Beam dynamics studies for the RF LINAC of the ELI-NP Gamma beam system

C. Vaccarezza on behalf of the ELI-NP GBS Team

Outline:

- ☐ New generation Compton sources:
  → ELI-NP GBS project
- ☐ The ELI-NP Gamma Beam System:
  - Source design
  - Photoinjector & Linac reference WP:
    - S-C-band solution
    - Gun-Solenoid study
  - The machine layout:
    - C-band Linac1-2
  - S2E simulation results:
    - Nominal WP and error sensitivity studies

Gamma-ray Compton Sources

Thanks to the extremely advanced characteristics:

- energy, tunability, mono-chromaticity, collimation, brilliance, time rapidity, polarizability etc.
- the new generation of Compton Sources will play a critical role for advanced applications in many fields: Nuclear resonance fluorescence, Nuclear photonics with (γ-p) (γ-n) reactions, New medical isotopes production, Material studies, Radioactive waste management and isotope identification, High brilliance Neutron sources ecc. ecc.

ELI-NP, the Nuclear Physics Pillar of ELI

is building an advanced Compton Source (Gamma Beam System) aiming at making a substantial step forward in *γ*-ray beam performances

New generation γ-source:

High Phase Space density electron beams vs Lasers

ELI-NP

Source

Specifications

Energy [MeV]	0.2 – 19.5
Spectral Density [ph/s·eV]	$0.8 – 4 \cdot 10^4$
Bandwidth rms [%]	≤ 0.5
# photons/pulse within FWHM bdw.	$\leq 2.6 \cdot 10^5$
# photons/s within FWHM bdw.	$\leq 8.3 \cdot 10^8$
Source rms size [μm]	10 – 30
Source rms divergence [μrad]	25 – 200
Peak brilliance [N_{ph}/s·mm^2·mrad^2·0.1%]	$10^{20} – 10^{23}$
Radiation pulse length rms [ps]	0.7 – 1.5
Linear polarization [%]	> 99
Macro repetition rate [Hz]	100
# pulses per macropulse	32
Pulse–to–pulse separation [ns]	16
Polarization axis wiggling [deg]	< 1
Synchronization to an external clock [ps]	≤ 0.5
Source position transverse jitter [μm]	< 5
Energy jitter pulse–to–pulse [%]	< 0.2
# photons jitter pulse–to–pulse [%]	≤ 3

GBS scheme: r.t. RF linac *vs* pulsed laser

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)	> 15
# 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	**LE Interaction**	**HE Interaction**
Pulse energy (J)	0.2	2x0.2
Wavelength (eV)	2.3,515	2.3,515
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
Sinchronization to an ext. clock	< 1 psec	< 1 psec
Pulse energy stability	1 %	1 %

Based on the electron-photon collider approach:

The rate of emitted photons is given by:

$$N_\gamma = L\sigma_T$$

Laser

where:

$$L = N_L N_e / 2\pi\left(\sigma_x{}^2 \ + w_0{}^2 \ /4\right)$$

leading to:

e^-

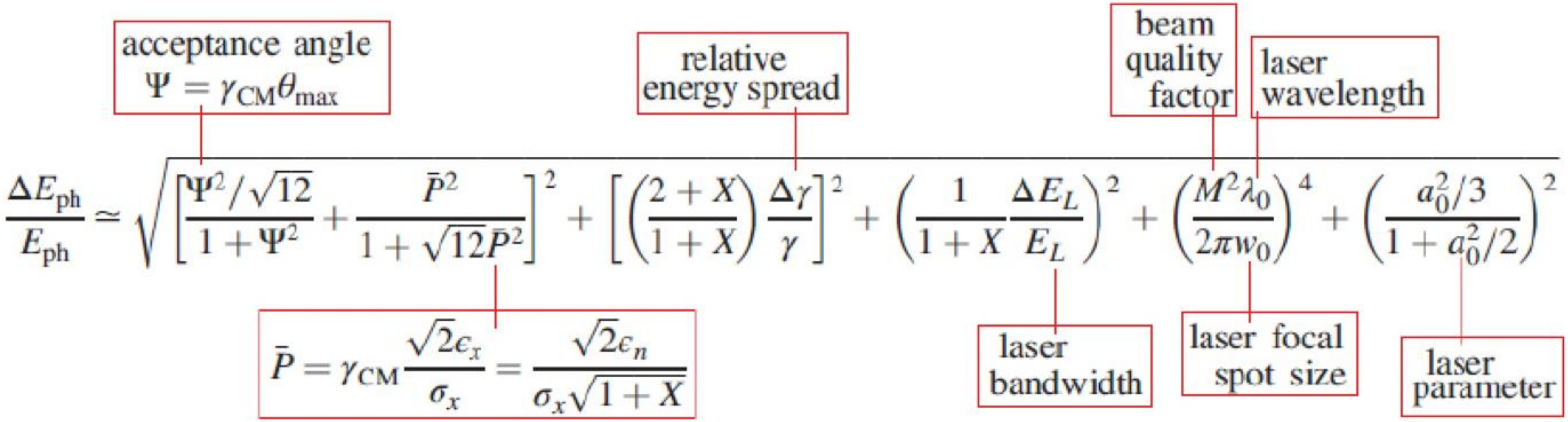
$$L = N_L N_e / 2\pi\left(\sigma_x{}^2 \ + w_0{}^2 \ /4\right)$$

$$N_\gamma[sec^{-1}] = 4.1 \times 10^8 \frac{U_L[J]Q[pC]f_{RF}n_{RF}}{h\nu_L[eV]\left(\sigma_x{}^2\,[\mu m] + \frac{1}{4}w_0{}^2\,[\mu m]\right)\sqrt{1+\left(\frac{c\sigma_t\delta}{4\sigma_x}\right)^2}}$$

Within the desired bandwidth:

normalized collimation angle
$\Psi = \gamma_{cm}\vartheta_{max}$

reduced rms transverse momentum $\bar{P}$



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

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

relative energy spread

beam quality factor

laser wavelength

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

laser bandwidth

laser focal spot size

laser parameter

Maximum Spectral Density $\propto$ *Phase Space density* η_n

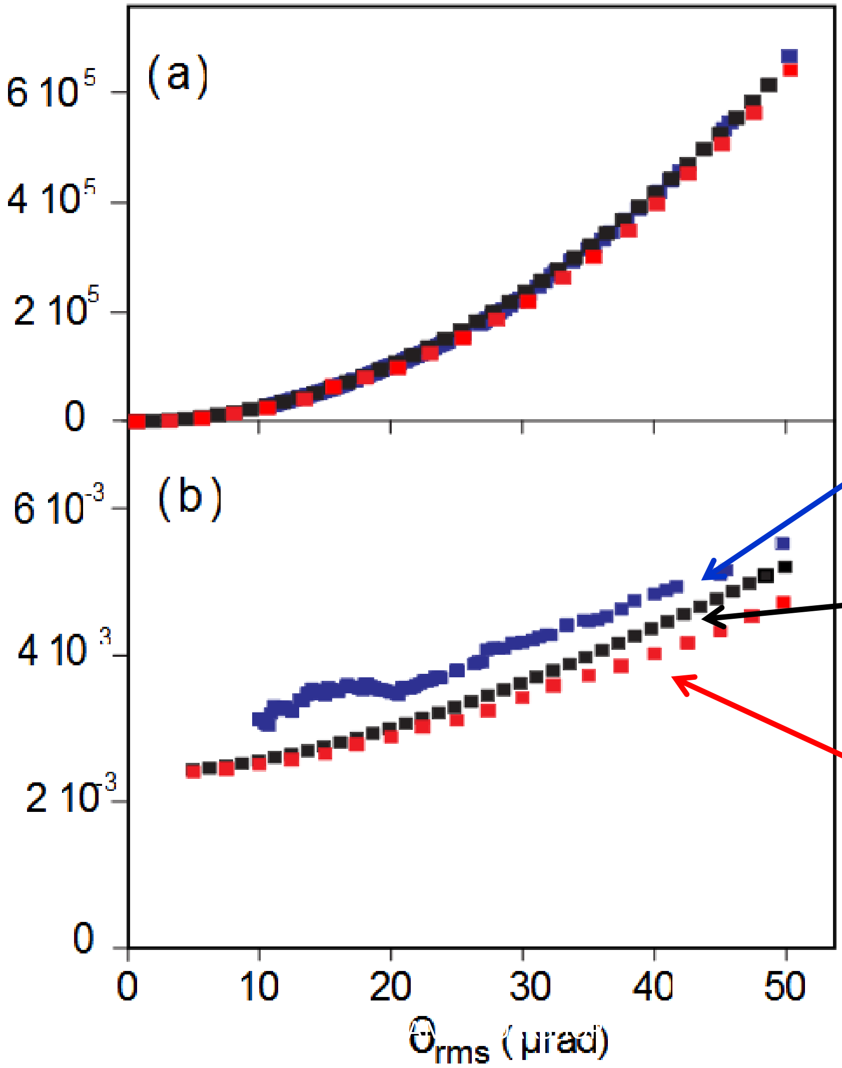
Courtesy of L. Serafini

Analytical model vs. classical/quantum simulation

V. Petrillo

Number of photons

bandwidth



CAIN (quantum MonteCarlo)
Run by I.Chaichovska and A. Variola

TSST (classical)
Developed by P. Tomassini

Comp_Cross (quantum semianalytical)
Developed by V.Petrillo

Beam Quality constraints

Electron Linac design to drive bright Compton back-scattering gamma-ray sources
A. Bacci, D. Alesini, P. Antici, M. Bellaveglia, R. Boni et al., J. Appl. Phys. 113, 194508 (**2013**
“Optimizing RF LINACS as drivers for Inverse Compton Sources: the ELI-NP Case”
C. Vaccarezza, *et al.*, Proceedings of LINAC2014, Geneva, Switzerland

Emittance

Maximization of *η* the electron density into transverse phase space :
which means very low emittances~ **0.4 mm-mrad**

$$\eta \equiv \frac{Q_b}{{\varepsilon_n}^2}$$

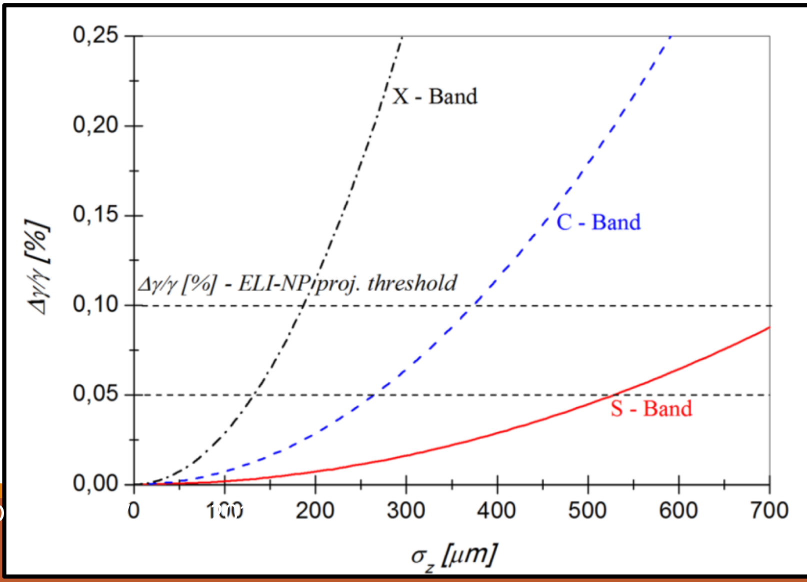
Energy Spread

Minimization of the beam energy spread: the **source spectral density requires Δγ/γ < 1%**, we have chosen a conservative threshold of 0.05 %

Energy Spread by **RF curvature**:

$$\frac{\Delta\gamma}{\gamma}_{rms} \approx 2\left(\pi f_{RF}\frac{\sigma_z}{c}\right)^2$$

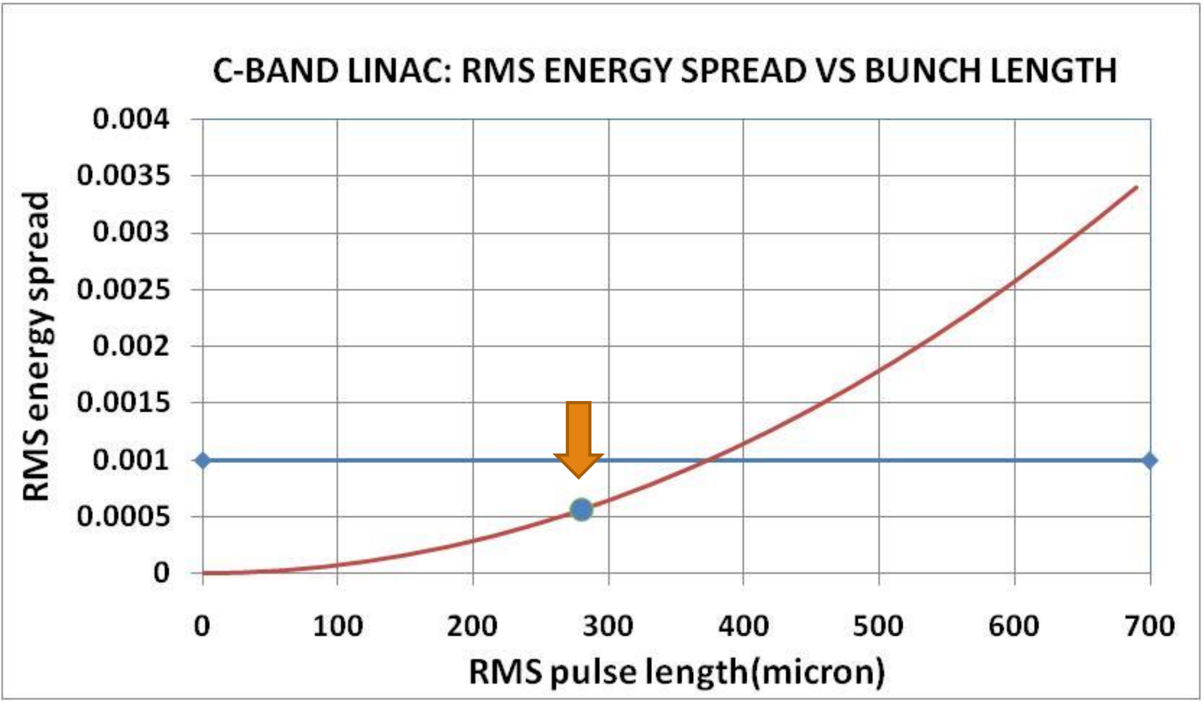
σ_z < 280 μm at the injector exit



The hybrid scheme for the Linac:

- Velocity bunching operation
- Long bunch at cathode for high phase space density :

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



- **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)**

Measured emittance

	Q (pC)	Emittance (mm-mrad)	Time pulse	$\Delta\gamma/\gamma$ (rms)	$B=I/\varepsilon^2$ (A/m^2)
FULL L-band (1) *(PITZ,Egun=60 MV/m)*	250	0.33 (100%) ***measured***	FWHM=21-22 ps, rise time=2 ps (cathode)	0.15%	$1.09 \cdot 10^{14}$
FULL S-band (2) *(LCLS injector @135 MeV, Egun=120 MV/m)*	250	0.4 (95%) ***measured***	FWHM=7.8 ps σ_z=740 μm rms (measured at 135 MeV)	0.1%	$1.9 \cdot 10^{14}$
FULL X-band (3) *(LLNL-SLAC,Egun=200 MV/m)*	250	0.35 (100%) ***computed***	σ_t= 0.79 psec, σ_z=237 μm rms	0.16 %	$8.15 \cdot 10^{14}$

[1] S. Rimjaem et al. "Emittance for different bunch charges at the upgraded PITZ facility",FEL Conference 2011
[2] J. Frisch et al. LINAC '10 ,Tsukuba,Japan WE201
P.Emma et al. "Beam brightness measurements in the LCLS injector",Mini-workshop on Compact X-Ray FELs using High Brightness beams, LBNL,2010
[3] F. Zhou et al., "X-band photoinjector beam dynamics",Proc. IPAC10,p.1761

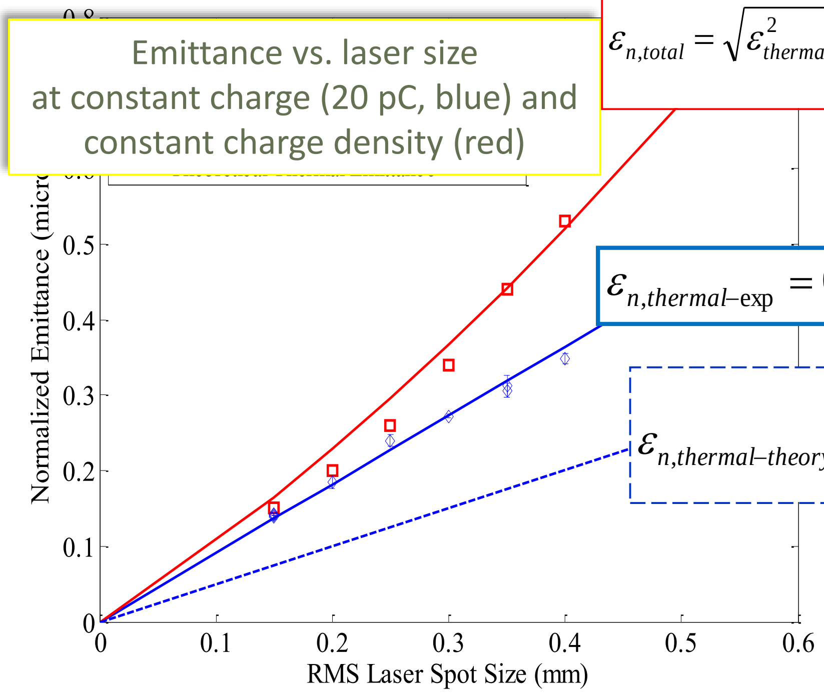
Ronsivalle pres. At ELI-NP Workshop, May 14-16 2012 Milano, Italy,

The thermal emittance

1.2um/(mm rms) historically used for SPARC simulations

The best value get at LCLS that is 0.9 um/(mm rms) the one used in ELI-NP simulations

D. H. Dowell ‘The LCLS Gun’- ICFA BD Workshop, March, 2010



Emittance vs. laser size
at constant charge (20 pC, blue) and
constant charge density (red)

$$\varepsilon_{n,total} = \sqrt{\varepsilon_{thermal}^2 + \varepsilon_{sc}^2} = \sigma_x \sqrt{(0.9\mu m / mm(rms))^2 + \left[\frac{2\pi^2 mc^2}{E_{cathode}\sin\phi_{rf-laser}} \frac{j\sigma_x}{I_A}\mu_x\left(\frac{\sigma_x}{L_x}\right)\right]^2}$$

$$\varepsilon_{n,thermal-\exp} = 0.9 microns / mm(rms)$$

$$\varepsilon_{n,thermal-theory} = \sigma_x \sqrt{\frac{\hbar\omega - \phi_{eff}}{3mc^2}}$$

parameterized
space charge form factor

$$\mu_x\left(\frac{\sigma_x}{L_z}\right) = 0.0653 - 0.0934\frac{\sigma_x}{L_z}$$

* K-J. Kim, NIM **A275**(1989)2001-218

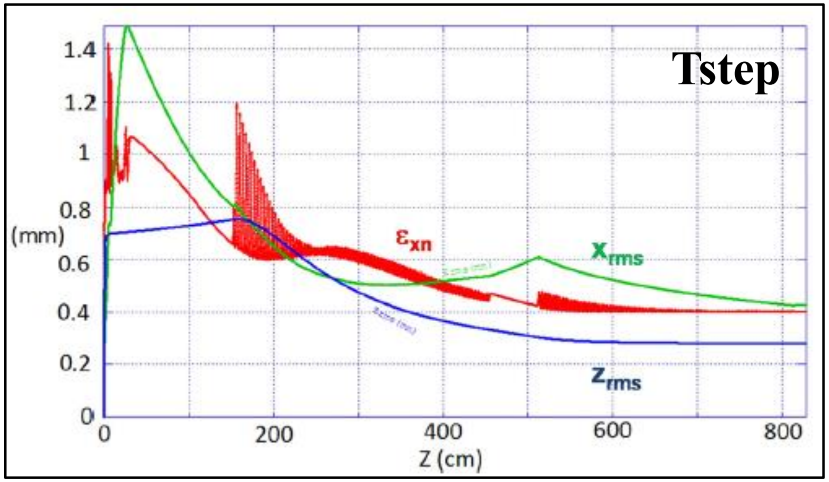
Codes comparison:

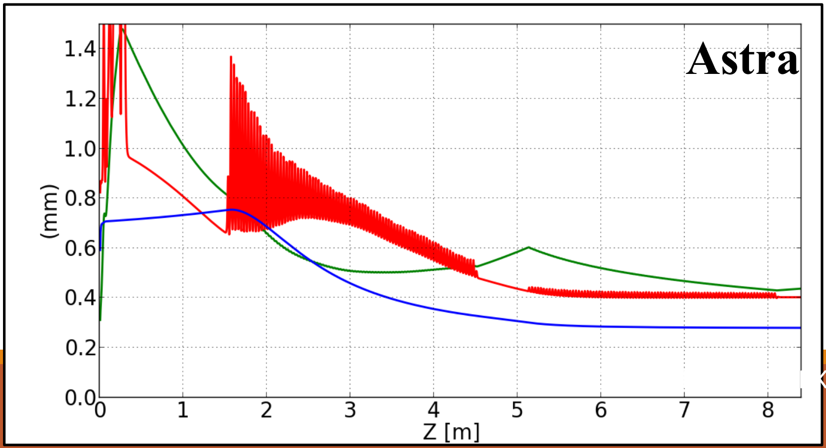
Tstep – Astra (double check)

The first injector optimizations was made by using the tracking code **Tstep** (a Parmela heir). Now the results have been tested with a second tracking code **Astra**

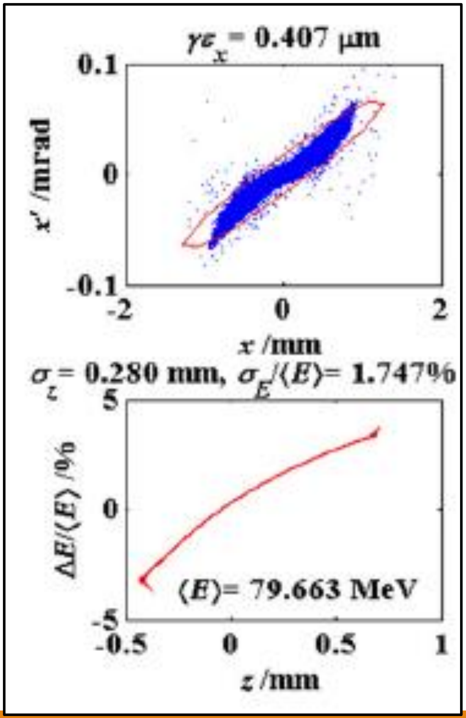
Two important benefits:

1) A **double check** of the simulated data in space charged dominated beams
2) The **possibility to use Giotto**, an Optimization Genetic Code which works with Astra





Tstep



Astra

$\gamma\varepsilon = 0.402\ \mu m$

$\langle E\rangle = 79.8\ MeV$

$\sigma_z = 0.279$ mm

$\sigma_E/\langle E\rangle = 1.65\%$

Today these values are a little bit differents:

Sol. 8 mm farther
$\gamma\varepsilon = 0.40\text{-}0.43\ \mu m$
$\langle E\rangle = 81.0\ MeV$
$\sigma_z = 0.280$ mm
$\sigma_E/\langle E\rangle = 1.65\%$

A. Bacci

The Gun Solenoid (Solenoid A)

A New design has been proposed from more motivations

1) The BD is very sensitive to the sol position. **A closer SOL to the cathode gives better emittance** (and about 8-10% field intensity variation for 10 mm of displacement) **A shorter SOL is better**

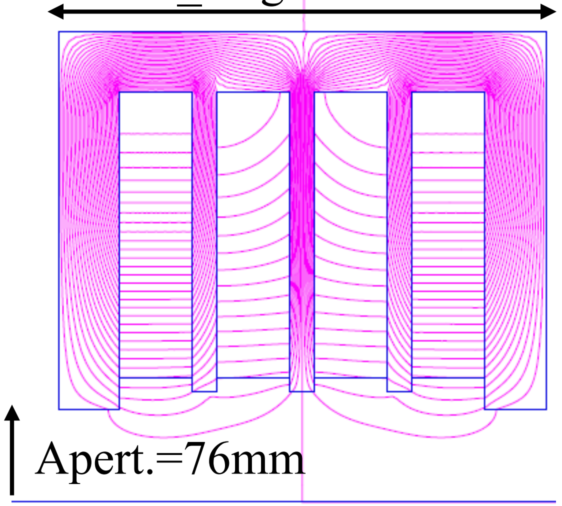
1) The **SPARC SOL is made by 4 coils** and the **coils alignment is a major issue**. **Two coils will be aligned more easily**

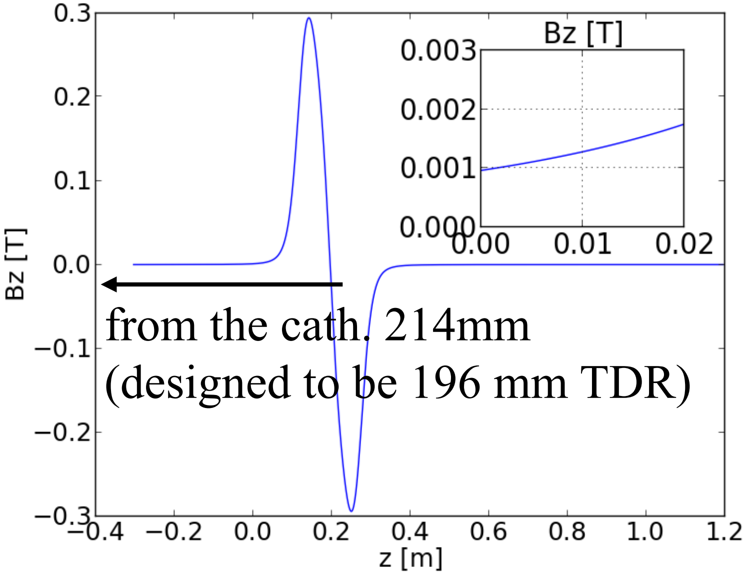
2) The **SPARC SOL has a large aperture D=76 mm, which is no more justified**, a decreasing in the aperture diameter results in lower currents, (actual aperture D=60mm).

3) The SPARC SOL works in the + + - - current configuration; **advantages for multipoles compensation or misalignments compensation** (empirical result). In the new SOL the **+ - is kept as possible working configuration**

Solenoid A – the new design

old





from the cath. 214mm

(designed to be 196 mm TDR)

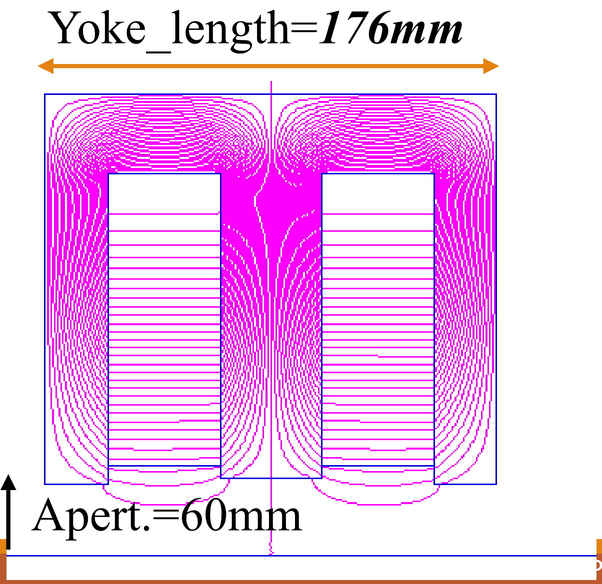
$B_{z,max}$ (++++) = 0.40 T

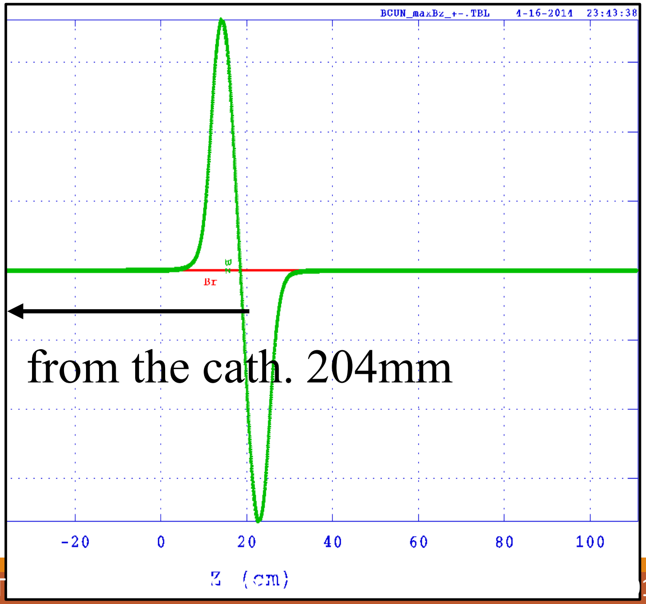
ref. B_z (++--) = 0.24/0.27 T

ref. I (++--) = 160/180

I_{max} = 270 A

new





from the cath. 204mm

$B_{z,max}$ (++)=0.40 T

$B_{z,max}$ (+ -)=0.39 T

ref. B_z (+ -)=0.329 T

nonlinearity by saturation (B_z.vs.I) < 0.15%

GFR 30mm (<1x10^{-3})

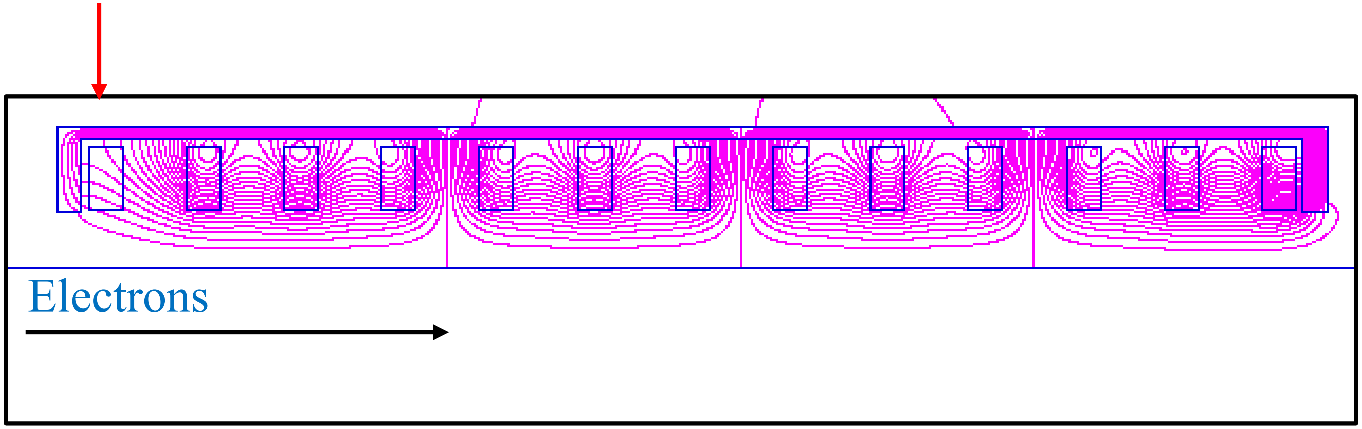
(form Opera 27mm, measured 20mm)

I_{max} = 176 A

The TW Solenoid(s) (The Solenoid B) **+++---+++---- conf.**

Coil never used:
true for Eli-np simulations
true also for SPARC operation

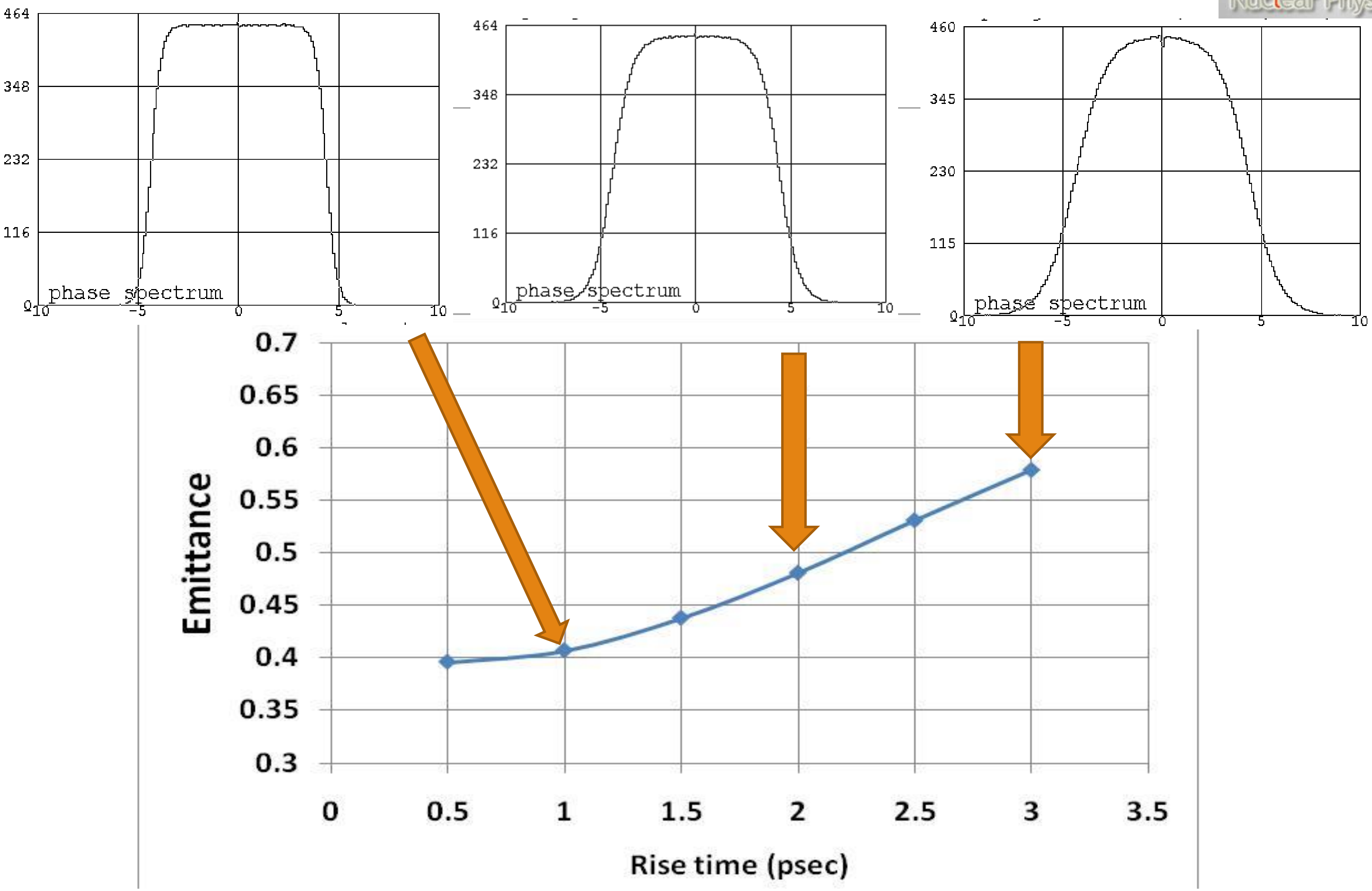
A new desing with 12 coils is ready to be installed



What was really a major issue: is the second TW solenoid necessary?
For all simulations, **reference** and **commissioning WPs, we used only solenoids on S1**.

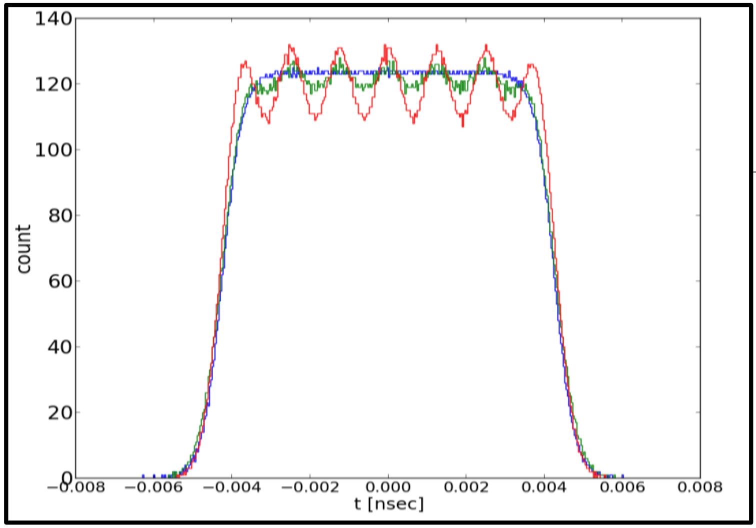
Wondering if it may be necessary at 500pC WP

SENSITIVITY TO LASER PULSE RISE TIME

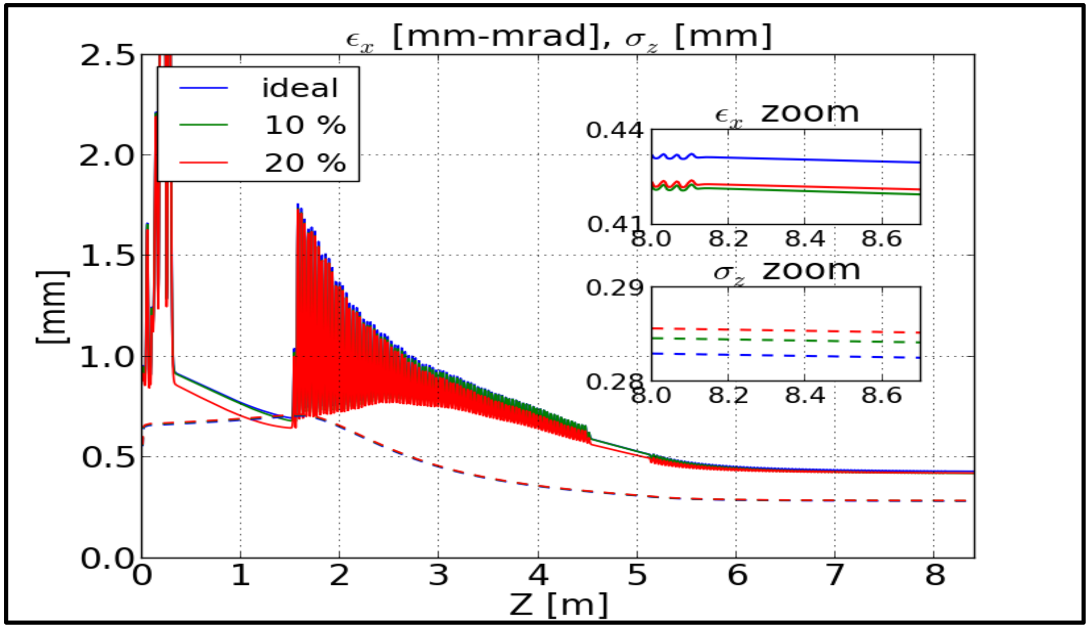


Ronsivalle pres. At ELI-NP Workshop, May 14-16 2012 Milano, Italy,

Longitudinal Laser Pulse shaping



longitudinal distribution; in blue the ideal case, in green a 10% ripples (p-p), in red 20% (p-p) ripples. All the cases have a rise-time of 1ps

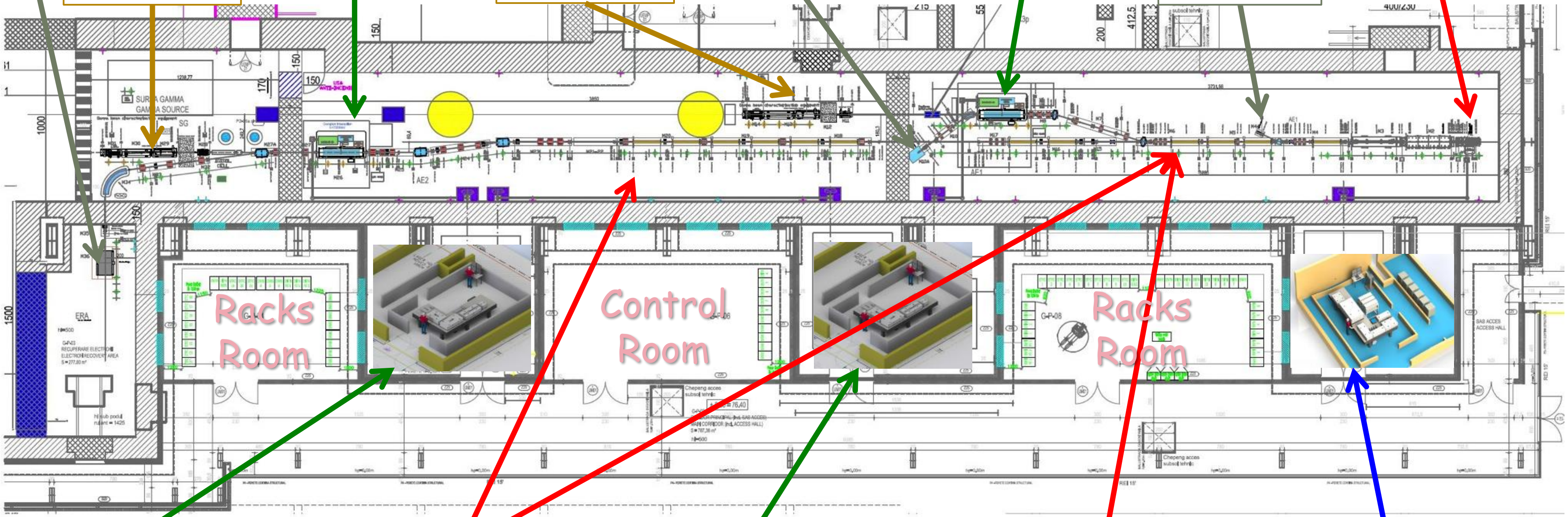


Transverse emittance (solid line) and bunch length (dashed line) for the three different flat-top cases: ideal (in blue), 10% ripple (in green)s, 20% ripples (in red).

The barely lower emittance, than the ideal case, is consequence of the longitudinal space charge, which by the density ripples gives lightly longer bunches.

Gamma Beam System – Layout

Master clock synchronization @ < 0.5 ps



e^- beam dump

Interaction Point High Energy

e^- beam dump

Interaction Point Low Energy

Photogun multibunch

γ beam coll&diag

γ beam coll&diag

e^- beam dump

Interaction Laser High Energy

e^- RF LINAC High Energy 720 MeV

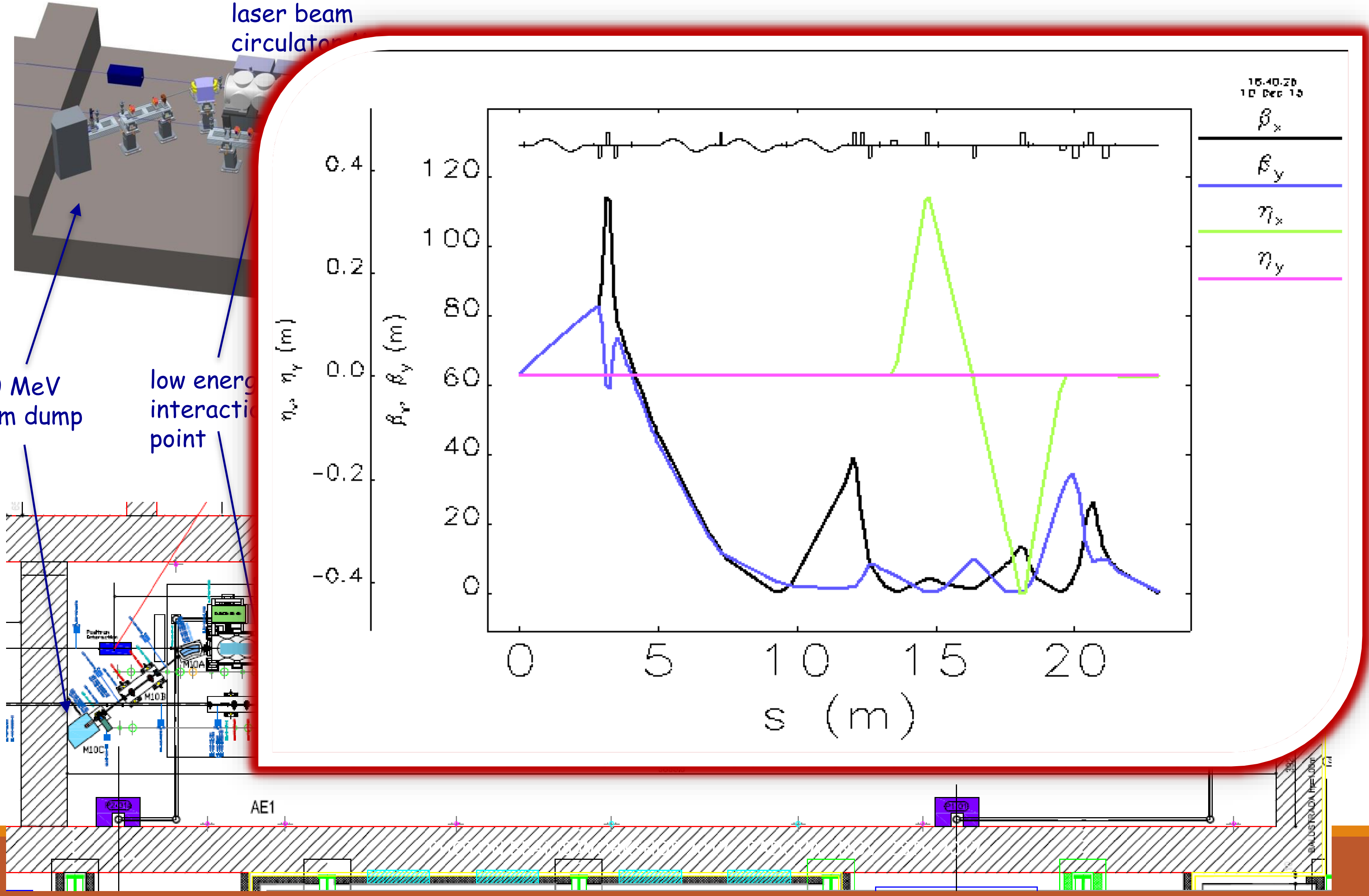
Interaction Laser Low Energy

e^- RF LINAC Low Energy 300 MeV

Photo-drive Laser e^- source

Courtesy of A. Variola

Accelerator Bay 1 – Layout

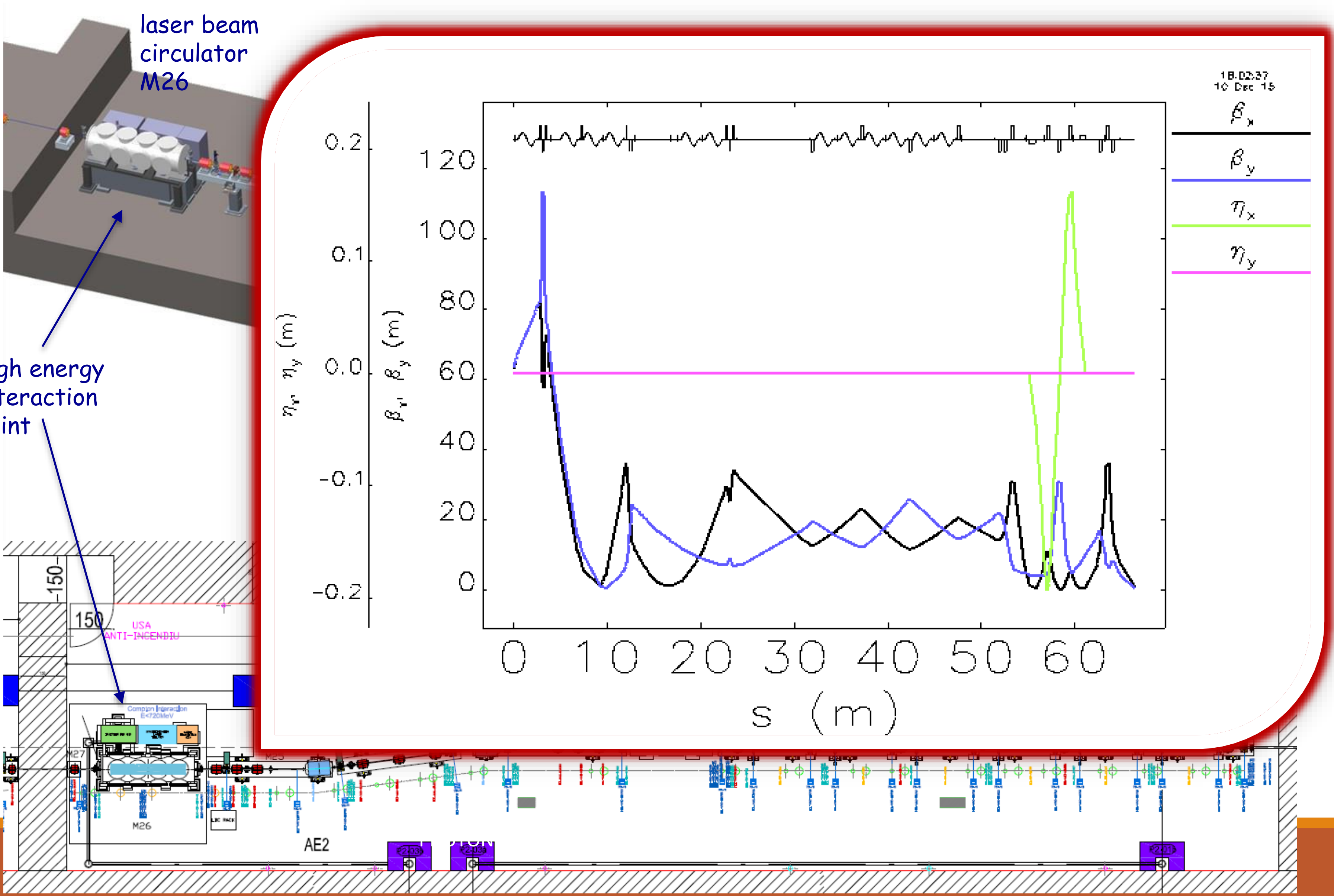


laser beam circulator

300 MeV beam dump

low energ interacti point

Accelerator Bay 2 – Layout

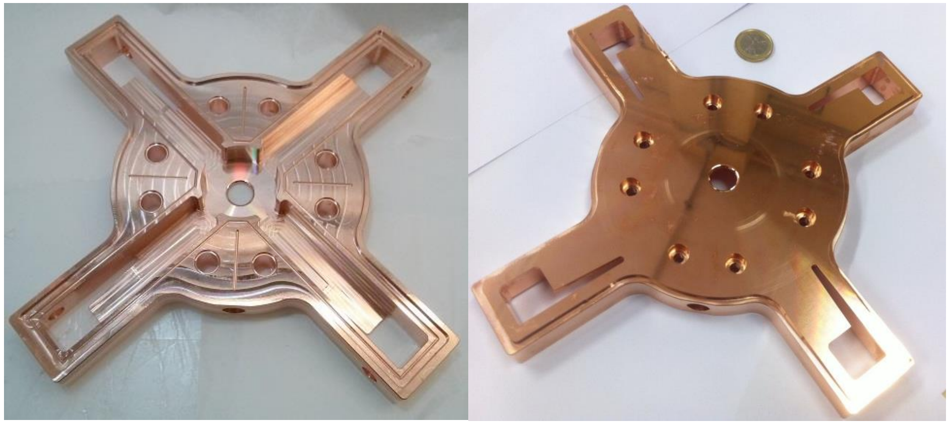

laser beam circulator M26

high energy interaction point

C-BAND STRUCTURES: FABRICATION

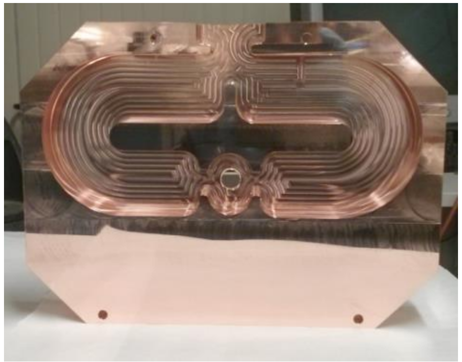
The **manufacturing of the cells** required several steps:

1)Rough machining
2)Stress relieving treatment in a vacuum furnace at 500° C for 1 hours
3)Milling of the cell (in particular waveguides apertures and pre-machining of the irises)
4)Ultra-precise manufacturing of irises and cells with lathe (precision ±3 μm and roughness ≤ 50 nm)



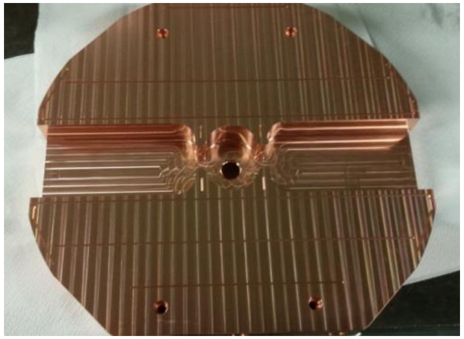
Manufacturing of the **input and output couplers**:

1)Rough machining
2)Stress relieving treatment in a vacuum furnace at 500° C for 1 hours
3)Milling



Cleaning of the machined components:

1)Removal of the machining oils with neutral soap
2)Removal of copper oxidations with weak acid (citric)
3)Almeco 19 at 48-50 degree for 5 minutes
4)Rinse with raw water
5)Ultrasound cleaning with ngl at 50 degrees
6)Rinse with raw water
7)Demineralized water in ultrasound at 20 degrees for 10 minutes
8)drying with nitrogen flow
9)packaging

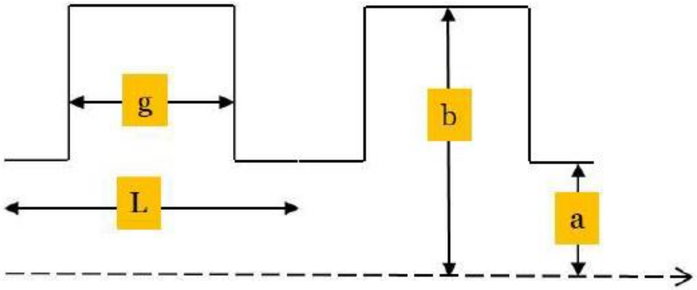


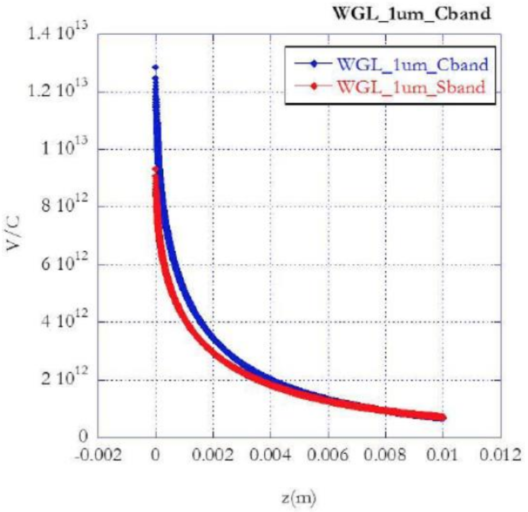
Machining and brazing have been done by Comeb (ELI-NP partner) and in the INFN-LNL oven under LNF supervision

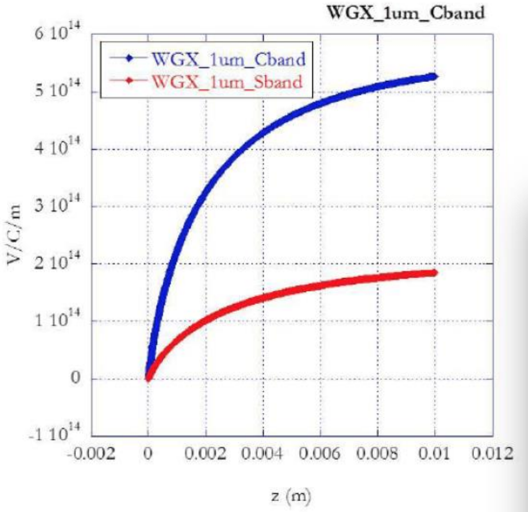
Long & Transv wake functions

$$W_{0\parallel}(s) \approx \frac{Z_0 c}{\pi a^2}\exp\left(-\sqrt{\frac{s}{s_1}}\right)\ (\mathrm{V/Cm}), \qquad s_1 = 0.41\frac{a^{1.8}g^{1.6}}{L^{2.4}}$$

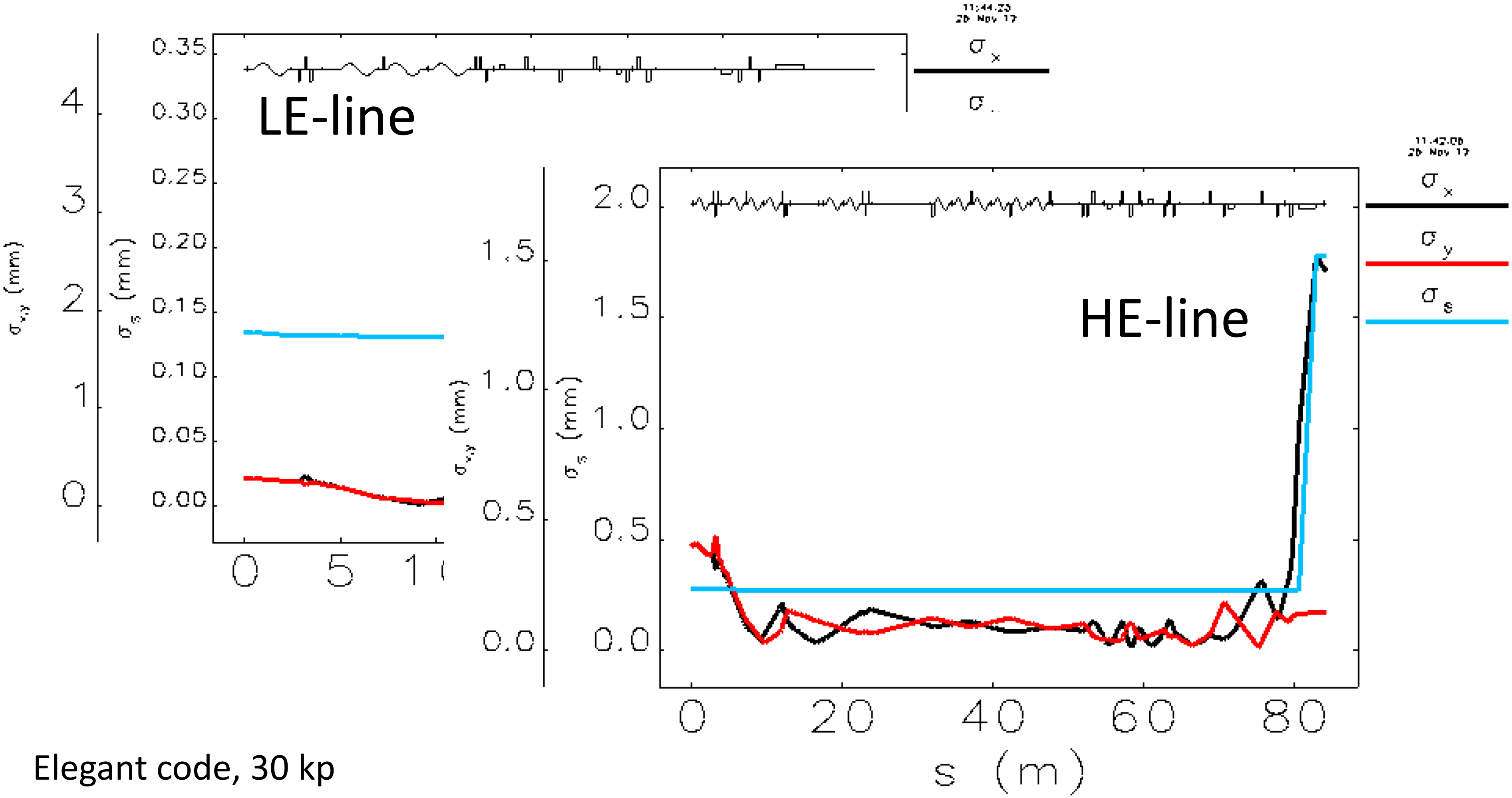
$$W_{0\perp}(s) \approx \frac{4Z_0 c s_2}{\pi a^4}\left[1-\left(1+\sqrt{\frac{s}{s_2}}\right)\exp\left(-\sqrt{\frac{s}{s_2}}\right)\right]\ (\mathrm{V/Cm^2}), \qquad s_2 = 0.17\frac{a^{1.79}g^{0.38}}{L^{1.17}}$$





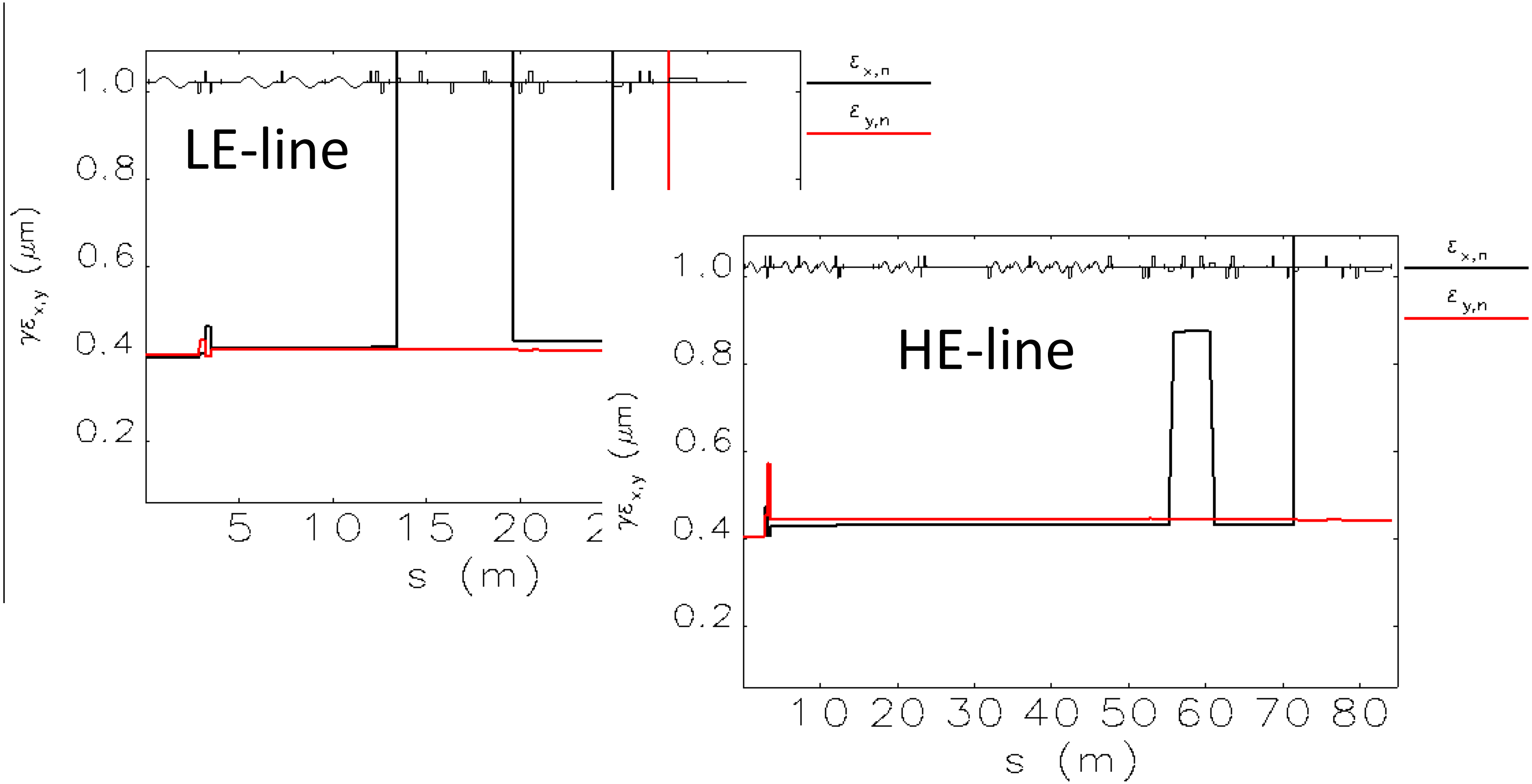


The beam envelope evolution along the C-band Linac



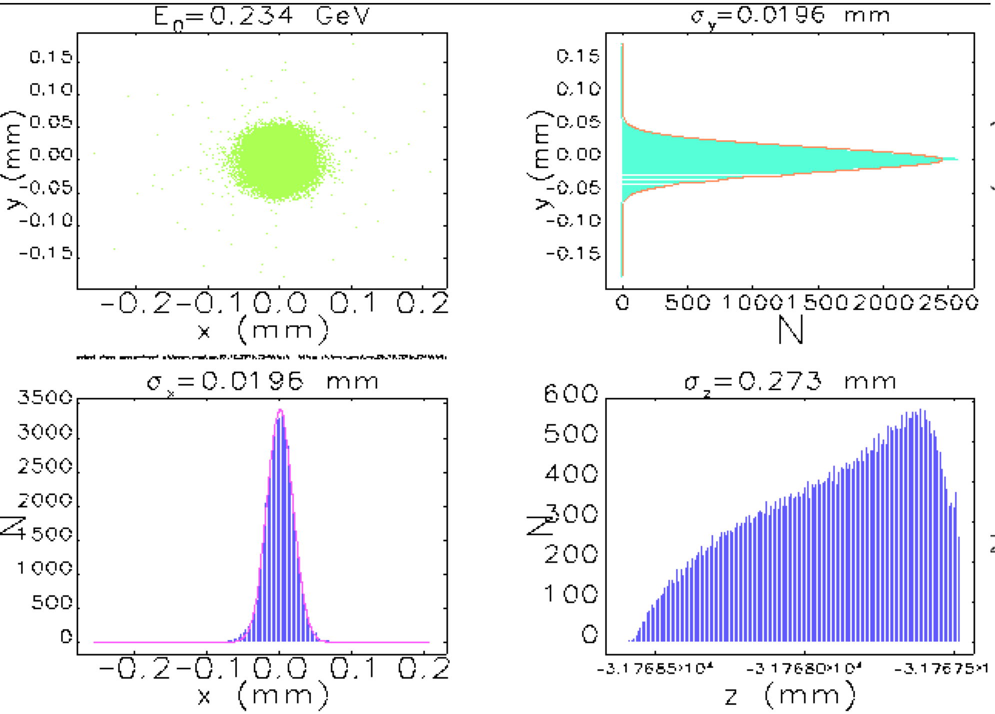
Elegant code, 30 kp

The beam emittance evolution along the C-band Linac

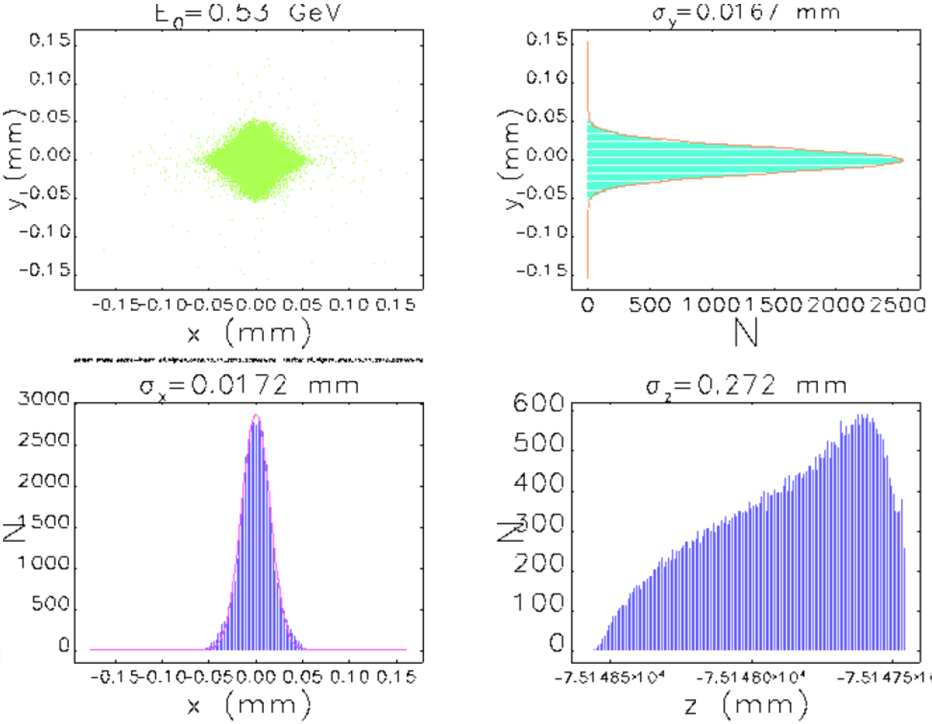


SB-Transverse beam size and distribution (Elegant tracking)

LOW ENERGY

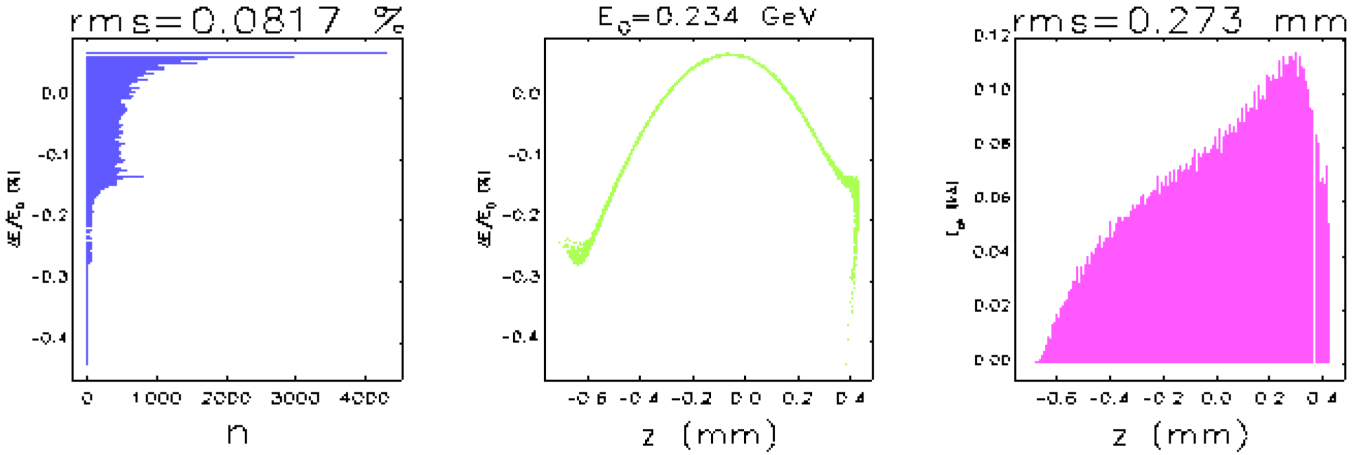


HIGH ENERGY

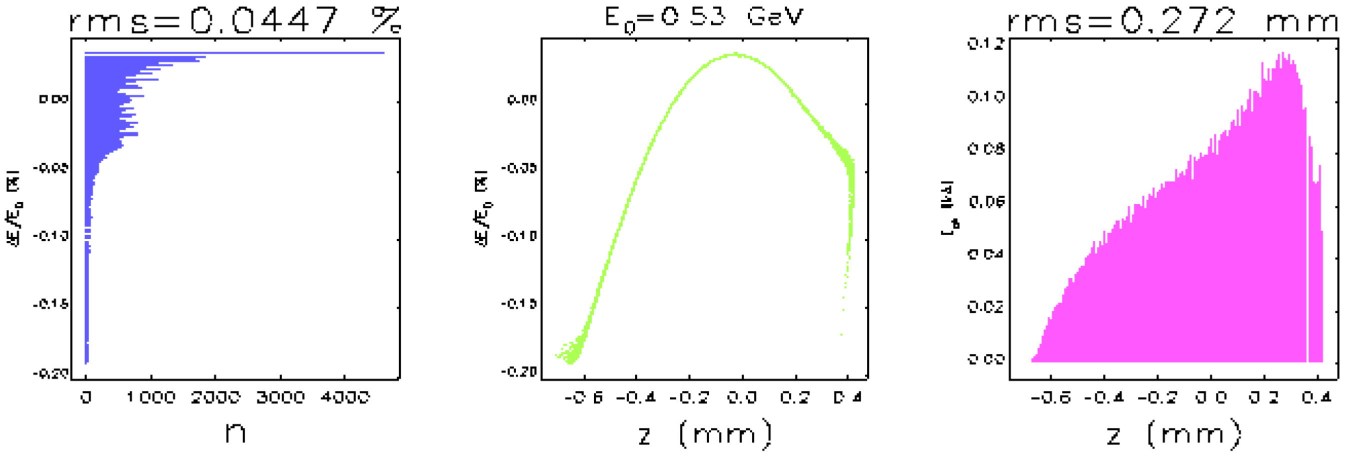


SB-energy spread & current

Lowen



Highen



Simulated gamma beams for different energies

Energy [MeV]	2.00	3.45	9.87	19.5
# photons/pulse within FWHM bdw.	$< 1.2\cdot10^5$	$< 1.1\cdot10^5$	$< 2.6\cdot10^5$	$< 2.5\cdot10^5$
# photons/s within FWHM bdw.	$< 4.0\cdot10^8$	$< 3.7\cdot10^8$	$< 8.3\cdot10^8$	$< 8.1\cdot10^8$
Source rms size [mm]	12	11	11	10
Source rms divergence [mrad]	≤ 140	≤ 100	≤ 50	≤ 40
Radiation pulse length rms [ps]	0.92	0.91	0.95	0.90

Machine error sensitivity studies

The method

- Misalignments and jitters have been introduced both in the injector and all along the linac with the aim to provide specifications for jitters and alignments of accelerating structures and magnets.

- Error matrices from injector and linac have been coupled one with each other randomly.

- Error value distributions are calculated according to the latin hypercube scheme (as reported in the TDR) by using a matrix of the latin hypercube that randomly factorizes in the range [-100 : +100]% of error values.

- Data analysis has been done on 100 bunches, each composed of 30k macro particles.

Photoinjector:

Injector sensitivity analysis has been performed over a random sampling of 100 runs, by using the codes Giotto* and Astra.

Errors on GUN		
RF Voltage [ΔV]	0.2	%
RF Phase [Δϕ]	0.2	deg
Errors on S-band Accelerating Sections		
RF Voltage [ΔV]	0.2	%
RF Phase [Δϕ]	0.2	deg
Alignment on transverse plane [Δxy]	70	µm
Errors on Solenoids (GUN & TW cavities)		
Alignment on transverse plane [Δxy]	70	µm
Errors on Cathode Laser System		
Arrival time [Δt]	200	fs
Pointing Instabilities [Δs]	20	µm
Energy Fluctuation	5	%

from SPARC experience

[*] A. Bacci, ULR: http://pcfasci.fisica.unimi.it/Pagine/GIOTTO/GIOTTO.htm

Linac

Errors on C-band Accelerating Sections		
RF Voltage [ΔV]	0.2	%
RF Phase [Δϕ]	1	Deg
Alignment on transverse plane [Δxy]	0,70,100	µm
Errors on Quadrupoles		
Geometric strength [Δk]	0.3	%
Alignment on transverse plane [Δxy]	0,70,100	µm
Rotation about incoming longitudinal axis [ΔΘ]	1	mrad
Errors on Dipoles		
Bend angle [ΔB]	0.1	%
Rotation about incoming longitudinal axis [ΔΘ]	1	mrad
Errors on Steerers		
Strenght Jitters [ΔB]	0.05	%
Errors on BPMs		
Noise	10	µm

twice field goodness and 100ppm precision/stability of PS

Static/dynamic from 100ppm precision /stability of PS plus strongly conservative consideration on field quality of some quad

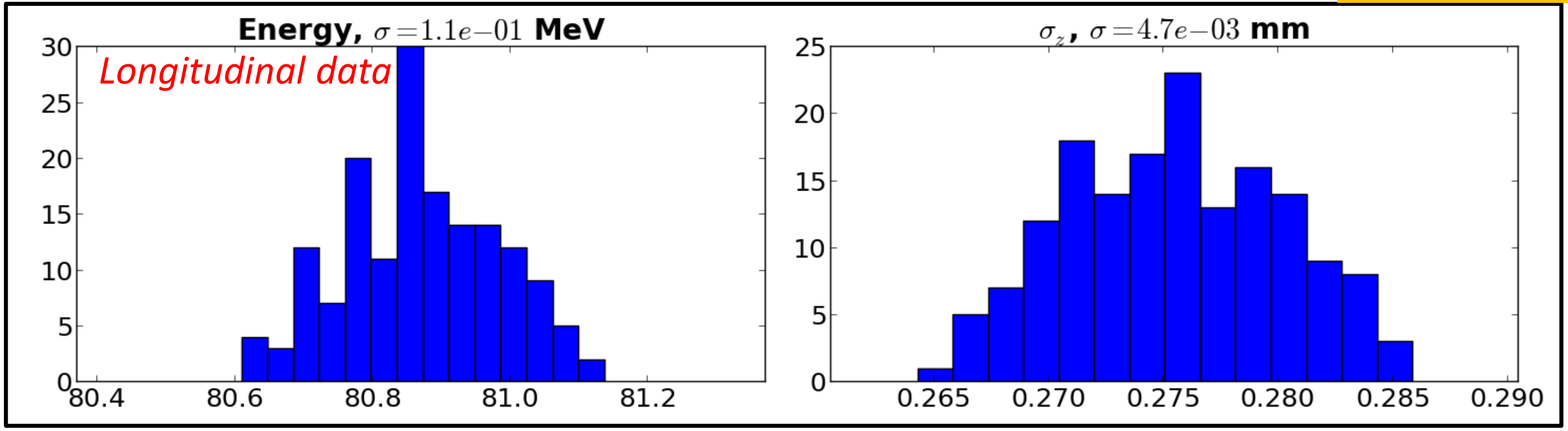
twice 100ppm precision /stability of bipolar PS

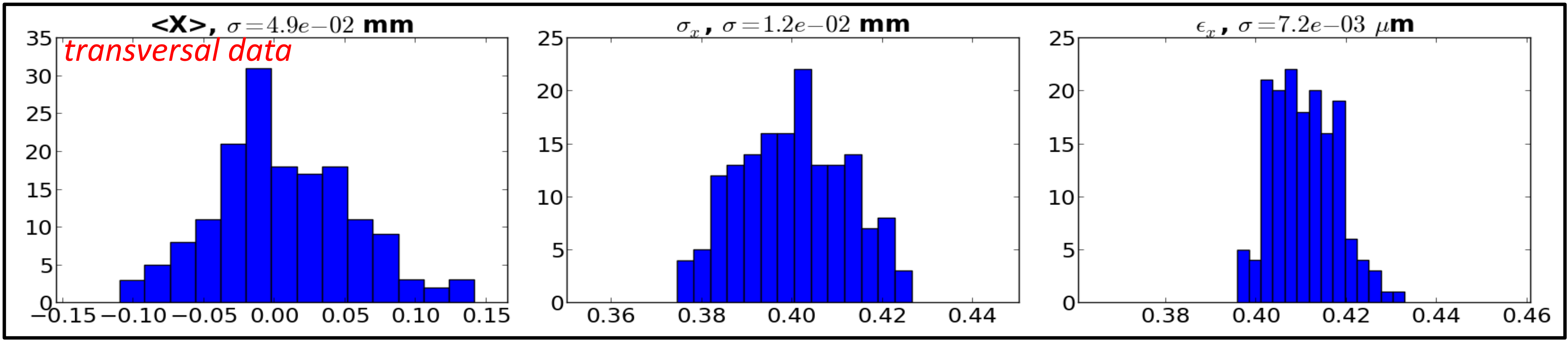
Results at the injector exit (160 runs)

Analysis made by the GIOTTO[*] code, which is paralelized (MPI)

CPU-TIME: 30k mps, Space-Charge ON, and a IV order Runge-Kutta, with 0-0.5 ps as time-step, keeps 4-6 hours.

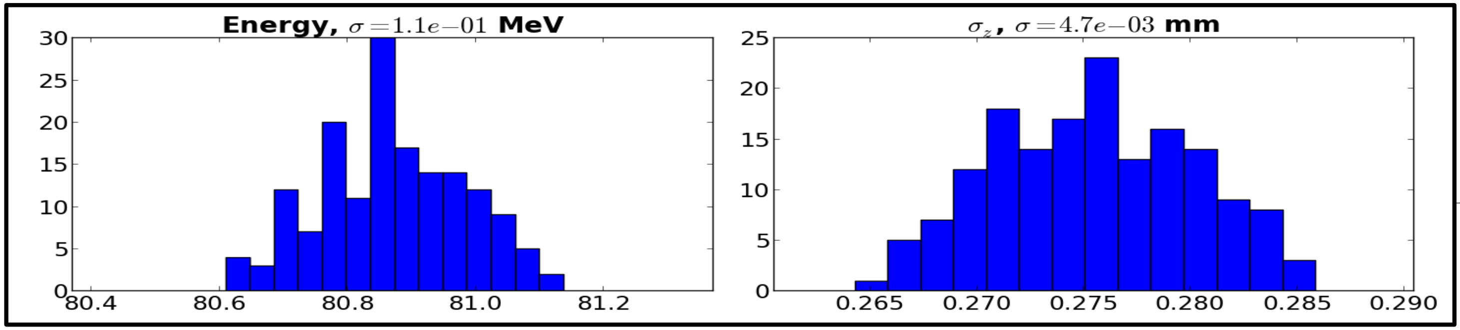
A. Bacci



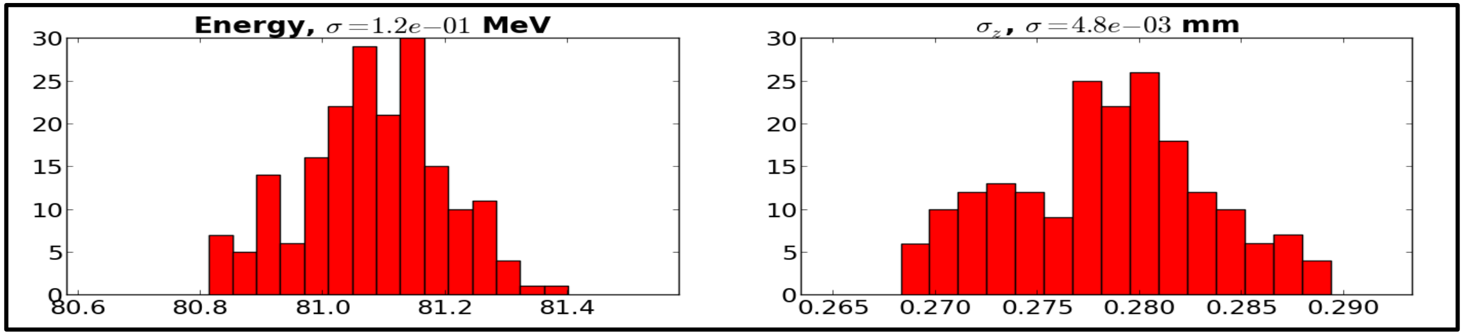


[*] *A. Bacci, ULR: http://pcfasci.fisica.unimi.it/Pagine/GIOTTO/GIOTTO.htm*

Frozen misalignments Three «screwed» machines(Longitudinal)

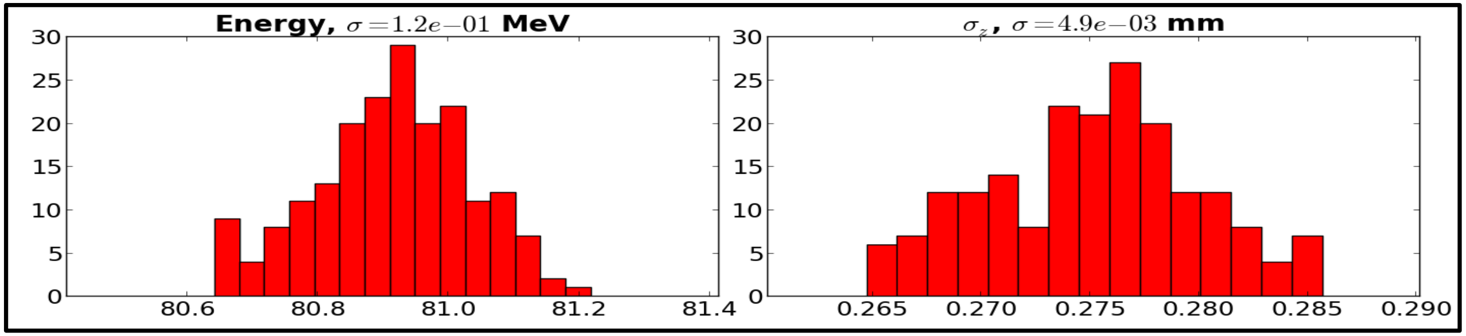


All jitters

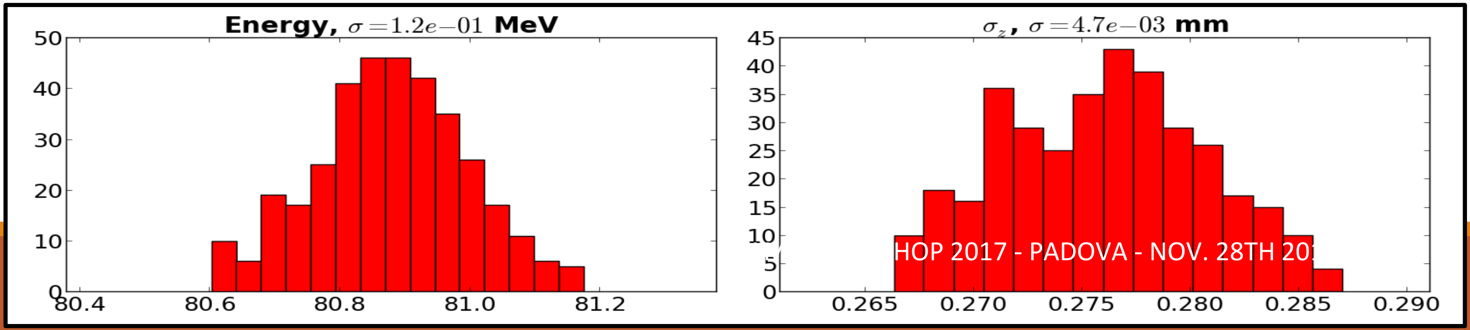


Machine_1

160 runs

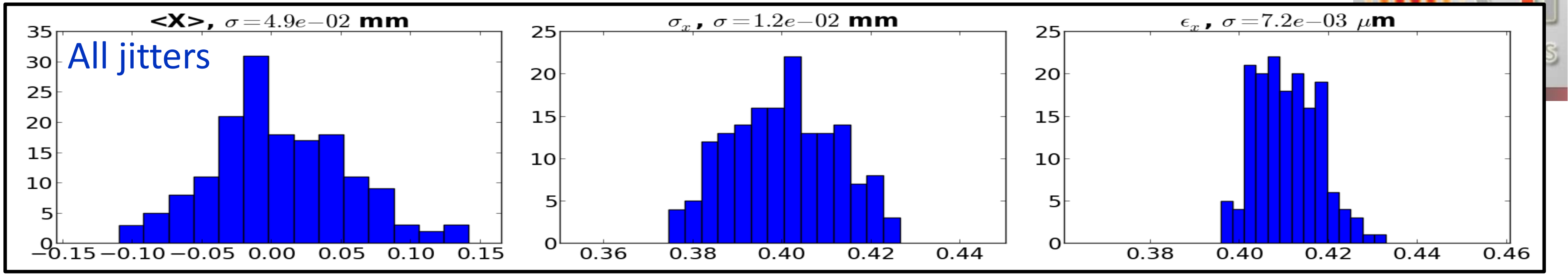


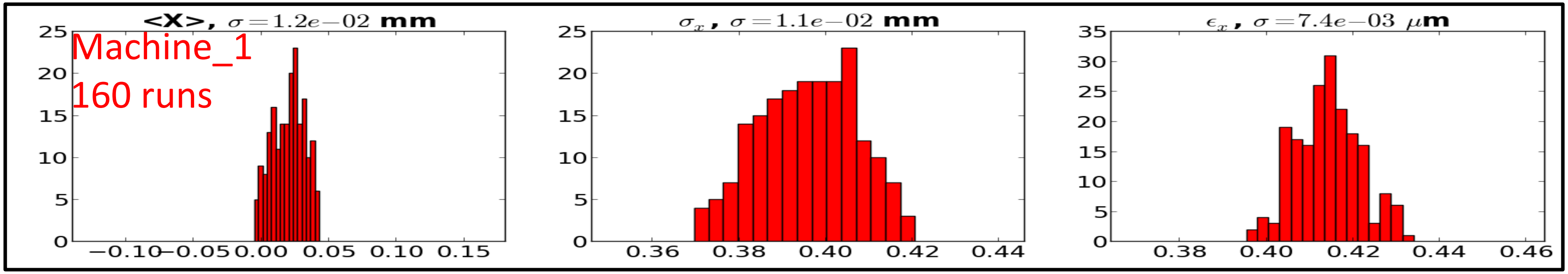
Machine_2

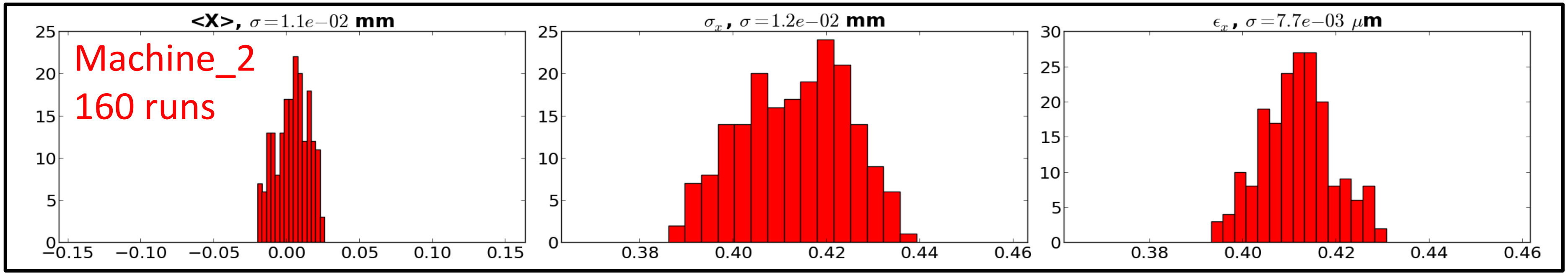


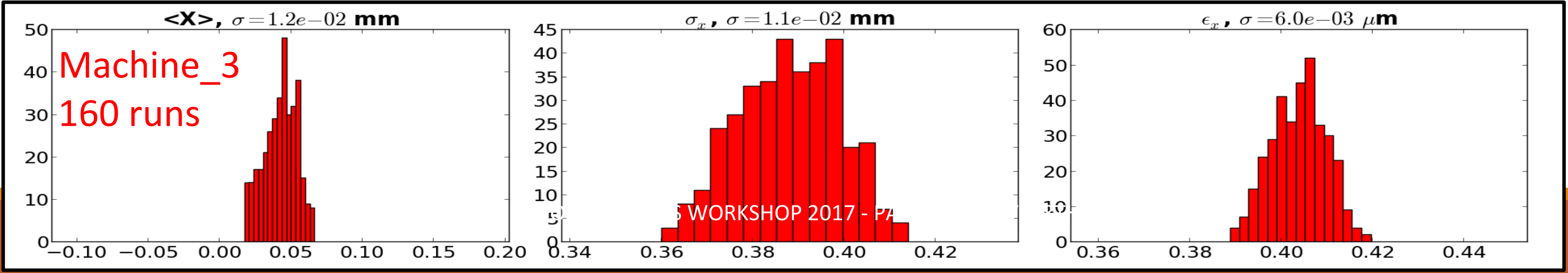
Machine_3

Frozen misalignments Three screwed machines(Transversal)



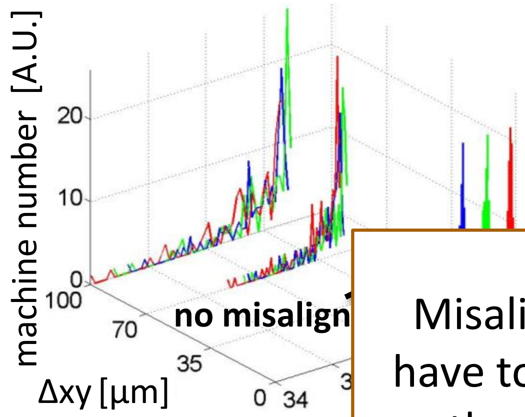






It comes out:

in the Linac the most critical parameters are the RF phase jitter on accelerating structures and misalignments on magnetic elements

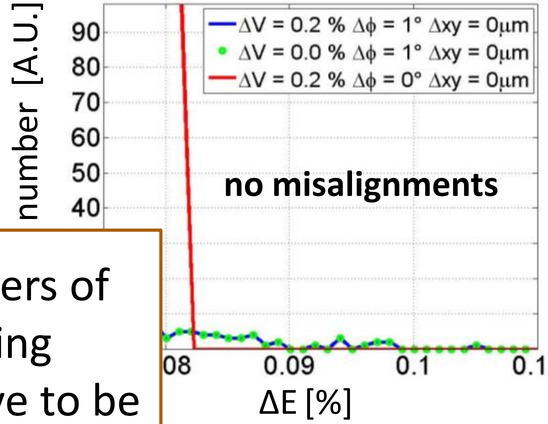


Misalignments have to be lower than 70µm

Electron beam spot size a

of Δxy=70-100µm, jitters on RF system and on

magnetic elements



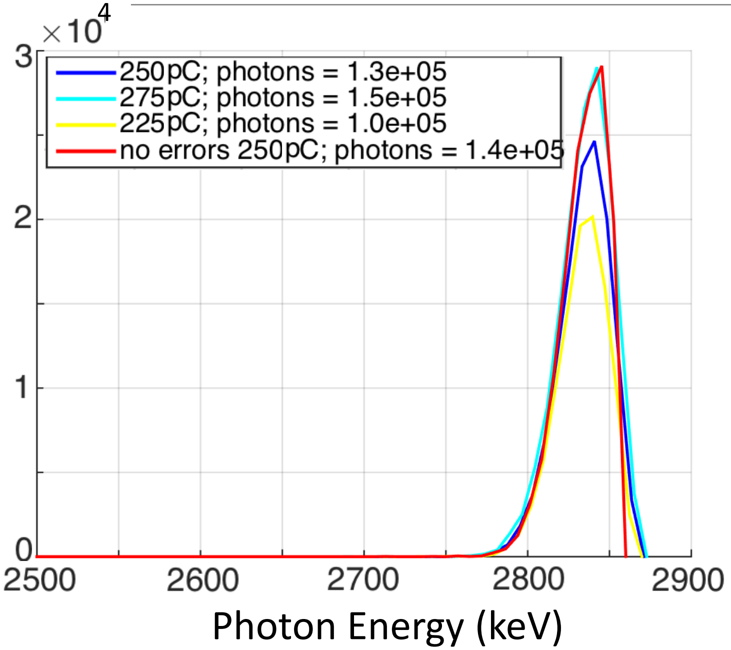
RF phase jitters of accelerating structures have to be lower than 1°

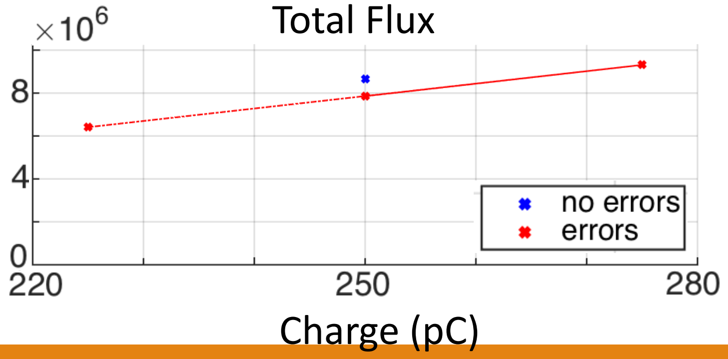
ad [%] for the nominal 250pC

beam in case of RF jitters

280 MeV @IP	Without errors	With errors	
Bunch charge	250	250 ± 25	pC
Energy spread	0.075	0.079 ± 0.039	%
Bunch length	280	273.3 ± 4.6	µm
$\varepsilon_{n_{x,y}}$	0.45	0.48 ± 0.03	mm mrad
Focal Spot Size	20.0	23.9 ± 1.5	µm
$\Delta C_{x\text{-}y}$	0	8 ± 2	µm

γ-source sensitivity





2.85 MeV @IP	**Without errors**	**With errors**	
Electron bunch charge	250	250 ± 25	pC
Collimation Angle [ϴ]	192.5	192.5	μrad
Total Flux	$8.7\bullet10^{6}$	$(8.0 \pm 1.7)\bullet10^{6}$	N_{ph}/pulse
Flux within FWHM BW	$1.4\bullet10^{5}$	$(1.3 \pm 0.2)\bullet10^{5}$	N_{ph}/pulse
BW	0.50	0.55 ± 0.02	%

"Snake" profile of the C-band Cavities

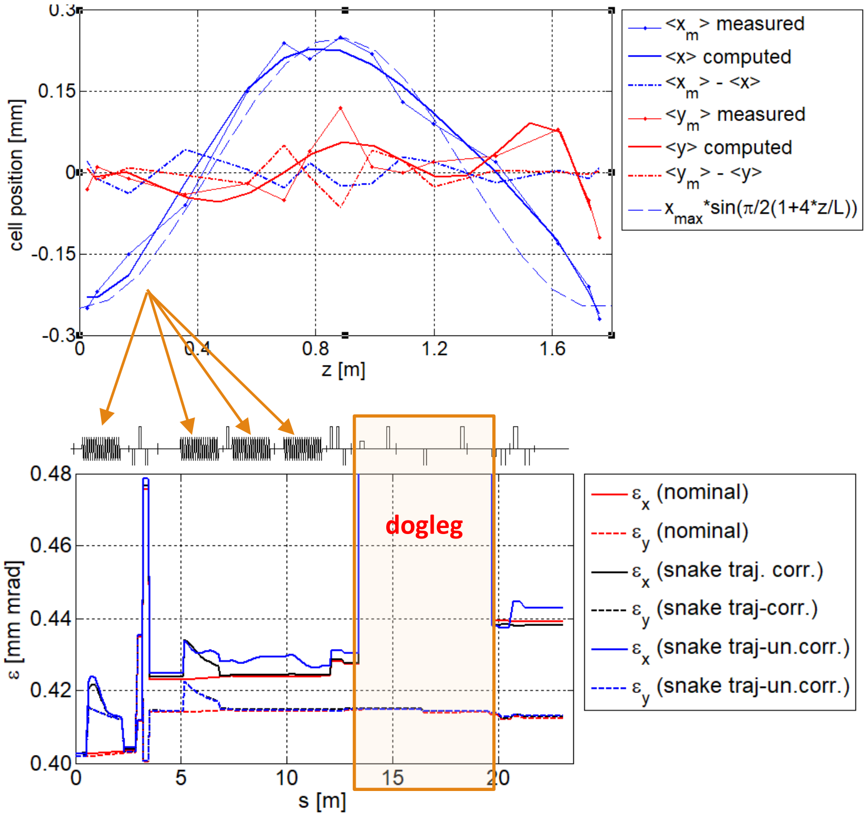
The Model

- The longitudinal axis of C-band cavities has been characterised with the laser tracker (accuracy ±0.041mm) (*)
- The cells have been dimensionally aligned with respect to a **best-fit line** that minimizes the beam quality degradation.

The Method

- Measured cell displacements have been inserted in the Elegant code (**)
- A gentle trajectory correction allows to avoid the beam quality degradation (spot size growth due to emittance dilution @IP)

234 MeV @IP	Nominal beamline	Snake profile (w/o correction)	Snake profile (w correction)	
Energy spread	0.82	0.82	0.82	‰
Bunch length	273.0	274	274	µm
$\varepsilon_{n_{x,y}}$	0.43	0.44	0.43	mm mrad
Focal Spot	19.7	19.9	19.7	µm
$\eta_{x\ (local)}$	2.59	4.69	2.29	mm



A "real" machine model: Quasi Constant Gradient C-band Cavities

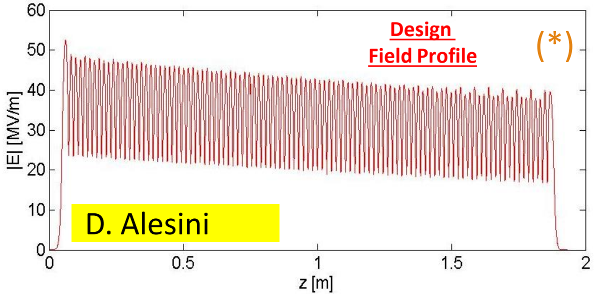
The Model

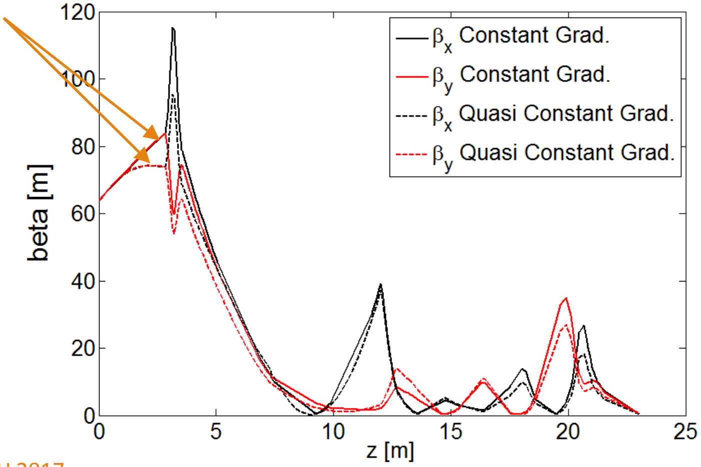
- C-band cavities shaped to have a *quasi-constant accelerating field* with E_{avg}=33 MV/m and a 15 % slope (*).
- Elegant code include RF focusing, adiabatic damping and RF kick based on the Serafini - Rosensweig model (**).

The Method

- Studies on the overall C-band linac matched for the 234 MeV e^- beam
- The focusing strength associated to the transverse RF field in the couplers scales as $K_r = \frac{1}{8}\left[\frac{\gamma'}{\gamma}\right]^2$ affecting the transverse beam dynamics (**).

234 MeV @IP *(n=17)*	Constant Gradient	Quasi Constant Gradient	
Energy	234.0	234	MeV
Energy spread	0.82	0.82	‰
Bunch length	273.0	274	µm
$\varepsilon_{nx,y}$	0.44	0.43	mm mrad
Focal Spot	19.6	20.5	µm

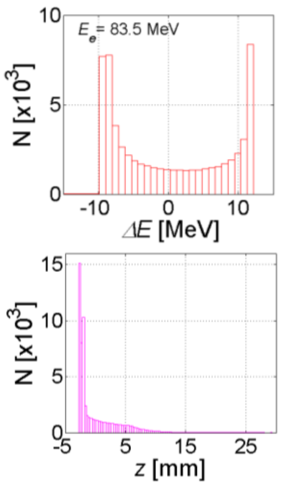


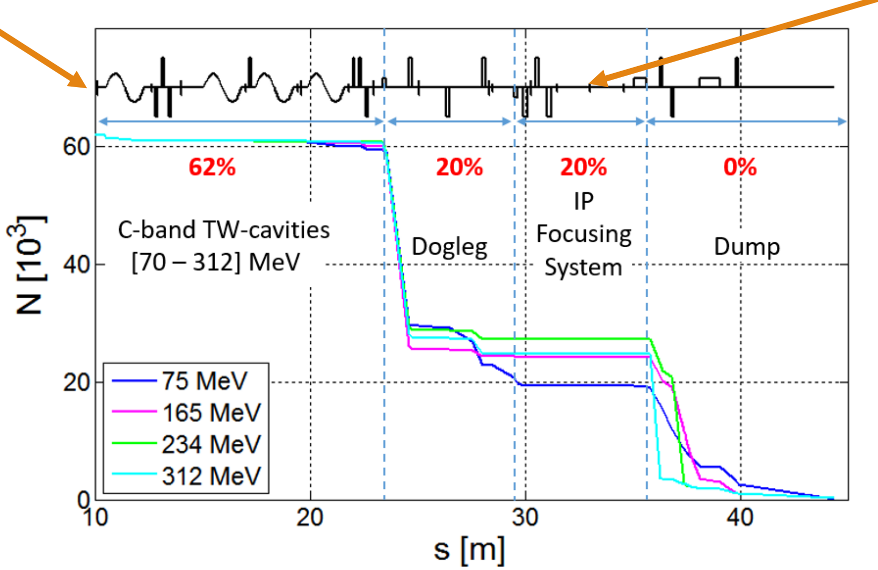


Dark current evaluation

- Electromagnetic fields in a high gradient RF cavity can result in electron emission from the metallic walls of the cavity itself and induce, in case these electrons are captured and accelerated by the accelerating fields, the so called “dark-current”.
- Simulations on the dark current transport in the ELI-NP GBS linac (both low and high energy) have been performed to evaluate beam losses and provide the basis for shielding and safety system specifications.
- 3 nC dark current, composed of 100 k macro-particles, over 1 µs RF pulse length with uniform cylinder transverse distribution on the cathode with a radius of 2.5 mm (worst case scenario at ELI-NP the RF pulse length is 1.5 µs).

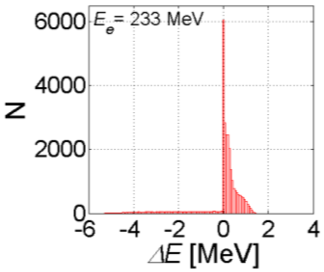
@ Injector Exit

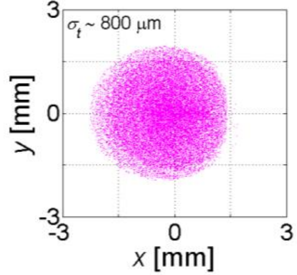


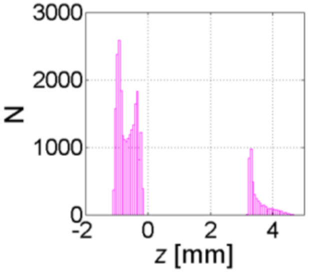


@ LE-IP

few % of the initial charge reachs the dump → few pC charge that spreads out over a 1 mm long pulse.







Conclusions

- ☐ The Eli-NP Gamma beam system has been presented focusing on the source design and the Linac optimization criteria.
- ☐ The machine beam dynamics consolidation studies have been described
- ☐ Implementation of dfs/trajectory/luminosity feedback in the control system is ongoing to be ready for the machine commissioning start.

Acknowledgements: all the collegues of GBS team