Overview of the Diagnostics of the ELI-NP Gamma Beam System: Challenges for the Electron-Photon Interaction Point Diagnostics

A. Mostacci on behalf of **GBS team**
Sapienza, University of Rome and INFN-Rome, Italy

The Extreme Light Infrastructure-Nuclear Physics (ELI-NP) facility is currently under construction near Bucharest (Romania); it will focus on laser-based fundamental research on nuclear physics. The facility will host two 10 PW laser systems and an advanced gamma beam source, called Gamma Beam System (GBS). GBS is a photon electron collider producing gamma rays from Compton back scattering of a laser light off a high charge, low emittance electron beam from a 720 MeV warm linac. The gamma rays will have tunable energy (0.2-19.5MeV) with worldwide outstanding performances, such as narrow bandwidth (0.5%) and high spectral density (10^4 photons/s/eV). To achieve such challenging performances, the luminosity will be raised by colliding up to 32 electron bunches (at 100 Hz repetition rate) with a properly recirculated laser beam. New class diagnostics need to be developed at the interaction point to allow efficient photon electron collisions. This infrastructure will create a new European laboratory with a broad range of science covering frontier fundamental physics, new nuclear physics and astrophysics as well as applications in nuclear materials, radioactive waste management, material science and life sciences.

OUTLINE

Overview of the Diagnostics of the ELI-NP Gamma Beam System: Challenges for the Electron-Photon Interaction Point Diagnostics

The **E**xtreme **L**ight **I**nfrastructure initiative

Advanced Compton Source for nuclear physics experiment in Magruele (Bucarest, Romania).

Electron-Photon Linear **collider**: beam physics issues for the Compton source Linac.

Overview of the whole **machine diagnostics**.

Interaction point diagnostics: what and why.

Status and conclusions.

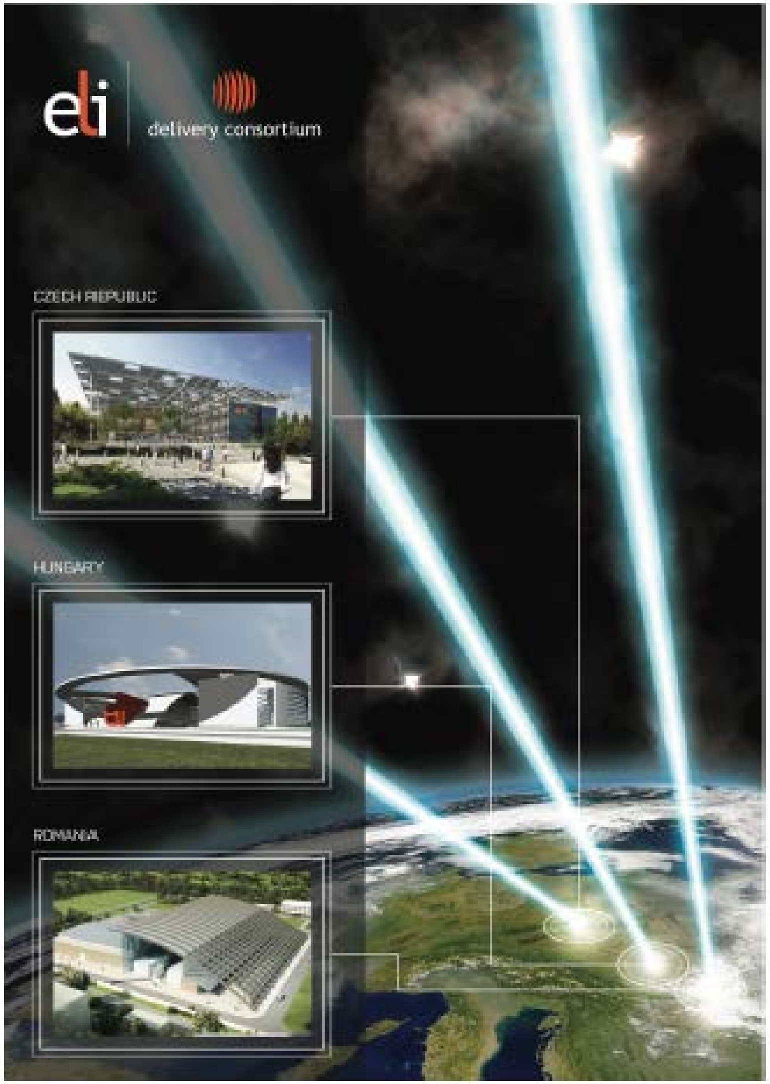
EXTREME LIGHT INFRASTRUCTURE

Three Pillars

ELI High Energy Beam-Line Facility (ELI-Beamlines) in Czech Republic: highly competitive source of extremely short pulse X-rays, accelerated electrons or protons for applications (also biomedical).

ELI Attosecond Light Pulse Source (ELI-ALPS) in Szeged (Hungary): ultrafast light sources (coherent XUV and X-ray radiation) including single attosecond pulses to investigate electron dynamics in atoms, molecules, plasmas and solids.

ELI Nuclear Physics Facility (ELI-NP) in Magurele (Romania): laser and gamma beams (low bandwidth, energies in the 20 MeV range) with unique characteristics perform frontier laser, nuclear and fundamental research.



THE NUCLEAR PHYSICS FACILITY FOR ELI-NP

Advanced Laser source (Thales)

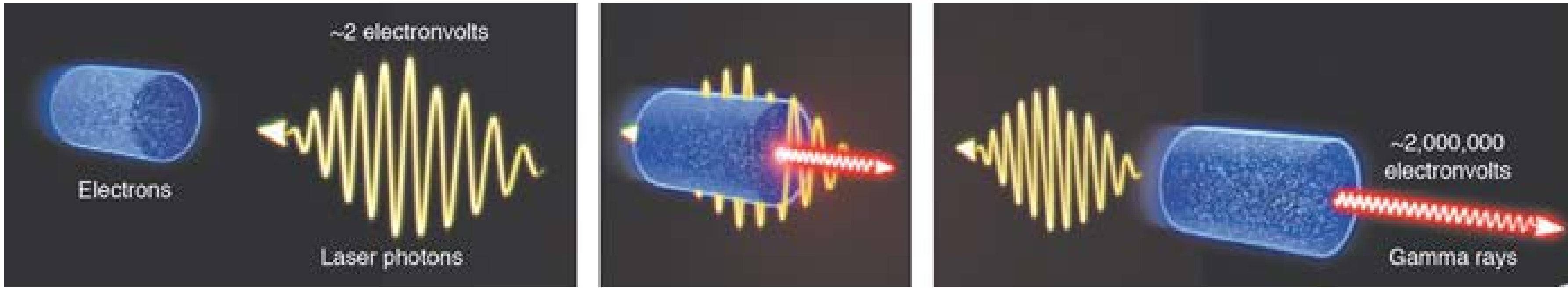
Two 10 PW APOLLON-type lasers with output energy higher that 200J, 20-30fs, intensity higher than 10^{23} W/cm^2

Advanced Gamma source (EuroGammaS Consortium)

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

Nuclear Photonics

LUMINOSITY PER UNIT BANDWIDTH



$$\frac{\Delta\nu_\gamma}{\nu_\gamma} \approx \sqrt{\left[\frac{(\gamma\theta)^2/\sqrt{12}}{1+(\gamma\theta)^2} + \frac{2\epsilon_n^2}{\sigma_x^2 + 4\sqrt{3}\epsilon_n^2}\right]^2 + \left(\frac{2\Delta\gamma}{\gamma}\right)^2 + \left(\frac{\Delta\nu}{\nu}\right)^2 + \left(\frac{M^2\lambda_L}{2\pi w_0}\right)^4 + \left(\frac{a_0^2/3}{1+a_0^2/2}\right)^2}$$

normalised collection angle $\gamma\theta$

electron beam

laser beam

Optimised bandwidth $$\frac{\Delta\nu_\gamma}{\nu_\gamma} \approx \left(\frac{\sqrt{2}\epsilon_n}{\sigma_x}\right)^2$$

Luminosity $$L = \frac{N_p N_e}{4\pi\sigma_x^2} f_{rep}$$

Spectral Luminosity $$L_\gamma = \frac{L}{\Delta\nu_\gamma} \propto \frac{Q}{\epsilon_n^2}$$

γ-ray Spectral density ⟷ **Phase space density**

Courtesy of L. Serafini

LUMINOSITY PER UNIT BANDWIDTH

PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 080701 (2017)

Analytical description of photon beam phase spaces in inverse Compton scattering sources

C. Curatolo,[1,*] I. Drebot,[1] V. Petrillo,[1,2] and L. Serafini[1]

[1]*INFN-Milan, via Celoria 16, 20133 Milano, Italy*

[2]*Università degli Studi di Milano, via Celoria 16, 20133 Milano, Italy*

(Received 9 March 2017; published 3 August 2017)

$$\frac{\Delta E_{\mathrm{ph}}}{E_{\mathrm{ph}}} \simeq \sqrt{\left[\frac{\Psi^2/\sqrt{12}}{1+\Psi^2} + \frac{\bar{P}^2}{1+\sqrt{12}\bar{P}^2}\right]^2 + \left[\left(\frac{2+X}{1+X}\right)\frac{\Delta\gamma}{\gamma}\right]^2 + \left(\frac{1}{1+X}\frac{\Delta E_L}{E_L}\right)^2 + \left(\frac{M^2\lambda_0}{2\pi w_0}\right)^4 + \left(\frac{a_0^2/3}{1+a_0^2/2}\right)^2}$$

collection angle

Optimise ... bandwid...

$$\Psi = \gamma_{\mathrm{CM}}\theta_{\max}$$

$$\bar{P} = \gamma_{\mathrm{CM}}\frac{\sqrt{2}\epsilon_x}{\sigma_x} = \frac{\sqrt{2}\epsilon_n}{\sigma_x\sqrt{1+X}}$$

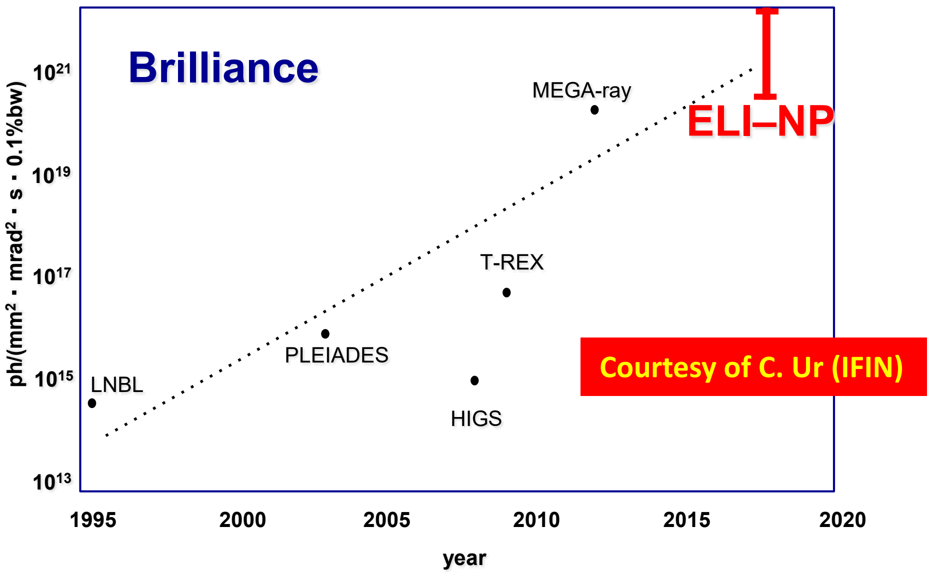
$$\ldots \Delta\nu_\gamma \propto \frac{Q}{\epsilon_n^2}$$

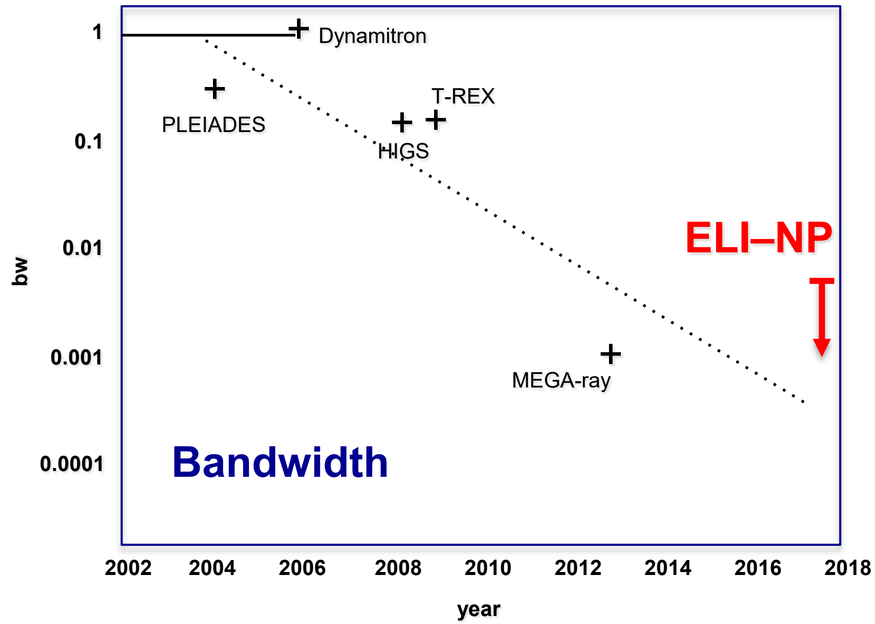
Luminosity $L = \frac{N_p N_e}{4\pi\sigma_x^2} f_{rep}$

γ-ray Spectral density ⟷ **Phase space density**

Courtesy of L. Serafini

COMPARISON WITH OTHER SOURCES





Gamma rays of 0.2-19.5MeV with rms bandwidth of $5\ 10^{-3}$.

Spectral density:
$>10^4$ photons/(s eV)

1 order of magnitude improvement in bandwidth

2 order of magnitude improvement in spectral density

Electron beam $Q = 250\,pC\ ;\ \varepsilon_n = 4.10^{-7}\,m\cdot rad\ ;\ \Delta\gamma/\gamma = 5\cdot 10^{-4}$

Laser beam $U_L = 400\ \ mJ\ ;\ M^2 = 1.2\ ;\ \dfrac{\Delta\nu}{\nu} = 5\cdot 10^{-4}$

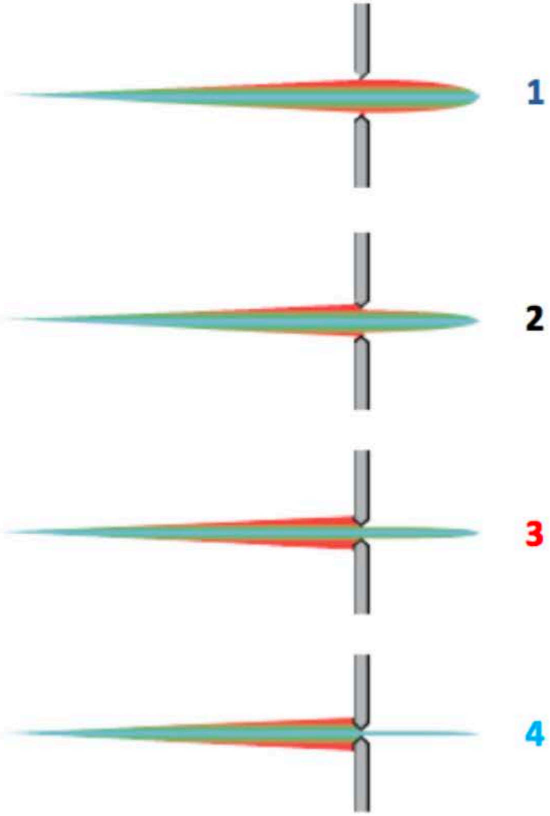
$w_0 < 28\mu m$,
λ=515nm (Yb:Yag laser)

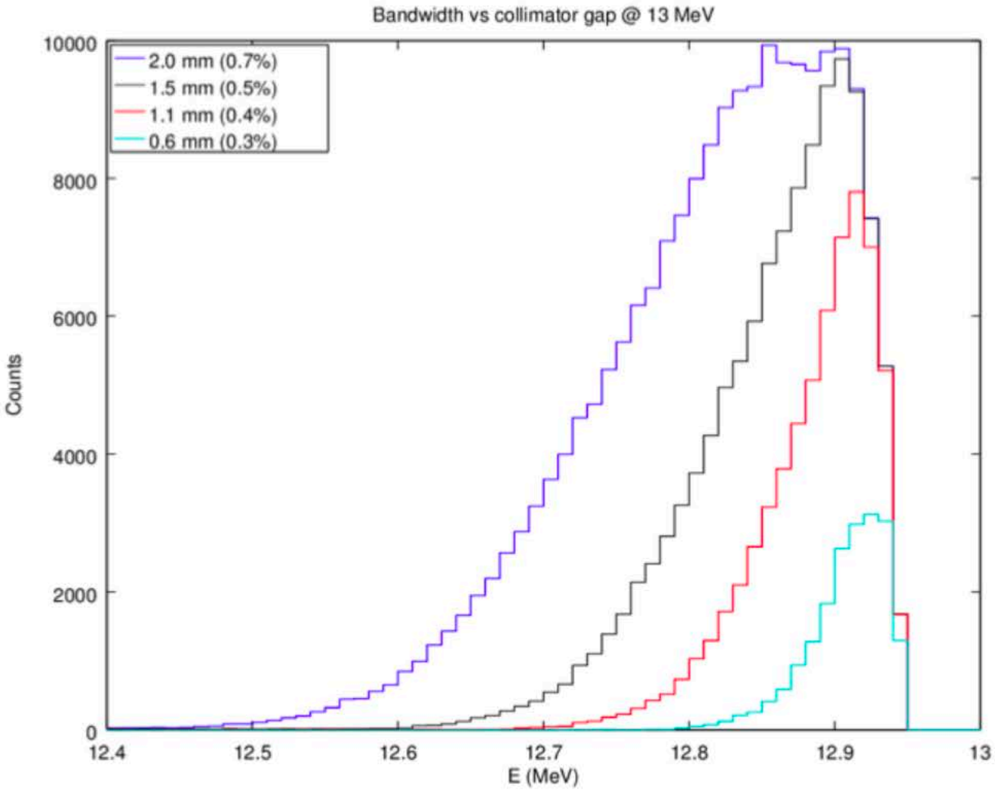
by L. Serafini

MONOCHROMATICTY FROM COLLIMATION

Inverse Compton radiation is not intrinsically monochromatic: **the energy is related to the emission angle**.

The required energy bandwidth can be obtained by **collimation of the γ-beam**.





P. Cardarelli, M. Gambaccini

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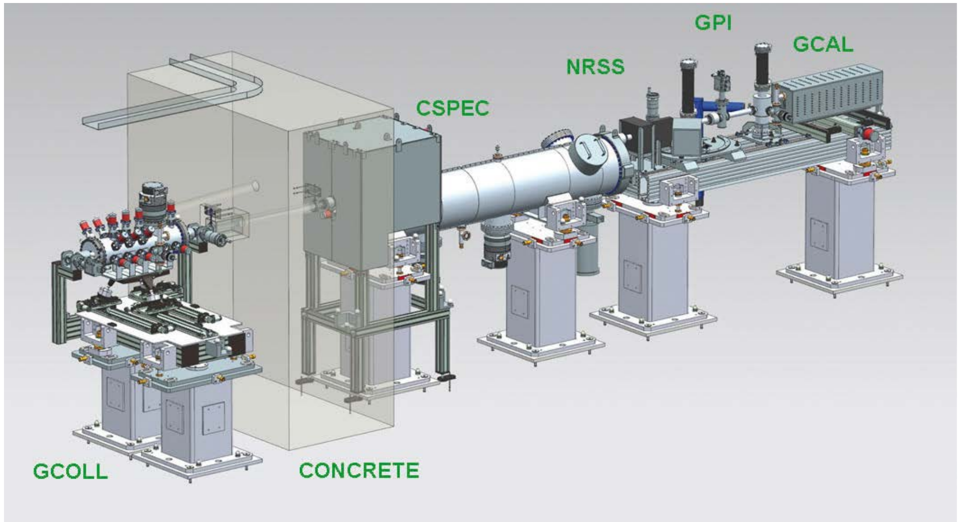
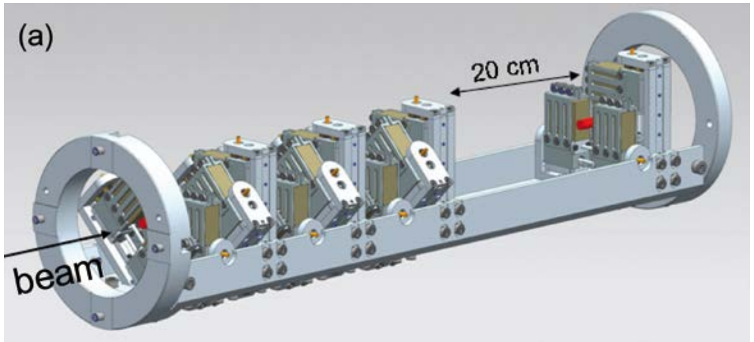
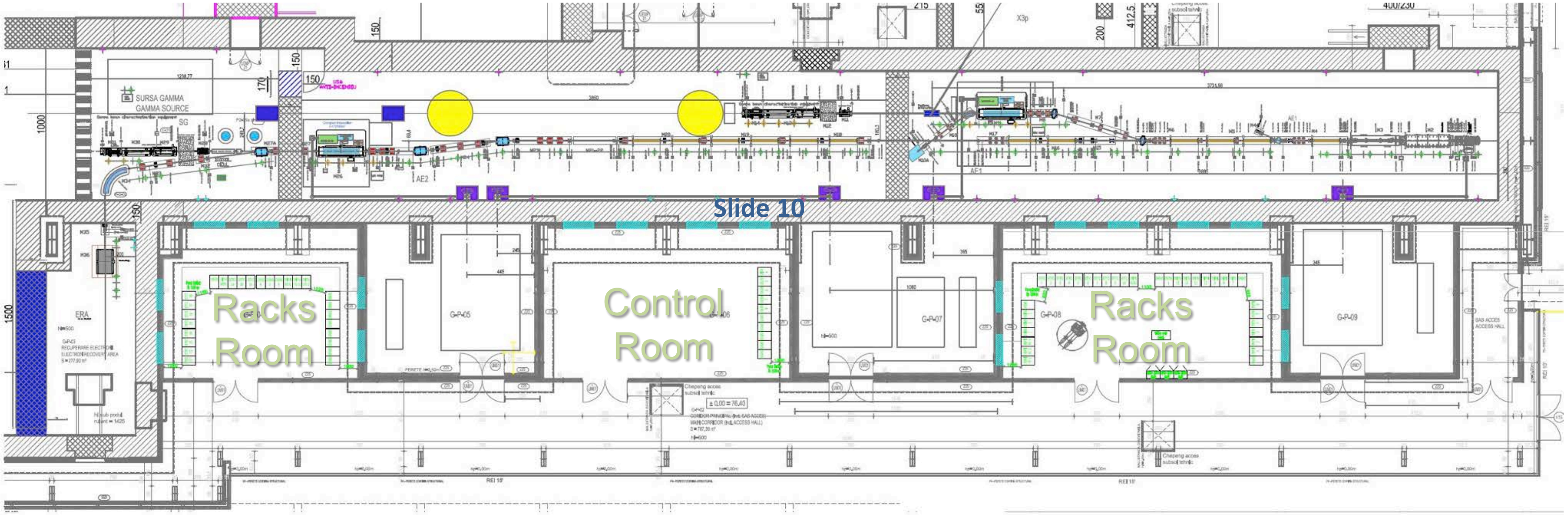




P. Cardarelli, M. Gambaccini

GAMMA BEAM SYSTEM (GBS) LAYOUT

Courtesy of C. Ur (IFIN)



GAMMA BEAM SYSTEM (GBS) LAYOUT

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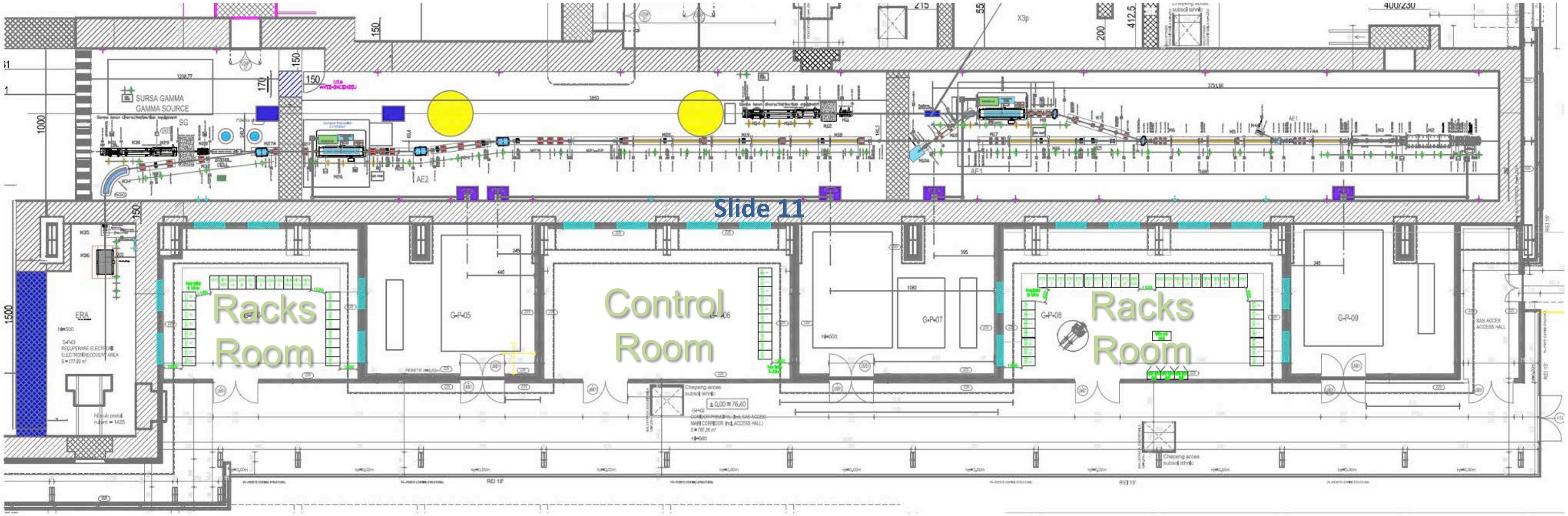
Low Energy Stage: Gamma rays up to 3.5 MeV



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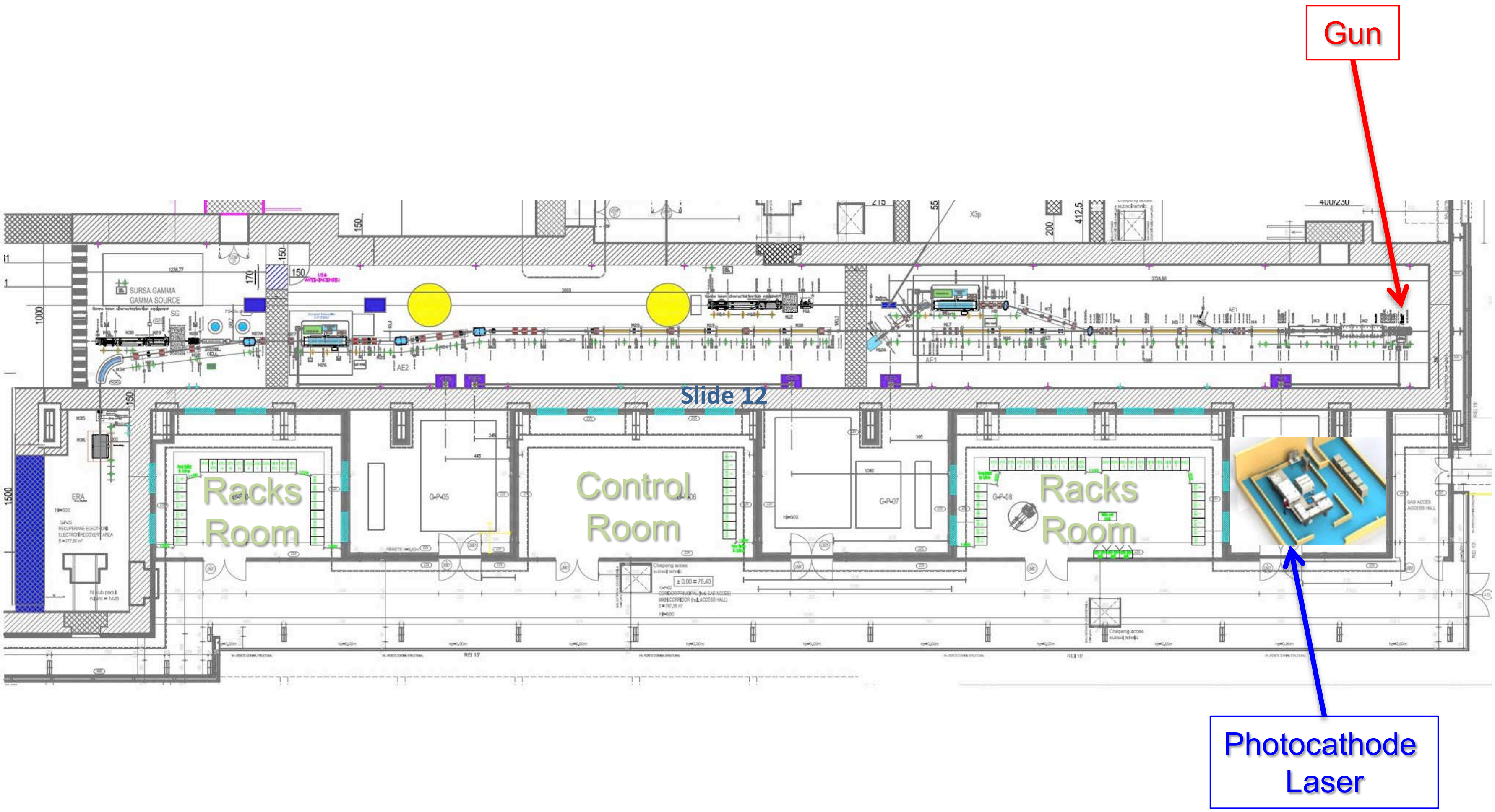

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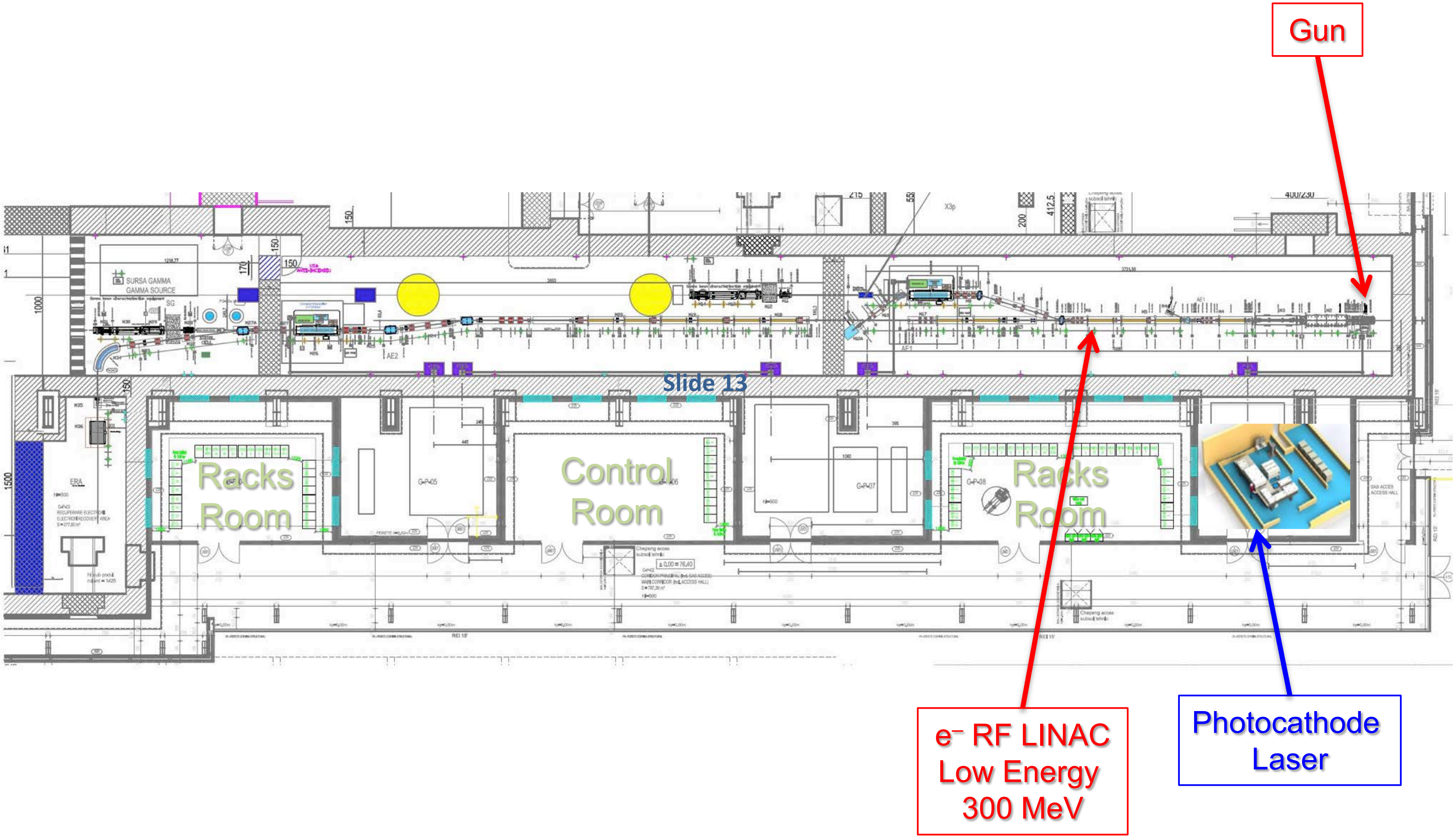

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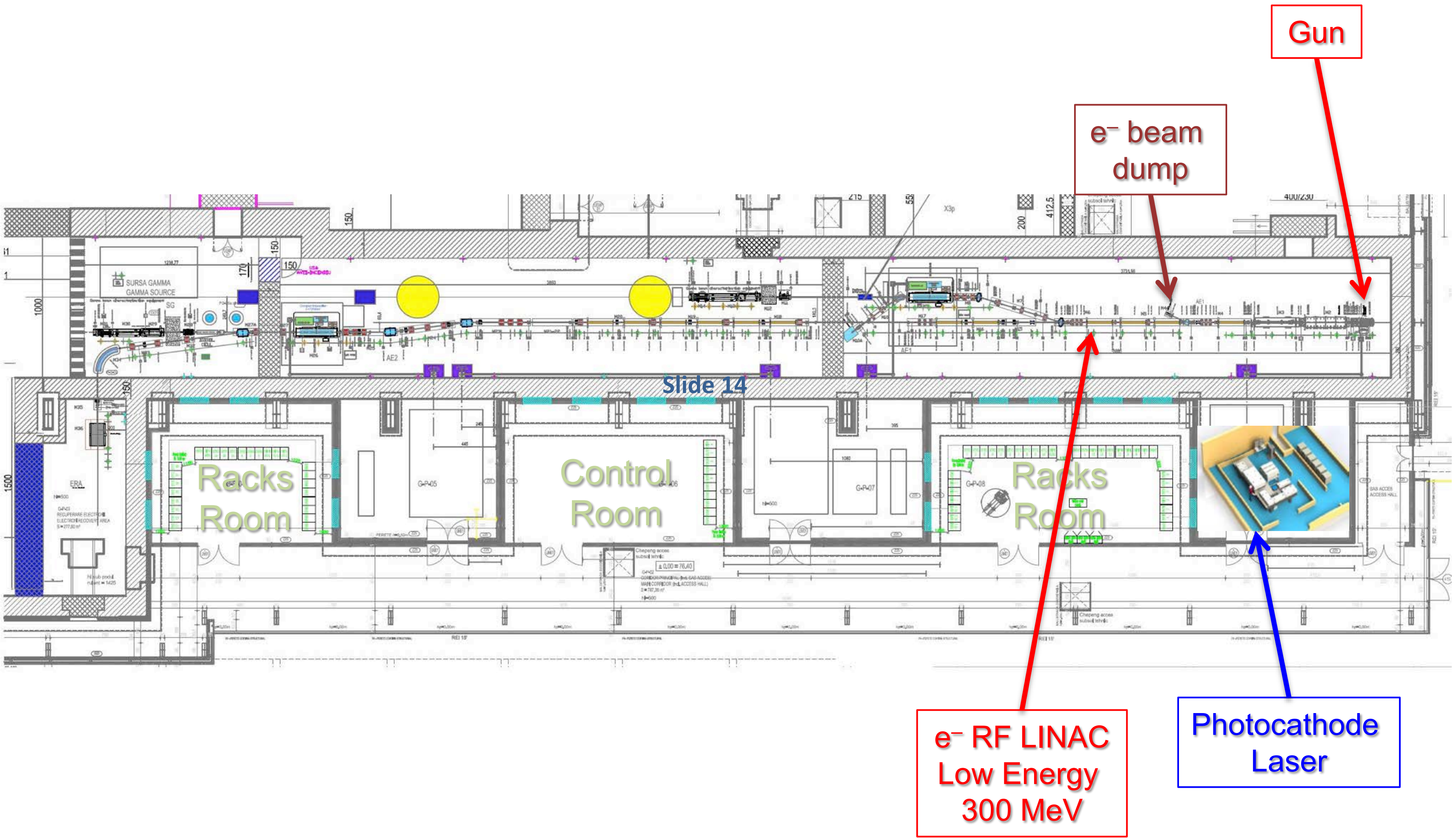

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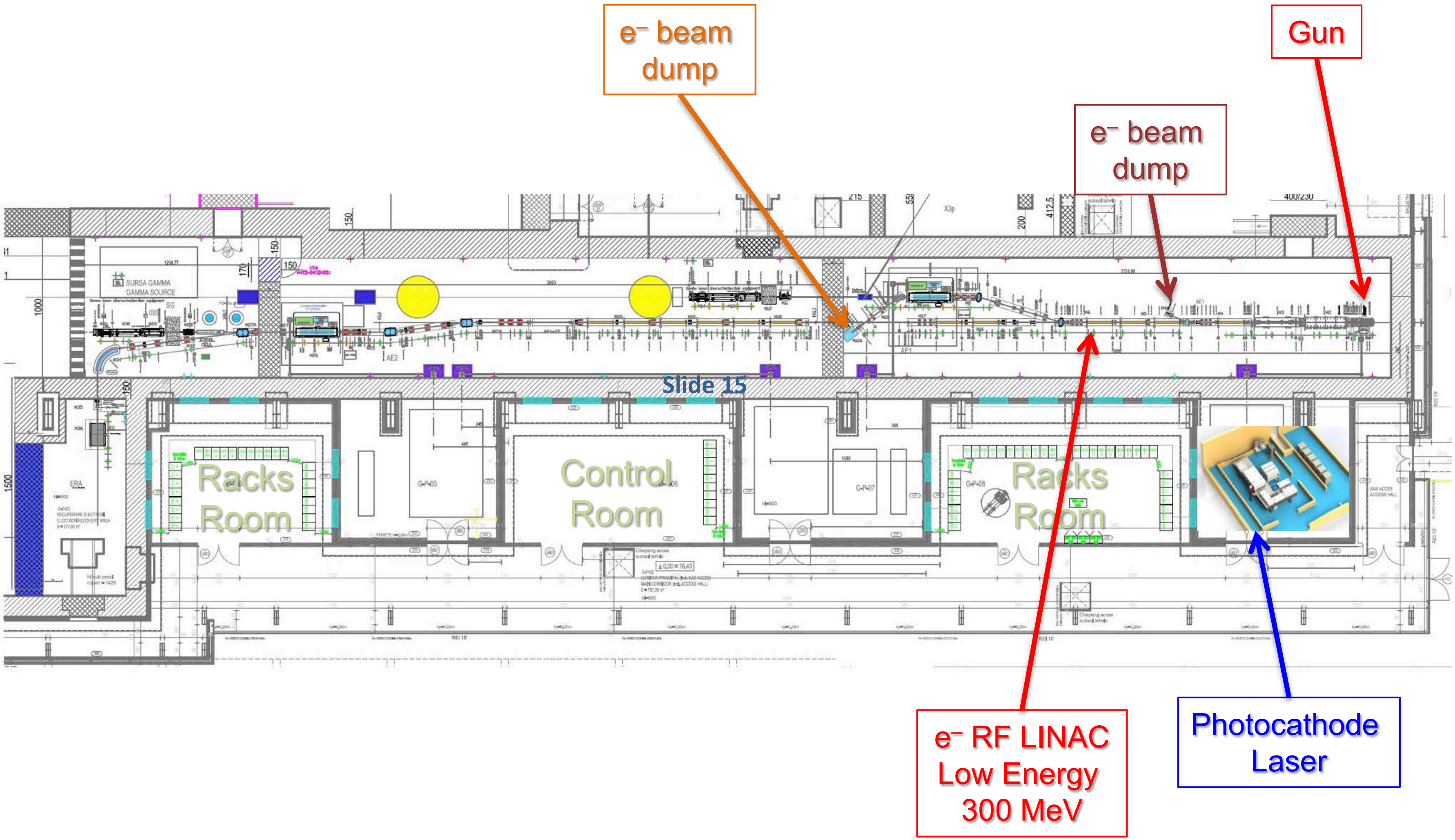

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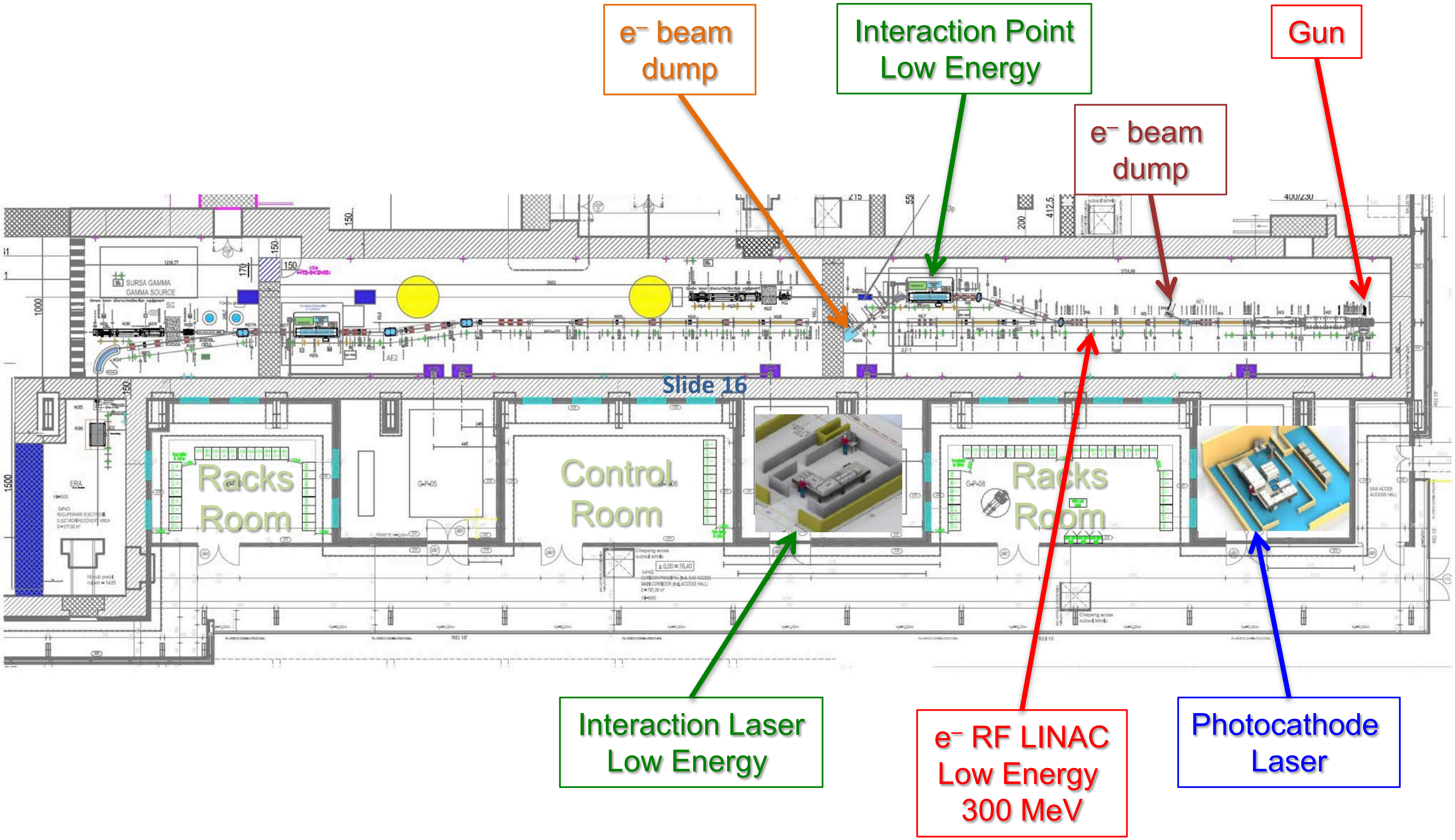

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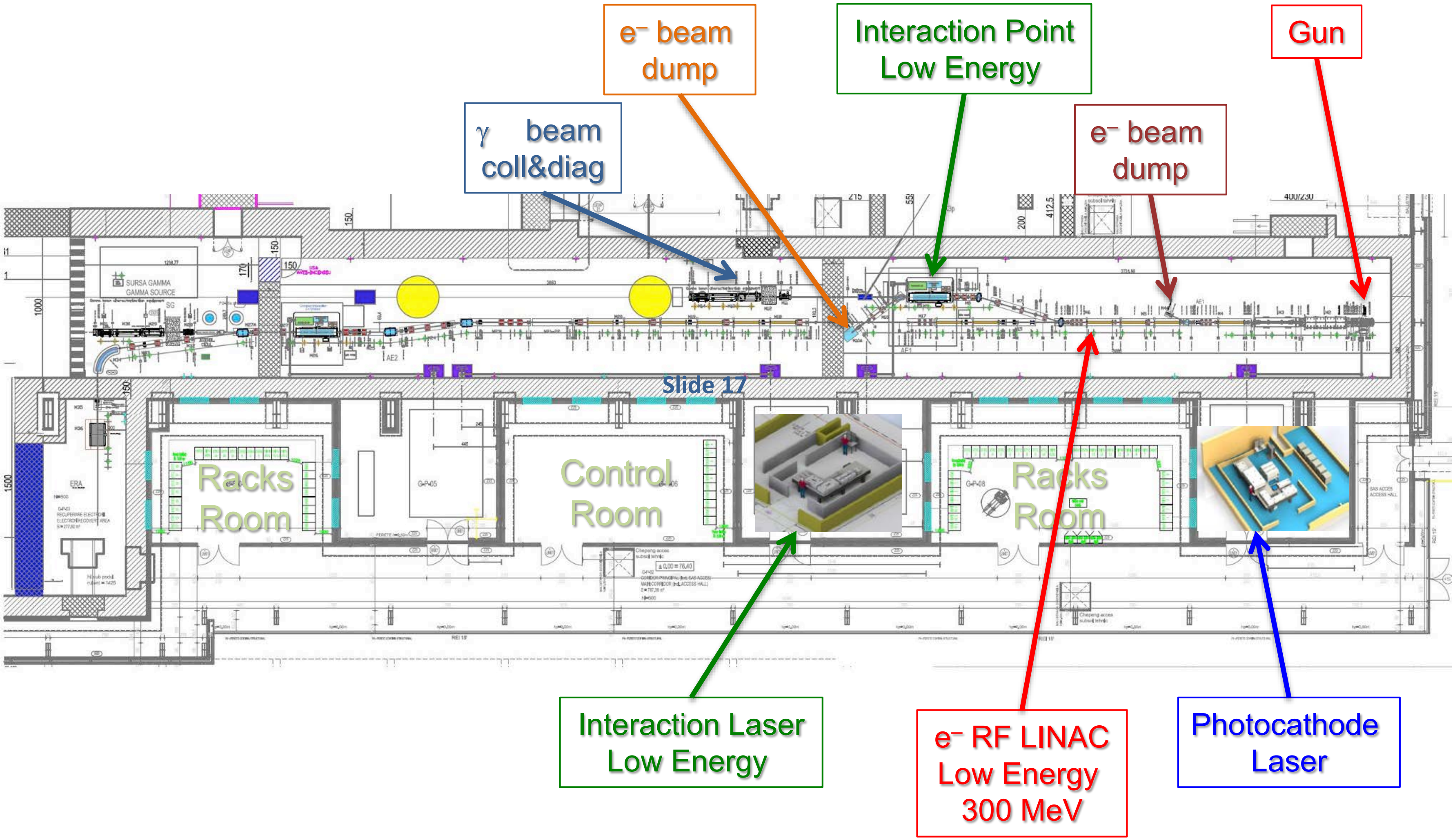

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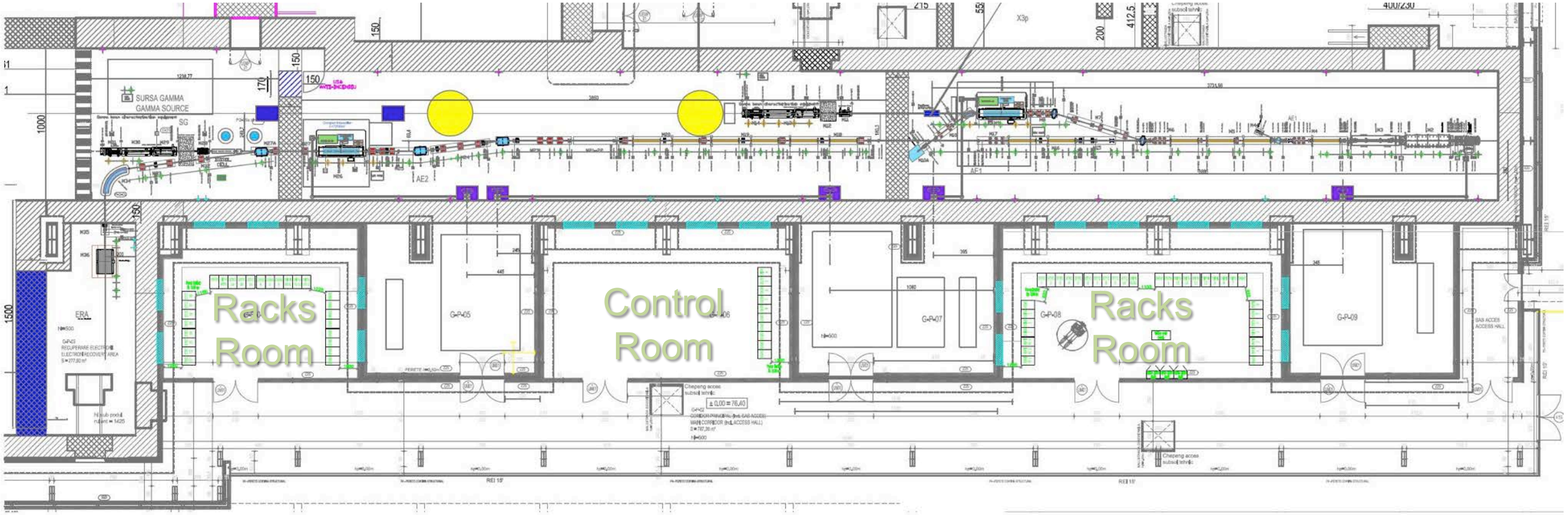

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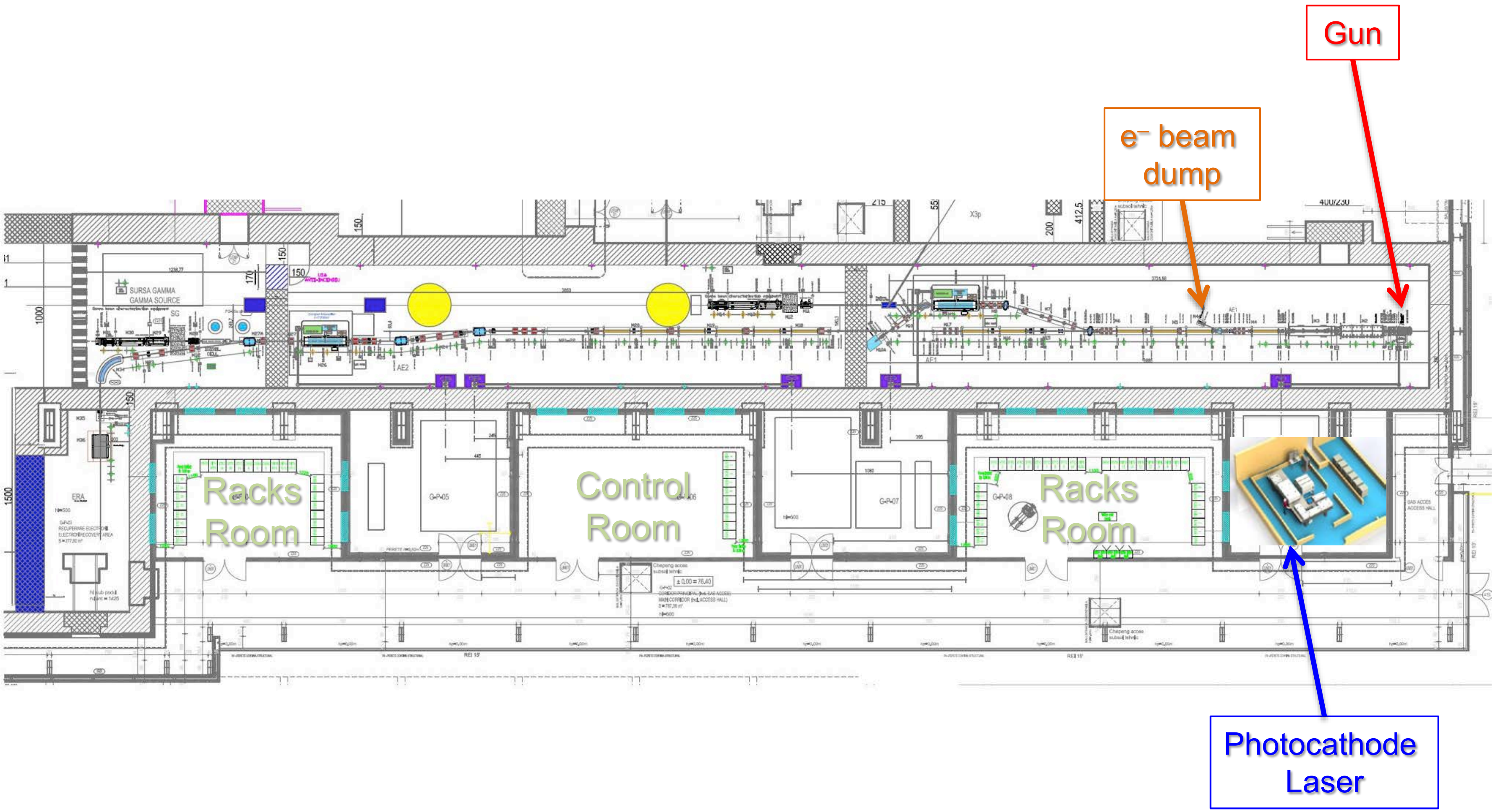

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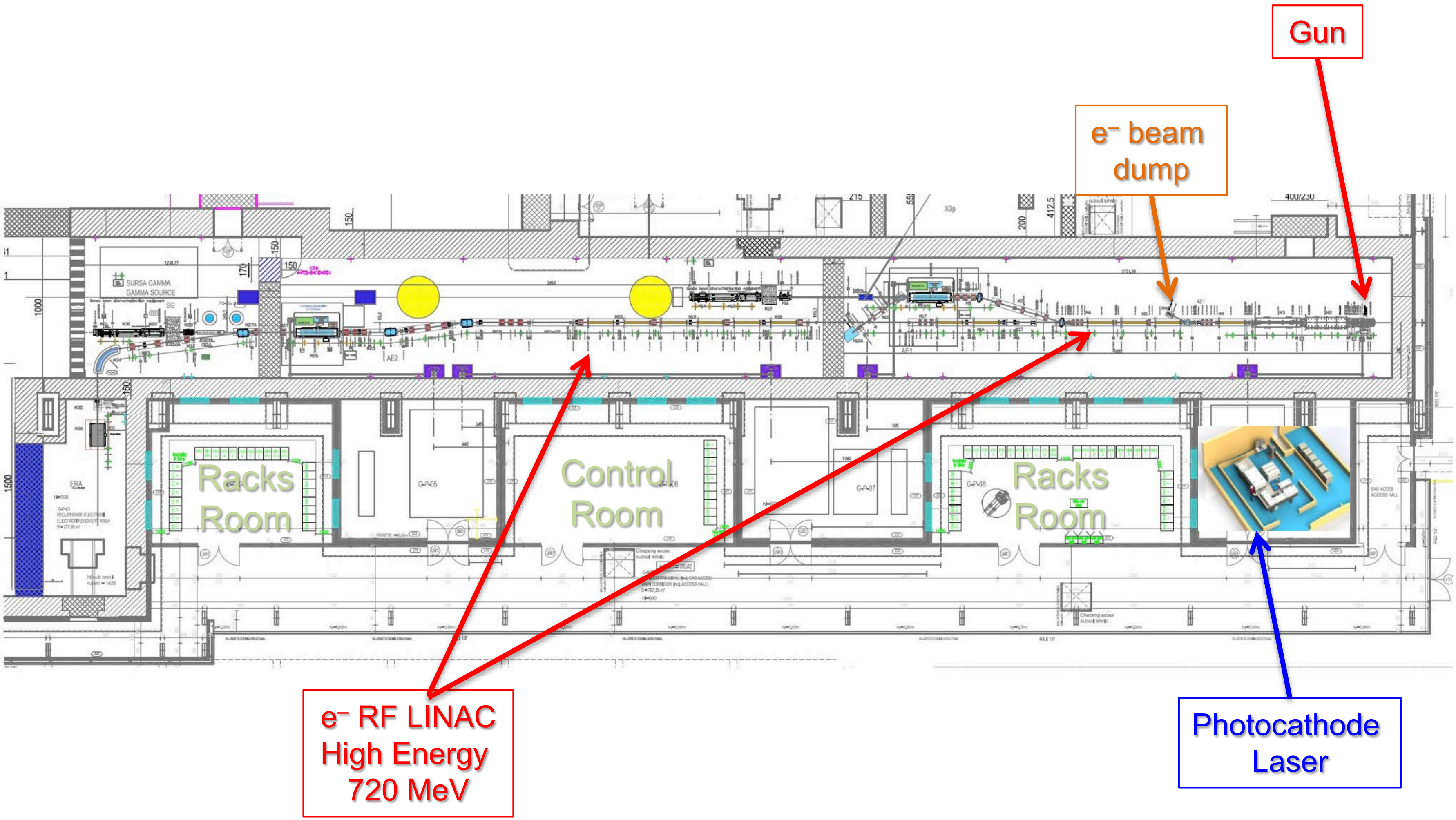

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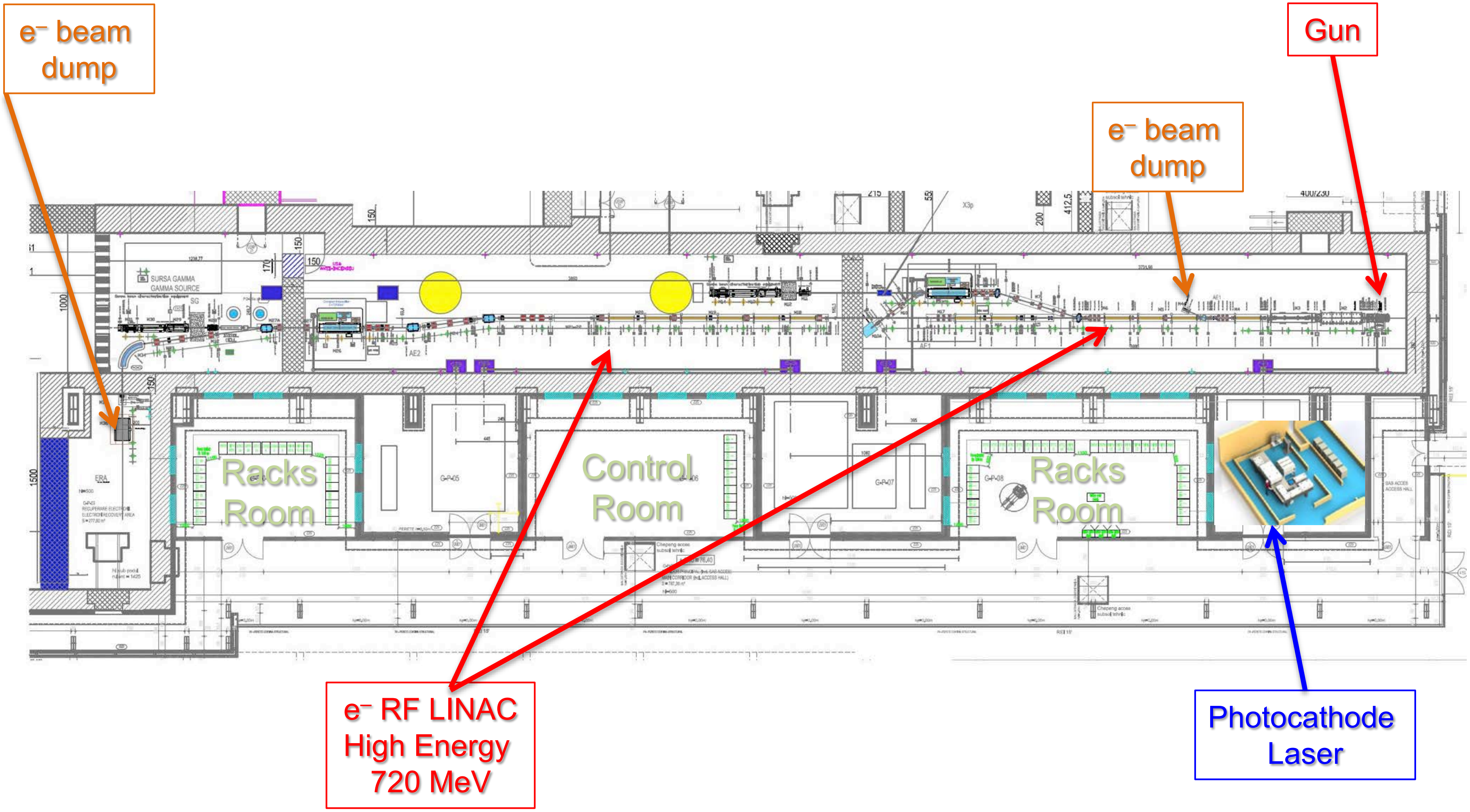

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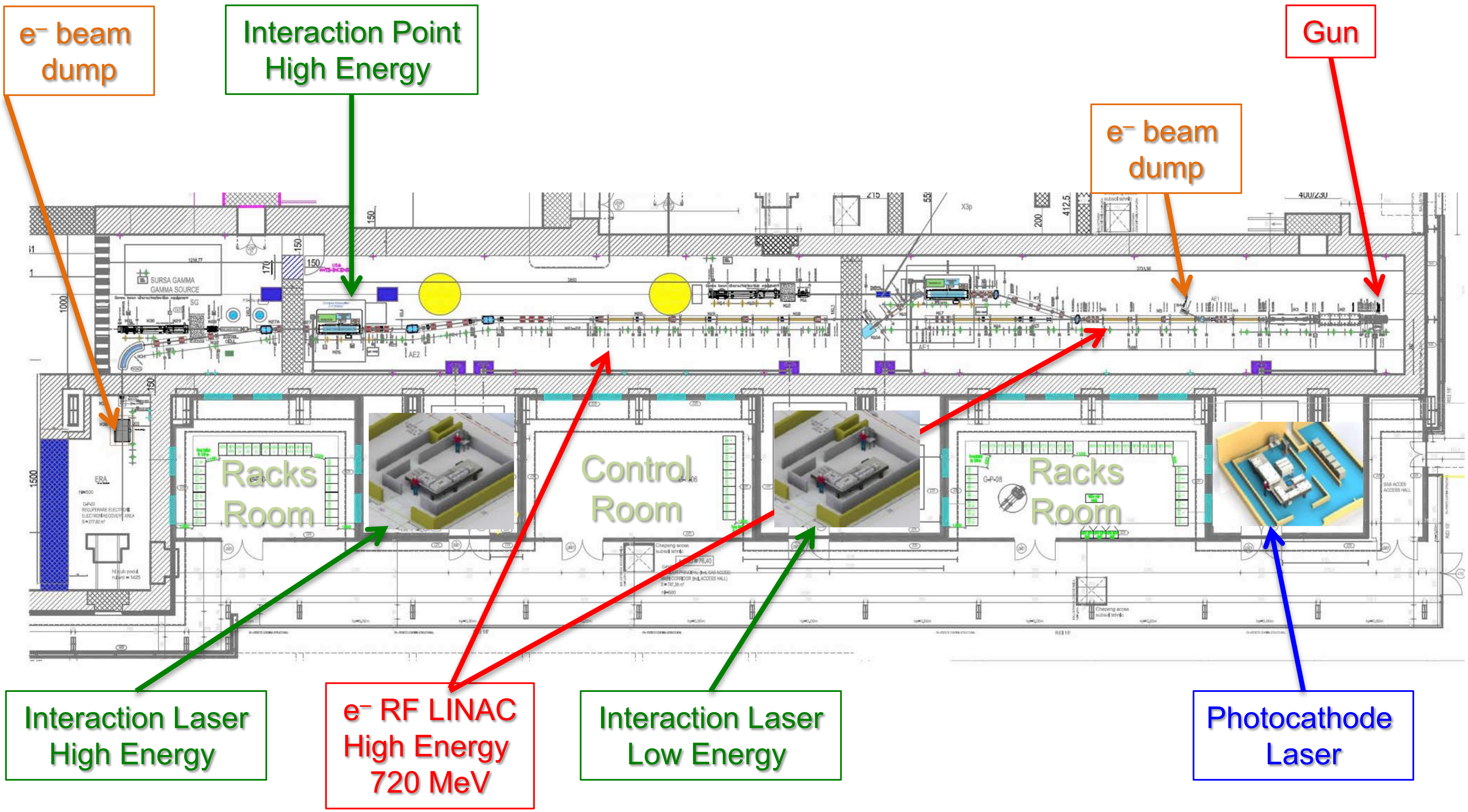

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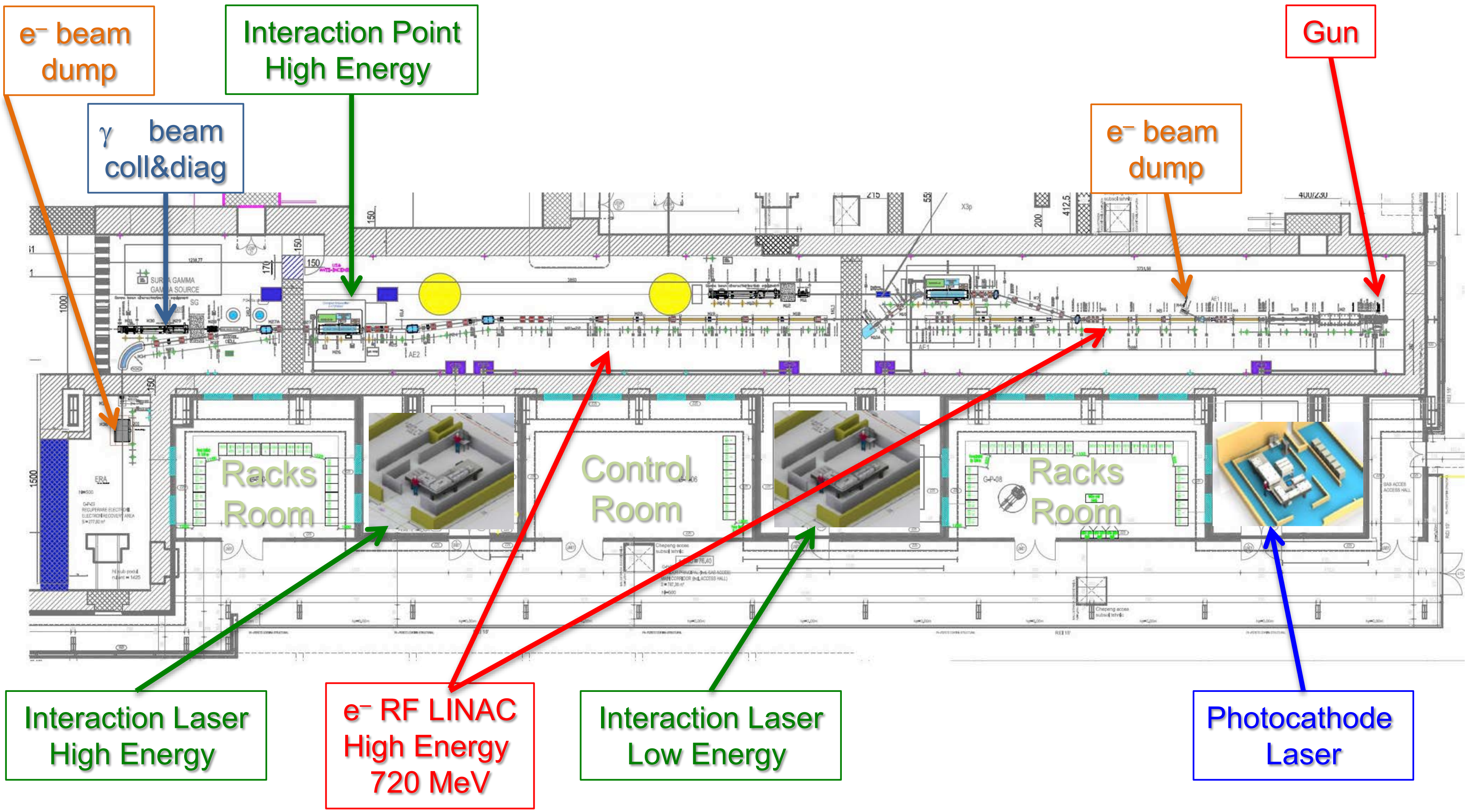
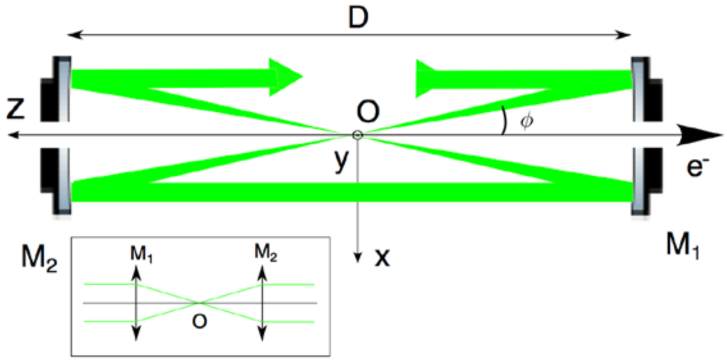


ELECTRON BEAM PARAMETERS @ IP

Energy (MeV)	280 - 720
Bunch charge (pC)	25-250
Bunch length rms (um)	100-400
Norm. emittance in both planes (mm mrad)	0.2-0.6
Bunch energy spread (%)	0.04 – 0.1
Spot size rms (um)	<15
Number of bunches in the train	≤32
Bunch separation in the train (ns)	16
Energy variation along the train (%)	0.1
Energy jitter shot to shot (%)	0.1
Emittance dilution due to beam breakup (%)	<10
Time arrival jitter (ps)	<0.5
Pointing jitter (um)	1
Repetition Rate	100 Hz

LASER CIRCULATOR DESIGN AND MAIN PARAM.

Planar confocal recirculator for preserving quality of the laser beam



PRSTAB 17, 033501 (2014)

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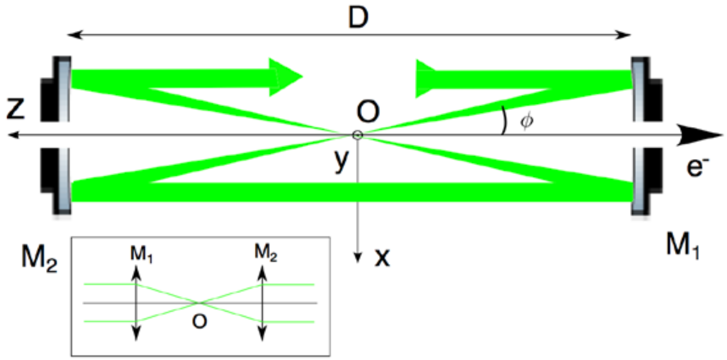

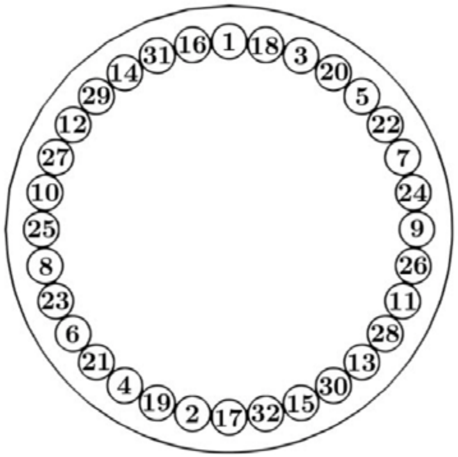

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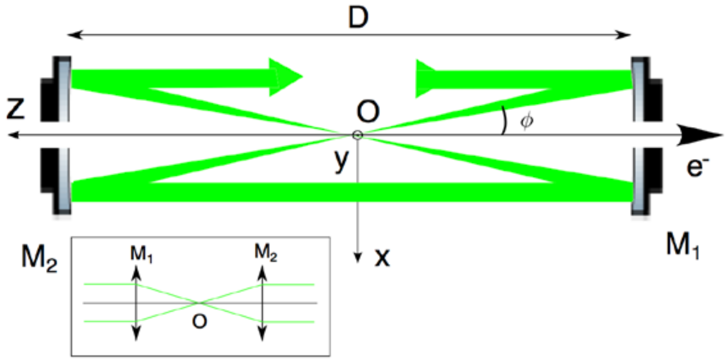

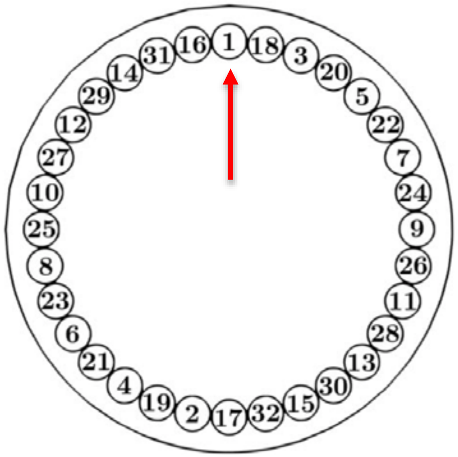

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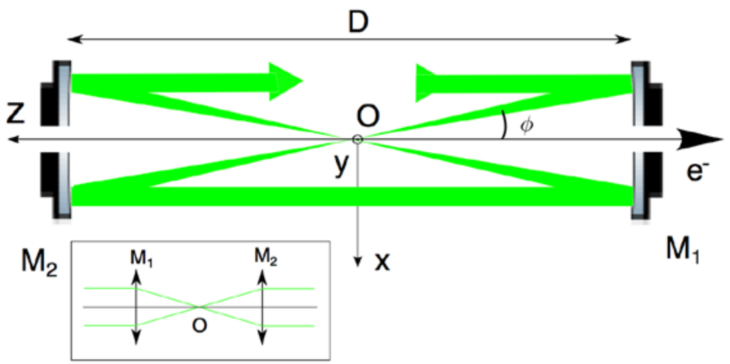

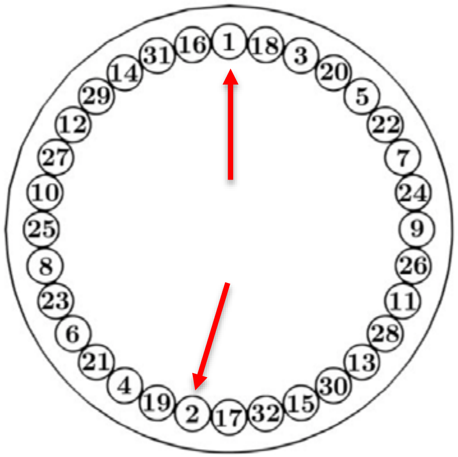

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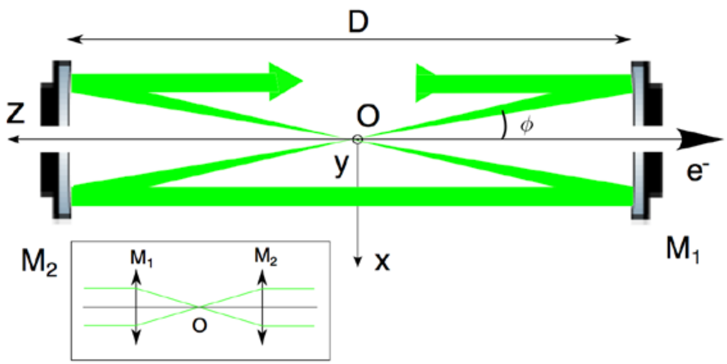

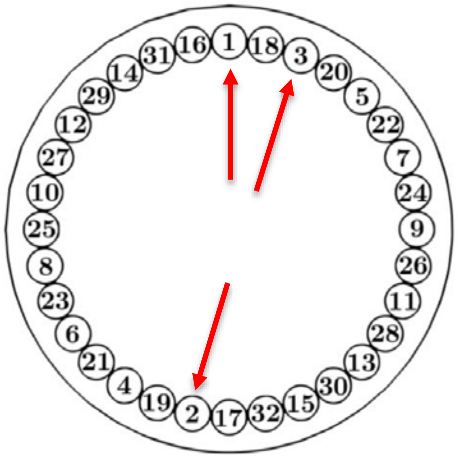

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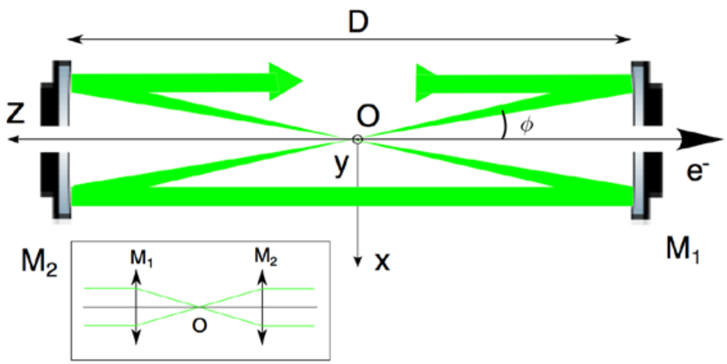

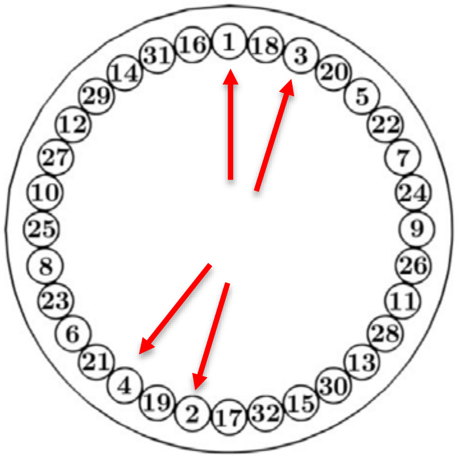

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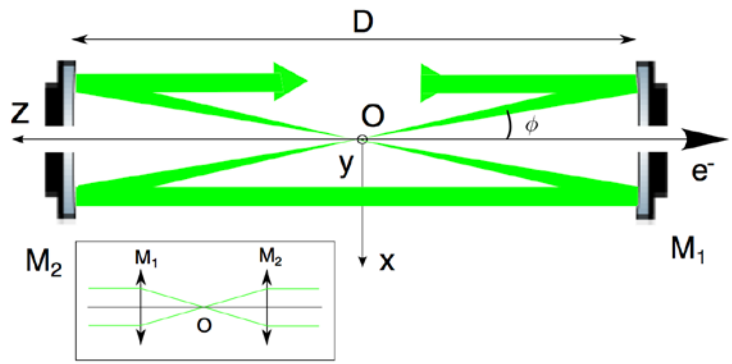

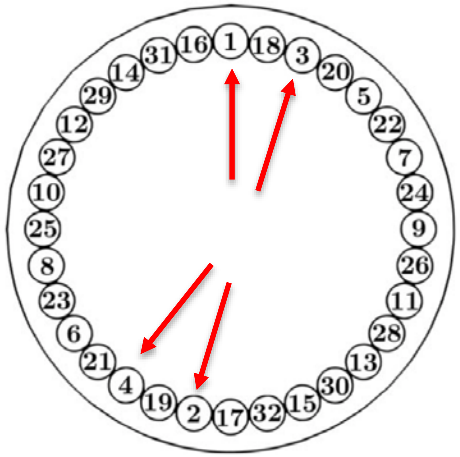

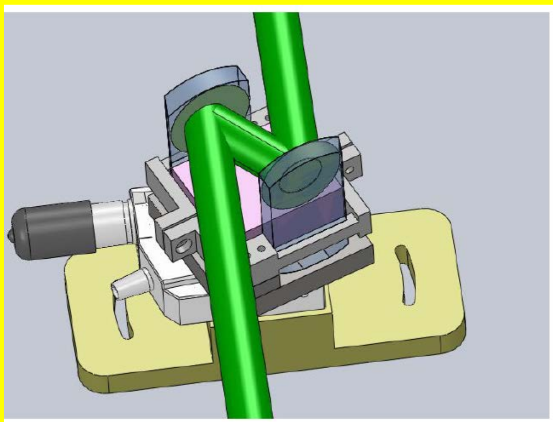

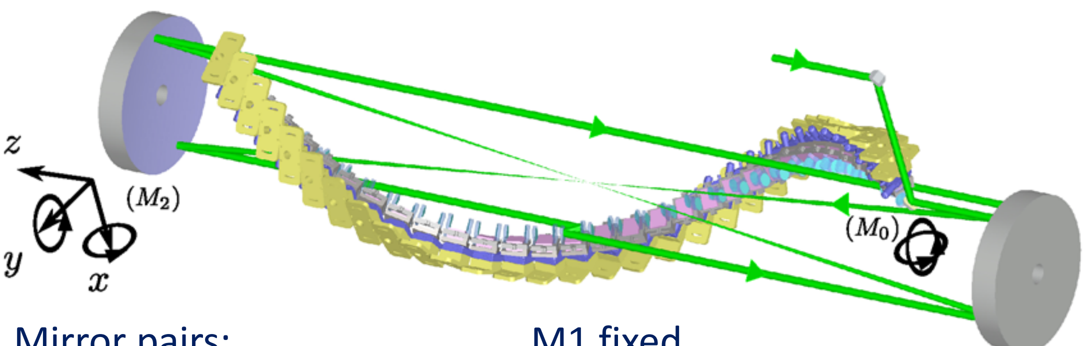

Mirror pairs:
interaction plane rotation
32 pulses synchronization

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

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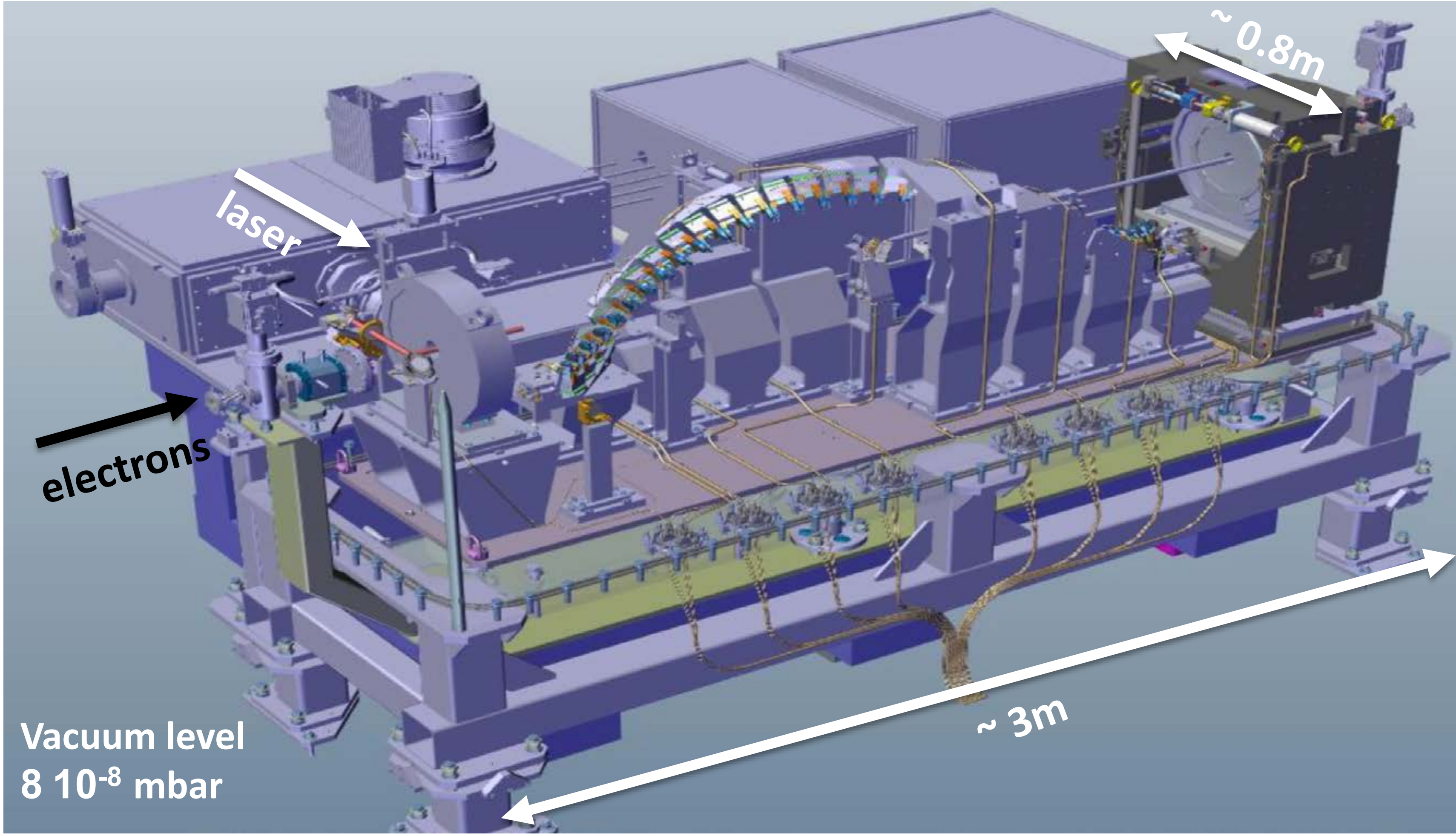
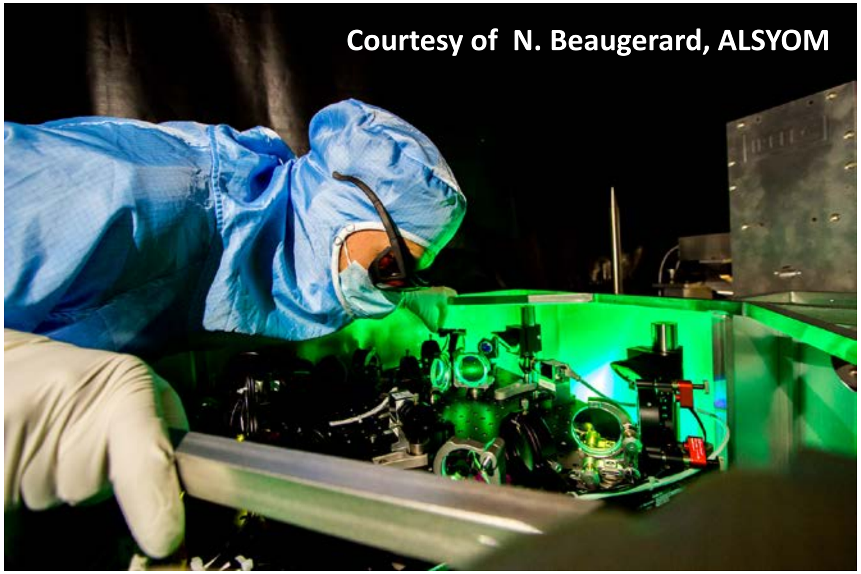
LASER CIRCULATOR

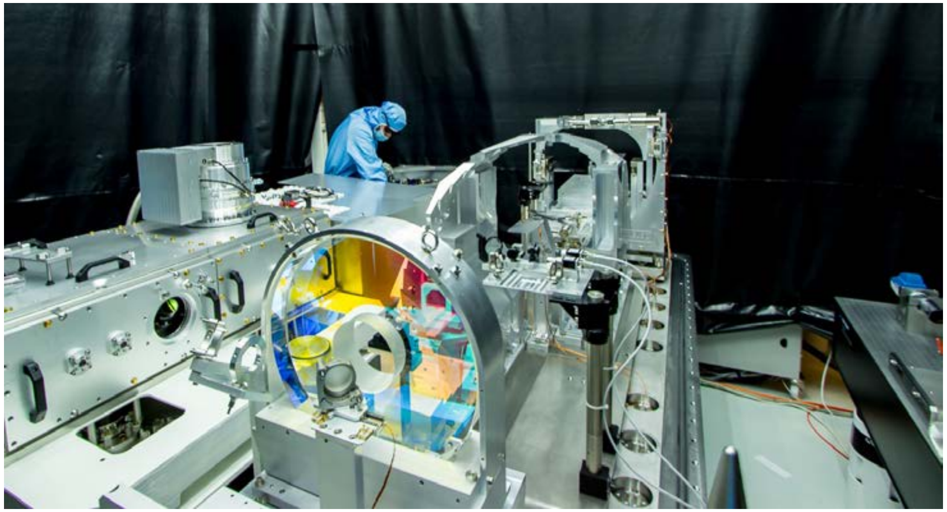


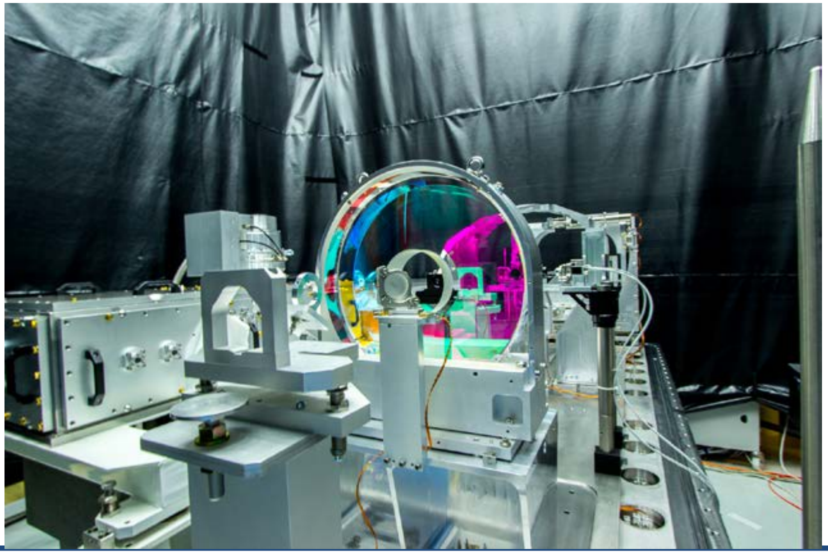
38 degrees of freedom for alignment/synchronisation → real-time flux monitoring beneficial

K. Cassou et al., LAL team

STATUS OF THE LASER CIRCULATOR







ELECTRON DIAGNOSTICS

We need accurate and precise beam measurement due to tight required beam performances.

Electrical

Electrical Signal + Signal Processing

Non destructive

Optical

Footprint of the electron beam

Image of the footprint

Centroid, RMS spot size

ELECTRON DIAGNOSTICS

We need accurate and precise beam measurement due to tight required beam performances.

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Beam Position/Trajectory

Cavity BPM (#4)

Strip Line BPM (#29)

Beam Charge

Beam Loss

Luminosity

Optical

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Envelope Scan

+ Quadrupoles → **Twiss Parameters.** (Quad Scan)

+ Dipole → **Energy** / **Energy Spread**

+ RF Deflector → **Bunch Length**

Longitudinal Phase Space

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+ RF Deflector → **Bunch Length**

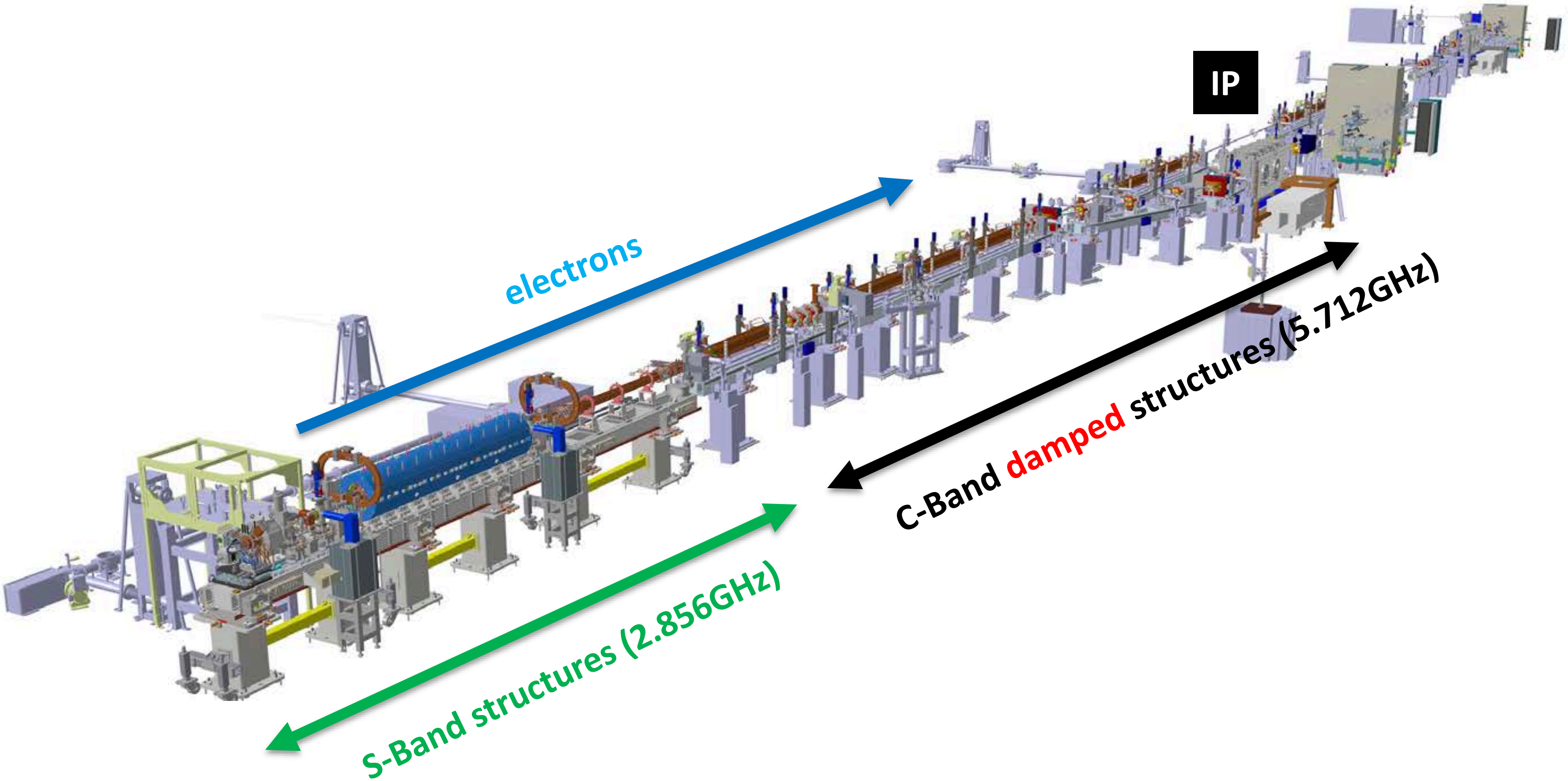
Energy Spread + Bunch Length → **Longitudinal Phase Space**

+ Gated Camera

32 bunches

DIAGNOSTICS

G. Franzini, F. Cioeta, D. De Cortis M. Marongiu, L. Sabato, M. Serio, A. Stella, V. Pettinacci



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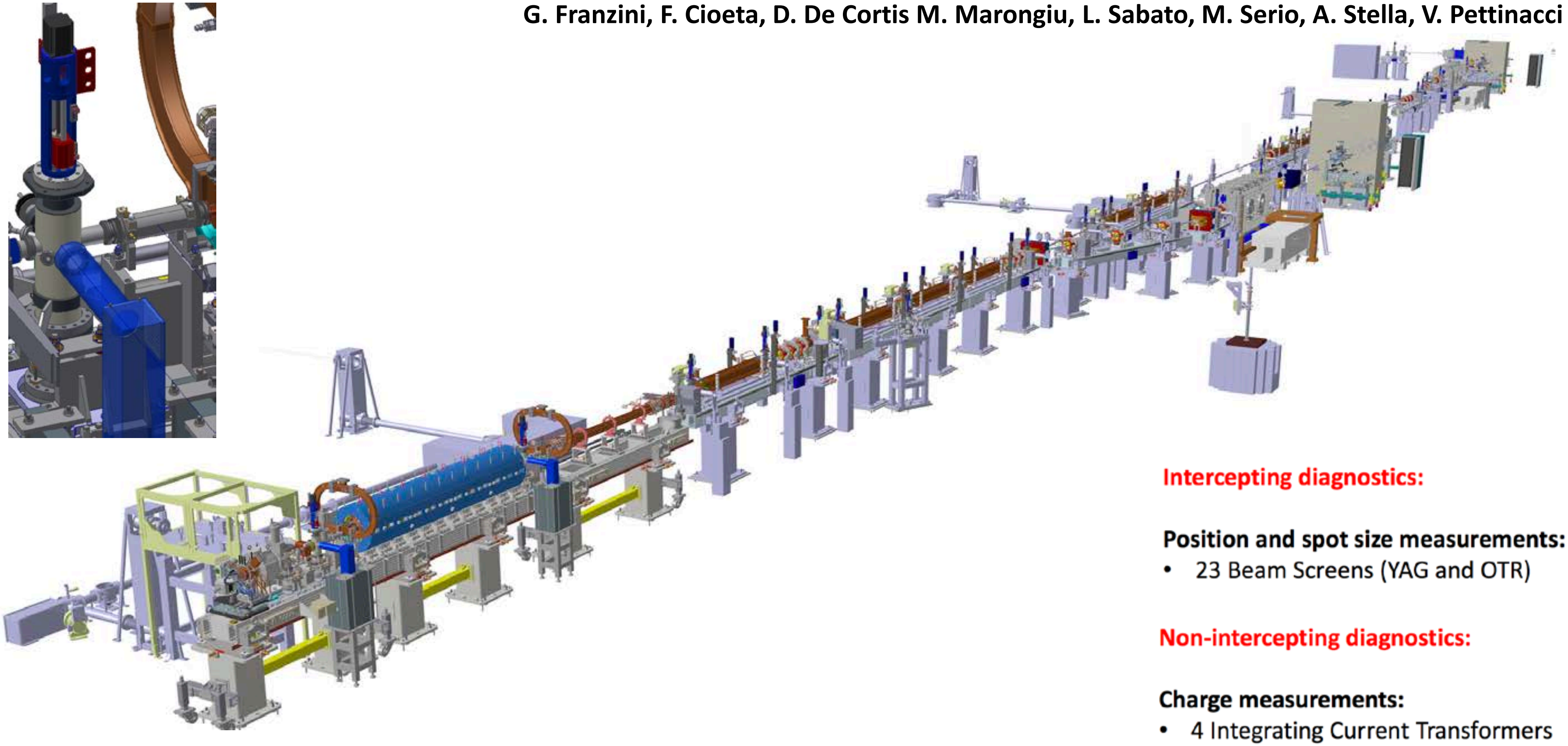


Intercepting diagnostics:

Position and spot size measurements:

- 23 Beam Screens (YAG and OTR)

Non-intercepting diagnostics:

Charge measurements:

- 4 Integrating Current Transformers (bunch by bunch)

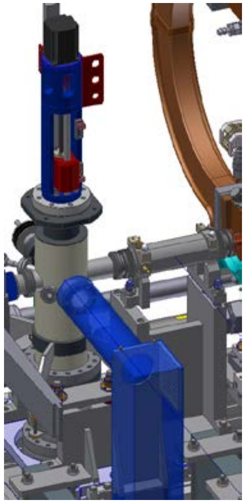
Position measurements:

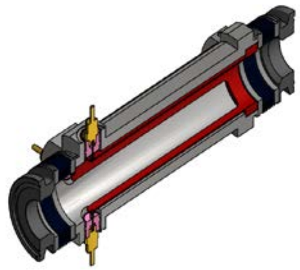
- 29 stripline BPMs (Macro pulse)
- 4 cavity BPMs (bunch by bunch)

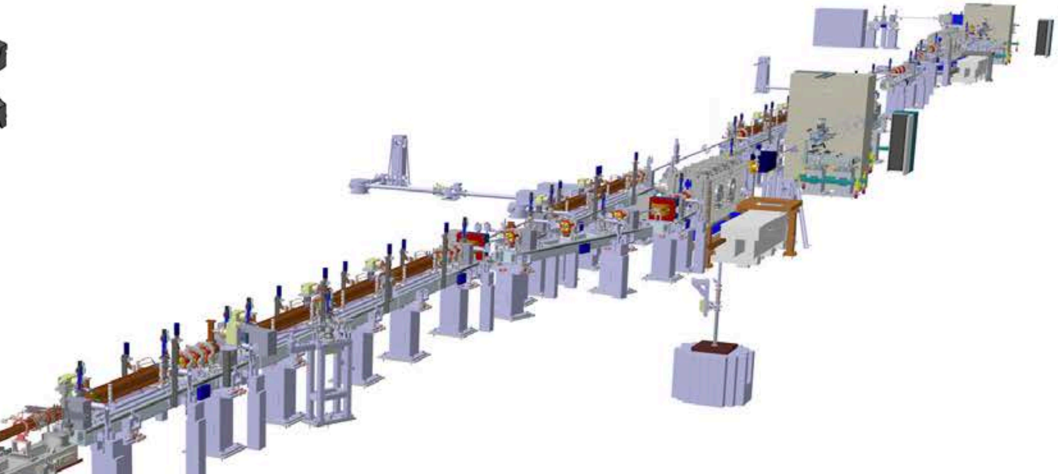
- Beam Loss Monitor System

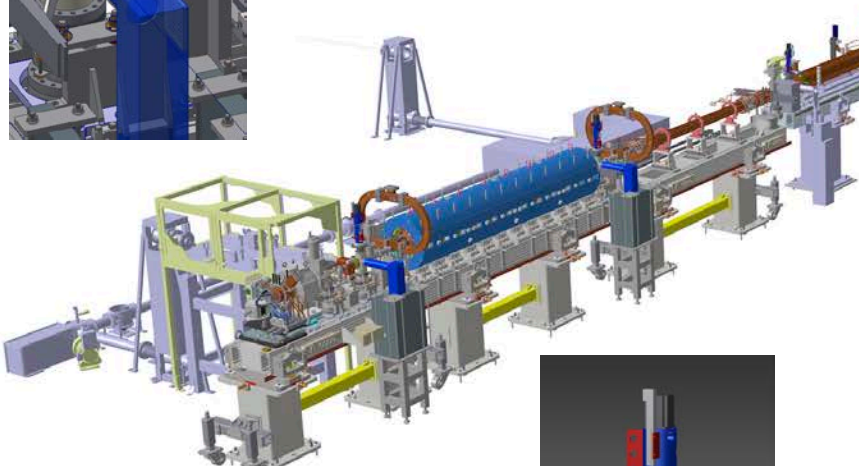
DIAGNOSTICS

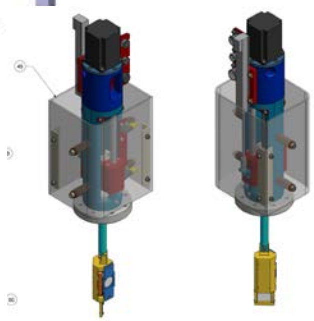
G. Franzini, F. Cioeta, D. De Cortis M. Marongiu, L. Sabato, M. Serio, A. Stella, V. Pettinacci











Intercepting diagnostics:

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- 23 Beam Screens (YAG and OTR)

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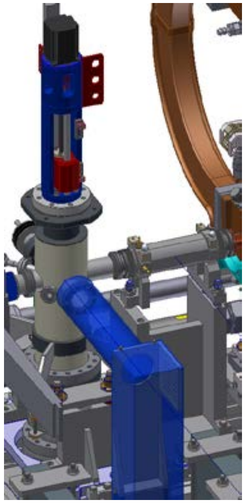

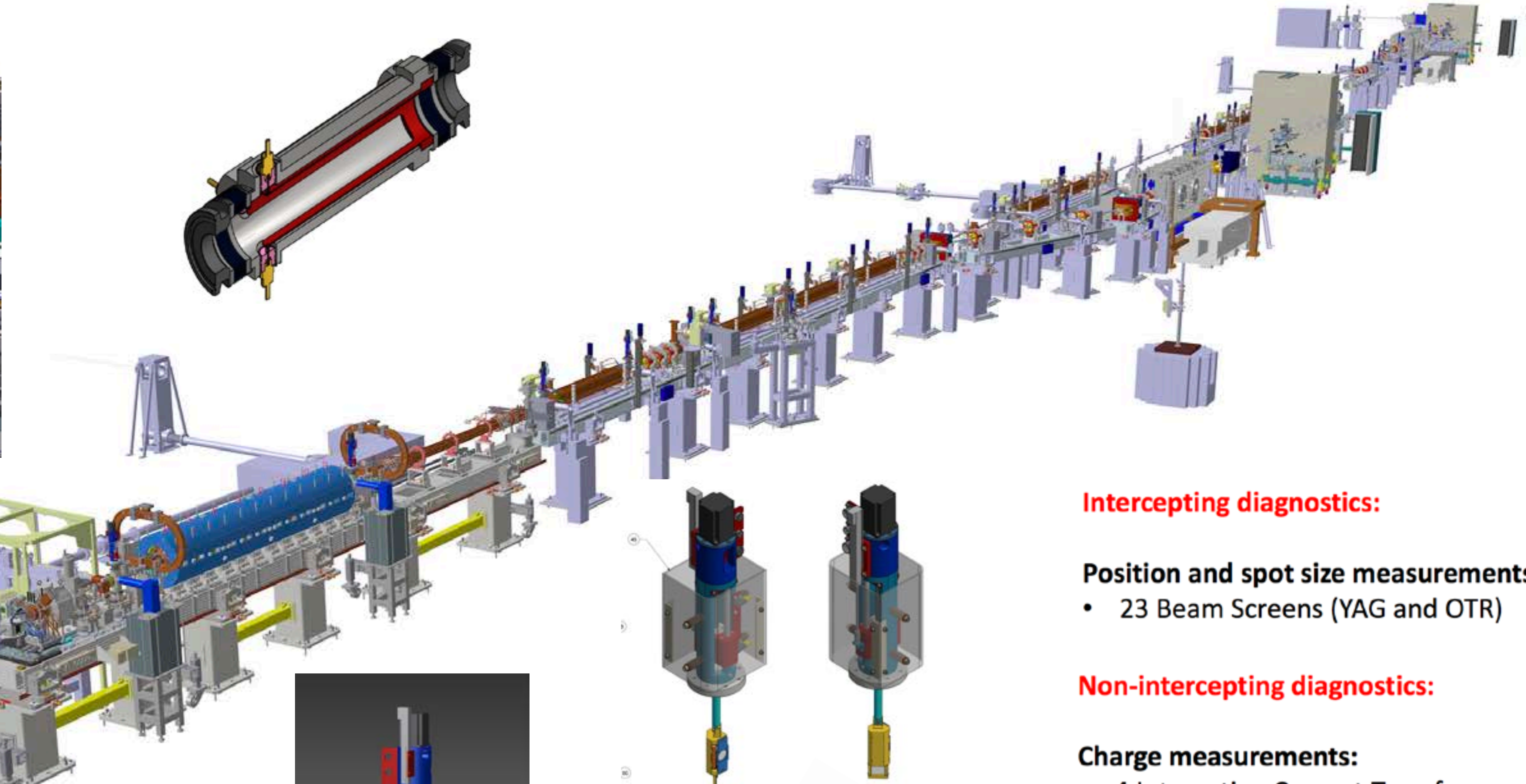

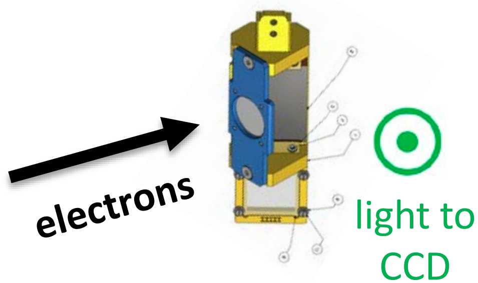

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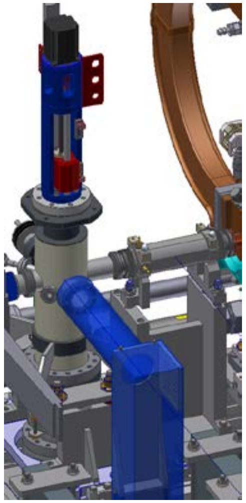

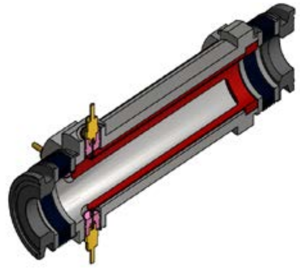

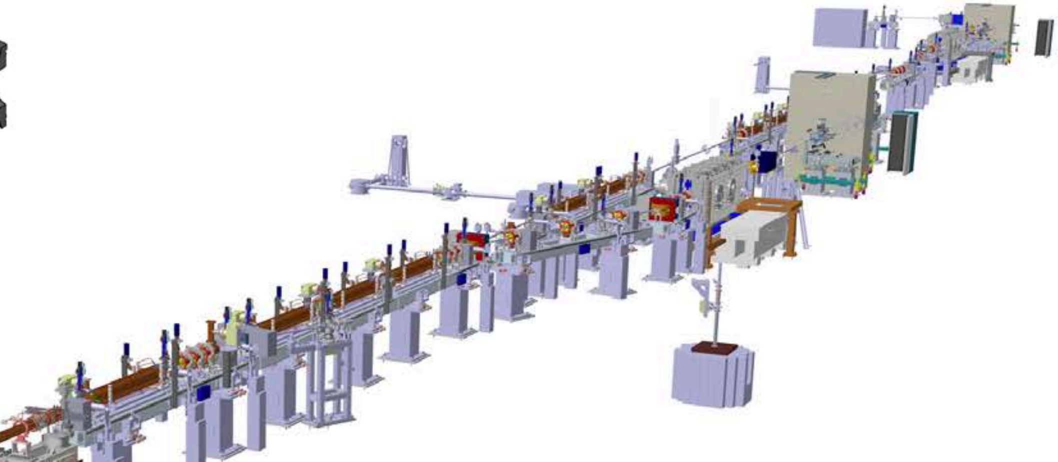

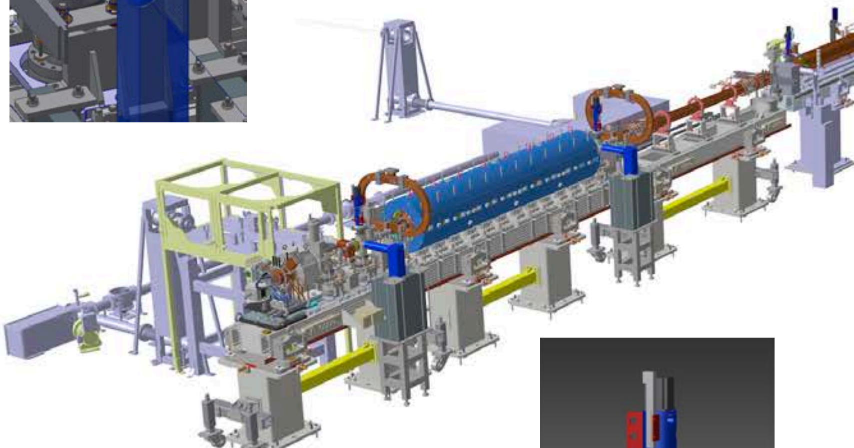

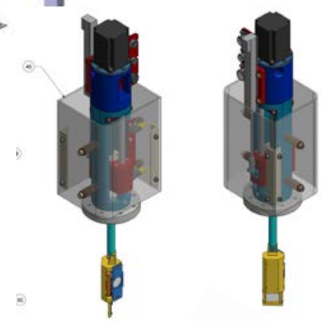

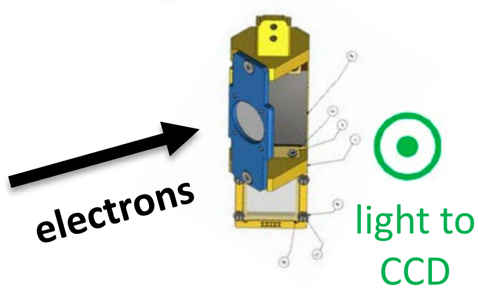

Possible upgrades
MOPCC13
TUPCF16

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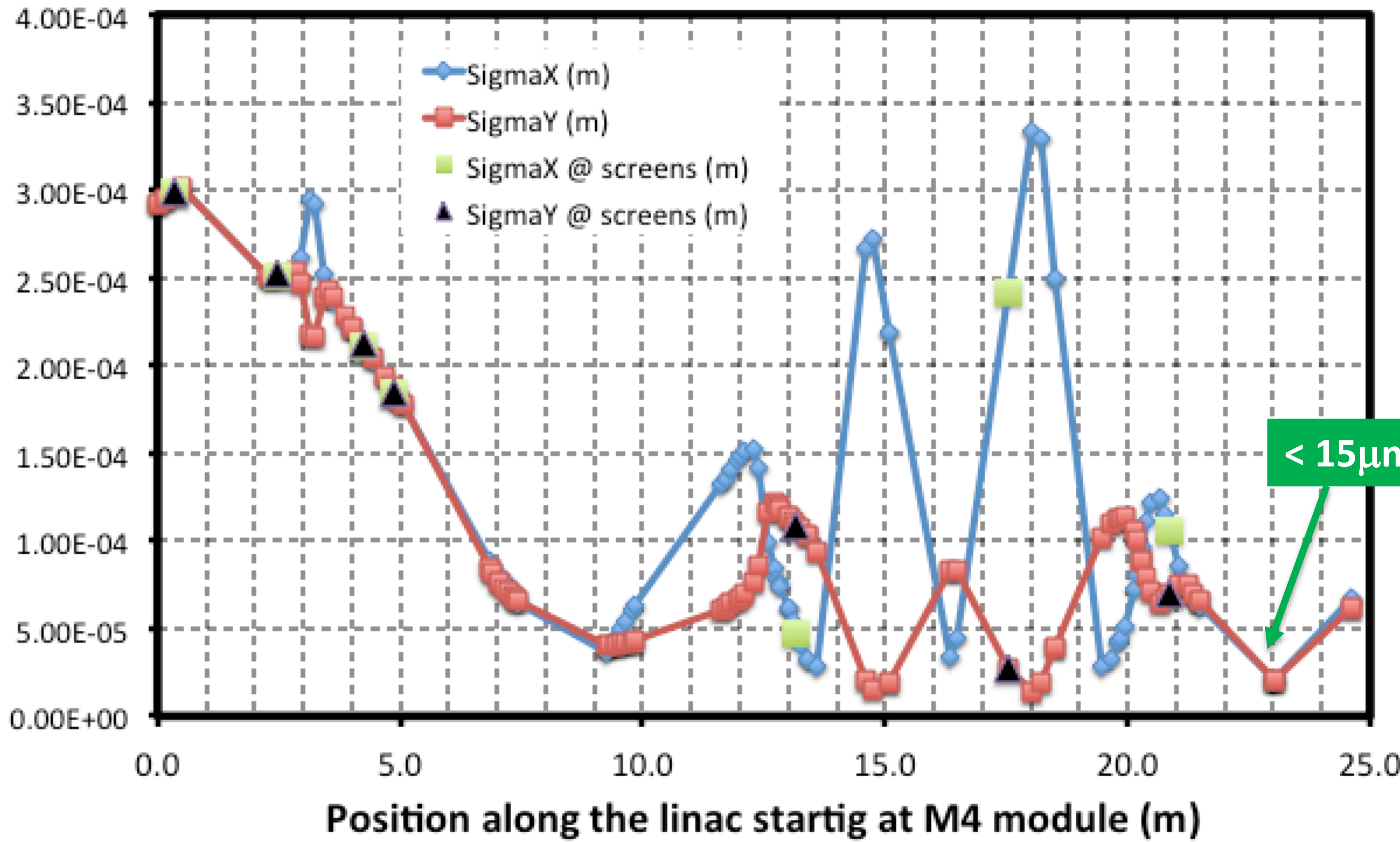
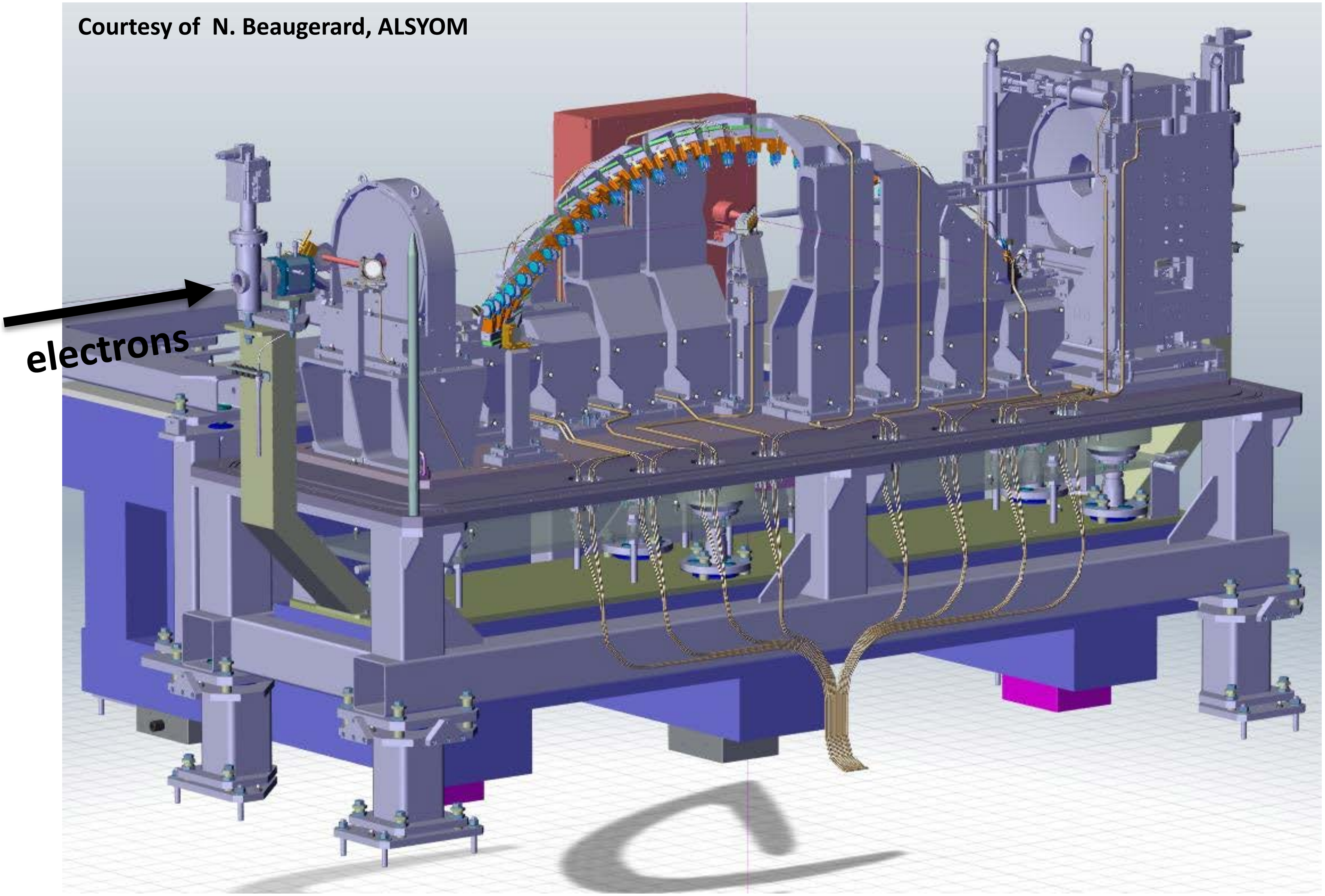
BEAM SPOT SIZE ALONG THE LINAC

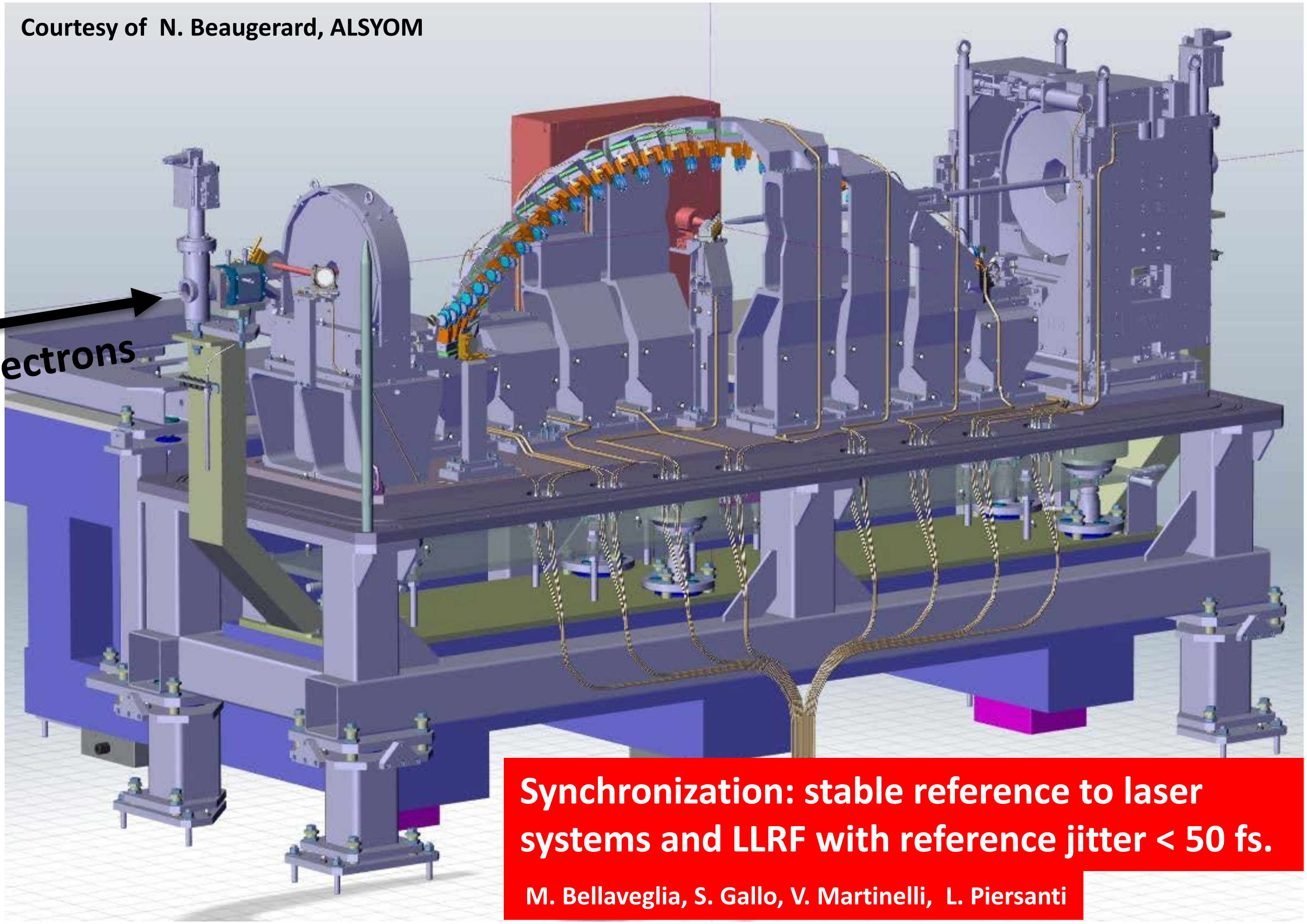


A. Girobono, C. Vaccarezza

INTERACTION POINT DIAGNOSTICS



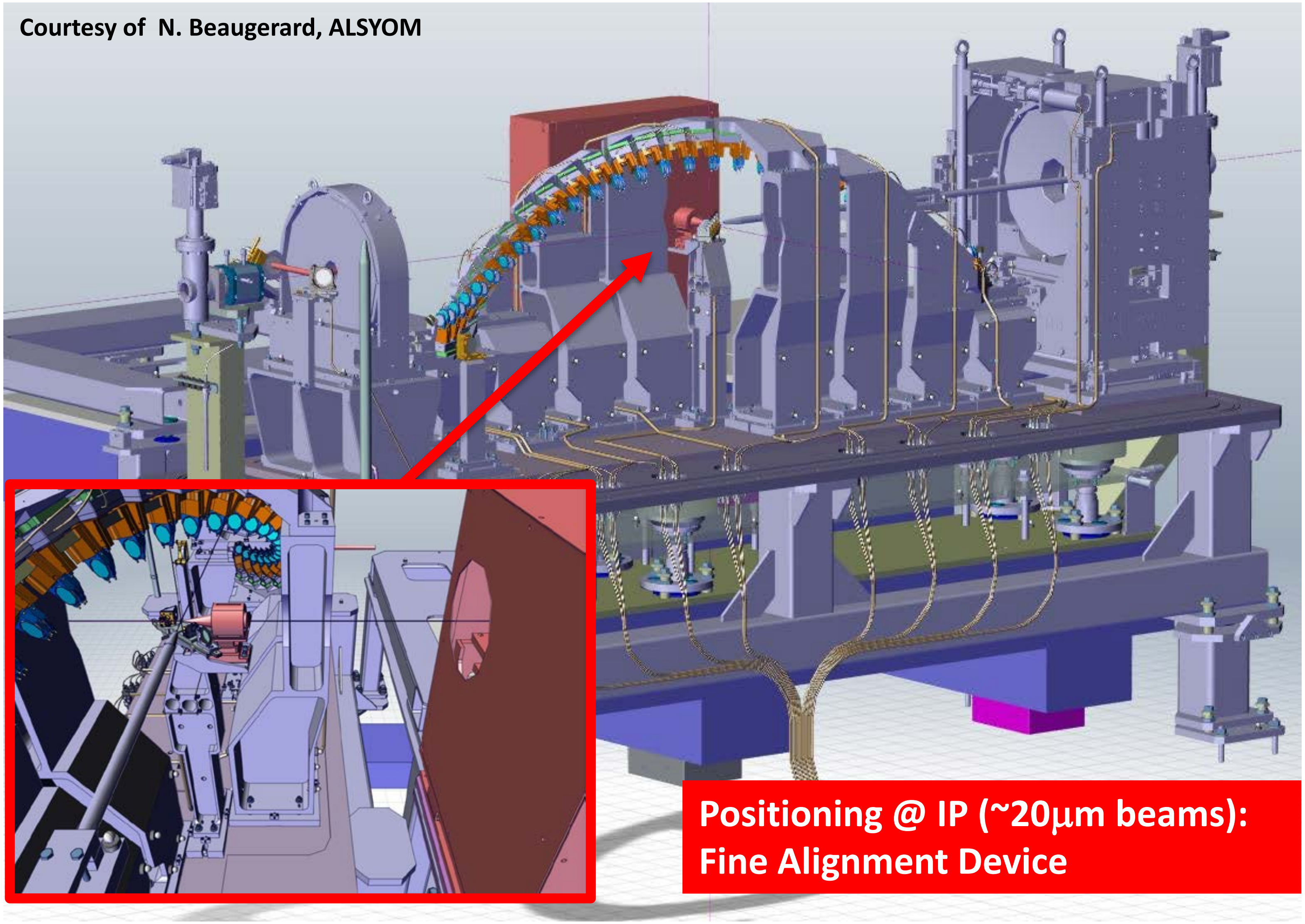
INTERACTION POINT DIAGNOSTICS



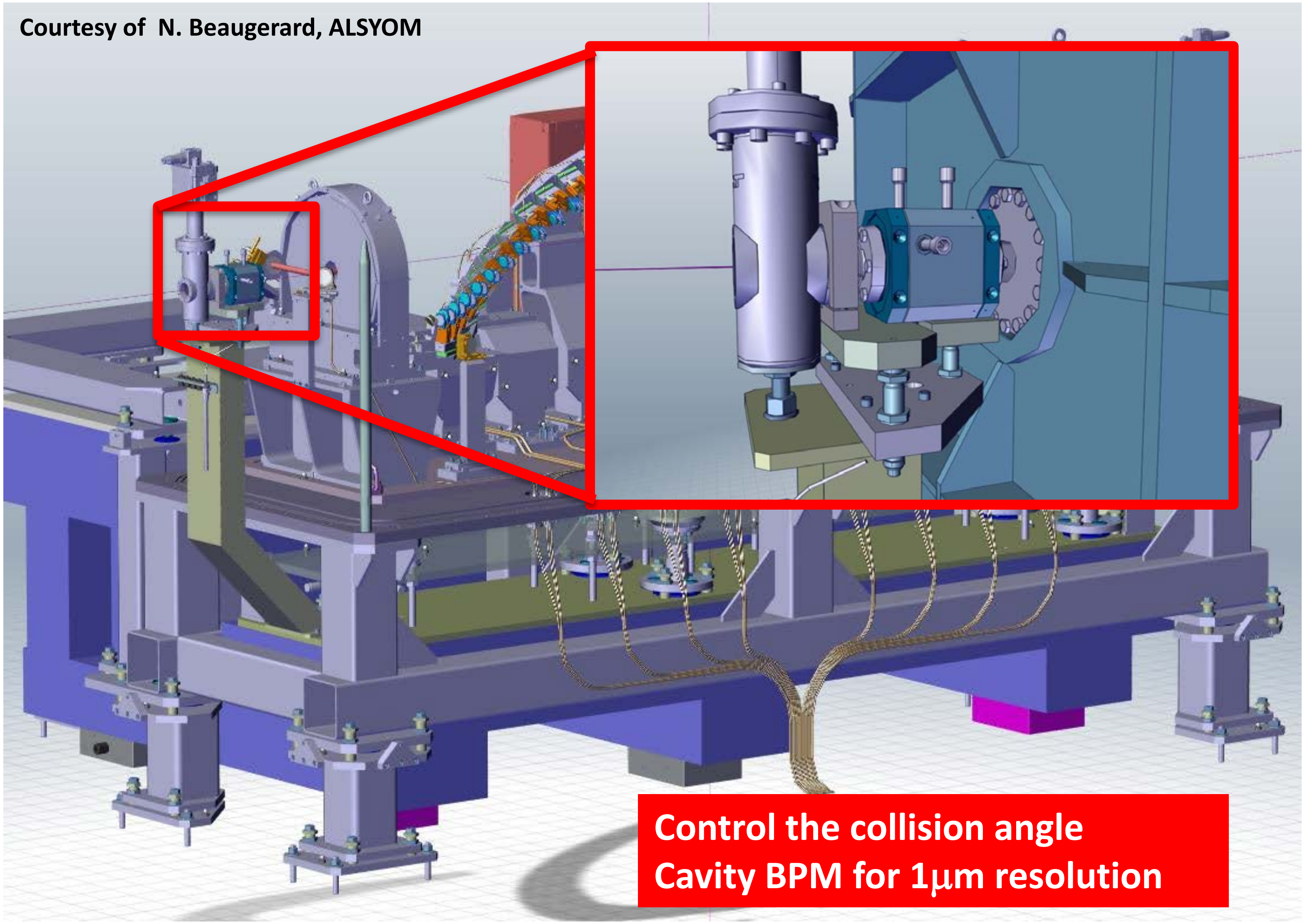
Synchronization: stable reference to laser systems and LLRF with reference jitter < 50 fs.

M. Bellaveglia, S. Gallo, V. Martinelli, L. Piersanti

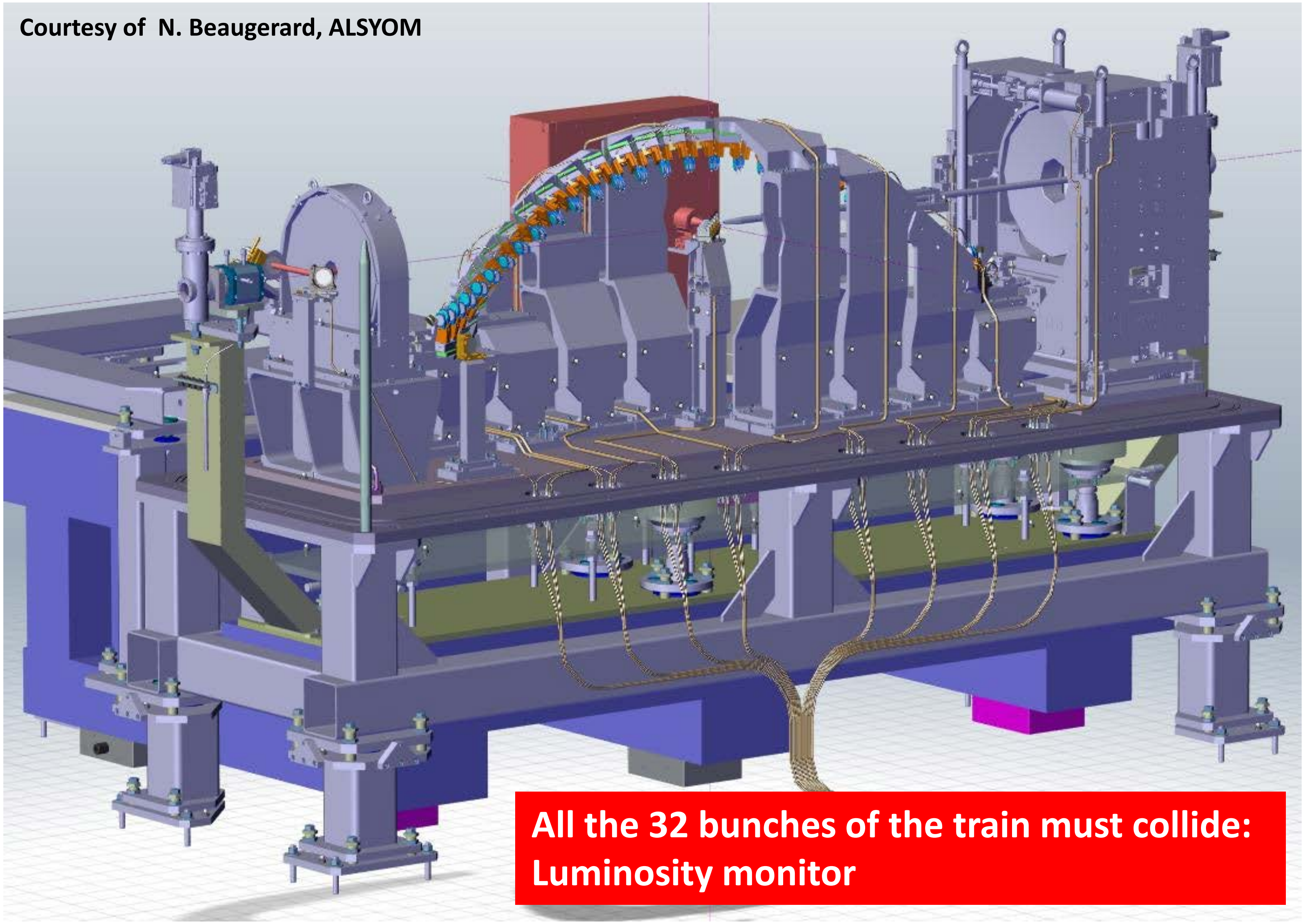
INTERACTION POINT DIAGNOSTICS



INTERACTION POINT DIAGNOSTICS

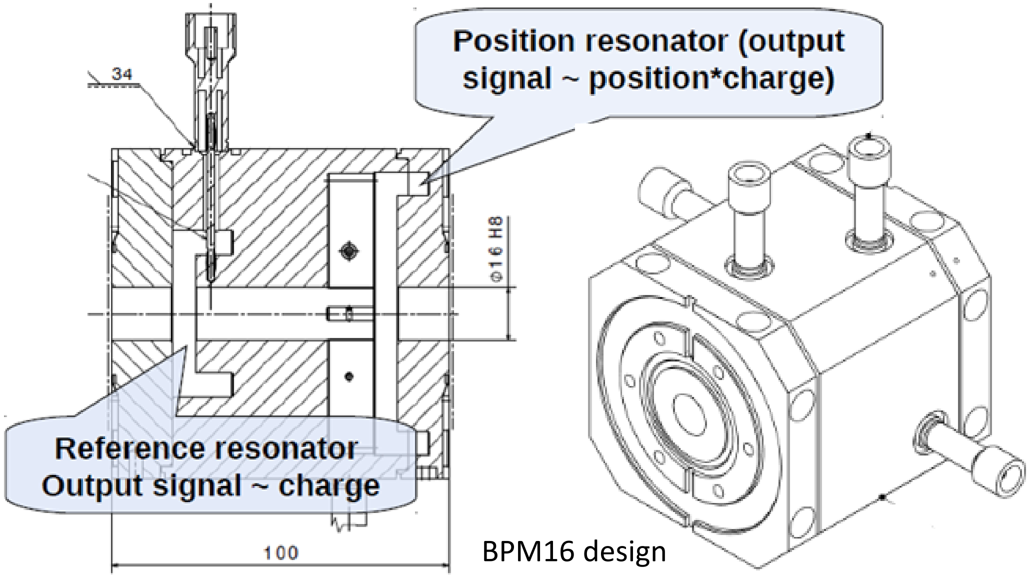


INTERACTION POINT DIAGNOSTICS

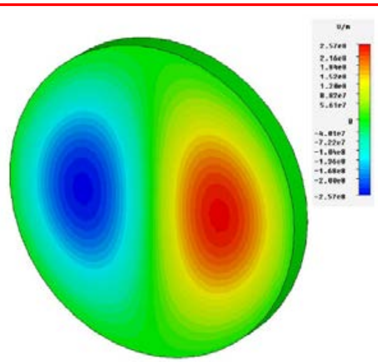


All the 32 bunches of the train must collide: Luminosity monitor

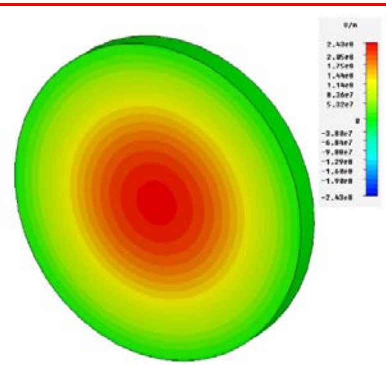
CAVITY BPM (PSI design)



BPM16 design



Mode TM_{110}



Mode TM_{010}

General Pickup Parameters

Parameter	Value
Material	Stainless Steel 316LN
Length [mm]	100
Inner Aperture [mm]	16
Distance from Pos. To Ref. Resonator [mm]	60

Position Cavity Resonator

Parameter	Value
Gap between res. walls [mm]	7
Q_L	40
TM_{110} Frequency [GHz]	3.284
TM_{010} Frequency [GHz]	2.252
Position Signal [V/mm/nC]	7.07
Angle Signal [µm/mrad]	4.3

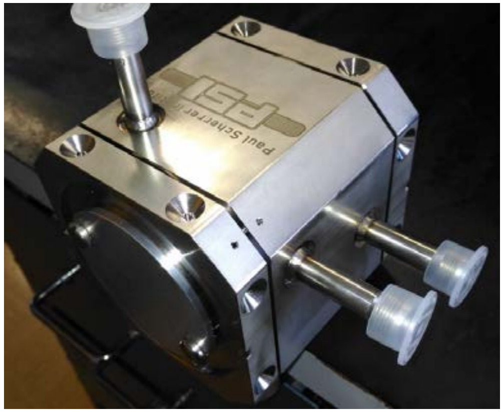
Reference Cavity Resonator

Parameter	Value
Gap between res. walls [mm]	7
Q_L	40
TM_{010} Frequency [GHz]	3.284
Charge Signal [V/nC]	135
Angle Signal [µm/mrad]	4.3

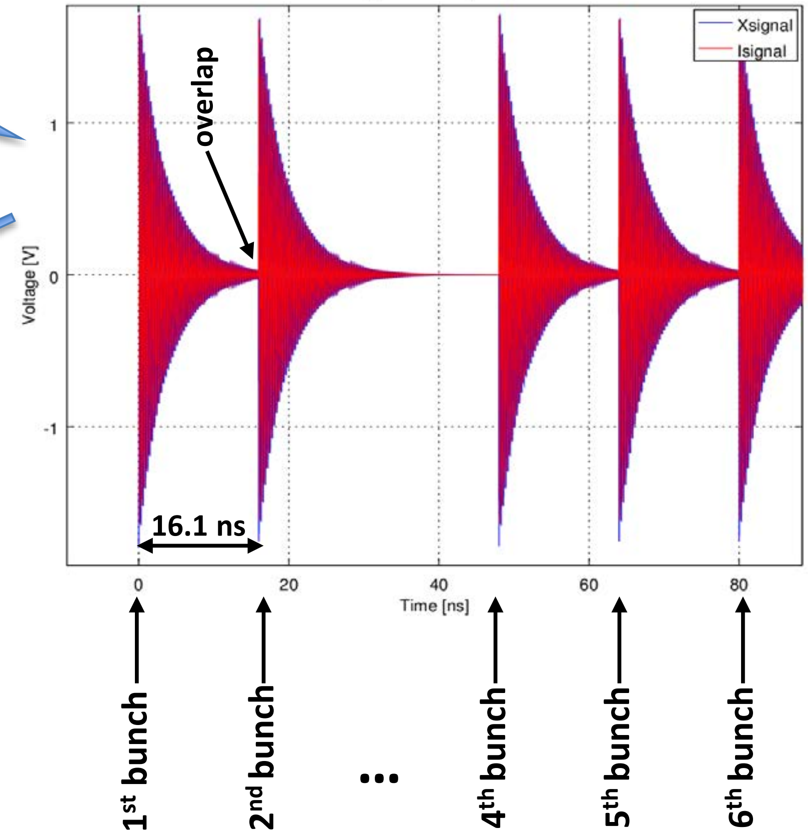
CAVITY BPM Features and output Signals

G. Franzini, M. Cargnelutti (I-tech), A. Stella

Cavity BPM



Output Signal



Libera for Cavity

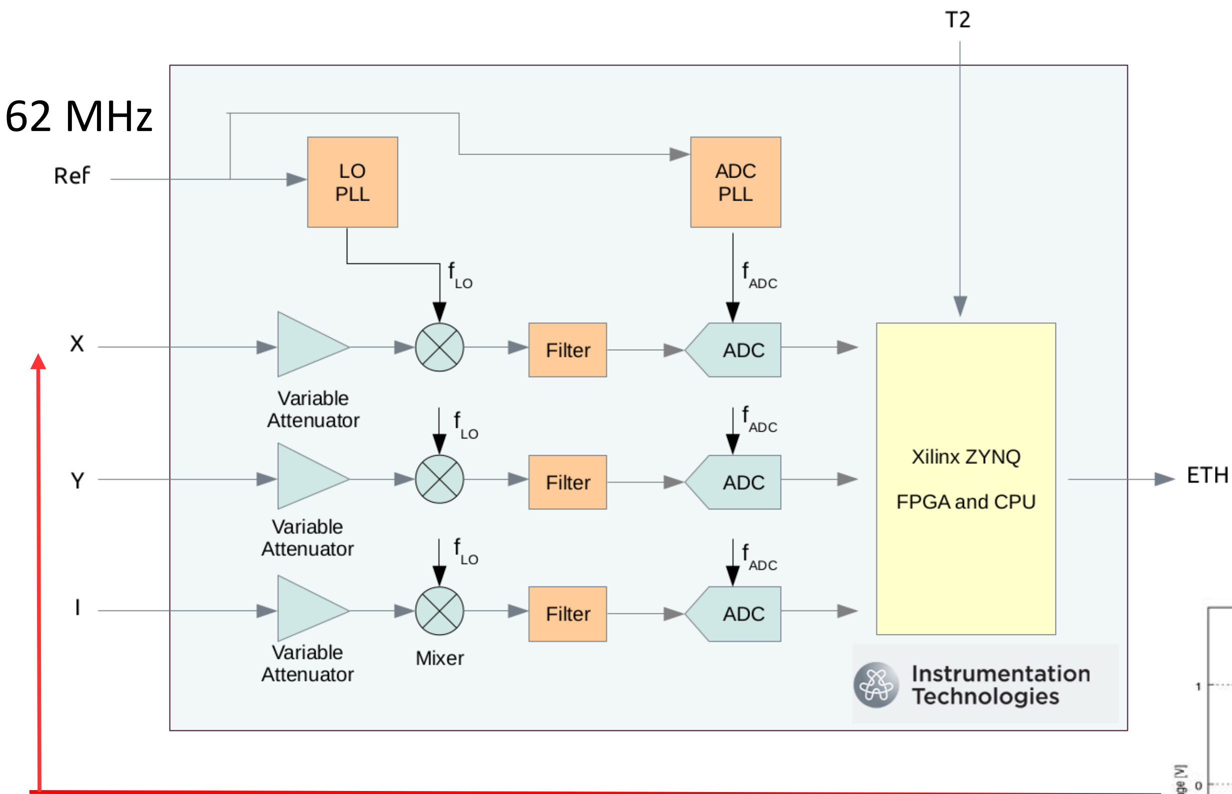
ADC	4 channels, 500MS/s, 14bit
SoC	ZYNQ 7035 / ARM Cortex A9
ADC buffer	4kS/channel (~8us)
Variable attenuation	31dB, channel-independent
Input signal freq.	C-band, S-band
Ref. signal freq.	Up to 250MHz

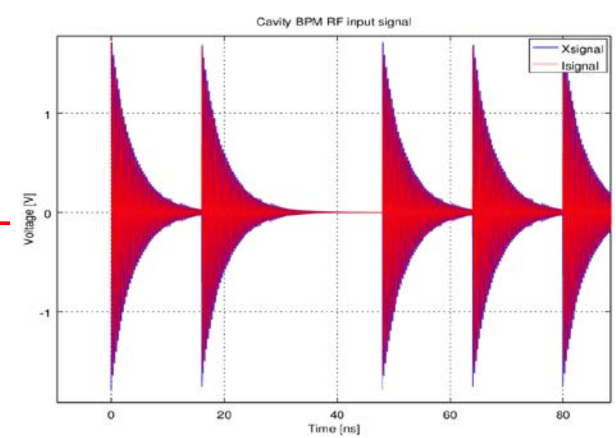
Instrumentation Technologies

Goal: 1 μm resolution

CAVITY BPM ELECTRONICS

G. Franzini, M. Cargnelutti (I-tech), A. Stella



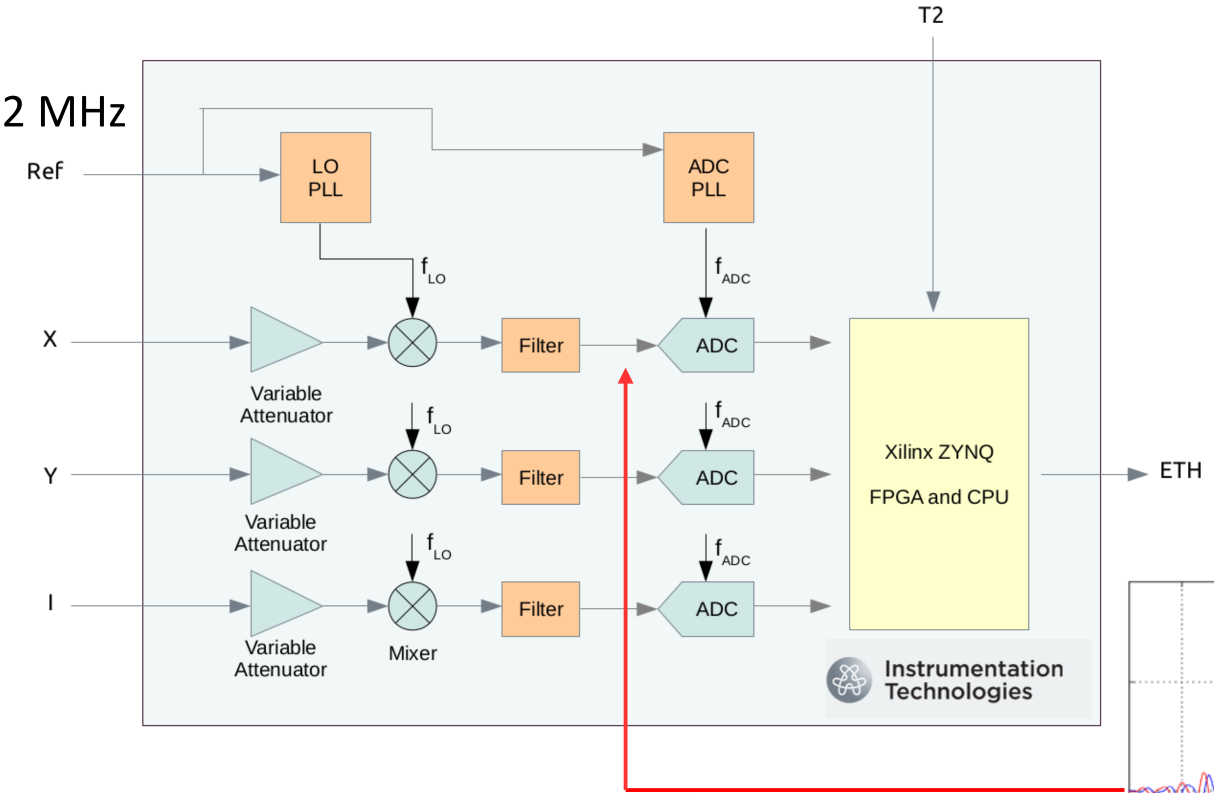


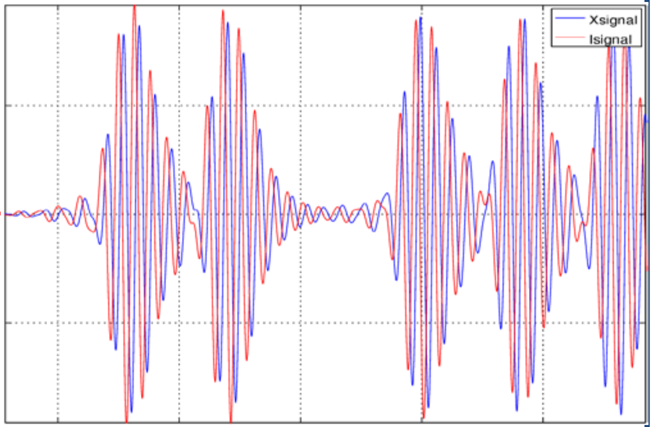
See also TUPCF16

CAVITY BPM ELECTRONICS

G. Franzini, M. Cargnelutti (I-tech), A. Stella

62 MHz





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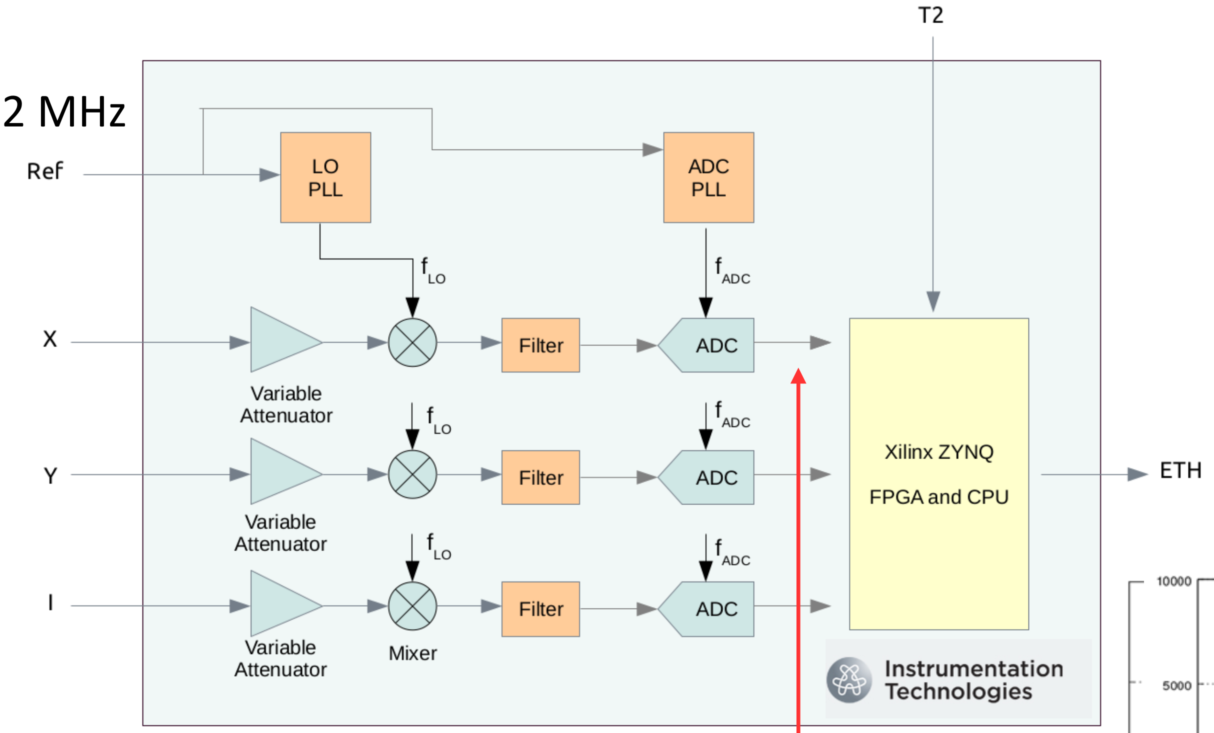
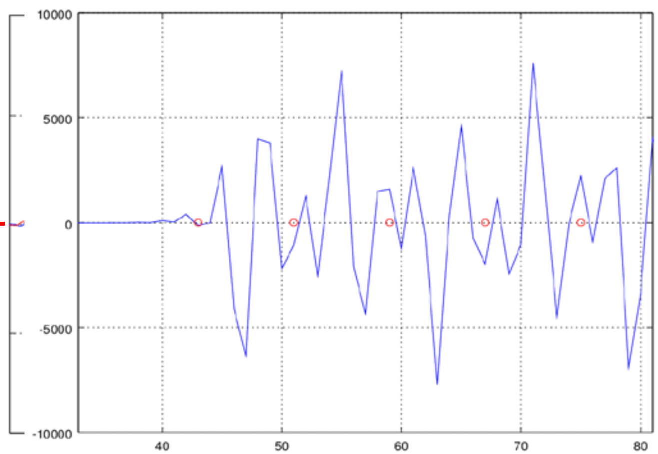
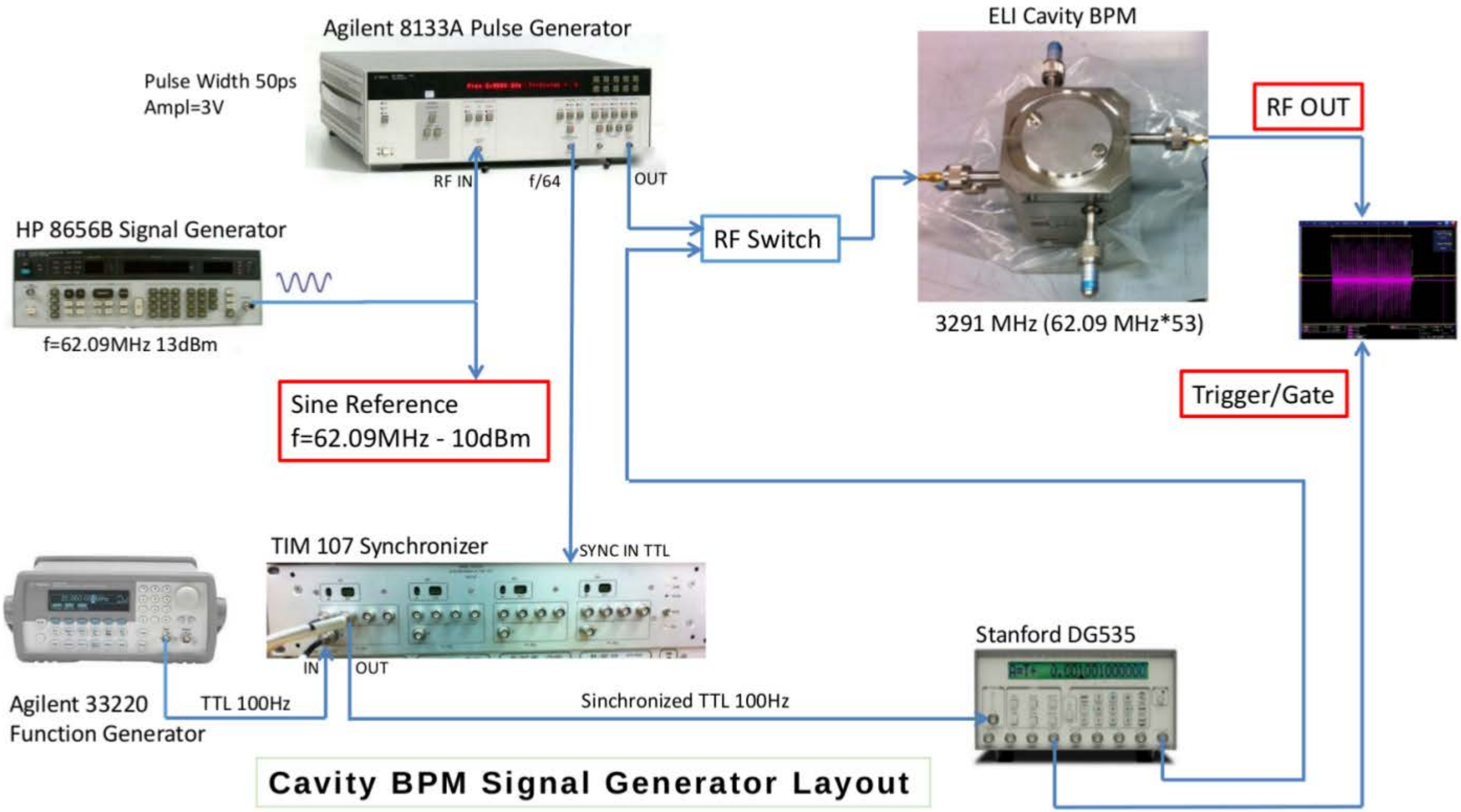




See also TUPCF16

CAVITY BPM ELECTRONICS: TEST bench

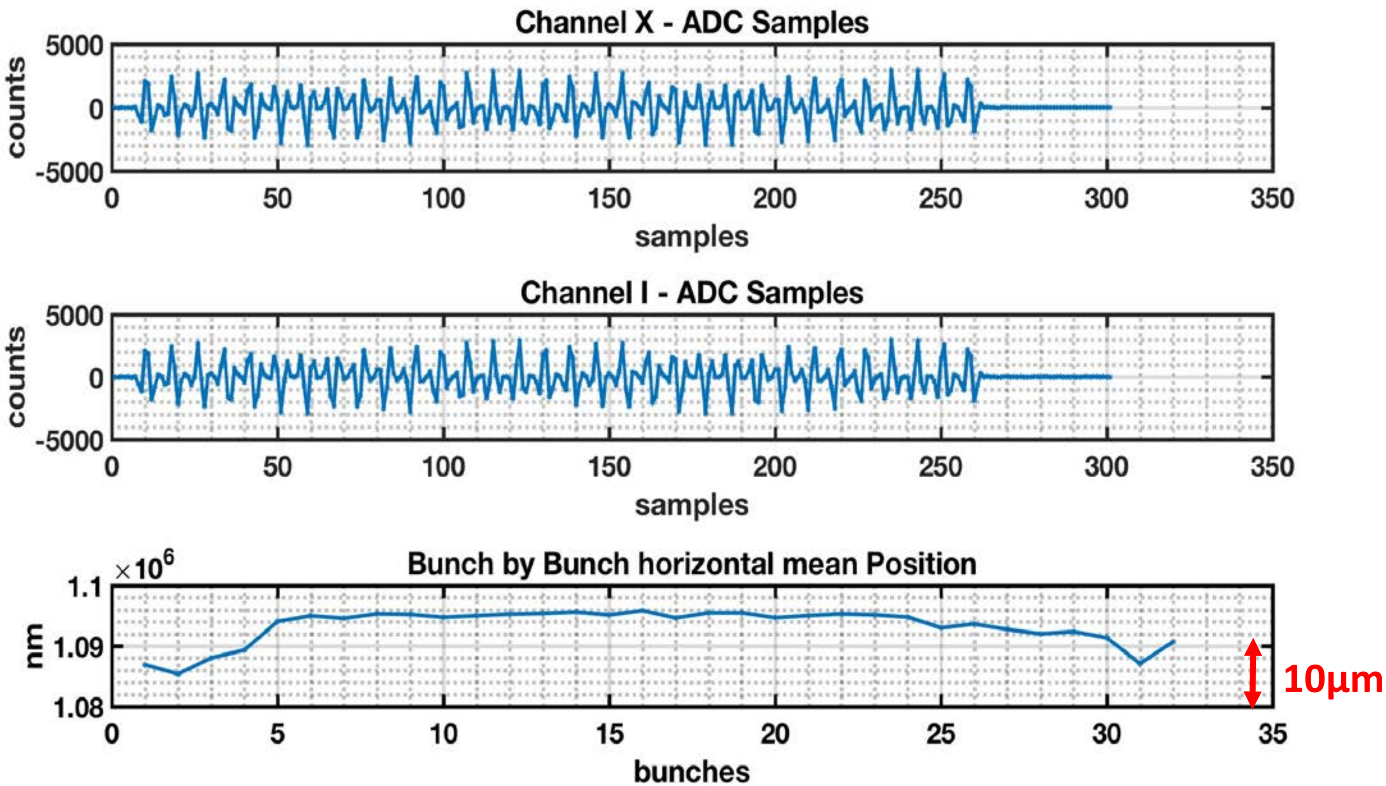
O. Coiro, G. Franzini, A. Stella



Cavity BPM Signal Generator Layout

CBPM ELECTRONICS: STATUS OF THE TEST

G. Franzini, M. Cargnelutti (I-tech), A. Stella



$$V_x = \sqrt{\sum_{i=1}^{8} {x_s}^2}$$

$$V_i = \sqrt{\sum_{i=1}^{8} {x_i}^2}$$

$$PosX = K_x \frac{V_x}{V_i}$$

The standard deviation of the calculated position for each of the 32 bunches is on average **0.3%** (3 µm over 1000 µm).

The calculated position for each bunch is more stable in the central region than on the edges of the train (**probably caused by the signal generator**).

THE FINE ALIGNMENT DEVICE

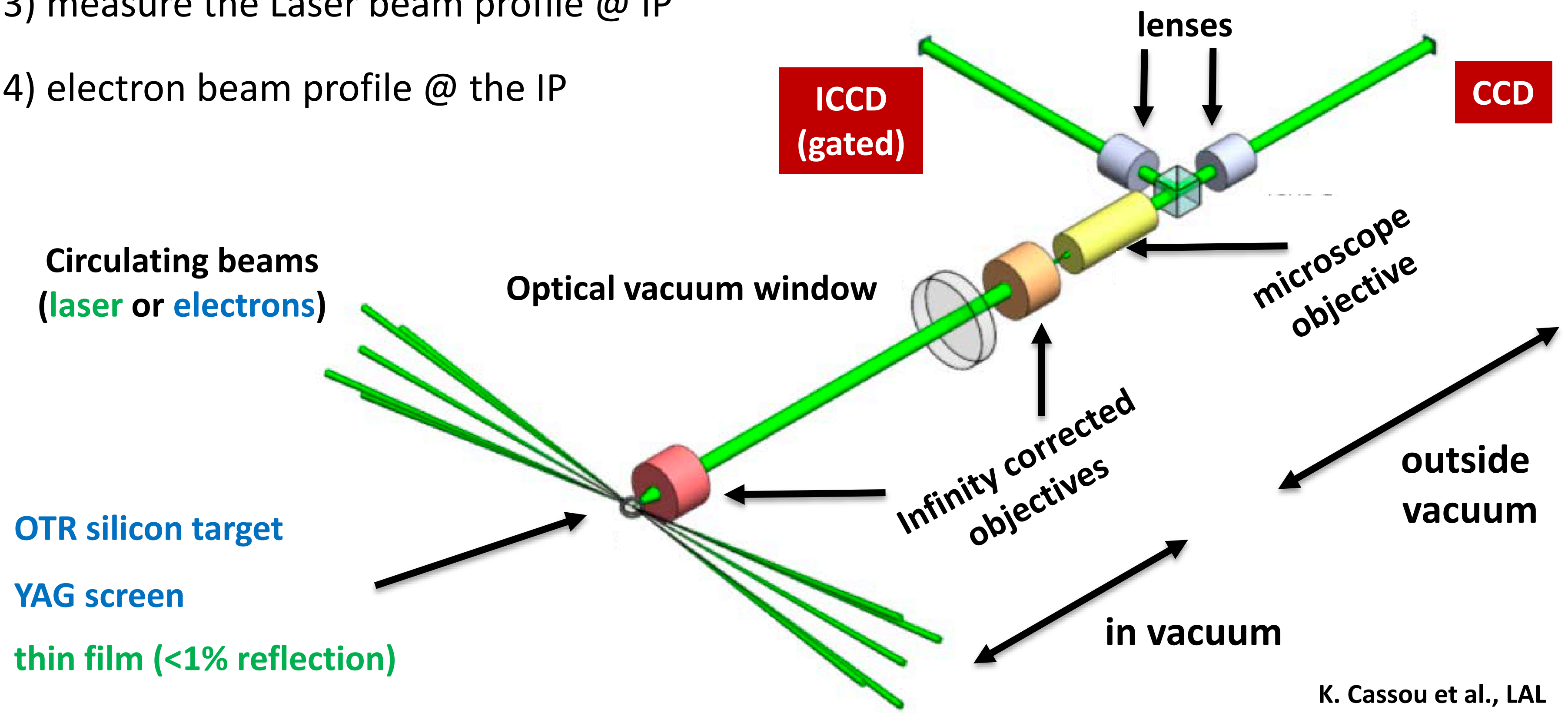
The **Fine Alignment Device** (**FAD**) is an optical imaging system with **μm resolution** to

1) align the Laser Beam Circulator (~5ns resolution due to the 16ns bunch spacing)

2) measure interference between the circulating beam and the reference (synchronization)

3) measure the Laser beam profile @ IP

4) electron beam profile @ the IP



K. Cassou et al., LAL

DESIGN OF THE FINE ALIGNMENT DEVICE

Replica of the IP outside the vacuum and image with standard microscope objectives

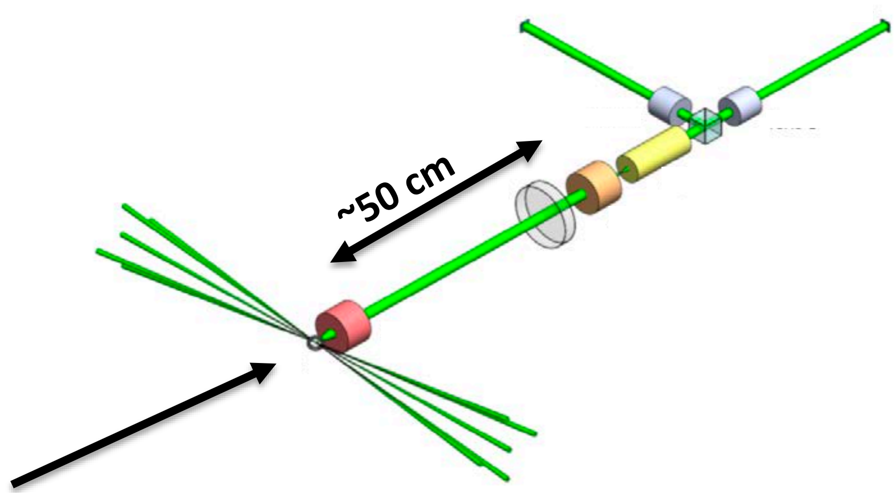
Analogy to long focal length optical systems used in quantum gas experiments.

Iterative design with ray tracing software (Zemax) to numerically optimize the lens spacing and curvatures to minimize the RMS wave-front error.

Use of easily available lenses.

Laser waist @ IP	**< 28μm**
Electron RMS spot @ IP	**< 15μm**

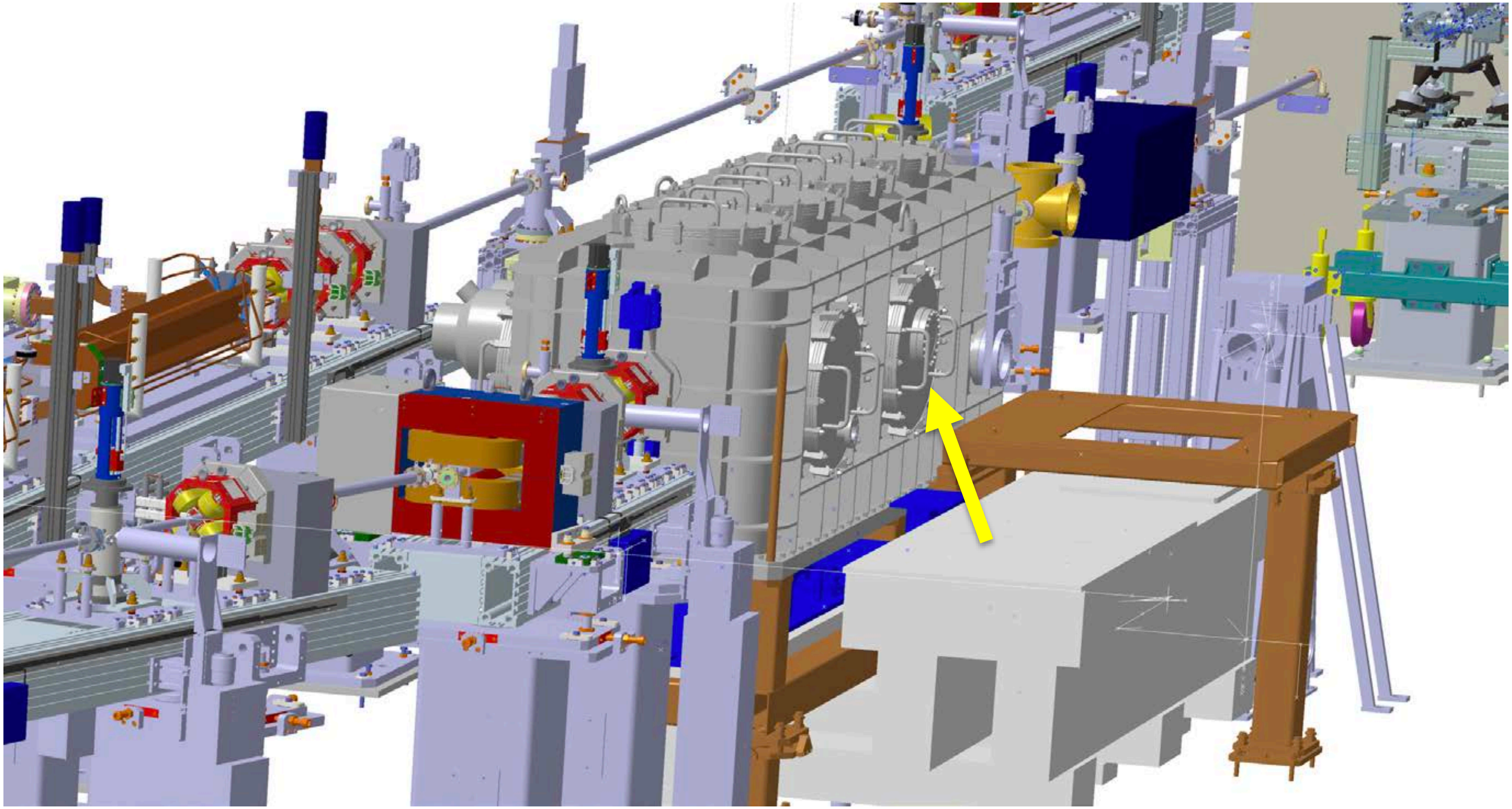
Description	Value (tolerance)
Numerical aperture	> 0.23
Resolving power	1.5 (0.5) um
Wavelength	515 (1) nm
Spectral band width	0.2 nm
Focus	3 mm
Time resolution	5 (2) ns
Working distance	> 60 (10) mm



K. Cassou et al., LAL

INTEGRATION OF THE FINE ALIGNMENT DEVICE

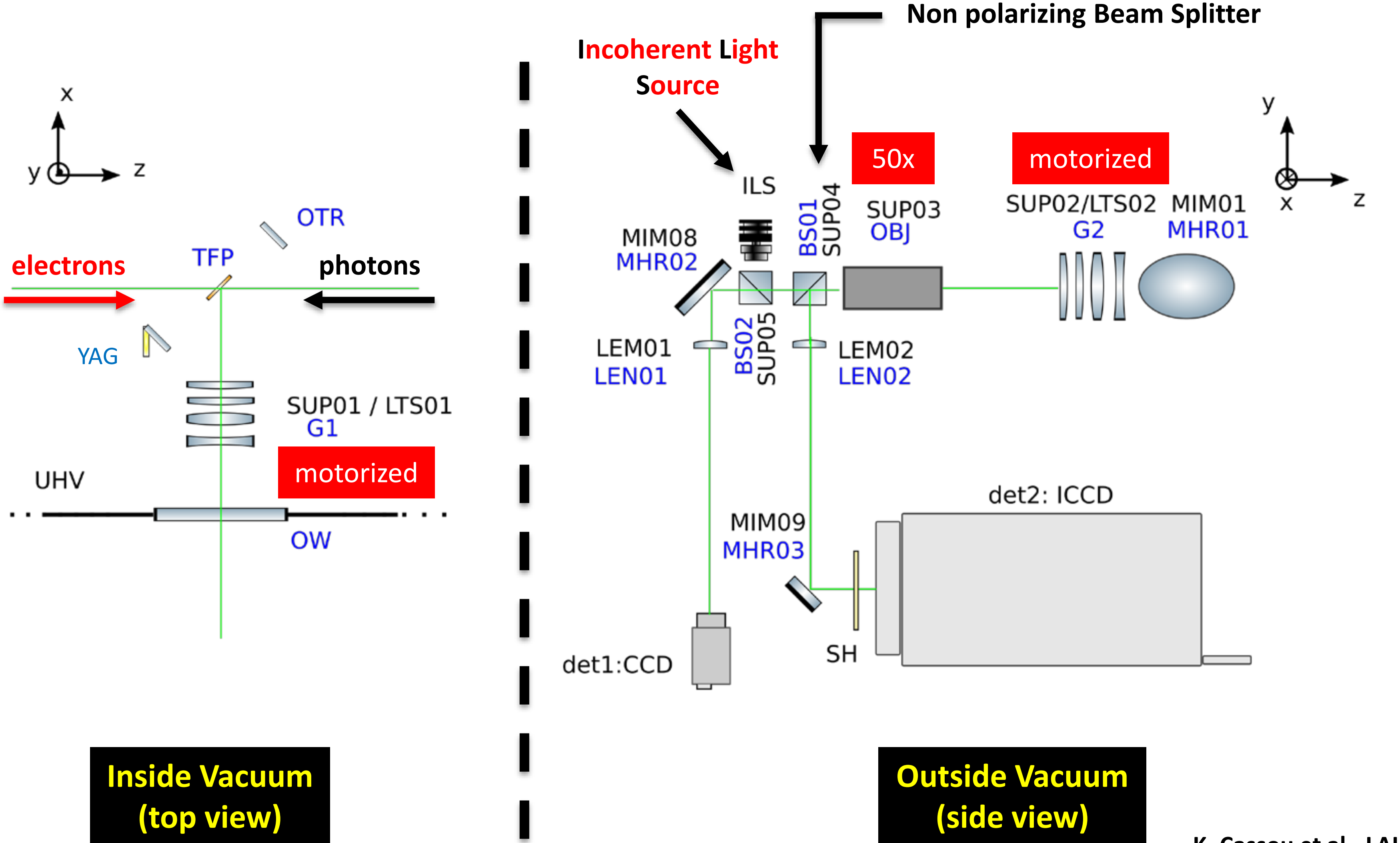
Integration in the center of the IP module.



V. Pettinacci, D. De Cortis

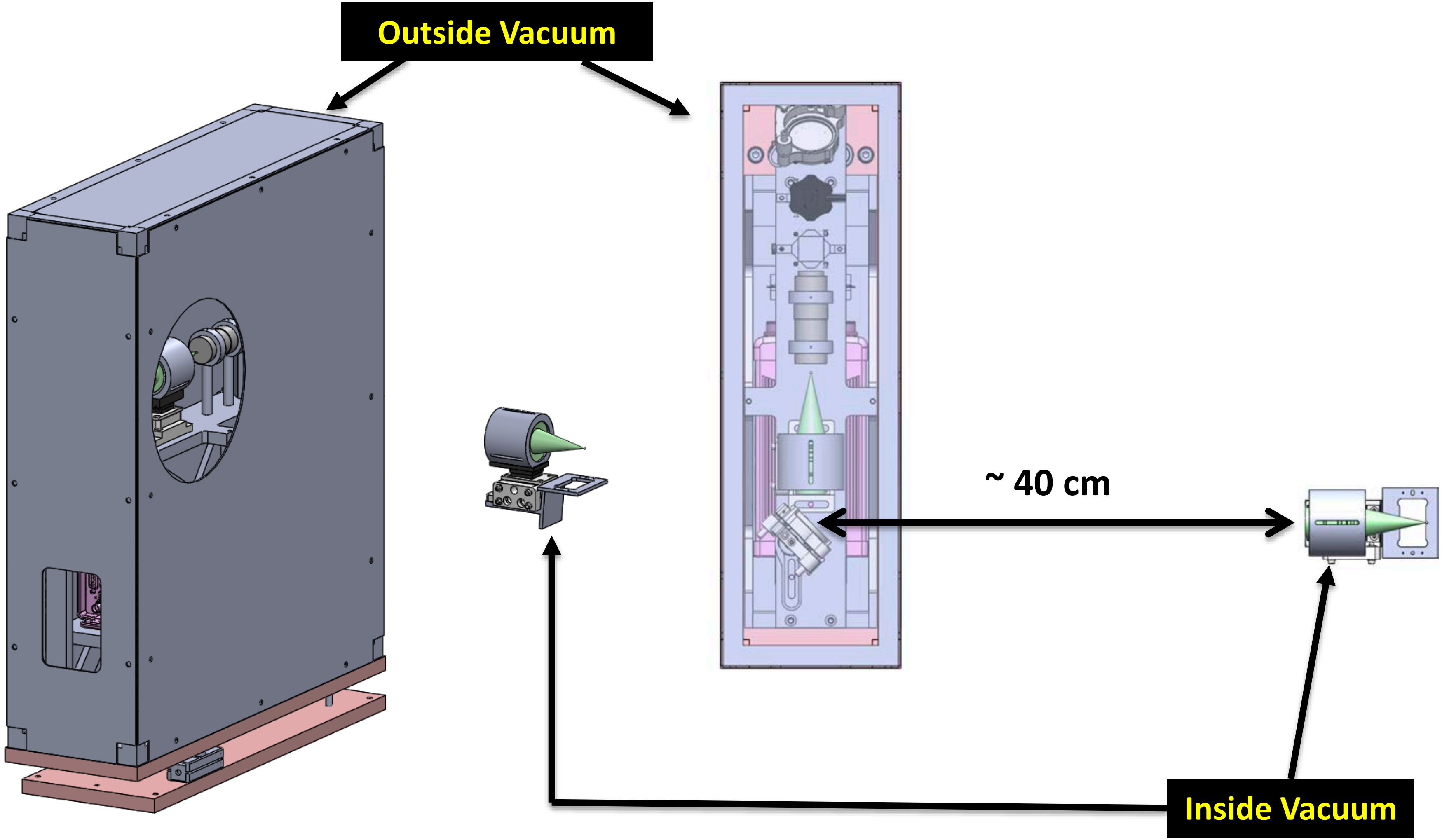
OPTO-MECHANICAL DESIGN OF THE FAD

Thorlabs 2 inch lenses



K. Cassou et al., LAL

REALISATION DESIGN OF THE FAD



K. Cassou et al., LAL

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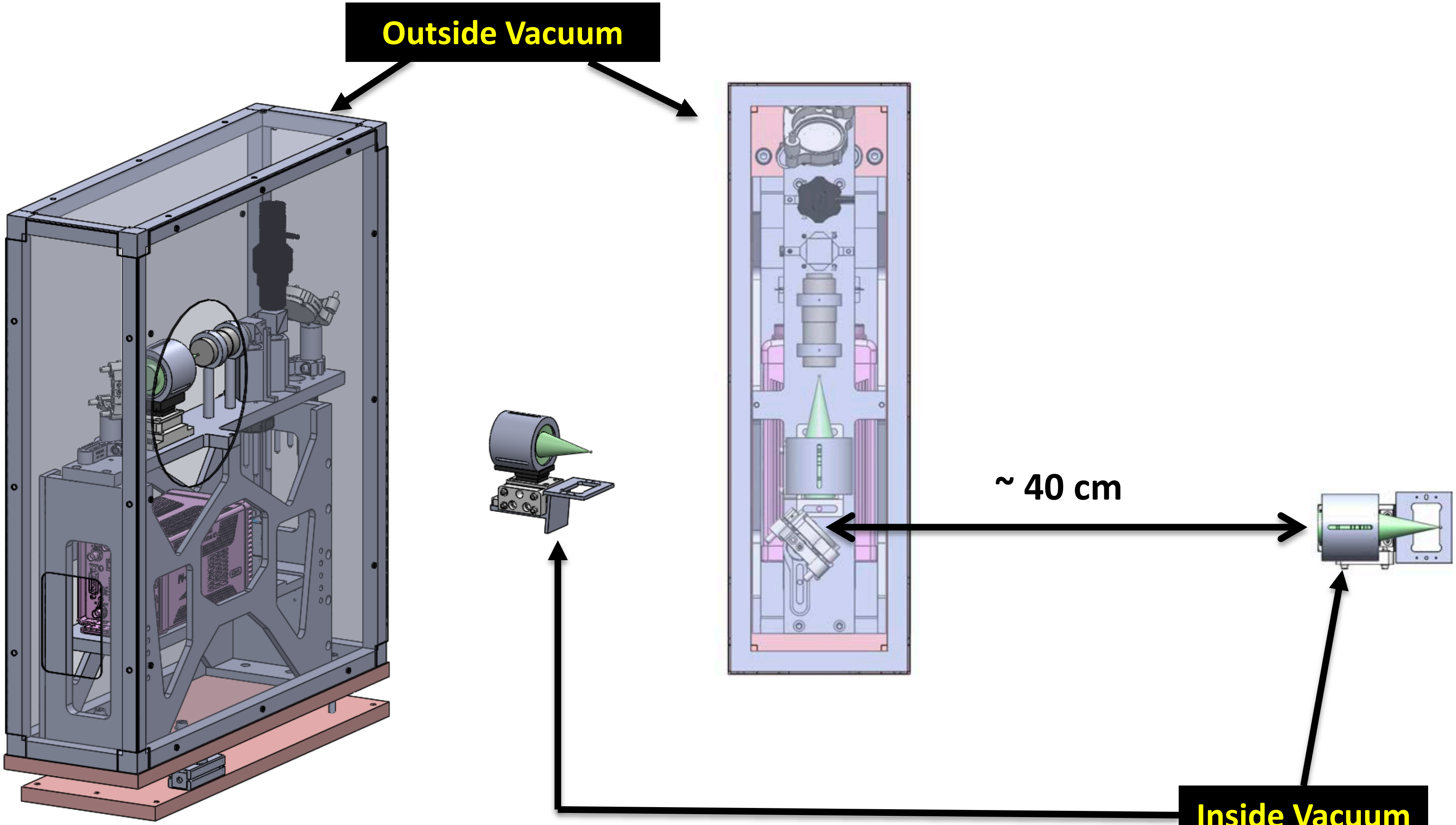
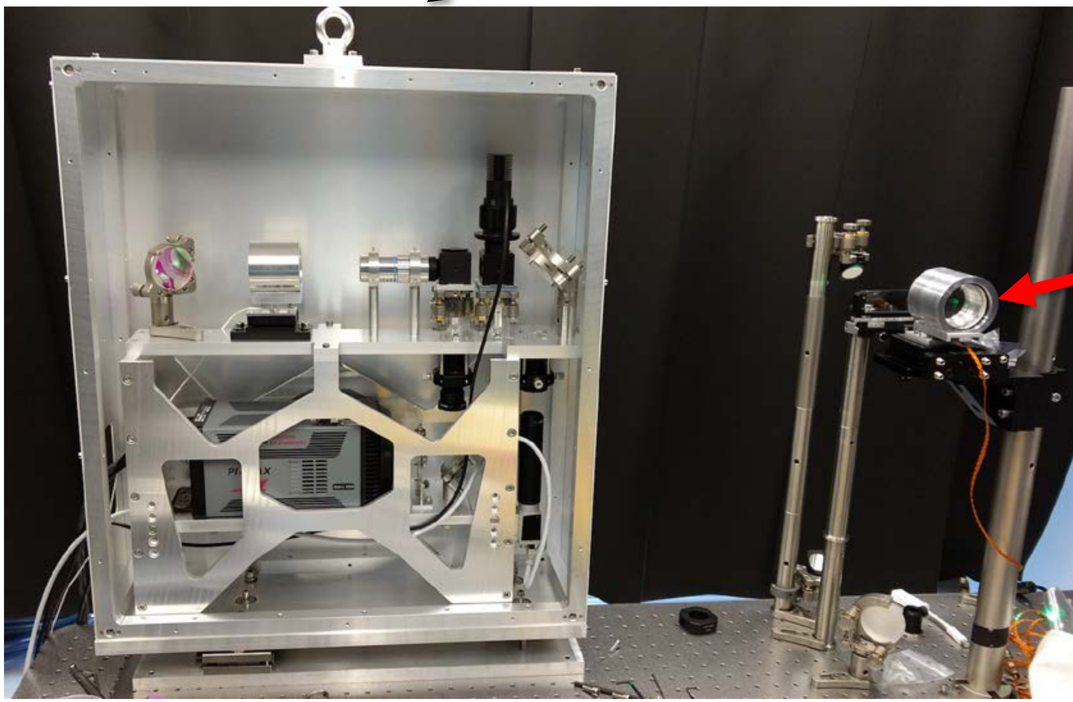
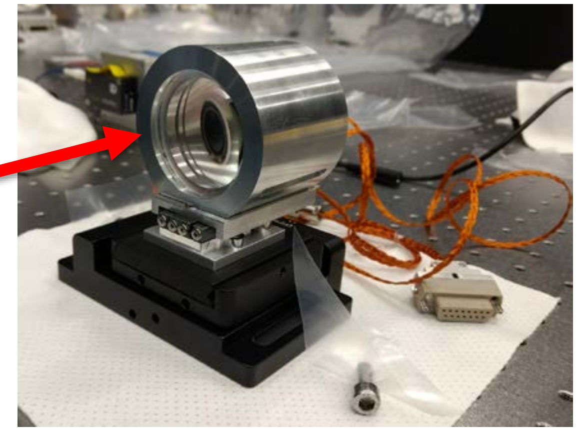


K. Cassou et al., LAL

PRODUCTION OF THE FINE ALIGNMENT DEVICE

Outside Vacuum

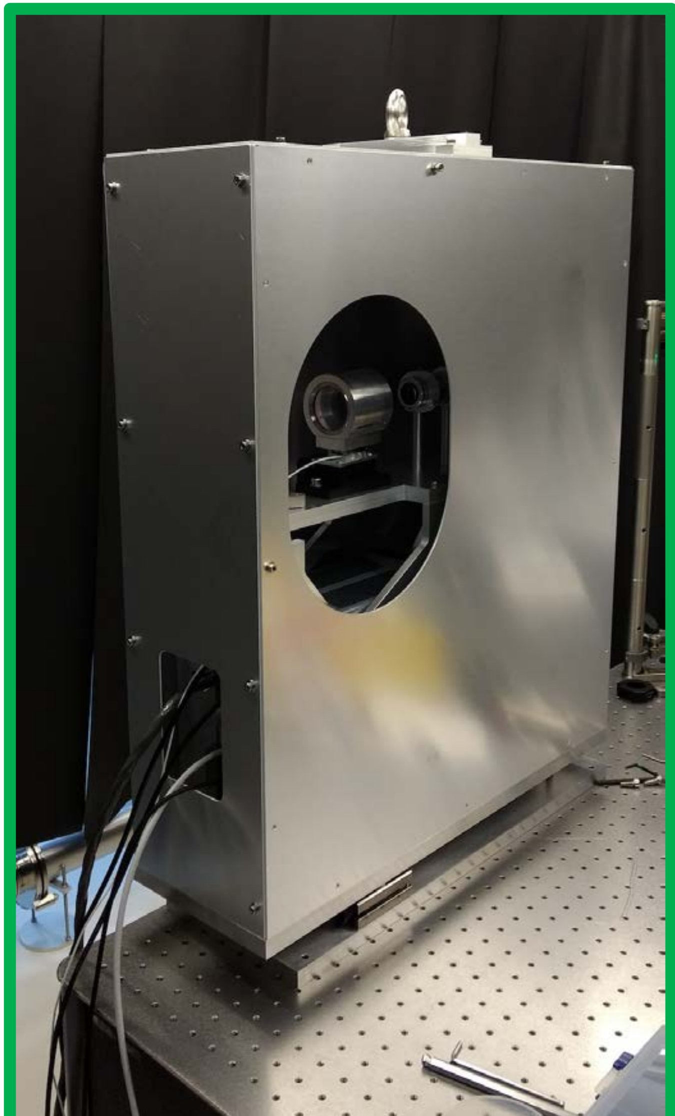




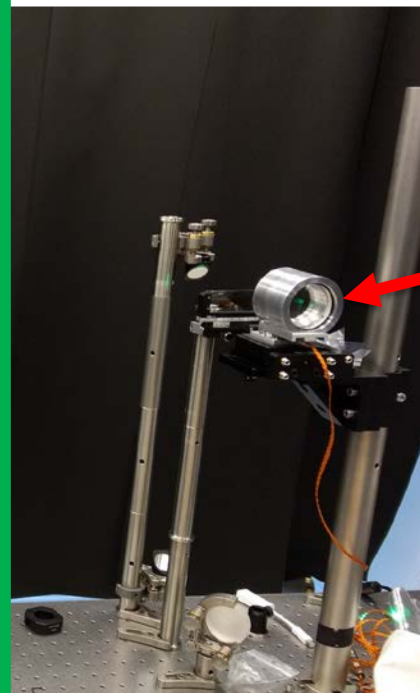
Inside Vacuum

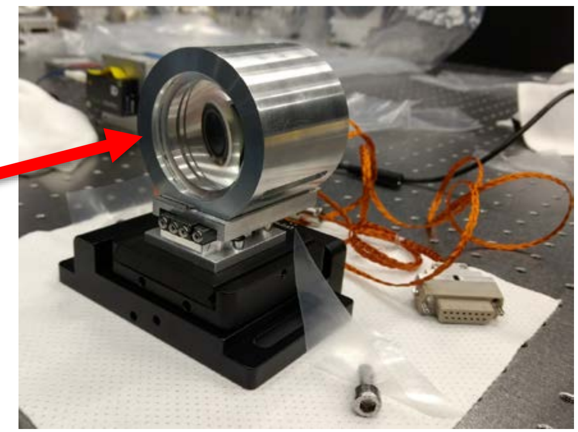
K. Cassou et al., LAL

PRODUCTION OF THE FINE ALIGNMENT DEVICE



acuum





Inside Vacuum

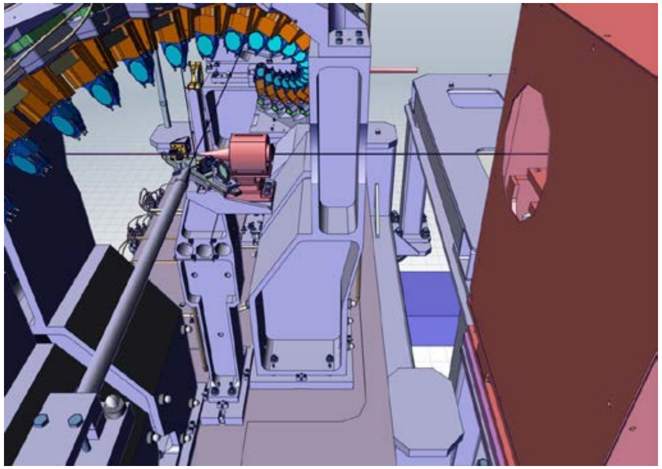
Shipped to ALSYOM clean room

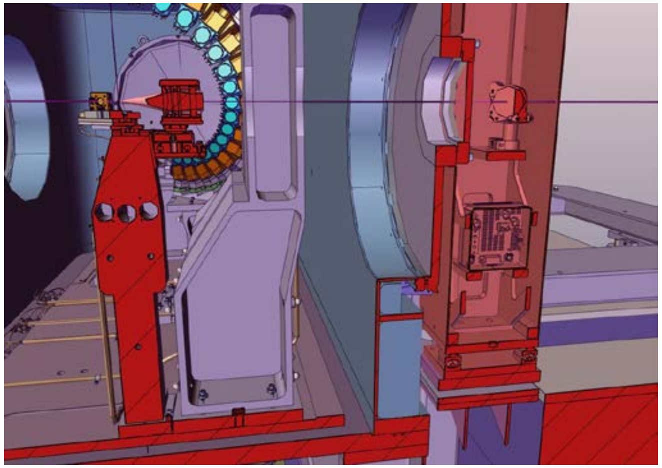
515 nm laser test

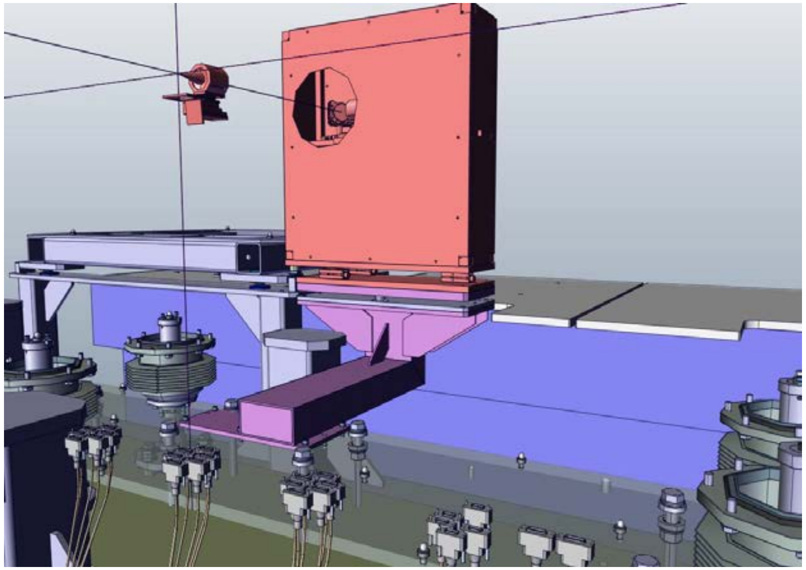
OTR radiation performance (Zemax)

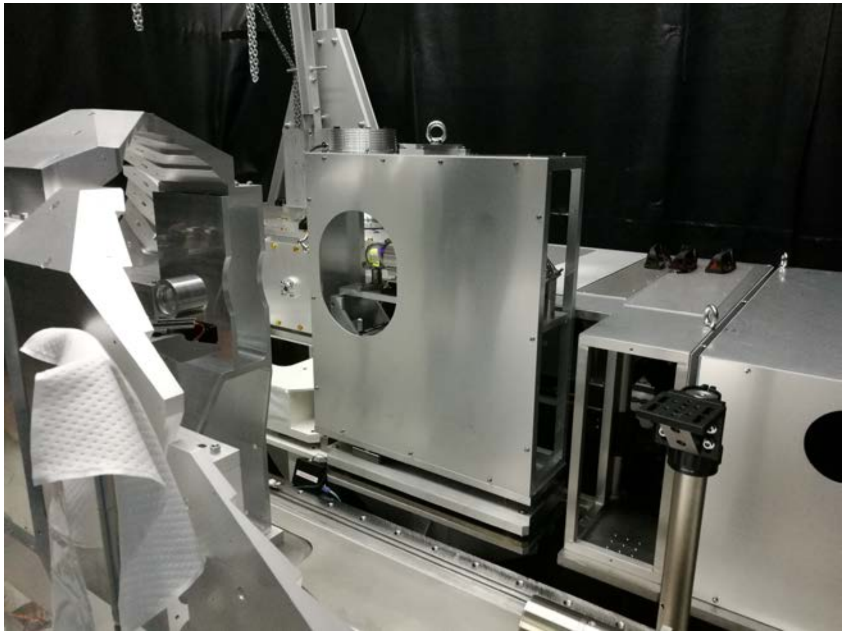
K. Cassou et al., LAL

INTEGRATION OF THE FINE ALIGNMENT DEVICE









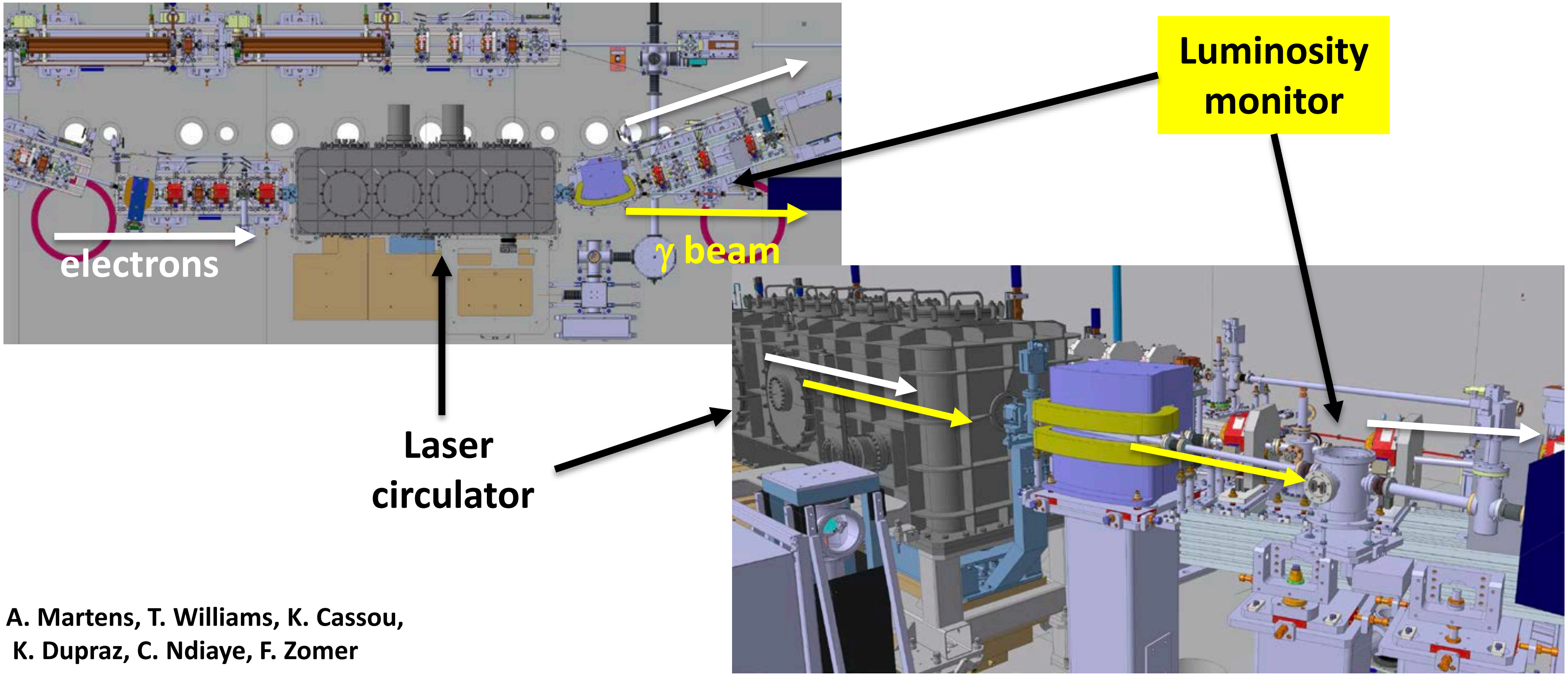
K. Cassou team

LUMINOSITY MONITOR

Fast monitoring device of γ-photons of each collision in the train (32 collisions, 16ns)

Measure the **relative γ-flux** of the 32 bunches **every 10ms** at few percent level.

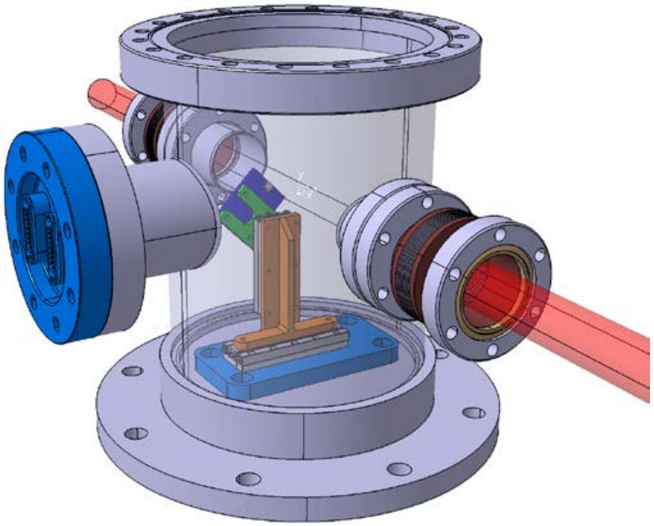
Monitor the **synchronicity and transverse overlapping** of the electron bunches and laser pulses in the 31 collisions with respect to the first one (average flux will be measured with a calorimeter).

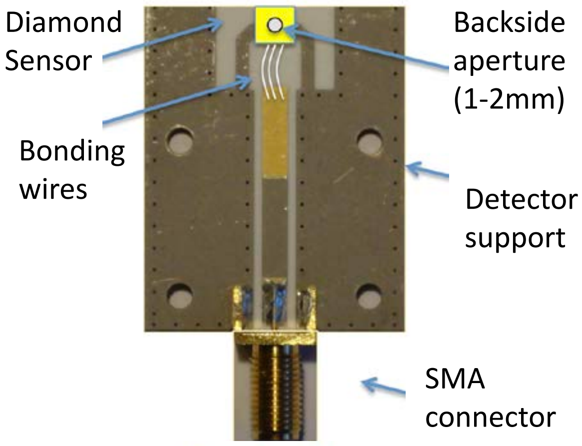


A. Martens, T. Williams, K. Cassou,
K. Dupraz, C. Ndiaye, F. Zomer

LUMINOSITY MONITOR: DIAMOND SENSORS

Diamond is naturally **fast** (**ns**, due to large drift velocities), **radiation hard**, **not invasive** (<1% of photons interact in 0.5mm thick diamond).





cividec Instrumentation

A. Martens, T. Williams, K. Cassou, K. Dupraz, C. Ndiaye, F. Zomer

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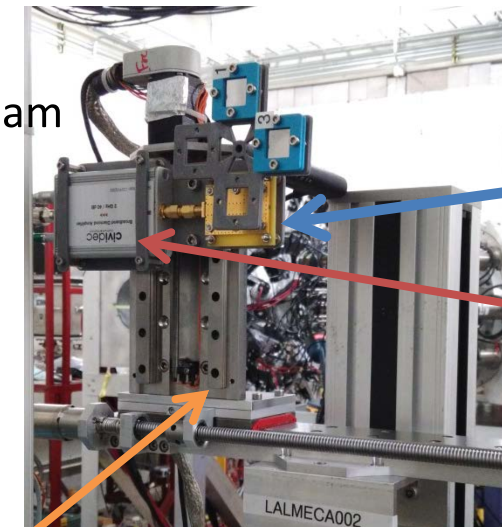
First experiment @ HIγS

Williams et al., NIMA 830 (2016) 391

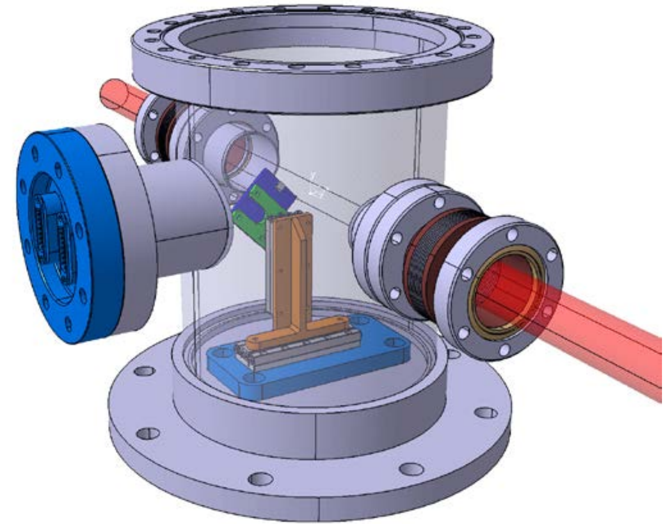
Gamma beam

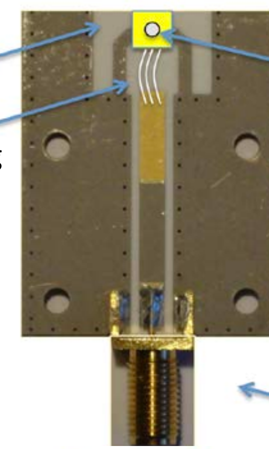


Diamond Sensor **cividec**

Amplifier (fast, GHz BW) **cividec**

Translation stages (positioning/scans)





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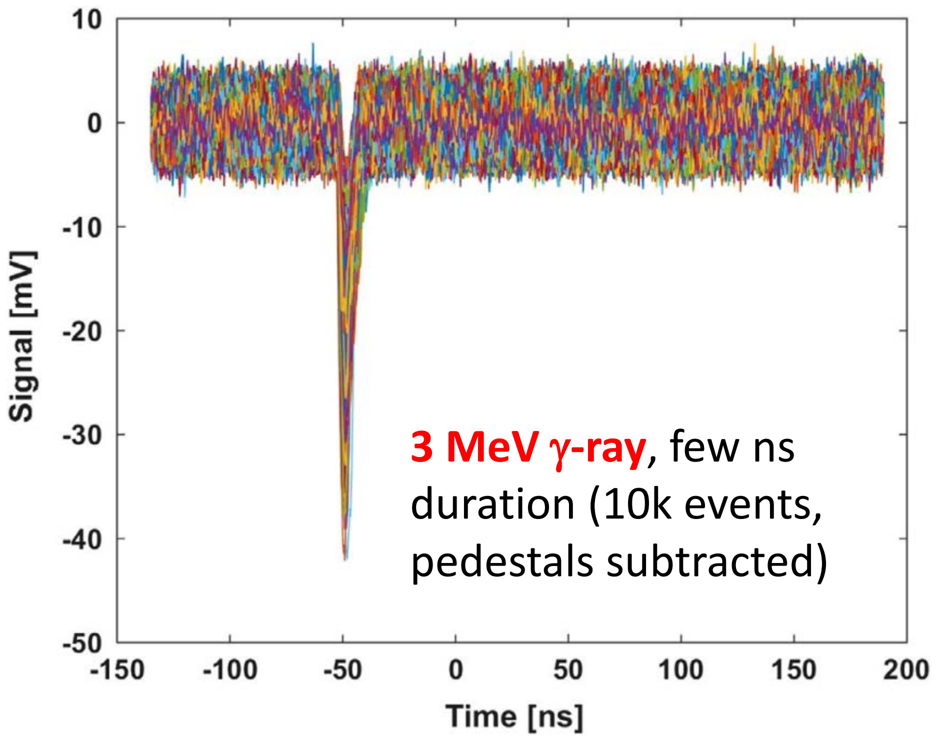
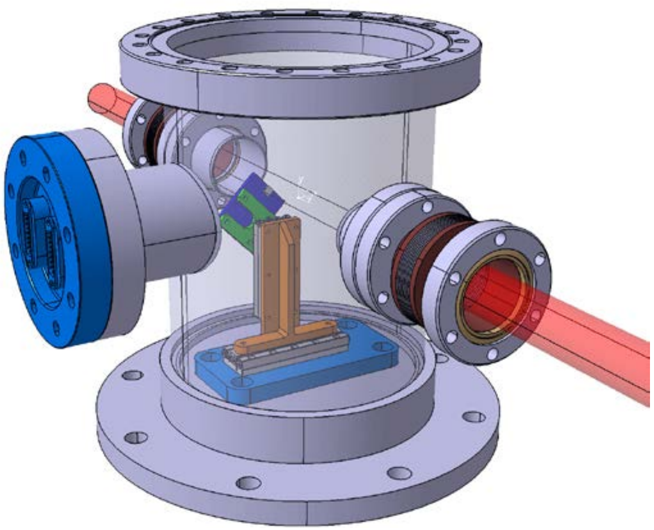
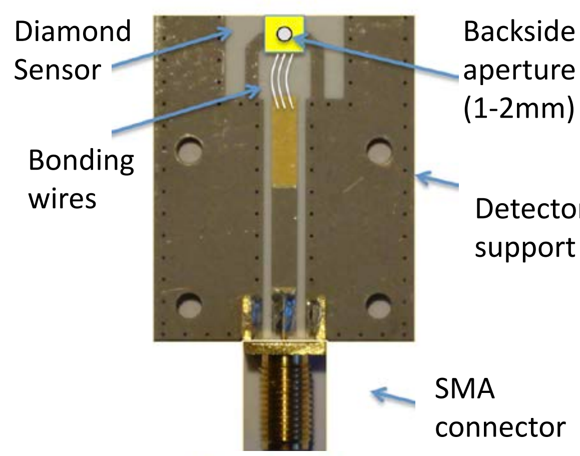
Williams et al., NIMA 830 (2016) 391







A. Martens, T. Williams, K. Cassou, K. Dupraz, C. Ndiaye, F. Zomer

LUMINOSITY MONITOR: DIAMOND SENSORS

Diamond is naturally **fast** (**ns**, due to large drift velocities), **radiation hard**, **not invasive** (<1% of photons interact in 0.5mm thick diamond).

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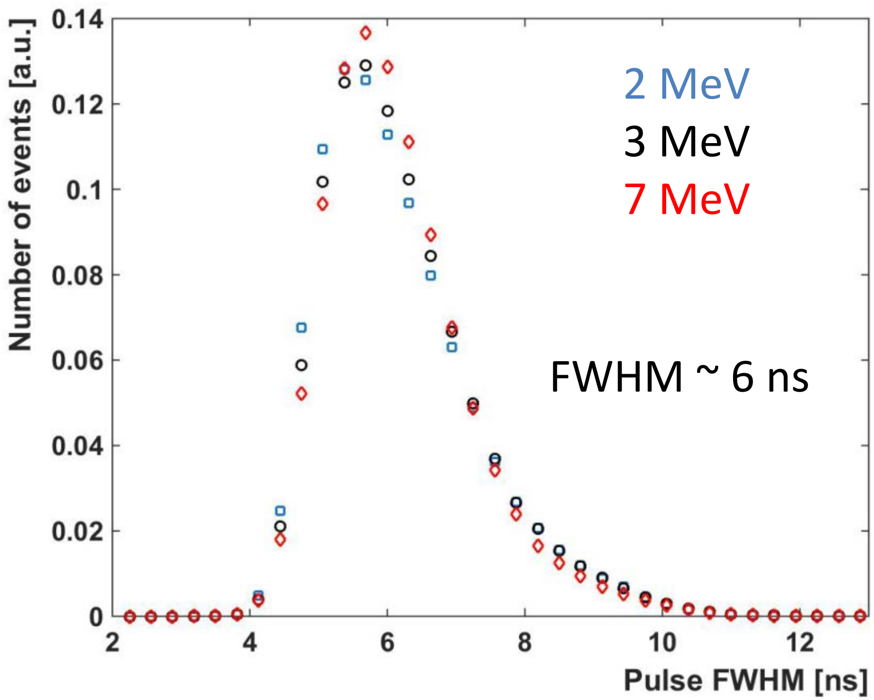

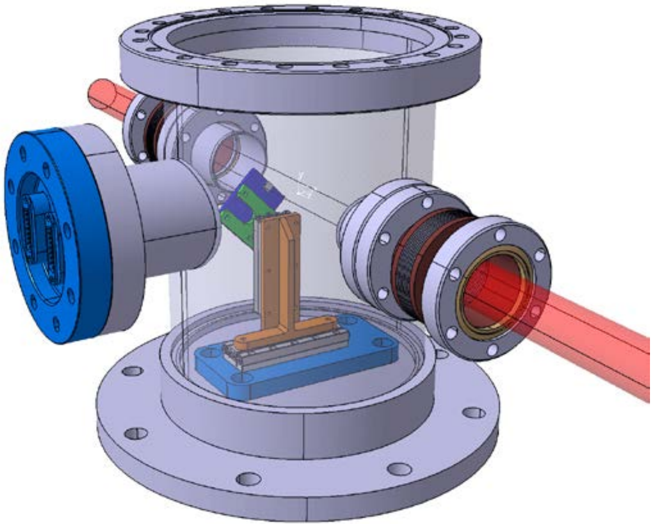

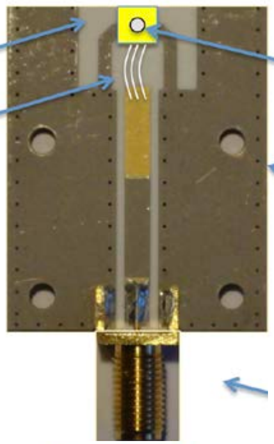

cividec Instrumentation

A. Martens, T. Williams, K. Cassou, K. Dupraz, C. Ndiaye, F. Zomer

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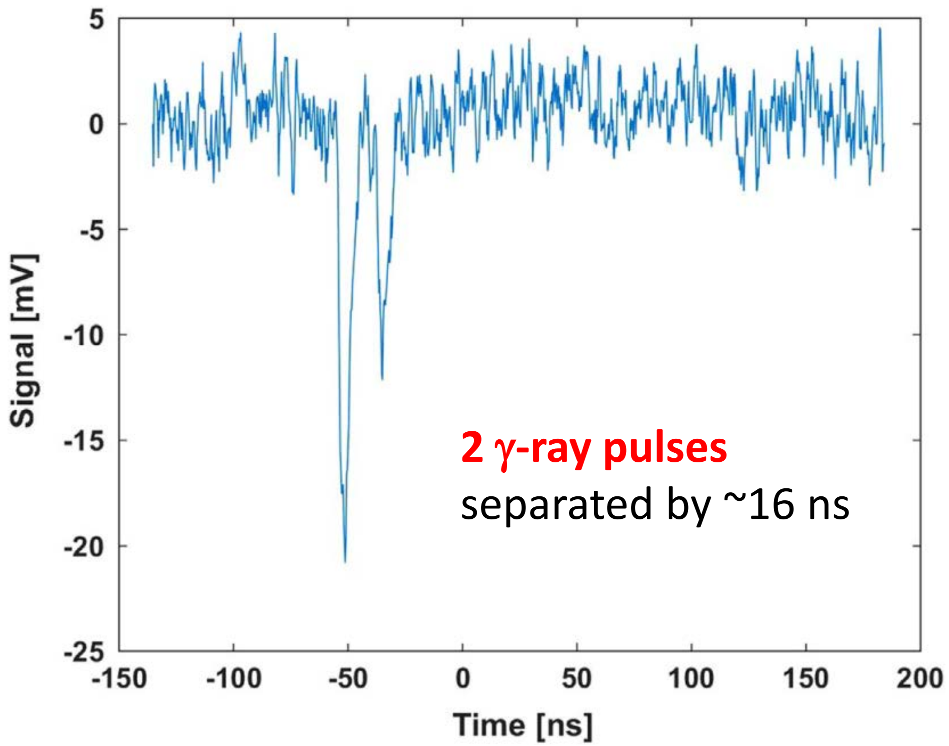

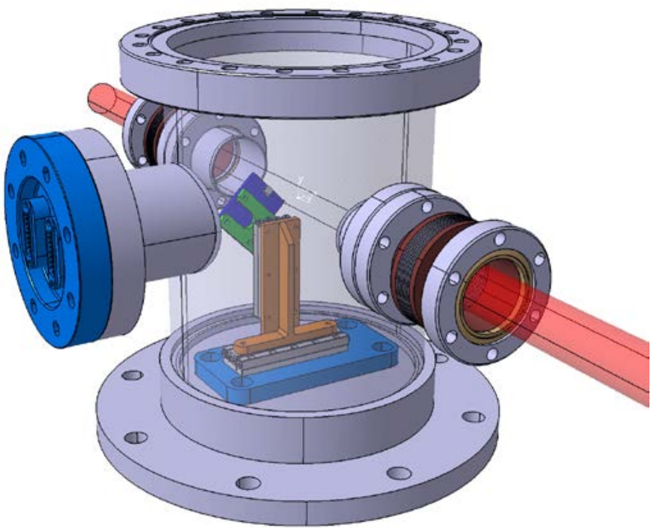

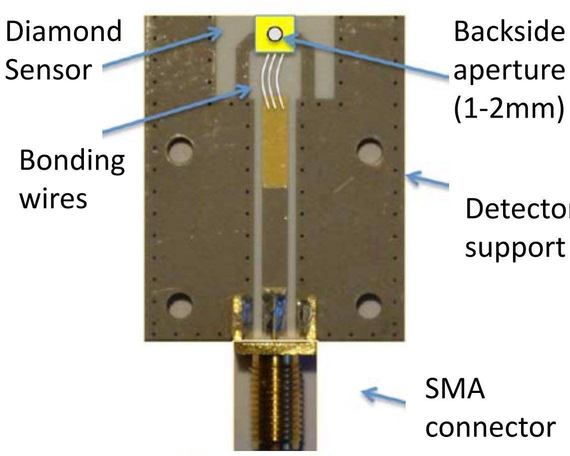

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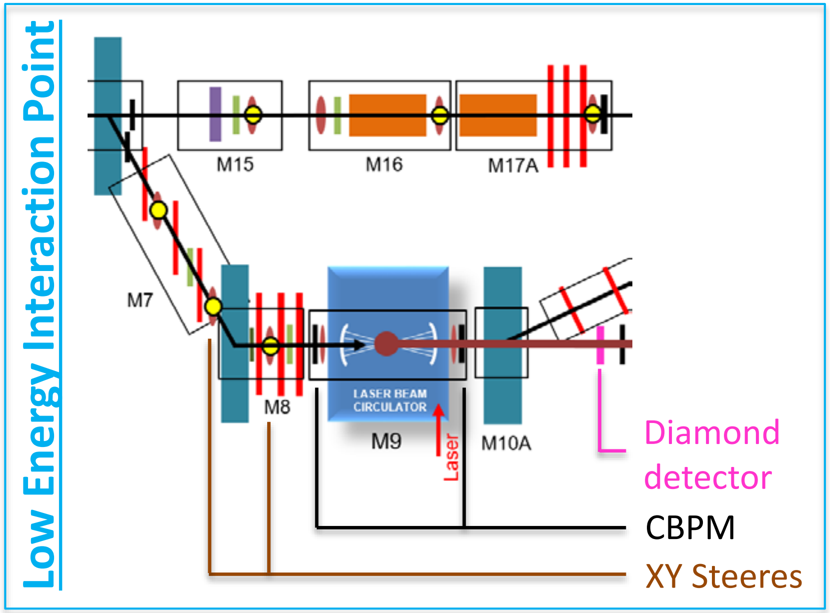
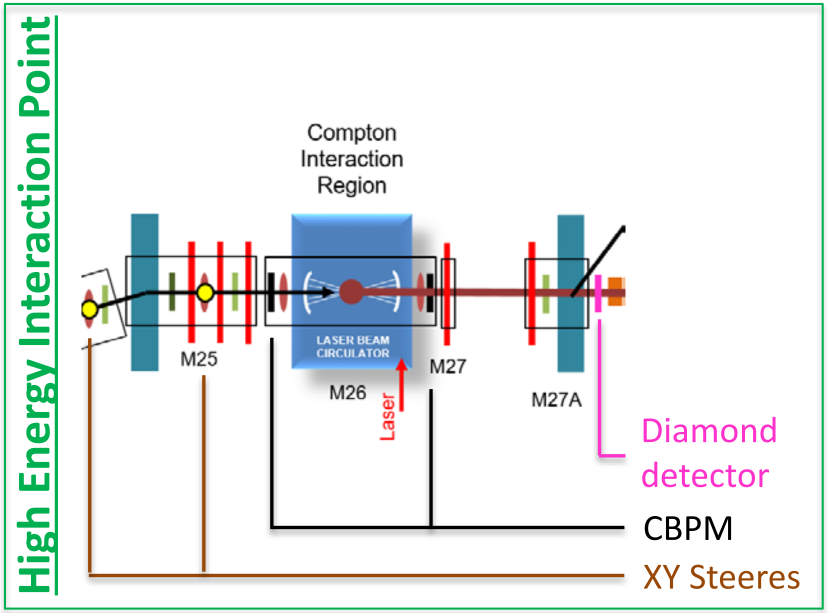
LUMINOSITY FAST FEEDBACK

Very preliminary design!





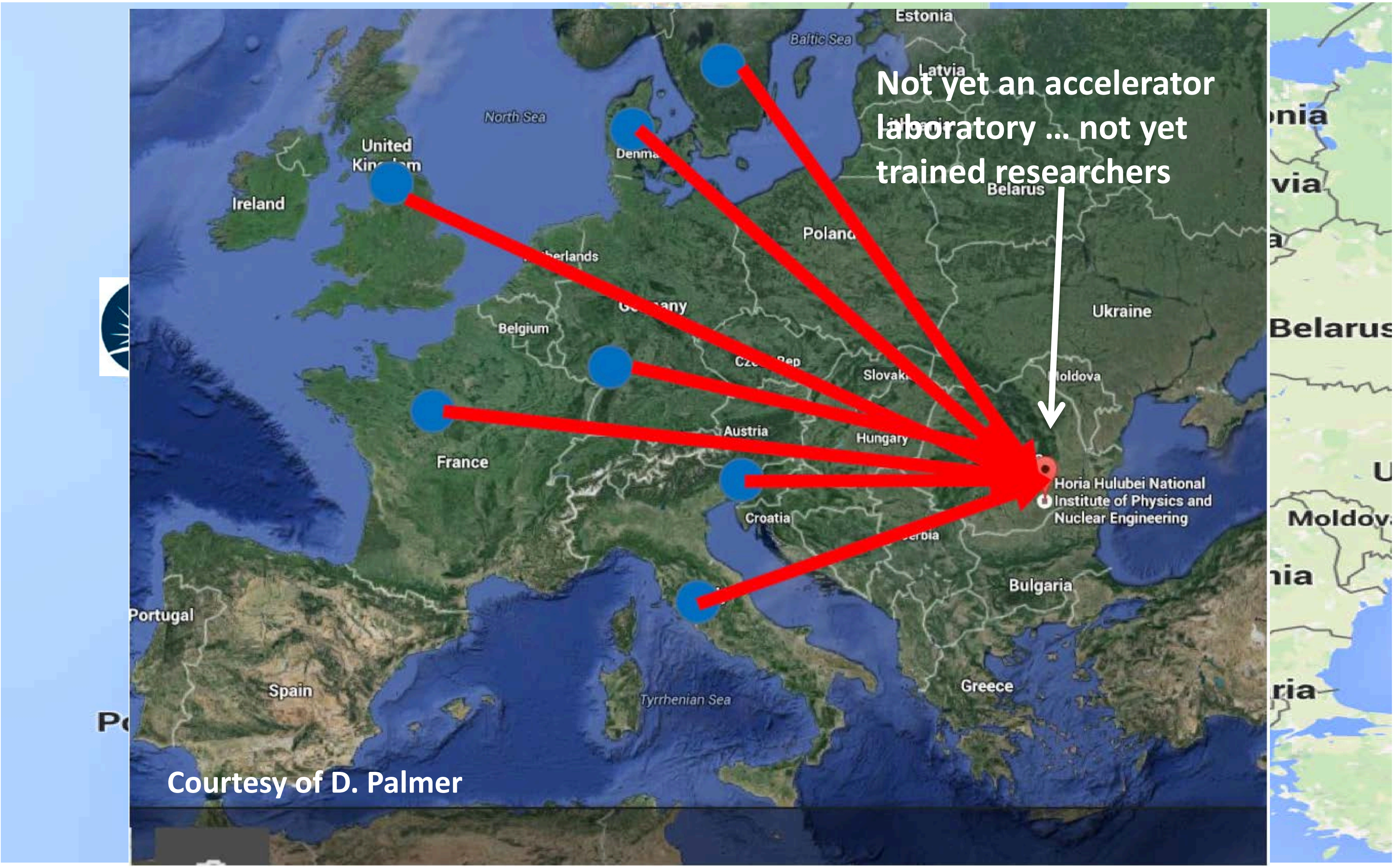
The Method

- **Starting Point** → beam optics and luminosity have been optimised
- 1st step → Trajectory bump calibration
  - Luminosity (and kicker strength) behaviour with respect to e^- beam angle and position @IP
- 2nd step → Online luminosity lock
  - Trajectory lookup and kicker strength correction

A. Giribono, S. Pioli

EUROPEAN SUBCONTRACTORS

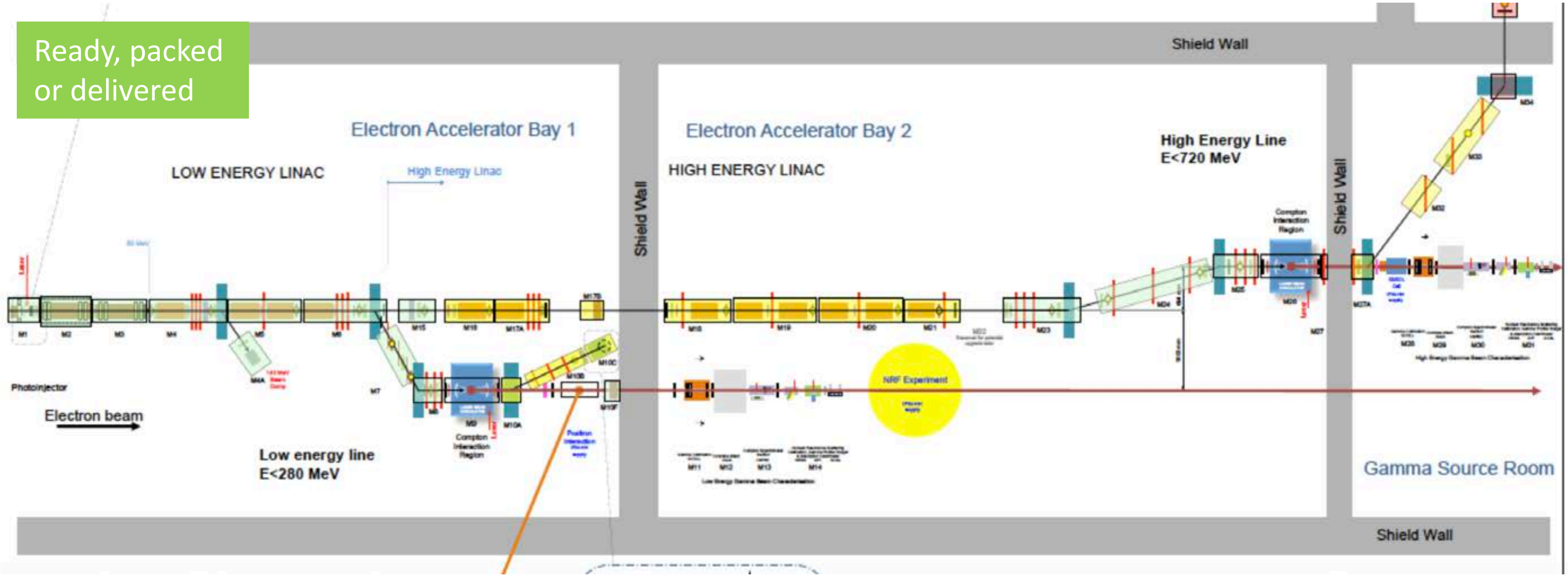
LOGISTICS ISSUES



Not yet an accelerator laboratory … not yet trained researchers

Courtesy of D. Palmer

STATUS OF THE ISTALLATION



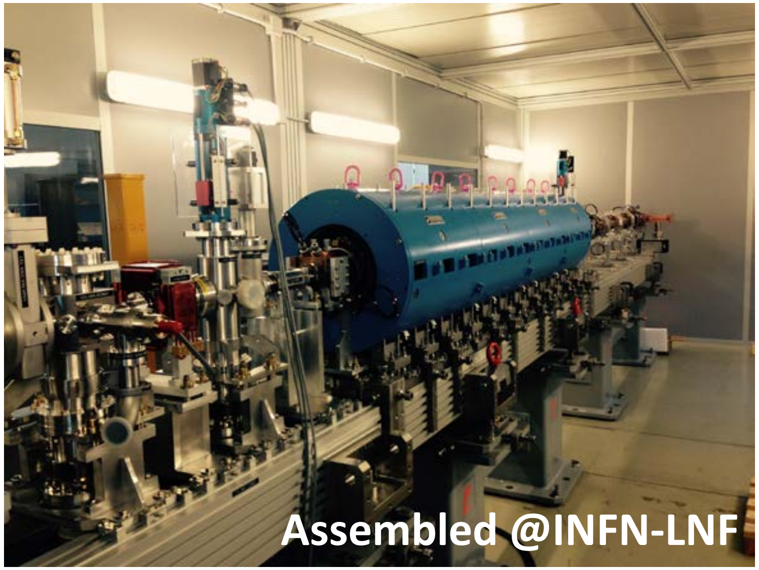
At the end of September **ALL the Low Energy Linac** will be at IFIN-Magurele.

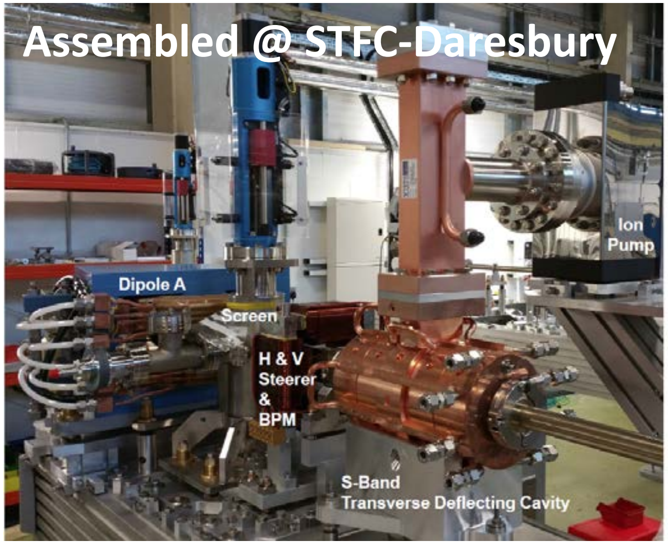
Clean rooms installed and tested, **Photo Cathode Laser** shipped (with its transport line), **Timing front end** positioned in the optical table, **IP1 laser** transport line delivered.

Laser Circulator is at ALSYOM (Bordeaux) and integration; acceptance test in September.

A. Falone

STATUS OF THE ISTALLATION





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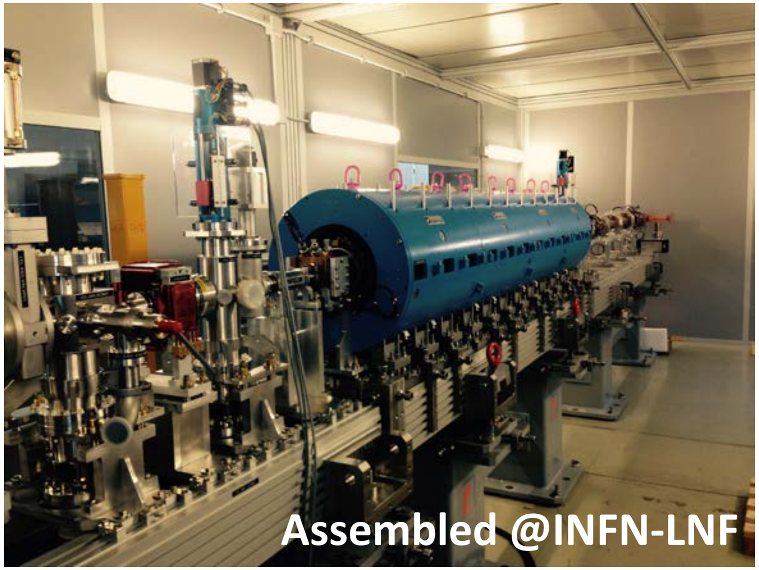

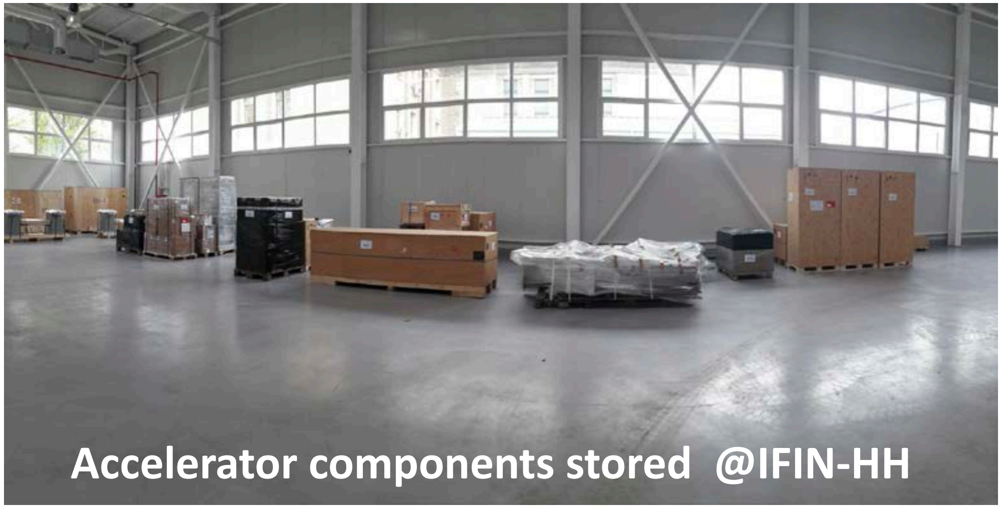

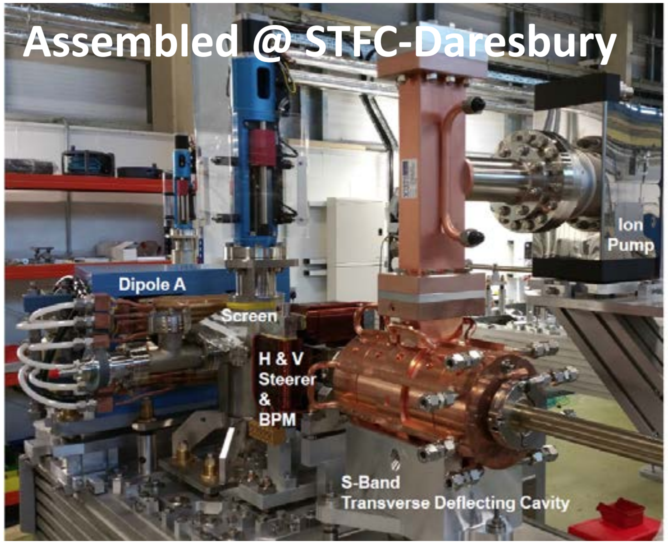

EUROGAMMAS PARTNERS

Contract with IFIN signed 19/04/2014

EUROGAMMAS GBS contributors

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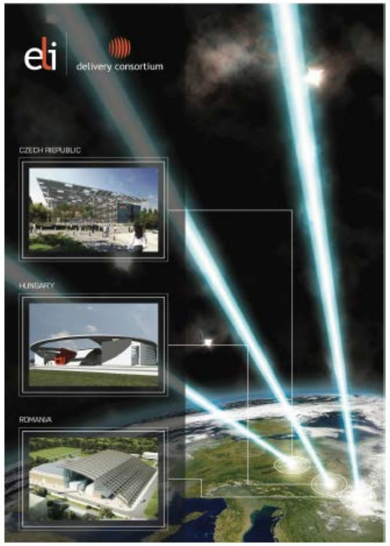
Machine Leader: A. Variola, INFN-LNF

CONCLUSIONS

A Gamma ray Compton source for nuclear physics research in the context of ELI initiative is being built.



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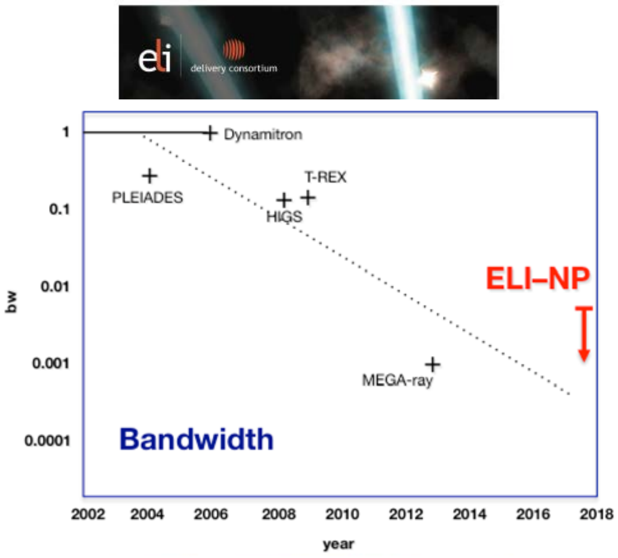
Such a source aims to improve of orders of magnitude the bandwidth and spectral density of available gamma beams for nuclear physics experiments (nuclear photonics).



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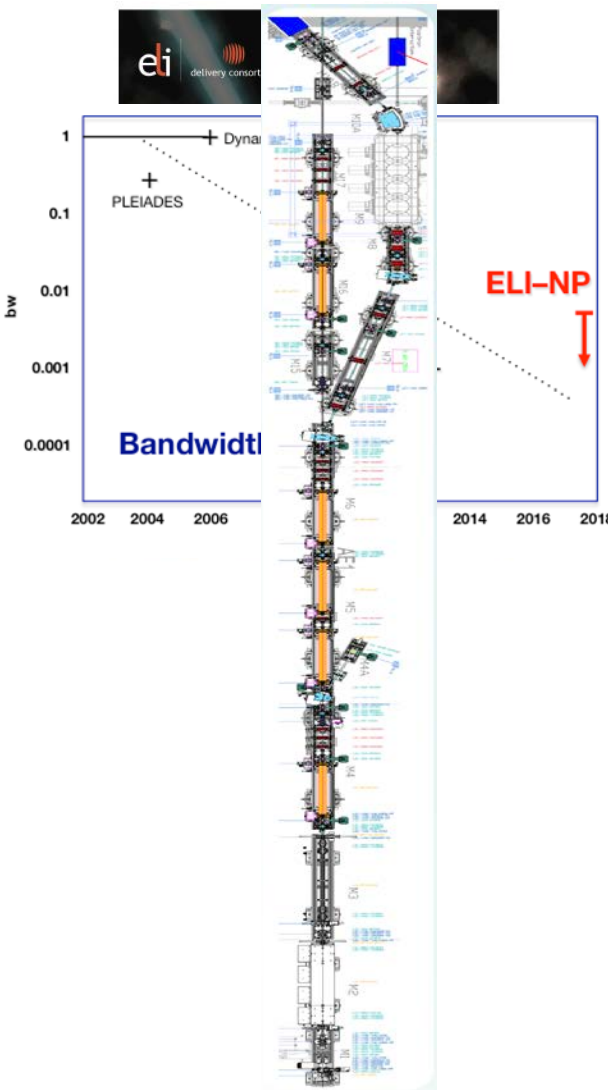
High repetition rate (100Hz), **multi bunch operation** (32 bunches) for the LINAC are foreseen to achieve the required spectral bandwidth.

Electron **diagnostics** concepts of high brightness Linacs.



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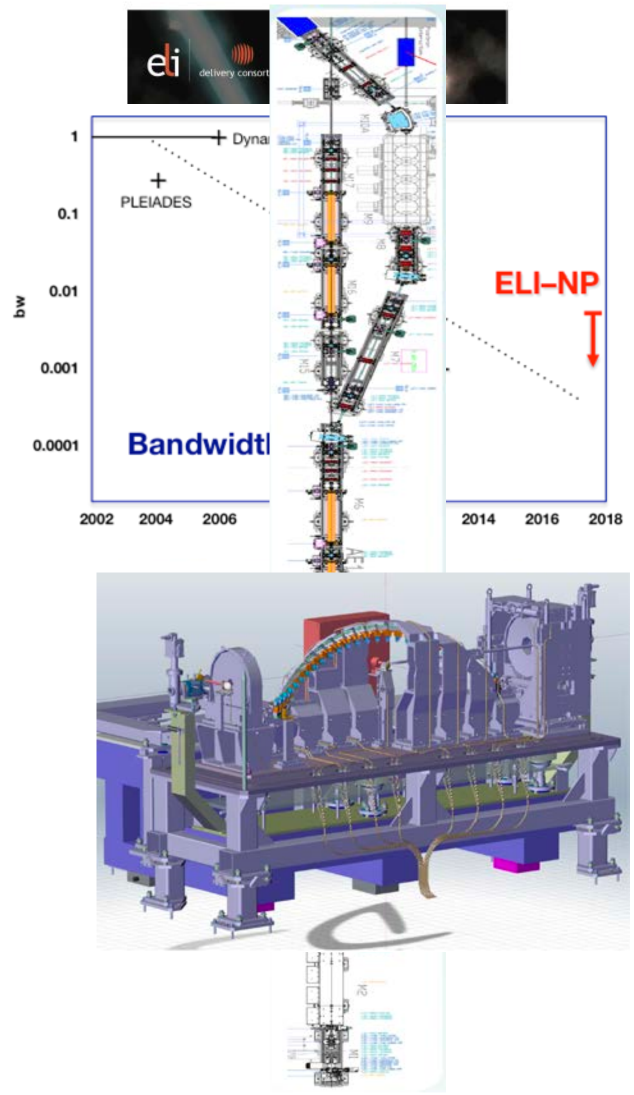

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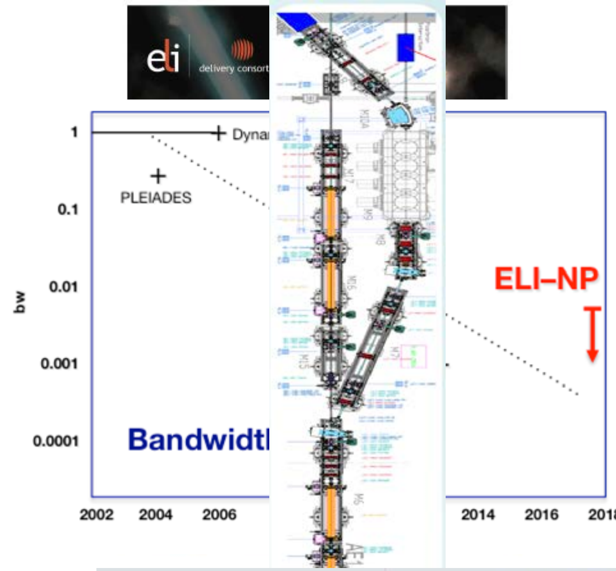
A consortium of **European research institutes and firms** is committed to build such an **advanced Compton source** in Romania.



Thank you !