

# Non-interceptive profile measurements via light-emission based tomography technique

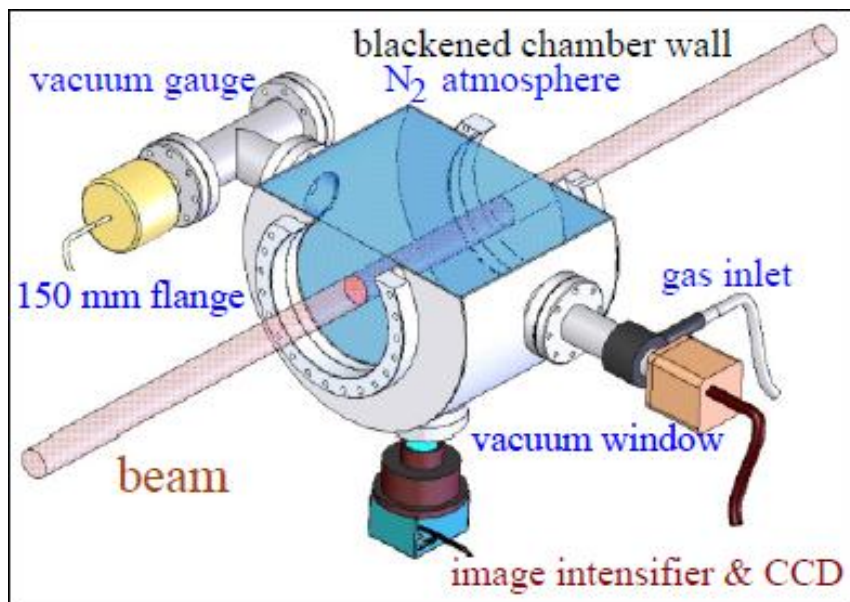
DITANET International Conference:  
Accelerator Diagnostic Techniques

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Co-authors: G. Adroit, R. Gobin, Y. Sauce, F. Senée, O. Tuske

# Non-destructive diagnostics

## Motivation



Schematic of BIF at GSI\*

## Increased demand

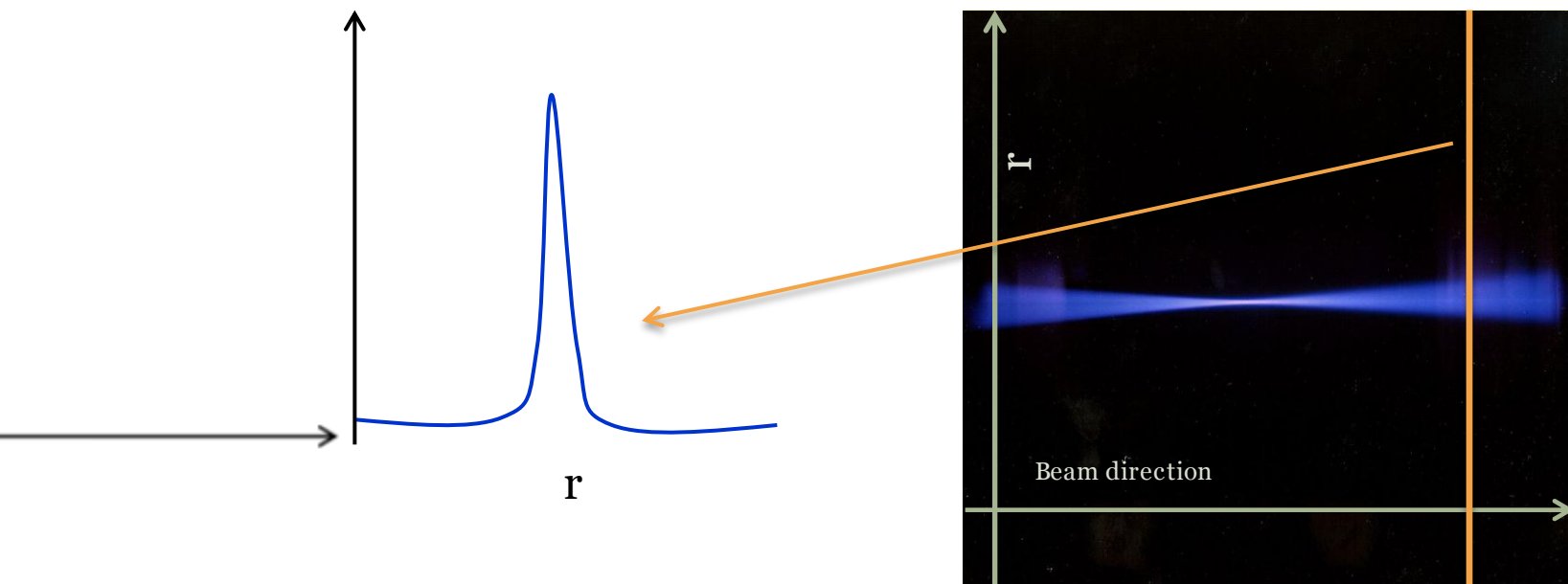
- It must not perturb the beam
- It must not be destroyed by **high current beam** (kilowatt beam power)

## Optical Profilers

- Beam Induced Fluorescence (BIF) Monitor at GSI\*
- Beam Ionization Optical profile monitors

\*F. Becker et al., Beam Induced Fluorescence Monitor for Transverse Profile Determination of 5 to 750 MeV/u Heavy Ion Beams, Proceedings of DIPAC 2007, Venice, Italy

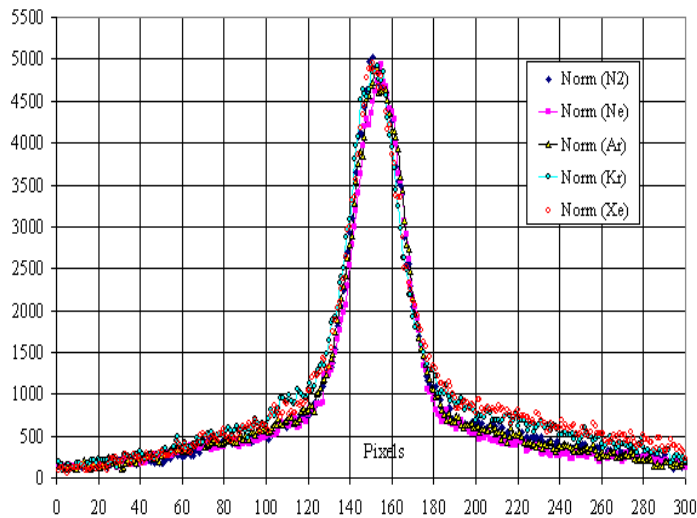
# Optical beam profile



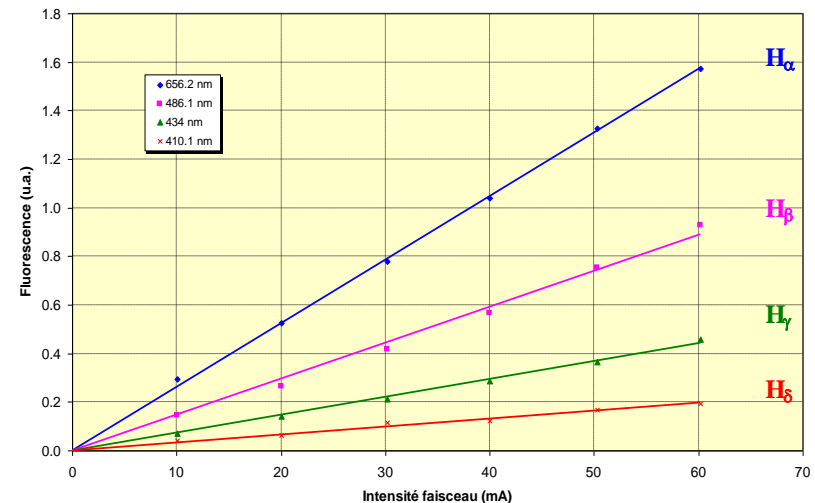
# Optical Profiler in IPN/CEA

## Beam profiles of proton beam

- ✓ Intensified CCD camera was used to capture beam image



Profiles obtained with different gases  
but with constant gas pressure.



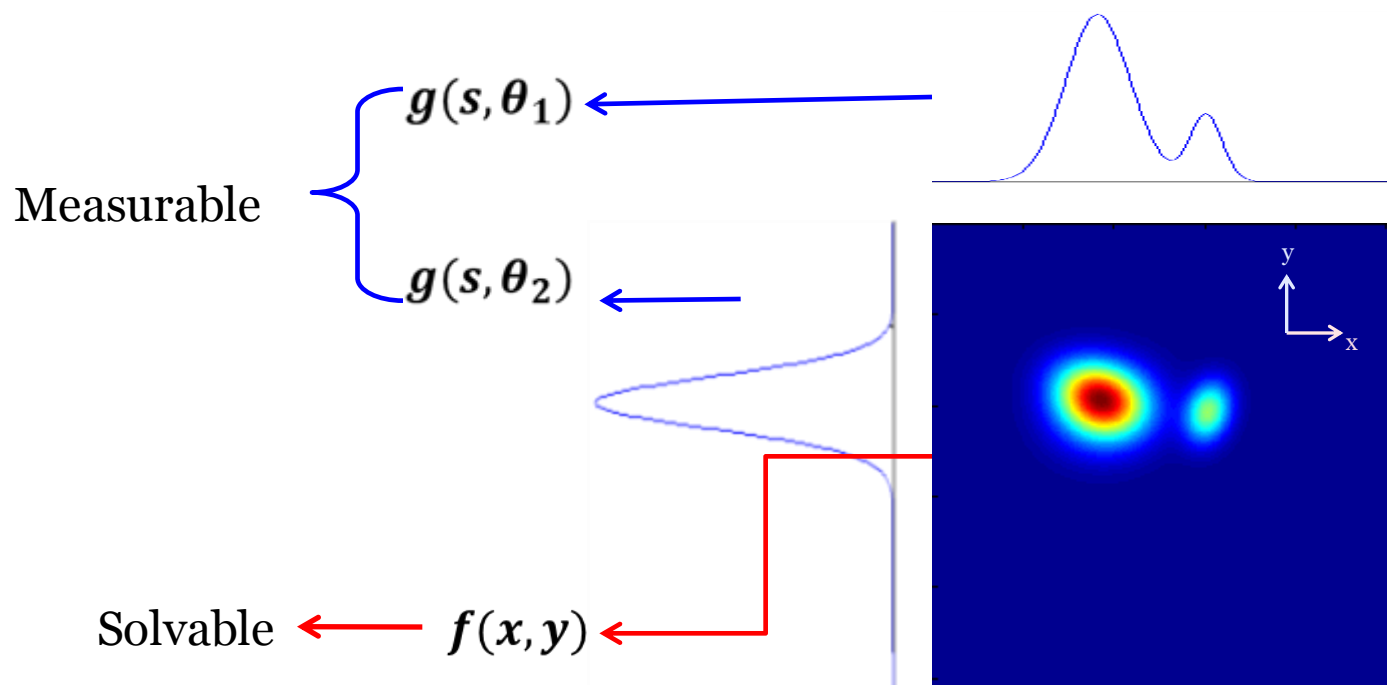
$$I_{lum} = I_{beam} \cdot \sigma \cdot n_0$$

\*P. Ausset, et. al., *Transverse Beam Profile Measurements for High Power Proton Beams*, Proceedings of EPAC2001, Paris, France

\*Pottin, B, (2001) Etude d'un profileur optique de faisceaux intenses de protons par absorption laser, Doctor of Science thesis. Institut de Physique Nudéaire

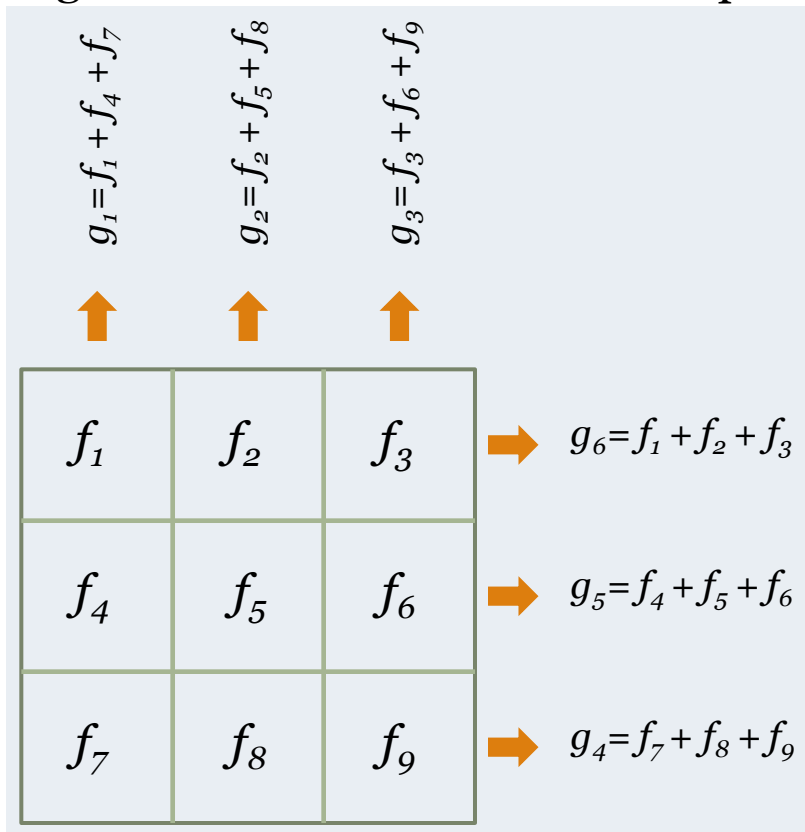
# Tomography

Tomography is the method used to reconstruct a 2D cross sectional image of an object given multiple flat scans taken from multiple angles around an object



# How?

## Algebraic Reconstruction Technique for 2 Projections



$$\begin{cases} g_1 = f_1 & + f_4 & + f_7 \\ g_2 = & f_2 & + f_5 & + f_8 & + f_9 \\ g_3 = & & f_3 & + f_6 & + f_7 & + f_8 & + f_9 \\ g_4 = & & & & & & & & & & \\ g_5 = & & & & f_4 & + f_5 & + f_6 & & & & \\ g_6 = f_1 & + f_2 & + f_3 & & & & & & & & \end{cases}$$

$$\begin{bmatrix} g_1 \\ g_2 \\ g_3 \\ g_4 \\ g_5 \\ g_6 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 \\ \hline 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \\ f_6 \\ f_7 \\ f_8 \\ f_9 \end{bmatrix}$$

$$\underbrace{\quad}_{\mathbf{g}} \quad \underbrace{\quad}_{\mathbf{A}} \quad \underbrace{\quad}_{\mathbf{f}}$$

Projections      Sparse Matrix      Image

# How?

Interested in finding a vector solution  $f$  to the vector equation:

$$g = Af$$

unknown slice vector

Sparse matrix or  
forward projection  
matrix

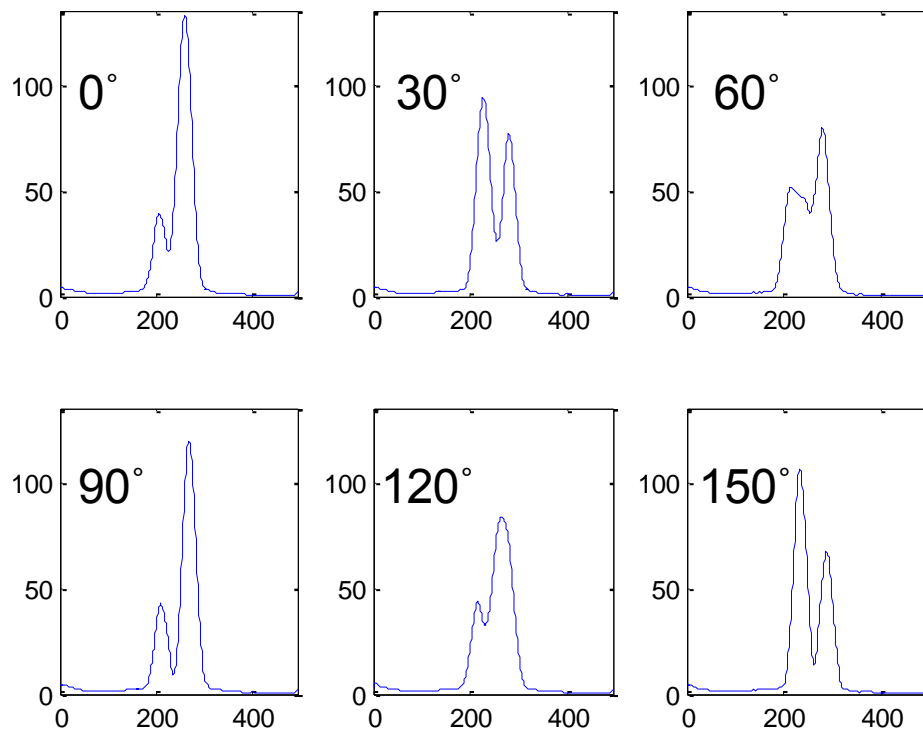
Projection  
data vector

Iterative Procedure

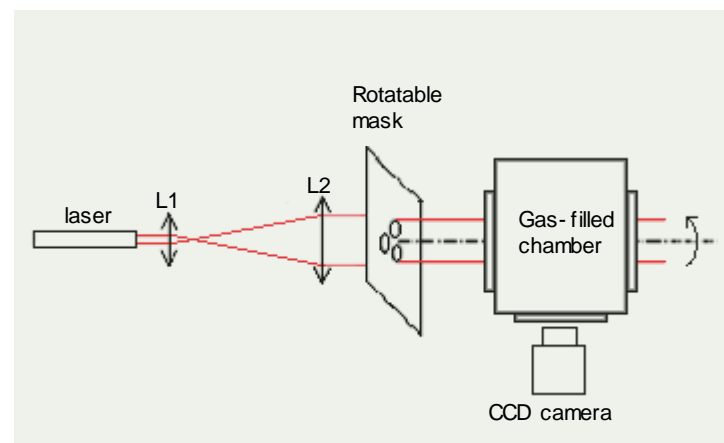
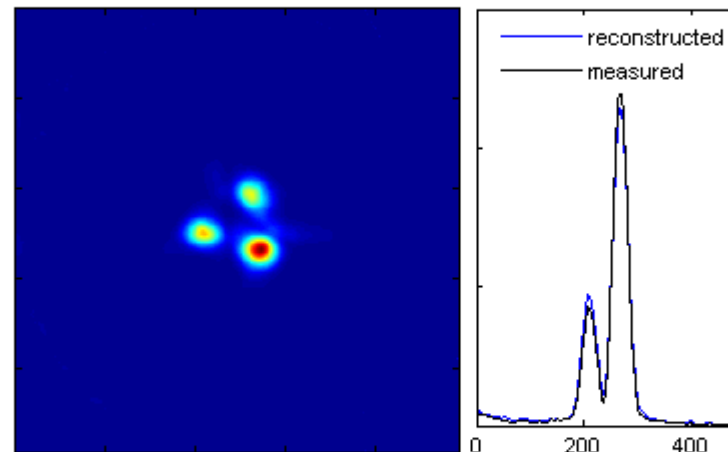
# Initial Tests of the Algorithm



# Initial Test

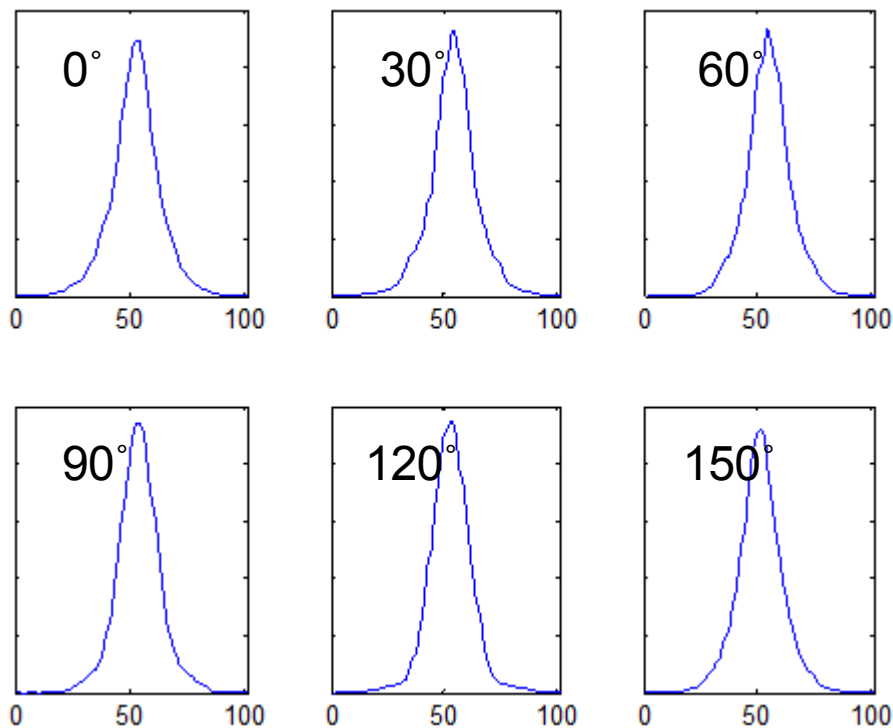


## Reconstructed spatial distribution



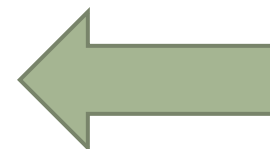
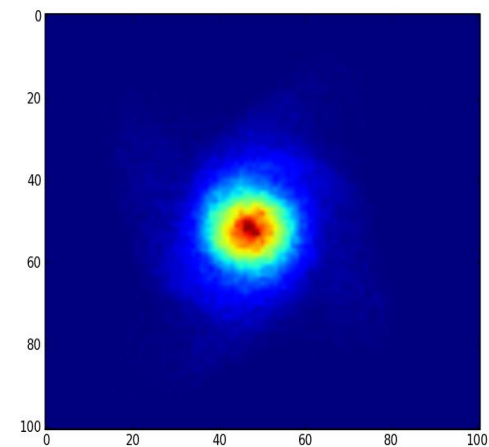
G. E. Belyaev, I.V. Roudskoy, D. Gardes, P. Ausseth and A. Olivier, Nucl. Instr. and Meth. in Phys. Res. A **578**, p. 47-54 (2007).

# Numerical Test

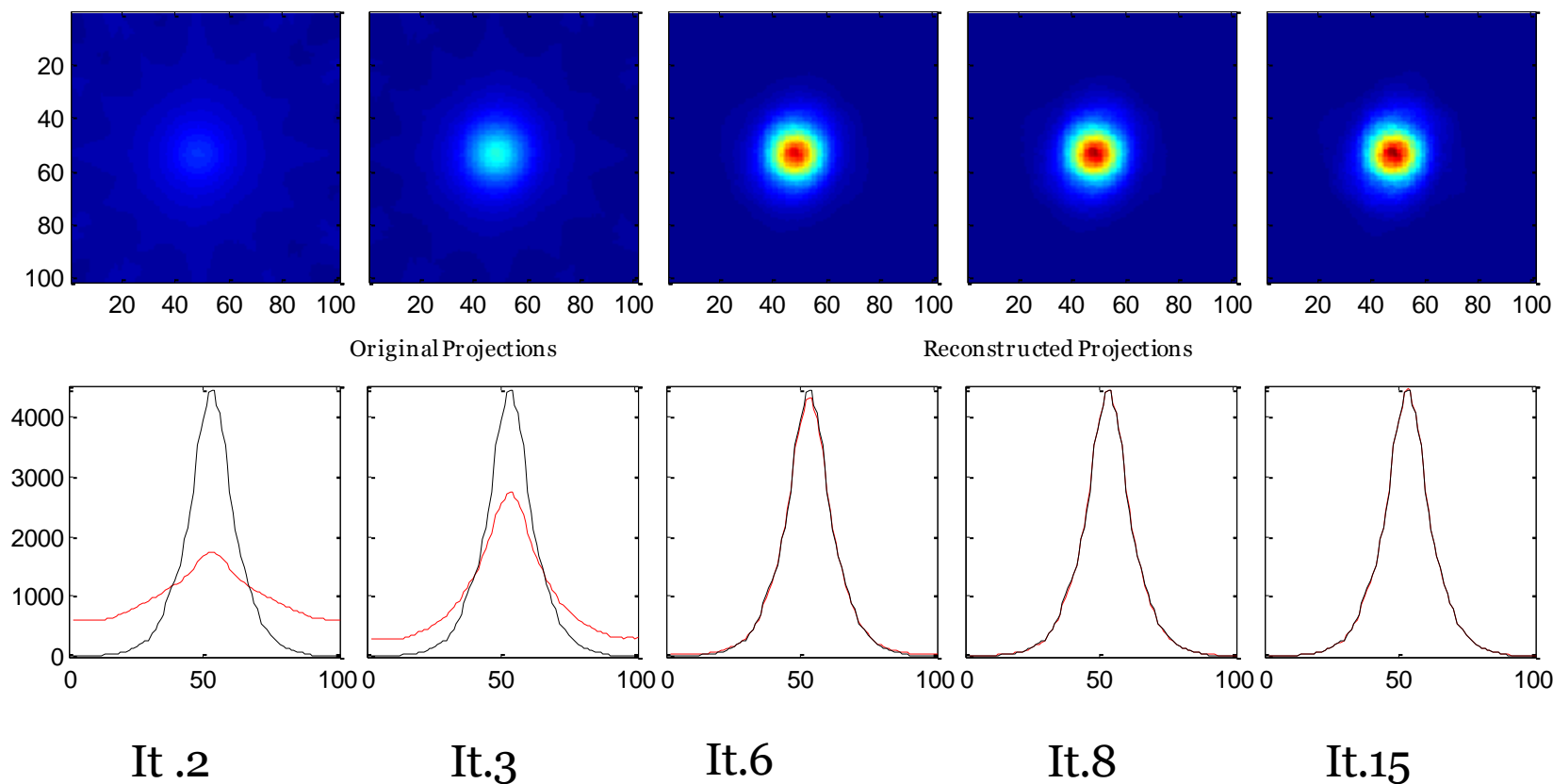


I HAVE

TEST IMAGE



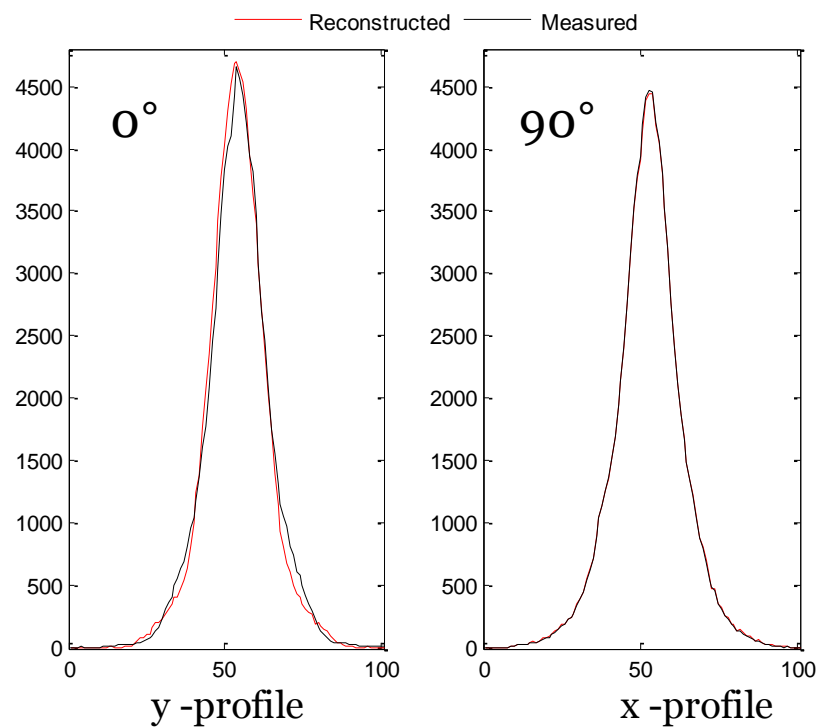
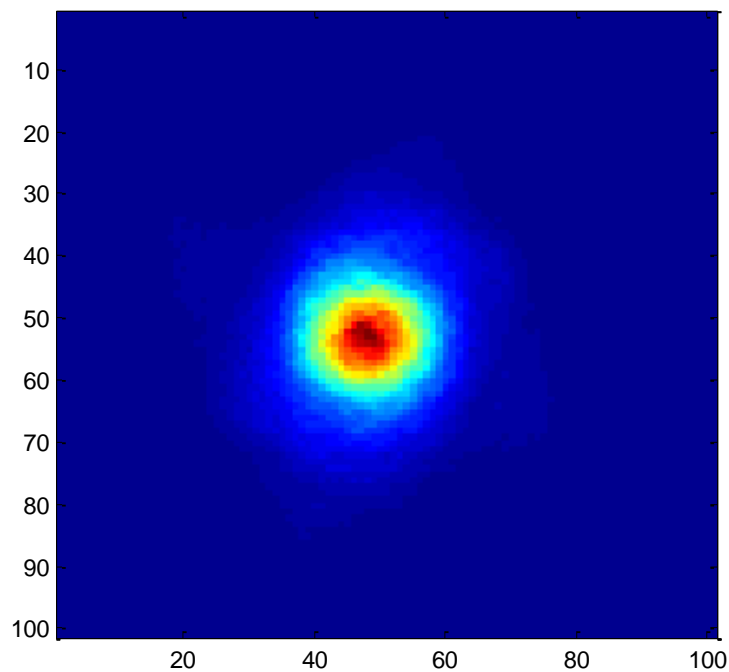
# Dependence on number of Iterations



Projections measured at  $90^\circ$

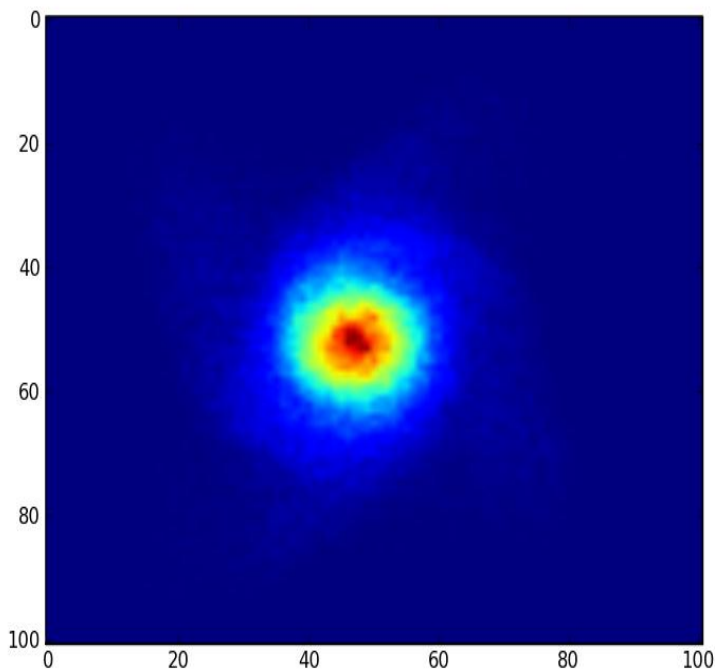
# Numerical Test

The reconstructed image after 15 iterations

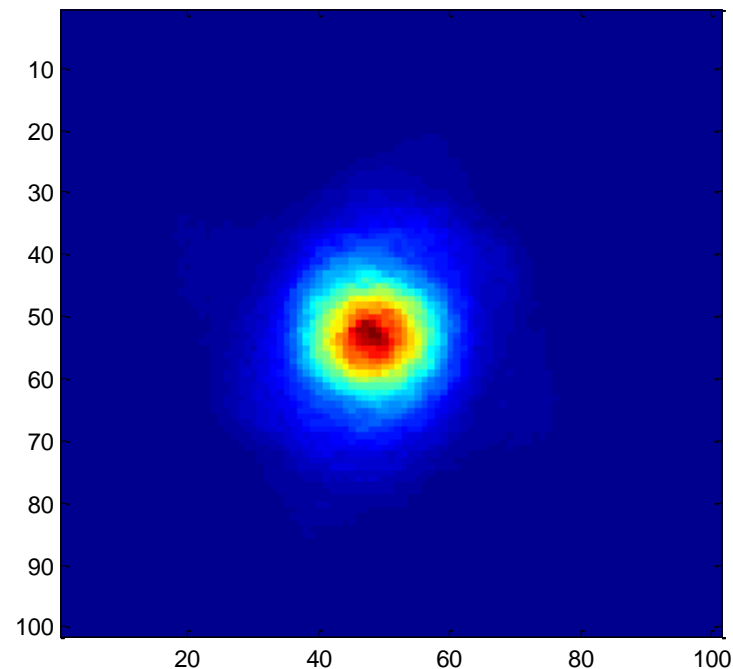


# Comparison with the source image

Original image



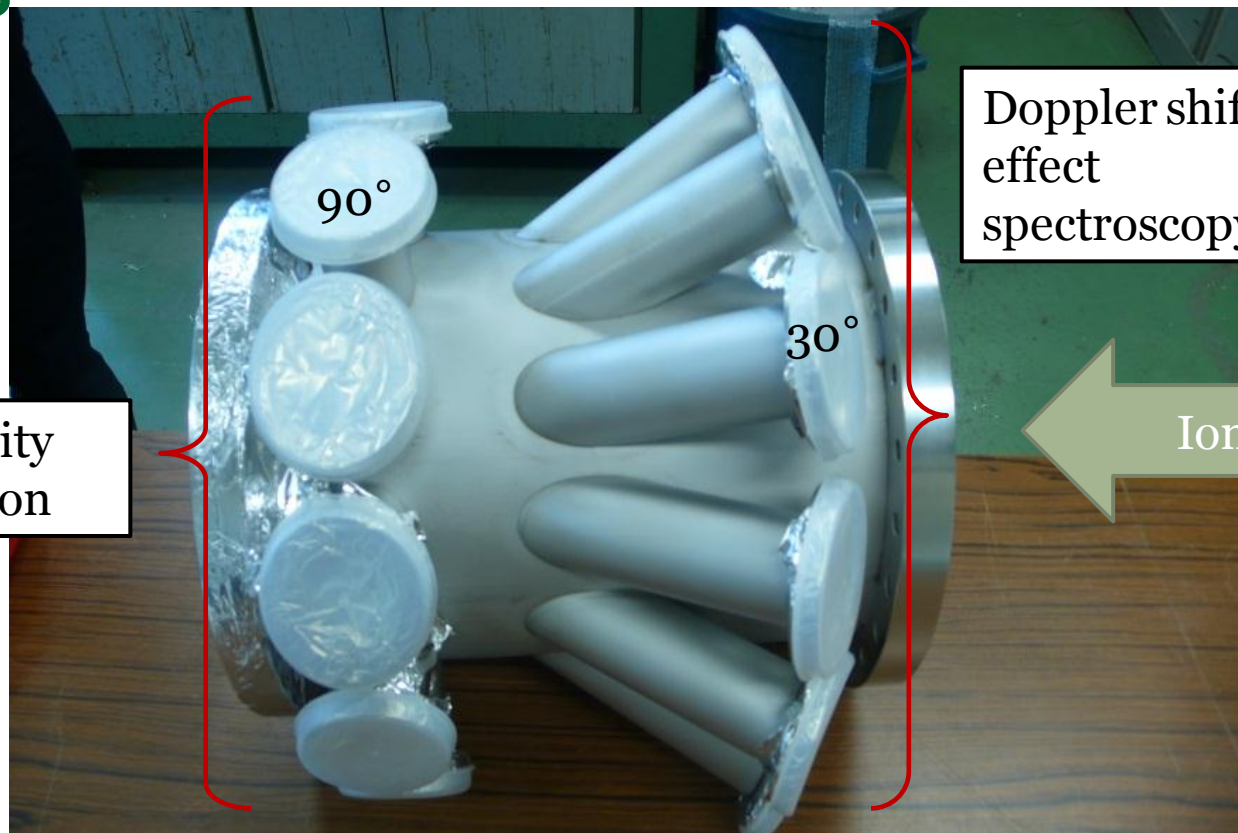
Reconstructed image





# Experimental Measurements With Ion Beams

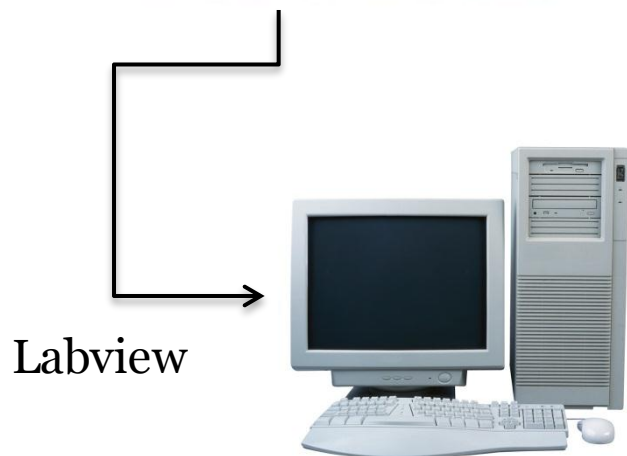
# Vacuum Chamber specially designed for Measurements



# Imaging and Detection



Focal Length (mm)		25
Iris Range		F1.4 ~ F16
Operation	Focus	Manual
	Iris	Manual
Angle Of View (H×V)	2/3"	19°58' × 15°02'
	1/2"	14°35' × 10°58'
	1/3"	10°58' × 8°14'
Focusing Range (From Front Of The Lens) (m)		∞ ~ 0.15
Object Dimensions at M.O.D. (H×V) (mm)	2/3"	53 × 40
	1/2"	38 × 29
	1/3"	29 × 22
Back Focal Distance (in air) (mm)		14.58
Exit Pupil Position (From Image Plane) (mm)		-32
Filter Thread (mm)		M25.5 × 0.5
Mount		C
Mass (g)		45

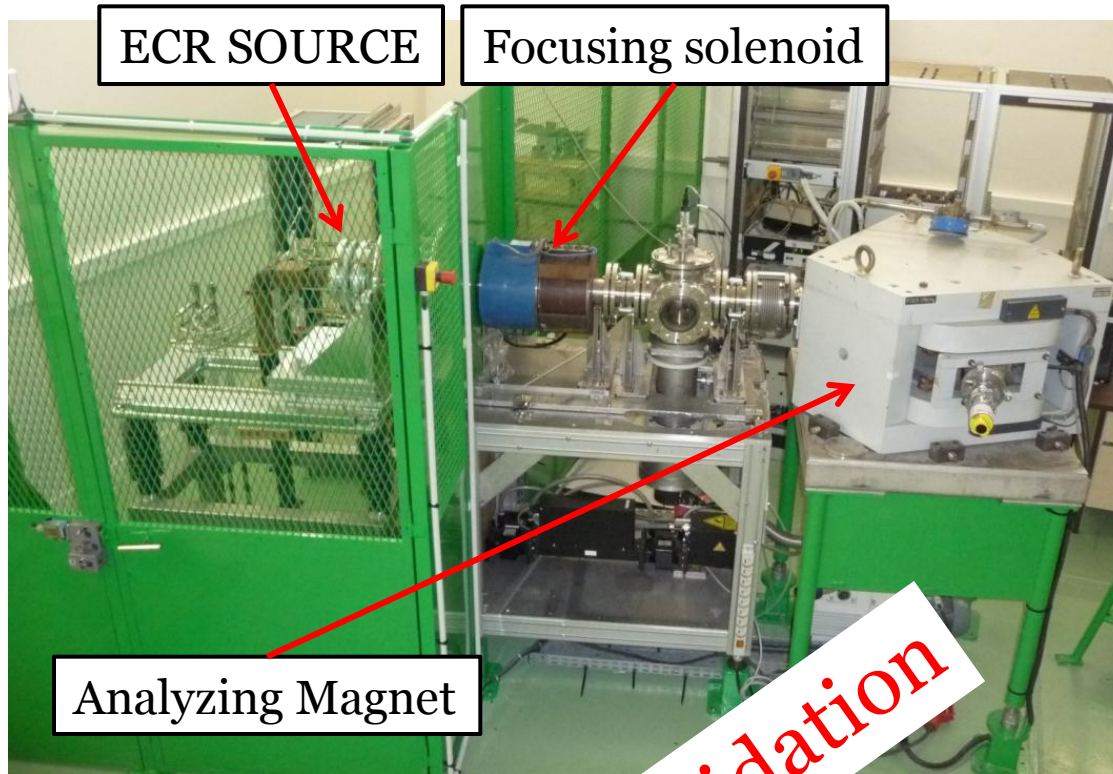


- Stingray F146B
- Fujinon HF25HA-1B objective

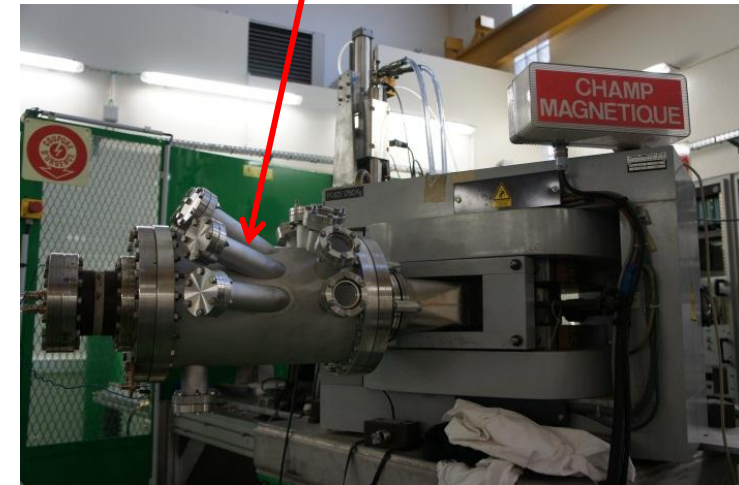


# Measurements in BETSI test bench

Banc d'Etude et de Tests des Sources d'Ions



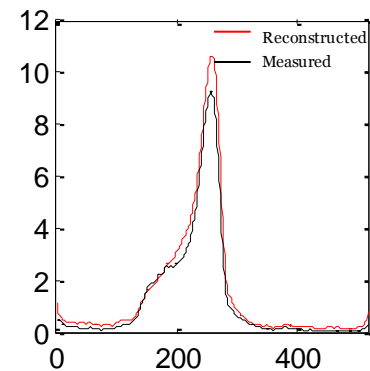
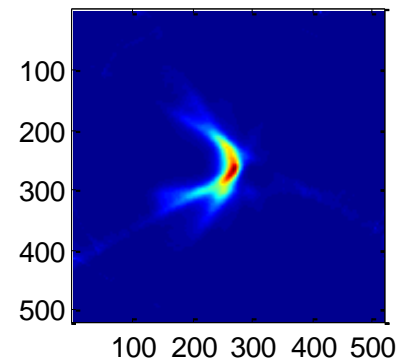
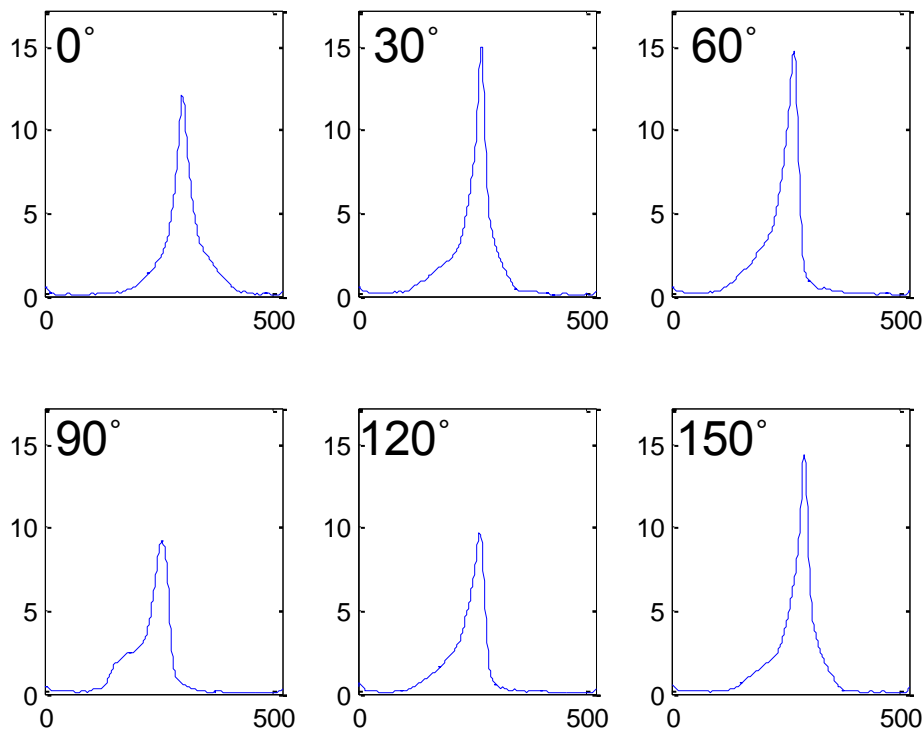
Tomographic chamber  
after the Magnet



ECR source  
H<sub>2</sub> dominated residual gas  
Low Intensity beams : 2mA  
H<sup>+</sup> current at the beam stop

**For validation**

# Measurements in BETSI



Bizarre "BANANA" shape beam !  
**NEED MORE VALIDATION**

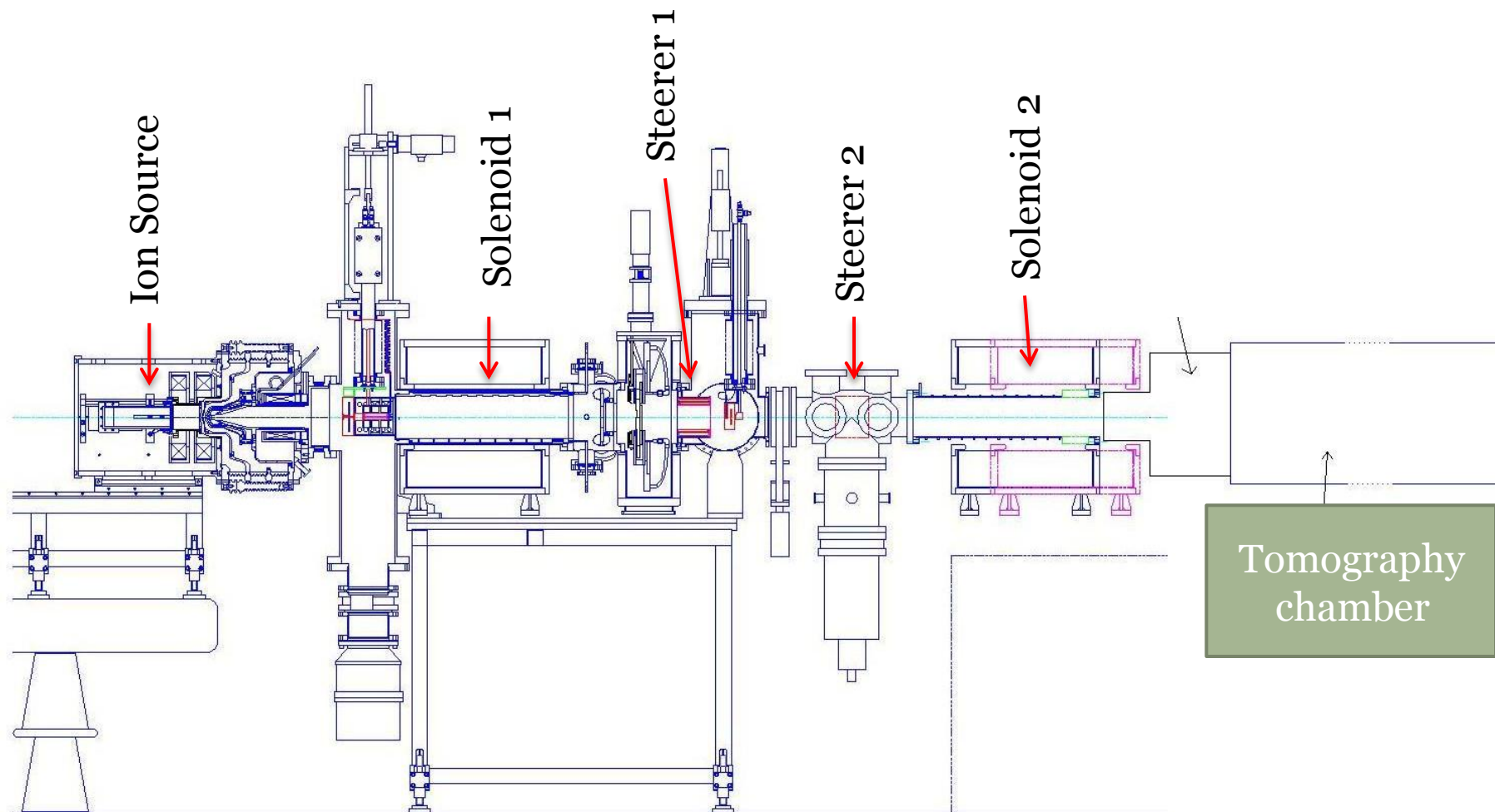
# Measurements in SILHI

## High Intensity Light Ion Source

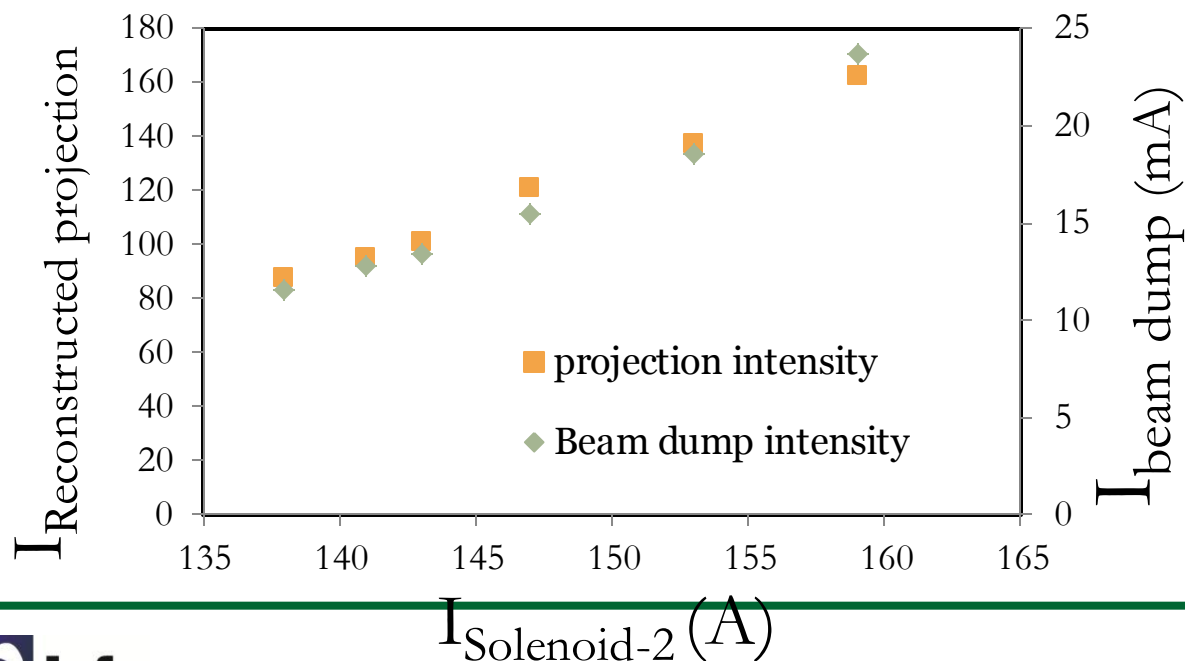
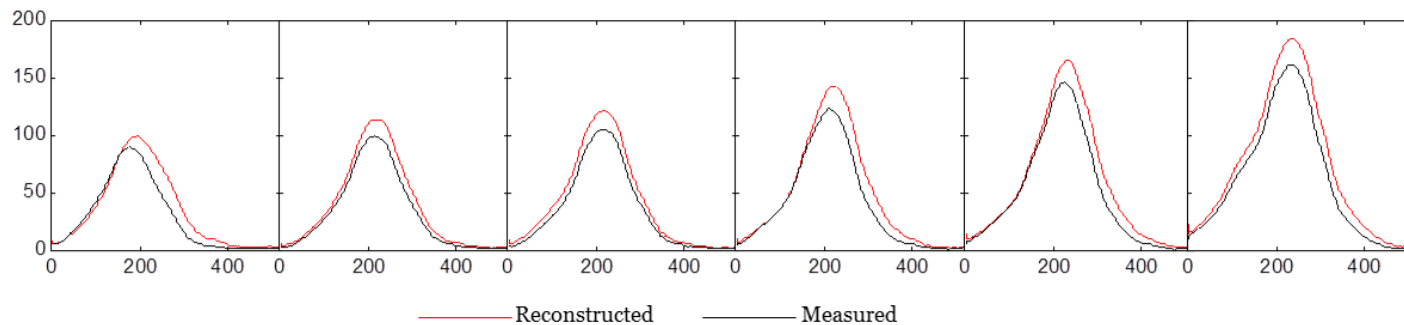


- ECRIS: 2.45 GHz - 875 Gauss.
- CW or pulsed mode.
- up to 130 mA at 95 kV → kilowatt of beam power

# Measurements in SILHI

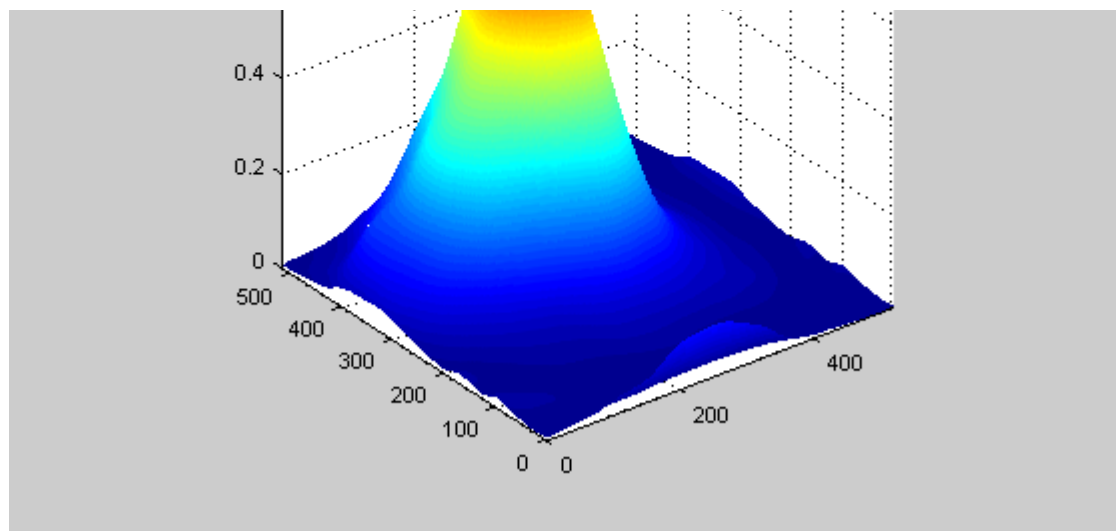
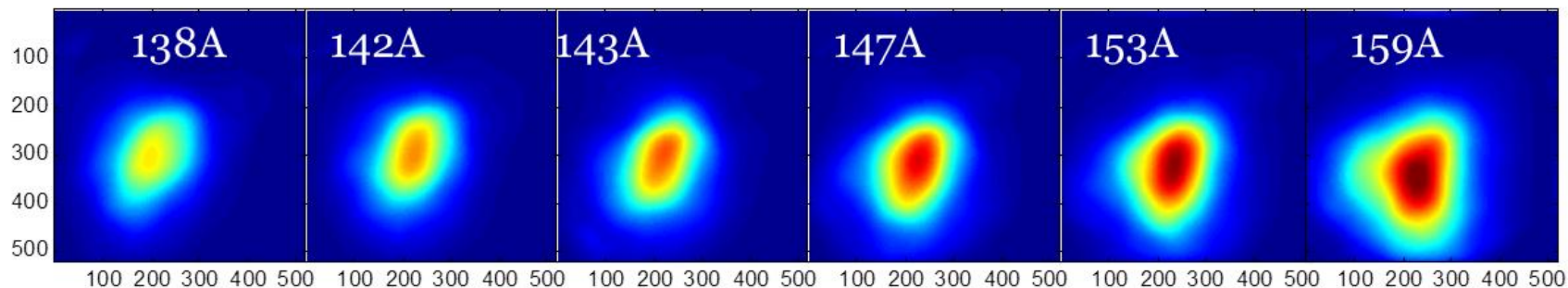


# Measurements VS Sol 2 current



**Same Linear dependence ✓**

# Measurements VS Sol 2 current



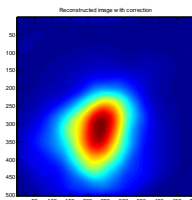
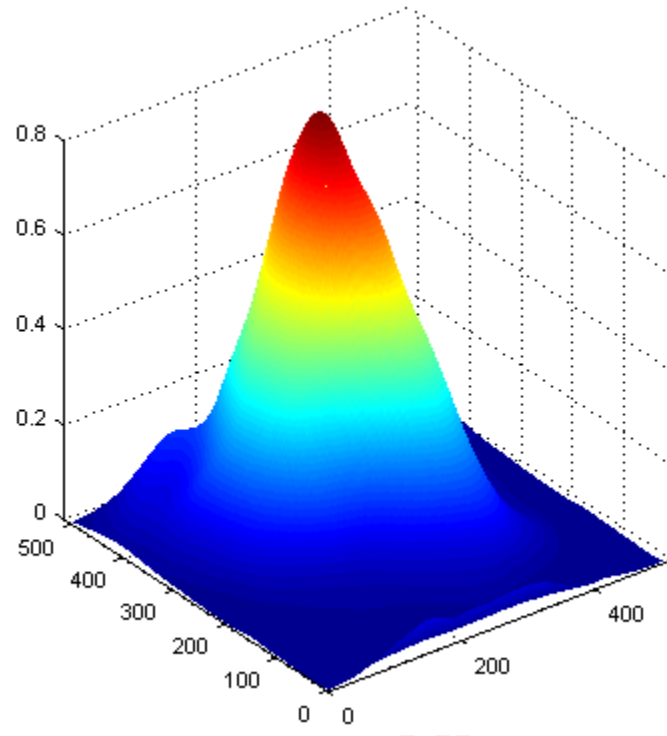
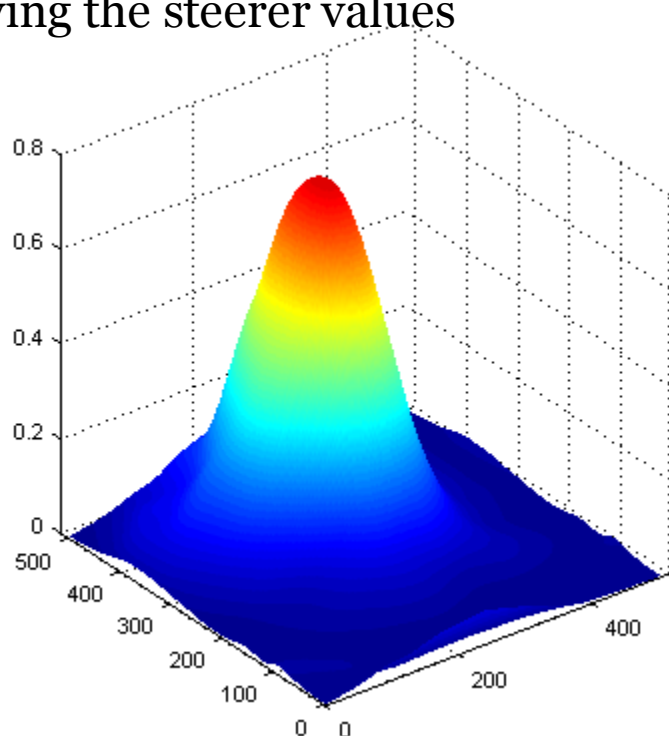
**BUT**  
 Beam Shape  
 Beam position  
 have changed !

→ Non linearity of the  
 solenoid for such beam size

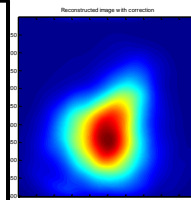
138A

# Measurements VS Steerer current

Varying the steerer values

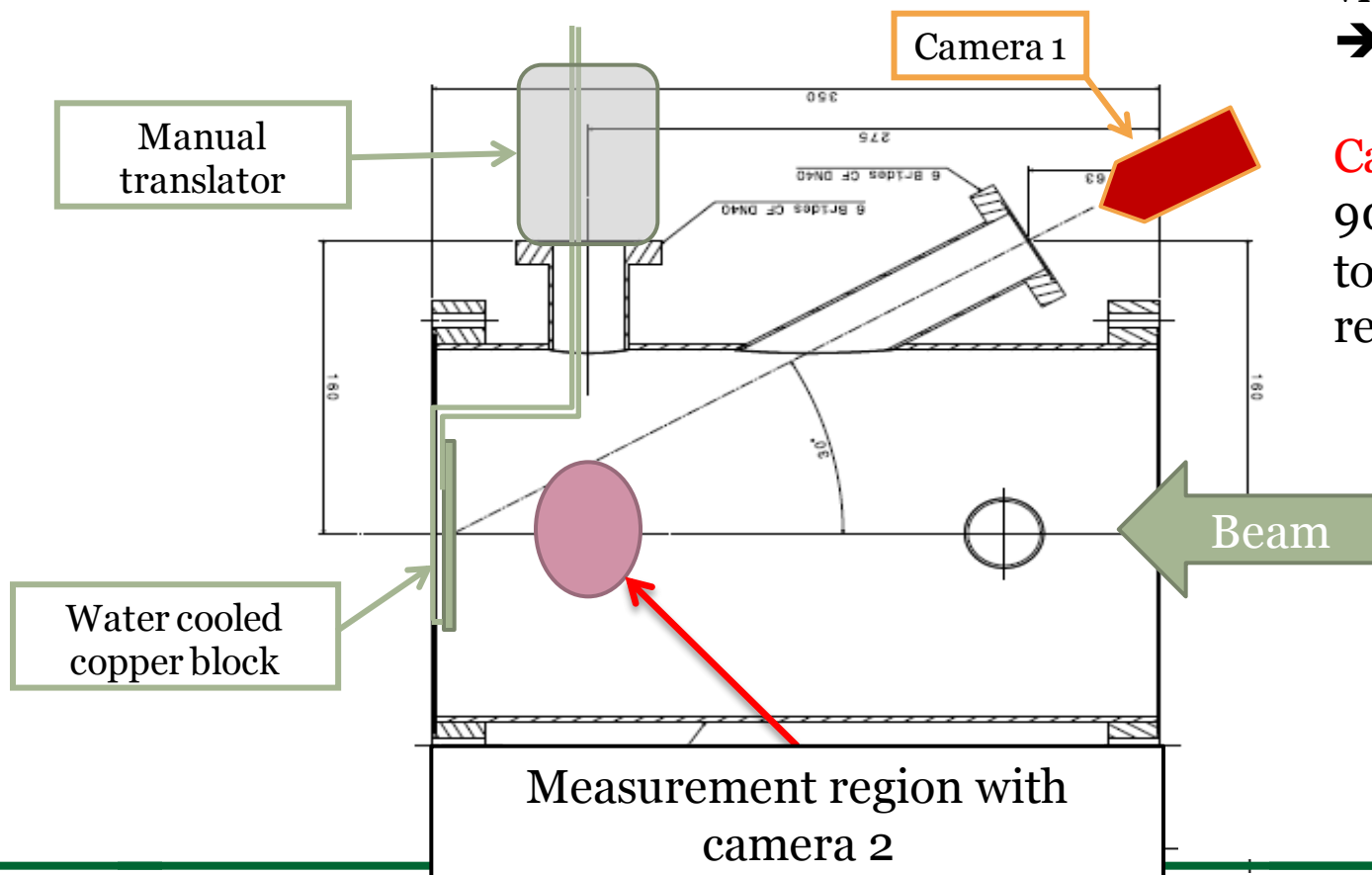


Position has changed ✓  
Intensity remains constant ✓  
**BUT**  
Beam shape has changed !



DH1 +0,2  
DV1 -0,7  
DH2 +0,5  
DV2 -0,5

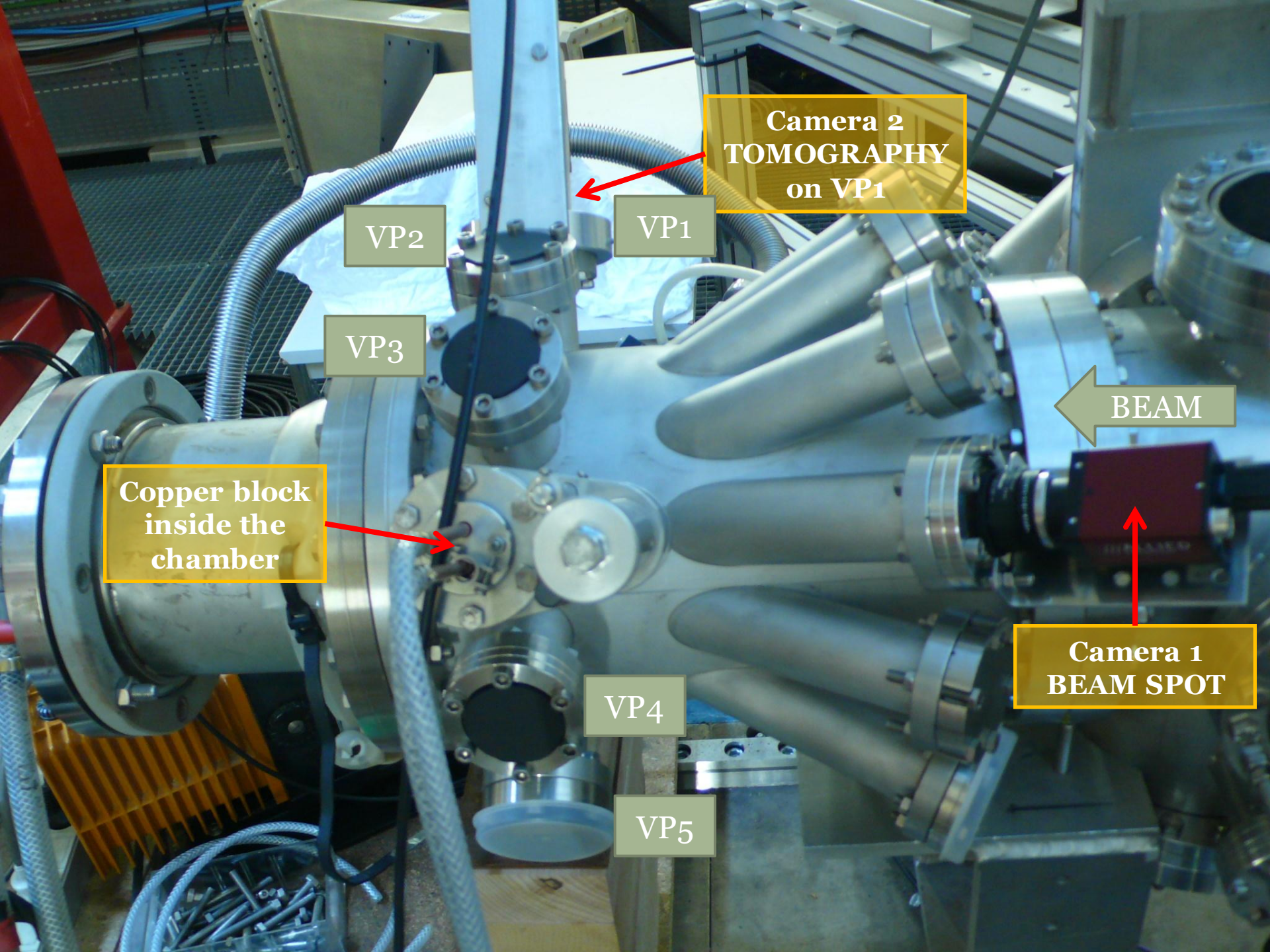
# Copper « Profiler »



**Camera 1** for the copper « profiler » mounted on the 30° viewport  
 → BEAM SPOT

**Camera 2** on the five 90°-viewport for tomographic reconstruction





Camera 2  
TOMOGRAPHY  
on VP1

VP2

VP1

VP3

← BEAM

Copper block  
inside the  
chamber

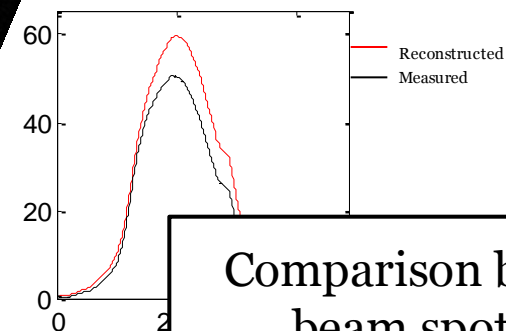
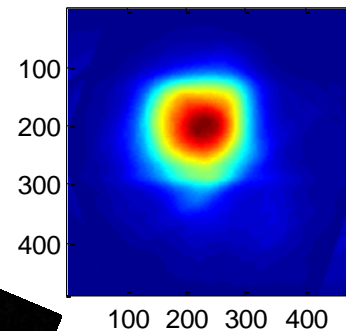
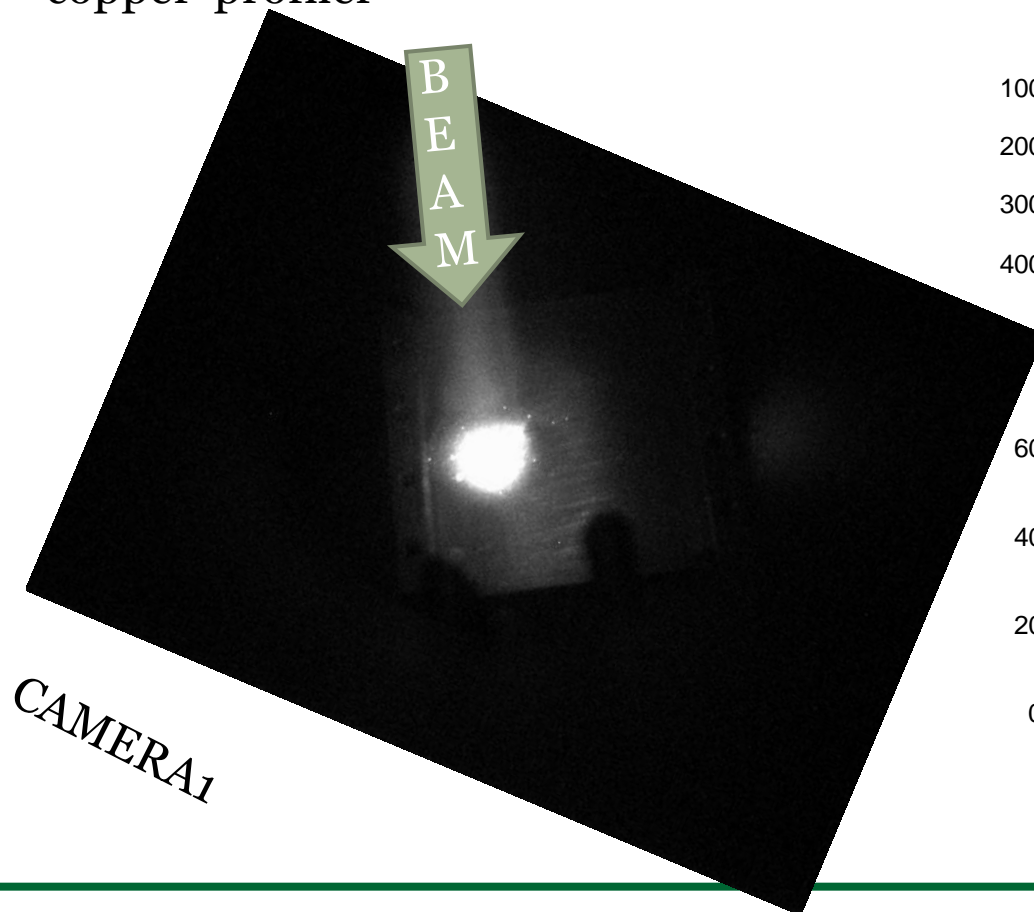
↑  
Camera 1  
BEAM SPOT

VP4

VP5

# Copper « Profiler »

Comparing the shape of the reconstructed image with 5 viewports with the copper "profiler"



Comparison between the beam spot and the reconstructed image shape is very much comparable even with 5 projections

# Summary

- It was demonstrated that tomography technique can reconstruct the spatial density of the beam both for low and high intensity beams.
  - 6 viewports seemed to be enough to reconstruct smooth beams.
- The algorithm written in MATLAB is very fast.
  - Future use of 6 simultaneous cameras is foreseen.

# Acknowledgements

- This work is supported by the DITANET Marie Curie European network.
- CEA Saclay
  - Romuald Duperrier
  - Wilfrid Farabolini
  - Guillaume Ferrand
  - Alain France
  - Francis Harrault

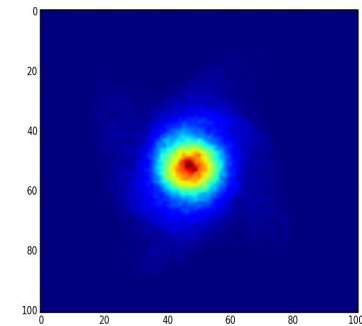
# Thank you for your attention



energie atomique • energies alternatives



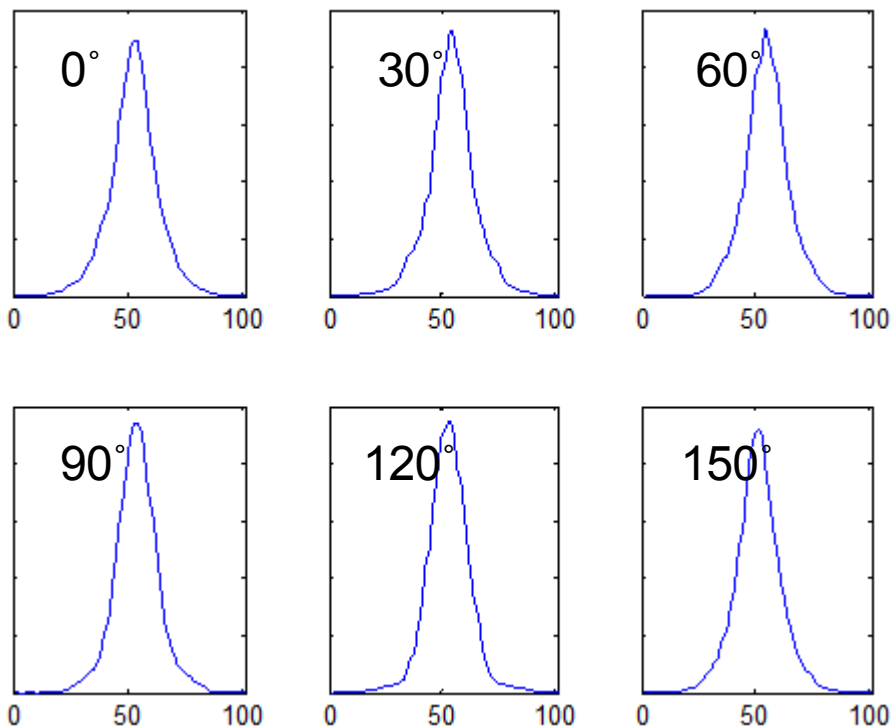
# Backup Slides



# Numerical Illustration with MATLAB

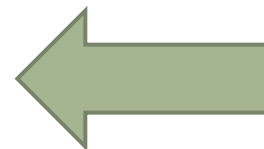
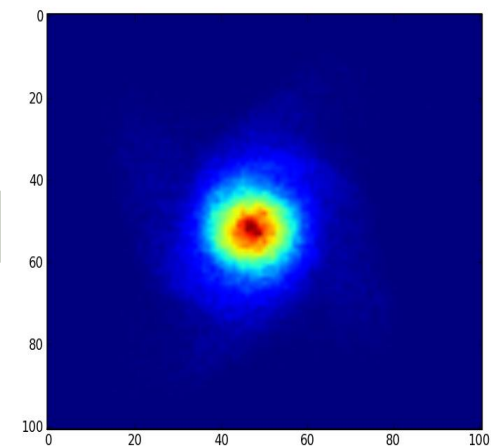
# Step 1

## Image to Projections of the TEST IMAGE



I HAVE

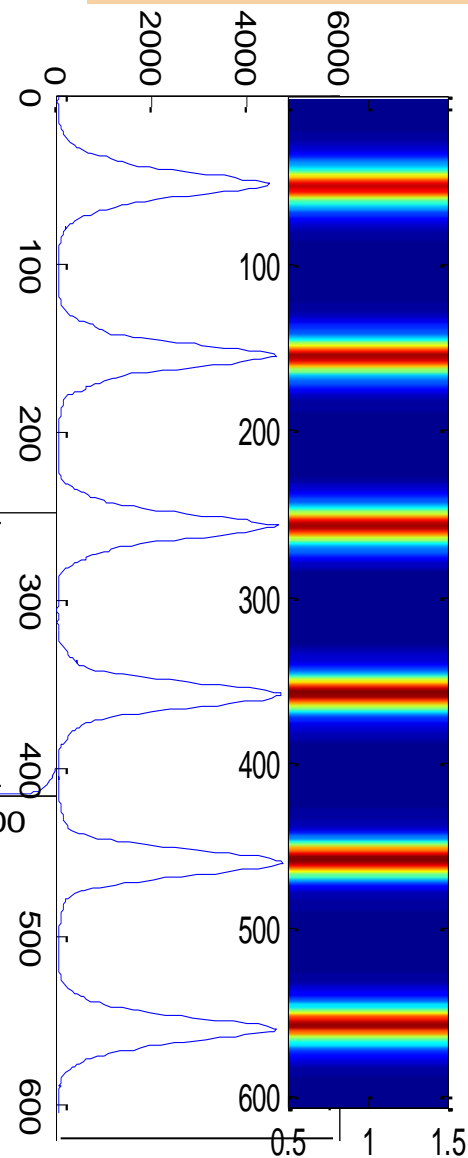
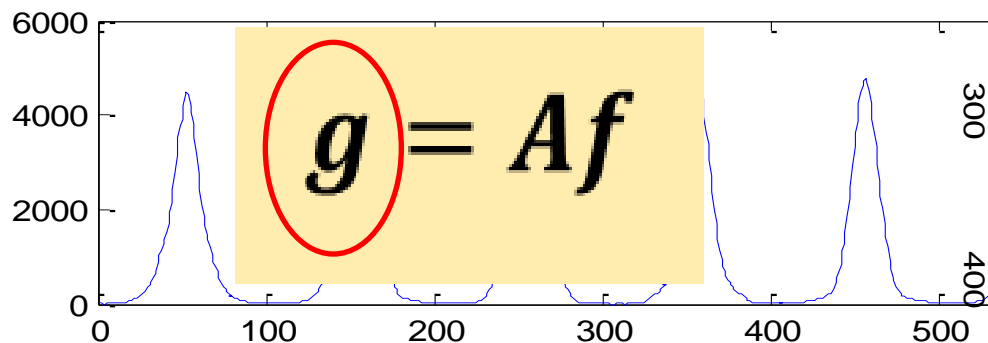
TEST IMAGE





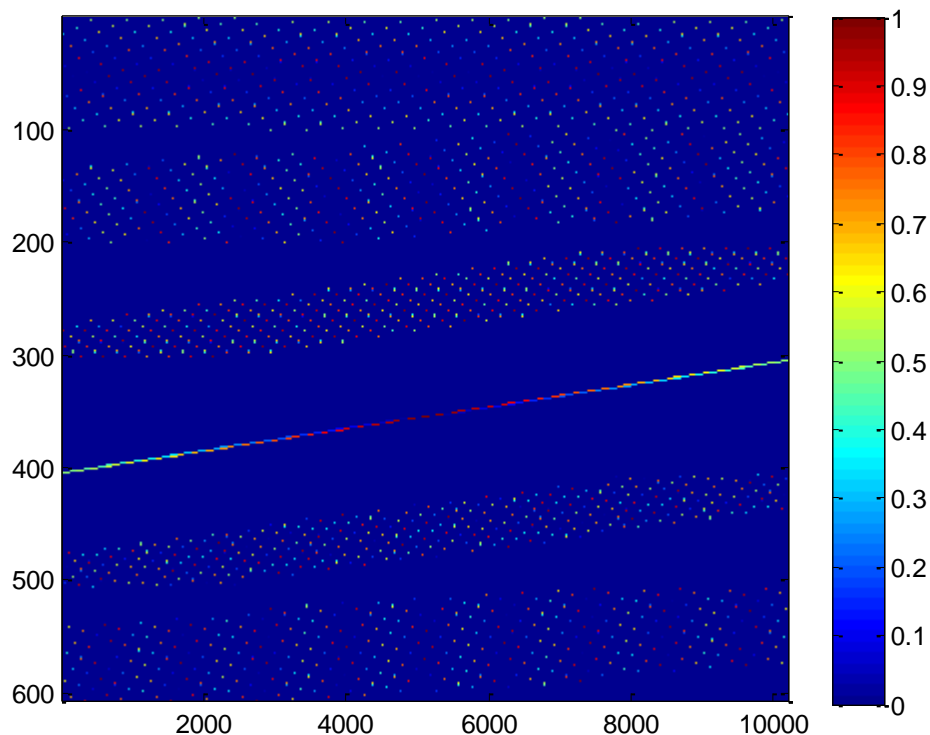
# Step 2

Construction of the Projection vector "g"



# Step 3

Sparse matrix is constructed



$$g = Af$$

6 projections

101 x 101 image

→ 606 x 10201 sparse matrix size



# Step 5, iteration 2

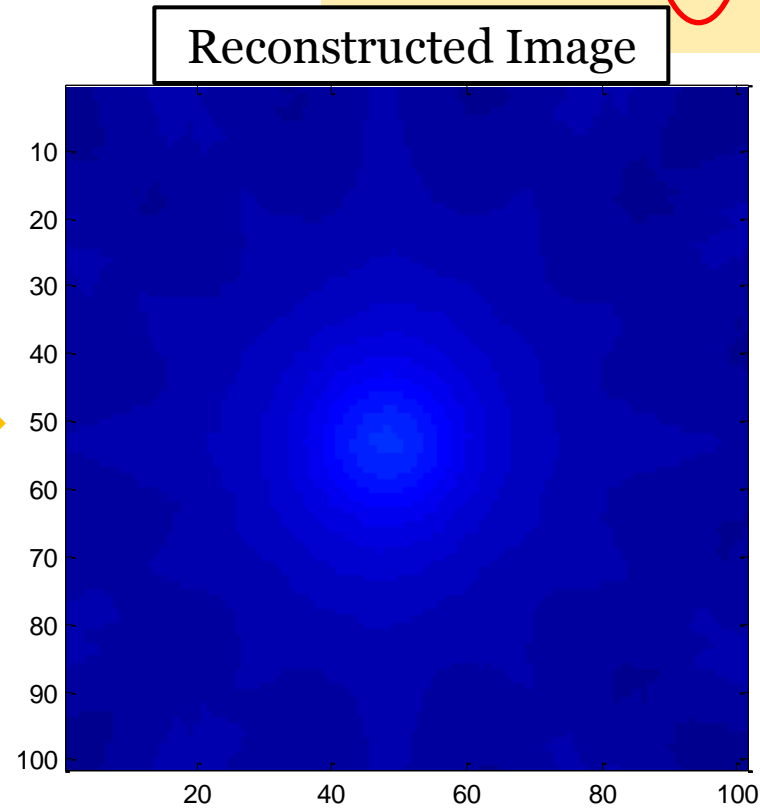
$f$  is reshaped to  $101 \times 101$  image matrix

$$g = Af$$

pixel values



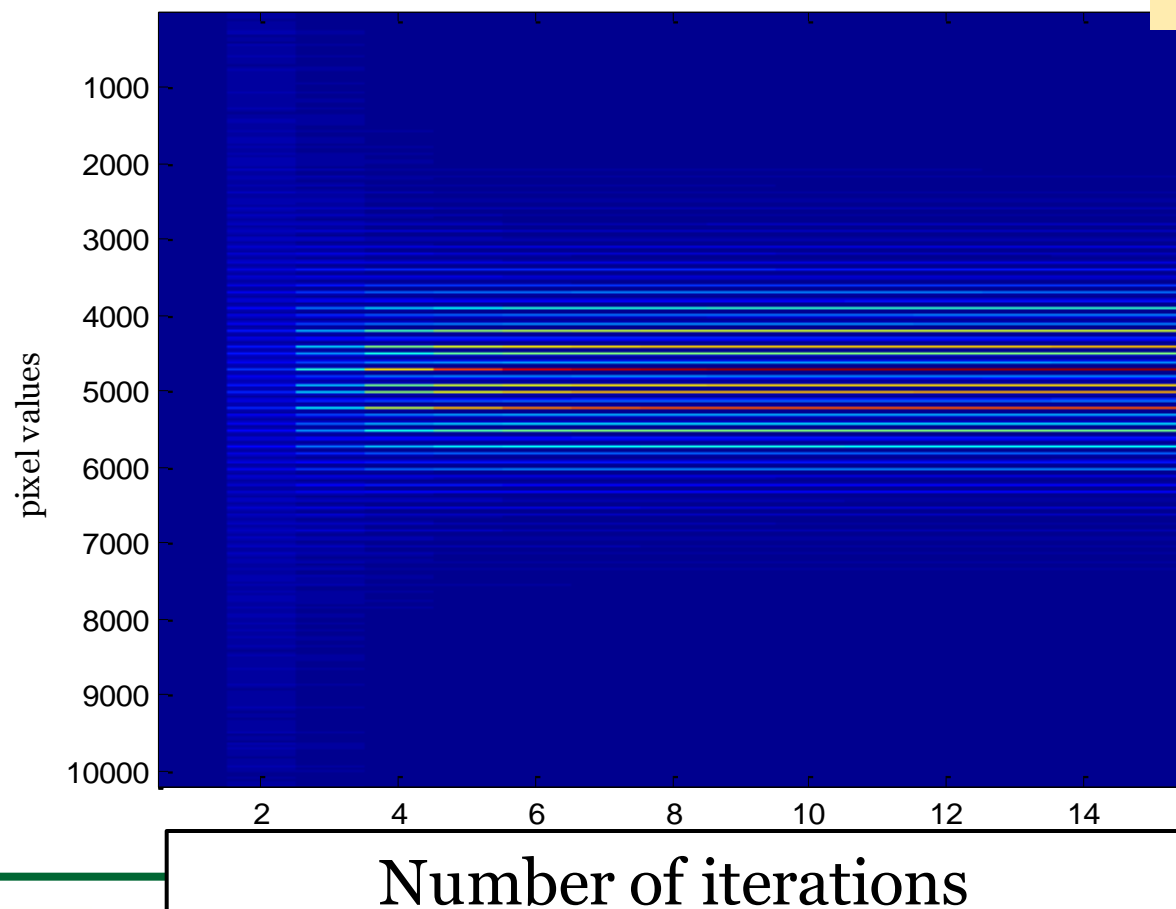
2



# An Illustration

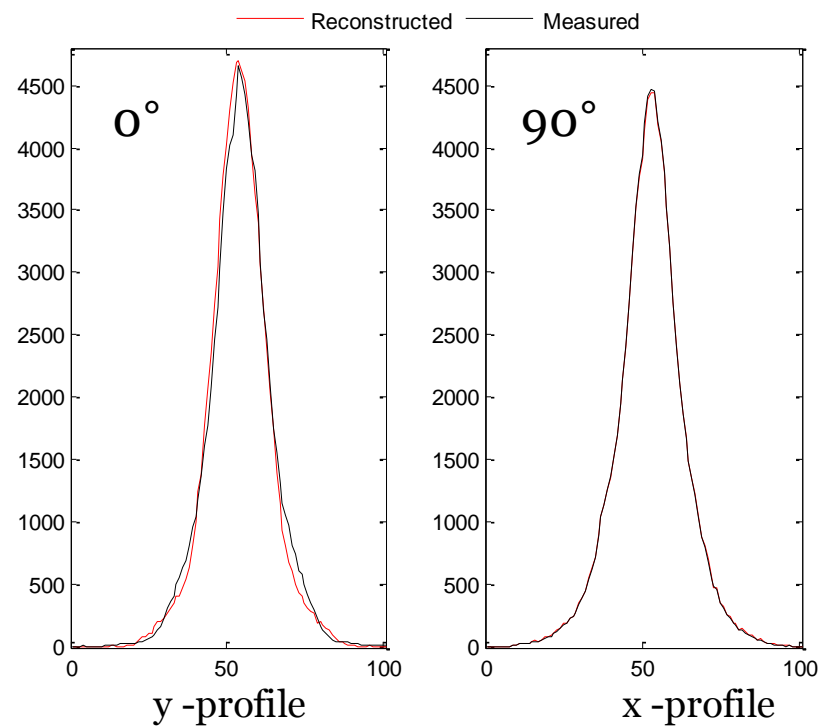
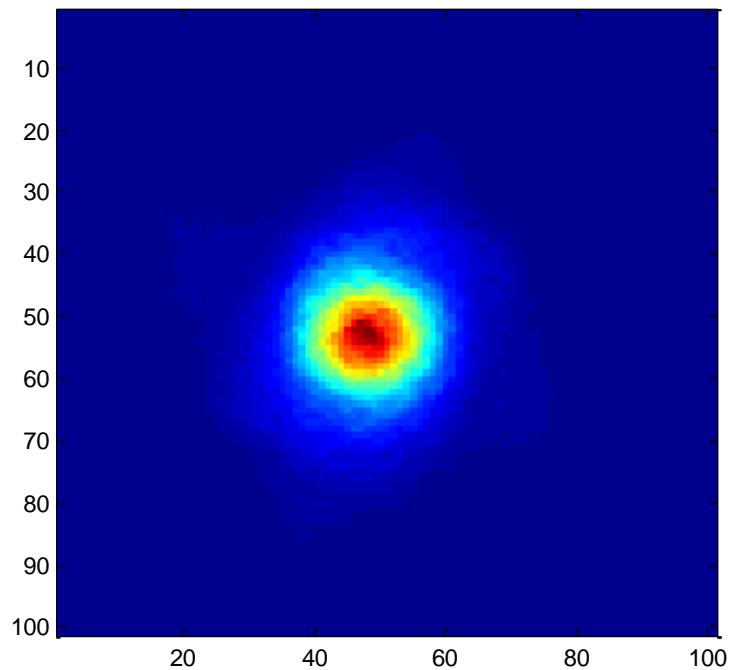
$f$  is solved iteratively

$$g = Af$$



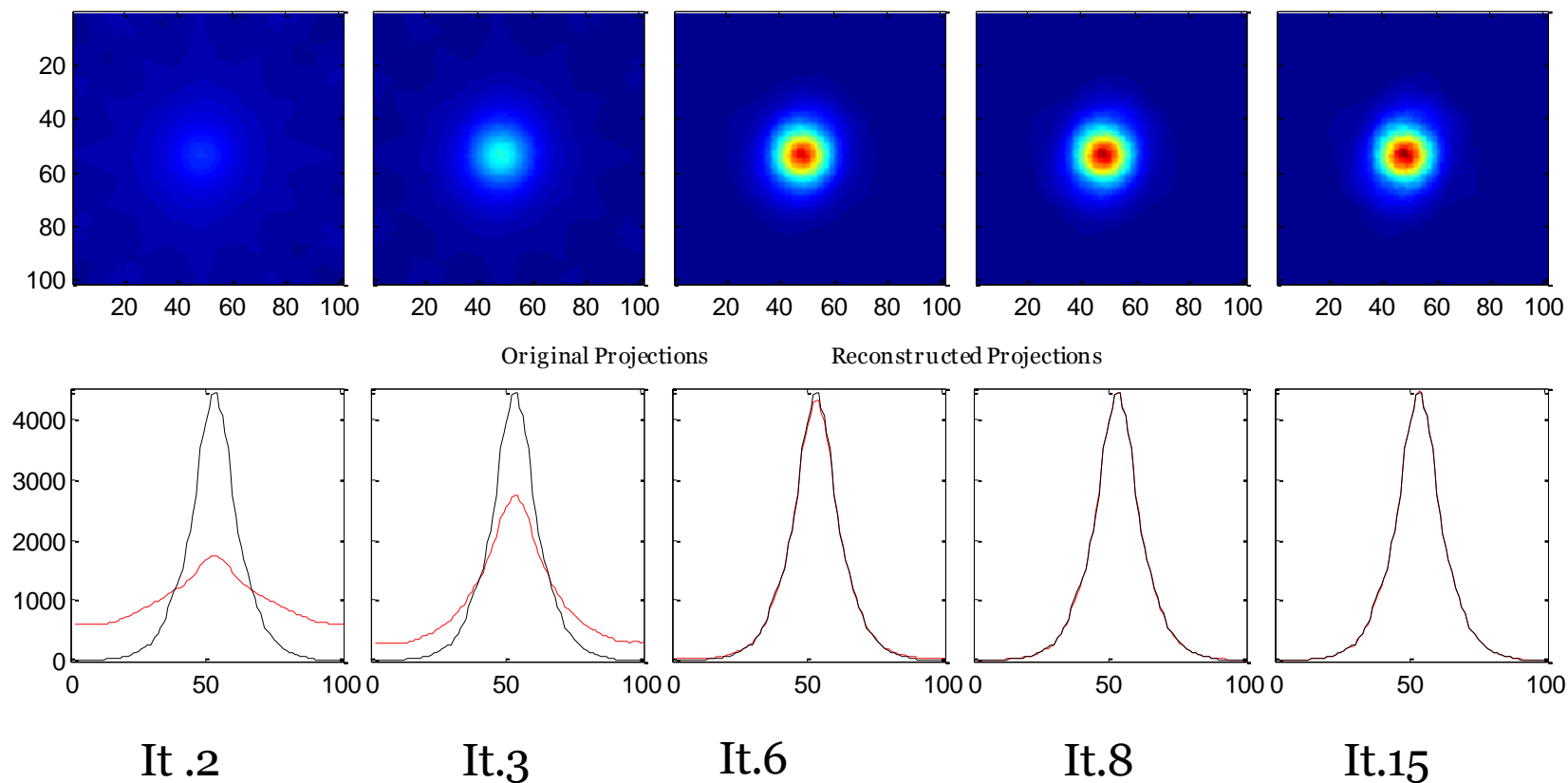
# An Illustration

The reconstructed image after 15 iterations



# An Illustration

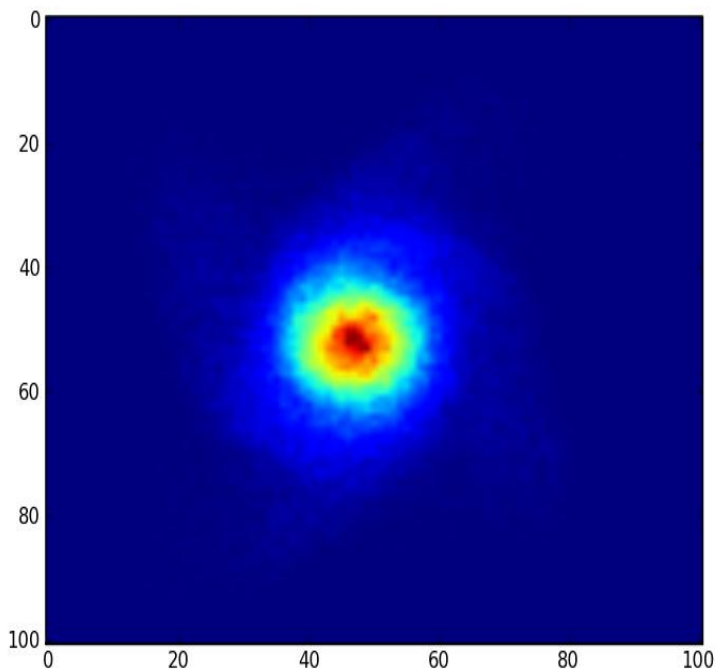
Reconstructed images with respect number of iterations



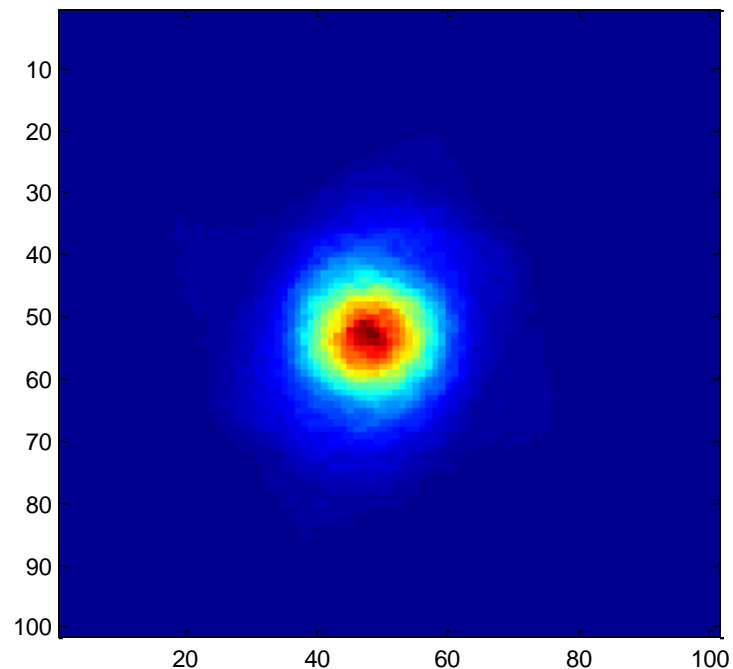
Projections measured at 90°

# An Illustration

Original image



Reconstructed image

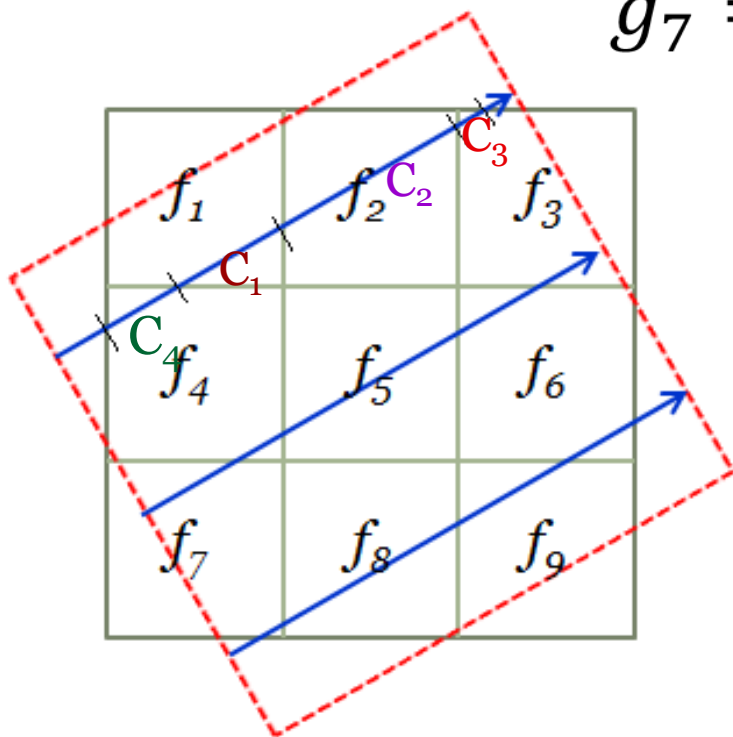




# How?

Algebraic Reconstruction Technique for more than 2 projections  
 Sparse matrix for more projection angles not equal to  $0^\circ$  and  $90^\circ$

$$g_7 = C_4 f_4 + C_1 f_1 + C_2 f_2 + C_3 f_3$$



More angles  $\rightarrow$  more complicated  
 sparse matrix

Number of rows

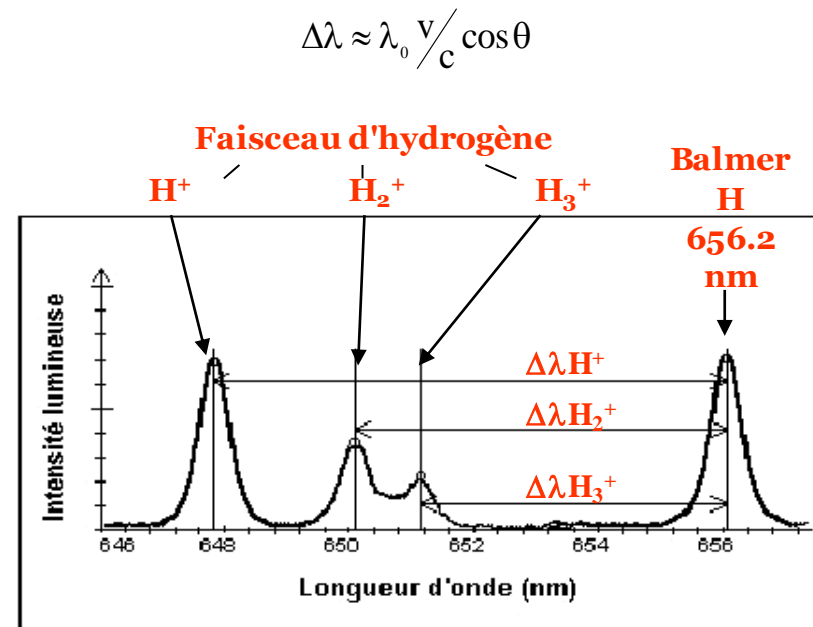
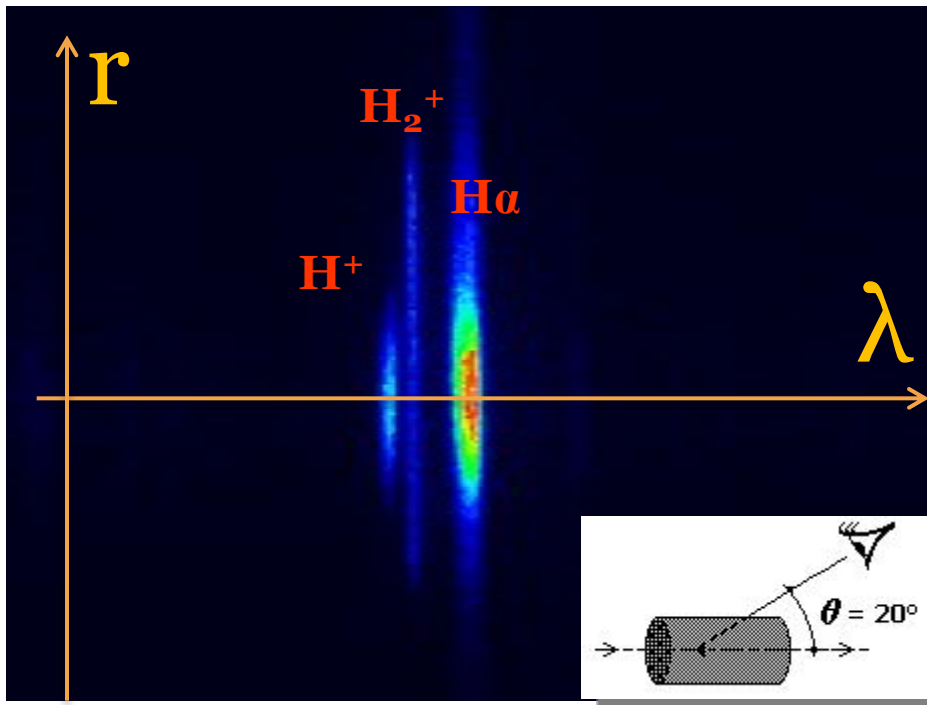
= length of one projection  $\times$  number of projections

Number of columns

= (length of one projection)<sup>2</sup>

# Optical Profiler in IPN/CEA

Doppler Shift Spectroscopy allows discrimination of different beam components



\*Pottin, B, (2001) Etude d'un profileur optique de faisceaux intenses de protons par absorption laser, Doctor of Science thesis. Institut de Physique Nucléaire

\*P. Ausset, et. al., *Transverse Beam Profile Measurements for High Power Proton Beams*, Proceedings of EPAC2001, Paris, France

# Tomography

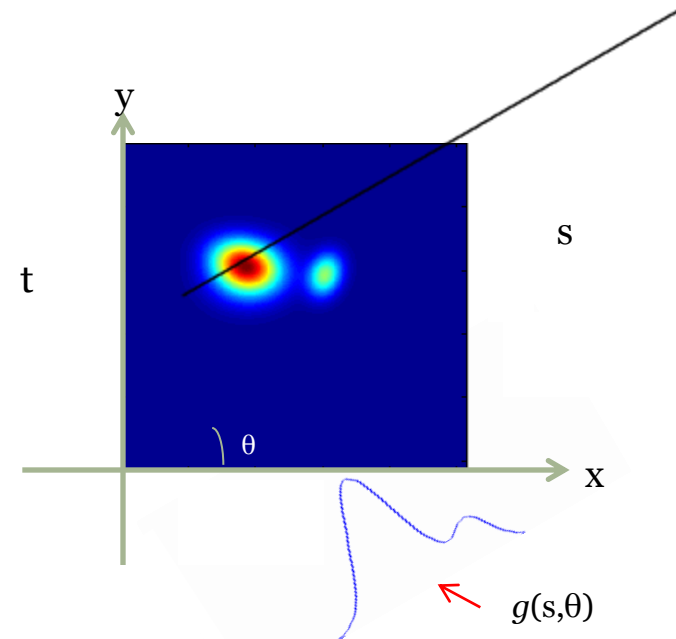
By Fourier Slice Theorem, EXACT value of  $f(x,y)$  can be calculated given an infinite number of projections

$$g_n(s) = \int_{-\infty}^{+\infty} f(x_n(s, t), y_n(s, t)) dt$$

$$= \int_{-\infty}^{+\infty} f(s \cos \theta - t \sin \theta, s \sin \theta + t \cos \theta) dt$$

Fourier Slice theorem:

$$\int_{-\infty}^{+\infty} g(s, \theta) e^{-j2\pi vt} dt = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} f(x, y) e^{-j2\pi(v \cos \theta x + v \sin \theta y)} dx dy$$



# How?

## Iteration process

$$\overline{f}_j^{(k+1)} = \frac{\overline{f}_j^{(k)}}{\sum_{i=1}^n a_{ij}} \sum_{i=1}^n \frac{g_i}{\sum_{j'=1}^m a_{ij'} \overline{f}_{j'}^{(k)}} a_{ij}$$

- $g$  Vector of projection data
- $f$  Vector of unknown slice data
- $A$  Matrix such that  $g = Af$
- $a_{ij}$  Value of element located at the  $i^{\text{th}}$  and  $j^{\text{th}}$  column of matrix  $A$
- $i$  Projection subscript
- $j$  Pixel subscript
- $g_i$  Number of counts in the  $i^{\text{th}}$  bin of the projection dataset
- $m$  Number of pixels
- $n$  Number of bins

$$\text{Image}^{(k+1)} = \text{Image}^{(k)} \times \text{Normalized Backprojections of } \left( \frac{\text{Measured projections}}{\text{Projections of image}^{(k)}} \right)$$