Recent and future developments in Particle Accelerators

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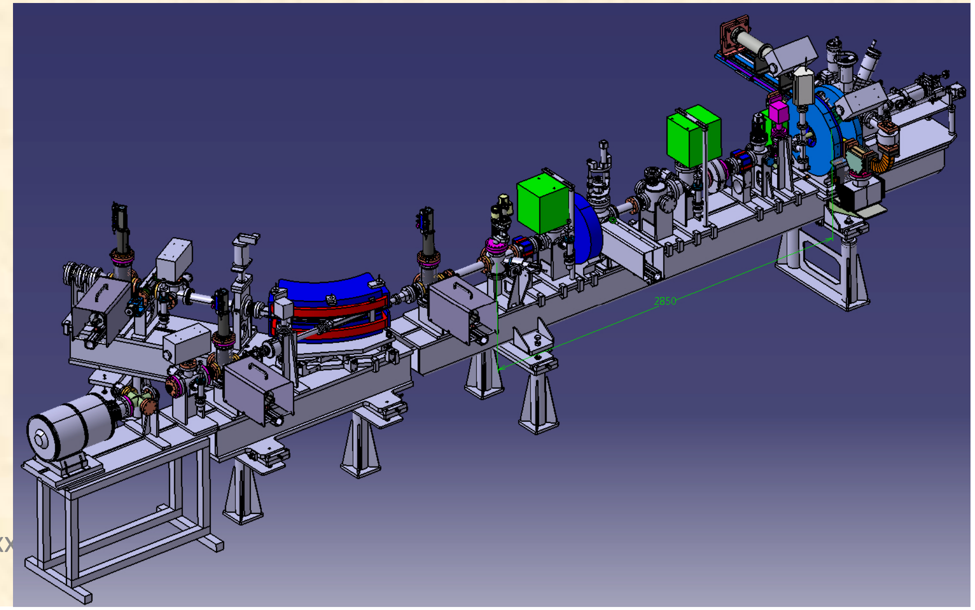
Table of content

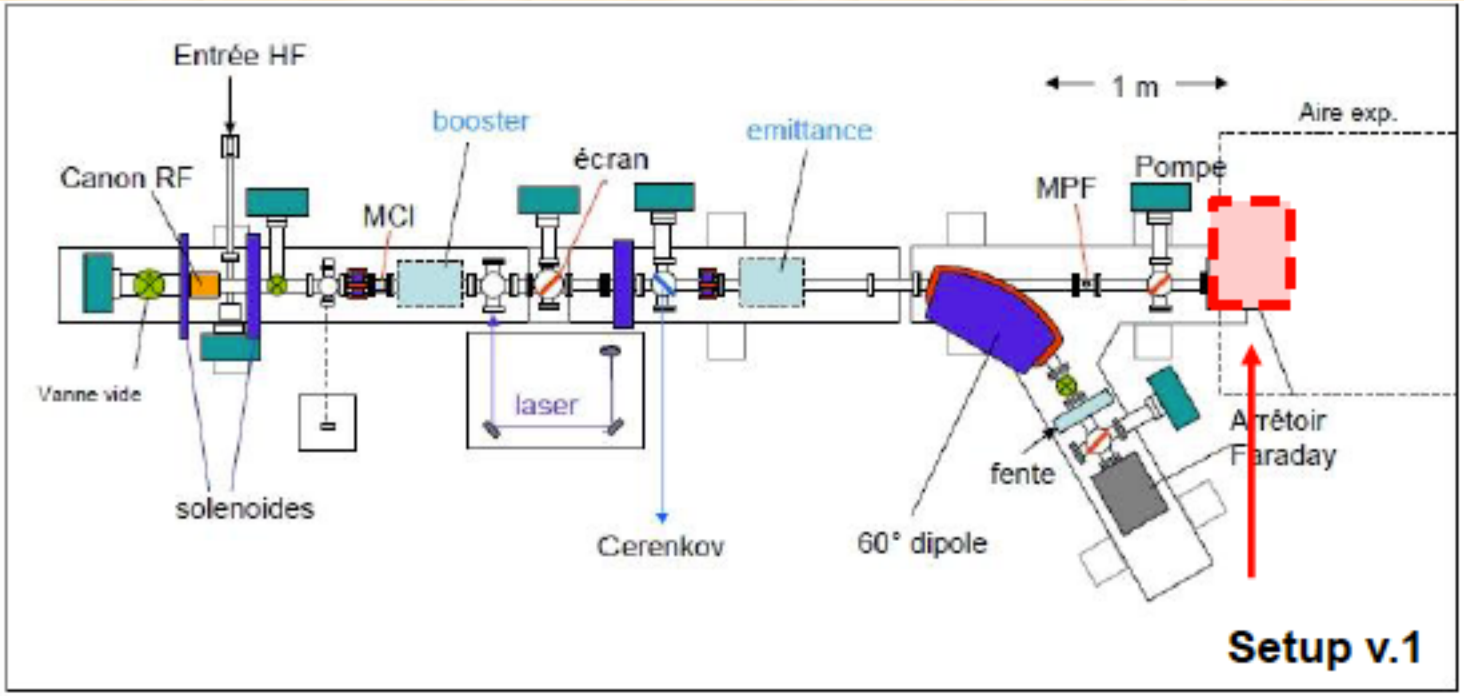
PHIL, PHOTOINJECTOR AT LAL

PHIL

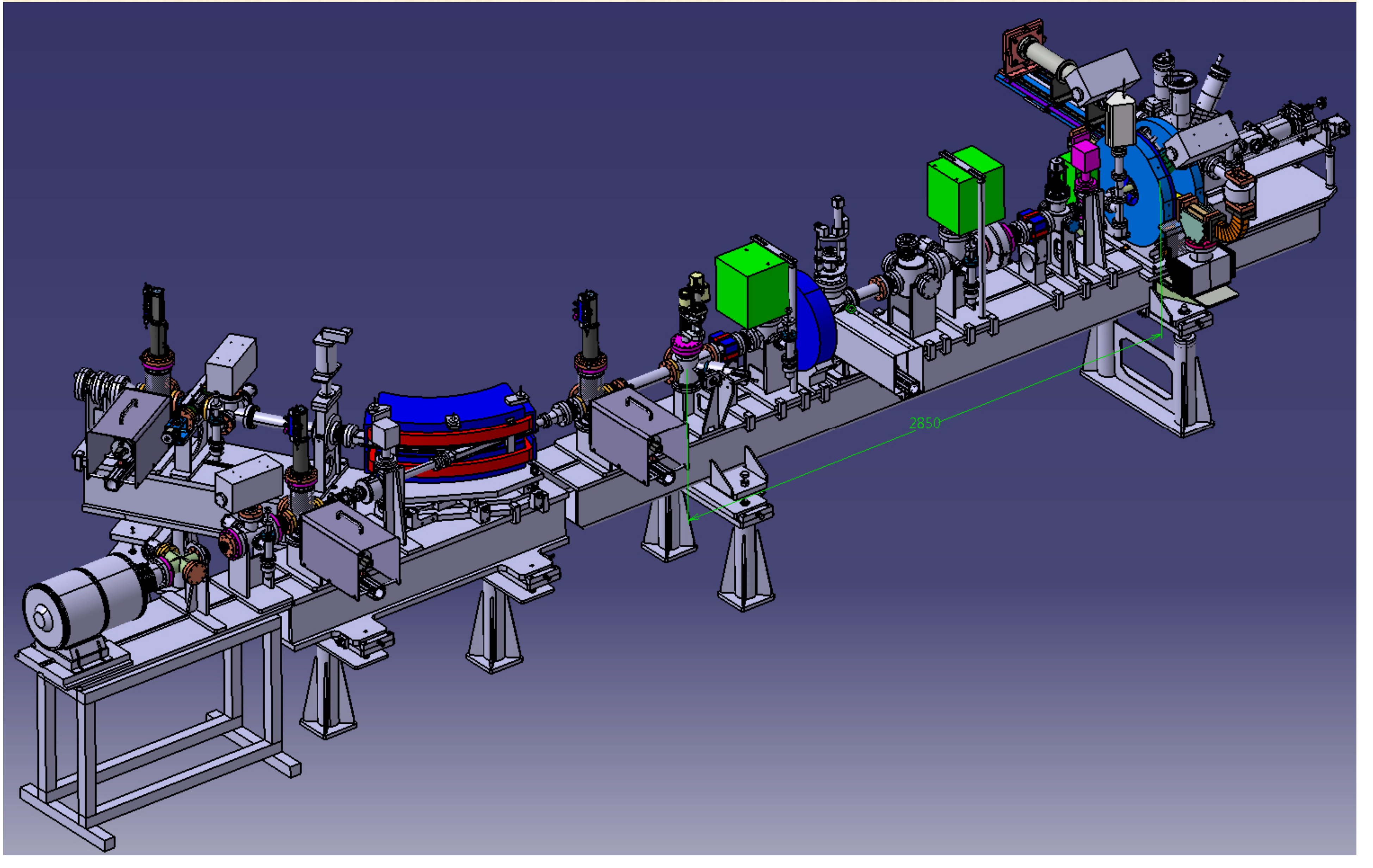
- As discussed this morning, the emittance of a beam is a measure of its quality.
- Thermionic emission is a thermal process
  => high emittance
- Photoemission gives a much lower emittance.
- LAL is doing R&D to produce low emittance beams.
- Test of new cathodes.
- User fcaility



PHIL (2)



- PHIL is a platform to test new accelerators technique.



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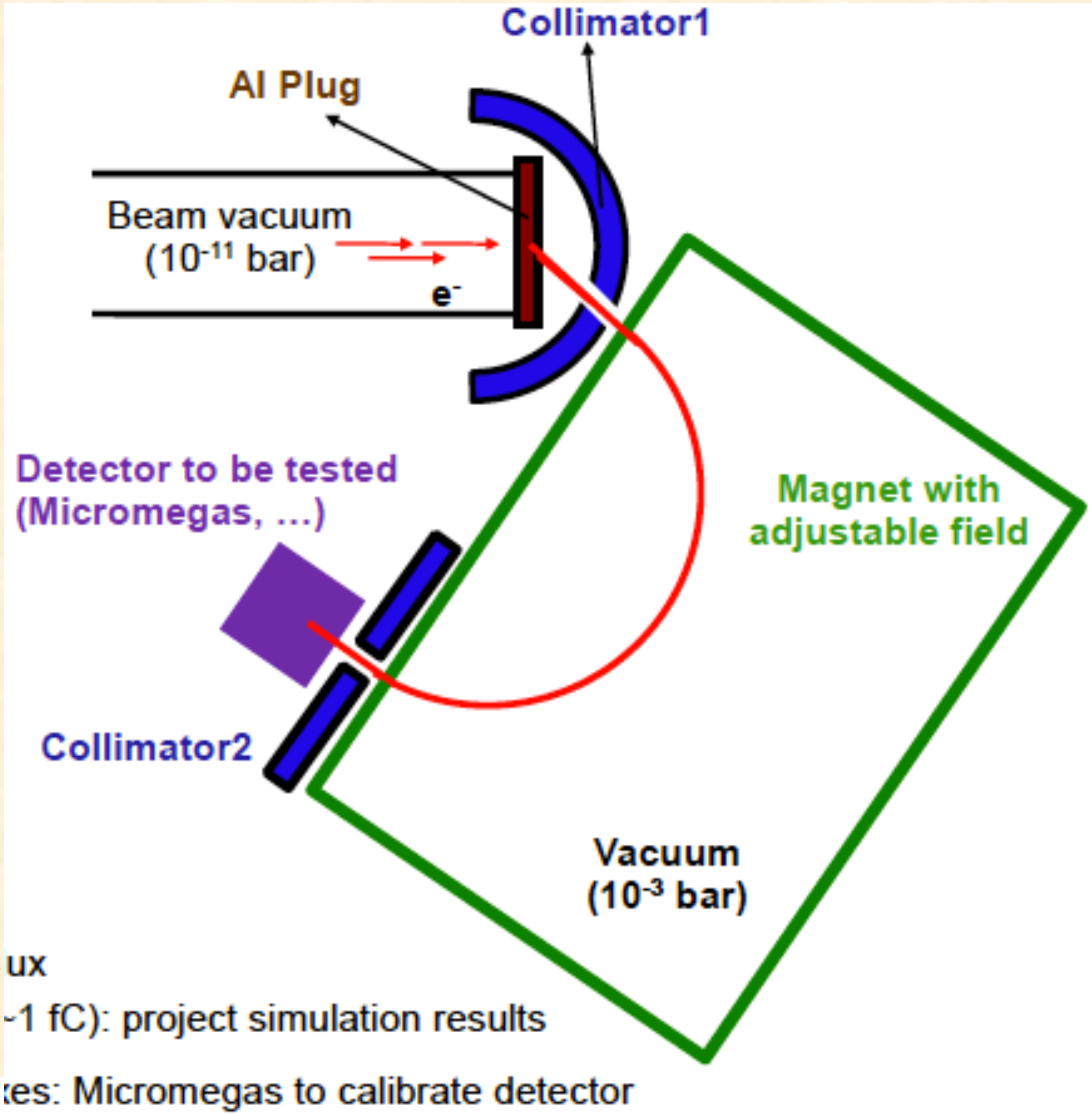
PHIL to test HEP detectors

- PHIL can be used as a source of electrons to test HEP detectors.
- From example micromegas (project of Sergey Barsuk, Leonid Burmistrov and Oleg Bezshyyko)



UA9, COLLIMATION AT LHC

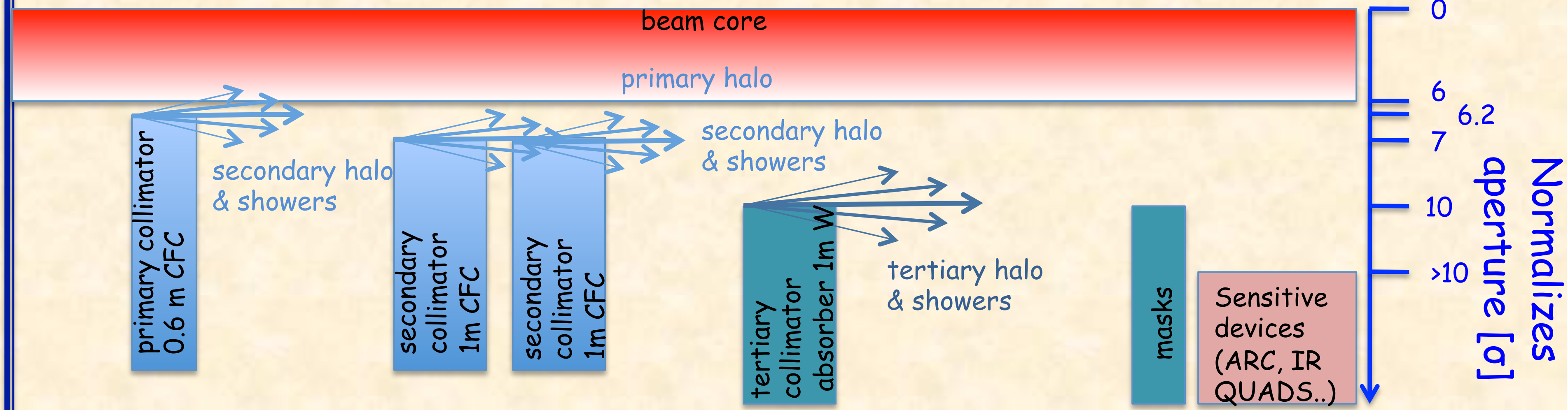
(Slides borrowed from Walter Scandale)

Collimation

- When a particle beam is produced and accelerated some particles may get far from the core of the beam.
- If these particles hit the HEP detectors they may do significant damages.
  => collimators are used to clean the beam by stopping these particles.
- This is a critical point: without collimators it would not be possible to operate the LHC safely.
  => critical R&D

Multi stage collimation as in LHC

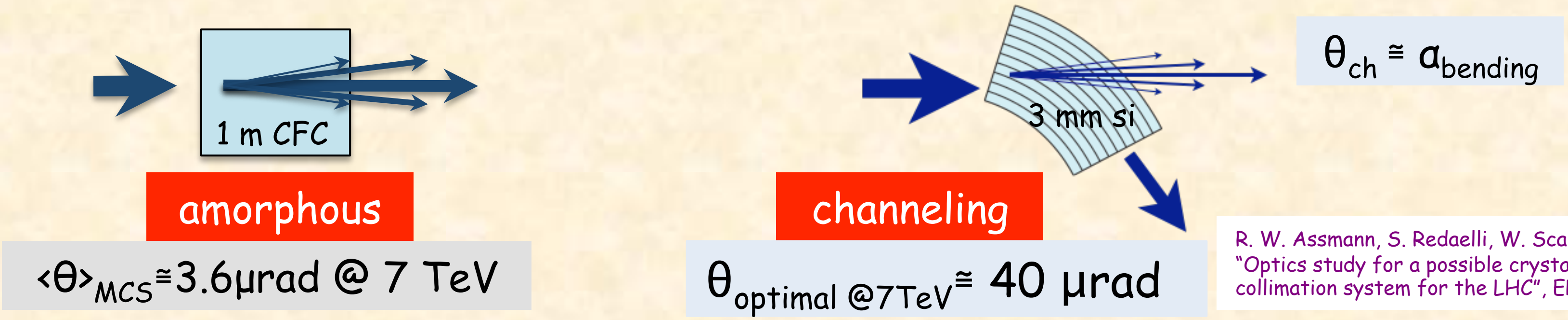
- The halo particles are removed by a cascade of amorphous targets:
  1. Primary and secondary collimators intercept the diffusive primary halo.
  2. Particles are repeatedly deflected by Multiple Coulomb Scattering also producing hadronic showers that is the secondary halo
  3. Particles are finally stopped in the absorber
  4. Masks protect the sensitive devices from tertiary halo



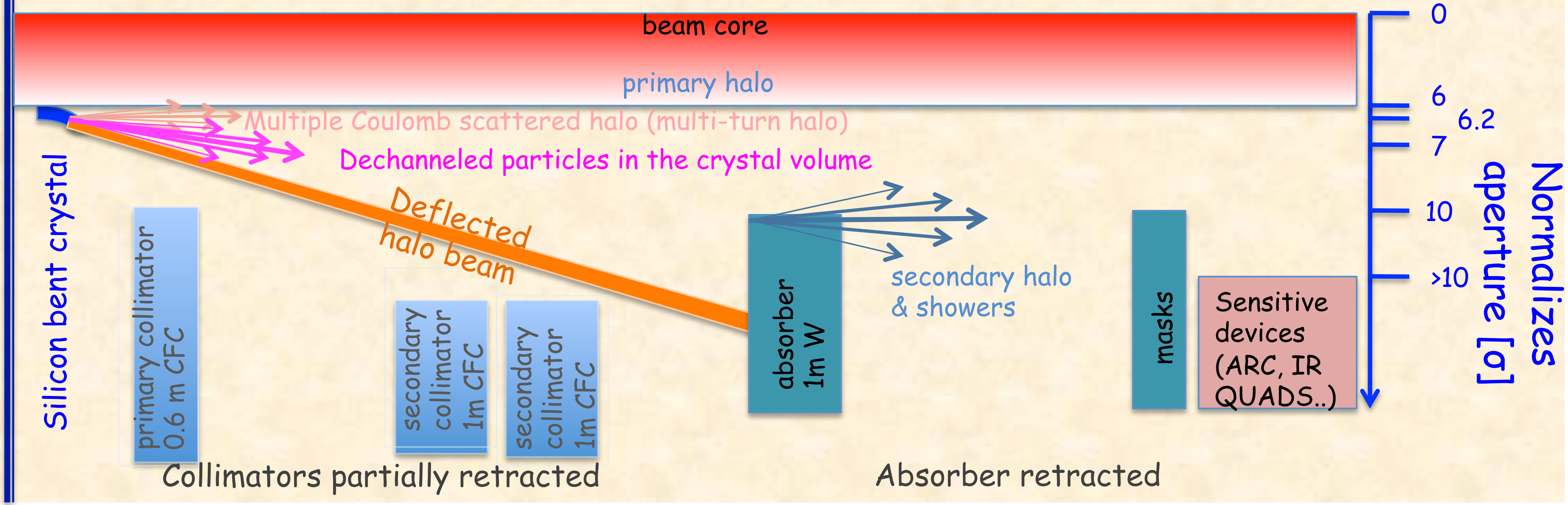
- Collimation efficiency in LHC ≅ 99.98% @ 3.5 TeV
  - ✓ Probably not enough in view of a luminosity upgrade
  - ✓ Basic limitation of the amorphous collimation system
    - ✧ p: single diffractive scattering
    - ✧ ions: fragmentation and EM dissociation

Crystal assisted collimation

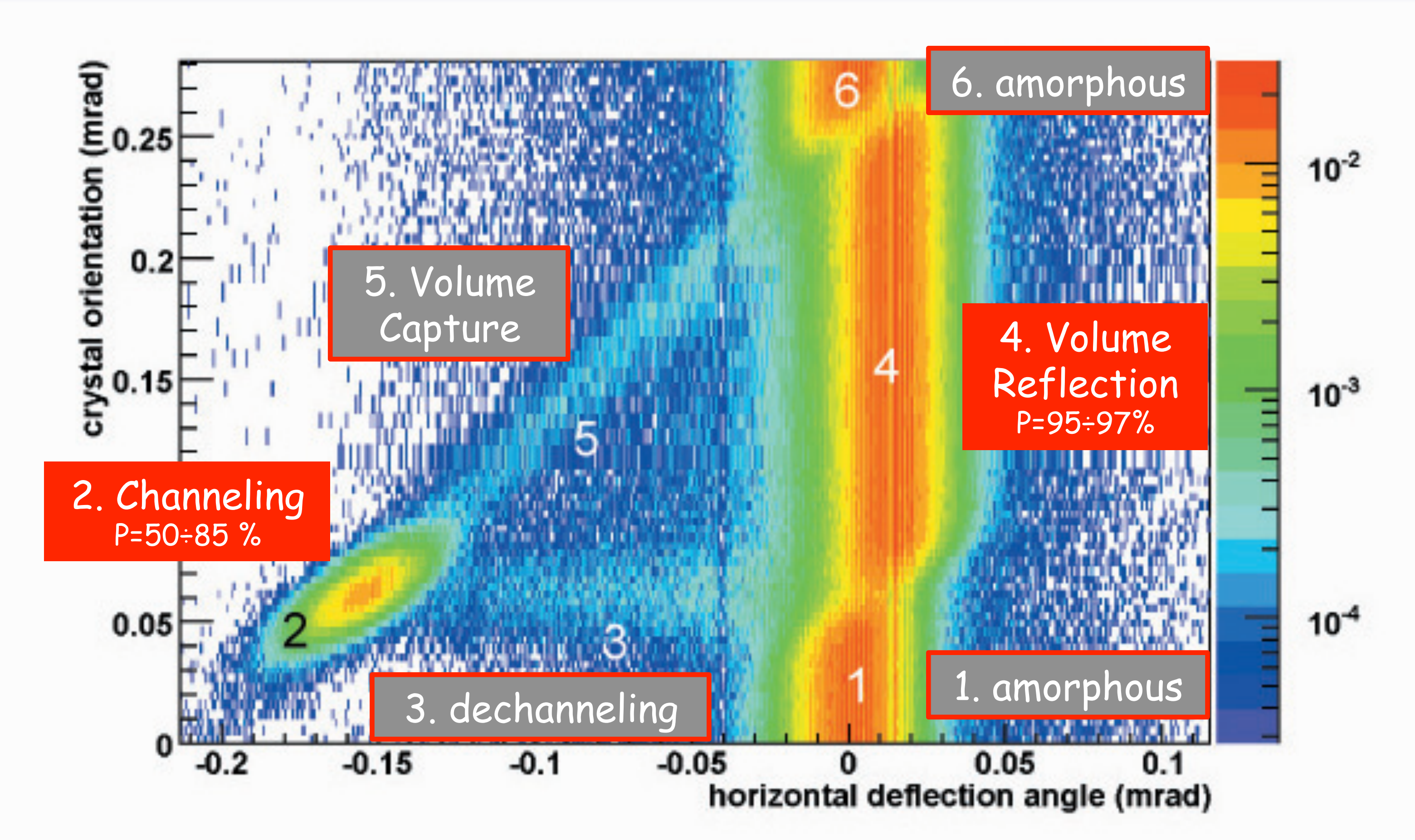
- Bent crystals work as a "smart deflectors" on primary halo particles
- Coherent particle-crystal interactions impart large deflection angle that minimize the escaping particle rate and improve the collimation efficiency



R. W. Assmann, S. Redaelli, W. Scandale, "Optics study for a possible crystal-based collimation system for the LHC", EPAC 06



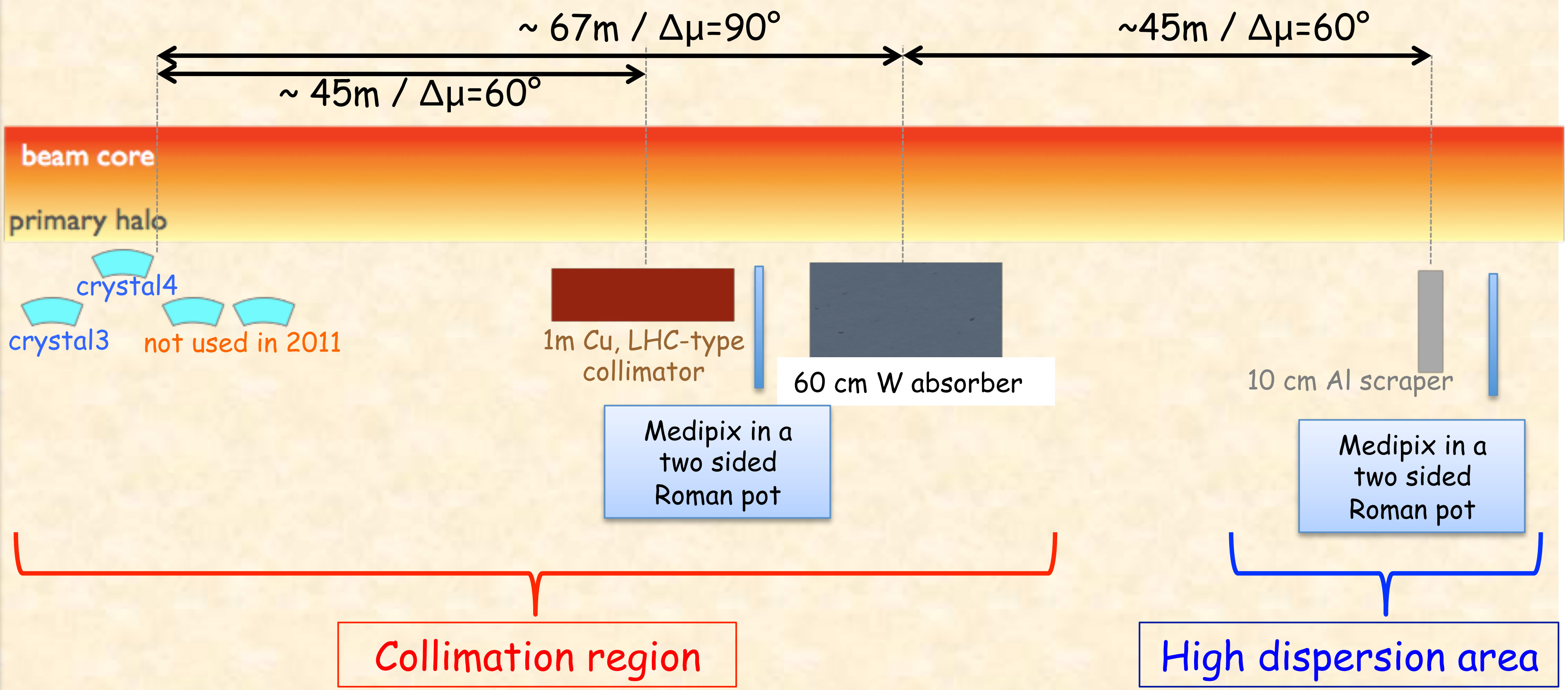
Coherent interactions in bent crystals



- Two coherent effects could be used for crystal collimation: W. Scandale et al, PRL 98, 154801 (2007)
  - ✓ Channeling ➔ larger deflection with reduced efficiency
  - ✓ Volume Reflection (VR) ➔ smaller deflection with larger efficiency
- SHORT CRYSTALS in channeling mode are preferred W. Scandale et al., Nucl. Inst. and Methods B 268 (2010) 2655-2659.

➔ ×5 less inelastic interaction than in VR or in amorphous orientation (single hit of 400 GeV protons)

UA9 schematic layout



Observables in the collimation area:

- Intensity, profile and angle of the deflected beam
- Local rate of inelastic interactions
- Channeling efficiency (with multi-turn effect)

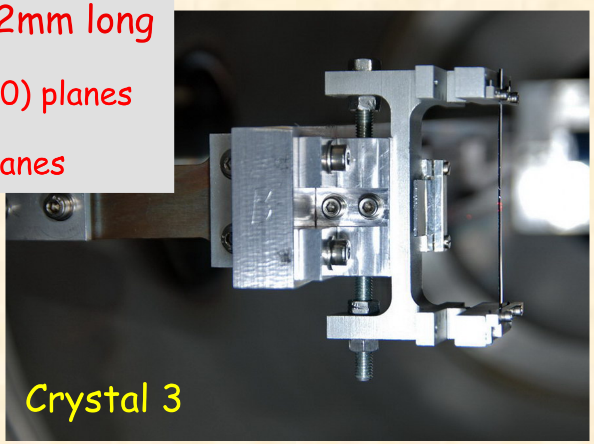
Observables in the high-D area:

- Off-momentum halo population escaping from collimation (with multi-turn effect)
- Off-momentum beam tails

Crystals

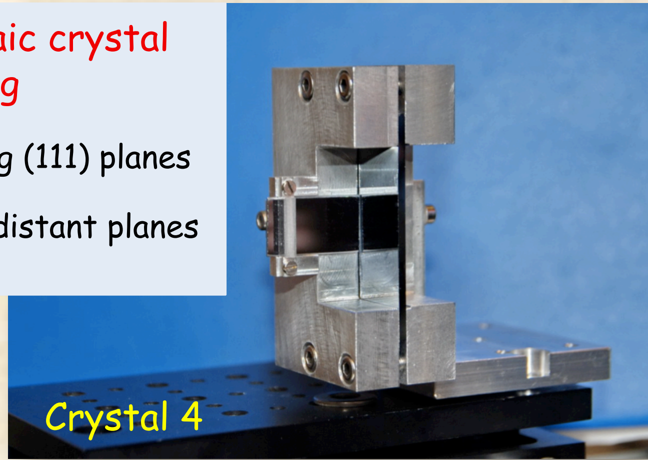
Strip crystal 2mm long

- Bent along (110) planes
- Equidistant planes



Quasimosaic crystal
1.9 mm long

- Bent along (111) planes
- Non-equidistant planes
  d1/d2 = 3



Residual imperfections:

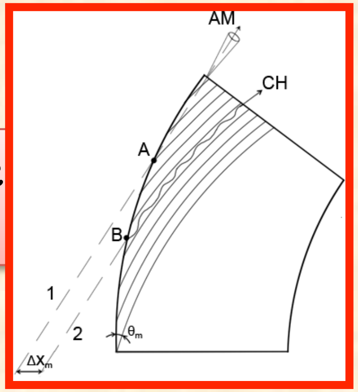
- ✓ Residual torsion ≈ 1 μrad/mm → different paths for different vertical hit points
- ✓ Amorphous layer size ≤ 1 μm
- ✓ Miscut ≈ 100 μrad

→ different paths at small impact parameter (amorphous layer size and miscut)

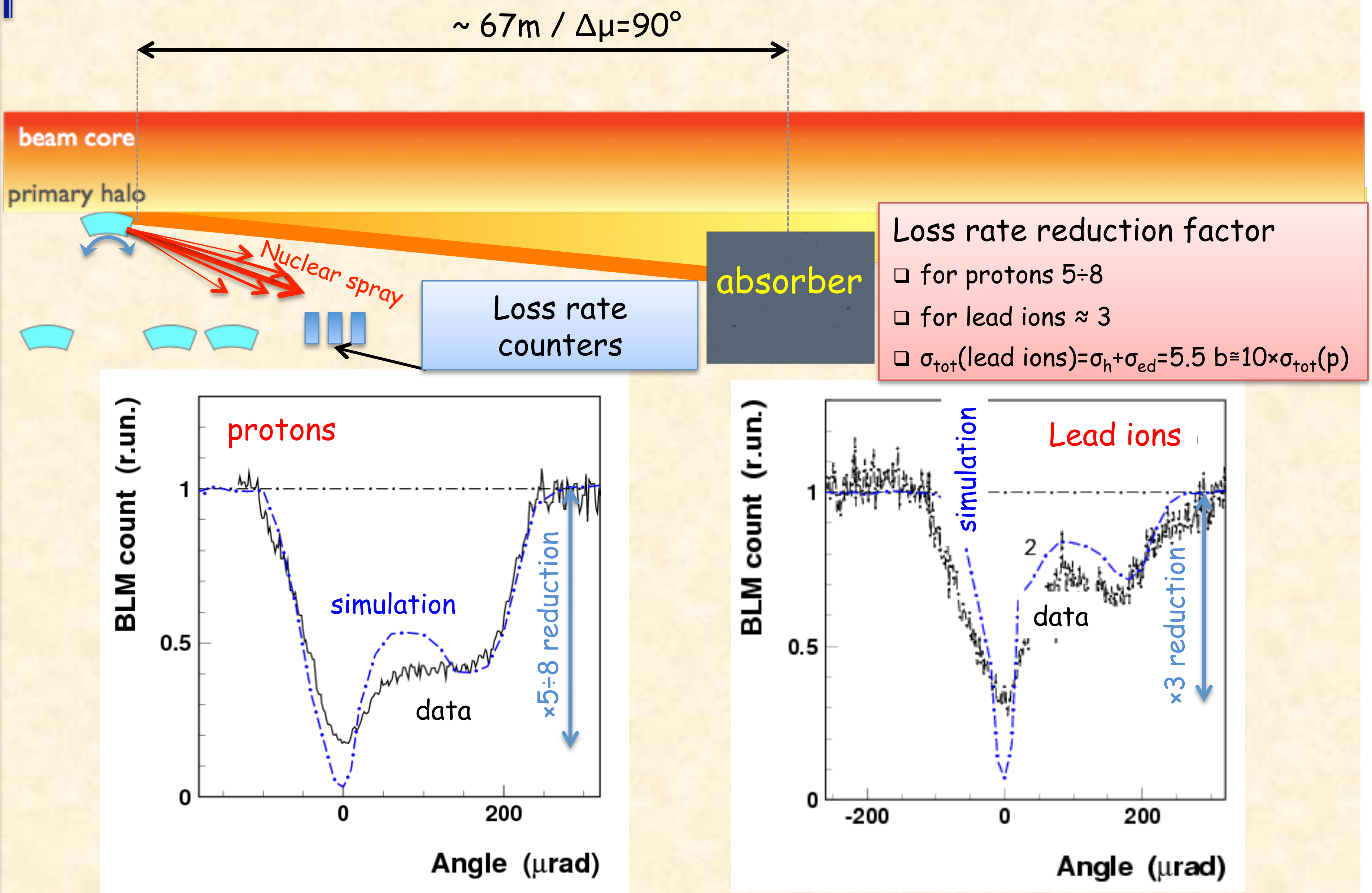
Torsion is no longer an issue

- torsion over the beam size < critical angle
- full mitigation of the detrimental effects

Schematic view of the residual miscut angle

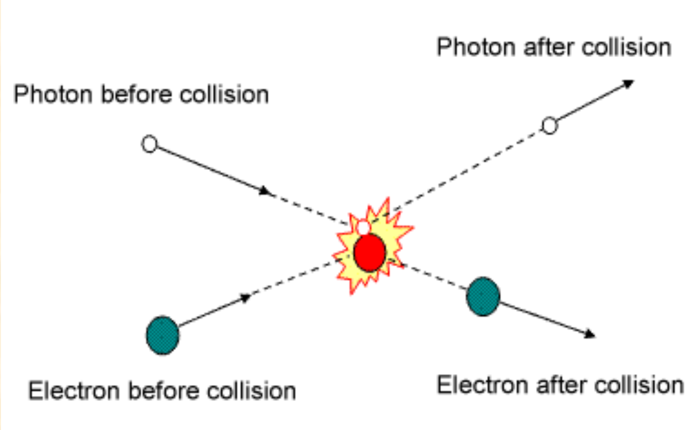


Loss rate reduction at the crystal



NEW ACCELERATORS AS X-RAYS AND GAMMA RAYS SOURCES

Compton scattering



$$\mathrm{Flux}_{cw} \propto \frac{\lambda P_L I_e \sigma_T}{\sqrt{\sigma_{electron}^2 + \sigma_{laser}^2}}$$

I_e: electron beam intensity
P_L: laser power
λ: laser beam wavelength
$\sigma_{electron}$=electron beam size r.m.s
σ_{laser}=laser beam size r.m.s

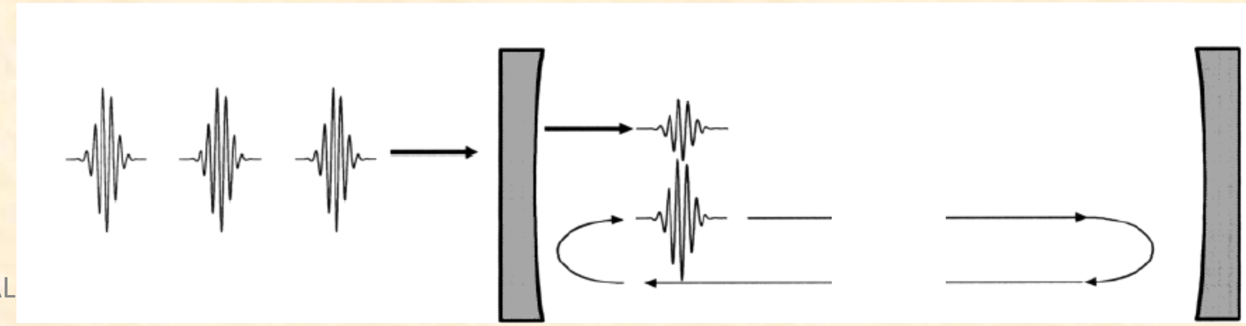
- Compton (Thomson) scattering is the exchange of energy that occurs when a photon collides with an electron.
- It can be used to boost low energy (IR) photons to X-rays or gamma ray energy by colliding them with high energy electrons.
- The source of photons is typically a laser (IR => eV).
- The cross-section for this process is very low.

Compton based sources at LAL

- LAL is involved in several Compton sources projects
  - MightyLaser installed at KEK in Japan
  - ThomX to be built at LAL
  - ELI-NP-GS to be built in Romania

Laser pulses stacking

- Small Compton cross-section
  => important to recycle laser and electrons
  => Use of a Fabry-Pérot cavity to accumulate and recycle the laser power.
- Allows significant enhancement factors on the laser power (1000-10000).
- This is very difficult
  => frequency combs
  => demonstrated in an accelerator with a CW laser by LAL at HERA
  => current prototype with pulsed laser tested by LAL at KEK in Japan.



Pulsed_laser/cavity feedback technique

Specificity ➔ properties of passive mode locked laser beams

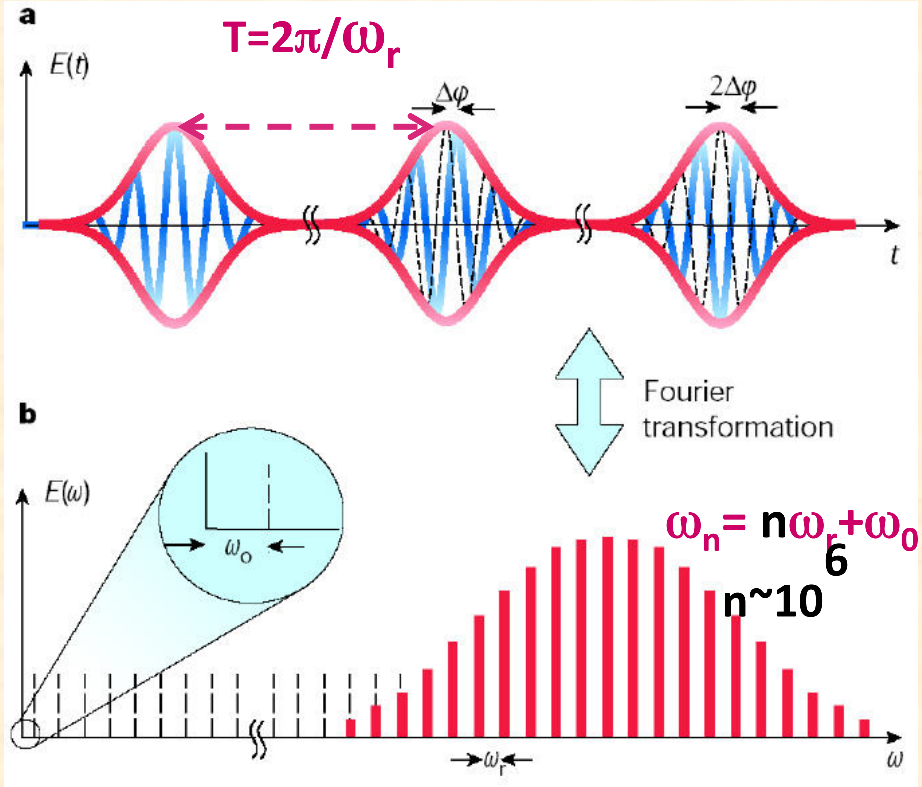
Frequency comb ➔ all the comb must be locked to the cavity

➔ Feedback with

2 degrees of freedom :

control of the

Dilatation & translation (PZT)



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

State of the art (Garching MPI) : **~70kW,** 2ps pulses @78MHz, stored in a cavity

(O.L.35(2010)2052) **~20kW,** 200fs pulses @78MHz

R&D at LAL on Fabry-Perot cavities

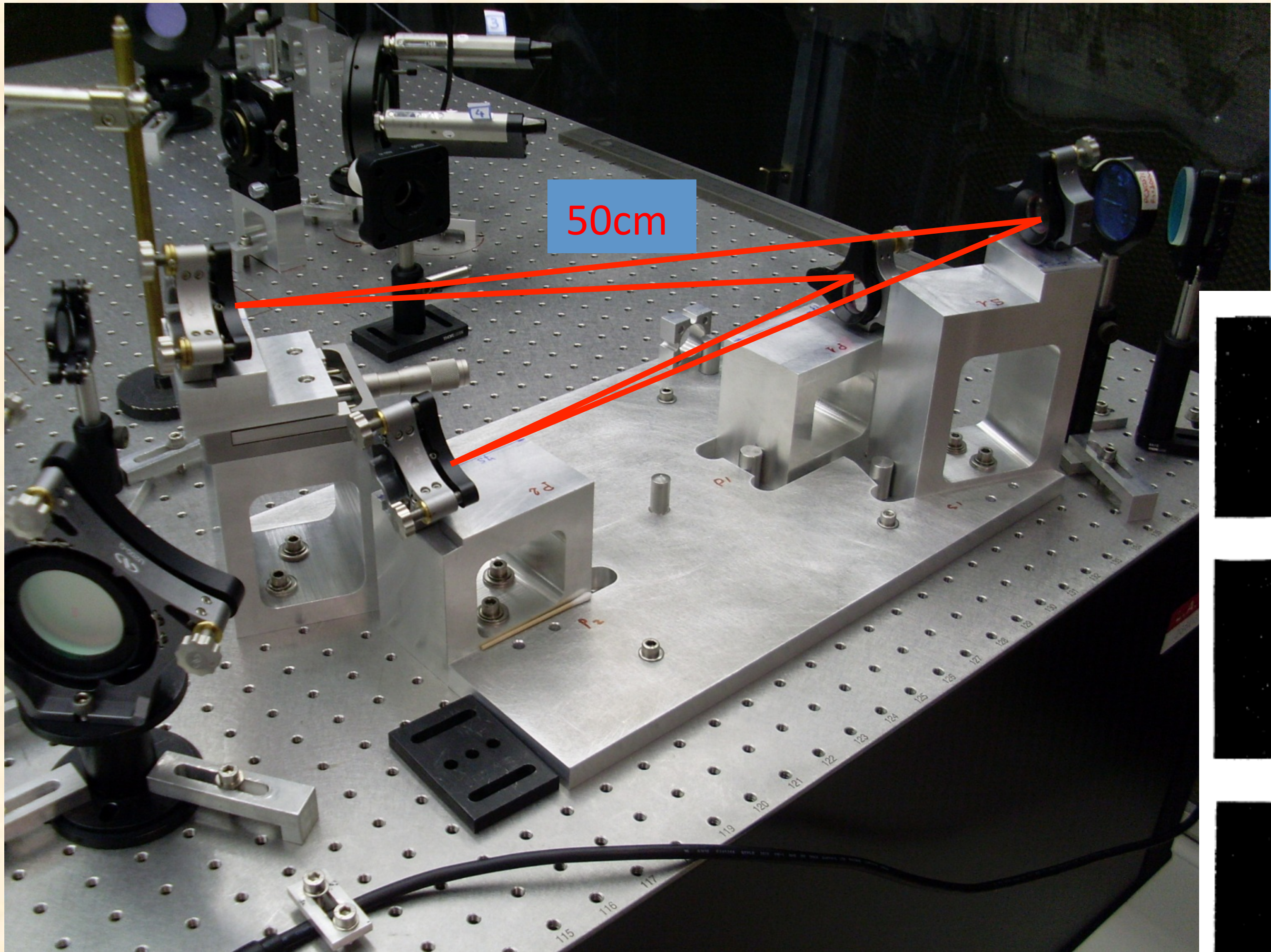
- LAL has been working on Fabry-Perot cavities for about 10 years.
  => Polarimetry measurement at HERA
  => High flux positrons source for the ILC
  => Mighty laser / ThomX
- We have 2 Fabry-Perot cavities installed in our lab for R&D and training (eg: feedback studies, alignment training…)
- We have developed a digital feedback system to control the length of the cavities.

Fabry-Perot cavities

Prototype of non planar 4 mirrors resonator (low finesse)

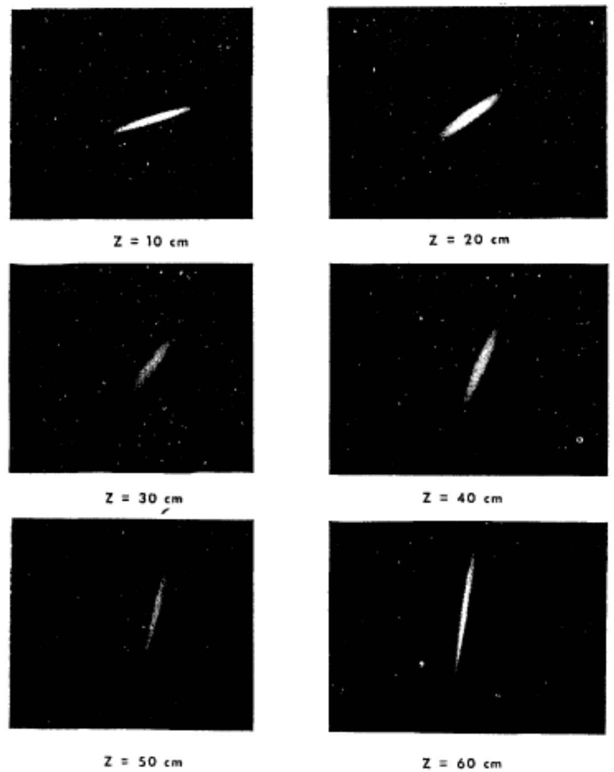
- Check the general astigmatism mode shape/propagation (*Arnaud, Bell Syst. Tech. (1970)2311*)

➔ ok

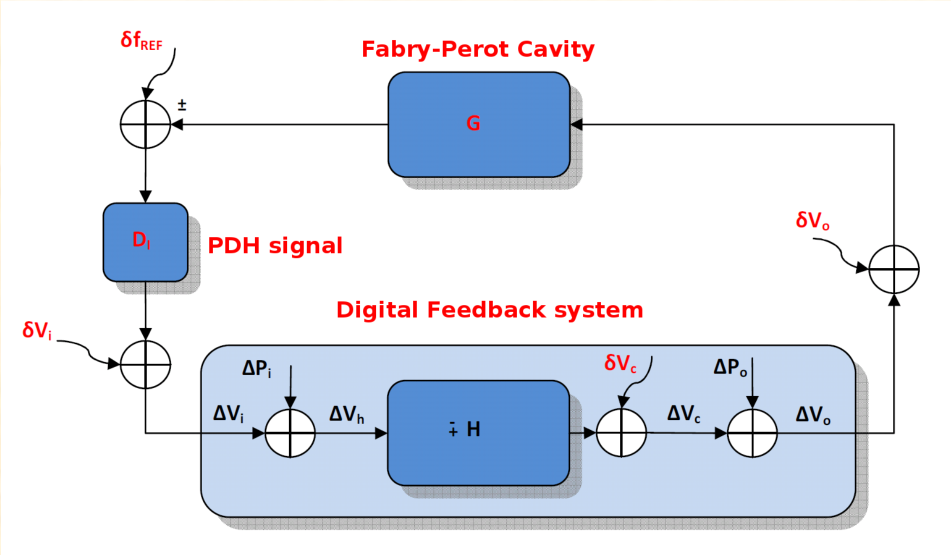


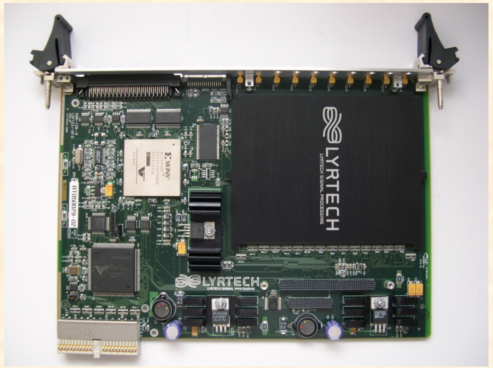
Ellipse intensity profile 'turning'

Kogelnik, Apl. Opt. 8(1969)1687



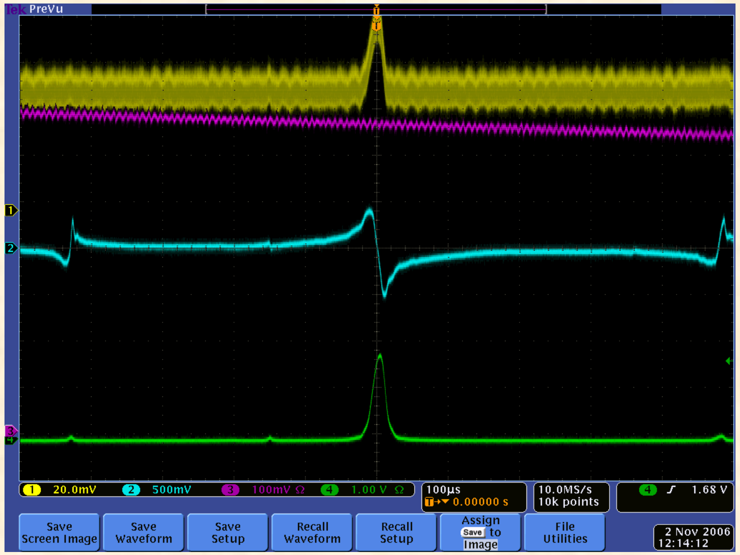
Digital feedback system





- The length of our cavities is controlled by a digital feedback system.
- Such system gives us more flexibility than an analogue one.
- Based on a FPGA Virtex II board.
- The laser is locked on the cavity using the Pound Drever Hall technique.
- The cavity is locked on the Accelerator clock using a phase lock loop.
- Developed over several years to suit the needs of various cavities.

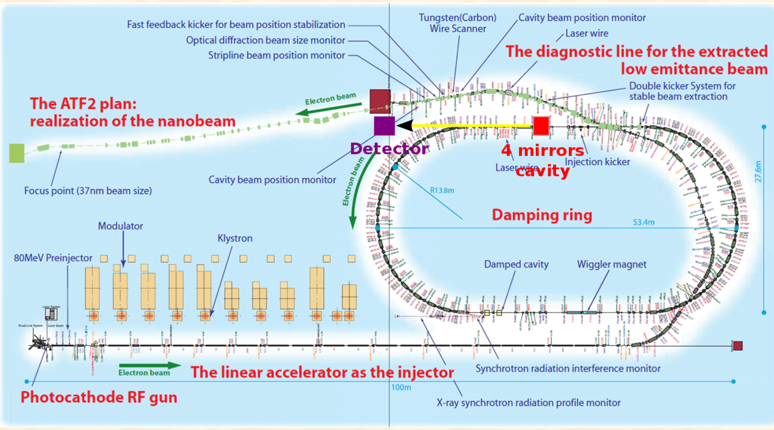
Cavity stabilisation: Pound Drever Hall technique

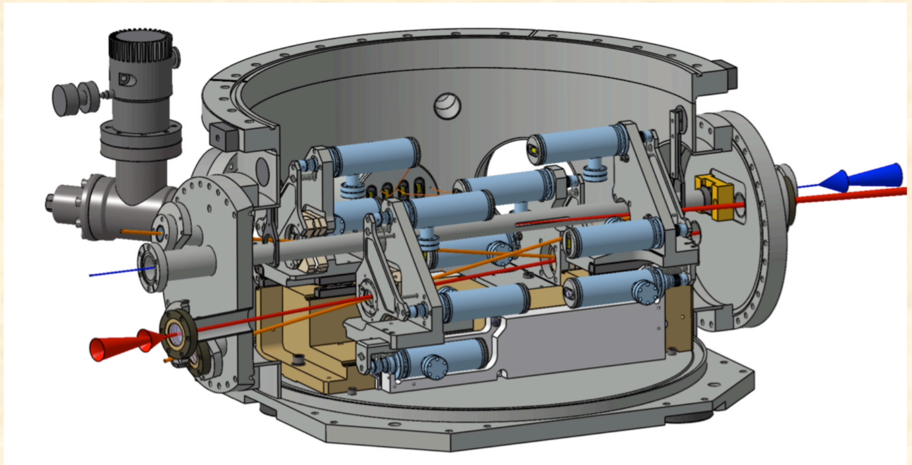


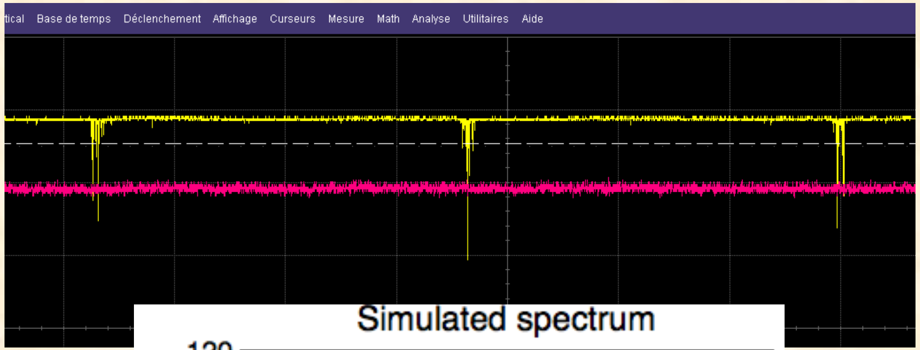
- We use the Pound Drever Hall technique to stabilise the cavity.
- The laser signal is modulated before being injected in the cavity.
- When close from the correct cavity length the signal “reflected” on the coupling port of the cavity is proportional to the correction to be applied on the piezo stack to adjust the laser cavity length.

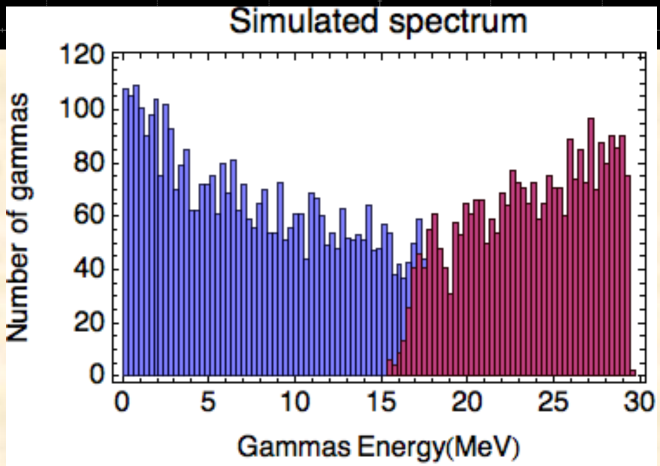
Mighty laser at KEK

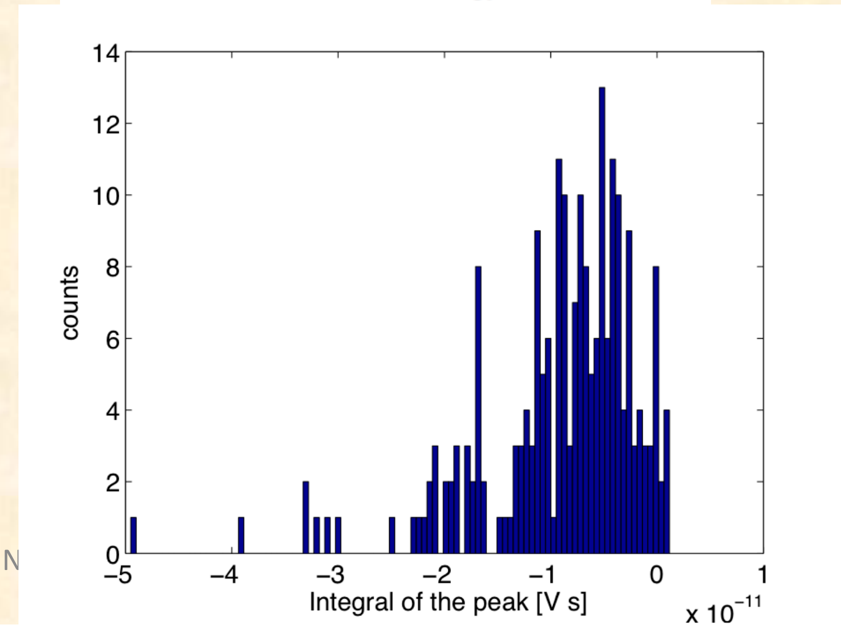
- To demonstrate our Compton production scheme we have installed a Fabry-Pérot cavity at the ATF at KEK.
- Our goal is to show that we can deliver a high instantaneous luminosity and a high integrated luminosity.









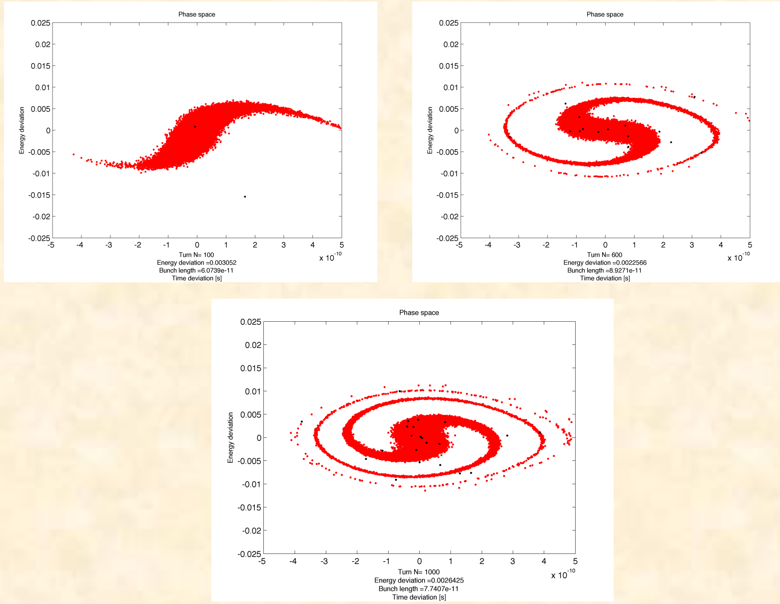


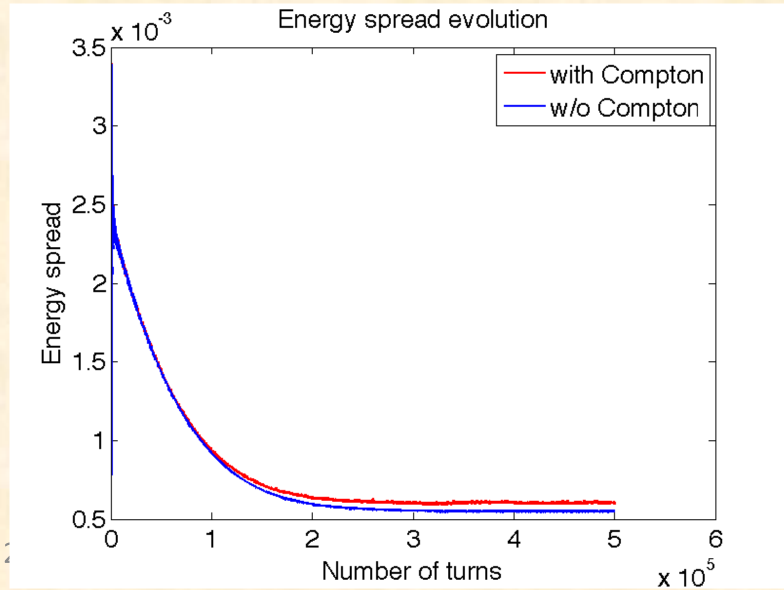
Data taking

- We achieved electron-laser collision during our first data taking shift and during each data taking run after.
- High flux of collimated gamma rays (25-30 MeV)
- PhD Thesis of Iryna Chaikovska (former student of KNU), graduated in 2012

Beam dynamics

- Beam dynamics play an important role in Compton machines.
- The particles that have been hit by the laser have a much lower energy and therefore they move in the phase space.
- Our results show that our prototype should not affect significantly the beam at the ATF.
- However this is unlikely to be the case in a dedicated machine and extensive beam dynamics simulations will be necessary for both ThomX and TTX.





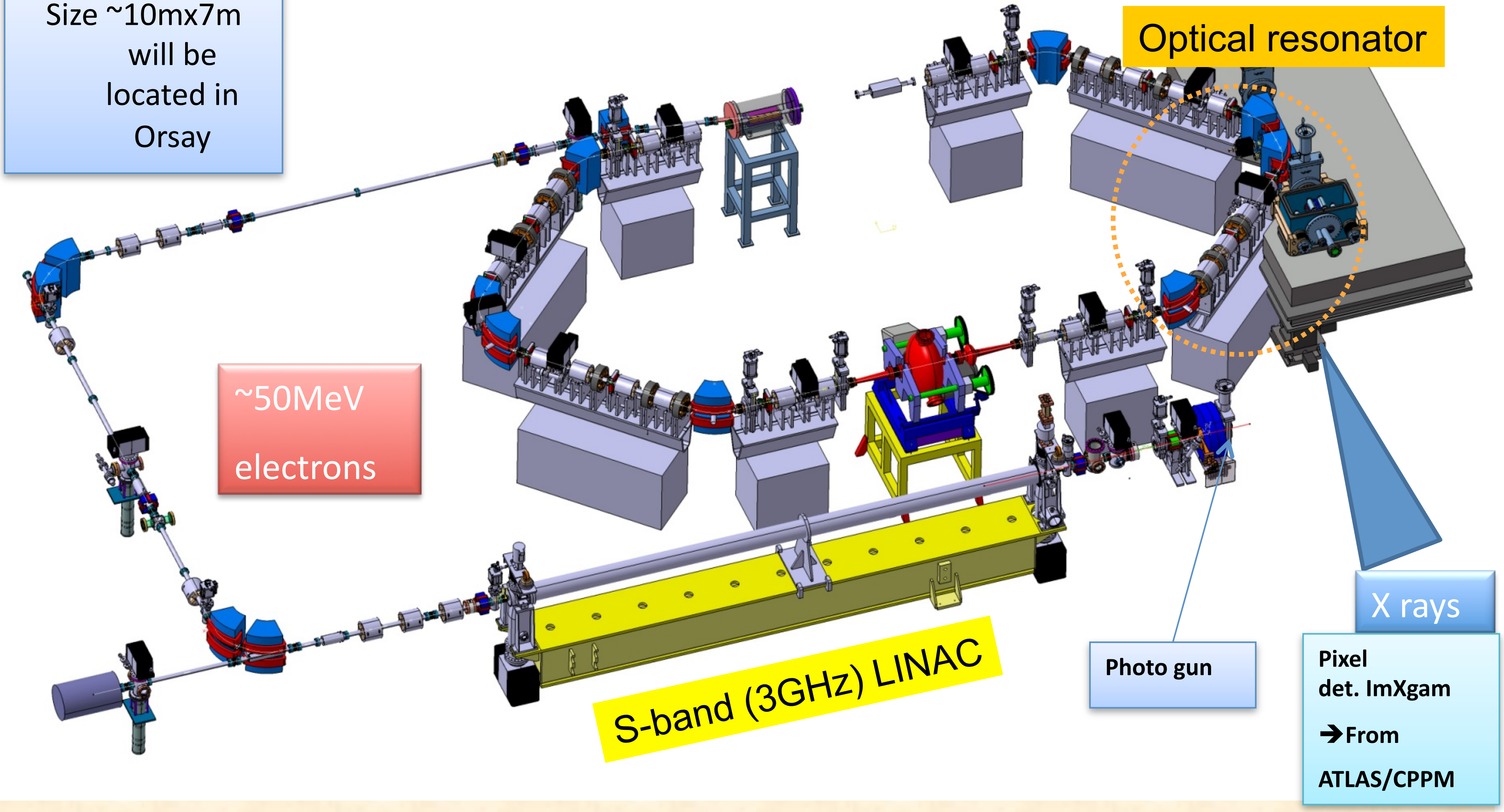
ThomX

- ThomX is a compact X-ray source to be built at LAL
- Funding granted in 2012 (about 20M€)
- Aim: have an X-ray source that can fit in an hospital or a museum

The machine

50 MeV electrons

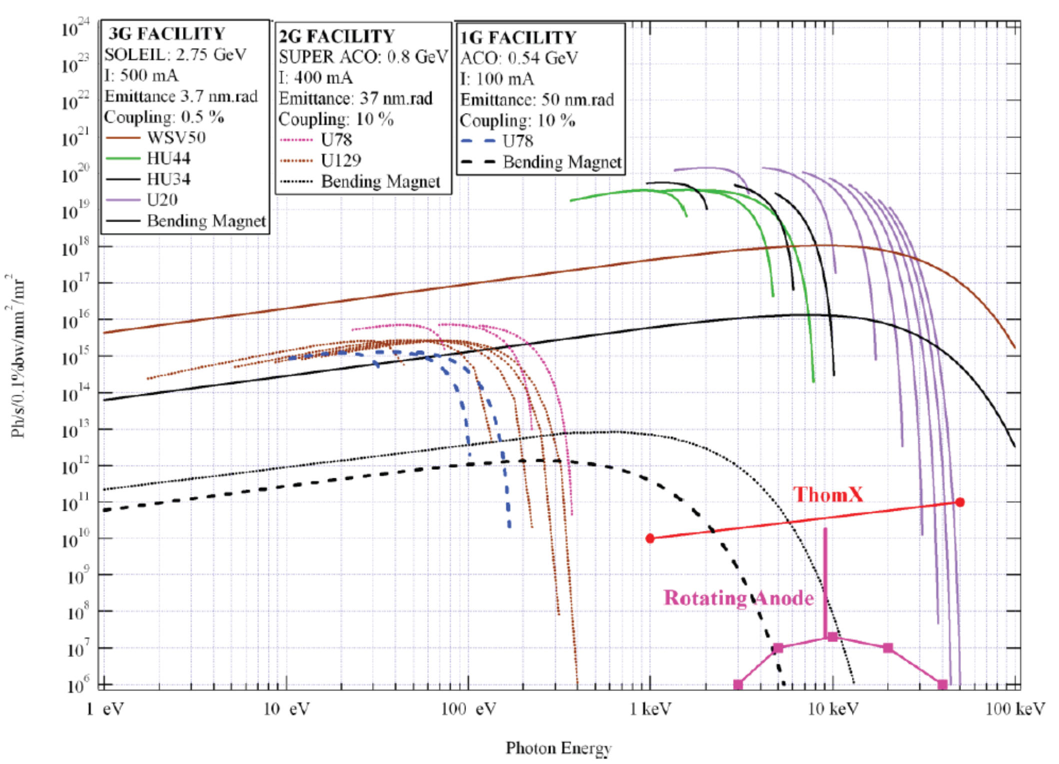
Size ~10mx7m will be located in Orsay

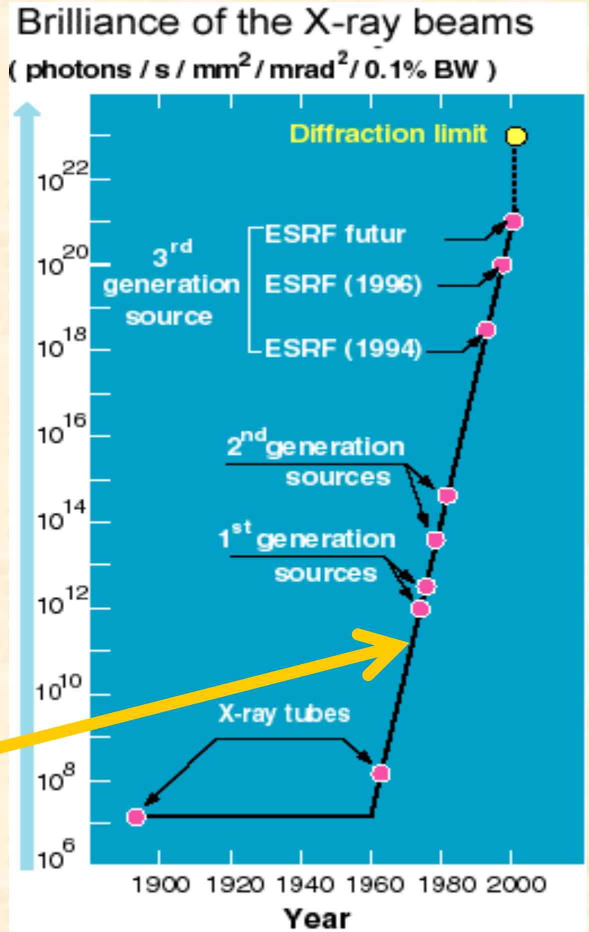


Main parameters

- Electrons:
  - 20-70 MeV (nominal: 50 MeV)
  - 1nC
  - 20ps rms
- Laser:
  - 30mJ/pulse => 100kW in Fabry-Pérot cavity
  - 1ps rms
- X-rays:
  - 6-92keV
  - 10^{11} to 10^{13} ph/s

Predicted flux



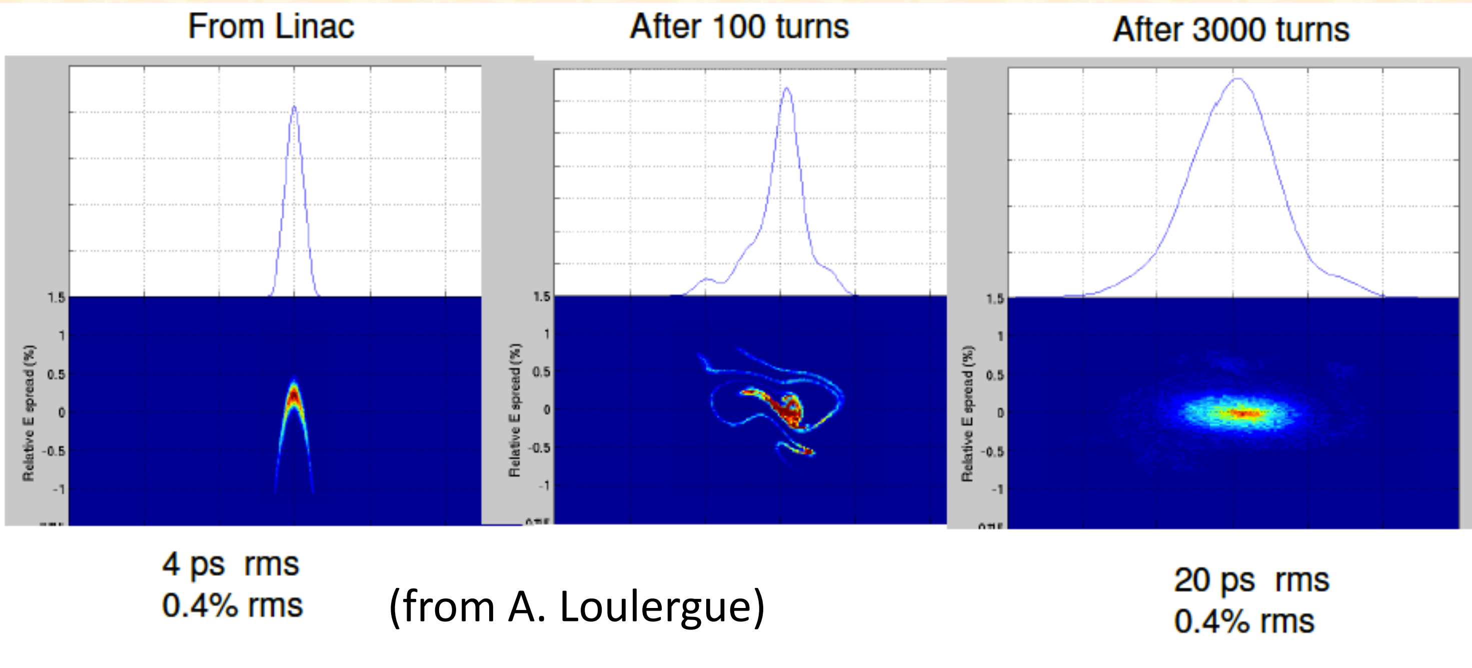


Flux ~ 10^{12} - 10^{13} ph/sec

Brightness ~ 10^{11} ph/sec/mm²/mrad²/0.1%bw

Beam dynamics

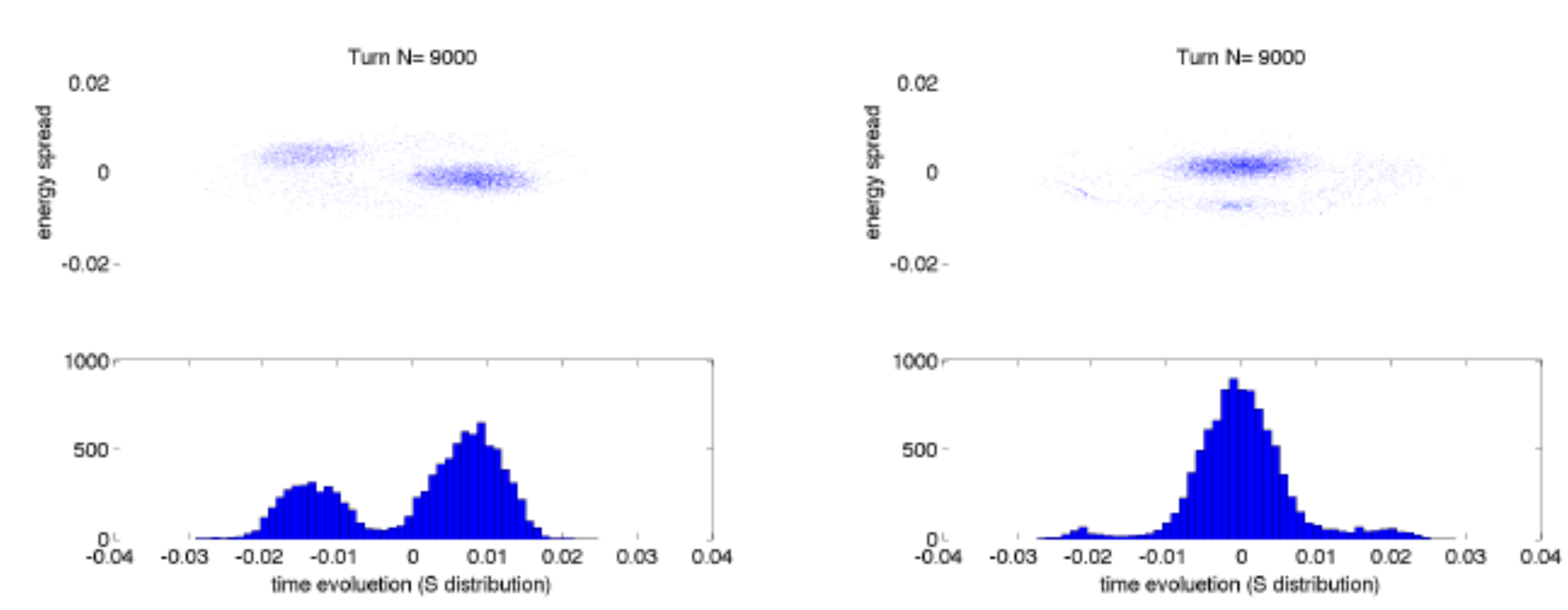
- CBS makes the beam lifetime very short
  => beam stored for only 20ms
- Damping is very long (1-2s)
- Injected bunch is very short (4ps)
  => turbulent process to fill the bucket (20ps)
- Strong collective effects (CSR, Resistive walls, …)



(from A. Loulergue)

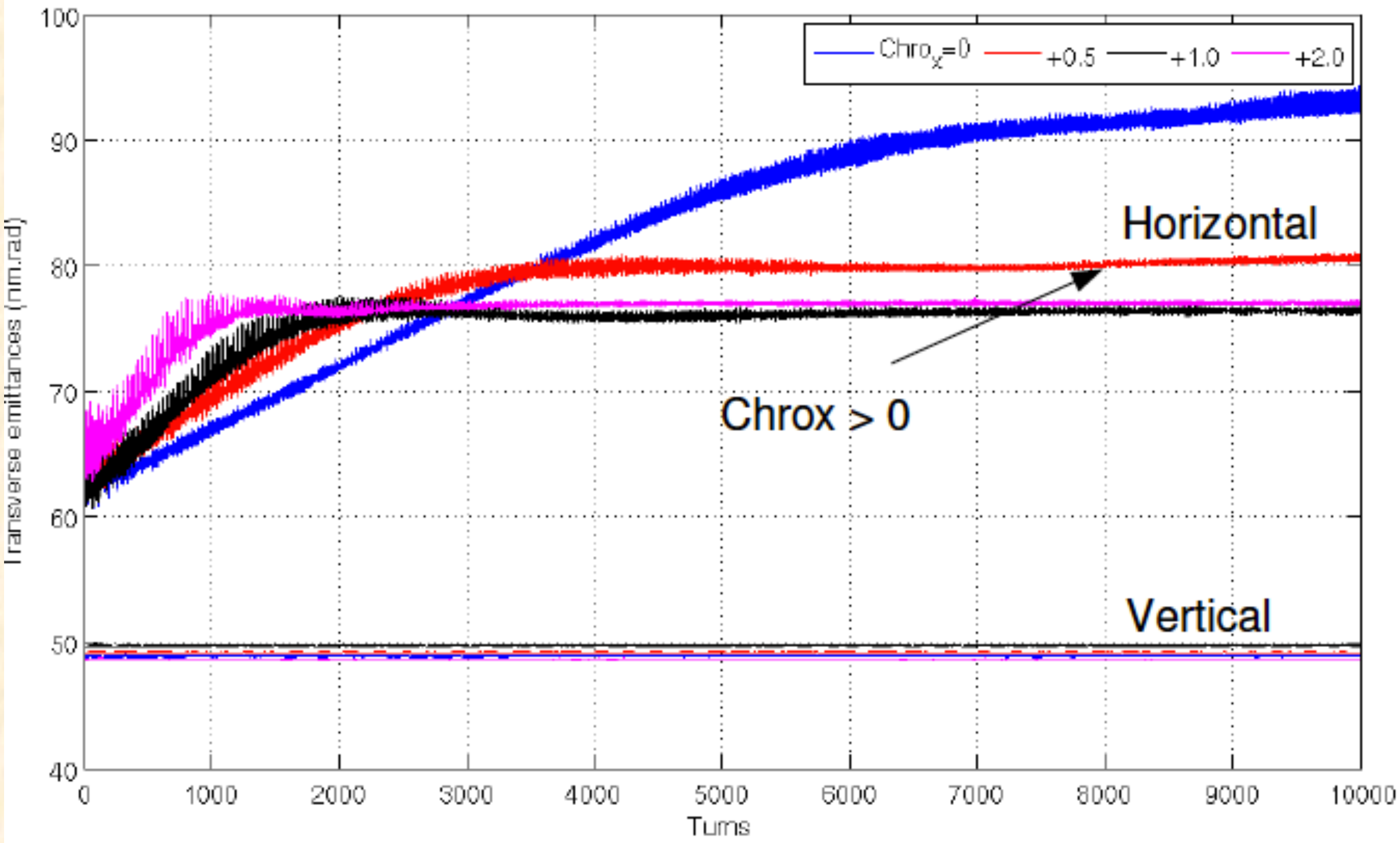
Beam dynamics (2)

- Sometimes the bunch can destroy itself due to coherent synchrotron radiation.
- Significant loss of flux!



- Thesis of Illya Drebot (KITP)

Beam dynamics (2)



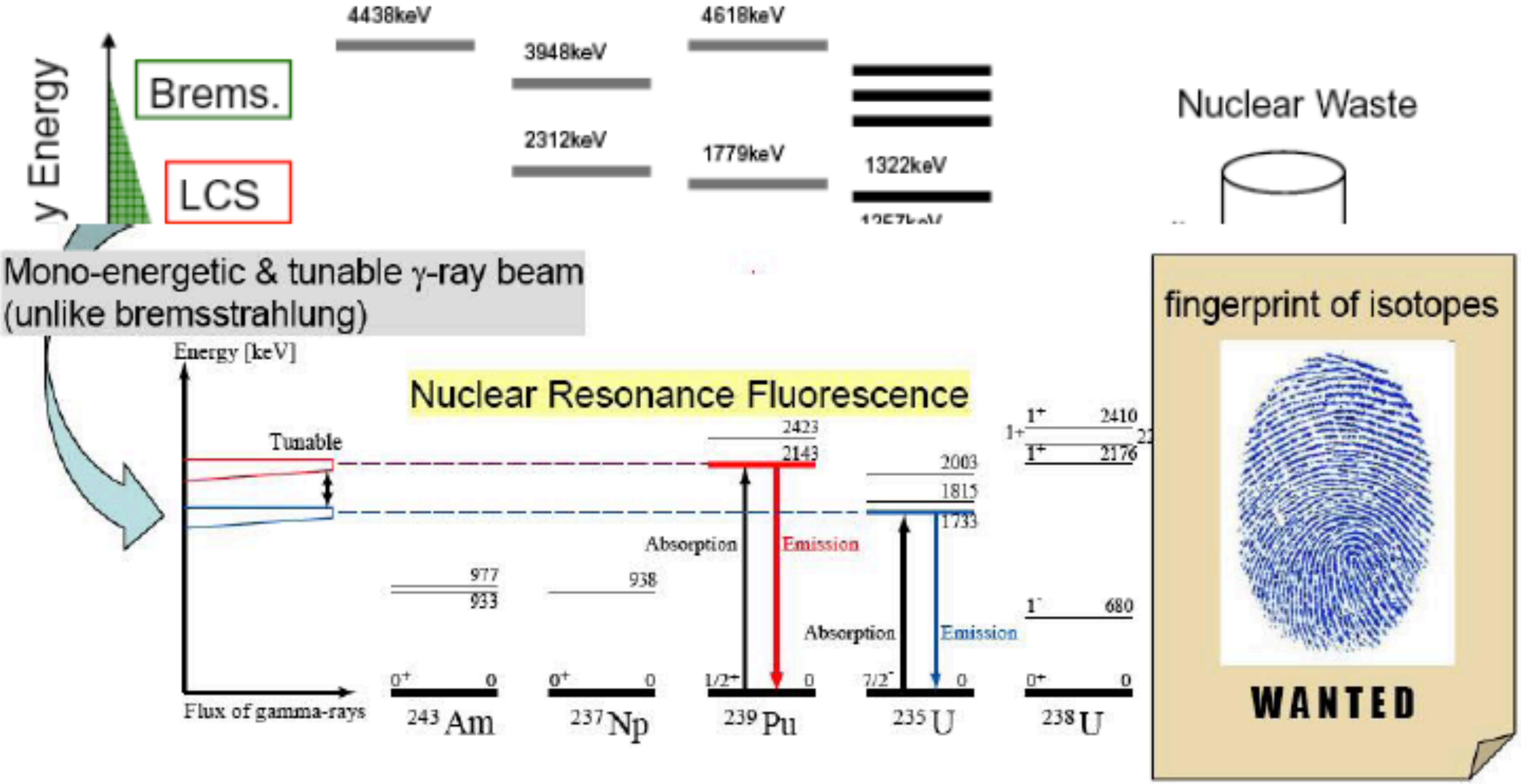
==> Get stable motion with positive chromaticities
Strongly instable with negative (not plotted)

(from A. Loulergue)

ELI-NP-GS

- LAL is working with universities and research institutes in Italy and in England to build a new gamma ray source in Romania (funded by the European Union Structural funds)
- The gamma ray source will have a very narrow bandwidth to be able to separate Nuclear Energy Levels.

Nondestructive Assay by Nuclear Resonant Fluorescence



R. Hajima et al., J. Nuclear Science and Technology, 45, 441-451 (2008).

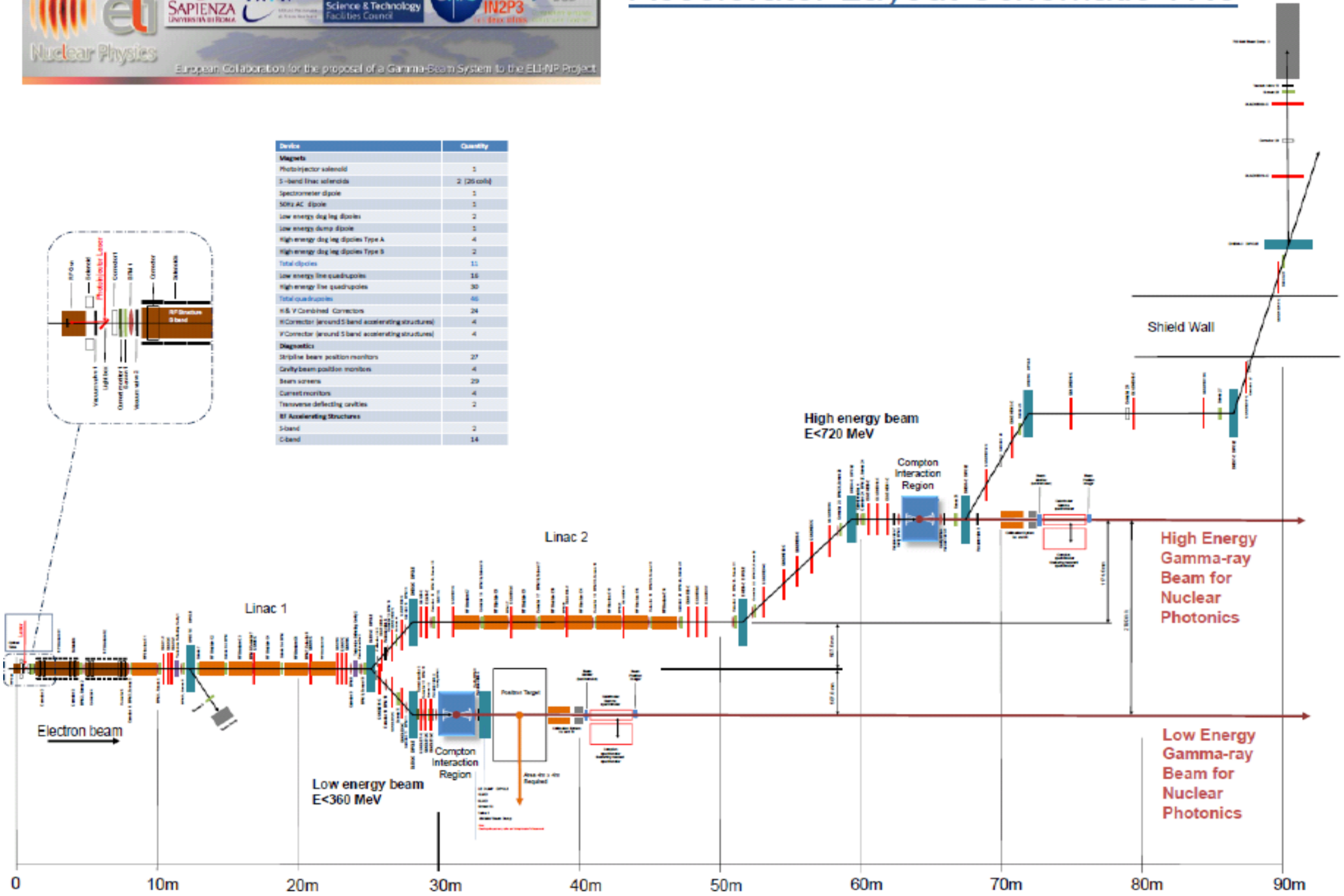
Low emittance requirements

- To achieve the narrow bandwidth required, the beam must have a very low emittance.
  => we can not use a ring, we must use a linac
  => The quality of the laser must also be controlled very accurately.

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

Accelerator Layout Schematic v7.0

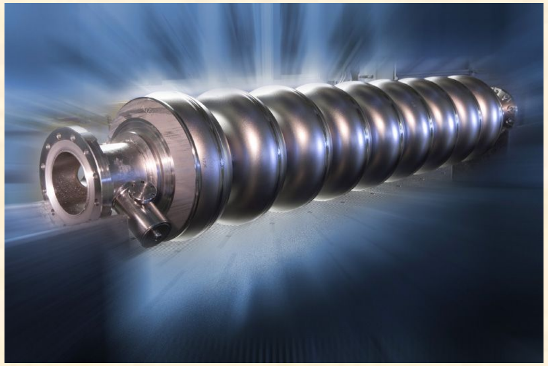
Device	Quantity
Magnets	
Photoinjector solenoid	1
S –band linac solenoids	2 (26 coils)
Spectrometer dipole	1
50Hz AC dipole	1
Low energy dog leg dipoles	2
Low energy dump dipole	1
High energy dog leg dipoles Type A	4
High energy dog leg dipoles Type B	2
Total dipoles	11
Low energy line quadrupoles	16
High energy line quadrupoles	30
Total quadrupoles	46
H & V Combined Correctors	24
H Corrector (around S band accelerating structures)	4
V Corrector (around S band accelerating structures)	4
Diagnostics	
Stripline beam position monitors	27
Cavity beam position monitors	4
Beam screens	29
Current monitors	4
Transverse deflecting cavities	2
RF Accelerating Structures	
S-band	2
C-band	14

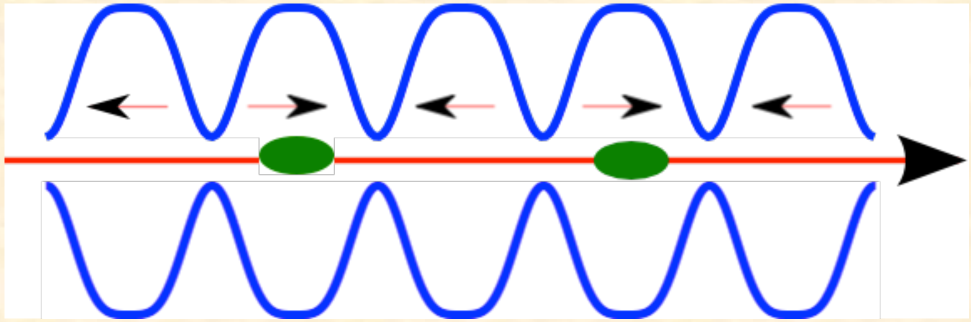


PLASMA ACCELERATION

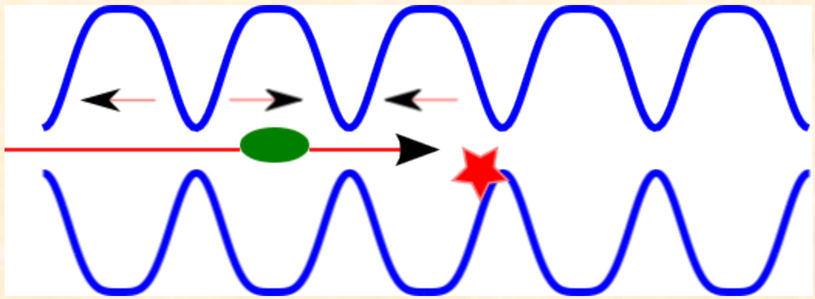
Limitations of current acceleration techniques

- In an accelerator particles are accelerated by an electromagnetic wave creating an accelerating gradient when the particles pass.





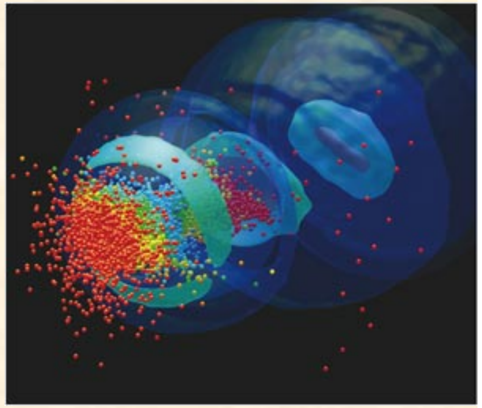
- If the gradient is too high an imperfection in the cavity may concentrate too much EM power and create a spark (breakdown) leading to the loss of the beam and possible damages to the cavity.
- So far accelerating cavities are limited to less than 100MV/m.



Plasma acceleration

- If the cavity is replaced by something that can not be damaged, much higher accelerating gradients can be reached.
- This can be done by creating a wakefield in a plasma.
- Different tools are used to create such plasma accelerator:
  - Lasers (Tajima and Dawson, PRL, 1979)
  - Electron beams (Hogan et al., PRL, 2005)
  - Proton beams (Caldwell et al., Nature Phys., 2009)

Example of wakefield
Source: http://www.arwenmarine.com

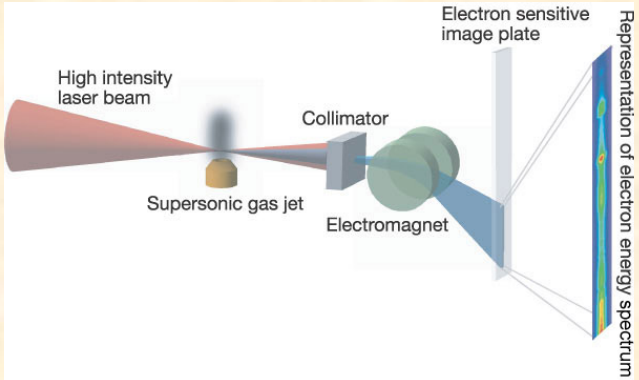


Wakefield in a plasma
Source: CERN Courier

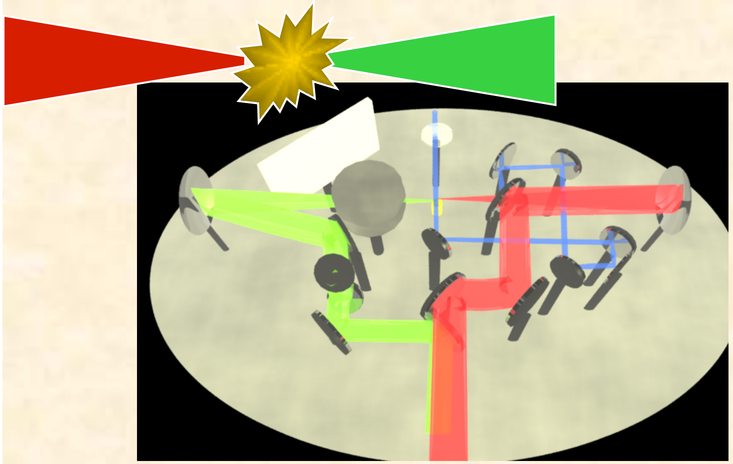
Laser-driven plasma acceleration

- First proposed in 1979 (Tajima and Dawson)
- In the 90s LULI demonstrated that injected electrons can be accelerated from 3 MeV to 4.5 MeV (Amarinoff et Al., PRL, 1998).
- Significant progress in 2004:
  Nature: "dream beam"
  - RAL/IC/UK: Mangles et al.
  - LOA/France: Faure et al.
  - LBNL/USA: C.G.R. Geddes et al.

Laser-driven plasma acceleration: “dream beam”



Mangles et al, doi:10.1038/nature02939

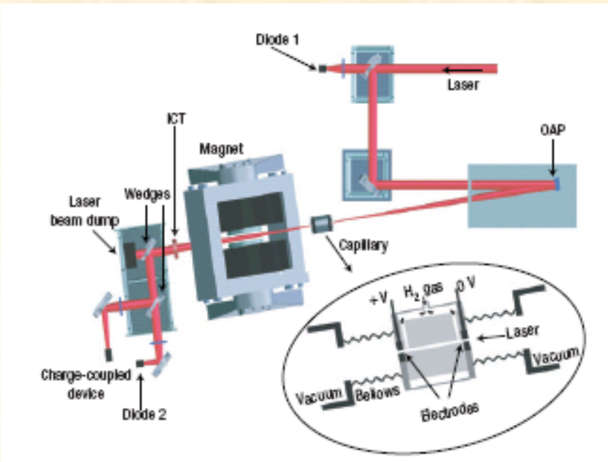


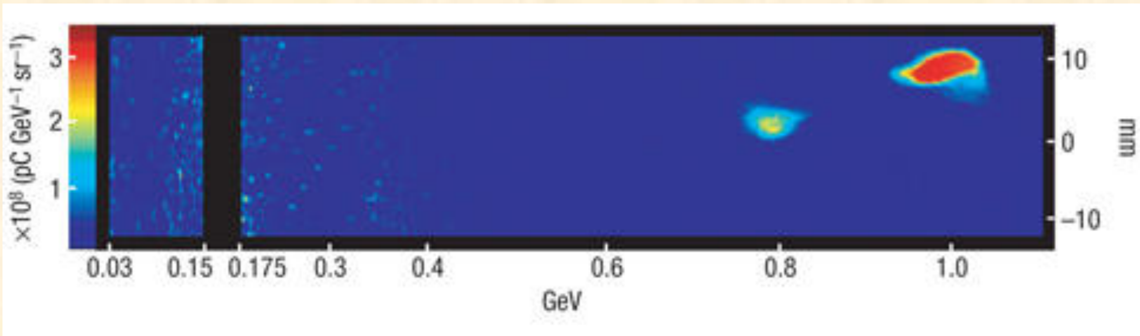
Faure et al., doi:10.1038/nature05393

- In the “dream beam” experiments the plasma was created in a gas jet.
- In this case the electrons are taken from the ions inside the plasma.
- In 2008 a beam of 800 MeV was produced using this technique (Kneip,..., ND, et al., PRL, 2009)

GeV LPA beam

- Another breakthrough occurred in 2005 when a Berkeley + Oxford collaboration reached an energy of 1 GeV.
- To do so they used a 33mm long capillary to extend the length over which the plasma has the right properties to accelerate electrons.
- The field created during this experiment was of the order of 100 GV/m!



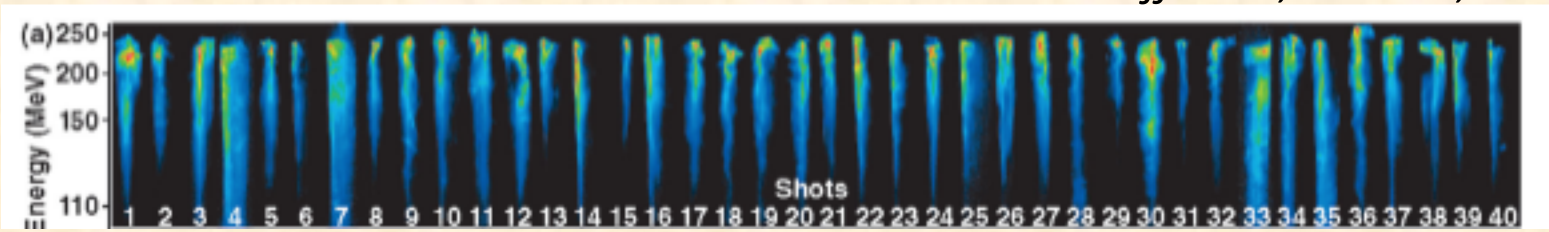


Leemans et al, doi:10.1038/nphys418

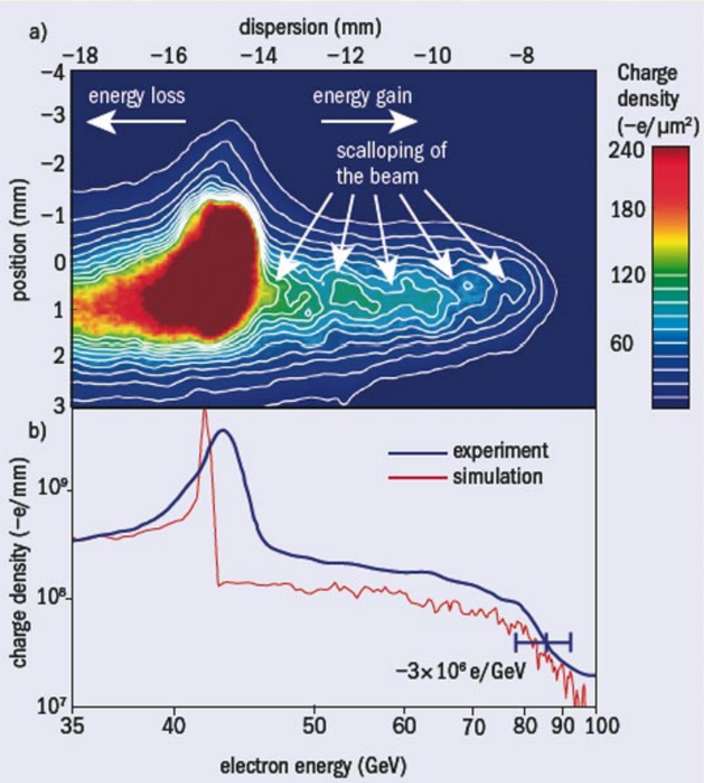
Typical features of LPA beams achieved so far

- Energy 50 MeV – 1 GeV
- Energy spread: from very large to a few percent
- Low repetition rate: 1Hz and less
  (eg: 1 shot every 20s at GEMINI)
- Low charge: 10-50pC
- Ultra-short pulses: 5-30fs (measure very difficult)
  => High peak current
- Shot to shot reproducibility is poor.
- Very small footprint for the "accelerator", laser included (few rooms).
- Simulations are difficult (particle in cell on large computers)
- Not all plasma acceleration experiments produce the beam predicted/expected…

J.Osterhoff et al., PRL 101,085002(2008)

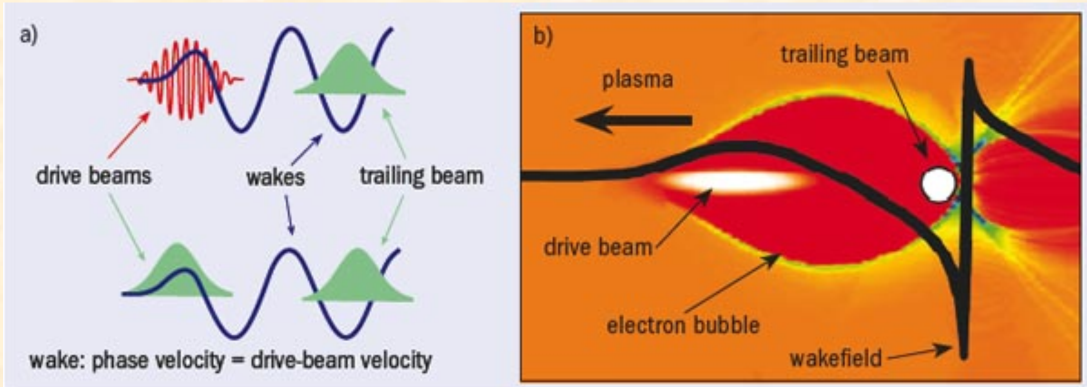


Electron driven plasma acceleration

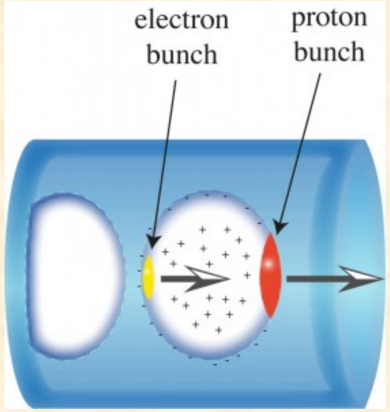


- Electrons can also be used to generate the wakefield required to accelerate other electrons.
- This has been demonstrated using the SLAC LINAC when the energy of some electrons of a bunch was doubled from 42 to 85 GeV.
- The field was about 50 GV/m.

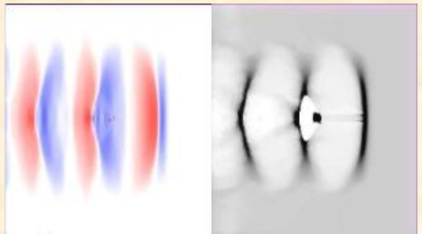
I Blumenfeld *et al.* 2007 *Nature* **445** 741
See also CERN Courier, May 2007 and CERN Courier, June 2007

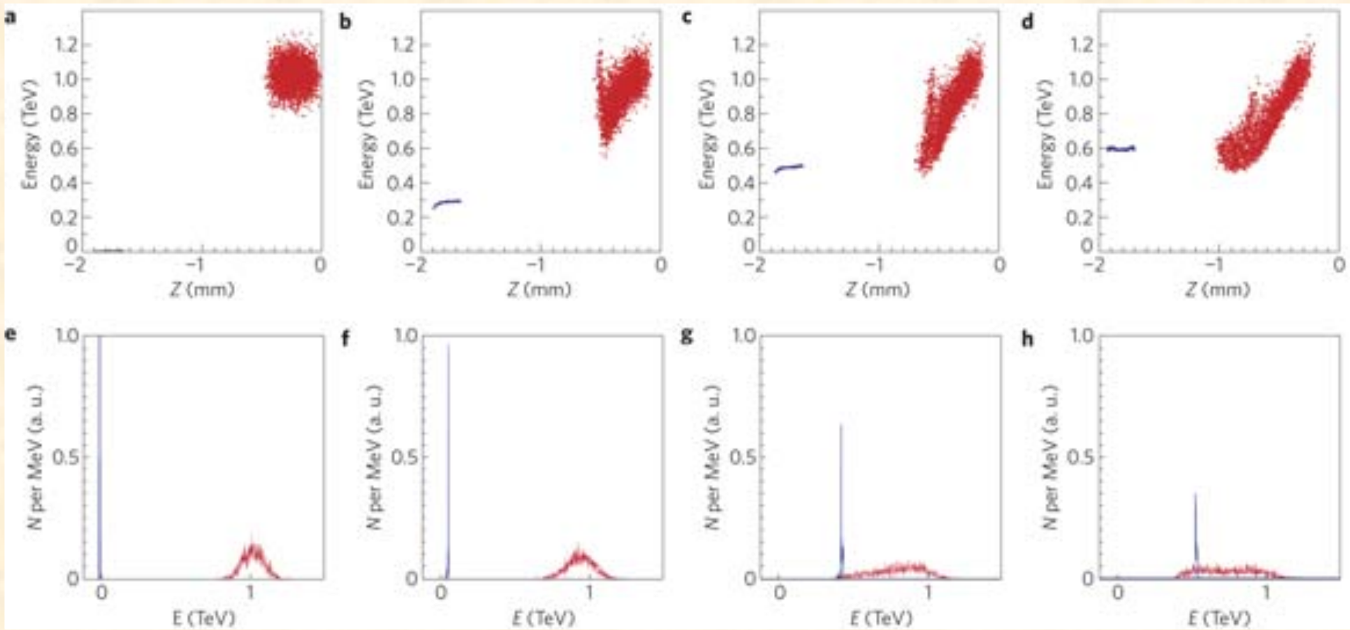


Proton driven plasma acceleration



- More recently there has been a proposal to use protons as drive beam to accelerate electrons.
- Simulations indicate that the CERN SPS beam could be used to accelerate electrons to 600 GeV.

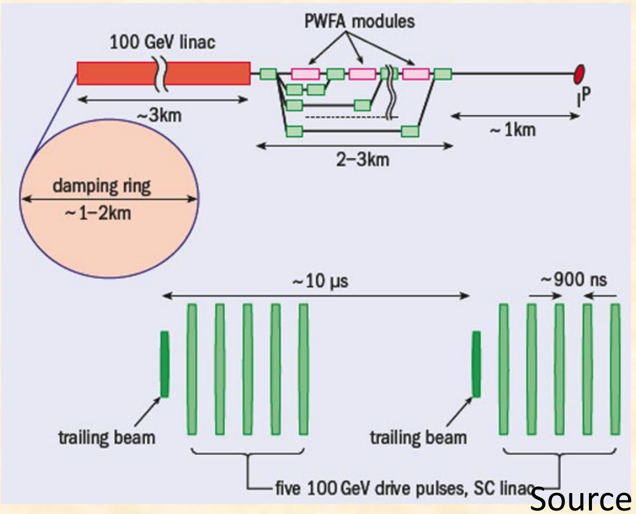




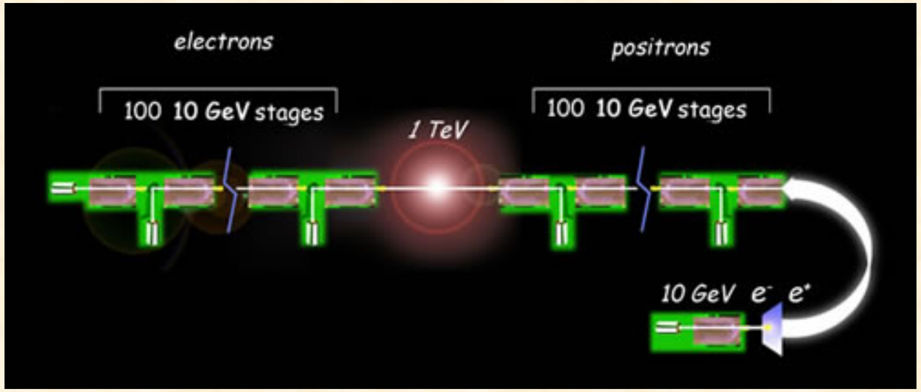
Caldwell et al.,
Nature Physics 5, 363 - 367
(2009)

Toward a plasma-based collider

- The next electron collider will require beams with an energy of between 500 GeV and a TeV.
- The production of such beam by a plasma-based collider has not yet been demonstrated, however there are proposal to stage several “accelerating sections” to achieve this.



Source:CERN Courier



Source:LBL

Limits

- Several important steps need to be made before such collider can be built.
- Plug to beam power efficiency is very low. In the case of laser-driven accelerators, fibre lasers may improve this but it may not be enough.
- Beam stability is another issue: at the moment each shot is different and goes in a slightly different direction…
- Very little is know about the quality (emittance) of such beam.

Outlook

- The discovery of a particle that looks like the Higgs is a big step for HEP.
- This is due in part to the tremendous work done to tame the LHC accelerator.
- However future progress in HEP and in other fields will require even better accelerators
=> lower emittance, better acceleration gradient
- Compact X-rays and gamma sources will allow new techniques in therapy, museums and nuclear physics.

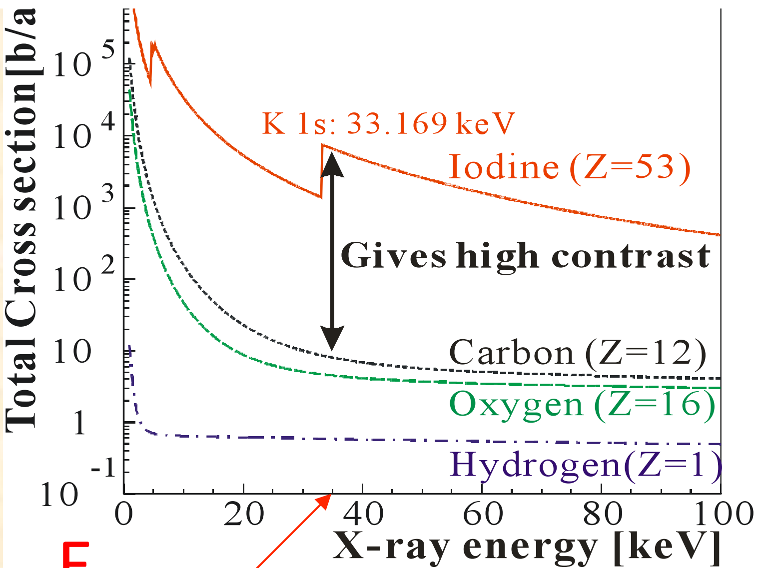
Motivations for a compact X-ray source: painting analysis

'K edge imaging'

- Heavy chimical elements are contained in painting pigments
  - Characterised by K absorption edges

Total Cross Section of X-ray attenuation

for various elements



E_{Kedge}

K-edge imaging
(Pb➔blanc, Hg➔ vermillion…)
of a Van-Gogh's painting

J. Dik et al., *Analytical Chemistry*, **2008**, *80*, 6436
http://www.vangogh.ua.ac.be/