SAPPHIRE day
(CERN, 19/02/2013)

Alessandro Variola (LAL)
variola@lal.in2p3.fr

LAL Compton collision studies and the Thom-X project

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-EQPX-51. Work also supported by grants from Région Ile-de-France.*

Outlook

- LAL Compton Program and projects
- Luminosity studies
- The ThomX project
- Conclusions

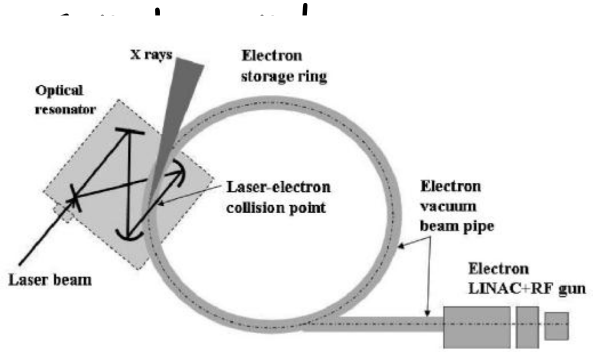
The context : LAL Compton program

BASIC FRAMEWOK -> Photon sources based on Compton backscattering effect. High average flux (frep) in X and γ domain

- Started with the PLIC project (pulsed FP cavity for the ILC polarimetry)
- Continued in the framework of the polarized positrons source proposals for the next LC
- Collaboration with theorist of INP Novosibirsk (V.Strakovenko)
- Starting of the ThomX collaboration for a compact X Ray source
- Mightylaser project @ ATF-KEK Japan (gamma rays but thinking to the ThomX project)
- 2011 ThomX approved by the EQUIPEX program
- ELI Romania project and optical re-circulator for gamma sources (See L.Serafini Talk). Preliminary study done…waiting for funding decisions.
- ???????

Studies and considerations on luminosity

- Optimal luminosity of Ring source coupled with a Fabry Perot cavity (laser stacking)
- Collision between a laser amplified in a passive circulating bunch in the ring



- Constraints and boundary conditions:

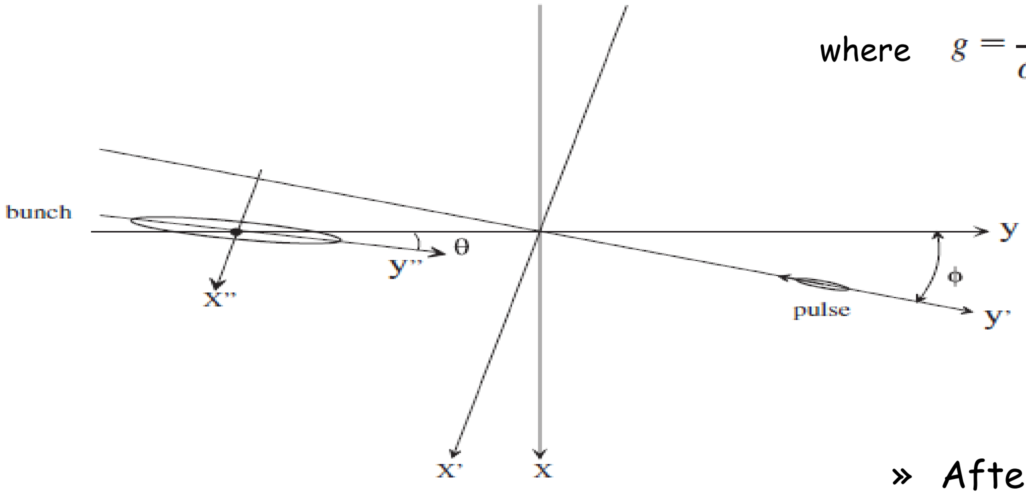
1) Usually bunch length longer than laser pulse (ring instabilities, WF, CSR…).
2) Electron beam can be crabbed
3) Technological constraints :
   a) there is a limit in which the mirror will not with stand the flux. A crossing angle, for high luminosity applications, is needed.
   b) can we assume that Ibunch and Plaser are constant independently form the frep?)
4) Polarization
5) Integration of the FP cavity in the accelerator

Tilted crossing

- The pulse cannot be crabbed……optimizing only t….
- We can define the geometrical luminosity factor as

$$G = \frac{g}{(2\pi)^3} \iiiint \exp\left[-\frac{F(x, y, z, T)}{2}\right] dx dy dz dT,$$

where $g = \frac{(1+\beta\cos\phi)}{\sigma_x\sigma_y\sigma_z\sigma'_x\sigma'_y\sigma'_z}$, •And F is a complex function of $\theta,\phi,\beta,\sigma_{e/\gamma}$



» After integration and reduction of the terms of F:

- $$G(\phi, \theta) = \frac{1}{2\pi\sqrt{\sigma_z^2 + \sigma_z'^2}\sqrt{f_e(\phi,\theta) + f_{ph}(\phi)}},$$

with

$$f_e(\phi, \theta) = \sigma_x^2\left(\frac{\cos(\theta-\phi) + \beta\cos\theta}{1+\beta\cos\phi}\right)^2 + \sigma_y^2\left(\frac{\sin(\theta-\phi)+\beta\sin\theta}{1+\beta\cos\phi}\right)^2,$$

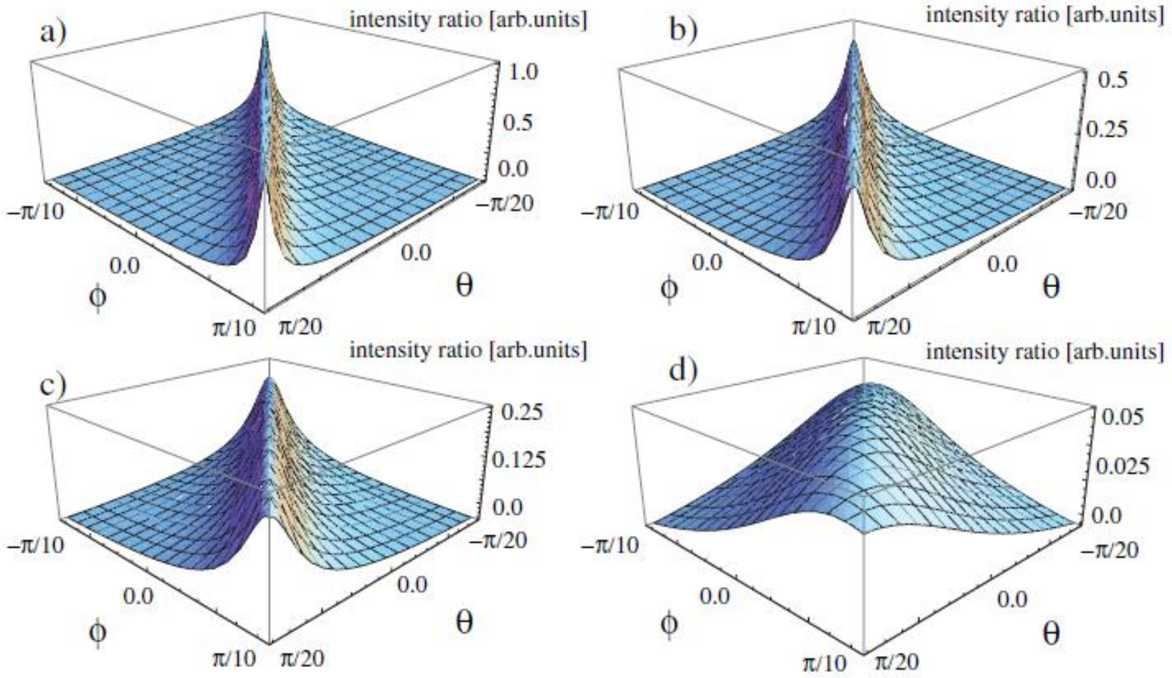
$$f_{ph}(\phi) = \sigma_x'^2 + \beta^2\sigma_y'^2\left(\frac{\sin\phi}{1+\beta\cos\phi}\right)^2.$$

$$\max G(\phi,\theta) \to \min f_e(\phi,\theta); \qquad \theta = \phi/2.$$

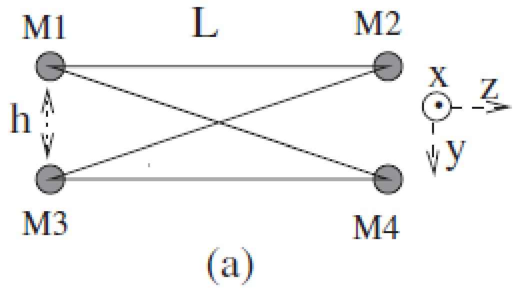
- Finally the gain in respect the 'classical collisions' is $\frac{G_{max}(\phi)}{G(\phi, 0)} = \sqrt{\frac{(\sigma_x^2 + \sigma_x'^2)\cos^2\frac{\phi}{2} + (\sigma_y^2 + \sigma_y'^2)\sin^2\frac{\phi}{2}}{\sigma_x^2 + \sigma_x'^2\cos^2\frac{\phi}{2} + \sigma_y'^2\sin^2\frac{\phi}{2}}},$

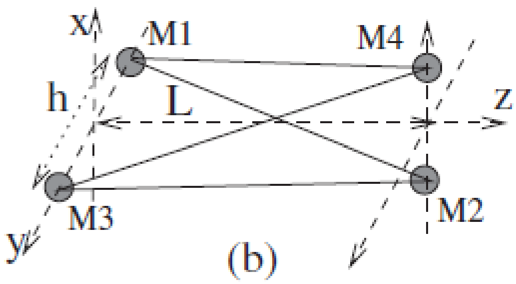
Tilted crossing

- Luminosity gain example: $\sigma_{xy/e\gamma}$ = 50 μm, laser length = 300 μm,
- Bunch length= a) 1.2 cm, b) 6mm, c) 3mm, d) 0.6mm
- In dependence form the parameters we can gain a factor 5-20 in luminosity using long electron bunches (so more charge per bunch…)



It has to be matched with the cavity eigenmodes
Taking care of the tolerances and the polarization



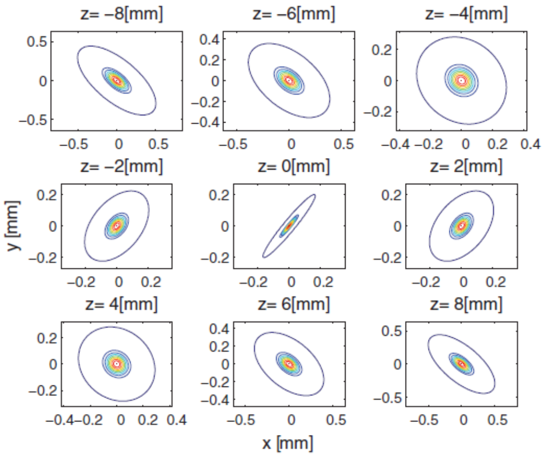


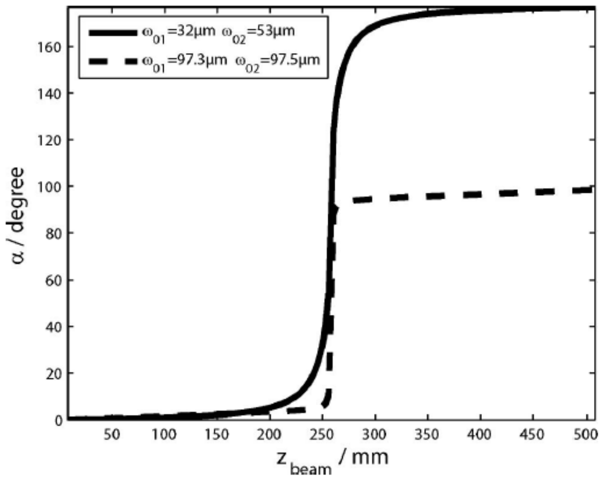
- 4 mirrors cavities:
- Little waist
- Mechanical stability

- 2D Bow tie
- ThomX

- 3D tetrahedron
- Mightylaser

- NUMERICAL SOLUTIONS for the modes





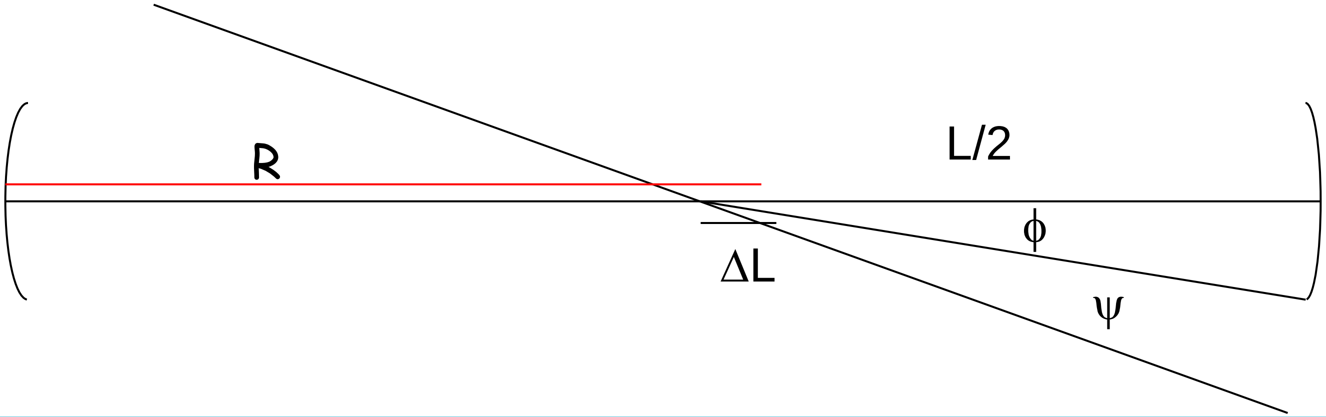
- Ellipse orientation profile vs z for two tetra cavities with different x and y waists

- F.Zomer et al. Applied Optics 48 6651 (2009)

1^{st} parameter => f_{rep}

frep is a question of TEHCNOLOGY
- Gain of the cavity $\Delta\nu/\nu \sim 2\,\lambda\, f_{rep}/c$ Finesse
- Mirrors coating damage ~ f ($\alpha = \Delta L/L$ const)
- At P_{laser} and I_{beam} = const $N_e/N_\gamma \sim f_{rep}$
-Type of accelerator (and beam properties) strongly f_{rep} dependent (ERL,Ring, Linac…)
- ε in theory is not f_{rep} dependent…but it is strongly N dependent and at I constant -> N-> f_{rep}….

- Example : let's assume a two mirror concentric cavity (small waist)
- Once defined the cavity "everything' depends on f_{rep}…..



$$\omega_0^2 = \frac{c\lambda_L}{4\pi\, f_{rep}}\frac{1}{\sqrt{2\alpha}} \quad \text{with}\ \alpha = \frac{\Delta L}{L}$$

$$\omega_{mirror}^2 = \frac{c\lambda_L}{2\pi\, f_{rep}}\sqrt{\frac{\alpha}{2}}$$

$$Tan\phi = \sqrt{\frac{1}{\pi\sqrt{2\alpha}}\frac{f_{rep}}{f_{laser}}}$$

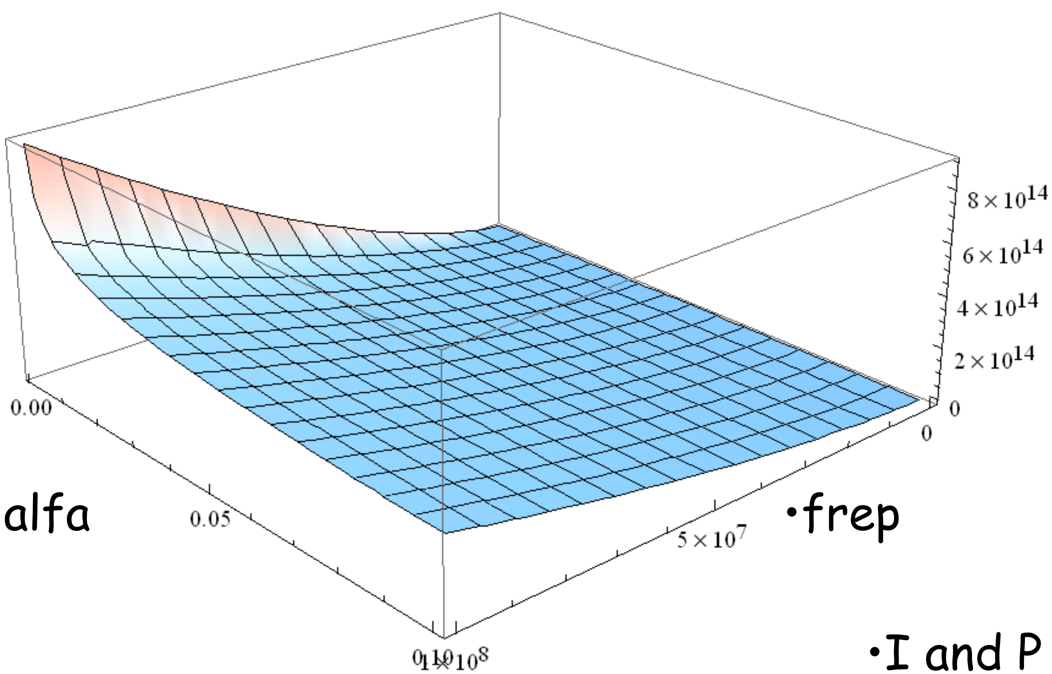
$$\Psi = Max[\frac{4(n)}{\gamma}, \frac{16\, f_{rep}\sqrt{\varepsilon\beta_{mirror}}}{c}]$$

frep…I acc and Laser Power

- Taking the classical luminosity formula with the hypothesis that the beam and the laser pulse have the same transverse dimensions:

$$L = \text{Cost}\ I\ N\gamma\ G = \text{Cost}\ \frac{I\ P\ G}{\text{frep}}$$

•I and P indipendent from f



•alfa

•frep

•I *P ~f

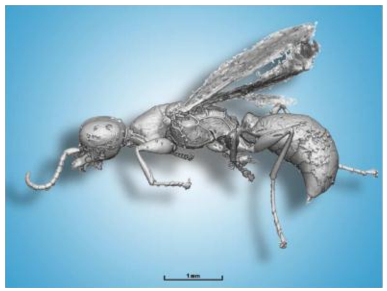
•I and P linear function of f

- The ThomX project

•Cultural heritage and medical science

- Transfer of the SR techniques to these new machines. Many fields can be interested…
- At present two contributors: Medical field (ESRF, INSERM Grenoble)
  Cultural Heritage (C2RMF CNRS – Louvre Museum)

•Painting analysis



•Paleontology

•Non-destructive analysis

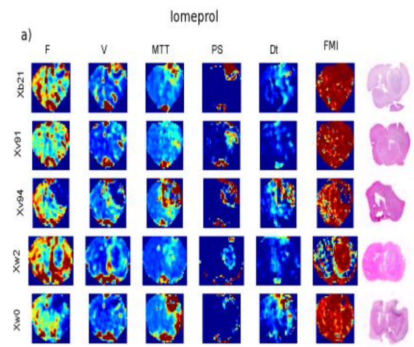
•*K-edge imaging* (Pb→white, Hg→ vermilion…) of a Van-Gogh's painting

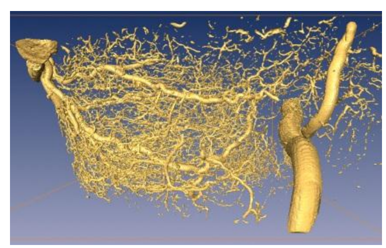
•J. Dik et al., *Analytical Chemistry*, **2008**, *80*, 6436

•Physiopathology and Contrast agents,

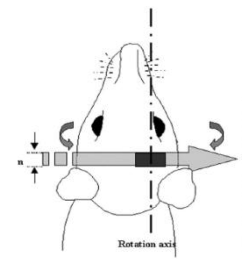
•Dynamic Contrast Enhancement SRCT

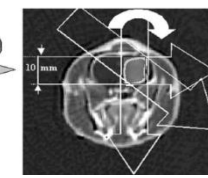
•Convection Enhanced Delivery =>Stereotactic Synchrotron RT





•J Cereb Blood Flow and Metab, 2007. 27 (2):292-303.



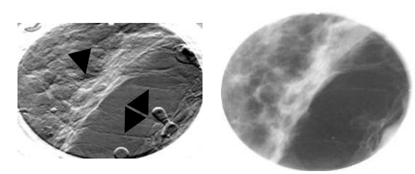


•Biston et al, Cancer Res 2004, 64, 2317-23

•Imaging,

•Mammography

•Microtomography



•Journal of Radiology 53, 226-237 (2005)

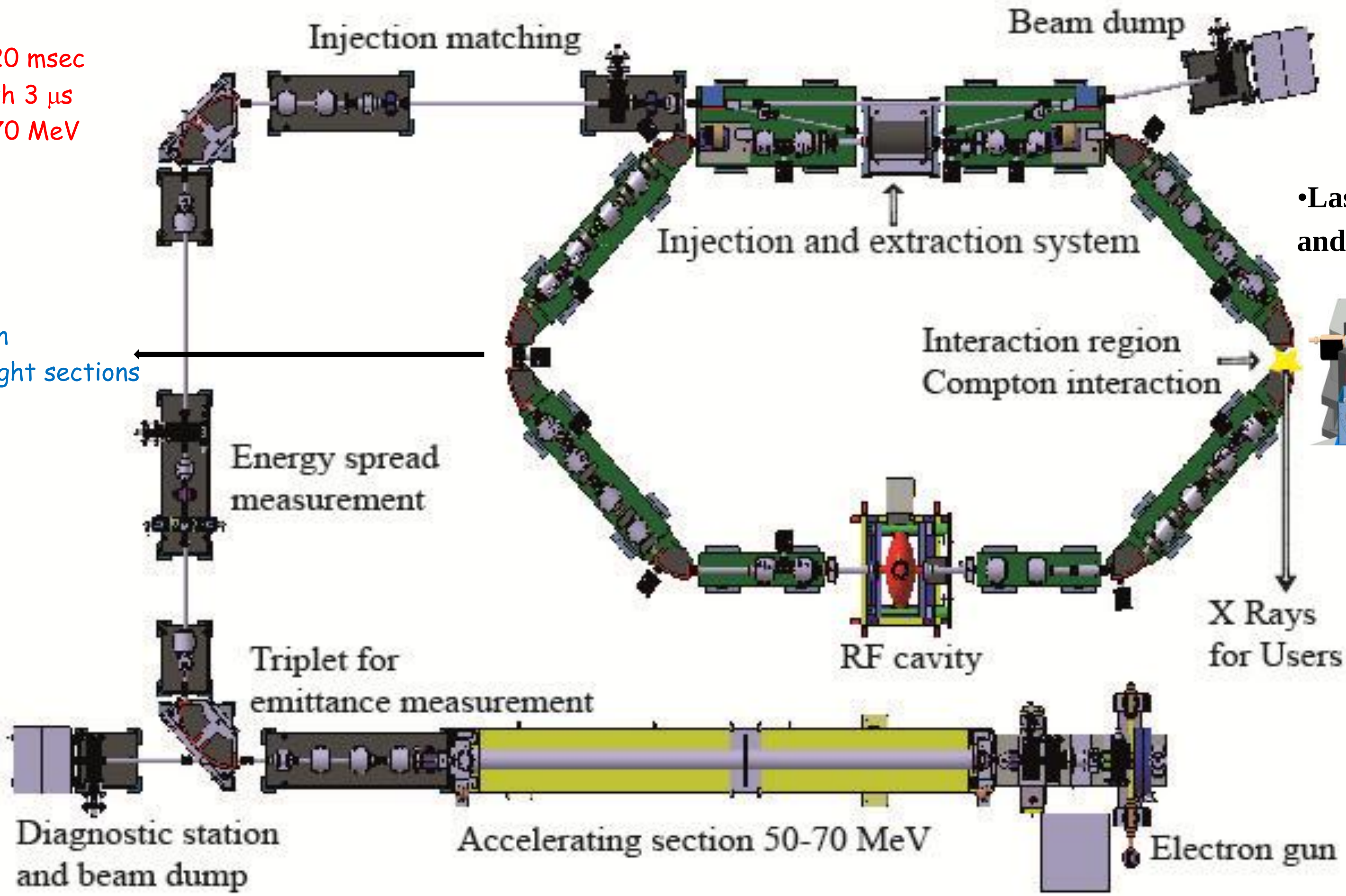
• Acknowledgments to G.Le Duc, P.Walter

How it works

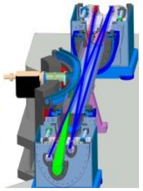
•ThomX scheme and design

- Cycle Frep = 20 msec
- RF pulse length 3 µs
- Energy 50 - 70 MeV

- 2 Ips
- Easy integration
- Frees the straight sections
- CSR line



•Laser
and FP cavity



• Acknowledgments to M.Jore, M Lacroix

Expected beams characteristics

•Injector, ring, laser, Fabry-Perot resonator and the source

Injector	
Charge	1 nC
Laser wavelength and pulse power	266 nm, 100 μJ
Gun Q and Rs	14400, 49 MW/m
Gun accelerating gradient	100 MV/m @ 9.4 MW
Normalized r.m.s emittance	8 π mm mrad
Energy spread	0.36%
Bunch length	3.7 ps

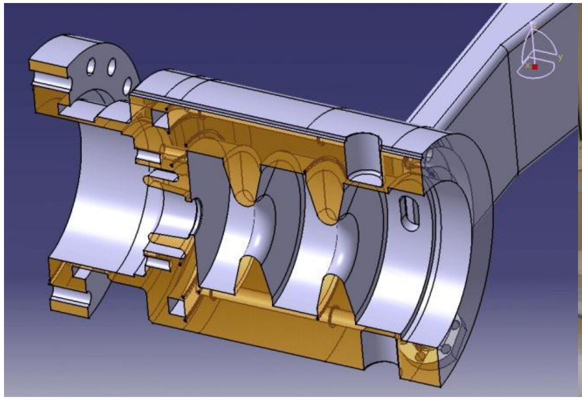
Laser and FP cavity	
Laser wavelength	1030 nm
Laser and FP cavity Frep	4 mirrors – 35.6 MHz
Laser Power	50 – 100 W
FP cavity finesse / gain	30000 / 10000
FP waist	70 μm

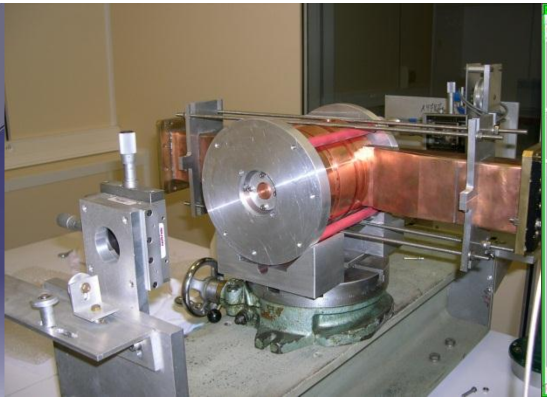
Ring	
Energy	50 MeV (70 MeV possible)
Circumference	16.8 m
Crossing-Angle (full)	2 degrees
$B_{x,y}$ @ IP	0.2 m
Emittance x,y (without IBS and Compton)	3 10^{-8} m
Bunch length (@ 20 ms)	30 ps
Beam current	17.84 mA
RF frequency	500 MHz
Transverse / longitudinal damping time	1 s /0.5 s
RF Voltage	300 kV
Revolution frequency	17.8 MHz
σ_x @ IP (injection)	78 mm
Tune x / y	3.4 / 1.74
Momentum compaction factor α_c	0.013
Final Energy spread	0.6 %

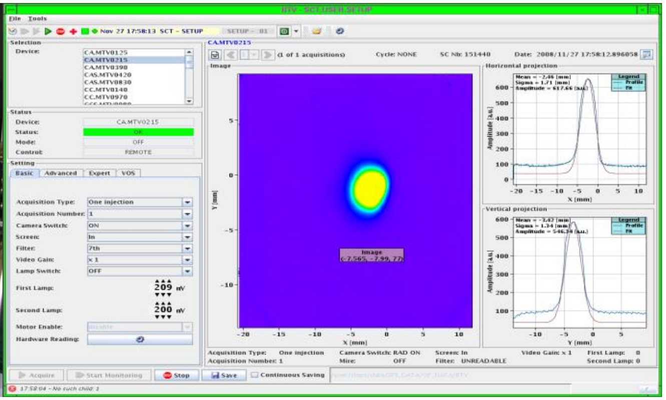
Source	
Photon energy cut off	46 keV (@50 MeV), 90 keV (@ 70 MeV)
Total Flux	10^{11}-10^{13} ph/sec
Bandwidth (with diaphragm)	1 % - 10%
Divergence	1/γ ~ 10 mrad without diaphragm @ 50 MeV

Injector

•Electron gun and accelerating section







•Probe Gun, LAL Design,

•Already tested in the CTF facility for high current

•Accelerating section => LIL type section

•4.6 m, 135 cells, 2.998.46 MHz @ 31 C°, mode $2\pi/3$.

•Q = 14800, 12.6 MV/m for the 50 MeV case

•Entrance => 160 cm from the cathode

•Phase stability required $\Delta\phi \leq 1°$

• Acknowledgments to R.Roux, P.Marchand, J.P.Pollina

Beam Dynamics

Injection and instabilities. Compton effect

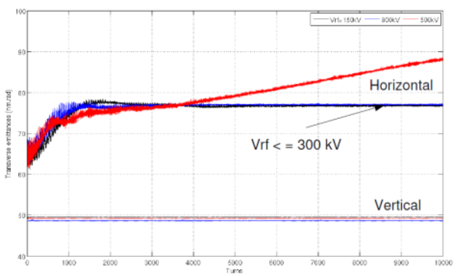
- Transient dynamics (no equilibrium)
- Compton recoil
- Collective instabilities
- CSR, Ions, Vacuum scattering, IBS…..
- Injection mismatching

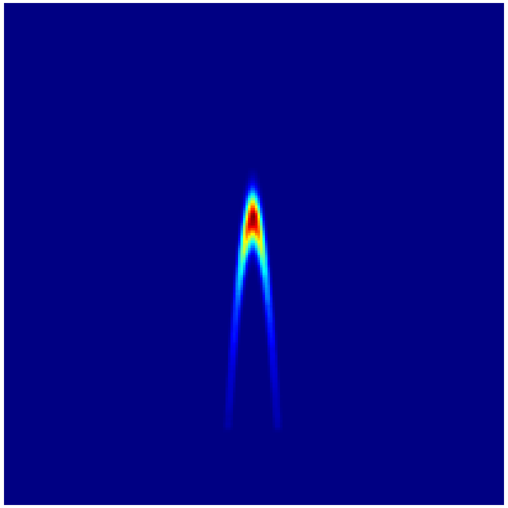
- Feedbacks!!!!
- Ion clearing
- Simulations

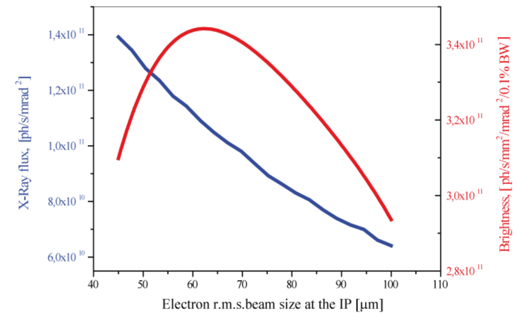
→

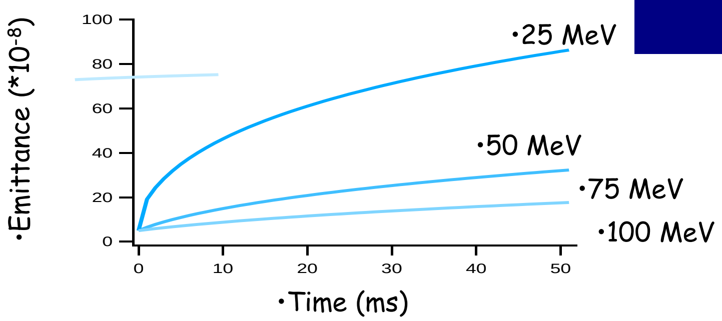
- 3 Phases
- Injection
- Turbulent regime
- Stabilization (thousand turns)

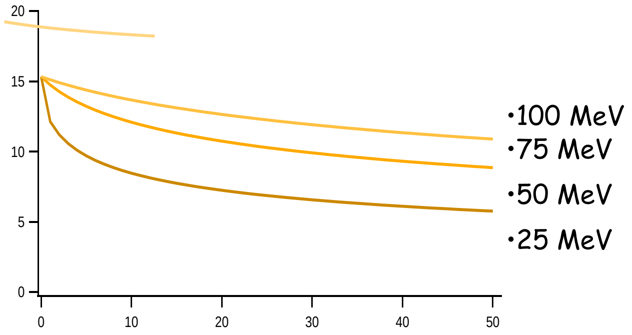
- Careful to the brillance !!!







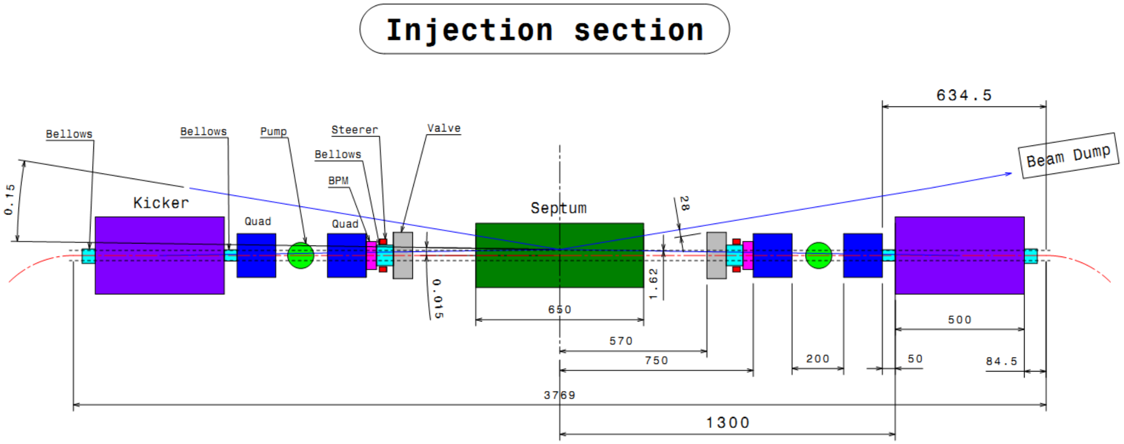


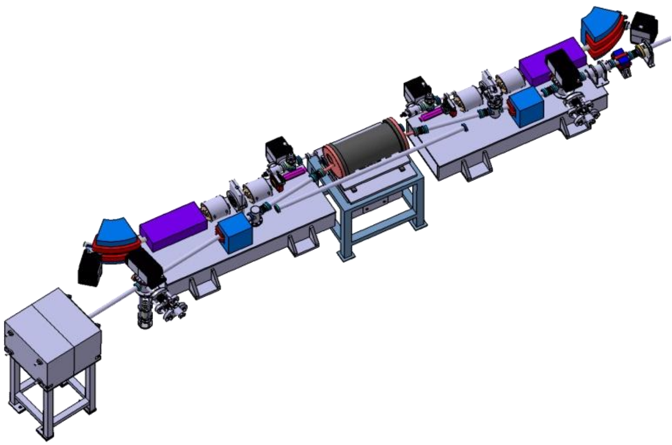


• Acknowledgments to A.Loulergue, C.Bruni

Injection

One septum, two kickers

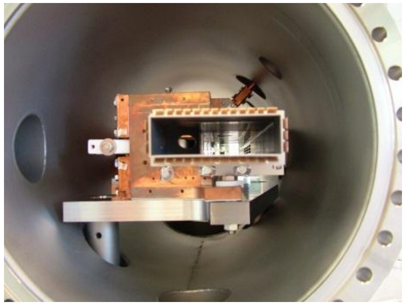




Equipment	Active length (mm)	Overall length (mm)	Transverse Beam stay clear H (mm)	Transverse Beam stay clear V(mm)	Septum thickness (mm)	Ceramic thickness (mm)
Septum magnet	250	650	30	12	3	
Injection kicker	250	450	40	28		6
extraction kicker	250	450	40	28		6

Equipment	Deviation (mrad)	Magnetic field length (mT)	Peak current (A)	Charging voltage (V)	Pulse shape	Pulse duration (µs)	Repetition rate (max) (Hz)
Septum magnet	150	100	960	150	full sine	130	50
Injection kicker	15	10	420	12500	half sine	0.050	50
extraction kicker	15	10	420	12500	half sine	0.050	50

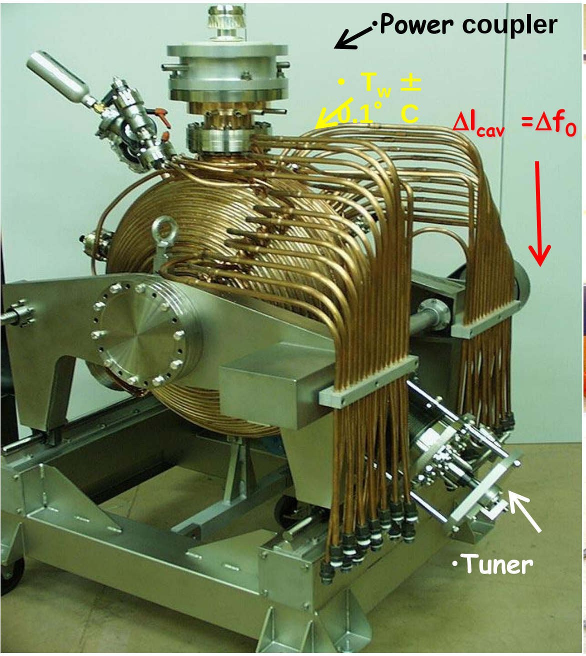
•R&D => pulsed power supplies for the kicker magnets (ring revolution 56 ns) = > a very high di/dt (~20 kA/µs), fast rise time and fast blocking of the negative current, and a very small time jitter

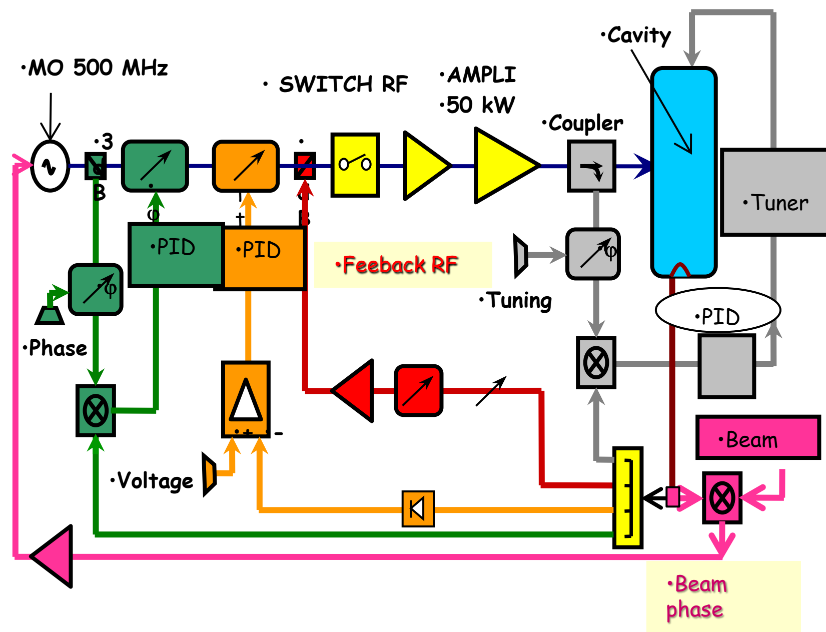


• Acknowledgments to P.Lebasque, T Vandenberghe

Ring RF

Cavity, Rf source and feedback





•'Elettra' type cavity

•3 different tuning knobs

Temperature (30÷60 C° , ±0.05 C°)

•Mechanical length adjustment Δl

•Tuner on the equator

•'SOLEIL' type transistor amplifier

•No HT, modularity (easy to maintain)

•Tested (5 years, +25,000h of operation)

•Operational efficiency 99.995%

•1 Module @352 MHz 330W => Can be extended to 500 MHz

•'Slow and Fast feedback

•Slow Amplitude, phase , frequency loops

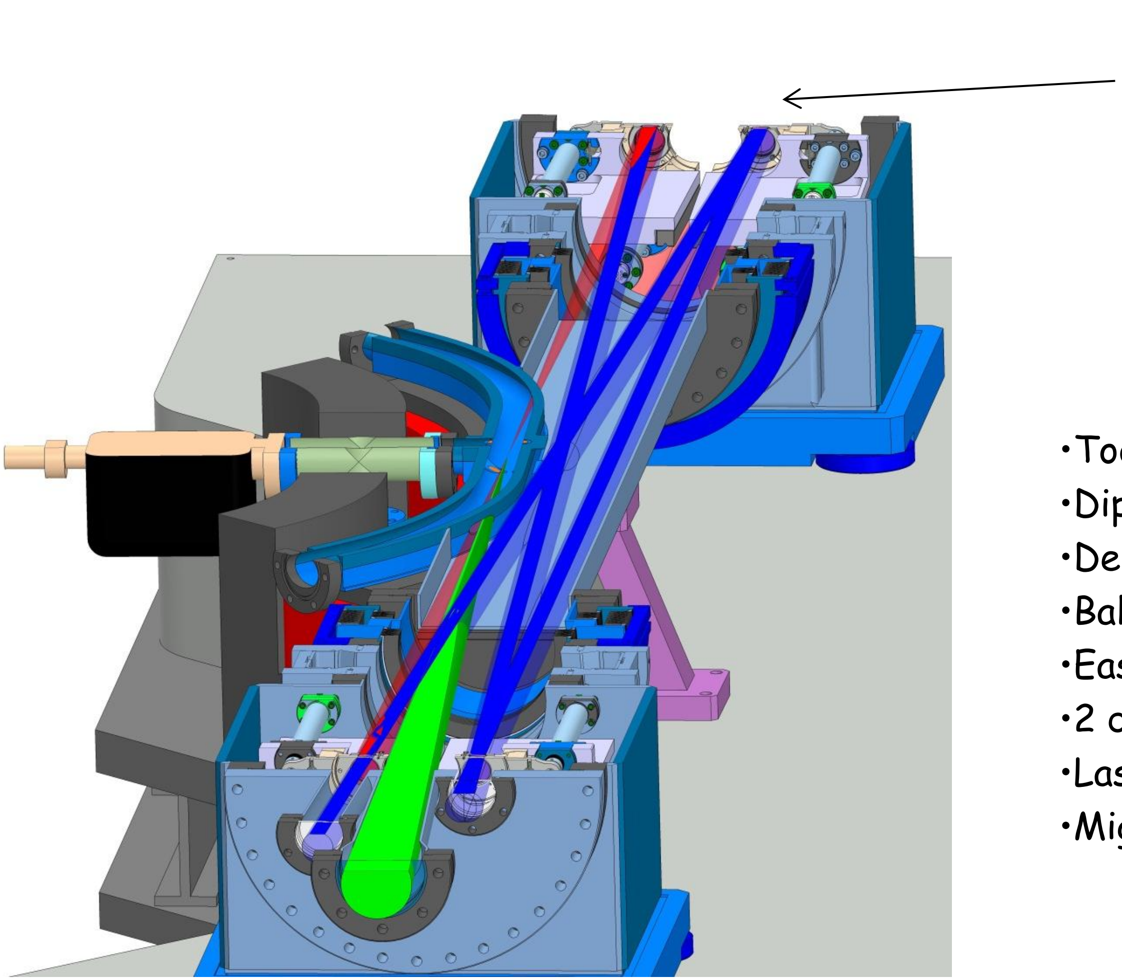
•Fast RF FB

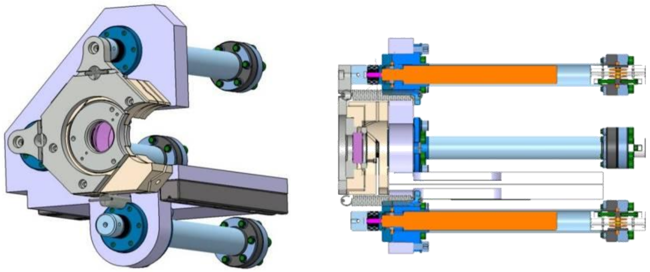
• Phase loop => beam oscillations @ 500 kHz, $\Delta\Phi_{inj}$, HOM,...

• Acknowledgments to P.Marchand

Fabry-Perot cavity

•Towards ThomX





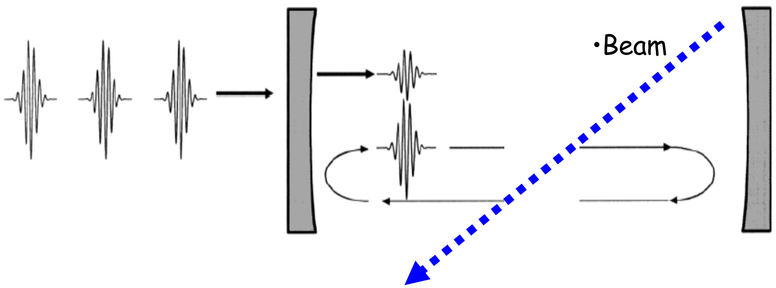
- Too long => Two monoblocks
- Dipoles Integration
- Dedicated BPM
- Bakable
- Easy to access, mounting
- 2 degrees collisions
- Laser insertion
- MightyLaser stabilization, adjustment

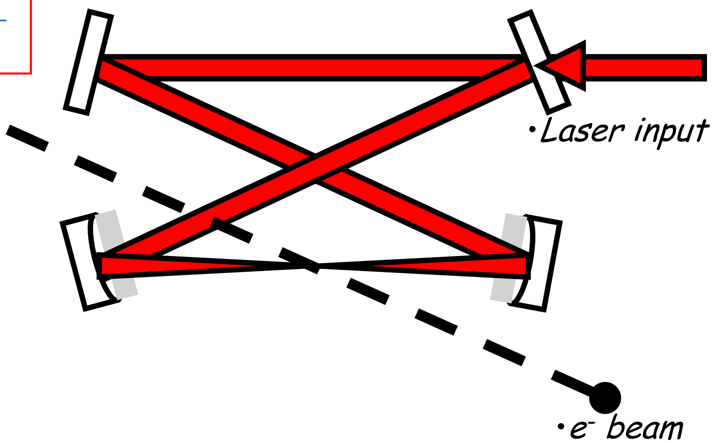
• Acknowledgments to M.Lacroix, Y.Peinnaud

Fabry-Perot cavity

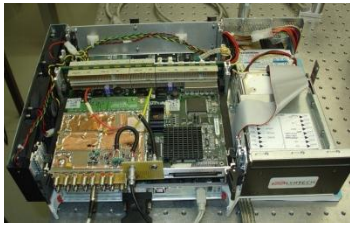
MightyLaser and PLIC experience

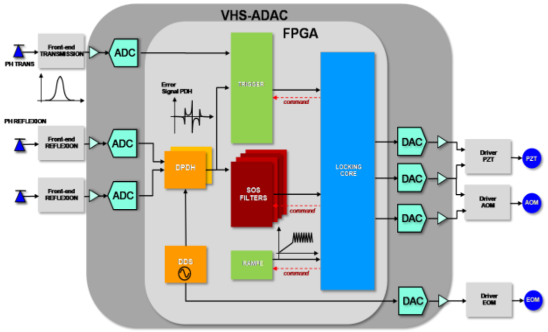
•Stable solution: 4-mirror cavity as in Femto laser technology



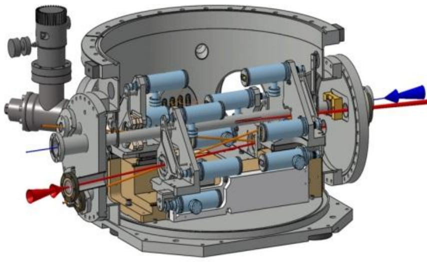


•Digital Pound-Drever-Hall feedback





•Vacuum and mechanics : MightyLaser experience



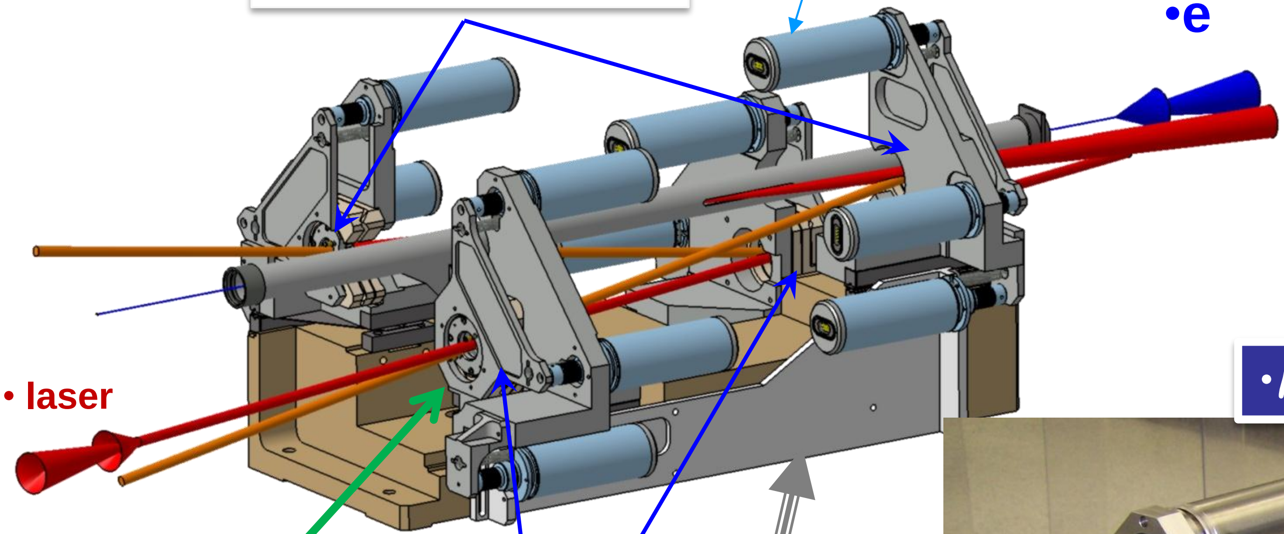
•PLIC and MightyLaser : record in stable finesse locking (30000).

• Acknowledgments to F.Zomer, R.Chiche, D.Jheanno, M.Lacroix, R.Cizeron

•Mirror positioning system

•2 spherical mirrors

•12 encapsulated Motors



•Invar base to ensure length stability

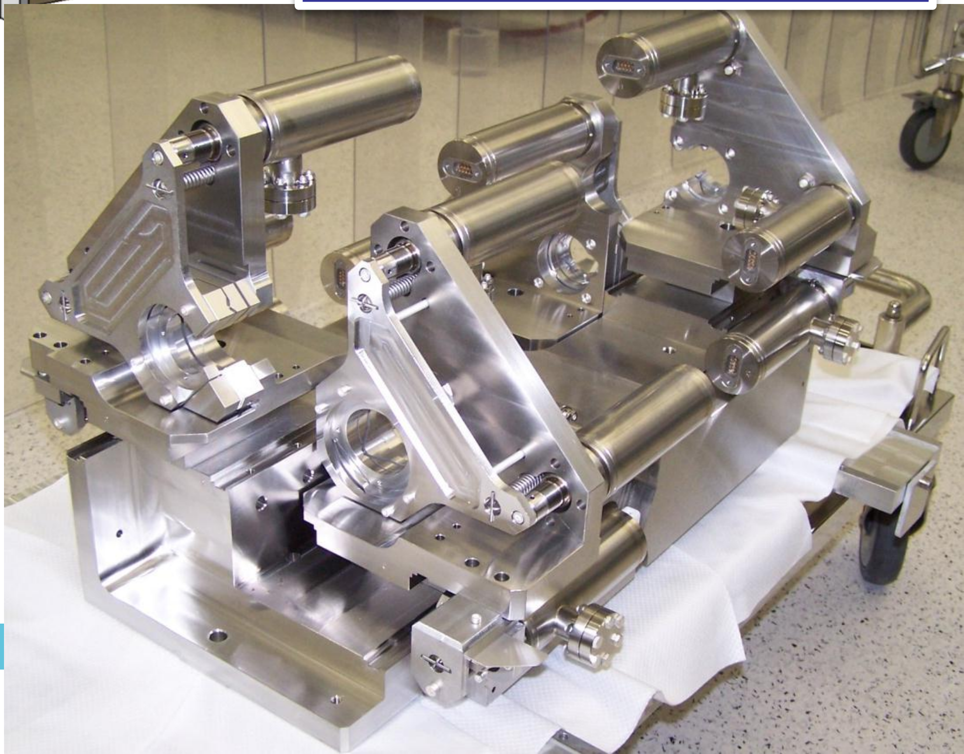
at mirrors

•Gimbal mirror mounts

•For

•vacuum

•Mounting in class 10 room



- In future we want to drastically increase the infra cavity power.

Phase 1 => 50 – 100 kW
Phase 2 => Increase. In theory we can achieve the MW

- Locking system
- Mirrors, coatings and substrates (collaboration with LMA lyon)
- Laser coupling
- Phase noise and reference
- Thermal lensing compensation
- X ray flux

• ThomX. If our resources are 'infinite'…what possible extensions for the future?

•The Thomx choice (storage ring) is the result of a compromise among flux, cost and integration constraints.

•But in ThomX we have:

1) A second IP
2) A Linac up to 70 MeV (50 baseline). LinearThomX
3) Extraction line up to 70 MeV (50 baseline). Energy spread and emittance

- deteriorated

•So what other solution or option can be implemented to provide other

•X rays beams characteristics?

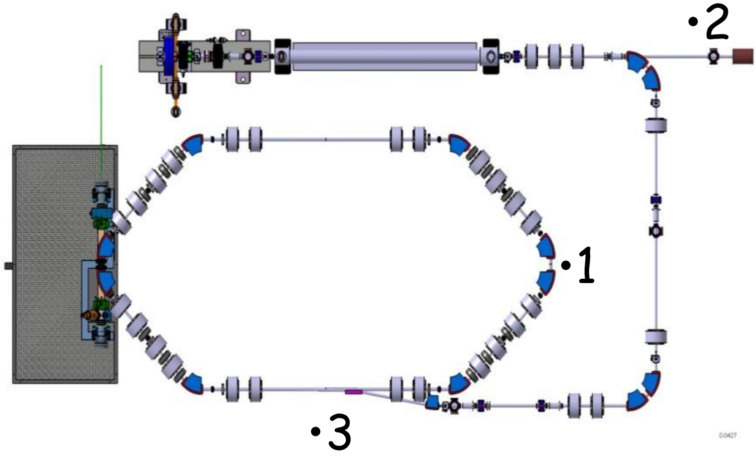
• The multi-line ThomX

•1) Second IP

•- It can be just a second IP. Slight modifications on the injection line to extract the X.

- It is inside dipoles. CSR mm waves.
- Integration of a $\pi/2$ collision geometry.

•The spectrum cut off is $\frac{1}{2}$ but we have very short pulses (n 10 fs)



•2) Linac, changing the gun laser.

- Single pulse (3 nC) on a high power laser (~ J) at low Frep (n Hz).

• Peak brilliance and time resolved experiments

- Trains with multibunch and ELI NP recirculator. LINEARTHOMX
- Good bandwidth with diaphragms.

•Good average flux (no diaphragm)

- Short pulse (less than ps) in head on collision (full energy cut-off)

3) Extraction line

- Single pulse (3 nC) on a high power laser (~ J) at low Frep (n Hz).

• Peak brilliance and time resolved experiments

- Integration of a $\pi/2$ collision geometry.

•The spectrum cut off is $\frac{1}{2}$ but we have very short pulses (n 10 fs)

Conclusions

- At LAL we started an important research activity on Compton sources and related technology

- We introduce the best crab scheme
- We have the poissibility to study all configurations cavity eingenmodes, evaluate the astigmatism effects and ellipse rotation, study the impact of polarisation
- Before to study a Compton source coupled with an optical resonator frep must be evaluated as primary parameter -> technology (my opinion…)
- In the field of the application we are actively working on Mightylaser And on the recirculator for ELI-NP
- We have been financed to built a compact compact synchrotron (ThomX)
- Exciting project at present, but with possible extension also in the future
- I think that all the optical, feedback, collision activity that we are working can be extended in a framework of a future gg collider…