High level software for ELI-NP-GBS 6D - beam characterization

LNF - Young researchers presentations - 3 luglio 2018

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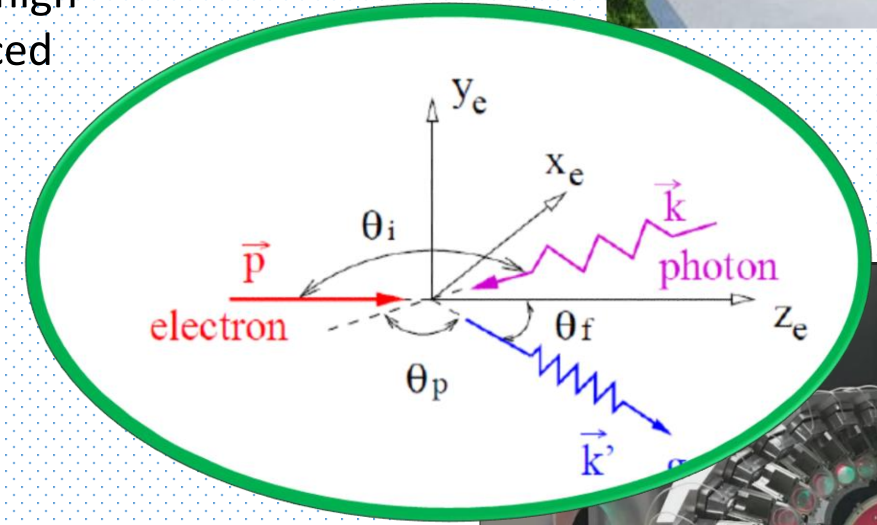
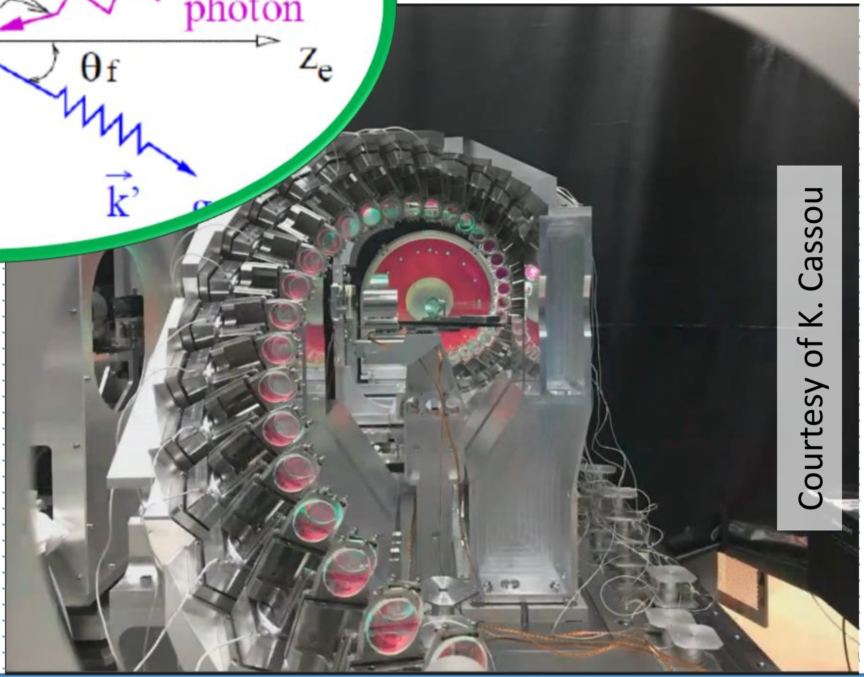
ELI-NP Gamma Beam Source

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.

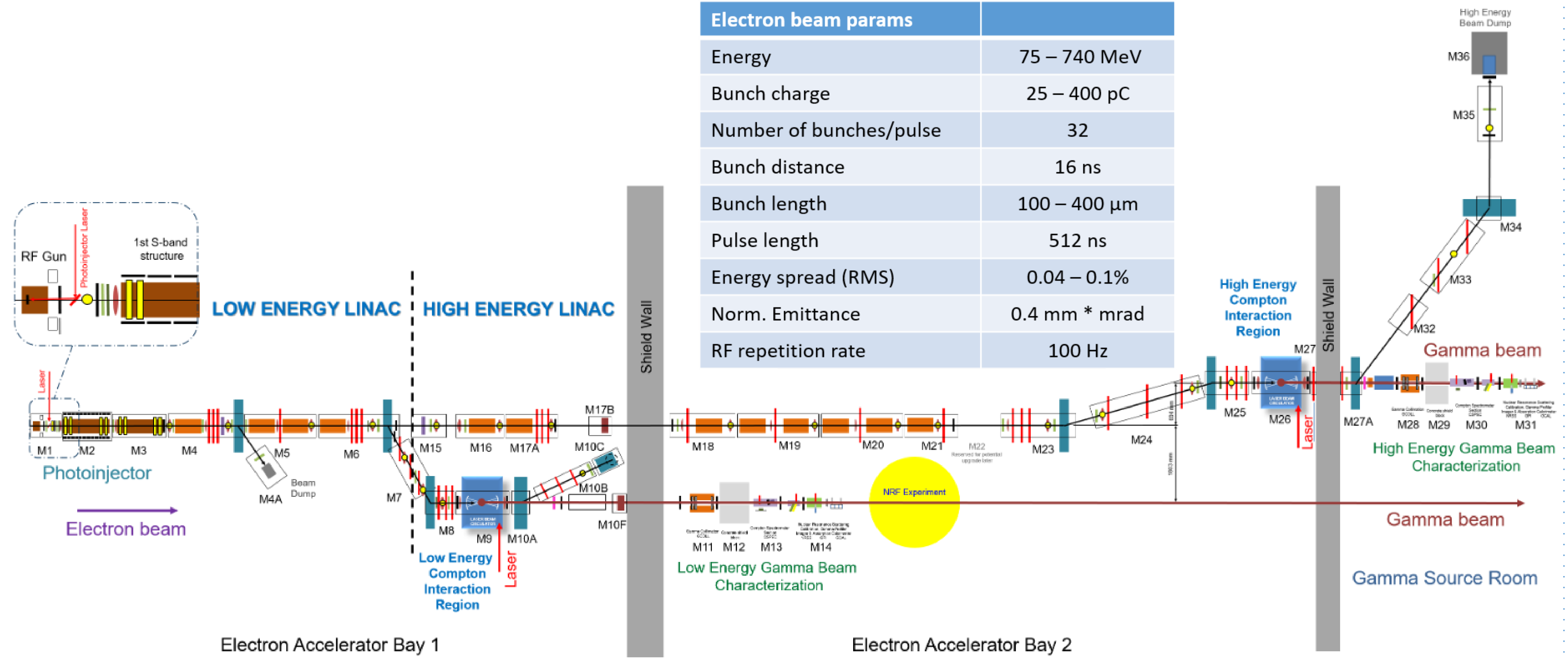
Parameter	Value
Energy [MeV]	$0.2 - 19.5$
Spectral density [$ph/s \cdot eV$]	$0.8 - 4 \cdot 10^4$
Bandwidth rms [%]	$\boxed{\leq 0.5}$
# photons/pulse within FWHM bdw	$\leq 2.6 \cdot 10^5$
# photons/s within FWHM bdw	$\leq 8.3 \cdot 10^8$
Source rms size [μm]	$10 - 30$
Source rms divergence [μrad]	$25 - 200$
Peak brilliance [$N_{ph}/s \cdot mm^2 \cdot mmrad^2 \cdot 0.1\%$]	$\boxed{10^{20} - 10^{23}}$
Radiation pulse length rms [ps]	$0.7 - 1.5$
Linear polarization [%]	> 99



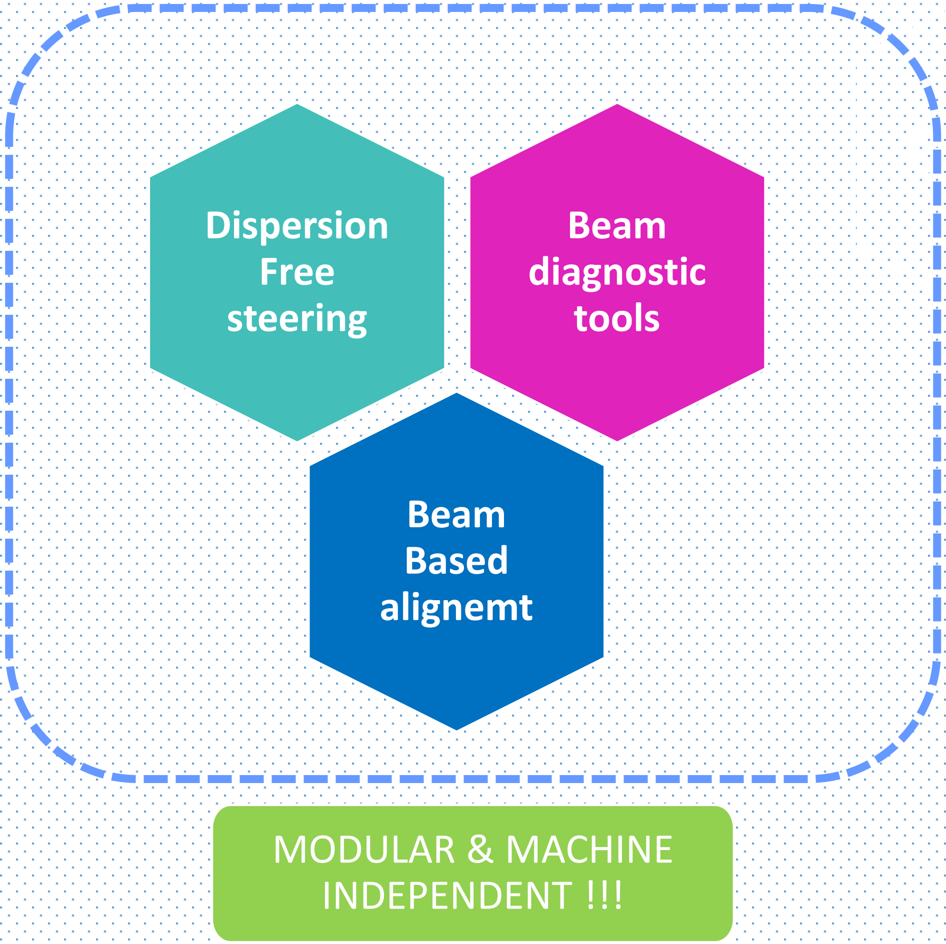


Eli-NP-GBS Accelerator Layout

Electron beam params	
Energy	75 – 740 MeV
Bunch charge	25 – 400 pC
Number of bunches/pulse	32
Bunch distance	16 ns
Bunch length	100 – 400 µm
Pulse length	512 ns
Energy spread (RMS)	0.04 – 0.1%
Norm. Emittance	0.4 mm * mrad
RF repetition rate	100 Hz



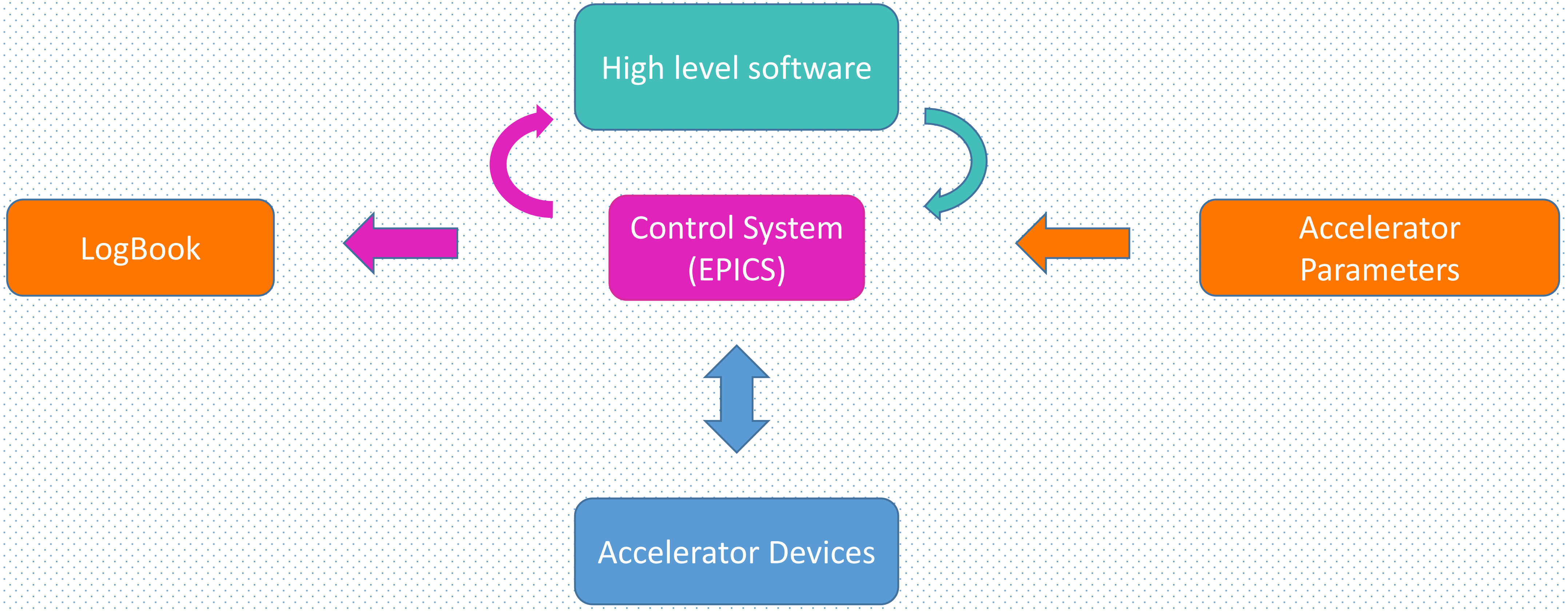
The High Level Software



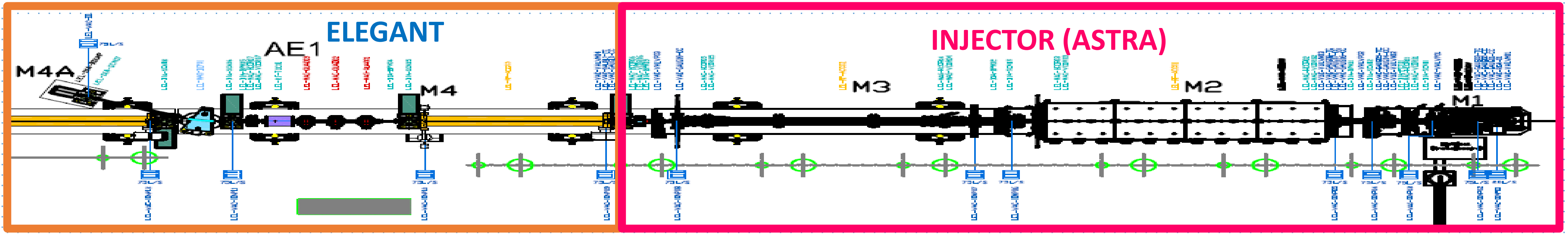
The purpose of the HLS is to allow automated operations to monitor and guarantee performances of the high brightness electron beam.

- **electron beam diagnostic measurements,** for beam characterization;
- **beam-based alignment,** to fit optic and mechanical center;
- **dispersion free steering software**, an algorithm for the simultaneous optimization of orbit and dispersion.

HLS interface with Control System



Beam diagnostic tools implementation and test



✓ **Gun Energy Measurement (ASTRA)**

- Dedicated fit function → evaluate the reliability of the fit
- Study of the error and jitters contribute → systematic error contribute

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

- Standard technic of measurements
- Correlation Longitudinal and Vertical Phase space

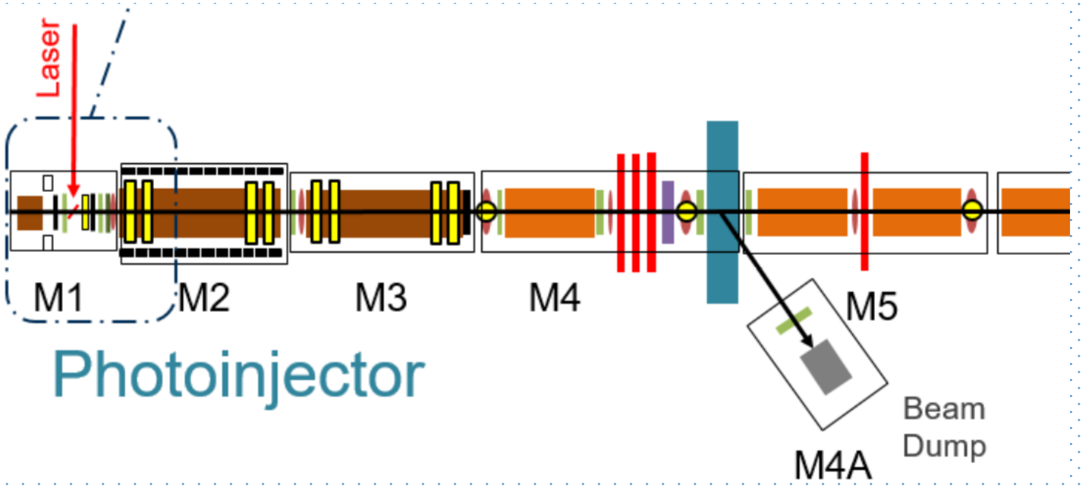
✓ **Emittance measurement (ELEGANT)**

- Standard technic of measurements

✓ **Energy Measurement (ASTRA & ELEGANT)**

- Measurements of accuracy & resolution → beam focalization and acceptance region

Gun-Energy Measurement



Moving GUN steerer magnets in a small range

- Simulate the steerer with ASTRA code
- Scan the steerer

Focalise the beam with Gun solenoid

- Not needed in the simulation

Measure centroid on the YAG screen for different steerer' scurrents

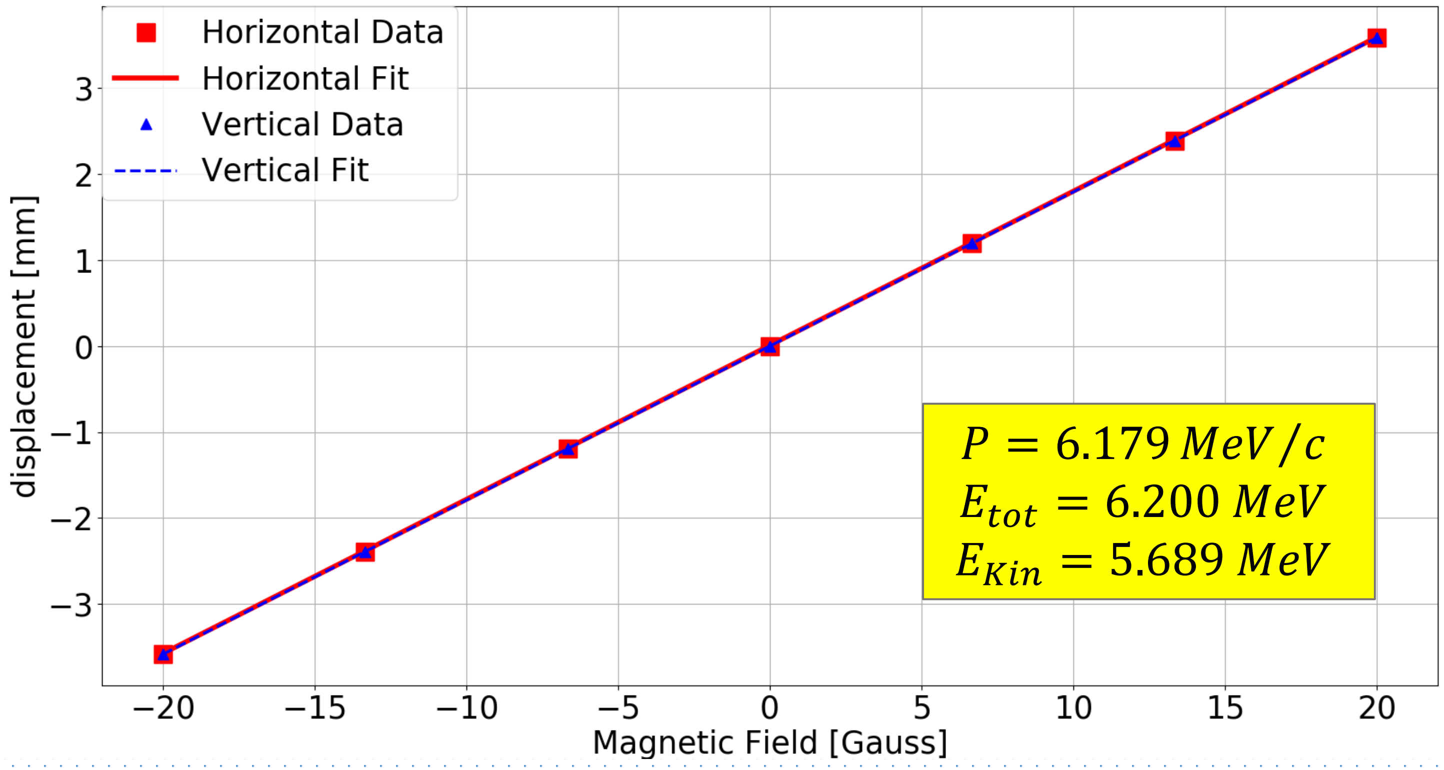
- Exitation curve simulated
- Analize data and compare results with the «real values»

The Python Script

- <u>Astra</u>:
  - Simulte the steerer magnet
  - scan magnetic field of the Steerer
  - Produce an output file at the Screen2 position (**z=1027.5 mm**) containing:
    - Beam centroid,
    - Magnetic Fields
    - Average momentum
- <u>Python script</u>:
  - read the results simulated by ASTRA :
  - Fit the results with:
    - Custom function (X^2 *method*)
    - Numpy library's function
  - Compare the results with the average momentum given by Astra's simulation

With both linear fit:

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



$P = 6.179\ MeV/c$
$E_{tot} = 6.200\ MeV$
$E_{Kin} = 5.689\ MeV$

$$\theta = \frac{L_{eff}}{\rho} \qquad \frac{1}{\rho[m]} = \frac{c\,[m/s] B_y[T]}{p[MeV]} 10^{-3} \qquad D = z_{target} - z_{dipole_{center}}$$

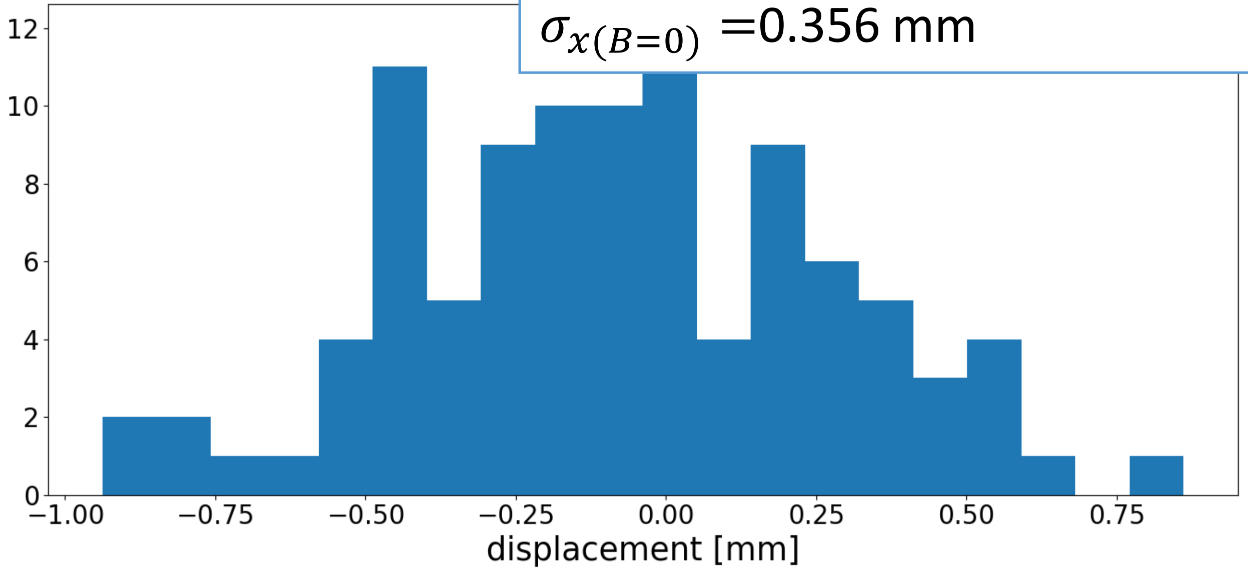
$$\text{displacement} = D tg(\theta) \sim D\Theta$$

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

Realistic beam energy measurement simulation

$< x(B = 0) >$= -0.0791 mm

$\sigma_{x(B=0)}$ =0.356 mm



- Insert Gaussian errors contribute in Astra Code

Solenoid position (x,y)	100 um
PC laser Arrival time jitter	200 fs
RF phase jitter	0.2 deg
Rf Voltage jitter	0.2 %
Steerer position (x,y,z)	100 um

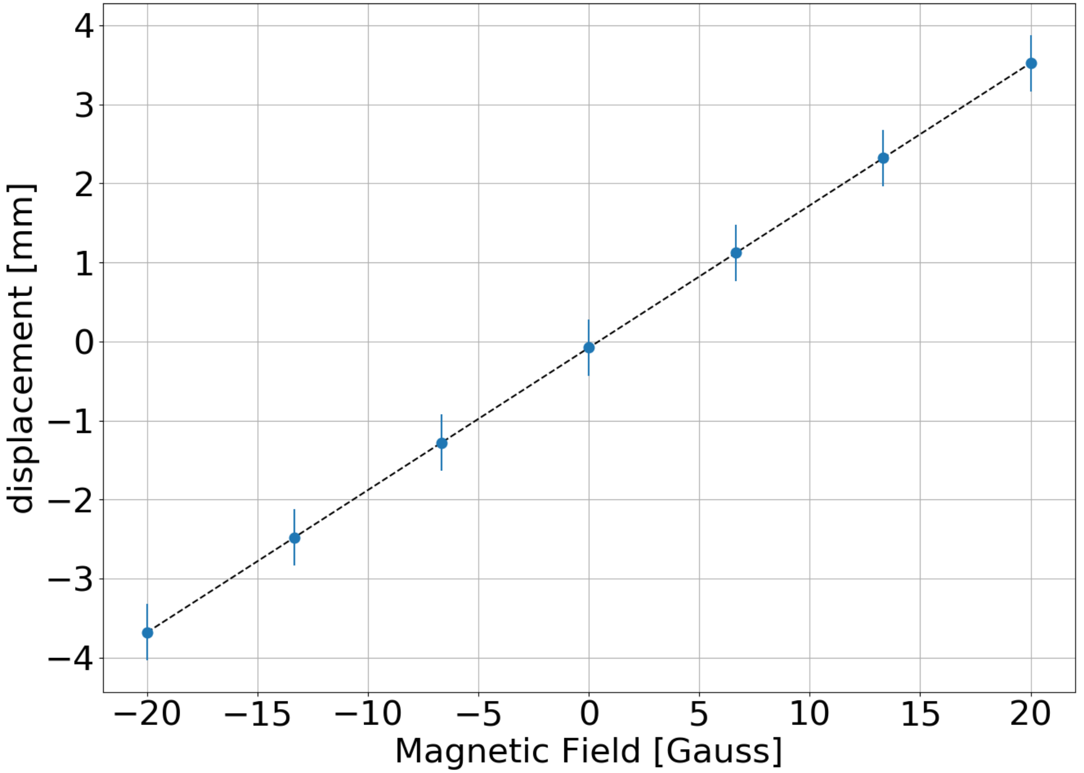
- Implement a bash script in order to execute automatically the scan
- Run the machine **100 time** for **30k particles**, considering Gaussian errors and scanning the current of the steerer (7 points).
- Averaging the centroid shift for all the run I find $< x >$ and from the standard deviation the σ_x
- Fit the results considering the error bars on the y-axis

6D phase space electron beam analysis and machine sensitivity studies for ELI-NP GBS

CrossMark

A. Giribono [a,b,*], A. Bacci [c], C. Curatolo [c], I. Drebot [c], L. Palumbo [a,b], V. Petrillo [c], A.R. Rossi [c], L. Serafini [c], C. Vaccarezza [d], A. Vannozzi [a,b], A. Variola [d]

The estimation of the error



Interpolating with Y=mx+q

$\boldsymbol{m} = 1801, \pm 101$

From this the momentum is:

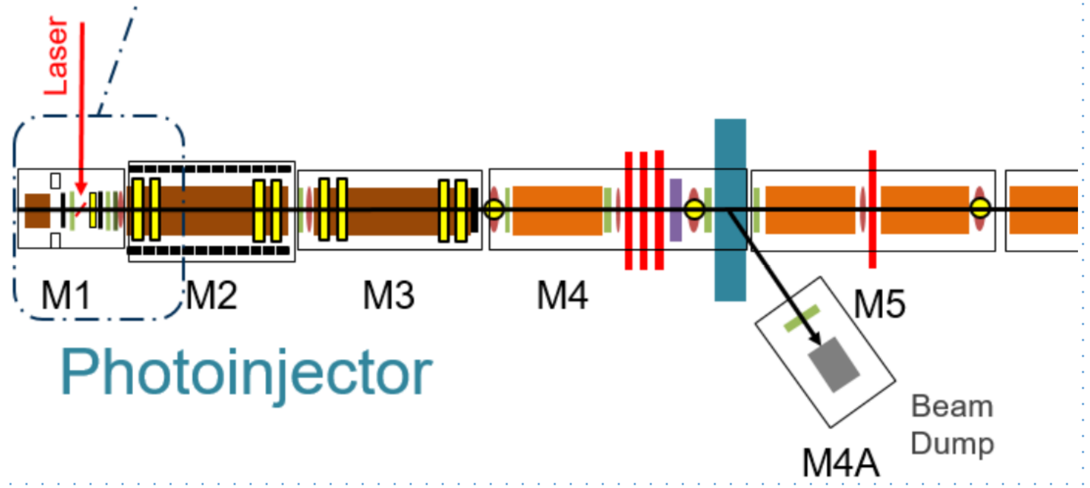
$$p = \frac{D[\mathrm{m}]c\left[\frac{\mathrm{m}}{s}\right]L_{eff}[\mathrm{m}]}{\boldsymbol{m}} 10^{-3}$$

$\boldsymbol{p = 6.18 \pm 0.35}$ **MeV**

Alignment Error — Fringe field — Error from fit

$$\sigma_P^2 = \left[\sigma_D^2\left(\frac{L_{eff}}{m}\right)^2 + \sigma_{L_{eff}}^2\left(\frac{D}{m}\right)^2 + \sigma_m^2\left(\frac{DL_{eff}}{m^2}\right)^2\right]\mathrm{c}^2 * 10^{-6}$$

Energy Measurement



Mooving Dipole magnets in a small interval

- Simulate the Dipole with ELEGANT
- Scan the Dipole

Focalise the beam with triplets

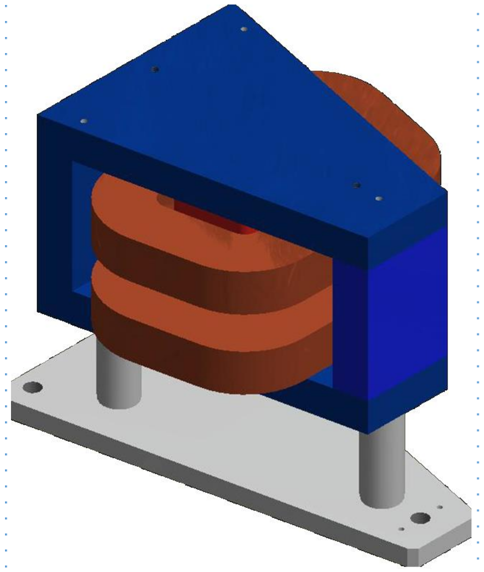
- If the energy sperad is high, for more accurated measurements, change a little bit the WP

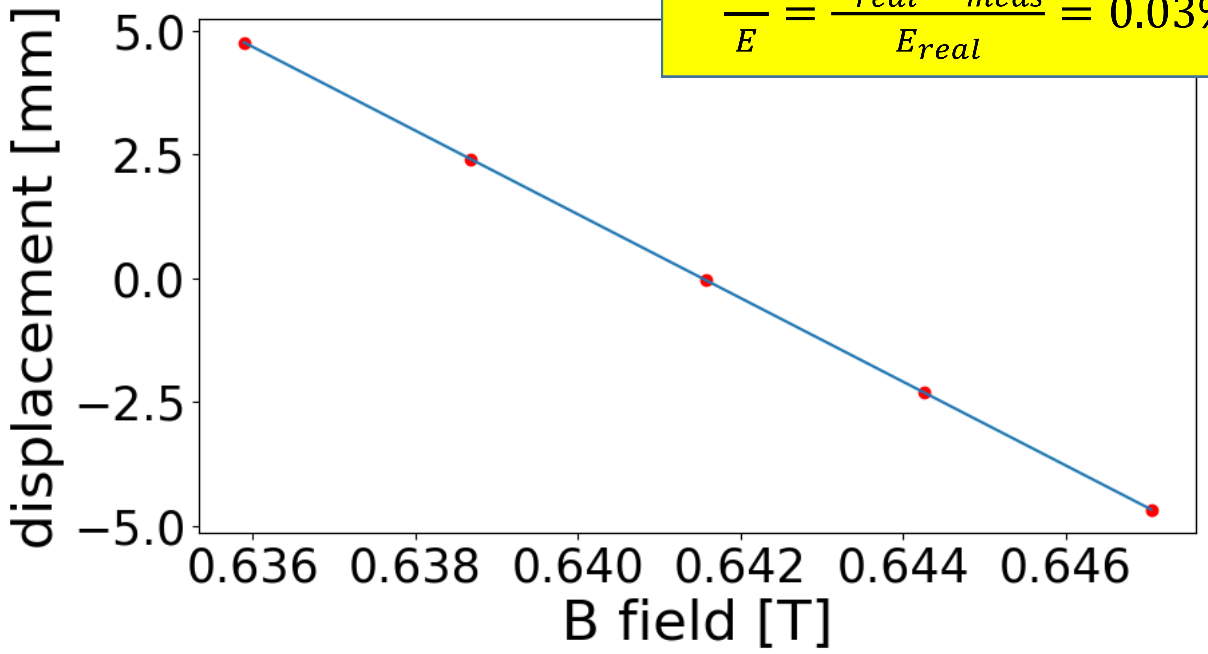
Measure centroid on the YAG screen for different currents of the Dipole

- Exitation curve simulated
- Analize data and compare results with «real values»
- Studing beam pipe dimention, YAG-screen dimention and acceptance region

Energy measurement with Lel-Dip01

real E=117.547 MeV
meas E=117.553 MeV
$\frac{\Delta E}{E} = \frac{E_{real} - E_{meas}}{E_{real}} = 0.03‰$



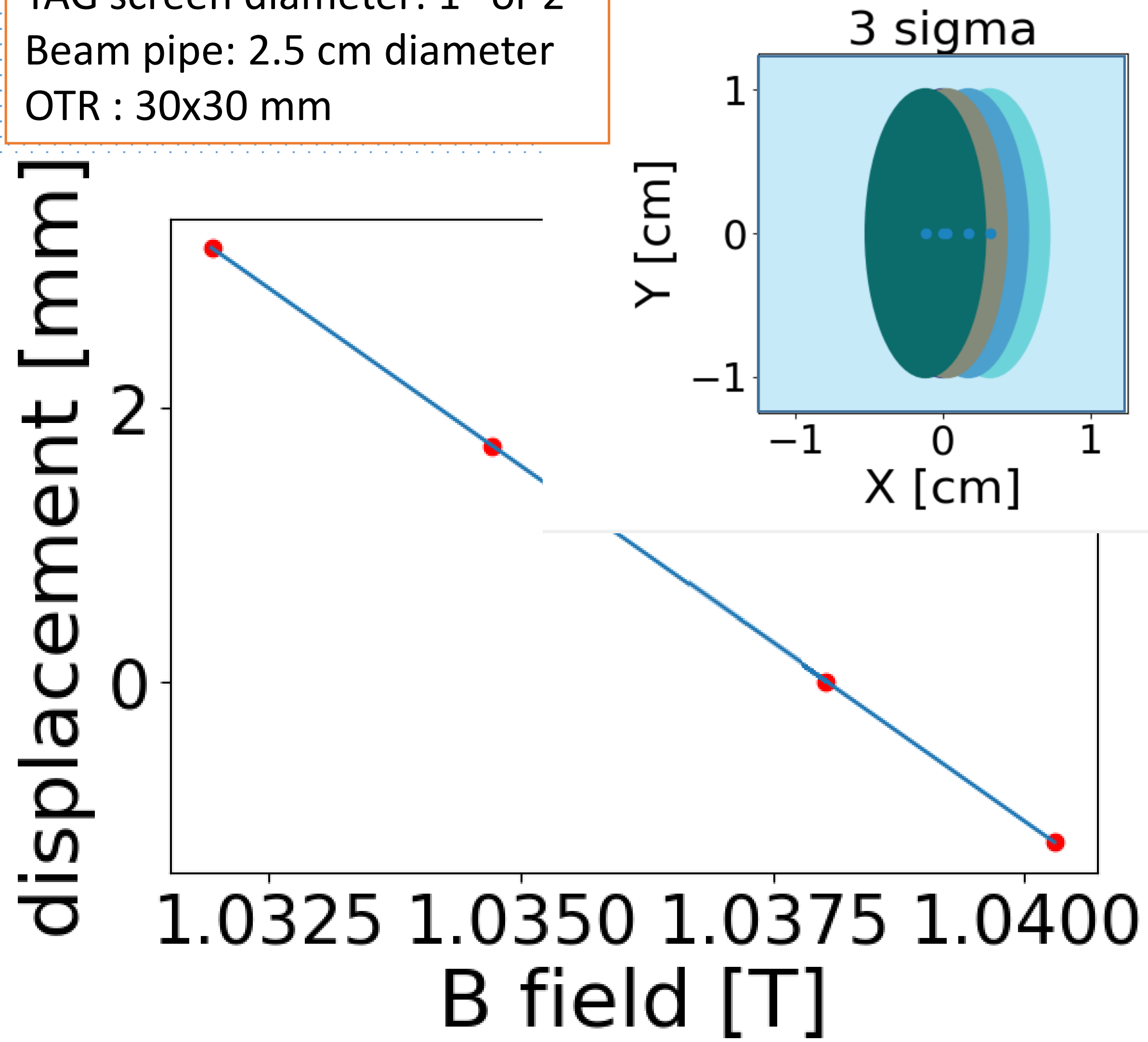


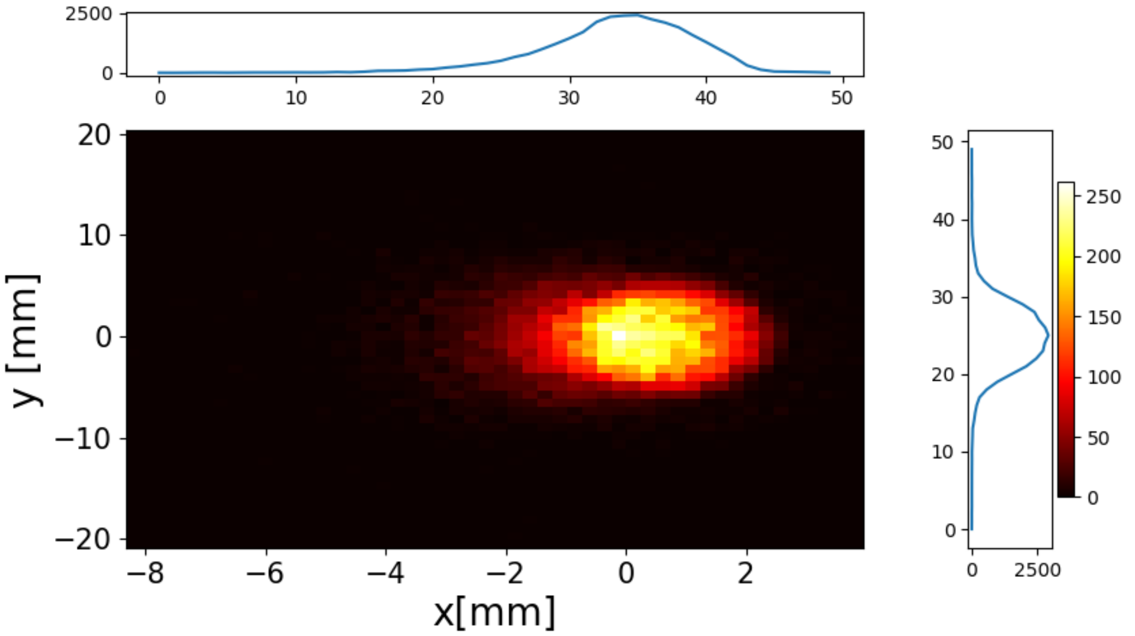
$$M_{x,sector} = \begin{pmatrix} \cos\theta & \rho\sin\theta & \rho(1-\cos\theta) \\ -\frac{1}{\rho}\sin\theta & \cos\theta & \sin\theta \\ 0 & 0 & 1 \end{pmatrix}$$

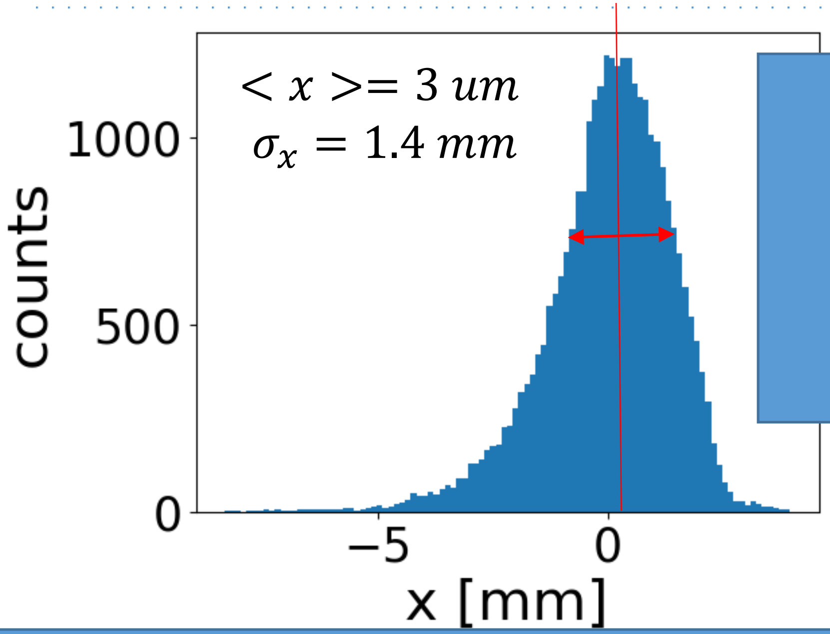
$$p = \frac{DcLm_e}{\text{angular\_coeff}} 10^{-6}$$

Measurement acceptance

YAG screen diameter: 1” or 2”
Beam pipe: 2.5 cm diameter
OTR : 30x30 mm

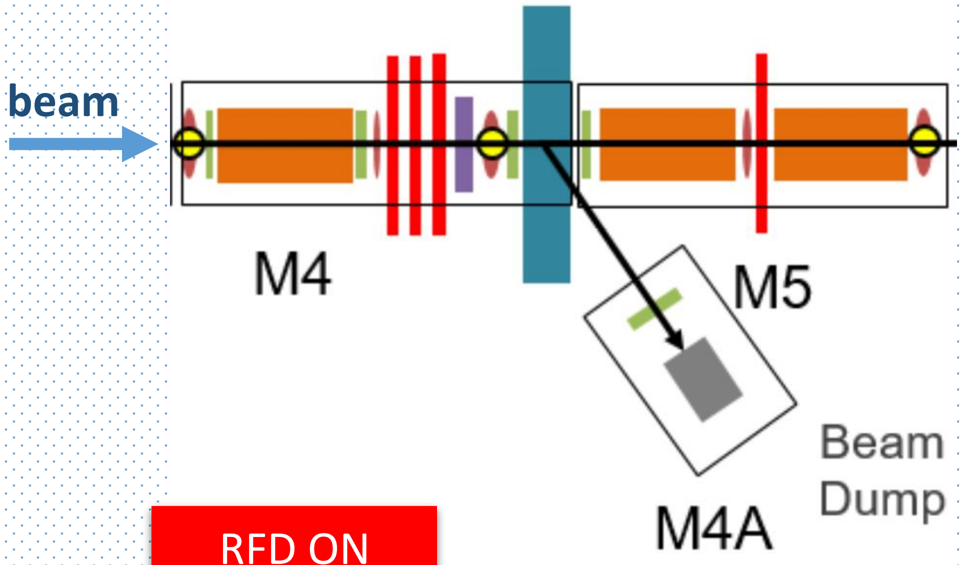






In <x> $\pm\ 2\sigma_x$
→ 95% of particle
In <x> $\pm\ 3\sigma_x$
→ 98% of particle

Length Measurement



RFD OFF

Measurement of vertical spot size a screen $\sigma_{y_{off}}$

- RFD simulated is a Traveling Wave S-Band with an integrated deflecting Voltage of 1 MV with a length of 25.6 cm

RFD ON

Bunch centroid as function of different phases in a small range at the zero crossing C_y

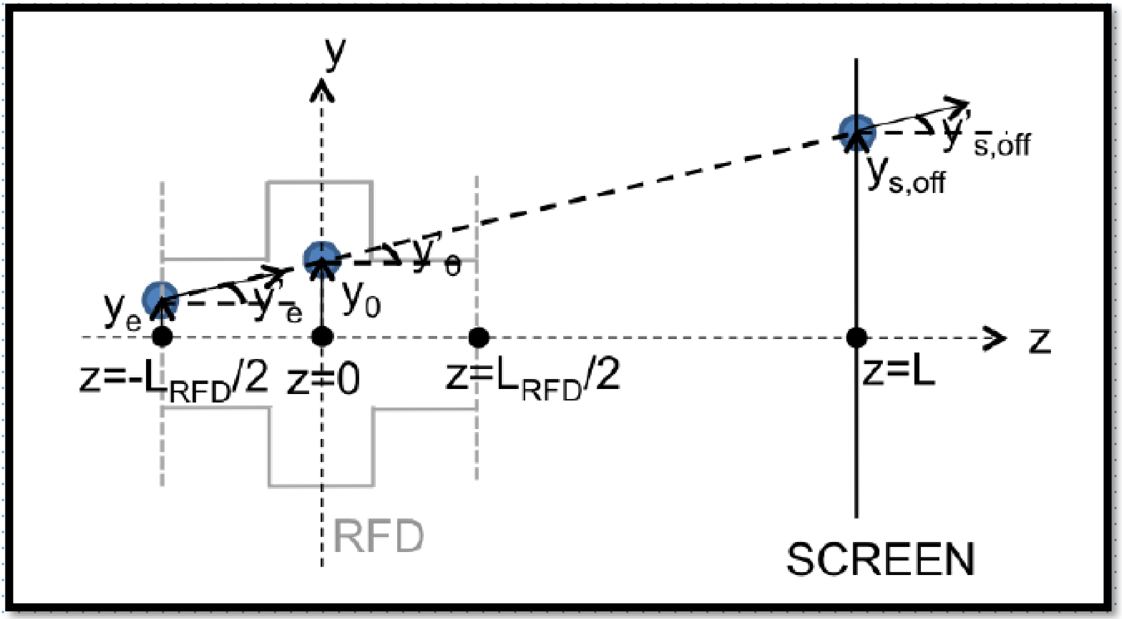
- In order to increase the resolution it can be necessary reduce the beam vertical size with Triplet.

RFD ON

Spot size at the zero crossing σ_y

- The Deflector calibration is measured from the FIT of the centroid.

The RFD for length measure



$$\begin{cases} y_{s,off} = & y_0 + L y'_0 \\ y'_{s,off} = & y'_0 \end{cases}$$

$$L = L_{drift} + L_{RFD}/2$$

$$\begin{cases} y_s = & y_0 + L\left(y'_0 + \Delta y'_0\right) \\ y'_s = & y'_0 + \Delta y'_0 \end{cases}$$

$$\Delta y'_{0_i}\left(z_{0_i}\right) = \frac{q}{p_{0_i} c} V\left(z_{0_i}\right) = C_{RFD0_i}\left[k z_{0_i}\cos(\varphi) + \sin(\varphi)\right],$$

Centroid

$$C_{y_s} = L C_{RFD0a}\sin(\varphi).$$

$$C_{y_s} \sim K_{cal}\varphi$$

Spot size

$$\sigma^2_{y_s} = \sigma^2_{y_s,off} + K^2_{cal}\sigma^2_{t_0},$$

$$\sigma_{t_0,m} = \frac{\sqrt{\sigma^2_{y_s} - \sigma^2_{y_s,off}}}{\left|K_{cal}(\varphi)\right|}.$$

The complete bunch spot after the RFD

Curtesy of L. Sabato

Standard — Energy Chirp — Energy Spread

$$\sigma_{y_s}^2(\varphi) = \boxed{\sigma_{y_s,off}^2 + K_{cal}^2(\varphi)\sigma_{t_0}^2} \boxed{-\frac{2K_{cal}^2(\varphi)}{2\pi f_{RF}}\tan(\varphi)\sigma_{t_0\delta_0}} + \boxed{\frac{K_{cal}^2(\varphi)}{(2\pi f_{RF})^2}\tan^2(\varphi)\,\sigma_{\delta_0}^2 +}$$

$$\boxed{+\,2K_{cal}(\varphi)\left(\sigma_{y_0t_0} + L\sigma_{y_0't_0}\right) - 2\frac{K_{cal}(\varphi)}{2\pi f_{RF}}\tan(\varphi)\left(\sigma_{y_0\delta_0} + L\sigma_{y_0'\delta_0}\right).}$$

Correlation Longitudinal and Vertical Phase space

$$\sigma_{y_s}^2(\varphi+\pi) = \sigma_{y_s,off}^2 + K_{cal}^2(\varphi)\sigma_{t_0}^2 - \frac{2K_{cal}^2(\varphi)}{2\pi f_{RF}}\tan(\varphi)\sigma_{t_0\delta_0} + \frac{K_{cal}^2(\varphi)}{(2\pi f_{RF})^2}\tan^2(\varphi)\,\sigma_{\delta_0}^2 +$$

$$-\,\underline{2K_{cal}(\varphi)\left(\sigma_{y_0t_0} + L\sigma_{y_0't_0}\right)} + \underline{2\frac{K_{cal}(\varphi)}{2\pi f_{RF}}\tan(\varphi)\left(\sigma_{y_0\delta_0} + L\sigma_{y_0'\delta_0}\right)}.$$

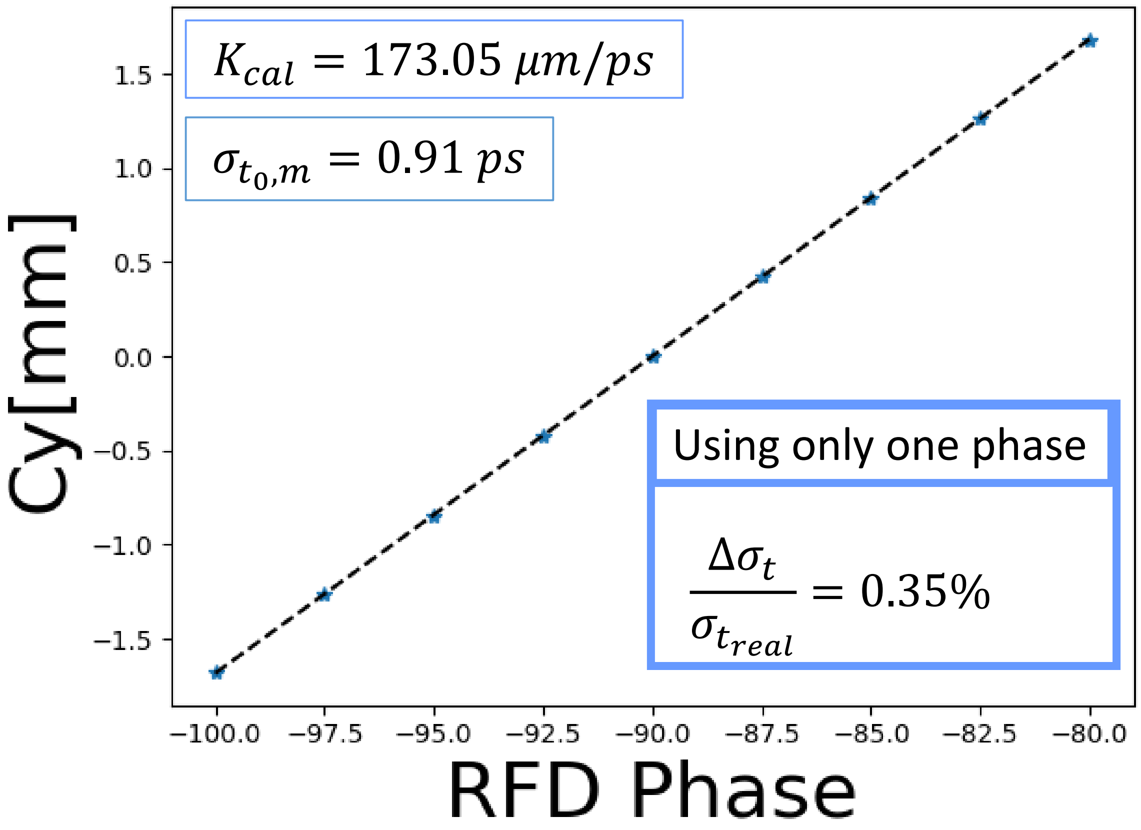
can be cancel measuring the vertical spot size for deflecting voltage 0 and π (Zero crossing)

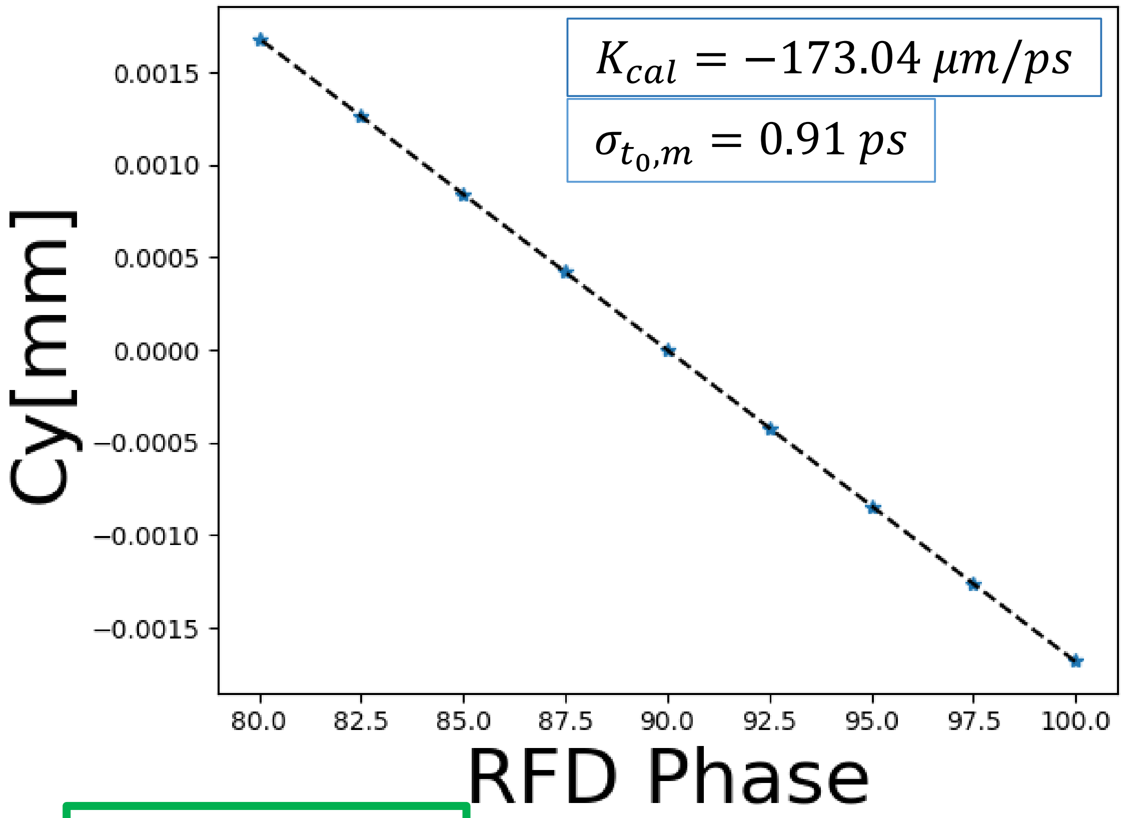
$$A^2(\varphi) = \frac{\sigma_{y_s}^2(\varphi) + \sigma_{y_s}^2(\varphi+\pi)}{2} =$$

$$= \sigma_{y_s,off}^2 + K_{cal}^2(\varphi)\sigma_{t_0}^2 - \frac{2K_{cal}^2(\varphi)}{2\pi f_{RF}}\tan(\varphi)\sigma_{t_0\delta_0} + \frac{K_{cal}^2(\varphi)}{(2\pi f_{RF})^2}\tan^2(\varphi)\,\sigma_{\delta_0}^2.$$

$$\boxed{\sigma_{t_0,m} = \frac{\sqrt{A_{y_s}^2 - \sigma_{y_s,off}^2}}{|K_{cal}(\varphi)|}.}$$

Cancellation of Correlation Contributions

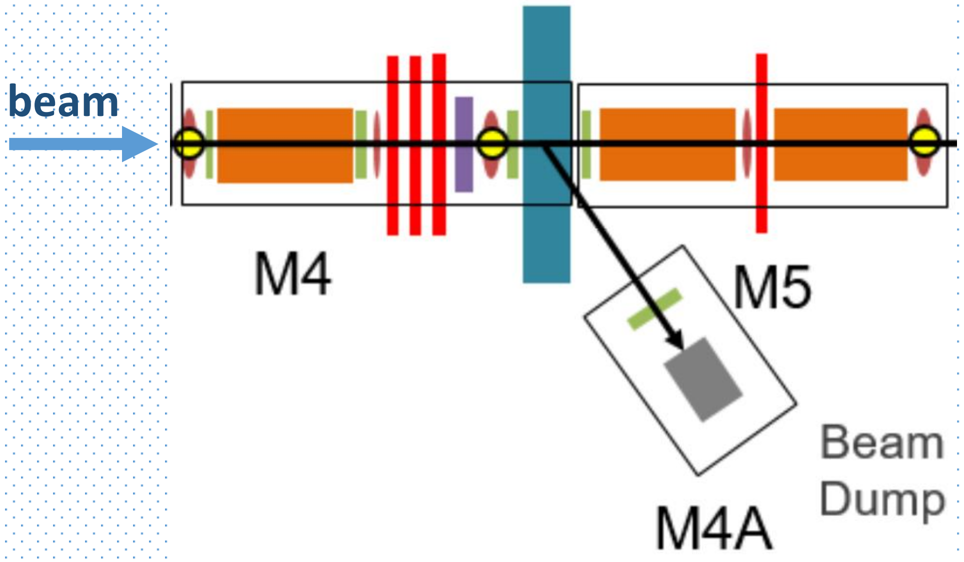




Using both phases

$$\frac{\Delta\sigma_t}{\sigma_{t_{real}}} = 0.33\%$$

Emittance Measurement



Mooving Quadropole-current finding the beam beam waist in X (or Y)

- Simulate the quadrupole with ELEGANT script
- Scan the Quadrupole strenght finding the waist

Move the quadrupole current around the waist

- Collect X spot (Y spot) as function of quadrupole current

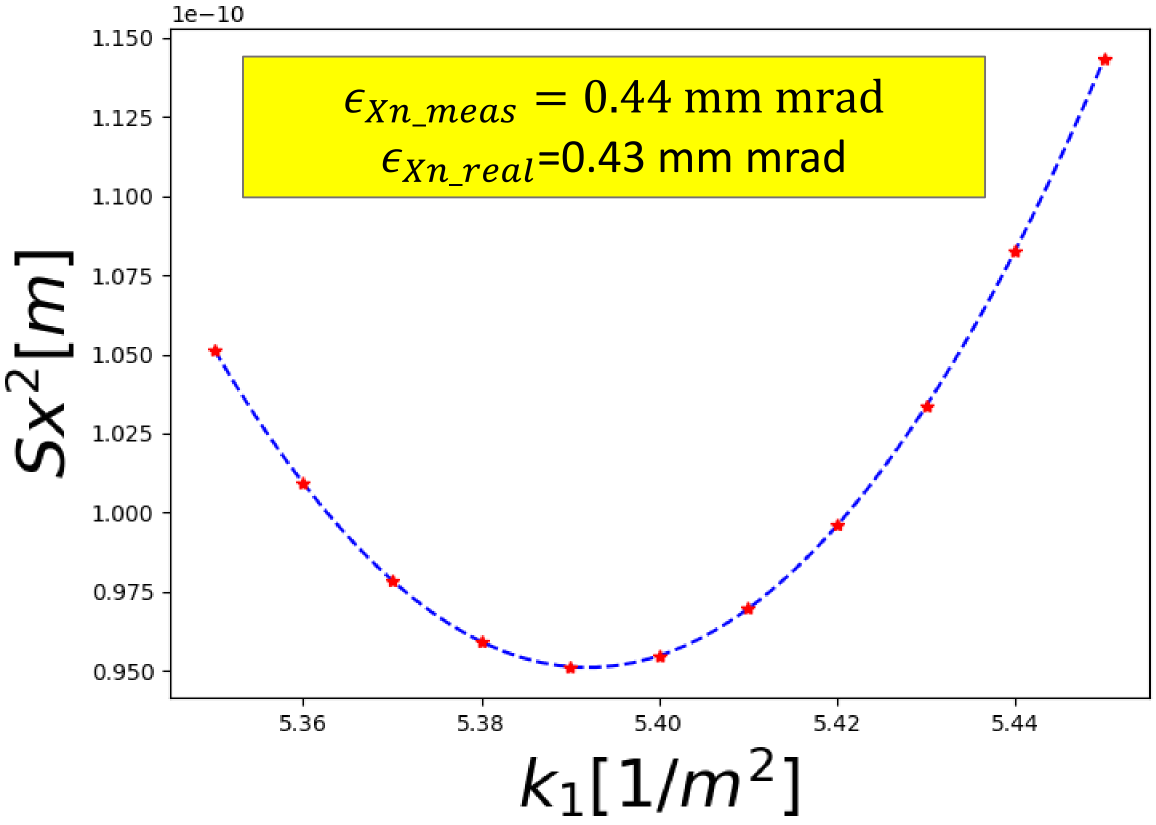
Repeat for 2nd axis

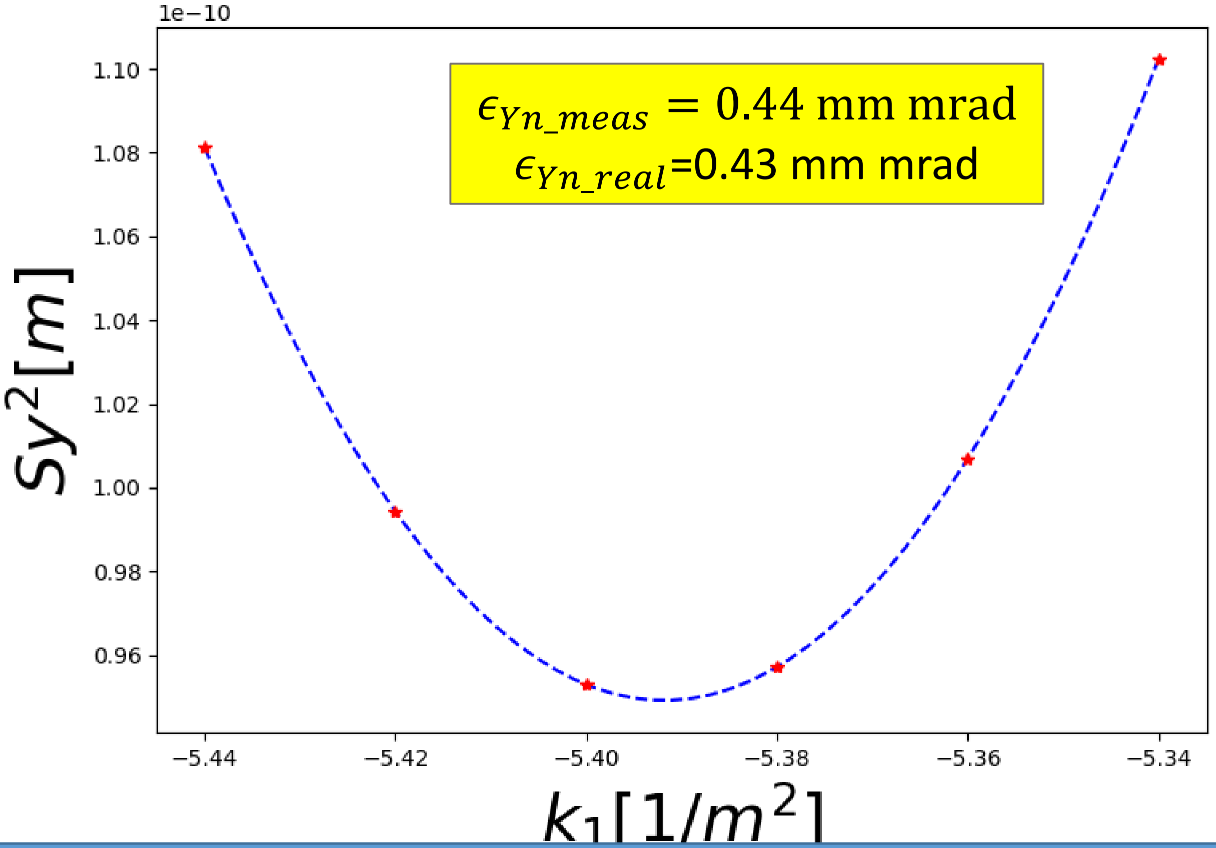
- Analize data and compare results with «real values»

Emittance measurement: X/Y axis

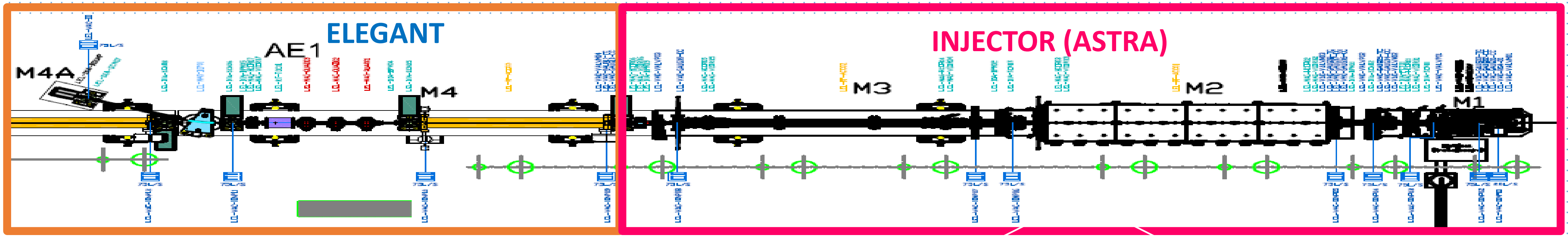
$$\sigma_{11}\,\sigma_{22} - \sigma_{12}^2 = \epsilon^2$$

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





Conclusion



Dispersion Free steering

Beam diagnostic tools

Beam Based alignemt