High level software for high brightness electron LINAC

University of Rome “La Sapienza”

Accelerator Physics PhD School - XXXI cycle

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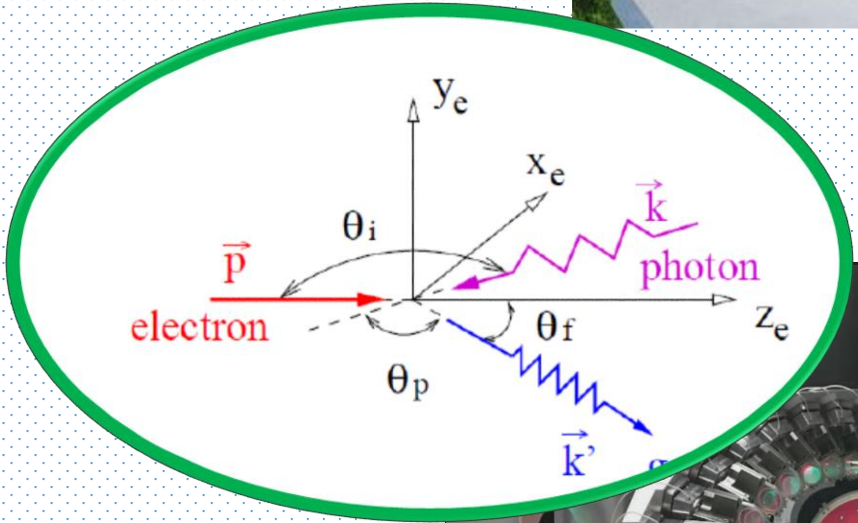
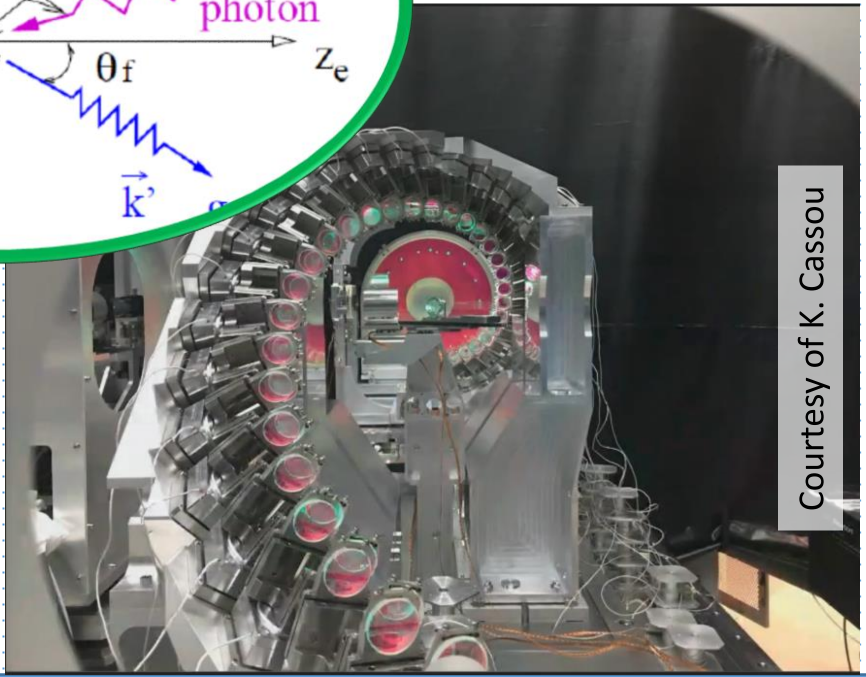
ELI-NP Gamma Beam Source

The ELI-NP-GBS is an intense and monochromatic gamma source based on Compton back scattering between a high-power laser and an accelerated electron beam produced by LINAC. The photon beams, in the 1-20 MeV energy range, are characterized by unprecedented performances in terms of mono-chromaticity, brilliance, spectral density, tunability and polarization.

Parameter	Value
Energy [MeV]	$0.2 - 19.5$
Spectral density $[ph/s \cdot eV]$	$0.8 - 4 \cdot 10^4$
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 $[\mu m]$	$10 - 30$
Source rms divergence $[\mu rad]$	$25 - 200$
Peak brilliance $[N_{ph}/s \cdot mm^2 \cdot mmrad^2 \cdot 0.1\%]$	$10^{20} - 10^{23}$
Radiation pulse length rms [ps]	$0.7 - 1.5$
Linear polarization [%]	> 99

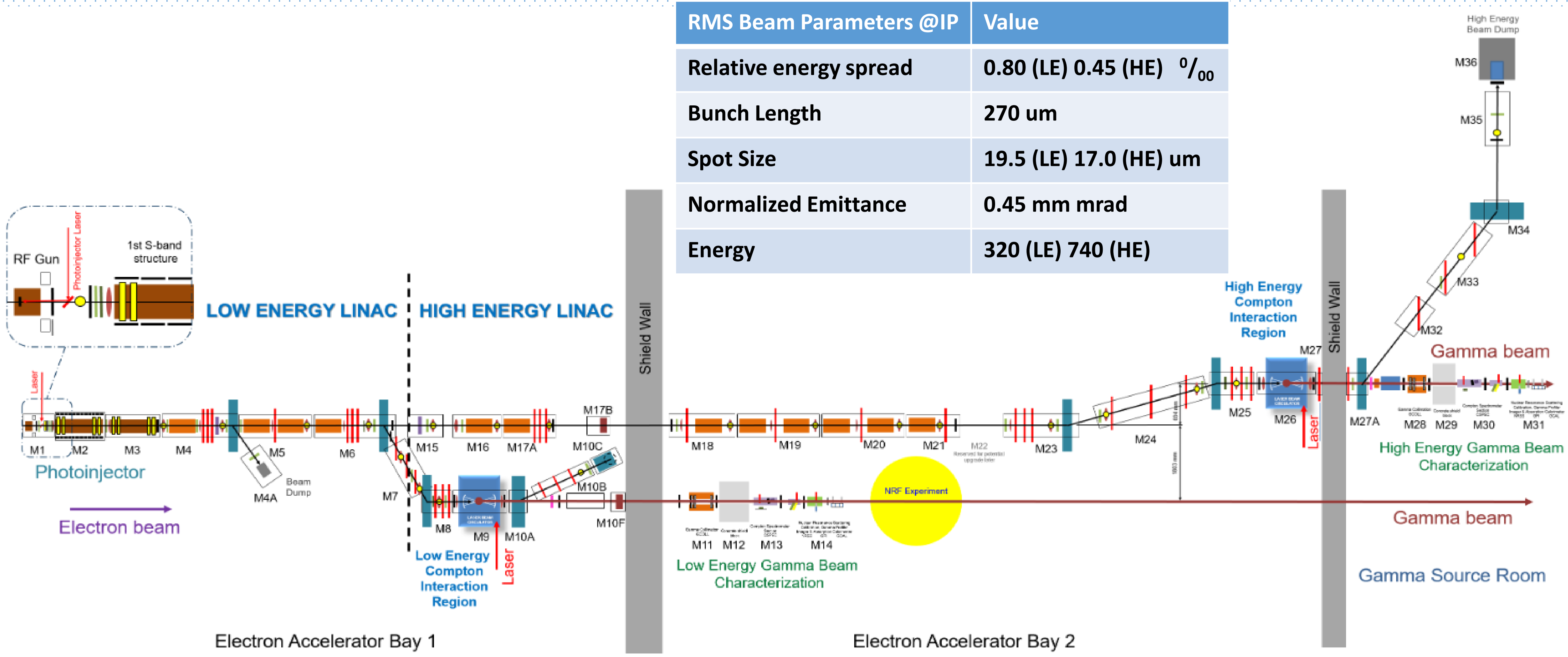




Courtesy of K. Cassou

ELI-NP-GBS Accelerator

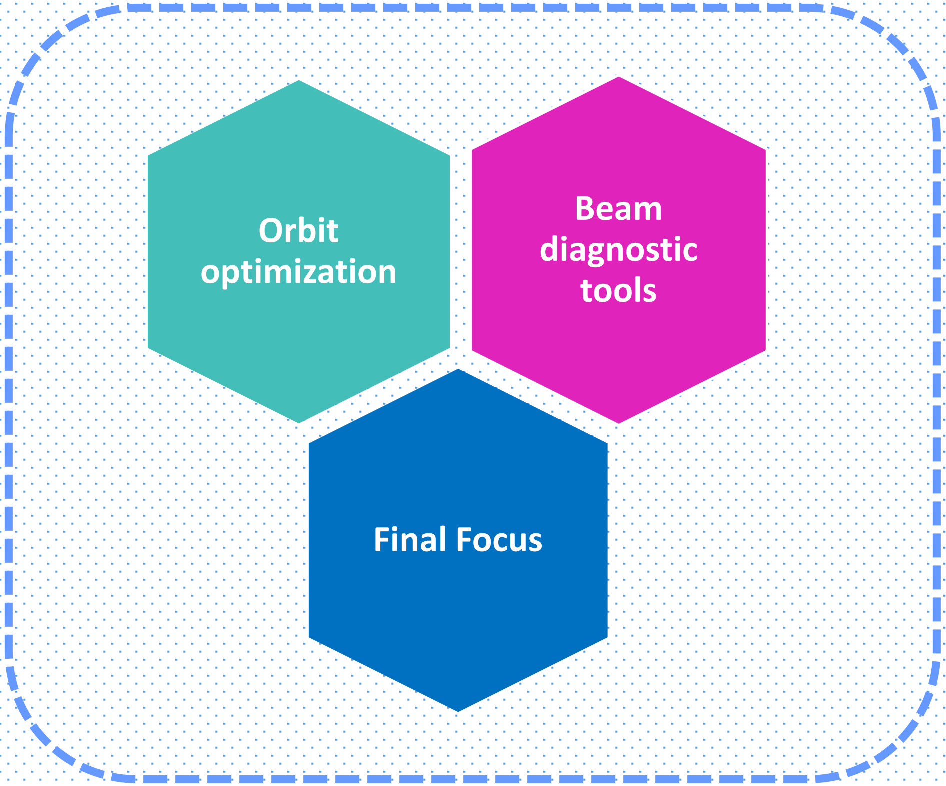
RMS Beam Parameters @IP	Value
Relative energy spread	0.80 (LE) 0.45 (HE) $^{0}/_{00}$
Bunch Length	270 um
Spot Size	19.5 (LE) 17.0 (HE) um
Normalized Emittance	0.45 mm mrad
Energy	320 (LE) 740 (HE)

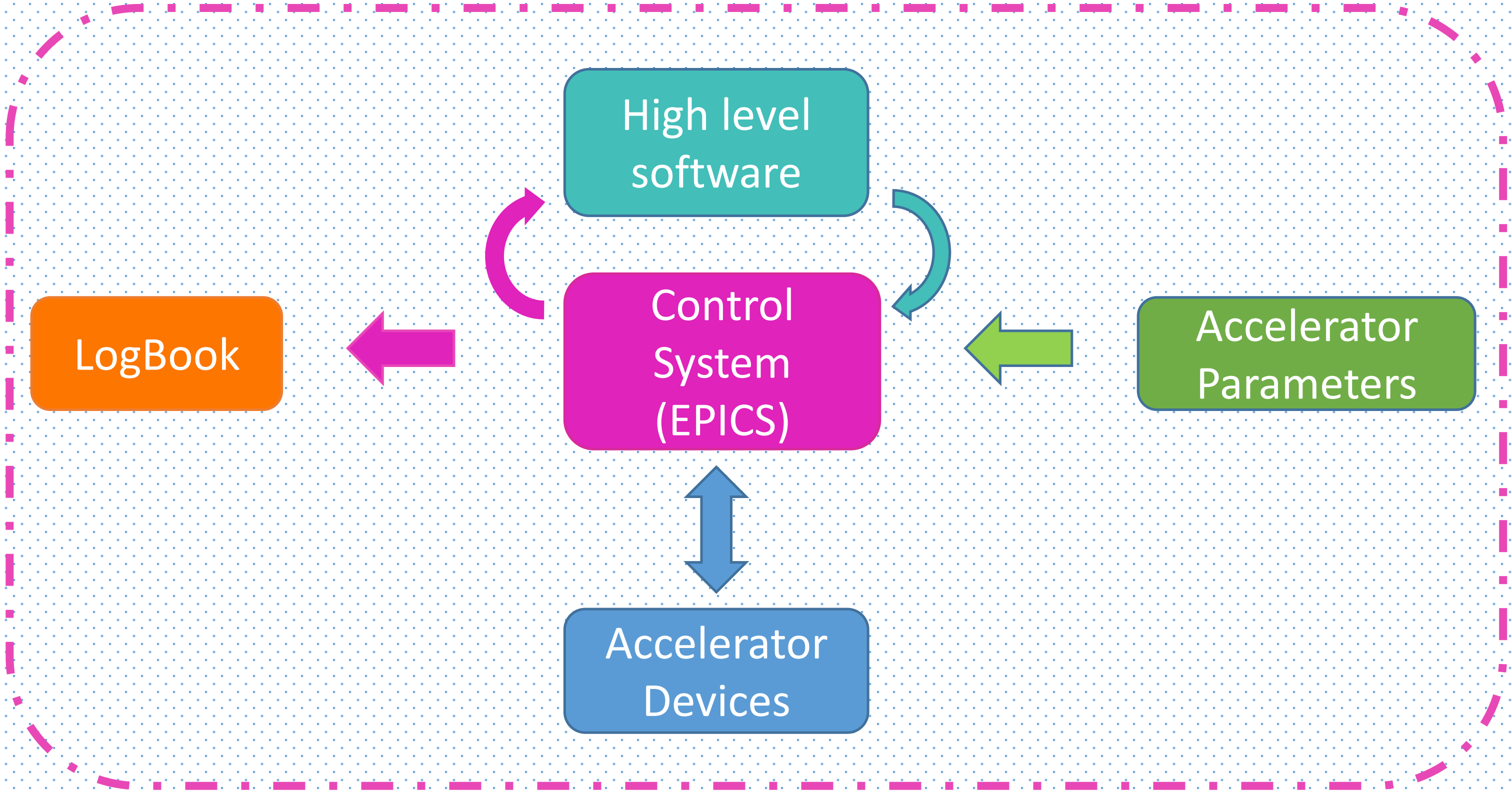


BOLINA: Beam Orbit for LINac Accelerators

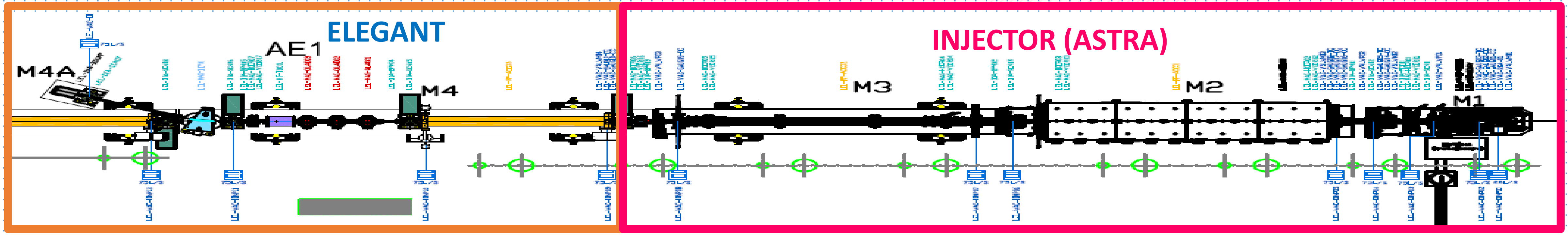
MODULAR & MACHINE INDEPENDENT !!!

The purpose of BOLINA is to allow automated operations to monitor and guarantee performances of the high brightness electron beam.





BOLINA's Beam diagnostic tools



Diagnostic is fundamental to understand the beam behaviour and characterise the beam. The tool interface with the control system when a measurement is required. BOLINA give measurement result back to the control system:

1) **Beam Energy**
   - Energy at the GUN exit (steering magnets)
   - Energy measurements using DIPOLES

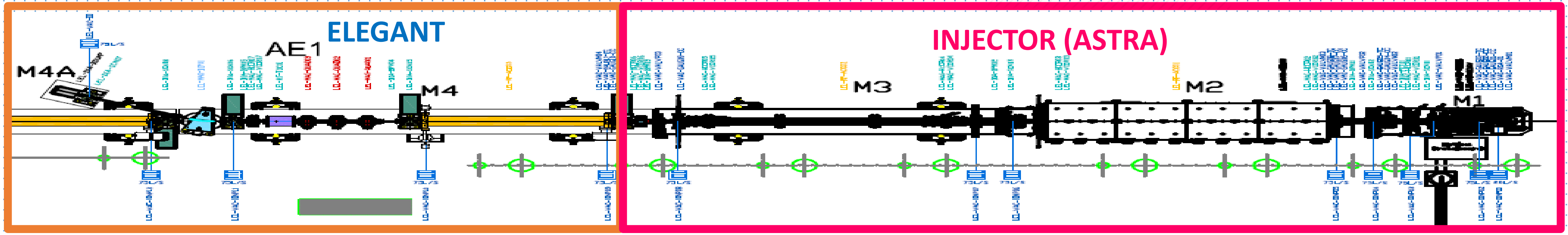
2) **Beam Length**

   Using Radio Frequency Deflectors (RFD)

3) **Beam energy spread**
   - Using RFD and Dipoles

5) **Emittance measurement**
   - Using the quadrupole scan technique

BOLINA's Beam diagnostic tools



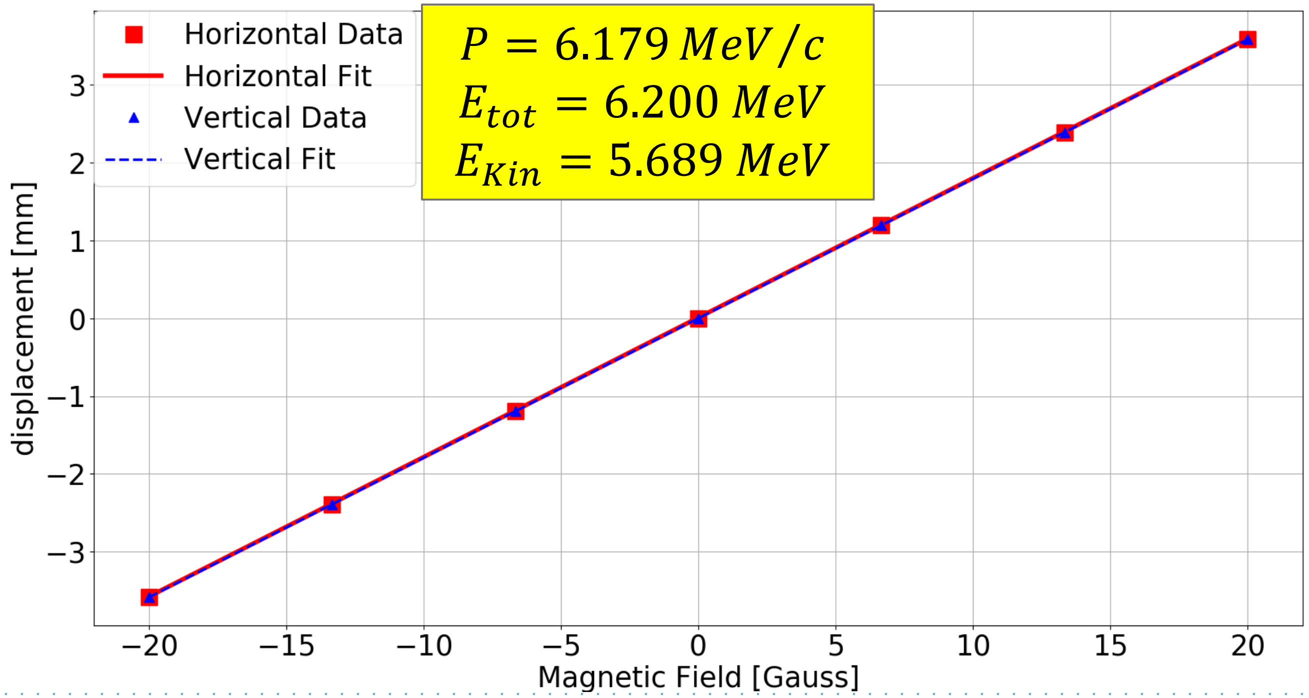
Gun Energy Measurement (ASTRA)

- Measuring steerer magnemagnetic field as function of the beam centroid offset.

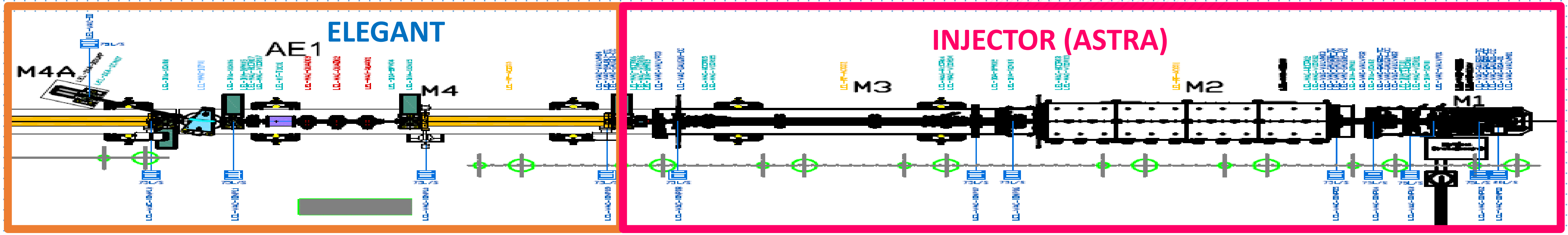
$$p = \frac{D[m]c\left[\frac{m}{s}\right]L_{eff}[m]}{\text{angular\_coeff}}10^{-3}$$

With both linear fit:

$$\frac{\Delta P}{P} = \frac{P_{real}-P_{meas}}{P_{real}} = 0.009\%$$

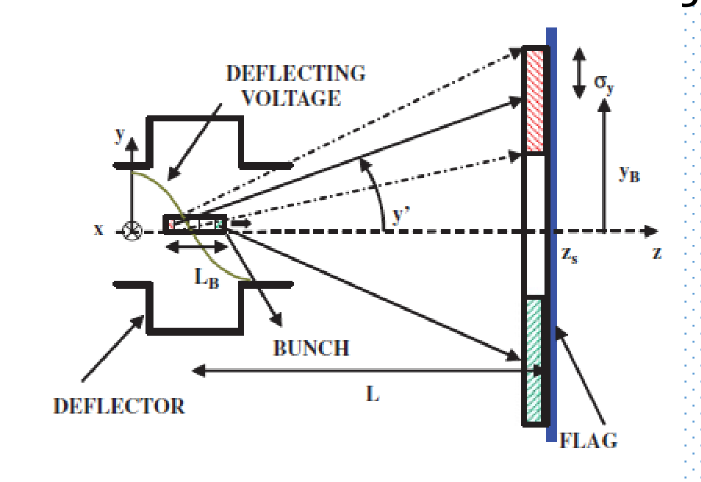


BOLINA’s Beam diagnostic tools



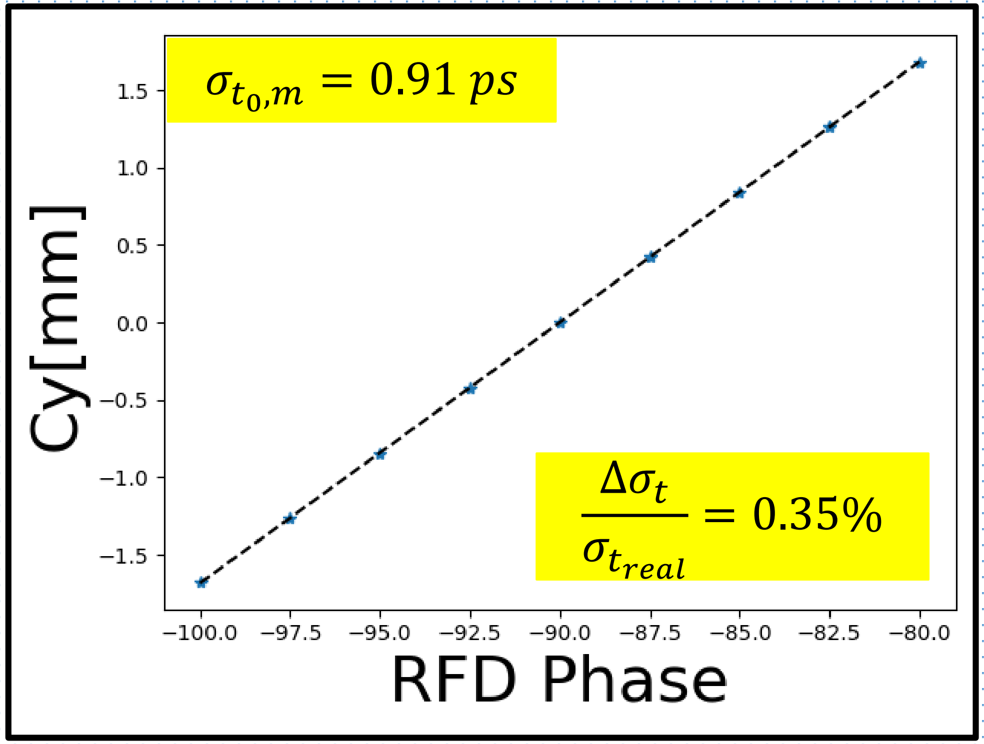
✓ **Length measurement: (ASTRA & ELEGANT)**

- measurements using Radio Frequency deflector at different phases near the zero crossing and measuring the spot size

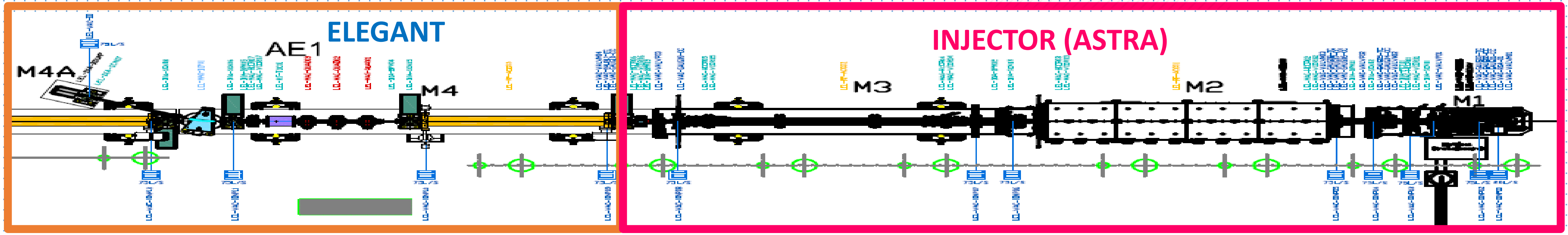


$$\sigma_{y_s}^2 = \sigma_{y_s,off}^2 + K_{cal}^2 \sigma_{t_0}^2,$$

$$K_{cal} = 173.05\ \mu m/ps$$



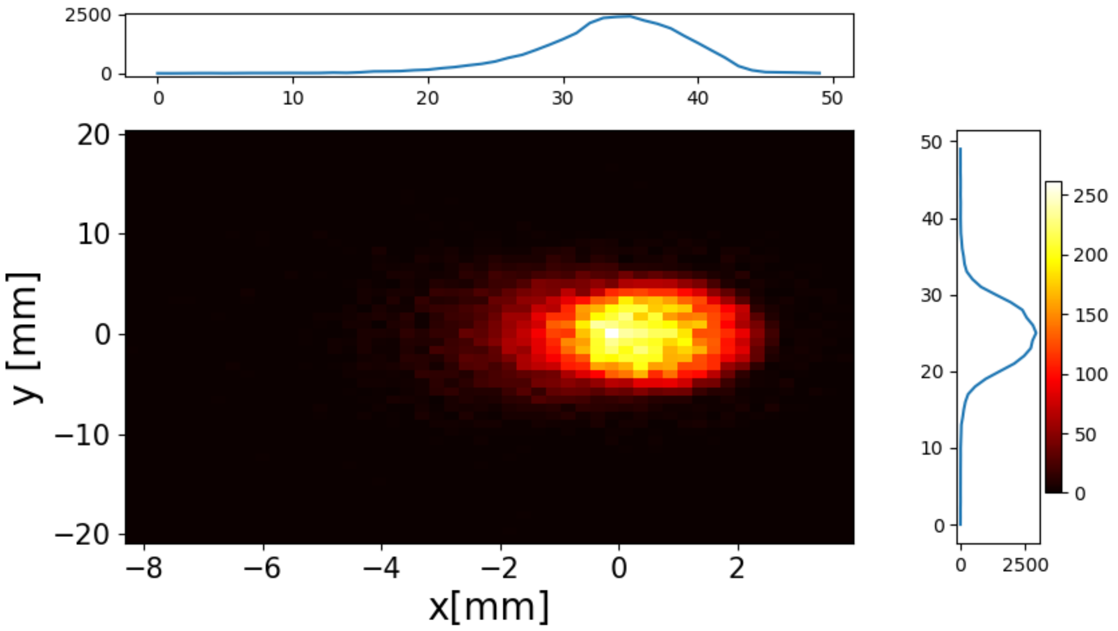
BOLINA's Beam diagnostic tools



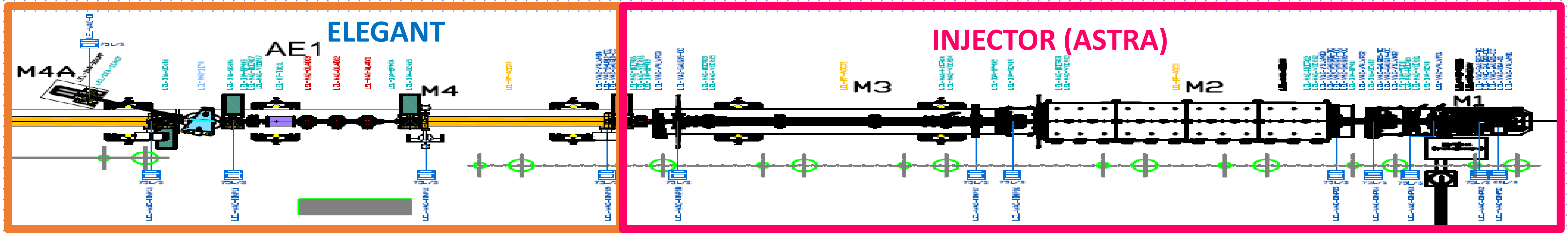
- ✓ **Energy Spread Measurement (ELEGANT)**
  - Dipole introduce dispersion. From the X spot size on the target in the diagnostic line target I evaluate the energy spread of the beam.

$$\sigma_\delta = \frac{\Delta p}{p} = \frac{L_D L_{Eff}}{\Delta x / x} Bc * 10^{-9}$$

real σ_δ=0.0058
meas σ_δ=0.0060
$\frac{\Delta(\sigma_\delta)}{\sigma_\delta} = 3\%$



BOLINA's Beam diagnostic tools

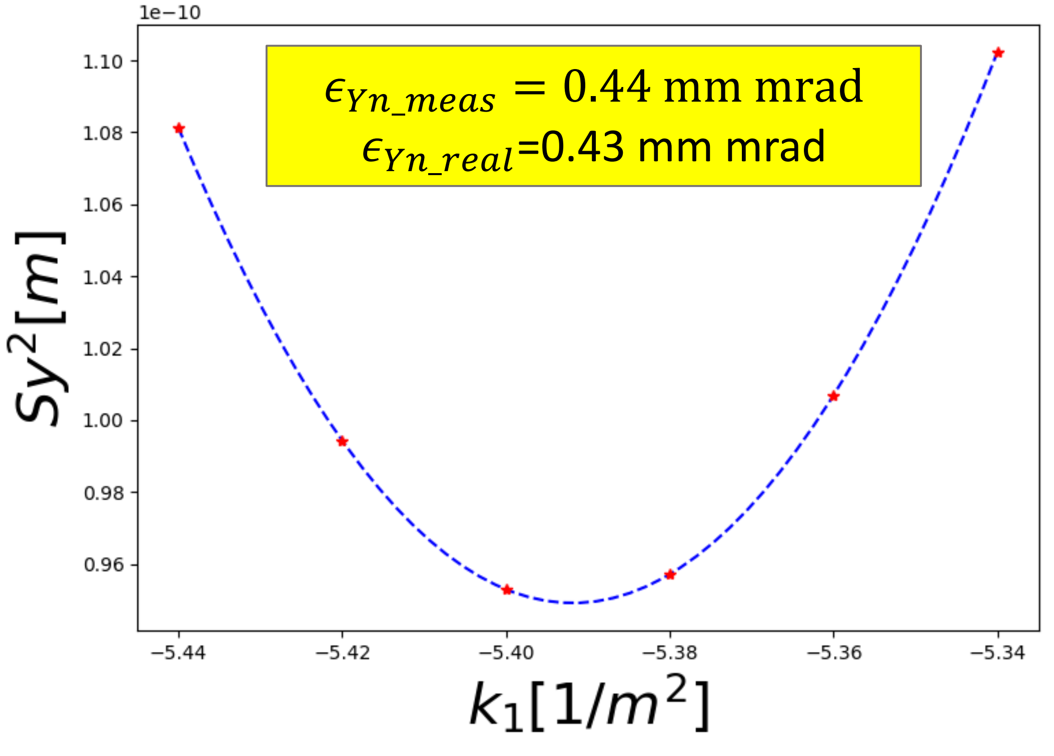


- **Emittance measurement (ELEGANT)**
  - Quadrupole Scan technic: Changing quadrupole fields near the waist.

$$\sigma_{1,11}(k) = \left(d^2\,\ell_q^2\sigma_{0,11}\right)k^2 + 2\left(d\,\ell_q\sigma_{0,11} + d^2\,\ell_q\sigma_{0,12}\right)k + \left(\sigma_{0,11} + 2d\,\sigma_{0,12} + d^2\sigma_{0,22}\right).$$

$$\begin{pmatrix}\sigma_{11} & \sigma_{12}\\ \sigma_{12} & \sigma_{22}\end{pmatrix} = \begin{pmatrix}< x_i^2 > & < x_i x_i' > \\ < x_i x_i' > & < x_i'^2 >\end{pmatrix} = \epsilon^2\begin{pmatrix}\beta & -\alpha\\ -\alpha & \gamma\end{pmatrix}$$

$$\sigma_{11}\,\sigma_{22} - \sigma_{12}^2 = \epsilon^2$$



BOLINA: Orbit correction

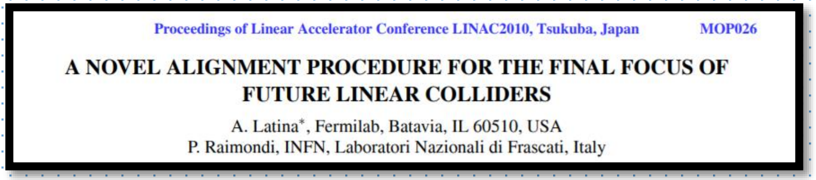
- Successful operation of modern particle accelerators require:
  - very small beam size at the interaction point;
  - low emittance.

- Ideal operation condition occurs when the electron beam trajectory passes through the electromagnetic center of all the elements.

- Errors (like elements misalignments) can affect the beam trajectory and degrade the beam quality forcing the operator to correct it using steering magnets.

- It is fundamental to correct at best the beam trajectory and to characterize the beam quality with online diagnostics and correction suits provided also with a feedback system granting the desiderated and optimized characteristics.

TRAJECTORY CORRECTION & FINAL FOCUS TOOL


Proceedings of Linear Accelerator Conference LINAC2010, Tsukuba, Japan MOP026

A NOVEL ALIGNMENT PROCEDURE FOR THE FINAL FOCUS OF FUTURE LINEAR COLLIDERS

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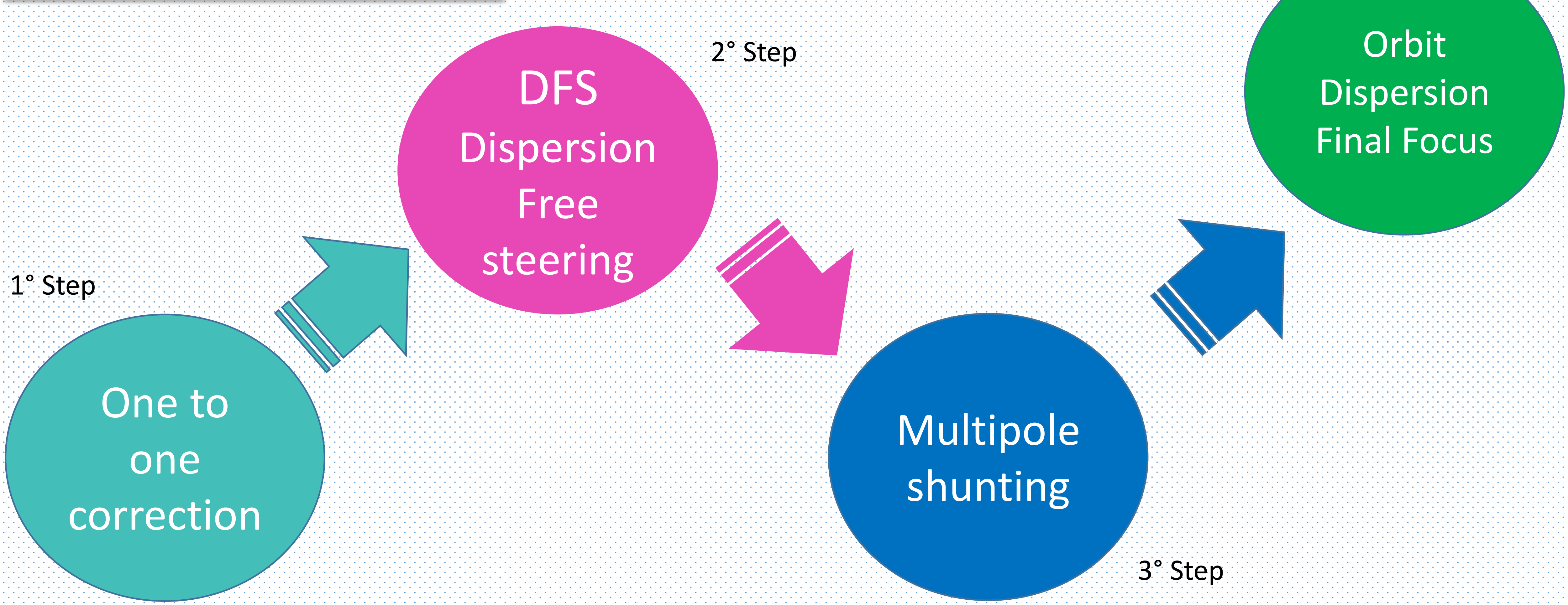


First step: Orbit correction

I
One to one correction

MULTIPOLE SWITCHED OFF

zeroing the beam position monitors values.

- The ***one-to-one correction**:* Given a trajectory **b** the goal of this technique is to find the correctors (steering magnets and dipoles) kicks $\boldsymbol{\theta}$ that minimize the equation

$$\overrightarrow{\boldsymbol{b}} + \boldsymbol{R}\,\vec{\theta} = 0$$

where **R** is the response matrix of the system that take into account all the elements of the accelerator.

Second step: Dispersion Free Steering

II
DFS

MULTIPOLE SWITCHED OFF

technique to minimize dispersion and correct the orbit.

- Dispersion η Measurement:
  - BPM vector **b** response for two test trajectory ($\mathbf{b}_{\delta_+}, \mathbf{b}_{\delta_-}$)
  - δ is relative energy difference

$$\eta = \frac{\mathbf{b}_{\delta_+} - \mathbf{b}_{\delta_-}}{\delta}.$$

If we consider the nominal dispersion $\boldsymbol{\eta_0}$, the formula to minimize is:

$$\begin{pmatrix} \vec{b} \\ \vec{\eta} - \vec{\eta}_0 \end{pmatrix} = -\begin{pmatrix} \boldsymbol{R} \\ \boldsymbol{D} \end{pmatrix} \vec{\theta}$$

Third step: Multipole shunting

III
Multipole shunting

POWERING EACH MULTIPOLE INDIVIDUALLY

center multipoles magnets with respect to beam orbit

- considers all BPM downstream not only the first one.
- Minimise:

$$\Delta b + \boldsymbol{S}\theta = 0$$

- The **S** matrix is constructed from the beam line optics in order to model the response of the beam to the steerer kick at the multipole.
- Δb change in beam trajectory

Last step: Simultanous optimization

IV
Orbit
Dispersion
Final Focus

MULTIPOLE AT THE NOMINAL VALUE

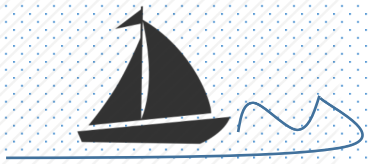
- Measurement of twiss beta:
  - activating first corrector to excite a positive (1+x) and negative (1-x) betatron oscillation and measure the beam trajectory $b_{x,y|\theta_{1+x}}$

$$\beta_x = \frac{b_{x,y|\theta_{1+x}} - b_{x,y|\theta_{1-x}}}{2\Delta\theta_{1,x}} .$$

- Considering the beta-beating response matrix **B**
- The system will simultaneously correct the orbit and minimize the dispersion and found the final focusing nominal value through minimization the formula:

$$\begin{pmatrix} \vec{b} \\ \vec{\eta} - \vec{\eta}_0 \\ \vec{\beta} - \vec{\beta}_0 \end{pmatrix} = - \begin{pmatrix} \boldsymbol{R} \\ \boldsymbol{D} \\ \boldsymbol{B} \end{pmatrix} \vec{\theta}$$

BOLINA: Final algorithm



- Weight $\omega_1, \omega_2, \beta$ are introduced in order to find the best trajectory that compensate the best BPM response vector and at the same time the best beta-beating or dispersion.

$$\begin{pmatrix} \vec{b} \\ \omega_1(\vec{\eta} - \vec{\eta}_0) \\ \omega_2(\vec{\beta} - \vec{\beta}_0) \\ 0 \end{pmatrix} = -\begin{pmatrix} \boldsymbol{R} \\ \boldsymbol{D} \\ \boldsymbol{B} \\ \beta\, \boldsymbol{ID} \end{pmatrix} \vec{\theta}$$

- The system can be solved in a least-squares sense using singular value decomposition (SVD).

CONCLUSIONS

- ✓ The Beam diagnostic tool is completed, and tested

Gun Energy Measurement (ASTRA)	$\frac{\Delta P}{P} = \frac{P_{real} - P_{meas}}{P_{real}} = 0.009\%$
Length measurement: (ASTRA & ELEGANT)	$\frac{\Delta\sigma_t}{\sigma_{t_{real}}} = 0.35\%$
Emittance measurement (ELEGANT)	$\frac{\Delta\epsilon_{Yn}}{\epsilon_{Yn}} = \frac{\epsilon_{Yreal} - \epsilon_{Yn_{meas}}}{\epsilon_{Yreal}} = 2\%$
Energy Measurement (ELEGANT)	$\frac{\Delta E}{E} = \frac{E_{real} - E_{meas}}{E_{real}} = 0.03‰$
Energy Spread Measurement (ELEGANT)	$\frac{\Delta(\sigma_\delta)}{\sigma_\delta} = \frac{\sigma_{\delta_{real}} - \sigma_{\delta_{meas}}}{\sigma_{\delta_{real}}} = 3\%$

- ✓ The Beam orbit reconstruction code is in developing phase.
  - ✓ The machine independent framework and the architecture are developed.
  - ✓ Elegant simulations are used to reproduce “experimental data” from the accelerator.
  - ✓ Orbit correction algorithm ongoing

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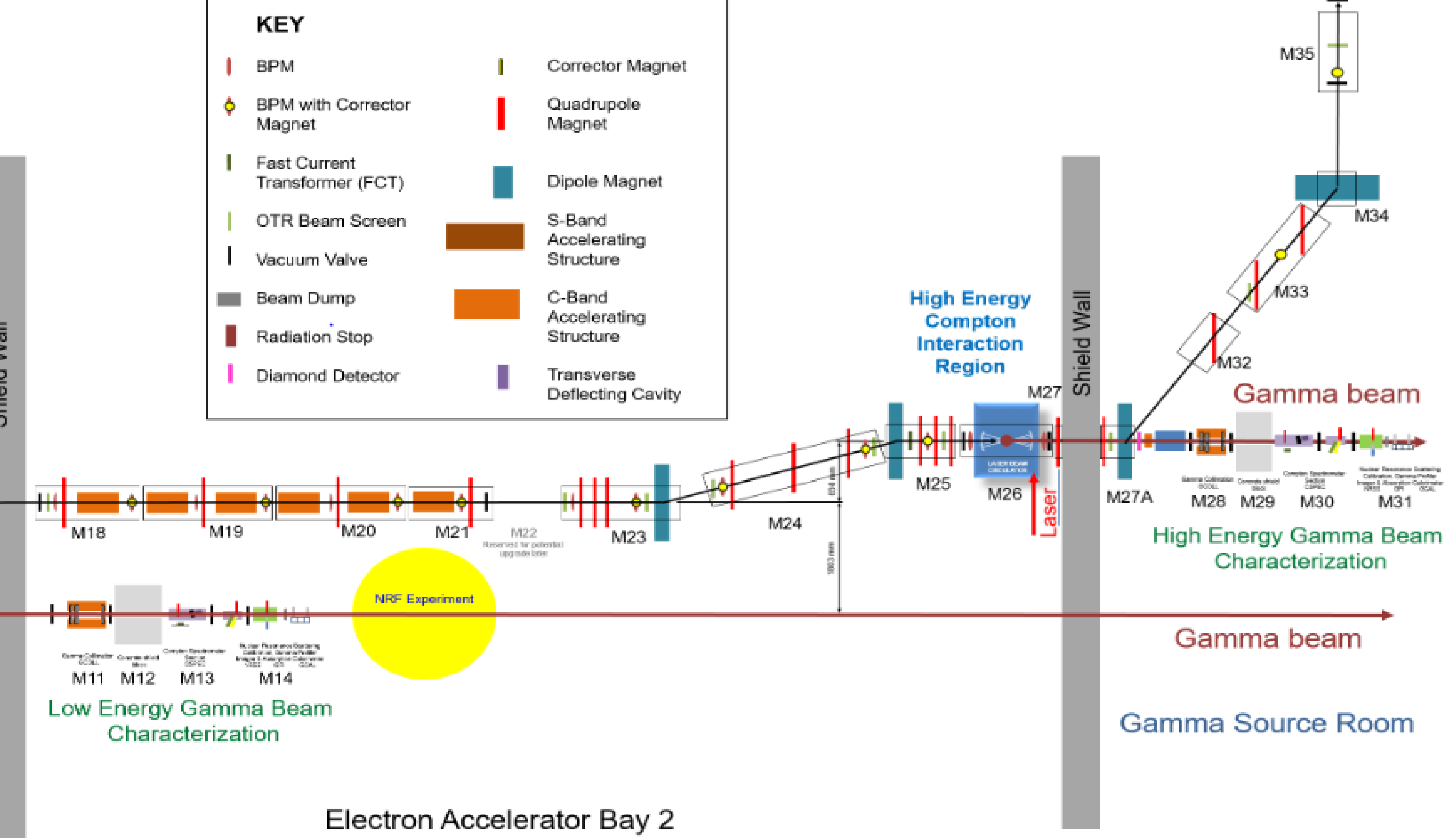
KEY
BPM
BPM with Corrector Magnet
Fast Current Transformer (FCT)
OTR Beam Screen
Vacuum Valve
Beam Dump
Radiation Stop
Diamond Detector
Corrector Magnet
Quadrupole Magnet
Dipole Magnet
S-Band Accelerating Structure
C-Band Accelerating Structure
Transverse Deflecting Cavity
Shield Wall
M18
M19
M20
M21
M22
M23
M24
M25
M26
M27
M27A
M28
M29
M30
M31
M32
M33
M34
M35
High Energy Compton Interaction Region
Laser
Gamma beam
High Energy Gamma Beam Characterization
NRF Experiment
M11
M12
M13
M14
Low Energy Gamma Beam Characterization
Gamma beam
Gamma Source Room
Electron Accelerator Bay 2

Electron Beam requirements at Interaction Point (IP)

RMS Beam Parameters @IP	Value
Relative energy spread	0.80 (LE) 0.45 (HE) $^{0}/_{00}$
Bunch Length	270 um
Spot Size	19.5 (LE) 17.0 (HE) um
Normalized Transverse Emittance	0.45 mm mrad

Narrow bandwidth (0.3%) and a **high spectral density (10^4 photons/sec/eV)** are the key feature for Nuclear Physics and photonics application.

$$\frac{\Delta\nu}{\nu} = \sqrt{\Psi^4 + \left[\frac{\epsilon_n}{\sigma_{tr}}\right]^4 + 4\left[\frac{\Delta\gamma}{\gamma}\right]_{e^-}^2 + \left[\frac{\Delta\nu}{\nu}\right]_L^2}$$

$$SPD = \frac{N_\gamma}{\sqrt{2\pi}h\frac{\Delta\nu}{\nu}} \quad N_\gamma = \sigma L \quad L = f\frac{N_e N_L}{2\pi(\sigma_t^2+\sigma_L^2)} \quad \sigma_{tr}^2 = \left(D\frac{\Delta\gamma}{\gamma}\right)^2 + \beta\epsilon$$