivity) OFHC Copper



Ti:Sa laser –

output: UV range (266nm), 10ps, 150µJ/pulse, sequence of trains made of 32 pulses separated by 16ns @ 100Hz repetition rate.



high gradient: 120 MV/m; 100Hz

Photo-gun laser parameters at cathode:

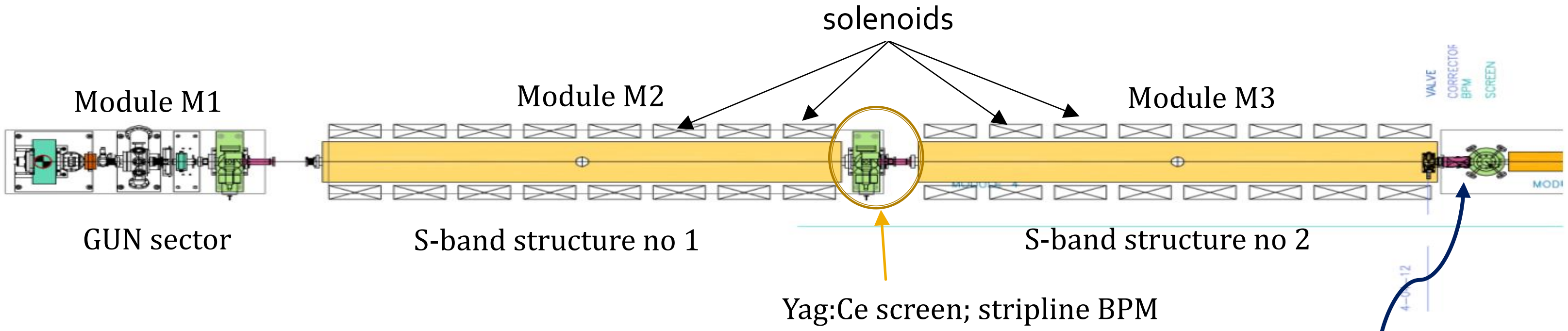
Laser pulse length (flat-top)	10 [ps]
Laser pulse rise/fall time FWHM	0,7 [ps]
Energy per pulse at 266 nm	150µJ
Laser spot size RMS radius on cathode	100-400 [µm]
Laser pulse energy jitter	2%
Time arrival jitter	<0.5 [ps]
Pointing jitter	<20 [µm]

Electron beam parameters:

Beam energy	5.7 [MeV]
Bunch charge	250 [pC]
Bunch length	~10 [ps]

S-band injector

S-band injector – 2 x Travelling Wave accelerating structures



solenoids

Module M1

Module M2

Module M3

GUN sector

S-band structure no 1

S-band structure no 2

Yag:Ce screen; stripline BPM

manufacturer: RI Research Instruments GmbH

e^- beam energy: ~100 MeV
bunch length: ~1 ps (~300μm)

Long bunch at the photo-cathode -> to control the emittance growth due to space charge effects.
S-band injector – reduction of the bunch length by the velocity bunching technique.

Dual-symmetric feeding structures – minimization of the multipole effects generated by asymmetric feeding.

Beam loading effects - compensated with modulation of input RF power.
No evidence of HOM dipole modes in experimental measurements.

S-band acc. structure parameters

Structure type	Constant gradient, TW
Working Frequency	2.856 [GHz]
Number Cells / Structure length	86 / 3m
Phase advance between cells	2π/3
Nominal RF input power / Average dissipated power	40 [MW] / ~3.5kW
Accelerating gradient	22 [MV/m]
Quality factor (Q)	13000
Shunt Impedance per unit length	55 [MΩ/m]
RF input pulse length	1.5 [μs]
Filling time	~850 [ns]

after LLRF tests sent to Frascati for modules assembly.

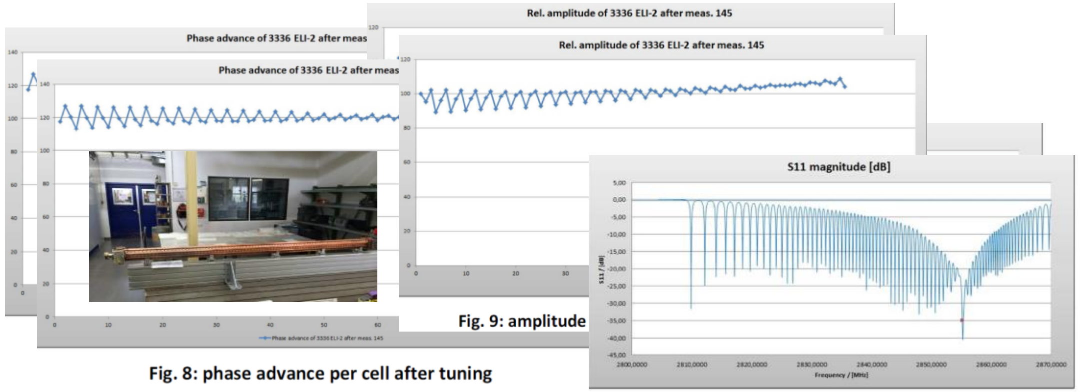


Fig. 8: phase advance per cell after tuning

Fig. 9: amplitude

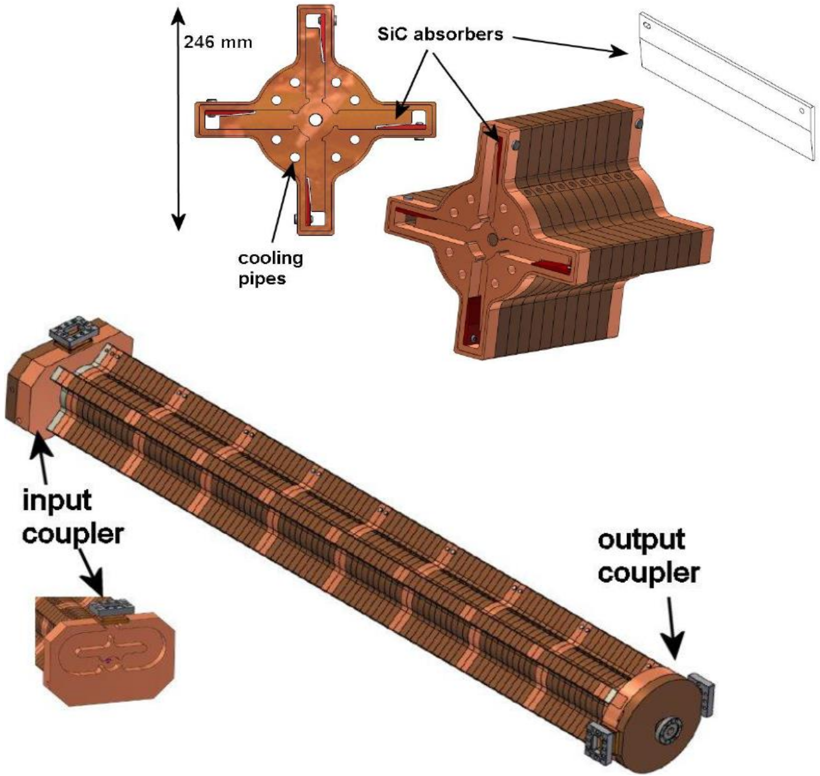
Fig. 10: reflection coefficient at the input port after tuning

C-band LINAC

C-band linac – 12 x TW acc. structures

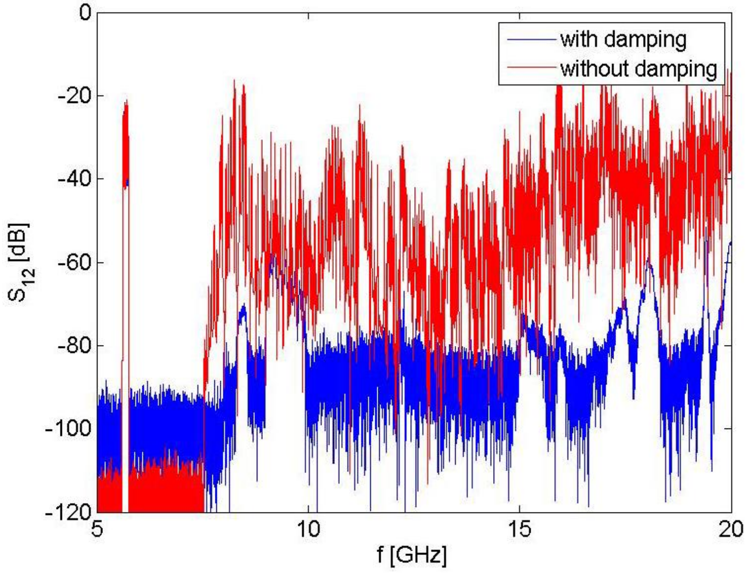
Effective damping of HOM dipoles modes

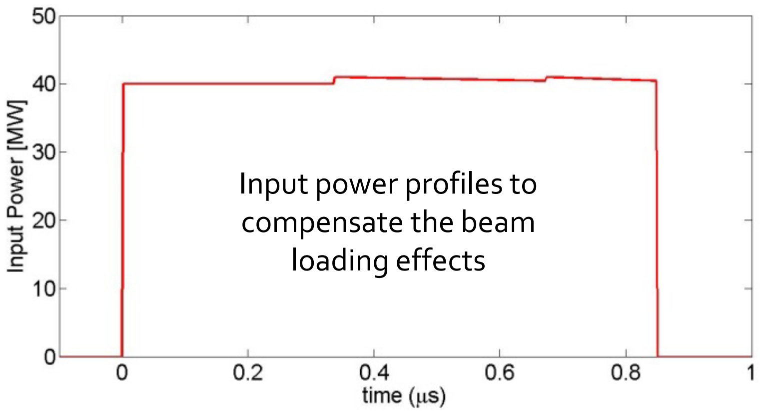
Waveguide dumping system - four waveguides in each cell -> excited dipole modes propagate and dissipate into RF loads.



Dual-symmetric feeding structures

Transmission Coefficient

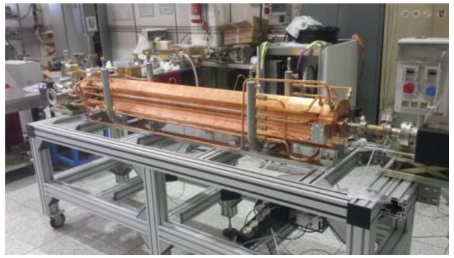




Input power profiles to compensate the beam loading effects

C-band acc. structure parameters

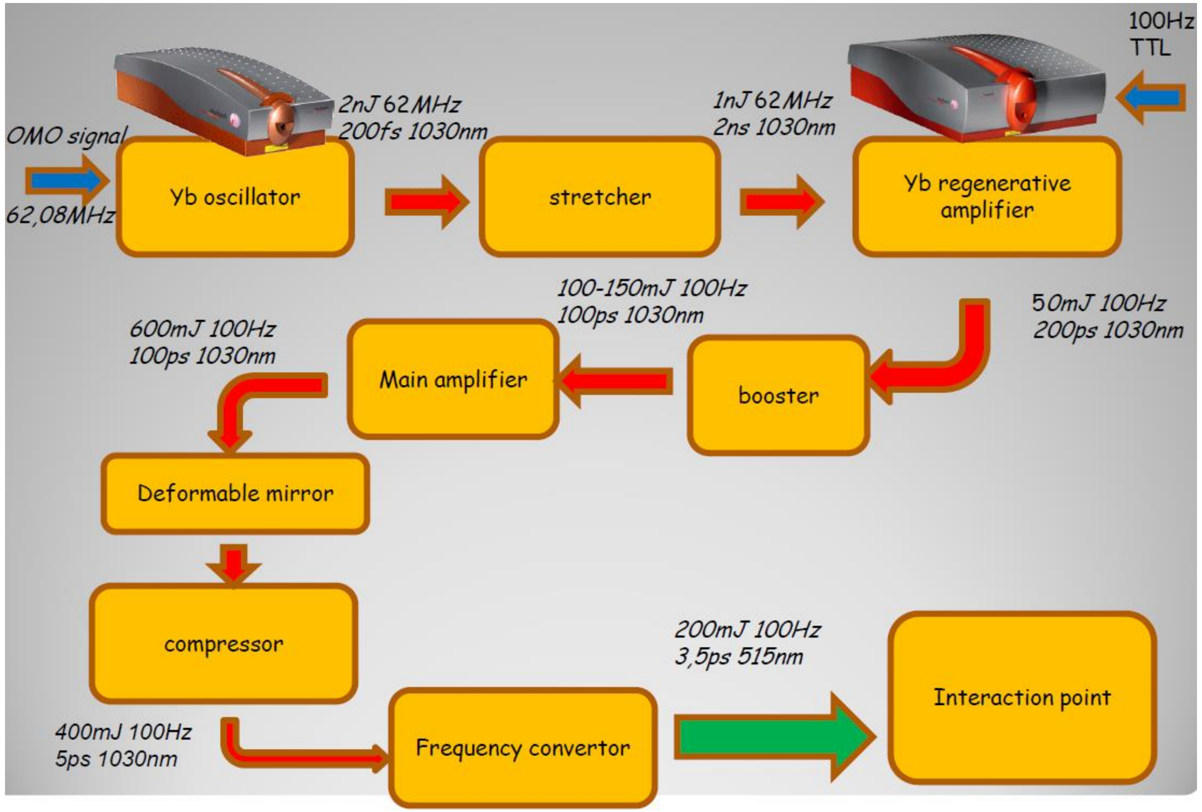
Structure type	Quasi-constant gradient, TW
Working Frequency	5.712 [GHz]
Number Cells / Structure length	102 + 1in + 1 out coupler / 1.8m
Phase advance between cells	2π/3
Nominal RF input power / Average dissipated power	40 [MW] / ~2.3kW
Average accelerating gradient	33 [MV/m]
Quality factor	8800
Shunt Impedance per unit length	74.5 [MΩ/m]
Max. RF input pulse length	0.8 [μs]
Filling time	310 [ns]
Working temperature	30 [°C]



D.Alesini et al., *“Design and RF Test of Damped C-band Accelerating Structures for the ELI-NP Linac”*
THPRI042, proceedings of IPAC2014, Dresden, Germany

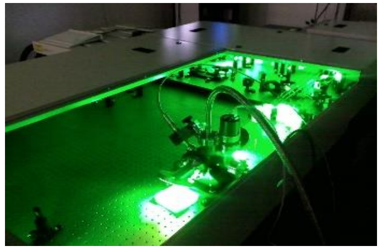
Interaction Points Lasers

Interaction Laser Architecture

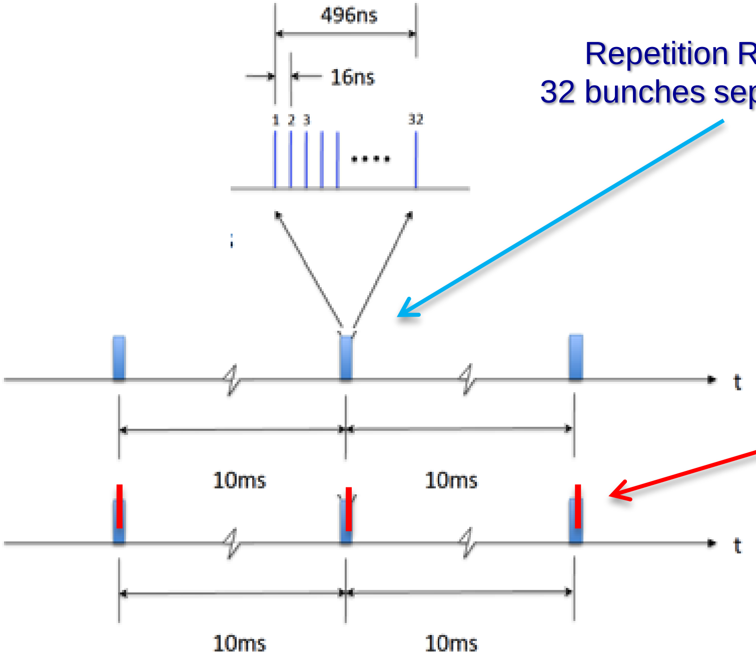


Interaction Lasers: cryo–cooled Yb:YAG

	Low Energy Interaction	High Energy Interaction
Pulse Energy [J]	0.2	2 x 0.2
Wavelength [nm]	515	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 external clock	< 1 ps	< 1ps
Pulse energy stability	1%	1%



Laser Recirculation at Interaction Points



Repetition Rate – 100 Hz
32 bunches separated by 16 ns

need

Laser pulse rep. rate – 100 Hz
→ ***laser recirculation***

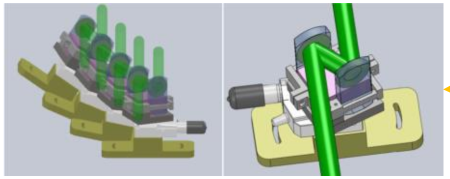
Laser Recirculator -> Single laser pulse is recirculated 32 times, synchronized with RF clock.

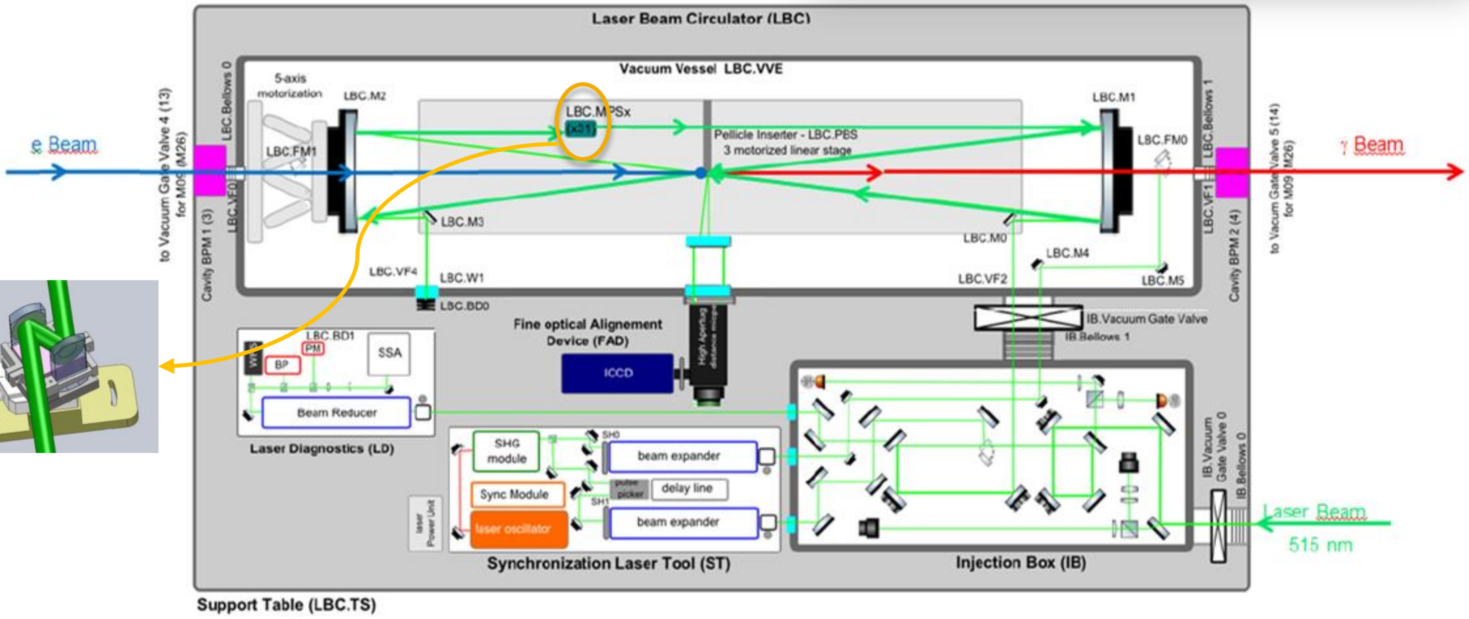
The laser beam is reflected and focused to the Interaction Point (IP) with the parabolic mirrors (sharing the same focal point.).
Mirror Pair System (MPS) - enables to shift the laser beam path in respect to parabolic mirrors and to delay in order to synchronize the laser pulse over the electron bunches.

2 parabolic reflectors M1& M2
- M1 fixed
- M2 : 5 degrees of freedom

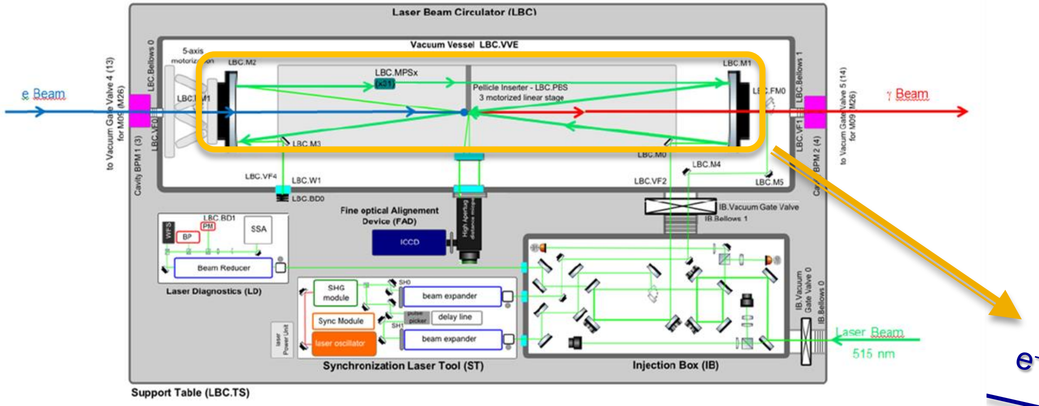
Designed by

Laser Recirculator:
- Highly complex optical implementation
- Extreme mechanical precision – mirrors parallelism ≤10 μrad; mirrors alignment tolerance ≤10 μm
- High vacuum
- High cleanness



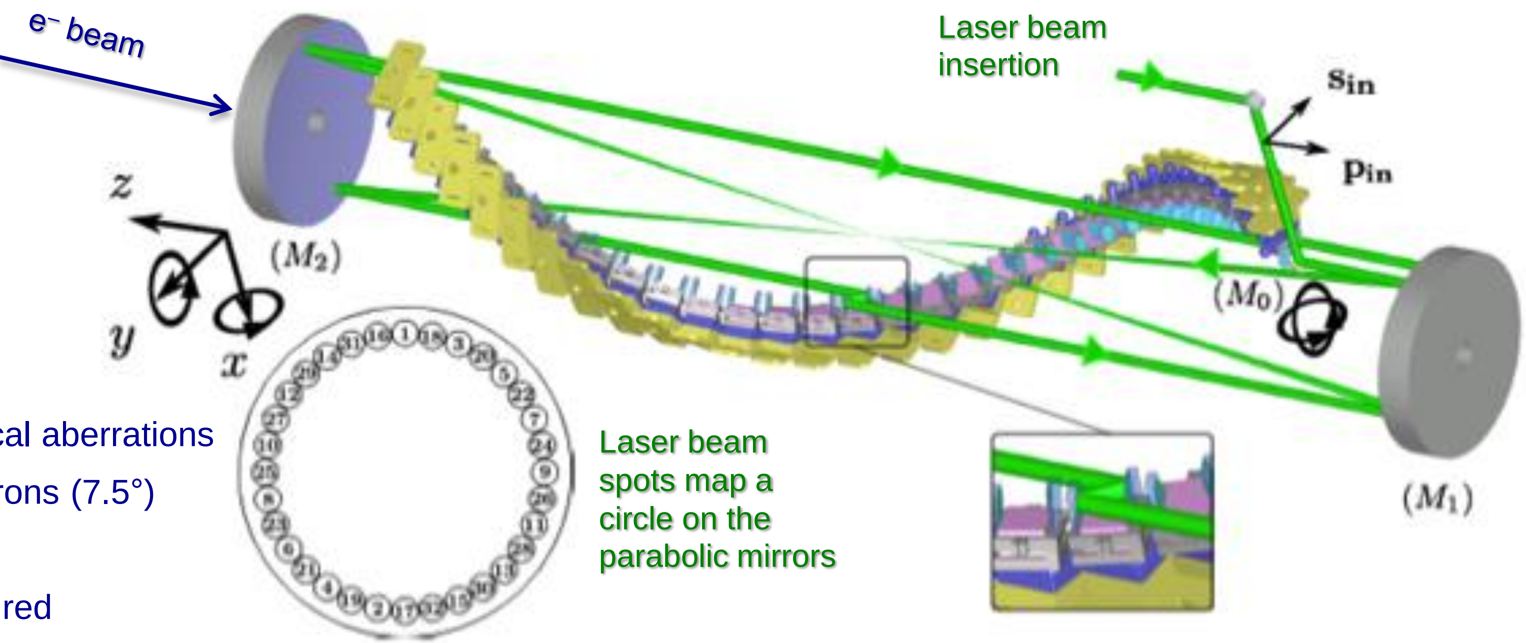


Laser Recirculation at IP



Designed by

'*Dragon–shaped*' Laser Recirculation



Laser beam insertion

Laser beam spots map a circle on the parabolic mirrors

Provide 32 passes of an intense laser pulse @ 100 Hz

- Focusing the laser beam on the electron beam without optical aberrations
- Keeping a constant crossing angle between laser and electrons (7.5°)
- Providing linearly polarized > 95% gamma–rays
- High damage threshold optics, high level of cleanness required
- Synchronization to an ext. clock <1 ps

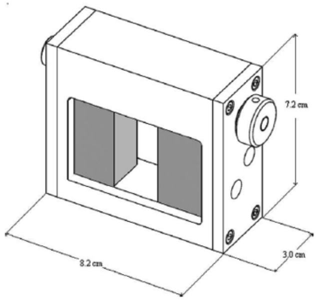
K.Dupraz et al., Phys.Rev. STAB 17 (2014) 033501

Gamma Beam Collimation and Diagnostics

Collimator System to obtain narrow bandwidth main requirements are:

- **Low transmission of gamma photons** (high density and atomic number)
- **Continuously adjustable aperture** (to adjust the energy bandwidth in the entire energy range)
- **Avoid contamination of the primary beam** with production of secondary radiation

Collimation aperture varies from 20 mm to less than 1 mm, depending on the beam energy

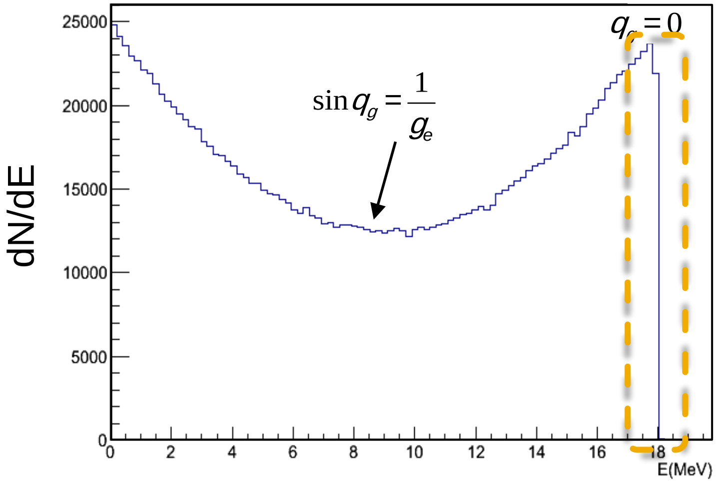


Tungsten slits – 20 mm thick

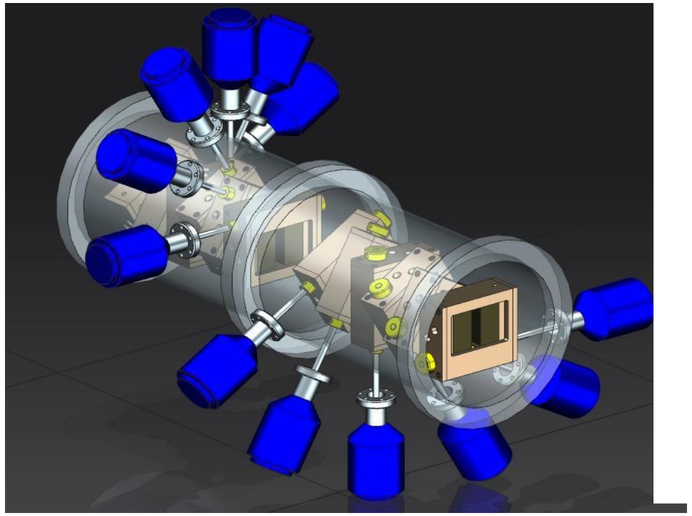
Low–energy configuration:
12 independent slits with 30º relative angle

High – energy configuration:
14 independent slits with 25.7º relative angle

Energy Spectrum



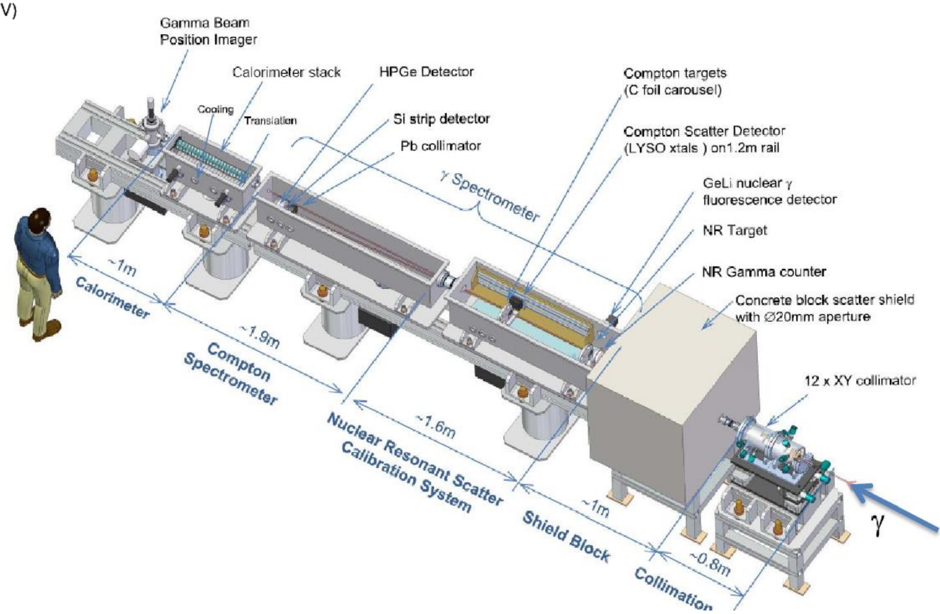
Collimator System



Gamma Beam Diagnostic System for:

***γ* Beam characterization**

- energy, intensity, profile



Gamma Beam System at ELI–NP

Advantages:

a) good and controllable monochromaticity
b) variable γ beam energy (variable energy of e^- beam)
c) low bandwidth after collimator
d) high degree of polarization (>95% of photons are polarized) full control of polarization of gamma beam
e) high intensity

Challenges:

a) requirements on the alignment
b) high brilliance e^- beams, low emittance and energy spread of e^- beam – compromise between emittance and bunch charge
c) high intensity laser
d) synchronization and phase space density of the two colliding beams are tight
e) multipass system

ELI–NP Nuclear Physics Research

Research Activities

HPLS

GBS

Experiments with HPLS

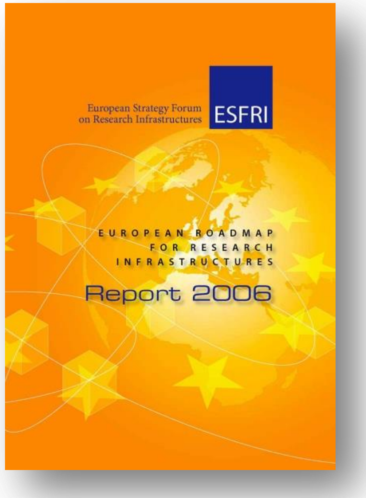
1. Laser–driven nuclear physics
2. Strong field QED
2. Irradiated materials sciences

Experiments with GBS

1. Nuclear Physics experiments
   - Nuclear Resonance Fluorescence Experiments
   - Photo-fission & Exotic Nuclei
   - Photo-disintegration and Nuclear Astrophysics (γ,n) experiments; (γ,p) experiments
2. Positron source for material science
3. Applications based on very brilliant γ beams
   - Nuclear materials and radioactive waste management *(isotope-specific identification; scan containers for nuclear materials and explosives)*
   - Food contamination
   - Radioscopy and tomography *(new methods for producing medical radioisotopes for diagnostic medical imaging and radiotherapy)*

Combined experiments

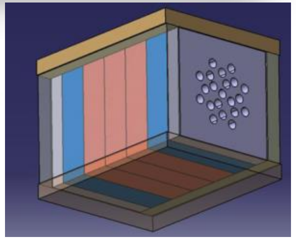
1. Probing the Pair Creation from the Vacuum in the Focus of Strong Electrical Fields with a High Energy γ Beam
2. The Real Part of the Index of Refraction of the Vacuum in High Fields: Vacuum Birefringence
3. Cascades of e^+e^- Pairs and γ – Rays triggered by a Single Slow Electron in Strong Fields

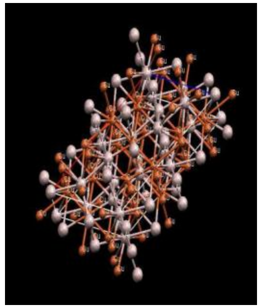

European Strategy Forum on Research Infrastructures ESFRI

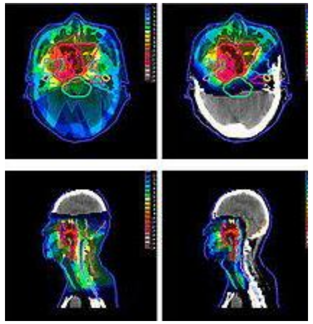
EUROPEAN ROADMAP FOR RESEARCH INFRASTRUCTURES

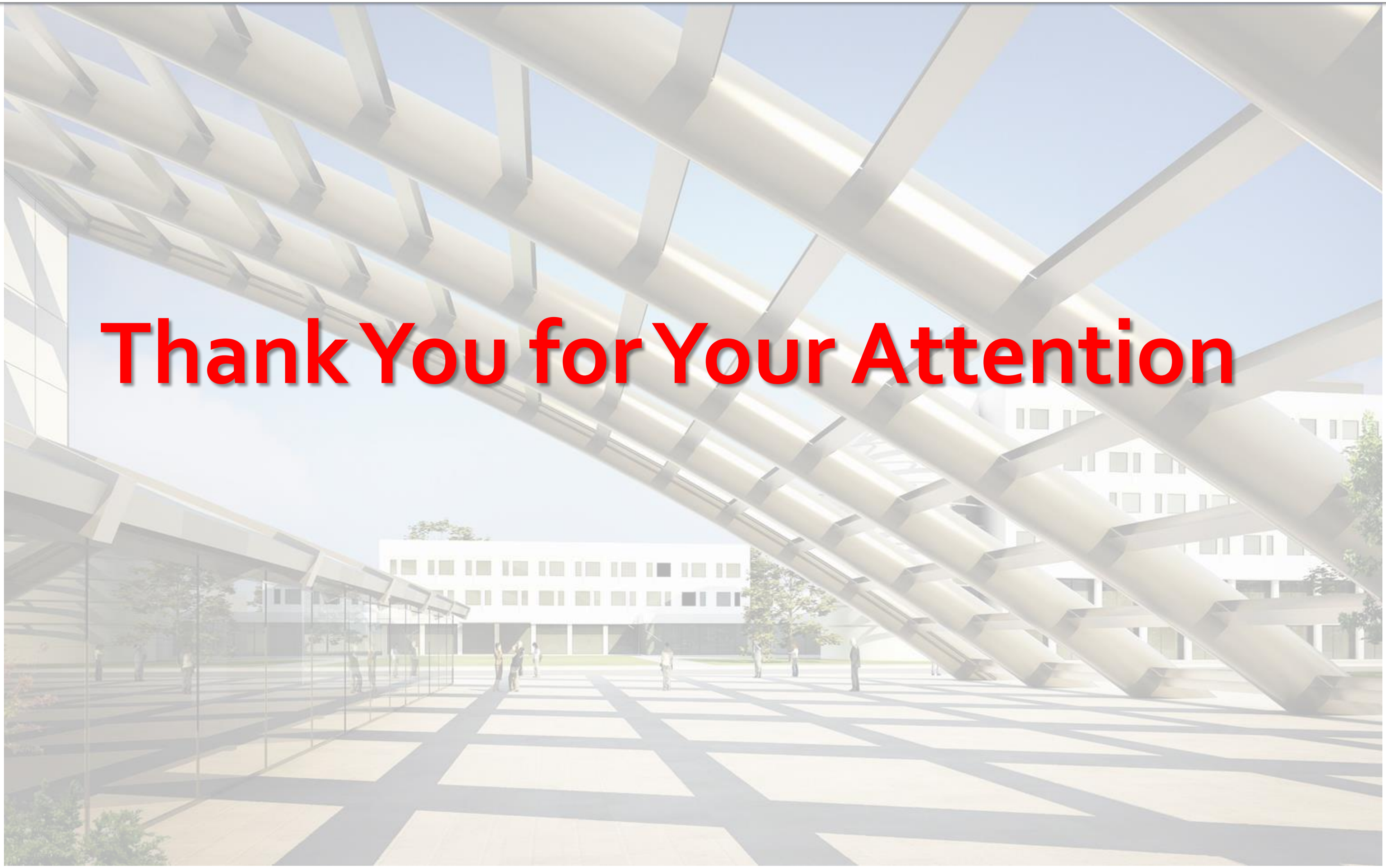
Report 2006


Si DSSSD


4PIN – neutron ^{3}He counter array

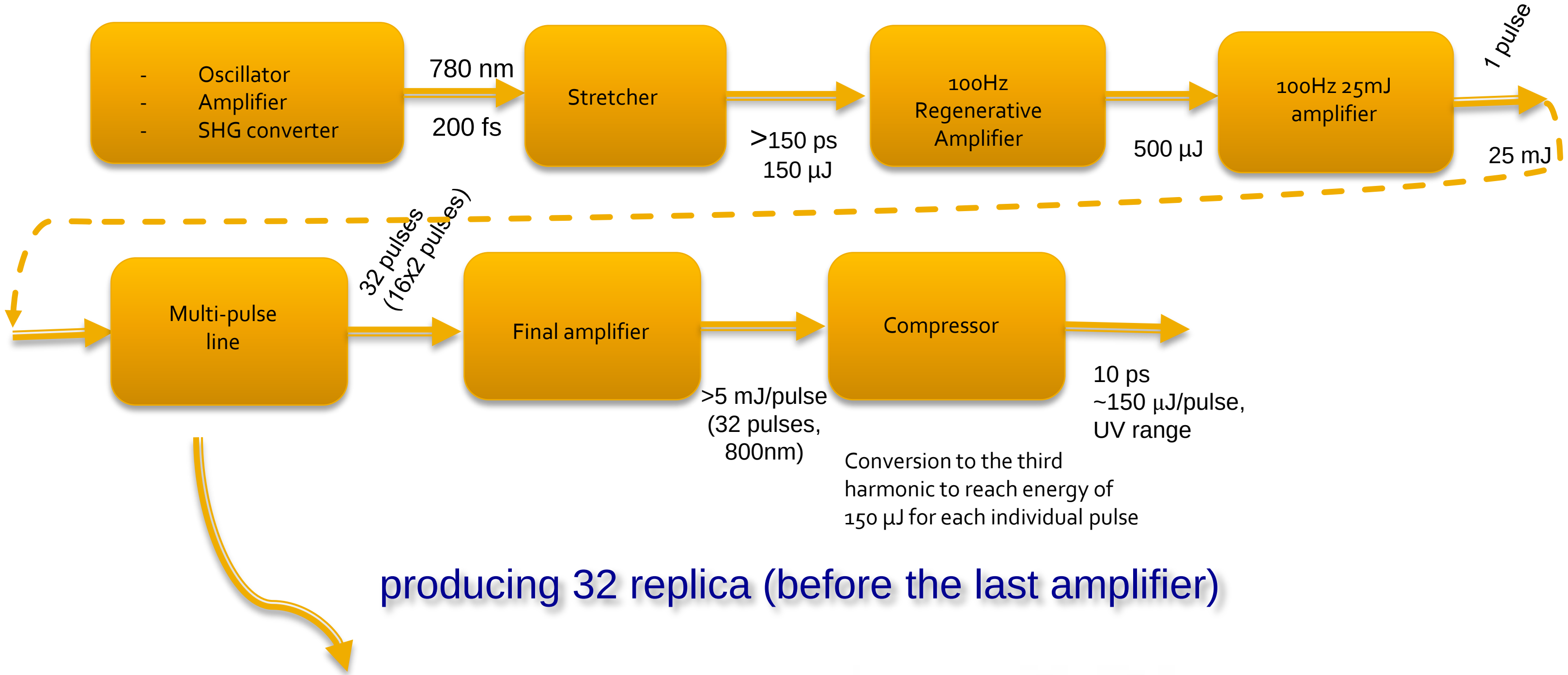






Thank You for Your Attention

Photo-gun laser



- Oscillator
- Amplifier
- SHG converter

780 nm

200 fs

Stretcher

>150 ps
150 µJ

100Hz
Regenerative
Amplifier

500 µJ

100Hz 25mJ
amplifier

1 pulse

25 mJ

Multi-pulse
line

32 pulses
(16x2 pulses)

Final amplifier

>5 mJ/pulse
(32 pulses,
800nm)

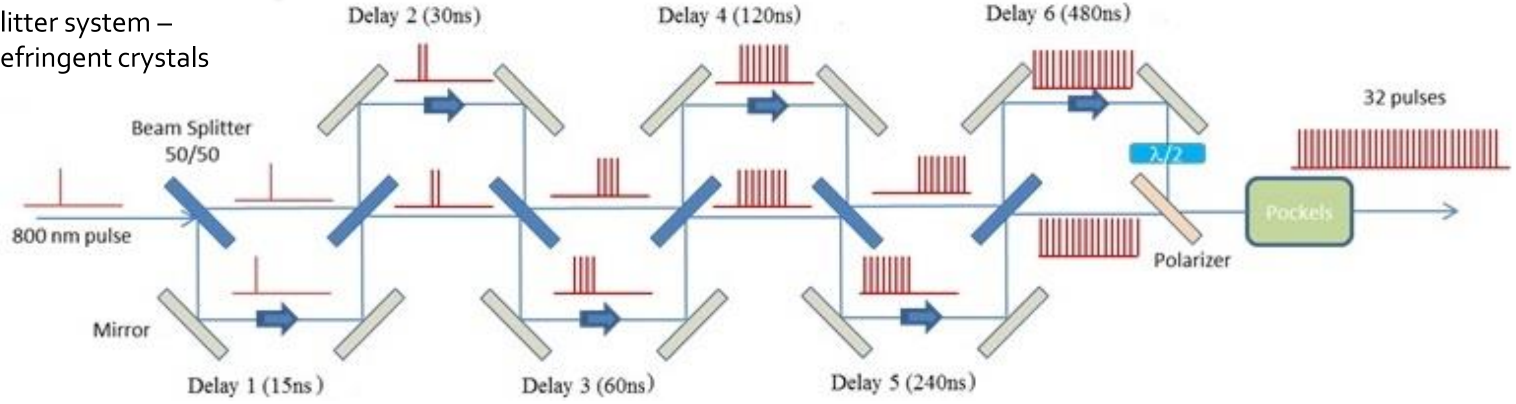
Compressor

10 ps
~150 µJ/pulse,
UV range

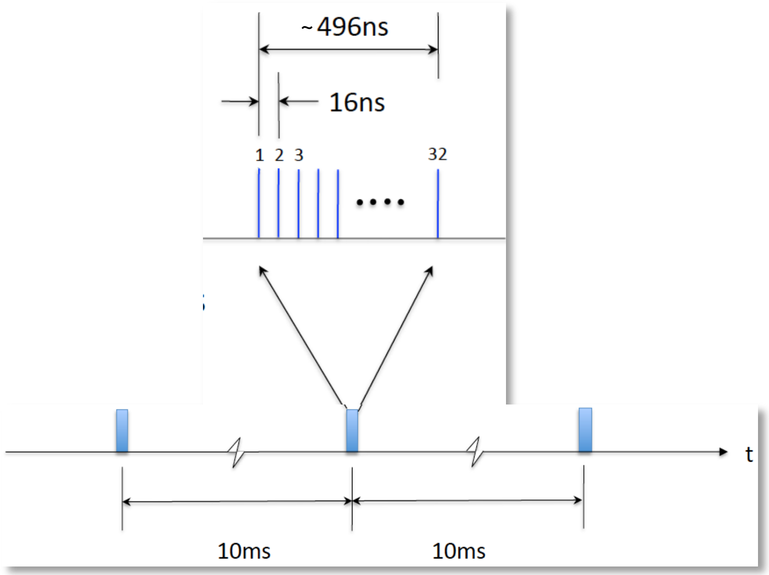
Conversion to the third
harmonic to reach energy of
150 µJ for each individual pulse

producing 32 replica (before the last amplifier)

Splitter system –
birefringent crystals

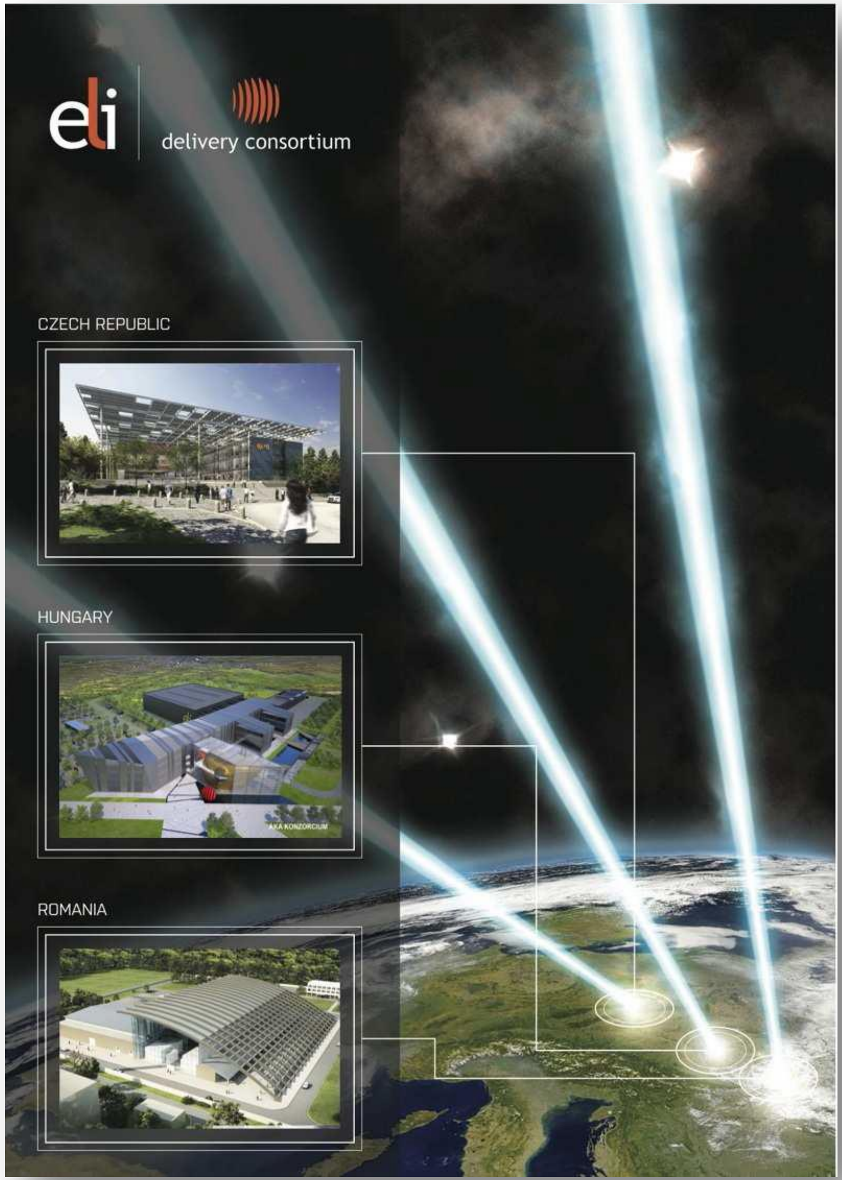


Time structure of the electron beam



32 laser pulses separated by 16ns @ 100Hz repetition rate with ~10ps pulse duration

Extreme Light Infrastructure (ELI)



the world's first international laser research infrastructure

pan–European distributed research infrastructure based presently on 3 facilities in CZ, HU and RO

ELI–Beamlines, Prague, CZ

High–Energy Beam Facility
- development and application of ultra–short pulses of high–energy particles and radiation

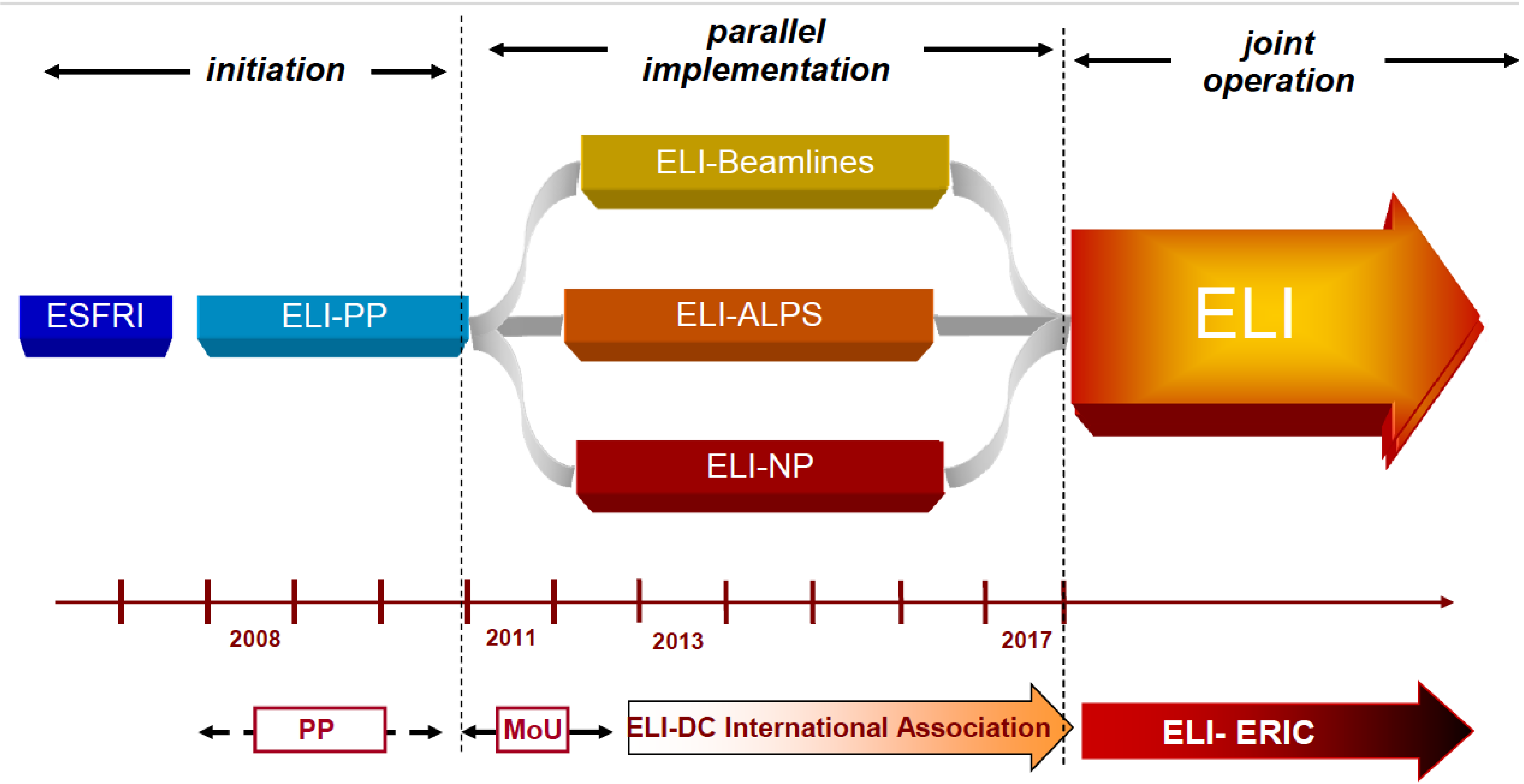
ELI–ALPS, Szeged, HU

Attosecond Laser Science Facility
- new regimes of time resolution

ELI–NP, Magurele, RO

Nuclear Physics Facility with ultra–intense laser and brilliant gamma beams (up to 20 MeV)
- novel photonuclear studies

ELI Roadmap



ELI Delivery Consortium