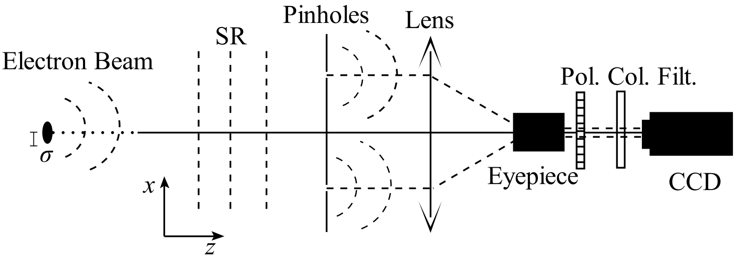
New interferometric aperture masking technique for full transverse beam characterization using synchrotron radiation

C. Carilli, U. Iriso, B. Nikolic, N. Thyagarajan, **L. Torino**
ltorino@cells.es

DEELS 2024, Soleil
10/06/2024

Synchrotron Radiation Interferometry (SRI)

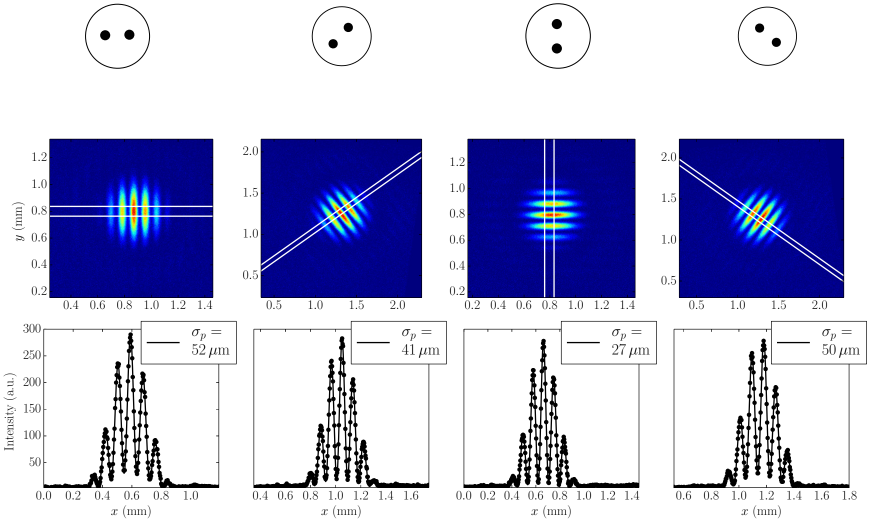


$$\sigma = \frac{\lambda L}{\pi D}\sqrt{\frac{1}{2}\ln\frac{1}{V}}$$

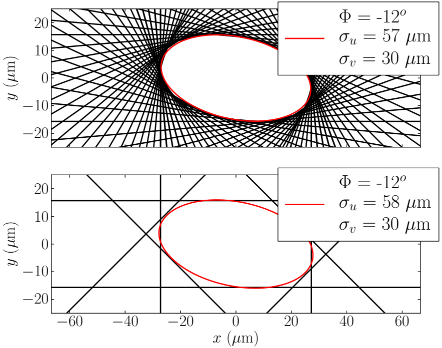
$$I = I_0 \left\{ \frac{J_1\left(\frac{2\pi a x}{\lambda f}\right)}{\left(\frac{2\pi a x}{\lambda f}\right)} \right\}^2 \times \left\{ 1 + V \cos\left(\frac{2\pi D x}{\lambda f}\right) \right\}$$

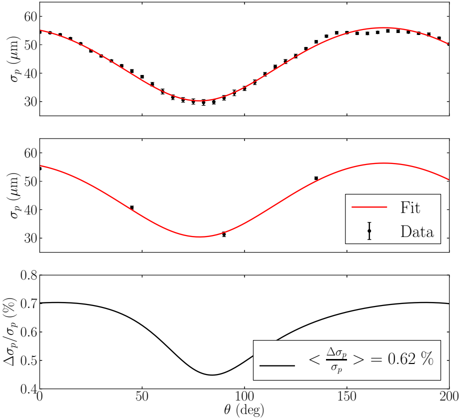
- I_0: Intensity
- a: Pinholes radius
- λ: SR wavelength
- f: Focal distance of the optical system
- D: Pinholes distance
- V: Visibility
- L: Distance from the source

Transverse Beam Reconstruction – 4 Projections



Transverse Beam Reconstruction – Results 4 Projections

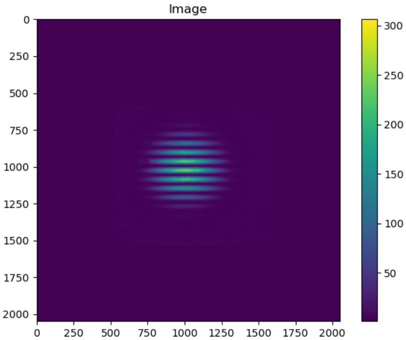




$$\sigma_p(\theta) = \sqrt{\sigma_u{}^2 \cos^2(\theta + \Phi) + \sigma_v{}^2 \sin^2(\theta + \Phi)}$$

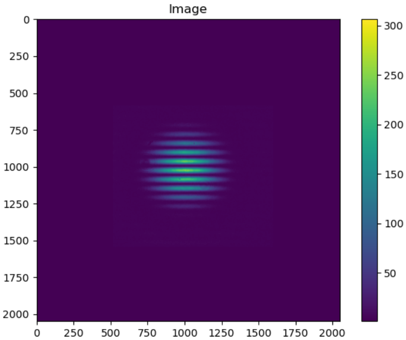
L. Torino and U. Iriso IBIC 2016, Barcelona, WEBL03
L. Torino and U. Iriso PRST-AB, 19, 122801 (2016)

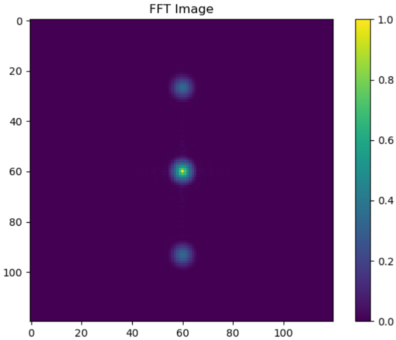
Image Vs Fourier plane



- Fringes:
  → aperture separation
  → pinhole radius
- Visibility:
  → pinhole illuminations
  → real visibility (γ)

Image Vs Fourier plane

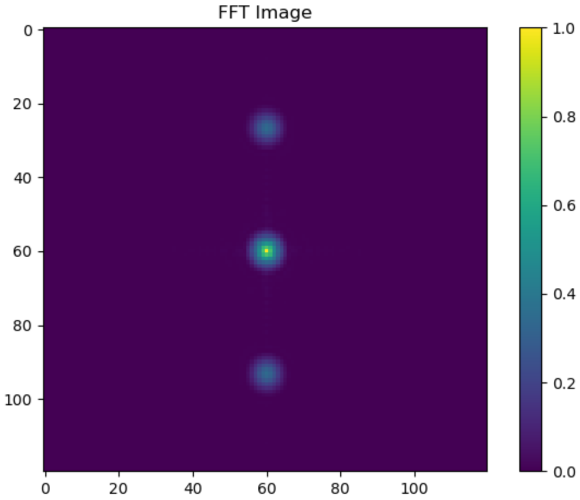




- Fringes:
  → aperture separation
  → pinhole radius
- Visibility:
  → pinhole illuminations
  → real visibility (γ)

- Separation between peaks:
  → aperture separation
  → pinhole radius
- Intensity of peaks:
  → pinhole illumination
  → real visibility (γ)

Fourier plane



- Central peak: "auto-correlation"
  - $I_{00} \propto i_{a0} + i_{a1}$
- Upper (lower) peak:
  - $I_{01} \propto \sqrt{i_{a0}} \times \sqrt{i_{a1}} \times \gamma$
  - $v \propto D$

I_{00}: Intensity central peak in the Fourier plane

I_{01}: Intensity peak in the Fourier plane related with apertures $a0$ and $a1$

i_a: Illumination of the aperture

γ: Real visibility

v: Distance between I_{00} and I_{01}

D: Distance between pinholes

Fourier plane

FFT Image

Normalizing for the central peak intensity:

$$I_{00} = 1$$
$$I_{01} \propto \frac{\sqrt{i_{a0} \times i_{a1}}}{i_{a0} + i_{a1}} \gamma$$

- Central peak: "auto-correlation"
  - $I_{00} \propto i_{a0} + i_{a1}$
- Upper (lower) peak:
  - $I_{01} \propto \sqrt{i_{a0}} \times \sqrt{i_{a1}} \times \gamma$
  - $v \propto D$

I_{00}: Intensity central peak in the Fourier plane

I_{01}: Intensity peak in the Fourier plane related with apertures $a0$ and $a1$

i_a: Illumination of the aperture

γ: Real visibility

v: Distance between I_{00} and I_{01}

D: Distance between pinholes

*M.J. Boland and al., Proceedings of IBIC2012, Tsukuba, Japan, WECC03

Fourier plane

FFT Image

Normalizing for the central peak intensity:

$$I_{00} = 1$$

$$I_{01} \propto \frac{\sqrt{i_{a0} \times i_{a1}}}{i_{a0} + i_{a1}} \gamma$$

$$\rightarrow I_{01} \Leftrightarrow V$$

V : **measured visibility** in image plane

Assuming a Gaussian non tilted beam and knowing i_{a0} and i_{a1} (or that $i_{a0} = i_{a1}$)

$\rightarrow$ Fit the two points with a normalized Gaussian ($\sigma_{\mathcal{C}}$) free parameter:

$$I(v) = e^{-v^2/2\sigma_{\mathcal{C}}^2}$$

- Central peak: "auto-correlation"
  - $I_{00} \propto i_{a0} + i_{a1}$
- Upper (lower) peak:
  - $I_{01} \propto \sqrt{i_{a0}} \times \sqrt{i_{a1}} \times \gamma$
  - $v \propto D$

I_{00}: Intensity central peak in the Fourier plane

I_{01}: Intensity peak in the Fourier plane related with apertures $a0$ and $a1$

i_a: Illumination of the aperture

γ: Real visibility

v: Distance between I_{00} and I_{01}

D: Distance between pinholes

*M.J. Boland and al., Proceedings of IBIC2012, Tsukuba, Japan, WECC03

Fourier plane

FFT Image

Normalizing for the central peak intensity:

$$I_{00} = 1$$

$$I_{01} \propto \frac{\sqrt{i_{a0} \times i_{a1}}}{i_{a0} + i_{a1}} \gamma$$

$$\rightarrow I_{01} \Leftrightarrow V$$

V : **measured visibility** in image plane

Assuming a Gaussian non tilted beam and knowing i_{a0} and i_{a1} (or that $i_{a0} = i_{a1}$)

$\rightarrow$ Fit the two points with a normalized Gaussian (σ_C) free parameter:

$$I(v) = e^{-v^2/2\sigma_C^2}$$

σ_C : **Coherence length**

Converting the coordinates:

$$\sigma = \frac{\lambda L}{\pi \sigma_C}$$

- Central peak: "auto-correlation"
  - $I_{00} \propto i_{a0} + i_{a1}$
- Upper (lower) peak:
  - $I_{01} \propto \sqrt{i_{a0}} \times \sqrt{i_{a1}} \times \gamma$
  - $v \propto D$

I_{00}: Intensity central peak in the Fourier plane

I_{01}: Intensity peak in the Fourier plane related with apertures $a0$ and $a1$

i_a: Illumination of the aperture

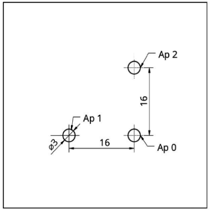
γ: Real visibility

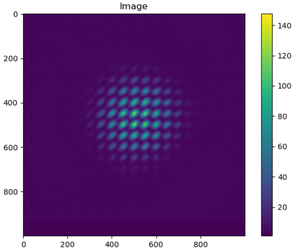
v: Distance between I_{00} and I_{01}

D: Distance between pinholes

*M.J. Boland and al., Proceedings of IBIC2012, Tsukuba, Japan, WECC03

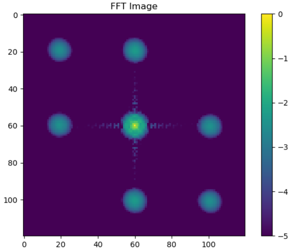
More apertures...



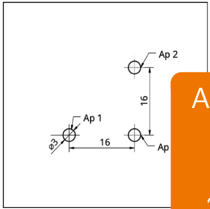


We have 4 independent peaks in the Fourier space:

- $I_{012} \propto i_{a0} + i_{a1} + i_{a2}$ (Before Normalization)
- $I_{01} \propto \frac{\sqrt{i_{a0} \times i_{a1}}}{i_{a0}+i_{a1}+i_{a2}} \gamma_{a0-a1}$
- $I_{02} \propto \frac{\sqrt{i_{a0} \times i_{a2}}}{i_{a0}+i_{a1}+i_{a2}} \gamma_{a0-a2}$
- $I_{12} \propto \frac{\sqrt{i_{a1} \times i_{a2}}}{i_{a0}+i_{a1}+i_{a2}} \gamma_{a1-a2}$



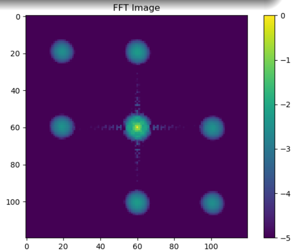
More apertures...



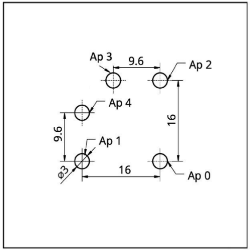
Assuming a Gaussian non tilted beam and knowing i_{a0}, i_{a1} and i_{a2} (or knowing that $i_{a0} = i_{a1} = i_{a2}$) $\rightarrow$ Fit the three points with a normalized 2D-Gaussian (σ_{Cx} and σ_{Cy} as free parameter) in each direction and retrieve the 2-D Beam

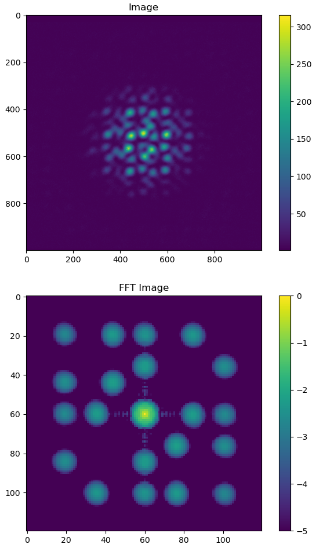
We have 4 independent peaks i

- $I_{012} \propto i_{a0} + i_{a1} + i_{a2}$ (Before Normalization)
- $I_{01} \propto \frac{\sqrt{i_{a0} \times i_{a1}}}{i_{a0}+i_{a1}+i_{a2}} \gamma_{a0-a1}$
- $I_{02} \propto \frac{\sqrt{i_{a0} \times i_{a2}}}{i_{a0}+i_{a1}+i_{a2}} \gamma_{a0-a2}$
- $I_{12} \propto \frac{\sqrt{i_{a1} \times i_{a2}}}{i_{a0}+i_{a1}+i_{a2}} \gamma_{a1-a2}$

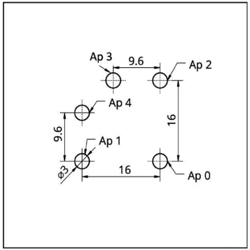


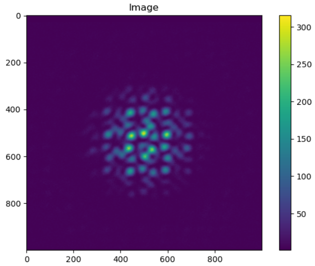
Even more apertures...





Even more apertures...

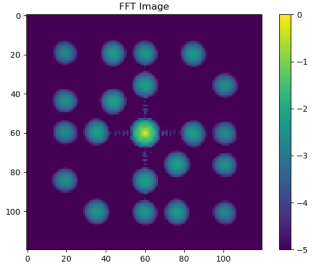




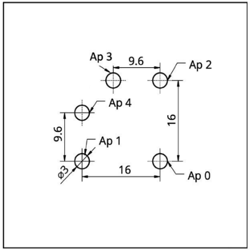
Parameter to reconstruct a Gaussian beam:

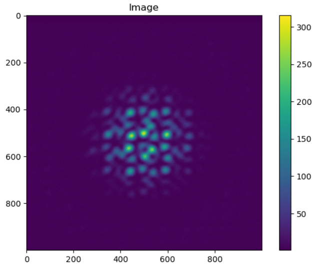
- σ_x, σ_y, Φ
- i_{a0}, i_{a1}, i_{a2}, i_{a3}, i_{a4}

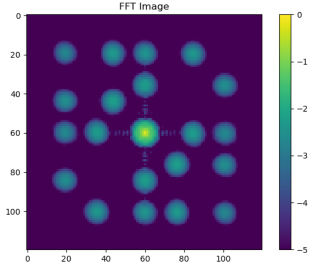
We have 9 points, just enough!



Even more apertures...







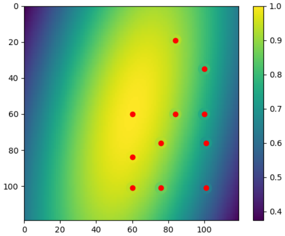
Parameter to reconstruct a Gaussian beam:

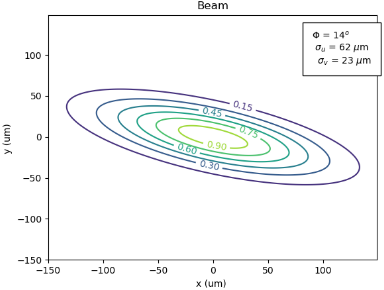
- σ_x, σ_y, Φ
- i_{a0}, i_{a1}, i_{a2}, i_{a3}, i_{a4}

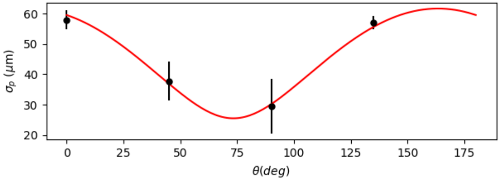
We have 9 points, just enough!

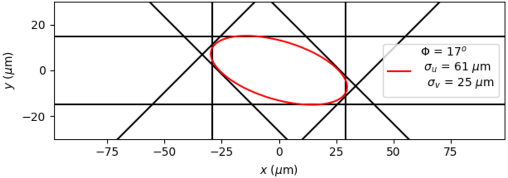
Self Calibration

Results 5 Holes Mask





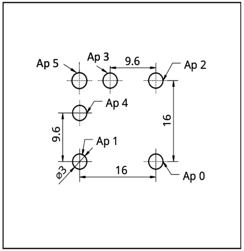


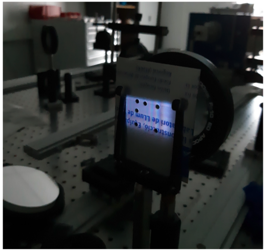


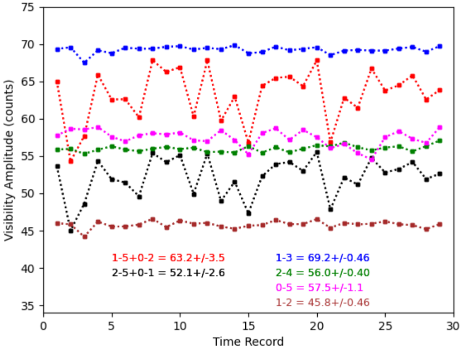
Beam size results are compatible with the one obtained with rotating mask SRI!

Non Redundant Aperture Mask

It is important to define a non redundant mask to avoid Bluring in the real and in the Fourier space





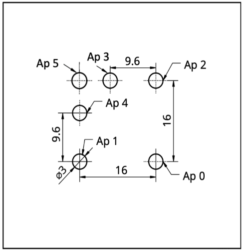


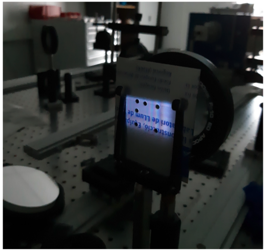
Red and **Black** redundant pinhole combination

*C. Carilli et al., arXiv:2406.02114, https://doi.org/10.48550/arXiv.2406.02114

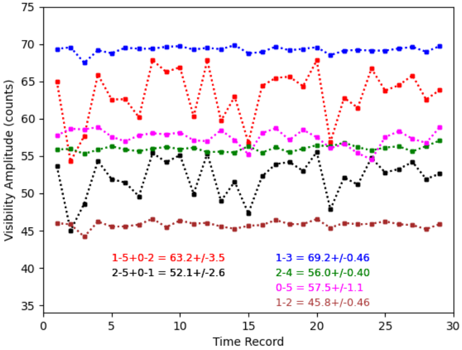
Non Redundant Aperture Mask

It is important to define a non redundant mask to avoid Bluring in the real and in the Fourier space





It is super-important fit and correct illuminations!



Red and **Black** redundant pinhole combination

*C. Carilli et al., arXiv:2406.02114, https://doi.org/10.48550/arXiv.2406.02114

Summary – 1

New technique for beam transverse characterization:

- Use non-redundant mask
- Fit and correct for aperture illuminations (Self Calibration)
- Work in the Fourier Space

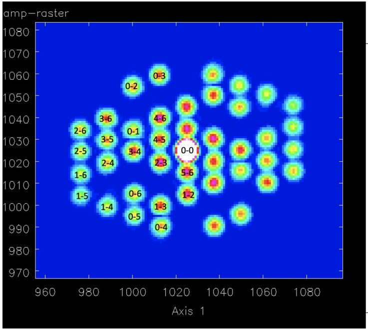
These techniques are well known (separately) in radio-astronomy and for the first time they are united to characterize a photon source

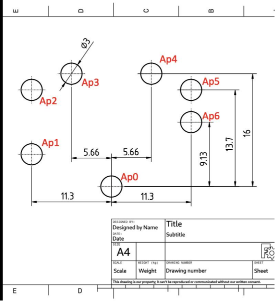
Advantages:

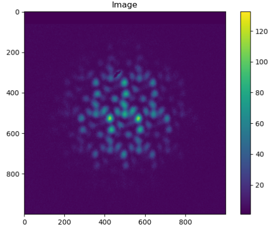
- Single shot measurement
- More light $\rightarrow$ low exposure time (0.5 ms 250 mA, $\lambda = 540/400$ nm)
- More holes can improve the resolution
  $\rightarrow$ Already tested 7 holes with promising results!

But we can do more!

7 Holes Non Redundant Mask







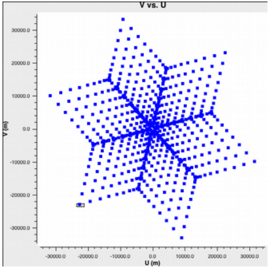
- Fourier space more filled and more complex $\rightarrow$ Library to find the baseline :)
- We have library to generate visibility, fit data and obtain the beam size (still $\beta-$version but working fine)
- Bonus: Astropy

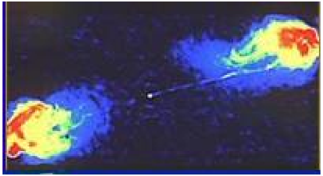
More holes and Model Fitting

The idea is to fill the Fourier space and reconstruct an arbitrary image

Very Large Array

Socorro, New Mexico





Summary – 2

- We developed a single acquisition full characterization of the electron beam using visible synchrotron radiation
- No worries about aperture illuminatins distribution
- Low impact of mirror deformation
- The technique is reliable and fast (low exposure time WRT pinhole)
- Data analysis can be optimized to be fast ($< 100\,\text{ms}$)
- Possible arbitrary beam reconstruction (maybe islands... High dynamic range achievable!)
- Possible application for optical path characterization, coherence monitor in beamlines, ...

We can still learn a lot from astronomical measurement techniques!

*B. Nikolic et al., arXiv:2405.12090v2, https://doi.org/10.48550/arXiv.2405.12090
*C. Carilli et al., arXiv:2406.02114, https://doi.org/10.48550/arXiv.2406.02114