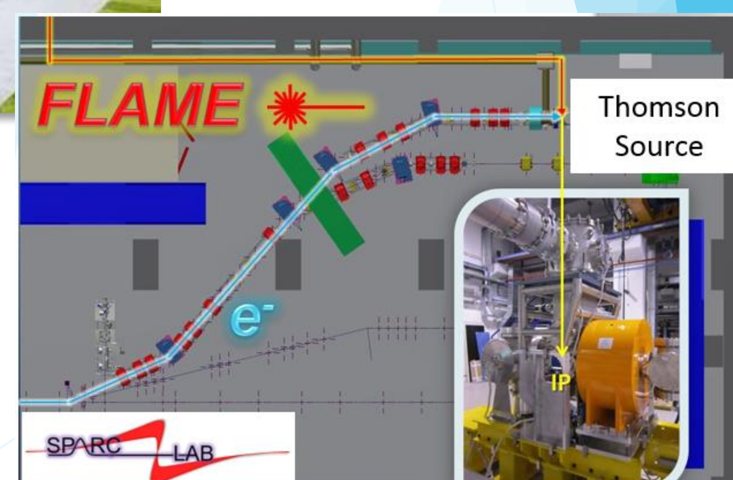
17/10/2016

Research Activity Report

6D Phase Space Electron Beam Analysis And Optimization For Rf Linac Based Inverse Compton Scattering Radiation Sources



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on behalf of the
SPARC_LAB and ELI-NP team

Outline

- 6D phase space electron beam analysis and optimization for RF linac based Inverse Compton Scattering Radiation Sources

    1. SPARC_LAB Thomson Source (20 – 500 keV)
    2. ELI-NP GBS (0.2 – 19.5 MeV)

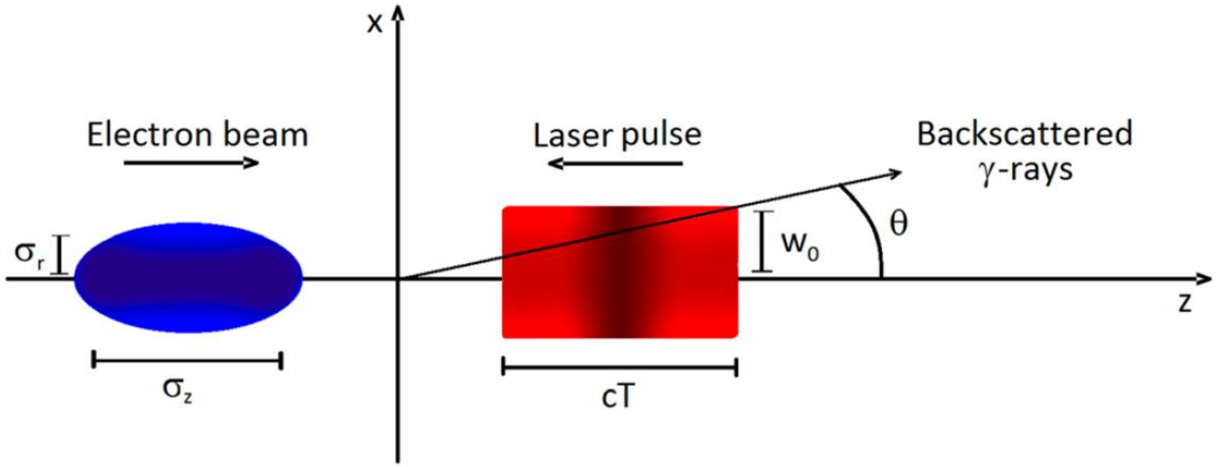
- SPARC_LAB Thomson Source

    - SPARC_LAB experiments
    - First and second commissioning phase

- ELI-NP GBS

    - Start to end simulations
    - Linac error sensitivity studies
    - Quasi-constant gradient C-band structures
    - Longitudinal long-range wake field effects in multi bunch operation

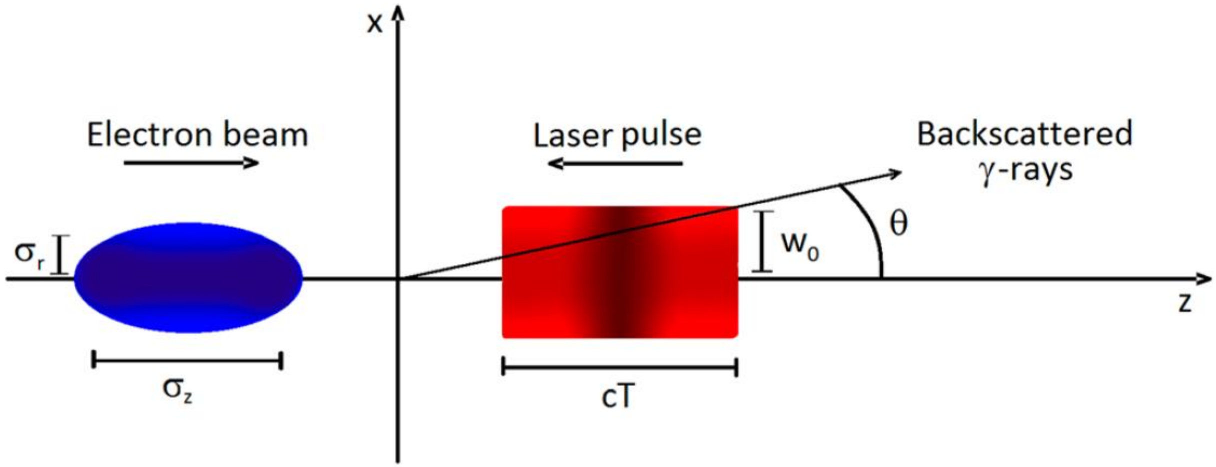
Inverse Compton Scattering Radiation Sources



$$N_\gamma^{bw} = \frac{4.1 \times 10^8 U_L[\mathrm{J}] Q_b[pC] \Psi^2}{h\upsilon_l[\mathrm{eV}]\left(\sigma_x^2[\mu\mathrm{m}] + \frac{W_0^2}{4}\right)}$$

$$\frac{\Delta\upsilon_\gamma}{\upsilon_\gamma} = \sqrt{(\gamma\theta)_{\mathrm{rms}}{}^4 + \left(\frac{\Delta\gamma}{\gamma}\right)^2 + \left(\frac{\varepsilon_n}{\sigma_x}\right)^4 + \ \ldots}$$

Inverse Compton Scattering Radiation Sources



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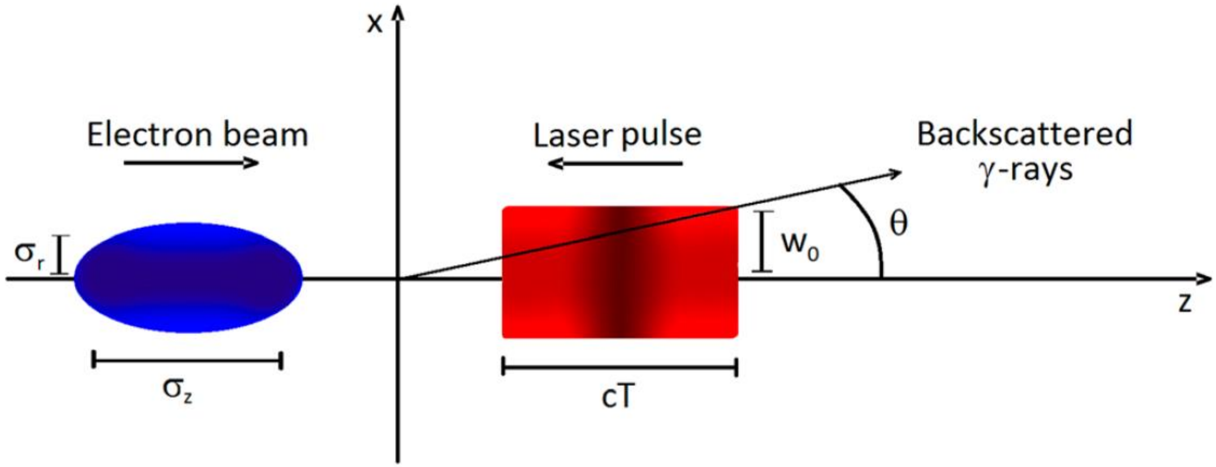
$$SPD \equiv \frac{N_\gamma^{bw}}{\sqrt{2\pi} h \Delta\upsilon_\gamma}$$

Inverse Compton Scattering Radiation Sources



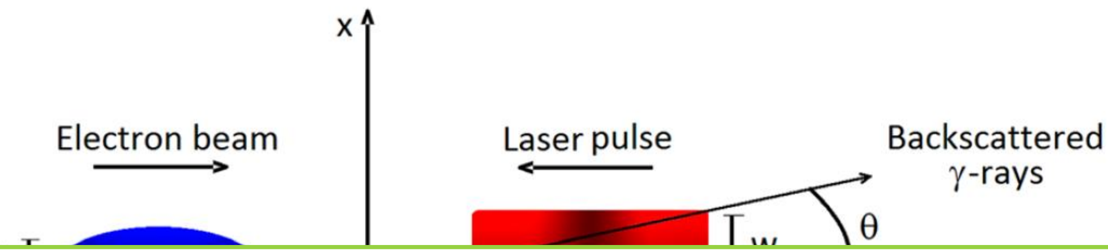
$$N_\gamma^{bw} = \frac{4.1\times10^8 U_L[\mathrm{J}] Q_b[pC]\Psi^2}{h\upsilon_l[\mathrm{eV}]\left(\sigma_x^2[\mu\mathrm{m}] + \frac{W_0^2}{4}\right)}$$

$$\frac{\Delta\upsilon_\gamma}{\upsilon_\gamma} = \sqrt{(\gamma\theta)_{\mathrm{rms}}{}^4 + \left(\frac{\Delta\gamma}{\gamma}\right)^2 + \left(\frac{\varepsilon_n}{\sigma_x}\right)^4 + \quad \ldots}$$

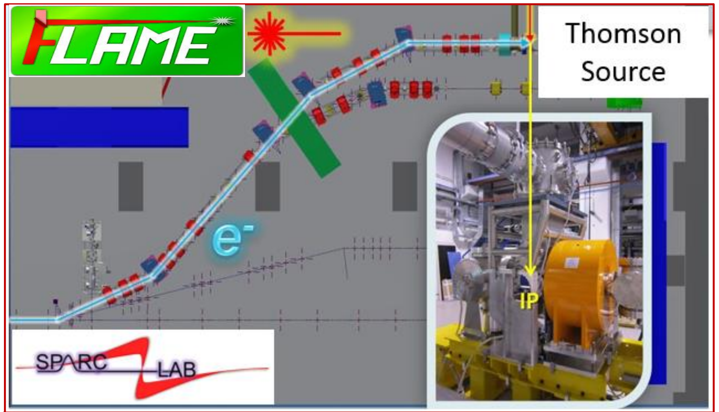
$$SPD \equiv \frac{N_\gamma^{bw}}{\sqrt{2\pi} h\Delta\upsilon_\gamma}$$

$$\hat{\eta} = \frac{Q_b}{\sigma_x^2\left[\left(\frac{\Delta\gamma}{\gamma}\right)^2 + \left(\frac{\varepsilon_n}{\sigma_x}\right)^4\right]^{1/2}} \quad \left[\frac{C}{m^2}\right]$$

Inverse Compton Scattering Radiation Sources



High Brigthness Photoinjector + Intense High Power Laser System



SPARC_LAB Thomson Source

ELI-NP GBS

$$\hat{\eta} = \frac{Q_b}{\sigma_x^2\left[\left(\frac{\Delta\gamma}{\gamma}\right)^2 + \left(\frac{\varepsilon_n}{\sigma_x}\right)^4\right]^{1/2}} \left[\frac{C}{m^2}\right]$$

The SPARC_LAB Thomson source

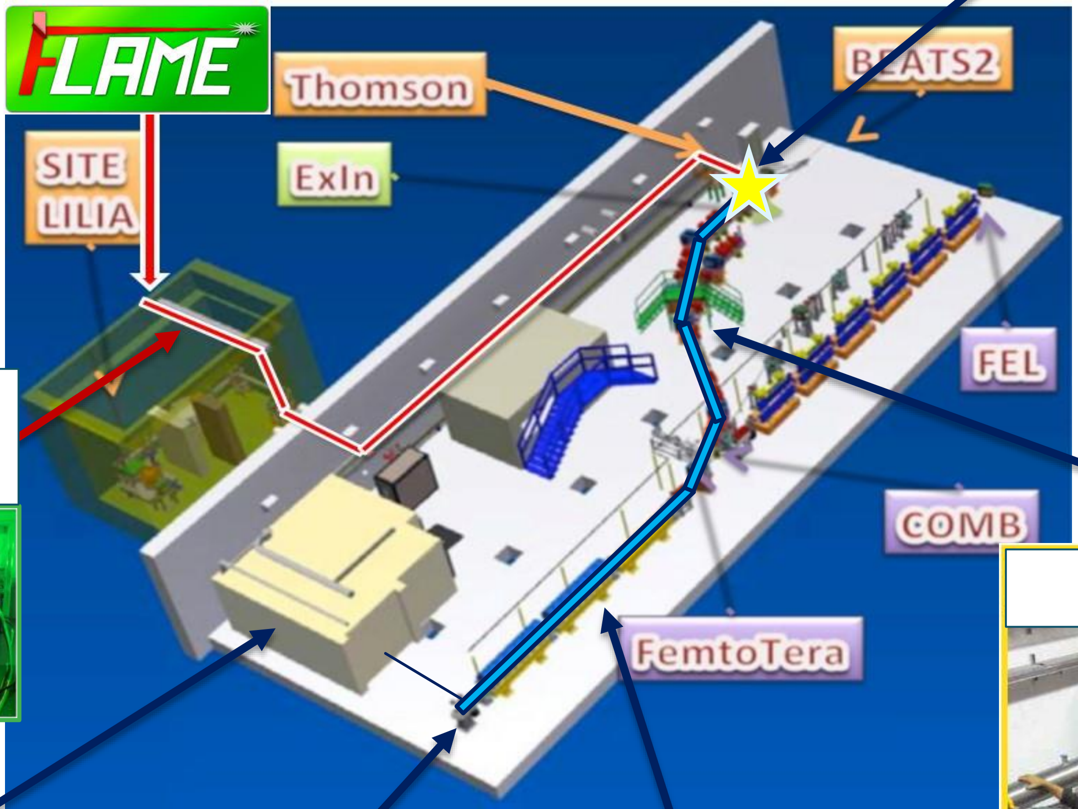
Peculiarities of the source are:

1. Energy tunability of the source in the range [20 – 500] keV
2. Moderate mono-chromaticity of the source with a BW (rms) ≤ 10%
3. Useful for medical imaging, cultural heritage, etc..

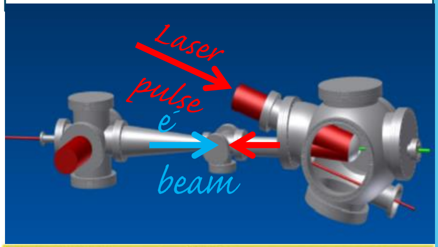
Beams Parameters @IP		
Electron Beam Q = 100 - 800 pC		
Energy	30 - 150	MeV
Energy spread	< 0.1	%
Bunch length	15 - 20	ps
$\varepsilon_{n_{x,y}}$	1 – 3	mm mrad
Focal Spot Size	5 - 20	µm
Laser Beam λ = 800 nm		
Energy	0.2 - 2	J
Focal Spot Size	10	µm

SPARC_LAB - Beam Specifications		
Energy	20 – 500	keV
Flux within FWHM BW	10^9	N_{ph}/pulse
BW (rms)	10	%
Source Size	10	µm

The SPARC_LAB Thomson source



Interaction Point



Optical transfer line

Double Dogleg

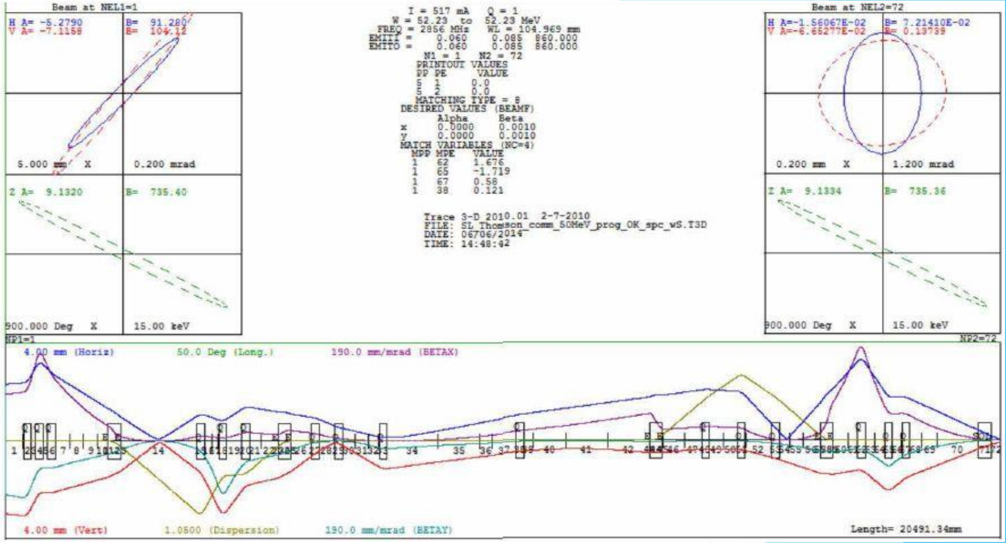
Cathode Laser Room
50 mJ Ti:Sapphire laser

RF GUN
5 MeV 1.6 cell S-band

LINAC
composed of 3 50MeV TW S-Band structures

The SPARC_LAB Thomson source

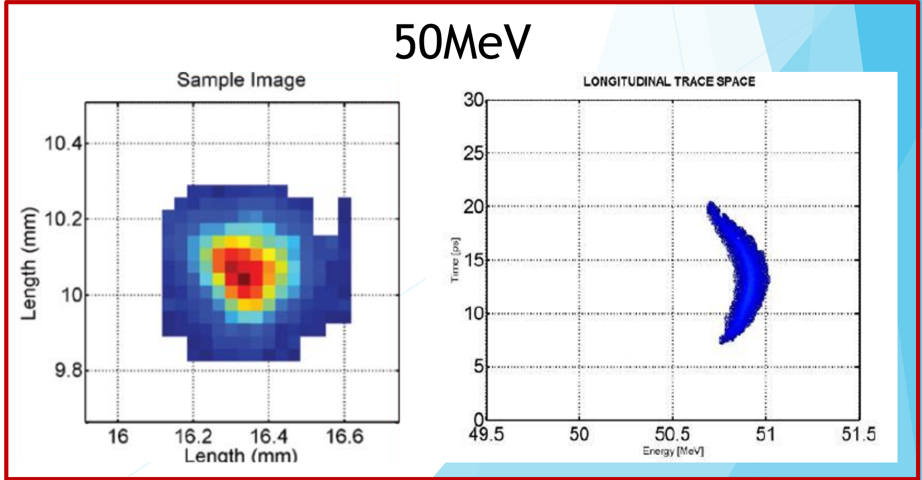
- Simulations of the beam envelope up to the IP have been performed with the TSTEP/TRACE 3D code (Elegant)
  - Space charge contribution
  - At IP $\sigma_{x,y} \approx 50\ \mu m$
  - Correction of the horizontal dispersion in the double dogleg



TRACE 3D simulation of Twiss parameters along the LINAC

- Measured parameters
  - Committed electron beams at 50 MeV (2014) and 30 MeV (2015) with 10^4 photons/shot
  - Spot size focusing limited by the background noise on radiation diagnostic system.

Beams Parameters @IP			
Energy	50.6 ± 0.2	30 ± 0.2	MeV
Energy spread	0.1	0.06	%
Bunch length	3.1 ± 0.2	2.2 ± 0.1	ps
$\varepsilon_{n_{x,y}}$	≈ 2.2	≈ 4.0	mm mrad
Focal Spot Size	90 ± 3	110 ± 9	µm



The ELI-NP γ-source

Peculiarities of the γ-source are:

1. Energy tunability of the γ-source in the range [0.2 – 20.0] MeV
2. Mono-chromaticity of the γ-source with a BW (rms) ≤ 0.5%
3. Peak brilliance of the γ-source > 10^{21} [N_{ph}/s·mm^2·mrad^2·0.1%]
4. Useful for nuclear physics and a wide range of applications

- 75 MeV ≤ Energy Tunability of Electron Beam ≤ 740 MeV
- 0.04% ≤ Energy Spread of Electron Beam (%) ≤ 0.1%
- 0.2 mm mrad ≤ ε_n ≤ 0.6 mm mrad
- 15 µm ≤ σ_t ≤ 30 µm

The ELI-NP γ-source

Technical Design Report

E-Gammas proposal for the ELI-NP Gamma beam System

With 79 tables and 252 figures

Beams Parameters @IP		
Electron Beam Q = 25 - 400 pC		
Energy	75 – 740	MeV
Energy spread	0.04 - 0.1	%
Bunch length	100 - 400	μm
$\varepsilon_{n_{x,y}}$	0.2 – 0.6	mm mrad
Focal Spot Size	> 15	μm
Laser Beam λ = 515 nm		
Energy	0.2 – 0.4	J
Focal Spot Size	> 28	μm

GBS - Beam Specifications		
Energy	0.2 – 20.0	MeV
Flux within FWHM BW	$\leq 2.6 \cdot 10^5$	N_{ph}/pulse
Peak brilliance	10^{20} - 10^{23}	N_{ph}/s·mm²·mrad²·0.1%
BW (rms)	≤ 0.5	%
Source Size	10 - 30	μm

SAPIENZA UNIVERSITÀ DI ROMA — INFN Istituto Nazionale di Fisica Nucleare — Science & Technology Facilities Council — CNRS IN2P3 Les deux infinis — UNIVERSITE PARIS SUD Comprendre le monde, construire l'avenir

Machine layout

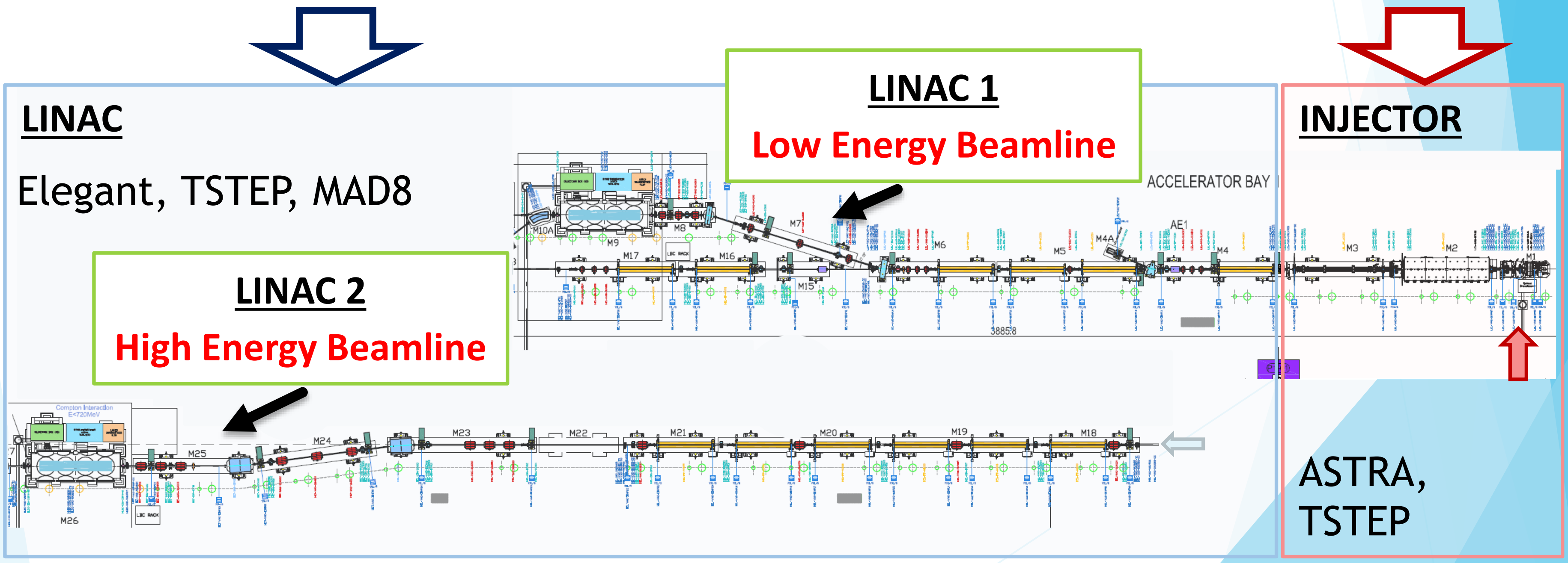
HYBRID SCHEME CONSISTING IN A SPARC-LIKE S-BAND HIGH BRIGHTNESS PHOTOINJECTOR FOLLOWED BY A C-BAND RF LINAC

C-BAND RF LINAC

Higher accelerating gradients provided by the C-band accelerating sections in the rest of the linac allow to compact its length.

S-BAND HIGH BRIGHTNESS PHOTOINJECTOR

In the RF gun a bunch long enough, $\sigma_z \approx 1mm$, is needed to reduce the emittance degradation in the space charge dominated regime.



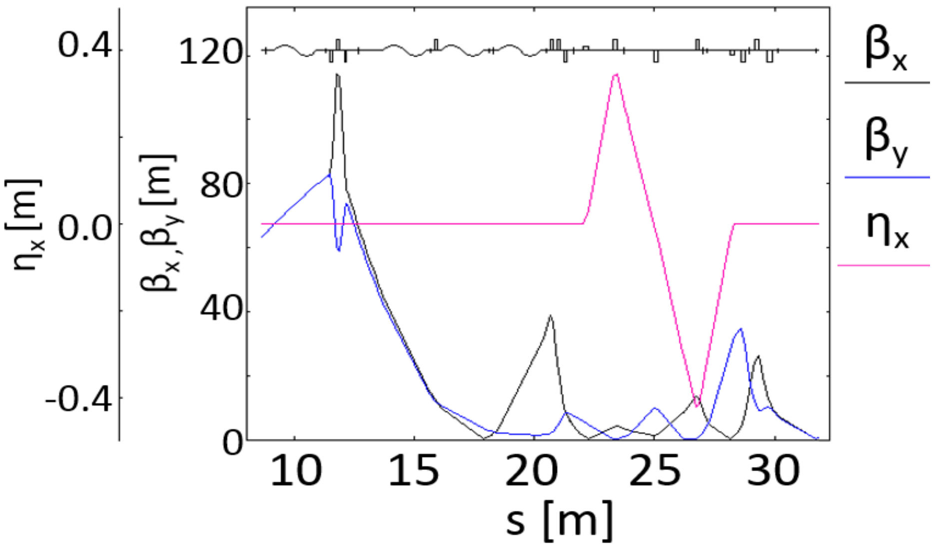
Start to end simulations

- Intensive e^- Beam Dynamics (BD) simulations for several Working Points (WPs) to optimise the photon beam parameters
- Several beams from the S-band injector tracked along the C-band booster linac
- C-band structures in off-crest operation to preserve the energy spread in the entire energy range.

	γ-source WP [MeV]	Energy @IP [MeV]	Energy @Inj Exit [MeV]	Energy spread [‰]	Bunch length [μm]	$\varepsilon_{n x,y}$ [mm mrad]	$\beta_{x,y}$ [m]	$\sigma_{x,y}$ [μm]
LINAC 1	0.20	75	70.5	1.14	275	0.51	0.16	23.5
	1.00	165	81.5	0.86	274	0.44	0.43	20.0
	2.00	234	81.5	0.82	273	0.44	0.43	19.5
	2.85	280	81.5	0.78	275	0.45	0.50	19.5
	3.50	312	91.5	0.80	278	0.41	0.55	19.5
LINAC 2	10.00	530	81.5	0.45	272	0.44	0.71	17.5
	13.00	605	81.5	0.43	273	0.44	0.71	17.5
	19.50	740	120 - 146	2.0 – 3.5	700	> 0.45	-	-

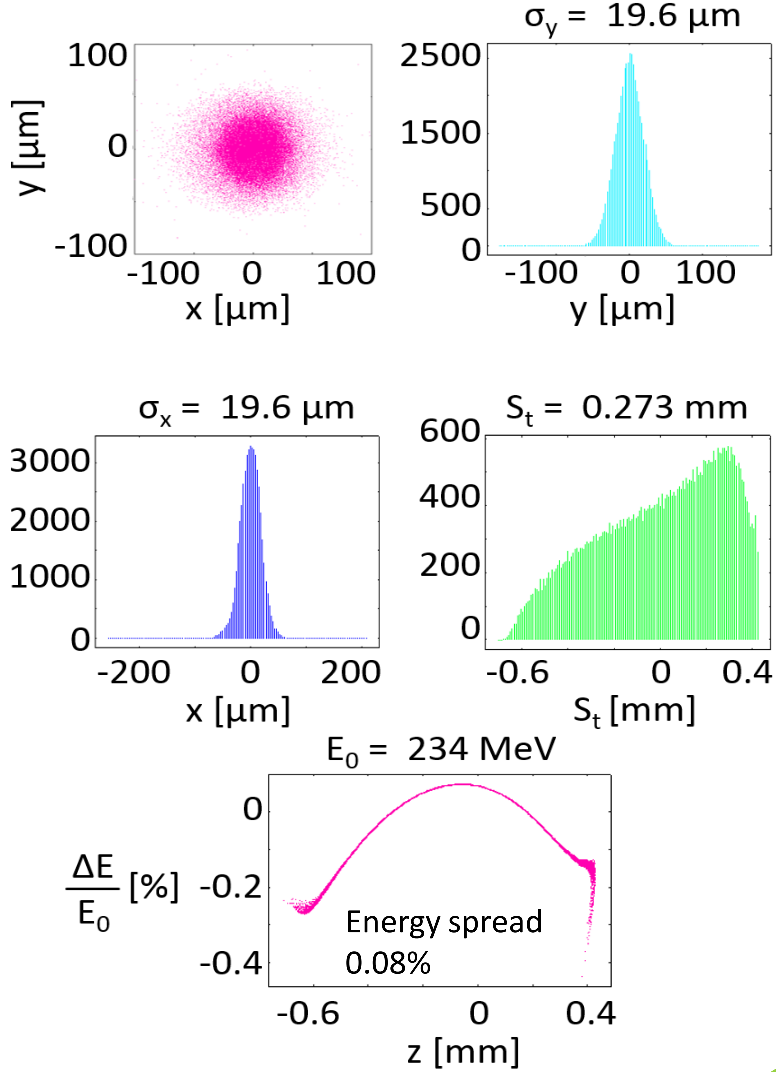
Start to end simulations

Example: 2.0 MeV γ-source WP



234 MeV @LE IP (Ref. case)		
Energy	234.0	MeV
Energy spread	0.82	‰
Bunch length	273.0	µm
$\varepsilon_{n_{x,y}}$	0.44	mm mrad
Focal Spot	19.6	µm

@LE IP



Linac error sensitivity studies

The Method

- BD simulations over a sample of 100 machine runs aimed to:
  1. Test the robustness of the linac to any possible error
  2. Provide jitter and alignment specifications for accelerating structures and magnets.
- Final BD simulations over a sample of 350 machine runs for several WPs for both Low Energy beam line and the High Energy beam line.
  1. Trajectory correction with Elegant routines
  2. Last vertical and horizontal steerers used to maximise the luminosity at IP
  3. Errors as indicated in the Table.

Linac Transfer Line Specifications		
C-band Accelerating Sections		
RF Voltage [ΔV]	< 2	‰
RF Phase [Δϕ]	< 1	Deg
Alignment on transverse plane [Δxy]	< 70	μm
Quadrupoles		
Geometric strength [Δk]	< 3	‰
Alignment on transverse plane [Δxy]	< 70	μm
Tilt about incoming longitudinal axis [ΔΘ]	< 1	mrad
Dipoles		
Bend angle [ΔB]	< 1	‰
Tilt about incoming longitudinal axis [ΔΘ]	< 1	mrad
Steerers		
Strenght [Δk]	< 0.2	μrad
BPMs		
Resolution	< 20	μm
Cavity BPMs		
Resolution	< 5	μm

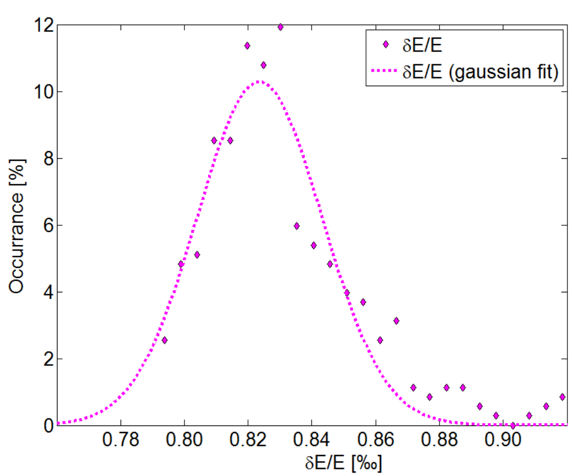
LE linac error sensitivity studies

2.0 MeV γ-source WP

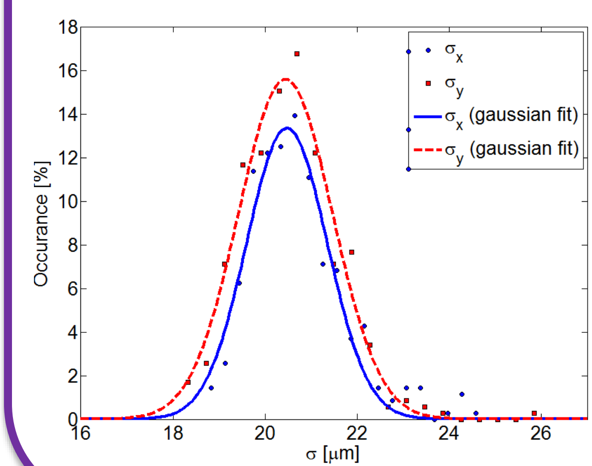
- Linac sensitivity studies done for each WP at LE IP.
- The analysis has been in terms of electron beam quality at LE IP.
- Deviation from the reference value of few percents.
- The parameters are still in specifications.

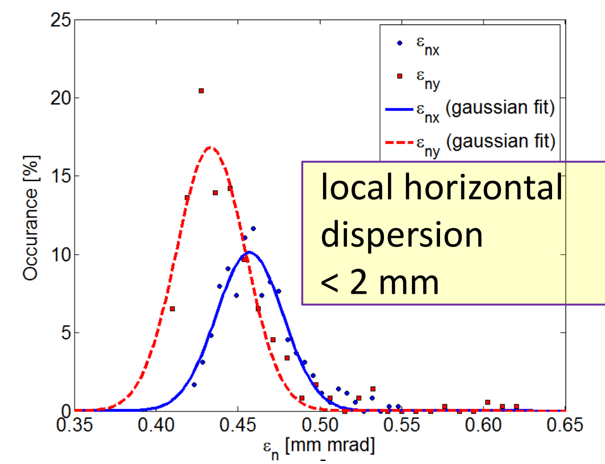
234 MeV @IP	Without errors	With errors	
Energy	234.0	234.3 ± 0.3	MeV
Energy spread	0.82	0.82 ± 0.02	‰
Bunch length	273.0	274.5 ± 6.0	μm
$\varepsilon_{nx,y}$	0.44	0.46 ± 0.02	mm mrad
Focal Spot	19.6	20.5 ± 1.0	μm
ΔC_{x-y}	0	0.2 ± 0.5	μm

@IP Energy Spread



@IP Transverse Spot Size and Normalised Emittance





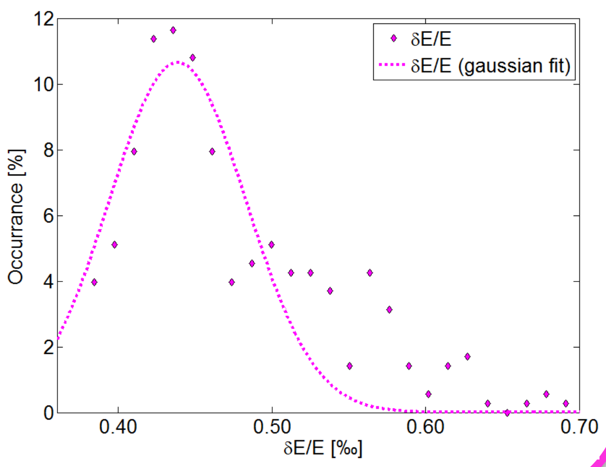
HE linac error sensitivity studies

10.0 MeV γ-source WP

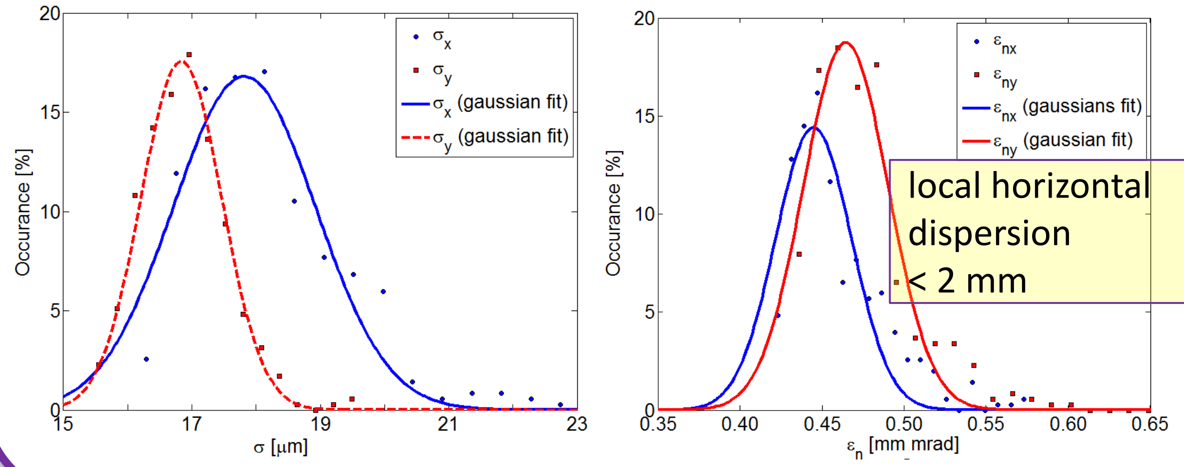
- Linac sensitivity studies done for each WP at HE IP.
- The analysis has been in terms of electron beam quality at HE IP.
- Deviation from the reference value of few percents.
- The parameters are still in specifications.

530 MeV @IP	Without errors	With errors	
Energy	529.6	529.8 ± 0.5	MeV
Energy spread	0.45	0.44 ± 0.05	‰
Bunch length	272.0	272.1 ± 5.2	µm
$\varepsilon_{n x,y}$	0.44	0.47 ± 0.02	mm mrad
Focal Spot	17.3	17.8 ± 1.1	µm
ΔC_{x-y}	0	0.1 ± 0.5	µm

@IP Energy Spread



@IP Transverse Spot Size and Normalised Emittance



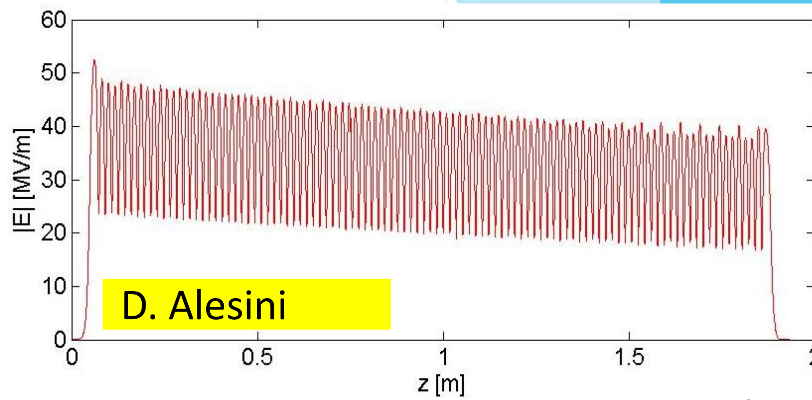
Quasi constant gradient C-band structures

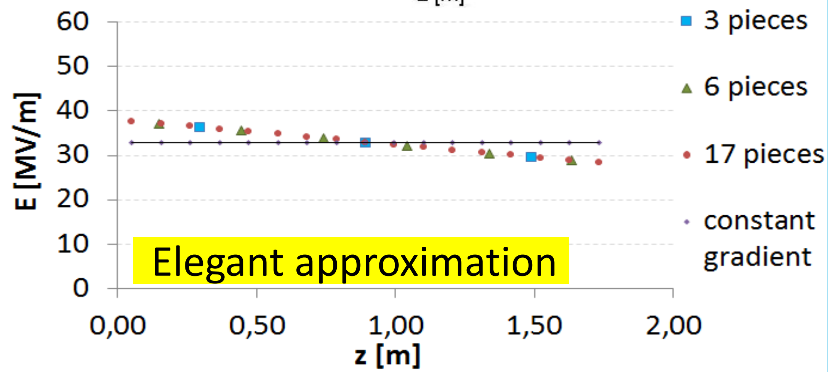
The Model

- C-band cavities splitted in more pieces to provide a good enough approximation to the real gradient profile.
- RF focusing carefully treated with Elegant routines based on the Serafini-Rosensweig model.

The Method

1. Studies on the **first** C-band cavity @33MV/m
2. Studies on the **overall** C-band linac matched for the 234 MeV electron beam.





Quasi constant gradient C-band structures

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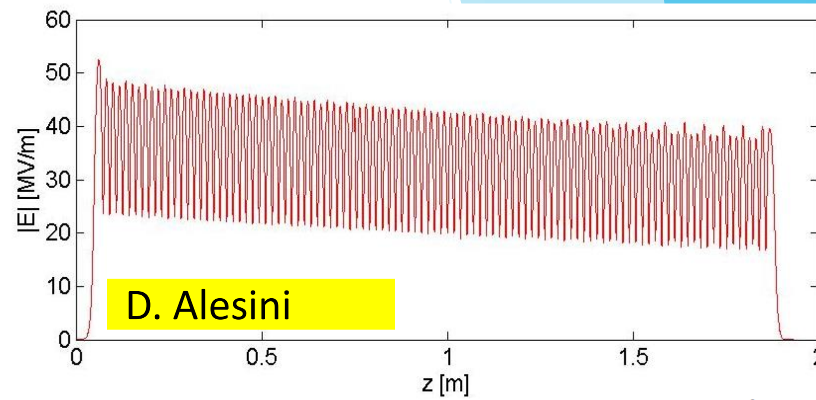
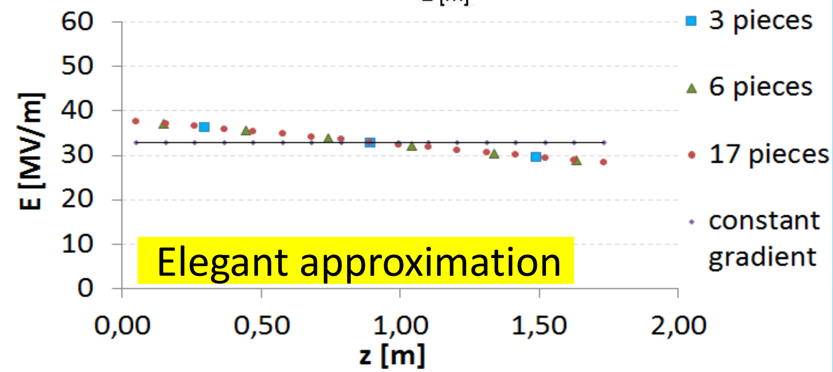
- RF focusing carefully treated with Elegant routines based on the Serafini-Rosensweig model.

The Method

1. Studies on the **first** C-band cavity @33MV/m
2. Studies on the overall C-band linac matched for the 234 MeV electron beam.

Quasi constant gradient behavior **affects mainly the transverse beam dynamics** resulting in a decrease of the spot size: the gradient at the entrance (38MV/m) is much stronger than the one in case of a constant gradient cavity (33MV/m).





Beam parameters @first C-band section exit					
Splitting factor	1	3	6	17	
Energy spread	0.910	0.911	0.912	0.912	%
Bunch length	274	274	274	274	μm
Energy	140	140	140	140	MeV
Spot Size	334	323	320	318	μm

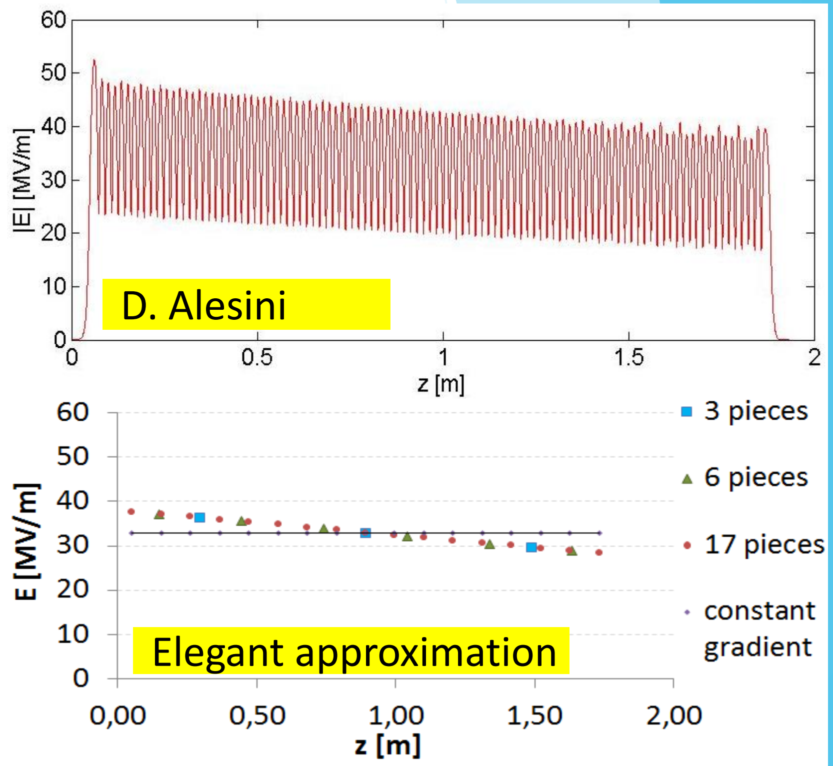
Quasi constant gradient C-band structures

The Model

- C-band cavities splitted in more pieces to provide a good enough approximation to the real gradient profile.
- RF focusing carefully treated with Elegant routines based on the Serafini-Rosensweig model.

The Method

1. Studies on the **first** C-band cavity @33MV/m
2. Studies on the **overall** C-band linac matched for the 234 MeV electron beam.



Quasi constant gradient C-band structures

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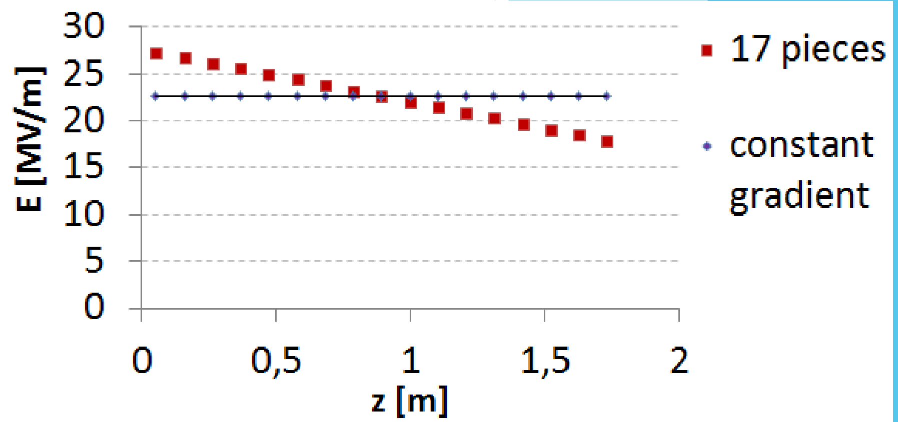
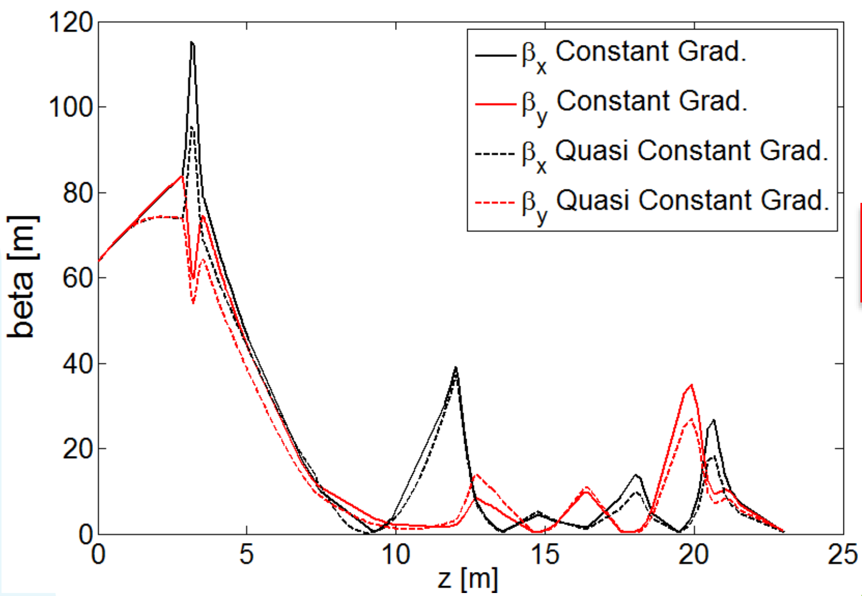


A "**quick**" matching of the beamline is needed



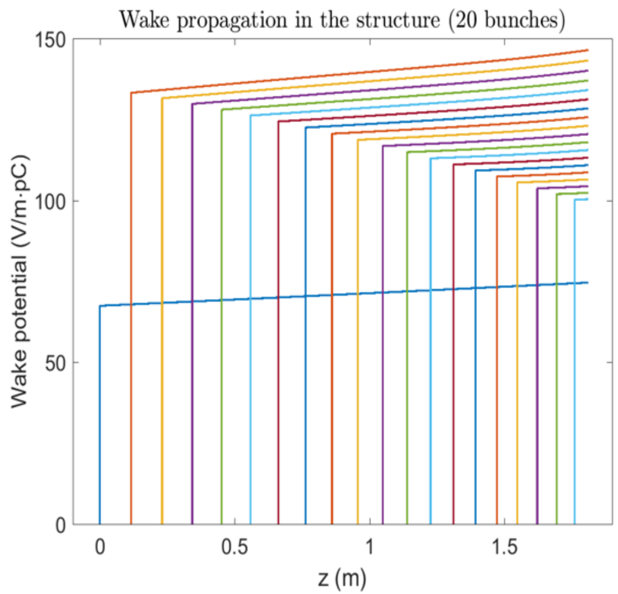
234 MeV @IP	Constant Gradient	Quasi Constant Gradient	
Energy	234.0	234	MeV
Energy spread	0.82	0.82	‰
Bunch length	273.0	274	µm
$\varepsilon_{n_{x,y}}$	0.44	0.43	mm mrad
Focal Spot	19.6	20.5	µm
$\Delta C_{x\text{-}y}$	0	20.5	µm

Multi bunch operation

- The multi bunch operation together with the 100 Hz rep. rate allows to increase the gamma flux
- In the multi bunch configuration **long range wake fields** arise both longitudinal and transverse
- Studies on the electron beam quality at LE IP in case of on-axis motion so that the **transverse long-range wake fields can be neglected**.

Multi bunch operation		
# bunches in the train	32	
Bunch separation T_b	16	ns
Energy variation along the train ΔE	<0.1	%

Model for long range longitudinal wake fields



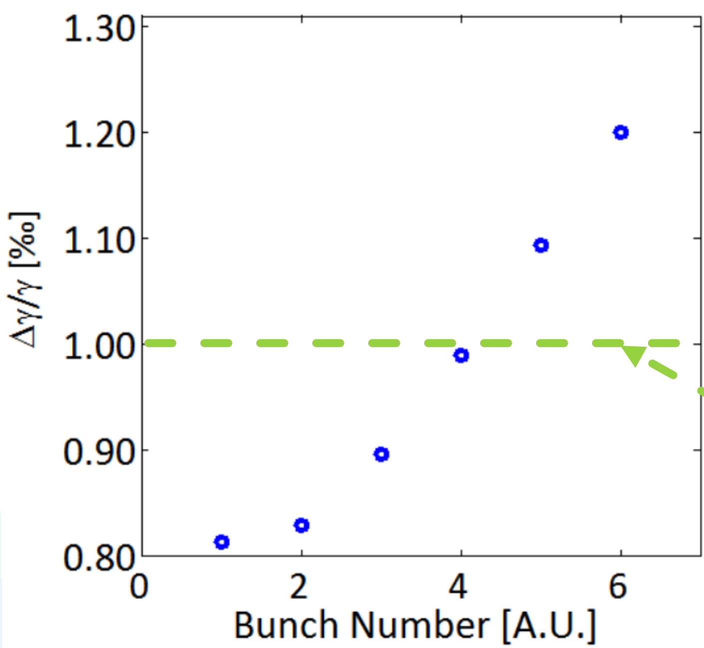
- Longitudinal wake fields propagation inside the C-band accelerating cavities calculated at different instances corresponding to the n^{th} bunch arrive (n=0,1, ... , 20)
- Full beam loading compensation technique can avoid the energy modulation along the train reducing the longitudinal phase space degradation at the collision with the laser pulse

L. Piersanti *et al.* "**The RF System of the ELI-NP Gamma Beam Source**", IPAC'16 May 2016

Multi bunch operation

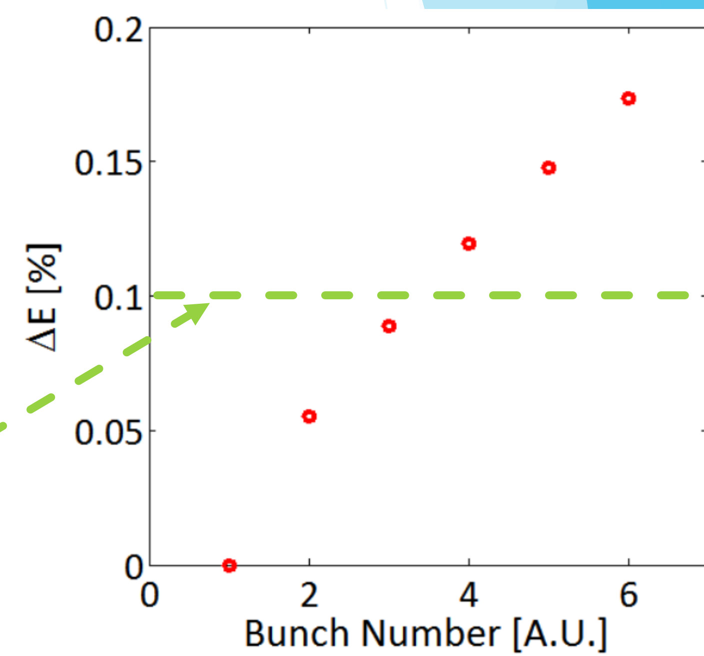
The Method

- Studies for the beamline matched for the 312 MeV electron beam
- Simulated with the Elegant code superimposing long-range wake fields to short-range wake fields
- After the passage of 20 bunches the wake field reaches a steady state, so we do not expect observable deviation from the bunch 20th to the last of the train



Relative energy spread

Maximum value to be compliant with the TDR



Cumulative energy deviation

A full beam loading compensation technique is needed
→ see L. Piersanti *et al.* "**The RF System of the ELI-NP Gamma Beam Source**", IPAC'16 May 2016

Conclusions

- Expertise coming from high brightness linear accelerators and high quality high power ps laser system enables the production of high spectral density monochromatic and tunable energy photon sources
- SPARC_LAB Thomson commissioning is still on going but interesting results have been observed
- Start to end simulations for the ELI-NP Gamma Beam System has been completed
- Machine sensitivity analyses has been completed and suggest that the machine is robust to errors in the specified range
- The effect of quasi constant gradient accelerating structures on the BD has been evaluated
- Longitudinal wake field effects in multi bunch operations have been considered underlying the importance of the full beam loading technique
- Analyses have been also carried out on sextuple terms, dark current completion, etc..

Thank you!!!

Sextupolar term on D-type QUADs

The Method

- Studies for the beamline matched for the 234 MeV electron beam.
- Sextupolar terms acts if a non zero dispersion occurs → errors have been included

Sextupole features		
Model	Thin Lens	
Type	Skew	
Length	1	mm
B_{max}	2.34	T
K_{eff_max}	138.4E+2	T/m^3

Slightly degradation of σ and ε at IP on vertical (circles) and horizontal (squares) planes. The beam is still in specifications