Movable emittance-meter data analysis methodology

Andrea Mostacci

on behalf of the SPARC collaboration

Outline

The emittance meter experiment at SPARC.

Single moving slit method for measuring emittance at low energy.

SPARC data analysis procedure

- Main building blocks
- Motivation for the analysis choices
- Example taken from the benchmark data

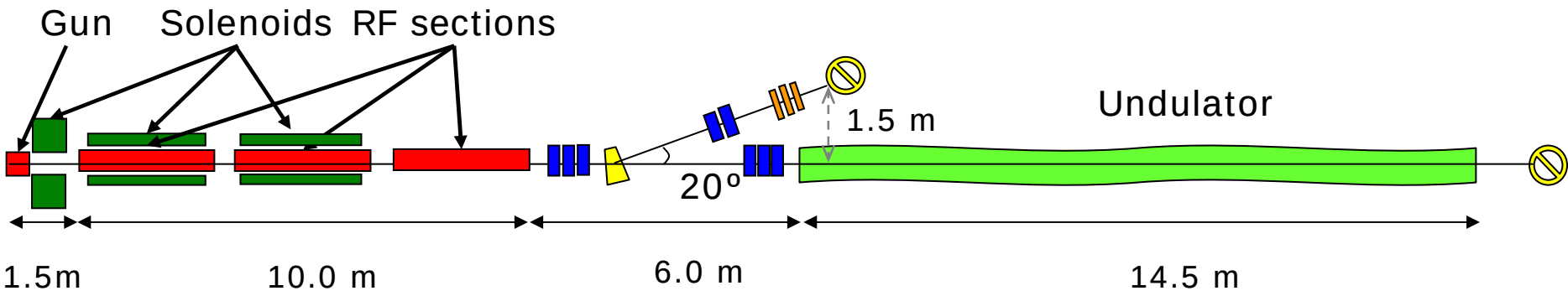
Conclusion

SPARC

Andrea.Mostacci@uniroma1.it

The SPARC(-Lab) facility

MAIN GOAL: R&D activity oriented to the development of a high brightness photoinjector to drive SASE FEL experiments

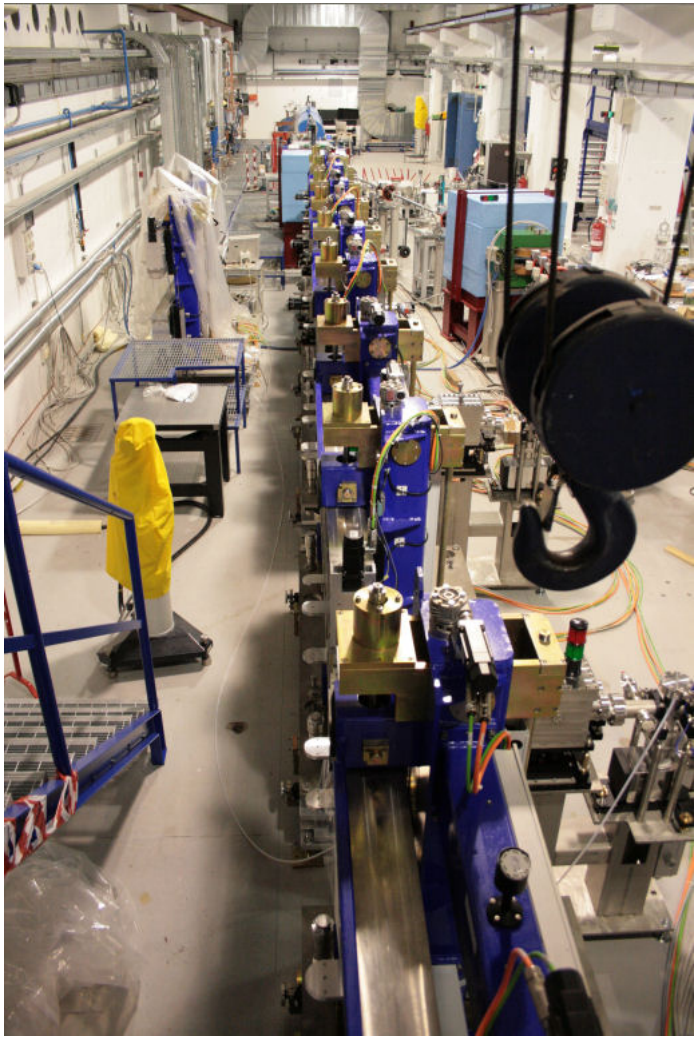


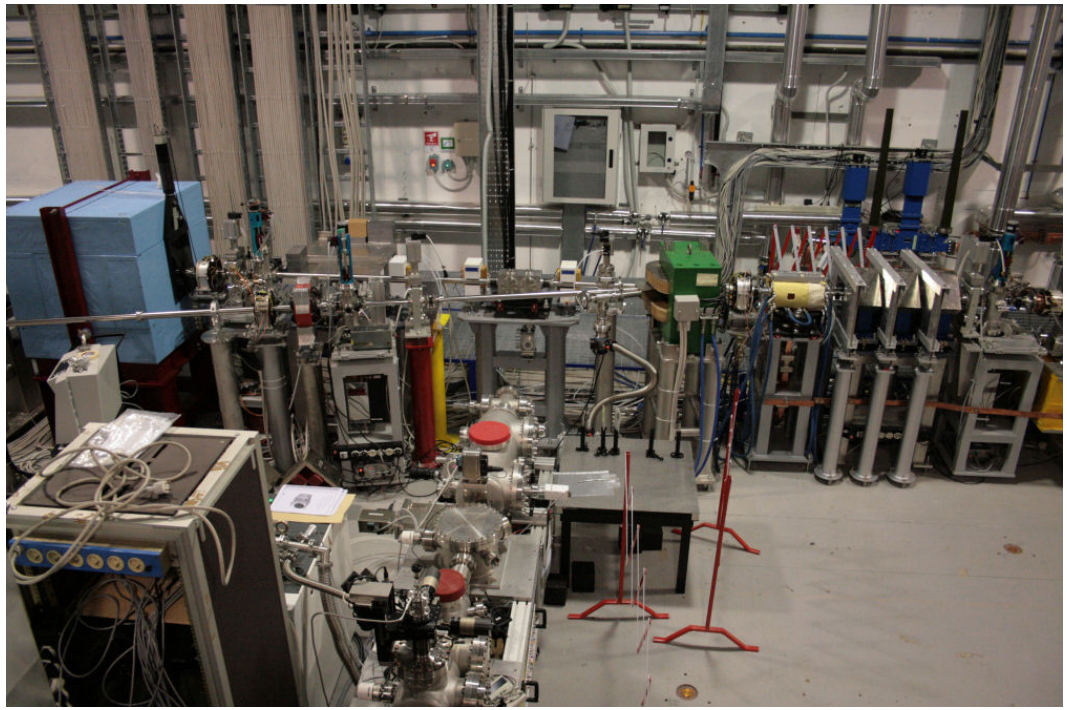
GUN PARAMETERS		LINAC PARAMETERS		FEL PARAMETERS	
Frequency	2856 MHz	Frequency	2856 MHz	Wavelength	530 nm
Peak Field	120 MV/m	Accelerating Field	25 MV/m	Undulator period	2.8 cm
Beam Energy	5.6 MeV	Beam Energy	155 MeV		
Charge	1 nC	Energy Spread	10^{-3}		
Emittance	< 2 mm-mrad	Peak Current	100 A		
Laser	10 ps (Flat Top with <2 ps rise time)				

SPARC

Andrea.Mostacci@uniroma1.it

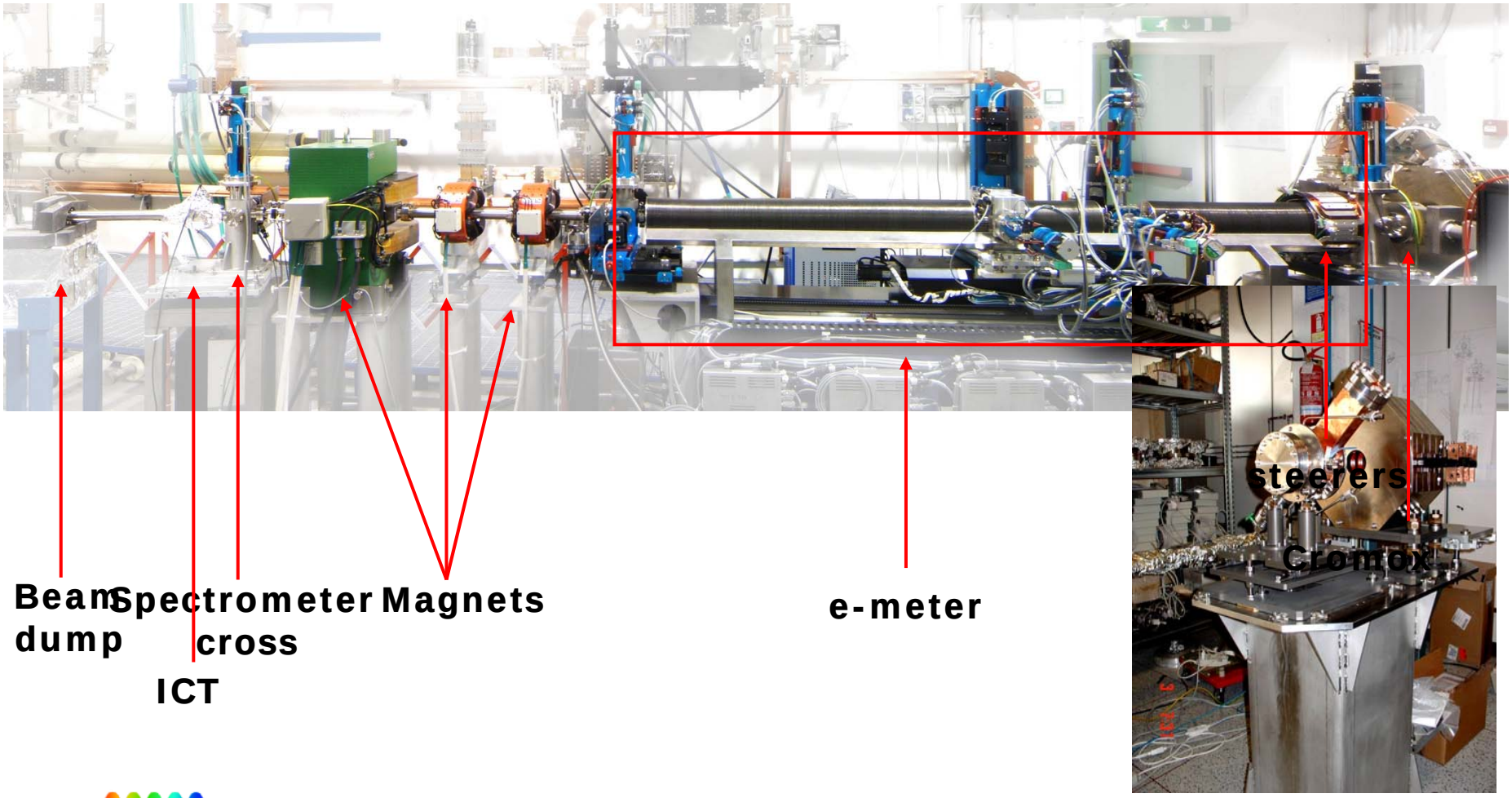
The SPARC(-Lab) facility today





Andrea.Mostacci@uniroma1.it

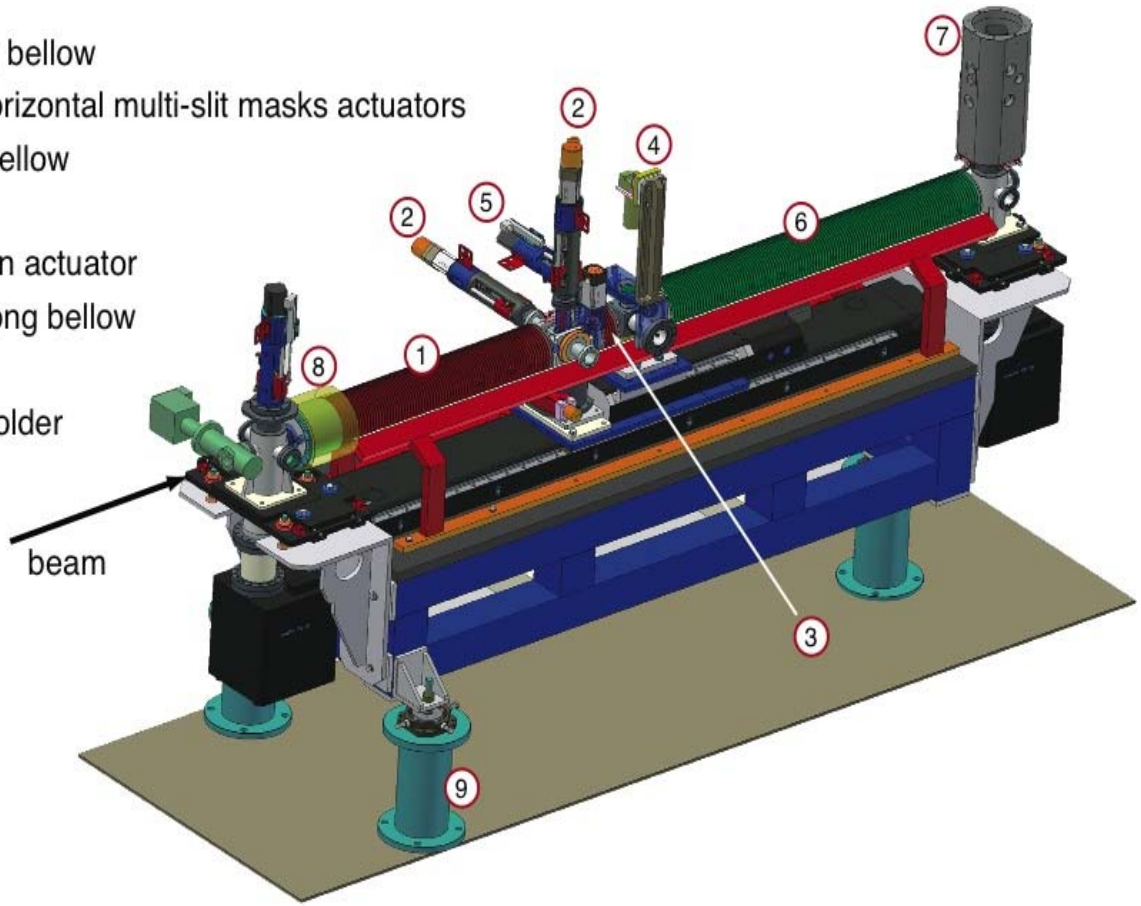
Emittance-meter relevant diagnostics

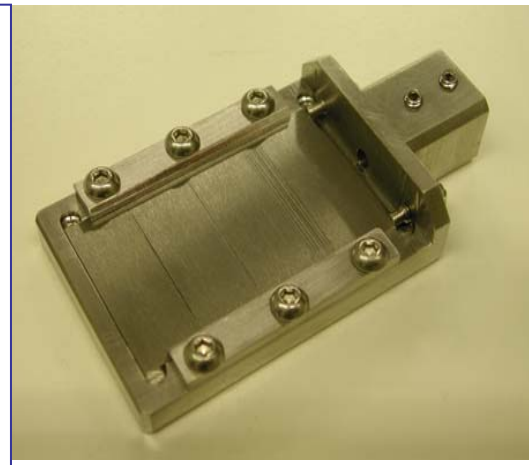


Andrea.Mostacci@uniroma1.it

E-meter specifications

1 - upstream long bellow
2 - vertical and horizontal multi-slit masks actuators
3 - intermediate bellow
4 - CCD camera
5 - Ce:YAG screen actuator
6 - downstream long bellow
7 - alignment tool
8 - steering coil holder
9 - leg extender





Slit width = 50 μm

8 bit CCD cameras

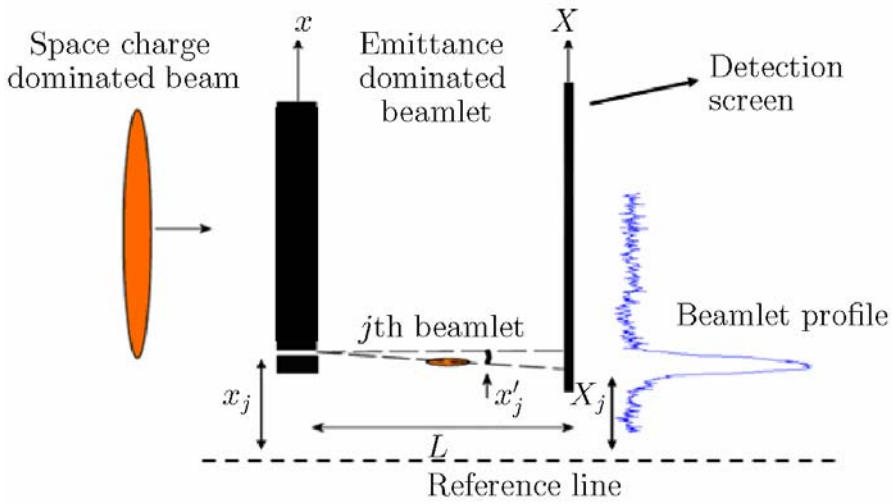
14.65 μm/pixel

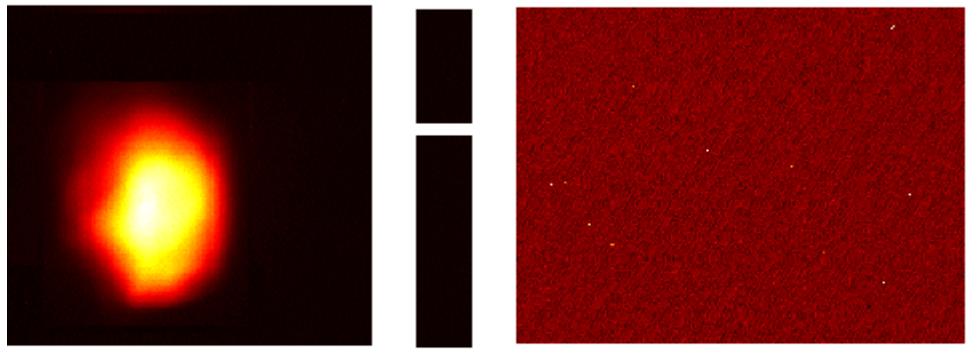
Emittance meter allows to measure emittance as a function of the position in the drift space after the gun.

Rev.Sci.Instr. Vol.77, Issue 8 - 2006

Andrea.Mostacci@uniroma1.it

Single moving slit measurement





± 3 σ of the beam transverse spot.

L=40 cm **13 positions**

$$\varepsilon^2 = \gamma^2 \left(\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2 \right) =$$

$$= \gamma^2 \left\{ \left[\sum_{j=1}^{N_b} \frac{A_j}{A_{tot}} \left(x_j - \langle x \rangle \right)^2 \right] \left[\sum_{j=1}^{N_b} \frac{A_j}{A_{tot}} \left[\sigma_j'^2 + \left(x'_j - \langle x' \rangle \right)^2 \right] \right] - \left[\sum_{j=1}^{N_b} \frac{A_j}{A_{tot}} x_j x'_j - \langle x \rangle \langle x' \rangle \right]^2 \right\}$$

$$x'_j = \frac{x_j - X_j}{L}$$ → **beamlet divergence**

$$A_{tot} = \sum_{j=1}^{N_b} A_j$$

$$A_j = \sum_{i=1}^{\mathcal{N}_j} I_{i,j}$$

$$X_j = K_{cal} \sum_{i=1}^{\mathcal{N}_j} \frac{I_{i,j}}{A_j} i$$

rms spread in divergence ←

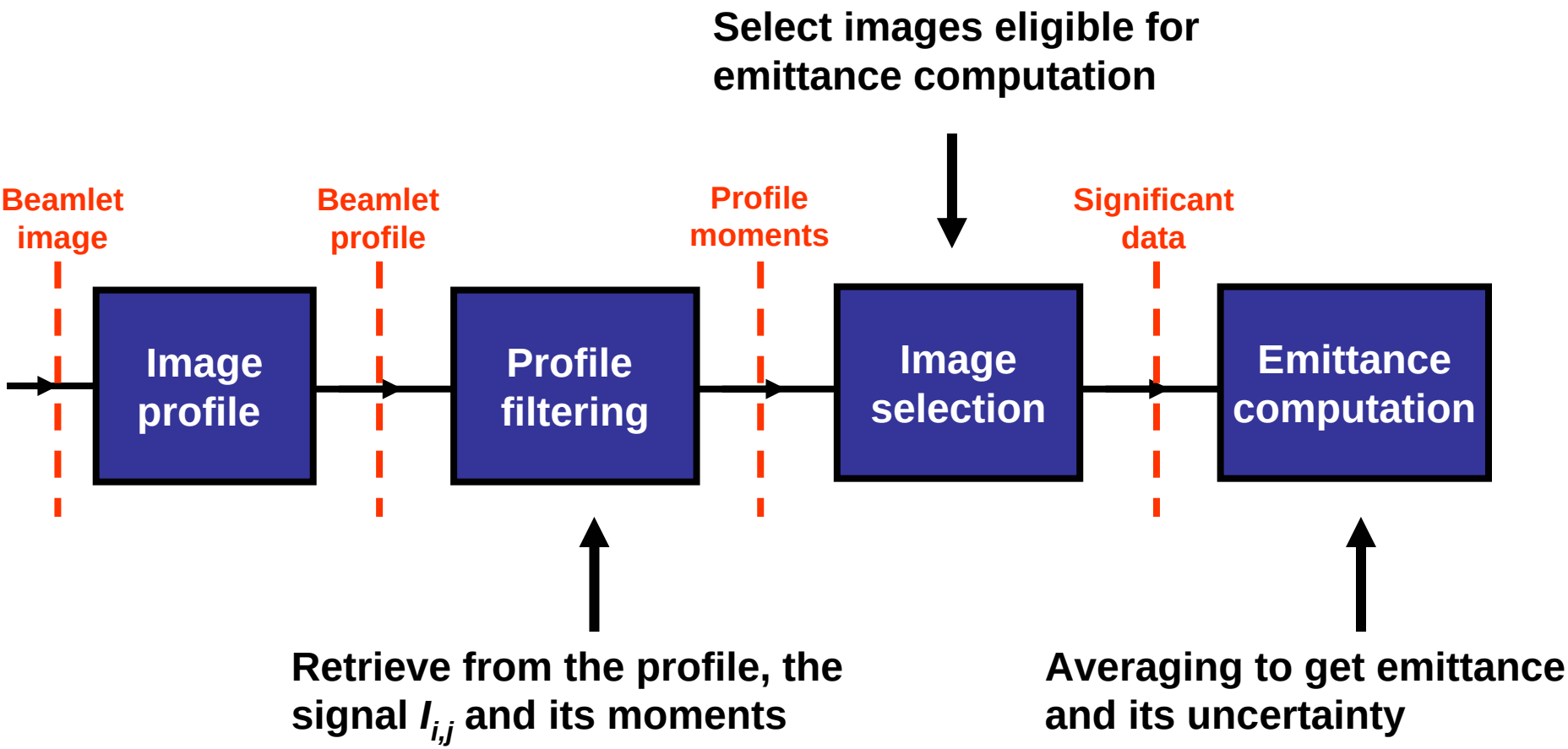
$$\sigma'_j = \frac{K_{cal}}{L} \sqrt{\sum_{i=1}^{\mathcal{N}_j} \frac{I_{i,j}}{A_j} \left(i - \frac{X_j}{K_{cal}} \right)^2}$$

SPARC

Andrea.Mostacci@uniroma1.it

Data analysis algorithm

Automatic procedure, used both in control room during data taking and and for the following data analysis.

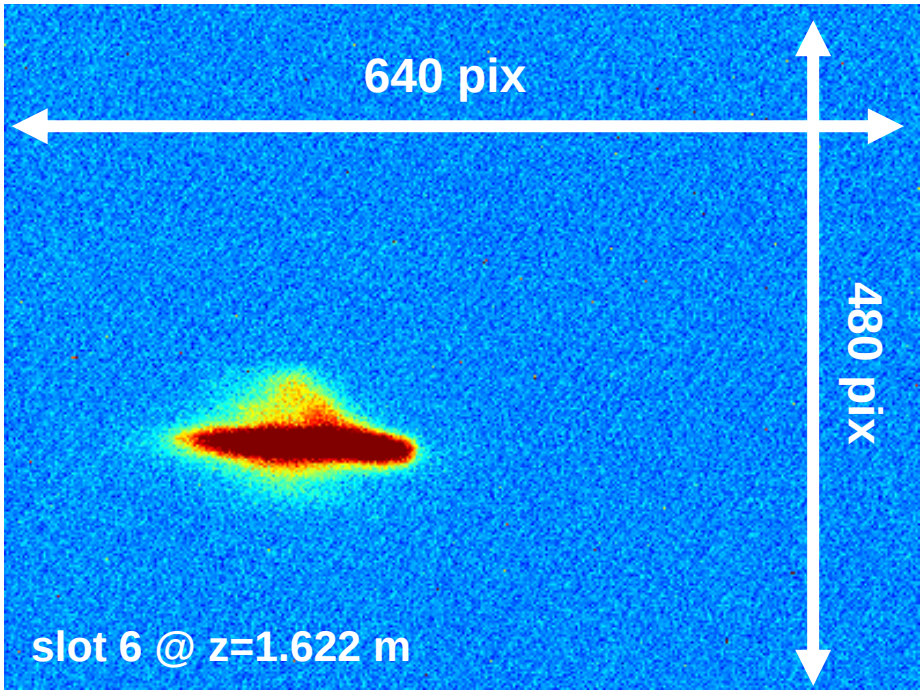


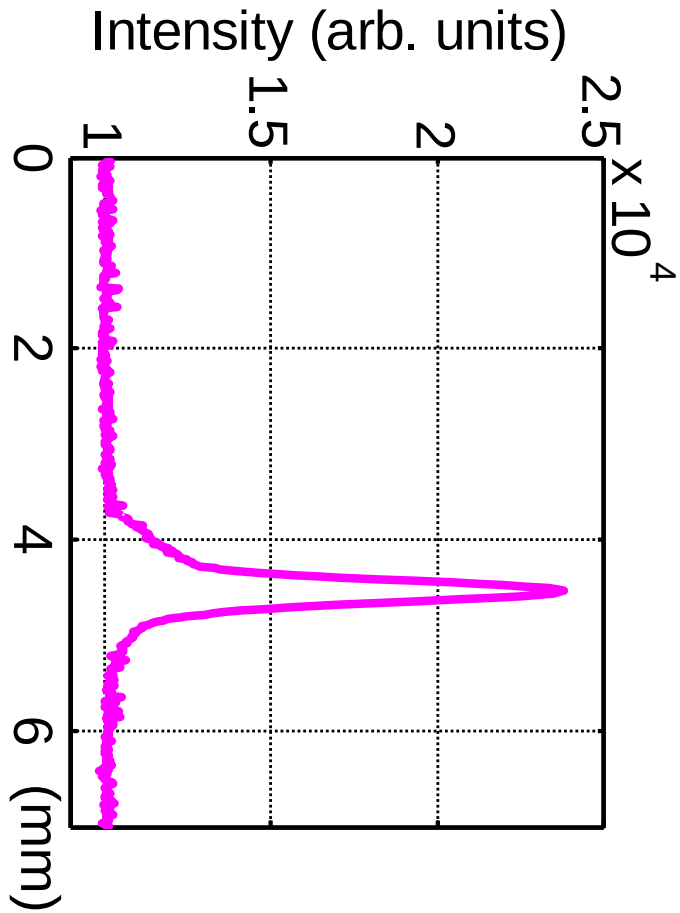
Rev.Sci.Instr. Vol.79, 2008

Andrea.Mostacci@uniroma1.it

From beamlet to profile

Typical beamlet profile:
beam signal over a baseline.





SPARC

Baseline: constant, 1e4 Intensity arb. units

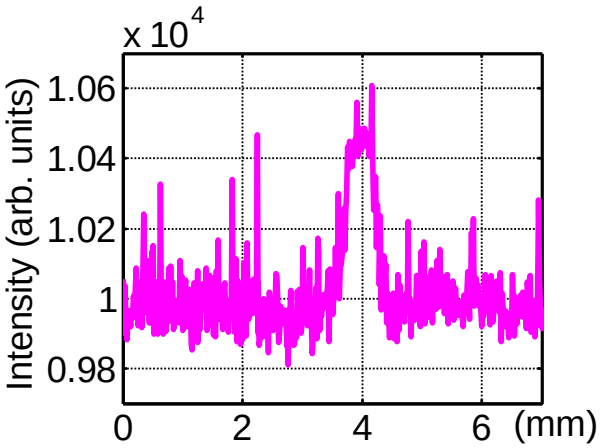
σ'_j **< 1 mrad**

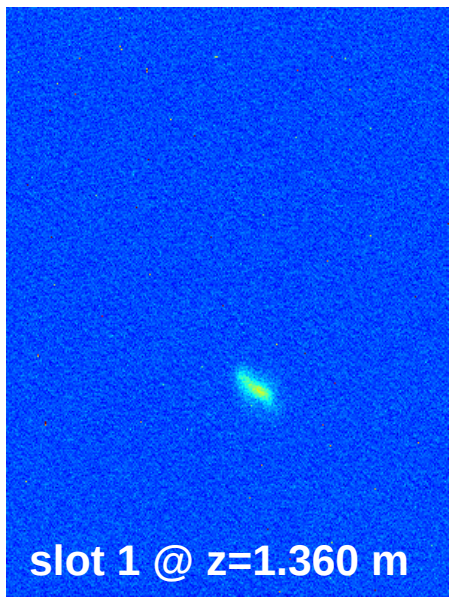
SNR: 2.5 - 30

Andrea.Mostacci@uniroma1.it

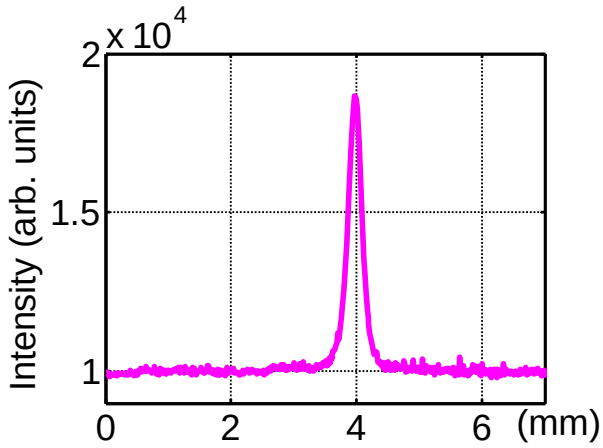
Typical beamlet profiles

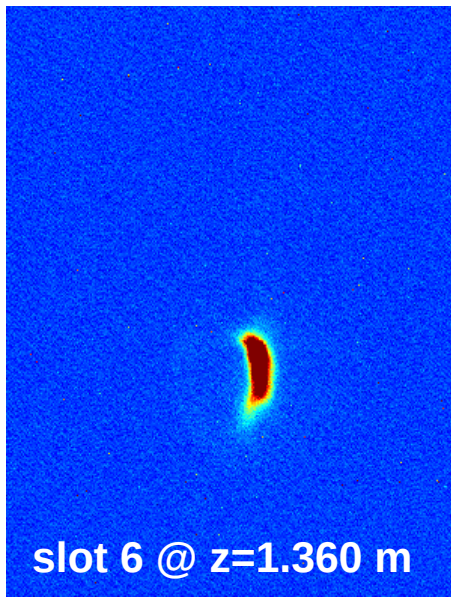
Lateral slit



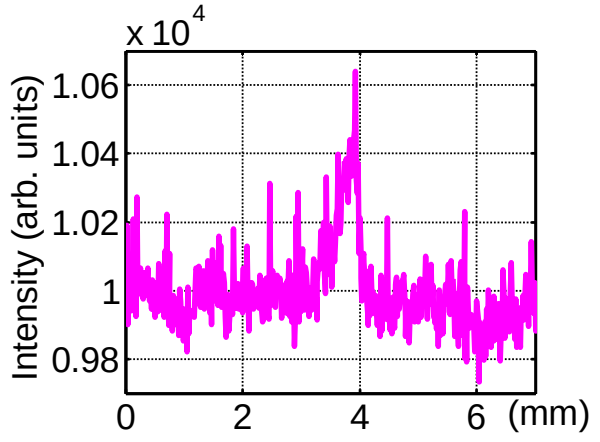


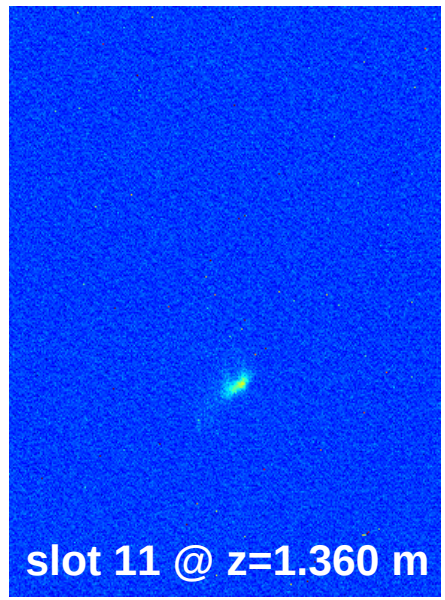
Central slit





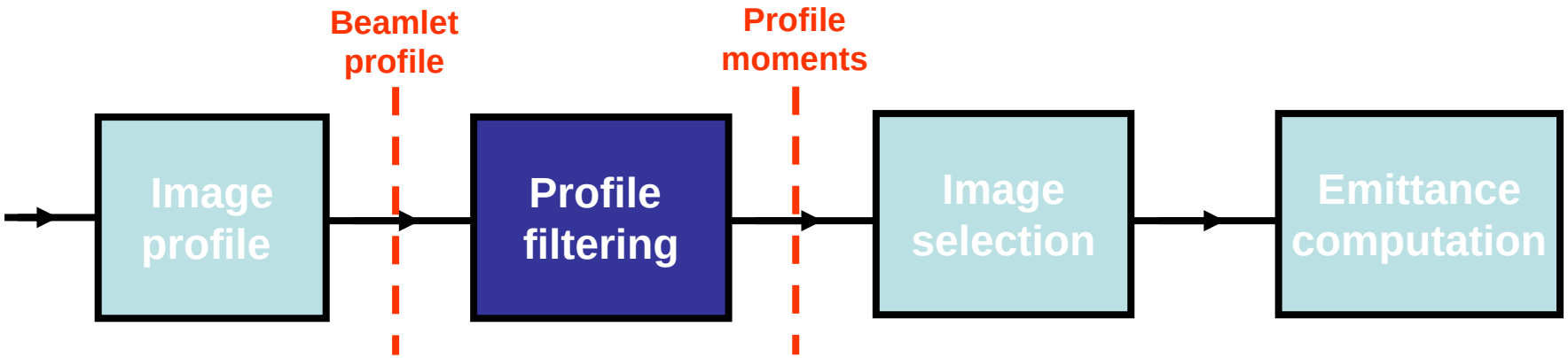
Lateral slit

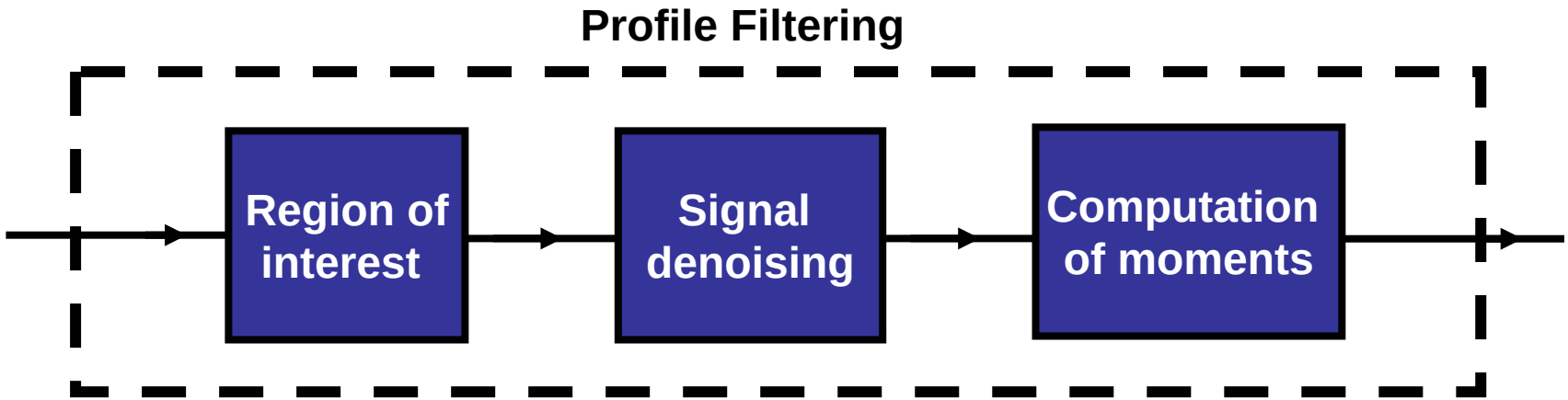




Andrea.Mostacci@uniroma1.it

Profile filtering





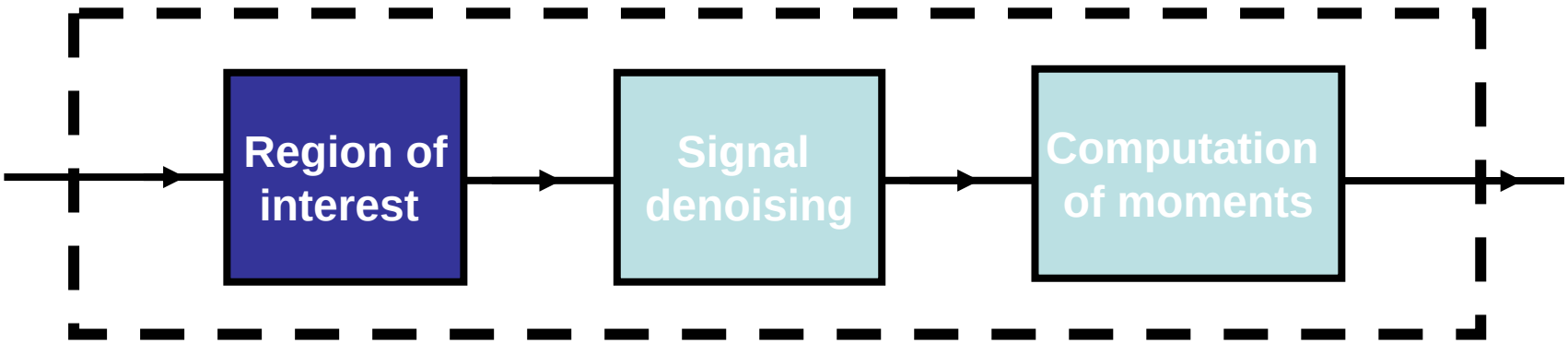
Andrea.Mostacci@uniroma1.it

Profile filtering: Region Of Interest

To select the profile ROI the signal is fitted with a Gaussian function of area A, mean m, rms value σ and base line h.

Initial parameters are calculated from the smoothed profile (moving average).

To calculate the initial values for base line h and rms width σ, an initial window corresponding to a width that would have a signal with angles spread 4 times bigger than our maximum value, centered around the maximum is taken; the base line is calculated averaging all the pixel out of window, while the initial rms value will be that of the signal inside the window.



Profile Filtering

Andrea.Mostacci@uniroma1.it

Profile filtering: Region Of Interest

To select the profile ROI the signal is fitted with a Gaussian function of area A, mean m, rms value σ and base line h.

Initial parameters are calculated from the smoothed profile (moving average).

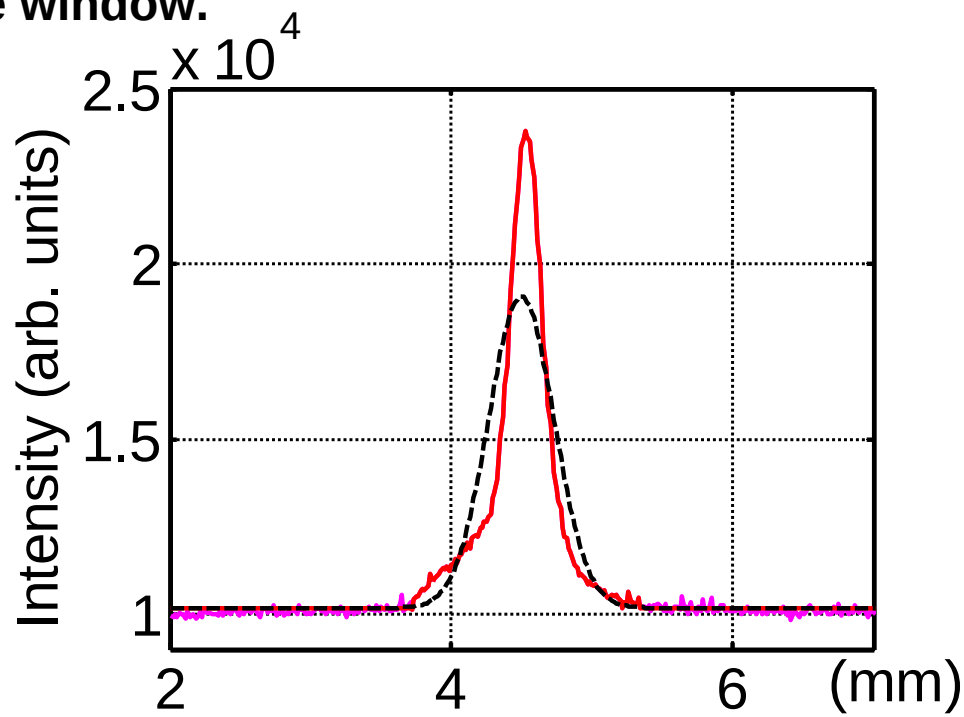
To calculate the initial values for base line h and rms width σ, an initial window corresponding to a width that would have a signal with angles spread 4 times bigger than our maximum value, centered around the maximum is taken; the base line is calculated averaging all the pixel out of window, while the initial rms value will be that of the signal inside the window.

Region Of Interest:
±5σ around the mean m

Violet line: original signal

Red line: selected signal

Black line: Gaussian fit

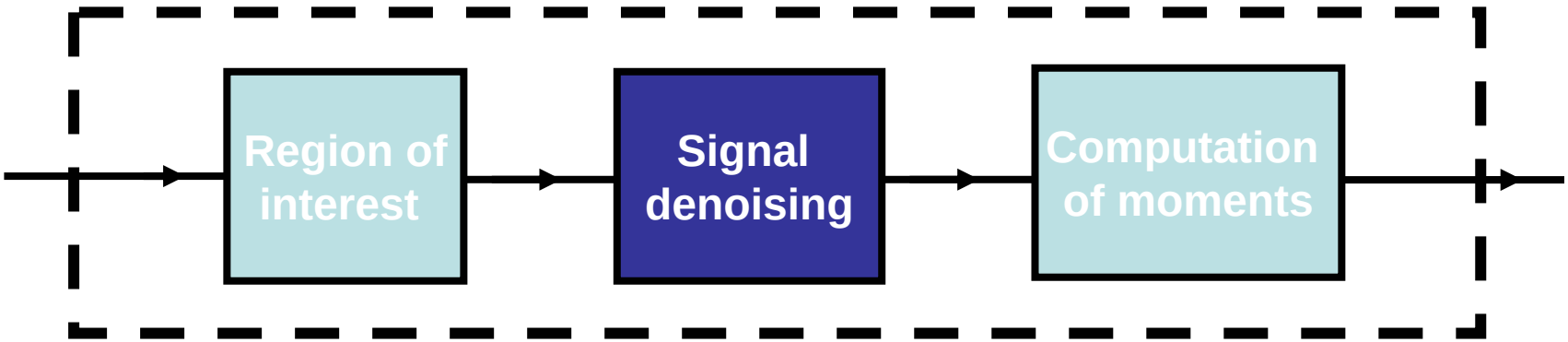


Profile filtering: signal denoising

The moments of the actual beamlet charge distribution are different from the parameters of the Gaussian fit used before for the ROI computation.

We consider the signal inside the ROI after the baseline subtraction.

Iterative procedure that computes profile centroid m and rms width σ, then shrinks the region of interest up to ±3σ around m and eventually recomputing the same parameters again. The procedure stops when new values match the previous iteration ones and it converges typically after 4-5 iterations.



Profile Filtering

SPARC

More details: D. Filippetto, SPARC-EBD-07-002

Andrea.Mostacci@uniroma1.it

Profile filtering: signal denoising

The moments of the actual beamlet charge distribution are different from the parameters of the Gaussian fit used before for the ROI computation.

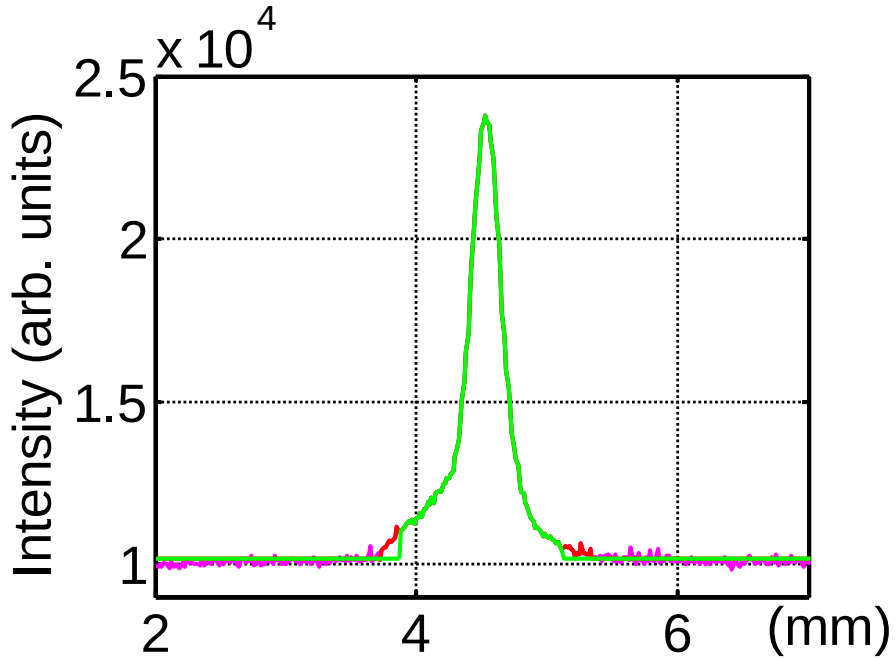
We consider the signal inside the ROI after the baseline subtraction.

Iterative procedure that computes profile centroid m and rms width σ, then shrinks the region of interest up to ±3σ around m and eventually recomputing the same parameters again. The procedure stops when new values match the previous iteration ones and it converges typically after 4-5 iterations.

Violet line: original signal

Red line: selected signal

Green line: filtered signal



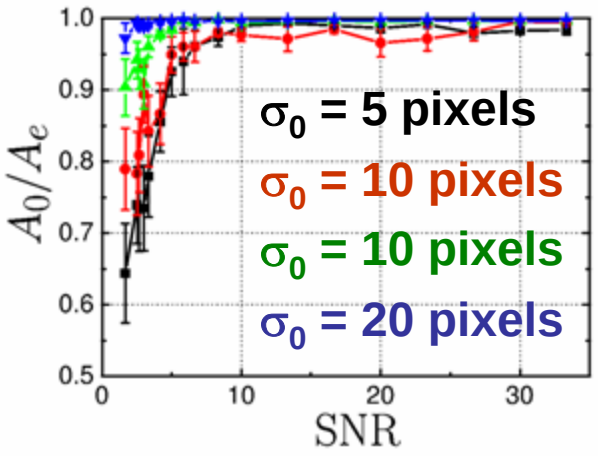
SPARC

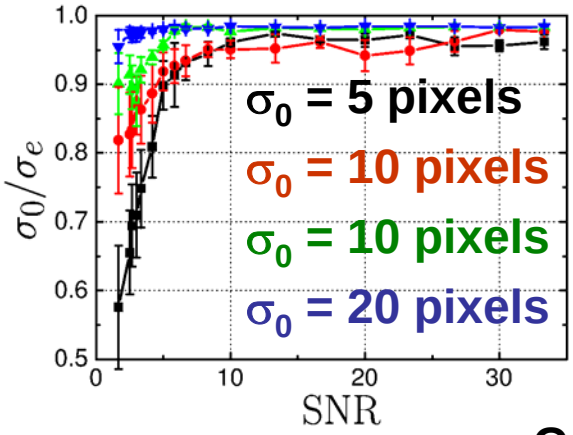
More details: D. Filippetto, SPARC-EBD-07-002

Andrea.Mostacci@uniroma1.it

Profile filtering validation

Lateral slits





Central slits

Averaging over 50 noisy Gaussian signals (error bars st. dev. of the average)

A_0, σ_0 Original signal parameters

A_e, σ_e recostructed signal parameters

A_0/ A_e differs from unity because of the fraction of the beamlet left out from reconstruction which decreases with increasing of SNR.

The precision (error bars) increases with σ_0.

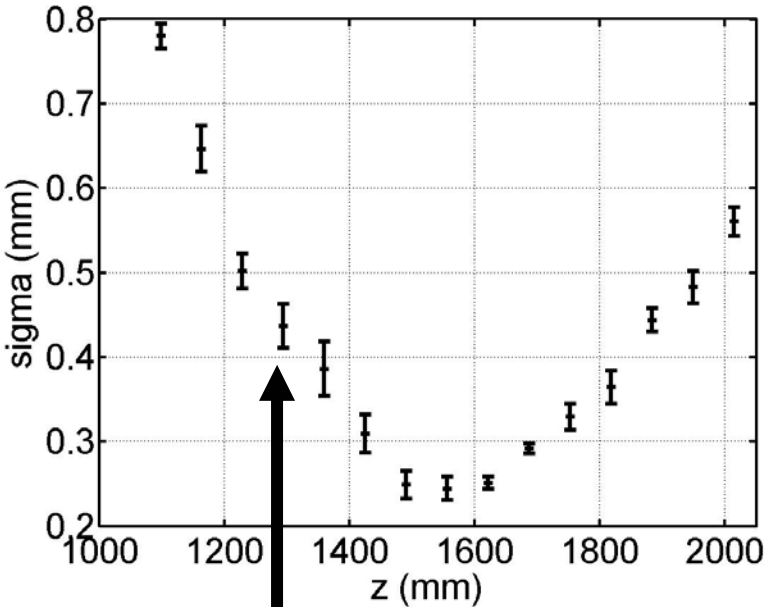
Noise affects the tails of the signal and σ_0/ σ_e is more sensible to it.

Additional error correction needed for lateral slits (low SNR).

More details: D. Filippetto, SPARC-EBD-07-002

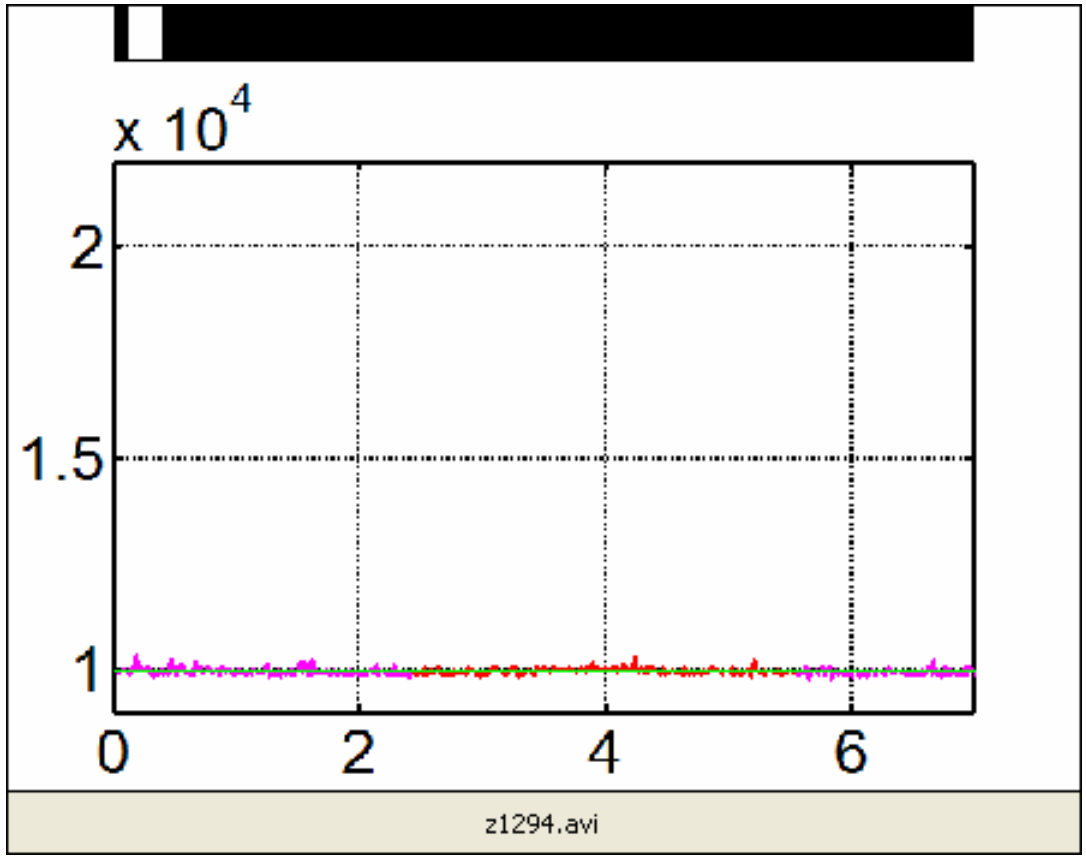
Andrea.Mostacci@uniroma1.it

Converging beam



Last slit

First slit



Violet line: original signal

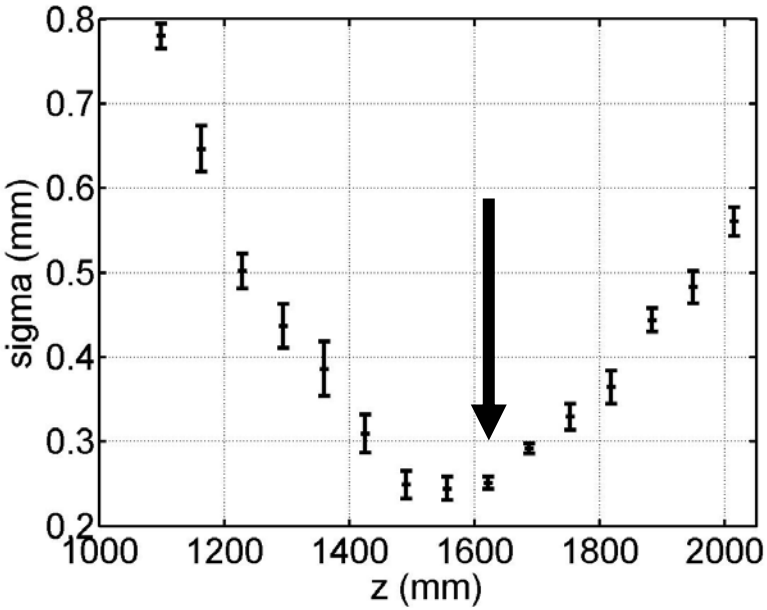
Red line: selected signal

Green line: filtered signal

SPARC

Andrea.Mostacci@uniroma1.it

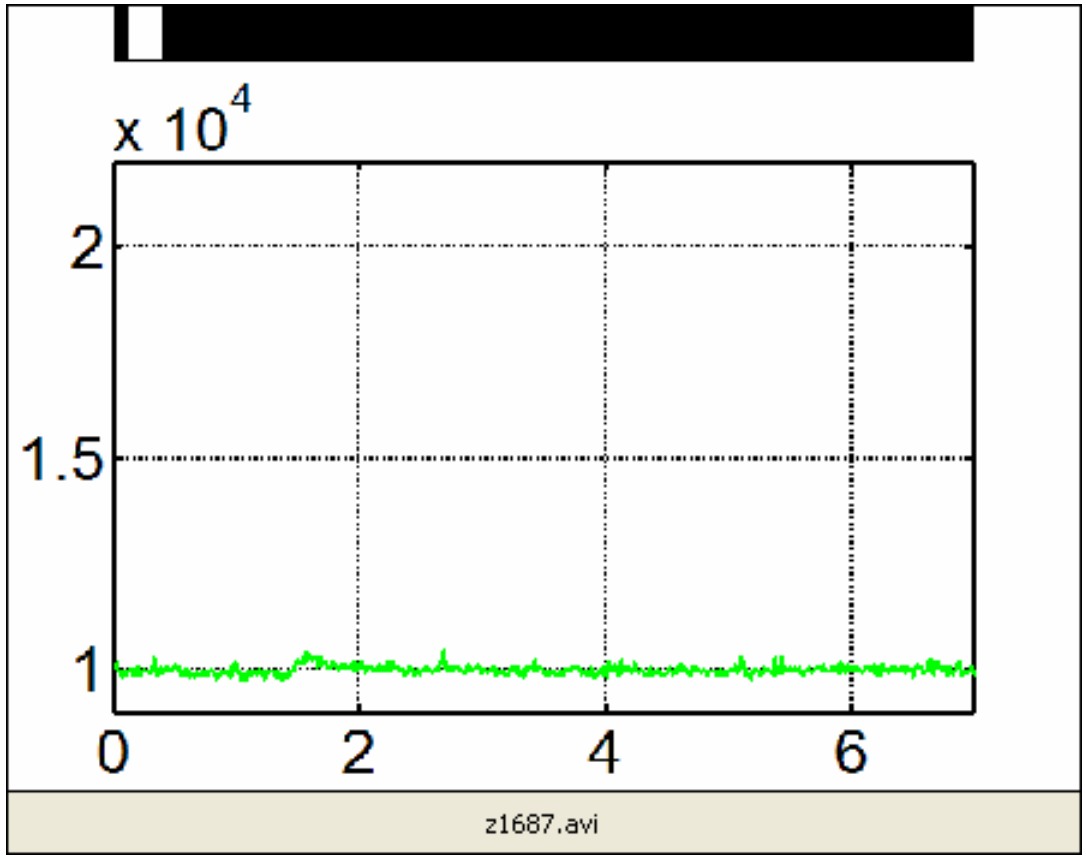
Diverging beam



Diverging beam: bigger centroids swing

Last slit

First slit



Violet line: original signal

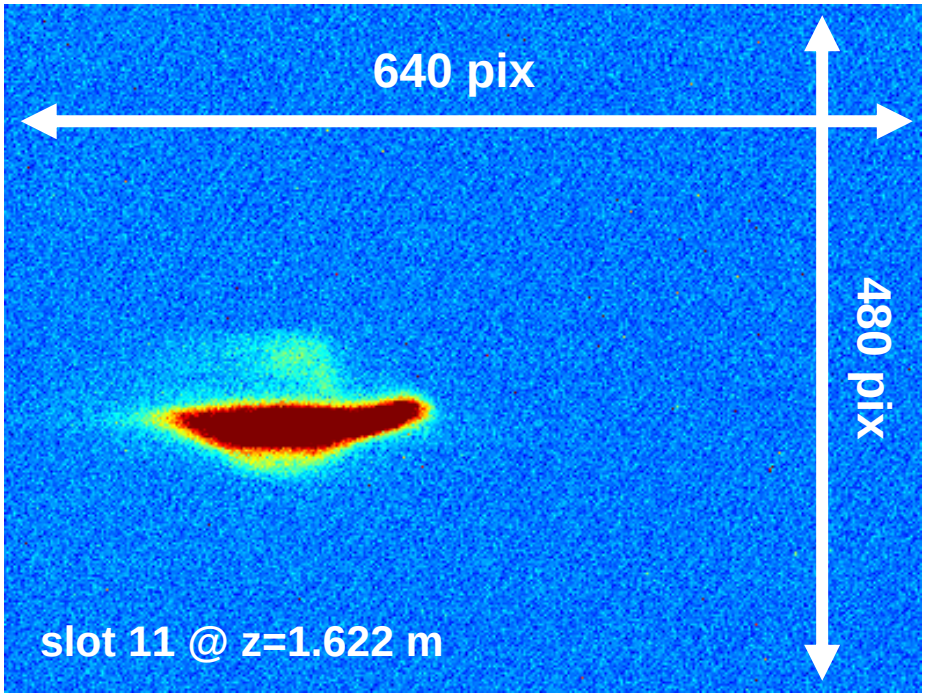
Red line: selected signal

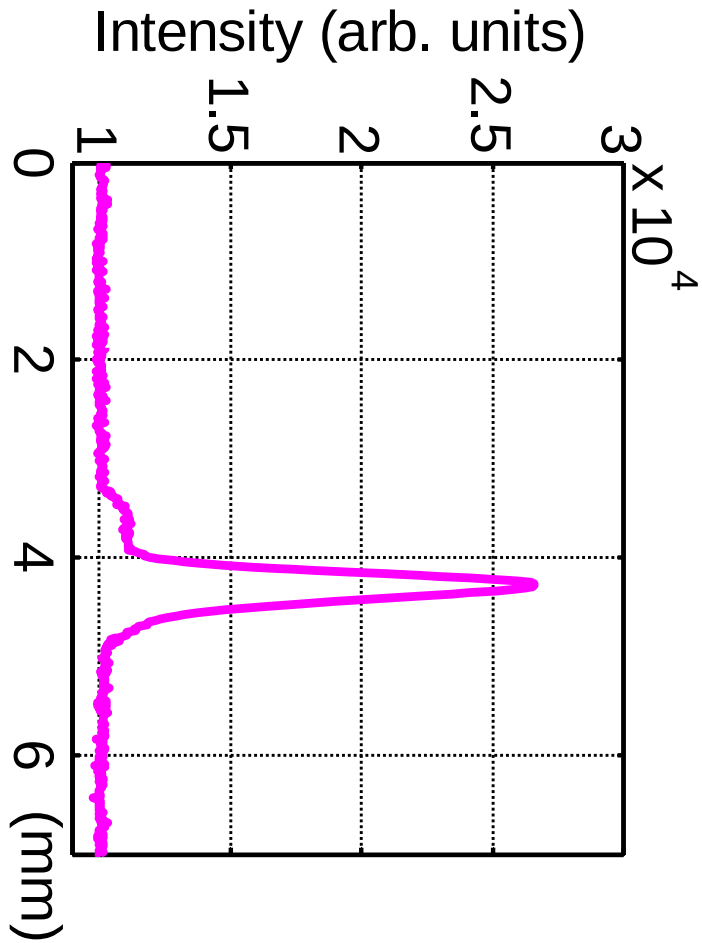
Green line: filtered signal

SPARC

Andrea.Mostacci@uniroma1.it

Profile filtering critical case

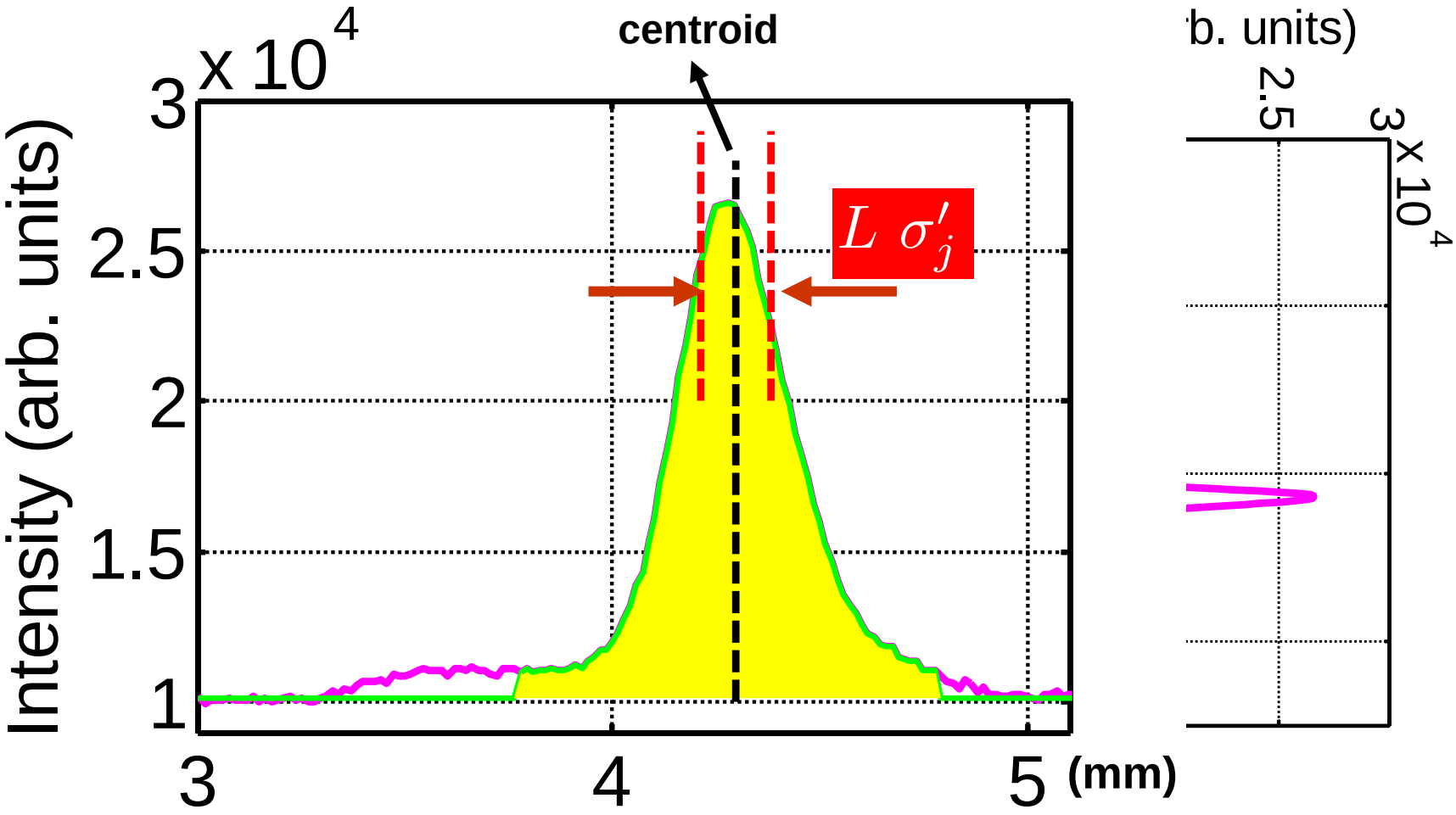




“Two” signals with one much bigger than the other.

Andrea.Mostacci@uniroma1.it

Profile filtering critical case



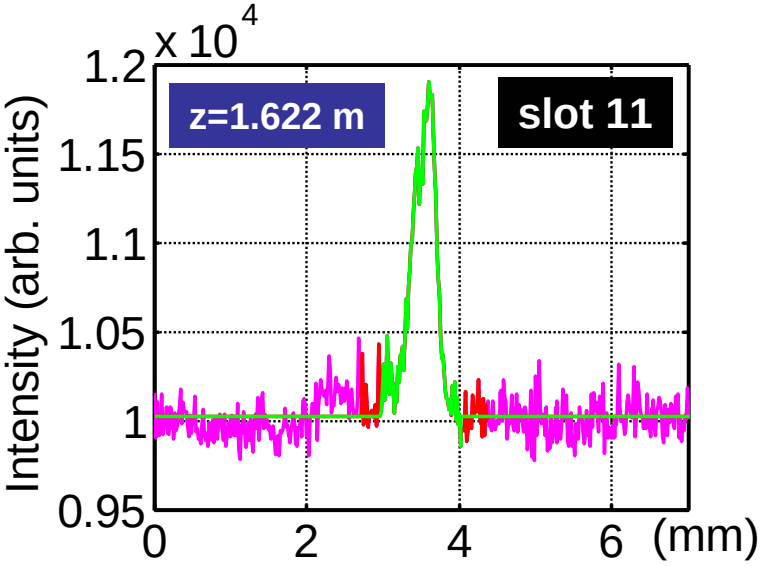
$$\frac{\text{Signal Charge} - \text{Approx. Charge}}{\text{Signal Charge}} < 6\%$$

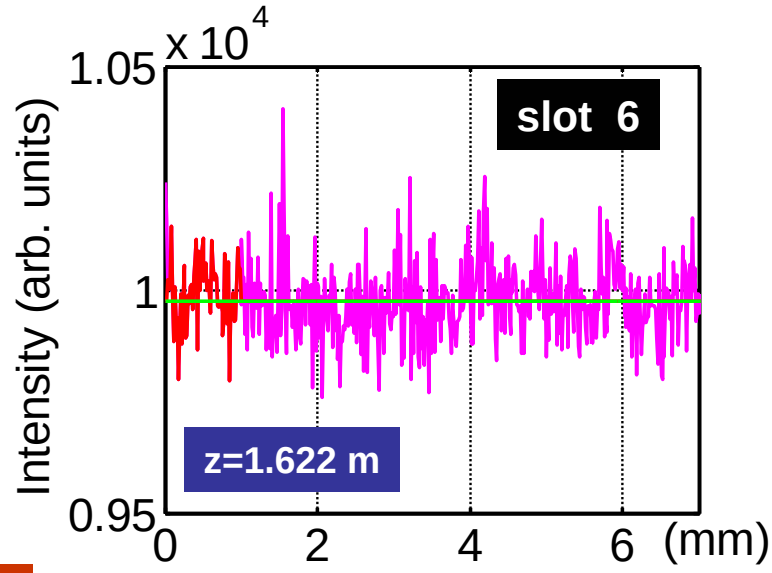
"Variable" charge cut

SPARC

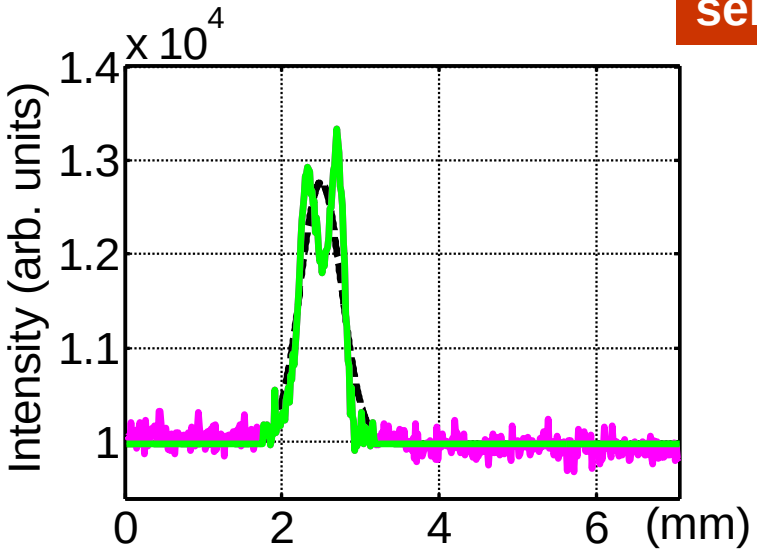
Andrea.Mostacci@uniroma1.it

Profile filtering: other examples





Need of an image selection criteria



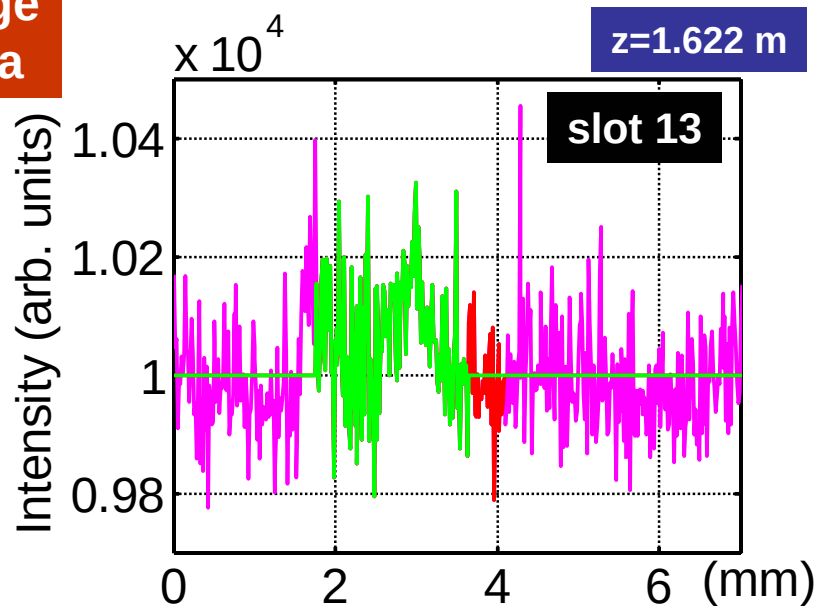
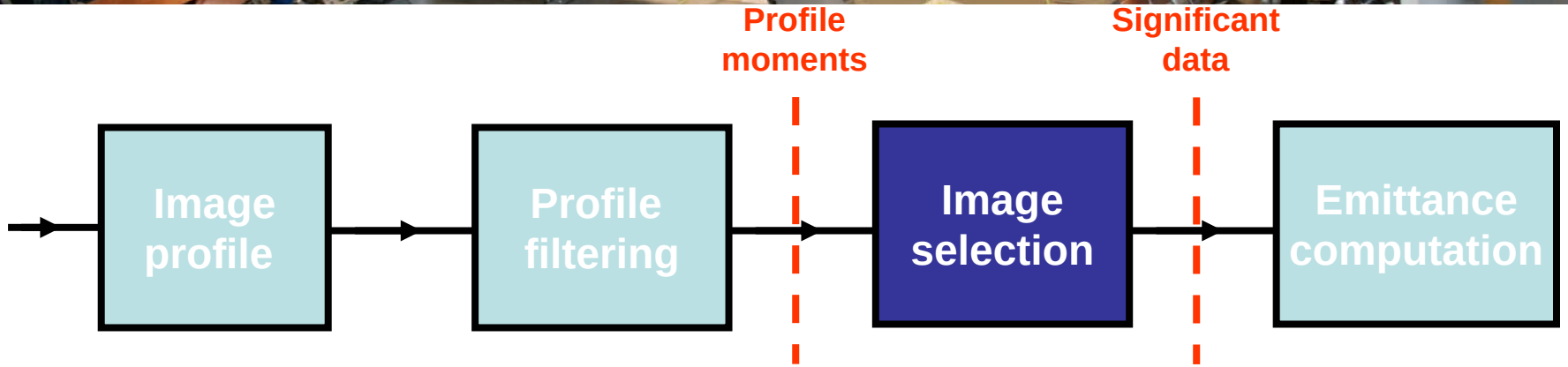


Image selection criteria



Comparison of images from the same slit

Consistency check on each image

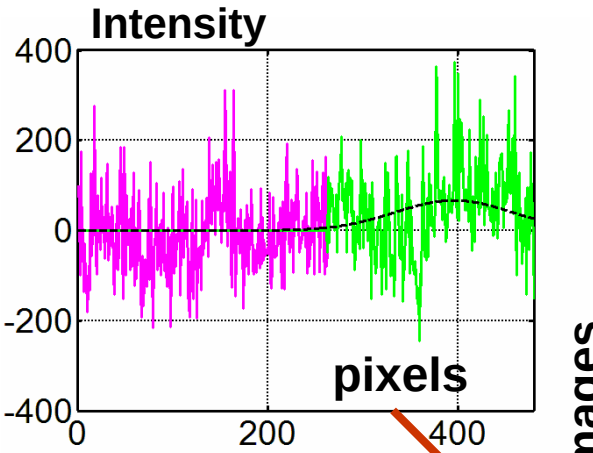
Comparison of images from different slit

Andrea.Mostacci@uniroma1.it

Single image correction

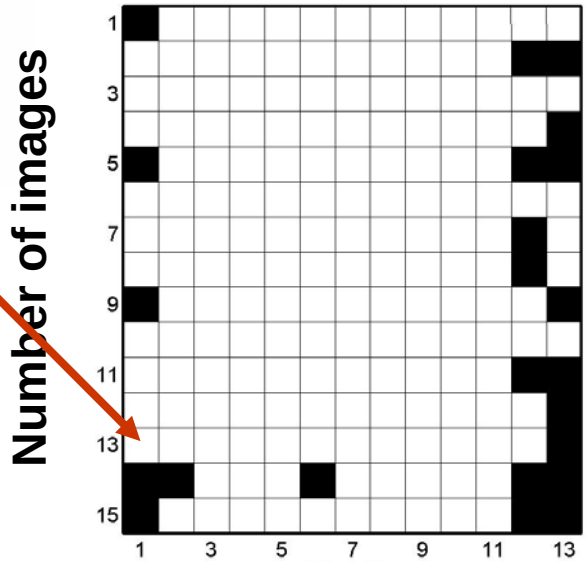
The program may fit noise resulting in beamlet divergence bigger and/or area is smaller than typical values.

Thresholds on the maximum spread in divergence and on the minimum signal area.

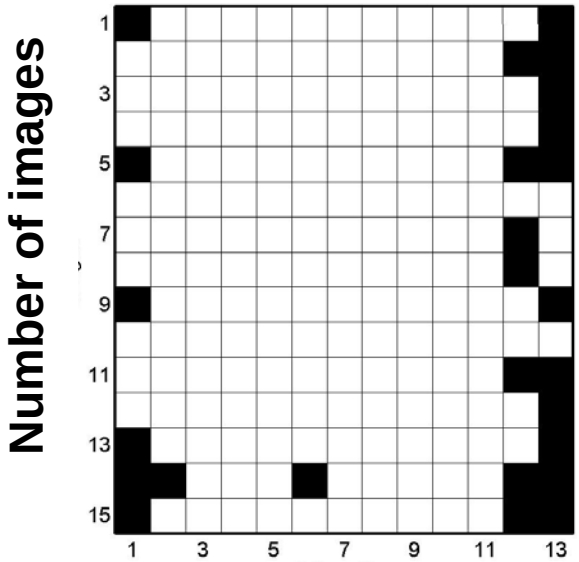


Measurement footprint

before the correction



after the correction



SPARC

Andrea.Mostacci@uniroma1.it

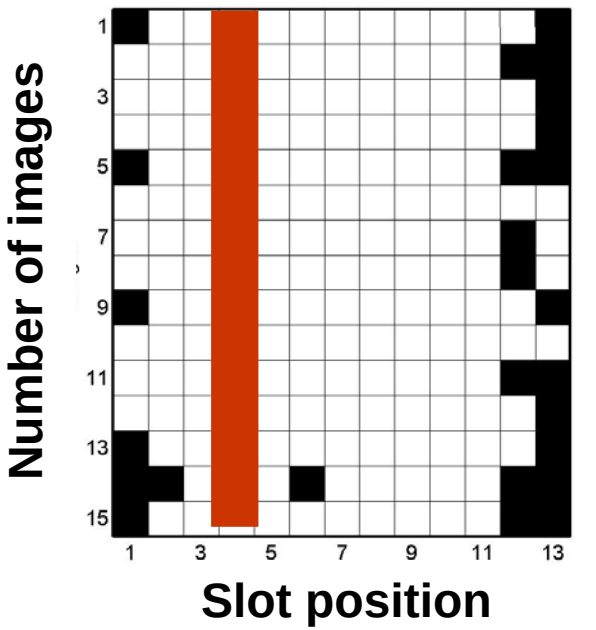
Image selection: average correction

Discard systematically bad data, at the price of loosing some good one.

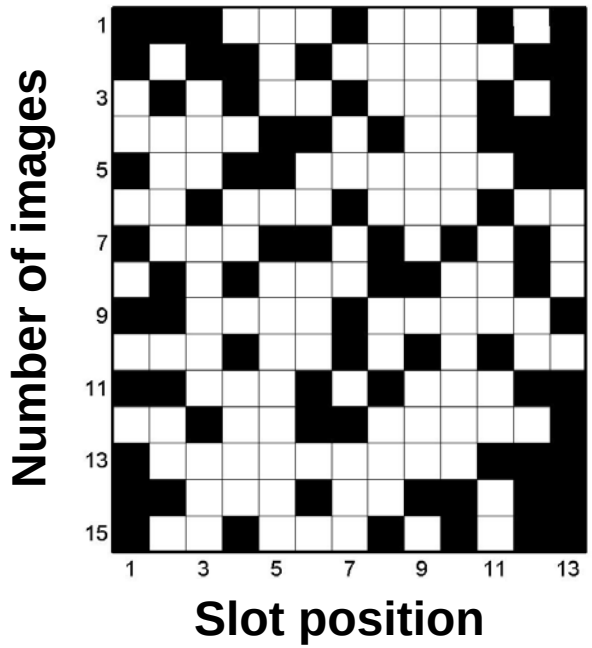
Average and standard deviation s_d on the slit values (area, centroid and beamlet spread) are computed. If a value is outside ± 1.5 s_d the profile is discarded.

If the average area is too small (below a threshold), all the slot is thrown.

before the correction



after the correction

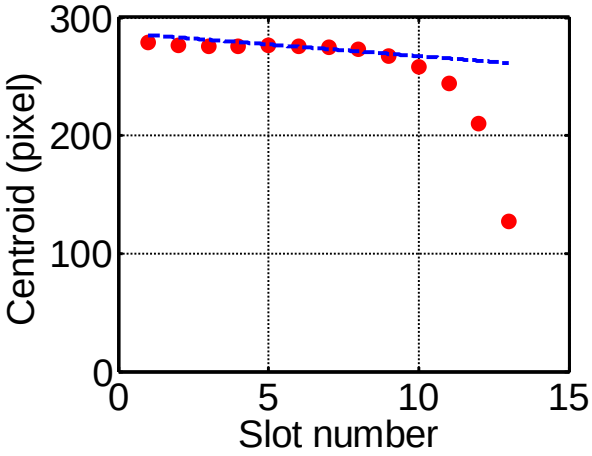


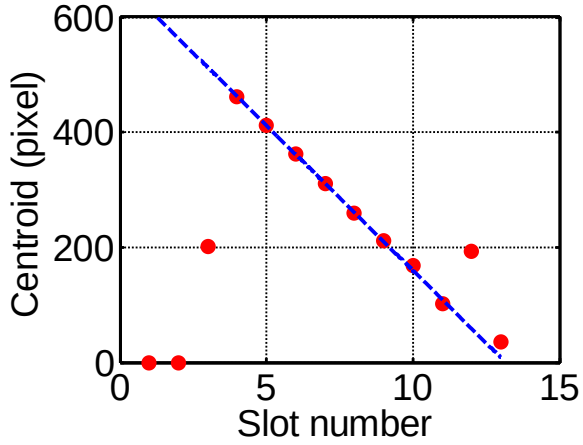
Extensive sensitivity study to check/revise those criteria.

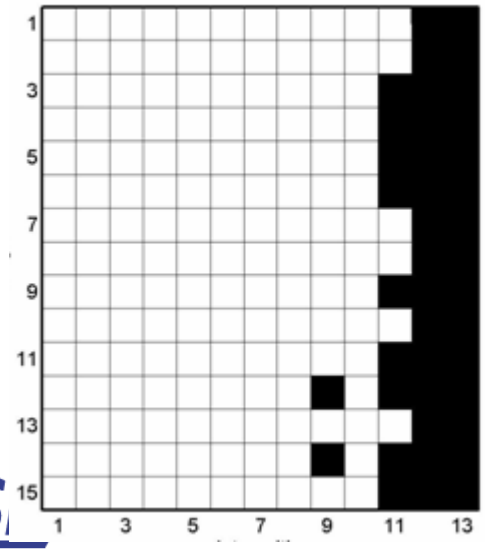
Andrea.Mostacci@uniroma1.it

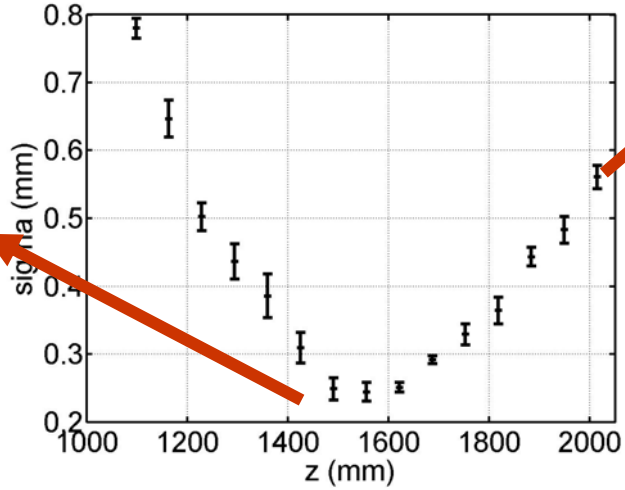
Image selection: lateral slit

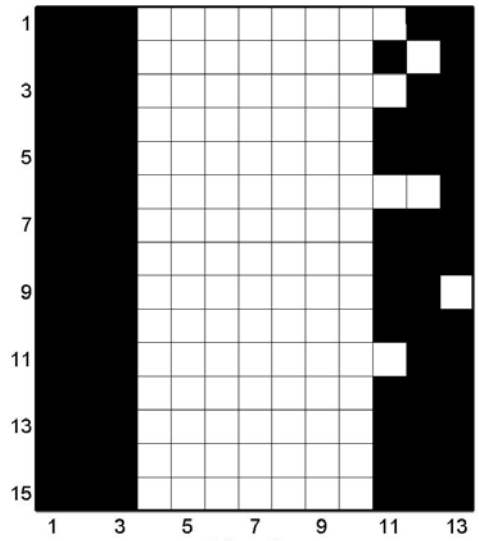
Lateral slit is tagged as wrong if their average centroid value is too different from the one predicted by the linear interpolation of the central slit centroids.



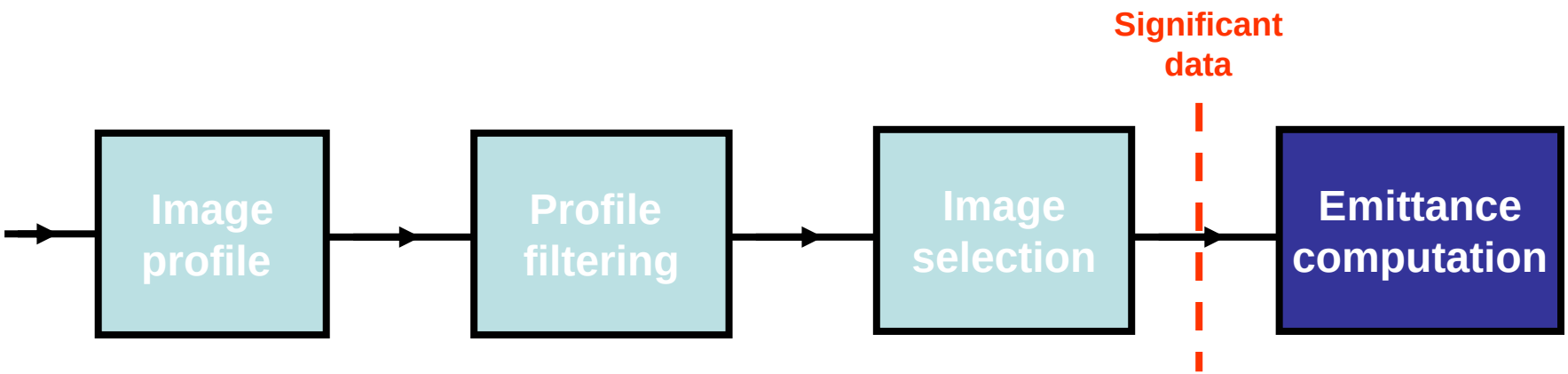






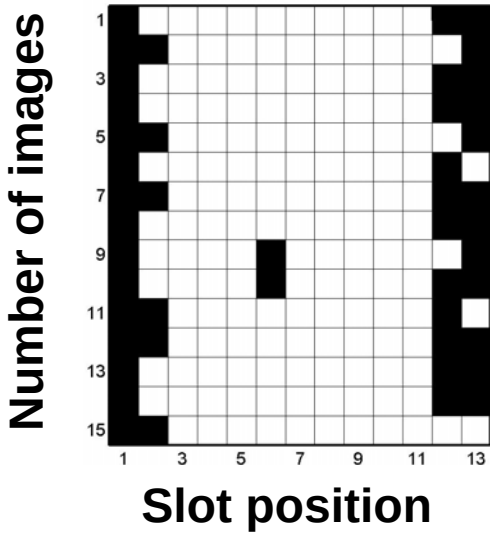


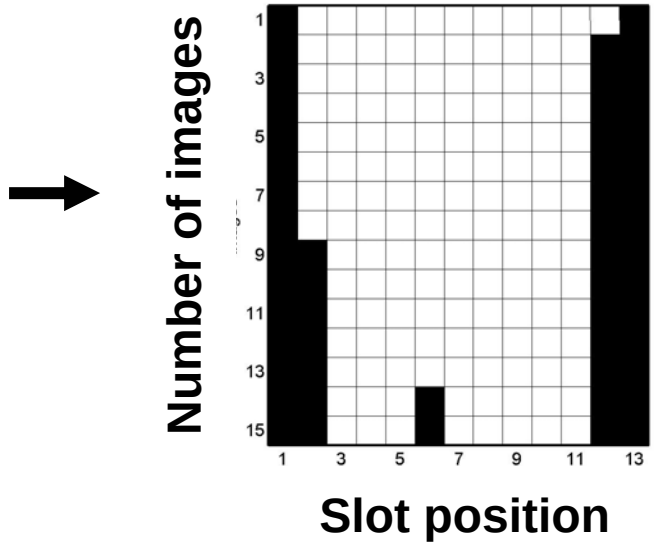
Emittance computation



Andrea.Mostacci@uniroma1.it

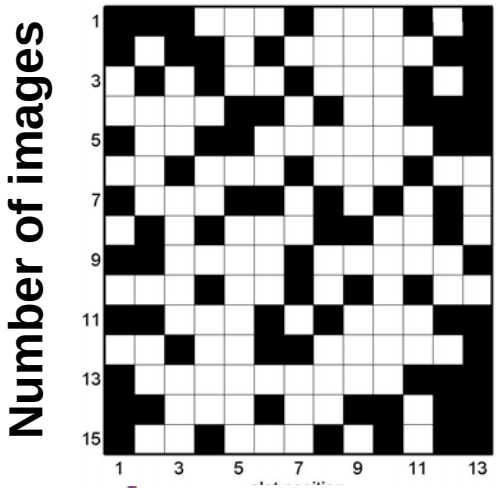
Data shuffling

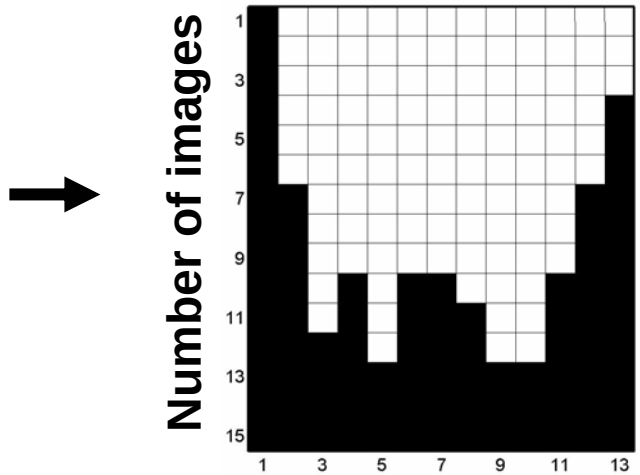




Each square is a different beam

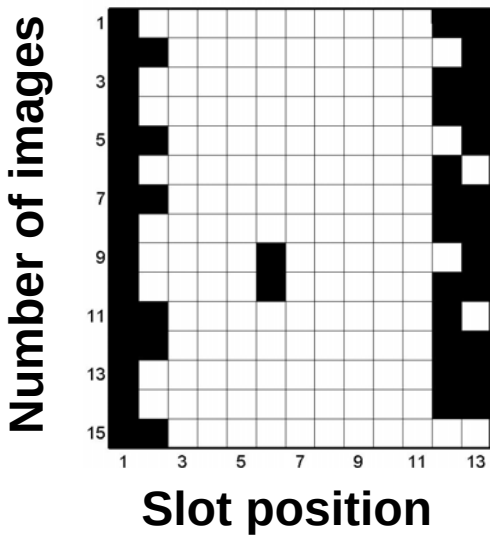
Each square is equivalent to the ones on the same column.

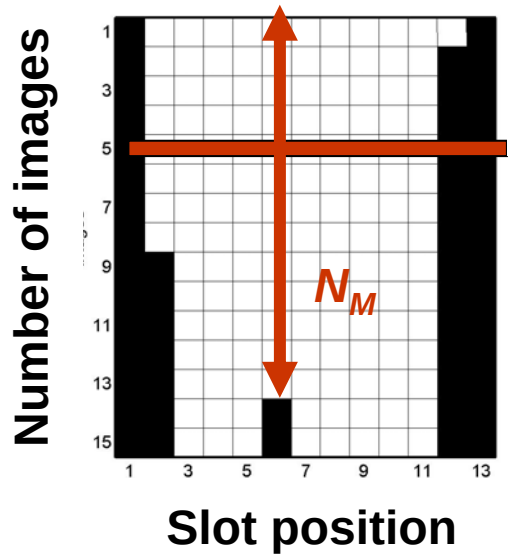




Andrea.Mostacci@uniroma1.it

Measurement uncertainty

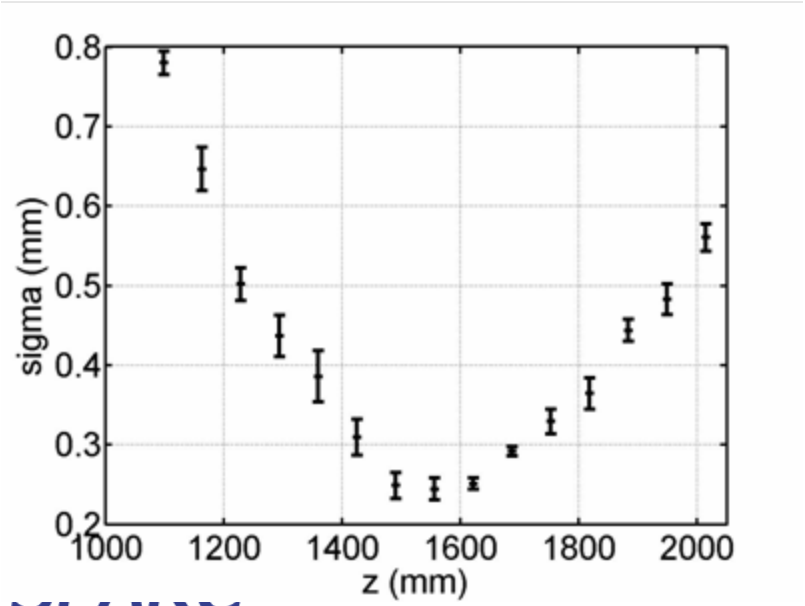


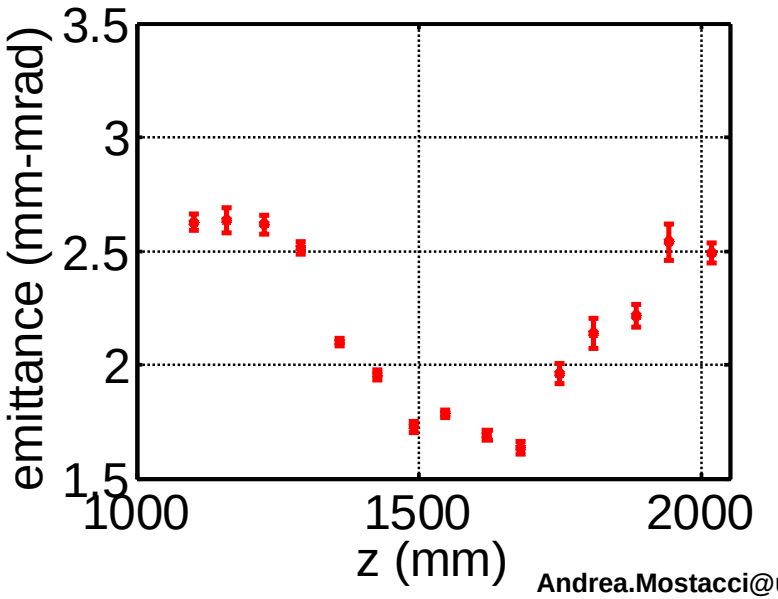


ε_k

$$\overline{\varepsilon} = \frac{\sum_{k=1}^{N_M} \varepsilon_k}{N}$$

$$u(\varepsilon) = \sqrt{\sum_{k=1}^{N_M} \frac{(\varepsilon_k - \overline{\varepsilon})^2}{N_M (N_M - 1)}} = \frac{\sigma}{\sqrt{N_M}}$$





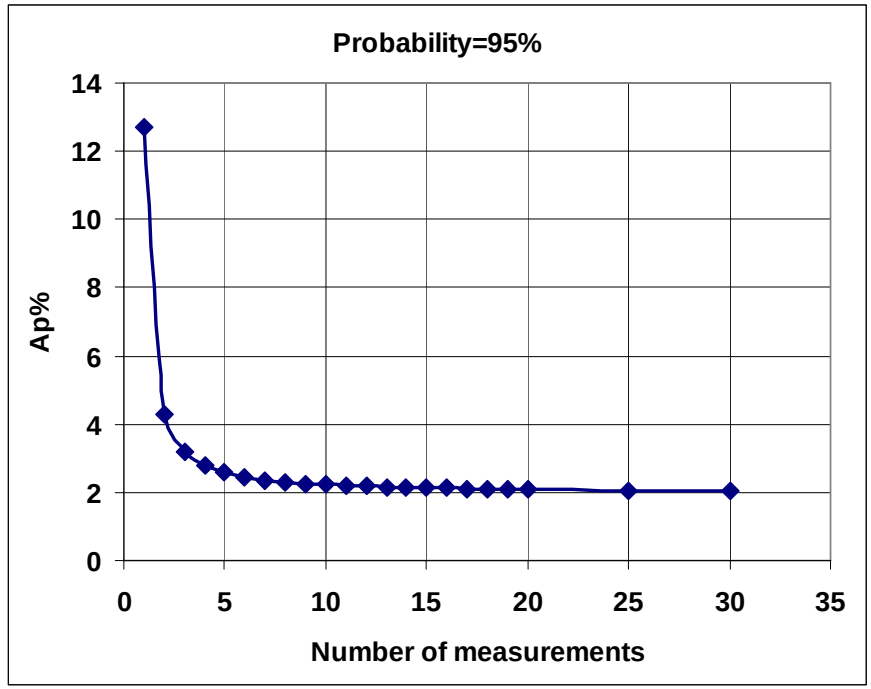
Andrea.Mostacci@uniroma1.it

Confidence level

In comparison between measurements and/or simulations the error bar on experimental data are equal to the statistical error multiplied by a factor depending on the confidence level (95%) that gives a measure of the goodness of the comparison.

$$\varepsilon = \bar{\varepsilon} + A_{P\%} \frac{\sigma}{\sqrt{N}}$$

***N*=number of measurements**
σ=standard deviation
***AP%* = a factor given by the t-distribution corresponding to a defined *P%* probability**

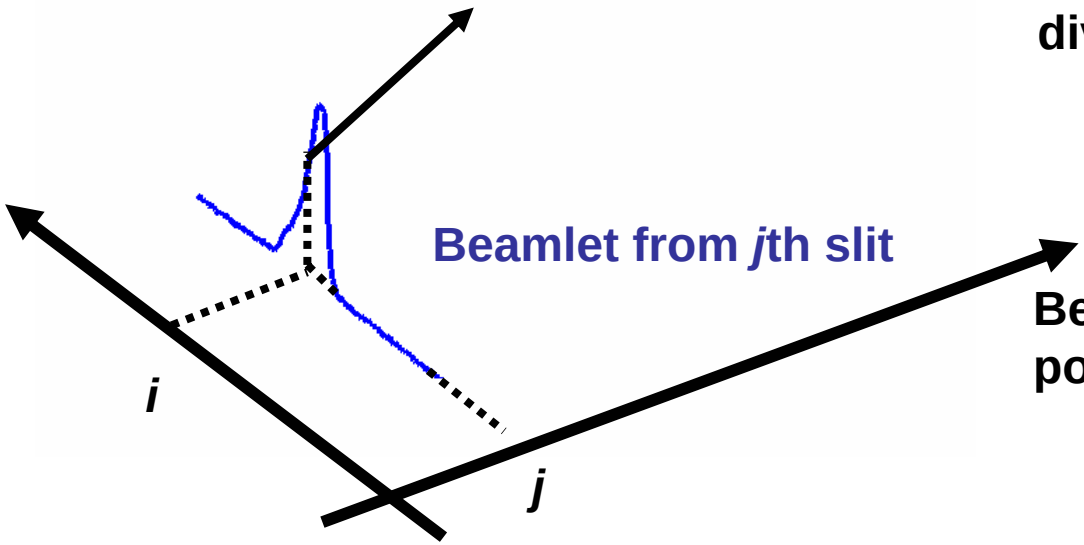


- ***Assumption:* the set of observations follow a normal distribution**

Andrea.Mostacci@uniroma1.it

Trace space reconstruction (I)

Graphical reconstruction of the phase space to retrieve emittance and Twiss parameters and permit better insight on beam dynamics.



position $x_j = jw$

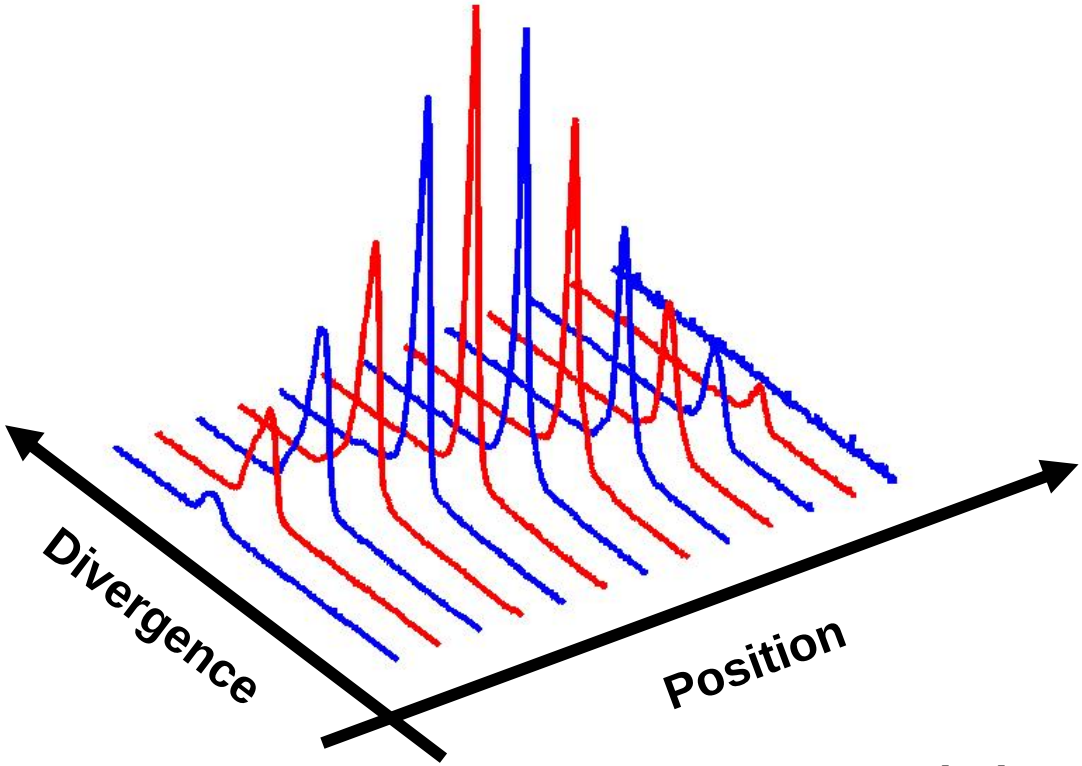
divergence $(K_{cal} i - jw)/L$

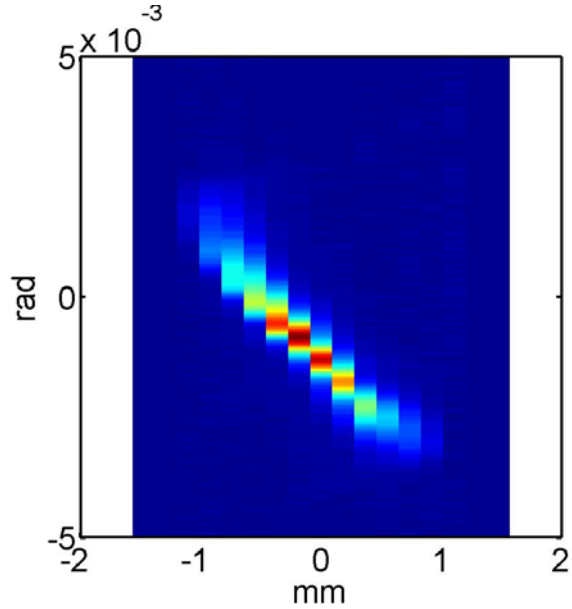
To combine the trace space in a data matrix, one needs to shift the vector $\overline{I_{i,j}}$ changing the index $i \rightarrow i - jw/K_{cal}$ (the divergence unit being K_{cal}/L) and use it as the jth of N_b columns (filling with zeros the missing data).

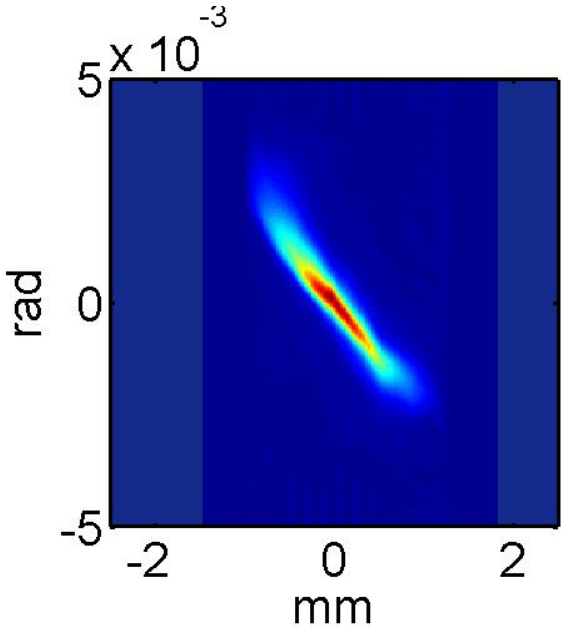
Andrea.Mostacci@uniroma1.it

Trace space reconstruction (II)

z=1.294 m



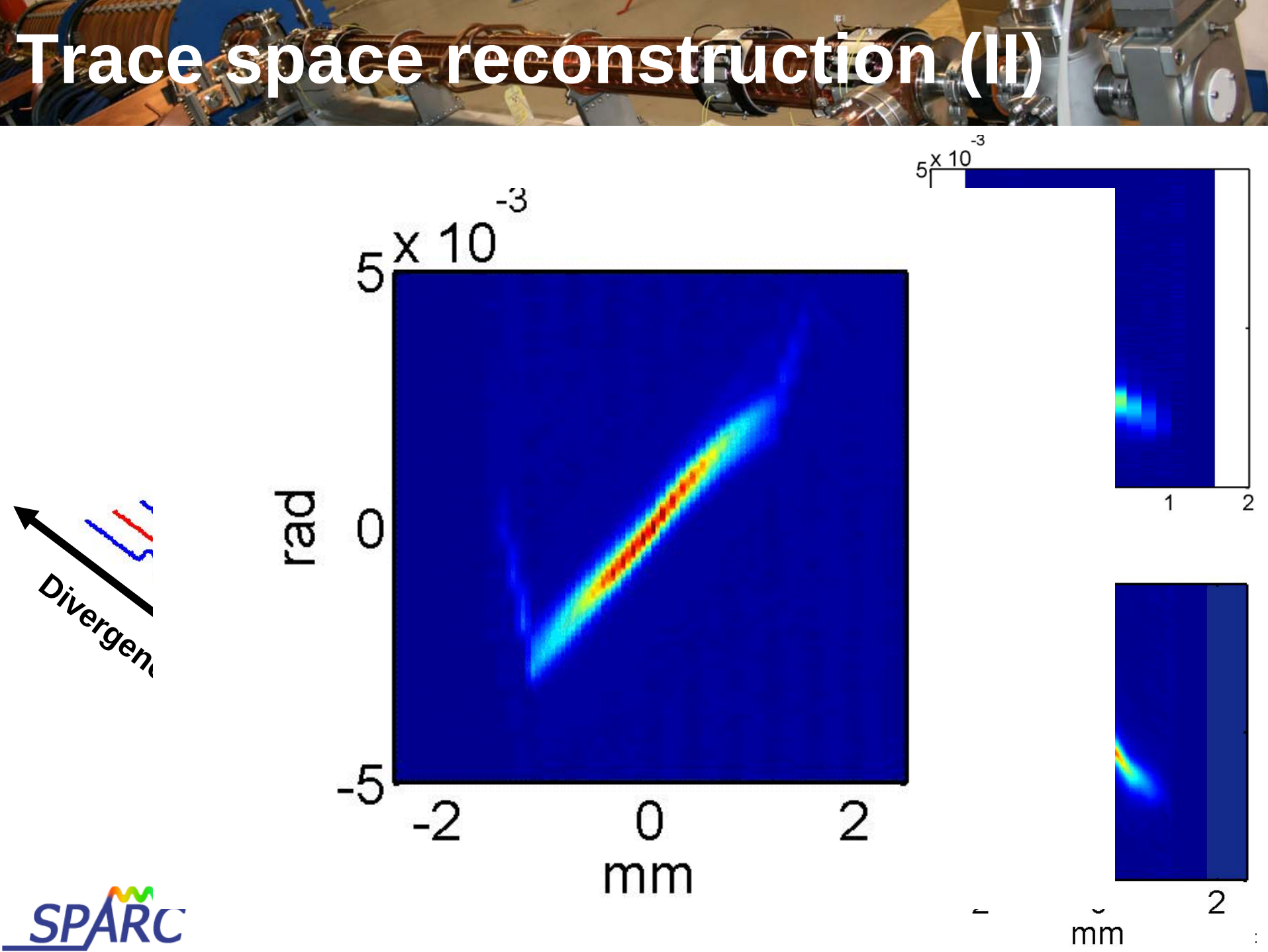




Interpolation along the trace space axis.

SPARC

Trace space reconstruction (II)



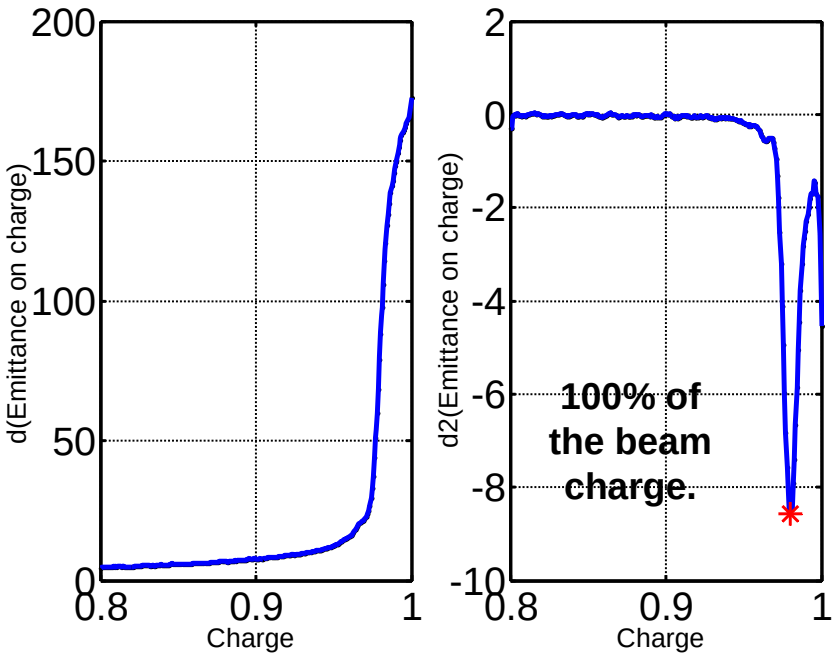
Evaluation of the charge cut

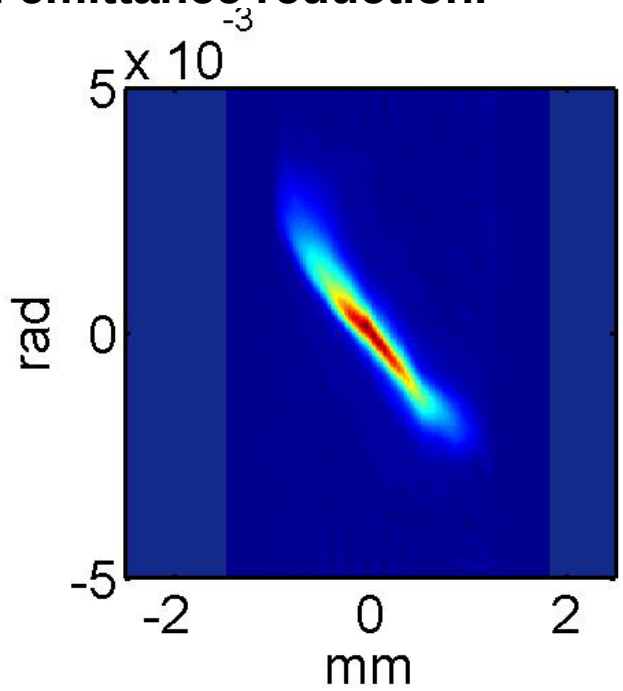
Profile filtering introduces a charge cut.

SPARC-EBD-07-003

Every pixel of a trace space is associated to its contribution to the total emittance, and all the pixels are sorted. Starting from the ones with highest contribution (outside the beam core), they are cut away calculating the first and second derivative of the emittance with respect to the charge.

Cutting the pixel outside the beam causes a strong emittance reduction, while cutting the pixel inside the beam results in a small emittance reduction.





Emittance from trace space: results

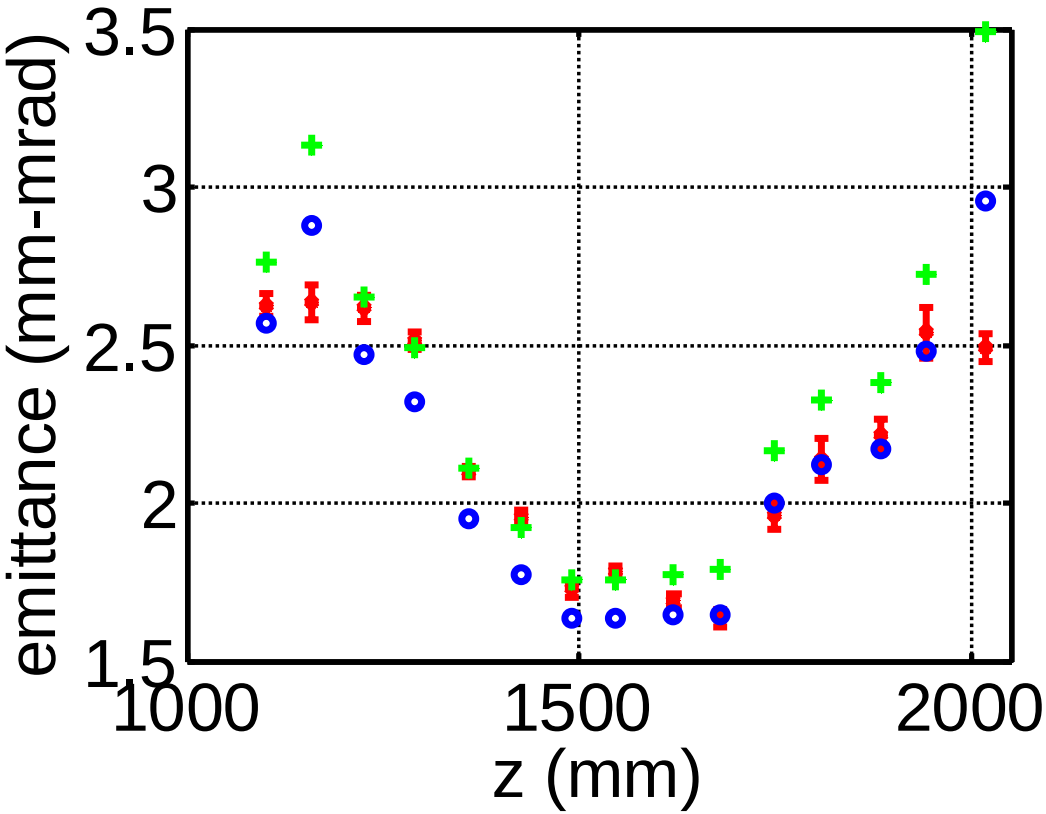


Image selection

95% charge cut

93% charge cut

SPARC

Andrea.Mostacci@uniroma1.it

Conclusion

Emittance meter allows the study of emittance evolution along the beam propagation axis just after a photoinjector.

The SPARC data analysis procedure is automatic, reasonably fast and robust enough so that it was implemented in the automatic control room procedure.

The SPARC data analysis main blocks are:

- **profile filtering for noise suppression**
- **the image selection**
- **uncertainty evaluation**
- **trace space reconstruction**

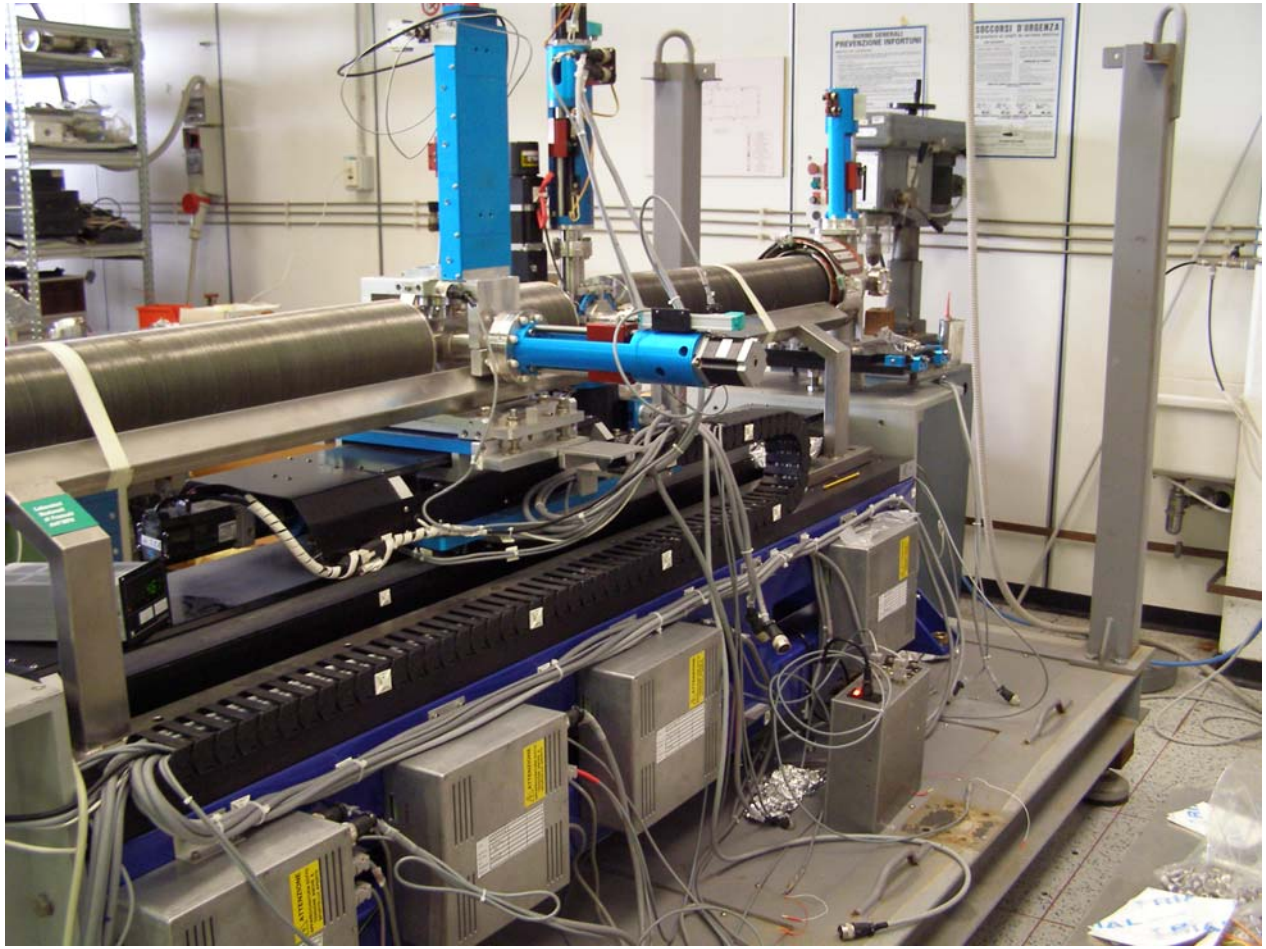
Quantitative estimation of the beam charge percentage actually associated to the emittance value retrieved by the automatic algorithm is found with reconstructed trace space analysis.

SPARC

Andrea.Mostacci@uniroma1.it

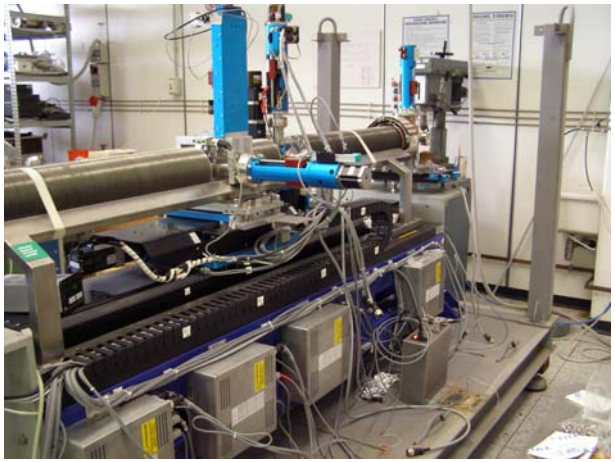
The emittance meter today

The movable emittance meter



Andrea.Mostacci@uniroma1.it

The emittance meter today



SPARC

ma1.it

The SPARC team