OPTIMIZING RF LINACS AS DRIVERS FOR INVERSE COMPTON SOURCES: THE ELI-NP CASE

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Outline:

- The High Brightness Beam Experience:
  - The Photoinjector Optimization
  - The bunch compression
- The ELI-NP Gamma Beam System
  - The RF LINAC design
  - The GBS layout

The High Brightness Beam Experience

The Brightness parameter is written as:

$$B = \frac{2I}{\varepsilon_n^2}$$

for the SASE Fel its relevance comes from the Pierce parameter ρ defined in the ideal 1-D model as *:

$$\rho = \left[\left(\frac{I}{I_A}\right)\left(\frac{\lambda_w A_w}{2\pi\sigma_x}\right)^2\left(\frac{1}{2\gamma_0}\right)^3\right]^{1/3}$$

where the current density $I/2\pi\sigma_x^2$ appears and that gives the highest possible Fel gain (shortest length), being:

$$L_g = \lambda_w/4\pi\sqrt{3}\rho \quad \text{and} \qquad P_{sat} \approx \rho P_{beam}$$

* Ming Xie, Proc. Of PAC 95, p. 183

The Photoinjector Optimization

- Focusing solenoid at the exit of the photoinjector

  (B. E. Carlsten, Nucl. Instr. Meth. Phys. Res., Sect. A **285**, 313 1989)

- Proper matching of the transverse space of the electron beam injected in the downstream accelerating sections (booster) to control the transverse emittance oscillations during the acceleration

  (L. Serafini and J.Rosenzweig, Phys. Rev. E **55**, 7565 (1997)

The matching condition:

Serafini-Rosenzweig showed that the rms normalized transverse emittance $\varepsilon_n = \sqrt{\langle x^2\rangle\langle \beta\gamma x'^2\rangle - \langle x\beta\gamma x'\rangle^2}$ oscillates with frequency $\sqrt{2K_r} = k_p$ if the bunched beam is rms matched in a focusing channel of gradient K_r (Brillouin flow equilibrium) and that the oscillations are damped under the invariant envelope condition:

$$\sigma_{\text{inv}}(\zeta) = \frac{2}{\gamma'}\sqrt{\frac{I(\zeta)}{I_0\gamma}}, \text{ with } \gamma' = eE_{acc}/m_e c^2 \text{ and } \zeta = z - \beta ct + z_0$$

so the key point is to inject the beam into an accelerating section at a laminar waist:

$$\sigma' = 0 \quad \text{with} \quad \gamma' = \frac{2}{\sigma_w}\sqrt{\frac{\hat{I}}{2I_0\gamma}}$$

that gives the invariant envelope condition for a TW accelerating field.

The Bunch Compression

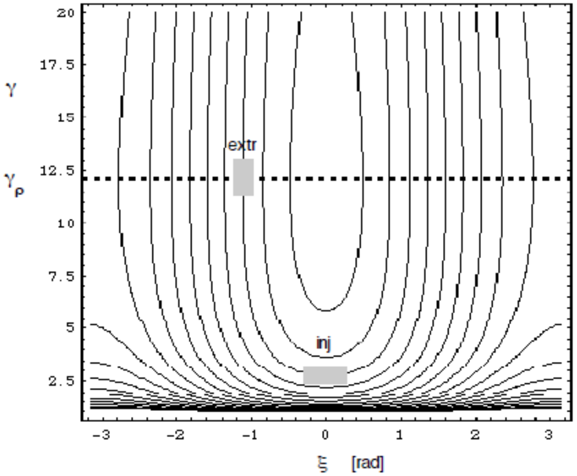
High peak currents are required by several applications such as short wavelengths free electron lasers, plasma wake field accelerators, and so on:

compression stage:

- Magnetic compressors
- Velocity bunching

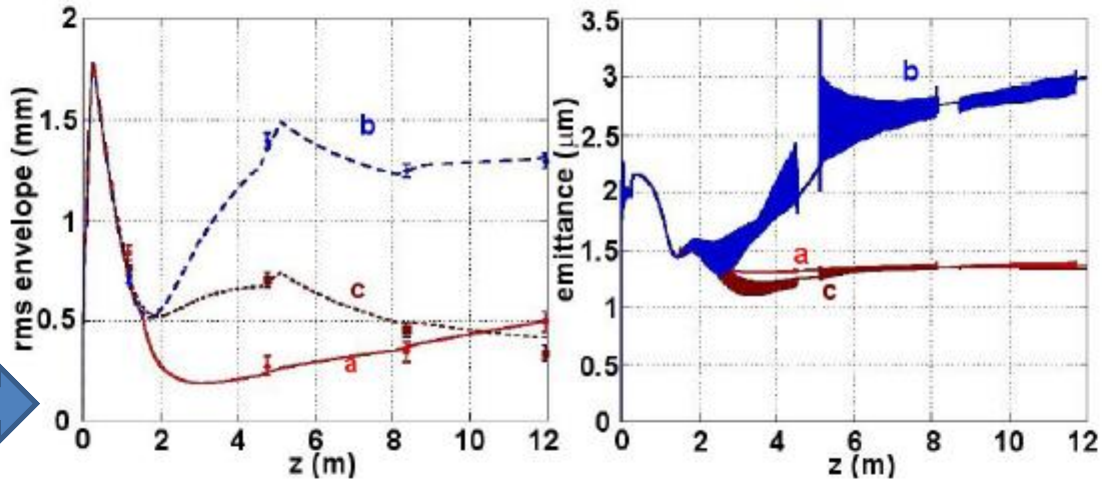
The velocity bunching technique

If the bunch is injected into the wave at zero phase at an energy lower than the synchronous one (γ_r) it will slip back in phase and go up in energy (accelerated by the wave); extracting the beam from the wave at the time it reaches the resonant γ_r (i.e. whn it is synchronous with the wave) the bunch undergoes a quarter of synchrotron oscillation and is compressed in phase.



Phase space plots of a slow RF wave (γ_r finite) showing the basics of the VB

To control the emittance dilution the RF compression process has to be integrated with the emittance compensating invariant envelope matching condition, as succesfully demonstrated at SPARC. (M. Ferrario *et al.*, Phys. Rev. Lett. **104**, 054801, 2010)



Measured envelopes and PARMELA simulations (left plot). Emittance evolution along the linac, PARMELA simulations (right plot). No compression (curves a), compression with long solenoids off (curves b), same compression with long solenoids set to 450 G (curves c)

The ELI-NP
Gamma Beam System

ELI-NP: F-I-UK Project

European Collaboration for a new generation gamma-ray source:

- ✓ Italy: INFN,Sapienza
- ✓ France: IN2P3, Univ. Paris Sud
- ✓ UK: ASTeC/STFC

Covering

- ✓ Underlying physics & Best machine layout
- ✓ Technical realization
- ✓ Infrastructure concern
- ✓ Management structure
- ✓ Training and education
- ✓ Implementation

arXiv.org > physics > arXiv:1407.3669

Search or Artic

Physics > Accelerator Physics

Technical Design Report EuroGammaS proposal for the ELI-NP Gamma beam System

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(Submitted on 14 Jul 2014)

The machine described in this document is an advanced Source of up to 20 MeV Gamma Rays based on Compton back-scattering, i.e. collision of an intense high power laser beam and a high brightness electron beam with maximum kinetic energy of about 720 MeV. Fully equipped with collimation and characterization systems, in order to generate, form and fully measure the physical characteristics of the produced Gamma Ray beam. The quality, i.e. phase space density, of the two colliding beams will be such that the emitted Gamma ray beam is characterized by energy tunability, spectral density, bandwidth, polarization, divergence and brilliance compatible with the requested performances of the ELI-NP user facility, to be built in Romania as the Nuclear Physics oriented Pillar of the European Extreme Light Infrastructure. This document illustrates the Technical Design finally produced by the EuroGammaS Collaboration, after a thorough investigation of the machine expected performances within the constraints imposed by the ELI-NP tender for the Gamma Beam System (ELI-NP-GBS), in terms of available budget, deadlines for machine completion and performance achievement, compatibility with lay-out and characteristics of the planned civil engineering.

Subjects: Accelerator Physics (physics.acc-ph)
Cite as: arXiv:1407.3669 [physics.acc-ph]
(or arXiv:1407.3669v1 [physics.acc-ph] for this version)

New generation γ-source

- Bright
- Mono-chromatic
- High Spectral Flux
- Tunable
- Highly Polarized

Photon energy	1-20 MeV
Spectral density	> 10^4 ph/sec.eV
Bandwith (rms)	<0.5 %
# photons/sec within FWHM bdw.	0.5÷1.5 10^9
Linear Polarization	>95 %

- Nuclear Resonance Fluorescence
- Nuclear Photo-fission
- Isotope Detection -> toward Nuclear Photonics

The electron-photon collider approach

The rate of emitted photons is given by:

$$N_\gamma = \Sigma_T L = \Sigma_T \frac{N_{el} N_{las}}{2\pi\left(\sigma_x^2 + \frac{w_0^2}{4}\right)} f \cdot n_{RF} \cdot \delta_\phi$$

leading to:

$$N_\gamma = 4.2 \times 10^8 \frac{U_L[J] Q[pC] f\, n_{RF}\, \delta_\phi}{h\nu[eV]\left(\sigma_x^2[\mu m] + \frac{w_0^2[\mu m]}{4}\right)}$$

with $h\nu = 2.4\ eV$, $Q = 250\ pC$, $U_L = 0.4\ J$, $\sigma_x \approx 15\mu m$, $w_0 \approx 28\mu m$, and $f = 100\ Hz$, over the entire solid angle we have a gamma ray flux:

$$N_\gamma \approx 3 \times 10^9 s^{-1}.$$

Within the desired bandwidth:

The frequency ν_γ of the radiation emitted within a small angle of scattering and electron incidence θ_c is:

$$\nu_\gamma = \nu_L \frac{4\gamma^2}{1+\gamma^2\theta_c^2+a_0^2/2}(1-\Delta)$$

and the rms bandwidth is:

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

so within the bandwith we have:

$$N_\gamma^{bw} = 1.4\times 10^9 \frac{U_L[J]Q[pC]f\, n_{RF}\,\delta_\phi}{h\nu[eV]\left(\sigma_x^2[\mu m]+\frac{w_0^2[\mu m]}{4}\right)} \cdot \sqrt{\left(\frac{\Delta\nu_\gamma}{\nu_\gamma}\right)^2 - \left(2\frac{\Delta\gamma}{\gamma}\right)^2 - \left(\frac{2\varepsilon_n^2}{\sigma_x^2}\right)^2 - \left(\frac{\Delta\nu}{\nu}\right)^2 - \left(\frac{M^2\lambda_L}{2\pi w_0}\right)^4 - \left(\frac{a_0^2/3}{1+a_0^2/2}\right)^2}$$

The required spectral density:

$$S = \frac{N_\gamma^{bw}}{\sqrt{2\pi}h\Delta\nu_\gamma} \qquad S_r(eV^{-1}) = \frac{0.35\times10^9 E_L Q \Psi^2}{h\omega\nu_L\left(\sigma_x^2+\frac{w_0^2}{4}\right)} \frac{1}{\sqrt{2\pi}h\Delta\nu_\gamma\left[\frac{\Delta\nu_\gamma}{\nu_\gamma}\right]_r}.$$

needs from the RF linac the maximum for the parameter

$$\frac{Q}{\sigma_x^2[\Delta\gamma/\gamma + (2\,\epsilon_n/\sigma_x)^2]}$$

with no further bunch compression we can optimize separetly the energy spread and transverse emittance i.e. the 4D transverse phase space density of the electron beam:

$$\eta \equiv \frac{Q}{\epsilon_n^2}.$$

ELI-NP requirements:

State of the art + Compact = S-band Photoinjector + C-band linac

ELI-NP GBS:
r.t. RF linac *vs* pulsed laser source

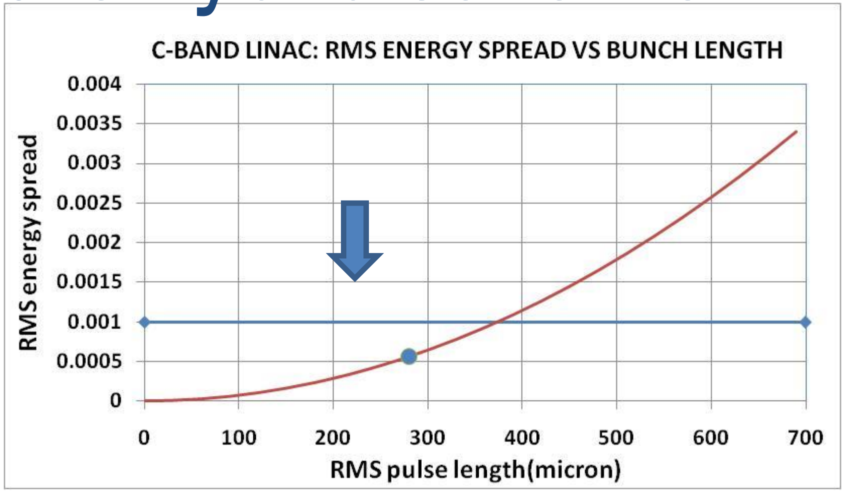
Electron beam parameter at IP	
Energy (MeV)	80-720
Bunch charge (pC)≤	25-400
Bunch length (μm)≤	100-400
$\varepsilon_{n-x,y}$ (mm-mrad)	0.2-0.6
Bunch Energy spread (%)	0.04-0.1
Focal spot size (μm)	>10
# bunches in the train	≤32
Bunch separation (nsec)	16
energy variation along the train	0.1 %
Energy jitter shot-to-shot	0.1 %
Emittance dilution due to beam breakup	< 10%
Time arrival jitter (psec)	< 0.5
Pointing jitter (μm)	1

Yb:Yag Collision Laser	Low Energy Interaction	High Energy Interaction
Pulse energy (J)	0.2	2×0.2
Wavelength (eV)	2.4	2.4
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
Sinchronization to an ext. clock	< 1 psec	< 1 psec
Pulse energy stability	1 %	1 %

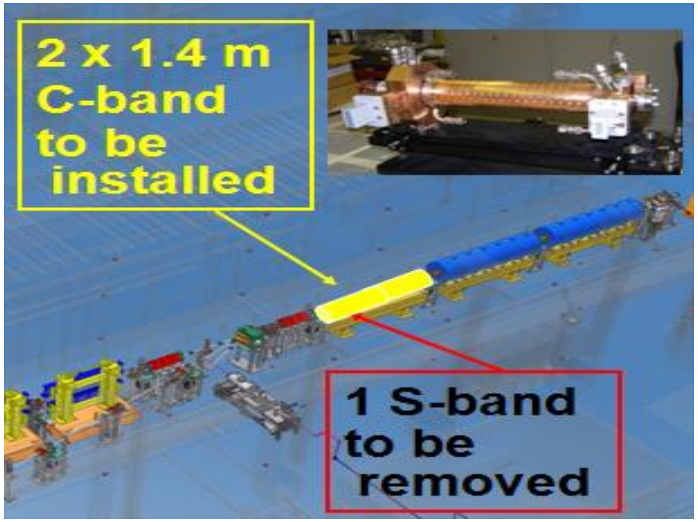
The ELI-NP RF Linac design: the hybrid scheme

- *Operation criteria:*
  - Long bunch at cathode for high phase space density :

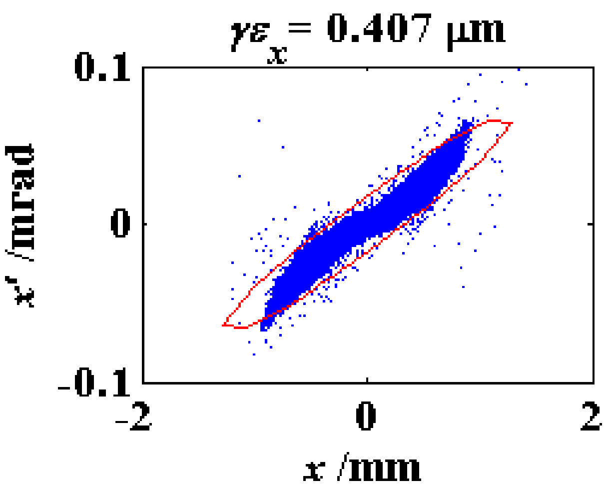
    $Q/\varepsilon_n^2 > 10^3$ pC/(µrad)^2
  - Short exit bunch (280 µm) for low energy spread (~0.05%)

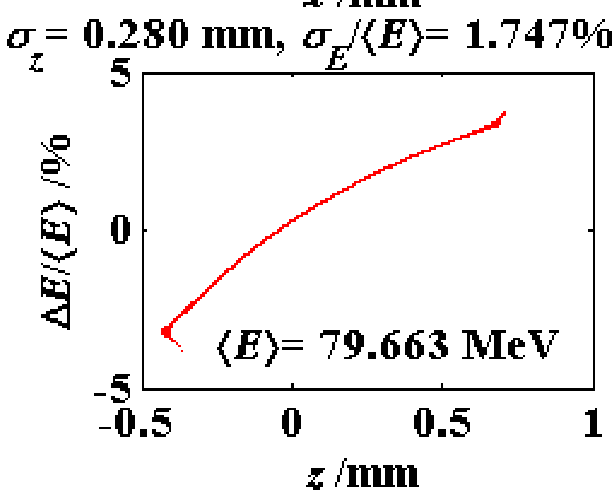


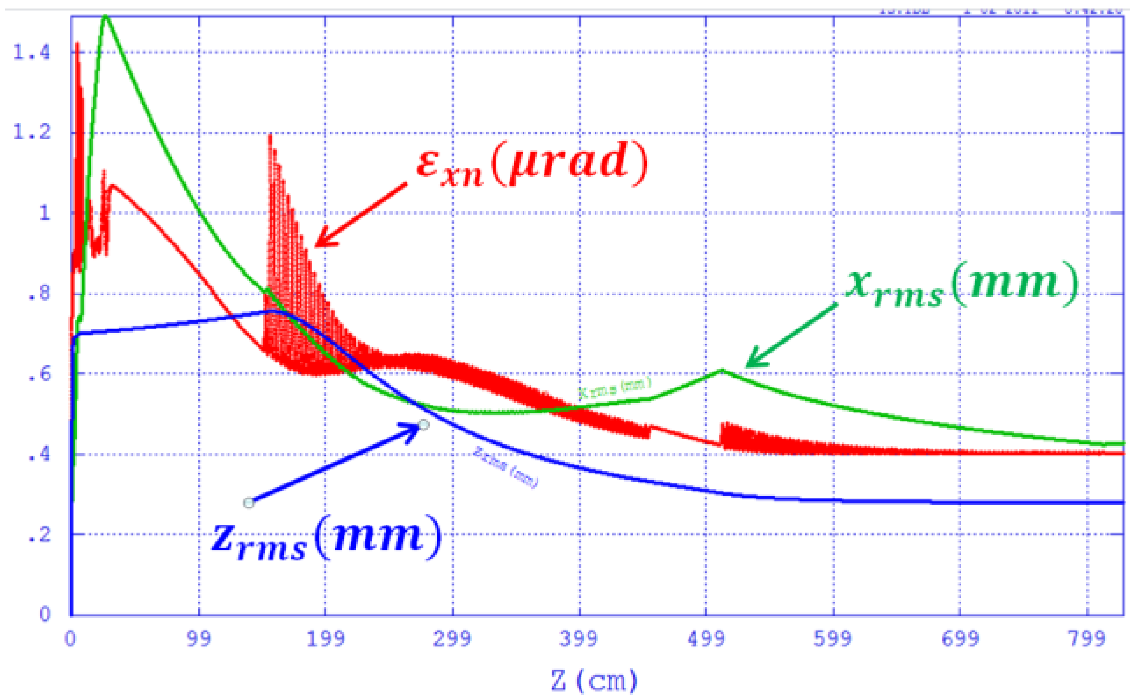
- *Advantages:*
  - Moderate risk (state of art RF gun, reduced multibunch operation problems respect to higher frequencies, low compression factor<3)
  - Economic
  - Compact (the use of the C-band booster meets the requirements on the available space)
  - Possibility to use SPARC as test stand



WP_{ref} from the photoinjector (Tstep tracking)







Egun=120 MV/m
E(S1)=E(S2)=21 MV/m
Q=250 pC

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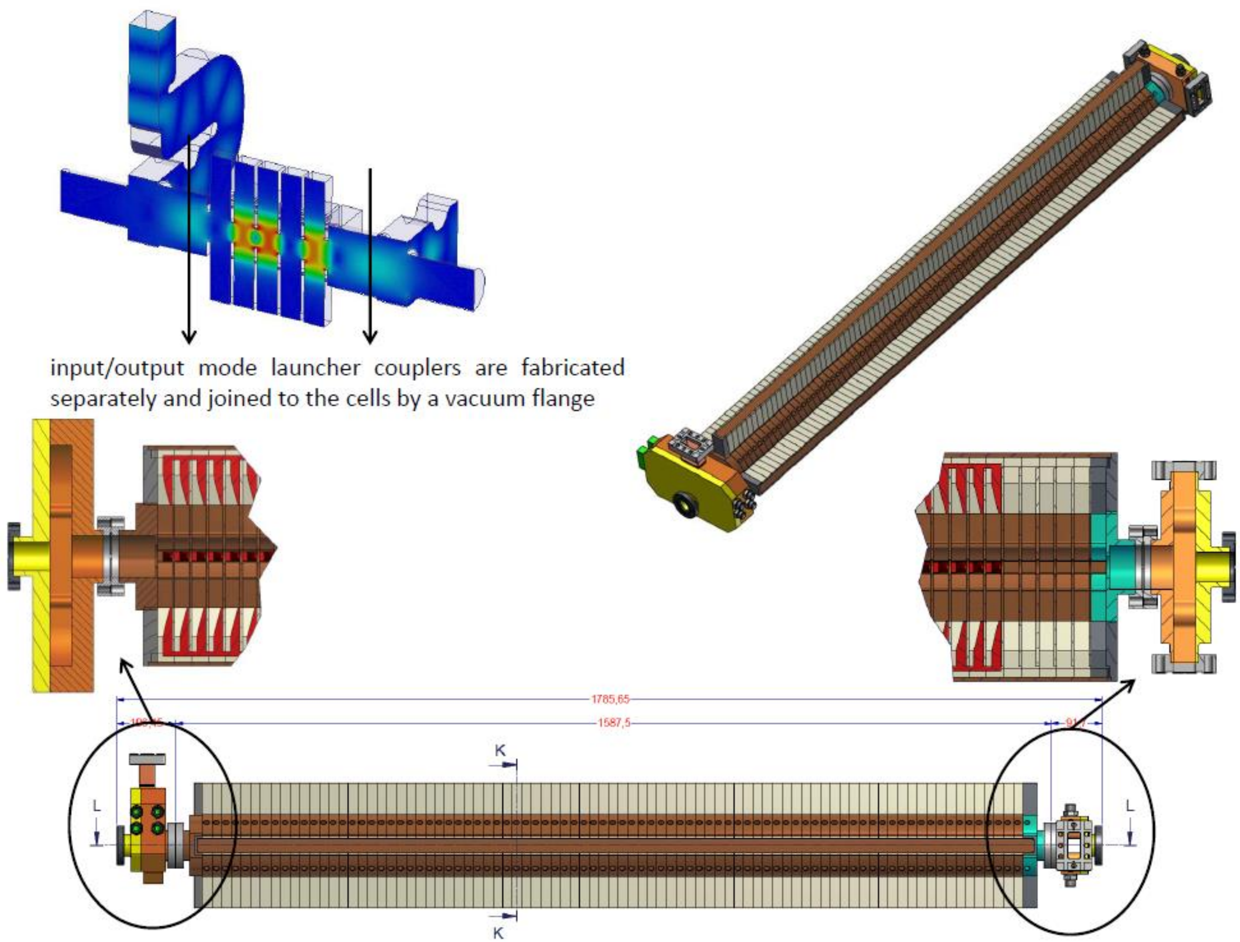
C-band structures

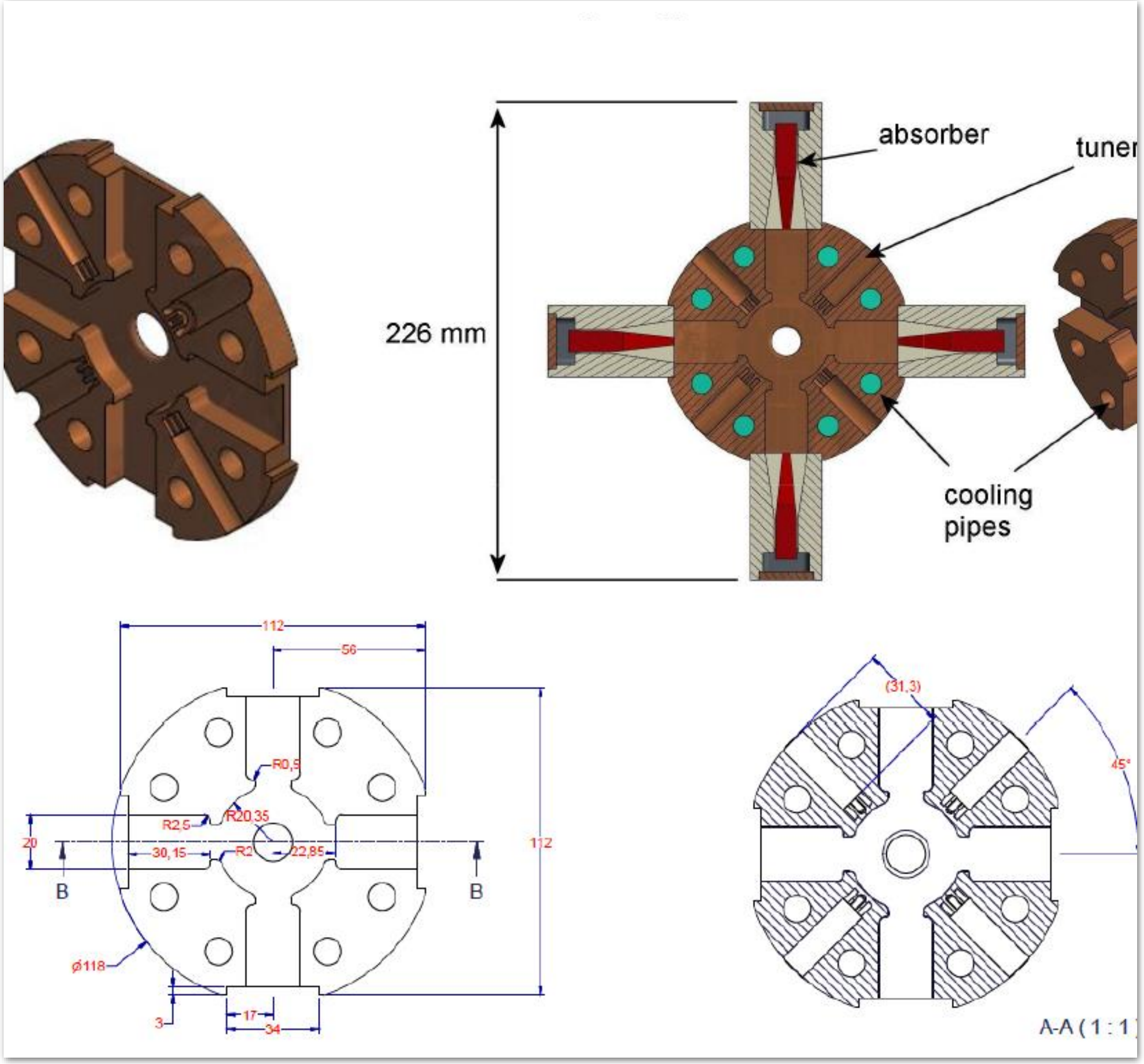
The beam loading effect and the Beam break UP (BBU) instability have been extensively studied to guarantee the multibunch operation feasibility.

In particular the beam loading in the structures will be compensated with a modulation of the input power to maintain the required energy spread along the bunch train.

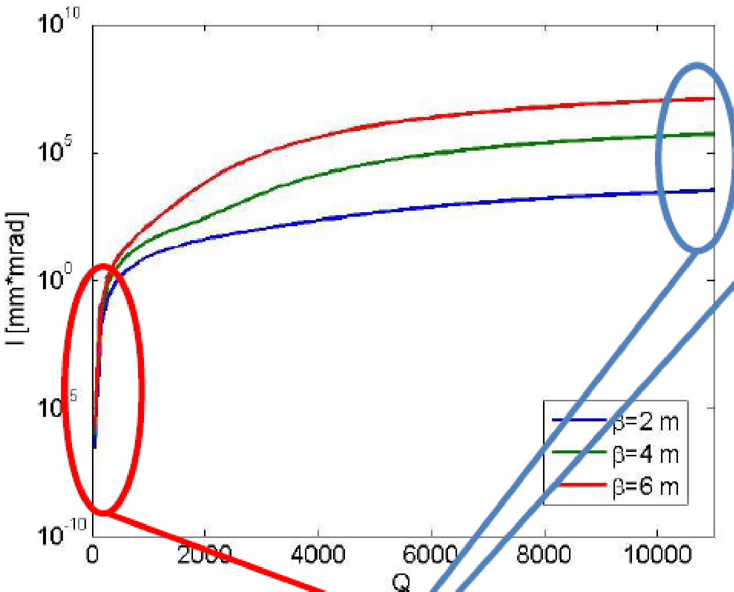


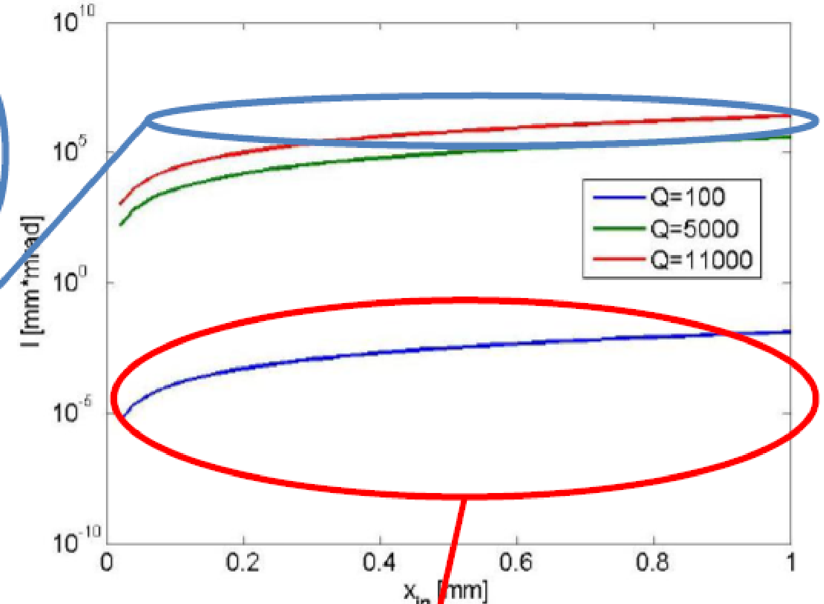
Central cells

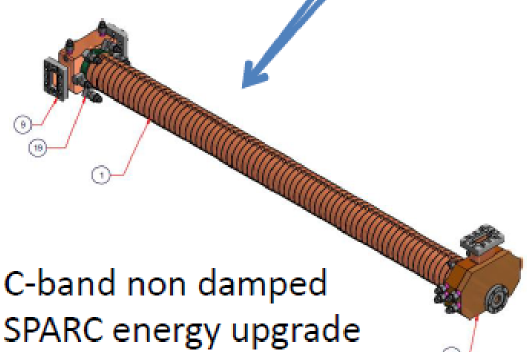
For the BBU a strong damping solution has been adopted for which each cell of the structure has four waveguides that allows the excited HOMs to propagate and dissipate into loads



Mitigation of multibunch effect with damped structure







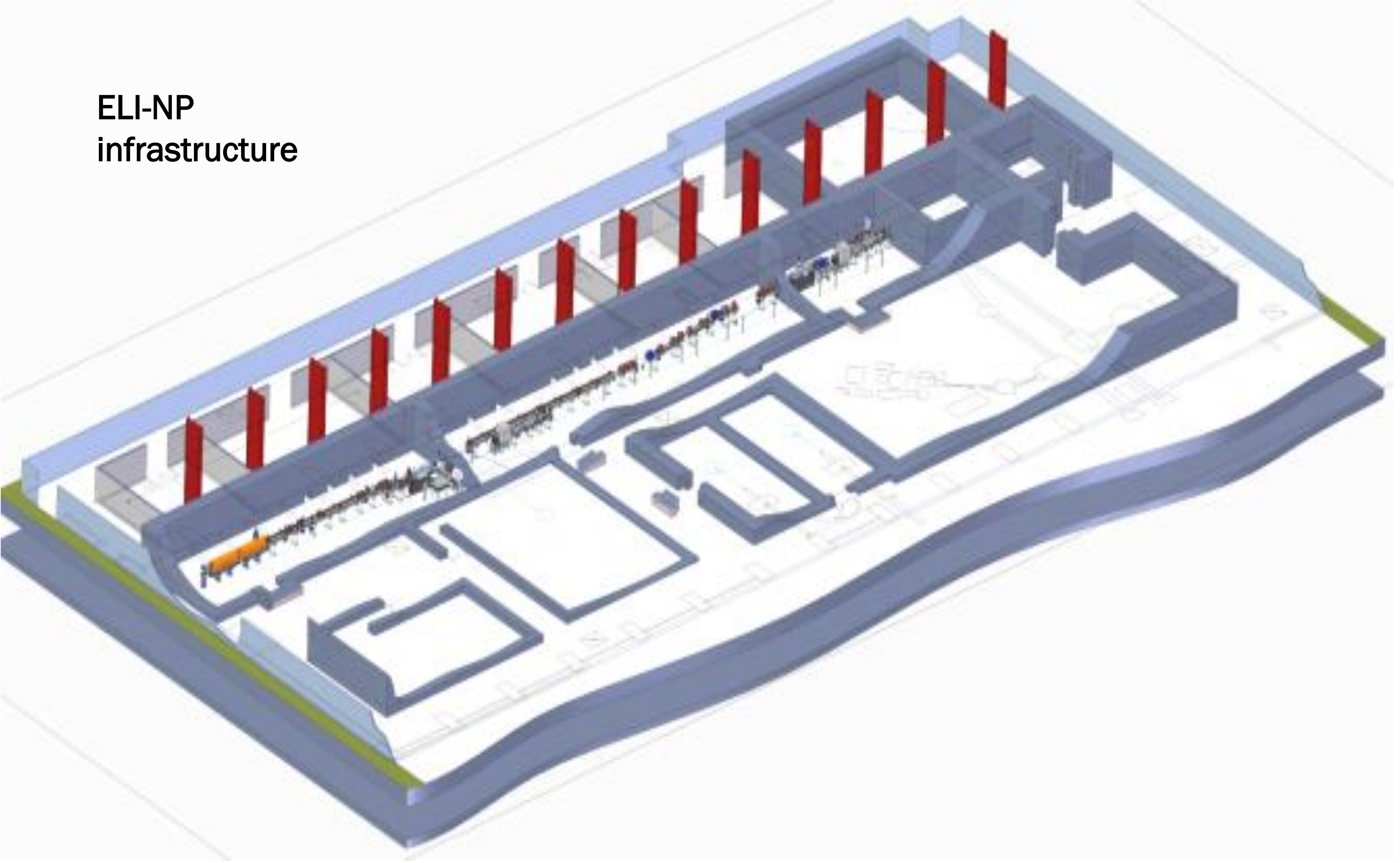
C-band non damped
SPARC energy upgrade

DAMPED STRUCTURES

D. Alesini

The machine layout

ELI-NP
infrastructure



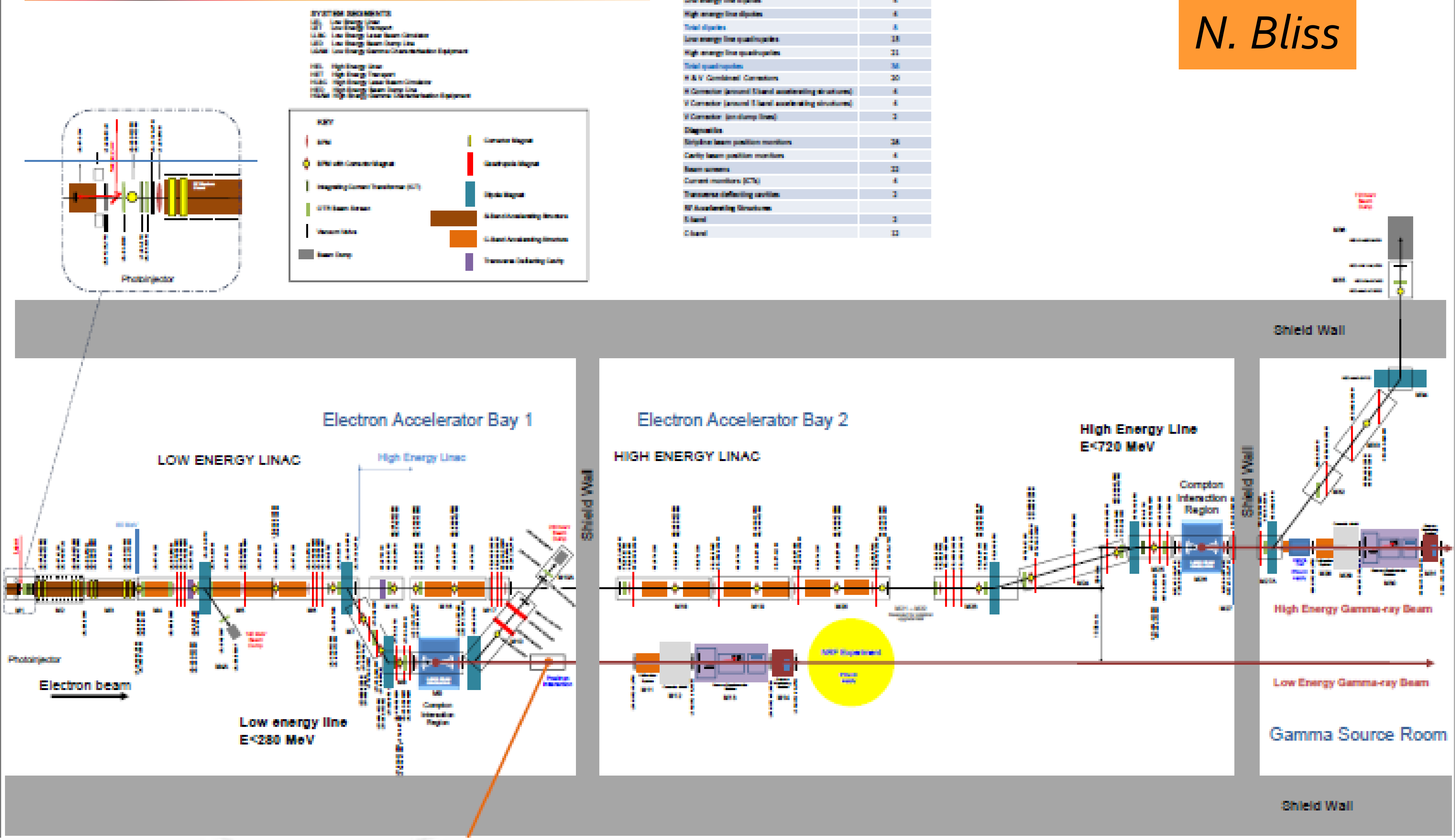
eli Nuclear Physics

European Collaboration for the proposal of a Gamma-Beam System to the ELI-NP Project

Accelerator Layout Schematic v12.4

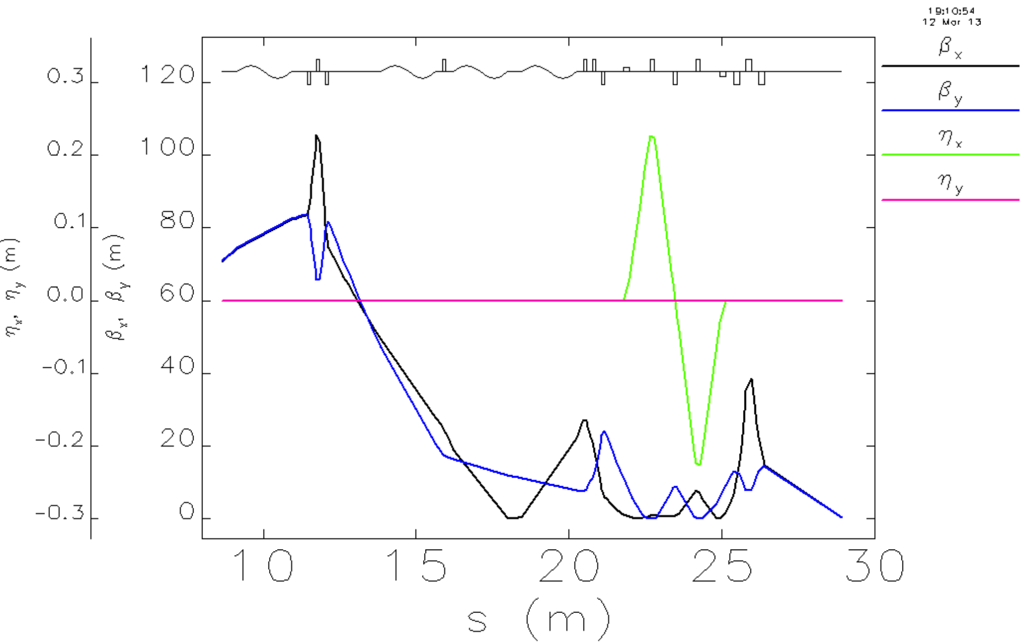
Device	Quantity
Magnets	
Photoinjector solenoid	1 (2 coils)
S-band linac solenoids	1 (12 coils)
Low energy line dipoles	4
High energy line dipoles	4
Total dipoles	8
Low energy line quadrupoles	18
High energy line quadrupoles	[illegible]
Total quadrupoles	[illegible]
H & V Combined Correctors	[illegible]
H Corrector (around S band accelerating structures)	4
V Corrector (around S band accelerating structures)	4
V Corrector (on dump lines)	2
Diagnostics	
Stripline beam position monitors	[illegible]
Cavity beam position monitors	4
Beam screens	[illegible]
Current monitors (CTs)	4
Transverse deflecting cavities	2
RF Accelerating Structures	
S band	2
C band	12

N. Bliss

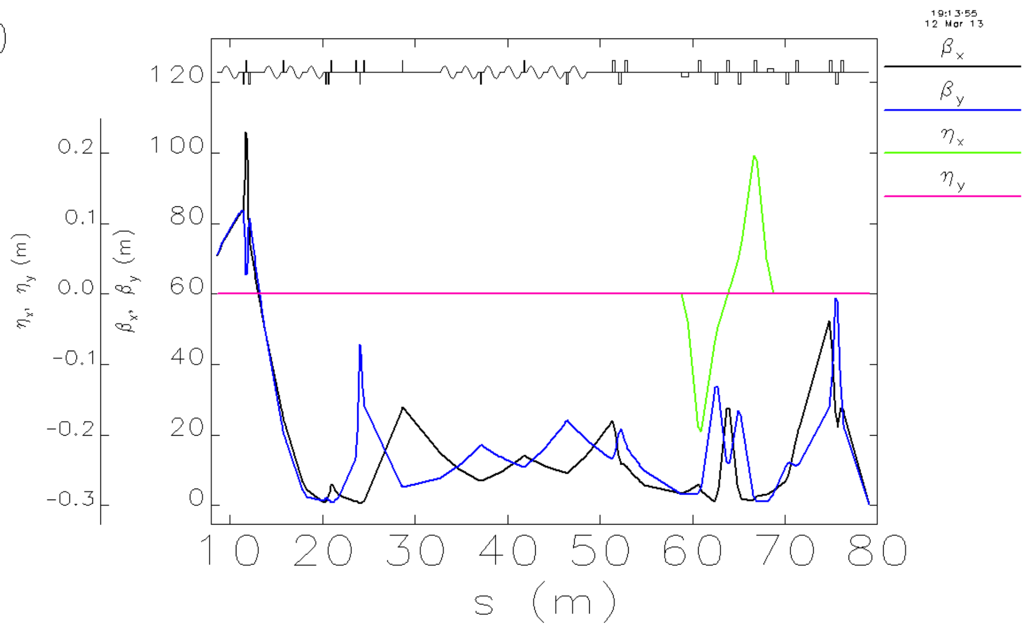


Linac & Transfer lines

Low energy

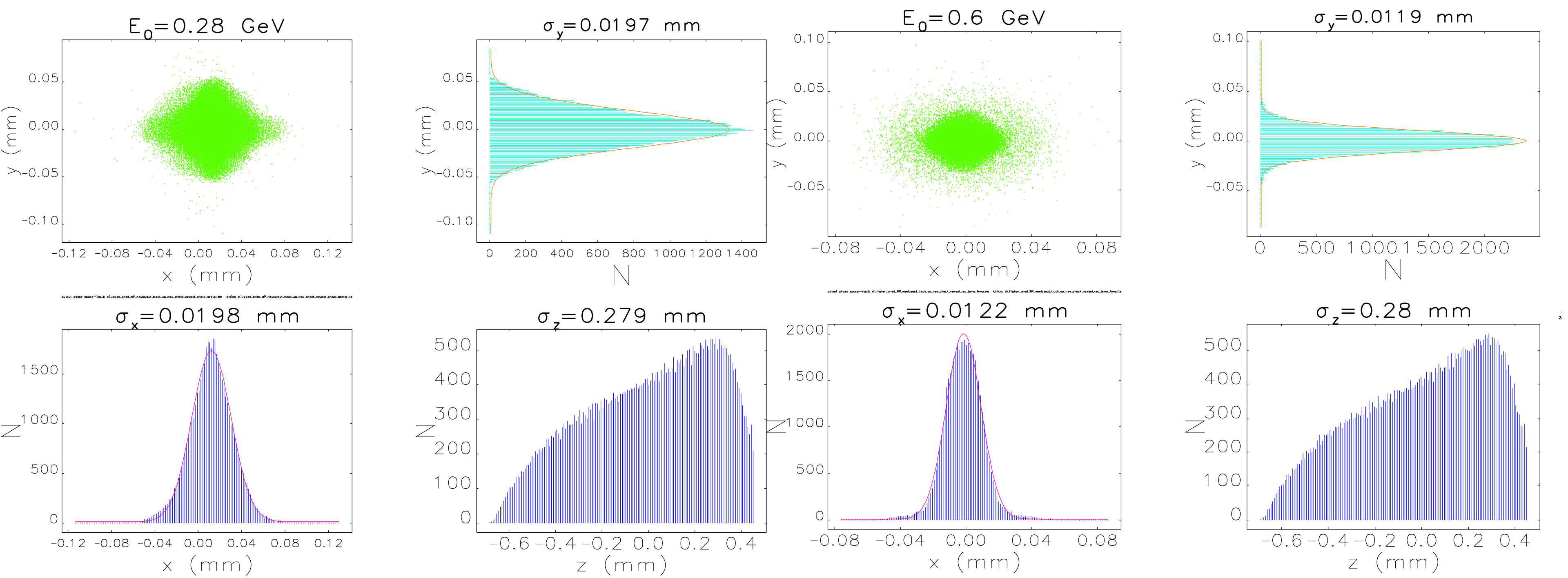


High Energy



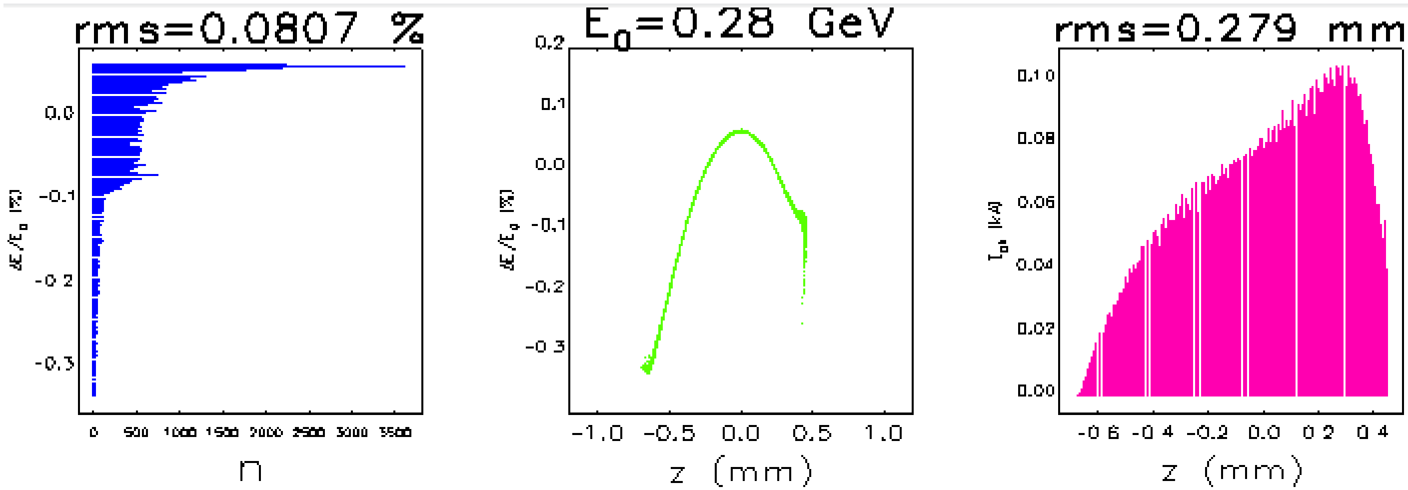
SB-Transverse beam size and distribution (Elegant tracking)

Low energy High energy

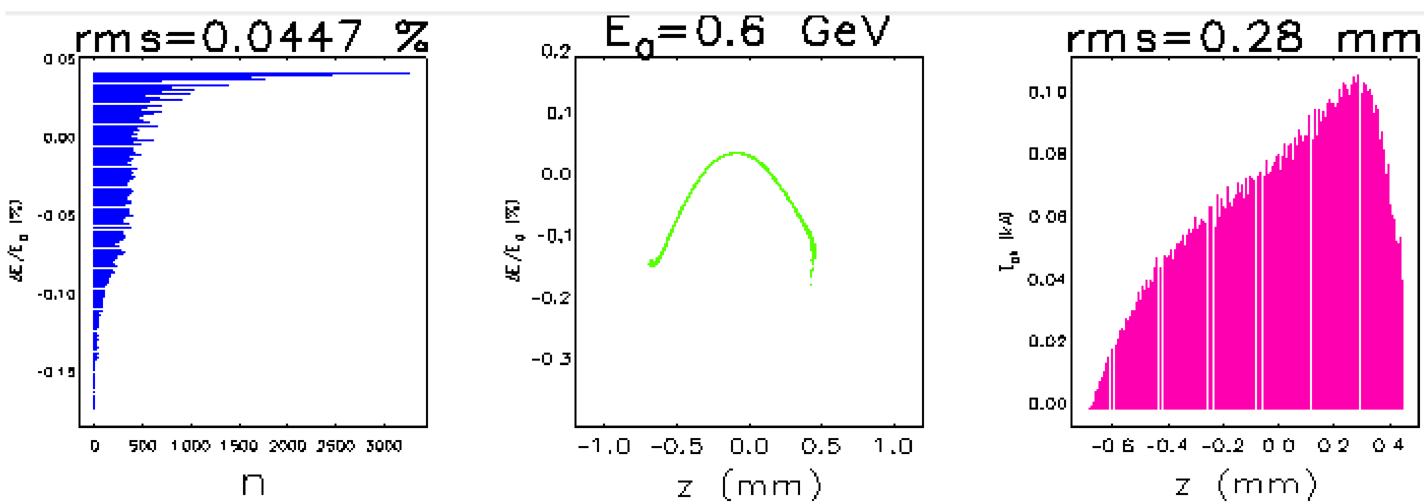


WPref_SB-energy spread & current

Lowen

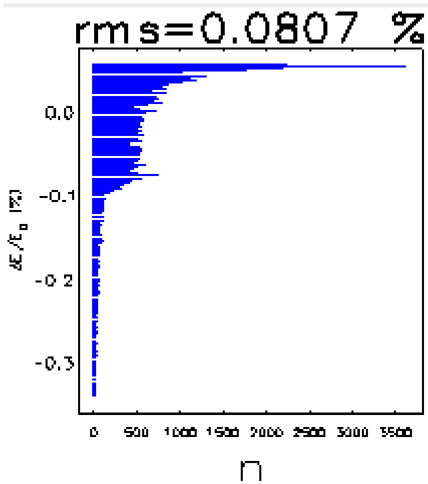


Highen

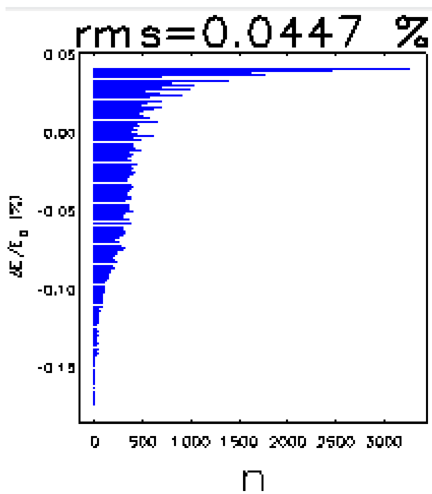


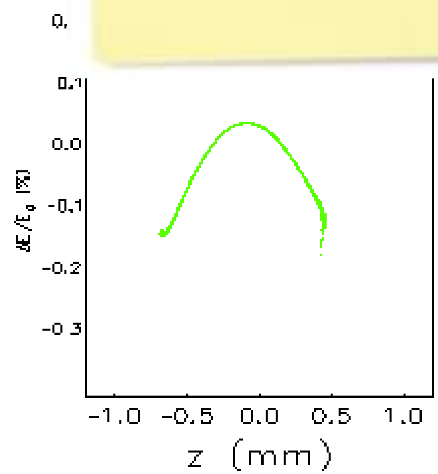
WPref_SB-energy sp

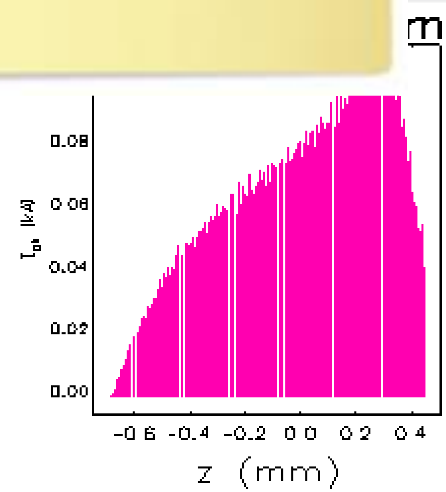
Lowen



Highen







from CAIN simulation:

- with 600 MeV electron beam
- in the 0.5 % bw
- within 88 mrad collimation angle
- 2.8×10^5 photons/shot obtained

Conclusions

- The key parameters of the new generation Compton source have been described together with the main common features with the high brightness beam expertise.
- A C-band RF linac has been presented based on the requirements of the gamma-ray source in the framework of the ELI-NP project.