Interactions between lasers and electrons

Nicolas DELERUE

30th March 2018

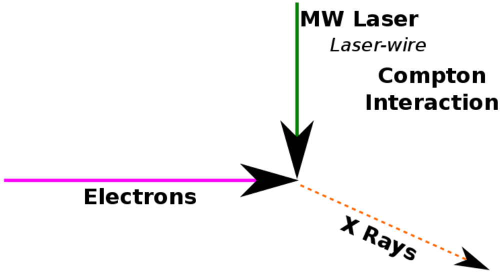
Outline

This is the work of a team

- The experiments I will present are complex.
- The results presented are the work of teams and I can not mention all contributors.
- I want to stress that important contributions have been made by engineers and technicians who helped build the experiments.
- Also, undergraduate project students, interns and graduate students have also played a key role.

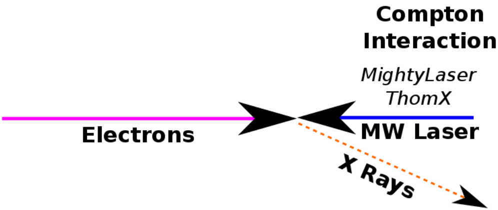
I will mention the name of a few students who have made important contributions.

Interaction between lasers and electrons at 90°



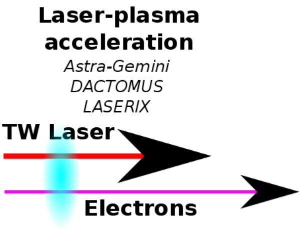
- Electrons and laser can interact at 90°.
- This interaction will produce X rays (or γ rays).
- Measure the beam profile ("laser-wire").

Interaction between lasers and electrons at 180°



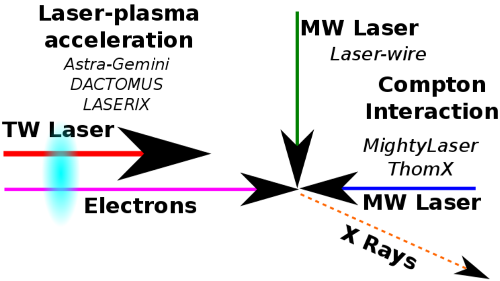
- Electrons and laser can interact at 180°.
- This interaction will produce higher energy X rays (or γ rays).
- Intense source of photons at wavelength difficult to reach.
- MightyLaser and ThomX.

Interaction between lasers and electrons at 0°



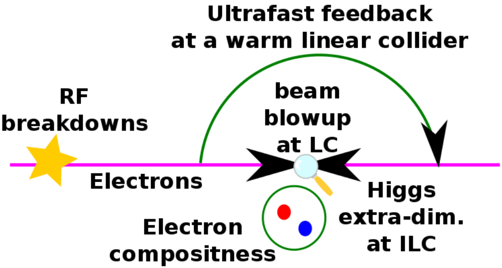
- Electrons and laser can propagate in the same direction through a plasma.
- The laser will transfer some of its energy to the electrons.
- The electrons will be accelerated.
- Astra-Gemini, DACTOMUS and LASERIX.

Interaction between lasers and electrons



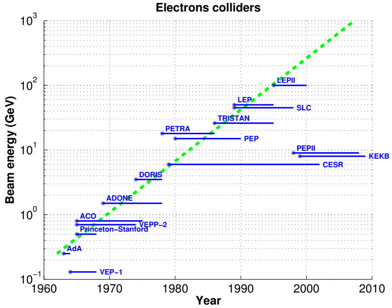
- Most of the studies I will present today were related to interactions between lasers and electrons.

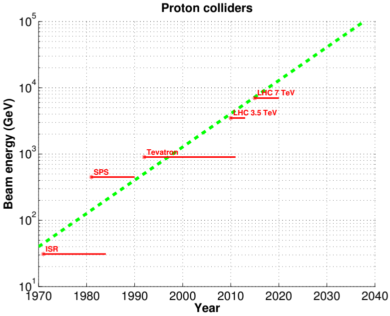
Other work



- I will not cover some of the work I did in high energy physics.
- I will also not cover some work related accelerator technology the I did early in my career (mostly at KEK).

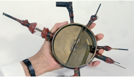
Particle accelerators



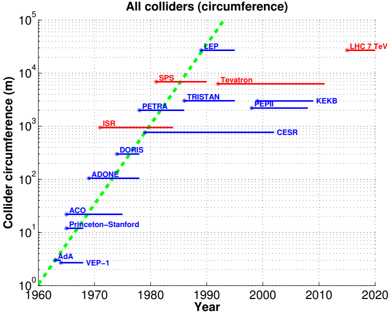


- Particle accelerators have been a key driver for particle and nuclear physics.
- During the XXth century they have steadily grown in size and in energy.

Particle accelerators



- One of the earliest accelerator could fit in the palm of a hand.
- The world largest collider is 27 km in circumference.
- Until year 1989 colliders doubled in circumference approximately every two years.
- However this trend has stopped.



Anne-Fleur Barfuss (M2): *Heritage of High Energy Physics Experiments*

Lasers

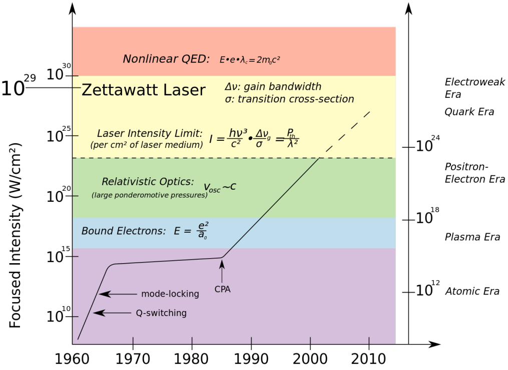
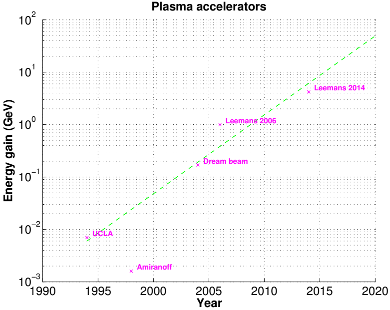


Image source: Wikipedia

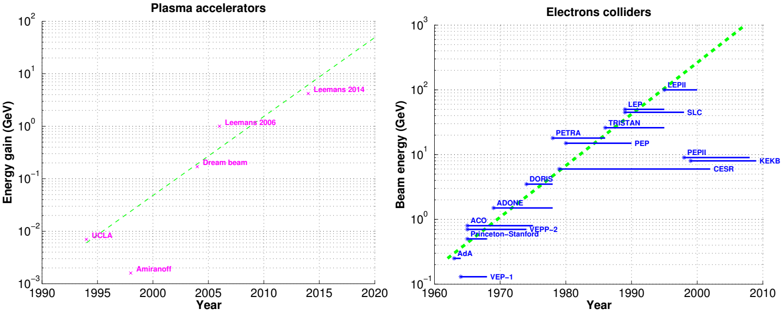
- The first experimental demonstration of a laser was in 1960.
- The introduction of Chirped Pulse Amplification (CPA) in the 1980s has allowed significant progress in peak intensity.
- More recently fiber lasers have allowed efficiency gains.

Laser-plasma acceleration

- Laser-Plasma acceleration was first proposed in 1979.
- The first important results were achieved in the 1990s.
- The latest published results show that electrons have been accelerated to energies of more than 4 GeV over a few cm.
- Higher energies have been reported at conferences.

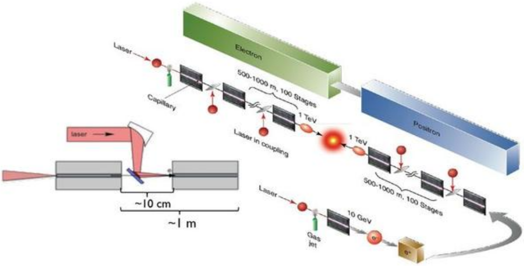


Laser-plasma vs colliders



- Although the trend in energy gain for plasma accelerators is impressive, it must be compared to colliders energy with care.
- Laser-plasma accelerators: maximum energy reached.
- Colliders: energy of two stable high current beams.
- There is a long way from one to the other.

Laser-plasma collider

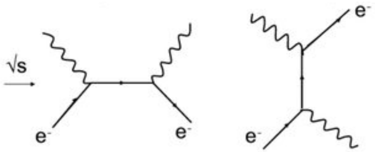


https://physicstoday.scitation.org/doi/10.1063/1.3099645

- A concept of particle collider based on plasma accelerators has nevertheless been proposed.
- However several issues need to be addressed: staging, stability, charge, repetition rate.

Outline

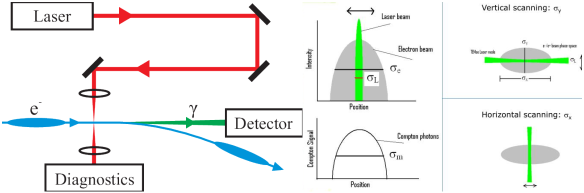
Theory of Compton scattering



$$\nu_o \simeq \nu_i[2\gamma^2(1+\cos\theta_o)]$$

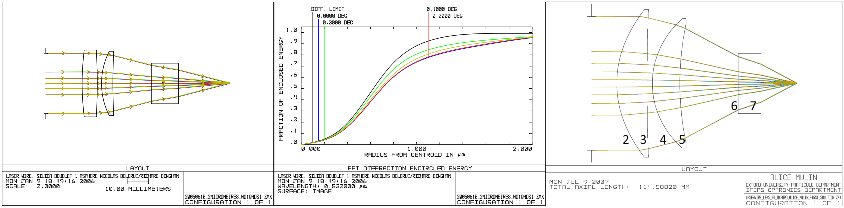
- Inverse Compton scattering occurs between an electron and a photon.
- The energy is transferred from the high energy particle (electron in our case) to the low energy particle (photon).
- But the cross section is low ($\sigma_T \simeq 6.65 \times 10^{-29}\,\mathrm{m}^2$).
- $\mathcal{P}_{\mathrm{scat}} = \mathcal{L} \times \sigma_T = 2.12 \times 10^{-24}$ per e^- and γ for a 25 µm x 10 µm interaction area.

Laser-wire



- Compton scattering can be used to probe the transverse profile of an electron beam.
- Unlike a normal wire-scanner the wire of a laser-wire is unbreakable.
- The laser can be focussed to a very small size.
- I made several contributions to the UK laser-wire activity.

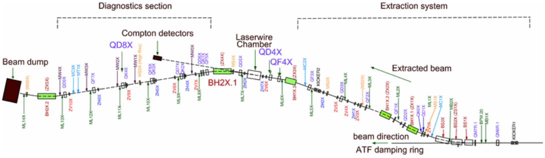
Lens design

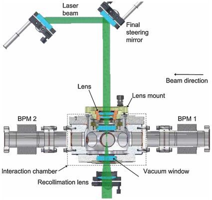


- Micrometer accuracy is needed to allow an optimum tonight of the ILC.
- This requires a very challenging focussing system.
- I designed and tested such a system for the ATF laser-wire.
- Later an improved design was reached with a student.

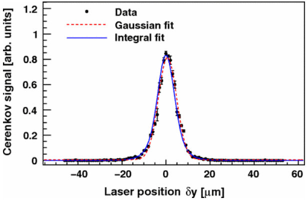
Alice Mulin (IFIPS): *Optical design F/1 lens*

ATF Laser-wire



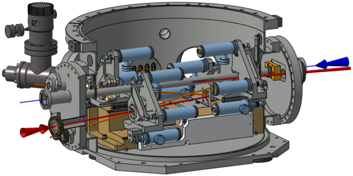


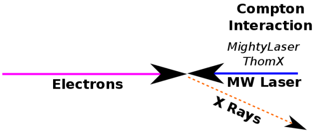
- The ATF laser-wire was a demonstrator for ILC laser-wire.
- Sub-micrometer beam size resolution was demonstrated.



Laurent Millischer (Central Paris), Myriam Qershi (D.Phil Oxford)

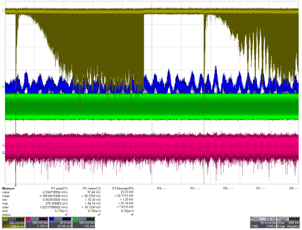
The MightyLaser experiment

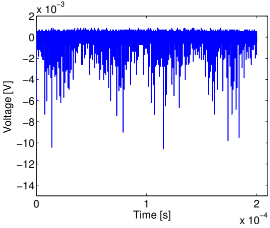




- The aim of the MightyLaser experiment, also at the KEK ATF was to demonstrate γ-rays production with a Fabry-Perot cavity.
- This has the advantage of requiring a much lower laser power as photons cross several thousand times the electron beam.
- I joined the project when most of the hardware had been built.
- I took the lead of the experimental campaigns in Japan.

First experimental campaign

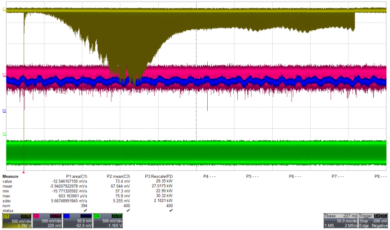


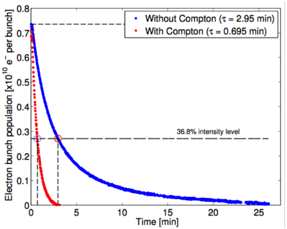


- The first experimental campaign demonstrated the principle.
- We were rather fast to find laser-electrons overlap.
- Some minor issues were identified and had to be addressed during a second experimental campaign.

Iryna Chaikovska (PhD U-Psud)

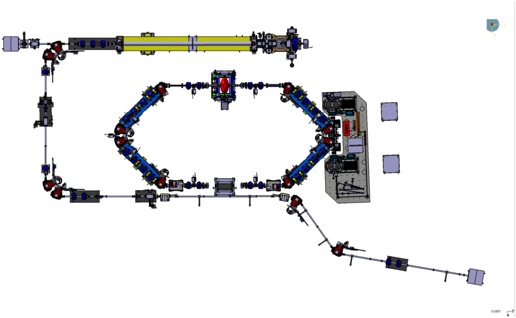
Second experimental campaign





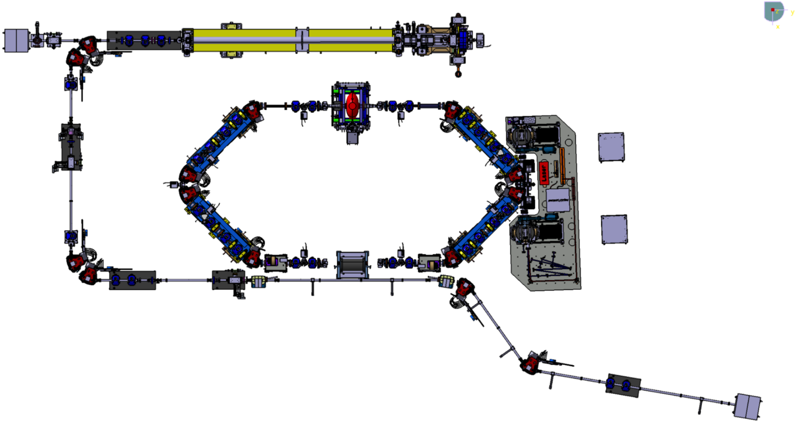
- The second experimental campaign was significantly delayed by the 2011 earthquake.
- The intracavity laser power was significantly increased (to 35 kW).
- Some thermal effect due to the power stored in the cavity were observed.
- Effect on the electron beam and its lifetime.

The ThomX project

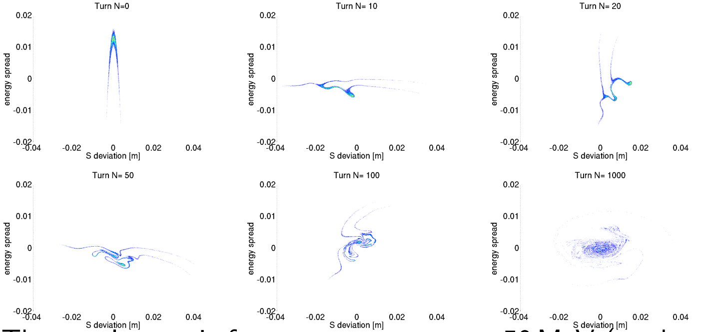


- The MightyLaser experiment can be seen as a demonstrator for a compact X-ray source to be built in Orsay: ThomX.
- My contribution to this project is the diagnostics, the synchronization system and some beam dynamics studies.

The ThomX project



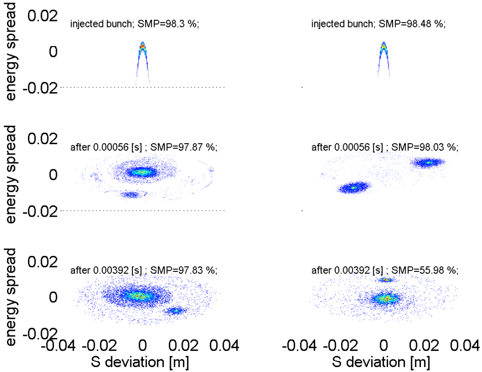
Beam dynamics in ThomX

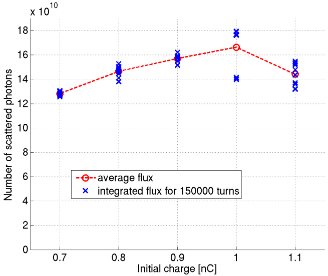


- The accelerator is foreseen to operate at 50 MeV (at the beginning).
- At injection the bunches coming from the linac expand turbulently in the much wider RF buckets from the ring.

Illya Drebot (PhD U-Psud)

Beam dynamics in ThomX: unstable bunches

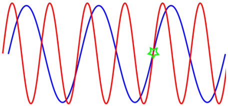




- Collective effects can be strong enough to destroy the bunch.
- Strategies to mitigate these effects will be studied soon.

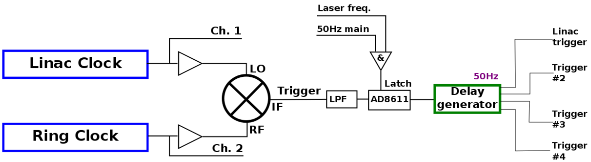
Illya Drebot (PhD U-Psud)

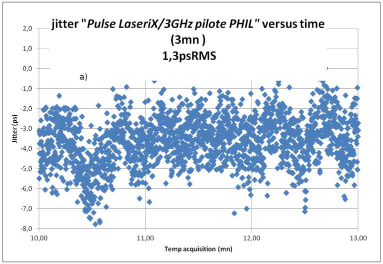
Synchronizing lasers and accelerators



- Several time during my career I have faced the problem of a pulsed laser having to be operated together with an accelerator.
- The laser frequency is set by its oscillator and the accelerator frequency is set by the RF.
- However for them to work together the laser pulse must be sent exactly when the electron pulse comes with picosecond accuracy.
- This requires a synchronization system.

Heterodyne synchronisation

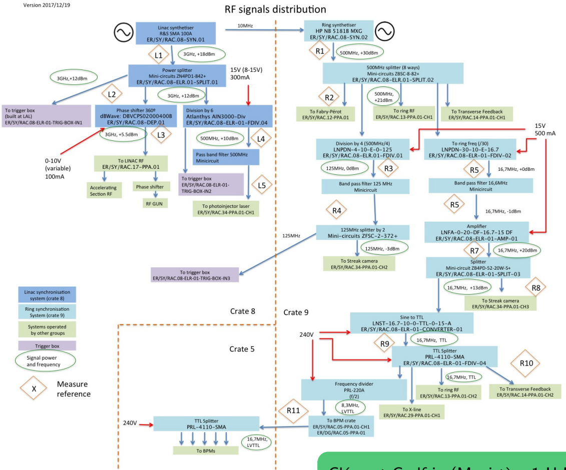




- In ThomX, the linac and the ring also use different frequencies.
- An heterodyne synchronisation scheme has been developed and is also used in ESCULAP.

Heidi Rösch (M1 Darmstadt)

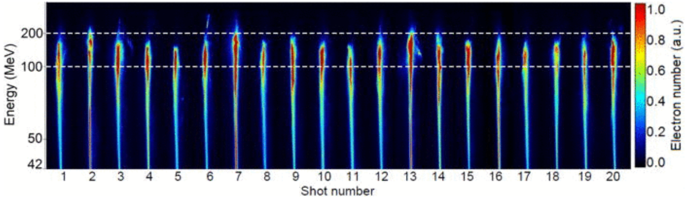
The ThomX synchronisation scheme



Clément Godfrin (Magistère 1 U-Psud),
Naomi Chmielewski and Karim Khaldi (L2 U-Psud)

Outline

Motivation for single shot measurements



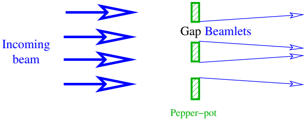
https://aip.scitation.org/doi/full/10.1063/1.4817747

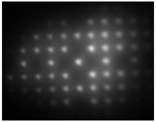
- Laser-plasma accelerators are not as stable as conventional accelerators.
- To be meaningful measurements must be done in a single shot.
- Hence I have worked on several single shot diagnostics.

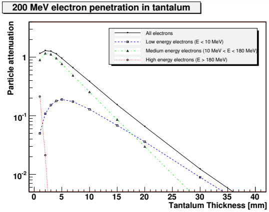
Single shot emittance measurement: Pepper-pot

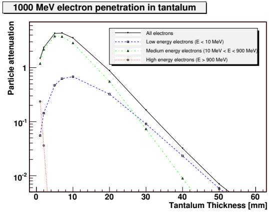
- Pepper-pots are conventionally used to measure single shot transverse emittance at low energy.
- I studied how thicker pepper-pot can work at higher energy.

Joe Hewlett, Michael McCann (BA and MPhys Oxford)





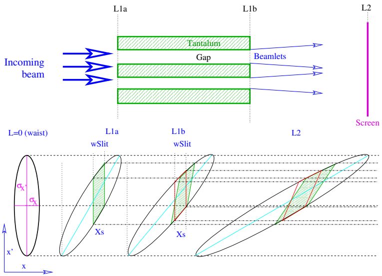


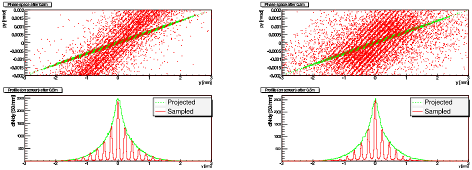


Pepper-pots at high energy

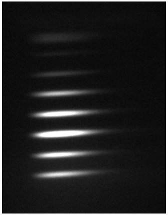
- It was important to check that the thickness did not affect the phase-space.
- This was done by calculations and GEANT4 simulations.

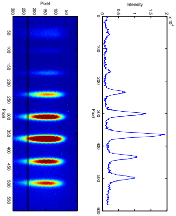
Joe Hewlett (MPhys Oxford)





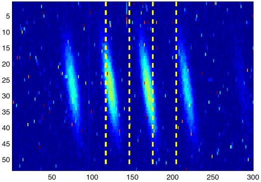
Pepper-pot experiments

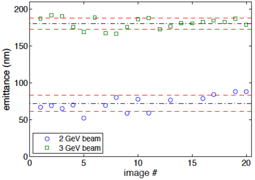




Frascati
Beam Test Facility
508 MeV

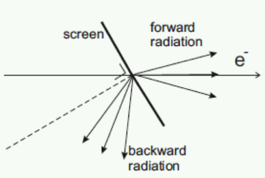
Nick Shipman (MPhys Oxford)

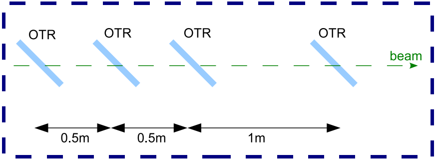




DIAMOND
Booster to Synchrotron line
3 GeV

Single shot emittance measurement: OTRs





- Another technique that was considered was to use Optical Transition Radiation screens to measure the beam size at several locations.
- This requires to check the scattering induced by a screen to ensure that it does not affect the measurement.

Scattering in a screen: calculations

- Derivation of the product scattering angle and particle energy:

$$p\theta_0 = \frac{13.6 \text{ MeV}}{\beta c}\sqrt{\frac{x}{X_0}}\left[1 + 0.038 ln\left(\frac{x}{X_0}\right)\right]$$

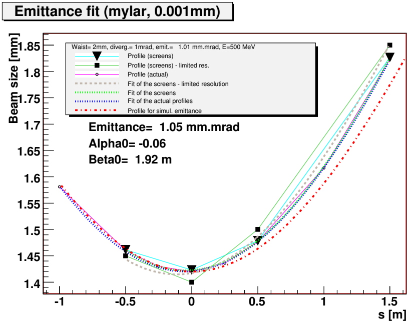
- Example: 10 µm Aluminium: $p\theta_0 = 139\,\text{MeV}\,\text{mrad}$
- This allows to estimate the size limit for the scattering to be negligible:

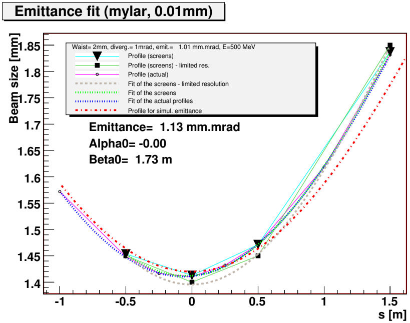
$$\sigma_0 << N_{\text{screens}} \frac{\epsilon_n}{\gamma \frac{p\theta_0}{p}}$$

- For 10 µm Aluminium and $\epsilon_N = 1\,\text{mm}\,\text{mrad}$ this gives 0.9 mm.

Howat Duncan (MPhys Oxford)

Scattering in a screen: Simulations





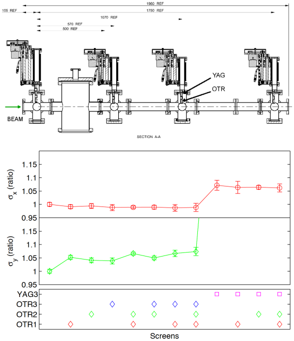
- Geant4 simulations were made to validate the simulations.

Stuart Moulder (MPhys Oxford)

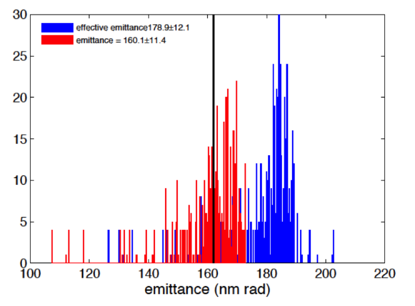
Single emittance measurement with OTRs

- An experiment was done at the DIAMOND light source to check the result.
- Beam size measured was not significantly affected by upstream screens.

Bas-Jan Zandt (MPhys Eindhoven)

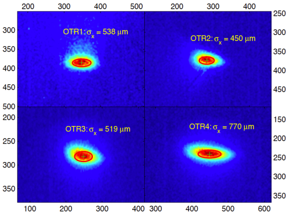


Single emittance measurement with OTRs: results



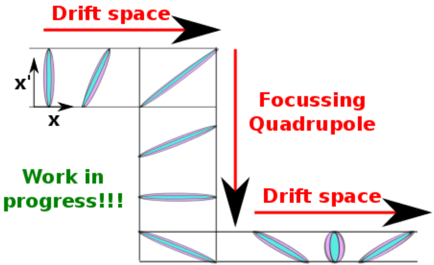
- The measurements were done in a highly dispersive area, so this had to be taken into account to reconstruct the correct transverse emittance value.
- After correction the transverse emittance measured by this method was very close from the value measured by quadrupole scanning.

Single emittance measurement with OTRs: interferences



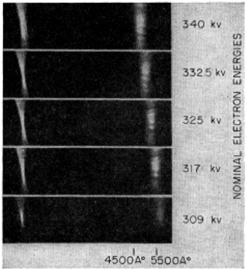
- Concerns were expressed about interferences in the OTR formation zone.
- The images we recorded did not show any such interference.
- Interferences would be visible for single wavelength but smeared out for large bandwidth.
- An experiment is planned at CLIO to study this further.

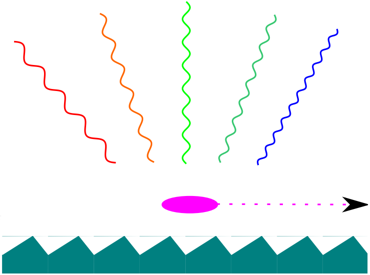
Phase space shearing



- Issue: at LPA the beam has a very large divergence but a very small size.
- Refocussing is needed but dispersion may affect the beam size.

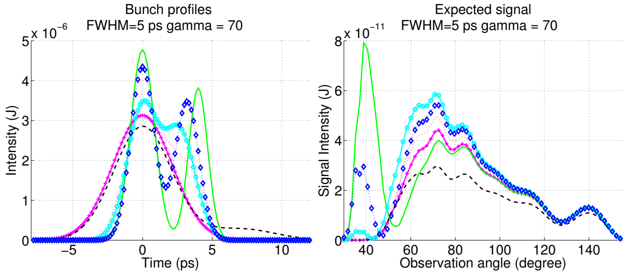
Coherent Smith-Purcell Radiation





- Bunch length measurement is a challenge for ultra-short bunches.
- One possibility for single shot measurements is to use the coherent radiative phenomena.
- Coherent Smith-Purcell Radiation (CSPR) is one of such phenomena.

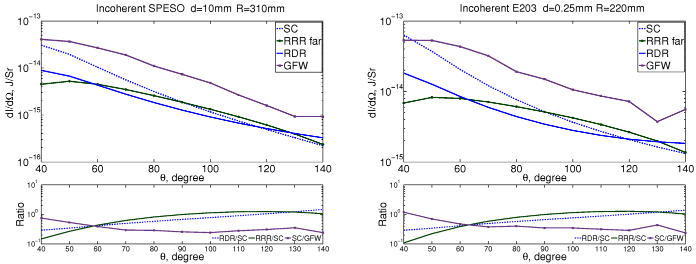
CSPR: Bunch profile reconstruction



- In CSPR the bunch longitudinal profile is encoded in the spectrum distribution of the radiation emitted.
- Bunch with different profiles will have different spectrum.

Vitalii Khodnevych (Kyiv National University)

CSPR: Comparison of models



- There are several different models describing CSPR.
- Although the signal yield may be different this model uncertainty has little influence on the sensitivity to the bunch longitudinal profile.

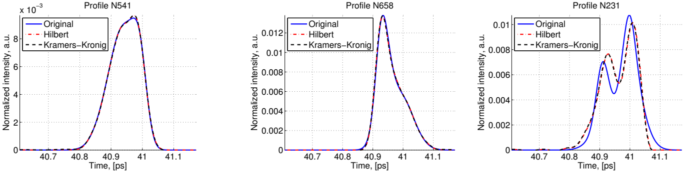
CSPR: Profile recovery

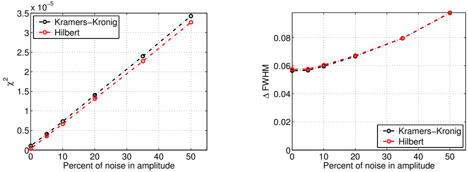
$$\Theta(\omega_0) = \frac{2\omega_0}{\pi} P \int_0^{+\infty} \frac{ln(\rho(\omega))}{\omega_0^2 - \omega^2} d\omega$$

- During the measurement process the phase of the beam profile is lost.
- This information can be recovered using an Hilbert transform often by using the Kramers Kronig relations (KK).
- Work to improve this technique in the case of CSPR.

Richard Tovey (MPhys Oxford)
Clémentaine Santamaria (Magistère U-Psud)
Vitalii Khodnevych (Kyiv National University)

CSPR: Profile recovery studies

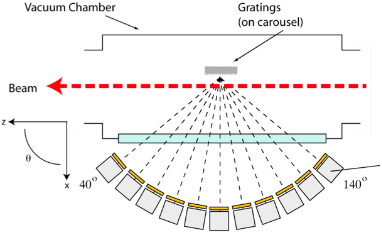


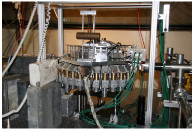


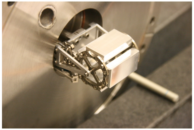
- In most case the profile is correctly reconstructed (top) but some pathological cases occur (bottom).
- We checked that the later case is not frequent.
- We also studied the effect of noise.

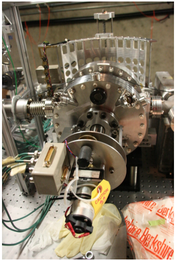
Vitalii Khodnevych (Kyiv National University)

CSPR: E-203





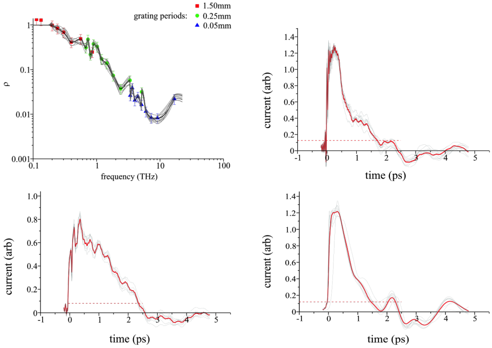




- I took part in several experiment related to CSPR.
- The first of them was E-203 on the FACET accelerator at SLAC.
- 20 GeV sub-ps beam.

Ewen McLean (MPhys Oxford)

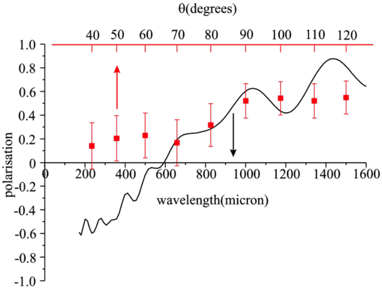
CSPR: E-203 results on bunch length



- We were able to measure the bunch longitudinal profile for different compression.
- Unfortunately we did not have the opportunity to make a measurement at the same time than other bunch profile measurement devices.

Mélissa Vieille Grosjean (PhD U-Psud), Solène Le Corre (ENS Lyon)

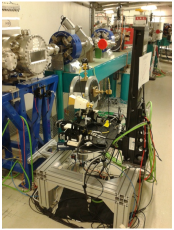
CSPR: E-203 results on polarization

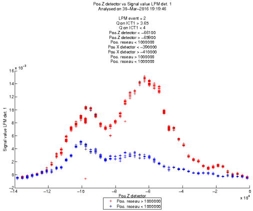


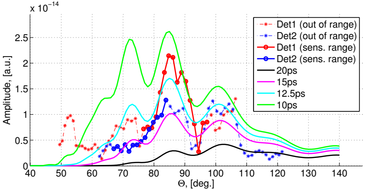
- We also studied the polarization of the radiation.
- This could have been a promising way of removing the background but the measurement do not agree with the theory.

Solène Le Corre, Clément Duval (ENS Lyon)

CSPR: Experiment at SOLEIL



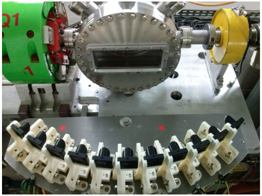


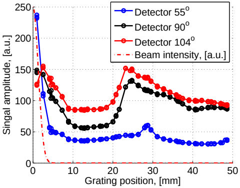


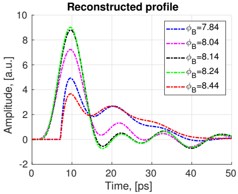
- Another CSPR experiment was done at SOLEIL.
- The measurement are done by a single detector on a translation stage.
- The aim of that experiment was to make a map of CSPR.

Mélissa Vieille Grosjean (PhD U-Psud), Vitalii Khodnevych (M2 U-Psud), Maksym Malovitsya (Kharkiv National University), Geoffrey Bonami (M1 INSTN)

CSPR: Experiment at CLIO



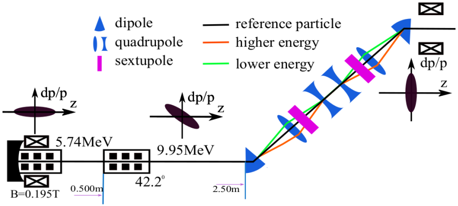




- To test the detector geometry an experiment has been installed at the CLIO Free Electron Laser in Orsay.
- We found new techniques to check data consistency.

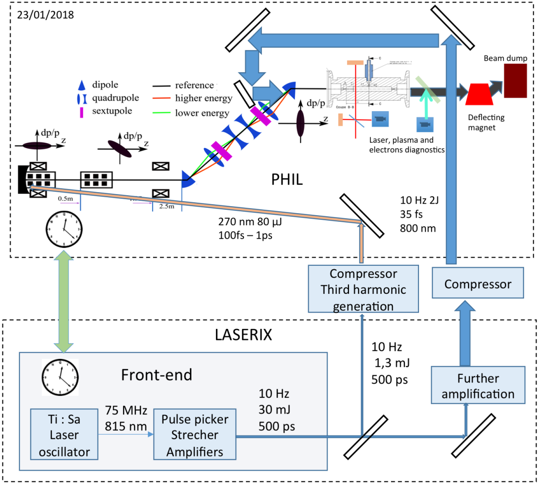
Vitalii Khodnevych (M2 U-Psud)

Laser-plasma acceleration: ESCULAP

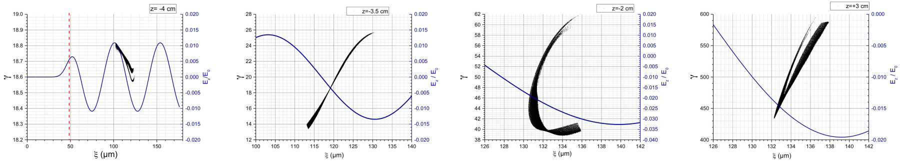


- ESCULAP is a laser-plasma acceleration experiment with external injection.
- It uses the PHIL photo injector and the Laserix High power laser.

ESCULAP: Layout

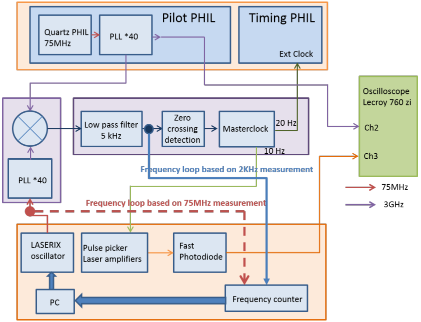


ESCULAP: simulations



- One of the difficulty is that the accelerating volume in the plasma is very small.
- In one of the scheme considered, the bunch is first compressed by the plasma and then accelerated.
- This requires a specific profiling of the plasma density.

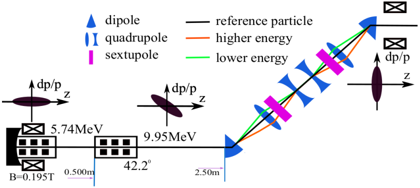
ESCULAP: synchronisation

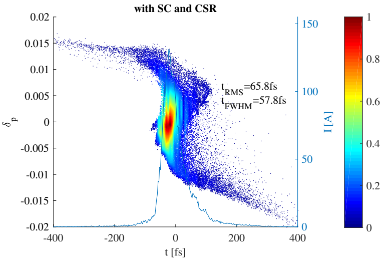


- PHIL and Laserix have been built separately.
- A synchronisation system is necessary to synchronize the two machines.

Heidi Rösch (M1 Darmstadt)

ESCULAP: compression

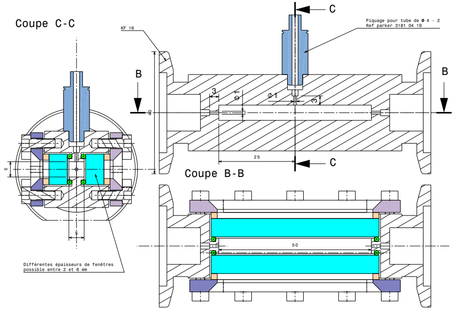




- To match the plasma wavelength the electron bunch must be compressed to less than 100 fs.
- This can be done using a magnetic compression chicane.

Ke Wang (PhD U-PSaclay)

ESCULAP: gas cell



- We are currently designing a gas cell that will allow to have the density profile we need in the plasma.

Outlook

- I have presented some of the topics on which I worked during the past 14 years.
- Experimental work has always its challenges.
- In the coming year two major experimental facilities will start in Paris-Saclay: ThomX and the APOLLON laser and I hope that ESCULAP will follow soon after.
- All of them will be opportunities for interesting experiments!