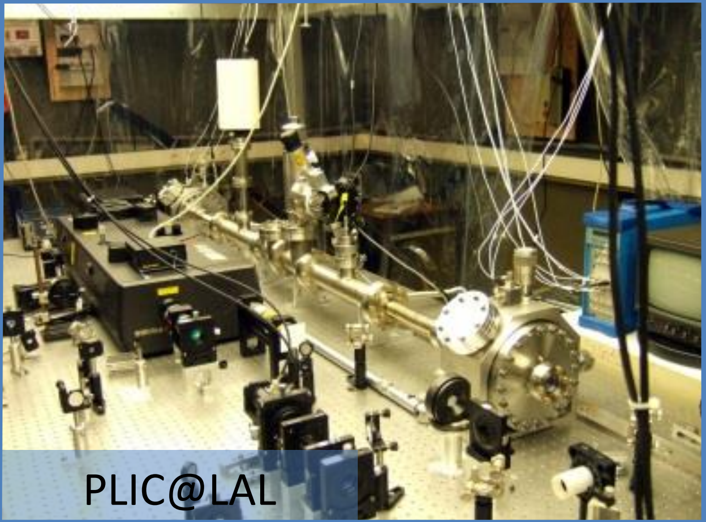
Developments of optical resonators and optical recirculators for Compton X/γ ray machines

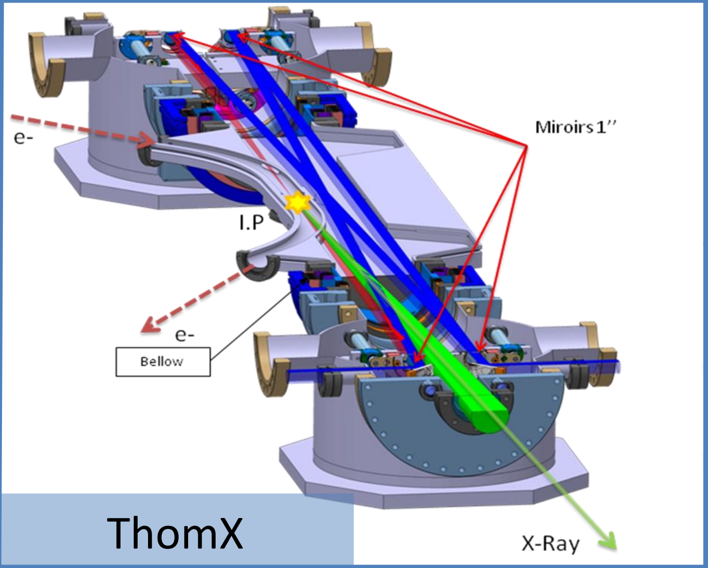
Aurélien MARTENS for MightyLaser, ThomX, ELI-NP-GS

LAL, CELIA, KEK, LMA, INFN, Alsyom, Amplitude

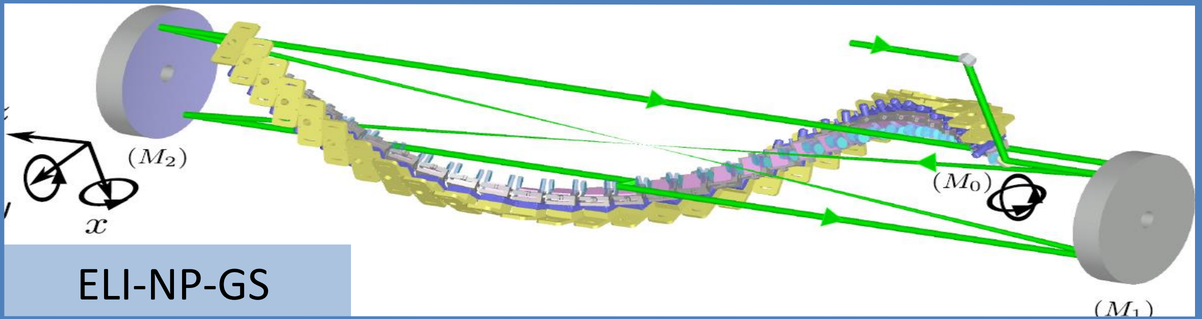


PLIC@LAL

MightyLaser

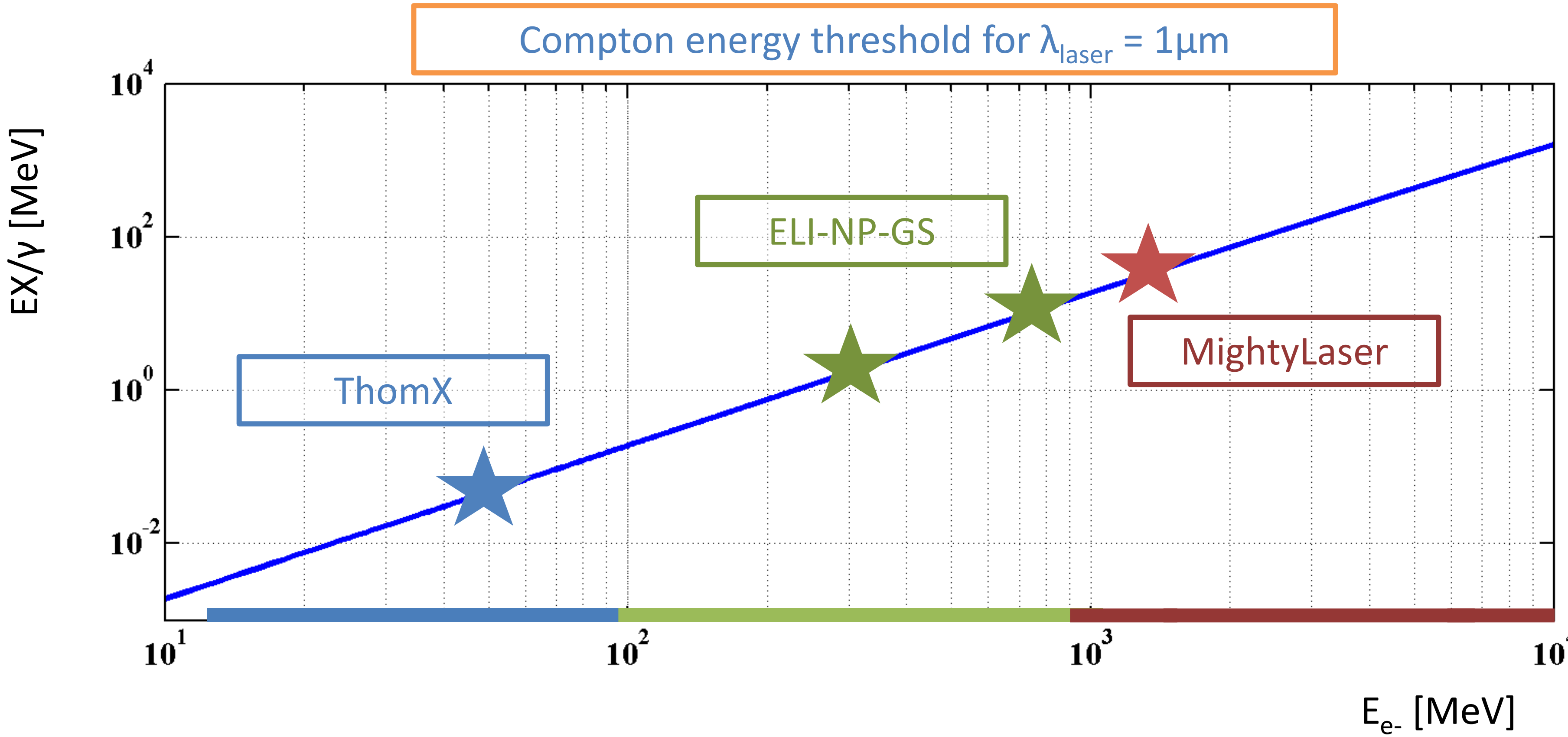


ThomX



ELI-NP-GS

Applications of Compton scattering: e⁻ + hν → e⁻ + X/γ



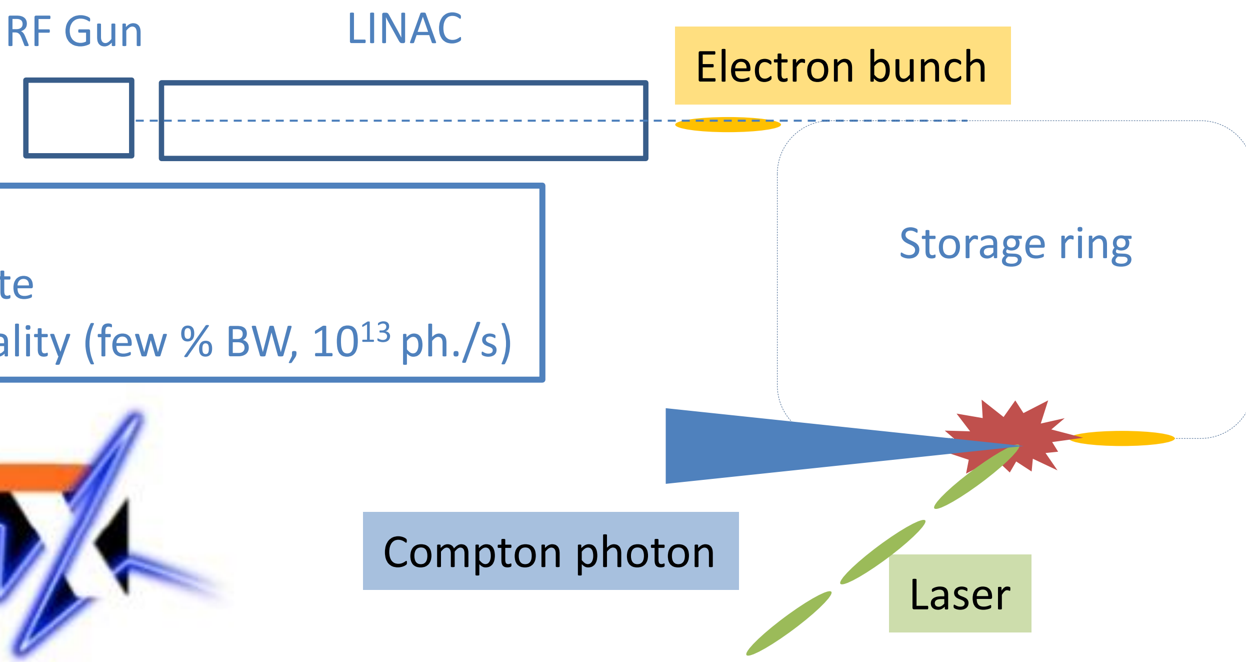
~10-1MeV
Low energy applications
Radiography & Radiotherapy
Museology
…

~1MeV-100MeV
Nuclear fluorescence
Nuclear physics
Nuclear survey
Nuclear waste management
…

>100MeV
High energy applications
Compton polarimeter
γγ collider
Polarised positron source
…

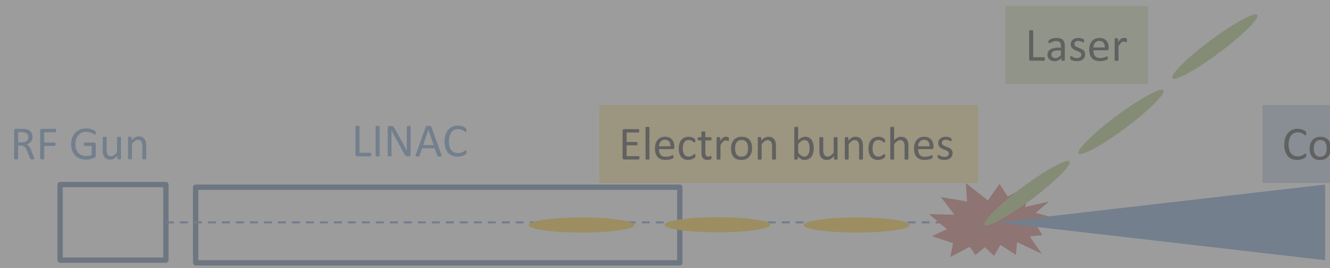
Examples of ICS sources

LINAC solution
→ ☹ lower repetition rate
→ but ☺ better beam quality (0.5% BW, 10^9 ph./s)



Ring solution
→ ☺ higher repetition rate
→ but ☹ lower beam quality (few % BW, 10^{13} ph./s)

Storage ring solution



LINAC solution
→ ☹ lower repetition rate
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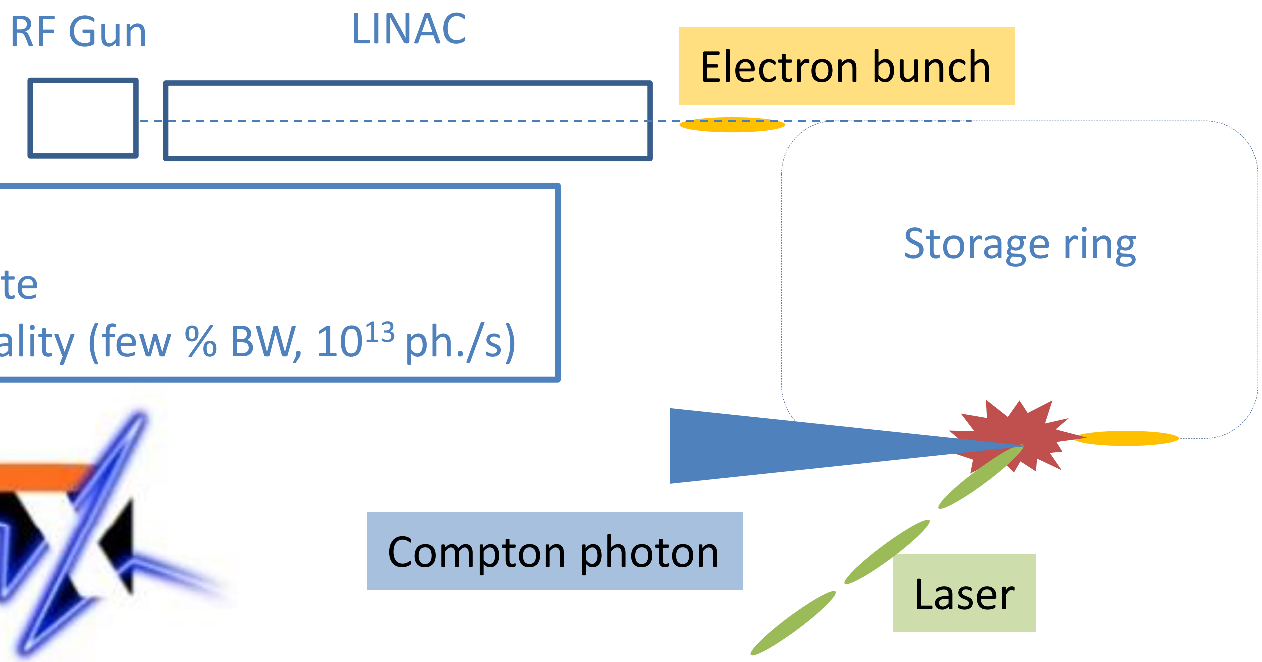
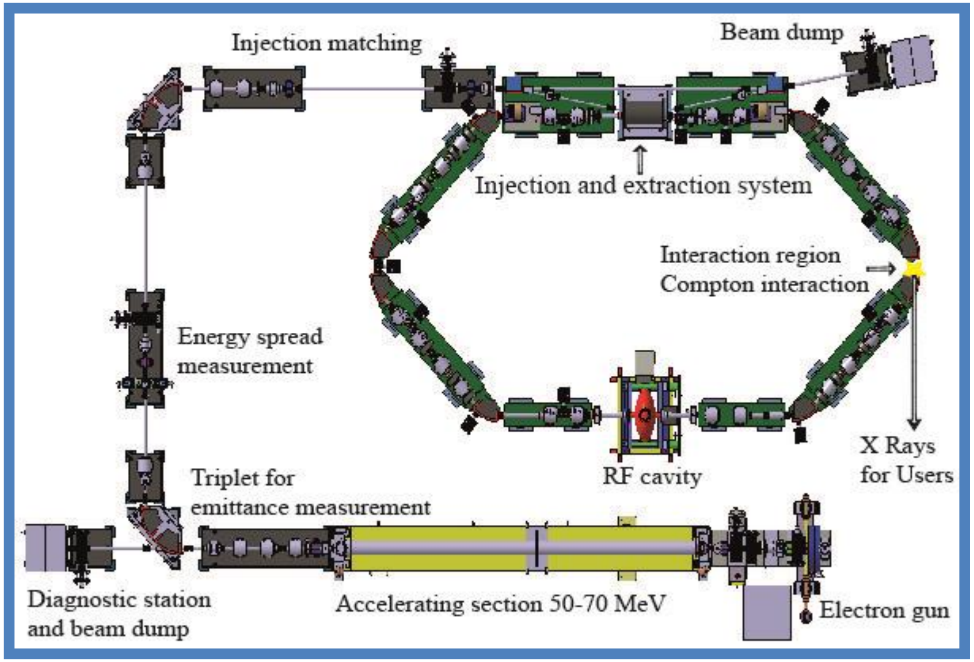
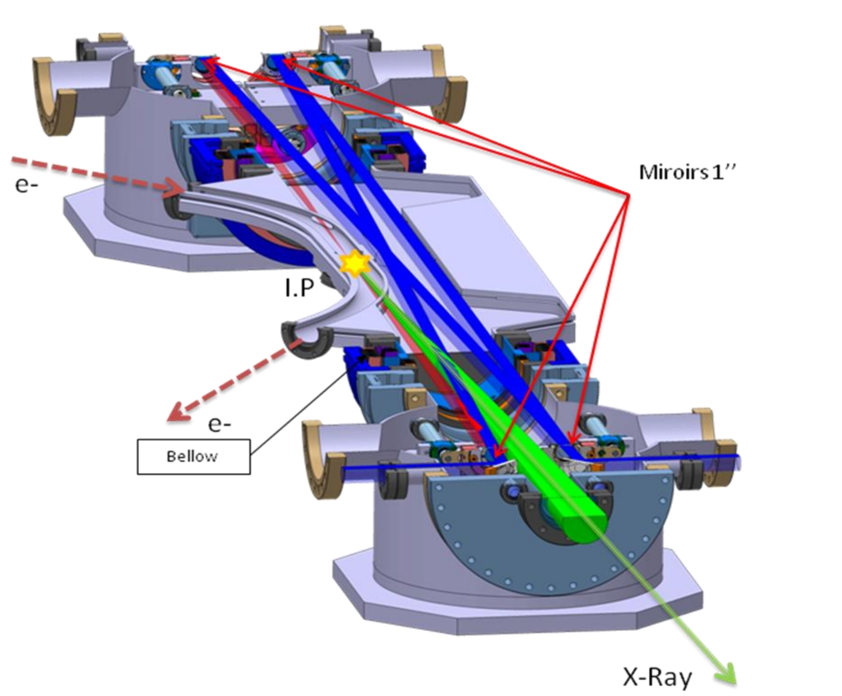


Ring solution
→ ☺ higher repetition rate
→ but ☹ lower beam quality (few % BW, 10^{13} ph./s)

ThomX

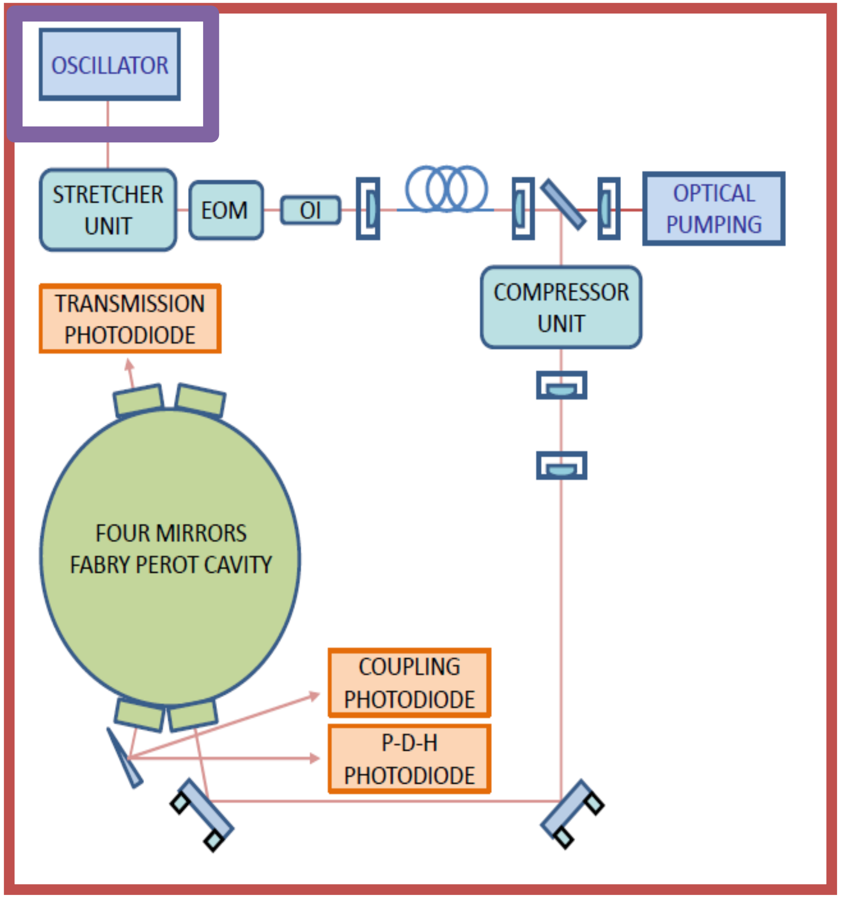
~50 MeV ring, 1 nC
→ complicated electron dynamics
17.8 MHz repetition rate
4-mirror planar optical cavity





10^{11} - 10^{13} γ/s
1%-10% spectral bandwidth (w/ diaphragm)
10 mrad divergence w/o diaphragm

ThomX R&D challenges



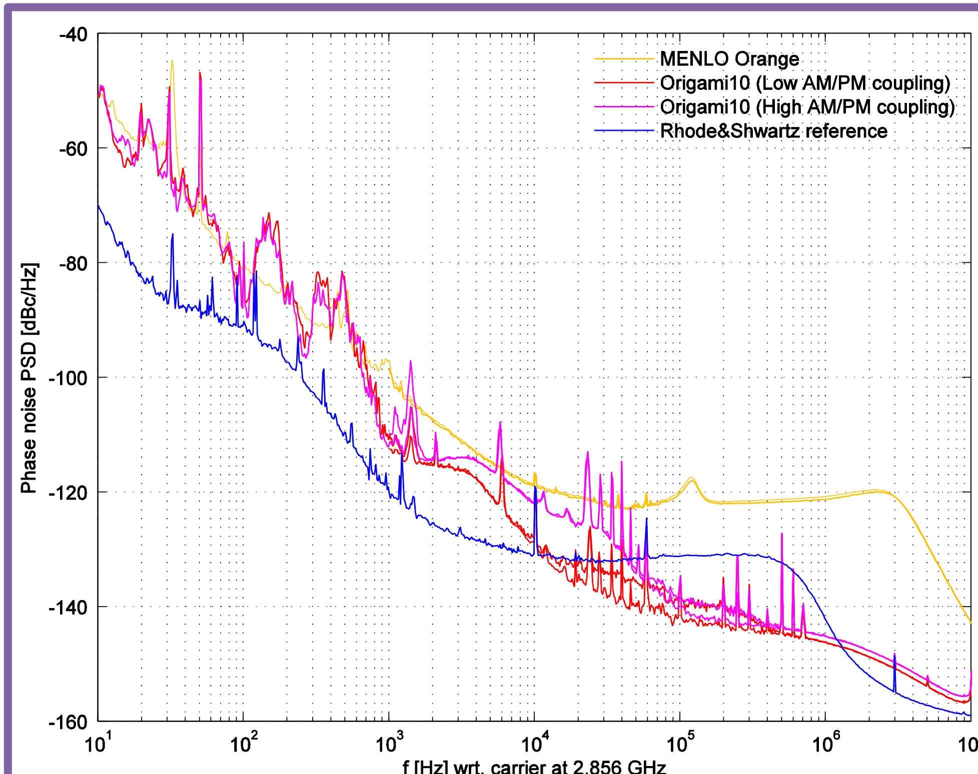
Oscillator phase-noise control is critical:

$$\frac{\Delta\nu}{\nu_{opt}} = 3\,.\,10^{-12}$$

$$\Delta\nu \sim 1kHz$$

Choice of oscillator requires R&D: CELIA

→Commercial vs home made (CELIA) lasers

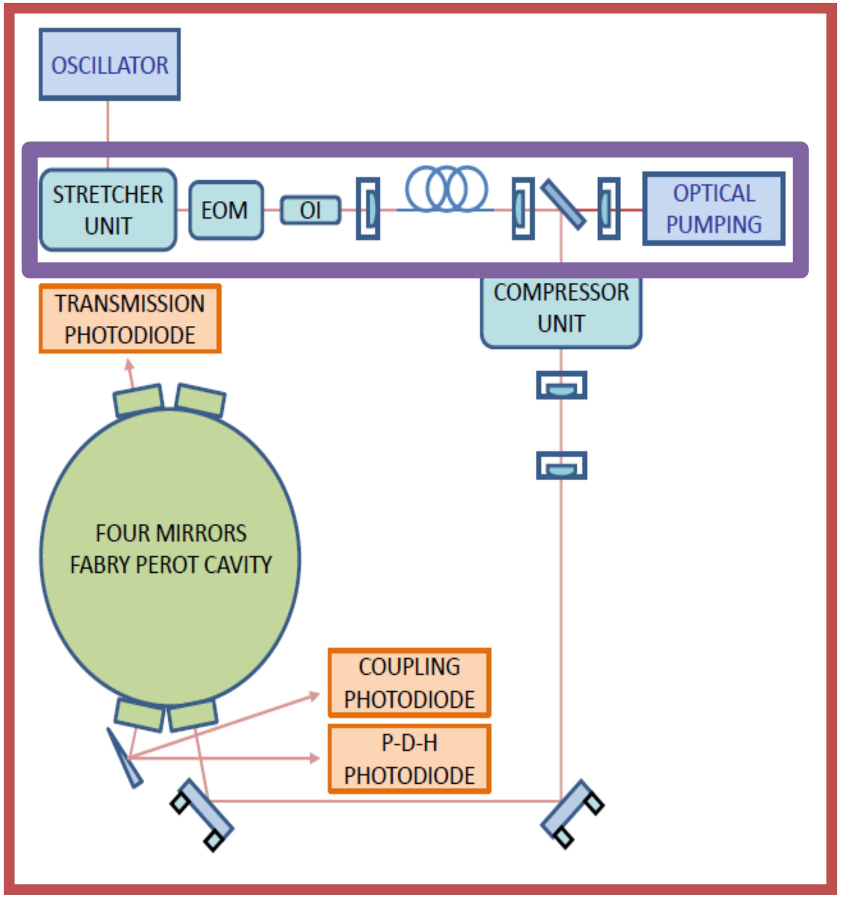


R&D on numeric feedback to lock the oscillator on:

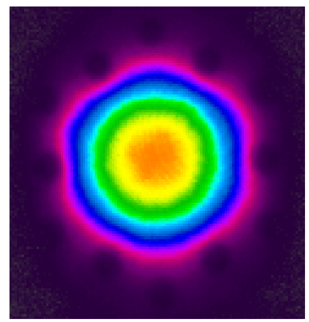
→ the optical cavity

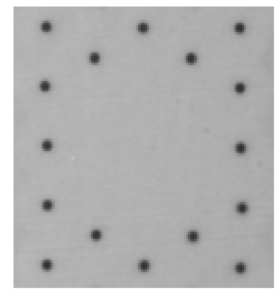
→ the accelerator RF

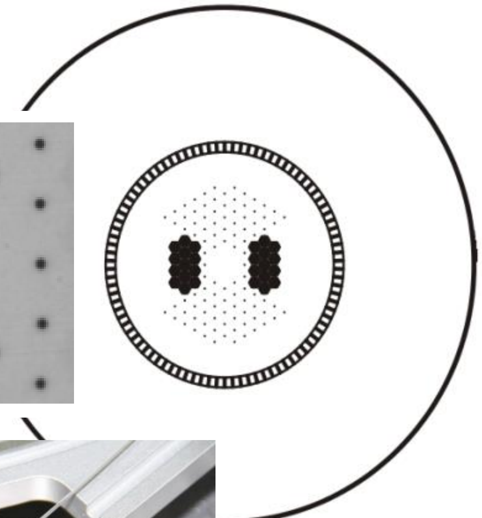
ThomX R&D challenges

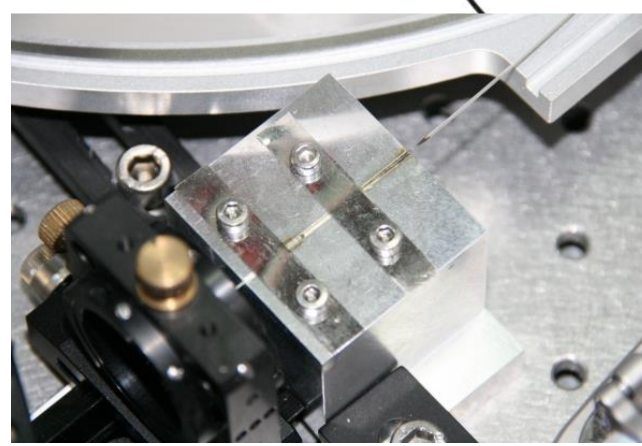


Three-stage CPA amplification R&D
→micro-structured fibres
→Ytterbium doped fibres
→connections must be robust, stable, reliable
100W obtained regularly in output



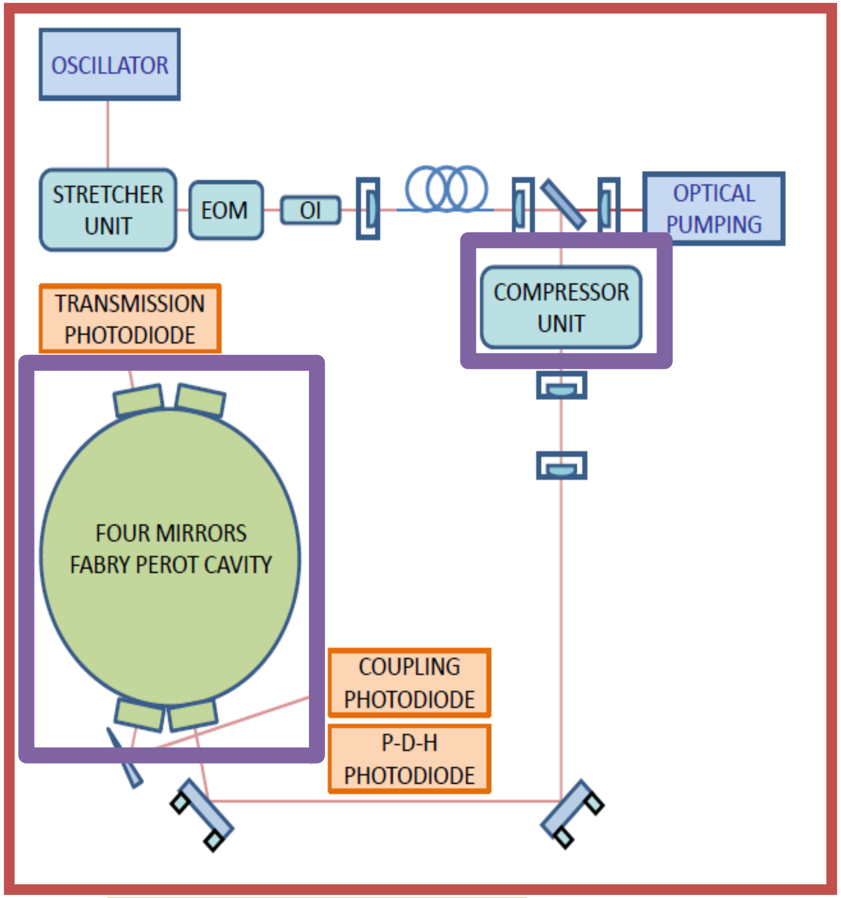






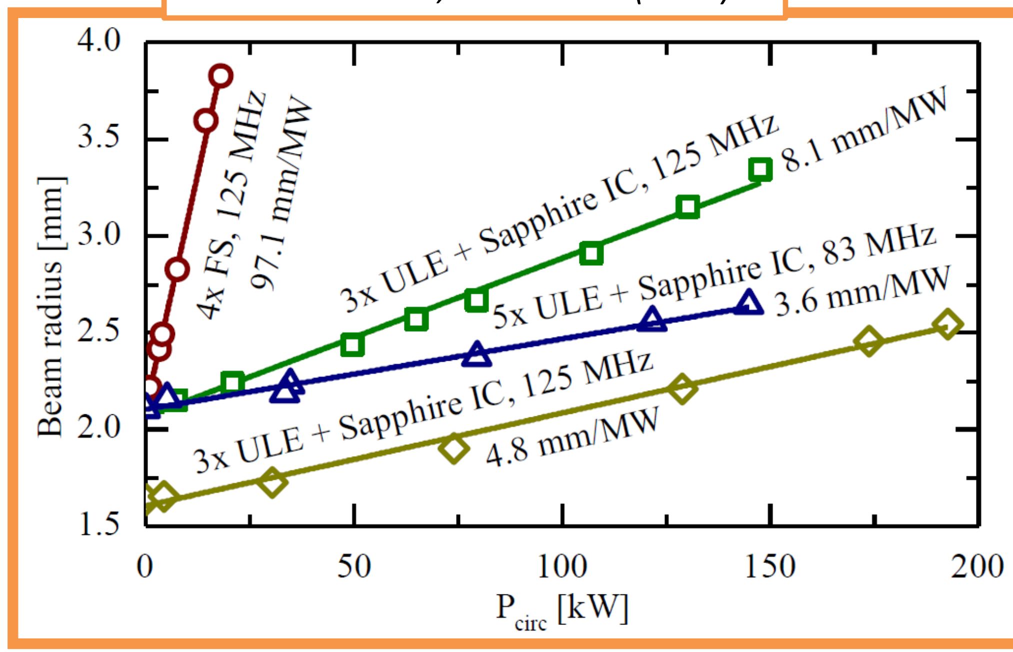
State of the art, best effort :
800W: Limpert et al., Opt. Lett. ***35*** *(2010) 94*
2kW: Otto et al., Opt. Lett. ***39*** *(2014) 6446*

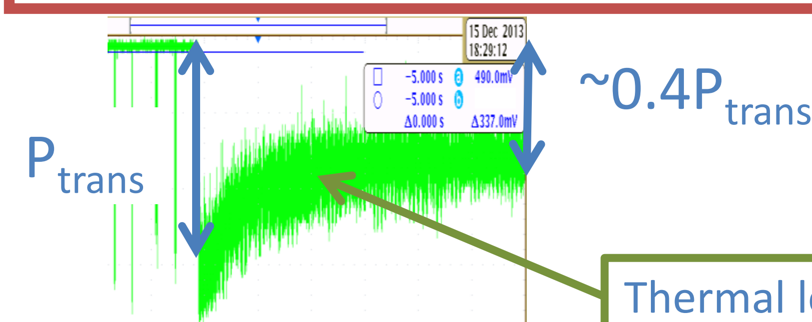
ThomX R&D challenges



Optics R&D:
- → Thermal effects in compressor (CVBG)
- → Thermal effects in optical cavity:
  - → substrate choice
  - → Spatial mode matching (adaptative optics)

H. Carstens et al., ASSL JTh5A (2013) 3



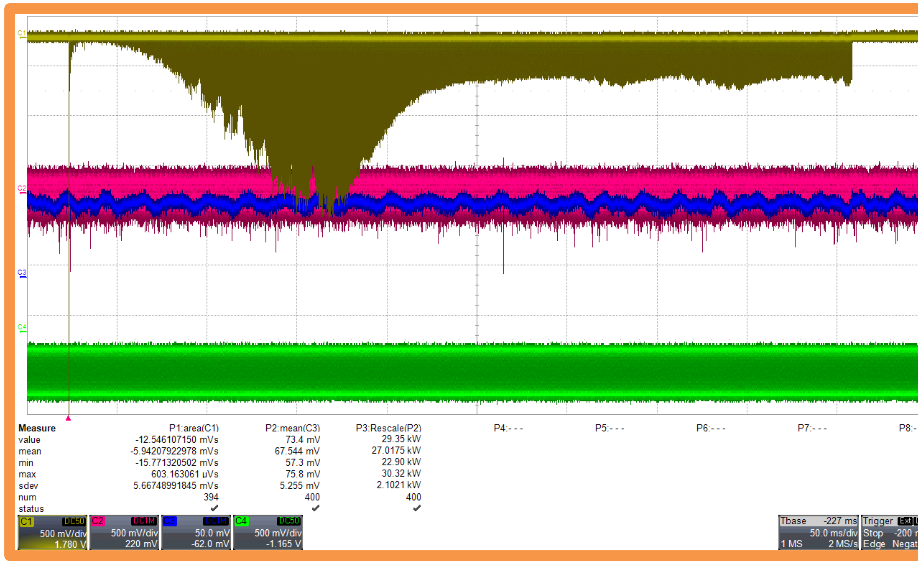


Thermal loading of the cavity takes few 100 ms (P_{trans} reduces)

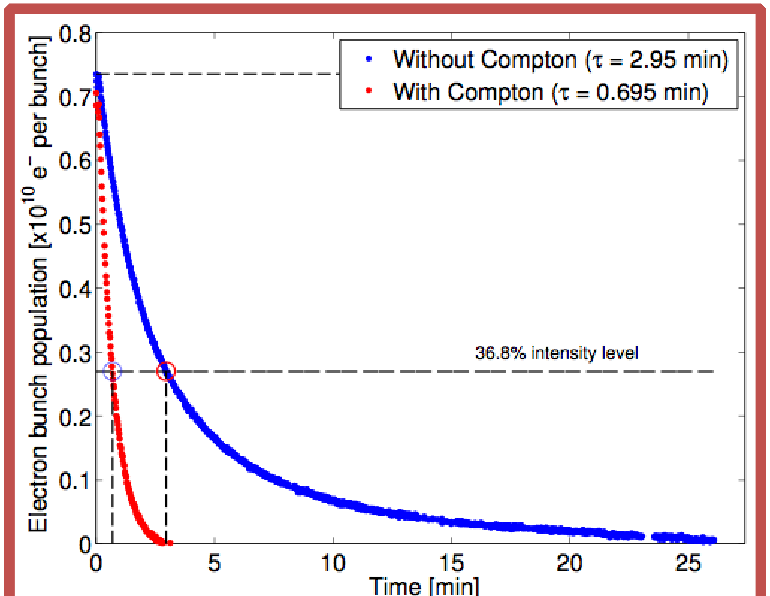
Past results: MightyLaser

Results obtained at the KEK ATF: collaboration with KEK colleagues
1.08MHz collision rate, ~1nC beam charge, 1.3GeV damping ring

Finesse ~ 30000
~50W seed laser-power
~100 γ/crossing @ ~25MeV
P_{cavity}>100kW (transient regime)
40kW (continuous regime)

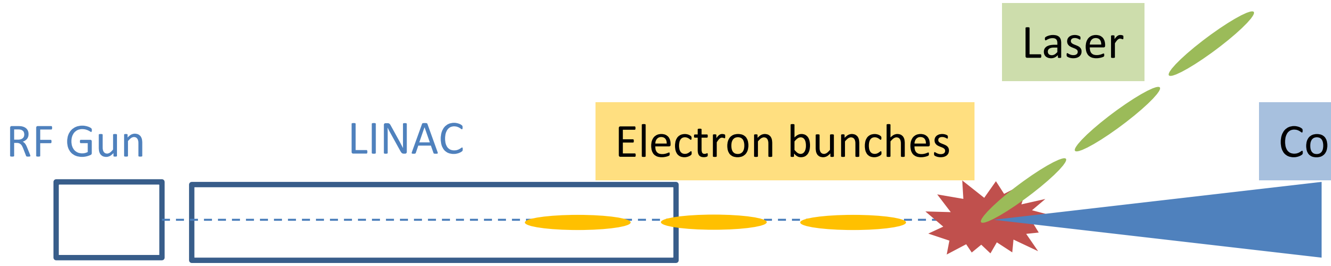


Photon yield as function of time measured with BaF2 scintillator block + PM
→Observation of emittance evolution
→Exhaustion of the electron beam



Optics being re-commissioned at LAL:
→ >10kW with 25W incident (finesse 3000 cavity)
→ x3 in coupling (better mode matching)

LINAC solution



LINAC solution
→ ☹ lower repetition rate
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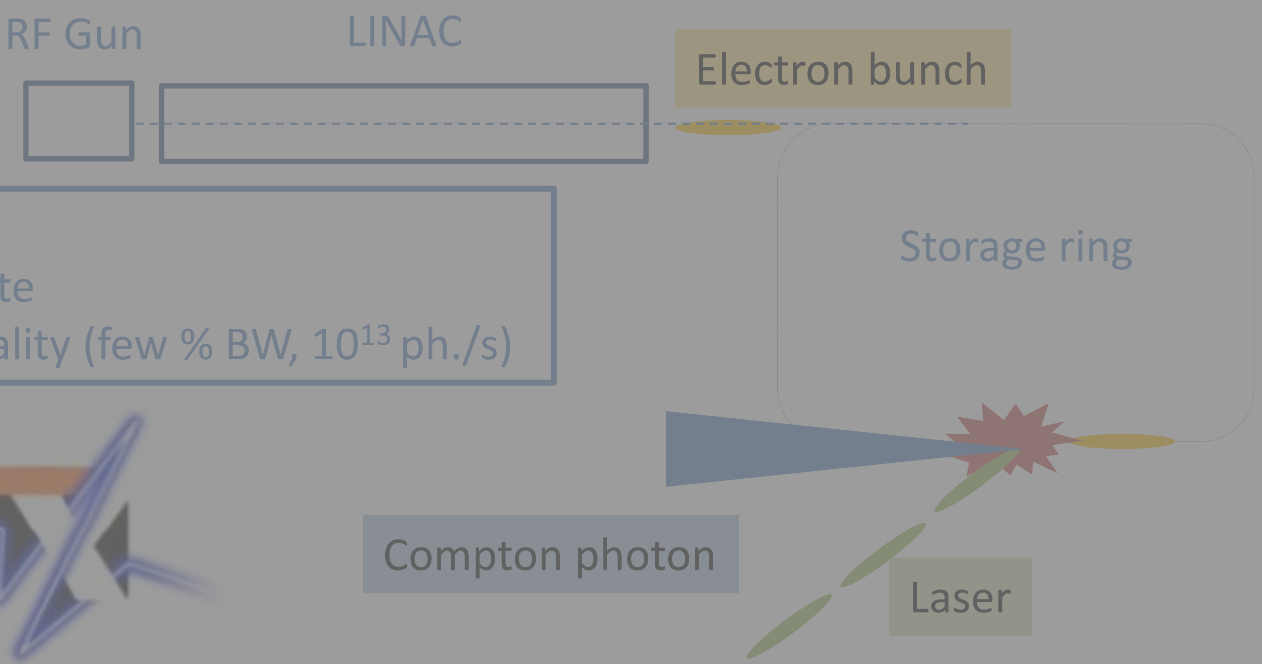

Ring solution
→ ☺ higher repetition rate
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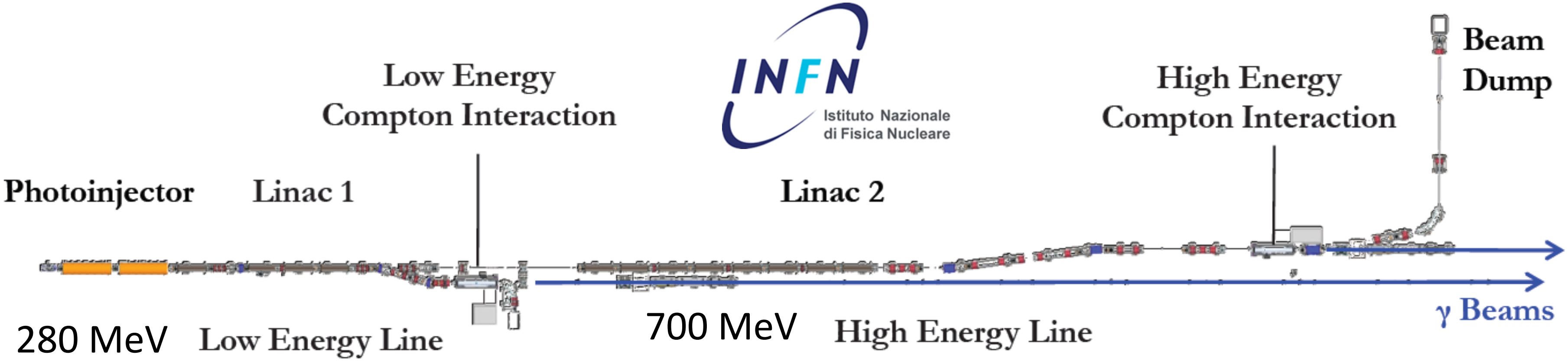
ELI-NP-GS in a nutshell



0m

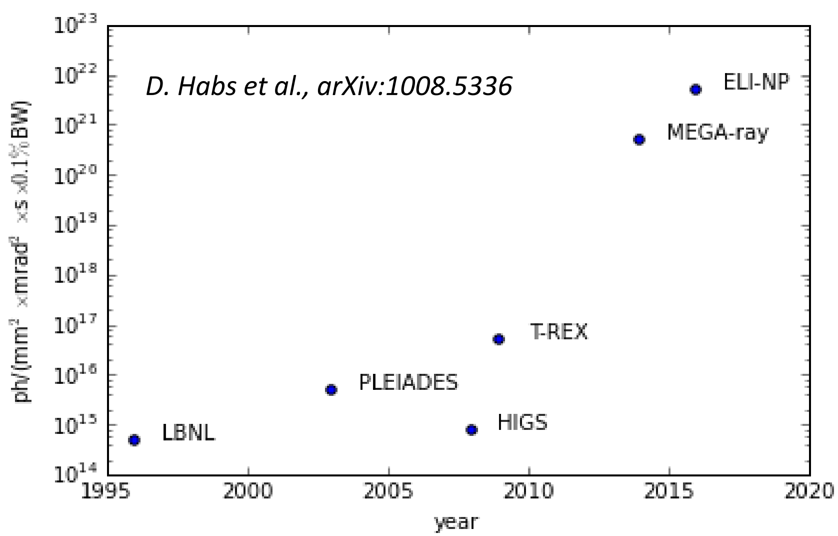
32 bunches separated by 15.6 ns, 100Hz
commissioning in 2016 and 2018

~90m

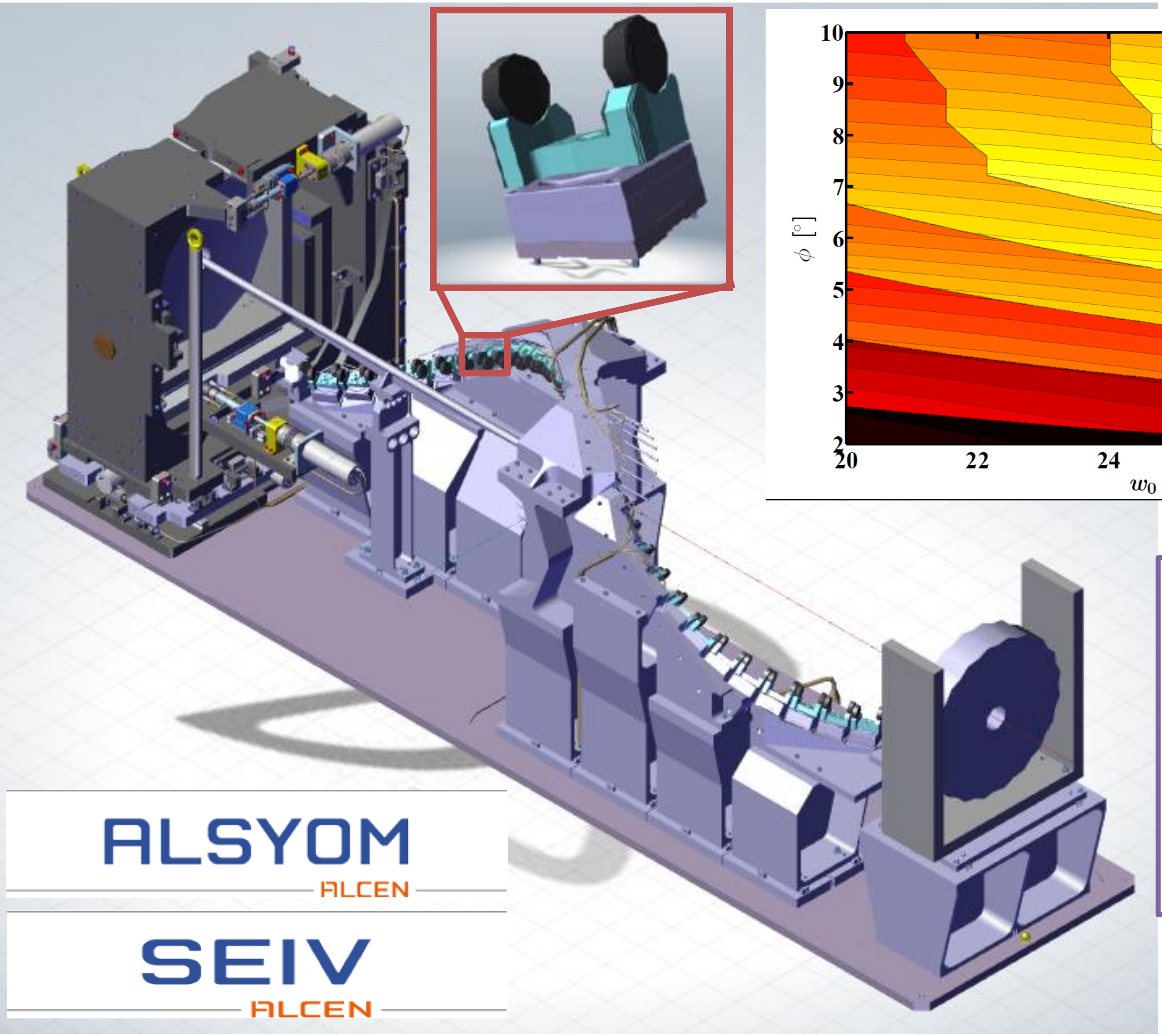
Tight constraints on photon beam:
→ divergence <0.2mrad
→ beam spot at 10m <1mm
→ bandwidth (BW) <0.5%
→ av. spectral density @20MeV: $8x10^3$ $(s.eV)^{-1}$
→ brilliance $1x10^{22}$ /(s.mm².mrad²0.1%BW)

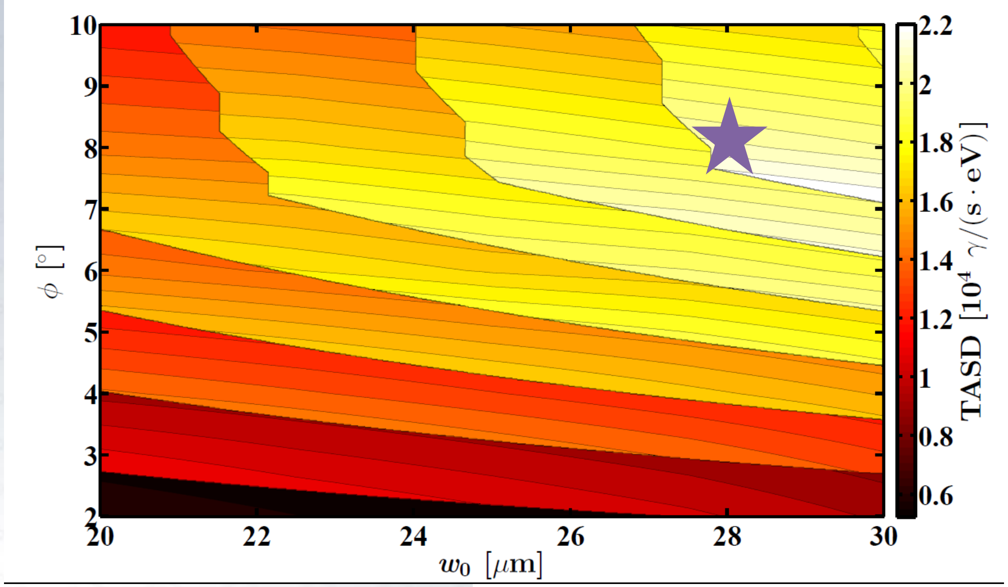
Curtis et al. Optics Letters ***36*** *2164 (2011)*

State of the art laser systems required



ELI-NP-GS recirculator design





Start-to-end simulation →optimize geometry to maximize spectral density (ph/(s.eV)) averaged over the number of passes (N=32)

*K. Dupraz et al, Phys. Rev. ST Accel. Beams **17** 033501 (2014)*

ALSYOM ALCEN

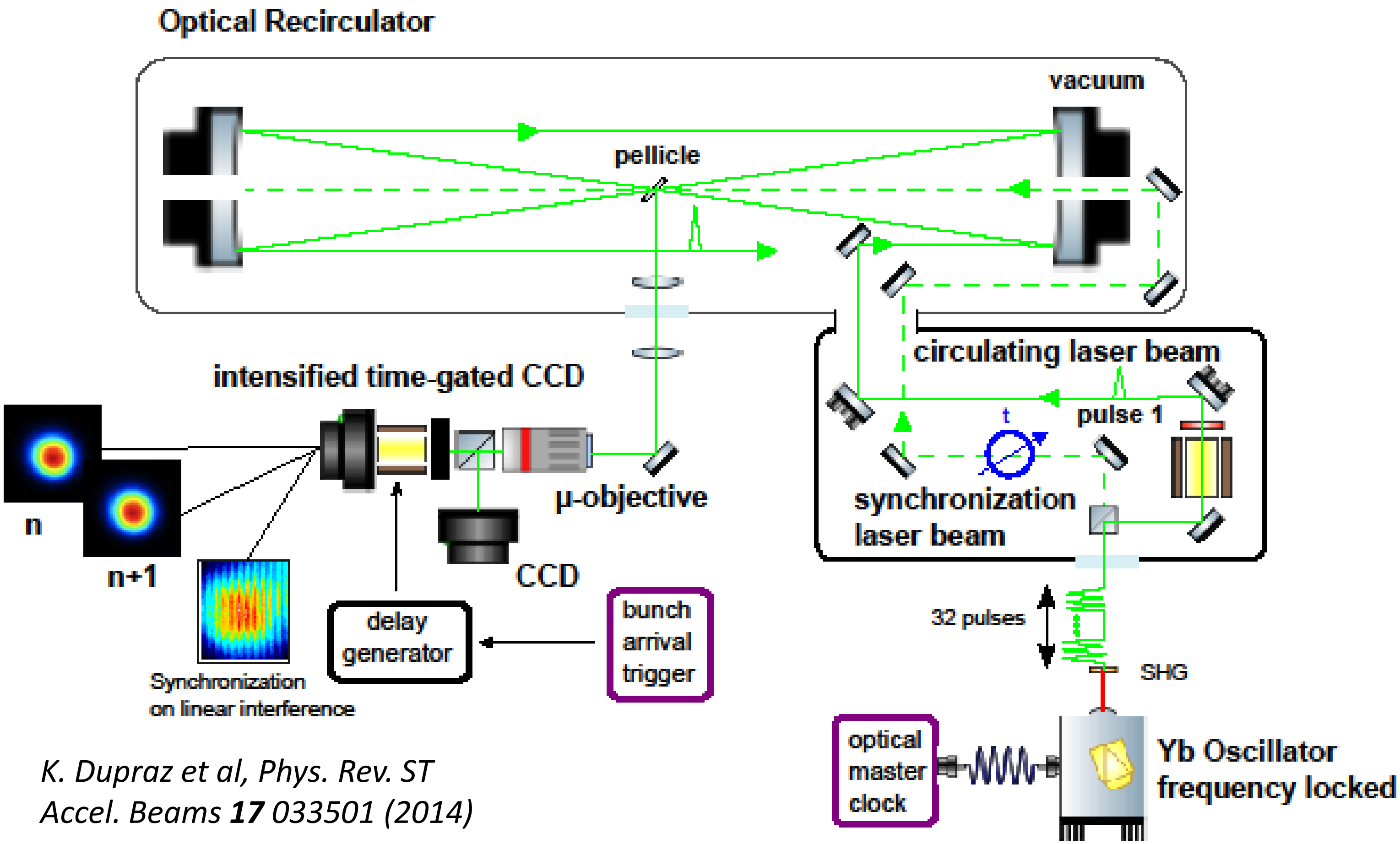
SEIV ALCEN

ELI-NP-GS alignement, synchronisation

Tight constraints on alignment & synchronisation:

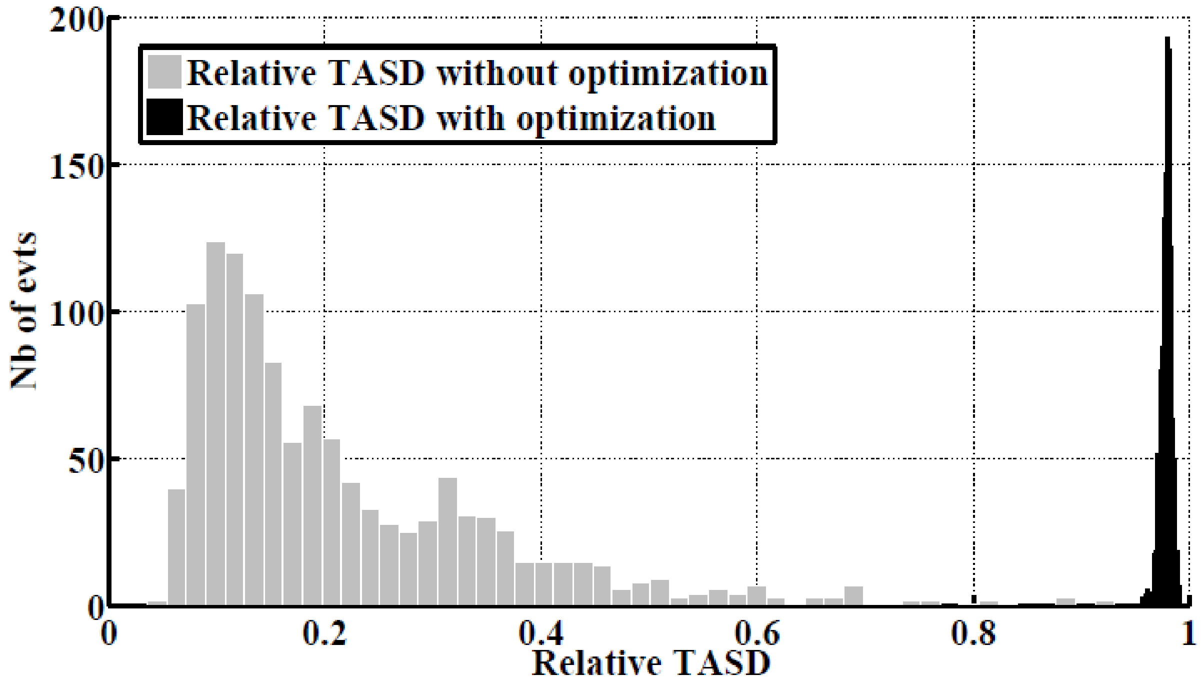
→ Transverse spread of IPs<~ 3 µm, typical divergence <few µrad

→ Synchronisation < 200fs



*K. Dupraz et al, Phys. Rev. ST Accel. Beams **17** 033501 (2014)*

ELI-NP-GS alignement, synchronisation



100µm, 100µrad alignment NOT ACCEPTABLE

Dedicated alignment procedure required

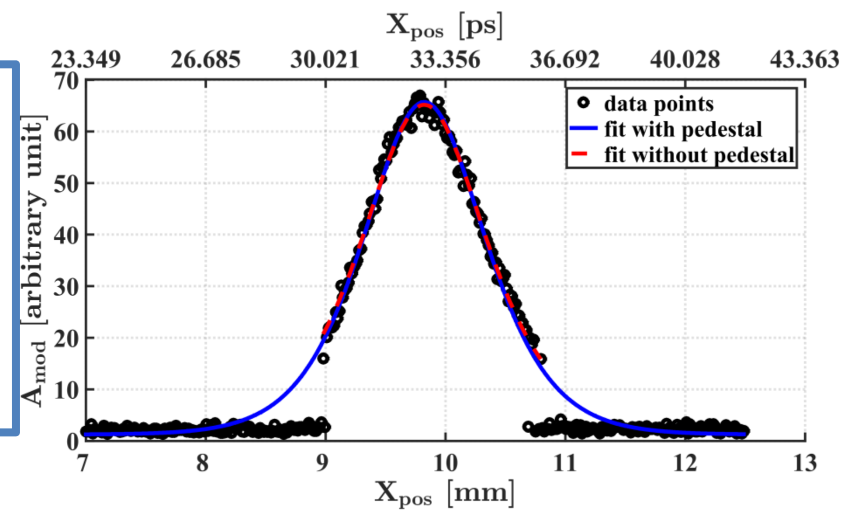
K. Dupraz et al, Phys. Rev. ST Accel. Beams ***17*** *033501 (2014)*

Demonstration of the synchronisation:

→ few 100fs for 1 pass with a 3 ps laser

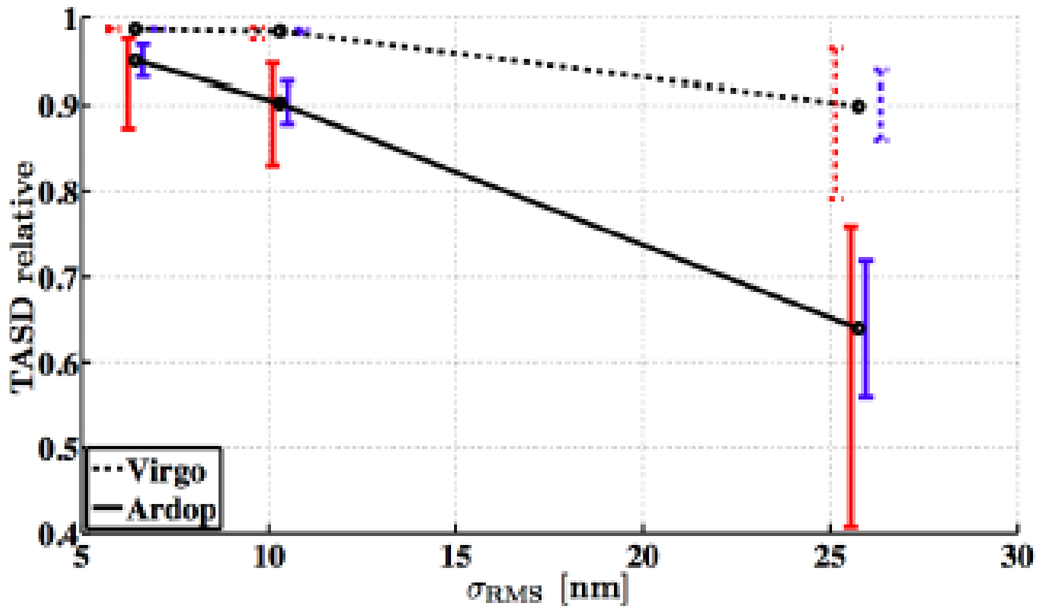
→ Experimental setup being updated with a few 200fs laser

→ Robustness to environmental fluctuations required



K. Dupraz PhD Thesis, LAL, Sept. 2015

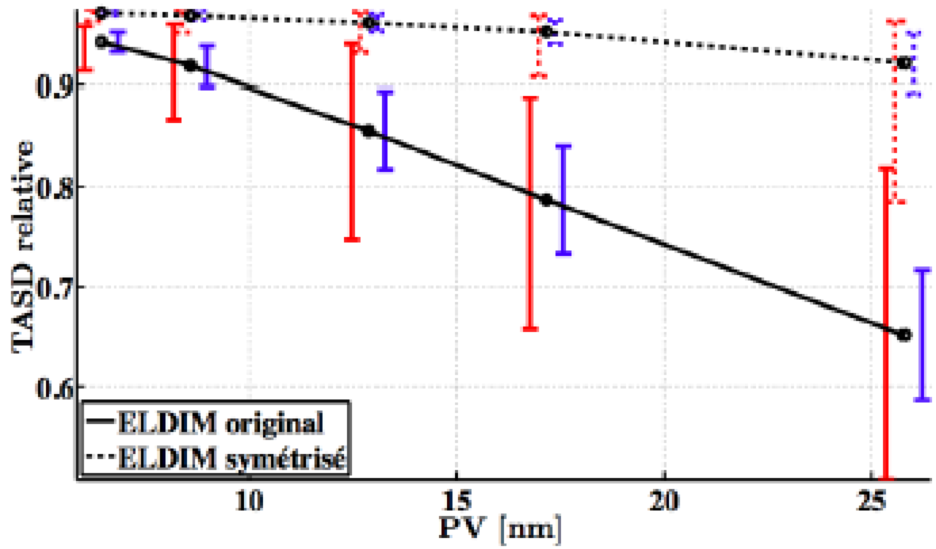
ELI-NP-GS optics



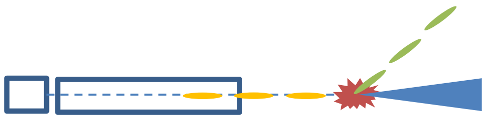
Beam quality depends strongly on:
→Parabola optical micro-structure
→Avoid peaks in surface PSD
→ Constrain PSD shape
→ σ_{RMS}<10nm
→ Good polishing company required

K. Dupraz PhD Thesis, LAL, Sept. 2015

Beam quality depends strongly on:
→MPS optical macro-structure
→Avoid systematical bias of all MPS
→Characterisation needed
→May need to perform a 'smart' ordering of MPS



Summary

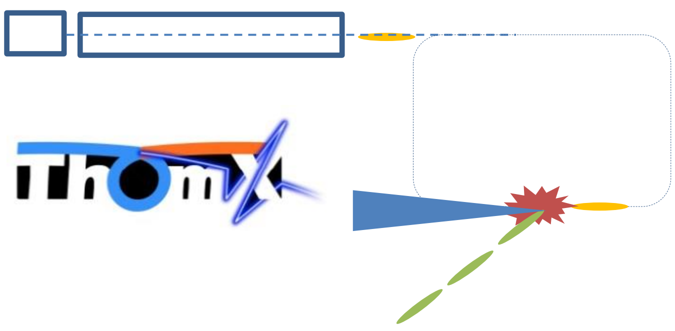


Original solution for high spectral density ICS source

→ Proof-of-principles and detailed simulations show it is feasible

→ Detailed prototype studies to be done in the automn

→ Main challenges related to optics quality, synchronisation, alignment



Active R&D on high average flux ICS source

→ Few 10kW operations routinely demonstrated in an accelerator (KEK)

→ Naive scaling ➔ few 100kW are reachable

→ Requires understanding and mitigation of thermal effects, and new effects that could dominate in the ~MW regime

What is the limit of the technology for high finesse cavities in pulsed regime ?

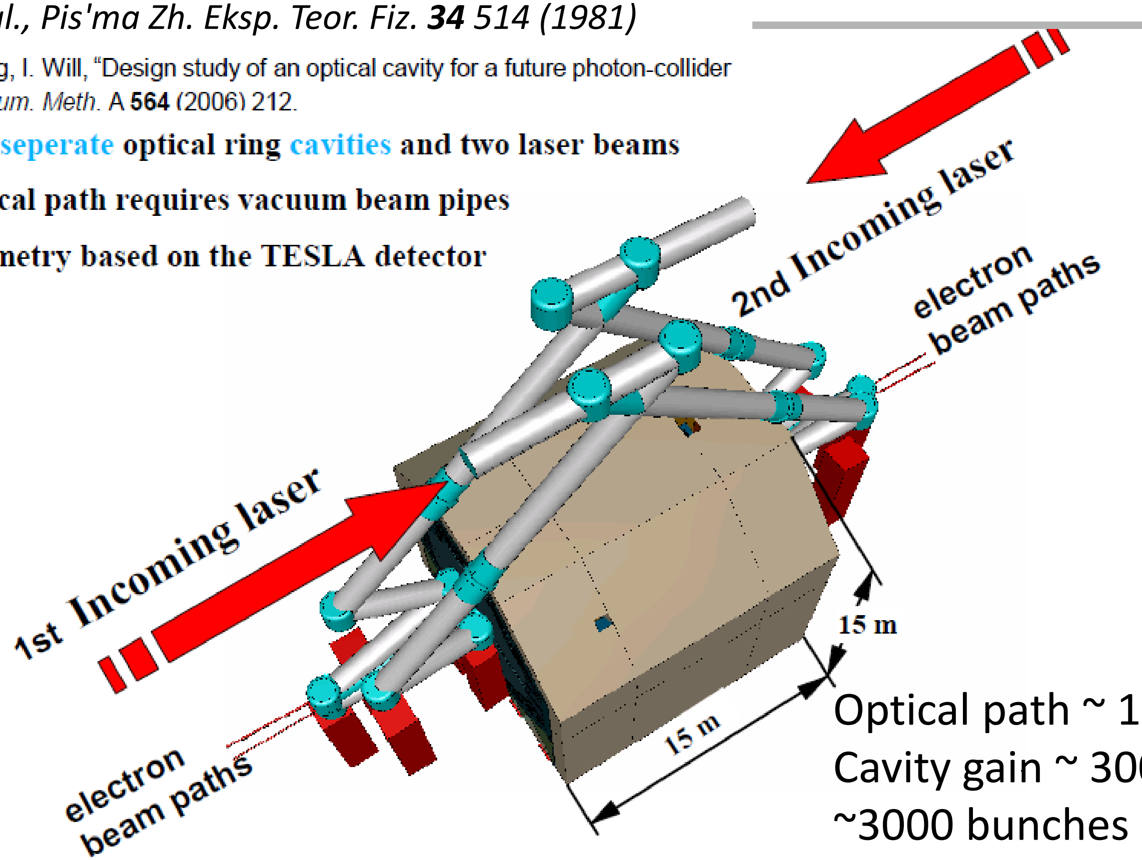
Backup slides

A γγ collider design

Ginzburg et al., Pis'ma Zh. Eksp. Teor. Fiz. ***34*** *514 (1981)*

G. Klemz, K. Monig, I. Will, "Design study of an optical cavity for a future photon-collider at ILC". *Nucl. Instrum. Meth.* A **564** (2006) 212.

- two seperate optical ring cavities and two laser beams
- optical path requires vacuum beam pipes
- geometry based on the TESLA detector

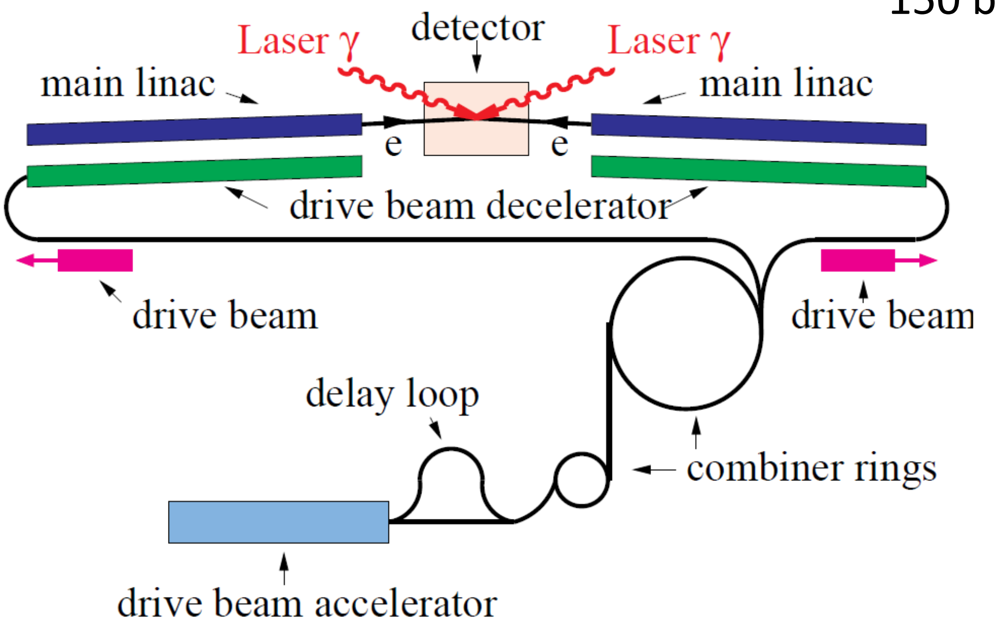


Optical path ~ 100m (3MHz rep. rate)
Cavity gain ~ 300
~3000 bunches at 5Hz rep. Rate
10J laser at interaction point (30mJ input)

Mechanical stability ☹
Optics breakdown fluence ☹ Surface quality for large optics ☹
Cannot cope with 30MW in cavity ☹ → **need to empty cavity between trains**
Dedicated laser locking procedure in this regime
Laser phase noise must be controlled ☹

Another γγ collider design

Asner et al., hep-ex/0111056
Bogacz et al., arXiv:1208.2827



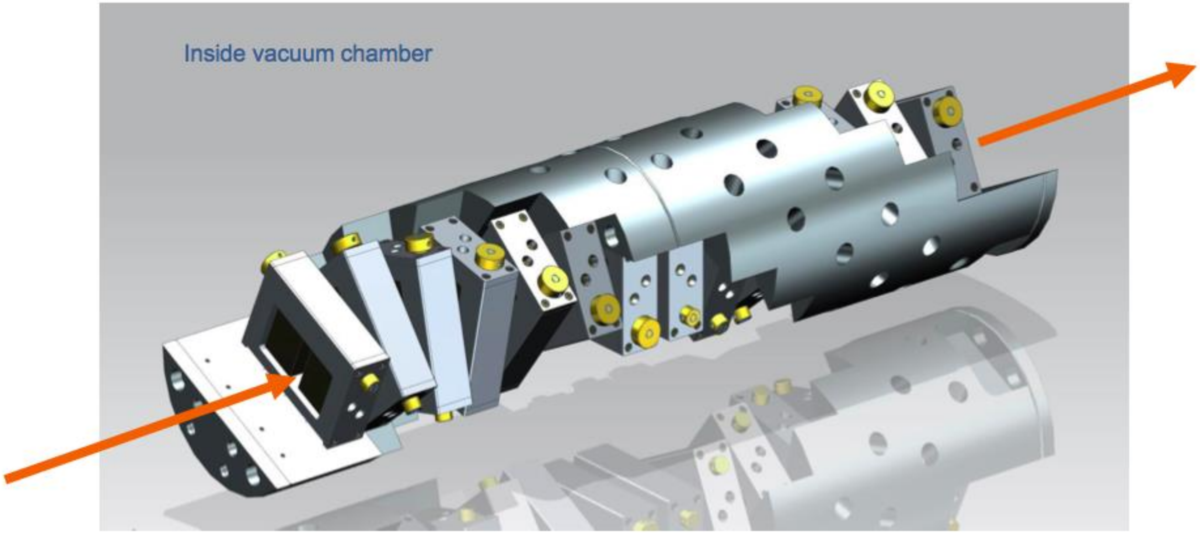
~150 bunches 10 trains at 100Hz rep. Rate

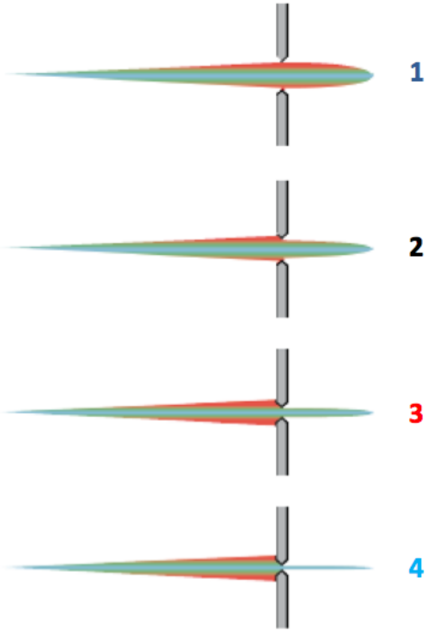
~1J per pulse few ps
~10-20µm laser focalisation
200000 pulses/sec

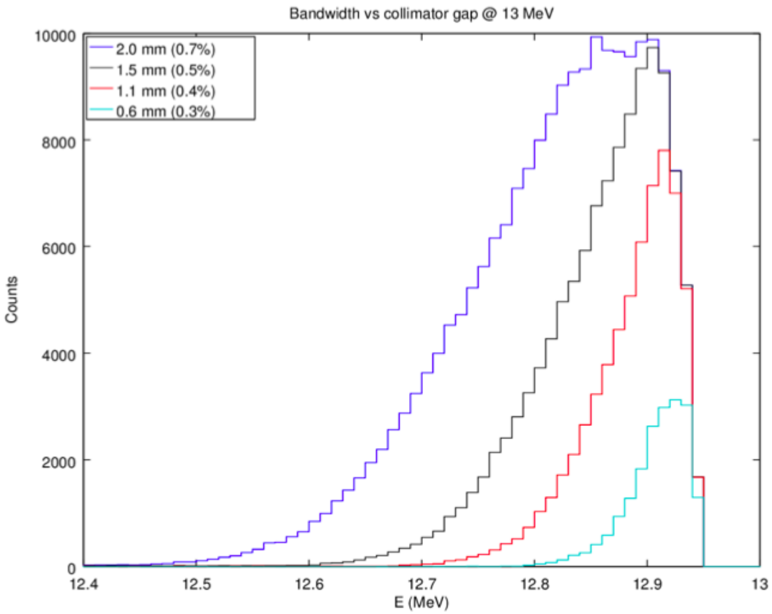
→ Optical recirculator or resonator required

Variable	Symbol	CLICHE [3]	SAPPHiRE
Laser beam parameters			
Wavelength	λ_L	0.351 μm	0.351 μm
Photon energy	$\hbar\omega_L$	3.53 eV $= 5.65\times10^{-19}$ J	3.53 eV
Number of laser pulses per second	N_L	169400 s^{-1}	200000 s^{-1}
Laser peak power	W_L	2.96×10^{22} W/m^2	6.3×10^{21} W/m^2
Laser peak photon density		5.24×10^{40} photons/m^2/s	1.1×10^{40} photons/m^2/s
Photon beam			
Number of photons per electron bunch	N_γ	9.6×10^{9}	1.2×10^{10}
$\gamma\gamma$ luminosity for $E_{\gamma\gamma}\geq 0.6E_{CM}$	$\mathcal{L}^{peak}_{\gamma\gamma}$	3.6×10^{33} cm^{-2}s^{-1}	3.6×10^{33} cm^{-2}s^{-1}

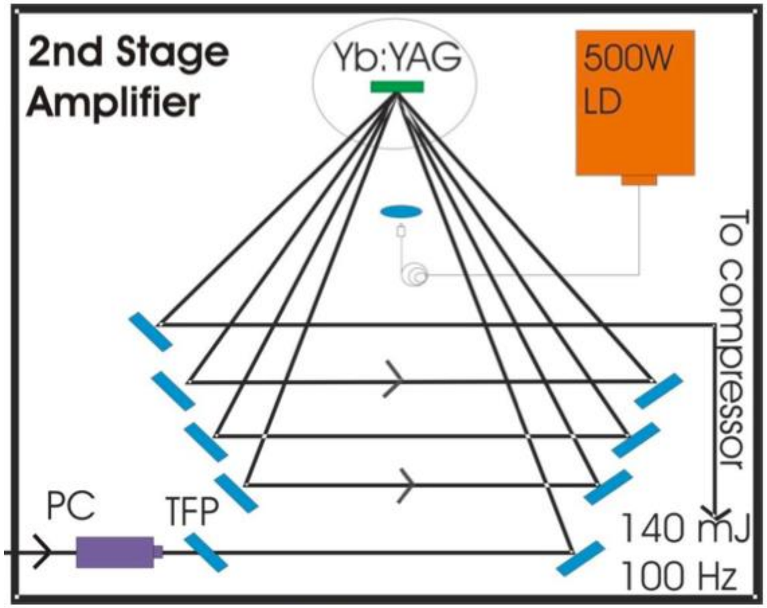
GBS Collimation

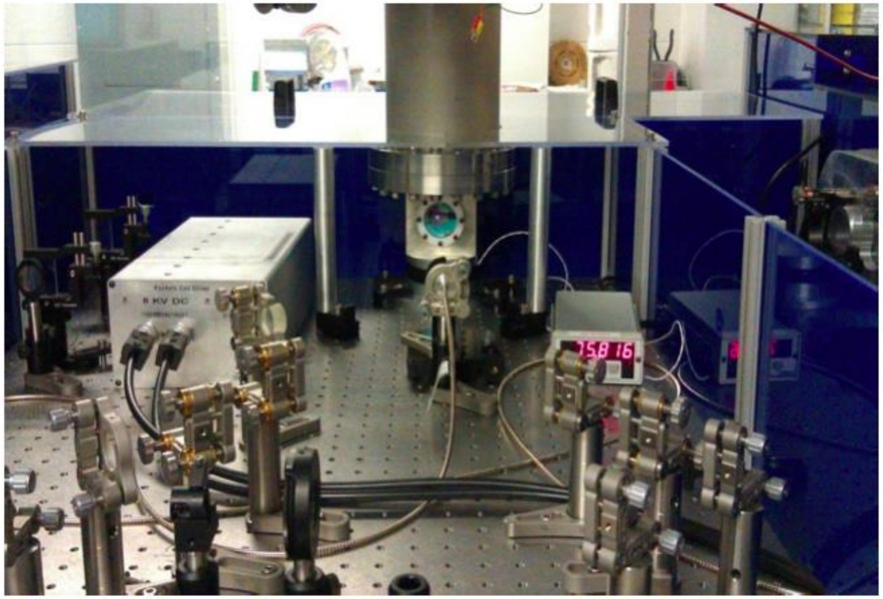


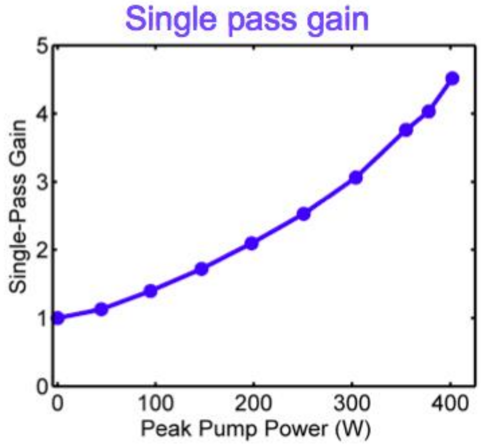


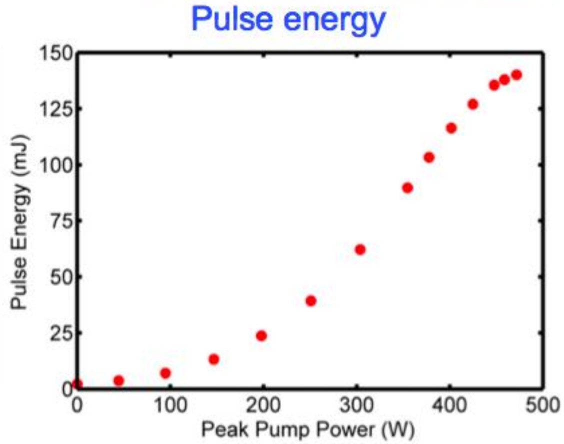


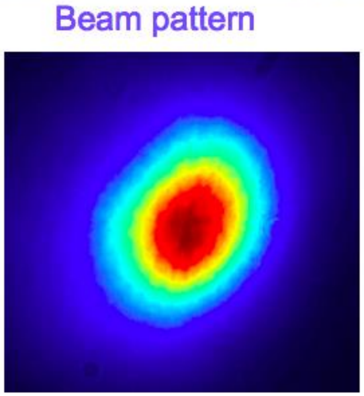
ELI-NP-GBS IP lasers





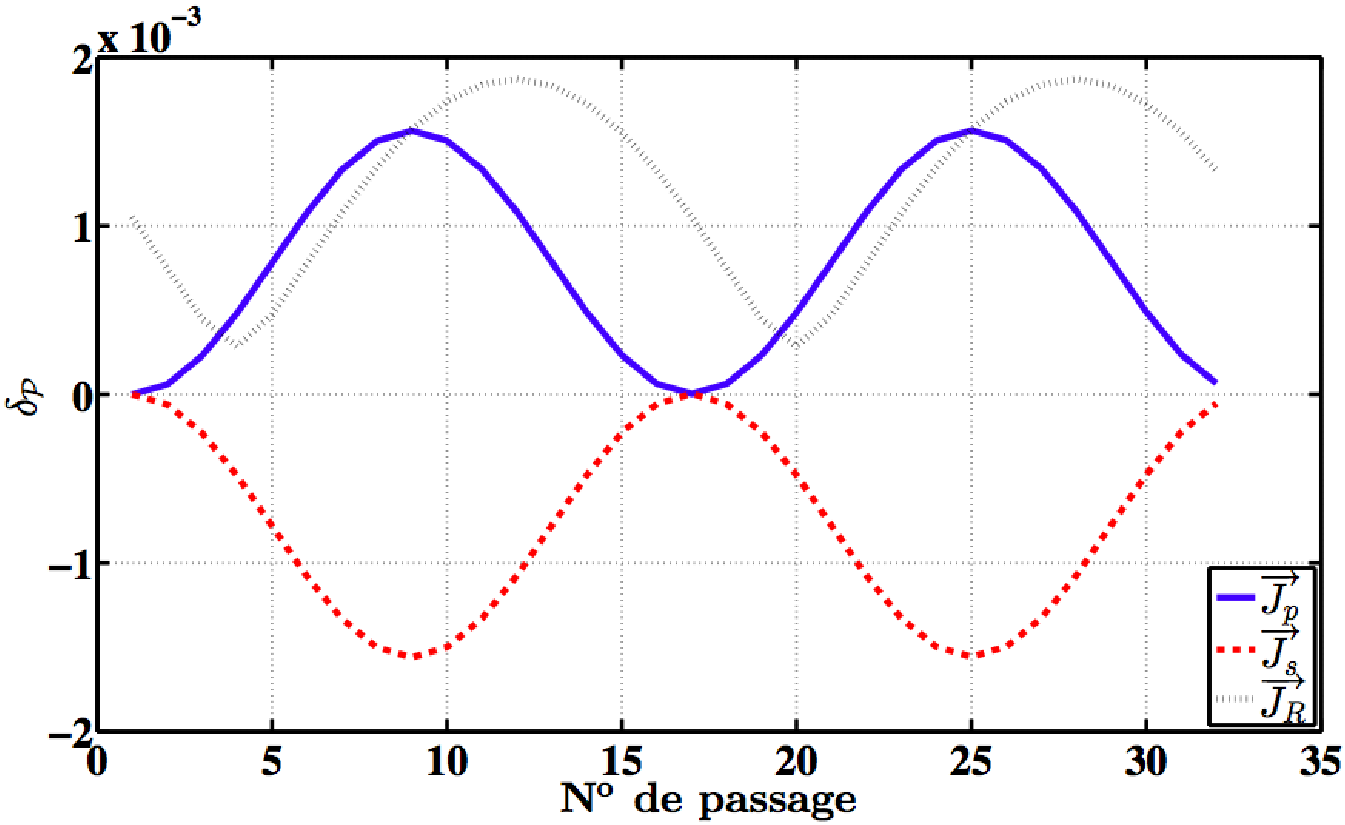






J.J. Rocca, Colorado State University, A. Curtis et al. Optics Letters, 36, 2164, (2011)

ELI-NP-GBS polarization



Optics surface quality