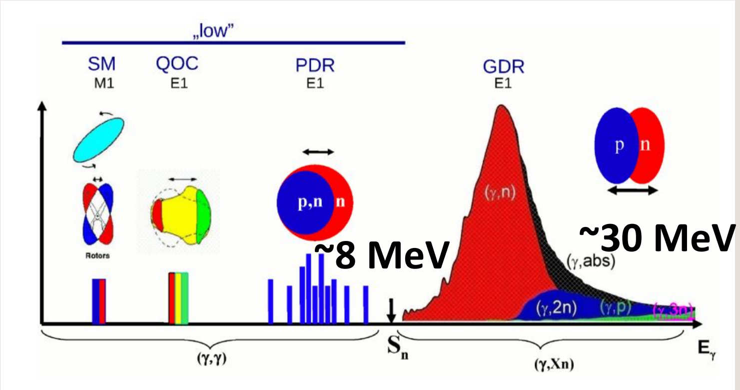
Gamma-rays at ELI-NP-GBS

GENERATION AND MONITORING

Gamma-ray requirements

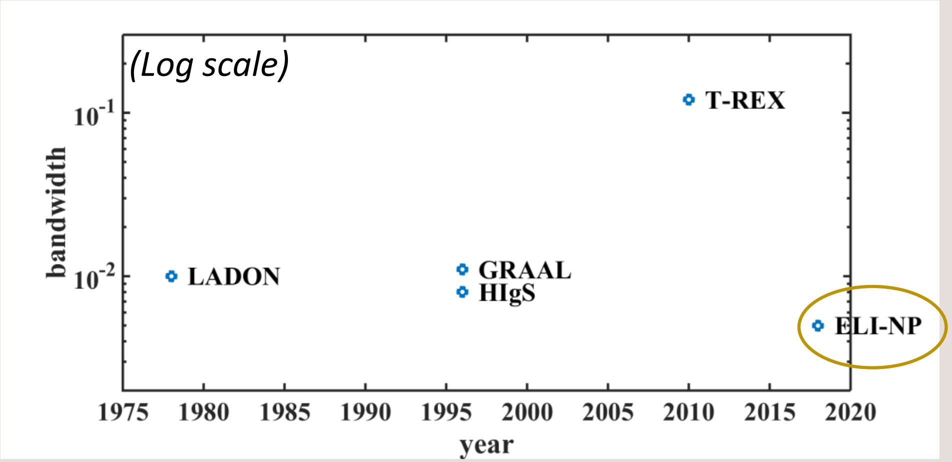
Gamma-beam specifications:

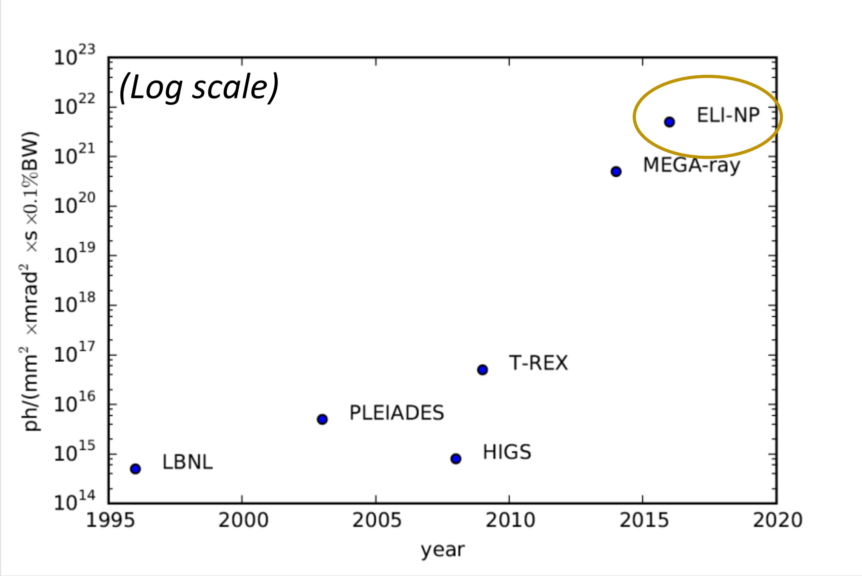
- Energies γ (E_γ) : 0.2 – 19.5 MeV
- Bandwidth (ΔE/E) : <0.5%
- Spectral density (TASD) : >5000 γ/(s.eV)
- Linear polarization: >95%



AIP Conference Proceedings 1462, 177 (2012)

Bandwidth + energy tunability ➔ Compton scattering





D. Habs et al., arxiv.org/pdf/1008.5336

➔ Highly challenging

Production of the gamma-beam

$$TASD \approx \frac{\langle flux \rangle}{bandwidth} = \frac{1}{\sigma_{E_\gamma}} \langle \frac{dN^{\sigma_{E_\gamma}}}{dt} \rangle$$

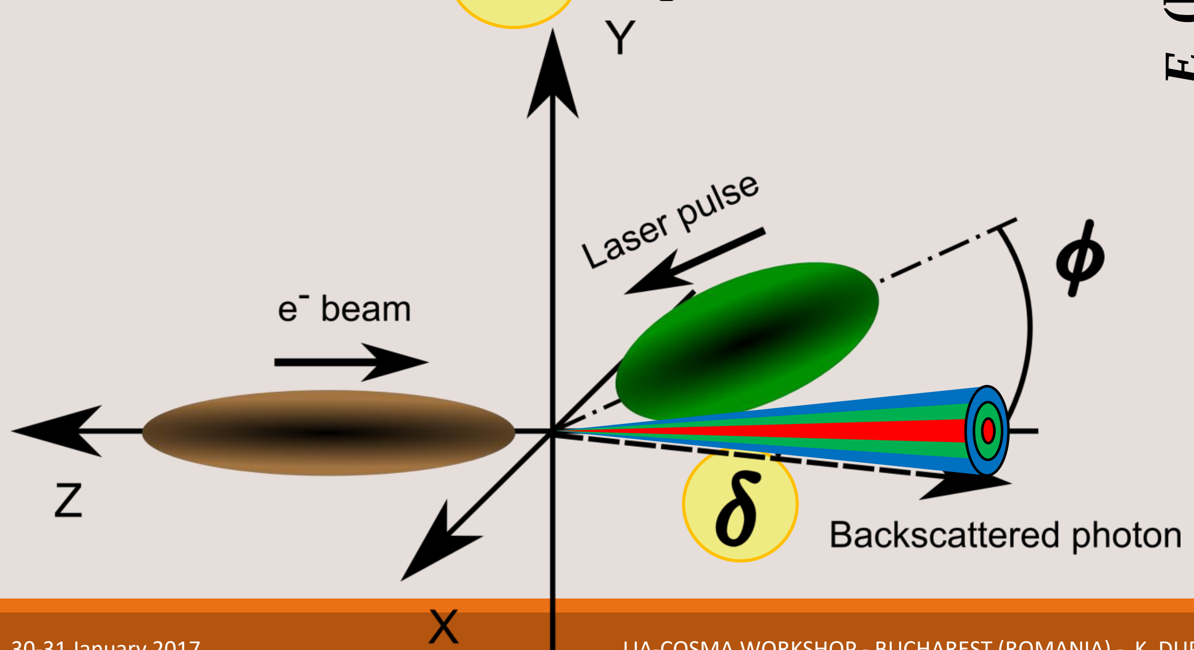
- Compton scattering = Gamma-ray production
- “Collimation” = Gamma-ray energy selection

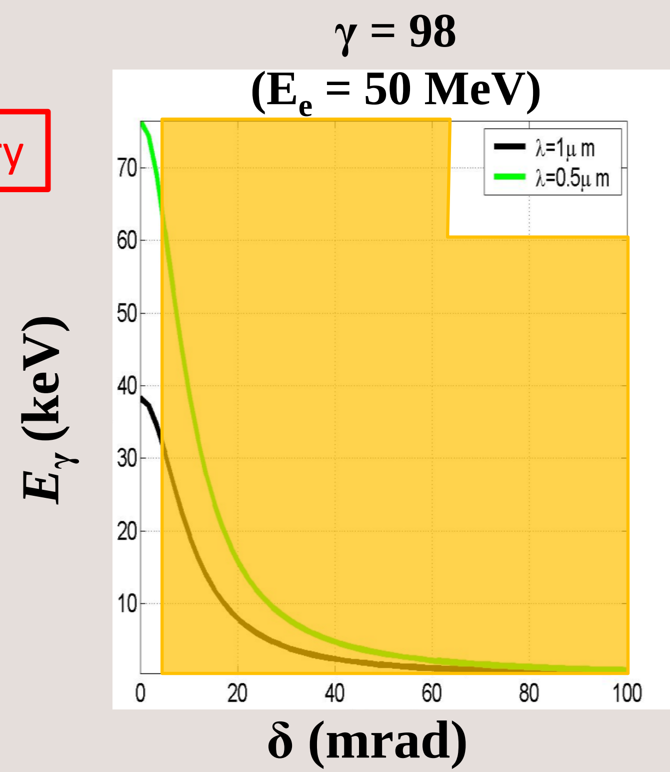
Cross-section ≈ physics

$$\langle \frac{dN}{dt} \rangle = \sigma_T \mathcal{L}$$

luminosity ≈ geometry

$$E_\gamma \simeq E_L \frac{4\gamma^2}{1+\gamma^2\delta^2+\frac{\phi^2}{4}}$$



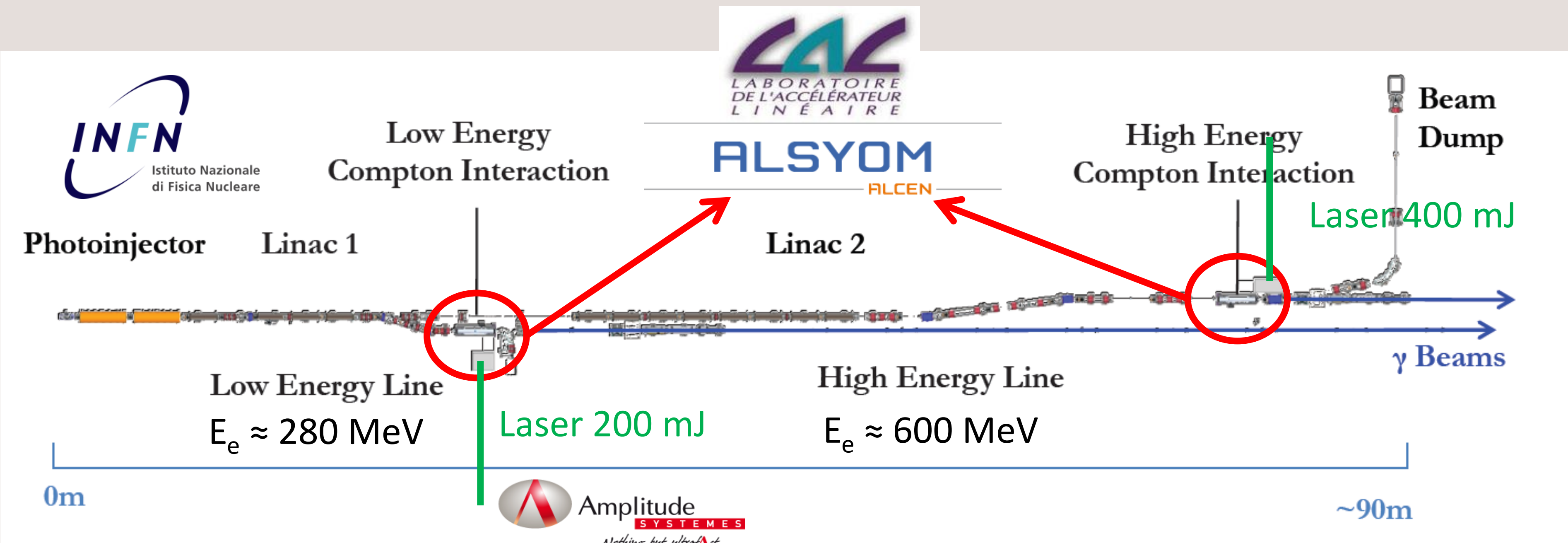


ELI-NP gamma beam source (accelerator)

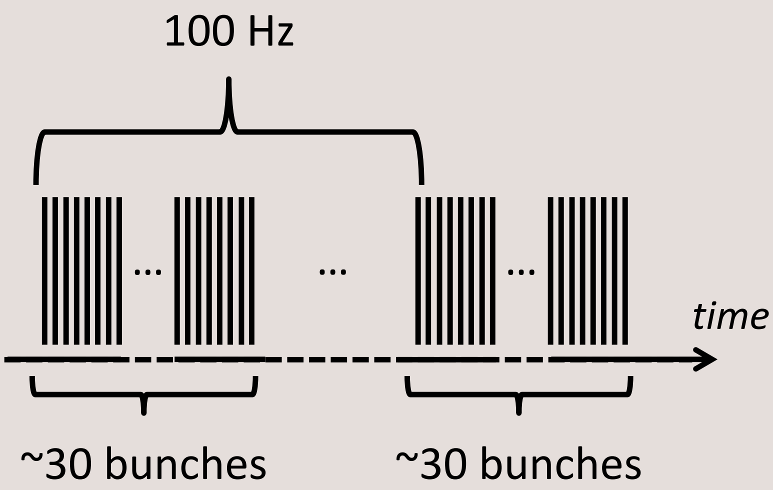
Requirements:

- 2 interaction points (Low/High Energies)
- Accelerator hall size fixed
- ➔compact accelerator design (hybrid band S and C = SPARC, Frascati)

= State of the Art, low development risk



ELI-NP gamma beam source (laser system)



LASER REQUIRED FOR COMPTON INTERACTION POINT

Accelerator characteristics constrained by electrons beam quality ➔

- Laser average power > 1 kW
- green light,
- high quality,
- pulsed mode > 100Hz @few ps

➔Better than state of the art !

= unreachable even with R&D

Solution

➔ **recycle laser power of 1 pulse@100Hz** ➔ 40W with Circulator of 32 passes (already State of the Art, cf. Amplitude Systemes)

➔ **optical system !**

- Resonant cavity = too much R&D risk for 100 Hz
- **Multipass (non resonant)**
  ➔ Laser beam circulator

Overview design

LINAC multi-bunch hybrid bands S and C (~80 – 750 MeV) at 100Hz

(space, cost and tunability)

high average power laser (3.5ps @515 nm, 100Hz, 200mJ-400mJ)

e^-

photons

Laser Beam optical Circulator

(efficiency, “robustness”)

Gamma-rays

Gamma-beam specifications:

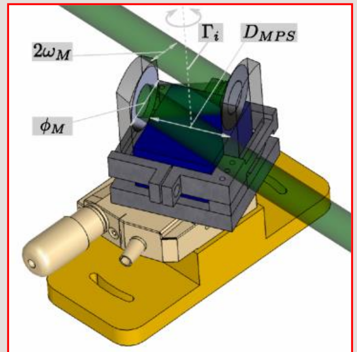
- Energies γ (E_γ) : 0.2 – 19.5 MeV
- Bandwidth (ΔE/E) : <0.5%
- Spectral density (TASD) : >5000 γ/(s.eV)
- Linear polarization: >95%

Optical system: laser beam circulator

Requirements:

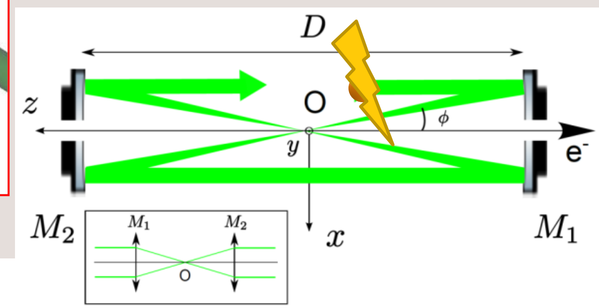
- Constant crossing angle ϕ (small bandwidth)
- Unique laser-electron beam interaction point

  ➔ 1 Mirror-Pair System (MPS) per pass = Optical plan switching

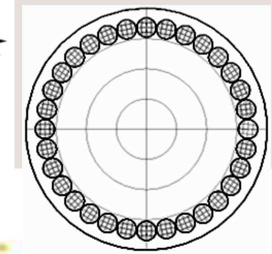


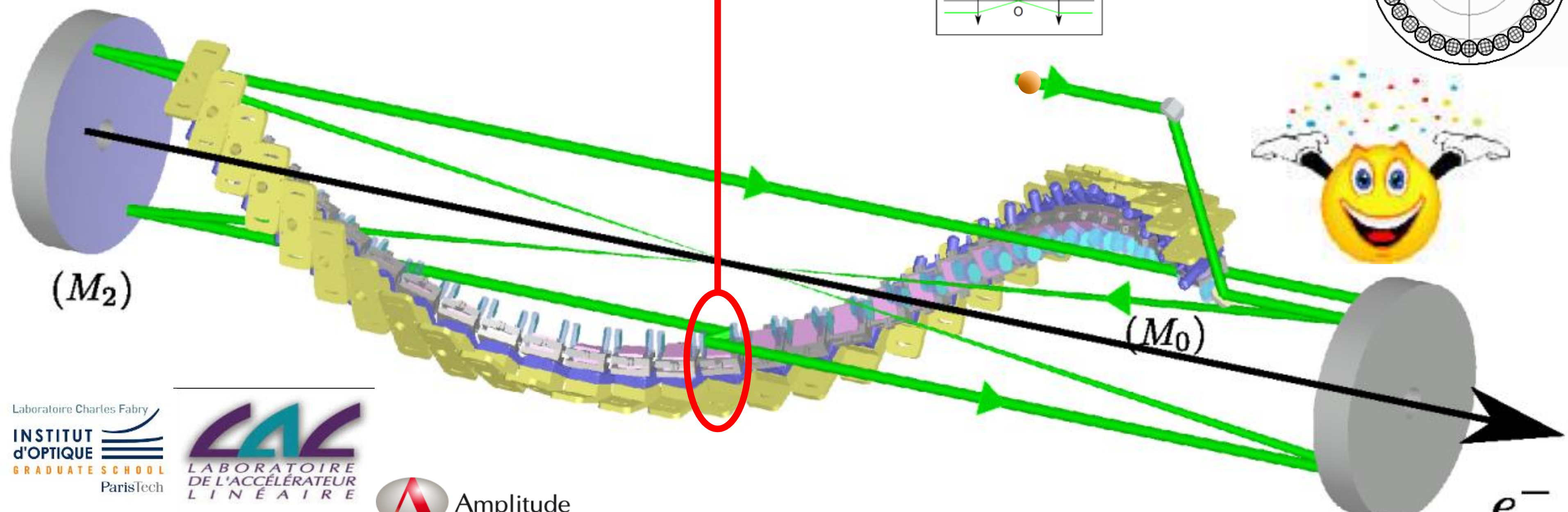
- No optical aberration

  ➔2 high-grade quality parabolic mirrors



2D



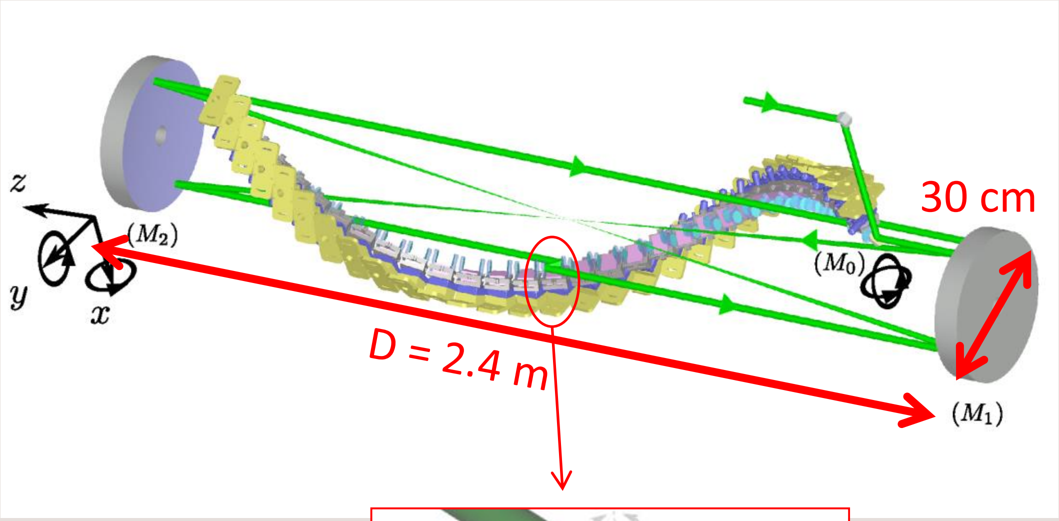


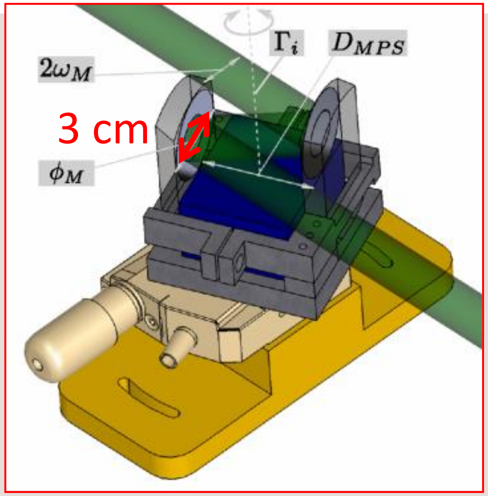
"Dragon-Shape"

3D

Recirculator constraints

- Mirror surface quality
- Frozen geometry (parabolic mirrors distance)
  => Tight alignment (few µm, µrad) with 7 degrees of freedom
- MPS parallelism (< 3 µrad)
- Synchronization (few 100fs)



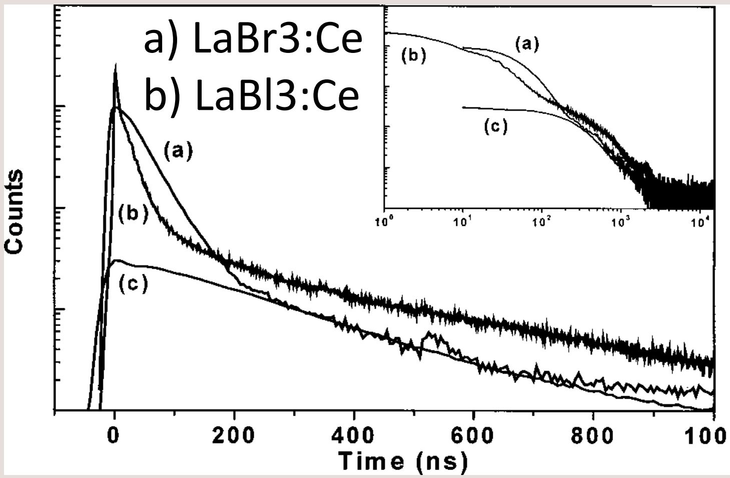


Online Monitoring

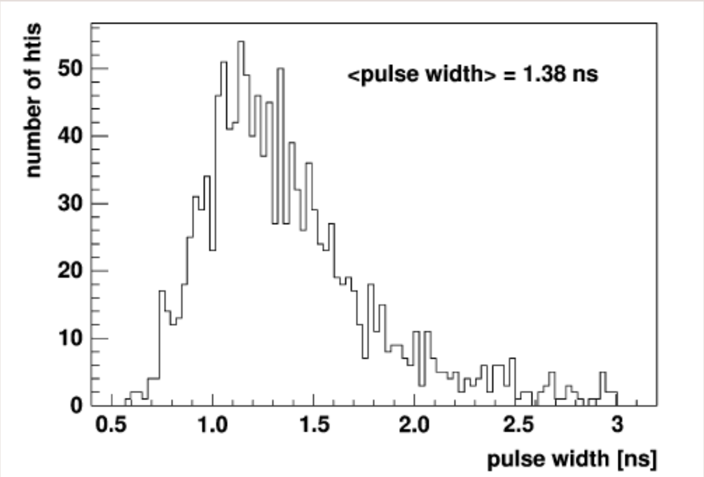
Diamond sensors

ELI-NP-GBS temporal structure:
32 pulses / 16 ns bunch separation @ 100 Hz repetition rate

Solution with scintillating material not convenient
➔Slow component polution
➔Difficult to insert in ELI-NP-GBS accelerator:
- (relatively) large volume occupied by the calorimeter
- high-vacuum implementation



Van Loef et. Al, Appl. Phys. Let. 10 (2001)



Kölbl et al., IEEE Trans. Nucl. Science 6 (2004)

A compact (easy to integrate), fast (few ns pulse width), radiation hard sensor is needed
➔ Diamond sensors
- O(1ns) pulse width
- Diamond sensors are naturally radiation hard (much more than scintillating materials)

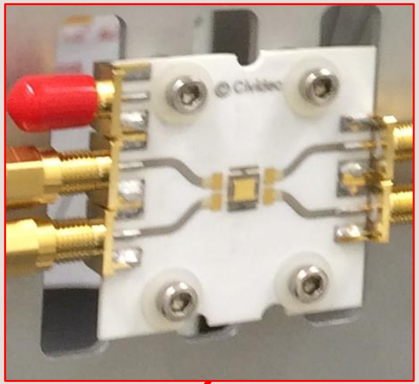
Online Synchronization

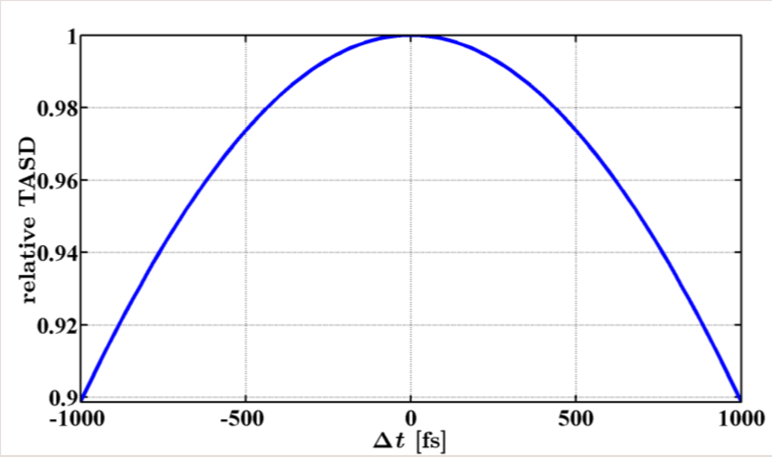
Diamond detector located on the gamma line

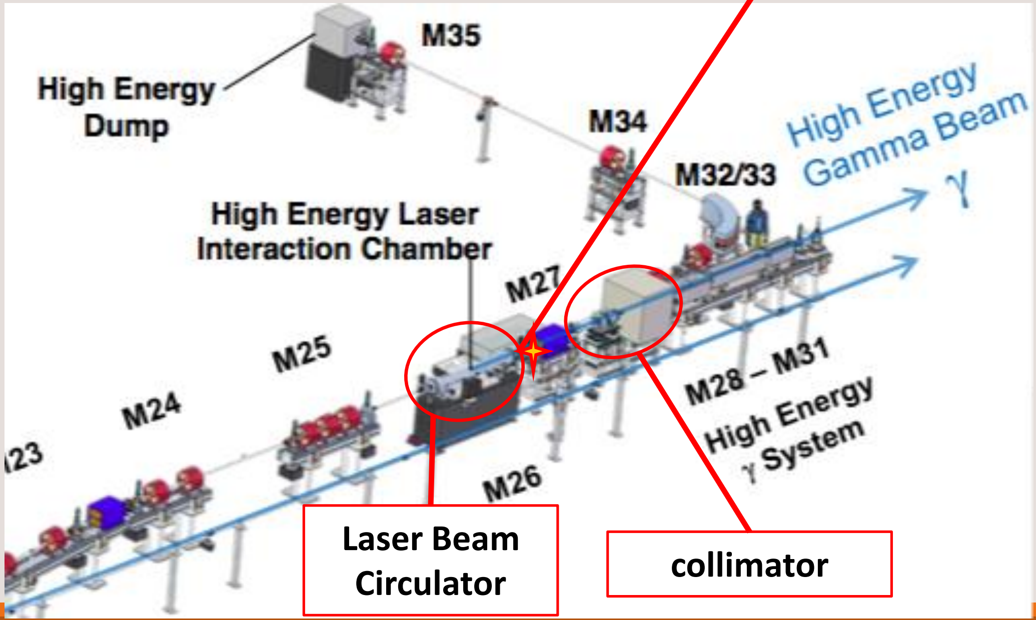
Wave Catcher (CAEN 734 digitizer)

- Plug-and-play DAQ
- High sensitivity
- High time resolutions (the 32 passes are distinguishable)

Diamond detector
$5x5mm^2$
+
Preshower
+
DAQ (CAEN 734 digitizer)

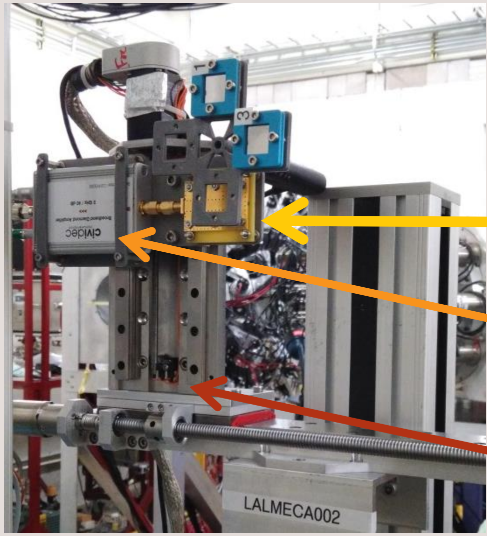






First experiments @ HIGS & newSUBARU

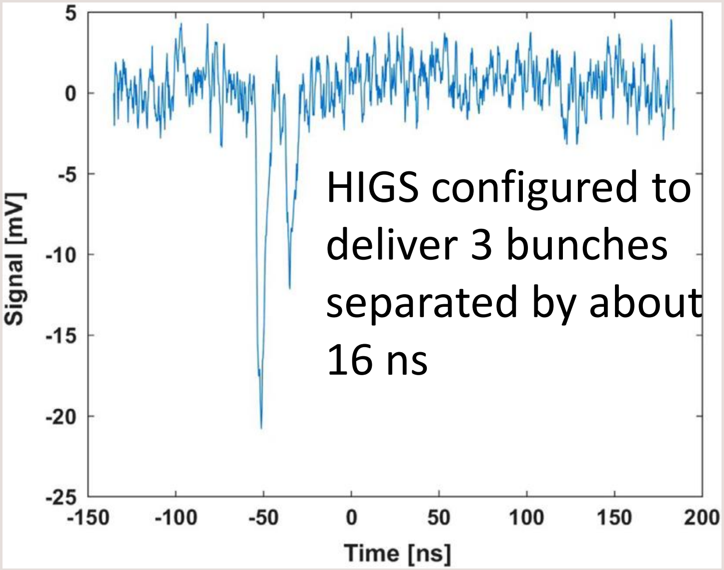
Thanks to HIGS/TUNL colleagues
and CIVIDEC Instrumentation (sensor provider)



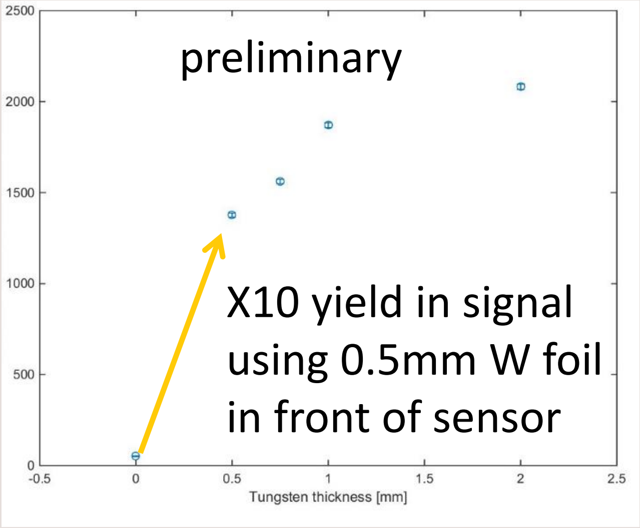
Diamond sensor

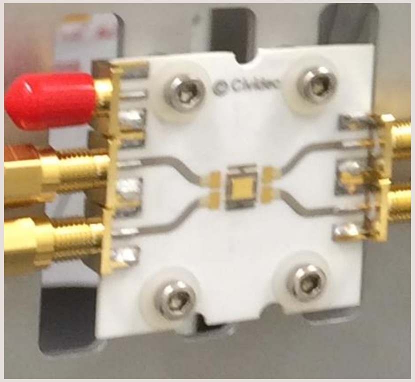
Amplifier (fast, GHz BW)

Translation stages
(positioning/scans)



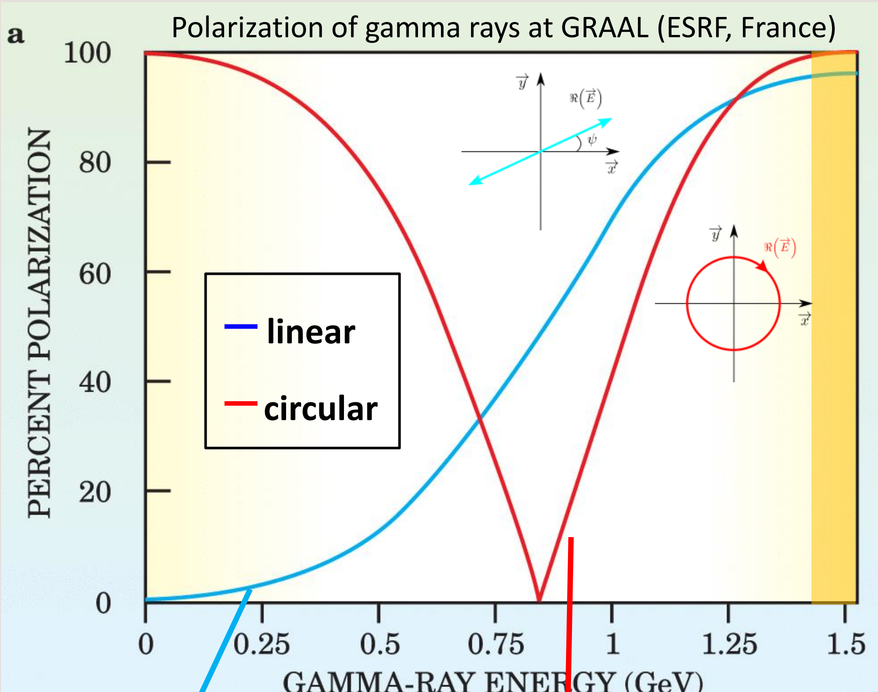
Williams et al., NIMA 830 (2016) 391



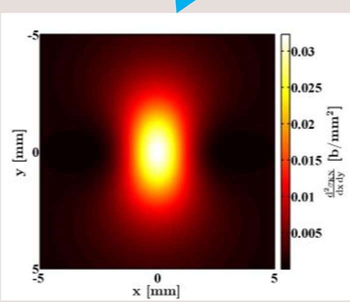


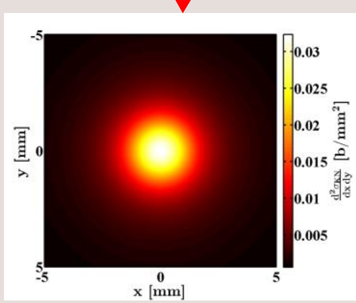
4 quadrant sensor
($1.5x1.5mm^2$ each)

Gamma-beam imaging



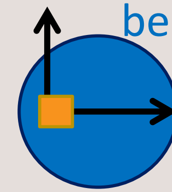
Carlo Schaerf, Physics Today 58(8), 44 (2005)

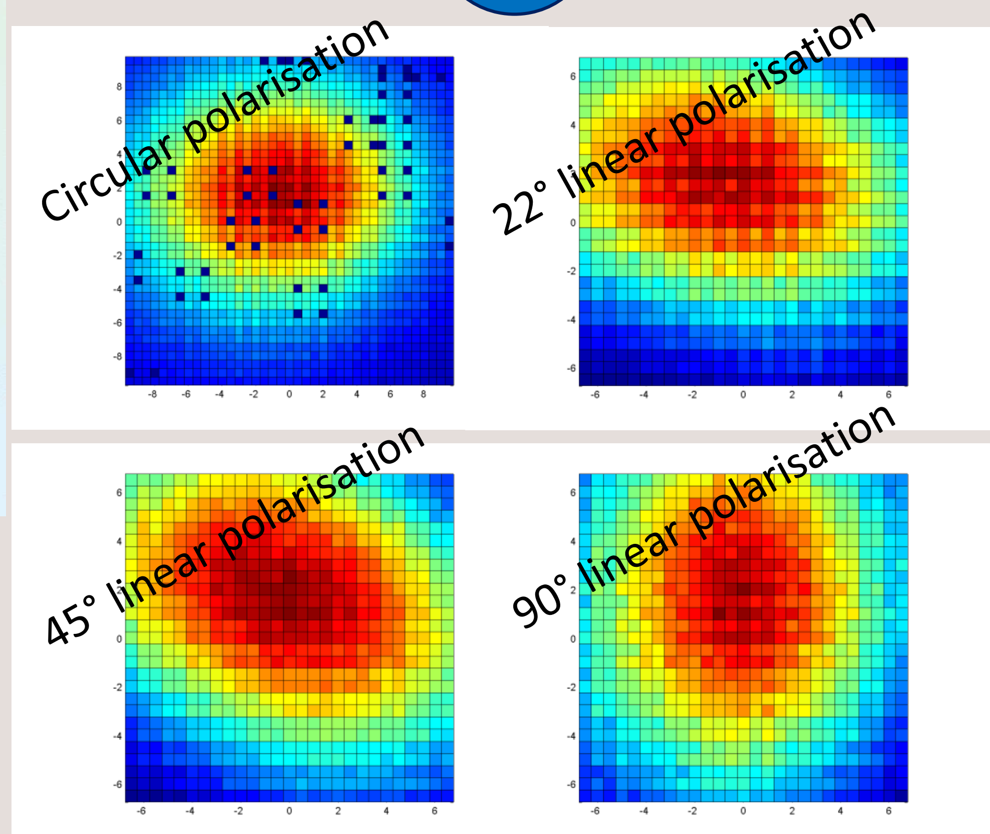




Scanning diamond

beam





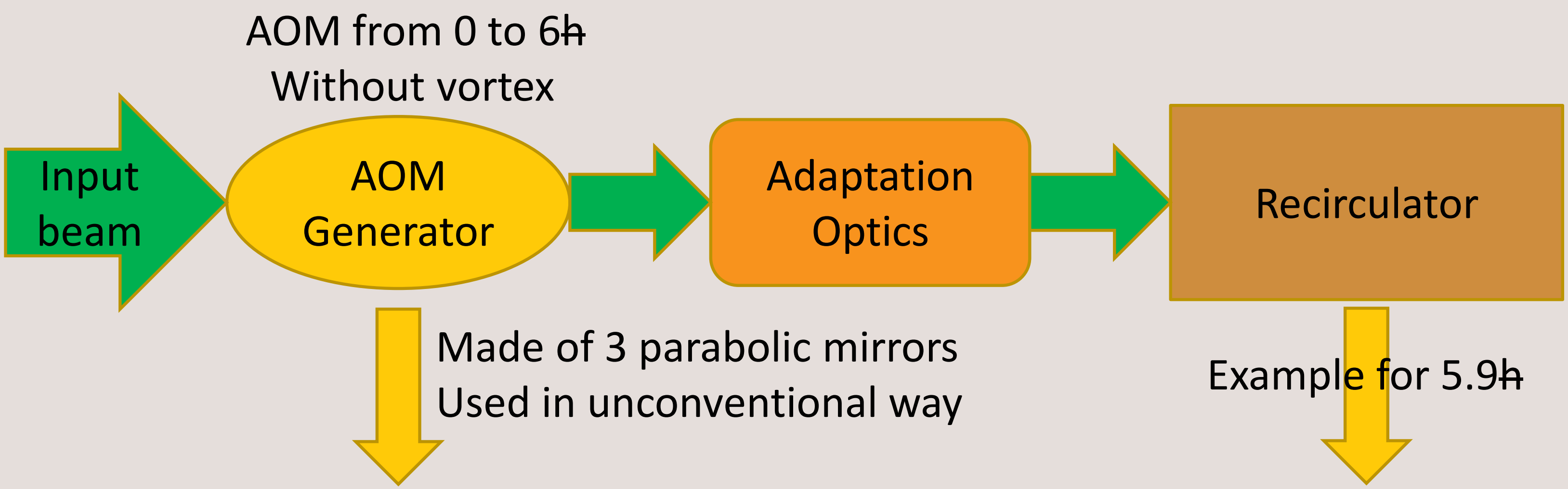
Gamma ray beam profile distribution ➔ Gamma ray beam polarisation

(for 100% polarized beam)

Prototype and Upgrade

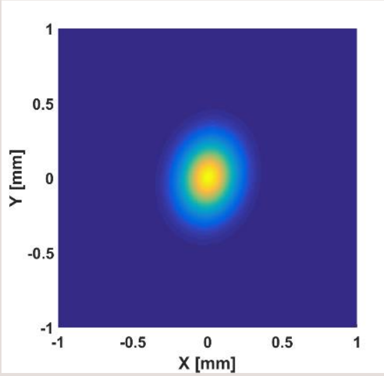
Prototype design

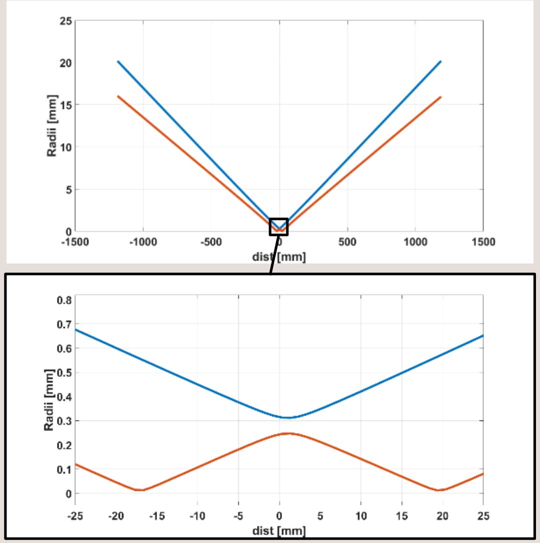
Possible upgrade:
Angular Orbital Momentum



parameters	Parab. 1	Parab. 2	Parab. 3
ROC [mm]	500	2185.95	108.09
phi angle [deg]	109.31	-154.56	-0.52
incident angle [deg]	11.31	70.83	0.38
plan angle switching [deg]	-	0.06	0.13
Propagation distance [mm]	50	50	50.04

Off-axis = 100 mm





➔ AOM is preserved inside recirculator
➔ Down to 15% of TASD @6ħ

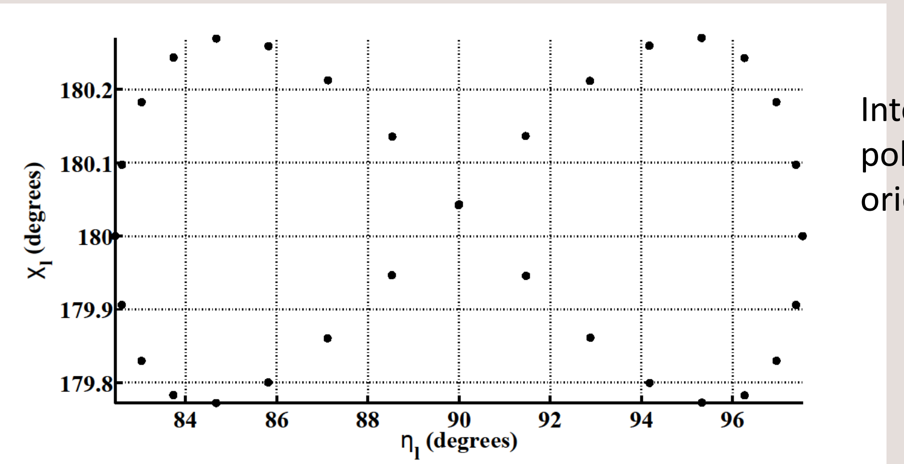
Summary

- Highly challenging machine to produced:
  - TASD: 5000 γ/(s.eV)
  - Bandwidth: < 0.5%
  - Degree of Polarization: > 95%
  - Polarization preserved
  - AOM preserved

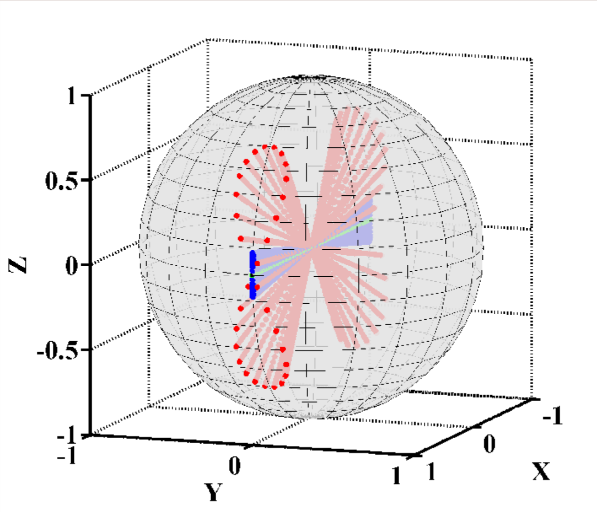
- Online monitoring with diamond detector for:
  - Electrons-Laser beams synchronization
  - Gamma-rays flux
  - Polarization

Thank you for your attention

Polarisation

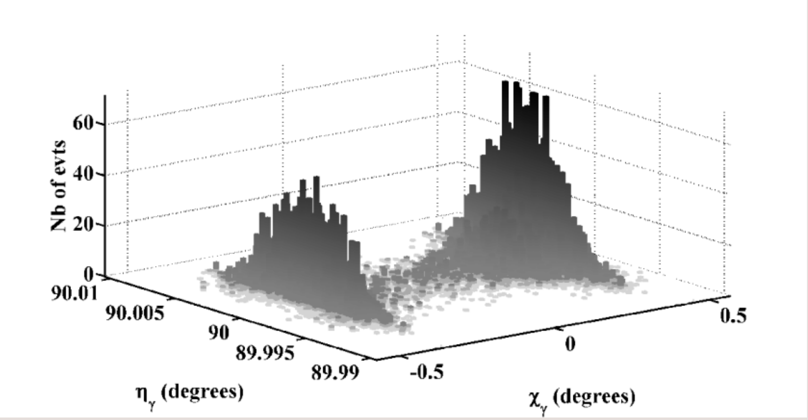


Interaction Point
polarisation
orientation

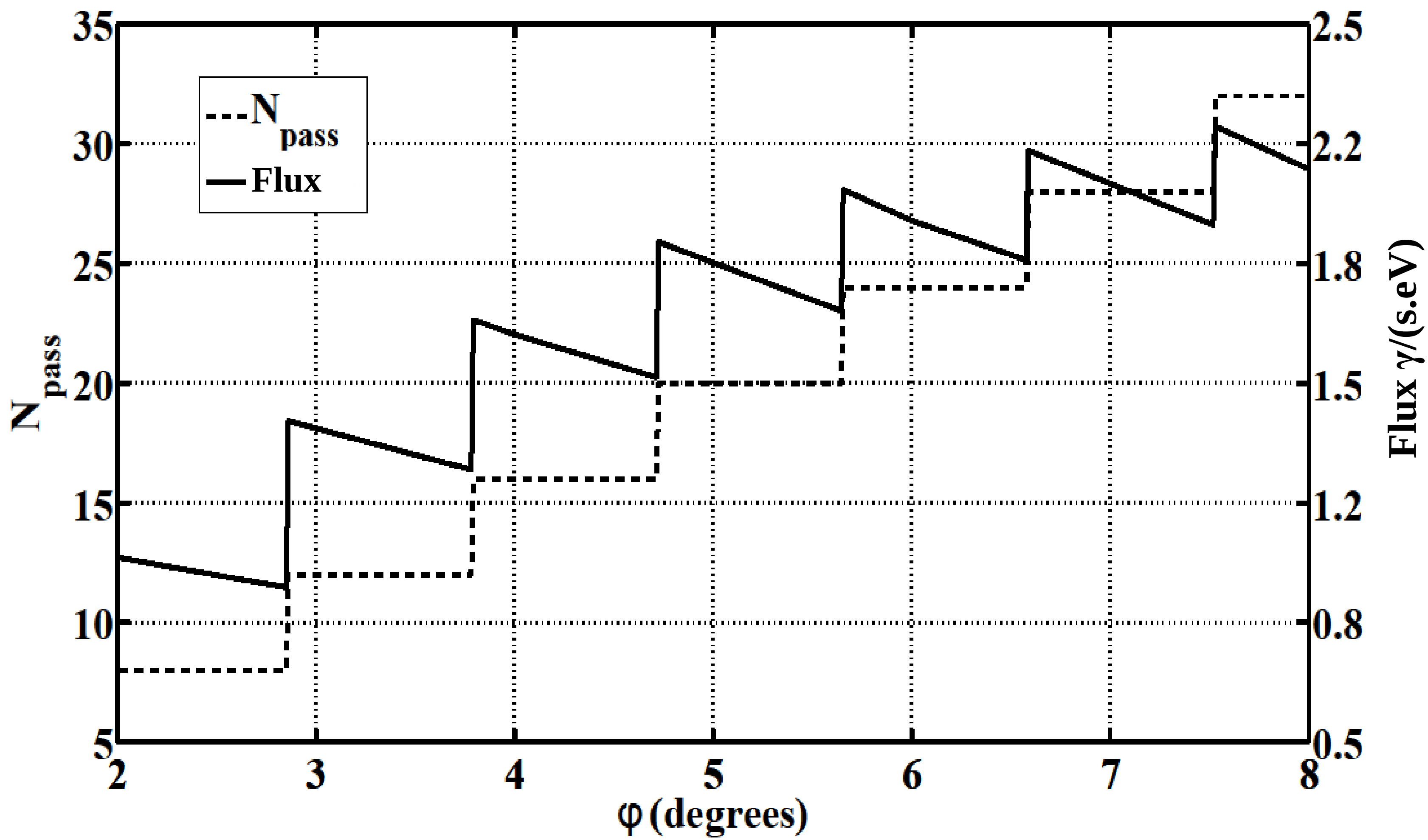


- Simulation with multilayer coatings and coating birefringence

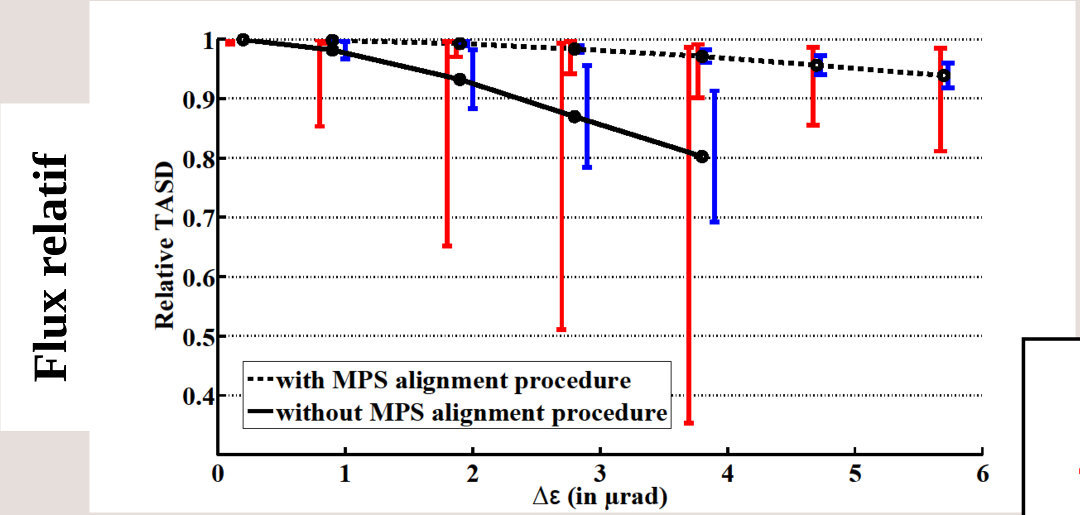
- Polarization preserved during circulation (>99%)
  - Linear
  - Circular

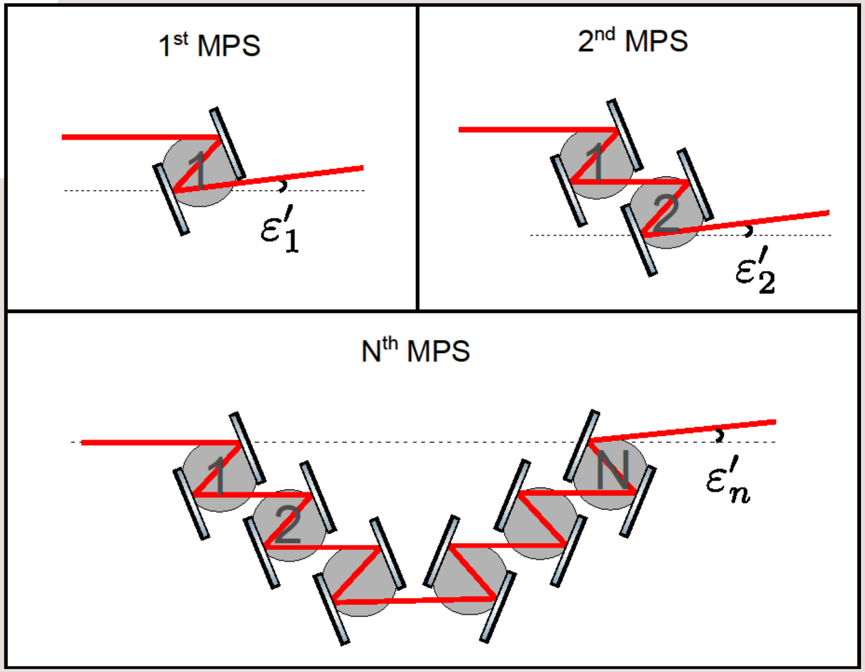


Optimization No. passes

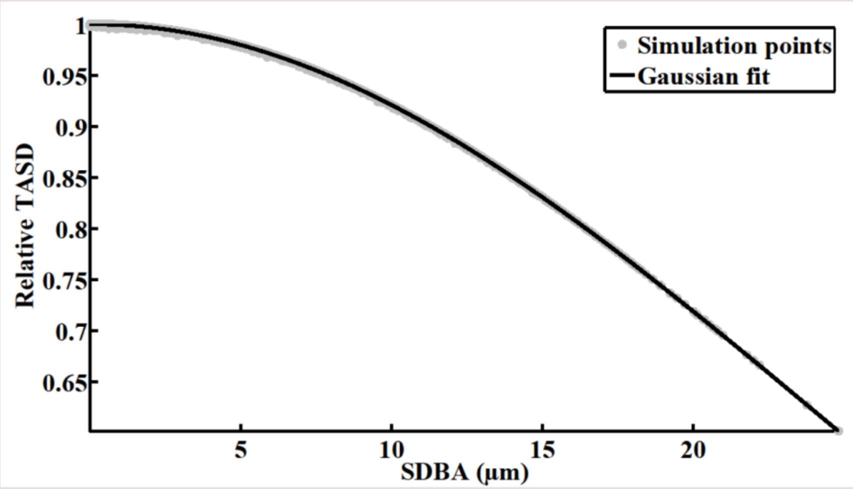


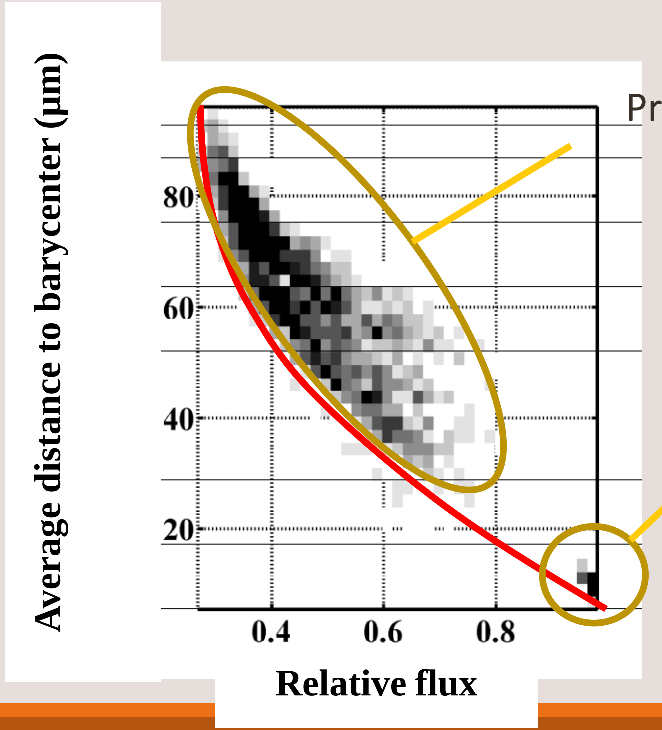
MPS parallelism





Alignment





Alignment algorithm

Time Average Spectral Density (TASD)

$$TASD \approx \frac{\langle flux \rangle}{bandwidth} = \frac{1}{\sigma_{E_\gamma}} \langle \frac{dN^{\sigma_{E_\gamma}}}{dt} \rangle$$

$$E_\gamma \simeq E_L \frac{4\gamma^2}{1+\gamma^2\delta^2+\frac{\phi^2}{4}}$$

Angular acceptance

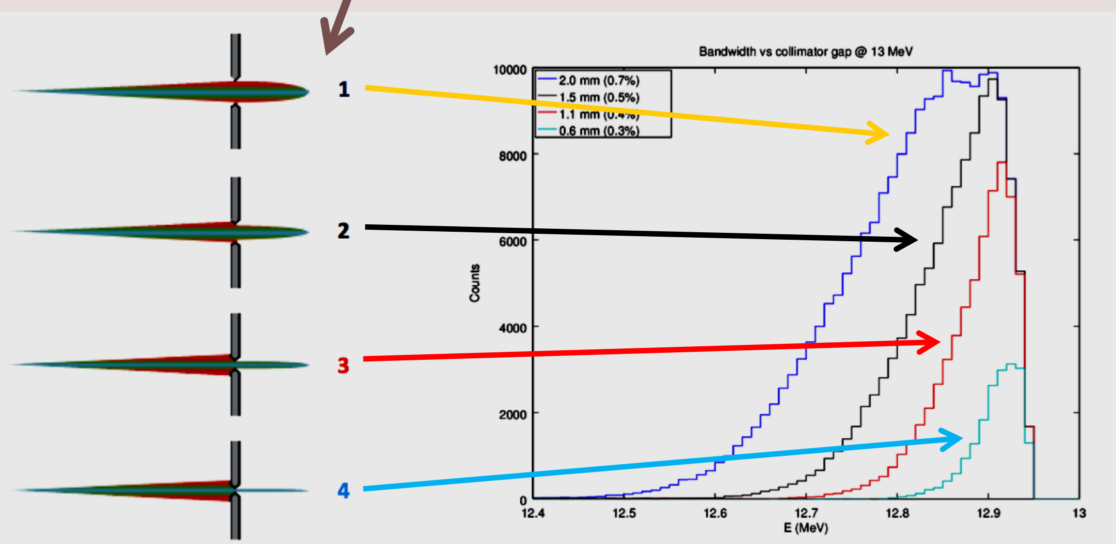
Electron beam parameters

Laser beam parameters

Nonlinear effects

$$\frac{\sigma_{E_\gamma}}{E_\gamma} = \sqrt{\left(\frac{\gamma^2\delta^2_{max}}{2}\right)^2 + \left(2\frac{\Delta\gamma}{\gamma}\right)^2 + \left(2\frac{\epsilon_n^2}{\sigma_e^2}\right)^2 + \left(\frac{\sigma_{E_L}}{E_L}\right)^2 + \left(\frac{M^2\lambda}{2\pi w_0}\right)^4 + \left(\frac{a_{0p}^2/3}{1+a_{0p}^2/2}\right)^2}$$

V. Petrillo et al., NIM A **693** (2012) 109–116



M. Gambiccini, P. Cardarelli et al. technical design meeting collimation and characterisation system review

For good TASD:

- Small crossing angle (ϕ)
- High duty cycle (f_{rep})
- Best spatio-temporal overlap between laser beam and electron bunch

- **Constant crossing angle**
- Small angular acceptance
- **Excellent electron beam quality**
- Excellent laser beam quality

ELI-NP gamma beam source (laser system)

ACCELERATOR CHARACTERISTICS

CONSTRAINED BY ELECTRONS BEAM QUALITY

Train at 100 Hz

Few bunches = ~30 bunches max (photoinjector limit)

250 pC (low charge)

~750 MeV max

LASER REQUIRED FOR COMPTON INTERACTION POINT

Laser average power > 1 kW

green light, 100 Hz

Solution

➔ **recycle laser power of 1 pulse@100Hz** ➔ 40W with Circulator of 32 passes (already State of the Art, cf. Amplitude Systèmes)

➔ **optical system !**

- Resonant cavity = too much R&D risk for 100 Hz
- **Multipass (non resonant)**
  ➔ **Laser beam circulator**

Optimization constraints

Synchronization (<few 100fs) for each pass

➔ Mirror-Pair System (MPS) rotation

Mechanical tolerances

Laser damage threshold (laser beam size)

Vignetting of the beam

Accelerator's Radio frequency

Beam focalization

Mirror shape

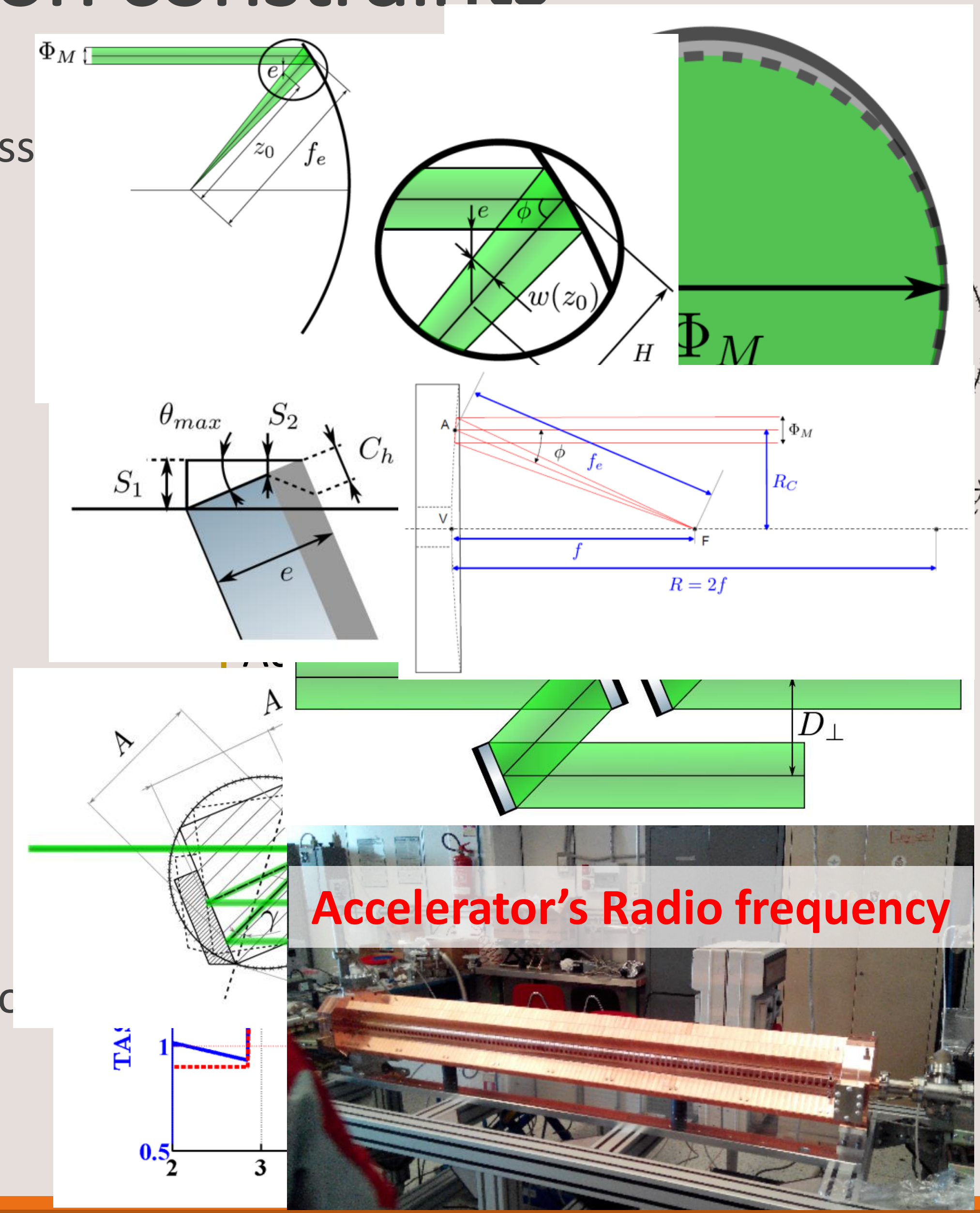
Parabolic mirror parameters

Circulator length (accelerator hall limit)

Maximum number of passes (photoinjecto
limit)

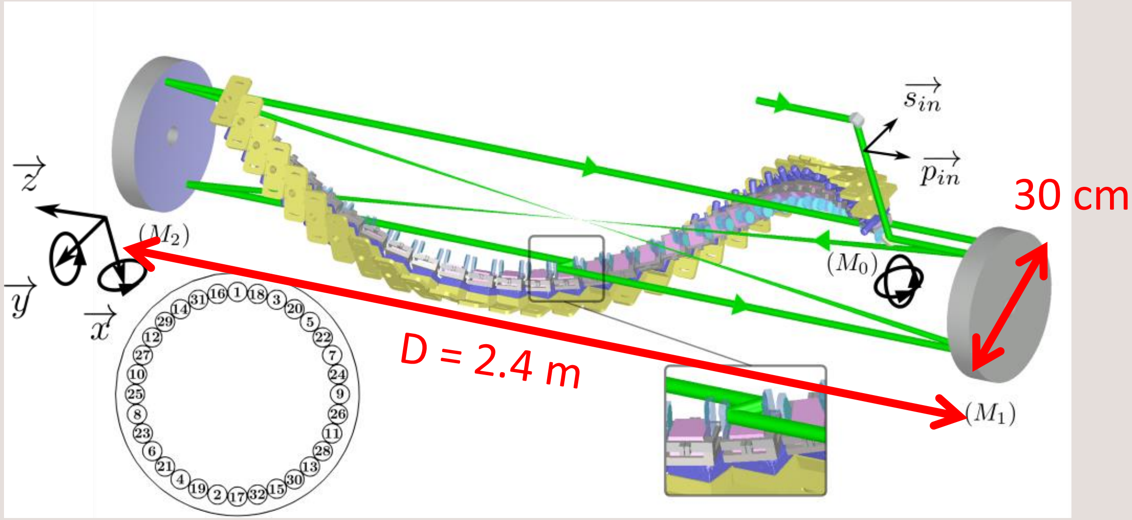
TASD (Time Average Spectral Density)

K. Dupraz et al. Phys. Rev. STAB ***17****, 033501 (2014)*



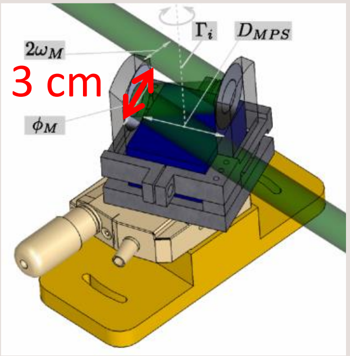
Geometry parameters

Geometry

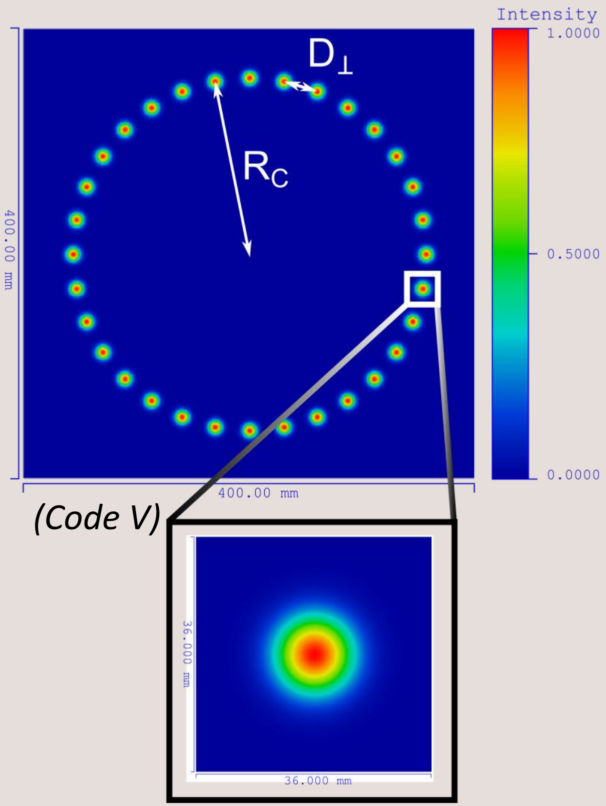


Parameters

Parameters	Value
N_{pass}	32
ϕ	8°
D_{MPS}	40.4 mm
θ	23.8°
R_C	166.2 mm
$D_\perp$	32.6 mm
w_0	28.3 µm



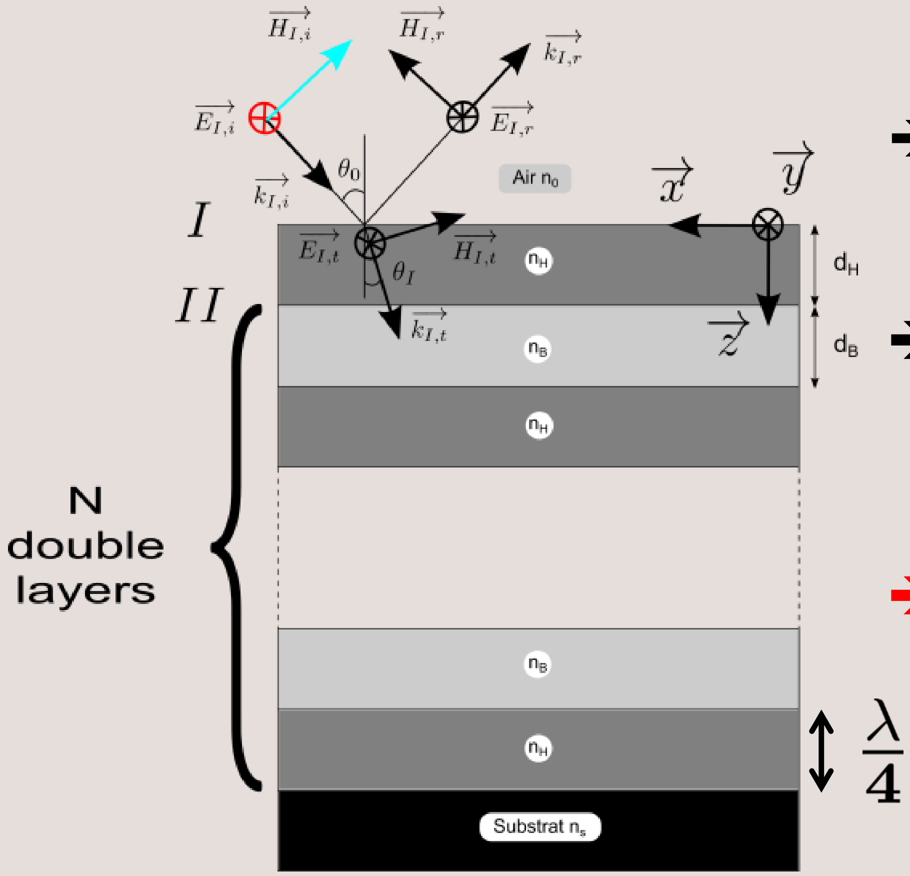
Beam profile



*K. Dupraz et al. Phys. Rev. STAB **17**, 033501 (2014)*

Coatings and Polarization

- Simulation with multilayer coatings (interferential coatings)



➔Constraint on reflectivity for S-wave and P-wave

➔**Laser beam polarization preserved at the IP despite misalignments (>98%)**

- Linear
- Circular

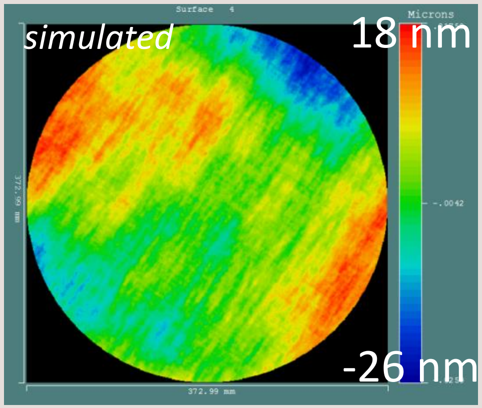
➔ **Laser beam polarization preserved for gamma-ray (checked with CAIN software)**

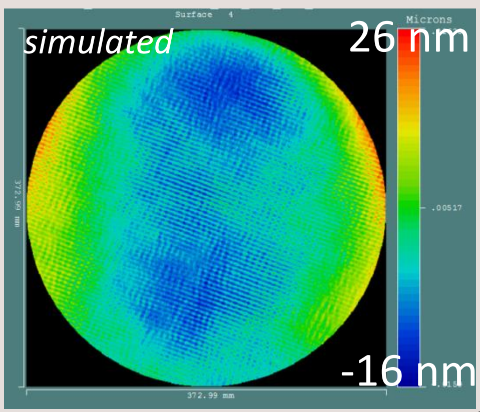
Optical quality and beam profile

TASD = Time Average Spectral Density
MPS = Mirror-Pair System

SURFACE DEFORMATIONS

IP BEAM PROFILE

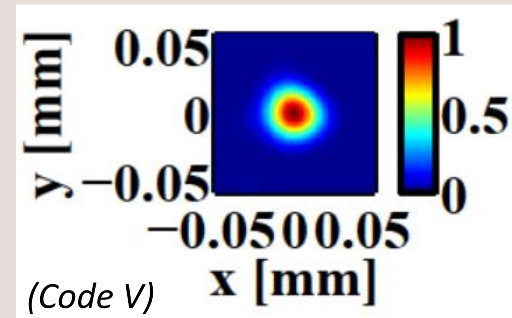




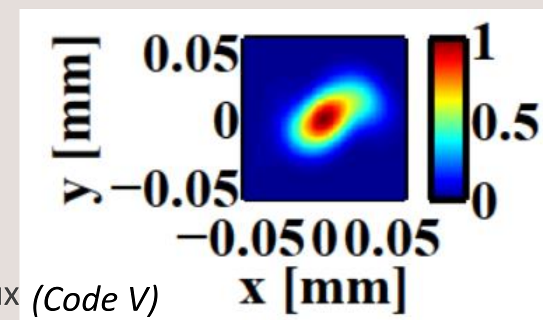
Surface deformations ➔ beam profile
➔ gamma-ray flux (TASD)

Equivalent polishing grade

Good



Bad



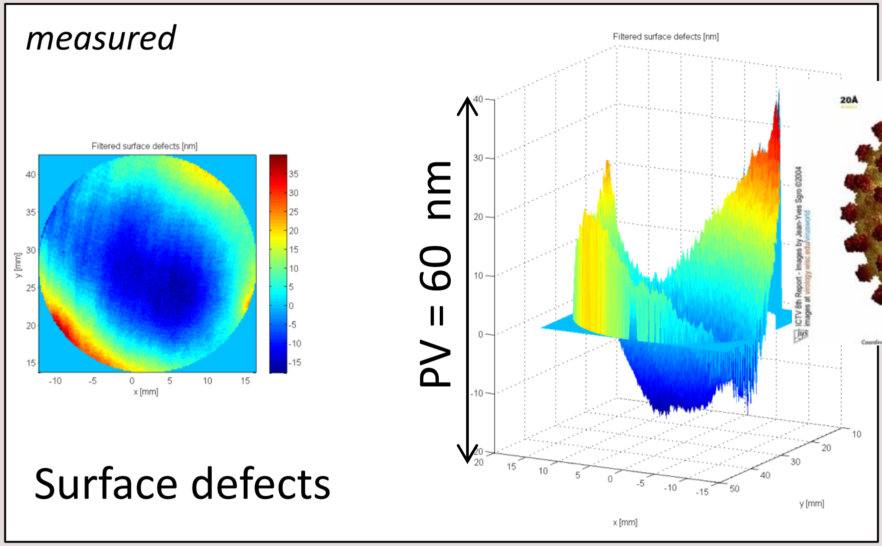
Difficult to relate surface quality to gamma-ray flux

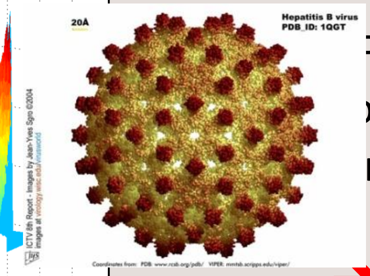
TASD is nonlinear with respect to the pass number
➔ the 32 passes have to be simulated

➔ Parabolic mirrors deformations < λ/80 RMS

➔ MPS mirrors < few nm of residual focus

Surface defects representation





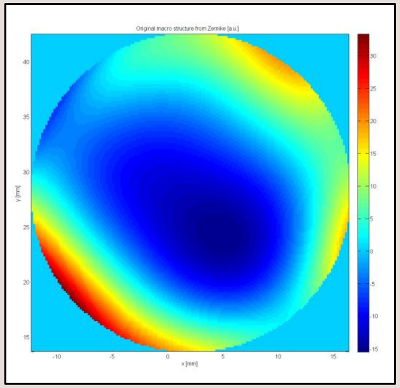
Hepatitis B virus

Polishers have process to ompensate macro + micro ructures

➔ **Surface defects are Polisher dependant**

=

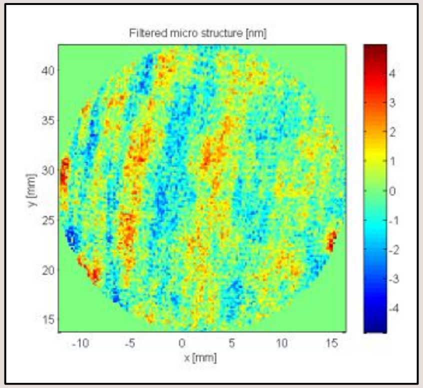
Zernike



Macro-structure

+

PSD



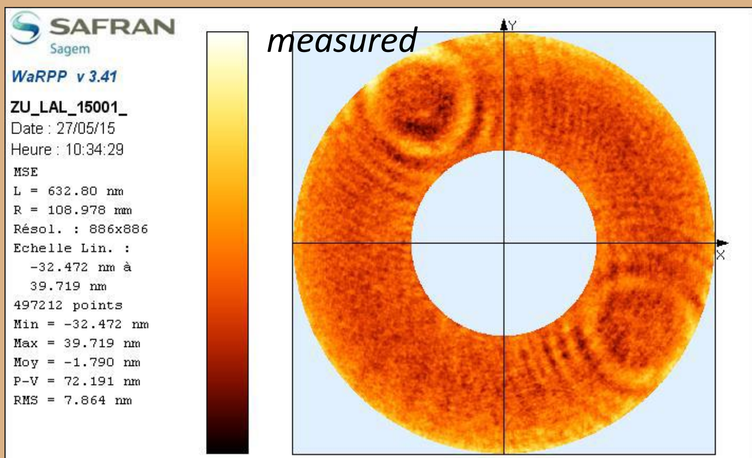
Micro-structure

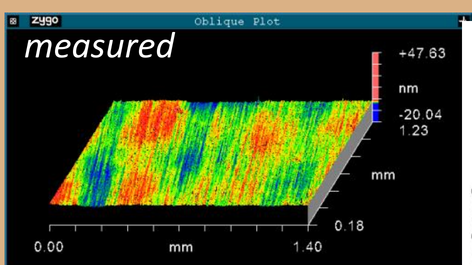
Real mirrors

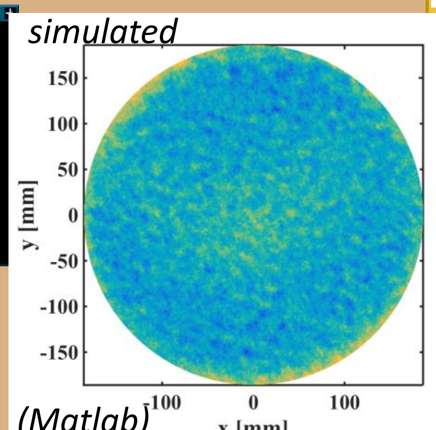
MPS = Mirror-Pair System

TASD = Time Average Spectral Density

PARABOLIC MIRRORS (REOSC-SAGEM)

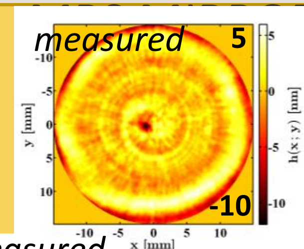


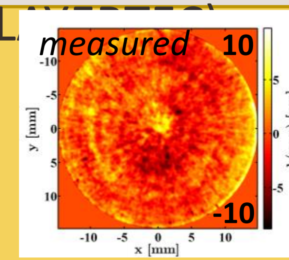


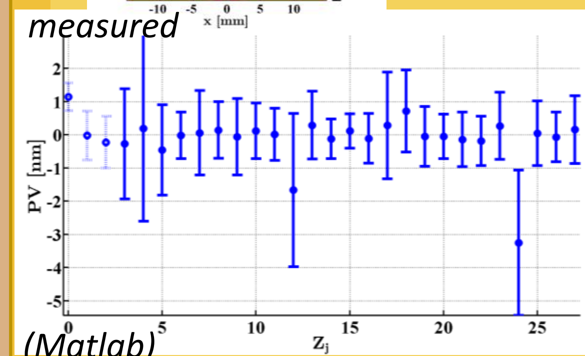


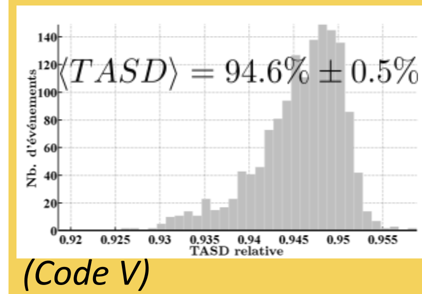
S (ELDIM, L

ELDIM

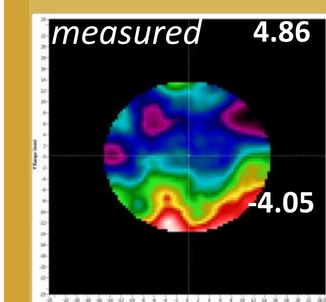


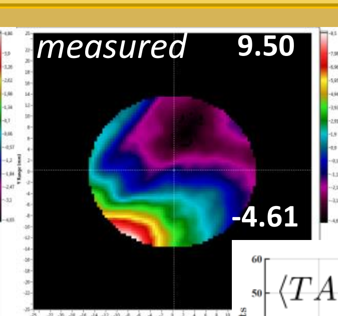


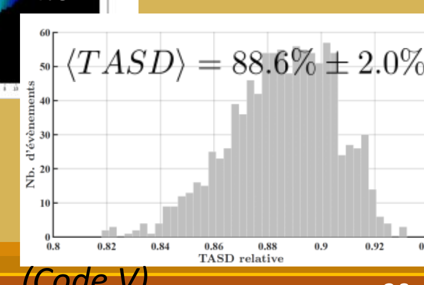




Layertec





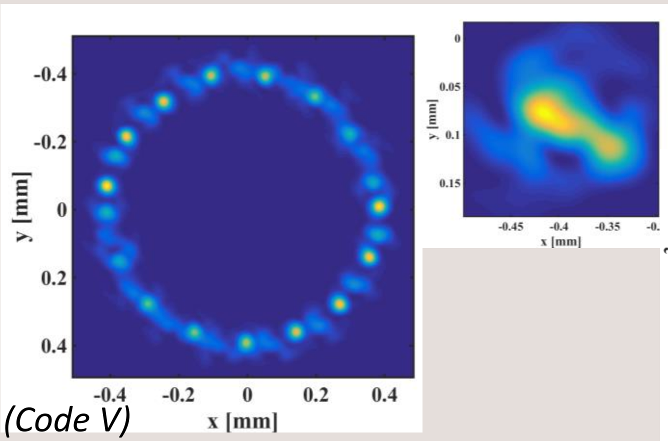


Results with the real mirrors

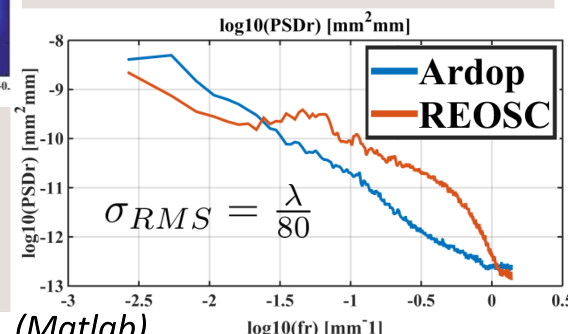
TASD = Time Average Spectral Density

ELDIM (MEASURED) + REOSC (SIMULATED)

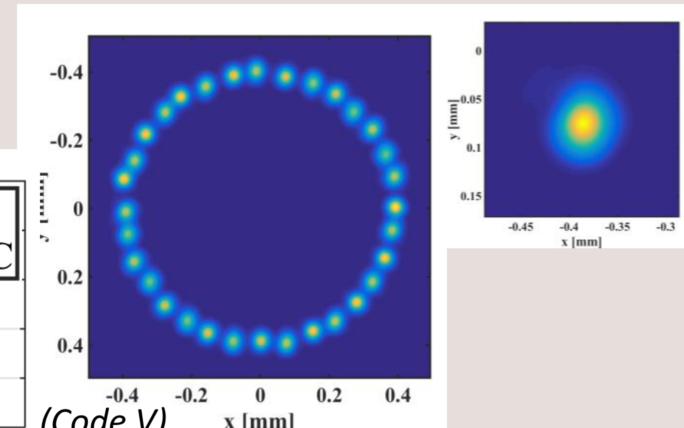
ELDIM (MEASURED) + ARDOP (SIMULATED)



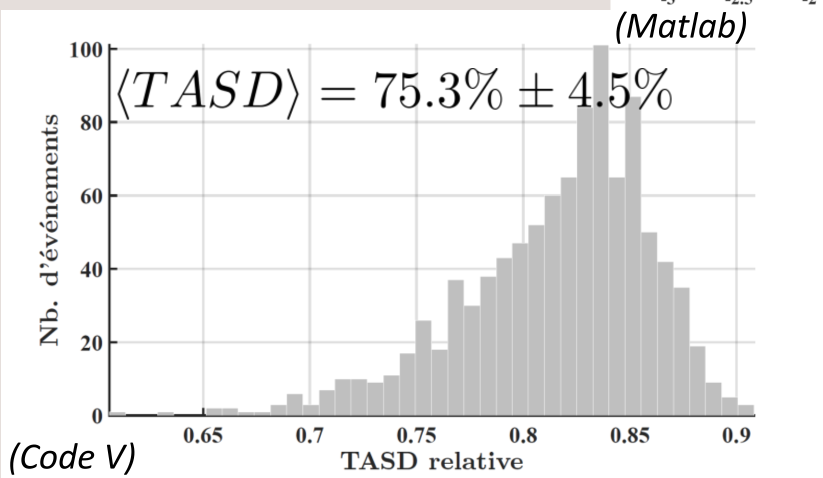
(Code V)



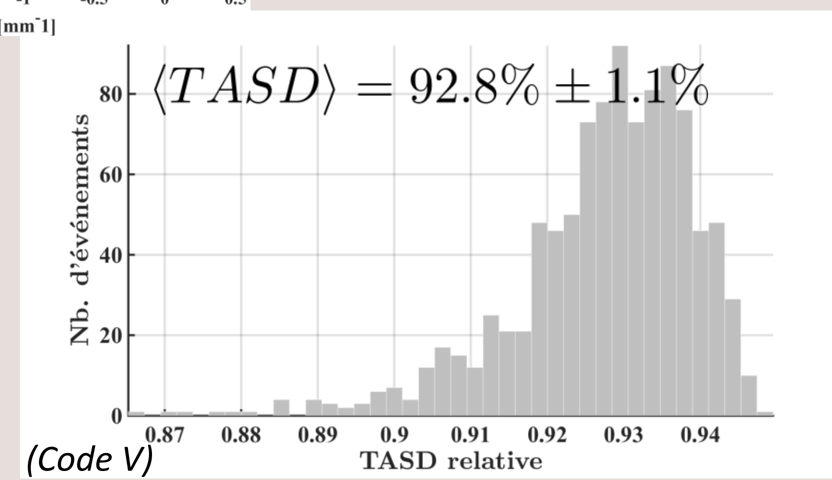
(Matlab)



(Code V)



(Code V)

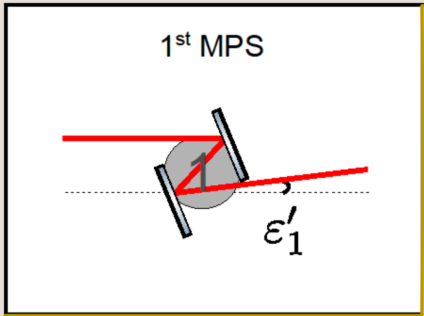


(Code V)

➔ **Parabolic mirrors deformations < λ/80 RMS**

➔ **MPS mirrors < few nm of residual focus**

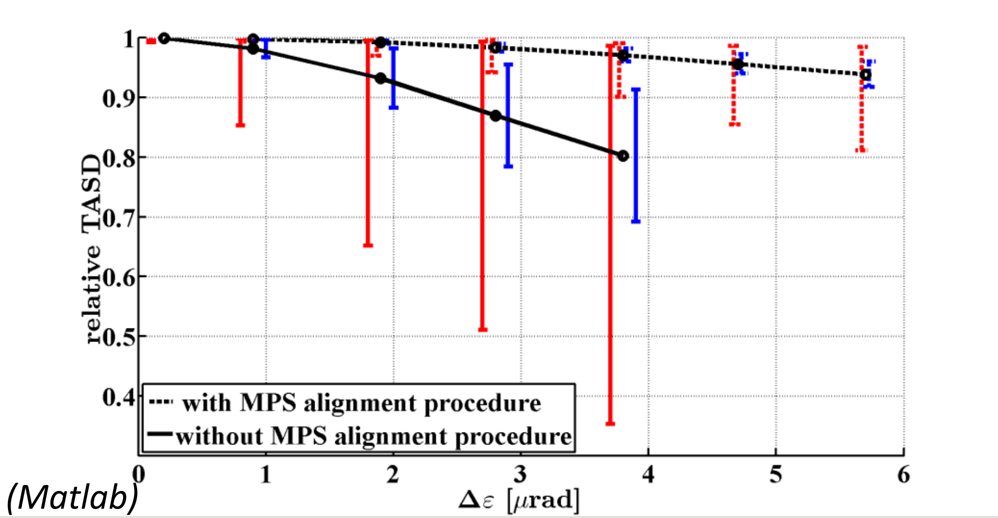
MPS parallelism



$$\Delta\varepsilon' = \sqrt{\sum_{i=1}^{N} (\varepsilon'_i)^2}$$

Big accumulation effect ➔dedicated parallelism alignment procedure:

Each stage beam angular deflection < ε'

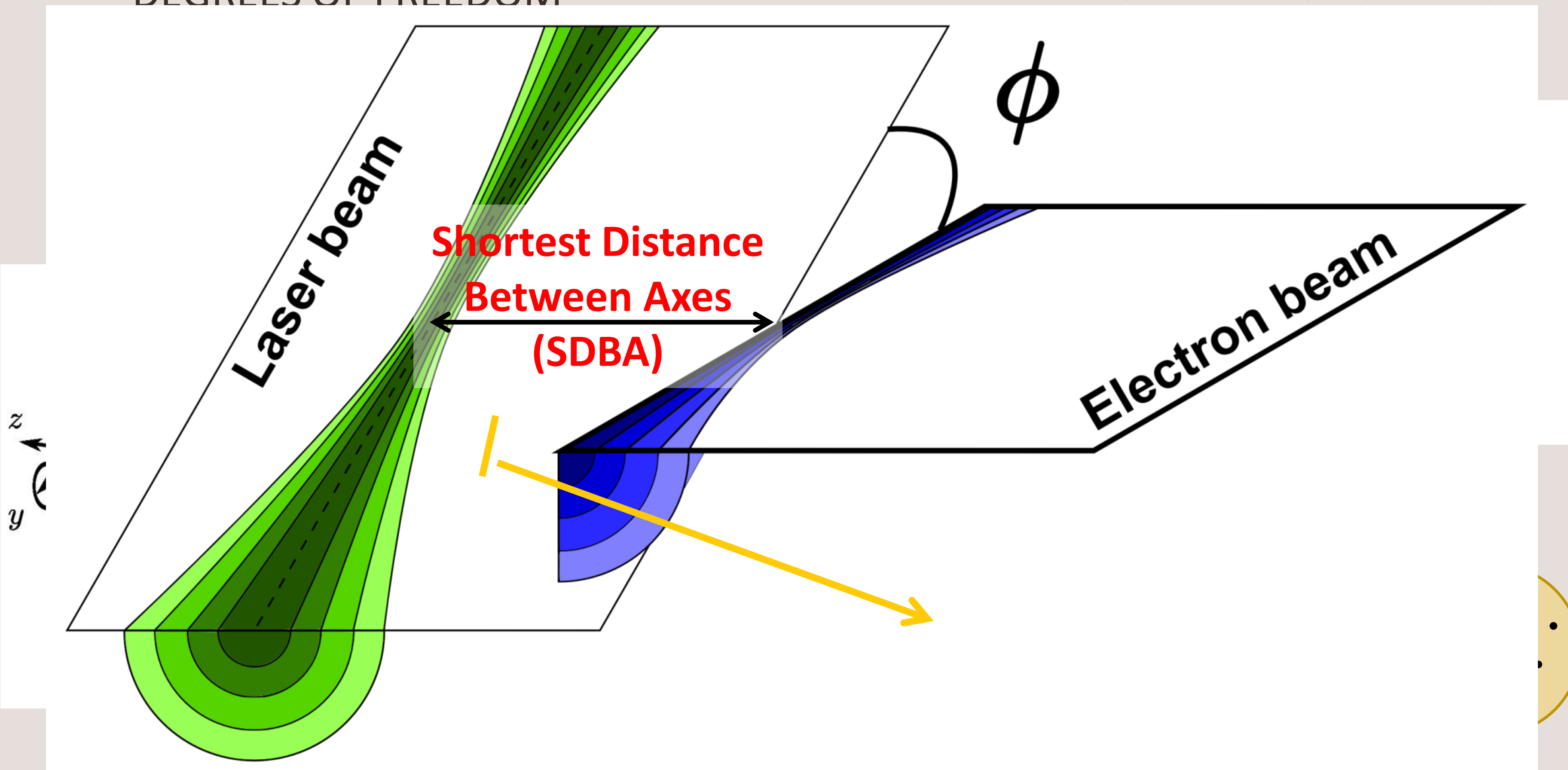


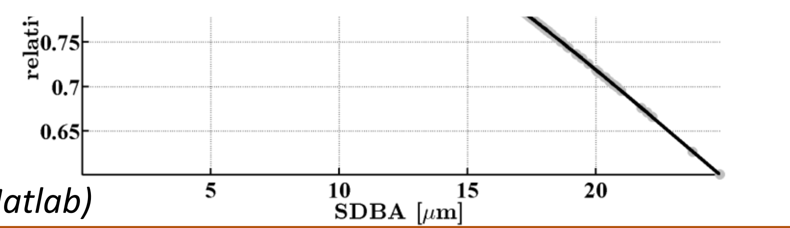
(Matlab)

Alignment

DEGREES OF FREEDOM

ALIGNMENT = OVERLAP OF 32 PASSES





(Matlab)

= misaligned = aligned = well aligned

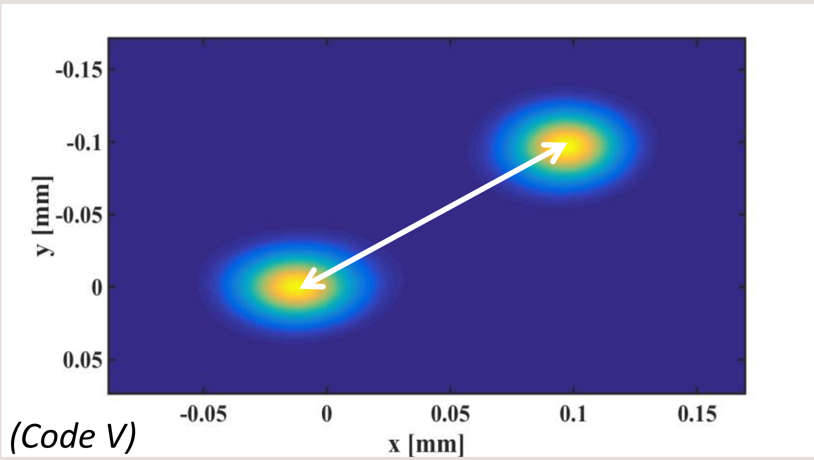
➔**Alignment algorithm**

➔ **Max TASD ~80%**

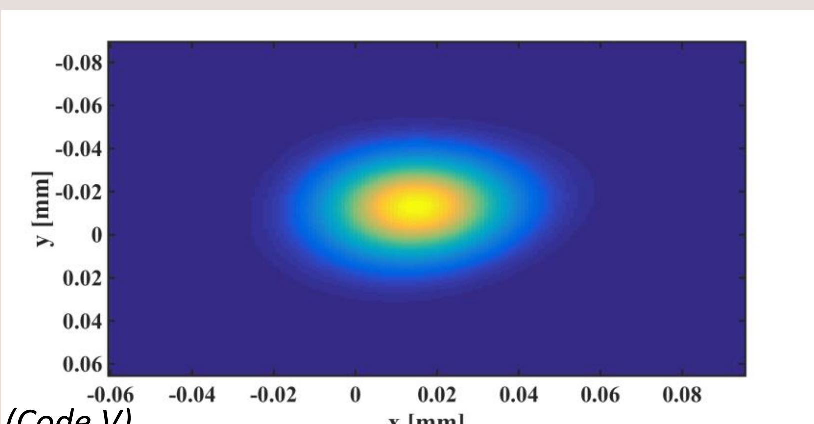
Observables

ON-IP (ELDIM (MEASURED) + ARDOP (SIMULATED))

Superimpose spots together



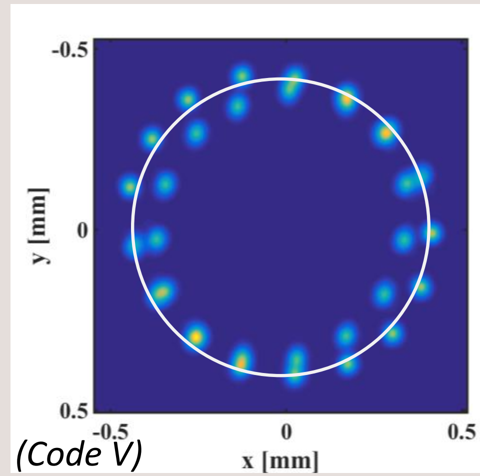
(Code V)



(Code V)

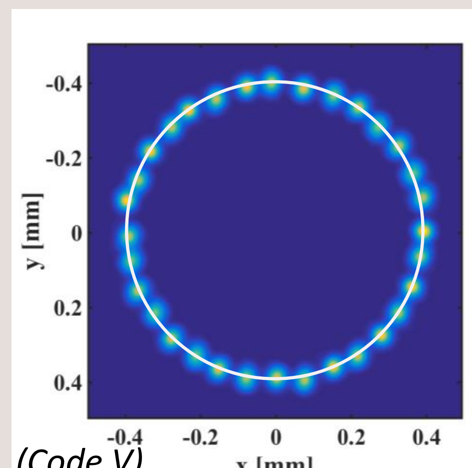
OFF-IP (ELDIM (MEASURED) + ARDOP (SIMULATED))

Superimpose spots on a circle



(Code V)

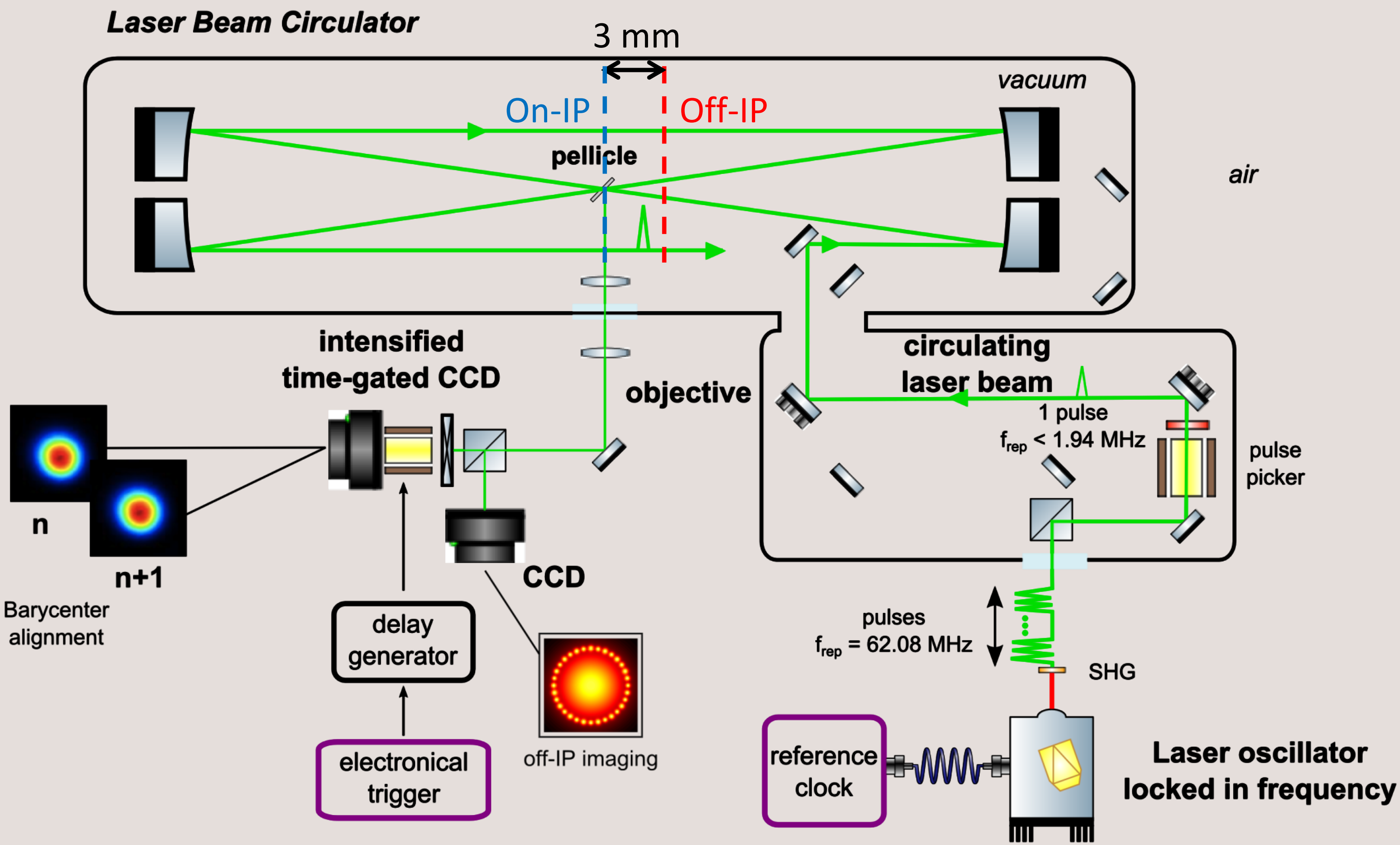
Before alignment



(Code V)

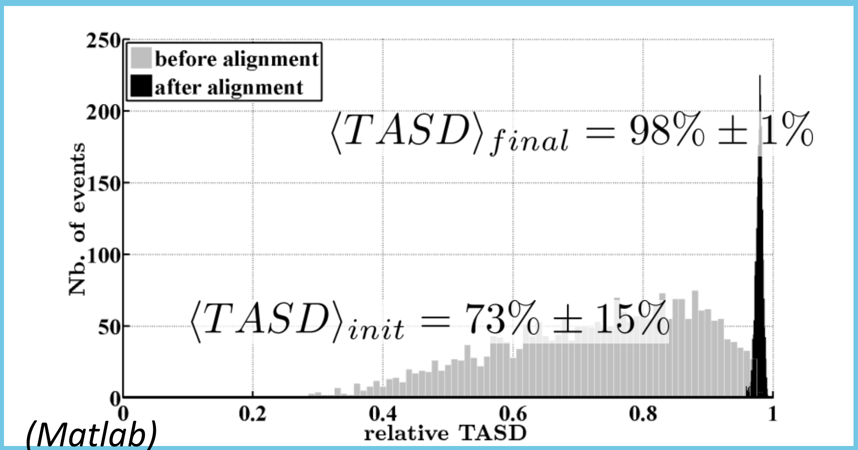
After alignment

Alignment tool

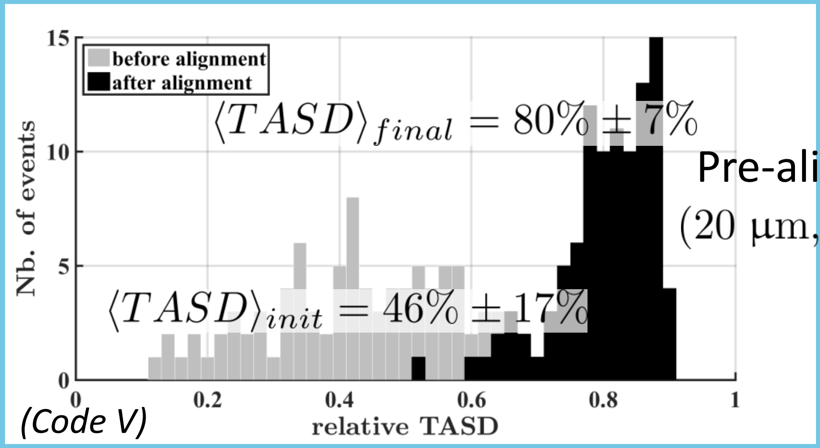


Results

WITHOUT MIRROR SURFACE DEFECTS



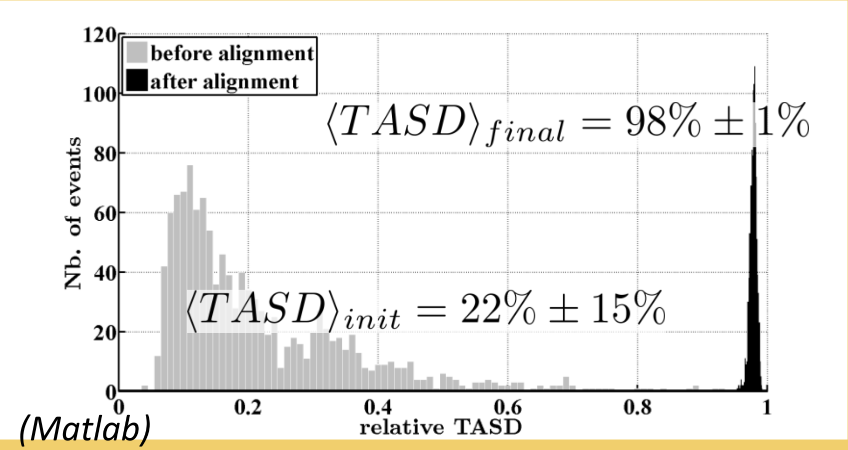
WITH MIRROR SURFACE DEFECTS (ELDIM + ARDOP)



Pre-alignment

$(20\ \mu m, 20\ \mu rad)$

(best)



Pre-alignment

$(100\ \mu m, 100\ \mu rad)$

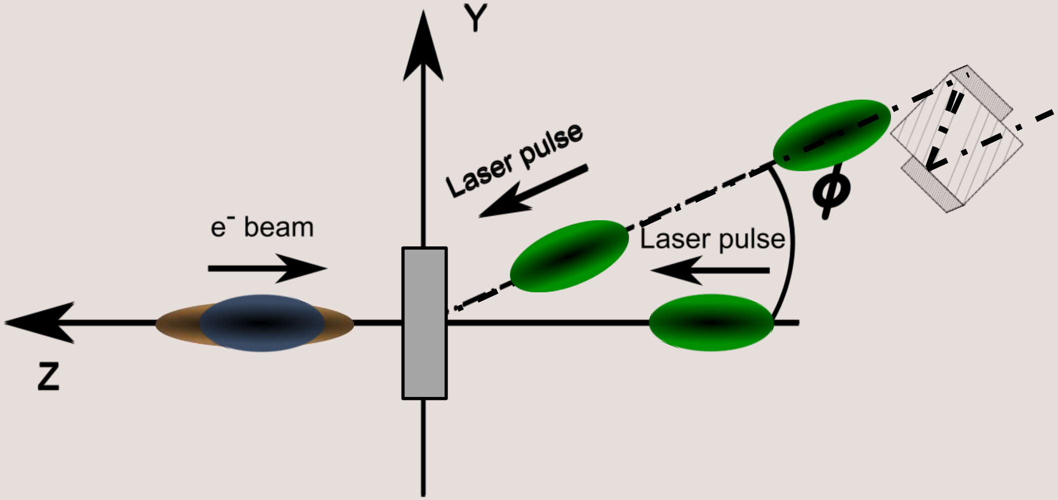
(relaxed)

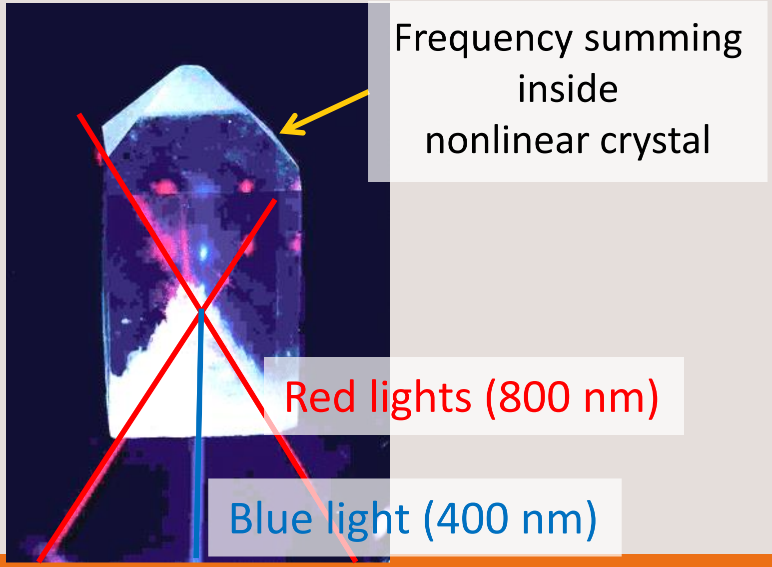
➔In progress

➔algorithm improvements on going

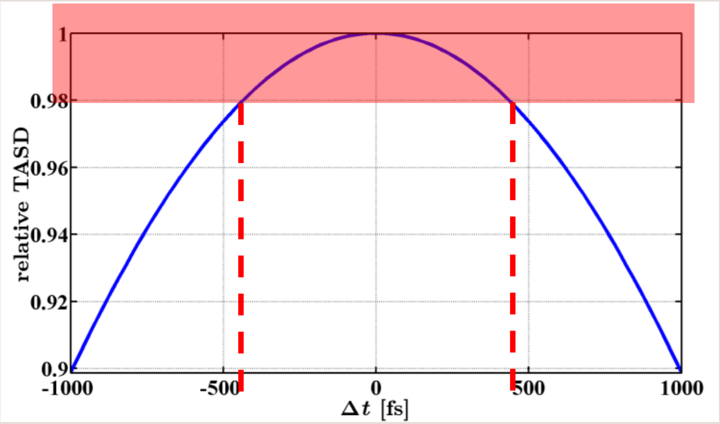
Synchronization

CROSS-CORRELATION (SUM OF FREQUENCIES)

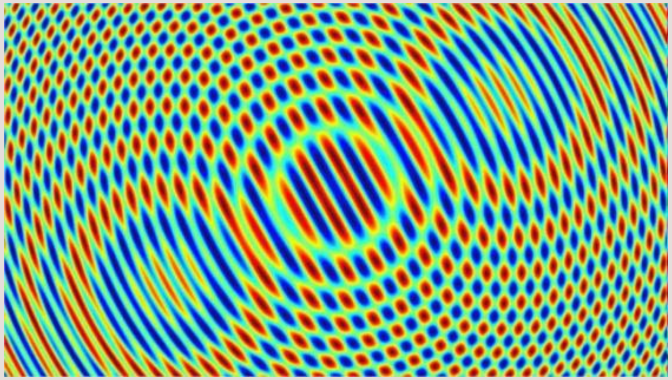




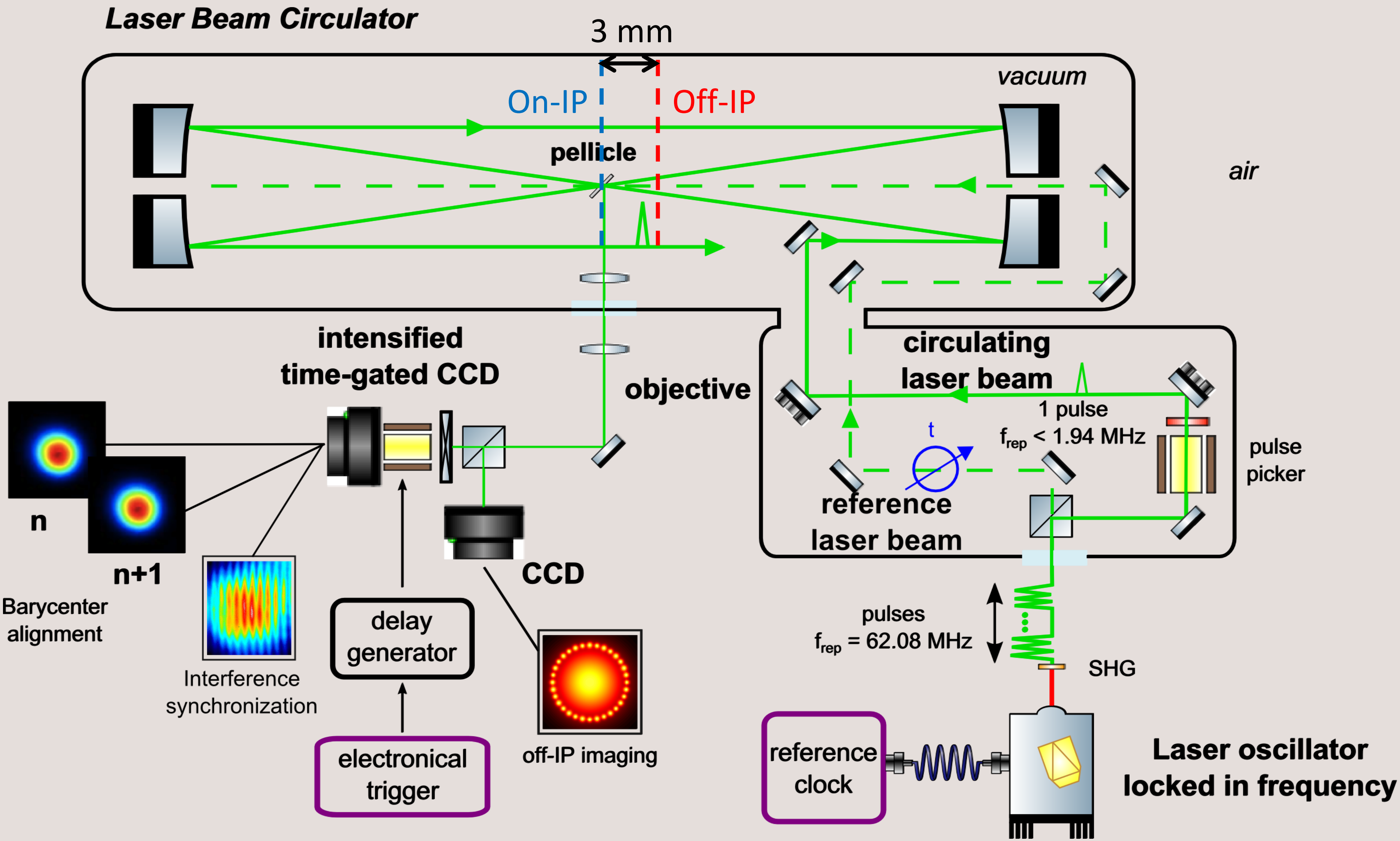
INTERFERENCES



➔Optical synchronisation



Synchronization tool

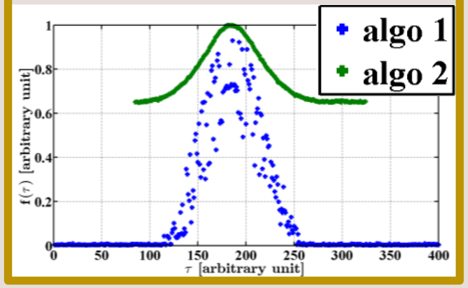


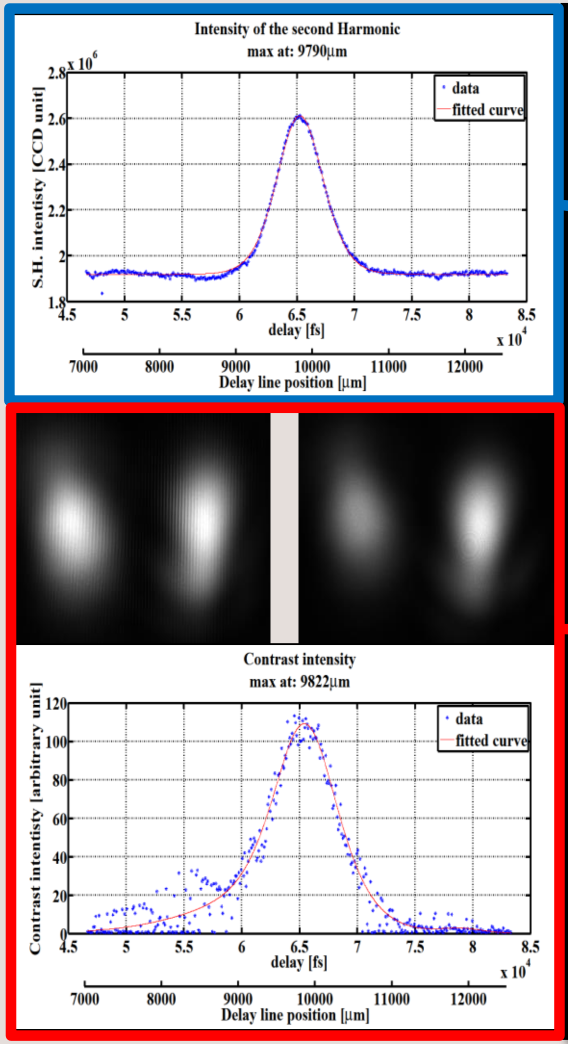
Synchronization (Proof of principle)

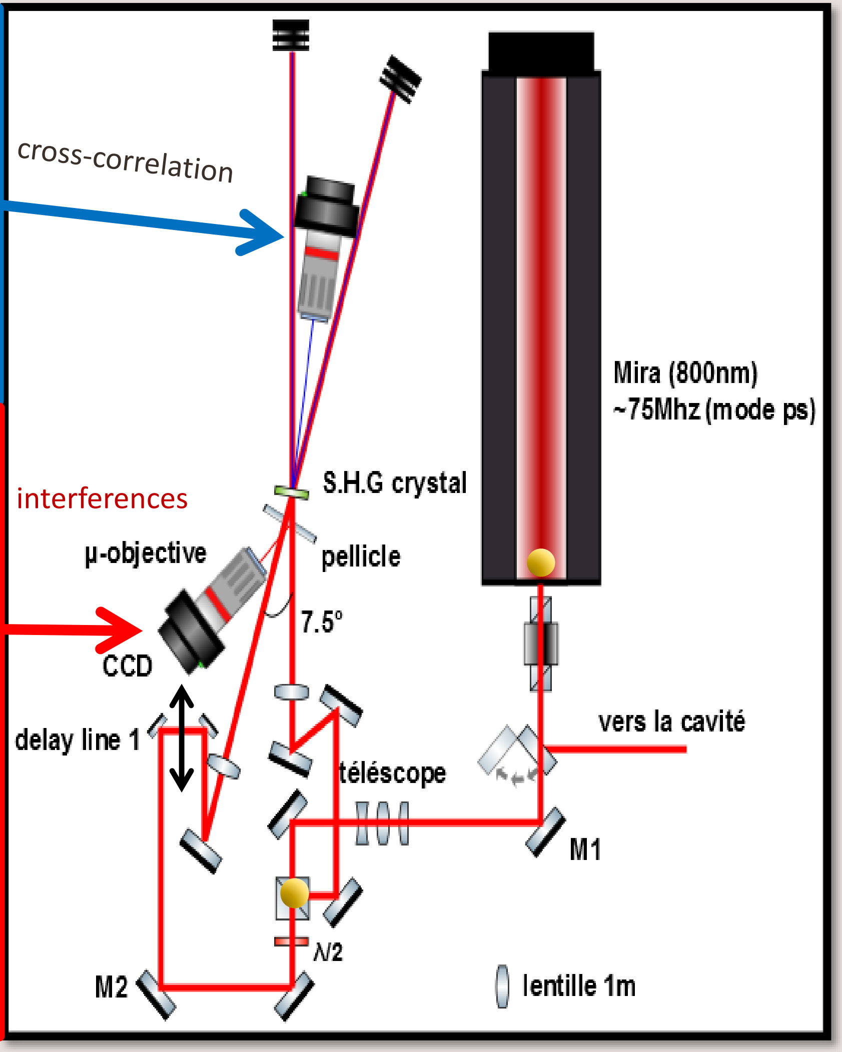
Synchronization
< **500fs**

➔ **Synchronization OK !**
➔ **Could be improved**

Comparison between 2 algorithms

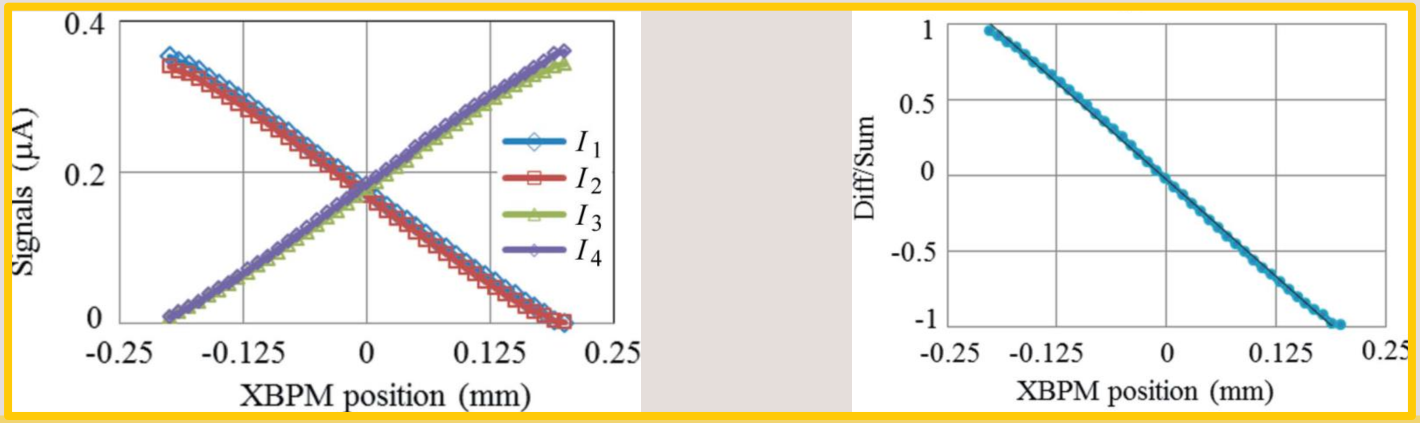






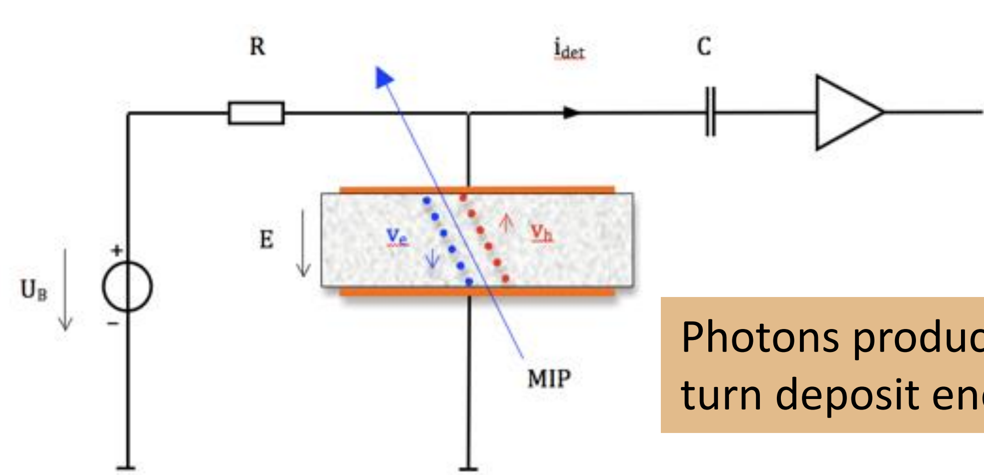
Diamond sensors (ctd.)

Desjardins, J. Synchrotron Rad. (2014). 21, 1217–1223



Diamond sensors have already been used for X-ray beam position monitoring

→ Few µm precision

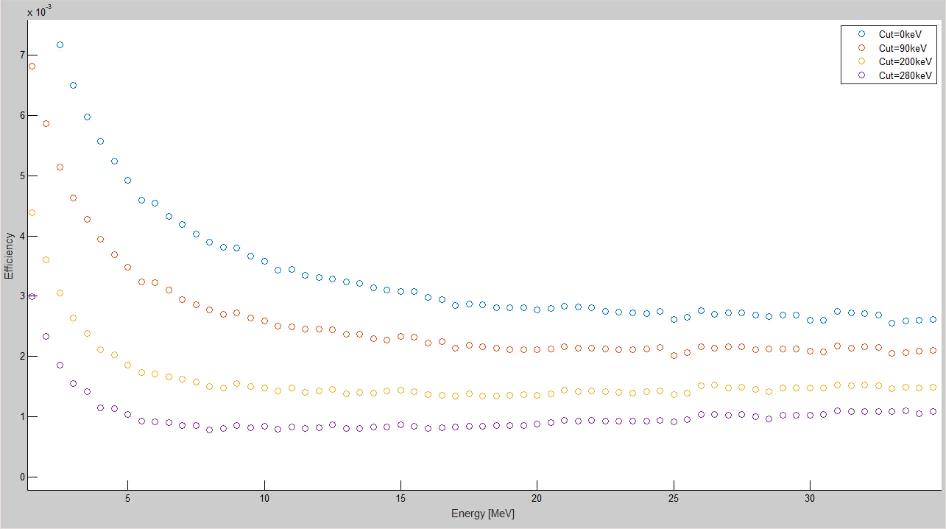


Principle of detection similar to that of semiconductors

Photons produce secondary electrons in diamond that in turn deposit energy

Energy response/Detection efficiency

Simulated (GEANT4) efficiency about few per mille



Slight dependence with energy

Collected charge in 500µm diamond roughly flat with energy