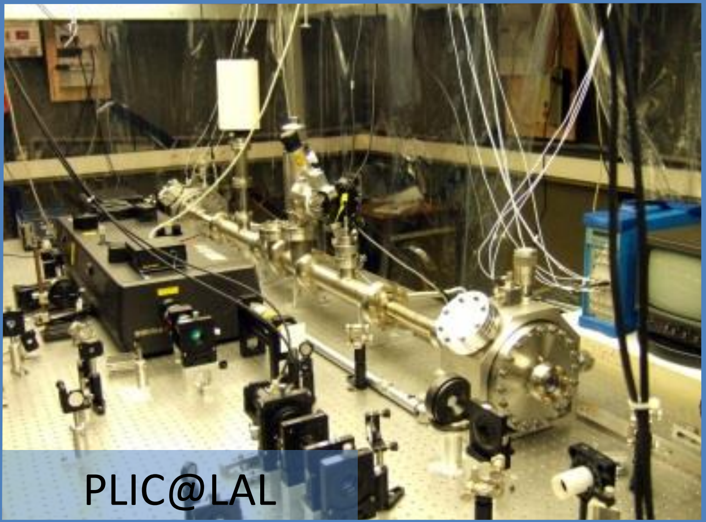
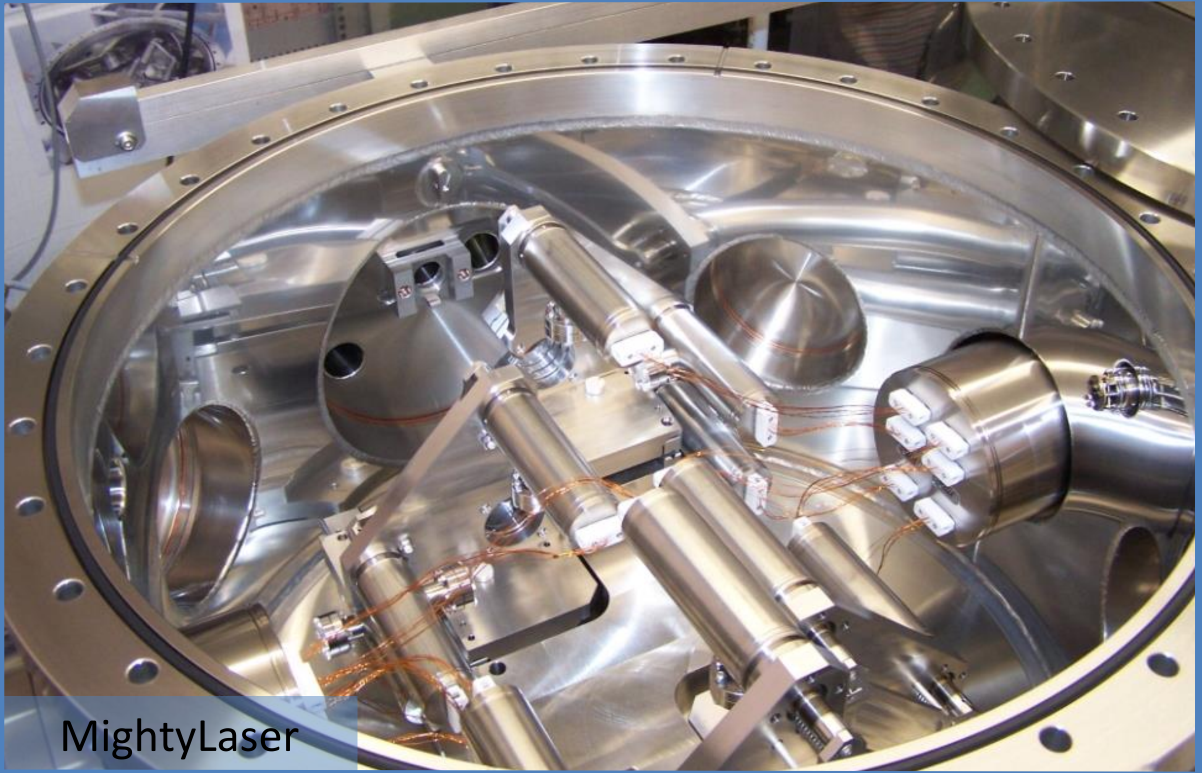
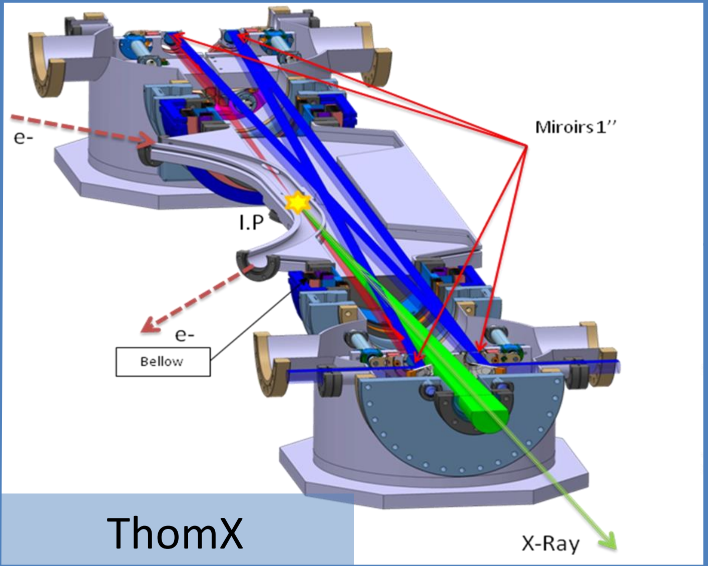
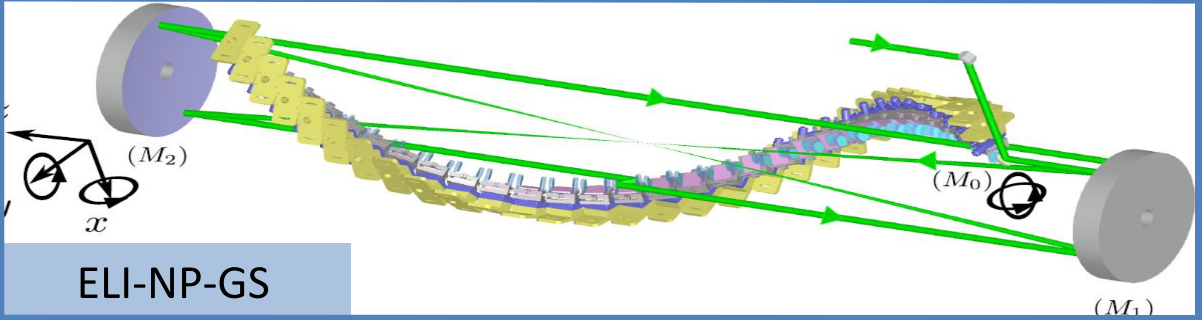
Developments of optical resonators and circulators for Compton X/γ ray machines

Aurélien MARTENS
(martens@lal.in2p3.fr)
for
MightyLaser, ThomX,
ELI-NP-GS
LAL, CELIA, KEK, LMA









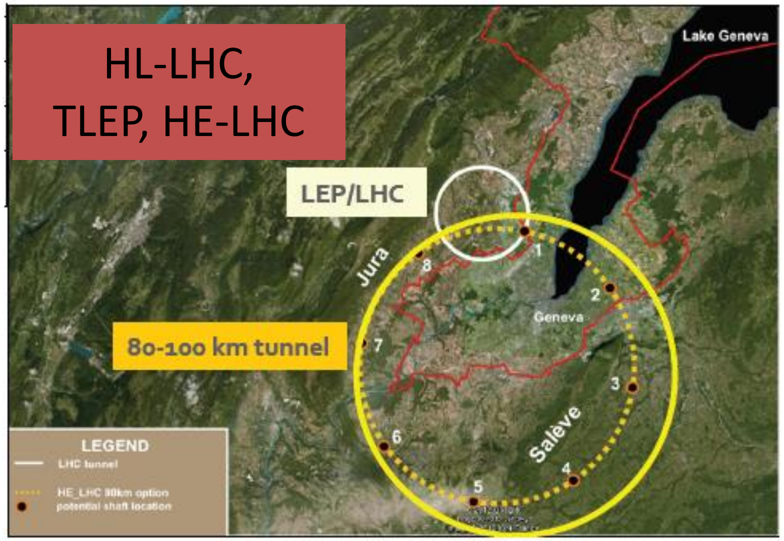
Outline

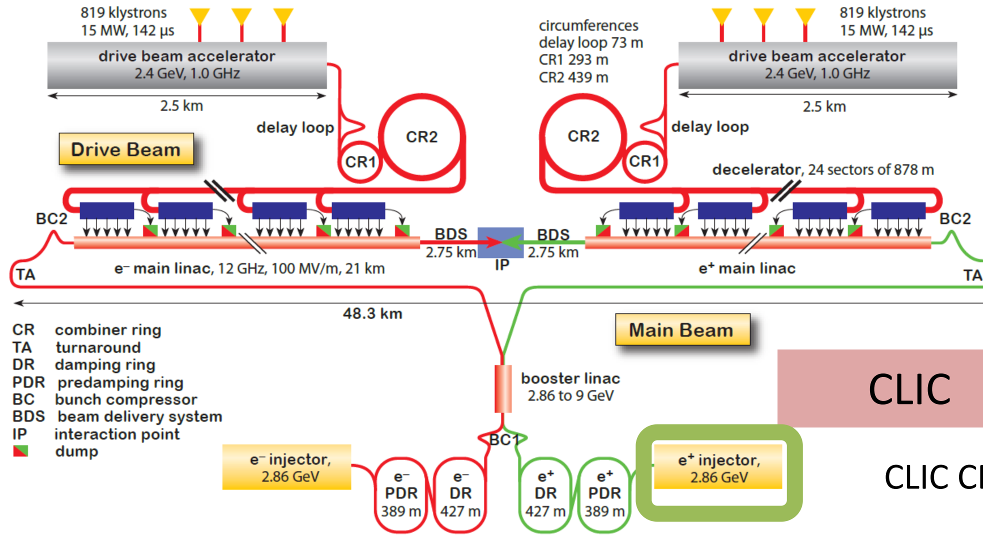
- Towards polarized positrons: Compton sources
- R&D program: Challenges, strategies, repercussions
- R&D cavity MightyLaser: setup, results, lessons
- ThomX project perspectives and applications
- ELI-NP-GBS perspectives and applications

Compton-based polarized positrons: motivation and challenges

The future of High Energy Physics?

HL-LHC,
TLEP, HE-LHC

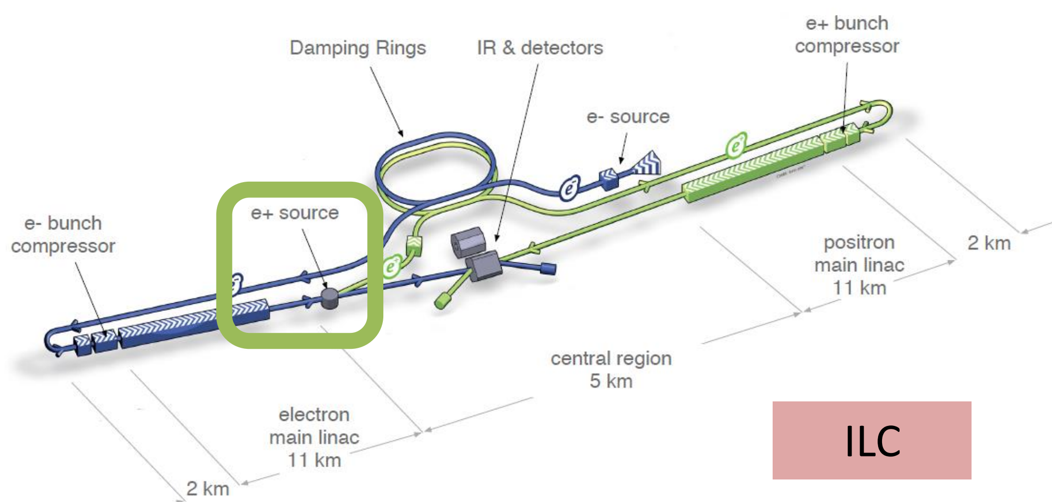




CLIC

CLIC CDR

Not discussed here:
- flavour facilities
- γ-γ collider
- etc.



Positron source:
One of the R&D issues

ILC

ILC TDR

Polarized positrons: physics case in short

V-A interactions → polarisation specific processes

Electron polarisation → determination of leptonic/fermionic asymmetries w/o angular analysis

$A_{FB} \propto A_f A_e$
$A_{LRFB} \propto A_f$
$A_{LR} \propto A_e$

SLC vs LEP

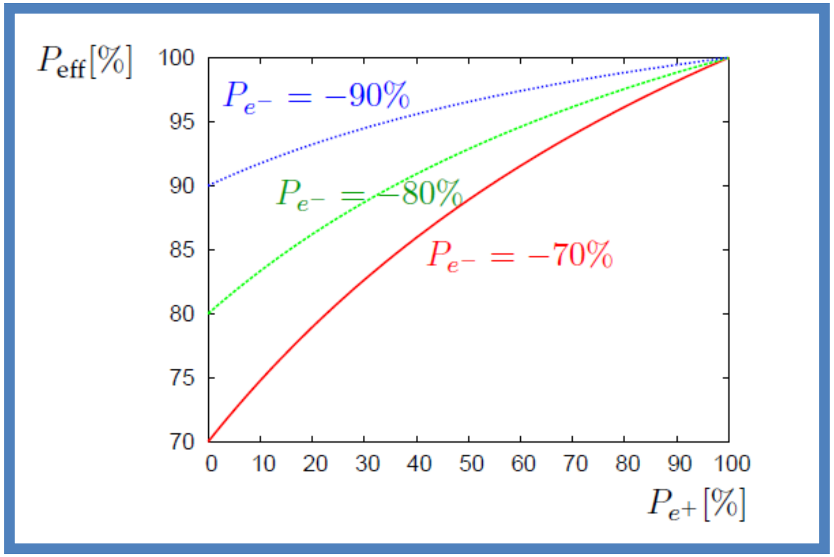
Positron polarisation → further increase in sensitivity

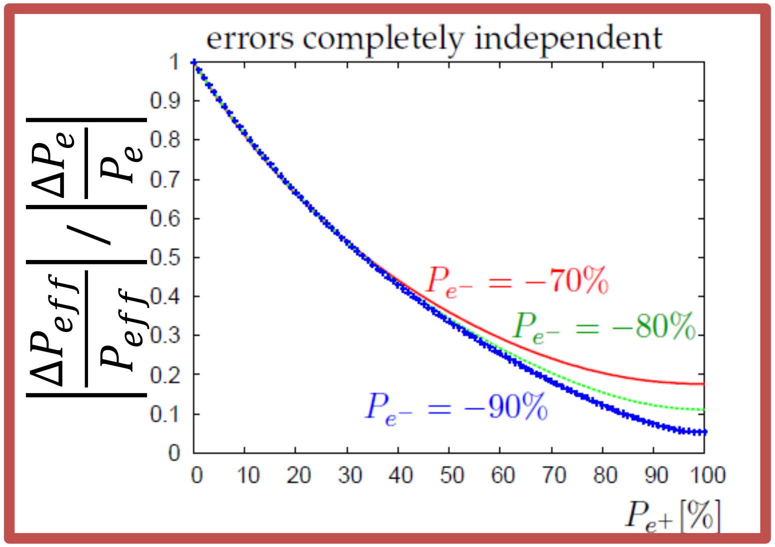
$$\sigma(P_{e^-}, P_{e^+}) = (1 - P_{e^-}P_{e^+})(1 - P_{eff}A_{LR})\sigma_0$$

Increase by up to 50% of x-section

$$P_{eff} = (P_{e^-} - P_{e^+})/(1 - P_{e^-}P_{e^+})$$

Reduce sensitivity to polarisation calibration





Moortgat-Pick et al.,
Physics Reports 460 (2008) 131–243

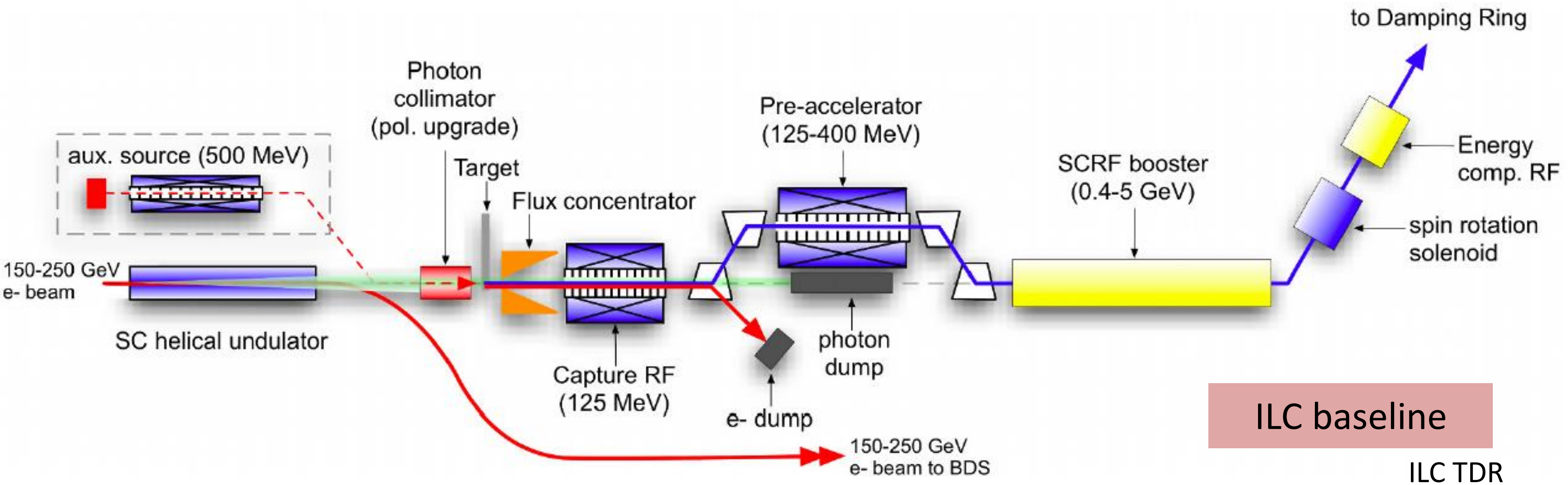
BEH physics and SUSY searches → background discrimination

Polarized positron sources (undulator)

Positrons historically produced by e- beam impinging on few X0 high Z target
→ unpolarized
→ 4×10^{10} @ 120Hz = $4.8 \times 10^{12}\ s^{-1}$

Polarised positrons require circularly polarized photons on thin target

ILC design:
→ at least 30% polarisation (60% better, upgrade option of the baseline)
→ 2×10^{10}/bunch w/ 1312 bunches @ 5Hz = $1.5 \times 10^{14}\ s^{-1}$



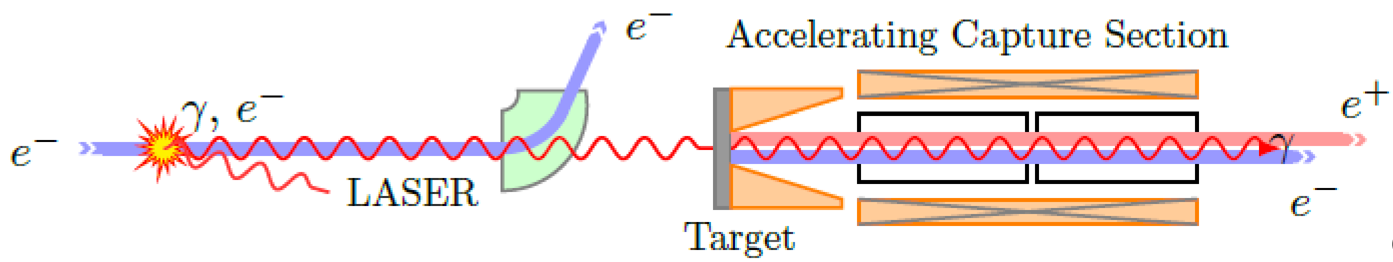
ILC baseline

ILC TDR

Polarized positron sources (Compton)

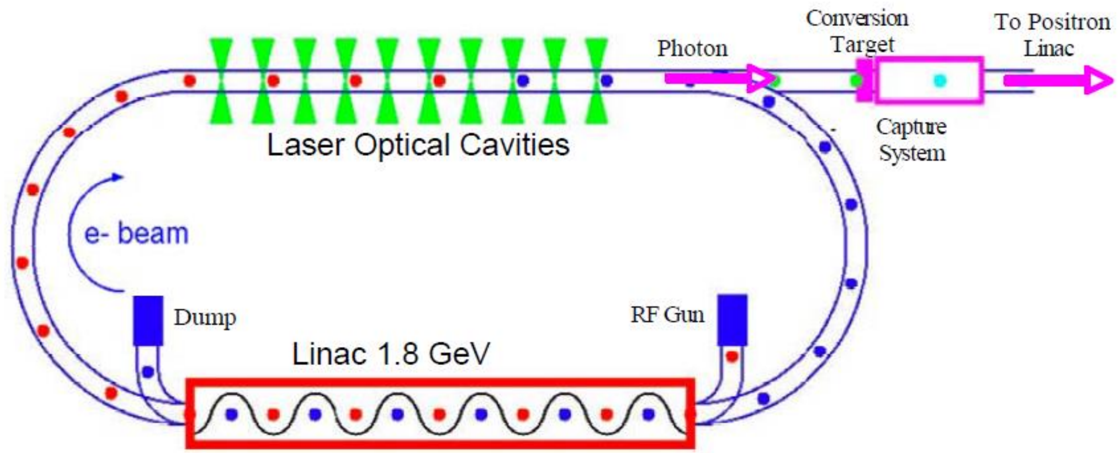
Polarized postitron source with the required flux and polarisation not (yet) demonstrated

Alternative to helical undulator based on Compton backscaterring



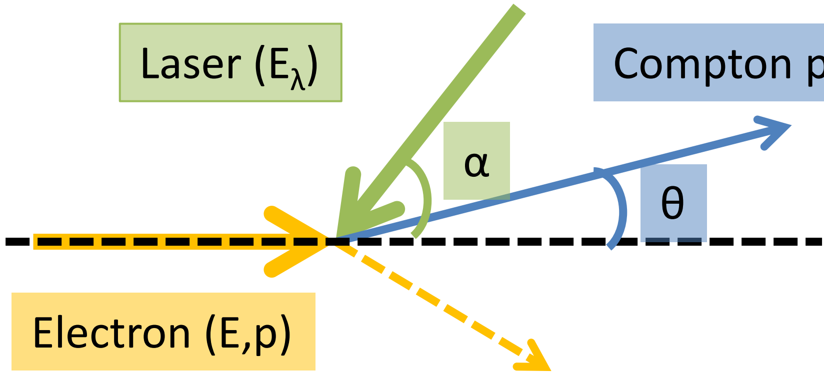
Chaikovska, PhD thesis

Energy Recovery LINAC scheme



The Compton backscatering process

Spin-averaged behaviour governed by Klein-Nishina formula



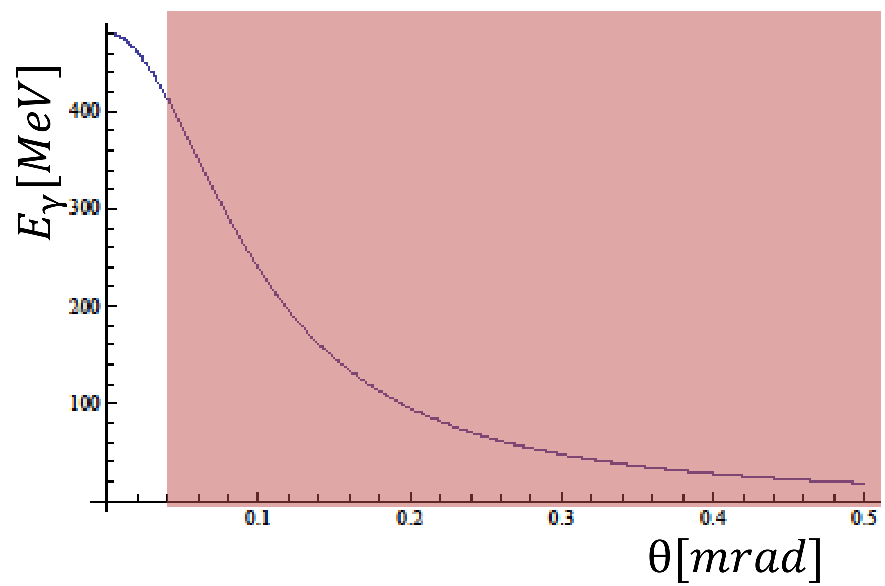
$$E_\lambda = \frac{hc}{\lambda} = 1.2eV \ @ \ 1\mu m$$

$$E = 5\ GeV$$

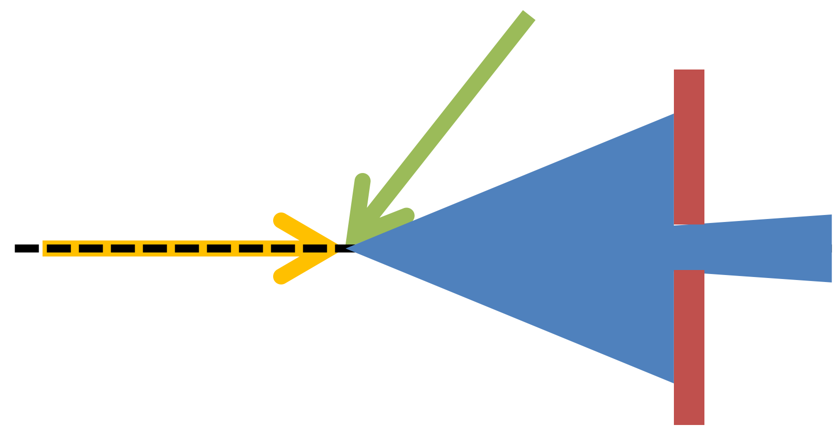
$$E_\gamma \simeq E_\lambda \frac{4\gamma^2}{1+\gamma^2\theta^2} \approx 400\ MeV$$

Low divergence photon source at high energies

$$\theta_{1/2} \simeq \frac{1}{\gamma} \approx 10^{-4}\ rad$$

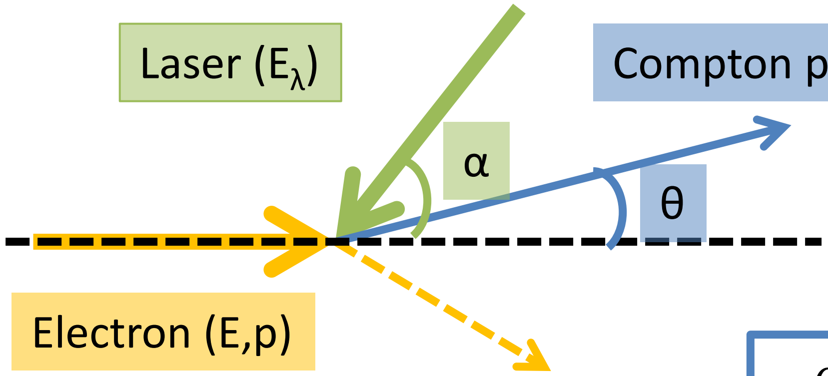


Monochromaticity improved by collimator



The Compton backscatering process

Spin-averaged behaviour governed by Klein-Nishina formula



$$E_\lambda = \frac{hc}{\lambda} = 1.2 eV \; @ \; 1 \mu m$$

$$E = 5 \; GeV$$

$$\frac{d\sigma}{d\cos\theta} = \frac{2\pi\alpha^2}{2m^2 + s\,(1 - \cos(\theta))} \simeq \frac{2\pi\alpha^2}{s\,(1 - \cos(\theta))}$$

Mild energy dependence of the cross-section

$$\frac{s - m^2}{m^2} \simeq 4\gamma \frac{E_\lambda}{m}$$

$$\sigma \simeq \frac{8\pi\alpha^2}{3m^2}\left(1 - \frac{s - m^2}{m^2}\right) \simeq 0.66 \; barn$$

The cross-section is very small (sic)

Basic requirements for a high-brilliance source

$\sigma \simeq 0.5\ barn$

$P_{laser} = N_q E_\lambda f_{rep} \approx 500W$ with $E_\lambda \approx 1.2$ eV

$f_{rep} \approx 50MHz$

$$n_\gamma = \sigma L = \sigma \frac{N_e (P_{laser}/E_\lambda)(f_{col}/f_{rep})}{4\pi\sigma_x\sigma_y}$$

$n_\gamma \approx N_e\,(f_{col}/f_{rep})$

$\sigma_x \approx \sigma_y \approx 0.1mm$

Exemple :

→ $f_{col} = f_{rep}$, $N_e=10^{10}$

→ Photon to positron conversion factor ~1%

→ $N_{e+}=10^{14}$ required (ILC)

→ Too large power required in cavity (500kW state of the art)

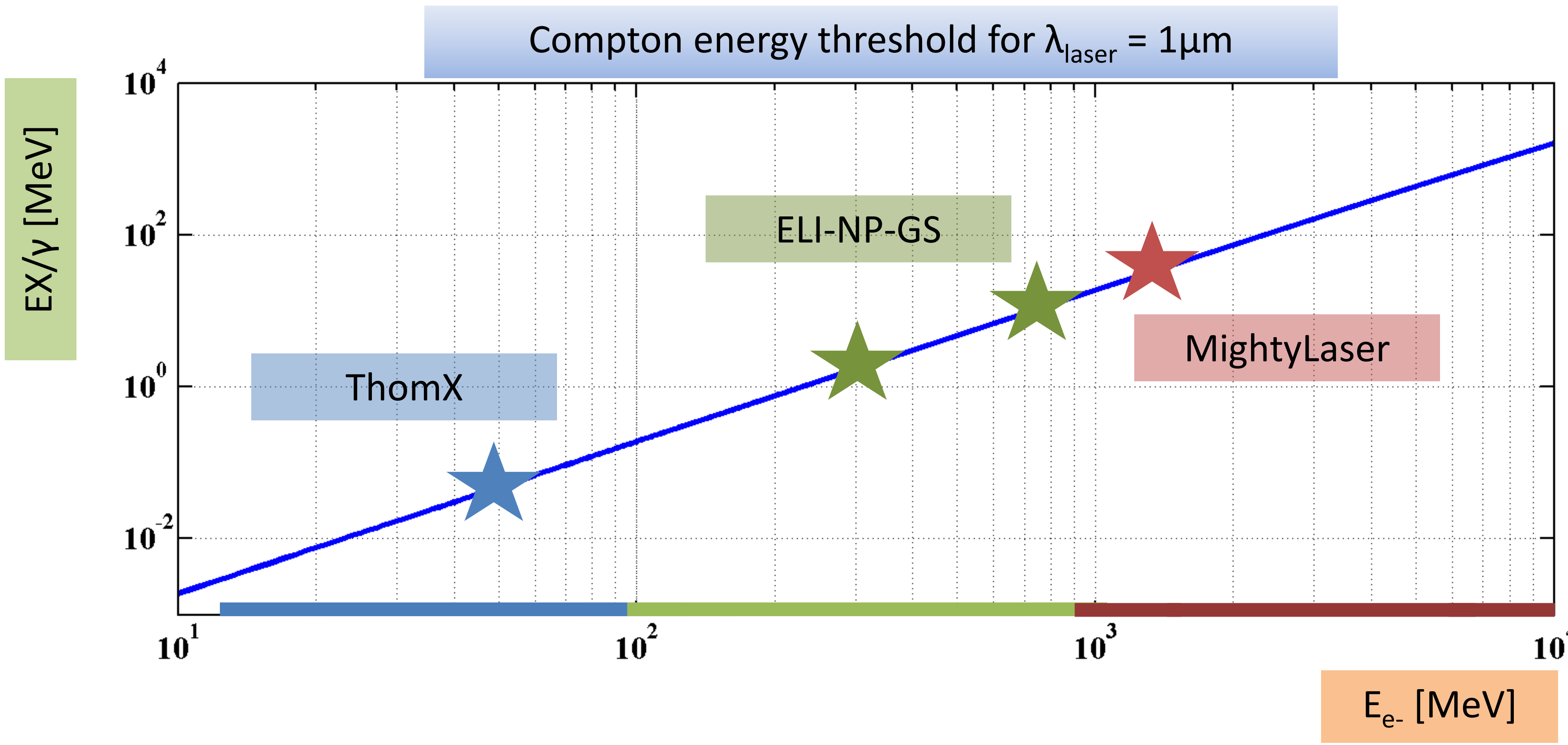
Challenging !!!

→ power

→ cavity stacking

→ top up in damping ring

Applications of Compton scattering: $e^- + h\nu \rightarrow e^- + X/\gamma$



~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
…

R&D work at LAL: MightyLaser

R&D program on radiation sources at LAL

R&D program ongoing at LAL and KEK on enhancement cavities for positron sources

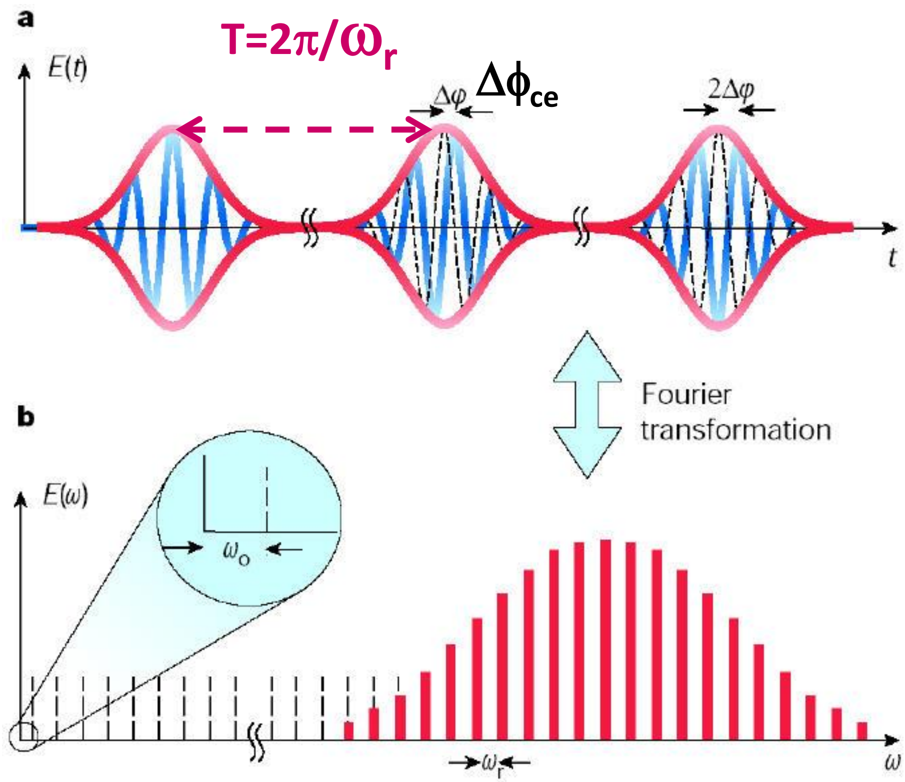
More general context: two paths investigated

High enhancement cavities	High laser power
High flux → High collision rate → electron ring	High beam quality → LINAC (emittance) → optical circulators
R&D with ThomX & MightyLaser	ELI-NP-GBS

Issues: oscillator phase noise, thermal effects, alignment, synchronisation, …

Properties of passive mode locked lasers

The whole comb must be locked:
dilatation (f_{rep})
translation (f_{CEP})



T. Udem et al. Nature 416 (2002) 233

$$F = \frac{\nu}{\Delta\nu} = 30000$$

$$\nu = 178.5MHz$$

$$\Delta\nu = 6kHz$$

Phase noise of the laser must be low to lock to a high finesse cavity

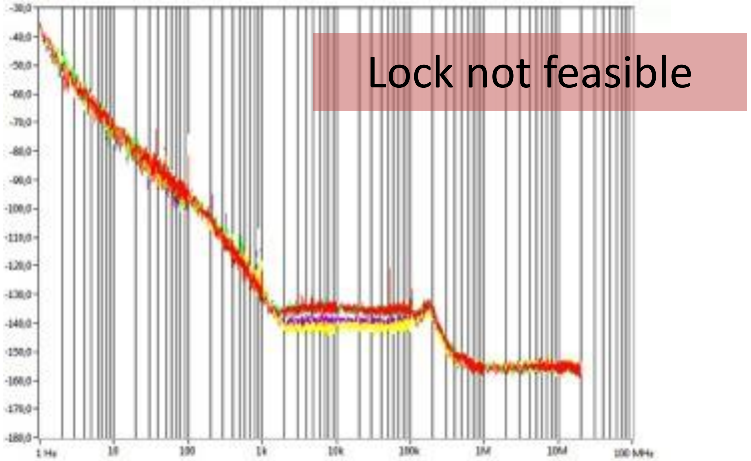
Noise limits coupling

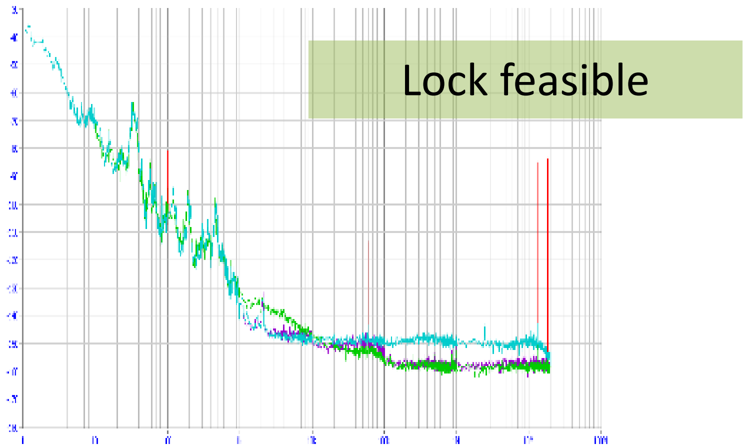
Laser choice: commercial products or not ?

OneFive Genki
- ✓ P = 2 W

OneFive Origami
- ✓ P = 200 mW

Memlo Orange
- ✓ P = 20 mW

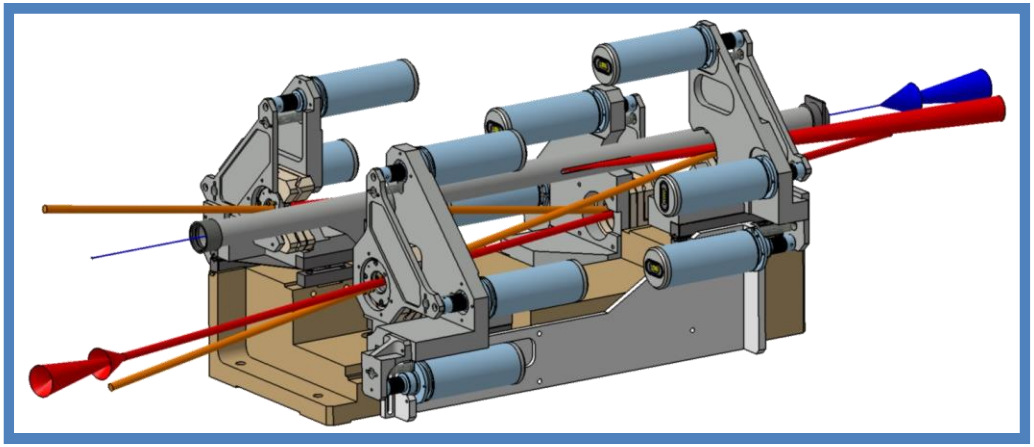


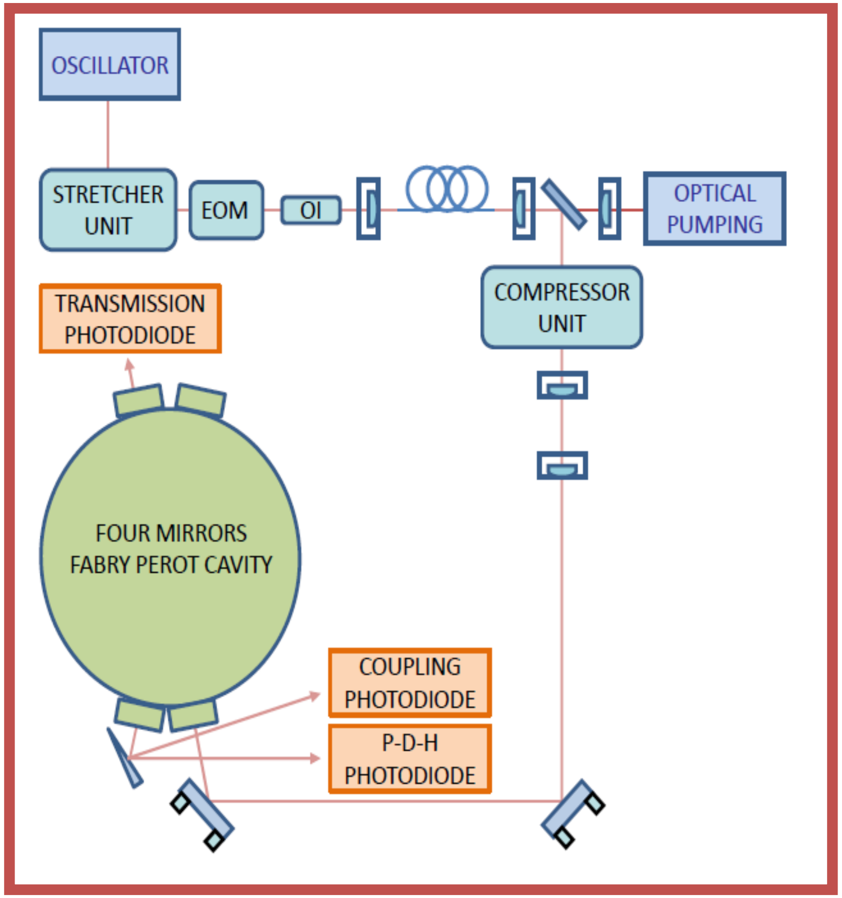


Careful choice of the oscillator required,
control of the phase noise introduced by amplification chain crucial

MightyLaser setup

R&D for polarized positron source for LC
→ circularly polarized laser
→ non planar geometry





Optical round-trip vs waist size
→ 4-mirror cavity
2 plane + 2 spherical mirrors
→ ellipticity

Yb 100fs MENLO Orange @ 178MHz, 20mW
3-stage amplifier → 50W
Stretcher/Compressor (thermal issues in fibers)
Sold fibers from Oscillator to output of amplifier

10MHz feedback required

Installation of the cavity

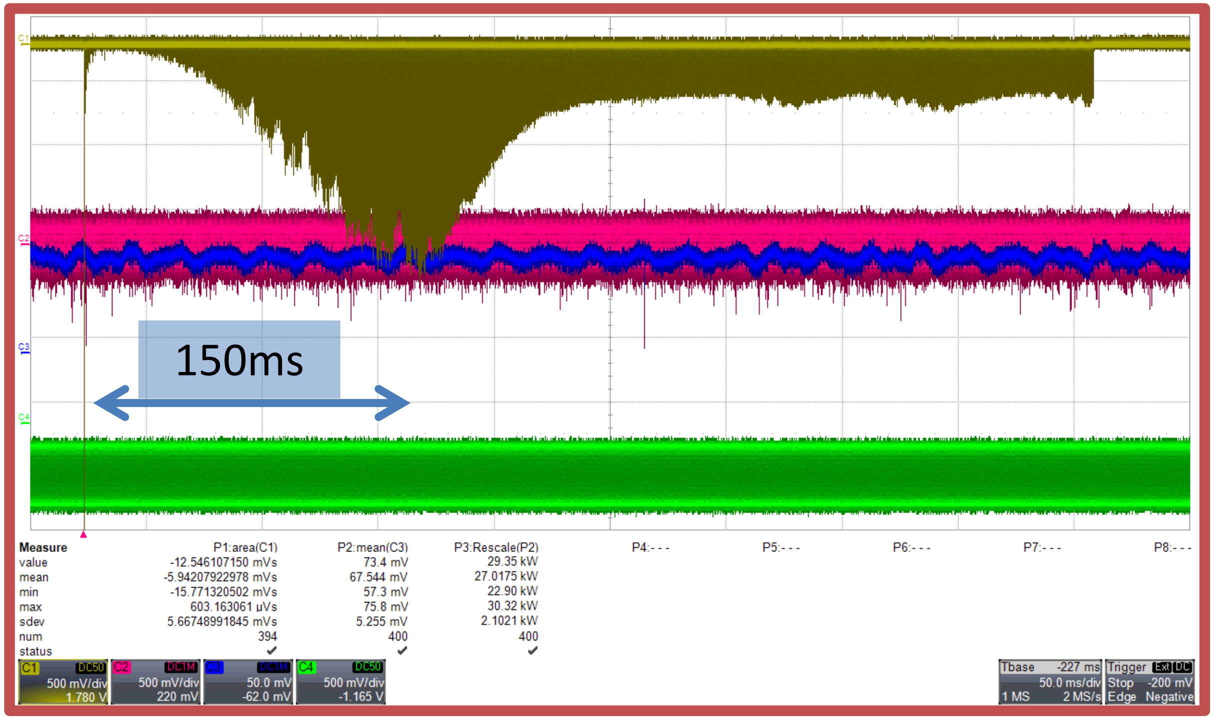
MightyLaser preliminary results

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

march'11 results
→ finesse 1000π
→ ~10W incident laser power
→ 10^6 γ/s @ ~25MeV
→ 0.2 kW (continuous regime)

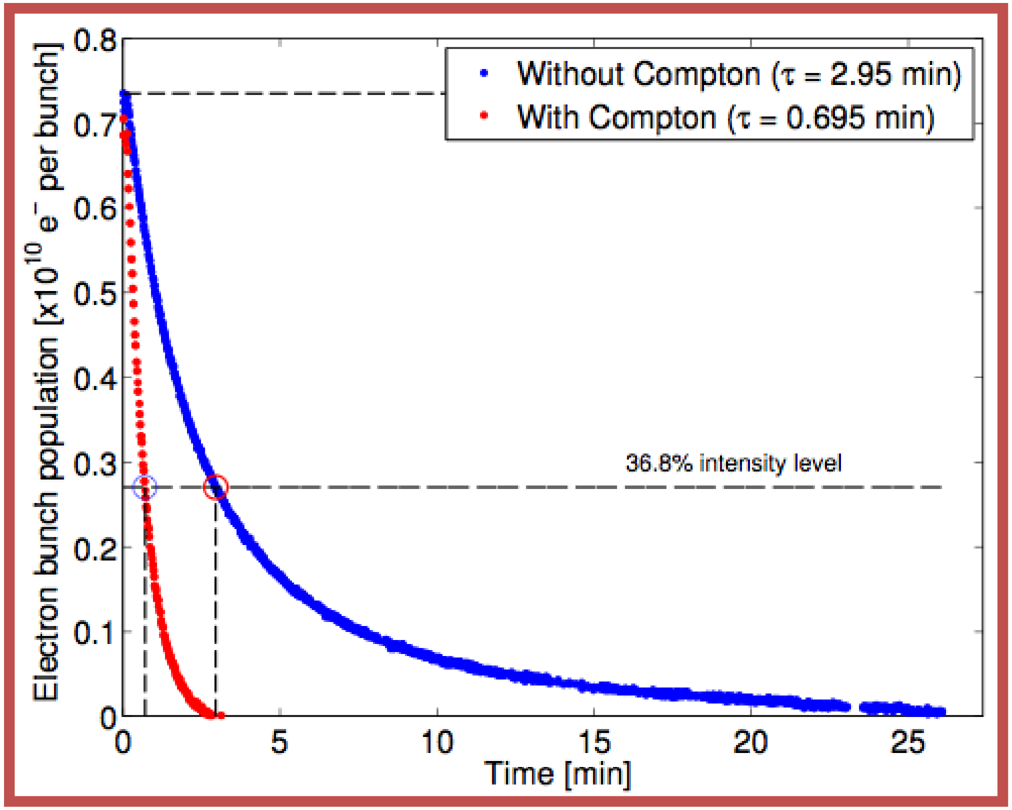
T. Akagi *et al* 2012 *JINST* **7** P01021
J. Bonis *et al* 2012 *JINST* **7** P01017

Evolution of the transverse size of the beam



MightyLaser preliminary results

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



December '13 results:
→ finesse ~10000π
→ 50W incident laser power
→ >100 γ/crossing @ ~25MeV
→ >100kW (transient regime)
→ 40kW (continuous regime)

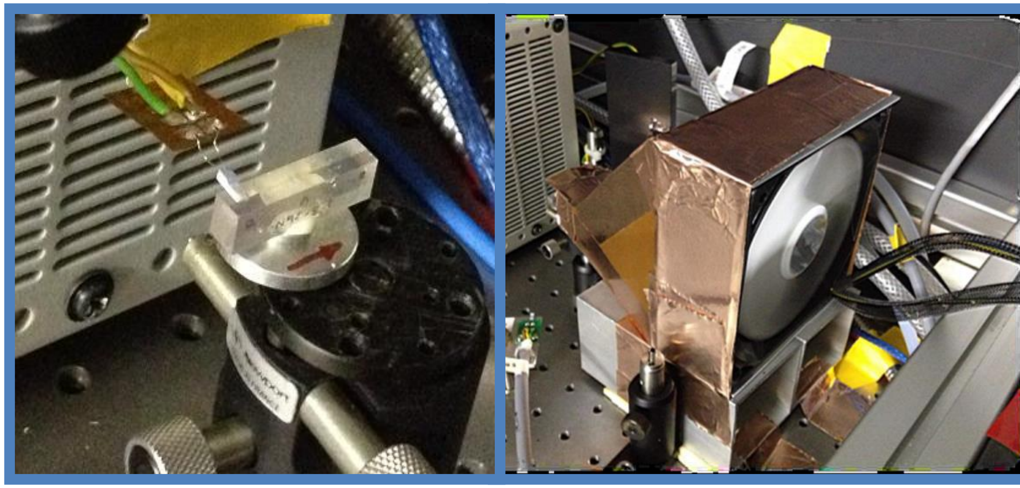
~10^8 γ/s roughly consistent with expectations

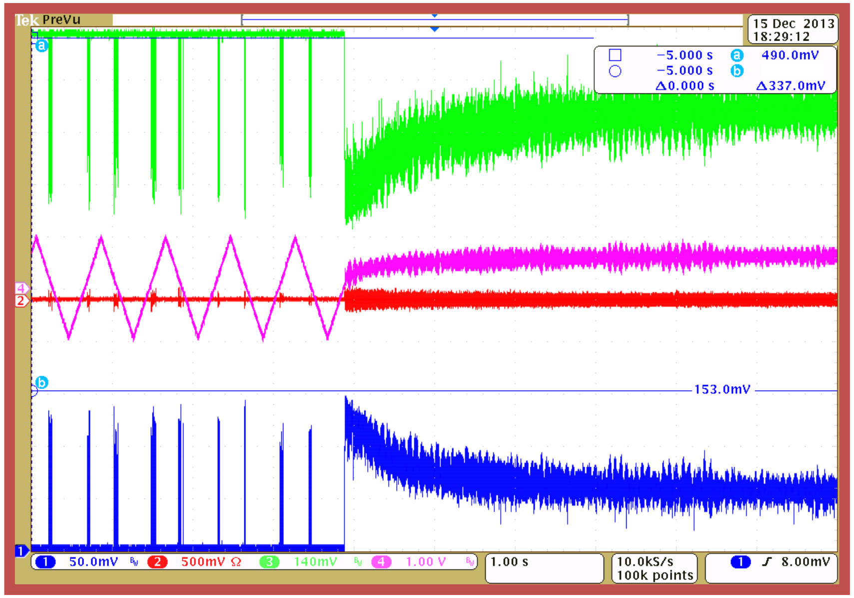
MightyLaser issues

Several bottlenecks identified:

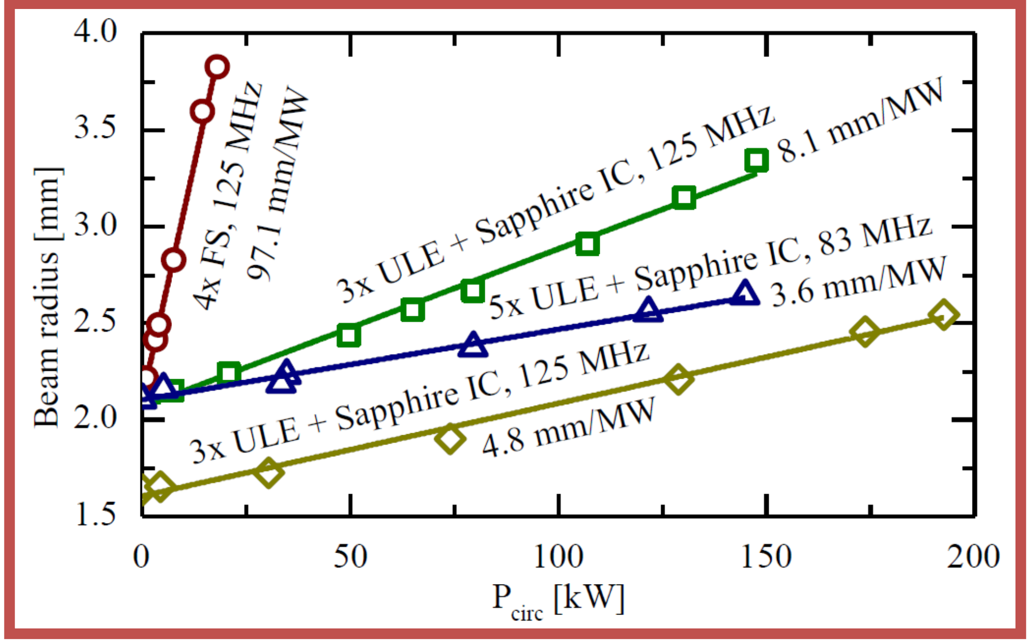
Thermal effects in compressor (CVBG)
Thermal effects in cavity
Oscillator noise

Use low expansion substrate…





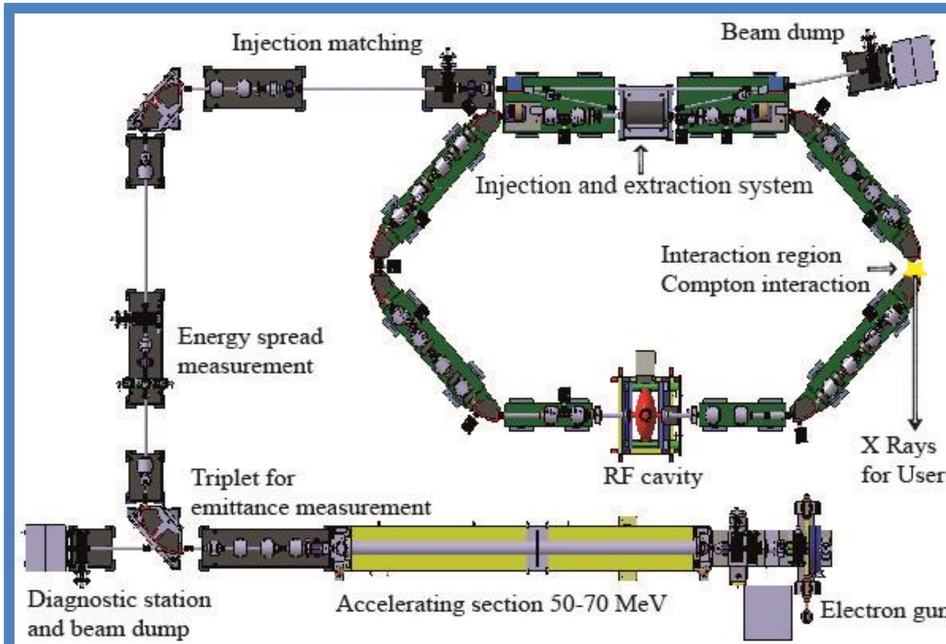
From H. Carstens et al., ASSL JTh5A (2013) 3

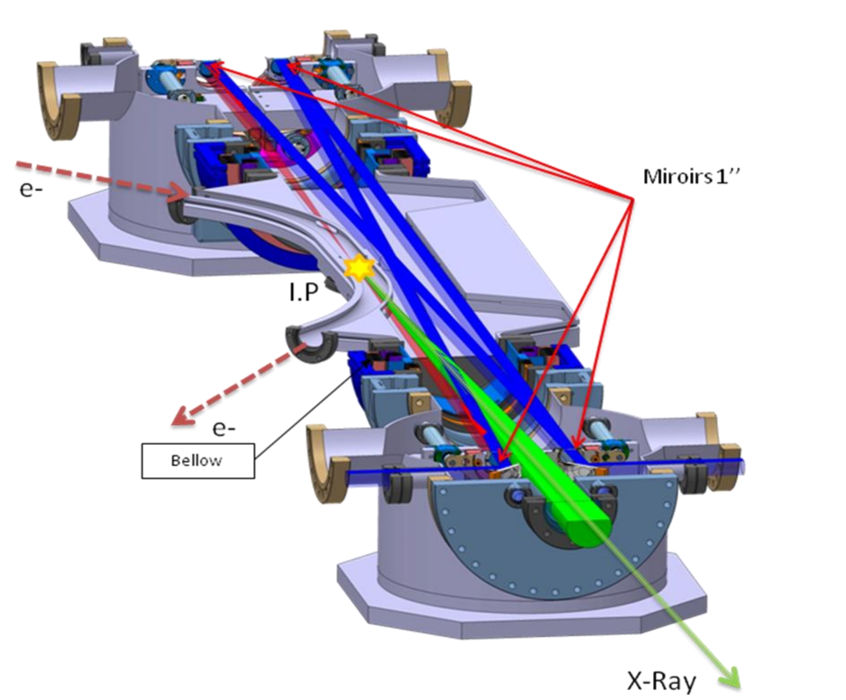


The ThomX project:
Implement solutions to MightyLaser issues

ThomX

~50 MeV ring, 1nC
→ electron dynamics complex
17.8MHz collision rate (35.6MHz cavity)
300kW expected in cavity
commissioning in 2016
Applications: medical and cultural heritage





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

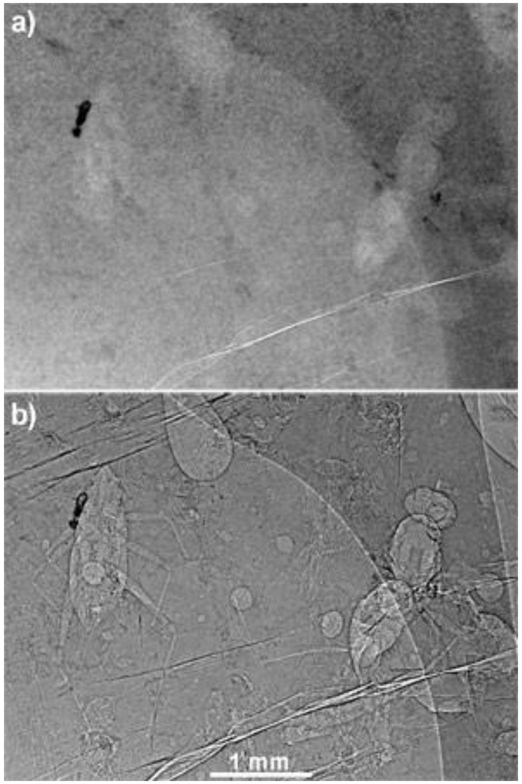
Pursue R&D of MightyLaser
Try to improve stored power by a factor 10

Programme Investissements d'avenir de l'Etat ANR-10-EQPX-51. Financé également par la Région Ile-de-France. Program « Investing in the future » ANR-10-EQOX-51. Work also supported by grants from Région Ile-de-France.

ThomX applications

Transfer techniques developped at the ESRF (Grenoble) & SOLEIL (Saclay)
→medical field: ESRF, INSERM (Grenoble)
→ Cultural heritage: formerly with C2RMF CNRS (Louvre) and now LAMS (Archeology)

Phase contrast



http://www.esrf.eu/news/general/amber/amber/

absorbtion-edge imaging on heavy elements (pigments)

J. Dik et al., *Analytical Chemistry*, 2008, *80,* 6436

The ELI-NP-GBS project:
A complementary strategy

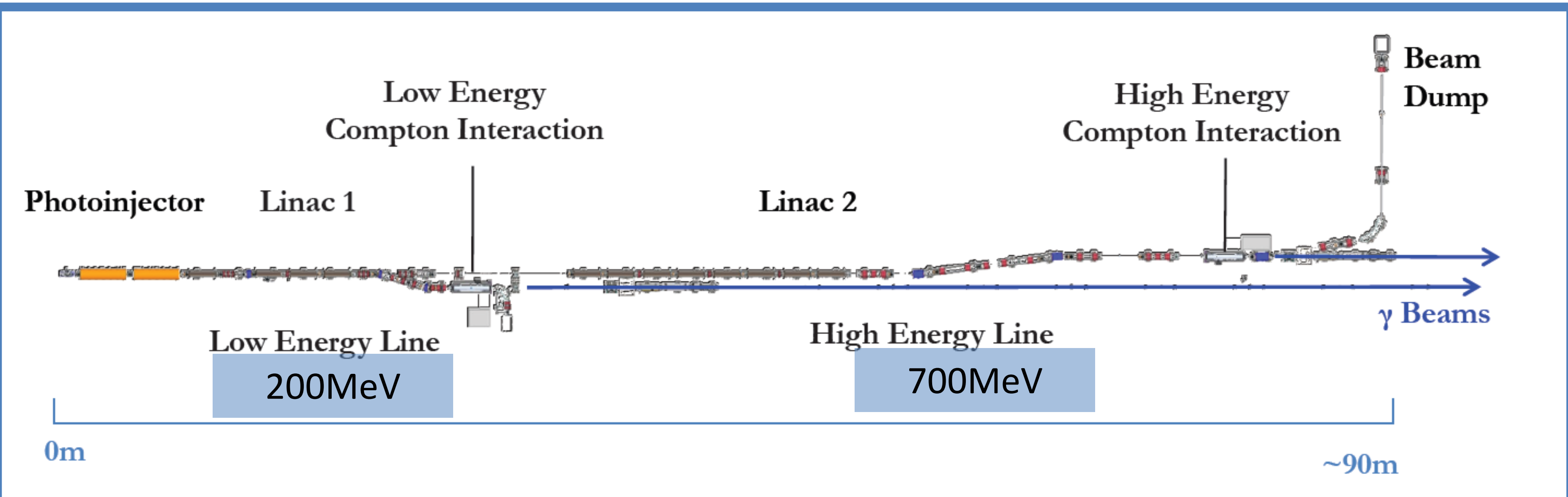
ELI-NP-GS in a nutshell

European Collaboration for the proposal of a Gamma-Beam System to the ELI-NP Project

ELI TDR in preparation

250pC hybrid S and C band technologies
32 trains separated by 15.6 ns
100Hz repetition rate

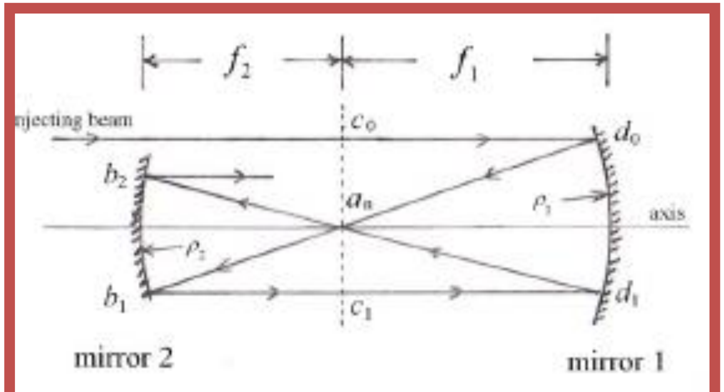
commissioning in 2016 and 2018

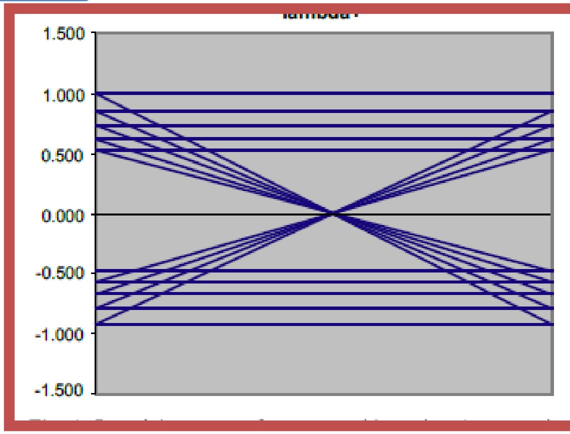


ELI-NP-GS circulator

$$n_\gamma = \sigma L = \sigma \frac{N_e (P_{laser}/E_\lambda)(f_{col}/f_{rep})}{4\pi \sigma_x \sigma_y}$$

f_{col} ~100Hz
→ Not a cavity !!!





Confocal circulator

Rollason, NIMA256(2004)560
Yamane, KEK-notes

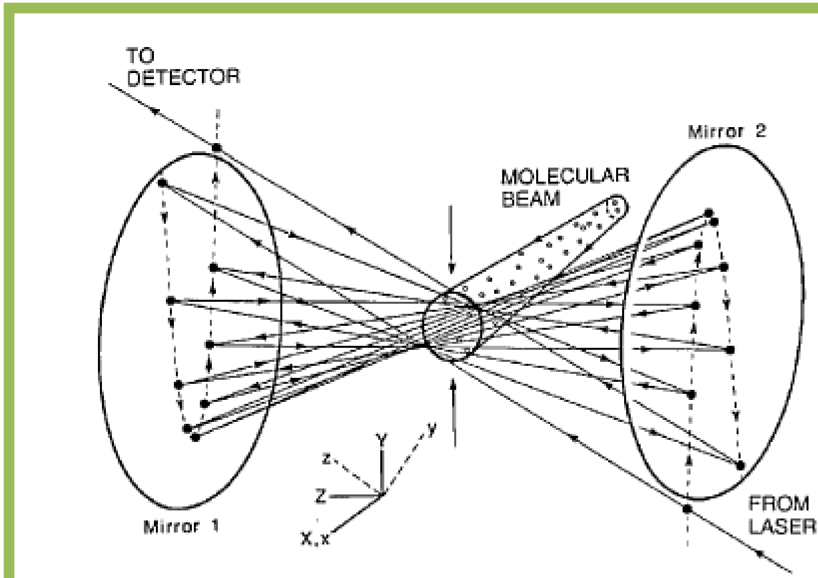
Crossing angle vary

→ γ ray spectrum ☹

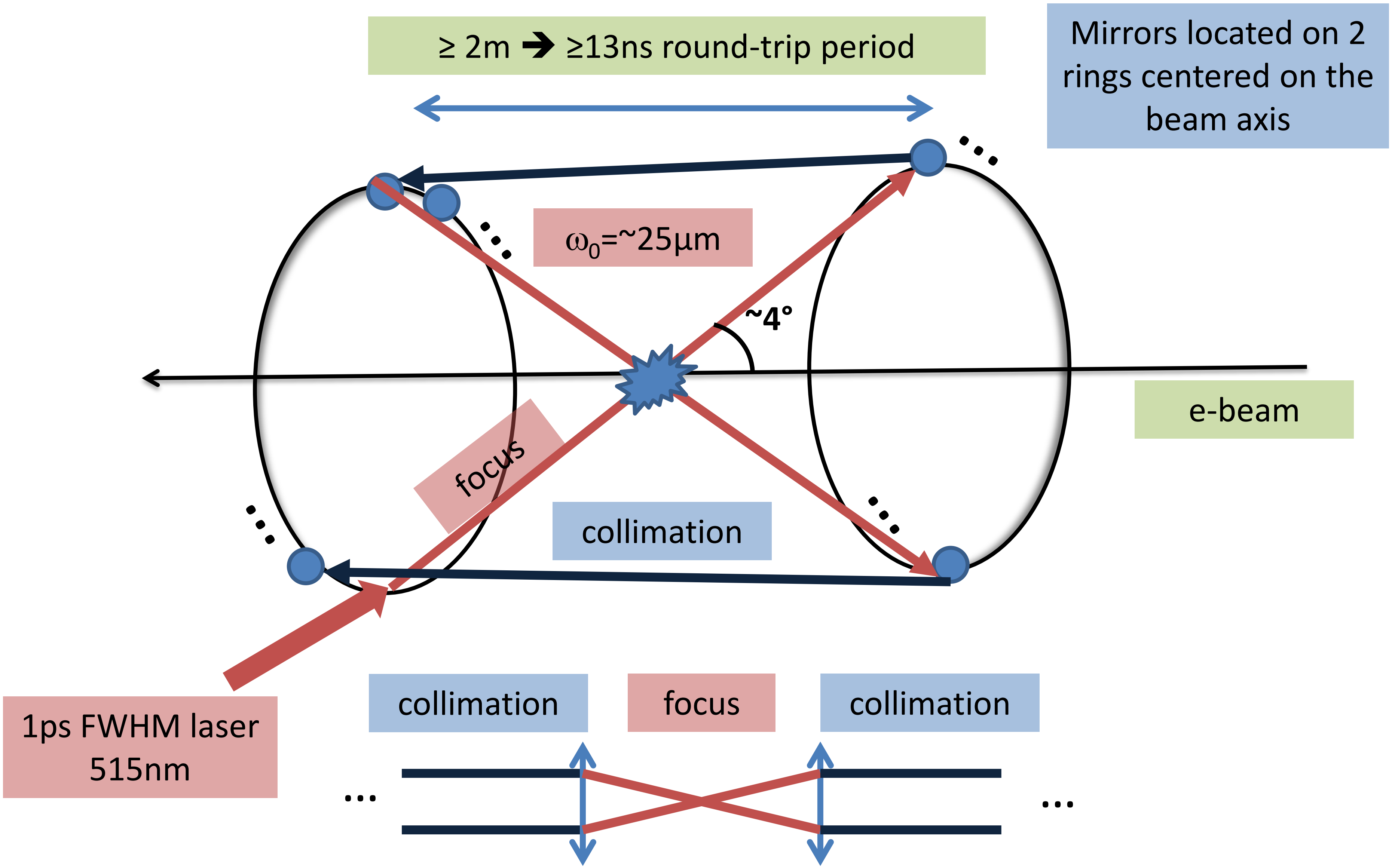
Herriot cell

Herriott, Appl Opt3(1964)523)

Wild focussing region
→ Luminosity ☹



ELI-NP-GS naïve solution

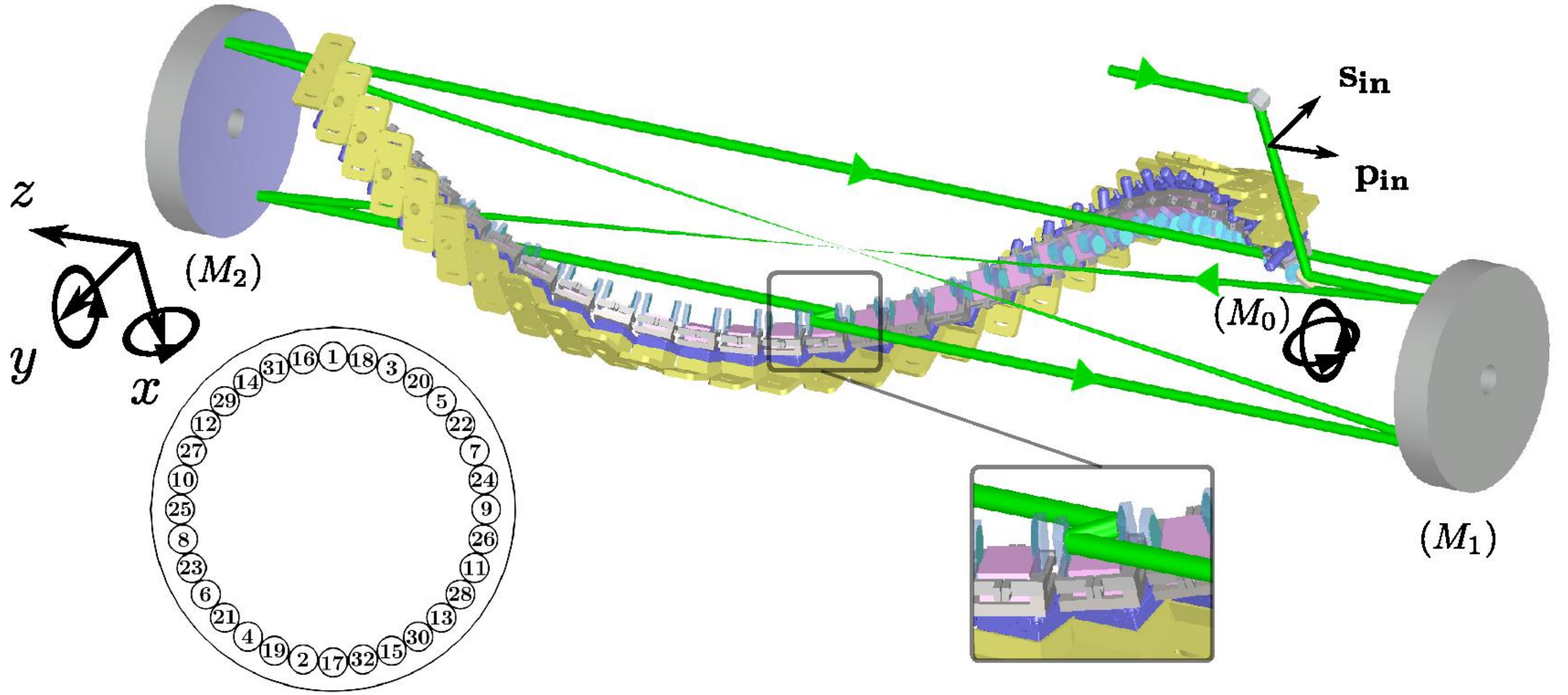


ELI-NP-GS optical system

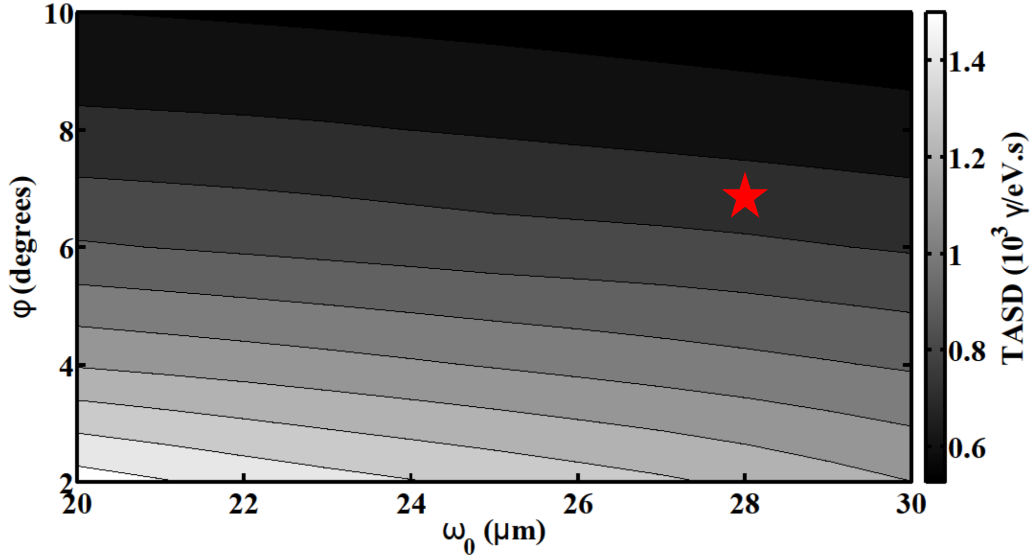
Tight constraints on photon beam:
→ divergence <0.2mrad
→ beam spot at 10m <1mm
→ bandwidth (BW) <0.5%
→ av. spectral density @20MeV: $8x10^3$ $(s.eV)^{-1}$
→ brilliance $1x10^{22}$ /(s.mm².mrad²0.1%BW)

K. Dupraz et al, submitted to Phys. Rev. ST Accel. Beams

laser: >200mJ@100Hz, 515nm

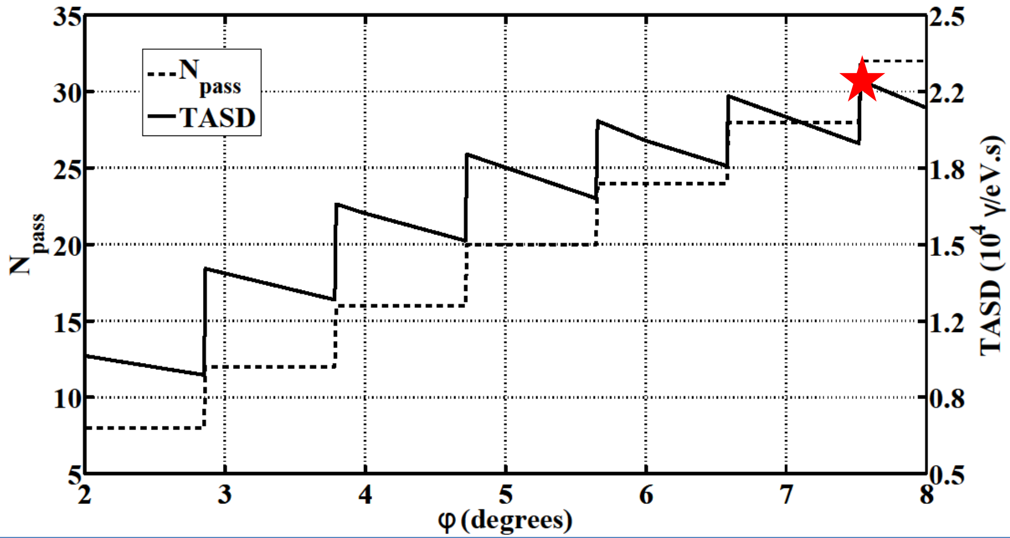


ELI-NP-GS optimisation



Extensive simulation
under Matlab and CodeV

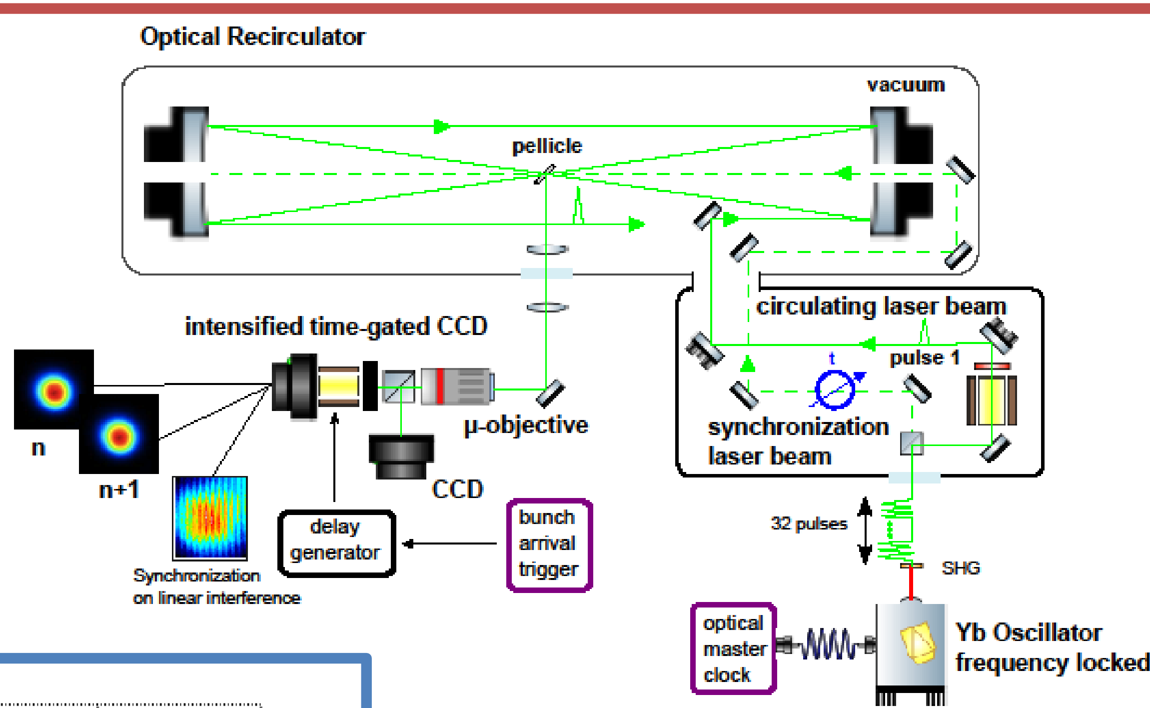
K. Dupraz et al, submitted to
Phys. Rev. ST Accel. Beams

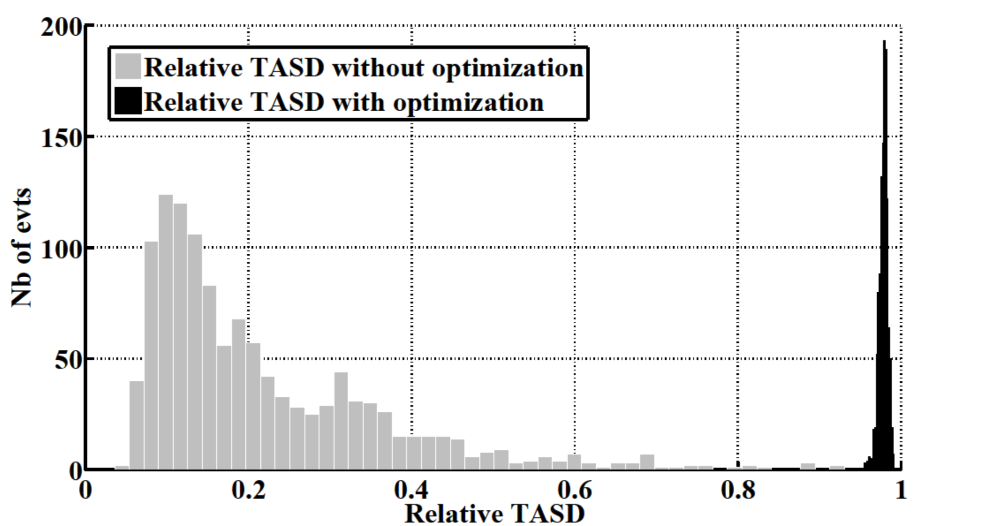


ELI-NP-GS alignement, synchronisation

Challenging:
<10µm alignement required
<200fs jitters required

But feasible ! → interferometry





K. Dupraz et al, submitted to Phys. Rev. ST Accel. Beams

Obtained by means of fringe visibility maximisation

ELI-NP-GS status

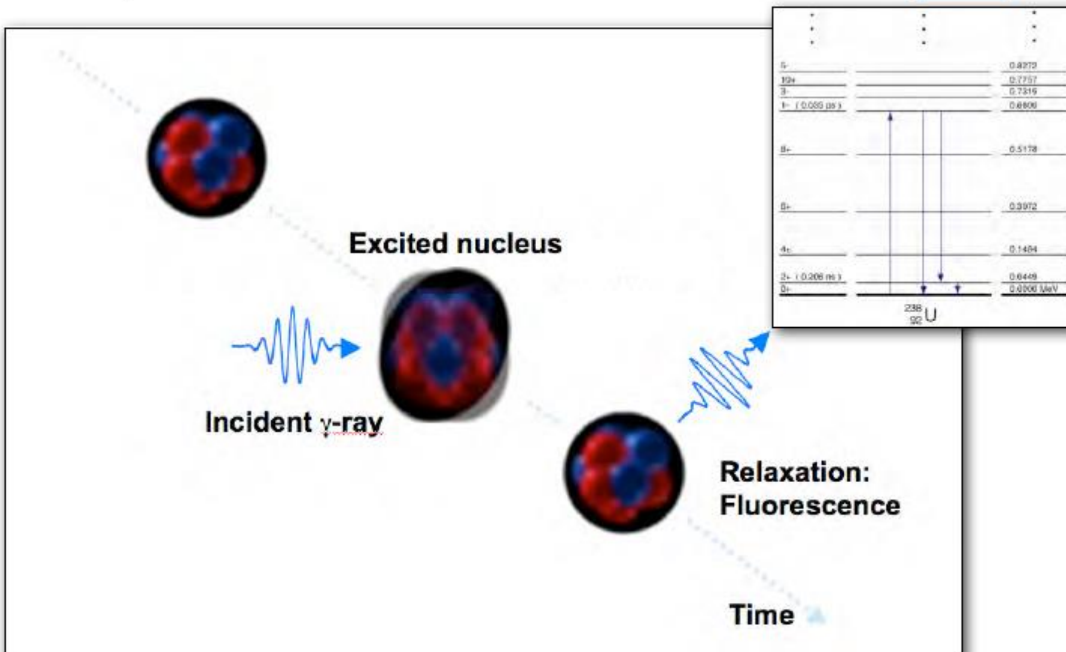
Offer deposited to Romanian contractor on the 3rd of February…

while the construction of the building progresses well !

ELI-NP-GS applications

Brand new gamma source with excellent spectral properties (100x state of the art)
Wide range of applications will certainly additionnally show up

Nuclear resonance fluorescence is easily excited narrowband laser-Compton sources



Nuclear Resonance Fluorescence depends upon the number of protons and the number of neutrons in the nucleus and is an isotope-specific material signature

NRF is the ID-card of nuclei →nuclear waste package management, non proliferation, etc.

Conclusion

Ultimate goal reach few MW in cavities: required for positron sources at ILC

	ThomX	ELI-NP-GS
Flux	10^{11} - 10^{13} γ/s	10^{9} γ/s
Bandwidth	1% - 10%	0.5%
Divergence	<10 mrad	50 - 100 μrad

High enhancement cavities

MigtyLaser lessons: R&D required
Thermal effects inside cavity
Compressor heating
Choice of oscillator

Expect several 100kW for ThomX

Still a lot of work ahead
→ Try to maximise the flux

High laser power + circulator

Tight constraints on:
Alignment
Synchronisation
Optics quality (large impinging energy)

ELI-NP-GS spectral density challenging

Exciting and hard times ahead:
→ commercial offer !!!