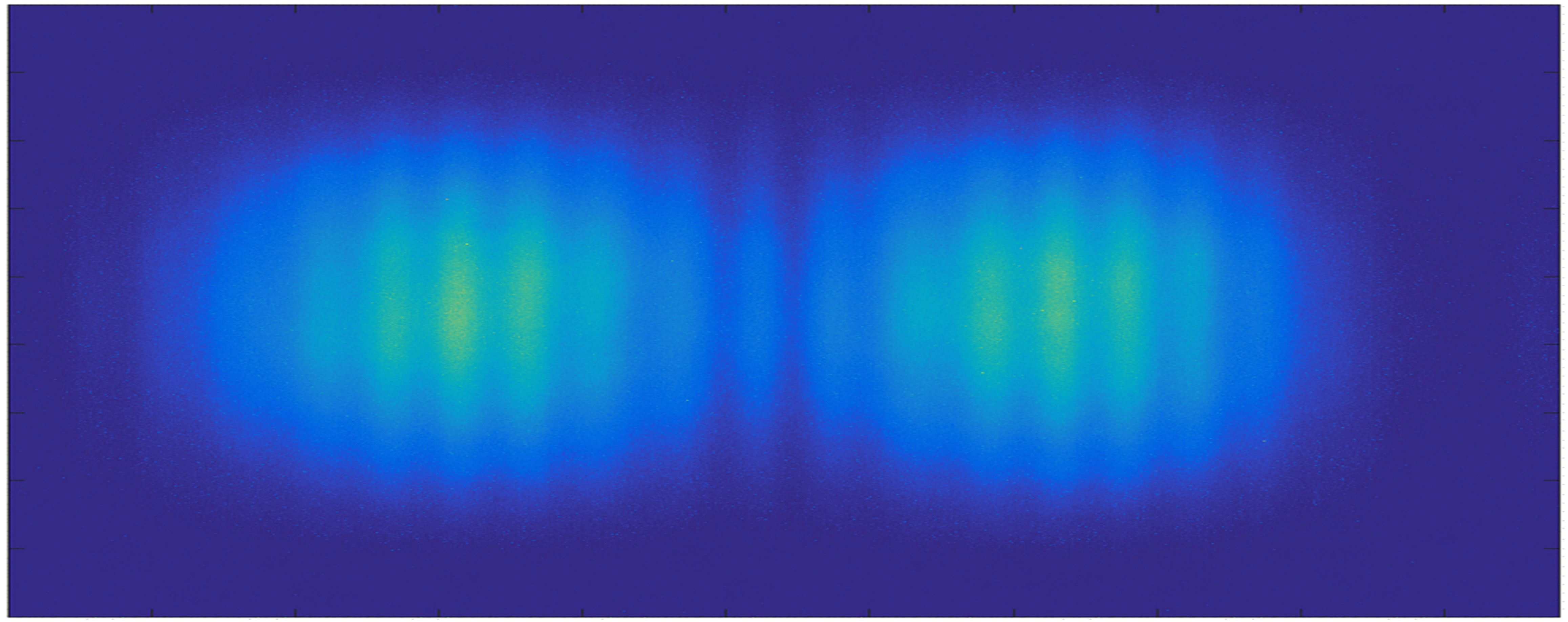
CERN

Beam Size Measurements Using Interferometry at LHC

Georges TRAD

E. BRAVIN, A. GOLDBLATT, S. MAZZONI,
T. MITSUHASHI, F. RONCAROLO



Outline

- Synchrotron Radiation at the LHC
- Present diagnostic system and its limitation
- A glimpse at the Interferometry
- LHC Interferometer
- Commissioning with beam
- Conclusions

- LHC (CERN) :
  Protons collider (27 Km circ.)
- Protons Energy at Injection:
  450 GeV, $\gamma=480$
- Protons Energy at Flat Top:
  6.5 TeV, $\gamma=6930$
  (Design: 7TeV, $\gamma=7460$)

LHC SR

Imaging at the LHC

SR Interferometry

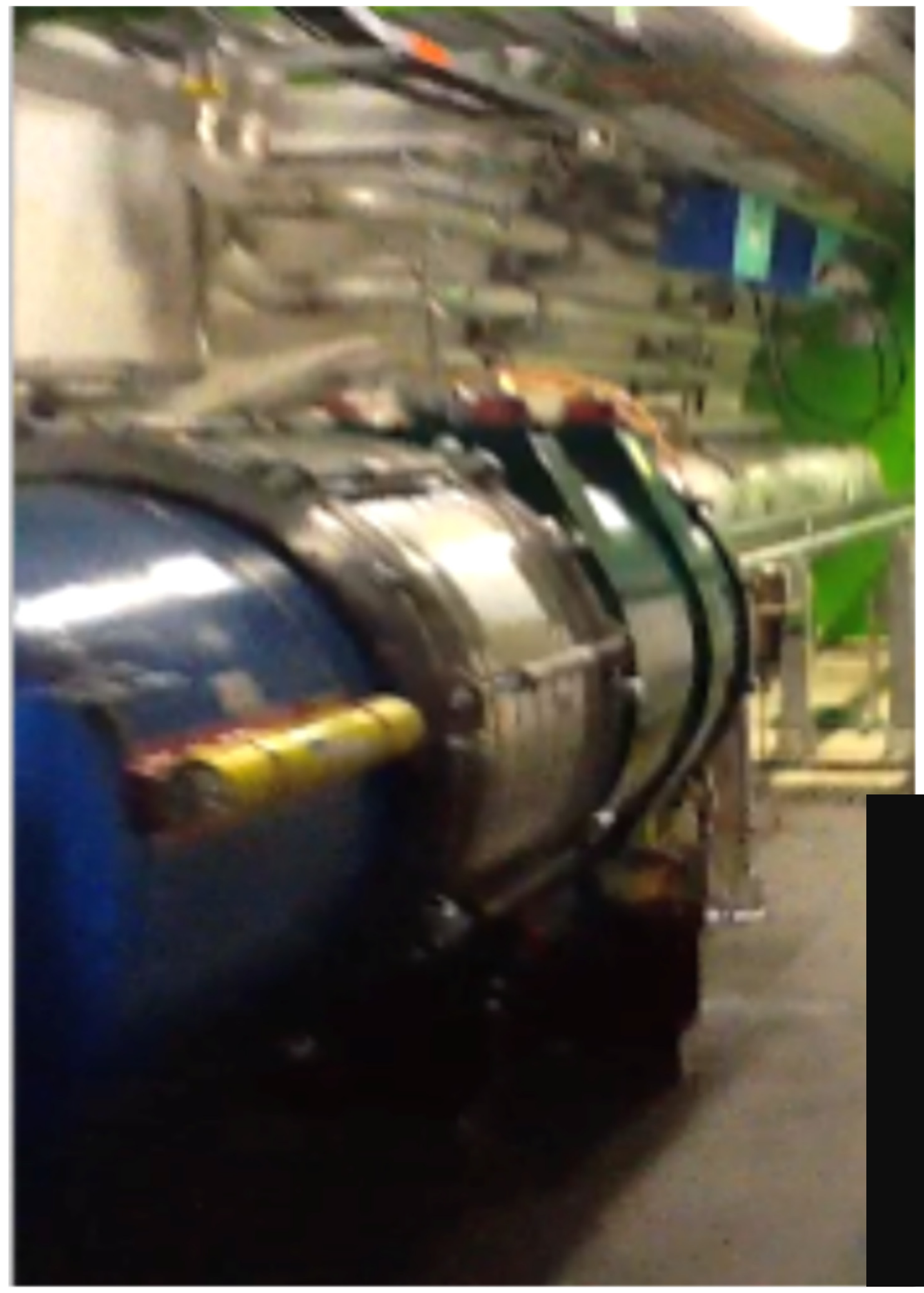
LHC Interferometer

Commissioning
At 6.5 TeV
At 450 GeV

2D Interferometer

- LHC (CERN) :
  Protons collider (27 Km circ.)
- Protons Energy at Injection:
  450 GeV, γ=480
- Protons Energy at Flat Top:
  6.5 TeV, γ=6930
  (Design: 7TeV, γ=7460)

- LHC (CERN) :
  Protons collider (27 Km circ.)
- Protons Energy at Injection:
  450 GeV, γ=480
- Protons Energy at Flat Top:
  6.5 TeV, γ=6930
  (Design: 7TeV, γ=7460)



Low Energy : Undulator main Light

Int. Energy : Undulator + D3 Edge

High Energy : D3 Edge + D3 core

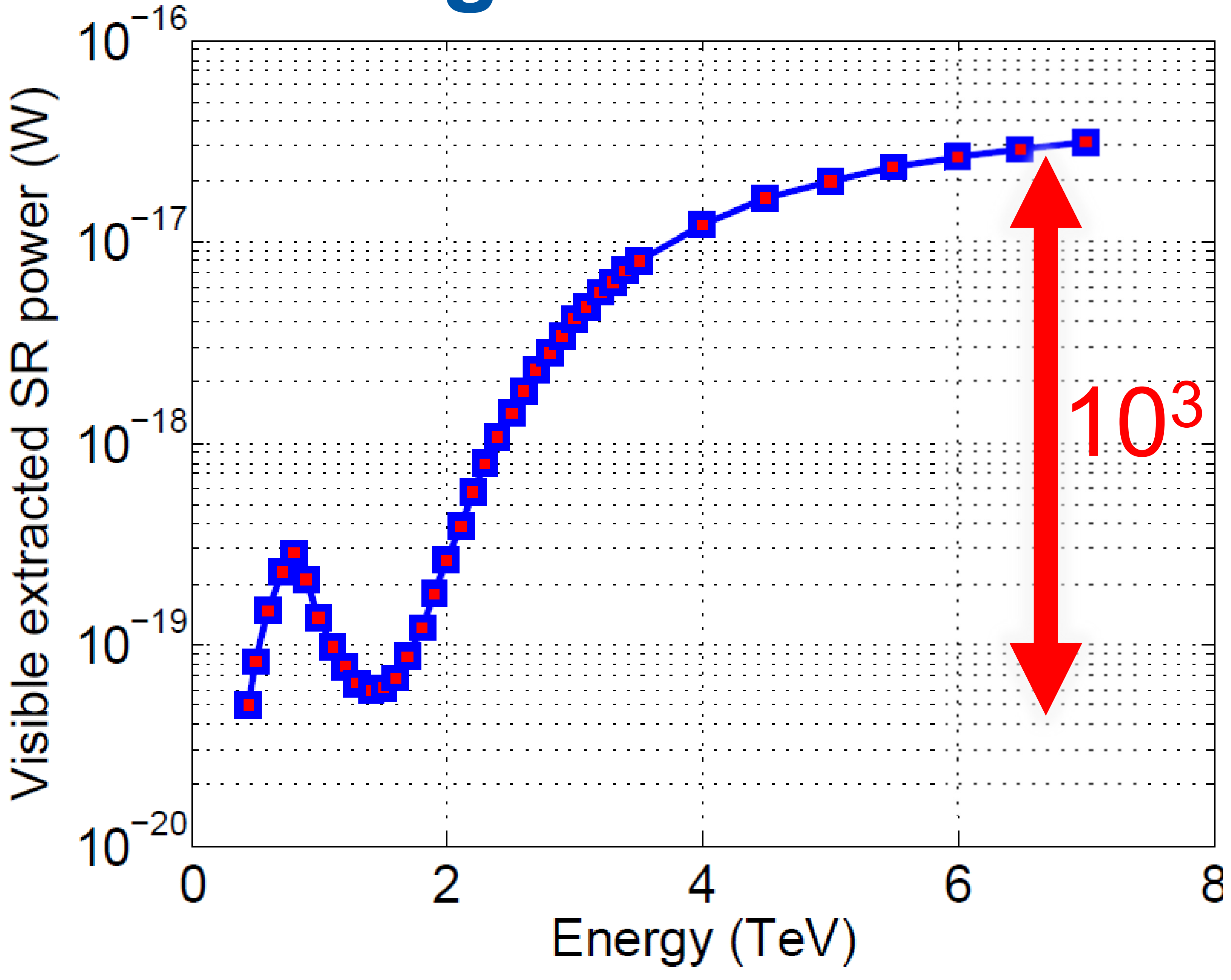
DIPOLE

D3, Length = 9.45 m
Bend.angle = 1.58 mrad
Radius curv.= 6 km

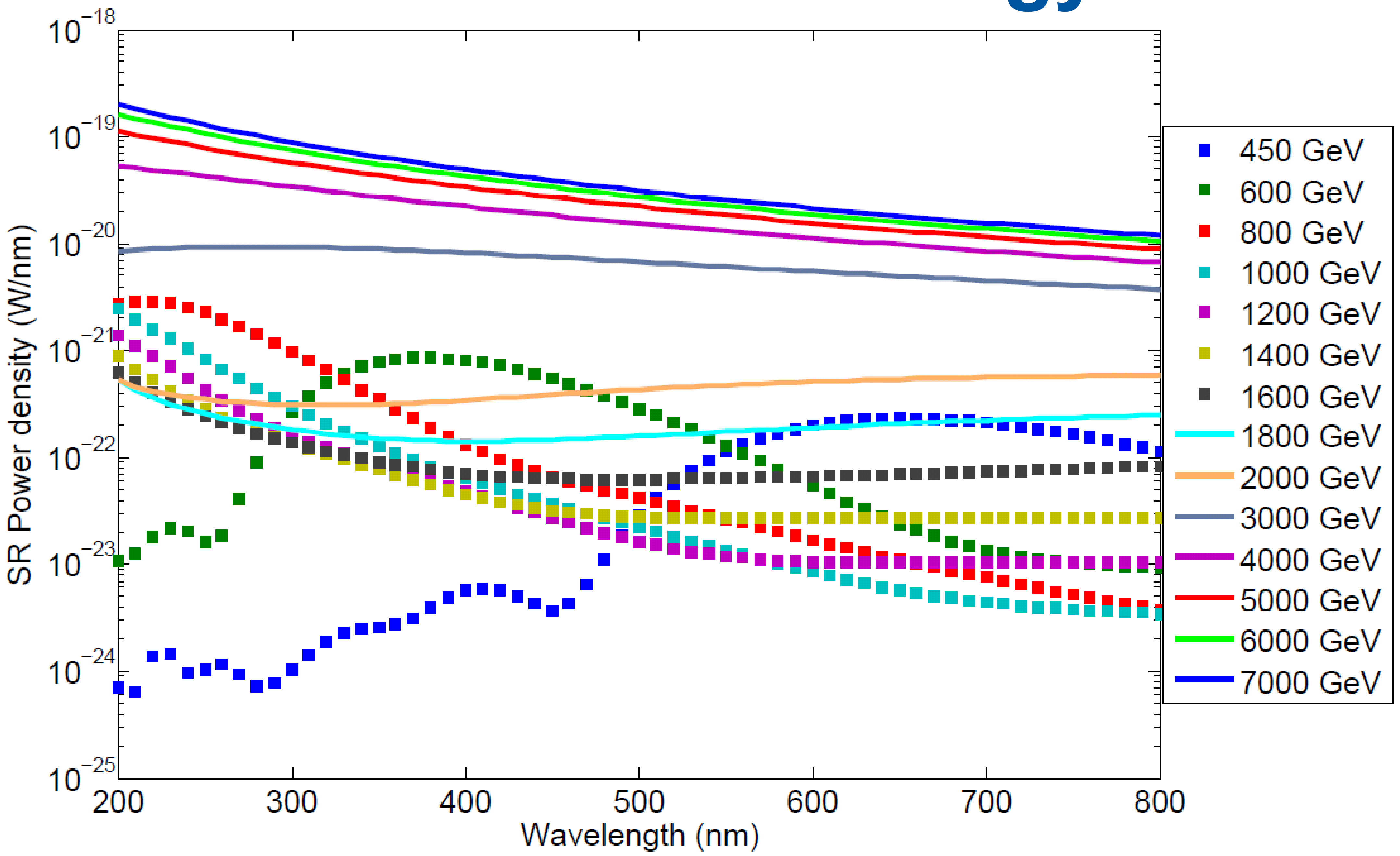
Undulator

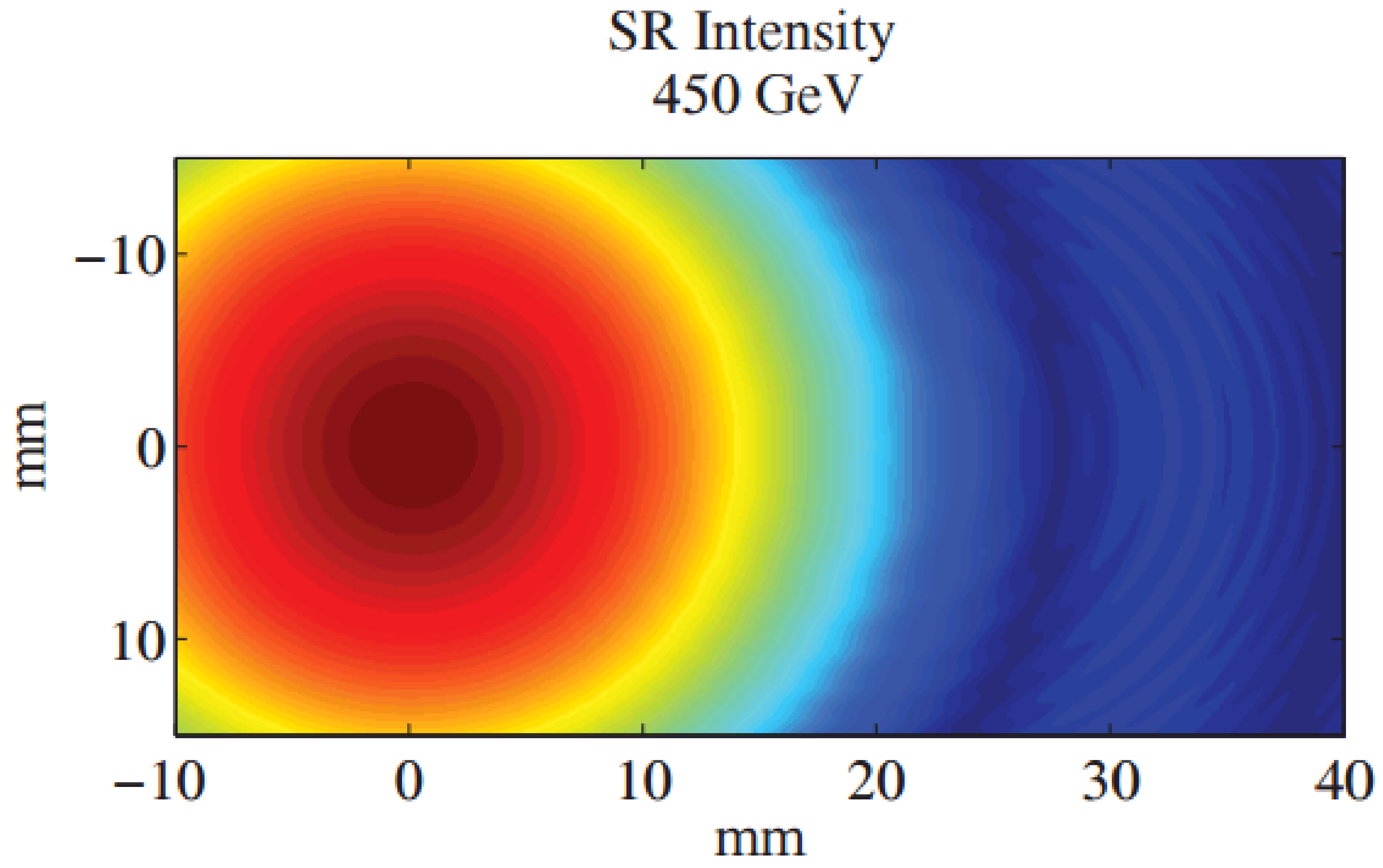
2 periods of 28cm
B= 5 T cte

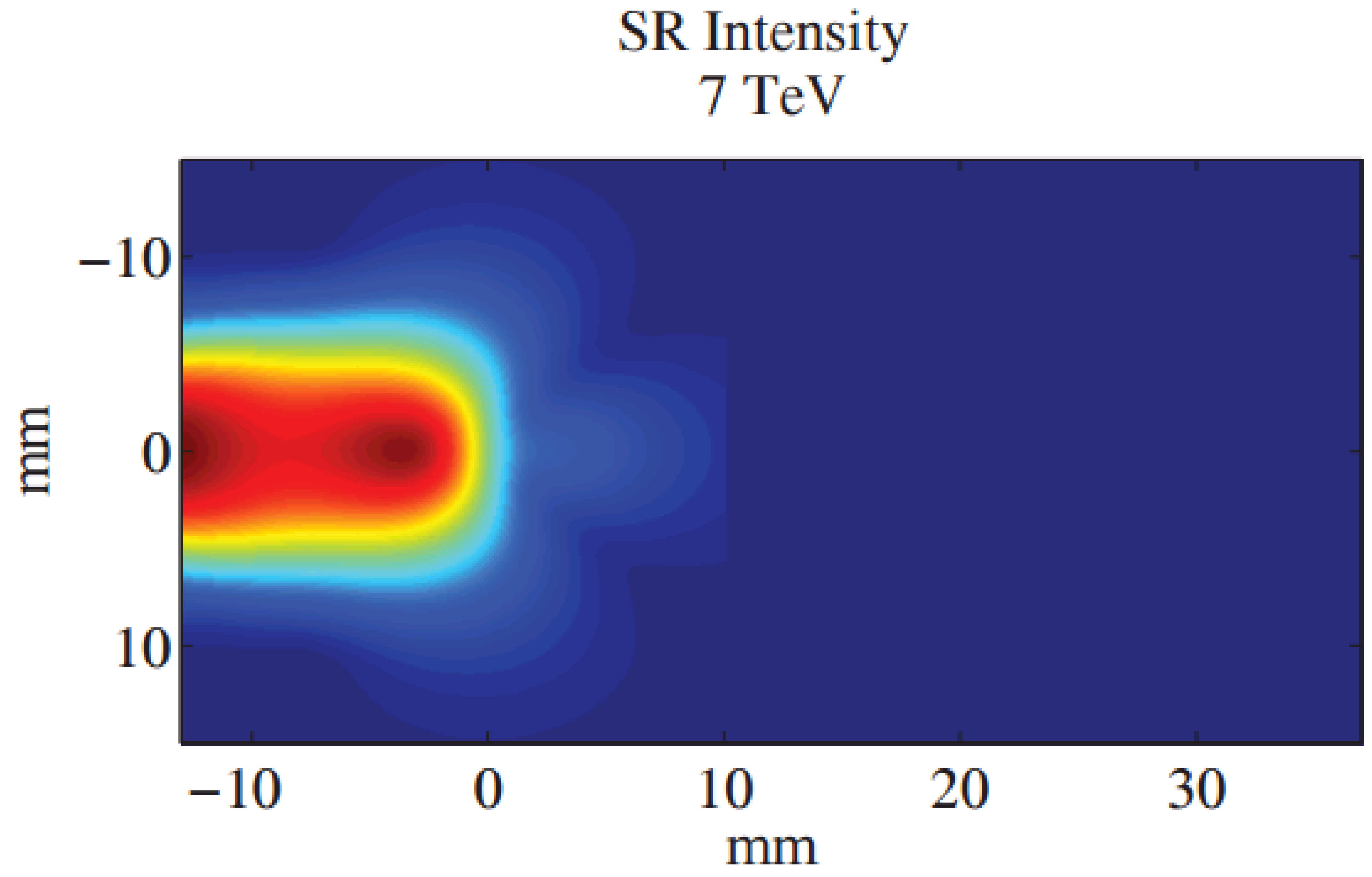
Extracted SR power/proton in the range of 200..800 nm



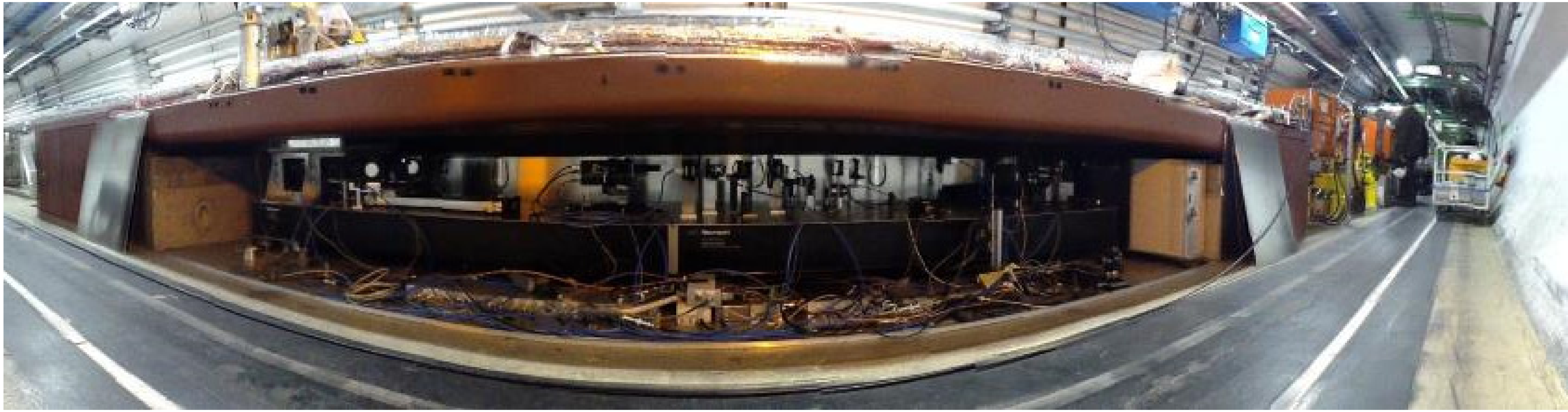
SR power density as function of beam energy



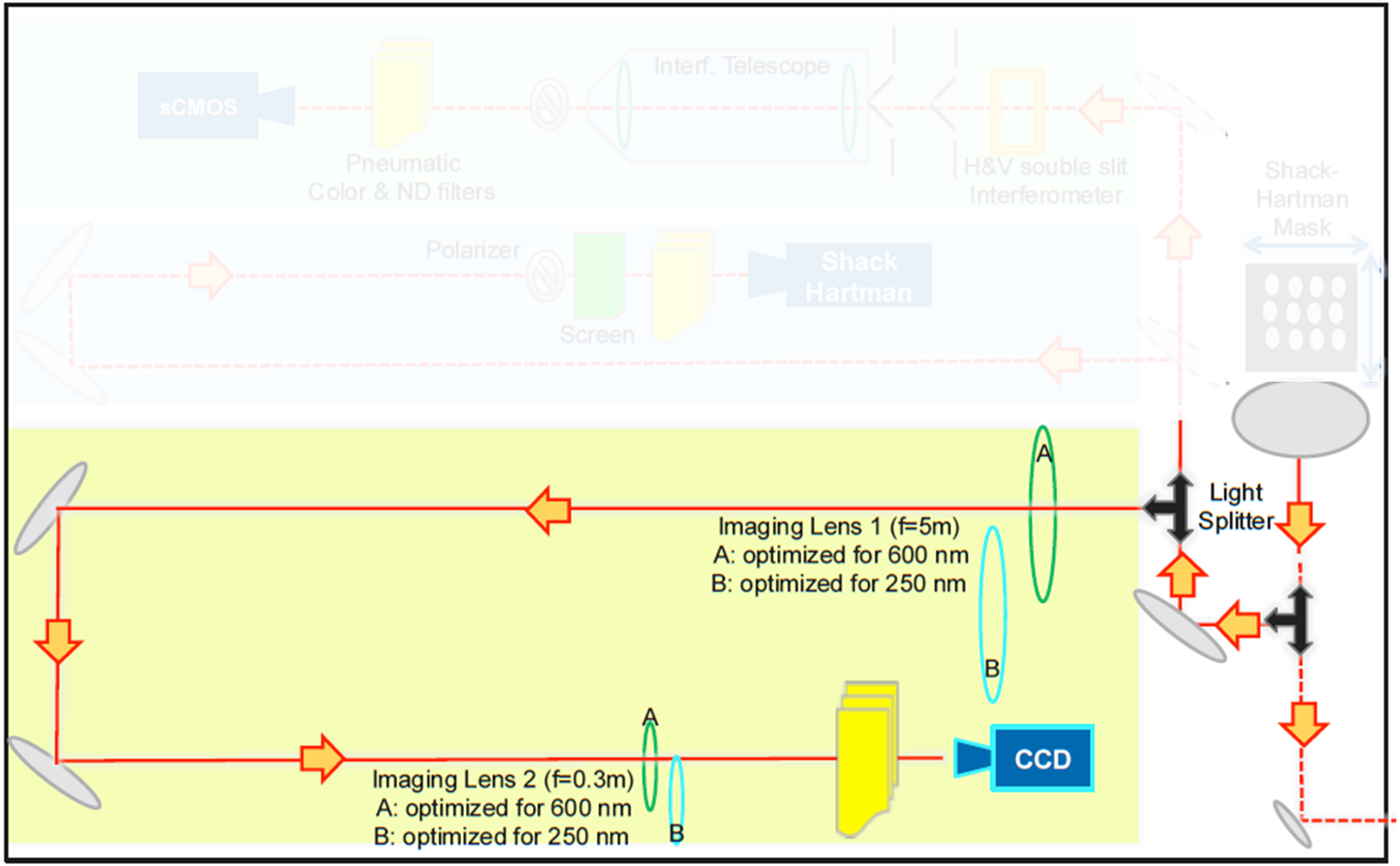




Beam Synchrotron Radiation Telescope



Beam Synchrotron Radiation Telescope



Imaging System

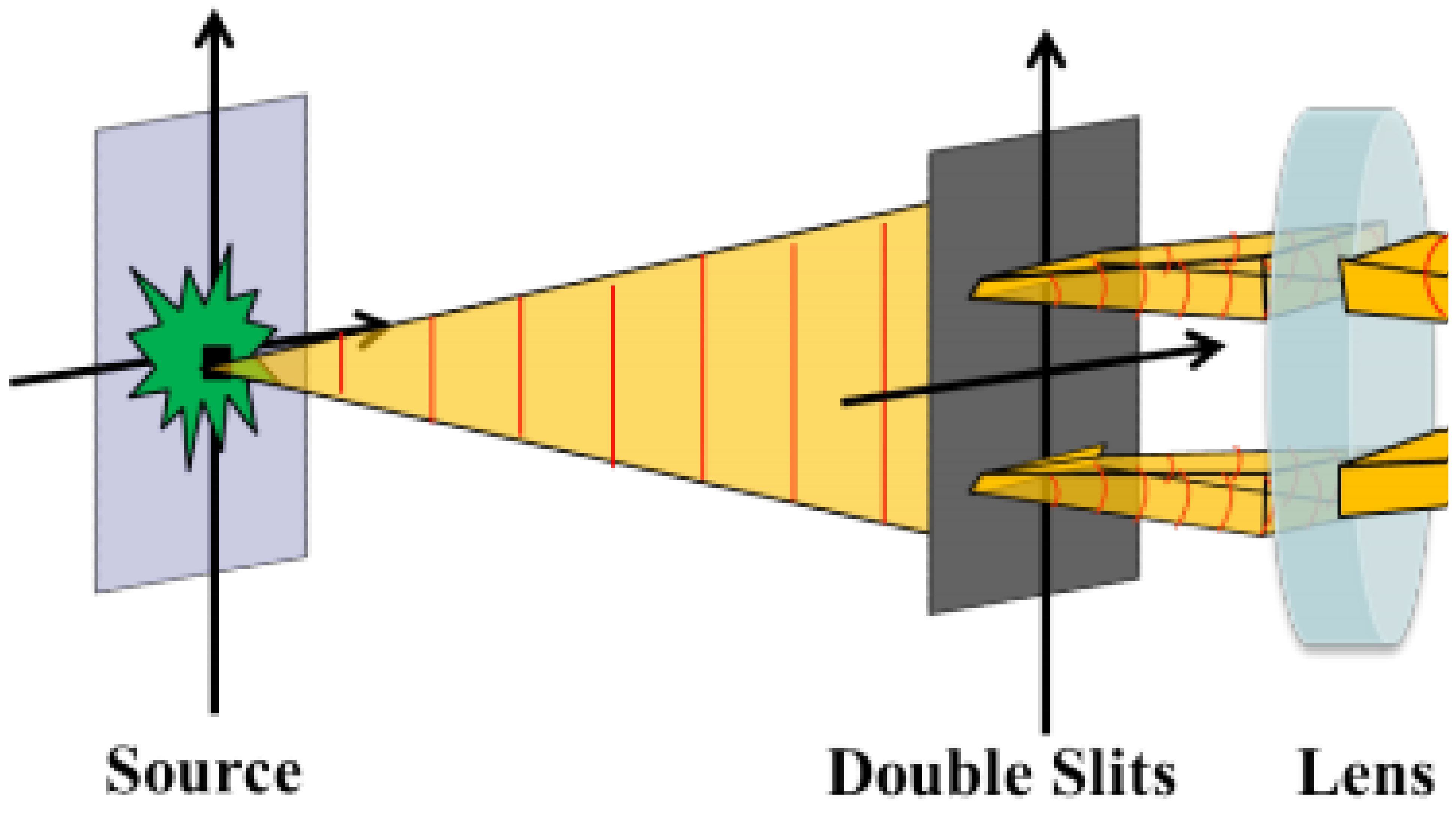
- Diffraction Limited Imaging system
- Switching between 2 Sets of lenses for visible and NUV operation
- Adaptable Focus to cope with SR source shift
- Resolution limited by SR characteristics (cone opening, wavelength and Incoherent depth of Field)
    - Simulated and measured: ~ 300 µm

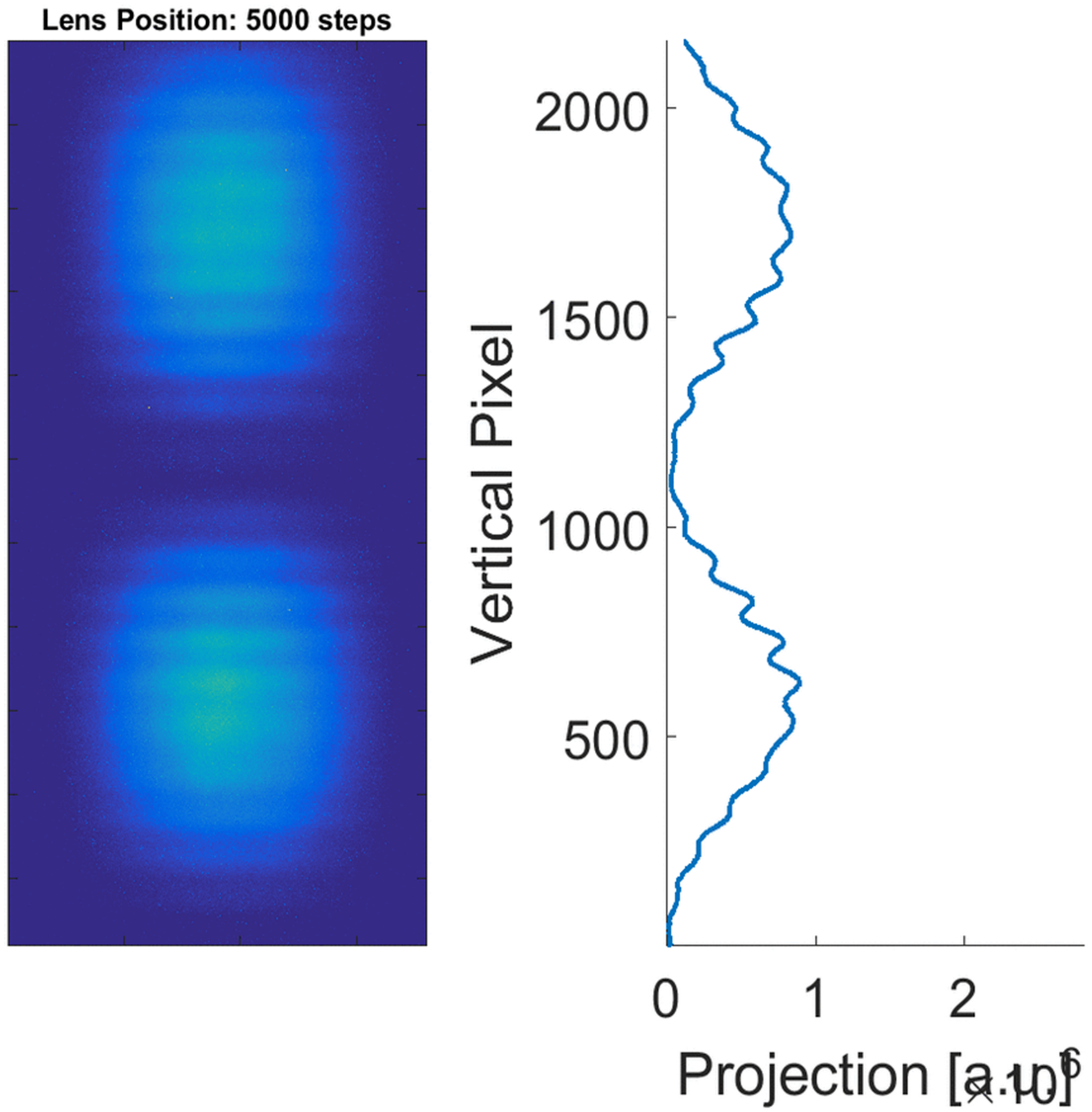
	σ_{min} [mm]	σ_{max} [mm]
450 GeV	0.63	2.35
7 TeV	0.16	0.6

$$\sigma_{Beam} = \sqrt{\sigma_{BSRT_{meas}}{}^2 - \sigma_{LSF}{}^2}$$

$$\boxed{\epsilon_{\varepsilon_{Beam}} = 2 \cdot \left(\frac{\sigma_{LSF}}{\sigma_{Beam}}\right)^2 \cdot \epsilon_{\sigma_{LSF}}}$$

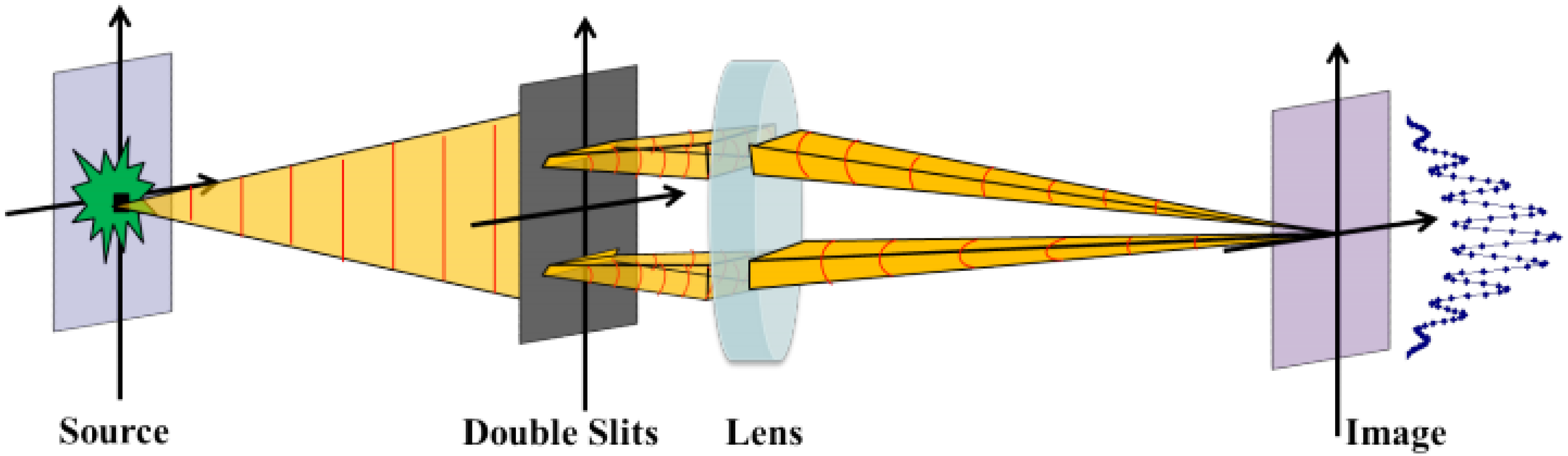
SR Interferometry





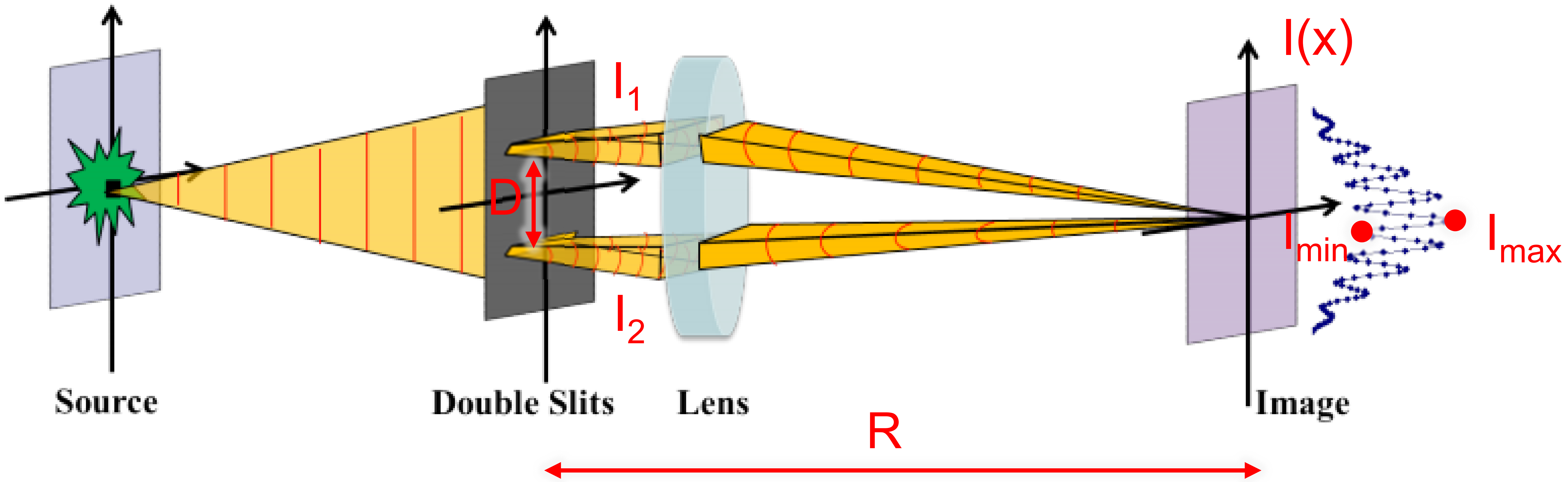
The spatial coherence of the SR is probed by measuring the fringe visibility and calculating the first order degree of mutual spatial coherence Γ at the slits plane

SR Interferometry



The spatial coherence of the SR is probed by measuring the fringe visibility and calculating the first order degree of mutual spatial coherence Γ at the slits plane

SR Interferometry



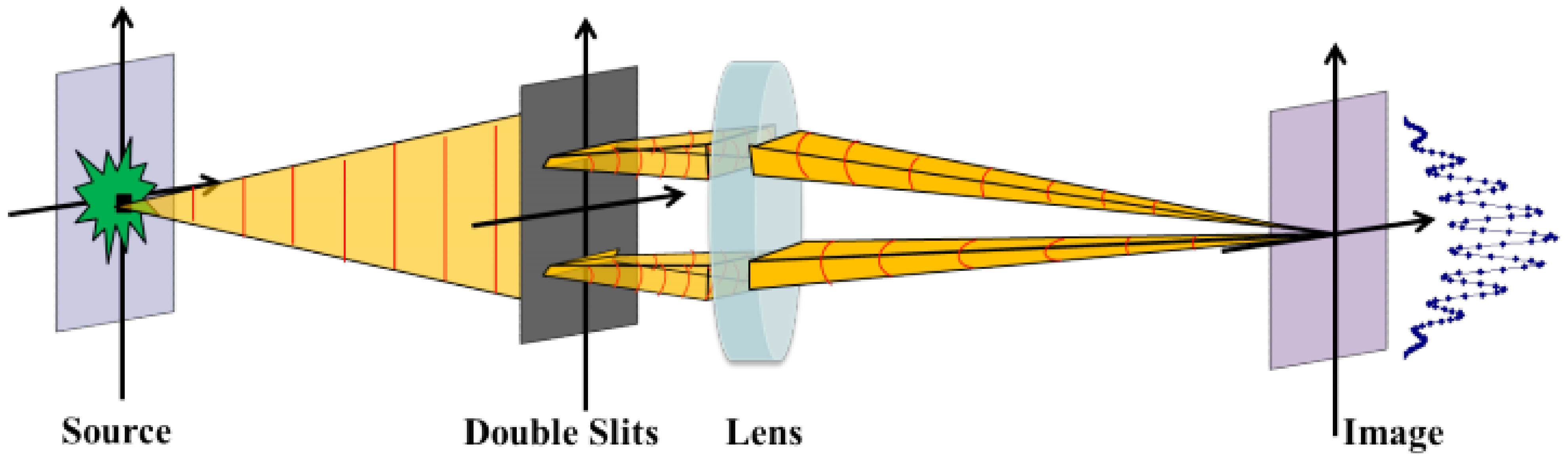
The spatial coherence of the SR is probed by measuring the fringe visibility and calculating the first order degree of mutual spatial coherence Γ at the slits plane

$$I(x) = I_0 \left[sinc\left(\frac{2\pi a}{\lambda_0 R} x \right) \right]^2 \cdot \left\{ 1 + |\Gamma| \, cos\left(\frac{2\pi D}{\lambda_0 R} x + \phi \right) \right\}$$

Fringe Visibility: $V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{2\sqrt{I_1 \cdot I_2}}{I_1 + I_2} |\Gamma|$

SR Interferometry

The beam size is derived based on the Van Cittert-Zernike theorem, where the degree of coherence Γ is the Fourier transform of the intensity distribution of the source



SR Interferometry

LHC SR

Imaging at the LHC

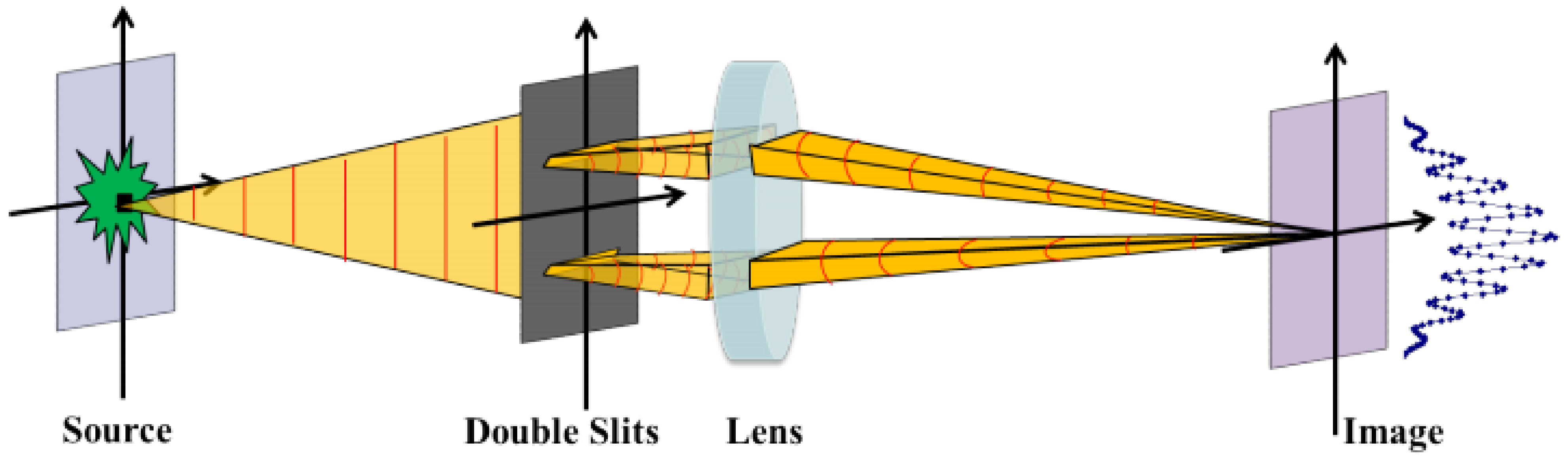
SR Interferometry

LHC Interferometer

Commissioning
At 6.5 TeV
At 450 GeV

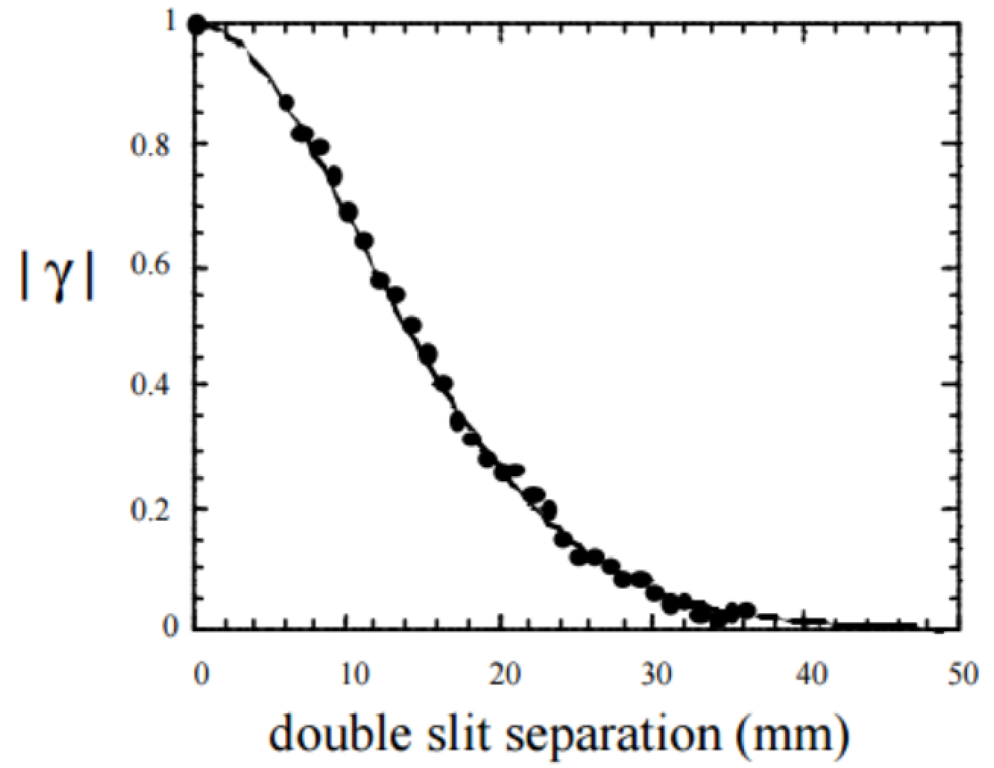
2D Interferometer

The beam size is derived based on the Van Cittert-Zernike theorem, where the degree of coherence Γ is the Fourier transform of the intensity distribution of the source



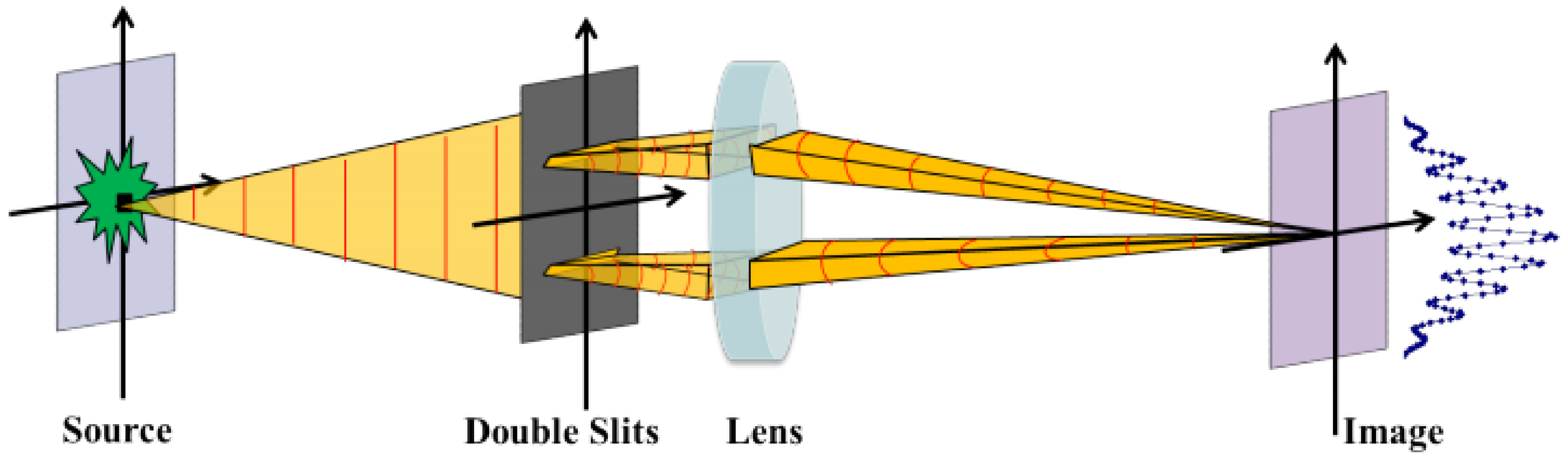
σ is analytically derived:

- **Slit Separation Scanning Mode**
  f(x) is obtained by applying an inverse Fourier transf. of the resulting curve Γ(D)



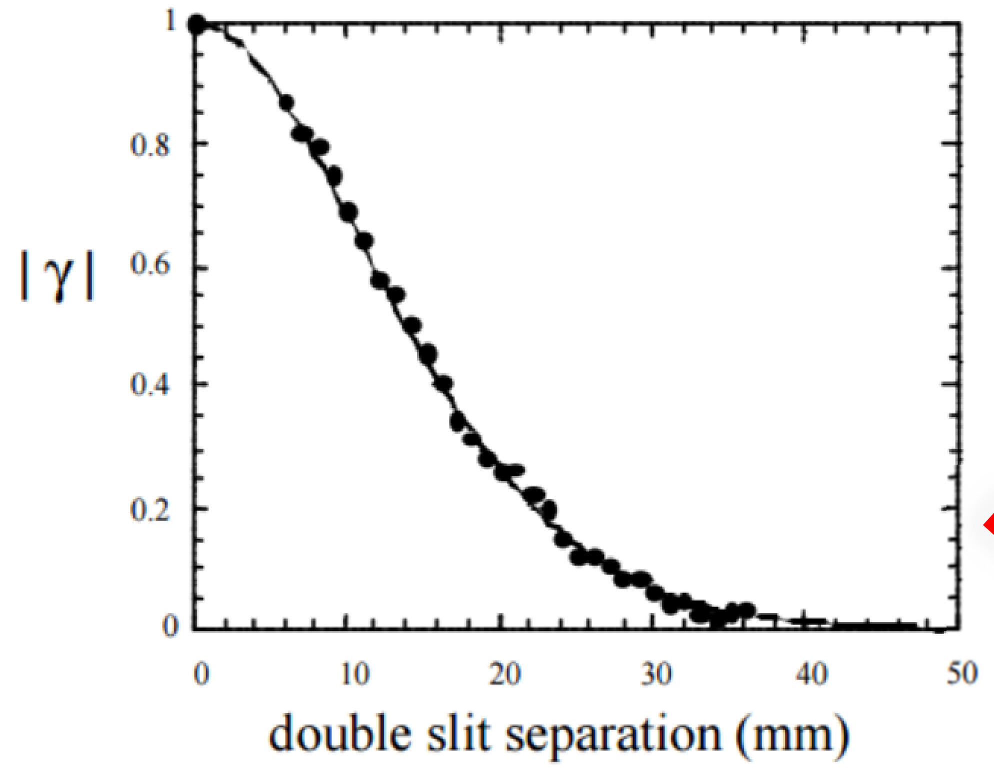
SR Interferometry

The beam size is derived based on the Van Cittert-Zernike theorem, where the degree of coherence Γ is the Fourier transform of the intensity distribution of the source

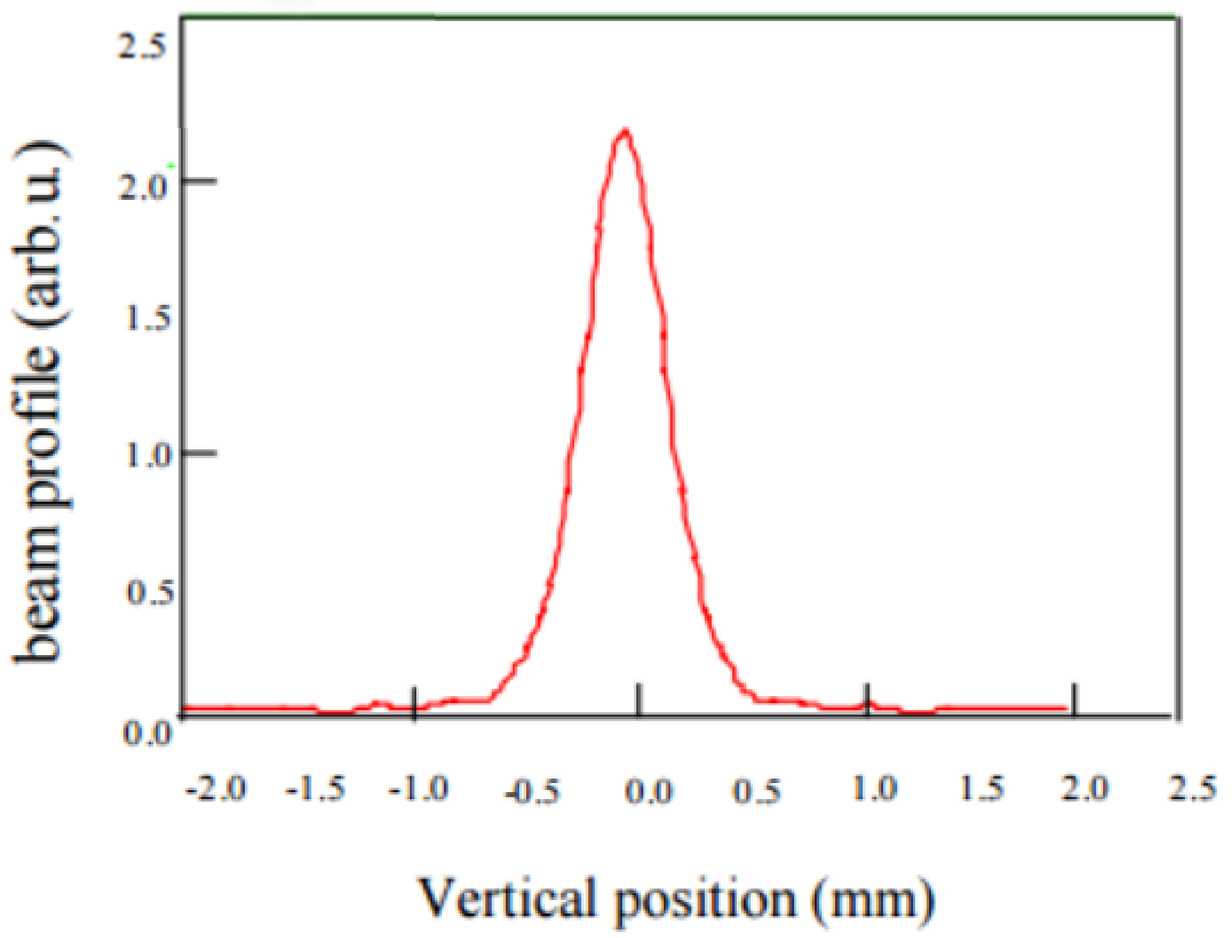


σ is analytically derived:

- **Slit Separation Scanning Mode**
  f(x) is obtained by applying an inverse Fourier transf. of the resulting curve Γ(D)

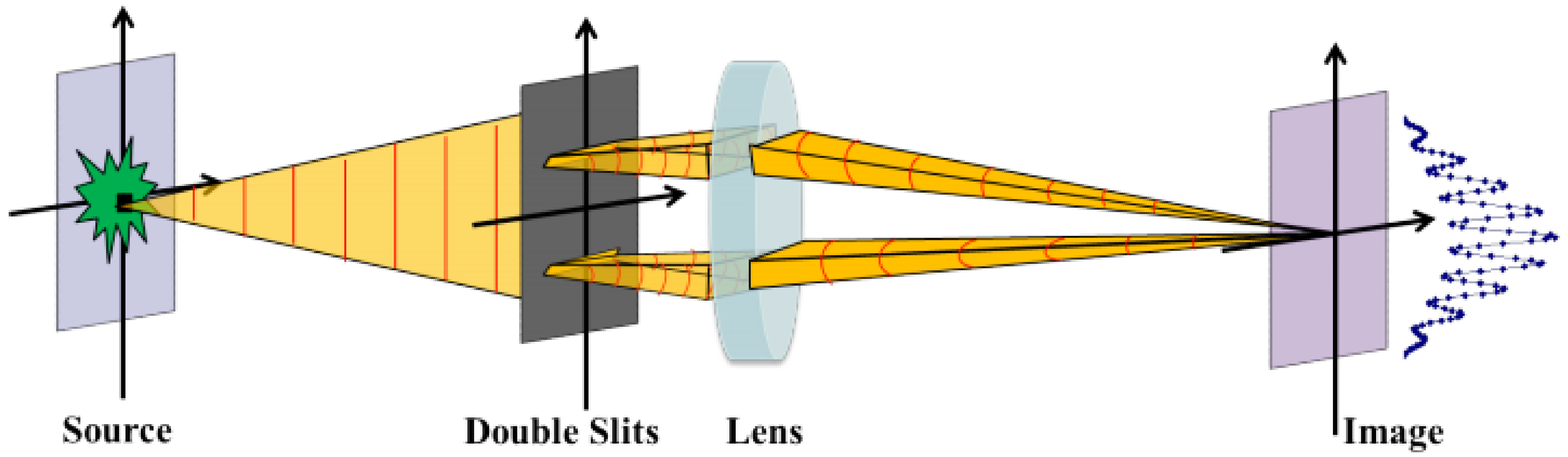


Inverse Fourier Transformation, Obtain beam profile



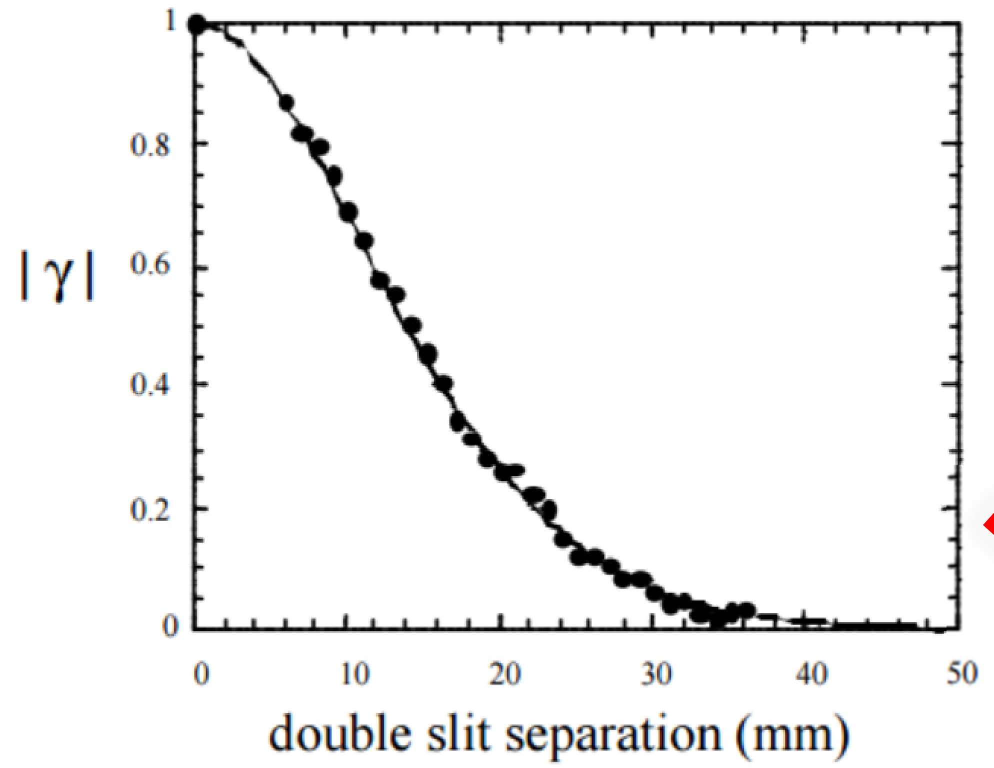
SR Interferometry

The beam size is derived based on the Van Cittert-Zernike theorem, where the degree of coherence Γ is the Fourier transform of the intensity distribution of the source

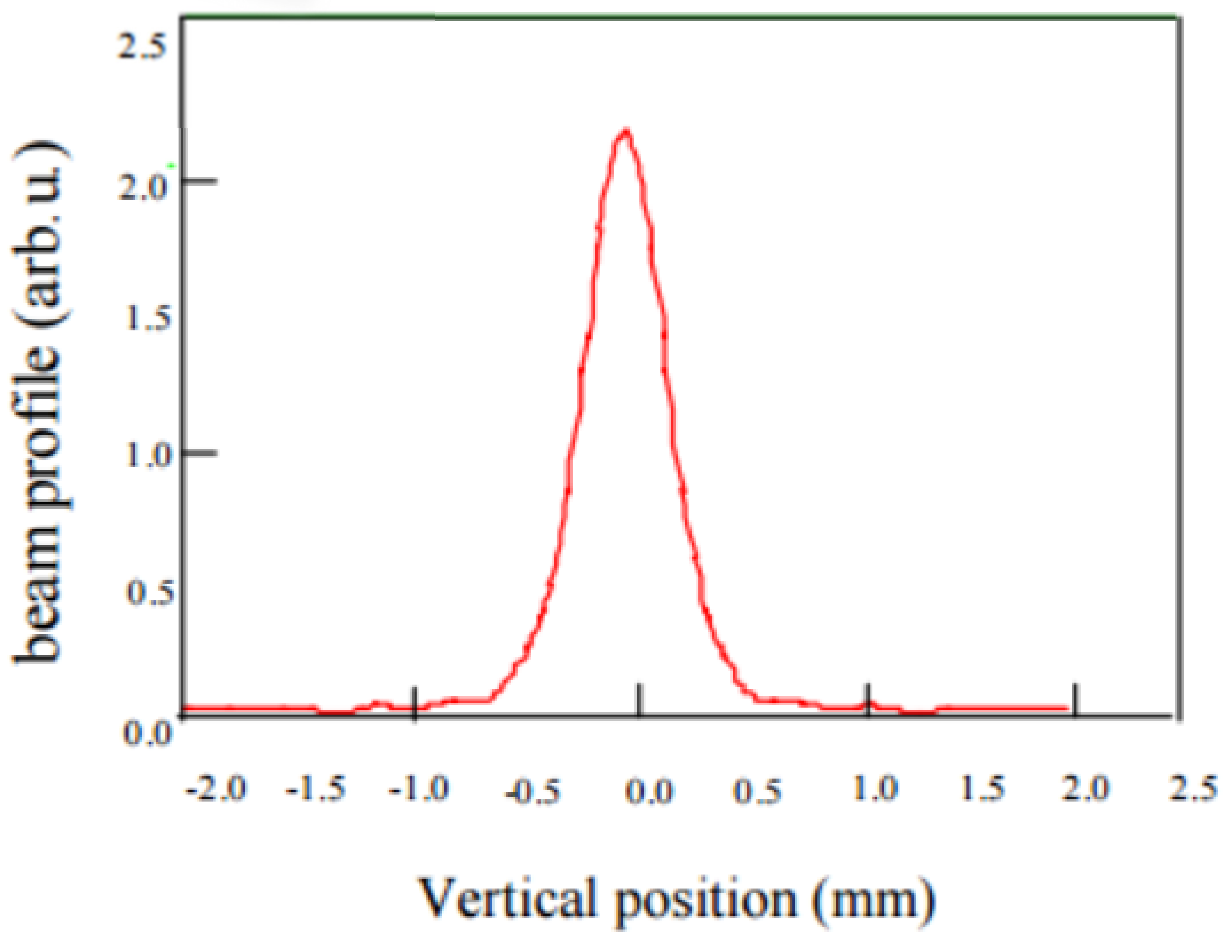


σ is analytically derived:

- **Slit Separation Scanning Mode**
  f(x) is obtained by applying an inverse Fourier transf. of the resulting curve Γ(D)



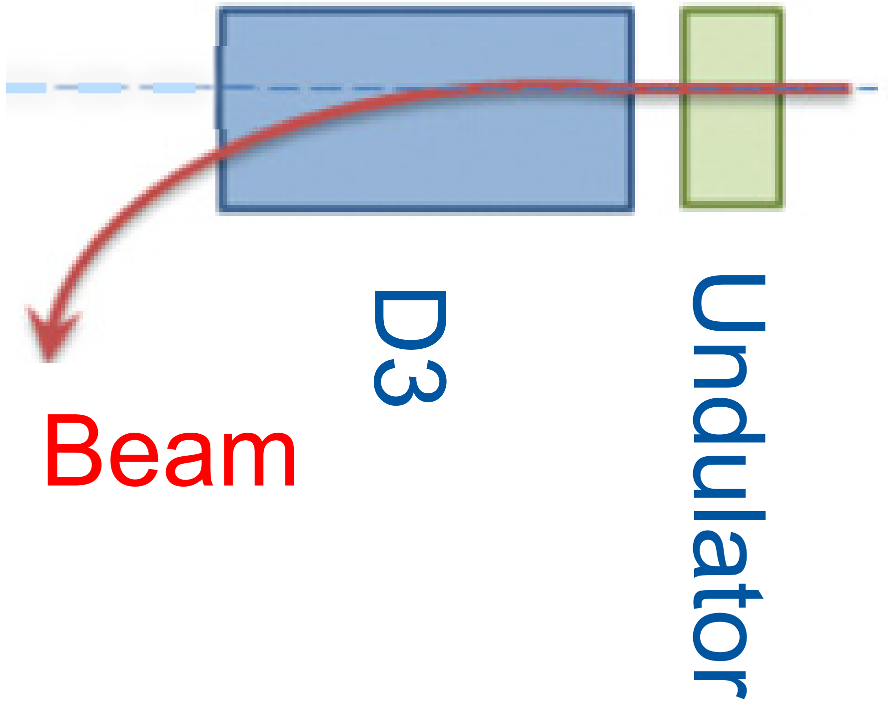
Inverse Fourier Transformation, Obtain beam profile



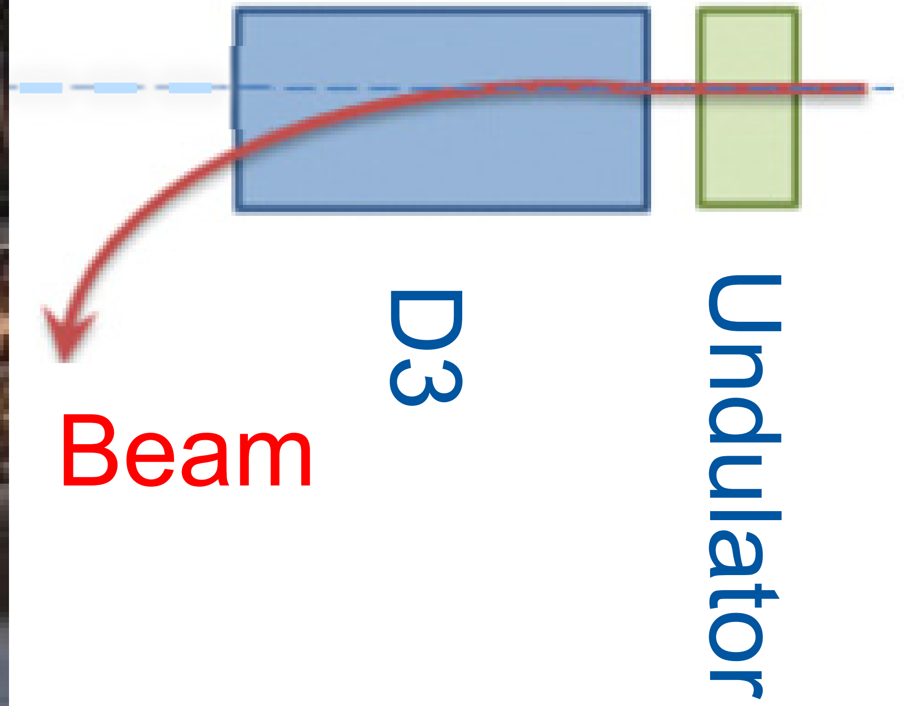
- **Fixed Slit Separation**
  (Hyp. Gaussian)

$$\sigma_x = \frac{\lambda_0 R_0}{\pi D}\sqrt{\frac{1}{2} ln \frac{1}{|\Gamma|}}$$

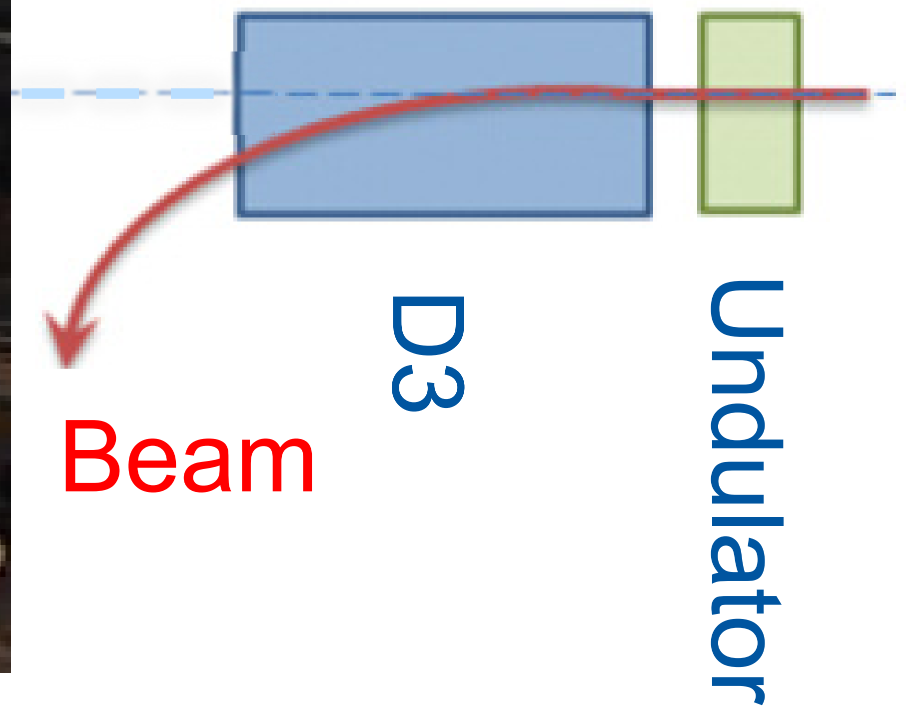
LHC Interferometer



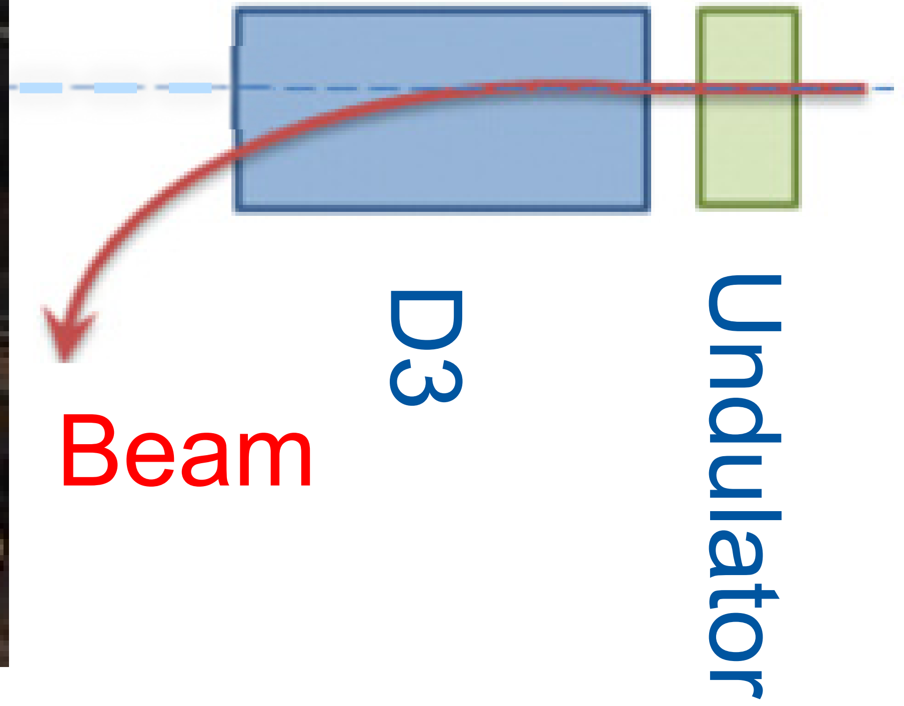
LHC Interferometer



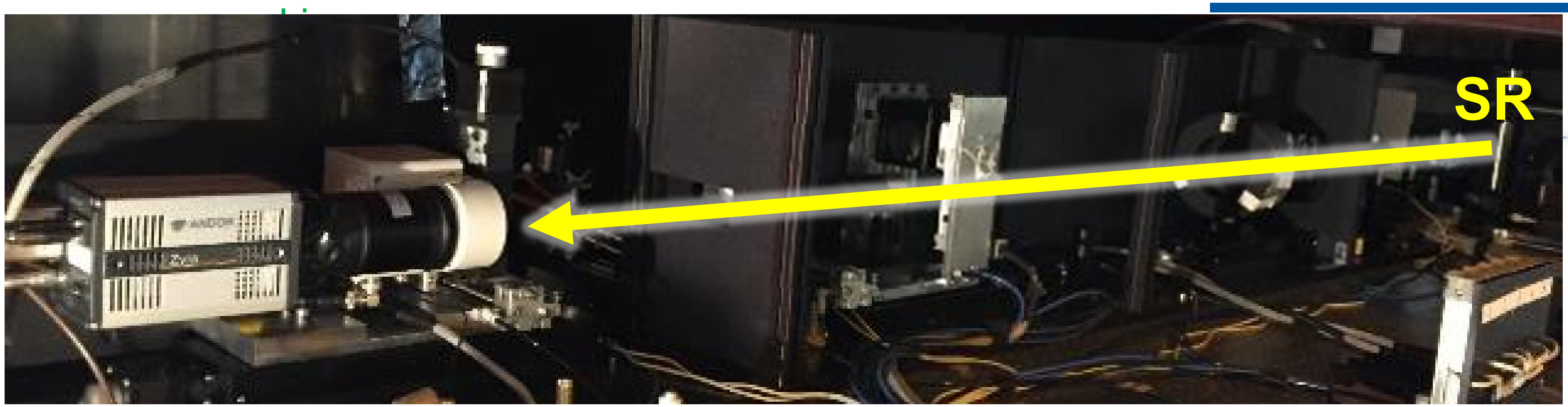
LHC Interferometer

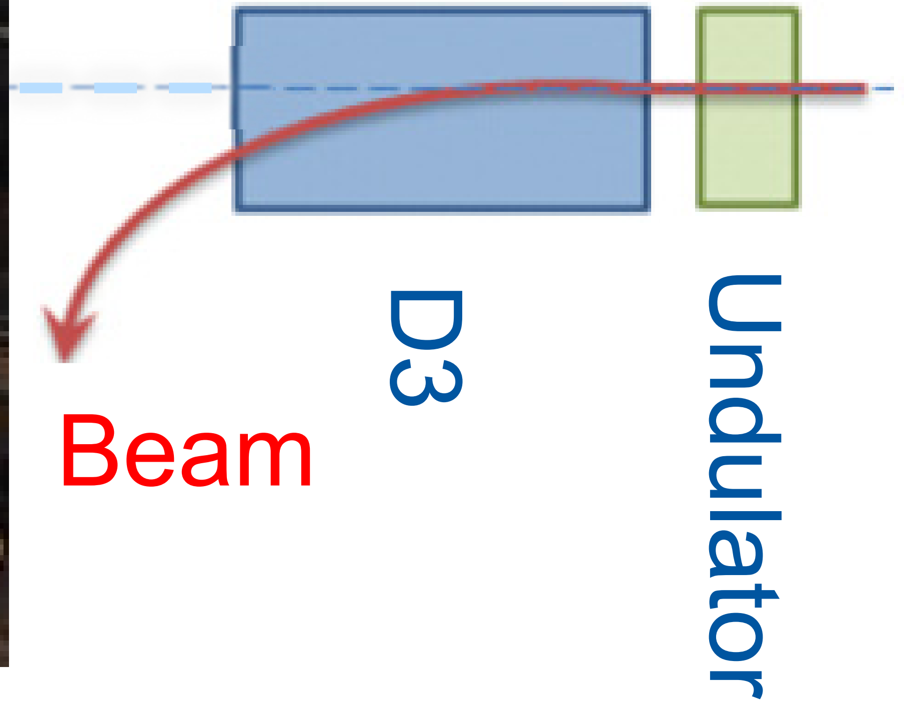


LHC Interferometer

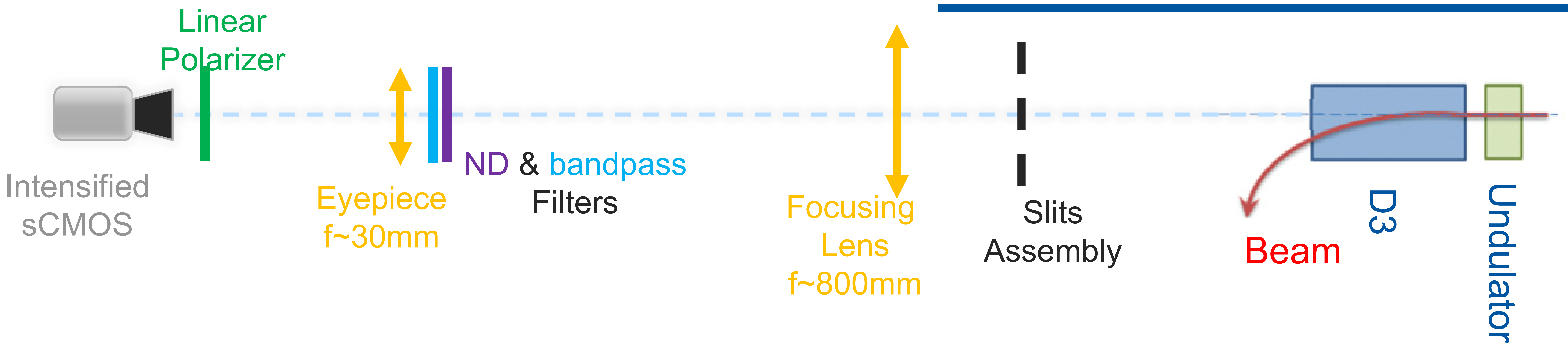


LHC Interferometer

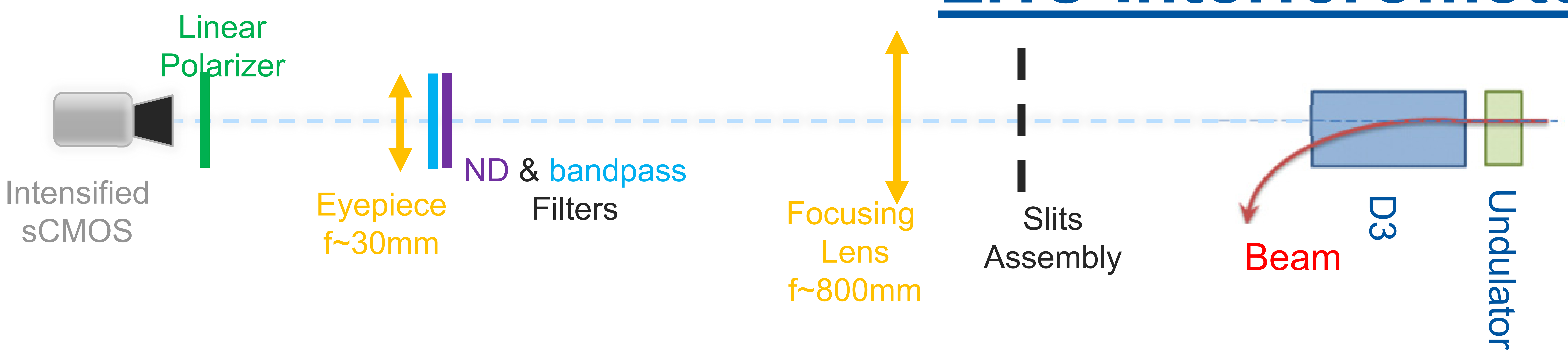


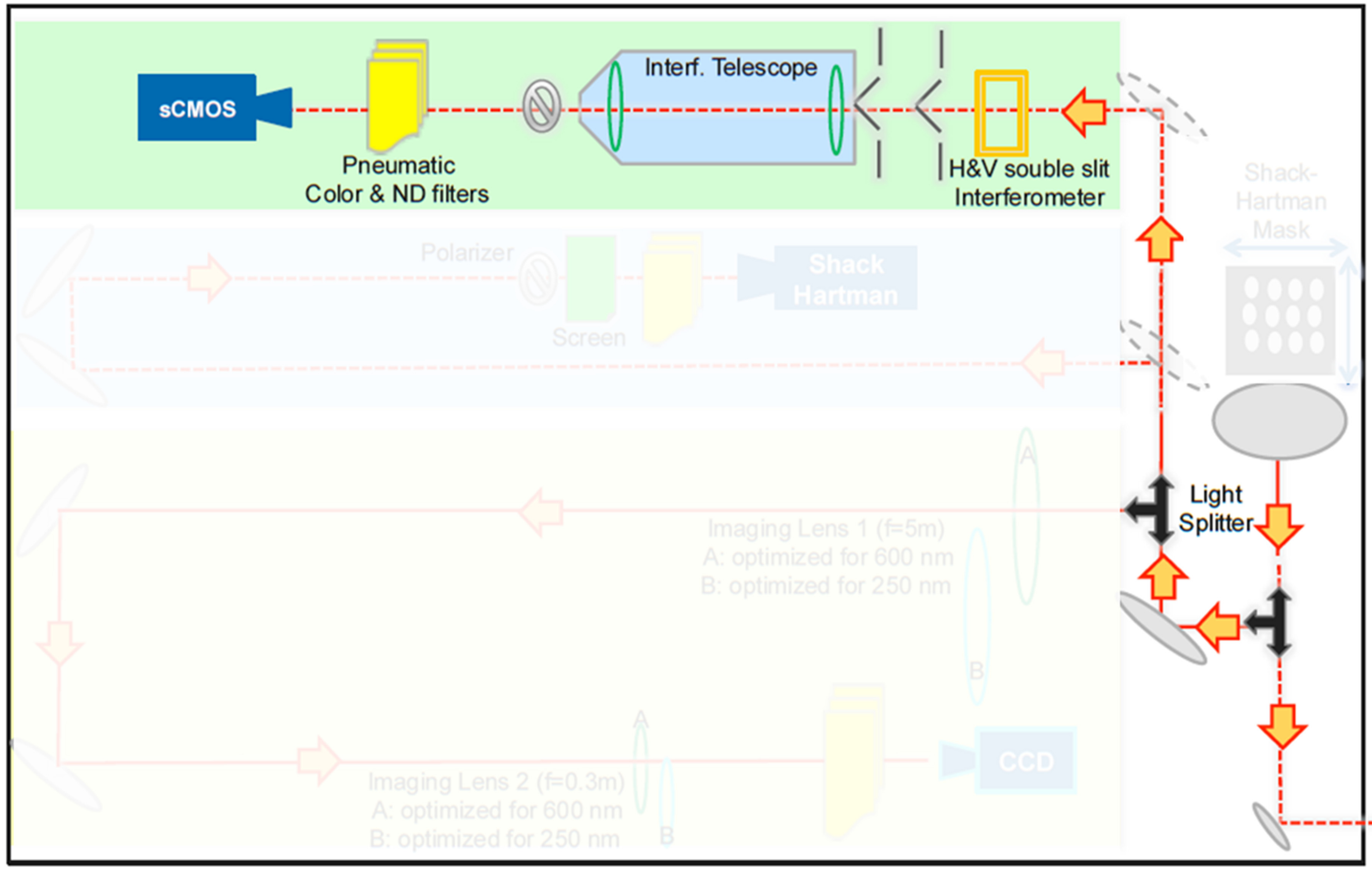


LHC Interferometer



LHC Interferometer





LHC SR

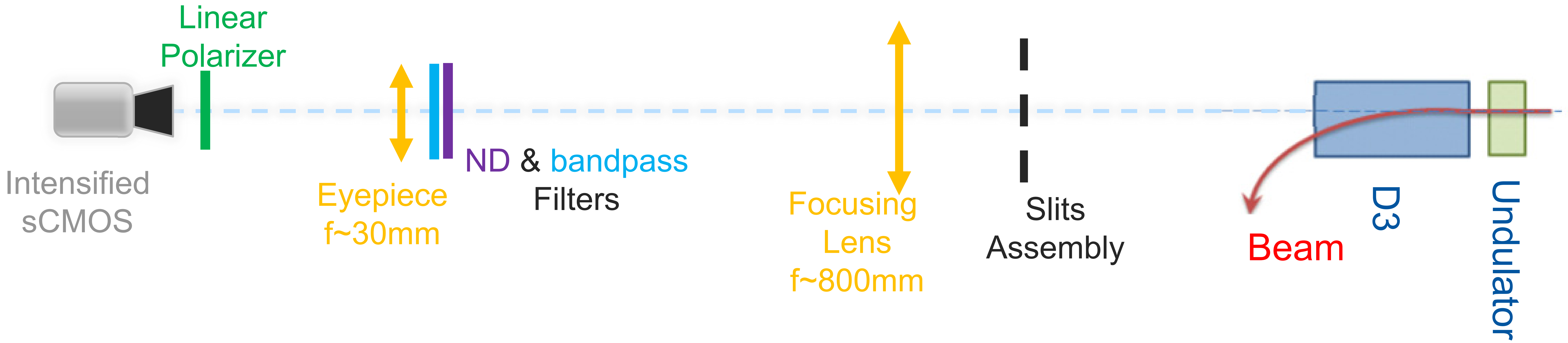
Imaging at the LHC

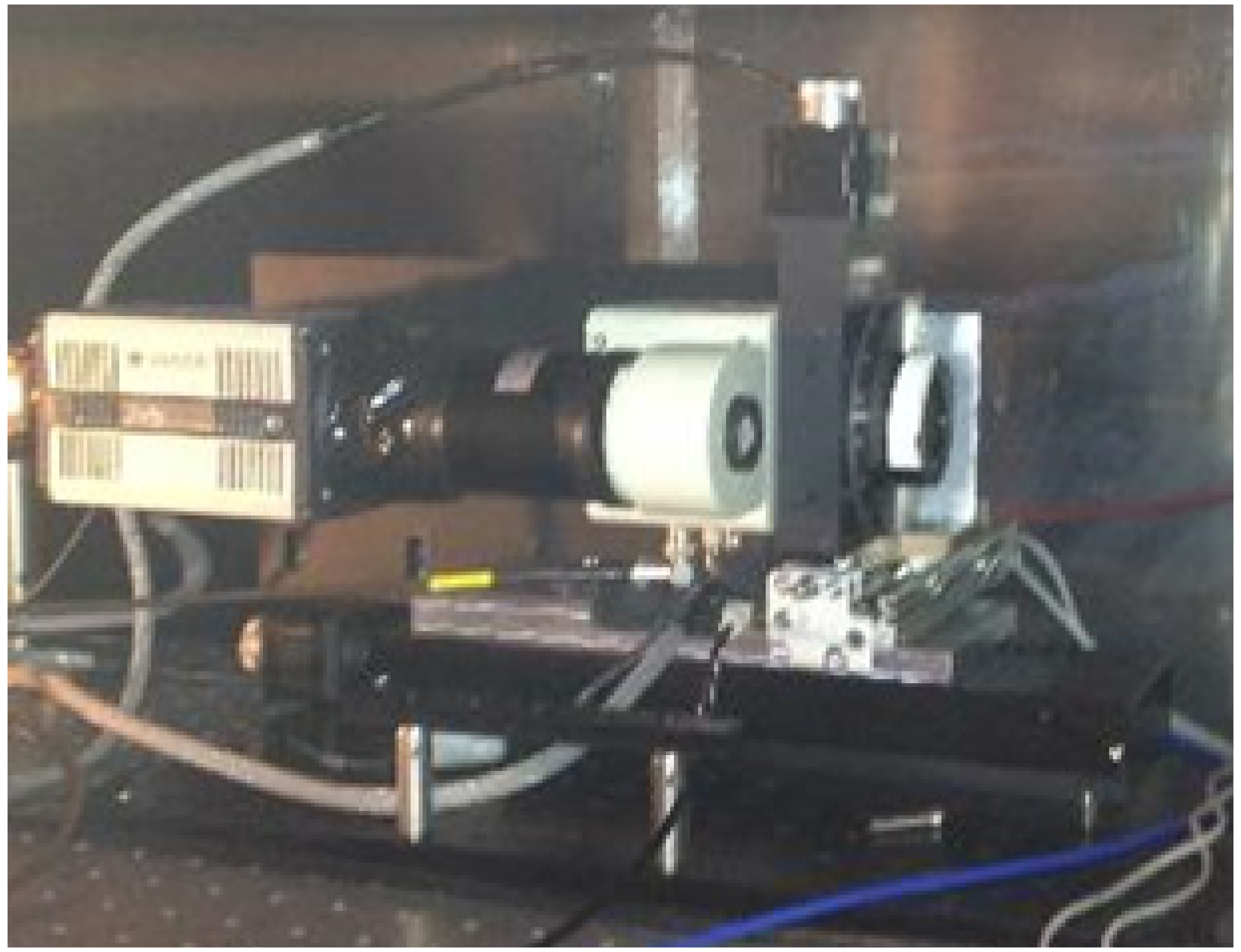
SR Interferometry

LHC Interferometer

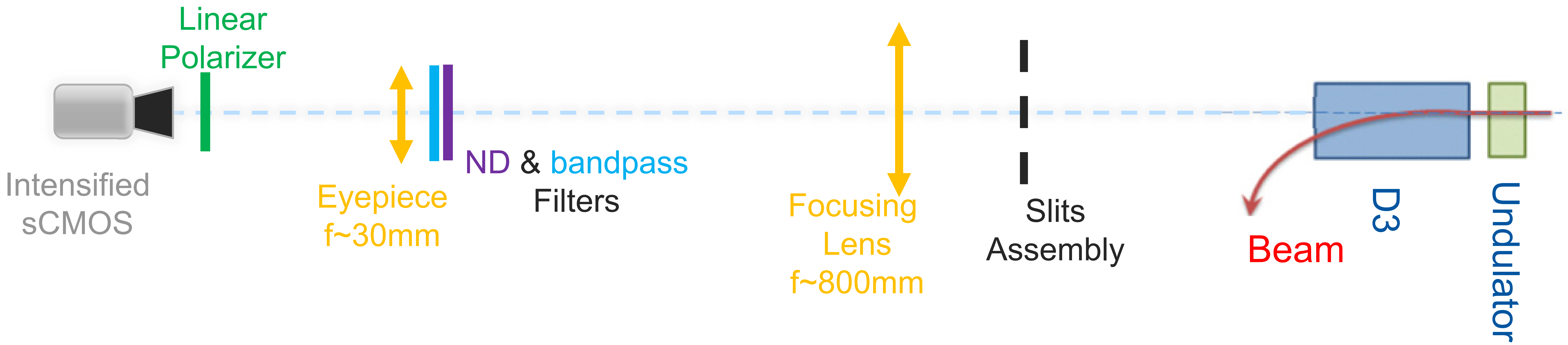
Commissioning
At 6.5 TeV
At 450 GeV

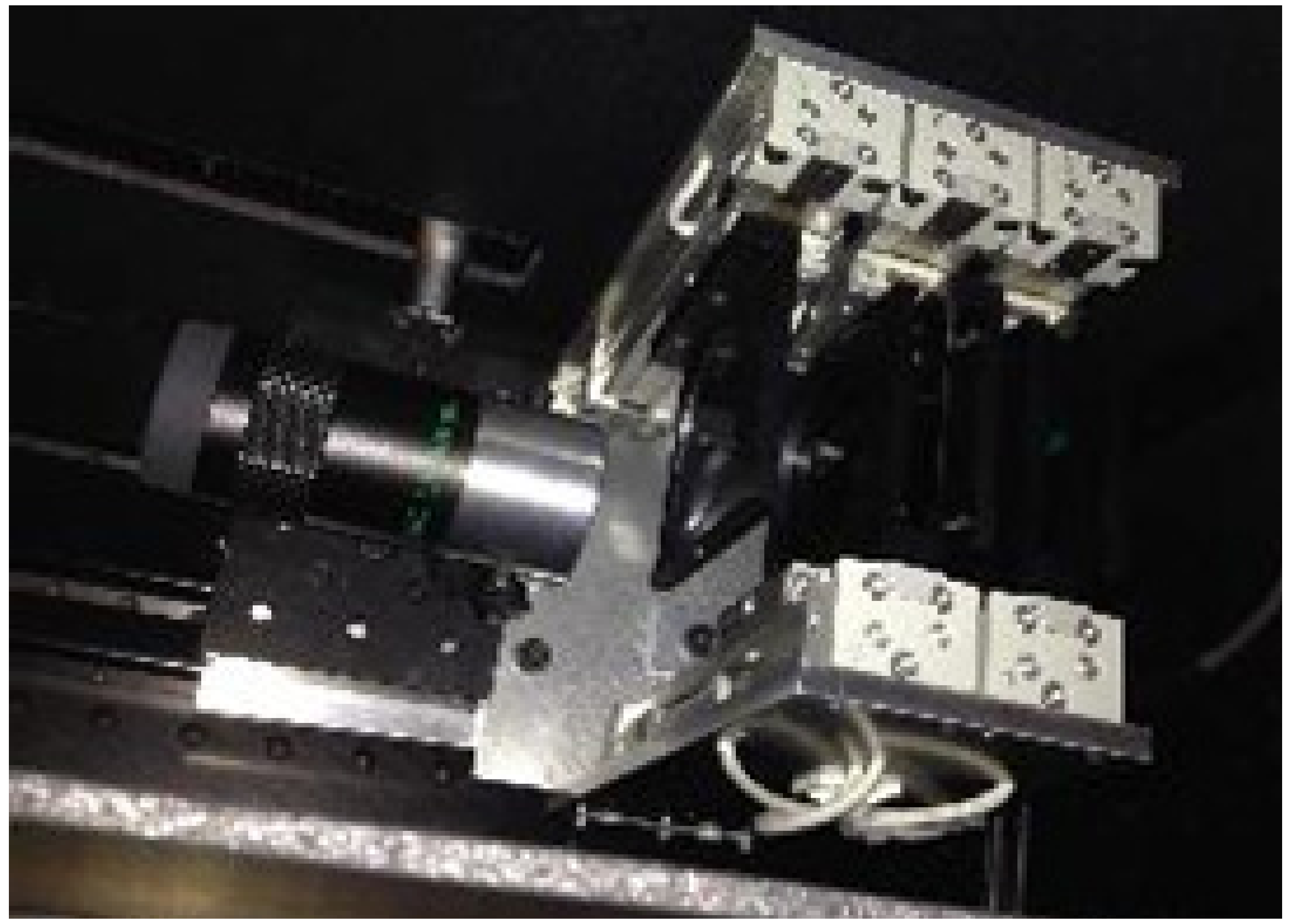
2D Interferometer

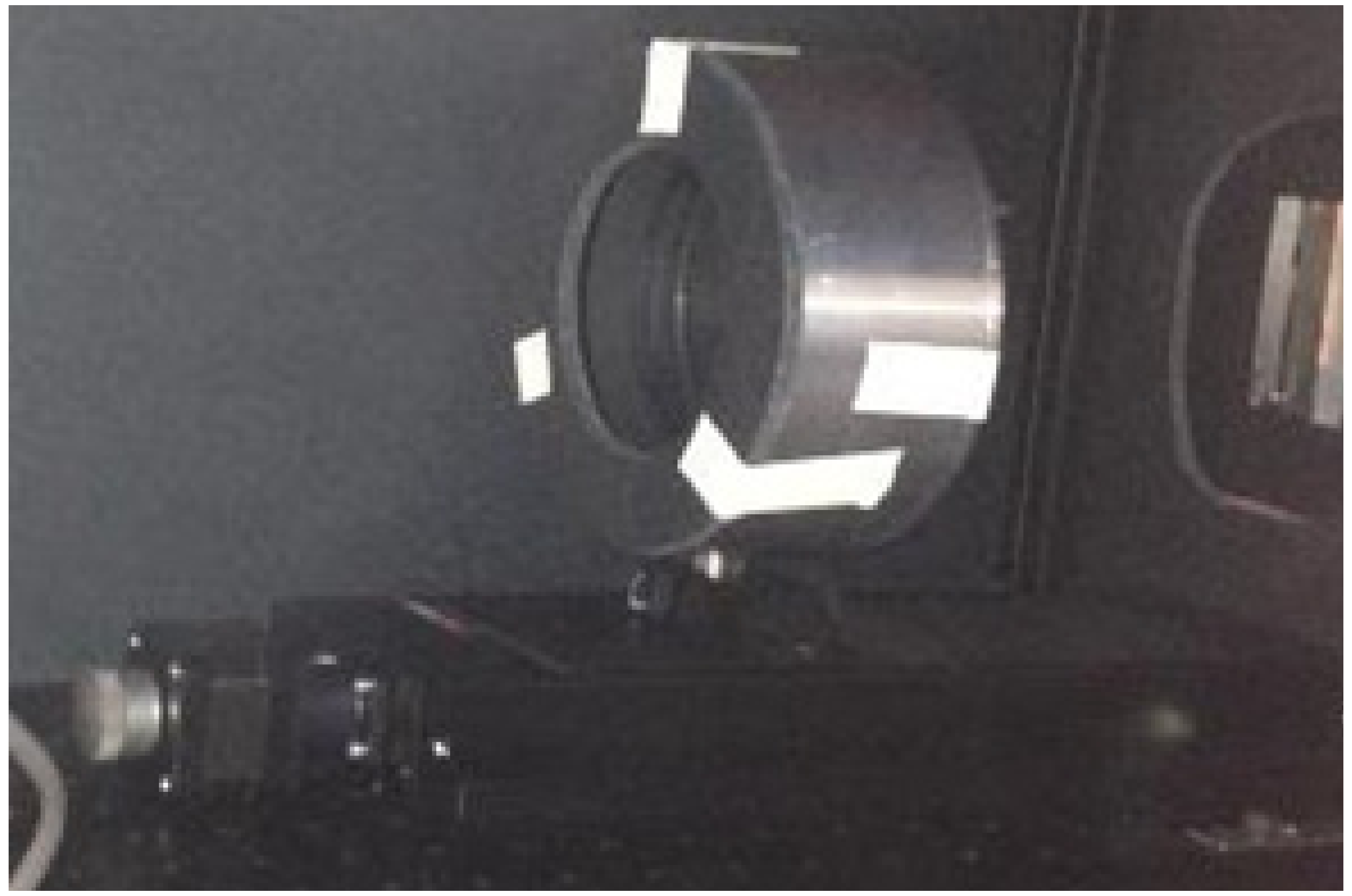




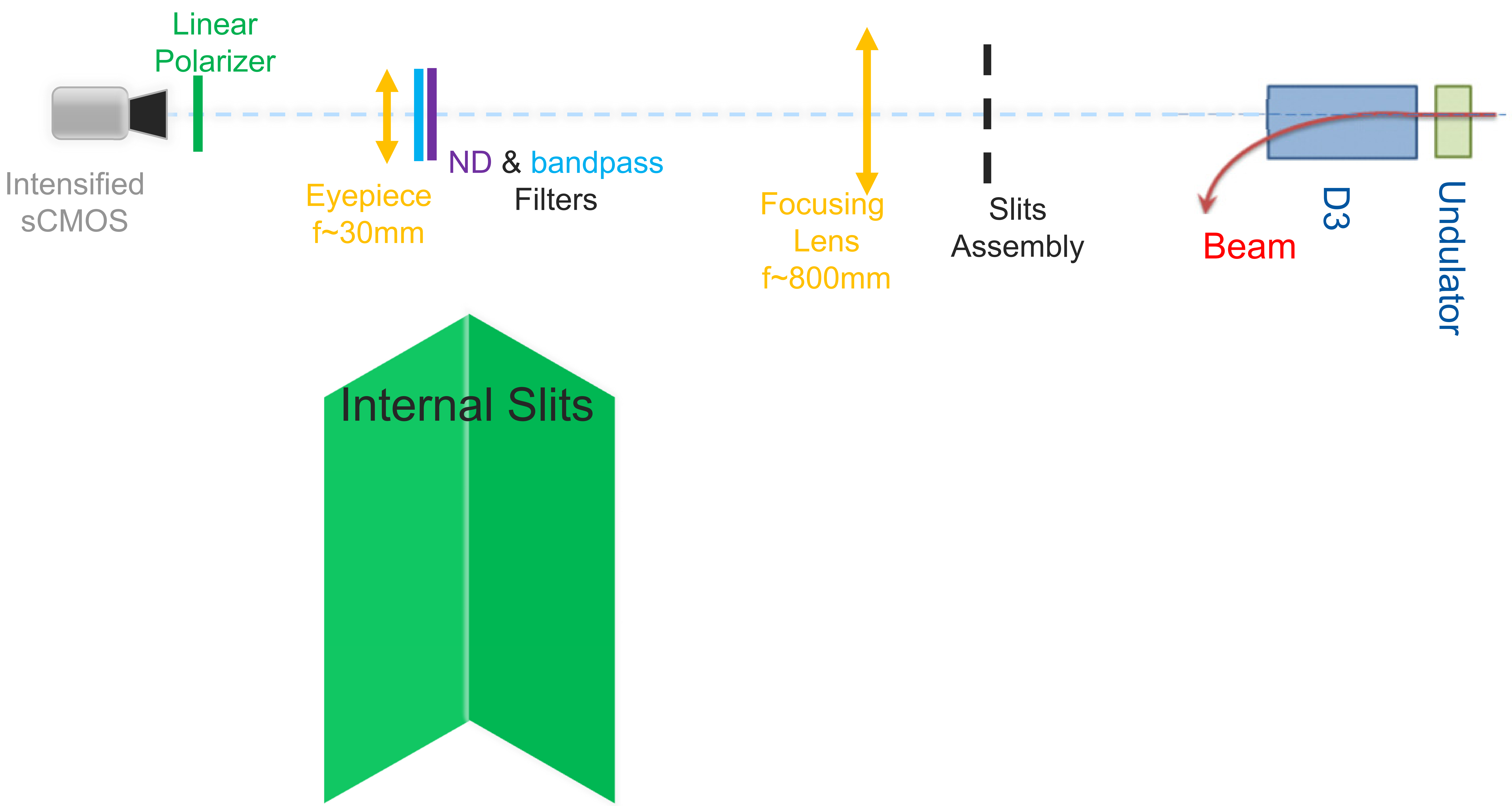
- sCMOS sensor
- Optical coupling to Image Intensifier
- HQ Linear Polarizer (polymer polarizing film between two high-precision glass substrates with flatness better than λ/6) motorized rotational stage allowing IN/OUT movement.
- All the assembly is motorized for magnification setting.

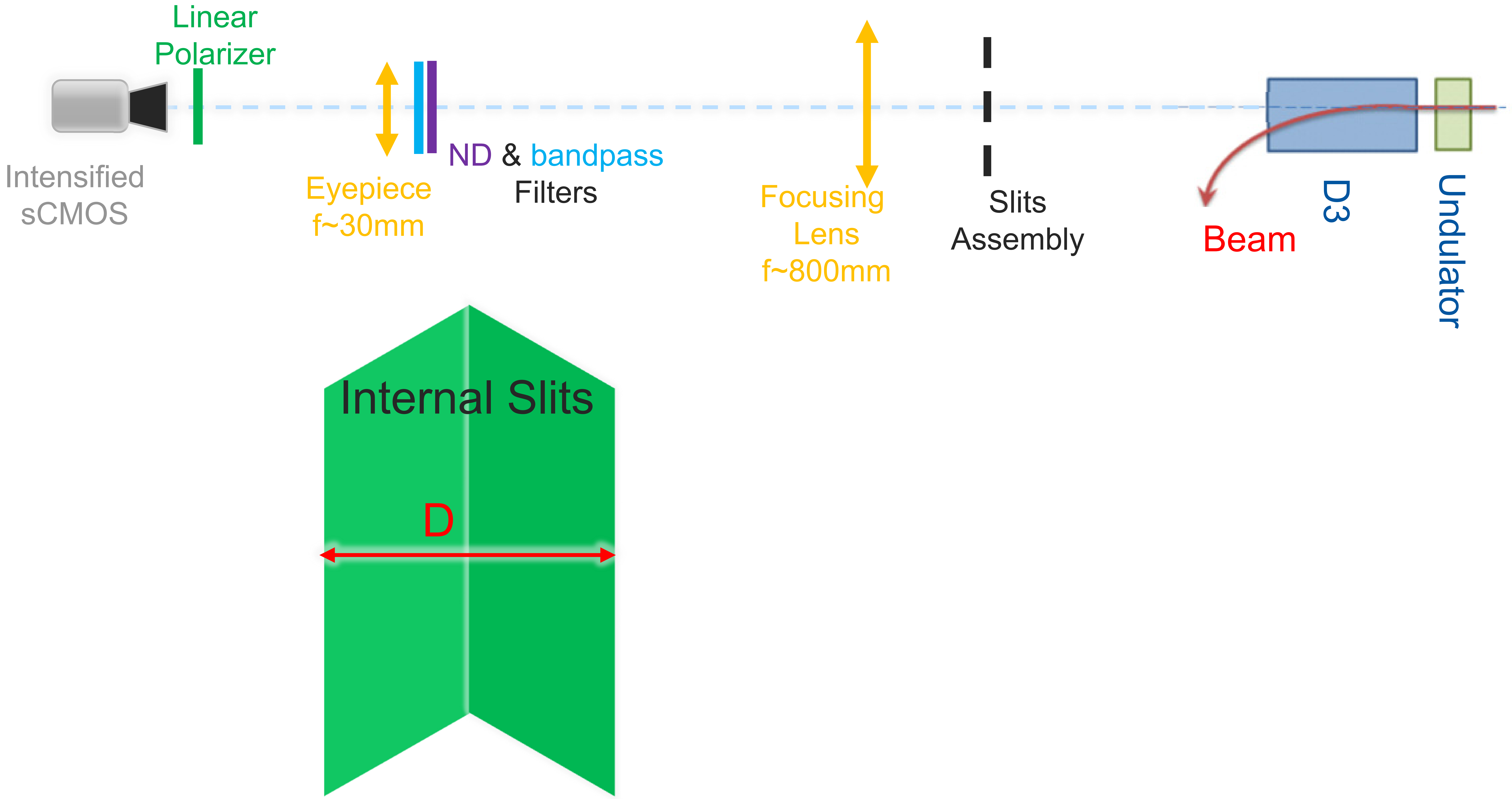


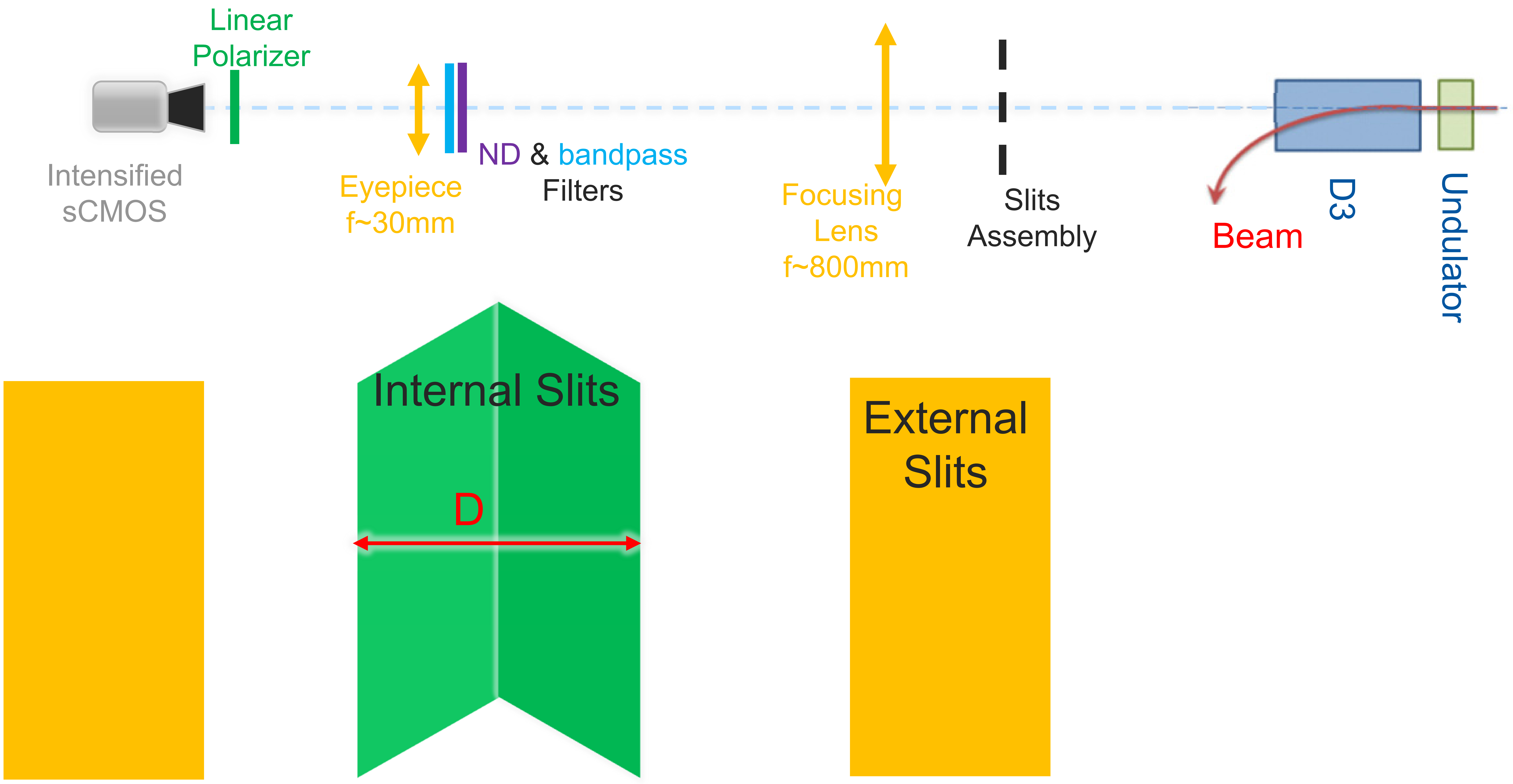


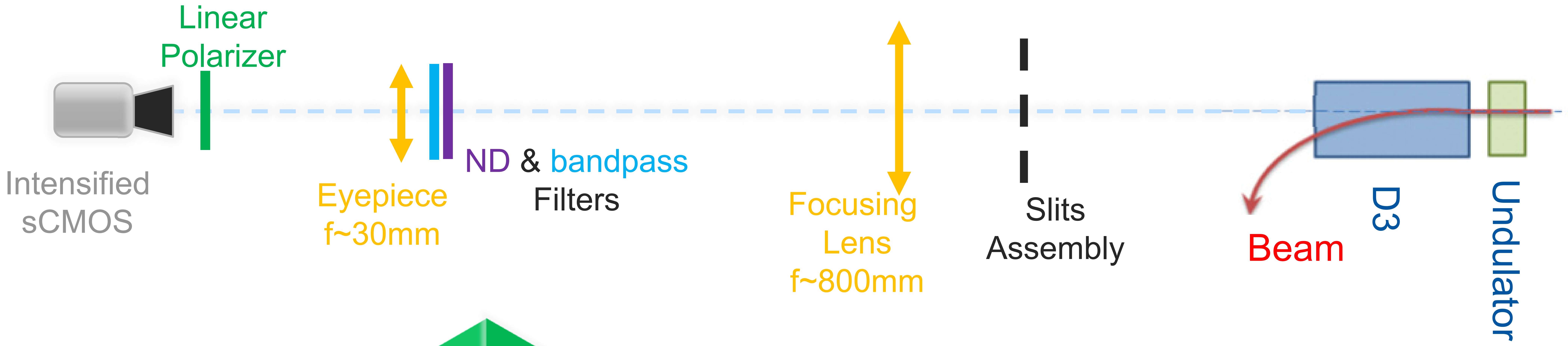


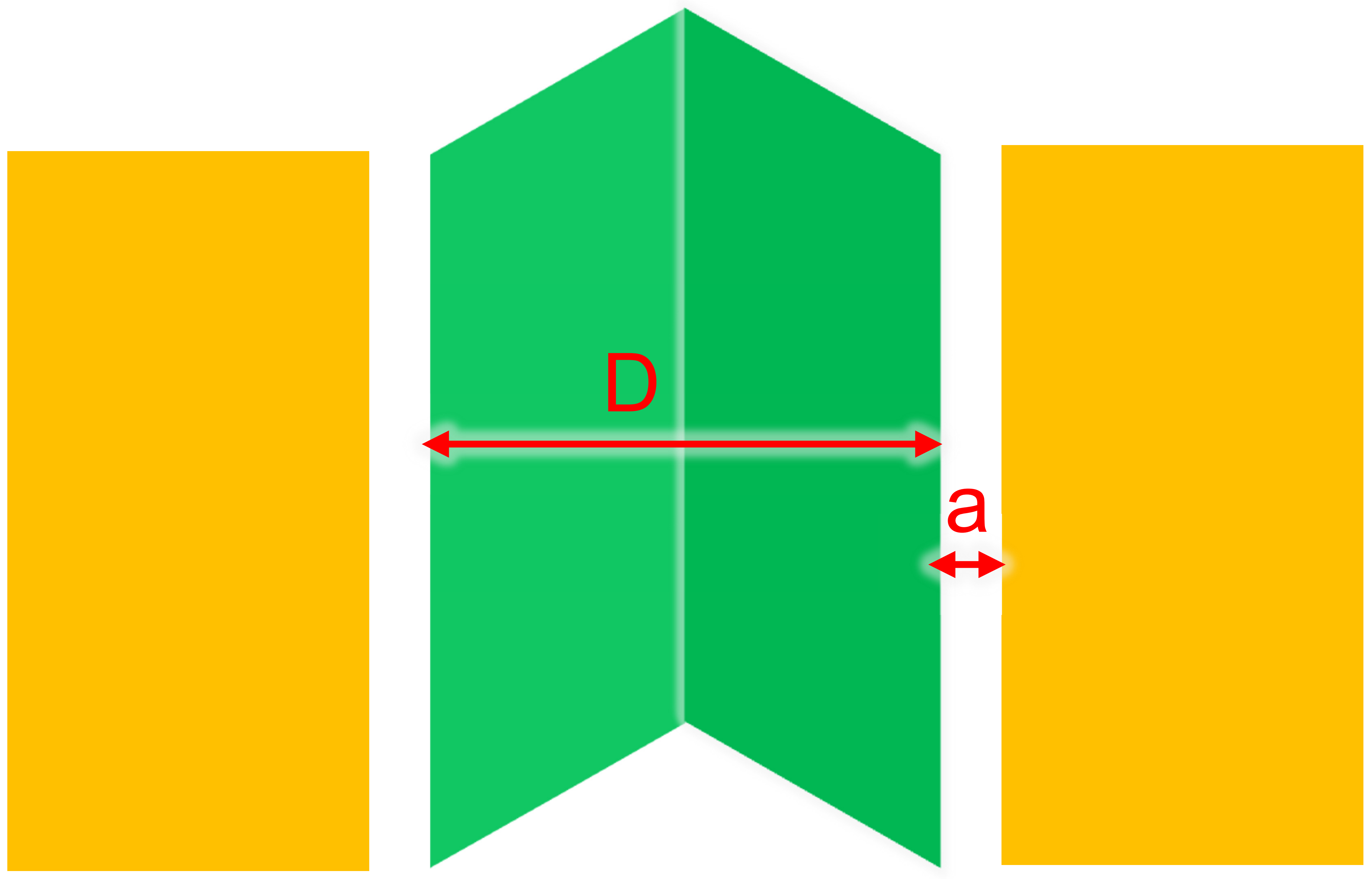
- Apochromat Lens and eyepiece
- Both Motorized to ease focusing
- Filters on Pneumatic mounts moving with the eyepiece

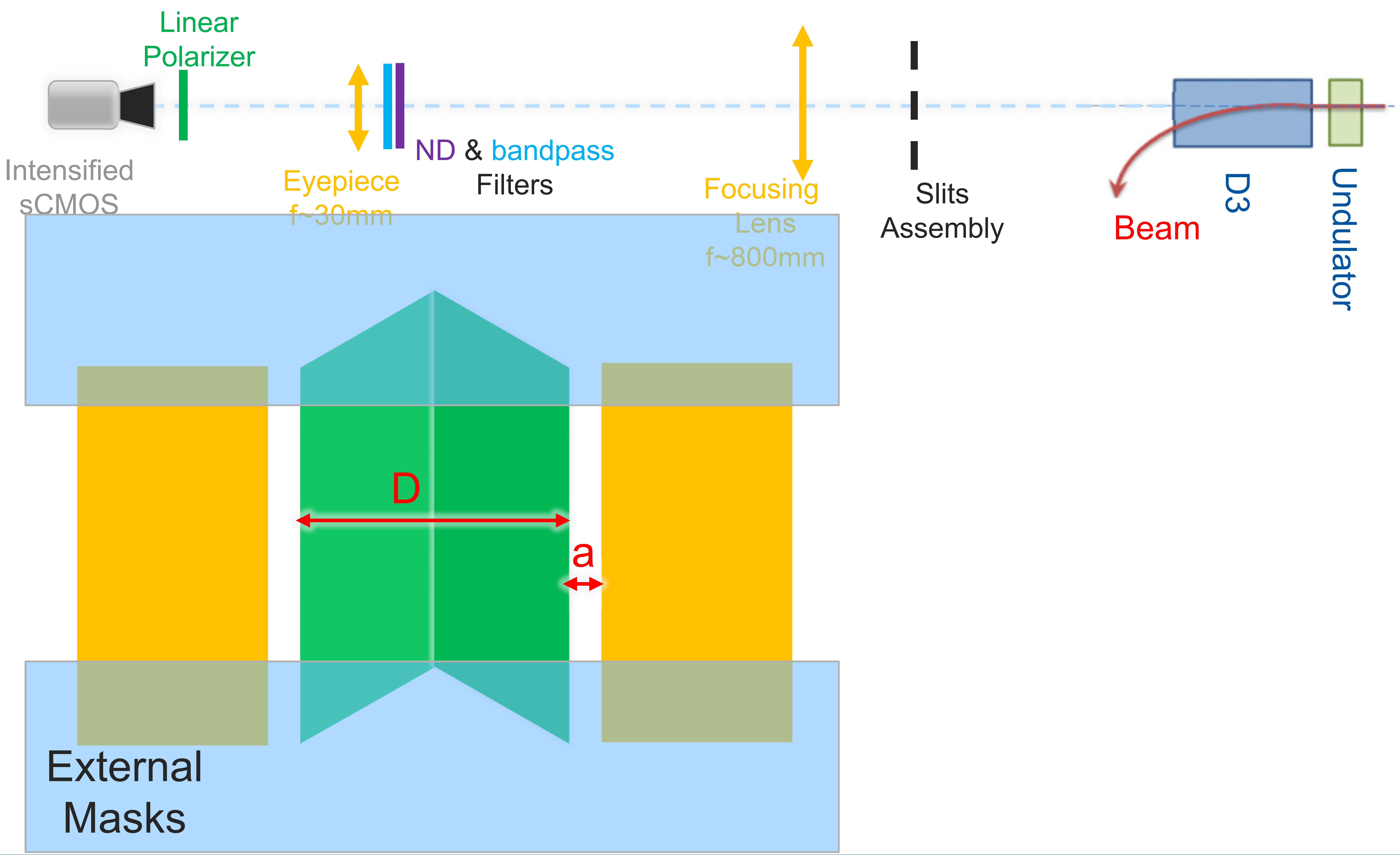

Linear Polarizer
Intensified sCMOS
Eyepiece f~30mm
ND & bandpass Filters
Focusing Lens f~800mm
Slits Assembly
Beam
D3
Undulator
Internal Slits

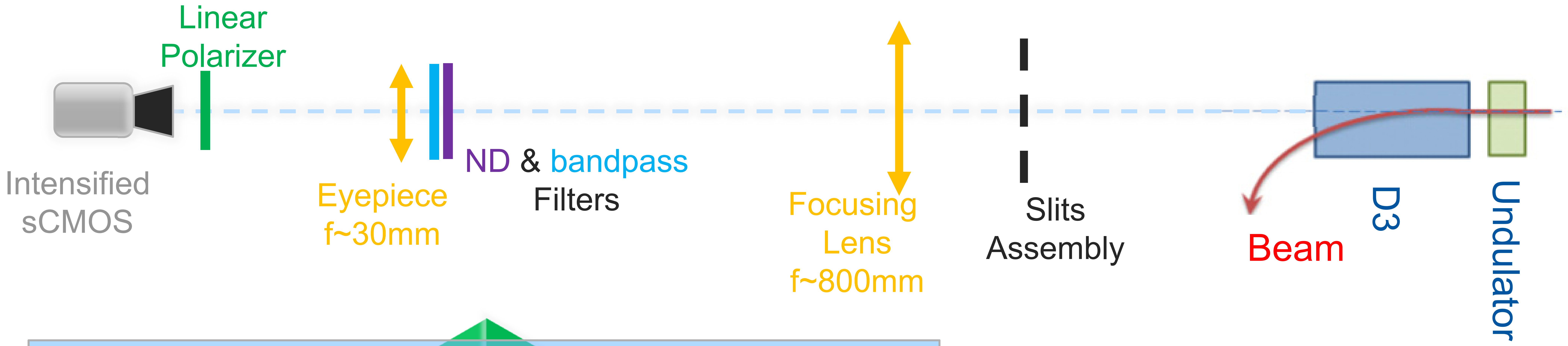

Linear Polarizer
Intensified sCMOS
Eyepiece f~30mm
ND & bandpass Filters
Focusing Lens f~800mm
Slits Assembly
Beam
D3
Undulator
Internal Slits
D

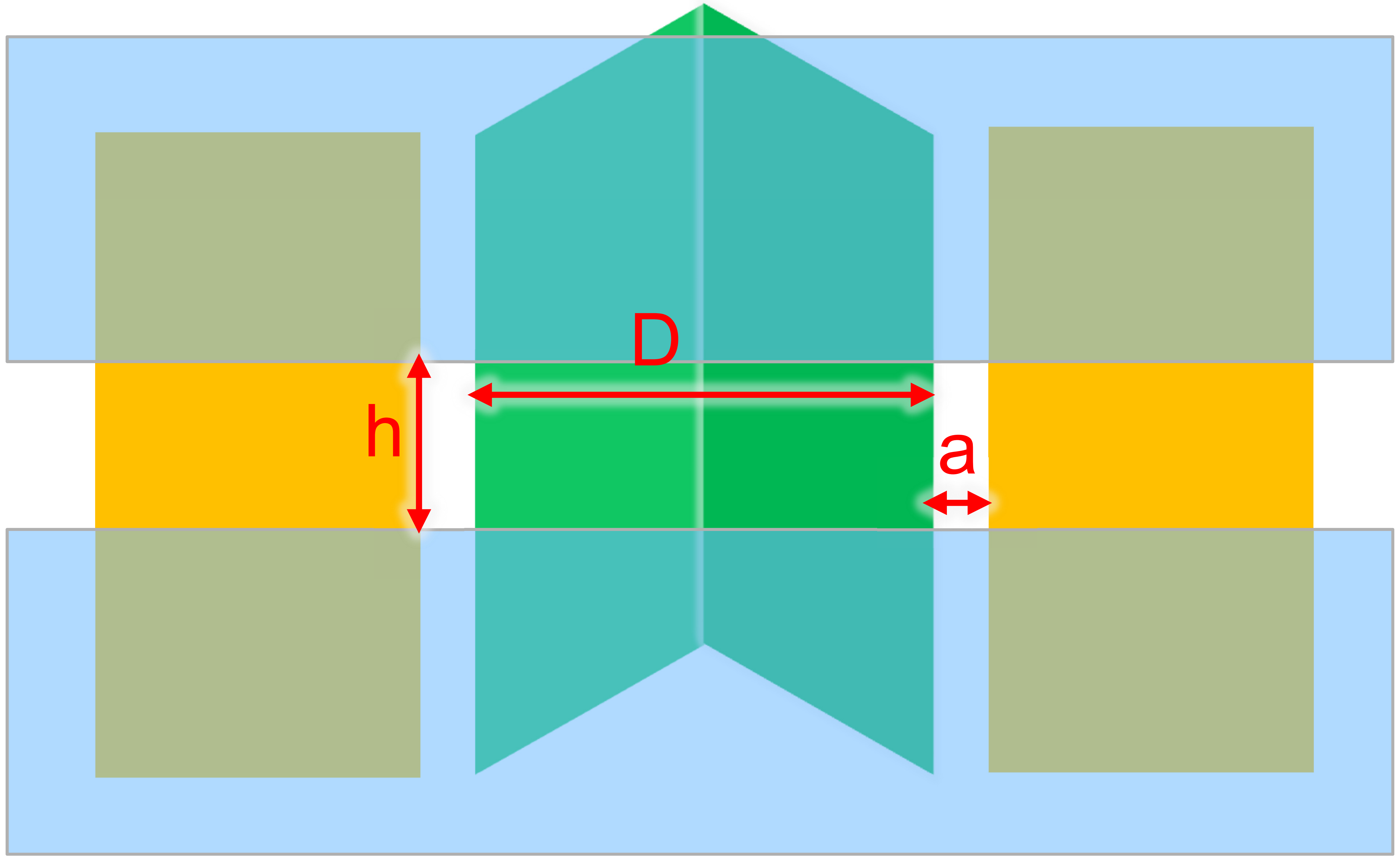

Linear
Polarizer
Intensified
sCMOS
Eyepiece
f~30mm
ND & bandpass
Filters
Focusing
Lens
f~800mm
Slits
Assembly
Beam
D3
Undulator
Internal Slits
D
External
Slits

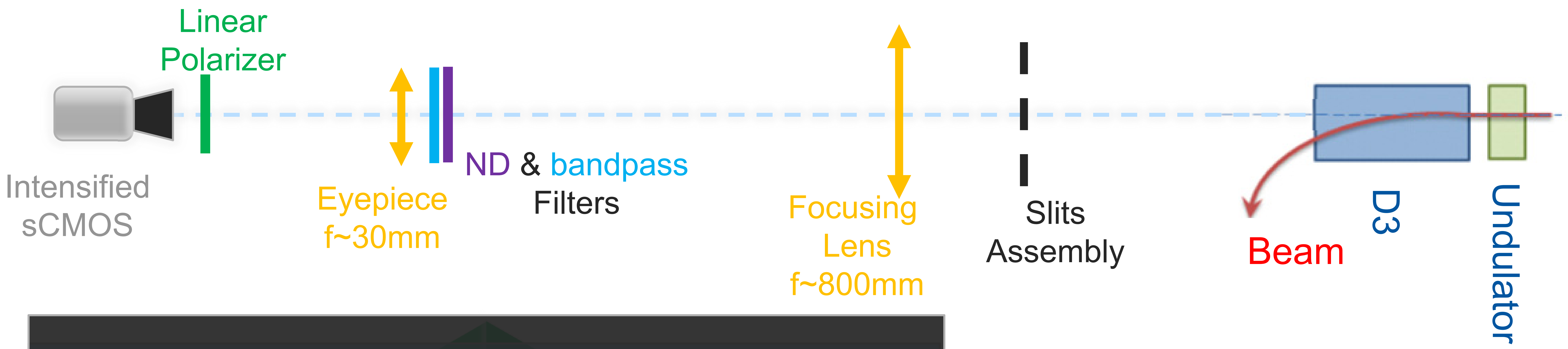

Linear Polarizer
Intensified sCMOS
Eyepiece f~30mm
ND & bandpass Filters
Focusing Lens f~800mm
Slits Assembly
Beam
D3
Undulator

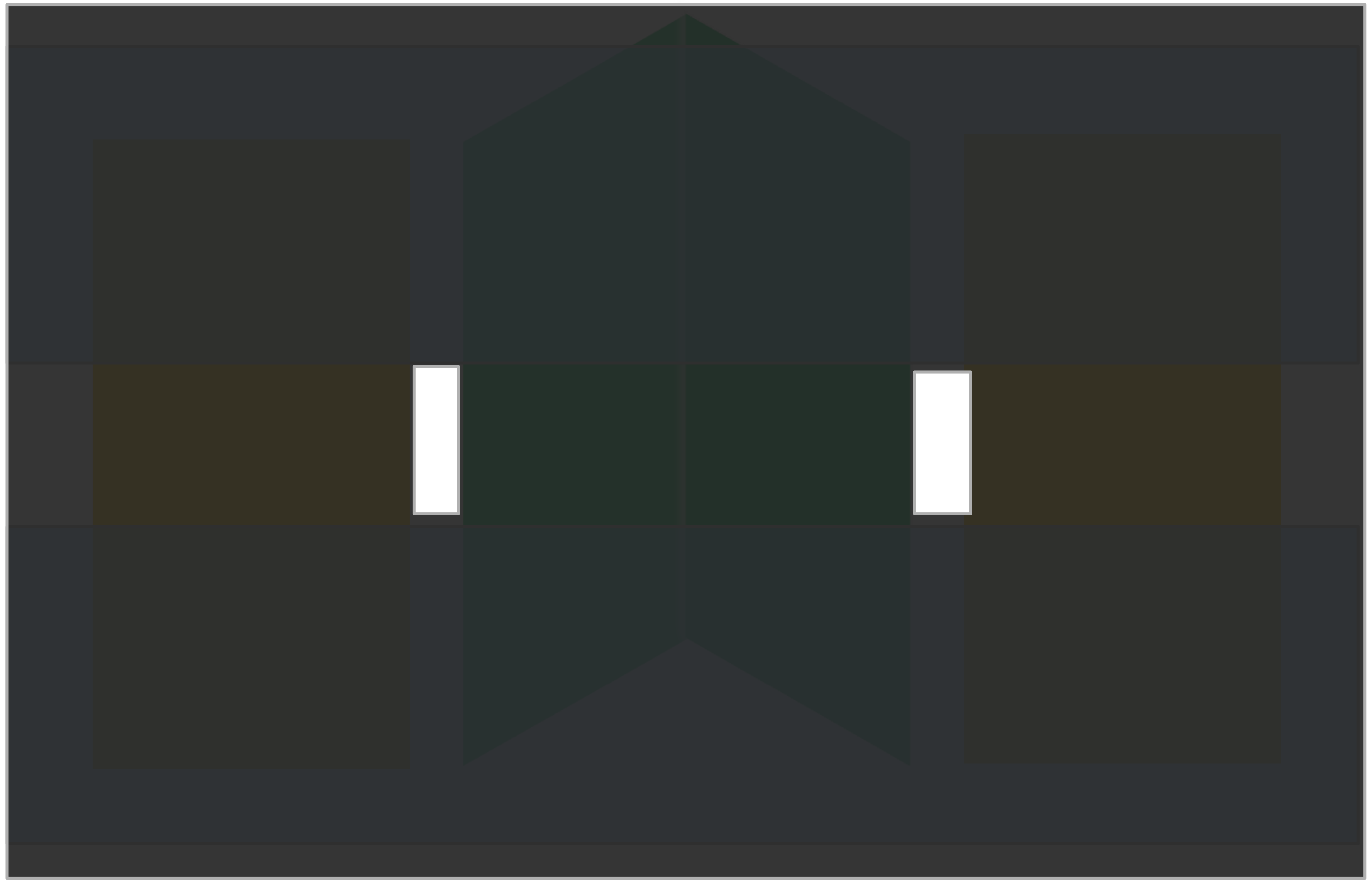

D
a

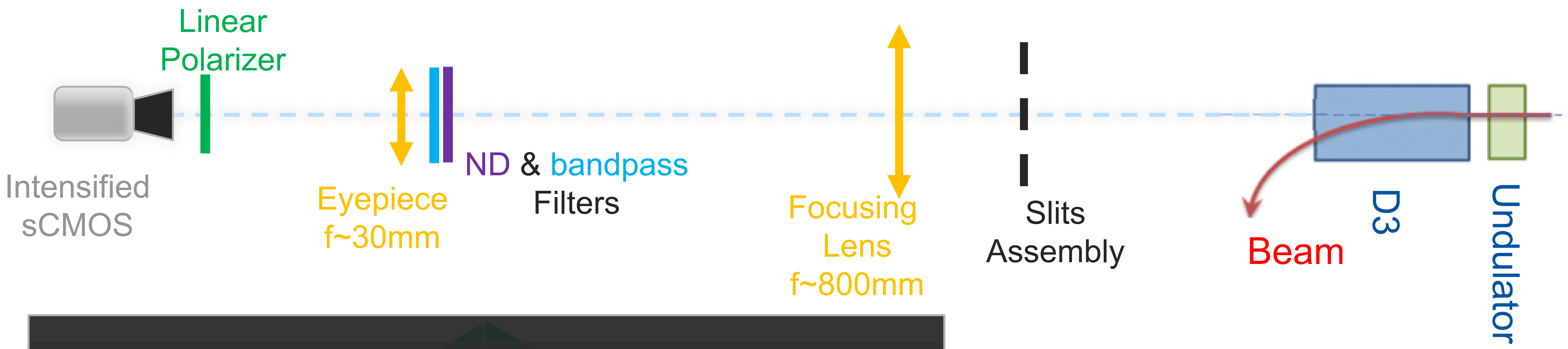

Linear Polarizer
Intensified sCMOS
Eyepiece f~30mm
ND & bandpass Filters
Focusing Lens f~800mm
Slits Assembly
Beam
D3
Undulator
D
a
External Masks

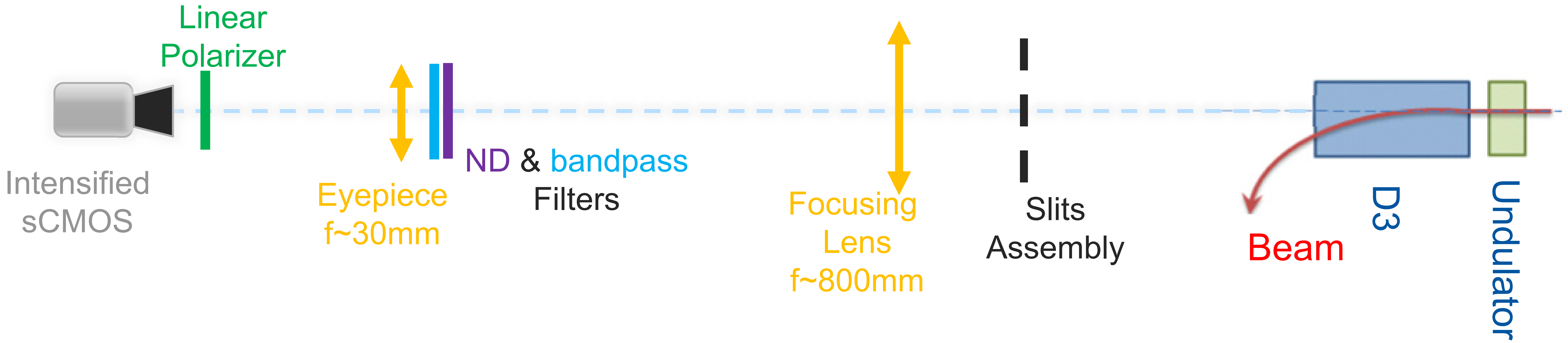

Linear Polarizer
Intensified sCMOS
Eyepiece f~30mm
ND & bandpass Filters
Focusing Lens f~800mm
Slits Assembly
Beam
D3
Undulator

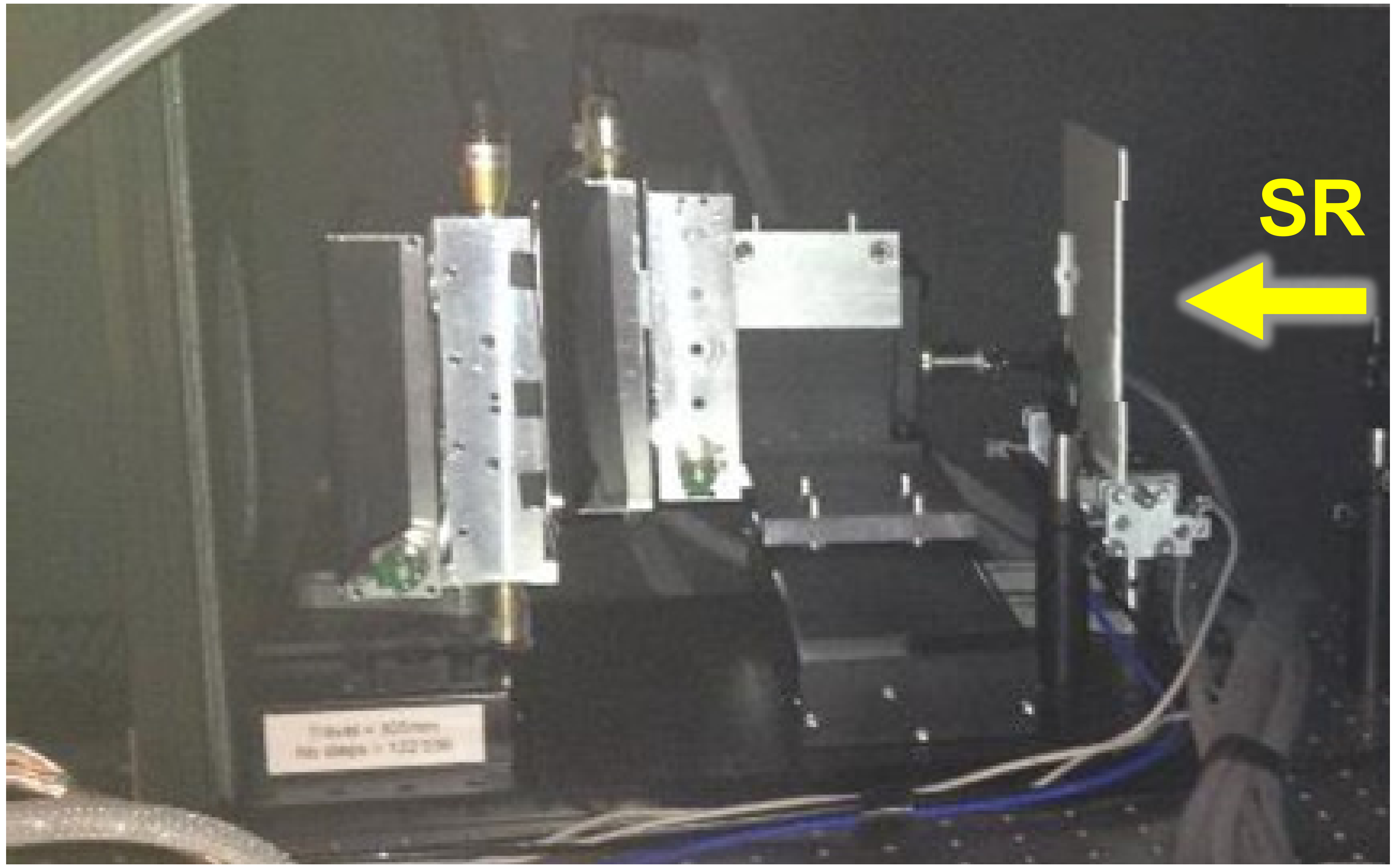

D
h
a

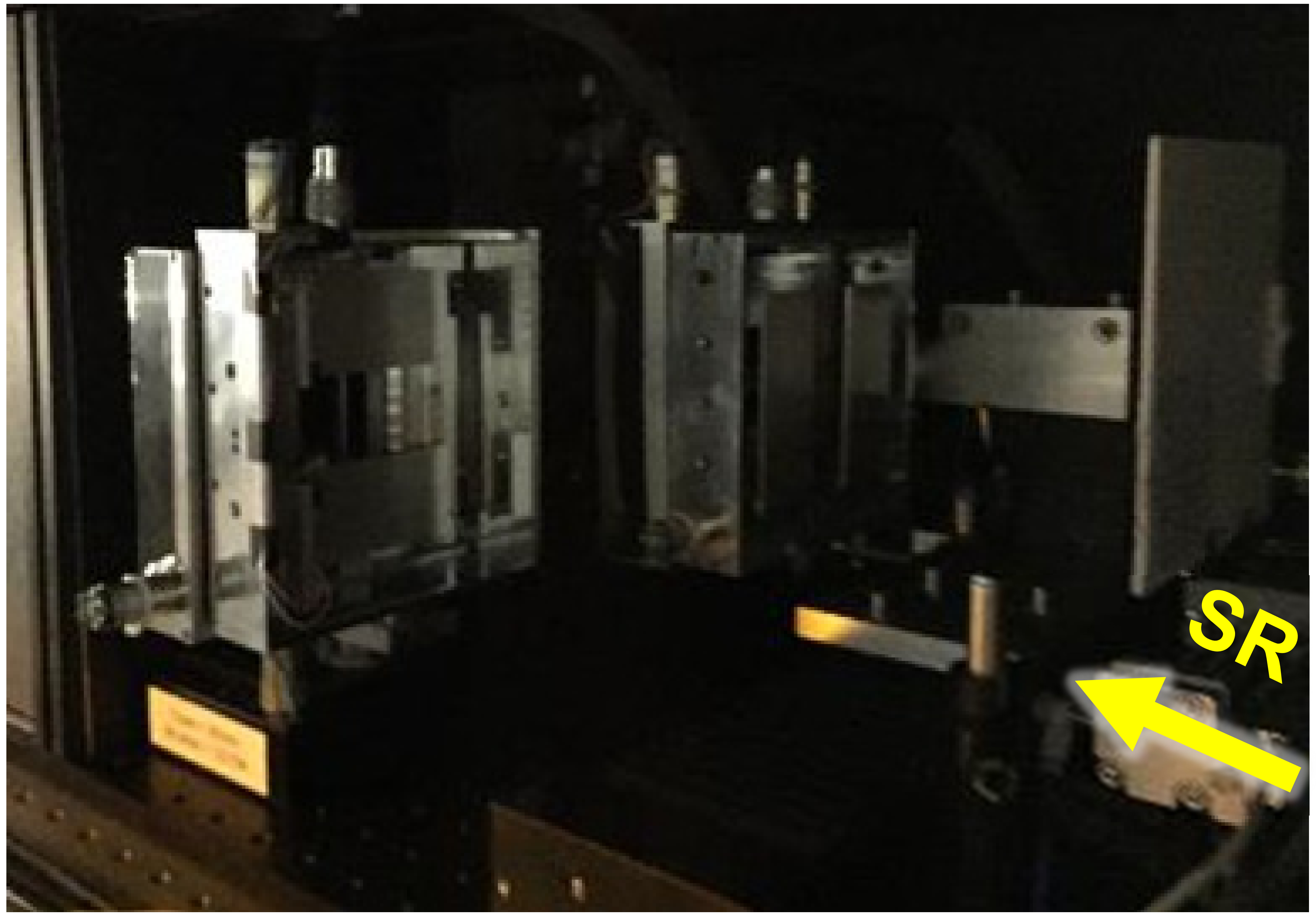

Linear Polarizer
Intensified sCMOS
Eyepiece f~30mm
ND & bandpass Filters
Focusing Lens f~800mm
Slits Assembly
Beam
D3
Undulator




Linear Polarizer
Intensified sCMOS
Eyepiece f~30mm
ND & bandpass Filters
Focusing Lens f~800mm
Slits Assembly
Beam
D3
Undulator


Linear Polarizer
Intensified sCMOS
Eyepiece f~30mm
ND & bandpass Filters
Focusing Lens f~800mm
Slits Assembly
Beam
D3
Undulator


SR


SR

Commissioning with Beam:

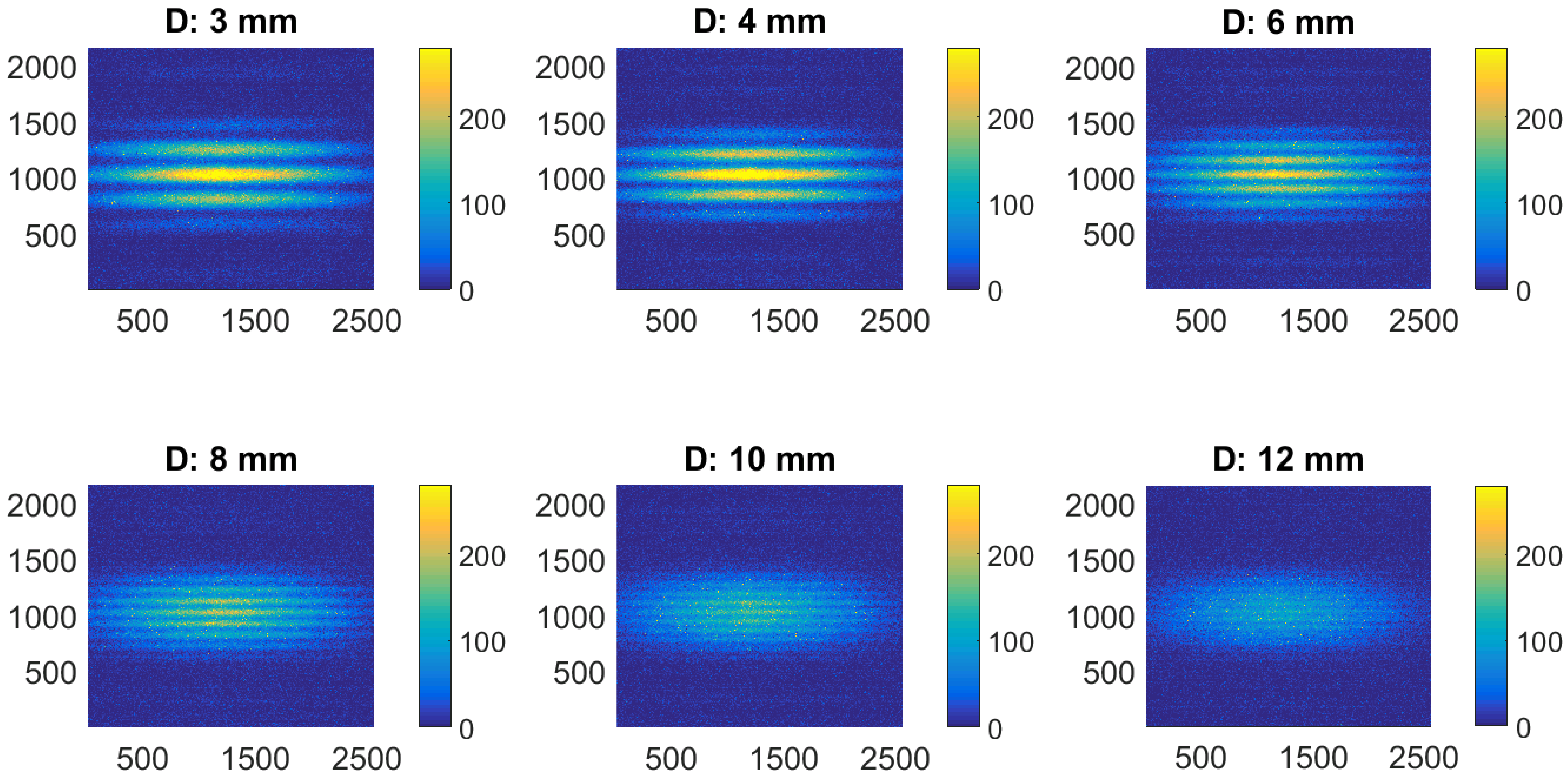
- Vertical beam size measurement at Top Energy
- Probing inferred size dependency on the setup
- Horizontal and vertical beam size measurement at Injection
- Benchmarking the results with respect to Imaging system

Slit Separation Scan to measure Vertical Beam size at the LHC

At E=6.5 TeV and λ= 560 nm

Slit Separation Scan to measure Vertical Beam size at the LHC

At E=6.5 TeV and λ= 560 nm



LHC SR

Imaging at the LHC

SR Interferometry

LHC Interferometer

Commissioning At 6.5 TeV

At 450 GeV

2D Interferometer

E = 6.5 TeV

λ = 560 nm +/- 5 nm

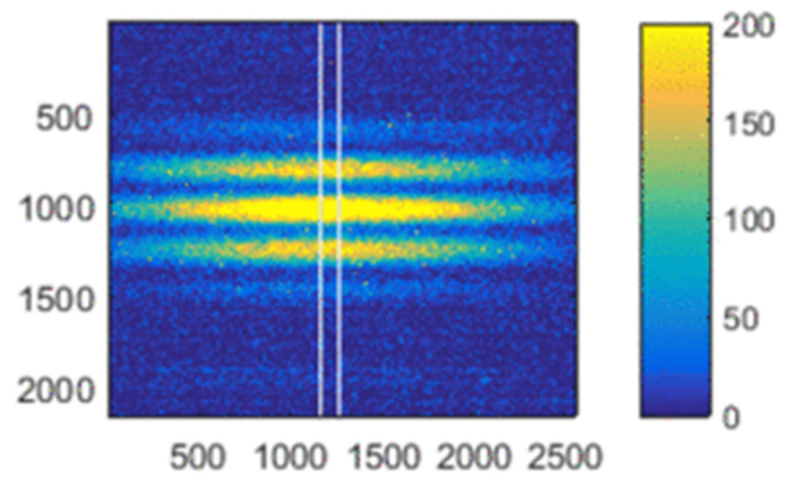
Expo = 1ms

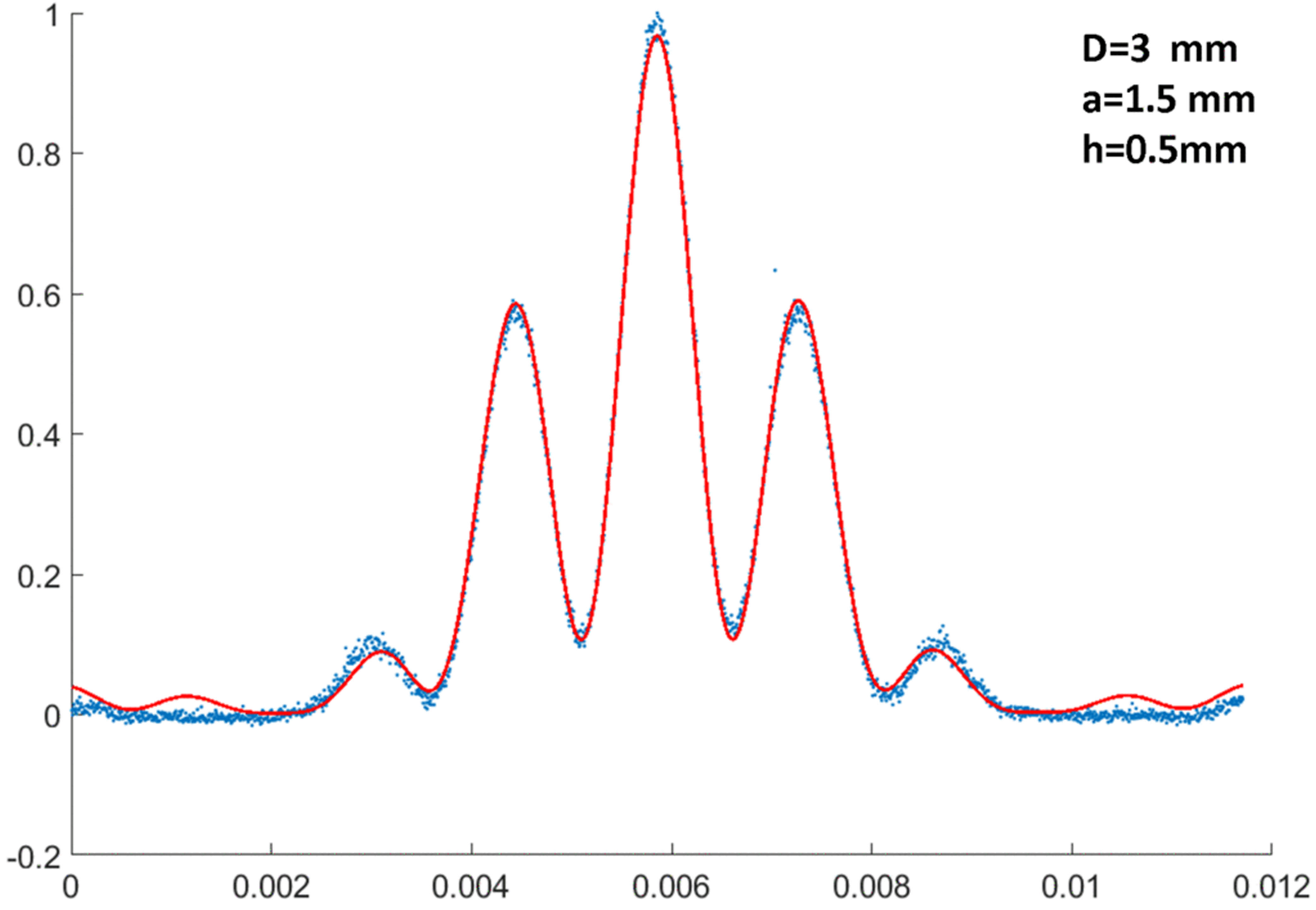
D : 3mm -> 12 mm

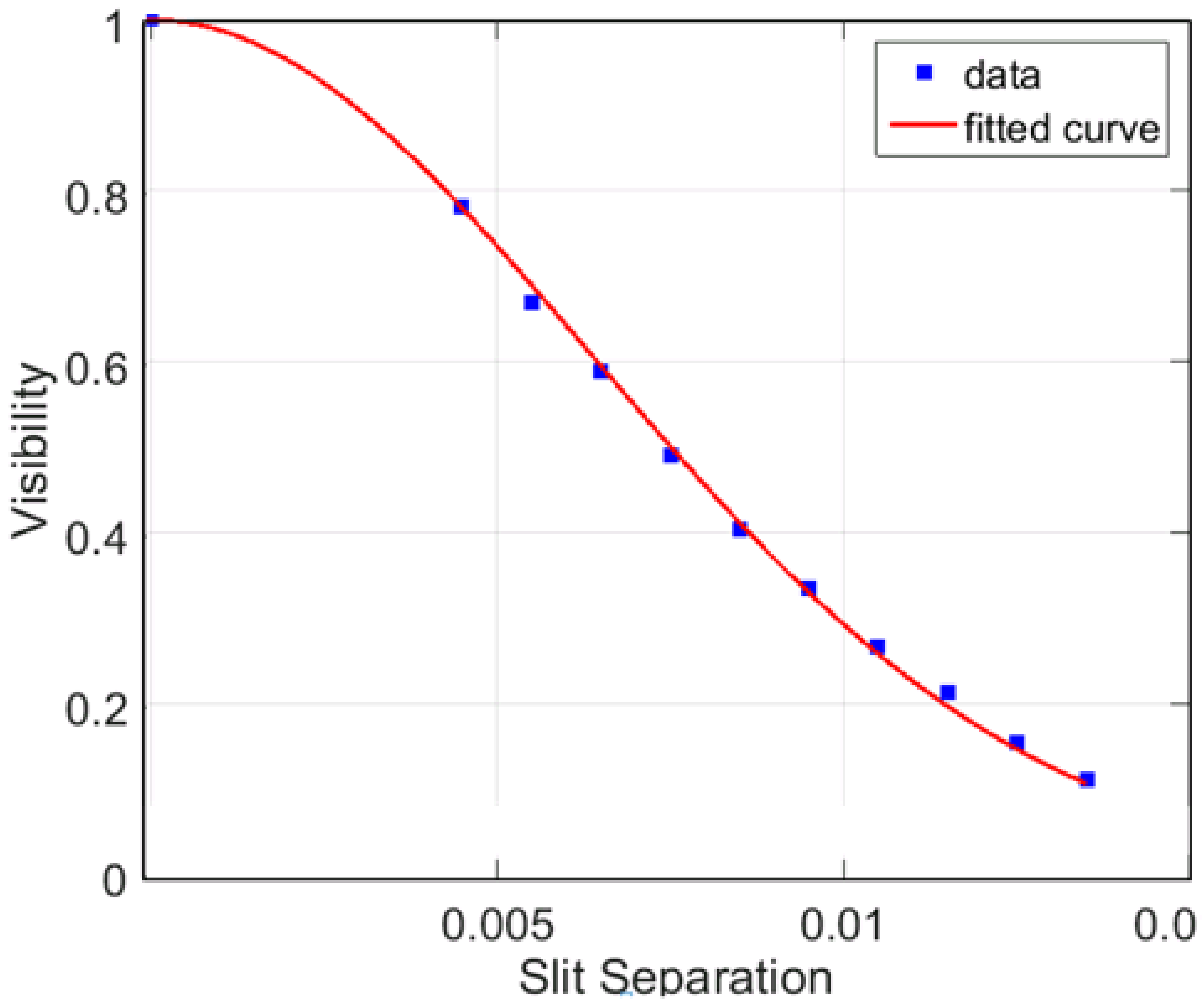
a =1.5 mm

h =0.5 mm

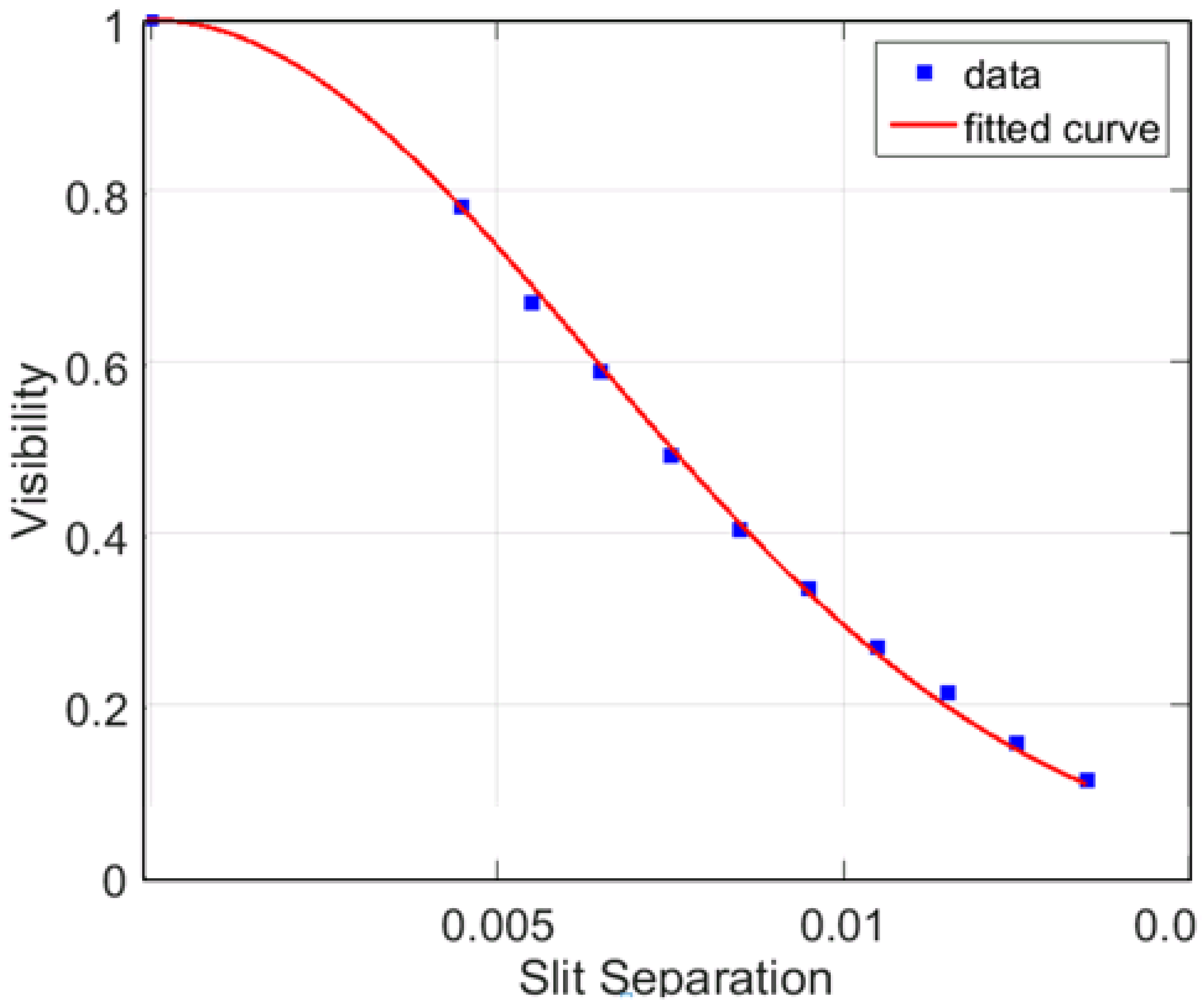
Filter : ND1

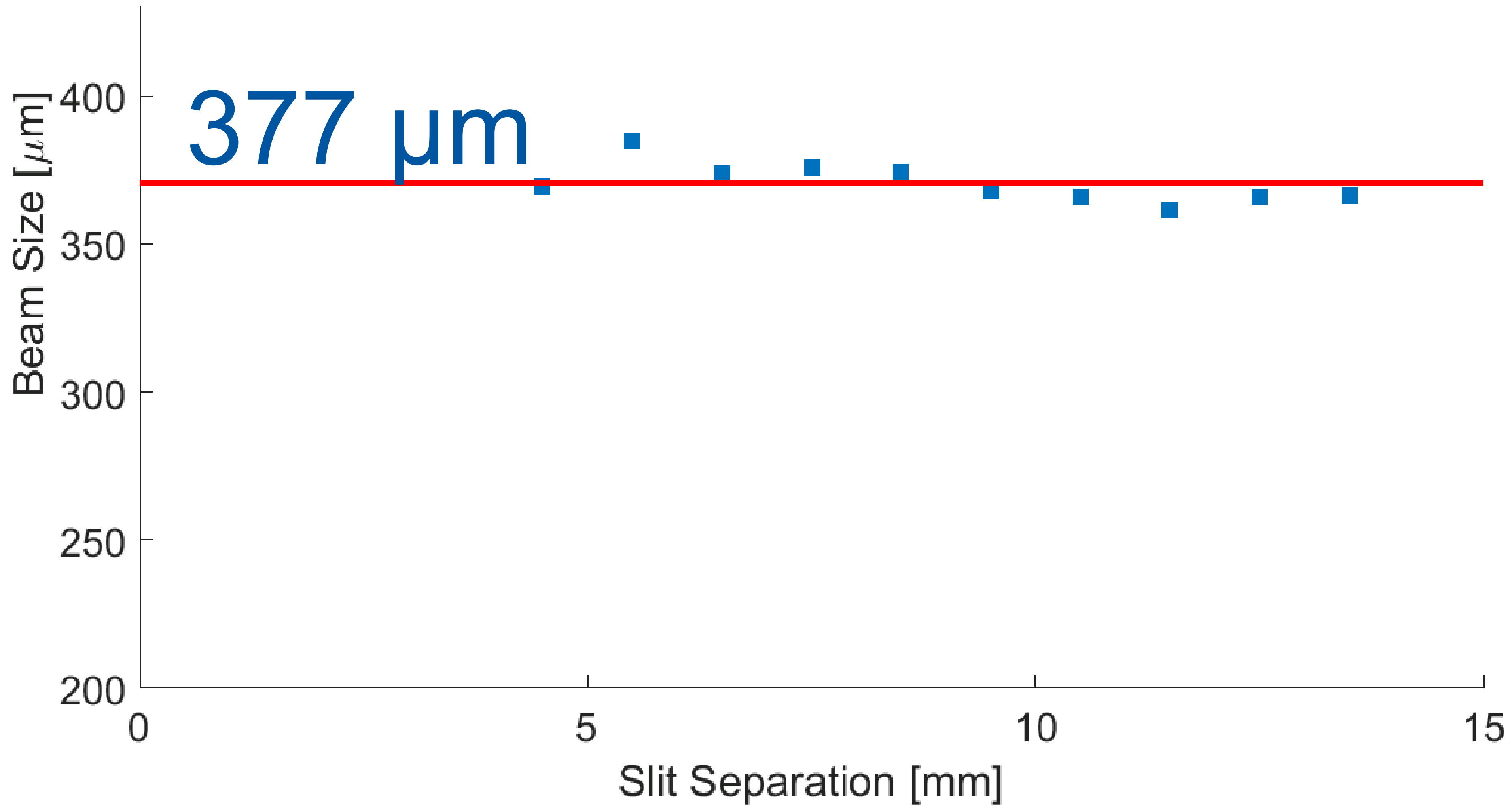






Beam Size: ~375 µm





Beam Size: ~375 µm

LHC SR

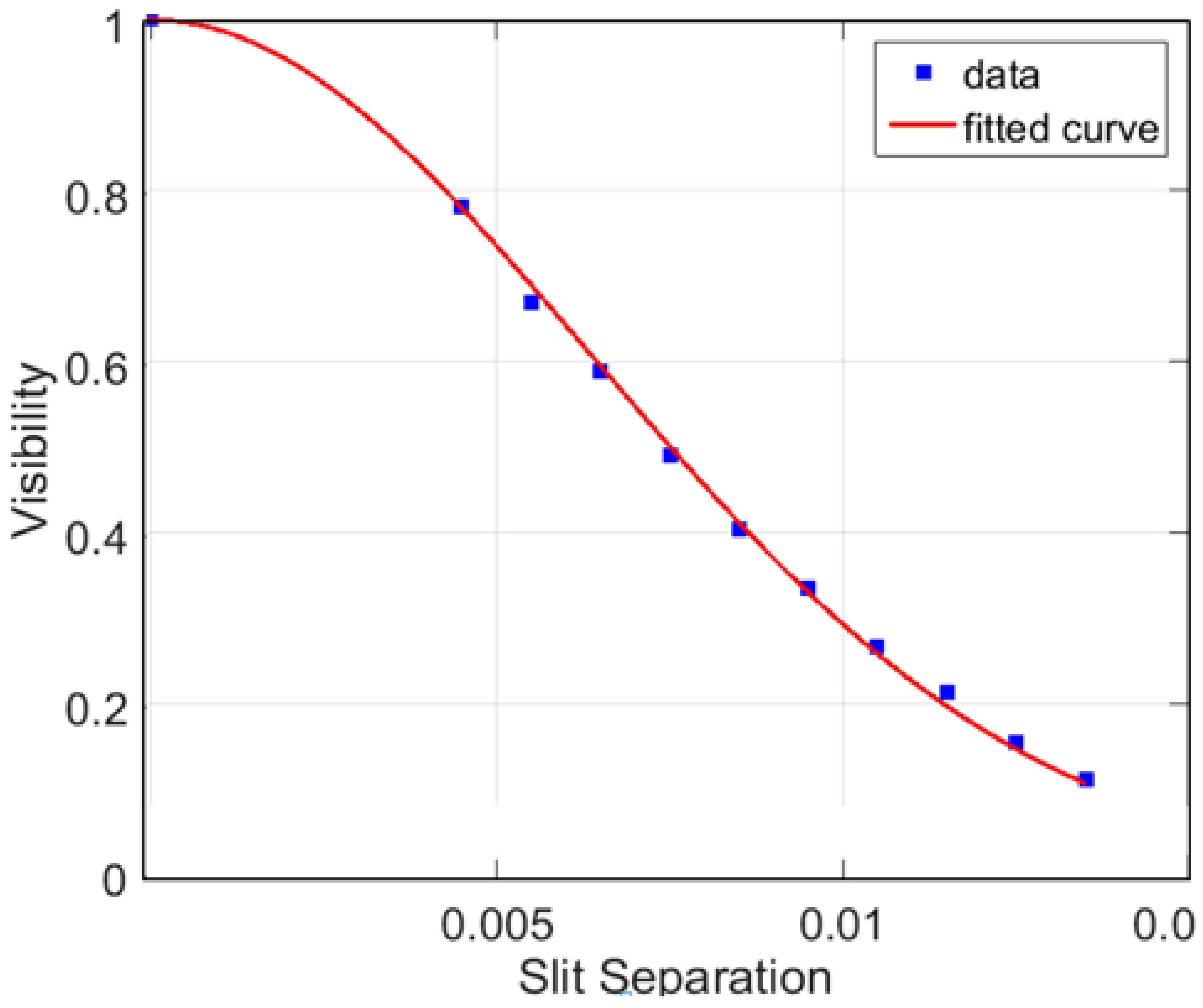
Imaging at the LHC

SR Interferometry

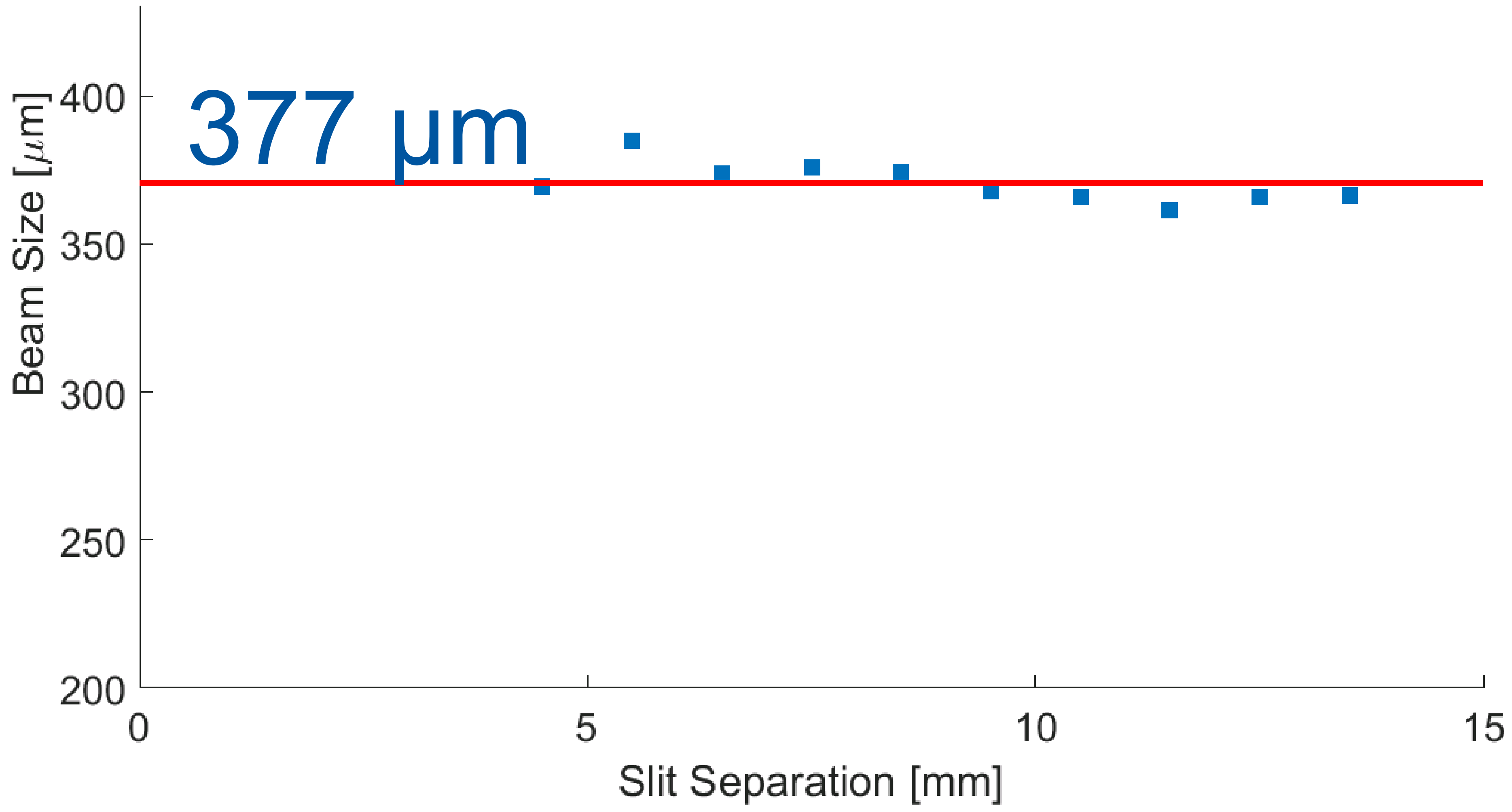
LHC Interferometer

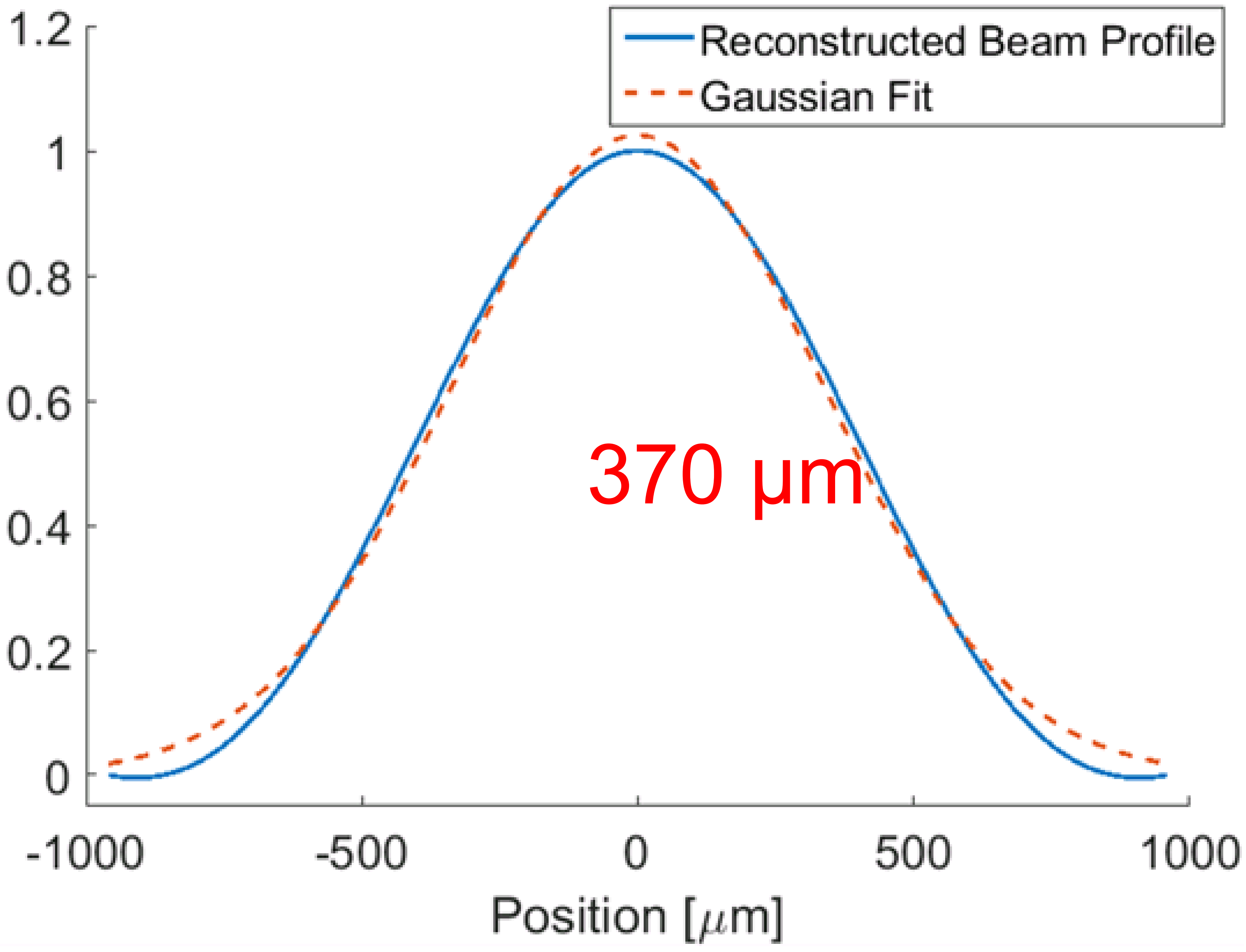
Commissioning
At 6.5 TeV
At 450 GeV

2D Interferometer



Beam Size: ~375 µm





- The Same measurement was done

At λ=400nm

(Different Intensifier Gain, ND filter)

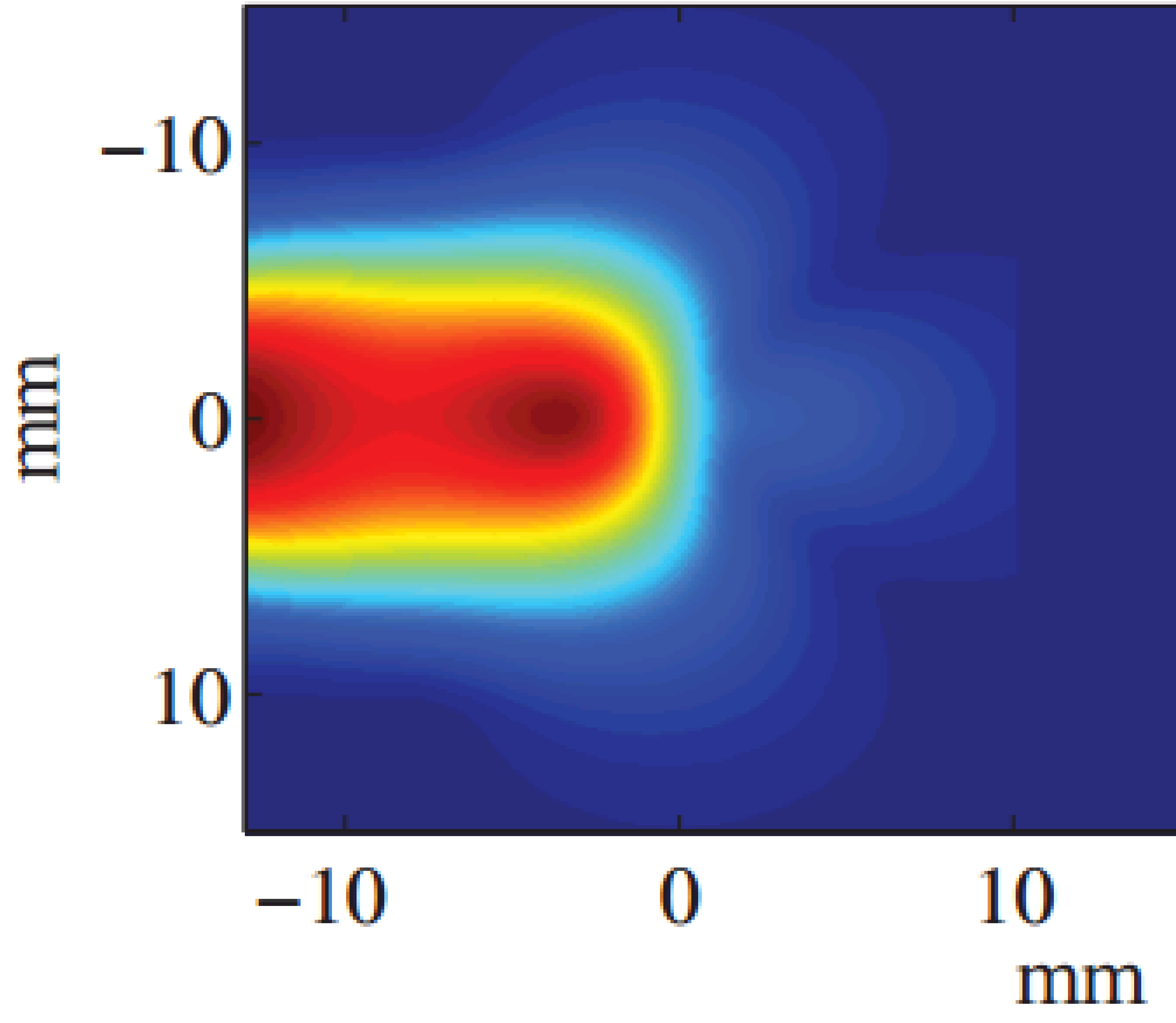
⇒ Beam Size: 369 μm

- ❑ The Same measurement was done At λ=400nm (Different Intensifier Gain, ND filter)
  $\Rightarrow$ Beam Size: 369 μm

- ❑ The Same measurement was done Changing the height of the slit
  $\Rightarrow$ No significant Beam size Change (<3%)

- The Same measurement was done At λ=400nm (Different Intensifier Gain, ND filter)
  ⇒ Beam Size: 369 μm

- The Same measurement was done Changing the height of the slit
  ⇒ No significant Beam size Change (<3%)



LHC SR

Imaging at the LHC

SR Interferometry

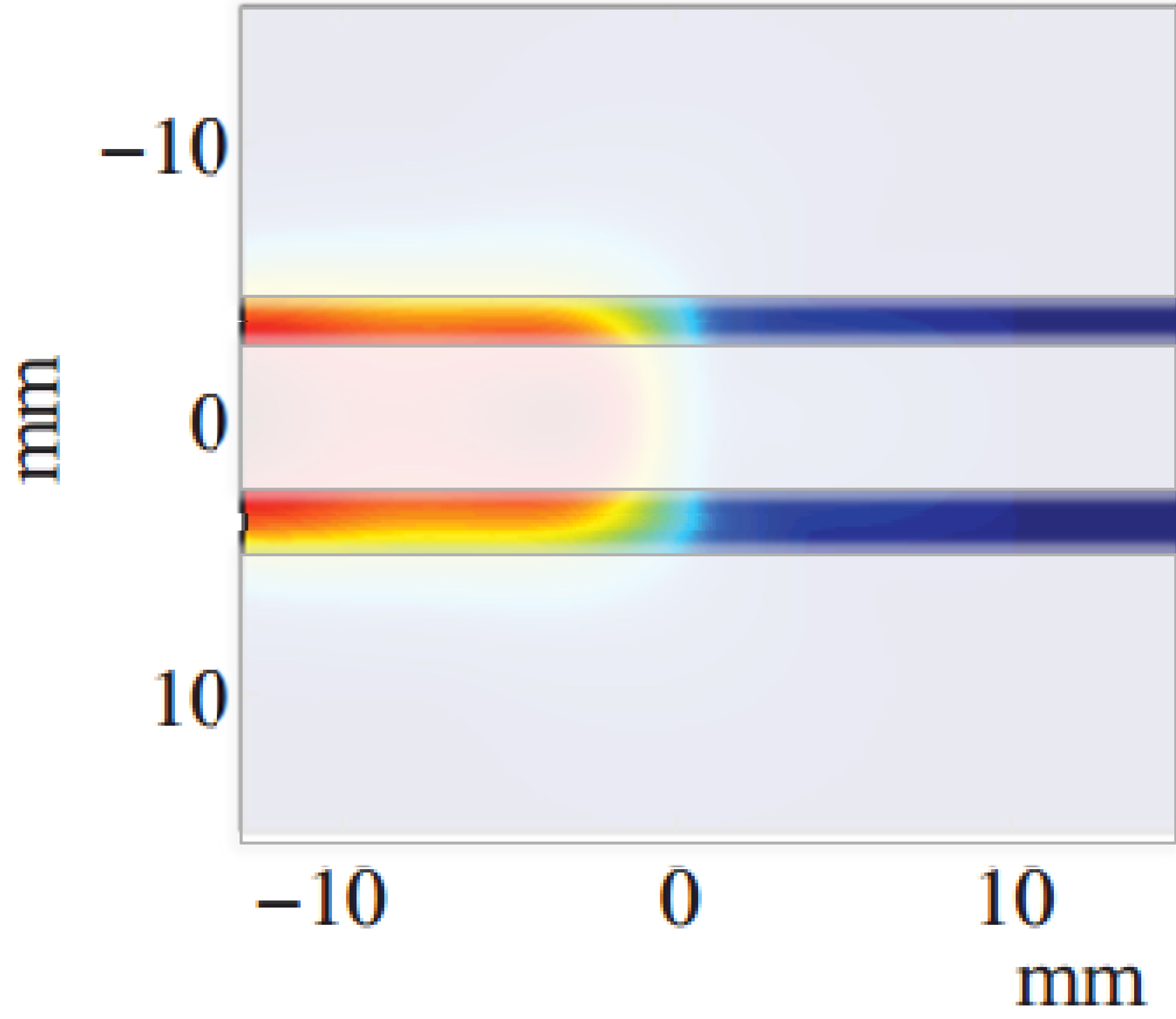
LHC Interferometer

Commissioning At 6.5 TeV
At 450 GeV

2D Interferometer

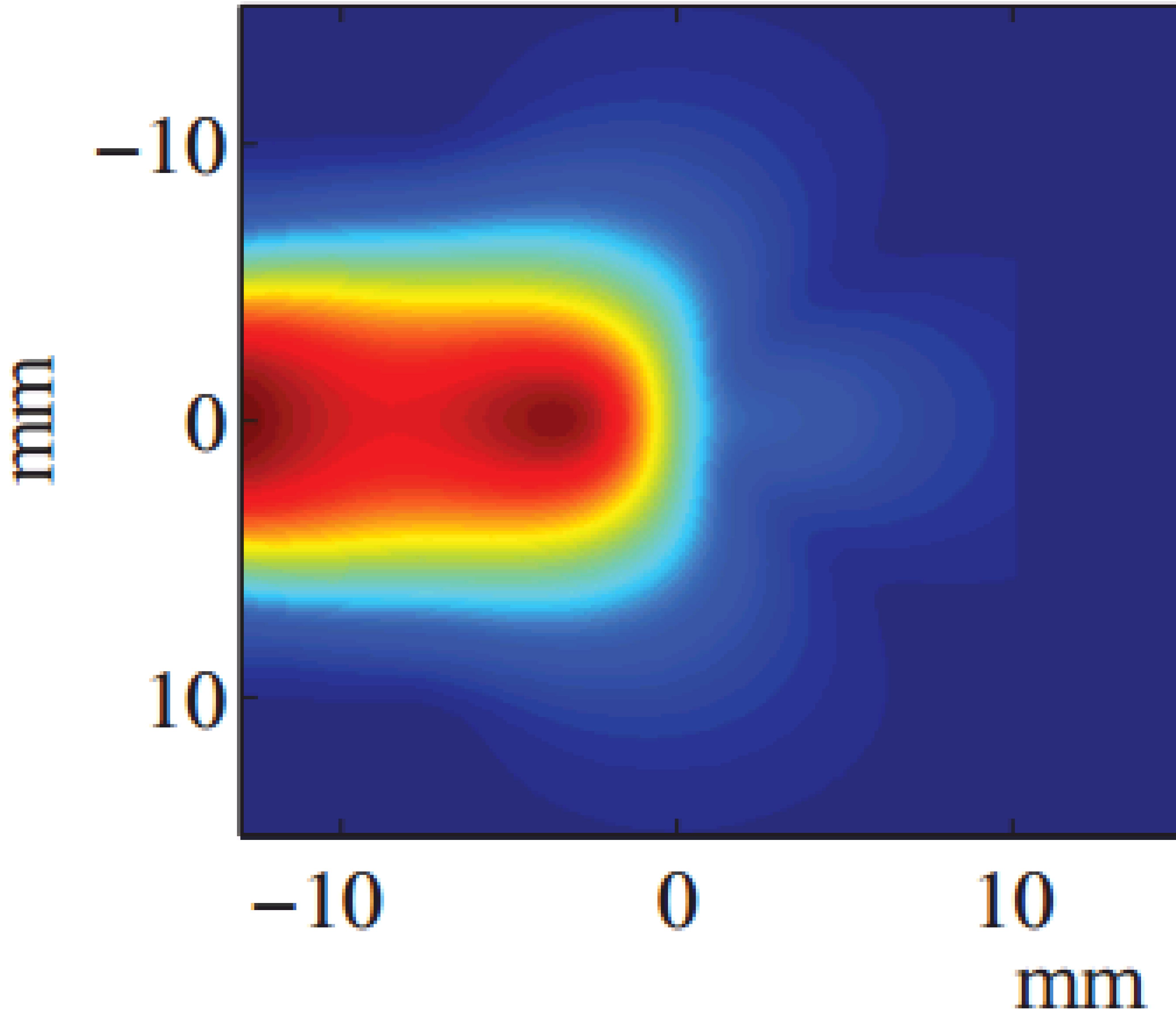
- ❑ The Same measurement was done At λ=400nm (Different Intensifier Gain, ND filter)
  ⇒ Beam Size: 369 μm

- ❑ The Same measurement was done Changing the height of the slit
  ⇒ No significant Beam size Change (<3%)



- The Same measurement was done At λ=400nm (Different Intensifier Gain, ND filter)
  ⇒ Beam Size: 369 μm

- The Same measurement was done Changing the height of the slit
  ⇒ No significant Beam size Change (<3%)



LHC SR

Imaging at the LHC

SR Interferometry

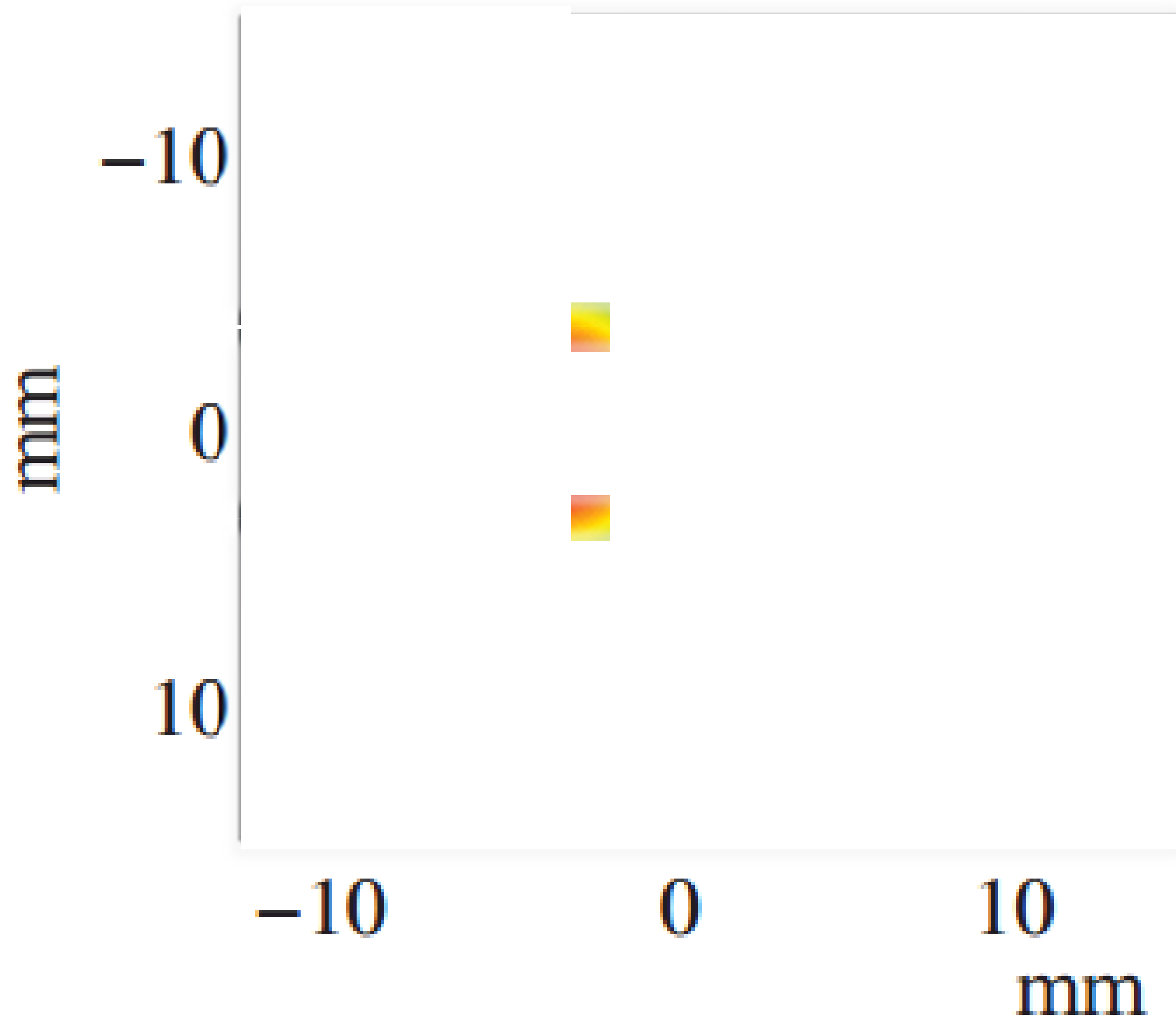
LHC Interferometer

Commissioning At 6.5 TeV
At 450 GeV

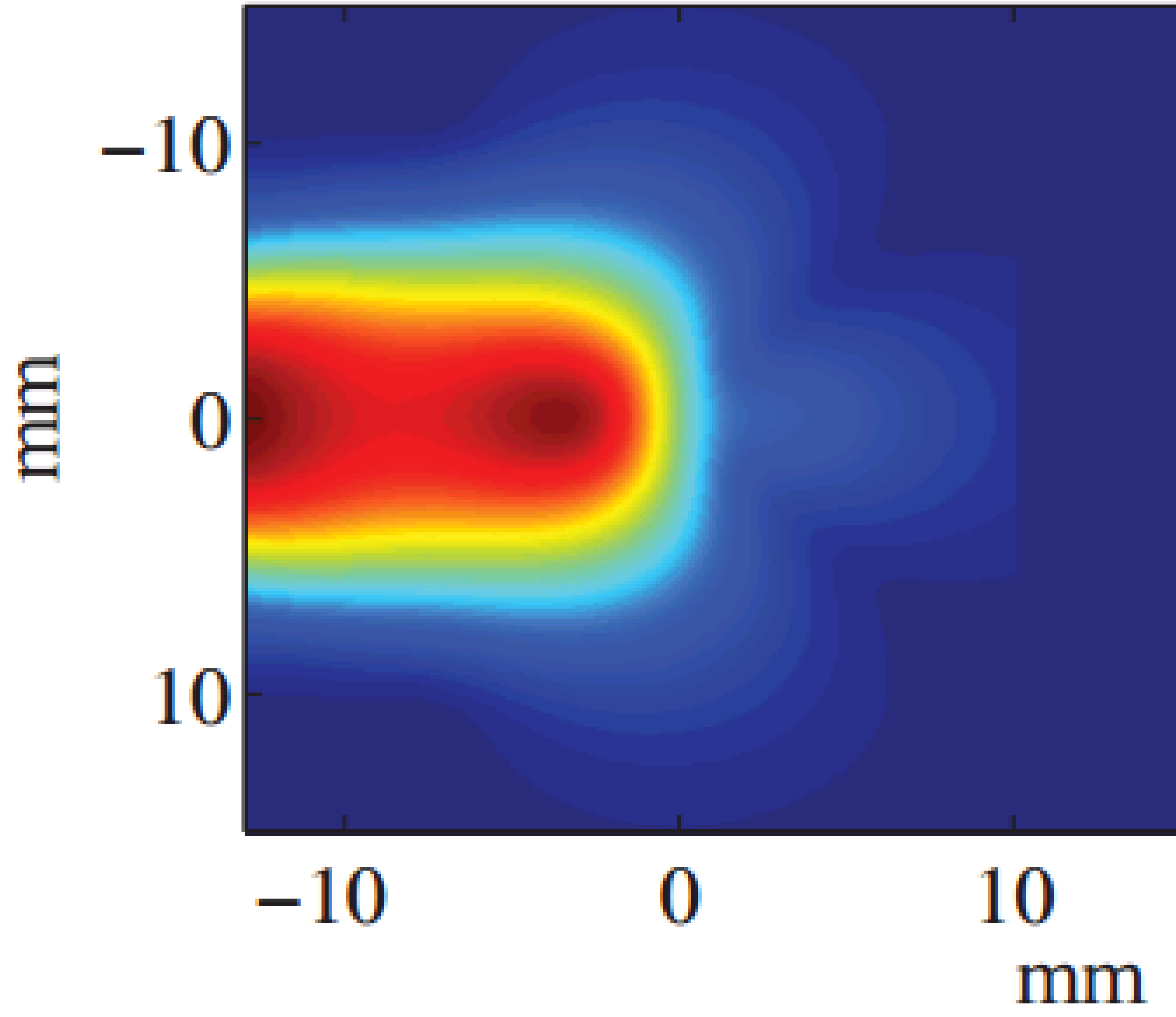
2D Interferometer

- The Same measurement was done At λ=400nm (Different Intensifier Gain, ND filter)
  ⇒ Beam Size: 369 µm

- The Same measurement was done Changing the height of the slit
  ⇒ No significant Beam size Change (<3%)



- The Same measurement was done At λ=400nm (Different Intensifier Gain, ND filter)
  ⇒ Beam Size: 369 μm



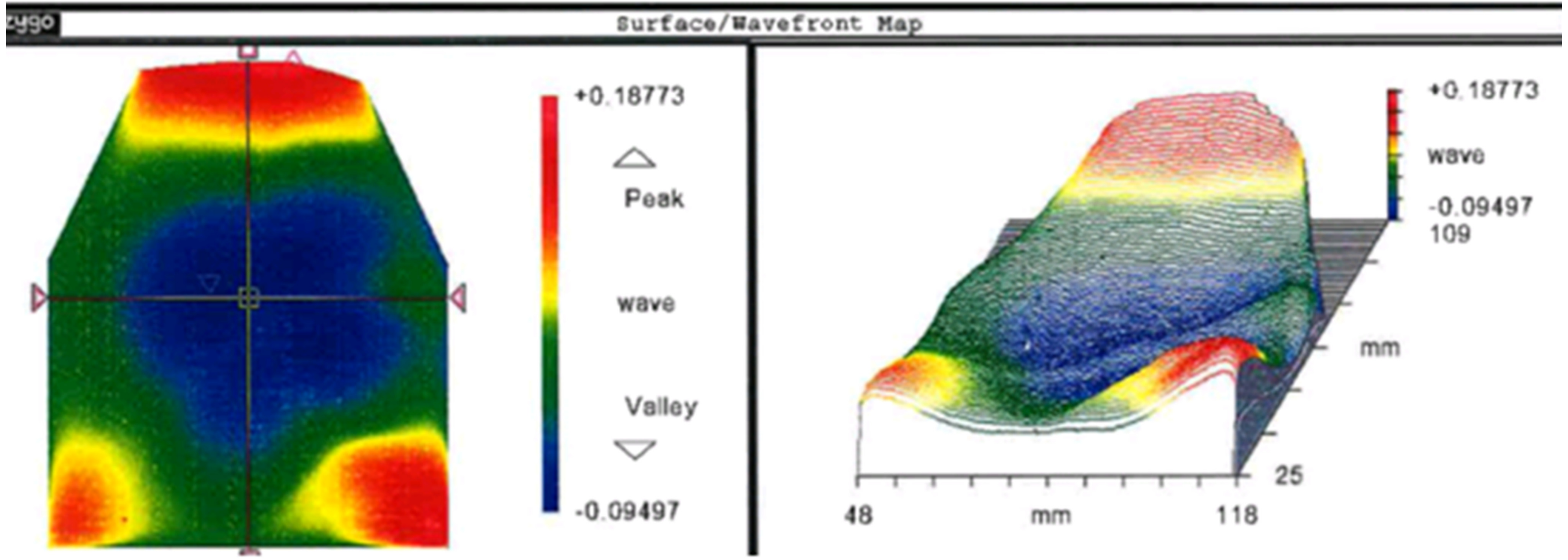
- The Same measurement was done Changing the height of the slit
  ⇒ No significant Beam size Change (<3%)

Very Robust Measurements!

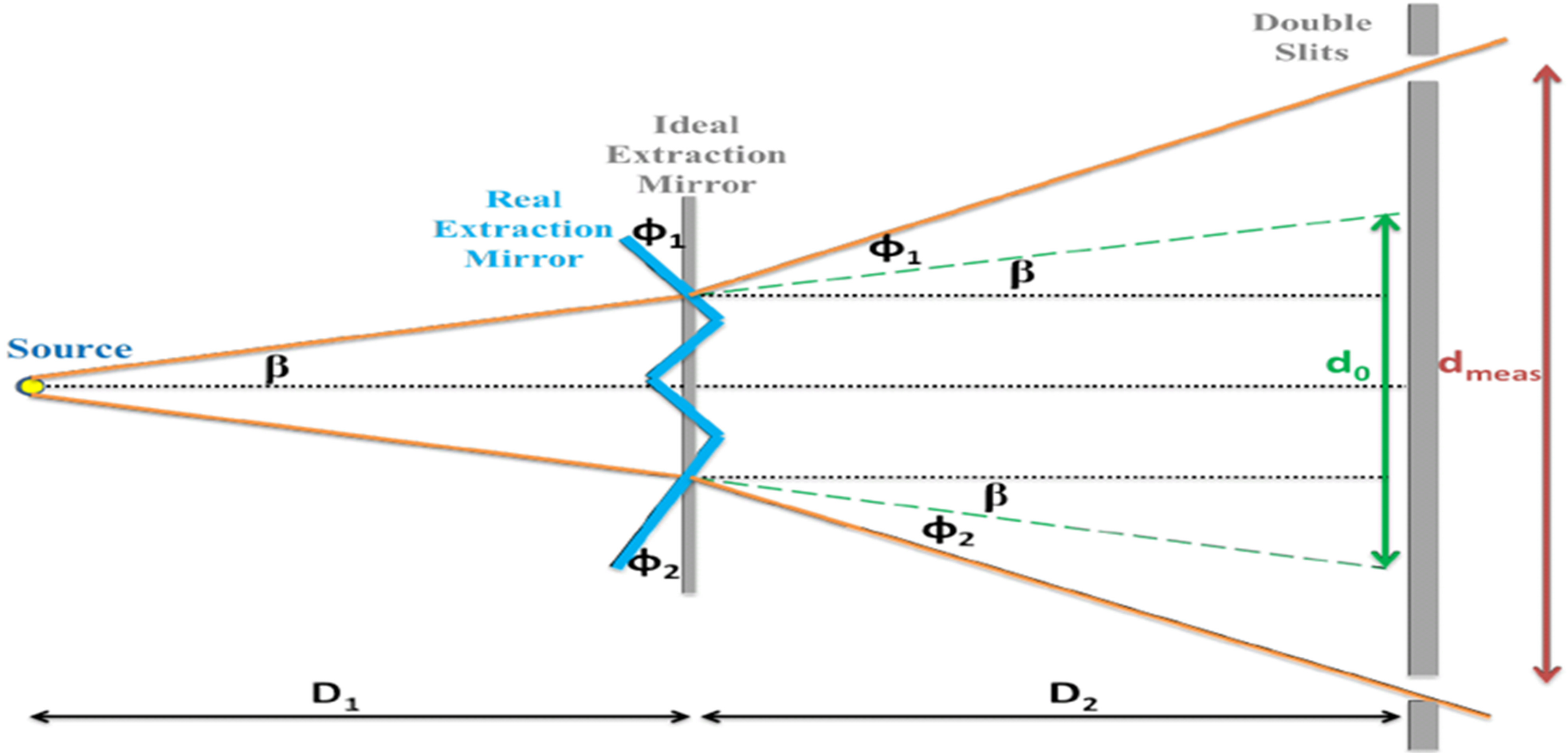
Commissioning with Beam

Commissioning with Beam

- Extraction Mirror Deformation
- Polarization
- Off-Center
- Frame Exposure
- Intensifier Saturation
- Detector Linearity



In-Vacuum mirror flatness is better than λ/4 (Full area)



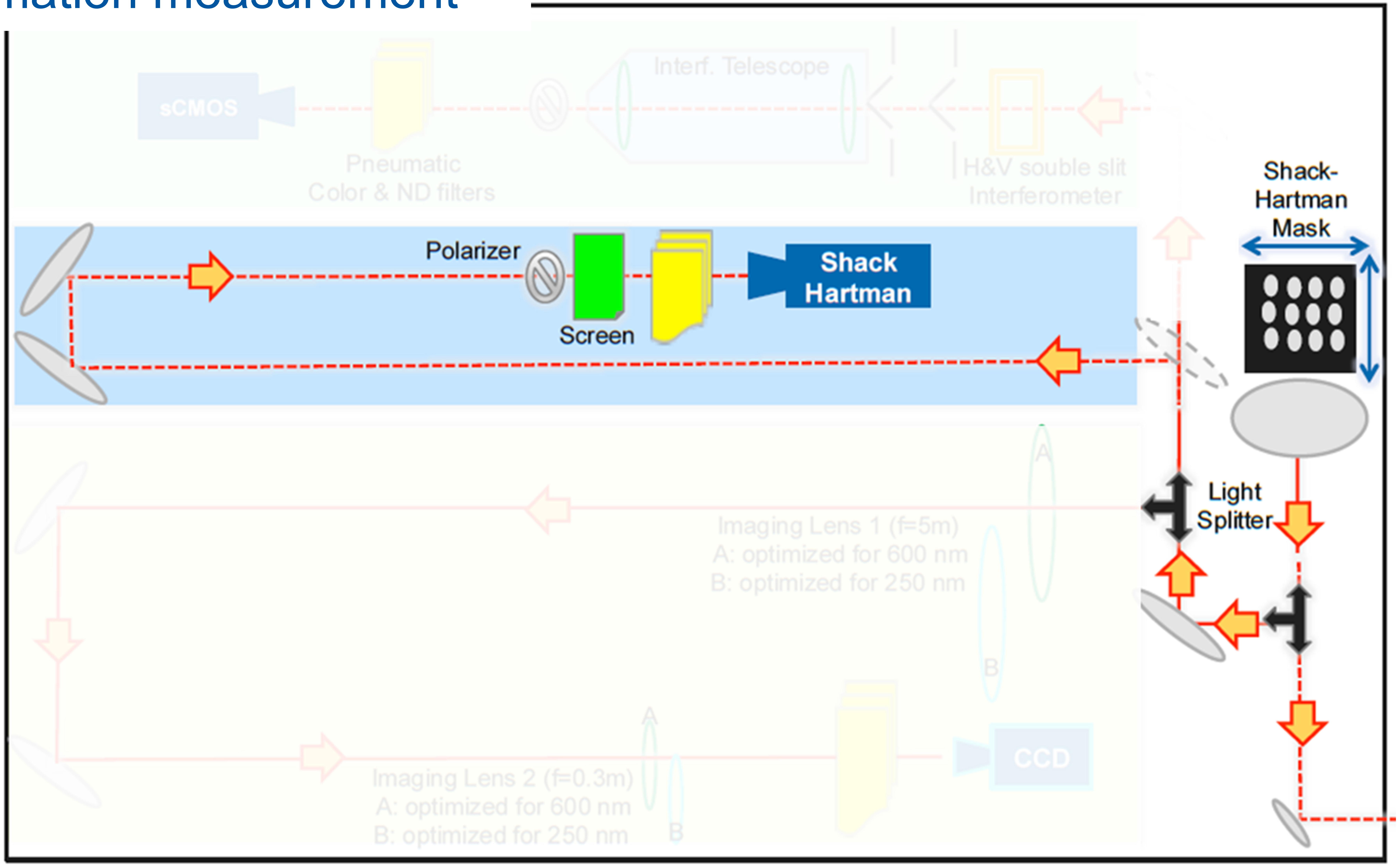
$$d_{meas} = 2D_1 \frac{d_0}{2\,(D_1 + D_2)} + D_2 \left[tan \left(atan \left(\frac{d_0}{2\,(D_1 + D_2)} \right) + \Phi_1 \right) + tan \left(atan \left(\frac{d_0}{2\,(D_1 + D_2)} \right) + \Phi_2 \right) \right]$$

where $d_0 = 2(D_1 + D_2)tan(\beta)$.

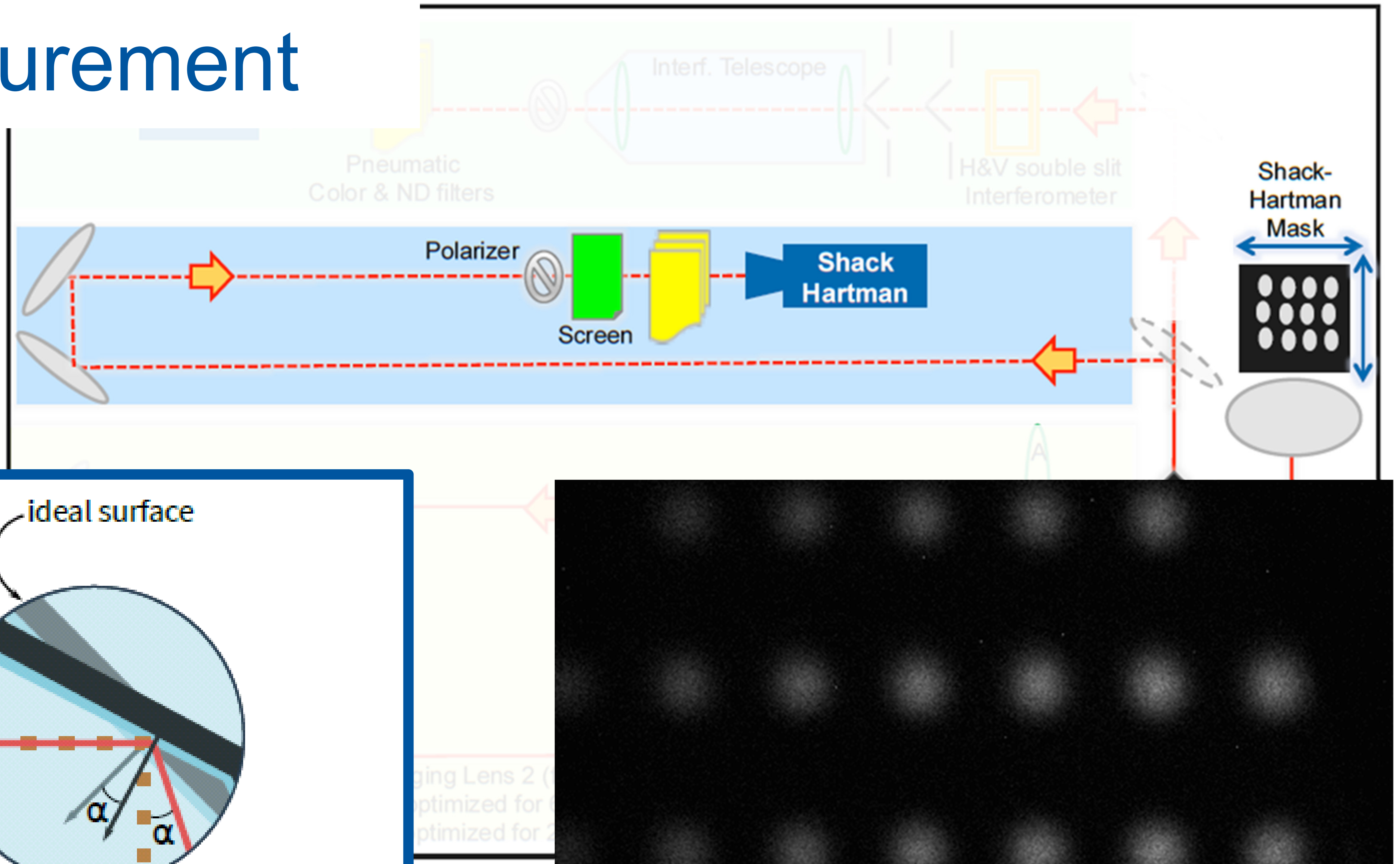
By Design D2 was kept as small as possible such as effect on beam size is minimized to the percent level

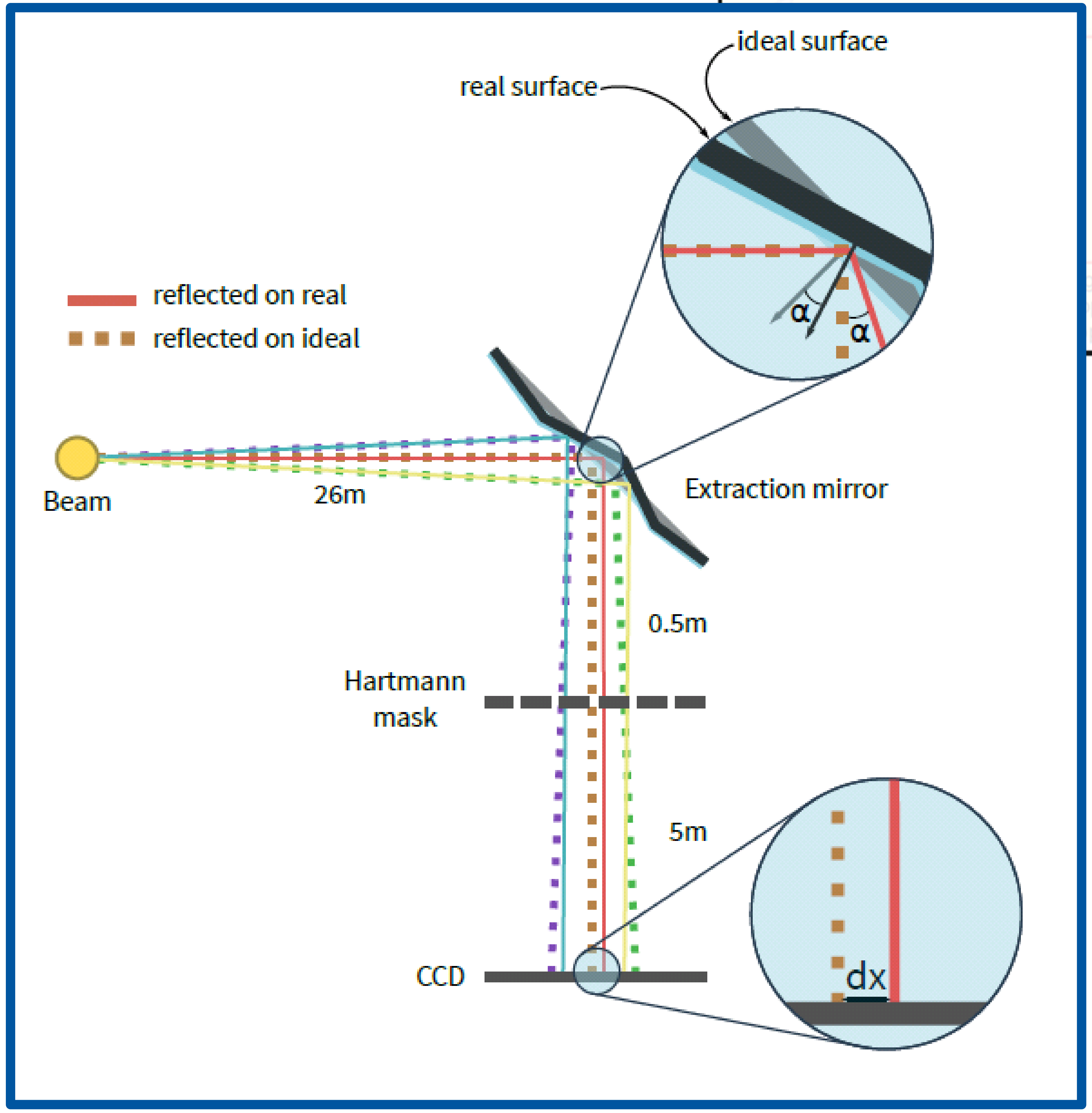
And with Beam circulating?

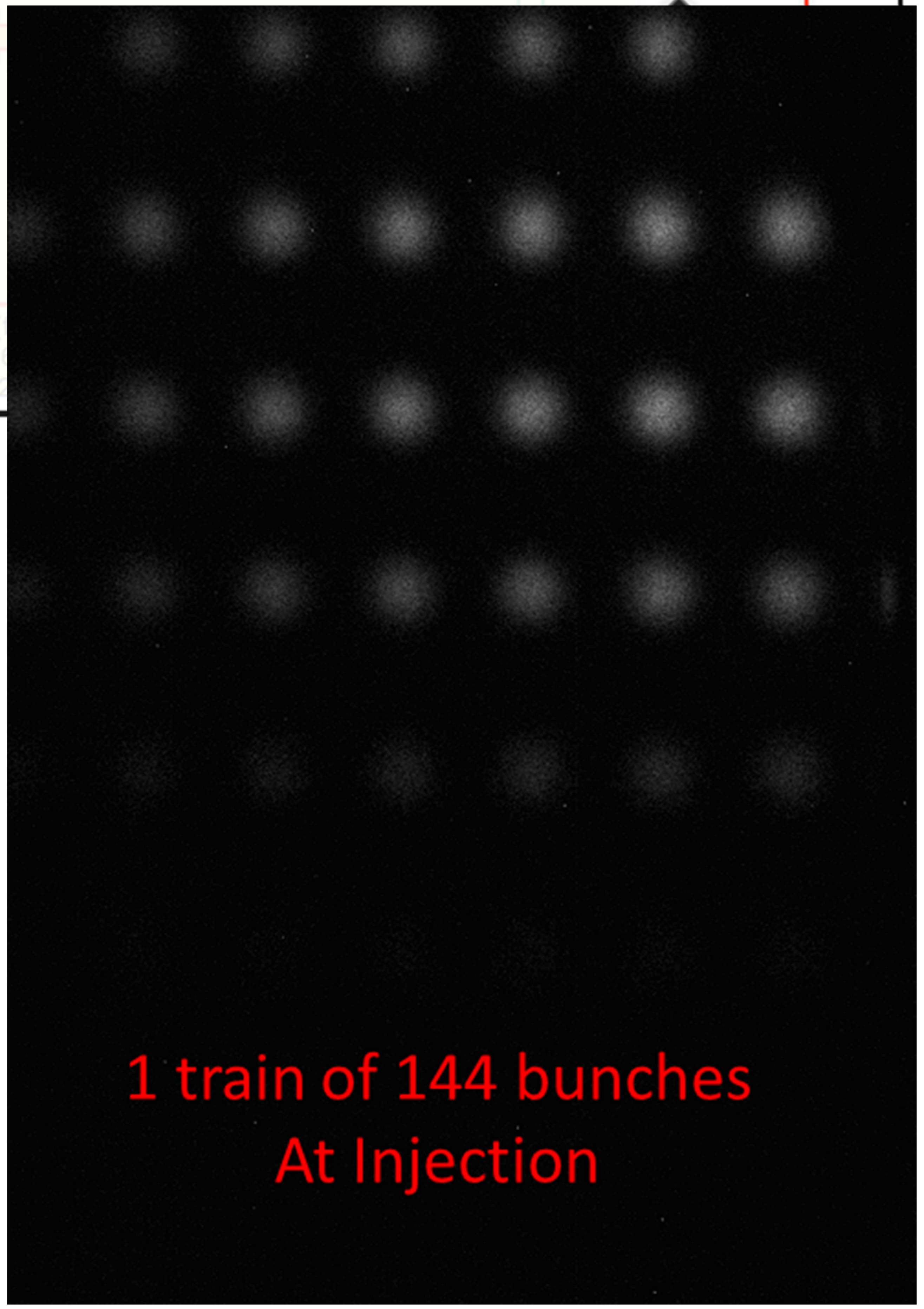
Hartmann mask Line for mirror deformation measurement



Hartmann mask Line for mirror deformation measurement







No deterioration of the extraction mirror surface flatness is caused by the full intensity circulating beam.

LHC SR

Imaging at the LHC

SR Interferometry

LHC Interferometer

Commissioning At 6.5 TeV At 450 GeV

2D Interferometer

Commissioning with Beam

- Extraction Mirror Deformation
- Polarization
- Off-Center
- Frame Exposure
- Intensifier Saturation
- Detector Linearity

LHC SR

Imaging at the LHC

SR Interferometry

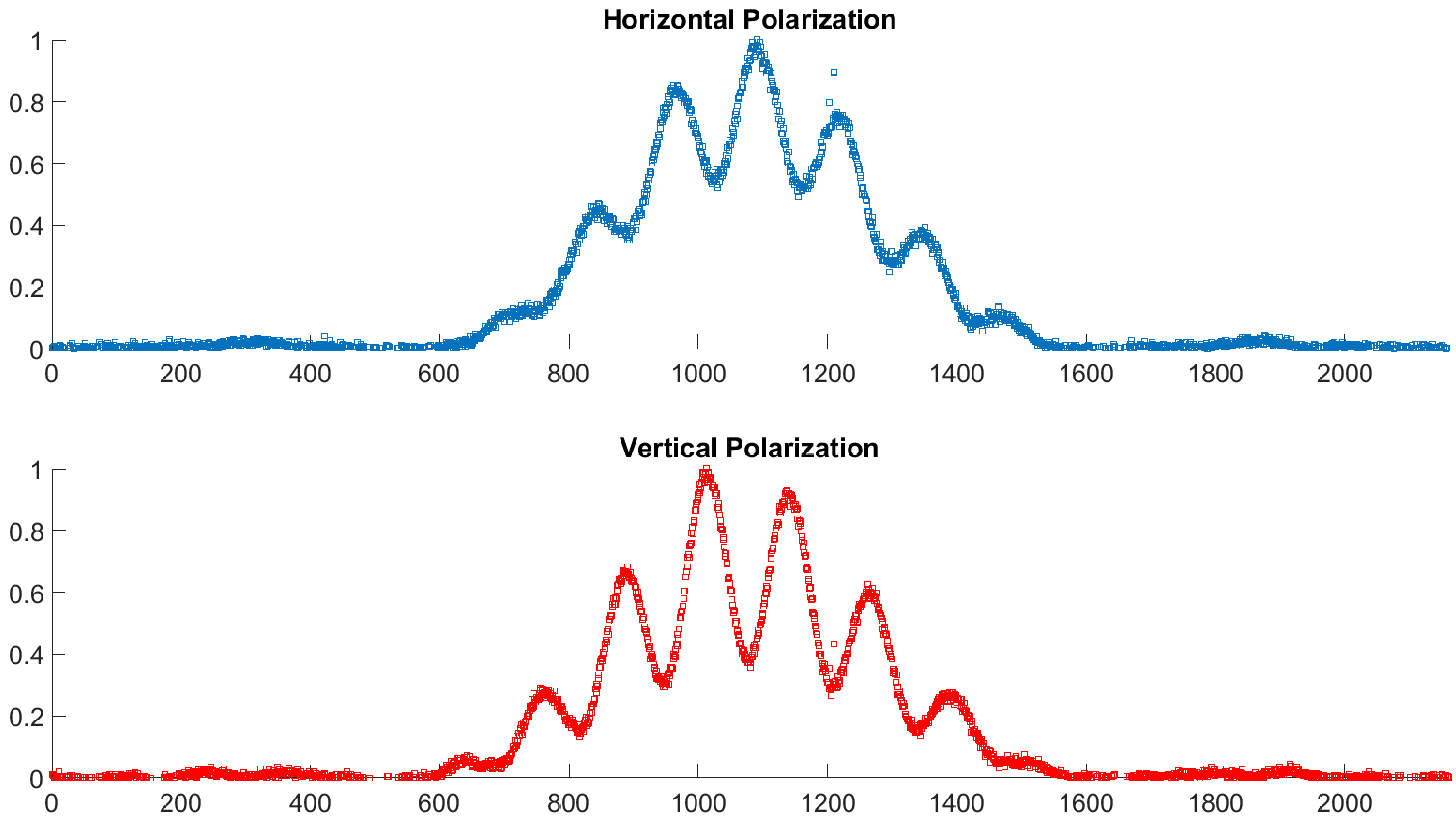
LHC Interferometer

Commissioning At 6.5 TeV

At 450 GeV

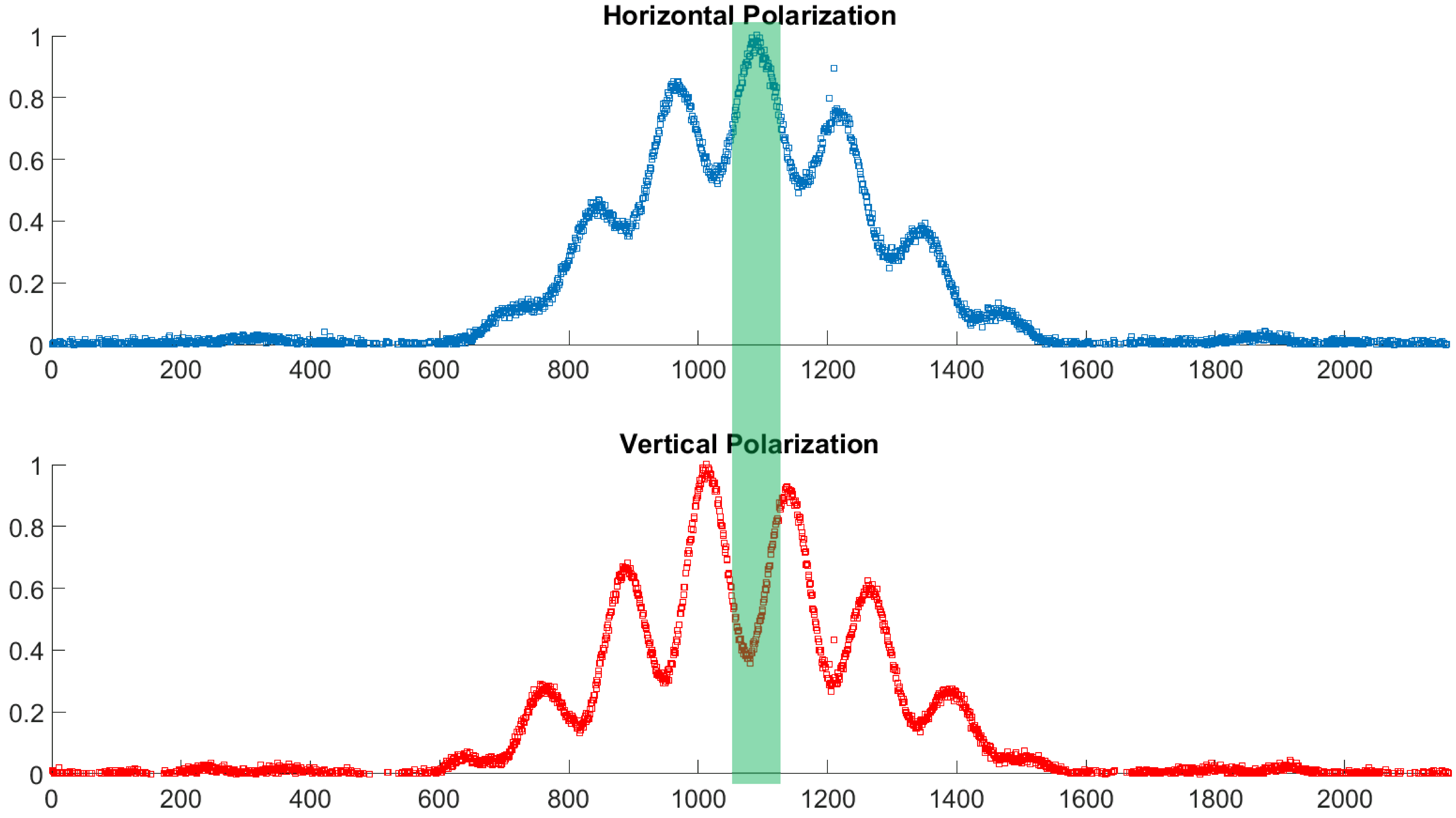
2D Interferometer

H&V polarizations of the SR lead to interference fringes shifted by π rad



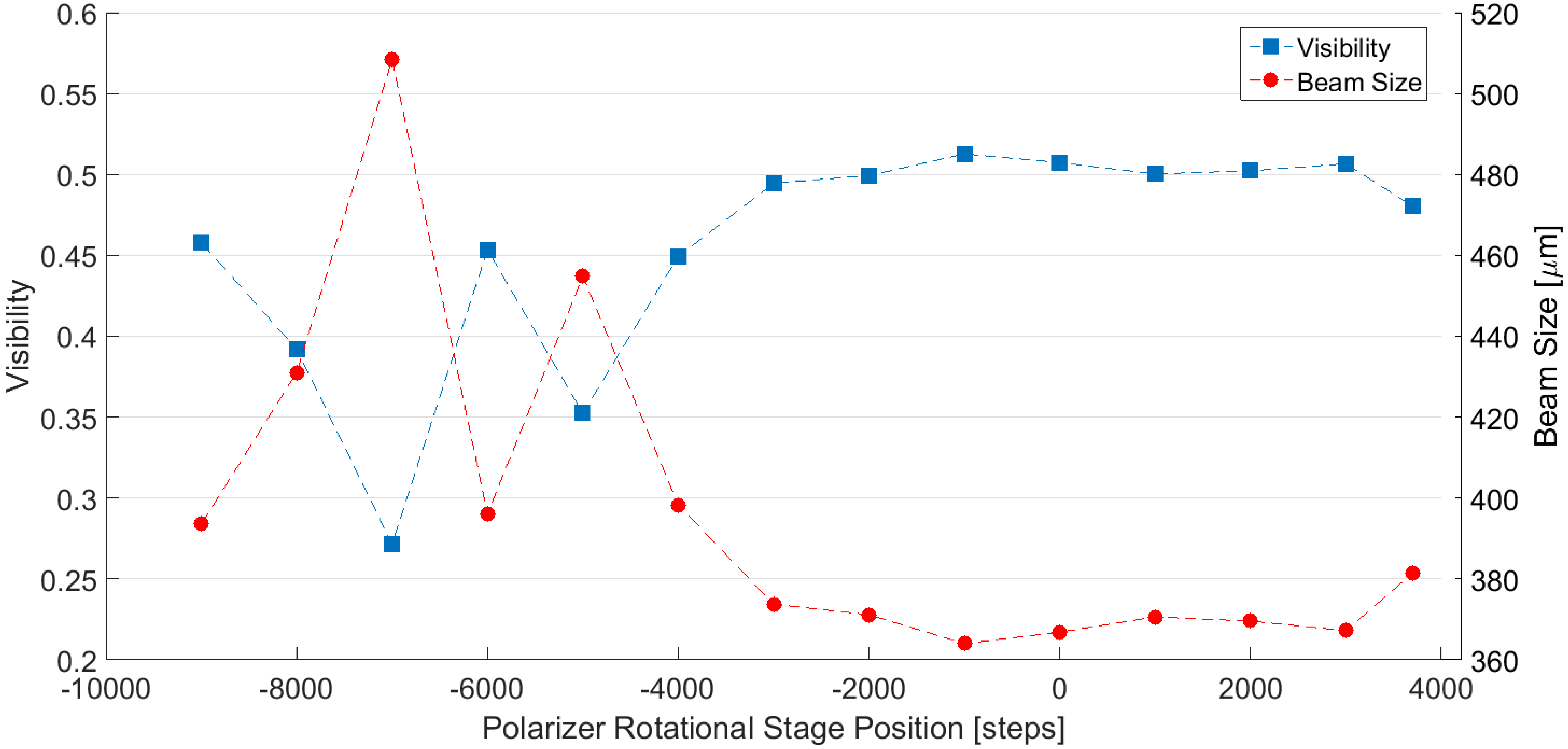
H&V polarizations of the SR lead to interference fringes shifted by π rad

=> loss of the visibility and an overestimation of the beam size.



H&V polarizations of the SR lead to interference fringes shifted by π rad

=> loss of the visibility and an overestimation of the beam size.



Polarizer angle scan to identify the nominal position

LHC SR

Imaging at the LHC

SR Interferometry

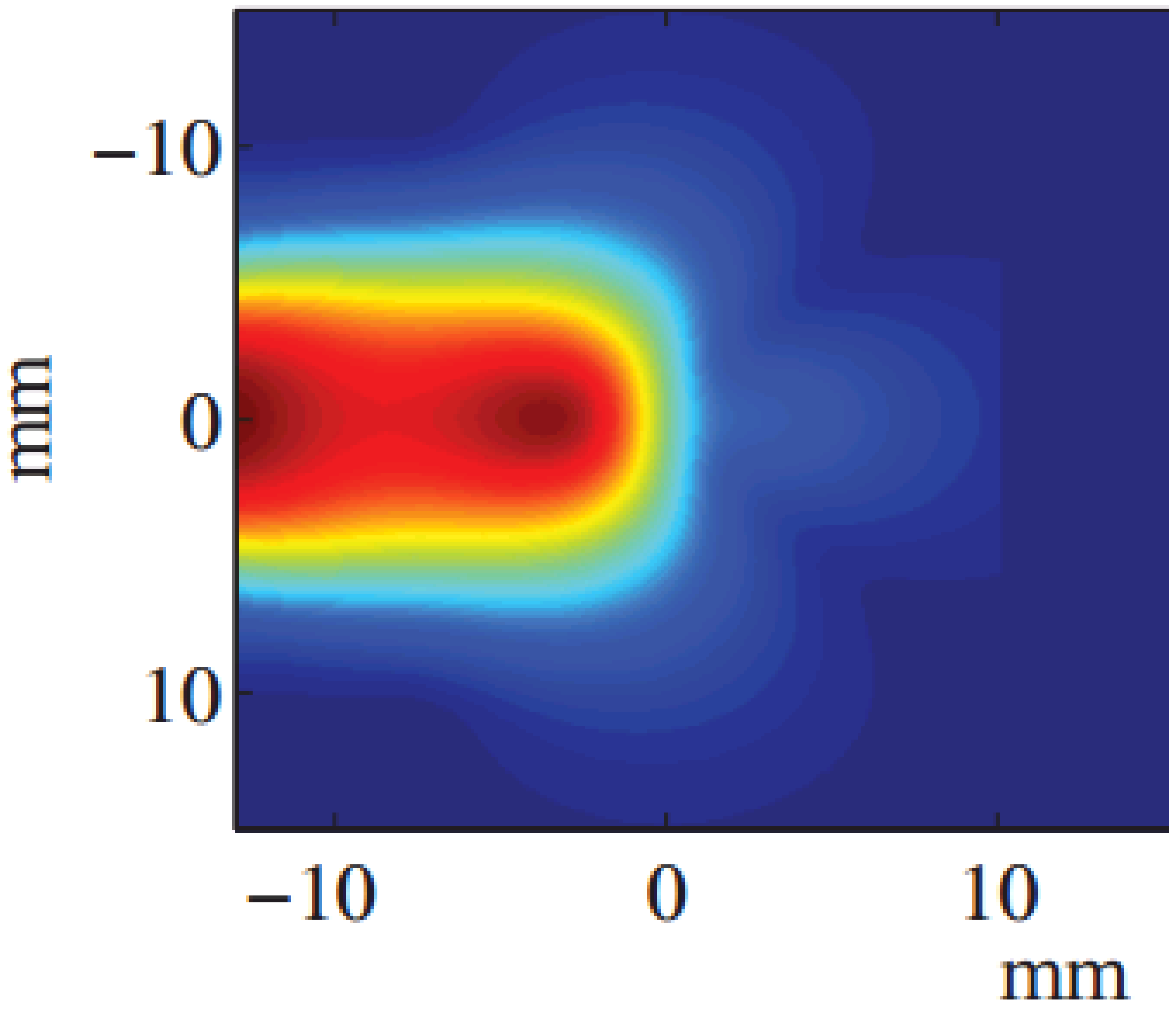
LHC Interferometer

Commissioning At 6.5 TeV
At 450 GeV

2D Interferometer

Commissioning with Beam

- Extraction Mirror Deformation
- Polarization
- Off-Center
- Frame Exposure
- Intensifier Saturation
- Detector Linearity


−10
0
10
mm
−10
0
10
mm

LHC SR

Imaging at the LHC

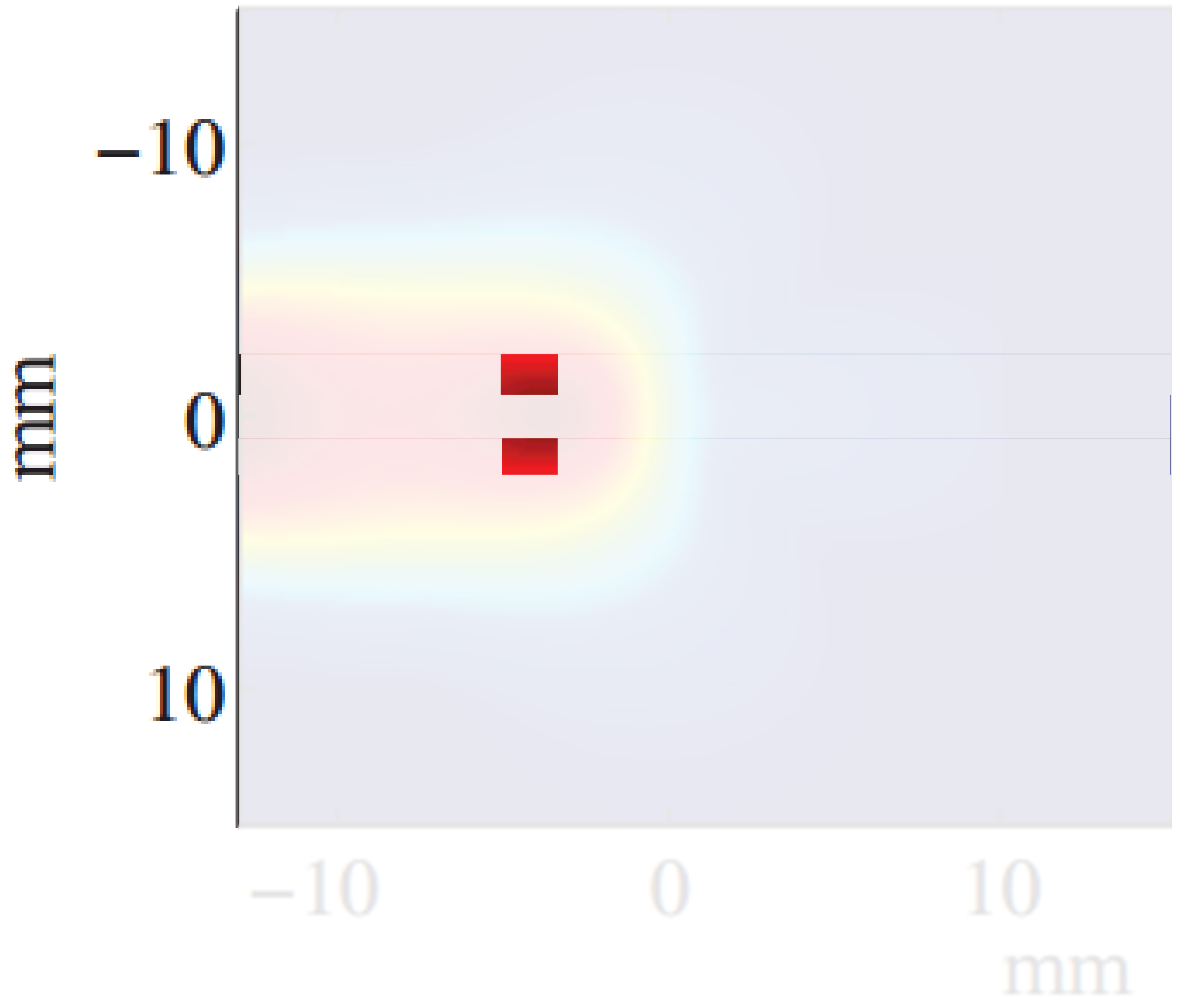
SR Interferometry

LHC Interferometer

Commissioning At 6.5 TeV

At 450 GeV

2D Interferometer



LHC SR

Imaging at the LHC

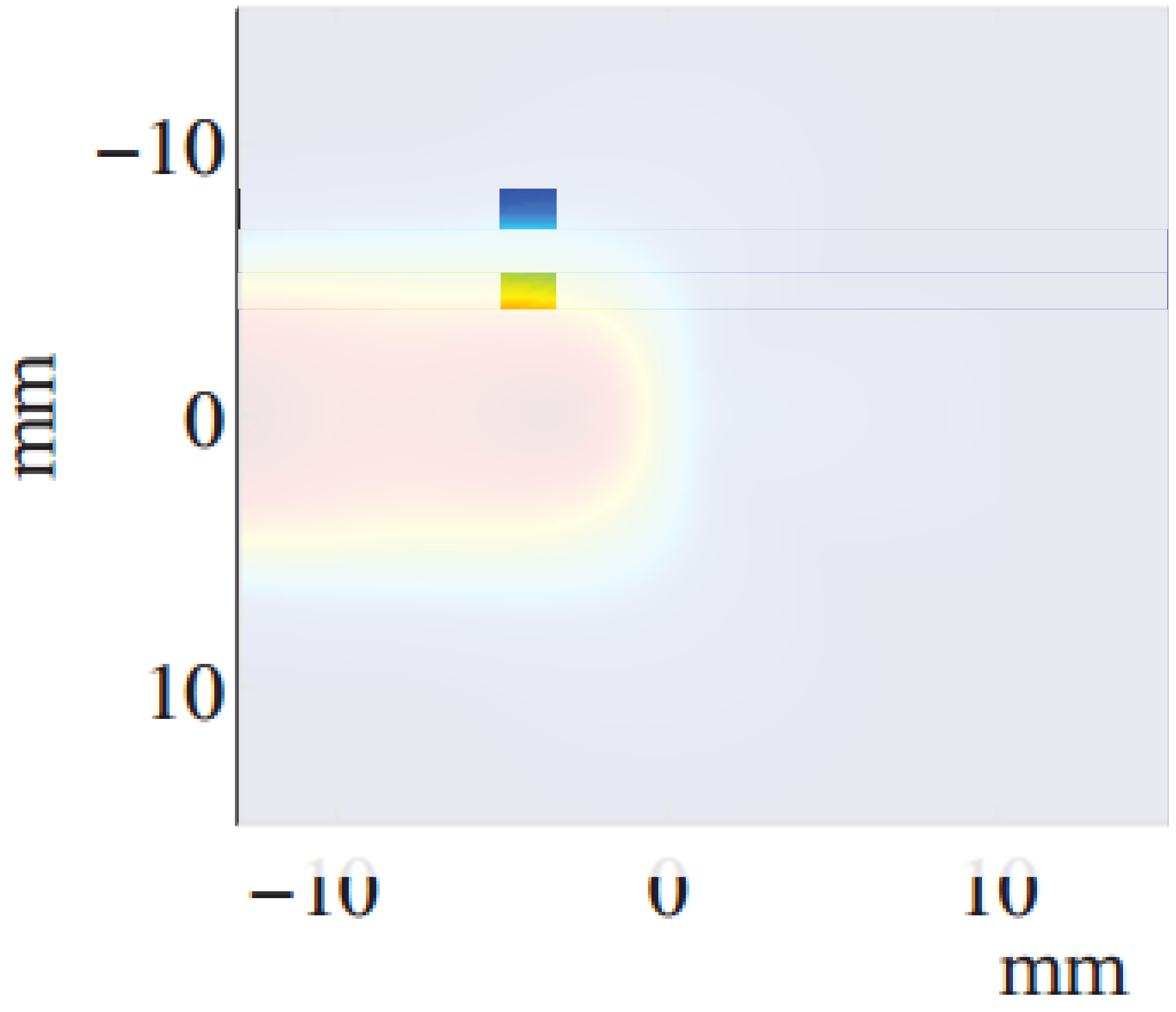
SR Interferometry

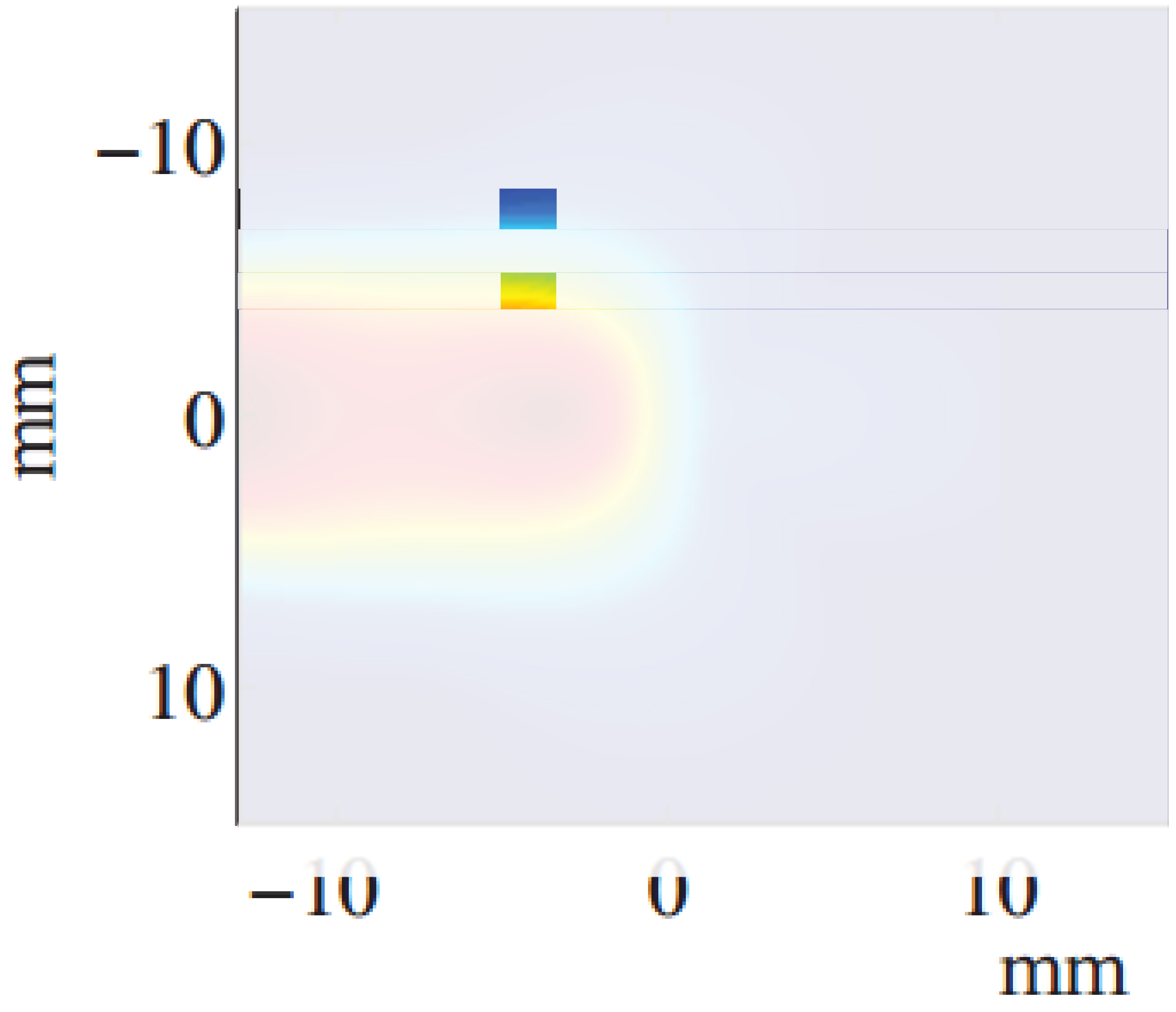
LHC Interferometer

Commissioning At 6.5 TeV

At 450 GeV

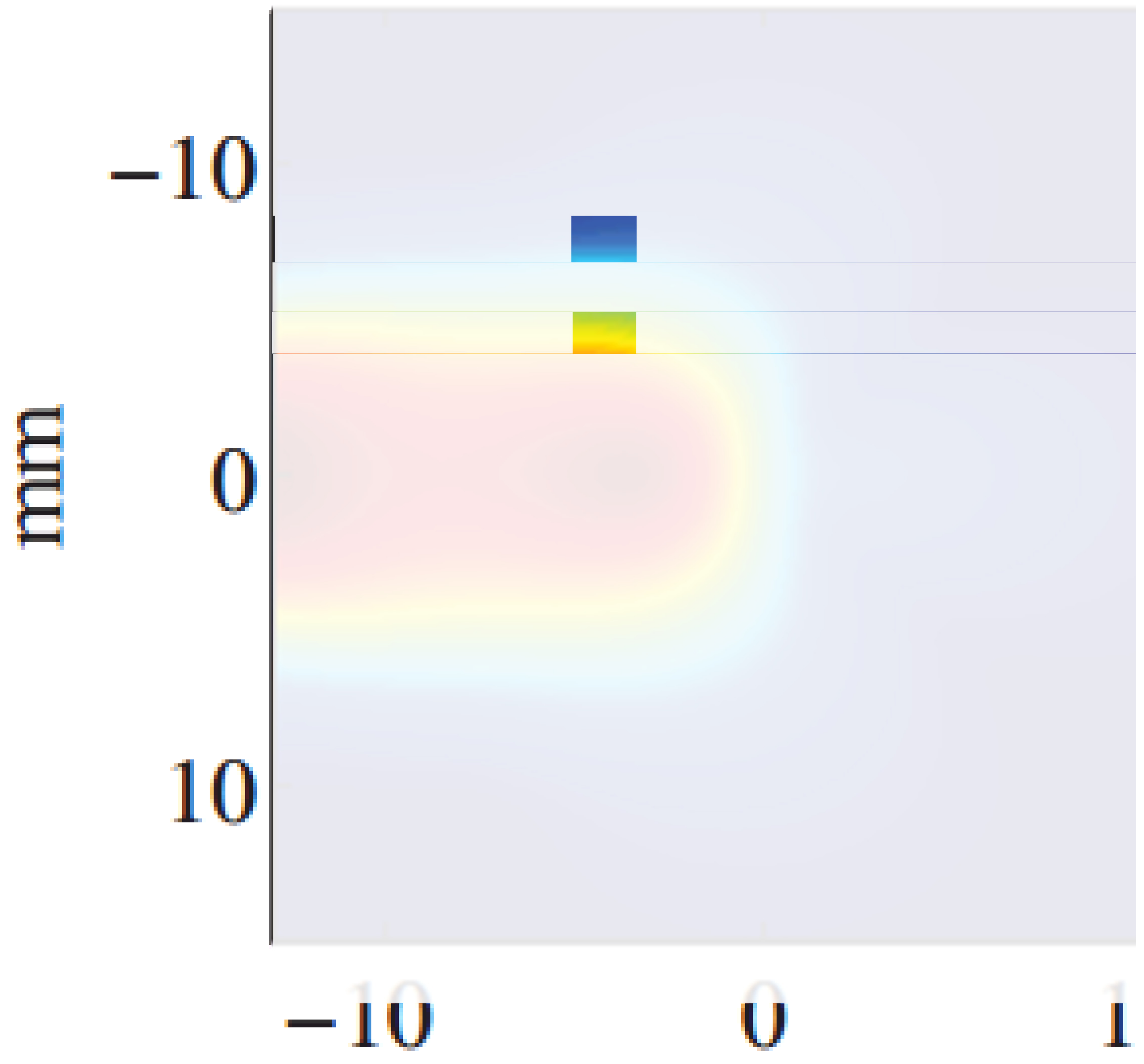
2D Interferometer

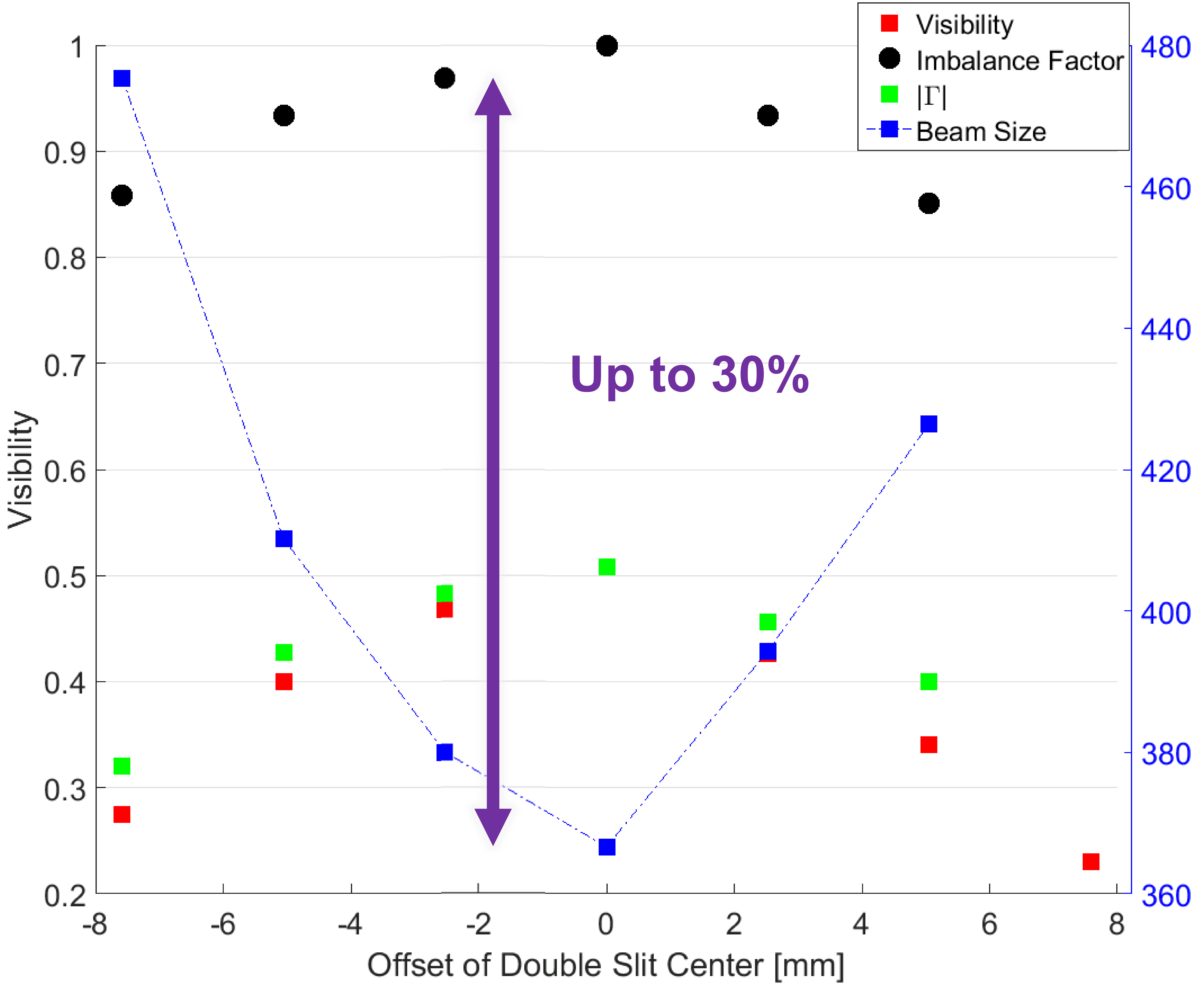




Light Imbalance at the slits when off-center w.r.t. the SR emission axis is:

- not only caused by the limited SR opening angle
  => Intensity imbalance factor not enough to correct
- but also the incoherent depth of field and the dependence of the SR horizontal opening angle on the offset.

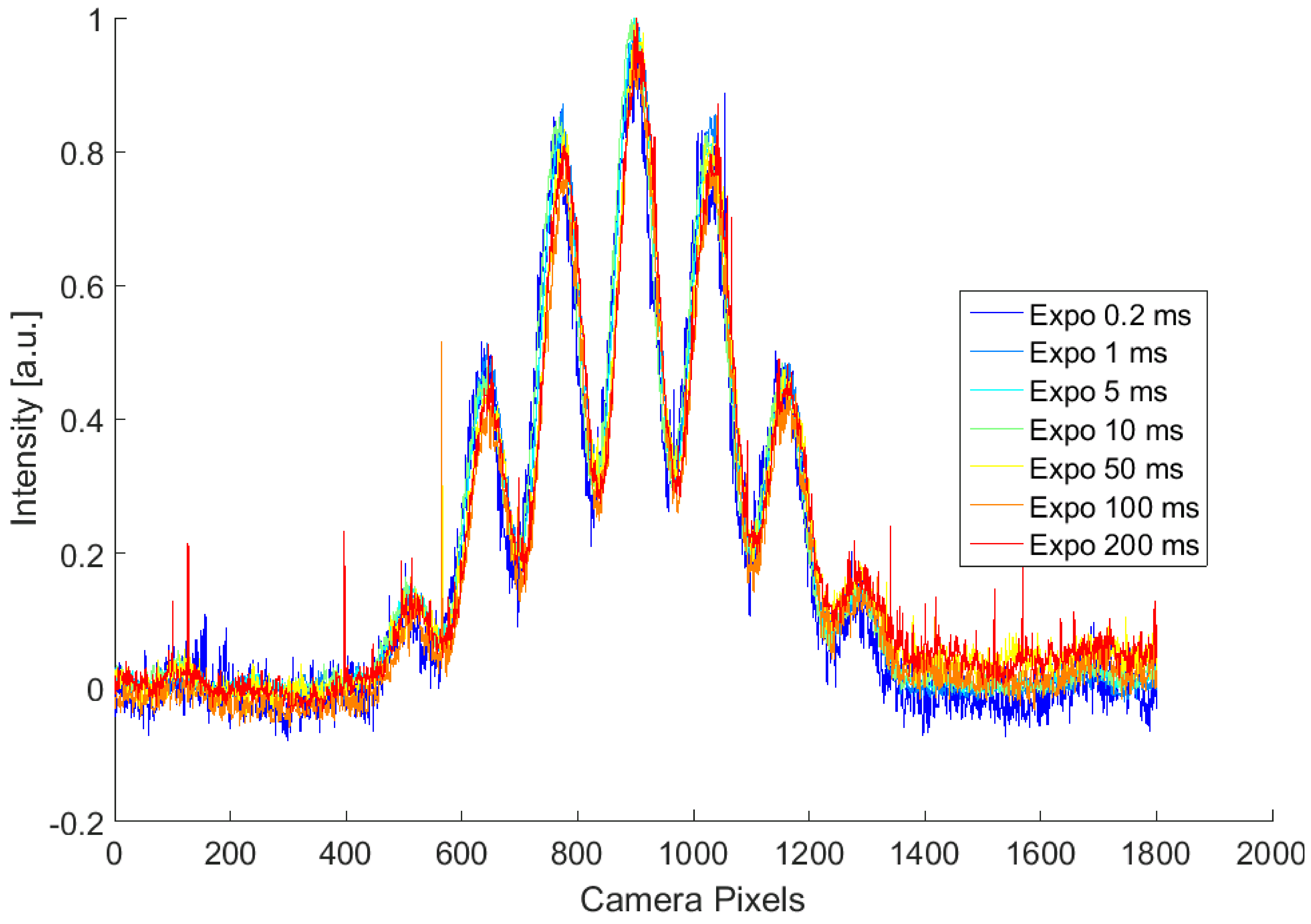

mm
−10
0
10
−10
0
1


Visibility
Imbalance Factor
|Γ|
Beam Size
Up to 30%
Visibility
Offset of Double Slit Center [mm]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
-8
-6
-4
-2
0
2
4
6
8
480
460
440
420
400
380
360

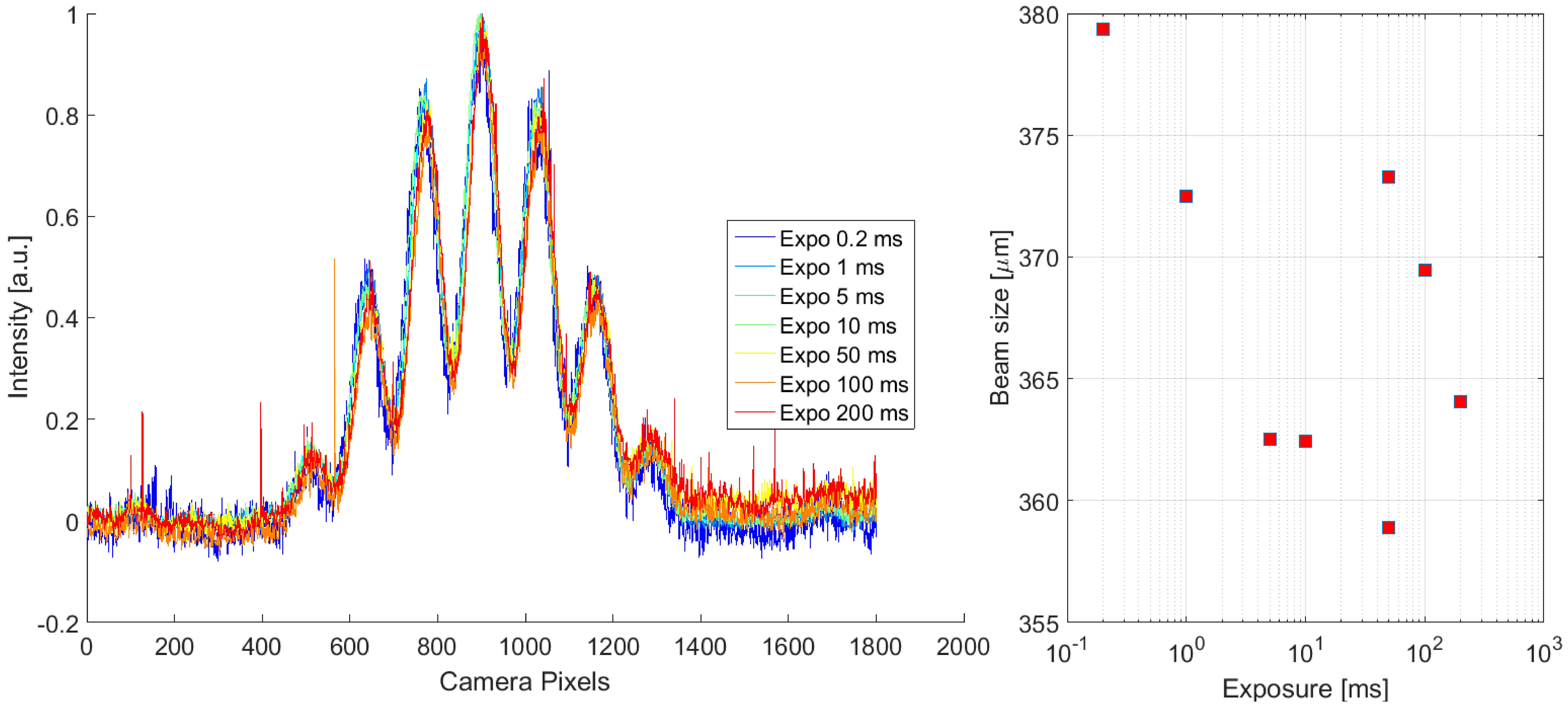
Commissioning with Beam

- Extraction Mirror Deformation
- Polarization
- Off-Center
- Frame Exposure
- Intensifier Saturation
- Detector Linearity

Beam oscillations and vibrations or air turbulence on the optical bench



Beam oscillations and vibrations or air turbulence on the optical bench

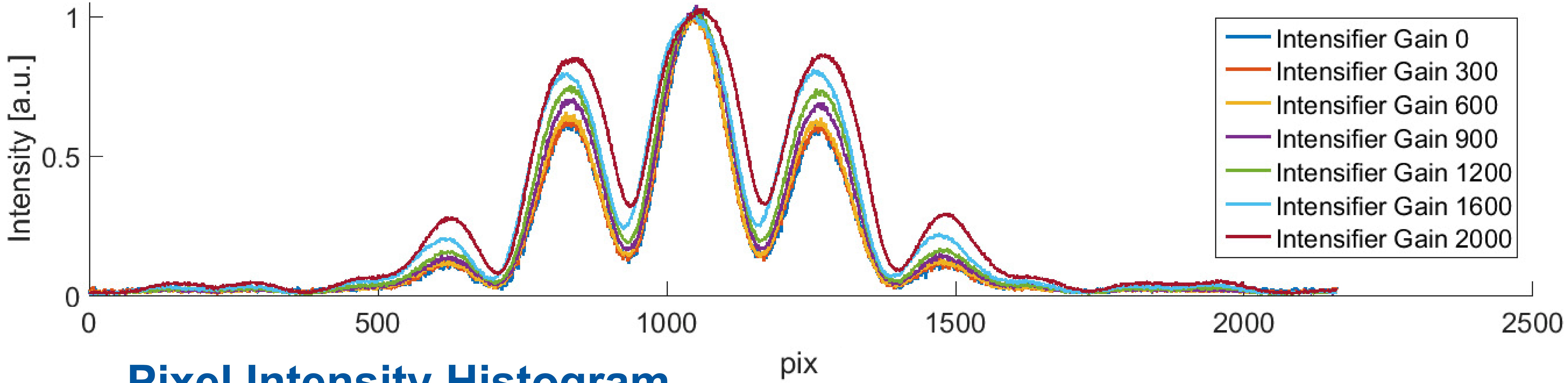


The measured beam size, 366 (MEAN) +/-5,6 µm (RMS),
=>had very little dependence on the exposure time

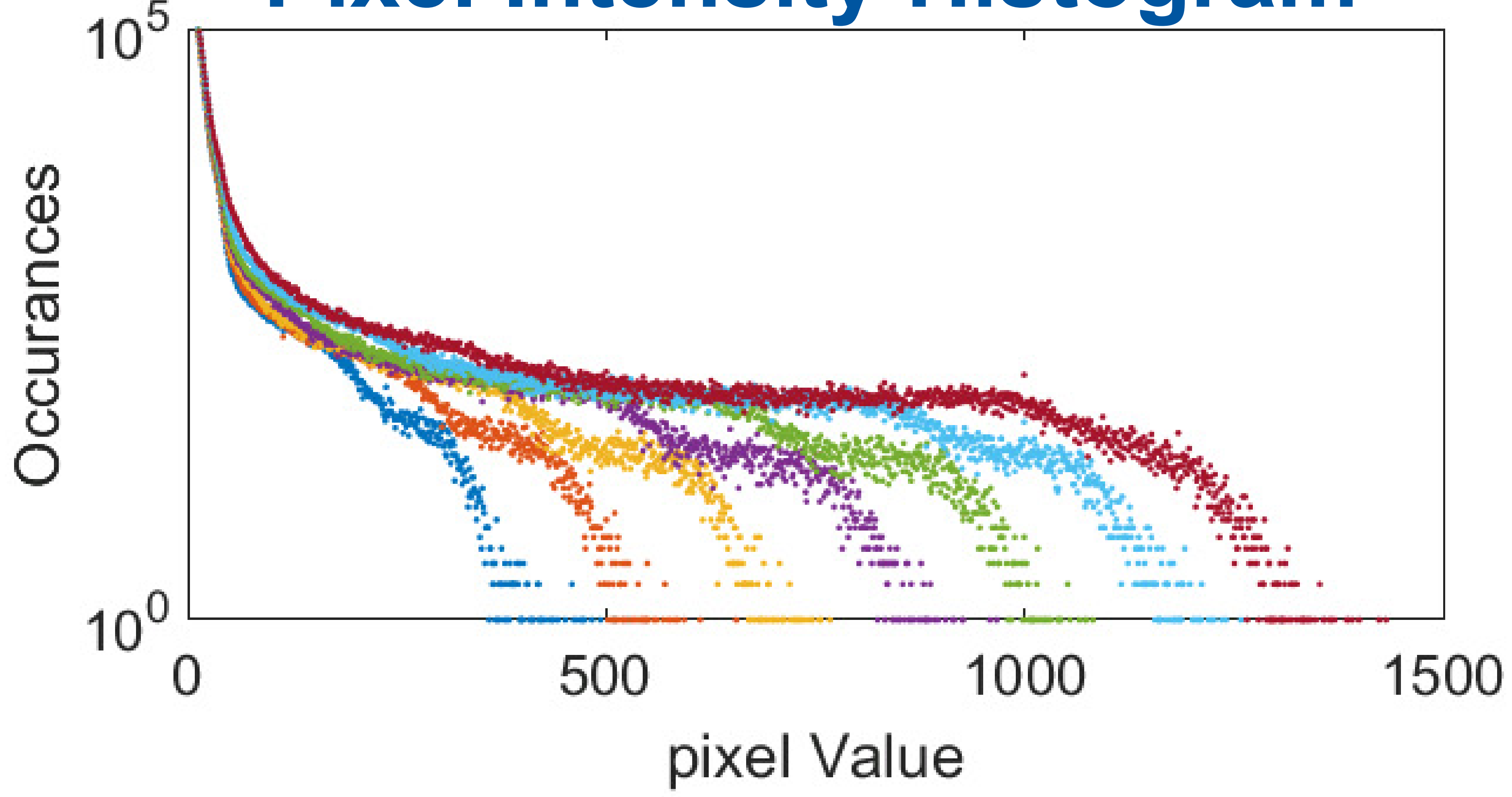
Commissioning with Beam

- Extraction Mirror Deformation
- Polarization
- Off-Center
- Frame Exposure
- Intensifier Saturation
- Detector Linearity

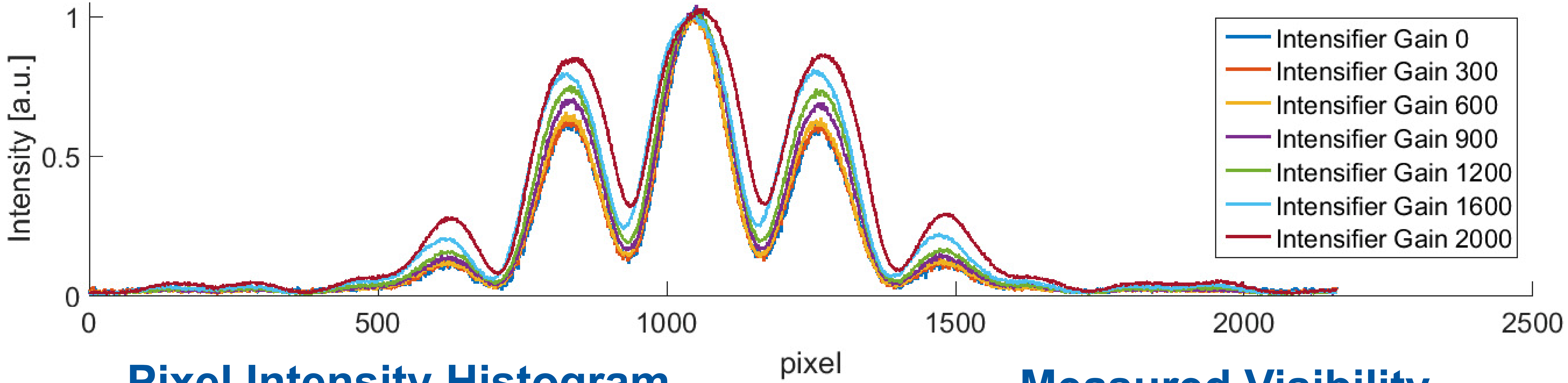
❑ Image intensifier Gain changed from 0 to 2000mV

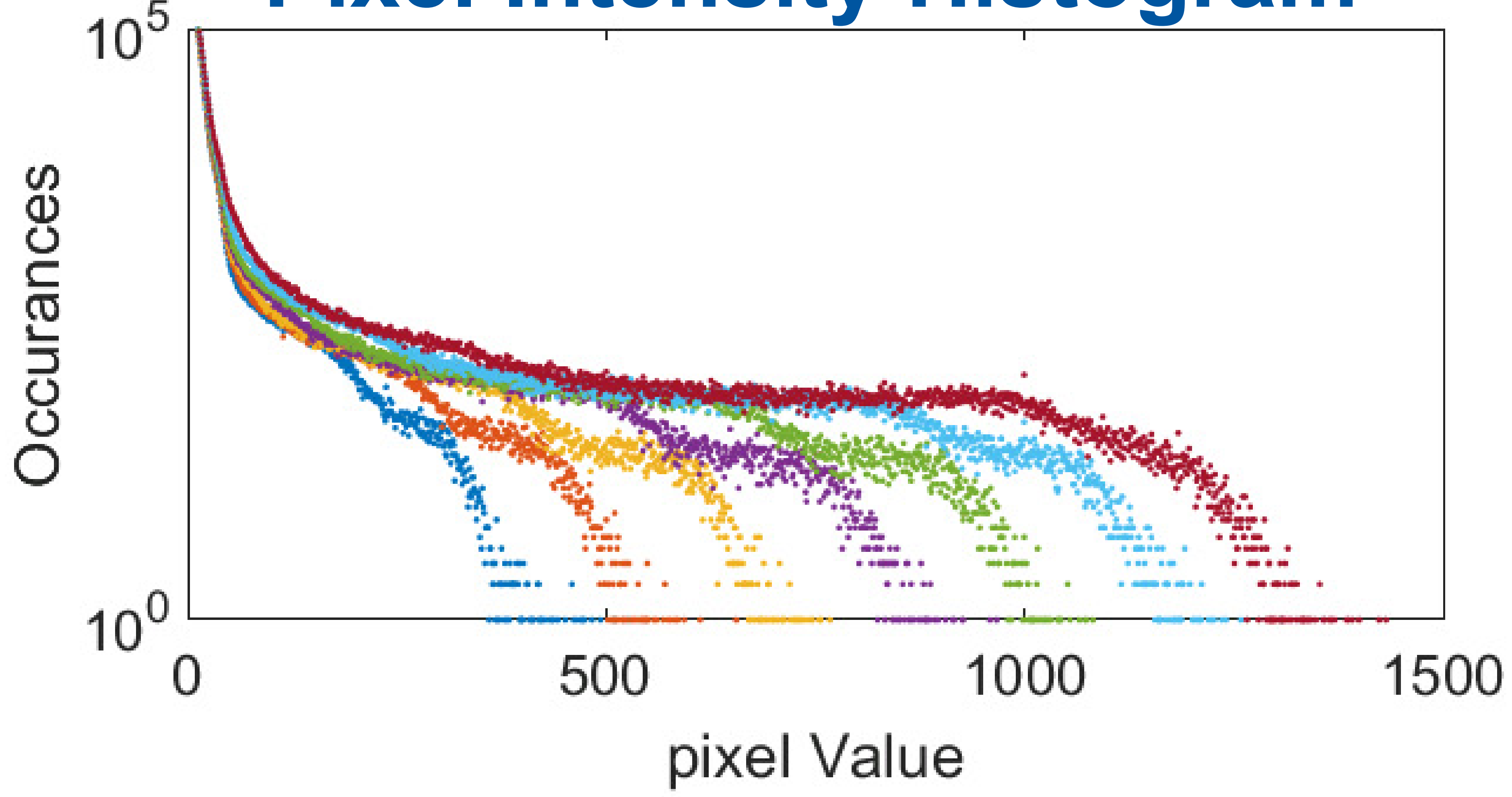


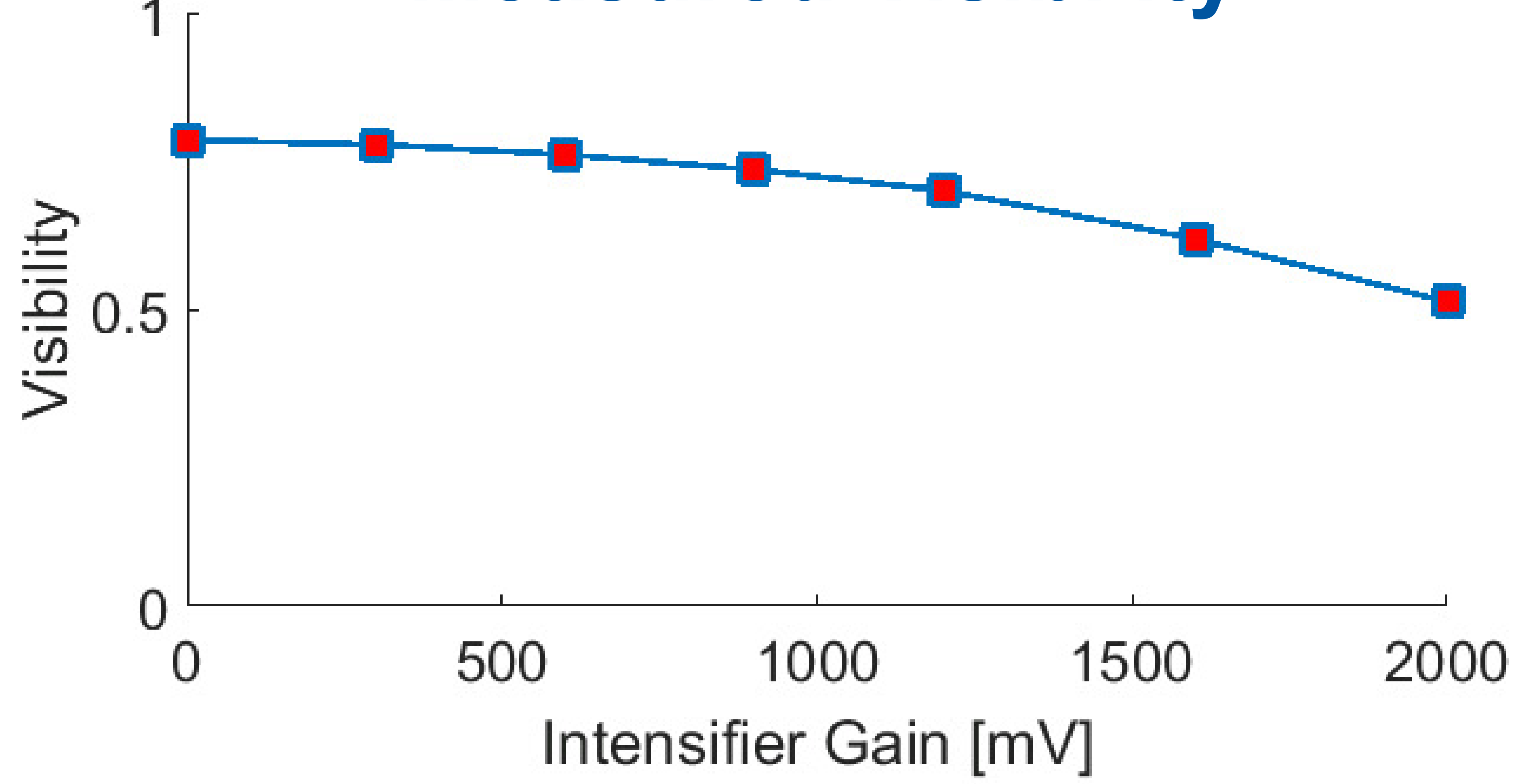
Pixel Intensity Histogram



- Image intensifier Gain changed from 0 to 2000mV



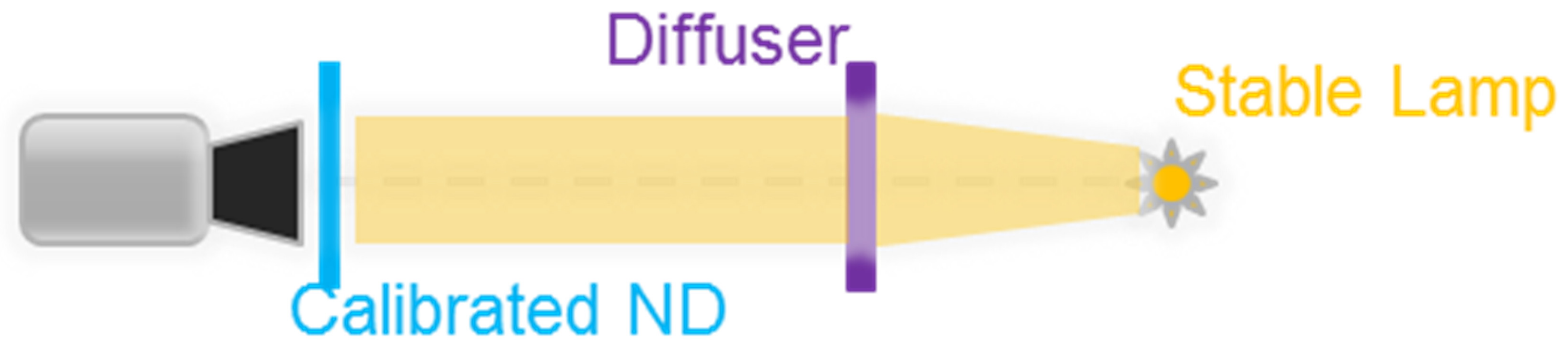




- For gain <900mV the brighter pixels remain at values <= 1000
  =>Change of visibility results in an error on the beam size of <= 4%

Commissioning with Beam

- Extraction Mirror Deformation
- Polarization
- Off-Center
- Frame Exposure
- Intensifier Saturation
- Detector Linearity


Diffuser
Stable Lamp
Calibrated ND

LHC SR

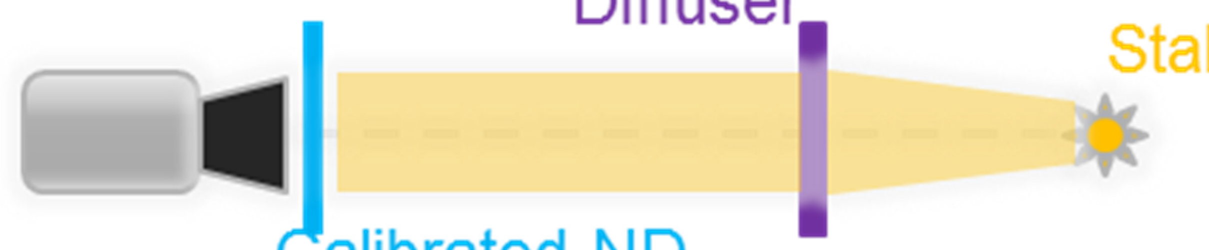
Imaging at the LHC

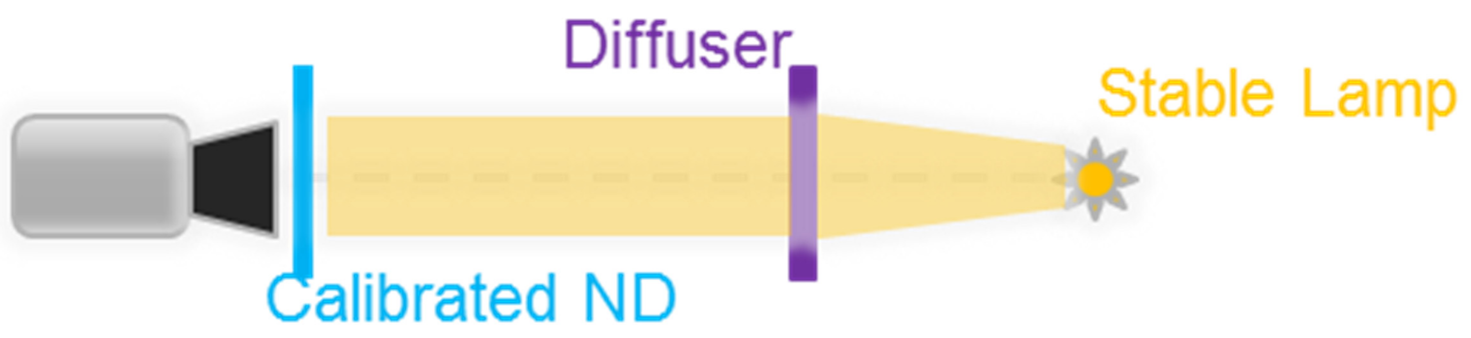
SR Interferometry

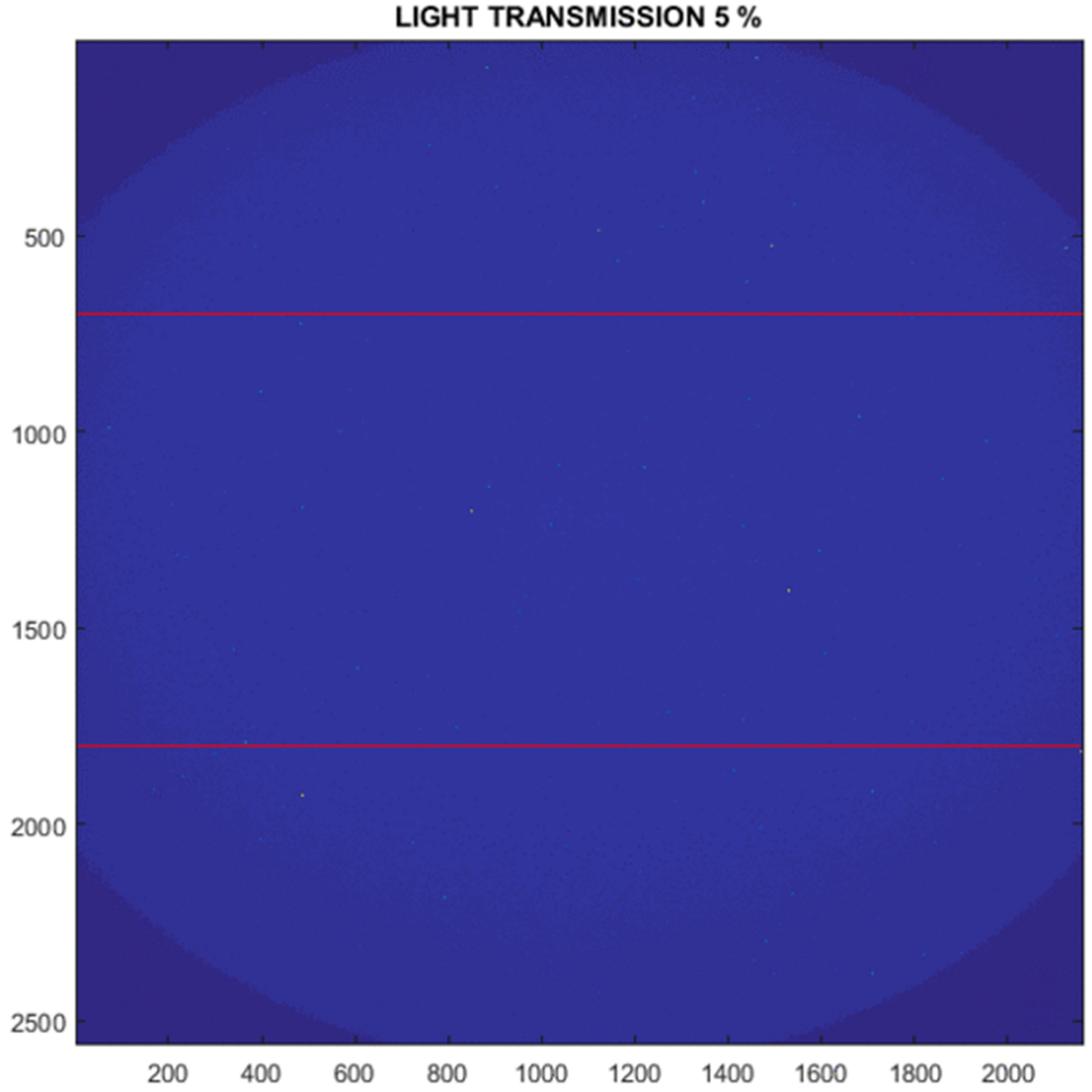
LHC Interferometer

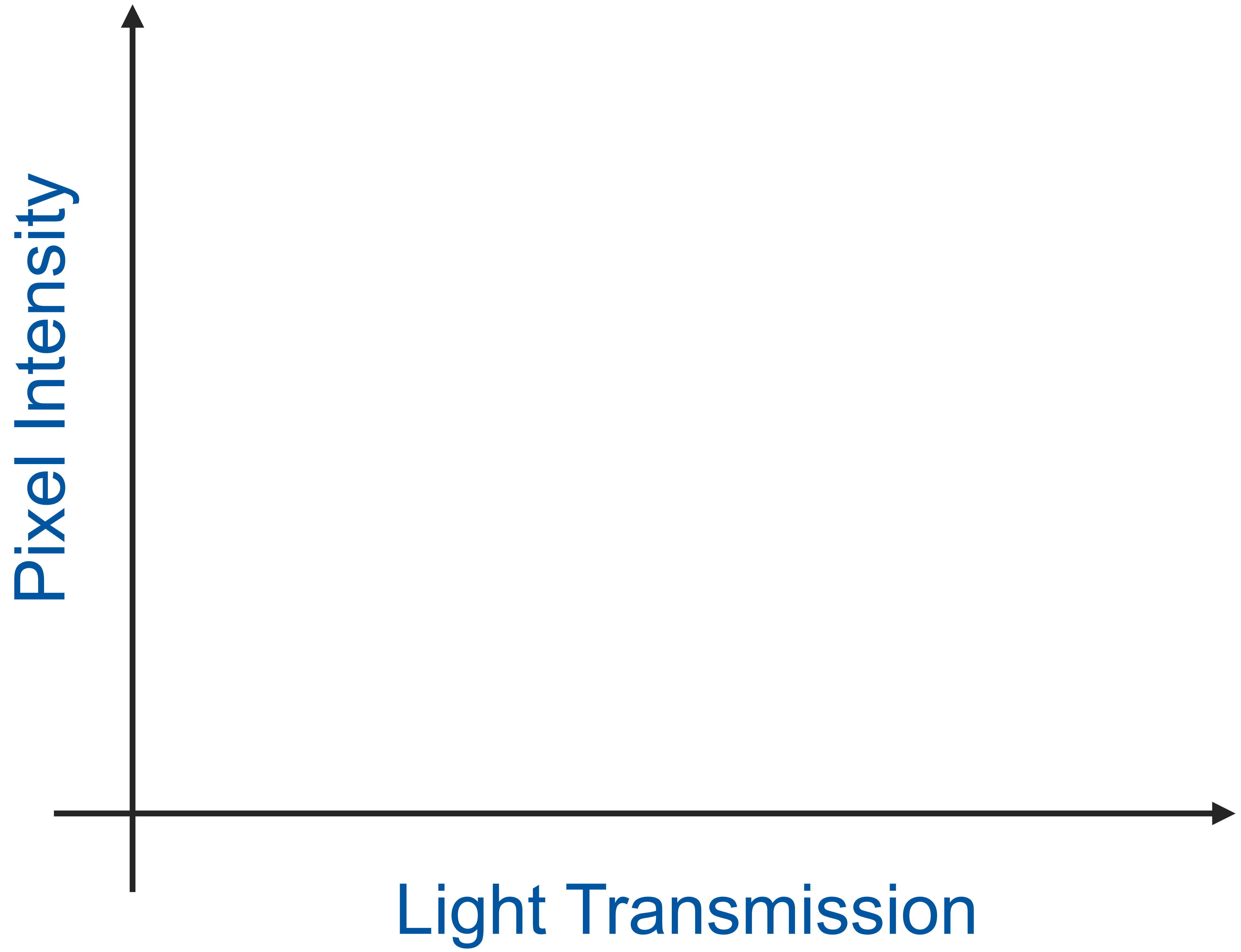
Commissioning At 6.5 TeV At 450 GeV

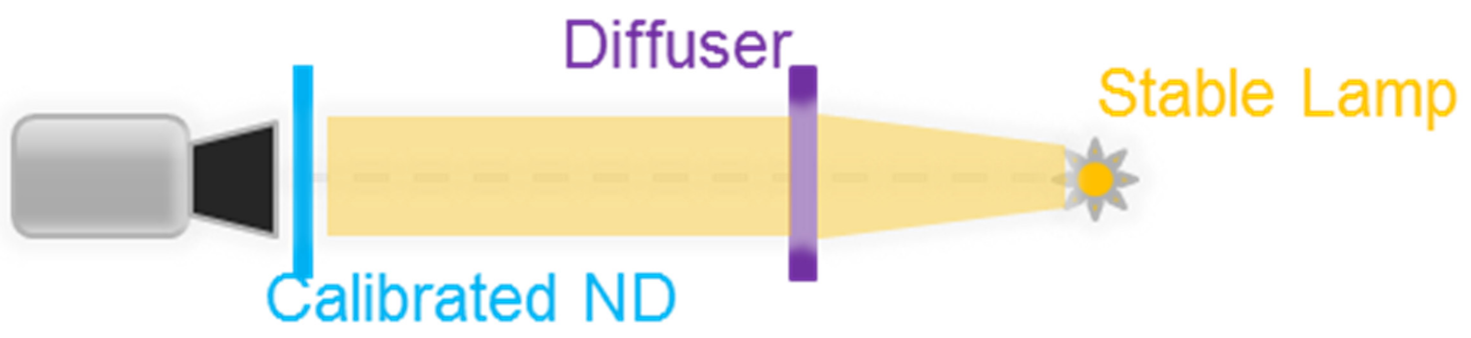
2D Interferometer

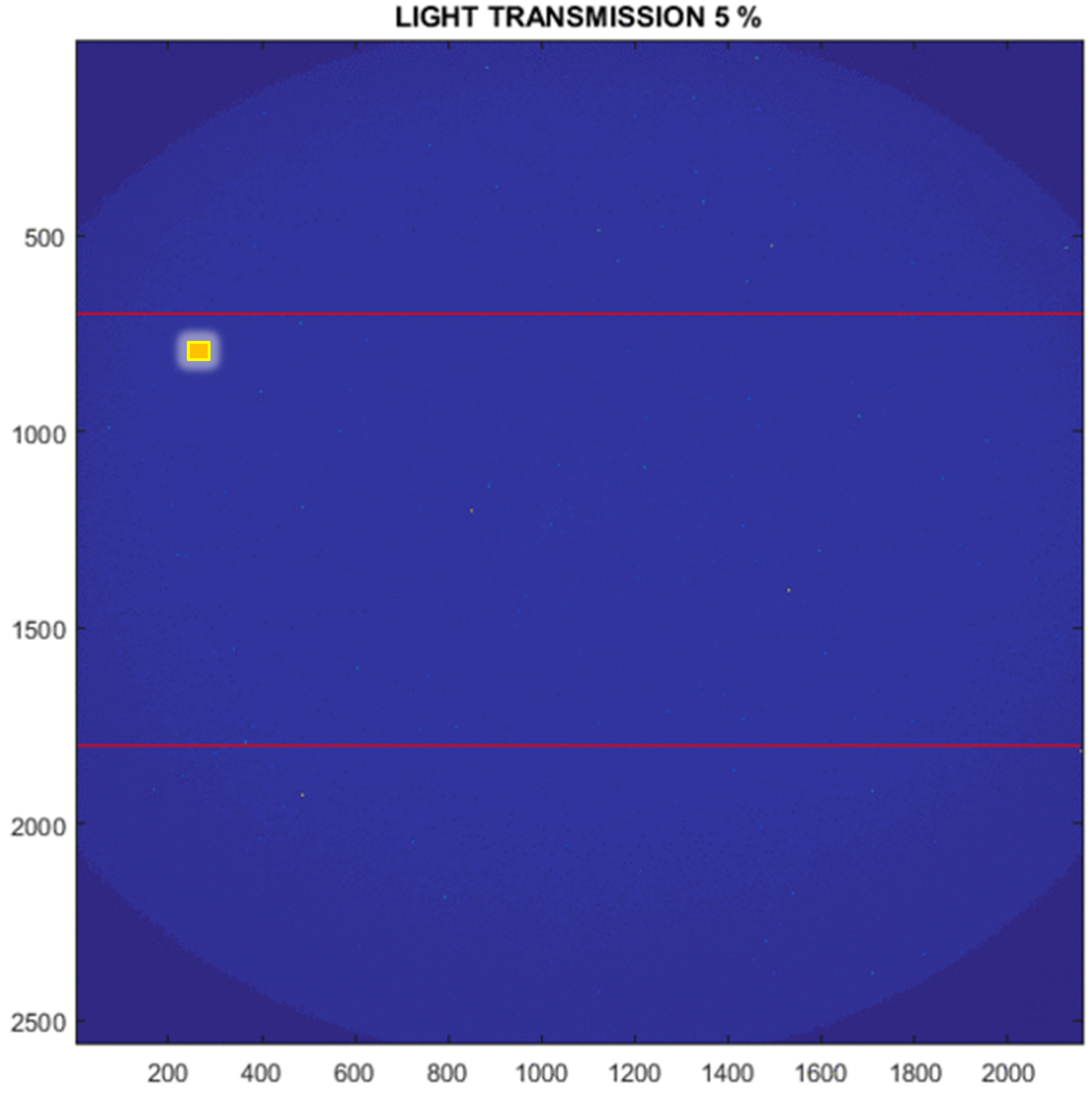


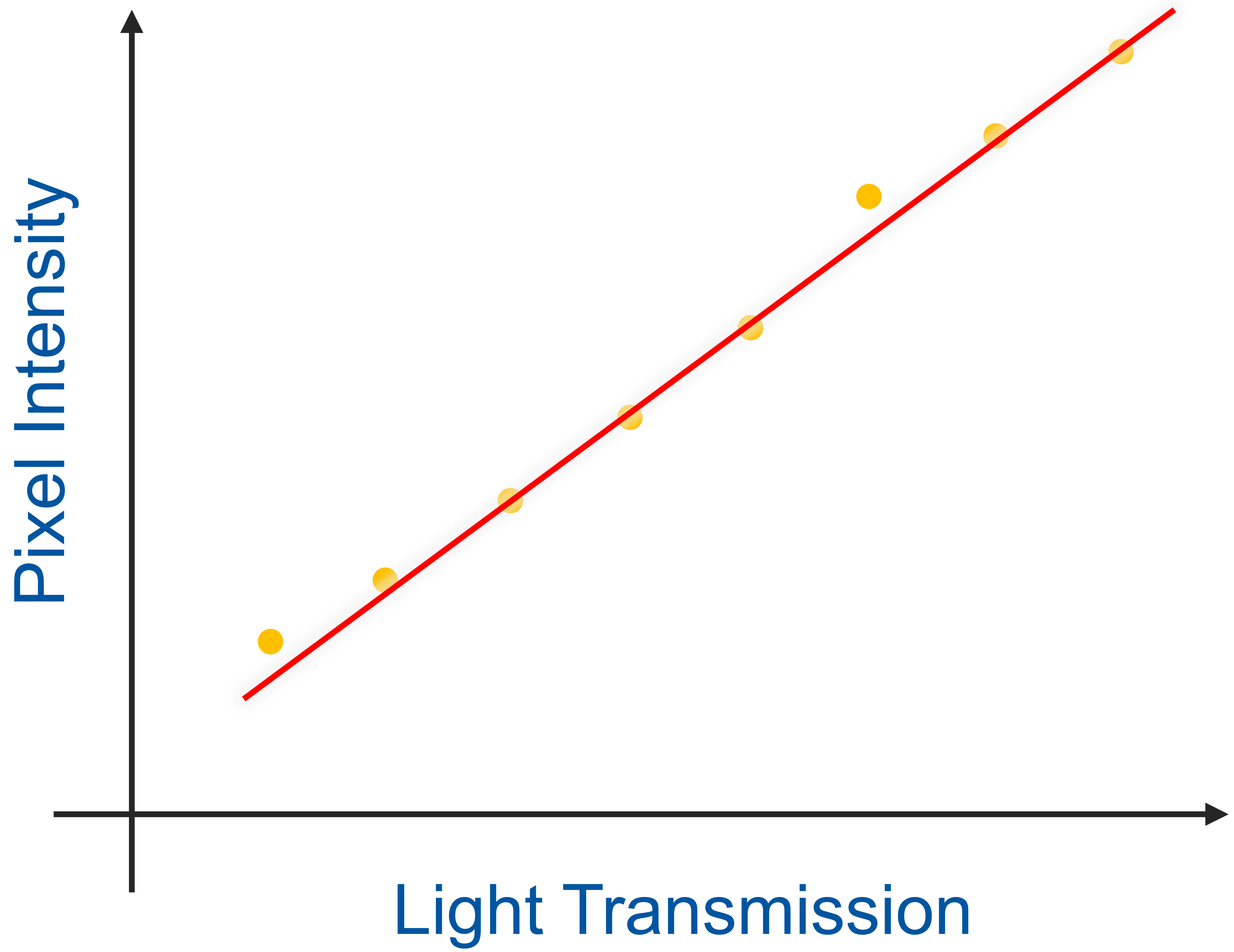

Diffuser
Stable Lamp
Calibrated ND

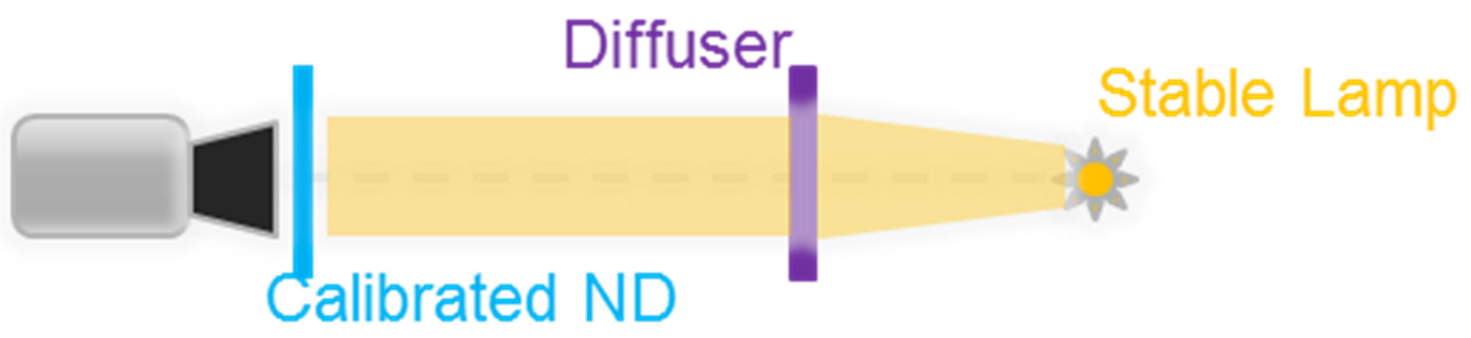

LIGHT TRANSMISSION 5 %
500
1000
1500
2000
2500
200
400
600
800
1000
1200
1400
1600
1800
2000

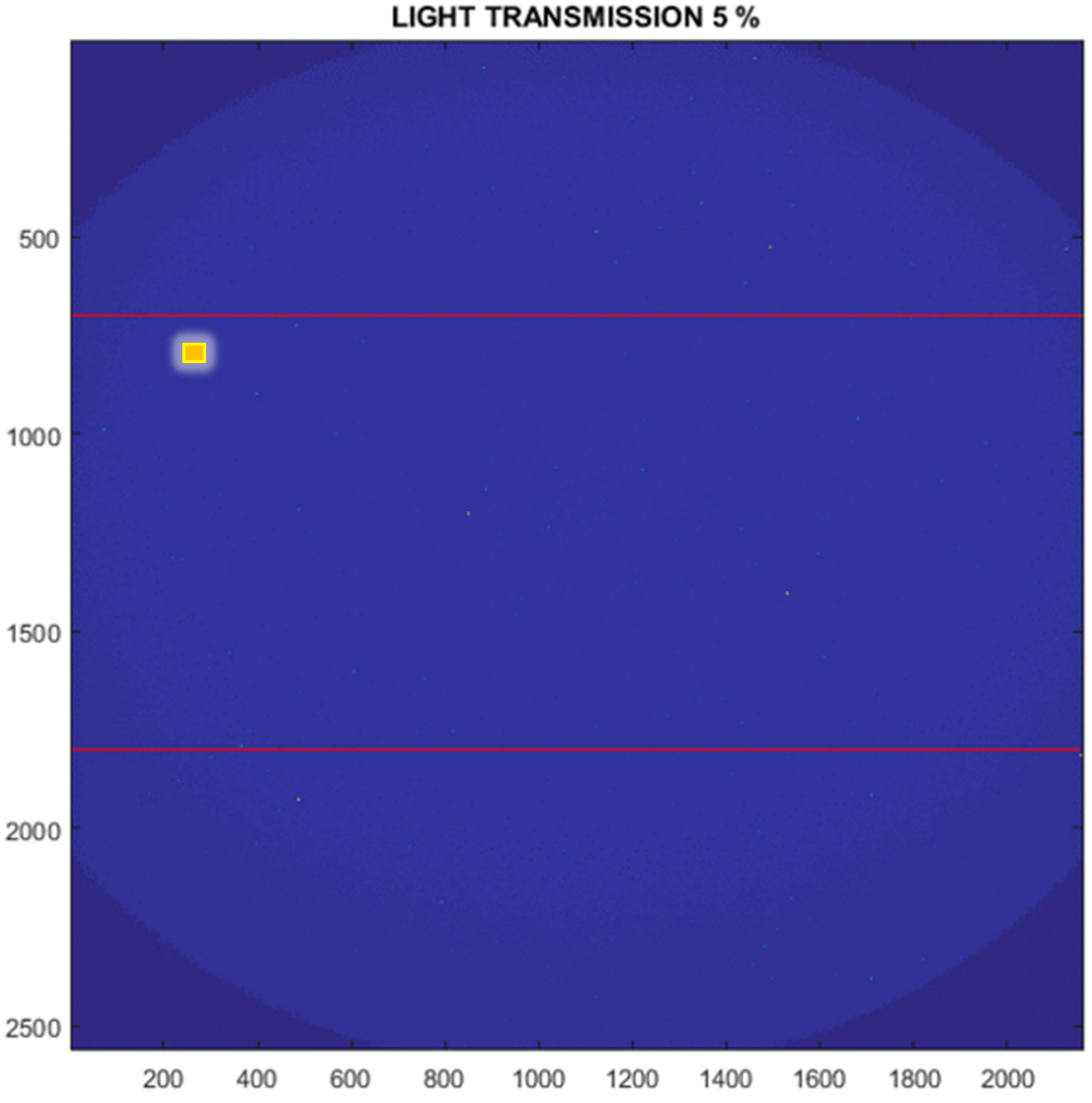

Pixel Intensity
Light Transmission

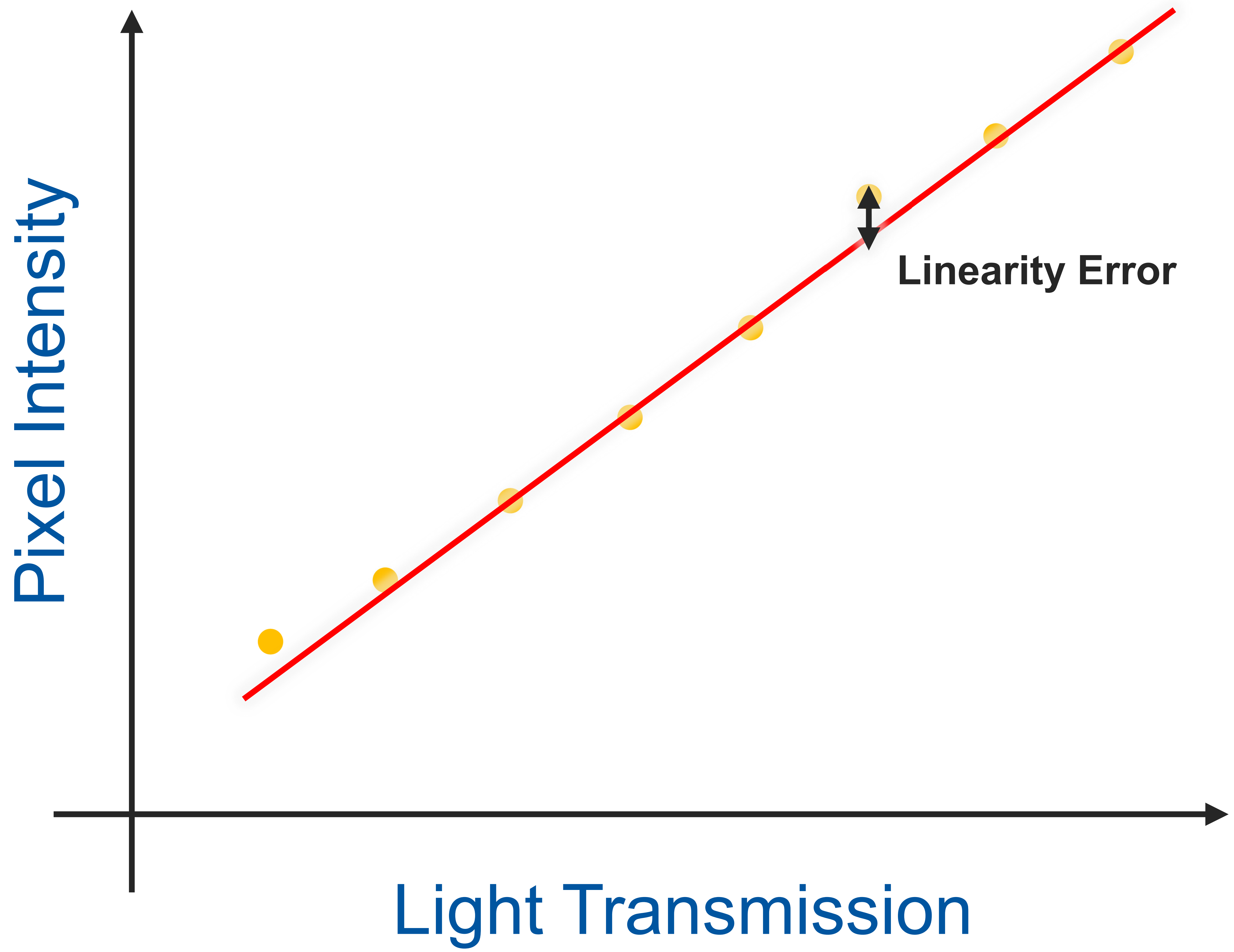

Diffuser
Stable Lamp
Calibrated ND


LIGHT TRANSMISSION 5 %
500
1000
1500
2000
2500
200
400
600
800
1000
1200
1400
1600
1800
2000


Pixel Intensity
Light Transmission


Diffuser
Stable Lamp
Calibrated ND


LIGHT TRANSMISSION 5 %
500
1000
1500
2000
2500
200
400
600
800
1000
1200
1400
1600
1800
2000


Pixel Intensity
Linearity Error
Light Transmission

LHC SR

Imaging at the LHC

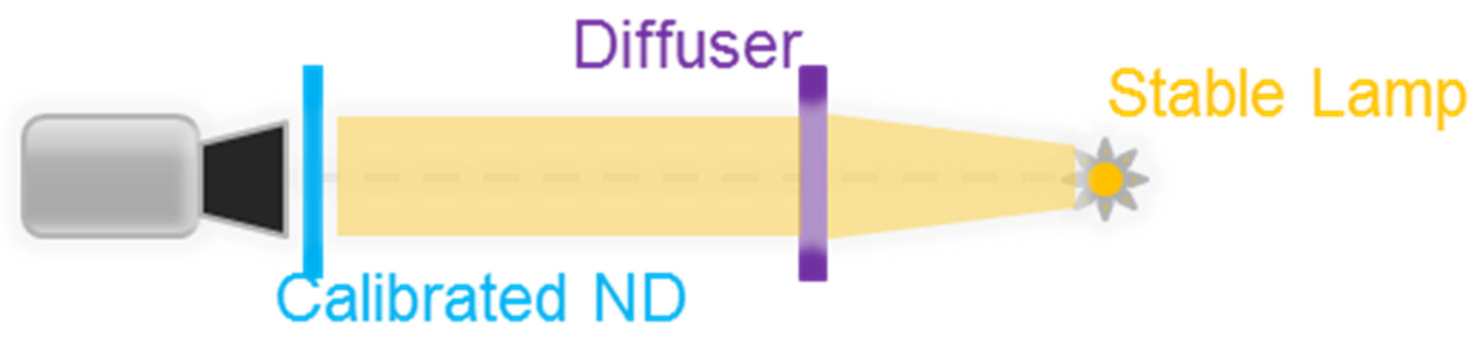
SR Interferometry

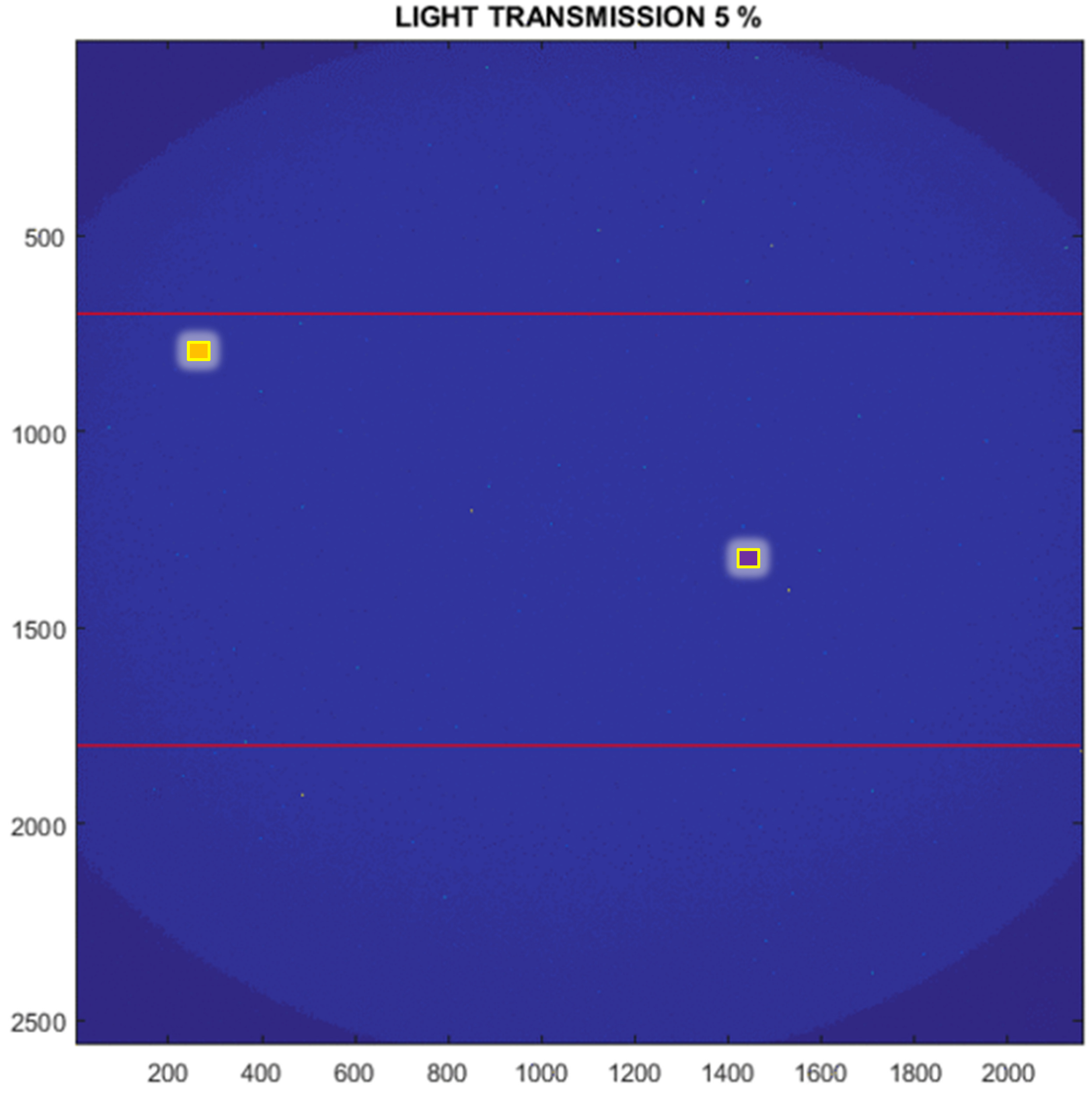
LHC Interferometer

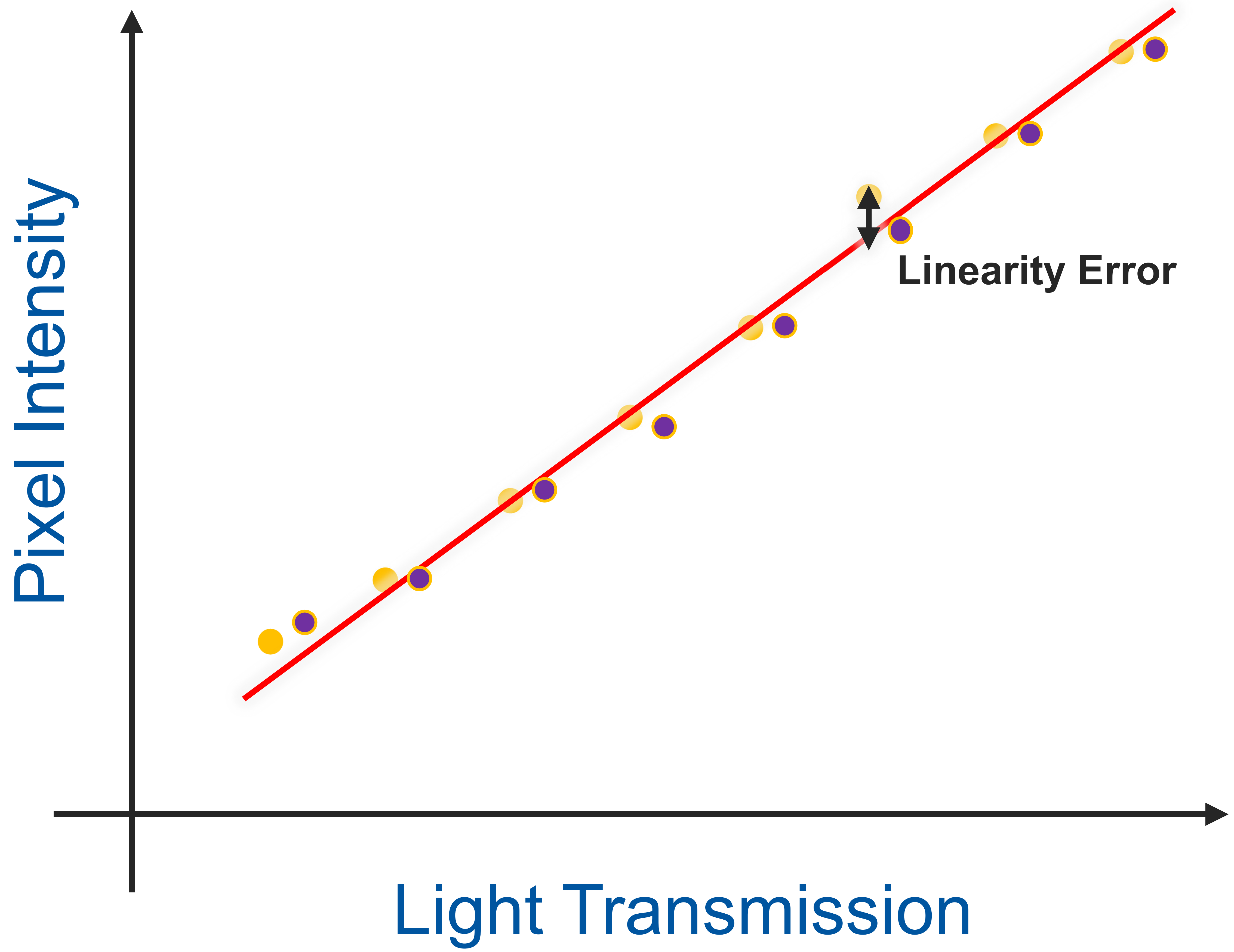
Commissioning At 6.5 TeV

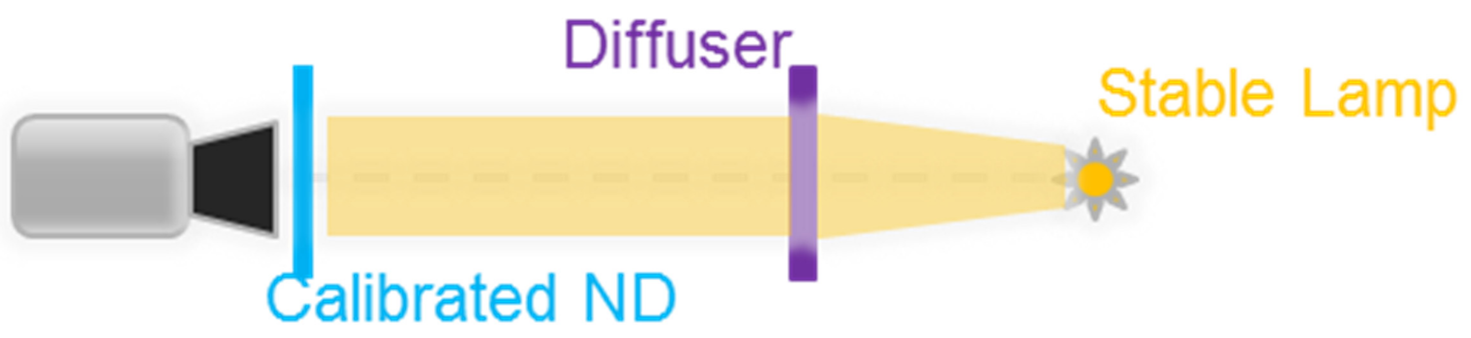
At 450 GeV

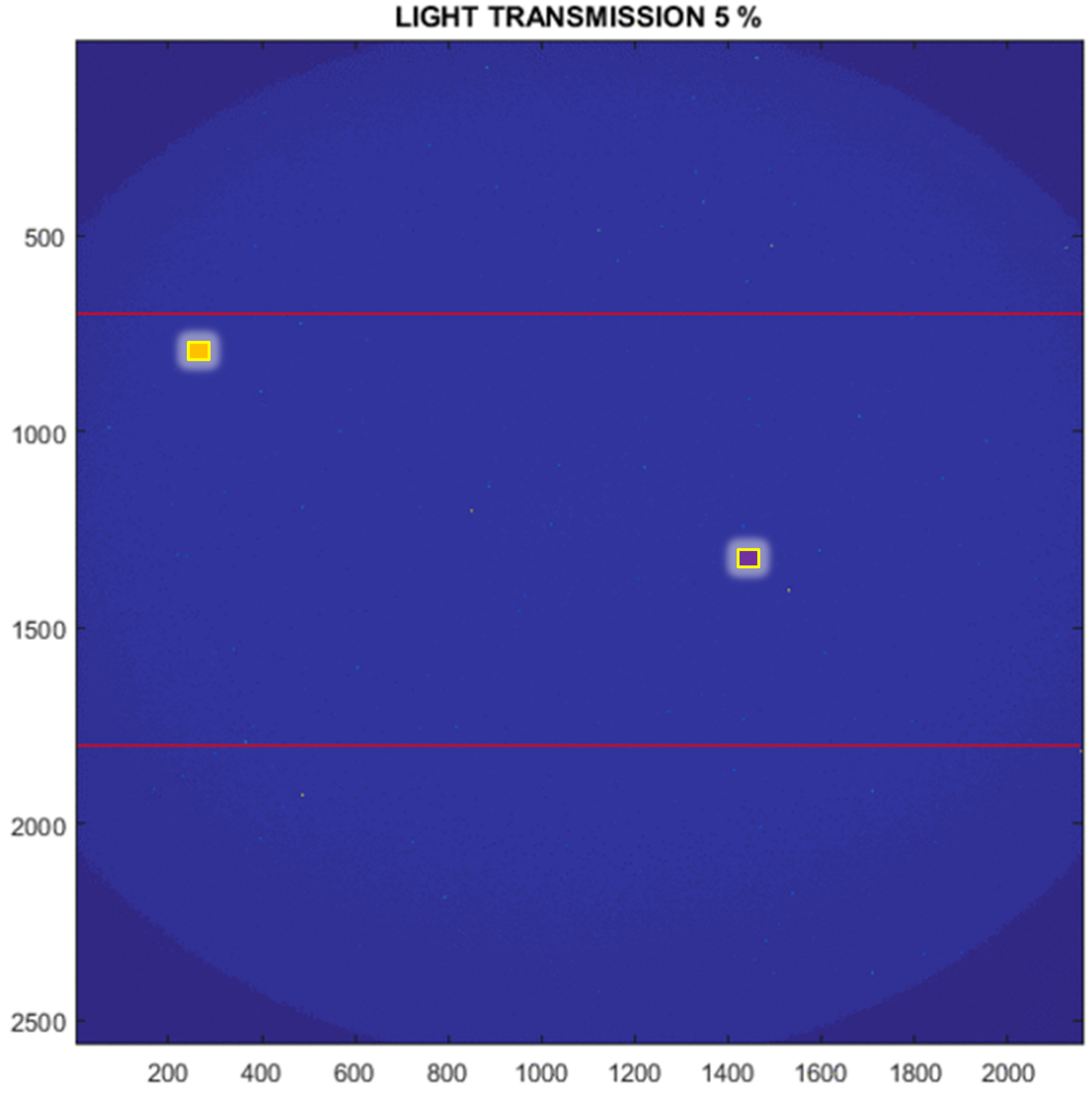
2D Interferometer

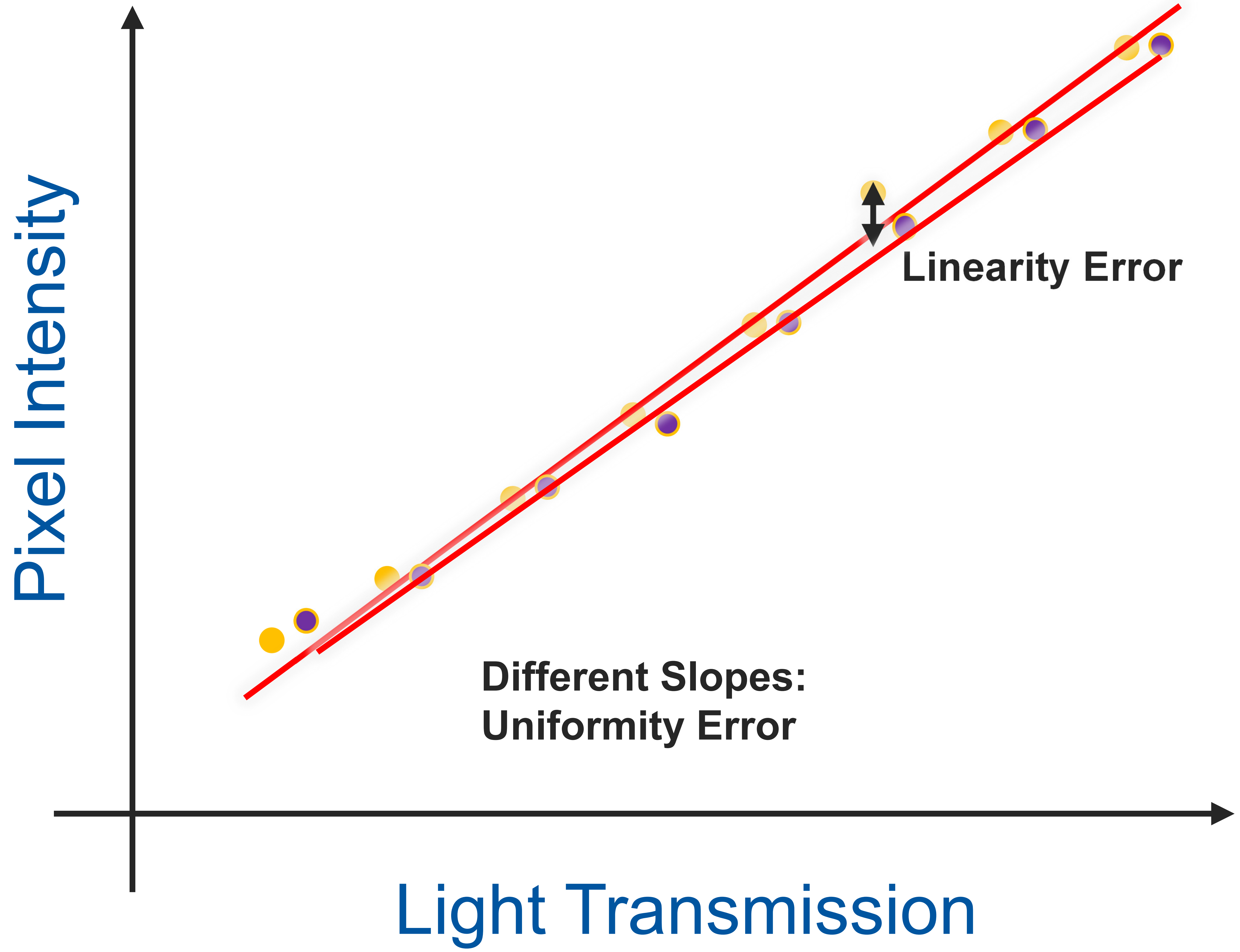


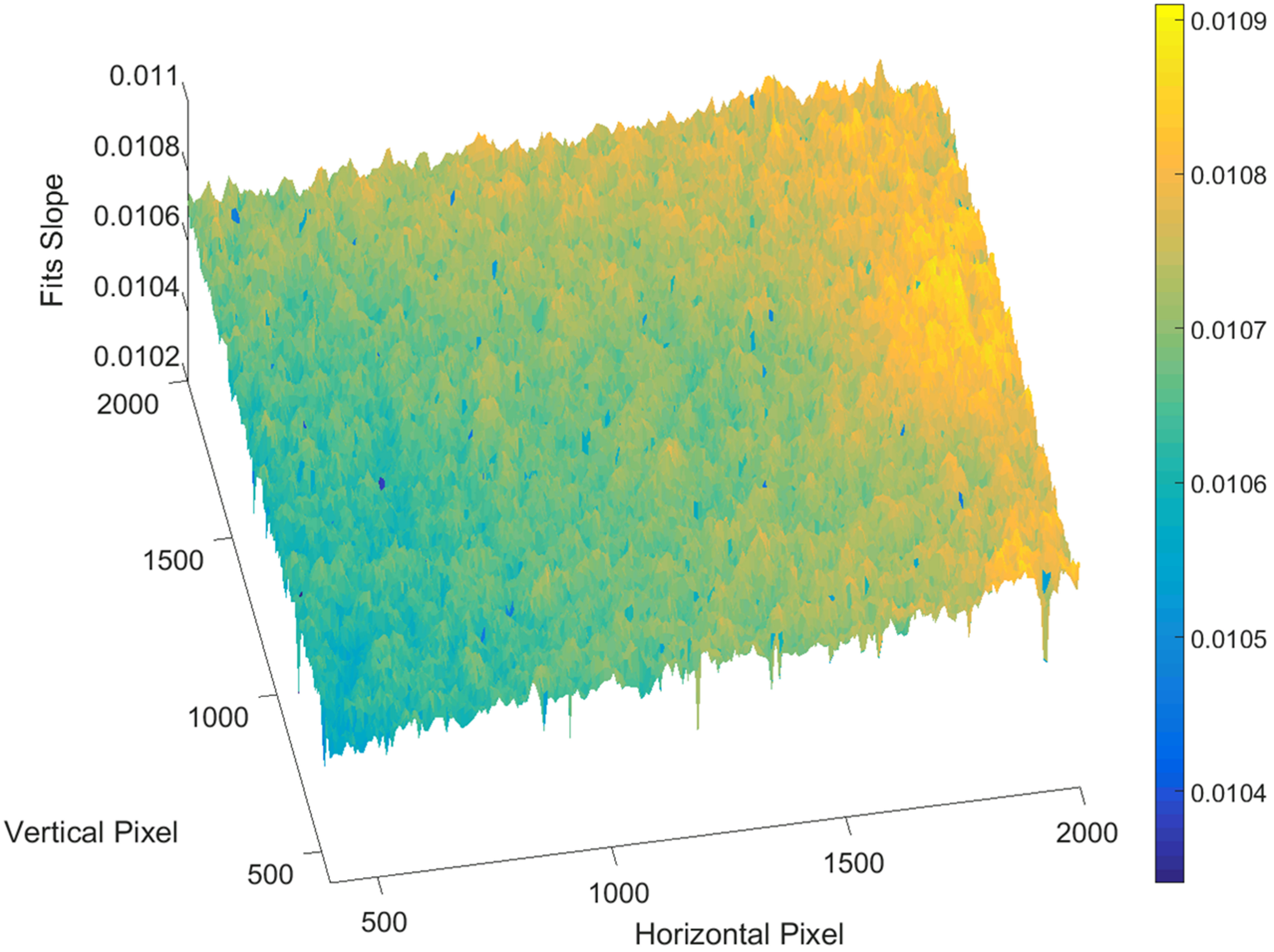


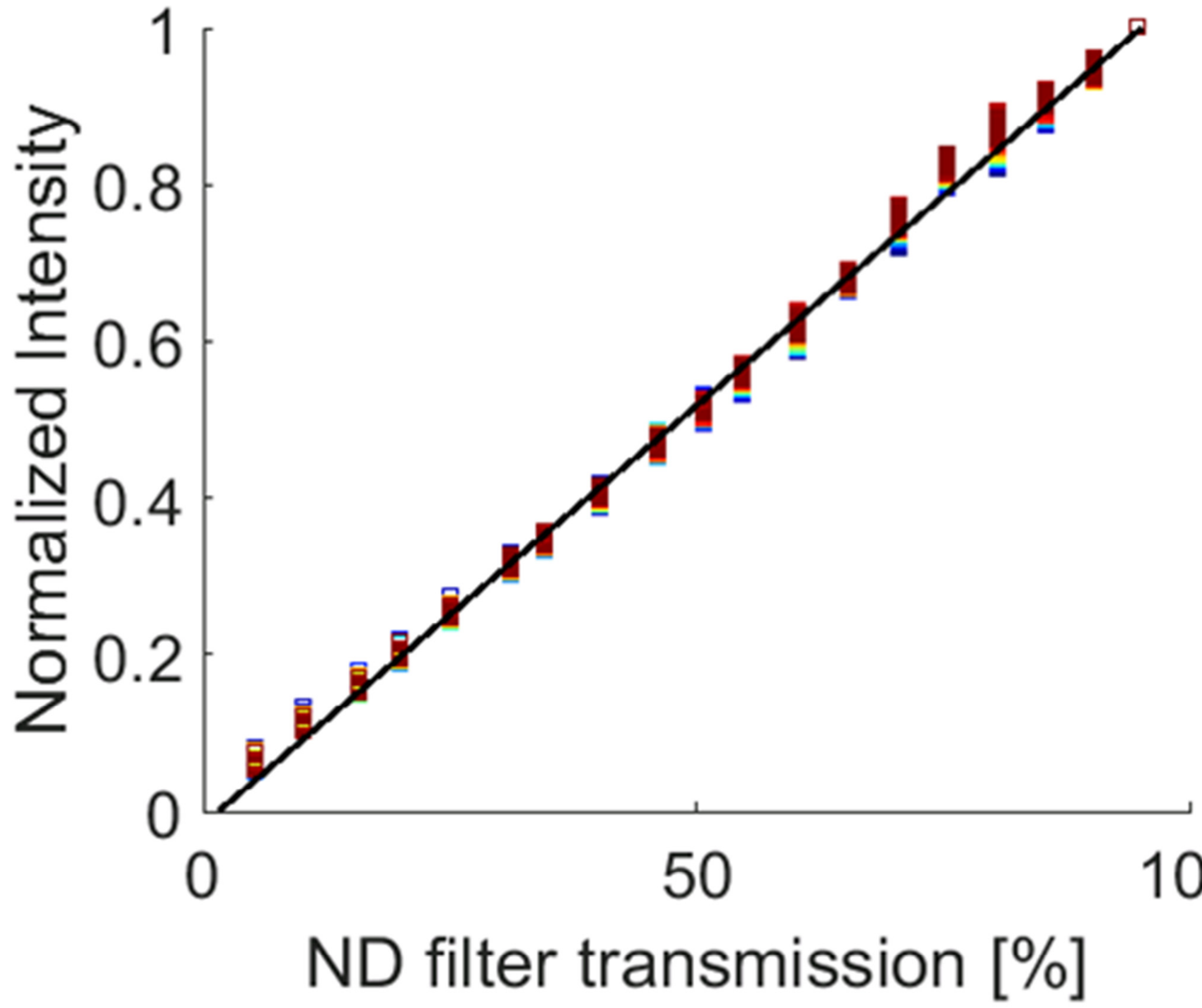



Diffuser
Stable Lamp
Calibrated ND

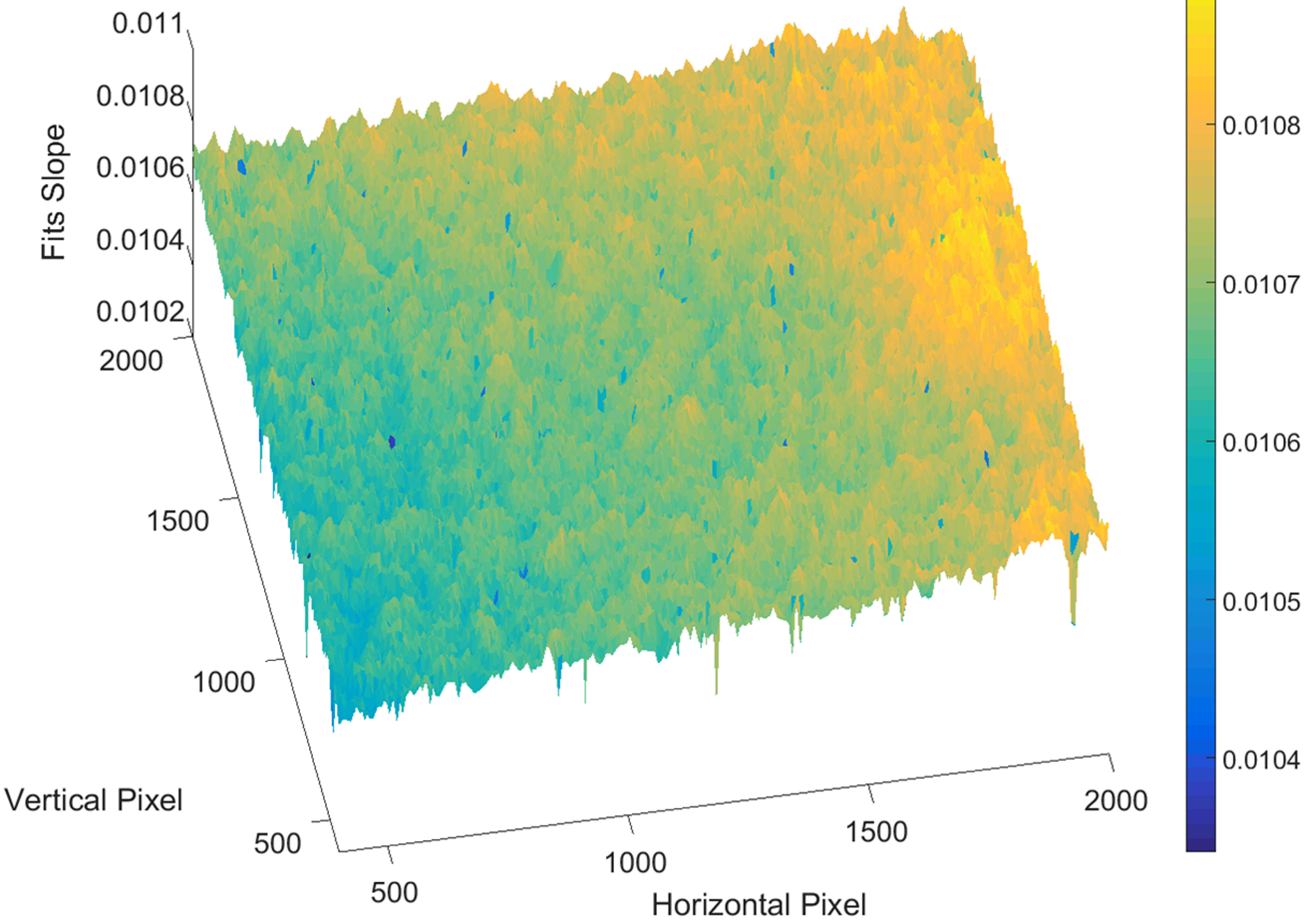

LIGHT TRANSMISSION 5 %
500
1000
1500
2000
2500
200
400
600
800
1000
1200
1400
1600
1800
2000

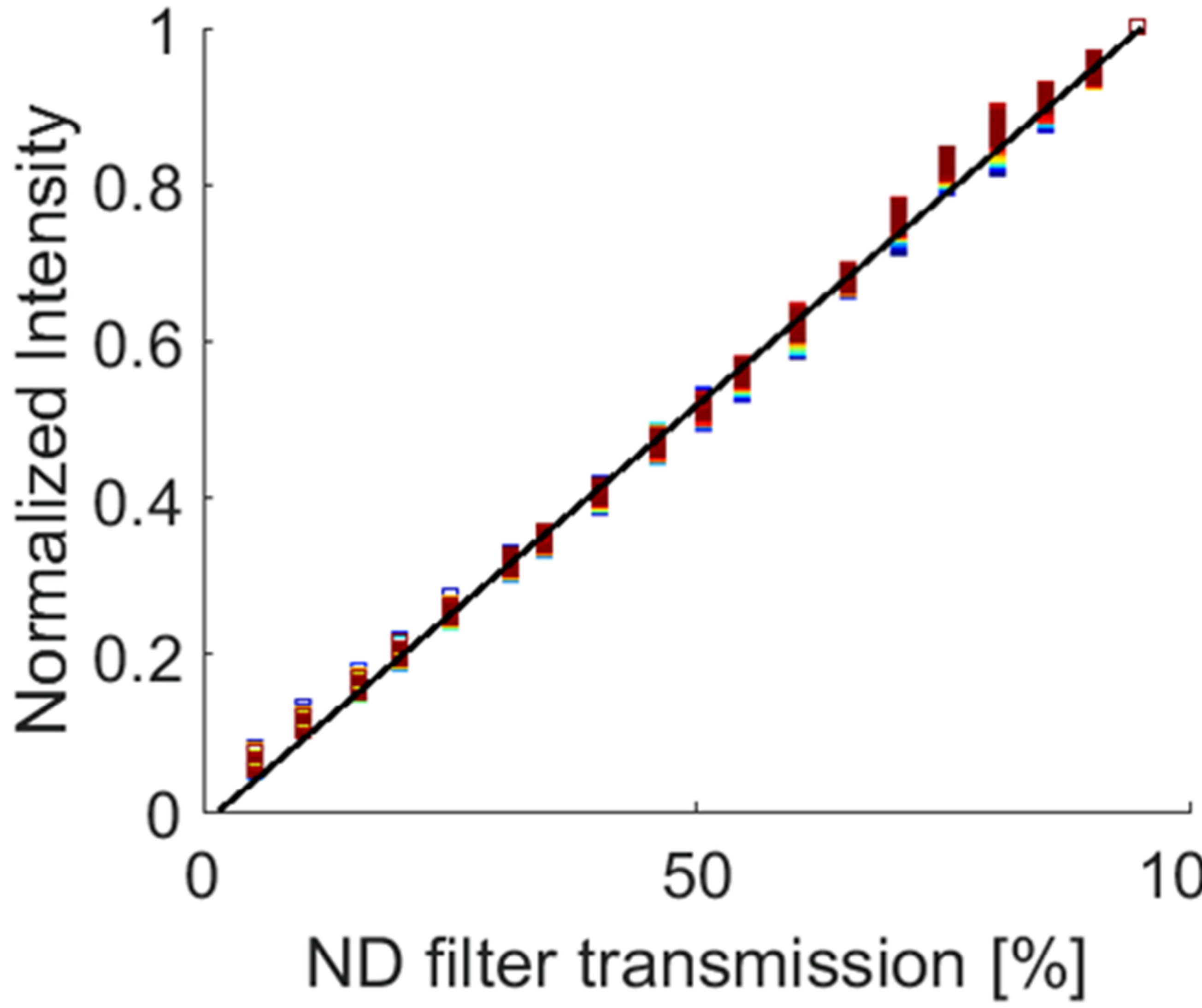

Pixel Intensity
Linearity Error
Different Slopes:
Uniformity Error
Light Transmission


Fits Slope
0.011
0.0108
0.0106
0.0104
0.0102
2000
1500
1000
500
Vertical Pixel
500
1000
1500
2000
Horizontal Pixel
0.0109
0.0108
0.0107
0.0106
0.0105
0.0104

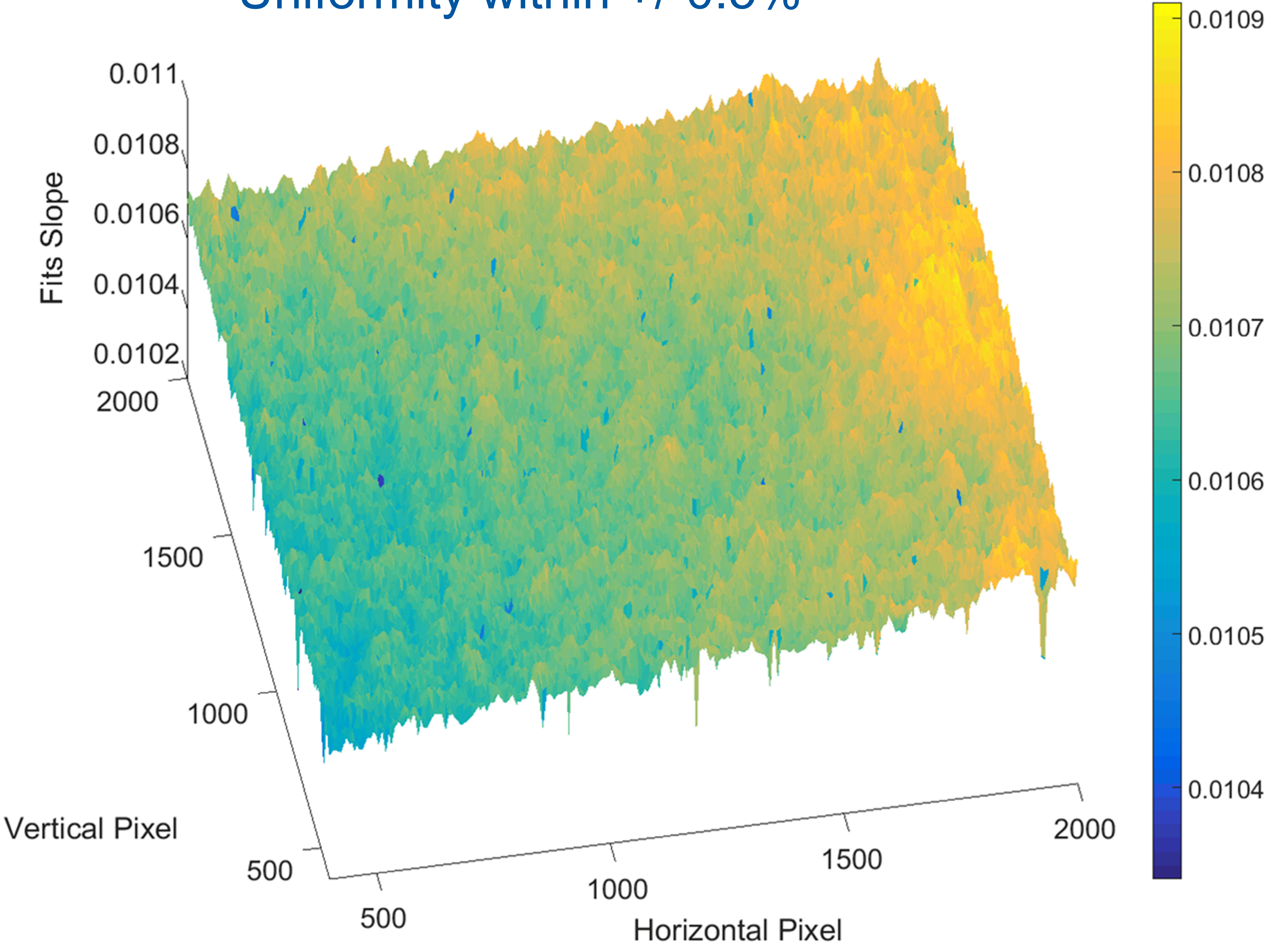

Normalized Intensity
1
0.8
0.6
0.4
0.2
0
0
50
10
ND filter transmission [%]

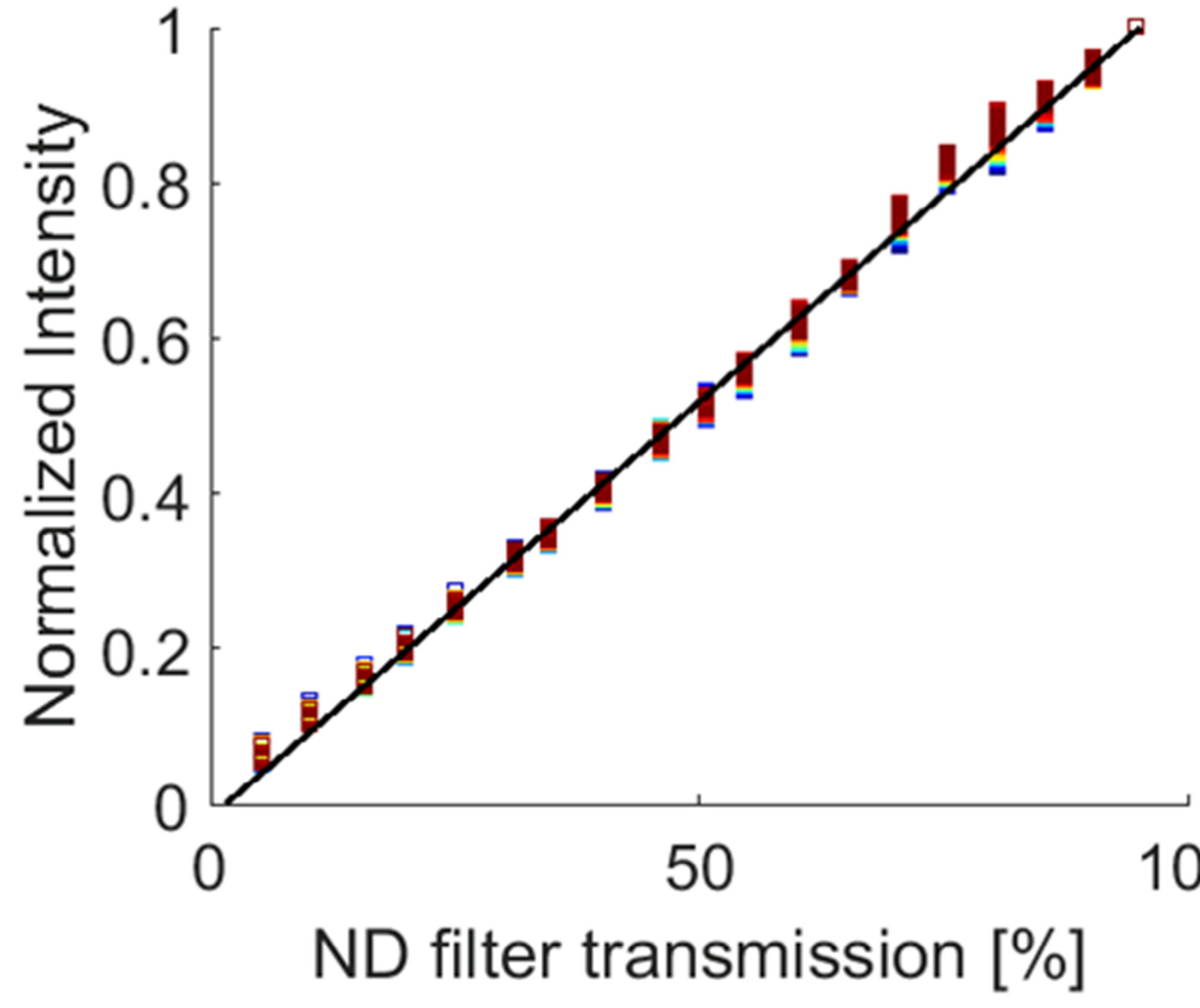
Uniformity within +/-0.5%

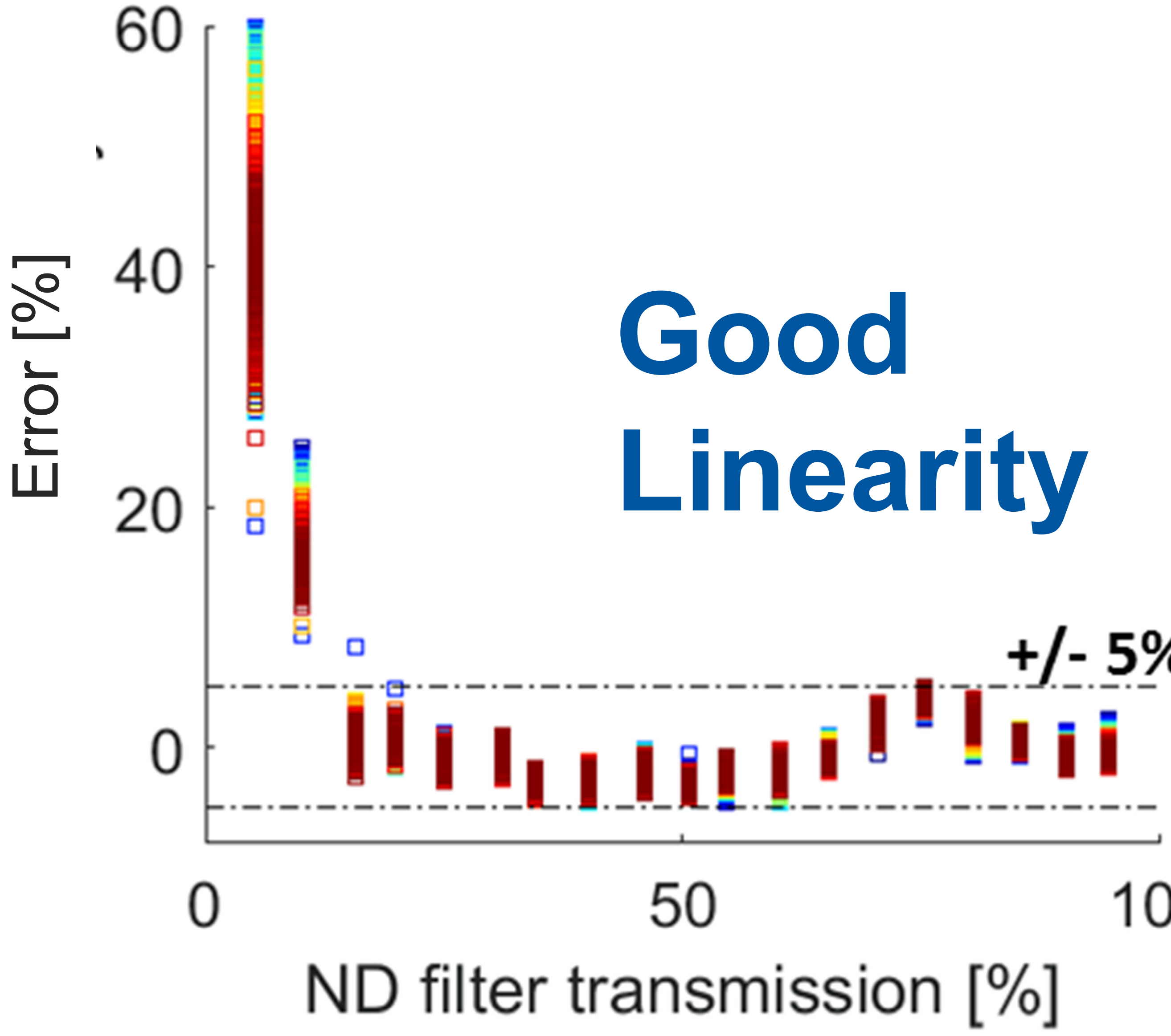




Uniformity within +/-0.5%





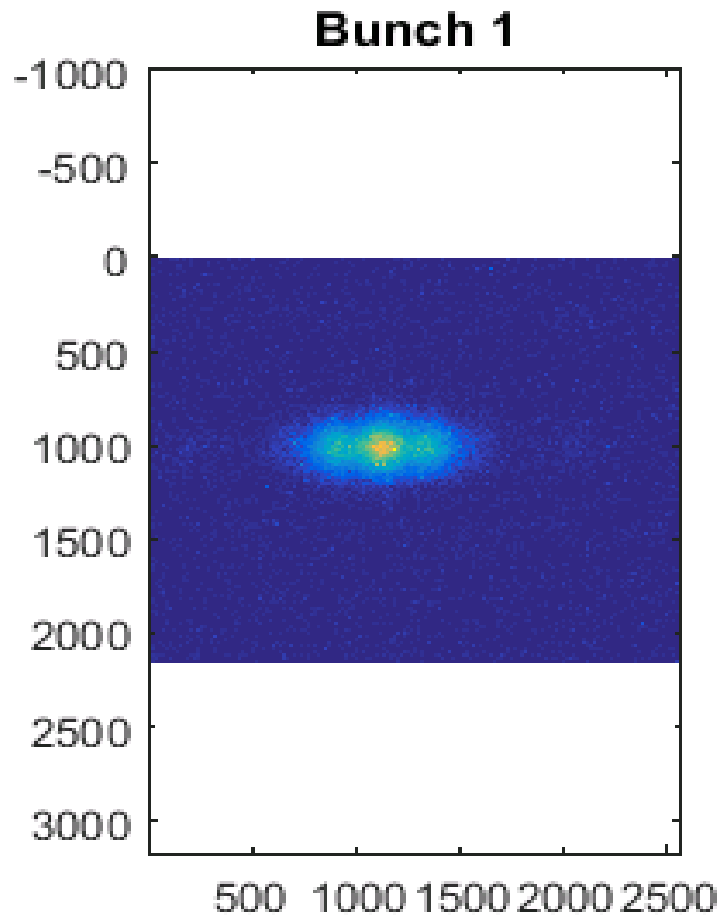


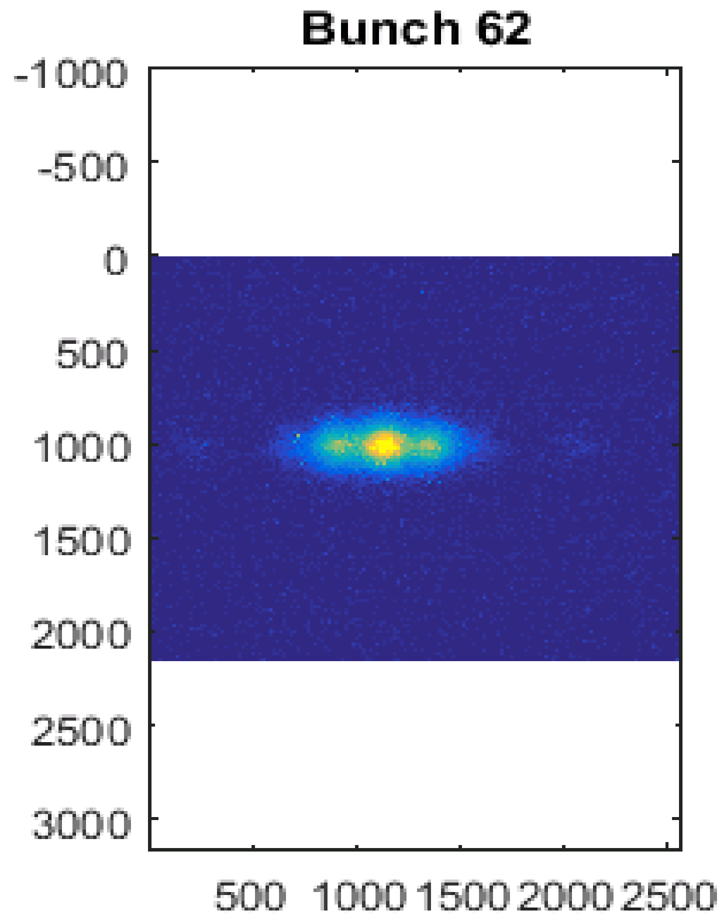
Good Linearity

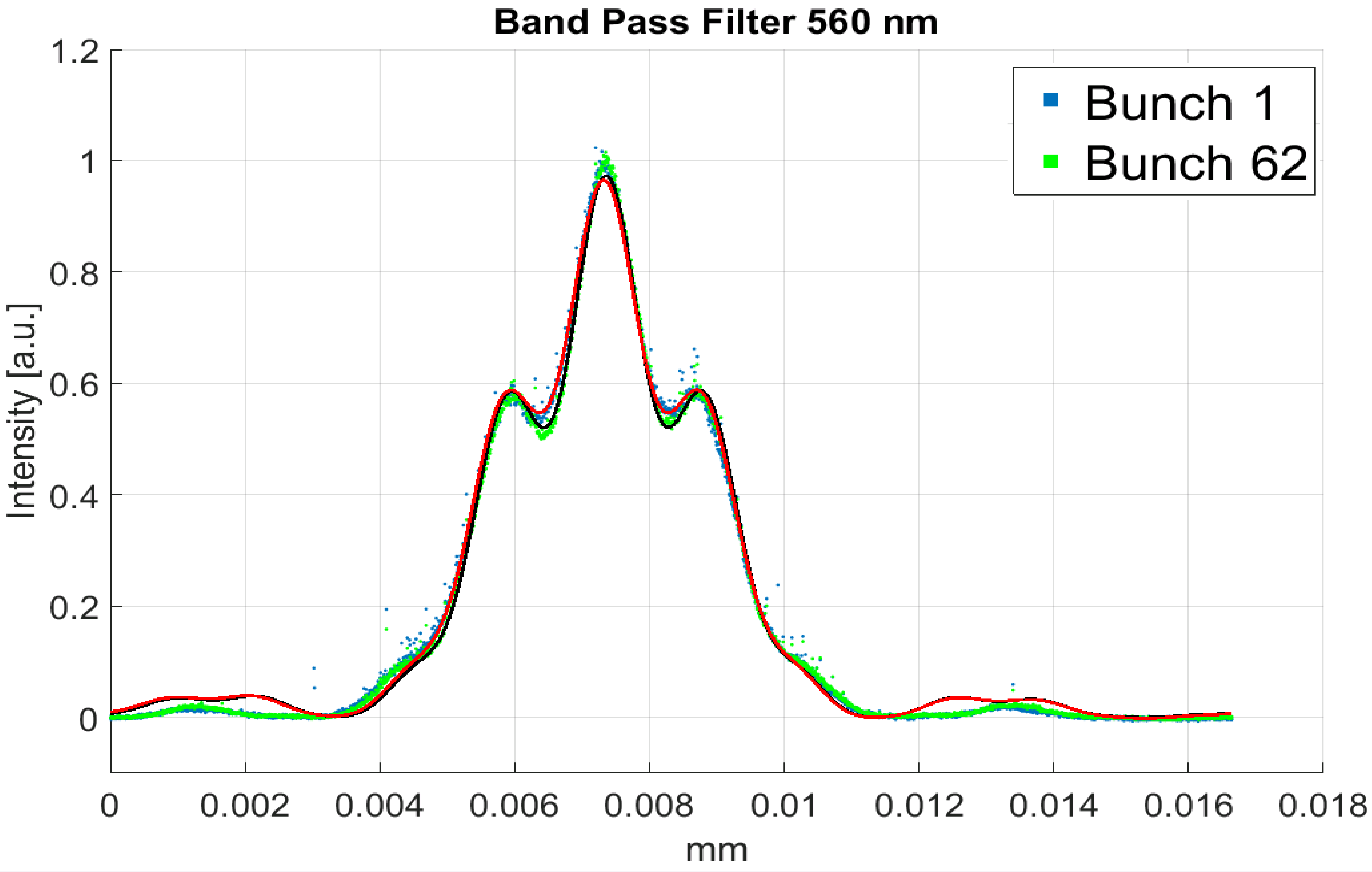
Interferometry at 450 GeV

- At Injection energy, beam size is >1 mm
  $\Rightarrow$ Visibility falls rapidly with increasing D
- Measurements with closest slit separation (2.5 mm and 3mm)
- Slit Width 1.5 mm limited by minimum magnification of the system
- Bandpass Filter 560 nm +/- 5 nm
- Long Exposure 200 ms
- Bunch by Bunch measurement

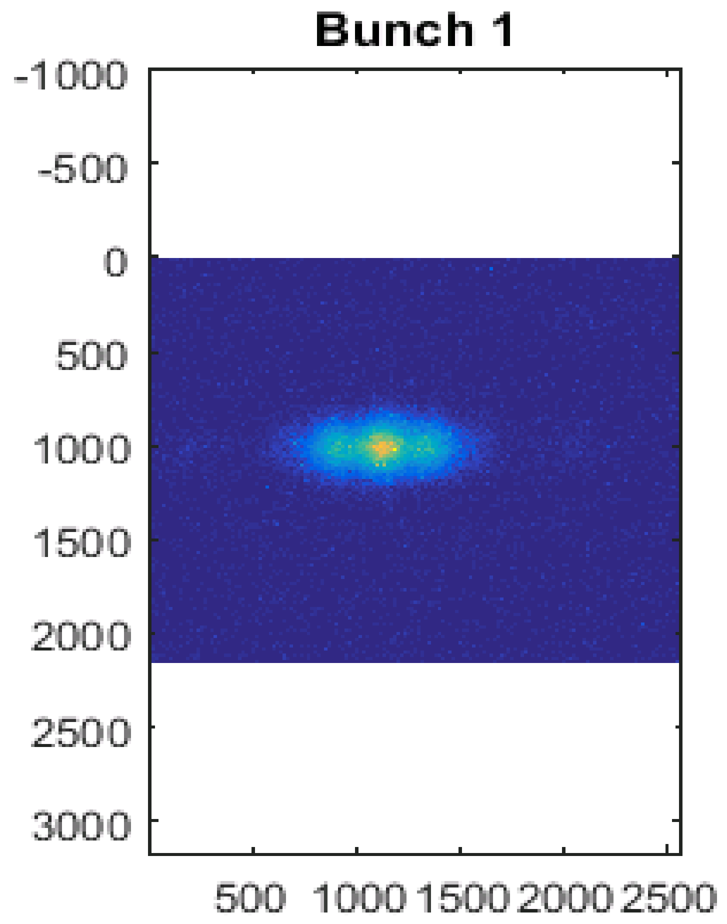
Horizontal size measurement
D=2.4mm, **a**=1.5mm, Expo= 200 ms at λ=560 nm.

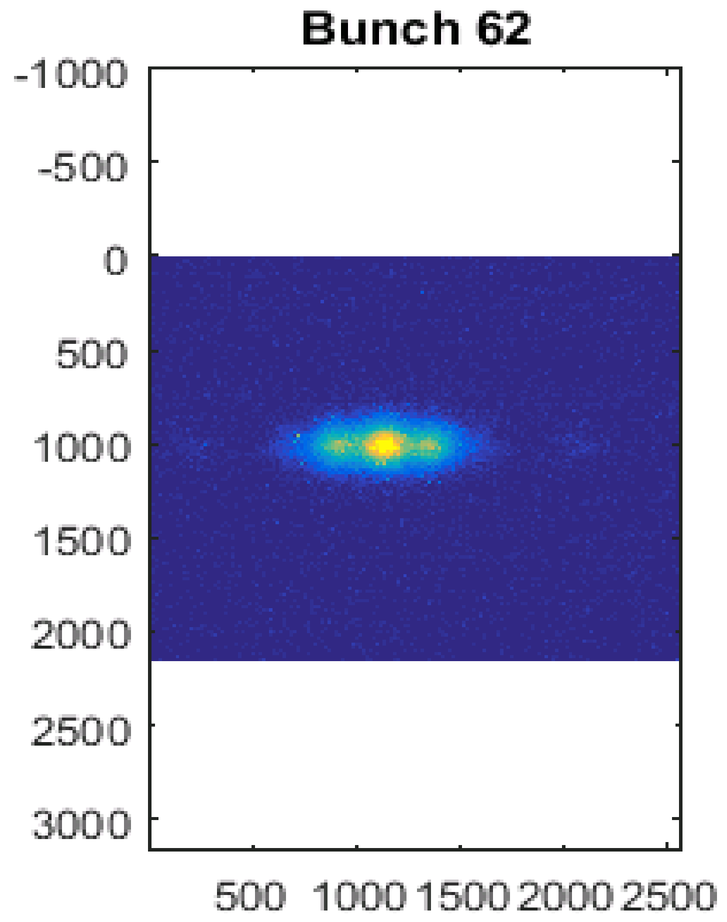


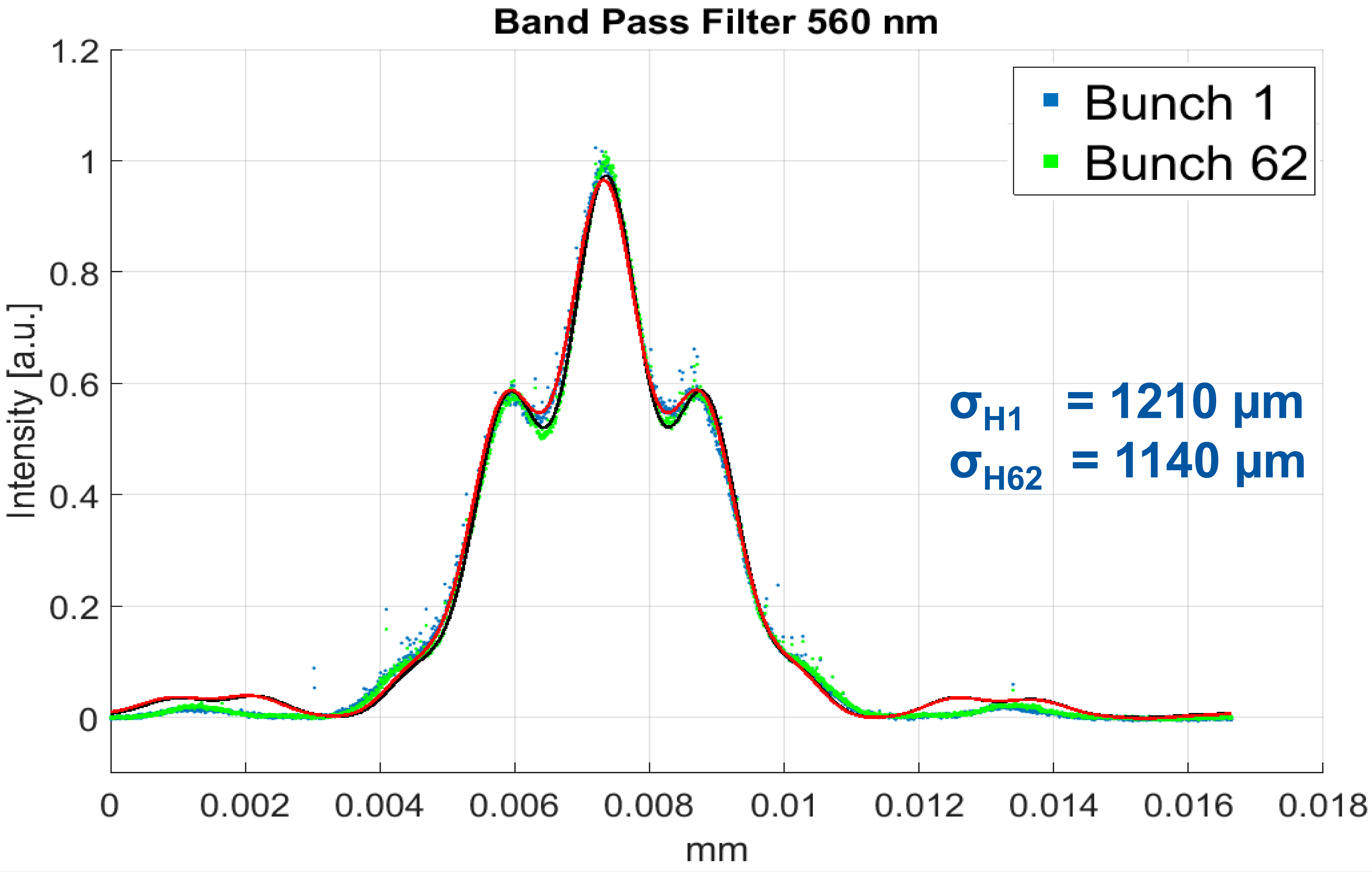




Horizontal size measurement
D=2.4mm, **a**=1.5mm, Expo= 200 ms at λ=560 nm.







σ_{H1} = 1210 μm
σ_{H62} = 1140 μm

LHC SR

Imaging at the LHC

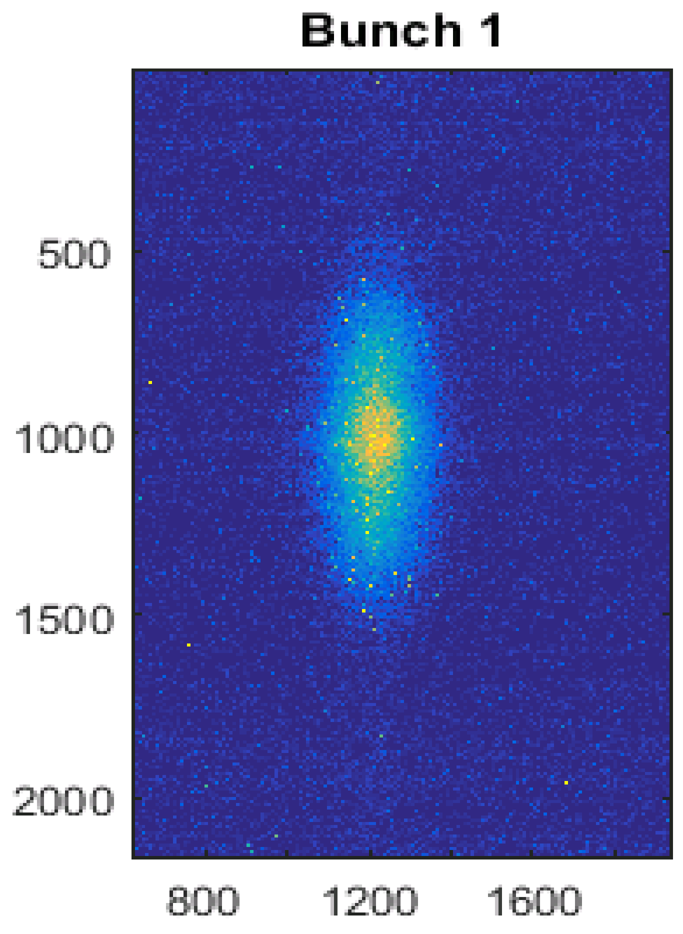
SR Interferometry

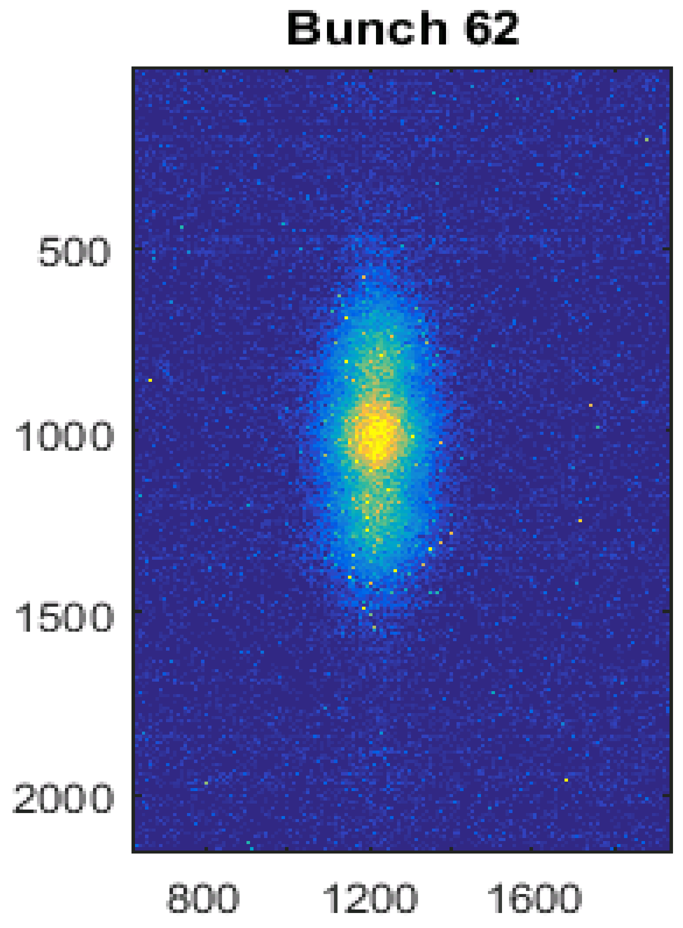
LHC Interferometer

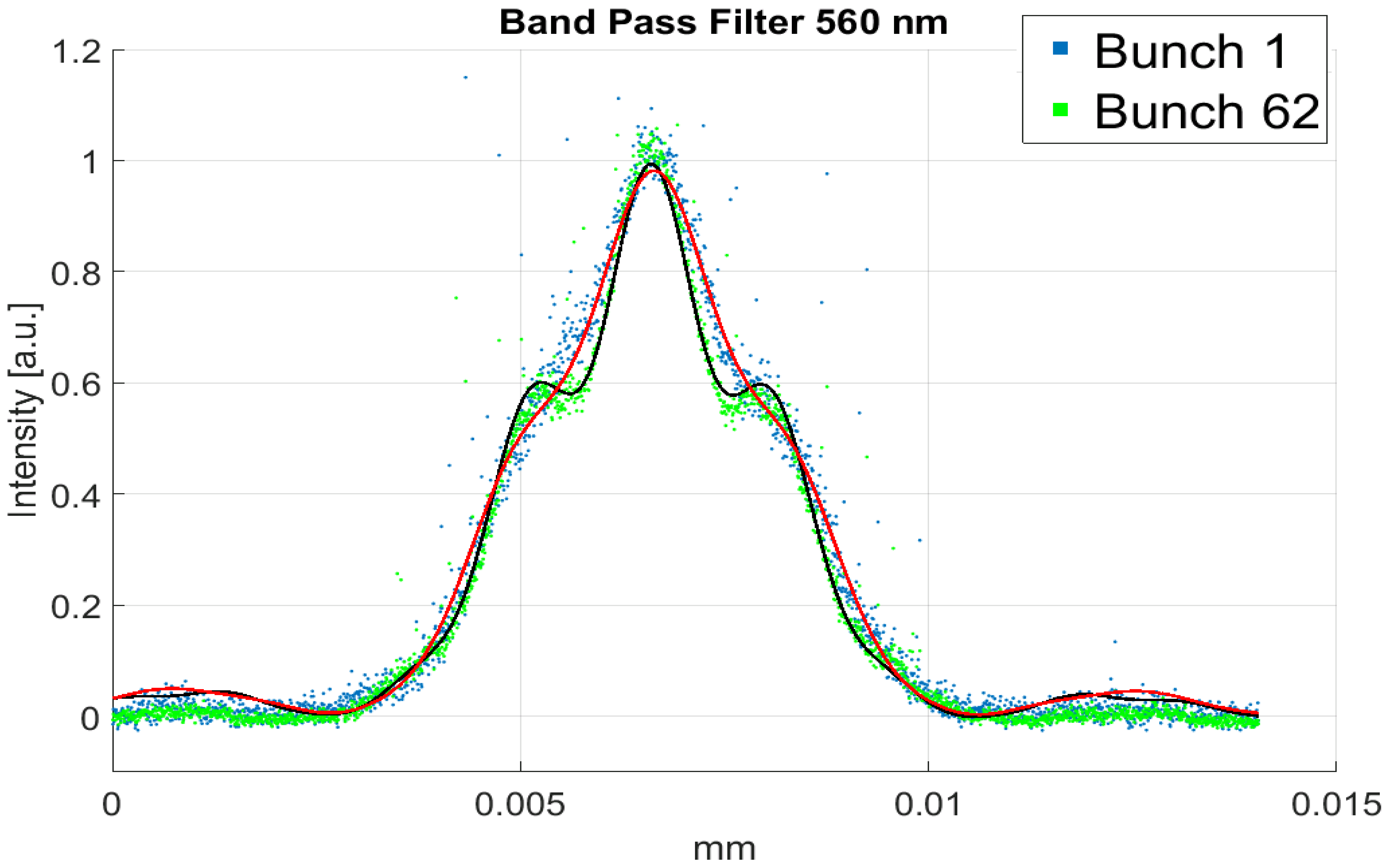
Commissioning
At 6.5 TeV
At 450 GeV

2D Interferometer

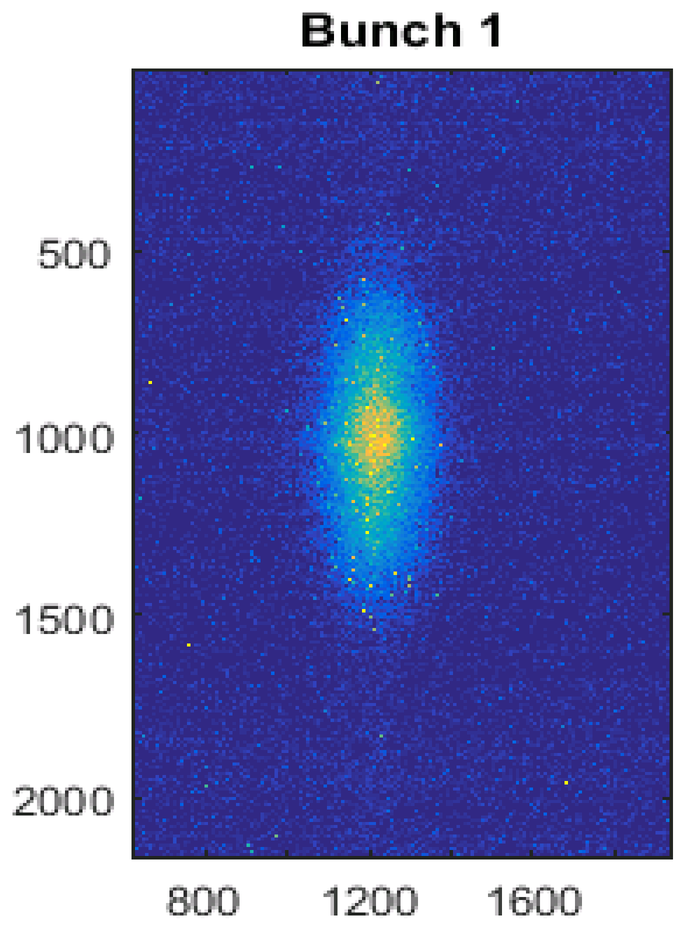
Vertical size measurement
D=2.6mm, **a**=1mm, Expo= 200 ms at λ=560 nm.

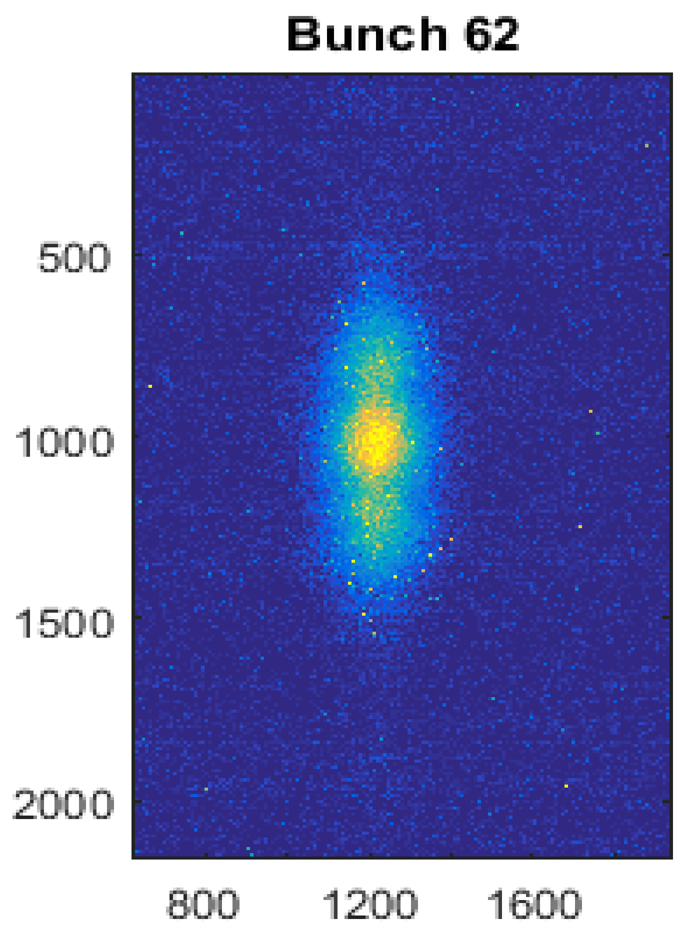


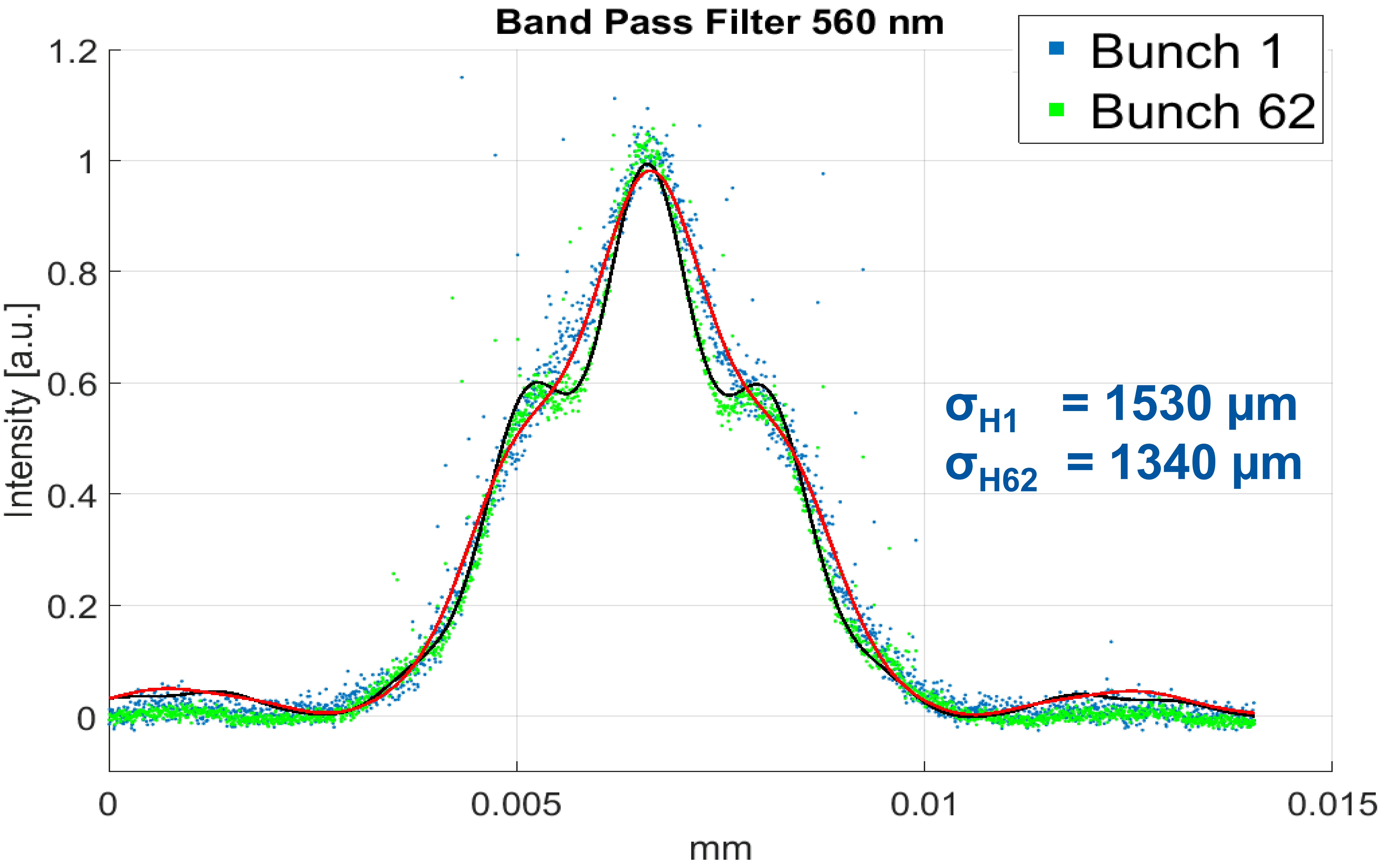




Vertical size measurement
D=2.6mm, a=1mm, Expo= 200 ms at λ=560 nm.







σ_{H1} = 1530 µm
σ_{H62} = 1340 µm

Benchmarking w.r.t. Imaging

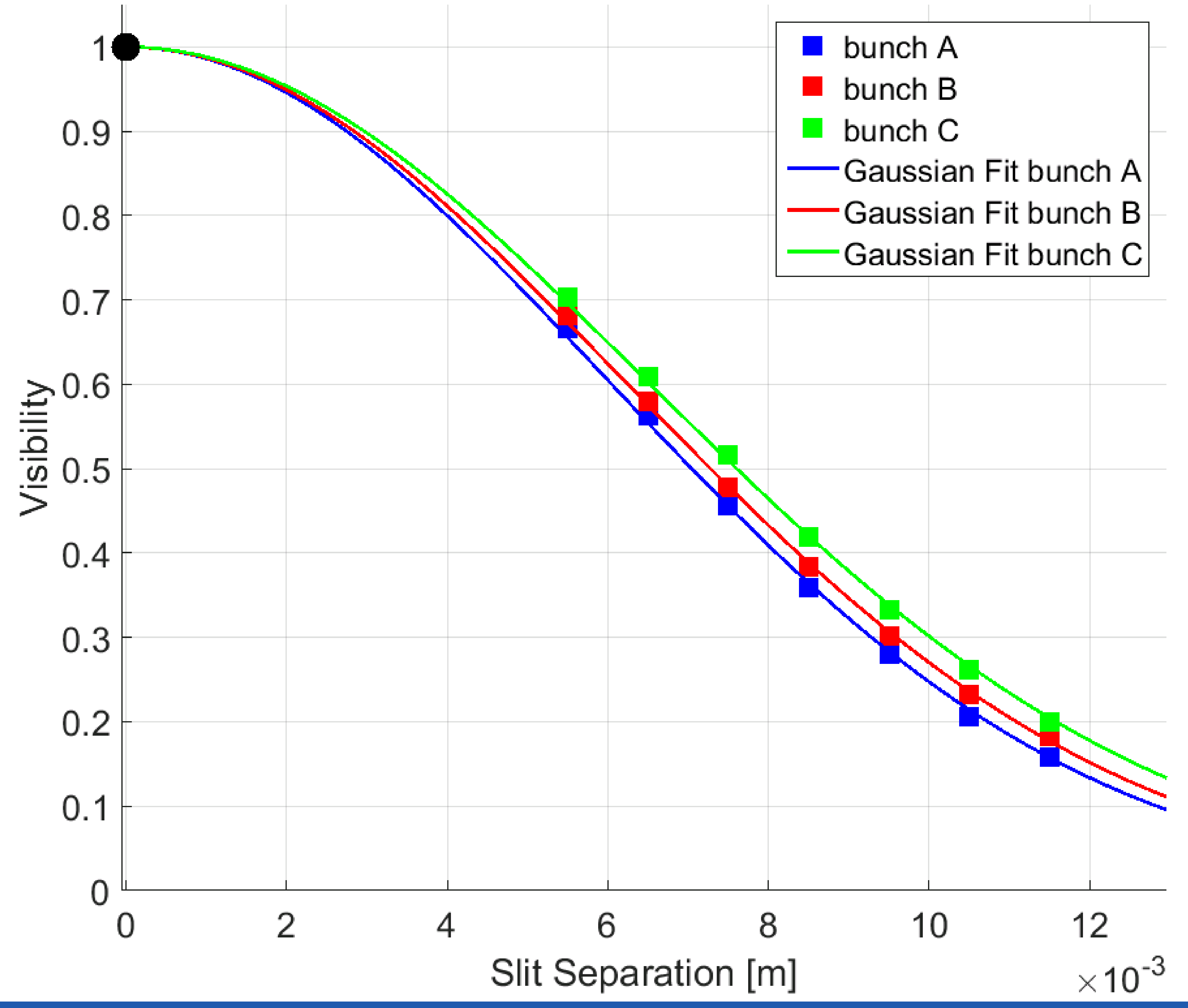
At Injection Energy

- Good agreement with Imaging
- Discrepancies with the imaging values are ~5%

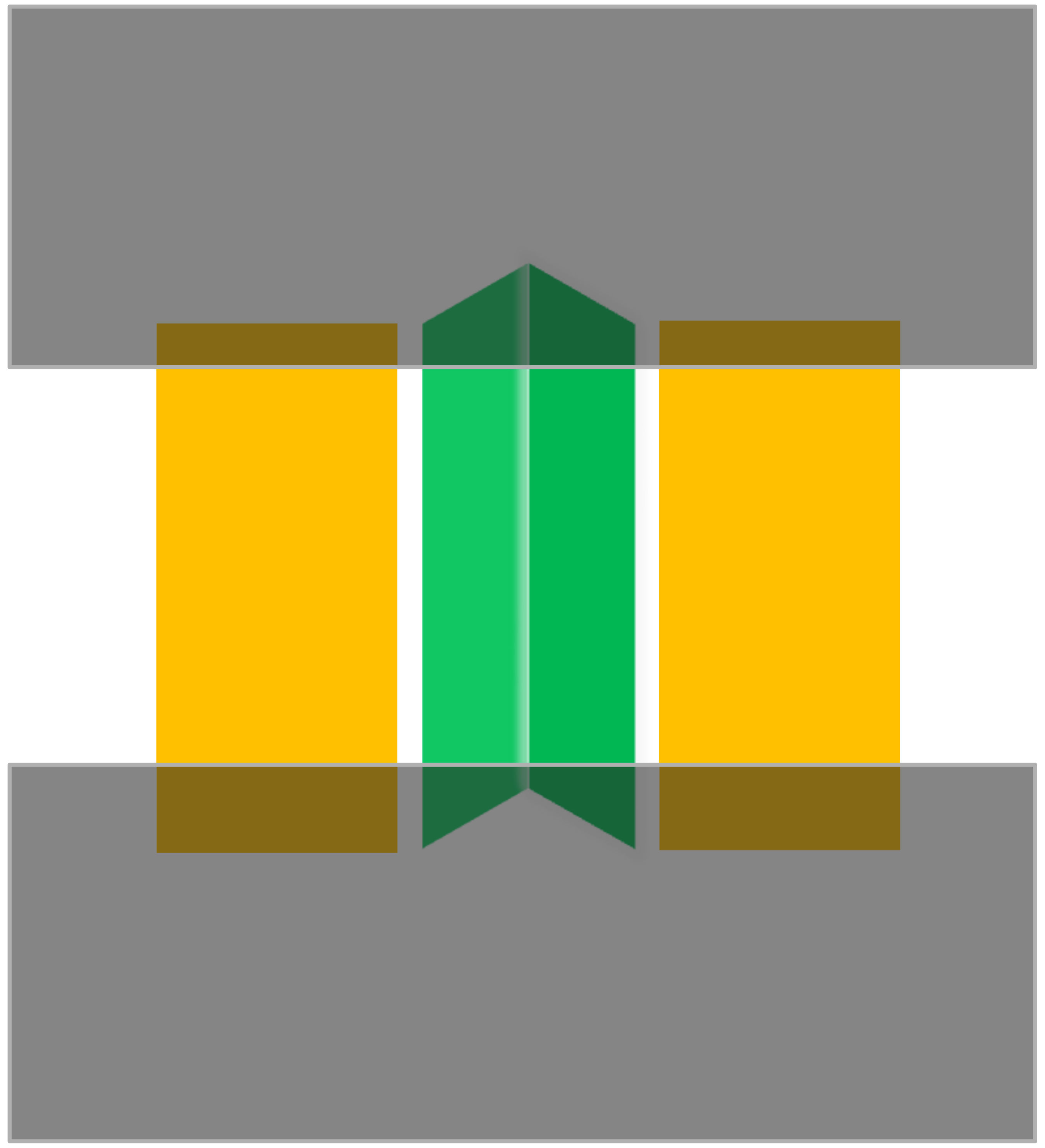
		bunch 1		bunch 62	
	σ [mm]	H	V	H	V
450 GeV	Imaging	1.22	1.6	1.15	1.4
	Interferometer	1.20	1.53	1.14	1.34

At Flat Top Energy

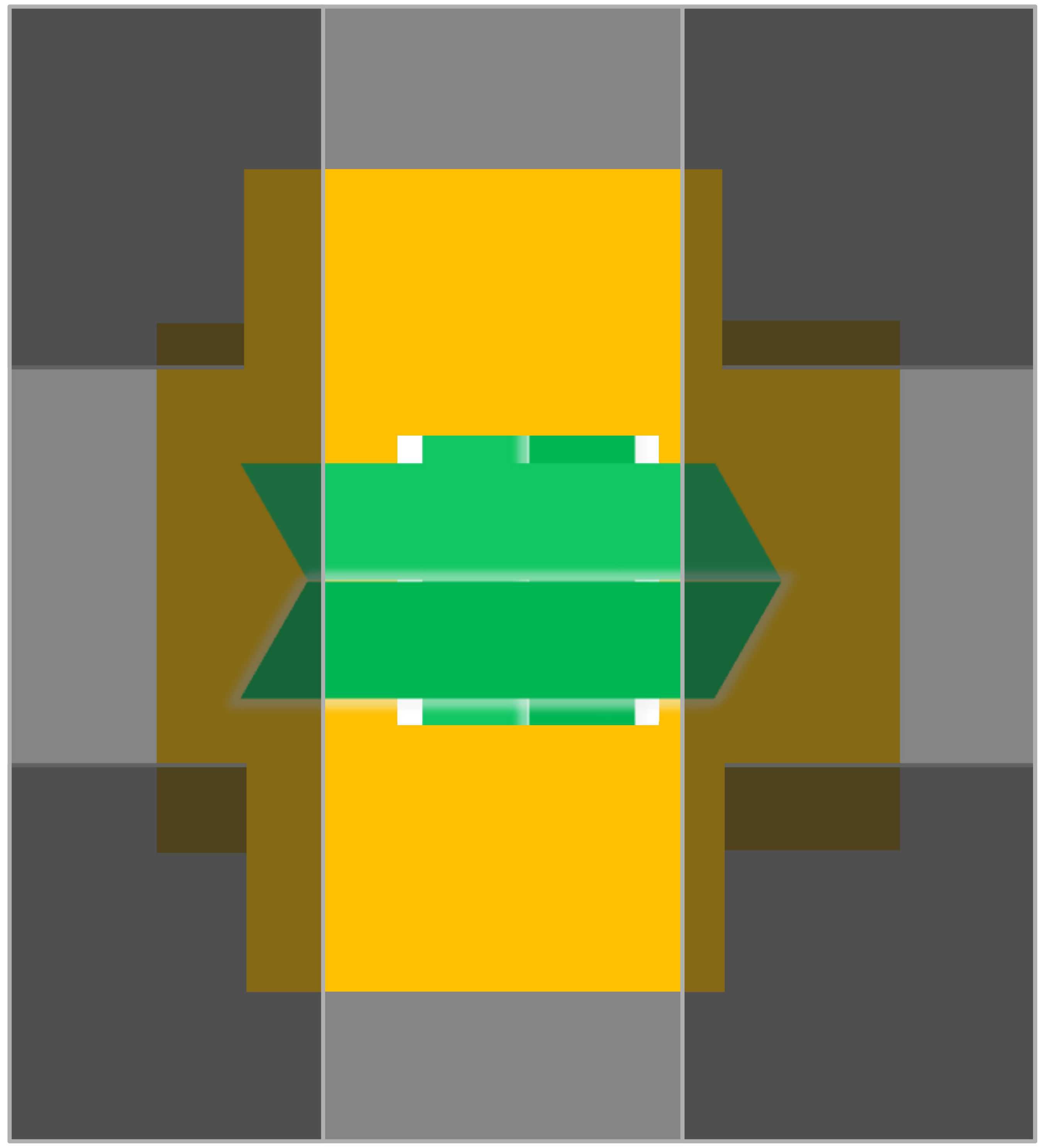
- Beam size from the interferometer larger by a factor of ~1,3.
- However, relative bunch by bunch size measured via interferometry is compatible with Imaging.



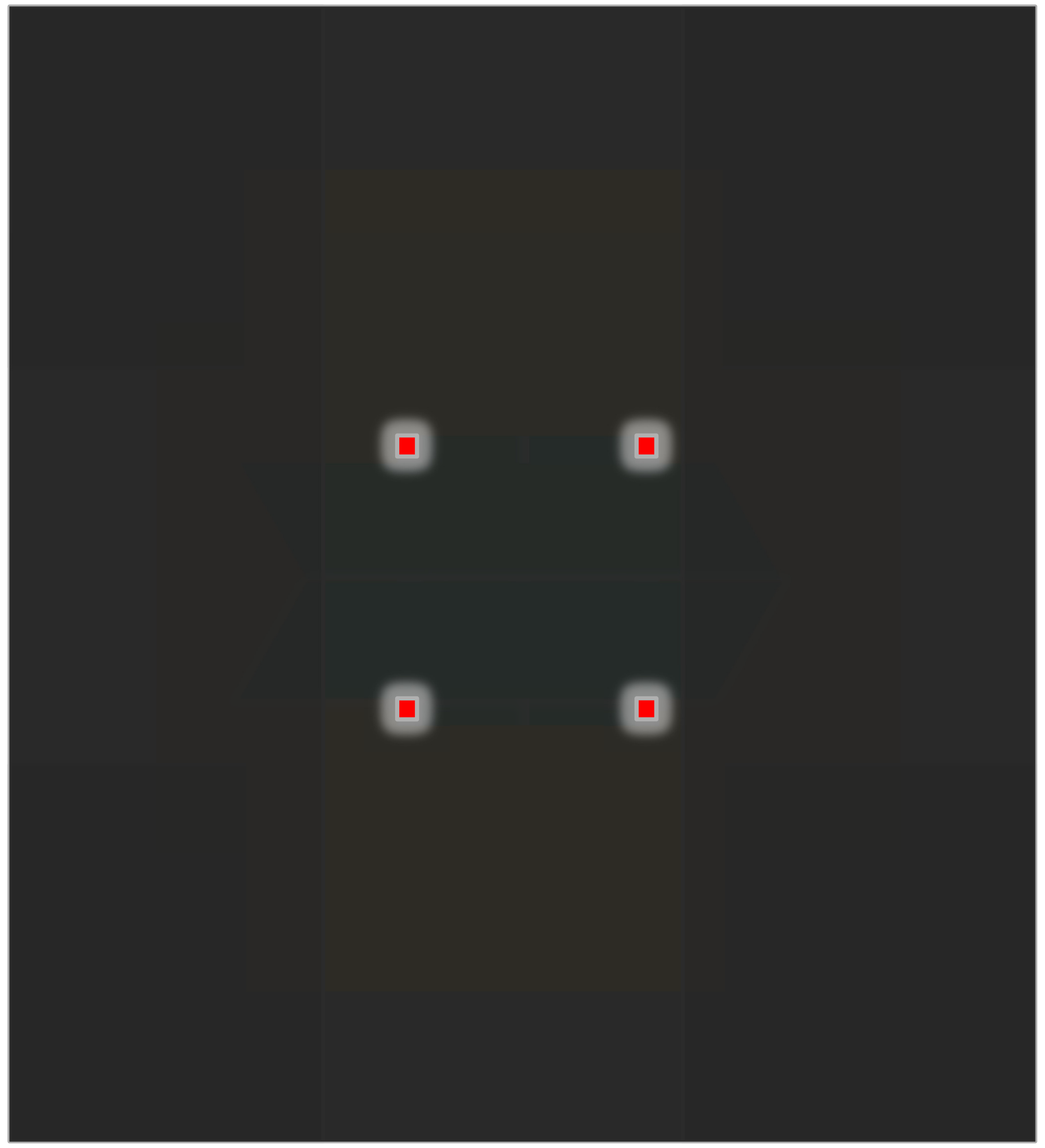
- Using H & V assembly simultaneously
- Independent scan of double slits separation
- SR sampled by 4 small slits distributed along the corners of a rectangle whose sides D_H and D_V
- Need Checking 2D measurement vs. 1D measurements



- Using H & V assembly simultaneously
- Independent scan of double slits separation
- SR sampled by 4 small slits distributed along the corners of a rectangle whose sides D_H and D_V
- Need Checking 2D measurement vs. 1D measurements

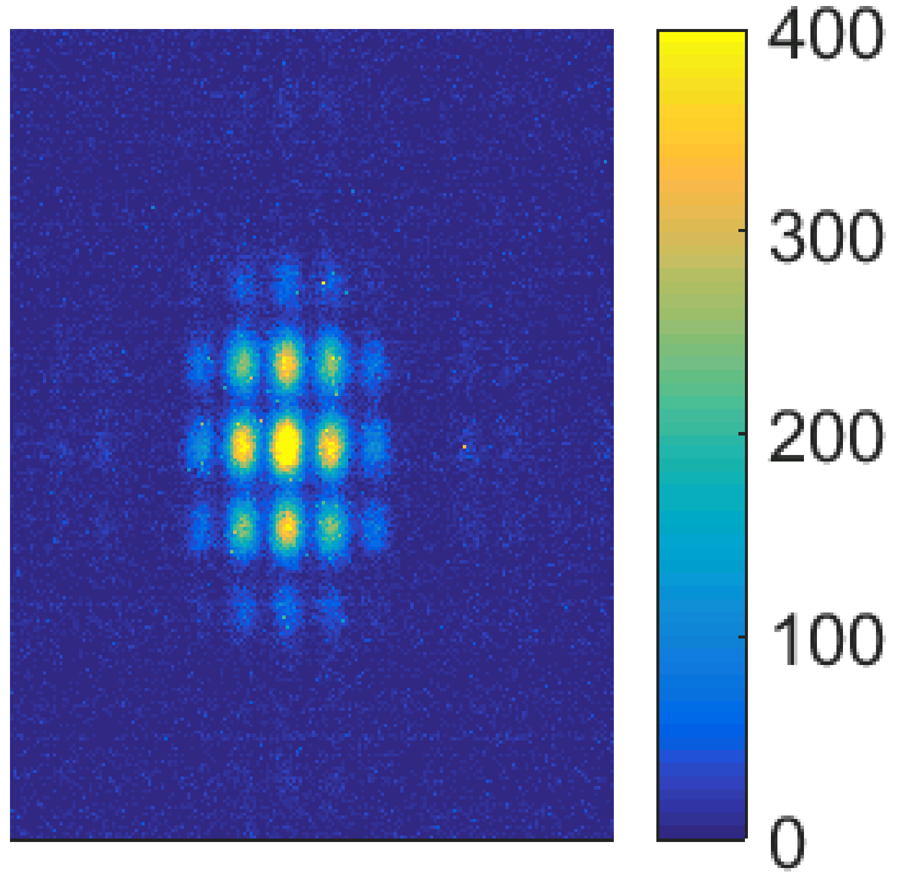


- Using H & V assembly simultaneously
- Independent scan of double slits separation
- SR sampled by 4 small slits distributed along the corners of a rectangle whose sides D_H and D_V
- Need Checking 2D measurement vs. 1D measurements

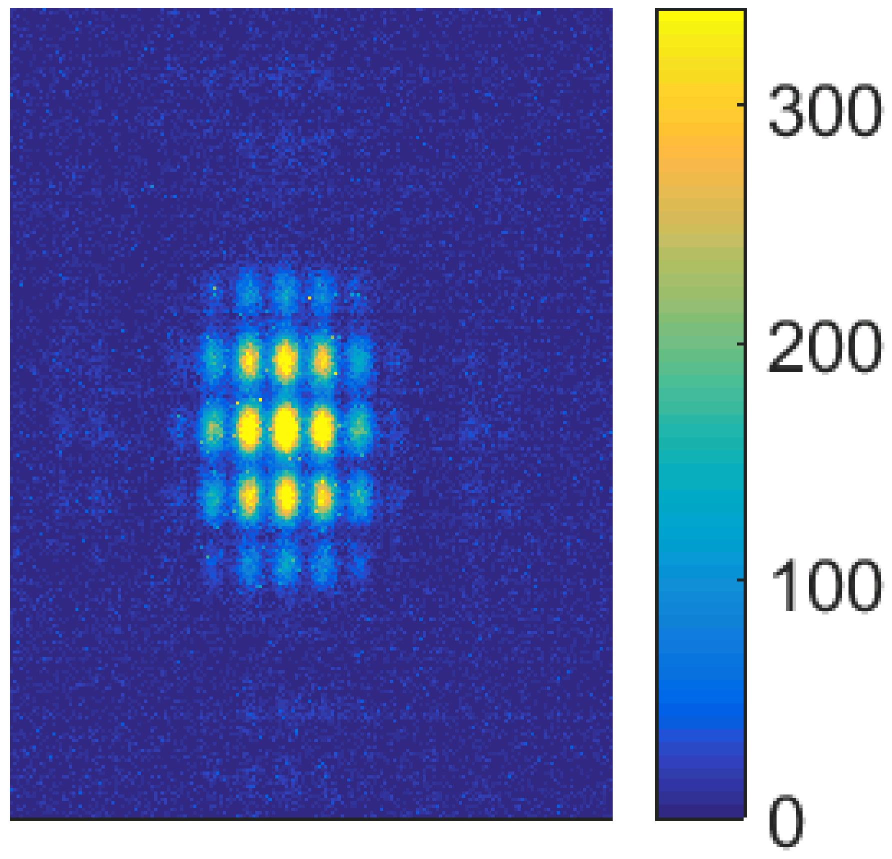


Slit Scan from D=3mm -> 11 mm

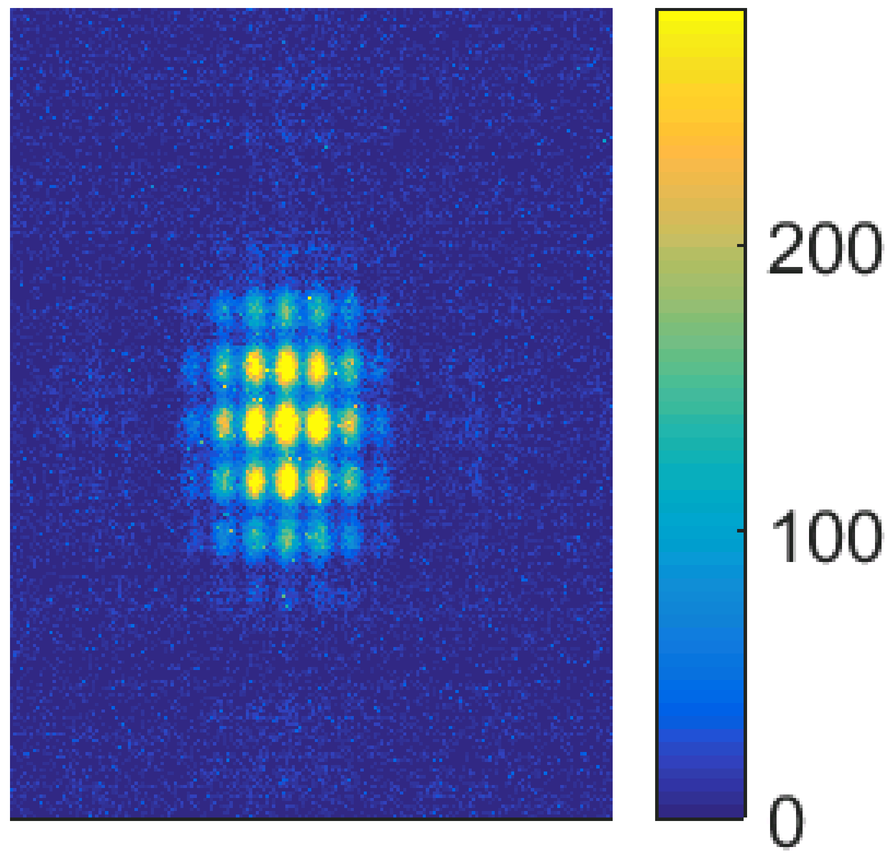
H&V : D=3 mm



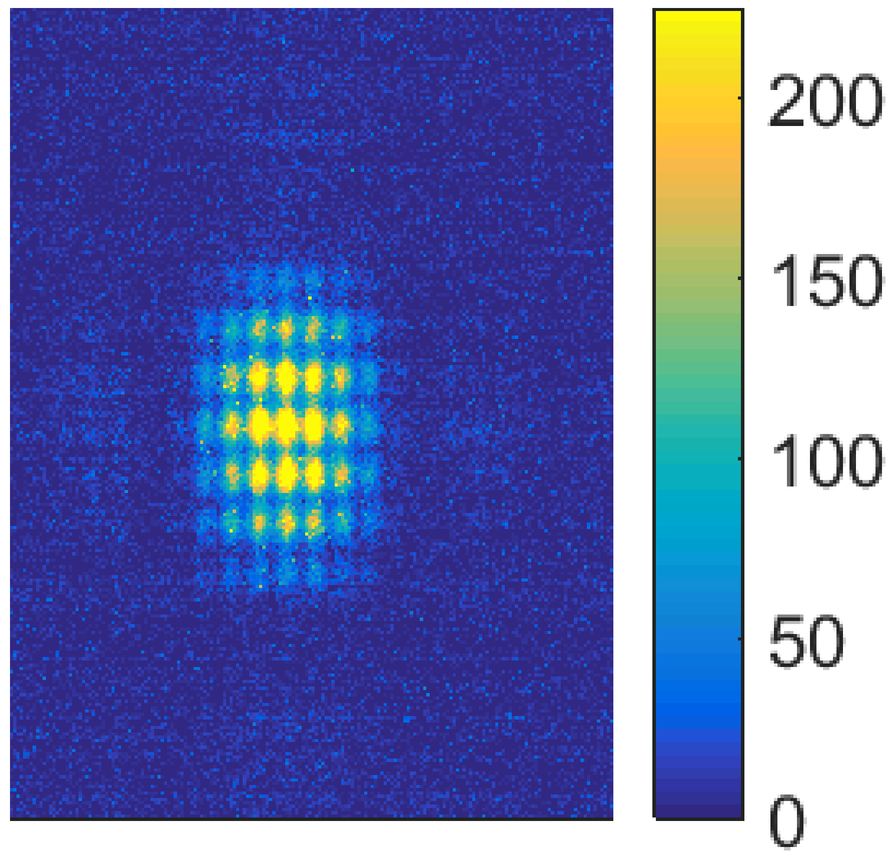
H&V : D=4 mm



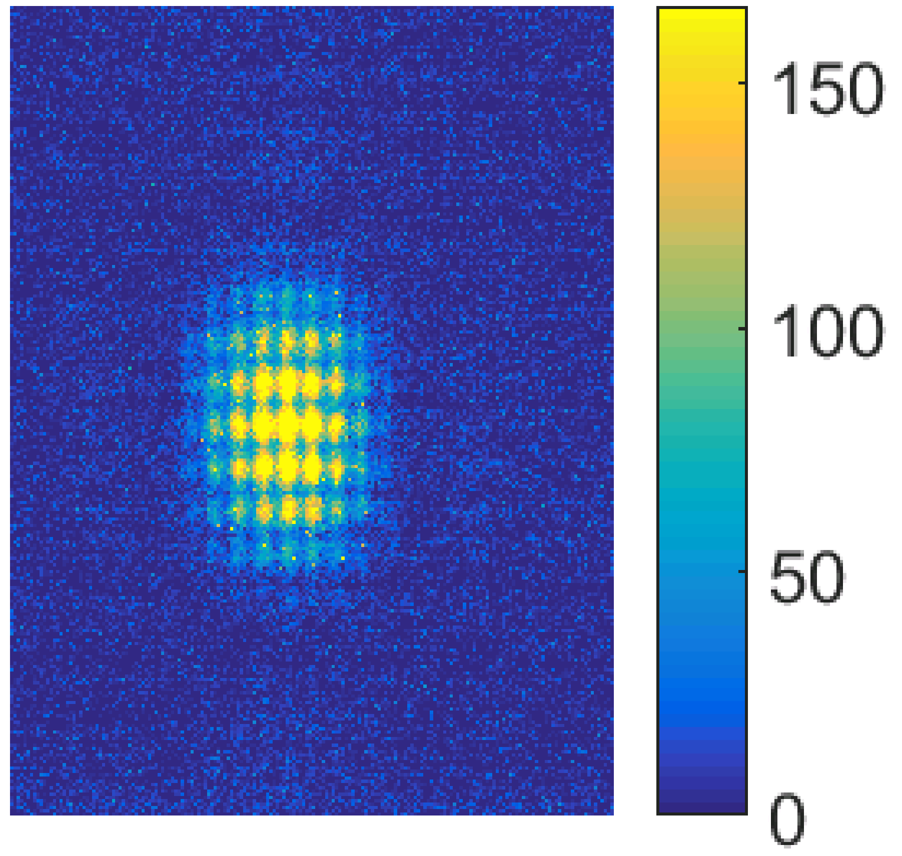
H&V : D=5 mm



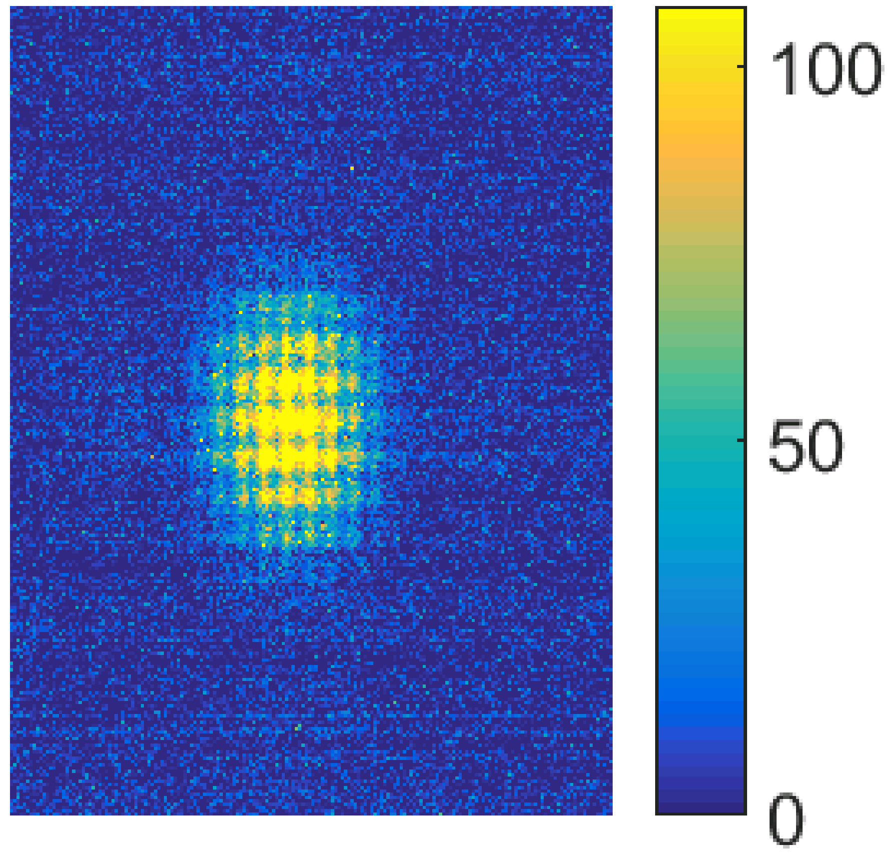
H&V : D=6 mm



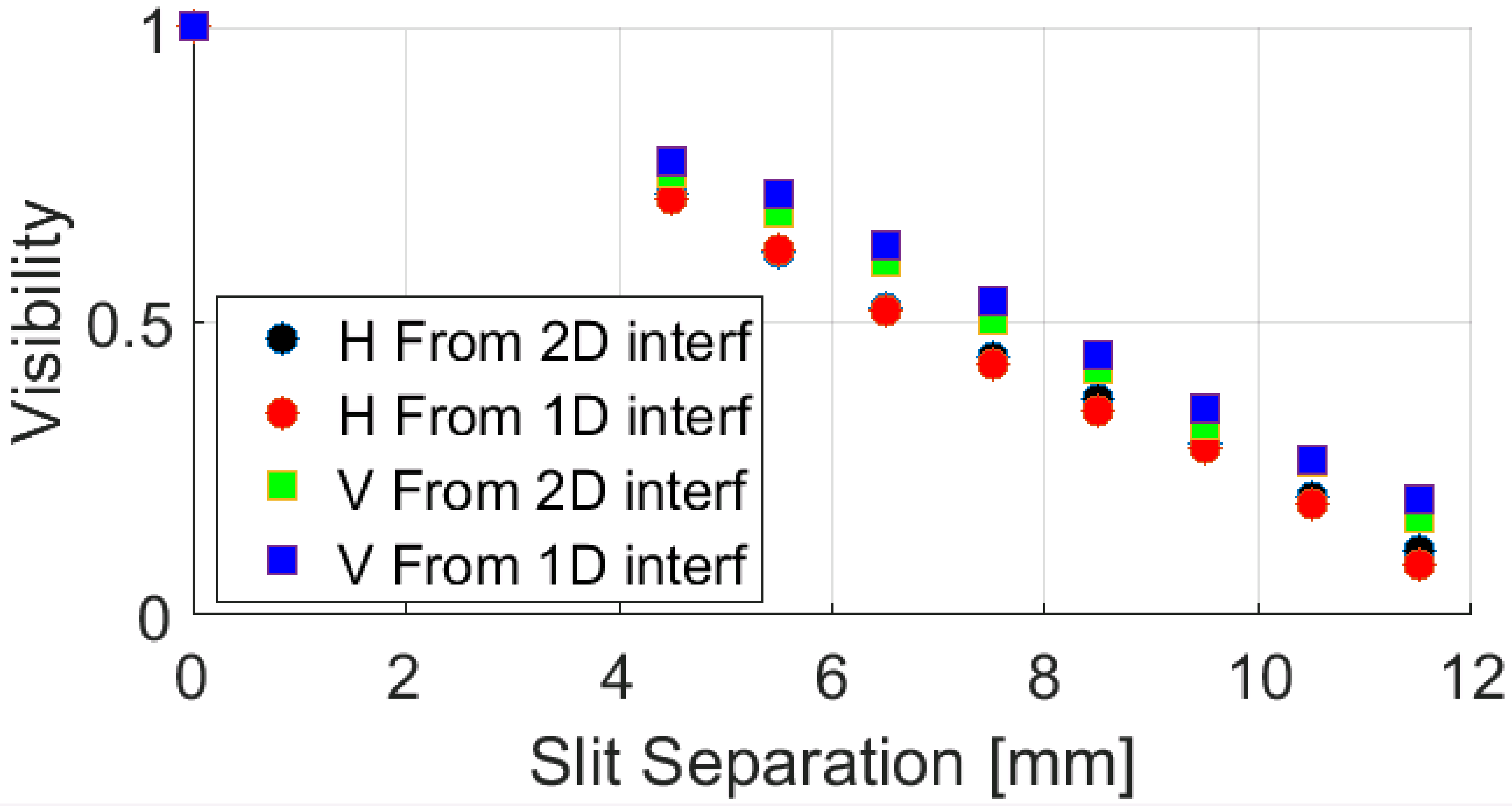
H&V : D=7 mm



H&V : D=8 mm

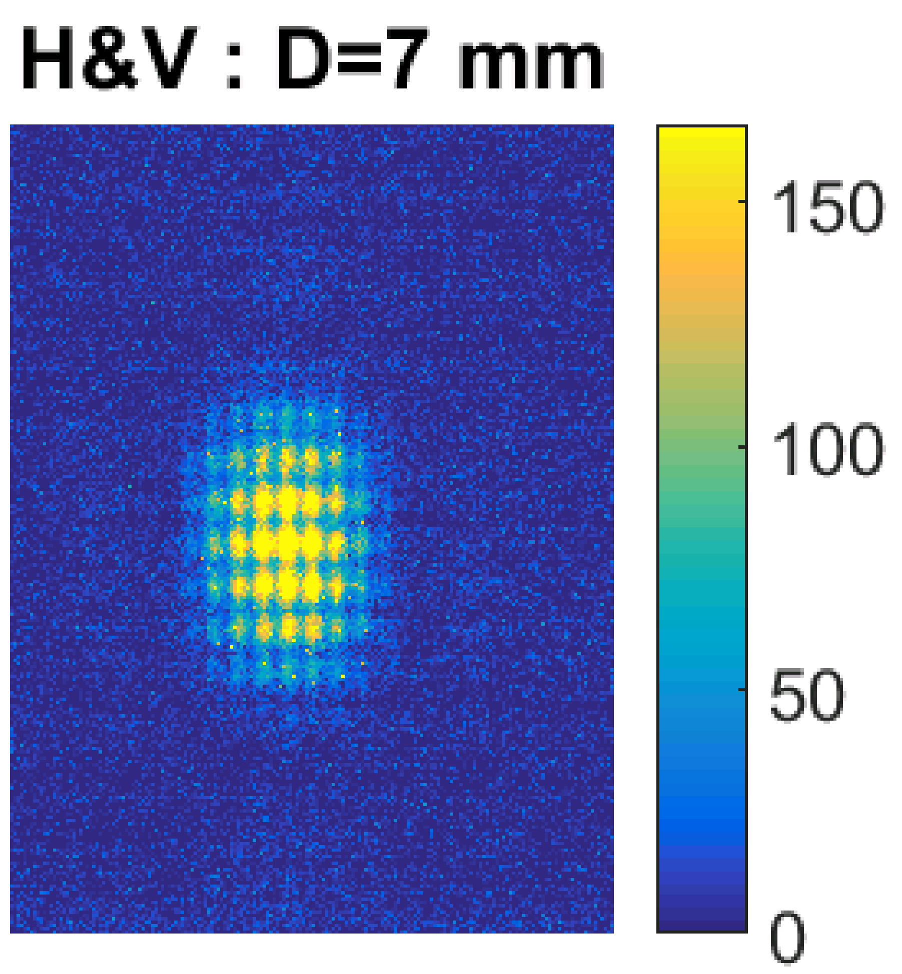


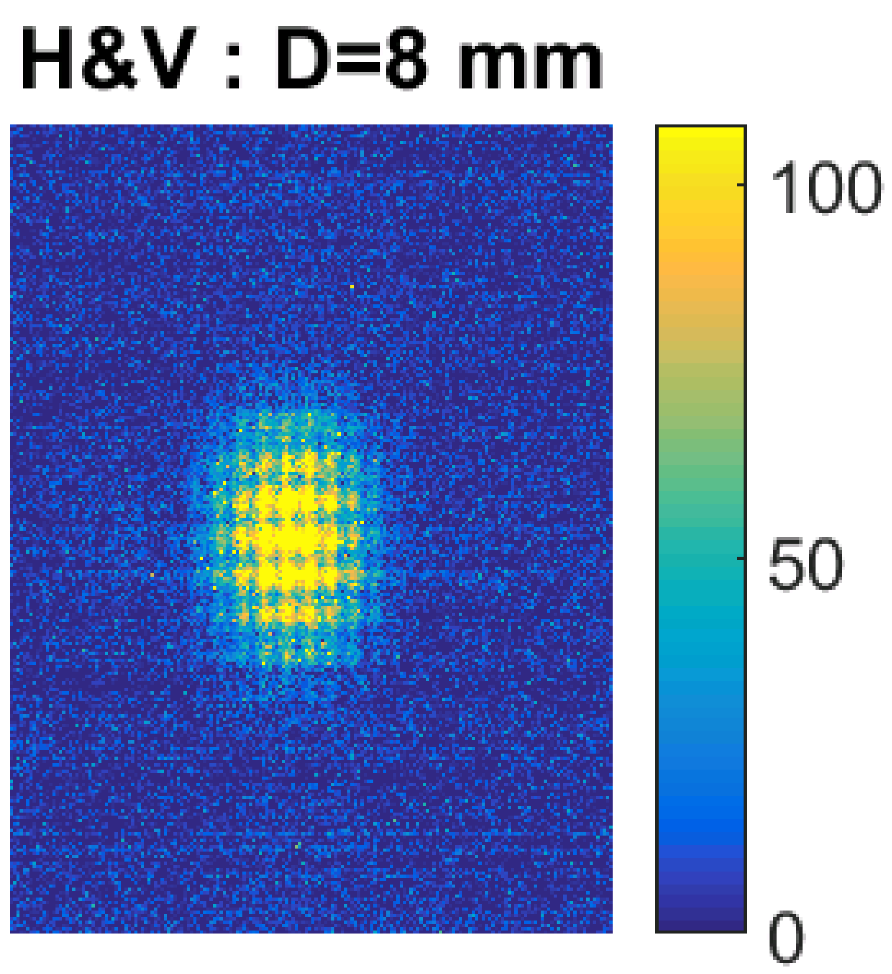
Comparison 2D vs 1D



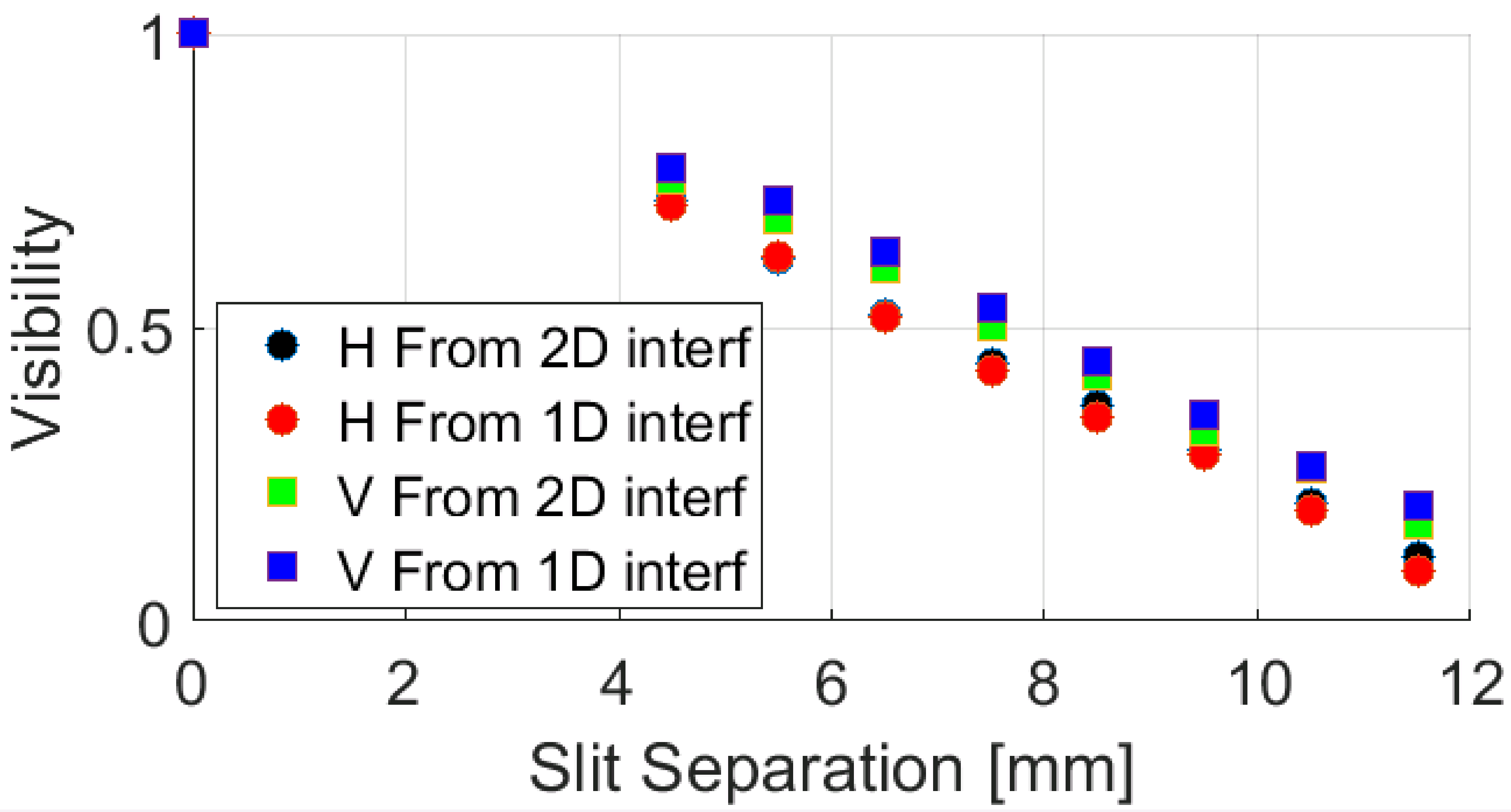
Slit Scan from D=3mm -> 11 mm

Excellent agreement obtained validates the feasibility of an LHC 2D interferometer setup with < 5% discrepancy on beam size.
(Coupling between the two planes is negligible and SR is enough)





Comparison 2D vs 1D



Conclusions

- We are at a good stage of the Interferometer Commissioning
  - Hardware tested and functional
  - Very good alignment

- Interferograms recorded at Injection and Top energy
  - Careful studies of possible systematics were carried out

- Preliminary beam size measurement are very encouraging
  - Consistent, reproducible and robust measurements

- Good agreement with imaging system at 450 GeV
- Discrepancy (scaling factor of 1.3-1.4) at 6.5TeV still under investigation

- 2D interferometer was found feasible

Thank you for your attention!