ARC-EN-CIEL

Accelerator Radiation Complex for ENhanced Coherent Intense Extended Light

# ARC-EN-CIEL: the present FEL activity and the scientific case


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**Acknowledgments to L. Giannessi (ENEA)**

4th Generation Light Sources and Ultrafaast Phenomena
Trieste, 14-15 December 2005

# MOTIVATION

- **FEL History in France**

**ACO (1983-1987), Super-ACO (1989-2003), CLIO (1992),**
**First pump-probe two-color experiments using a UV FEL and synchrotron radiation (1994)**

- **FEL source for 1 keV for user applications**

- **FEL physics : to exploit harmonic generation and seeding schemes:**

**choice of the seeding source : High Harmonics produced in gas**
**-> improved coherence and compactness, reduction of fluctuations**

- **"CW" operation**

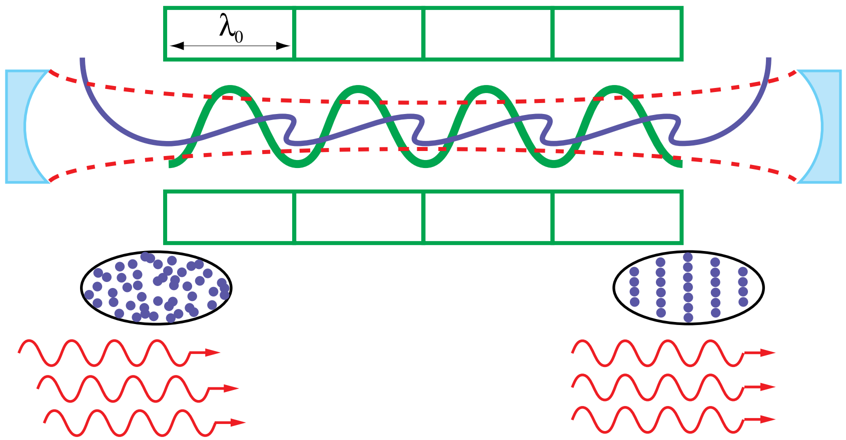
- **Expertise on accelerators (SC...)**

- **Close synergy between FEL and conventional laser sources communities in the same facility**

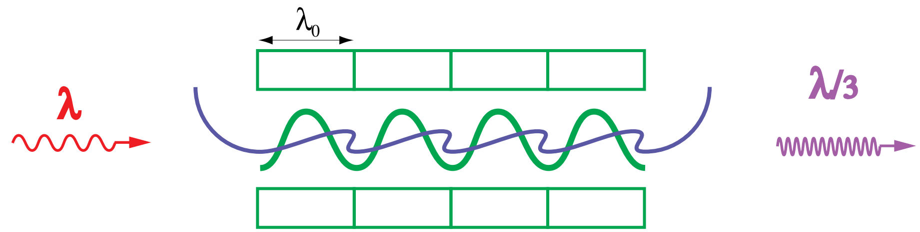
# FEL CONFIGURATIONS

$$\lambda = \frac{\lambda_0}{2n\gamma^2}\left(1+\frac{K^2}{2}\right) \qquad K = 0.94\,\lambda_0\,(\mathrm{cm})\,B_0\,(\mathrm{T})$$

## Oscillator

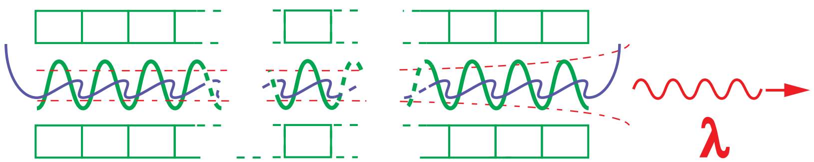



## Harmonic Generation

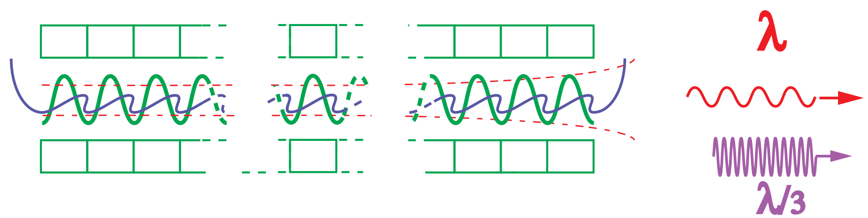



## HGHG


## SASE




## NHG



# SASE

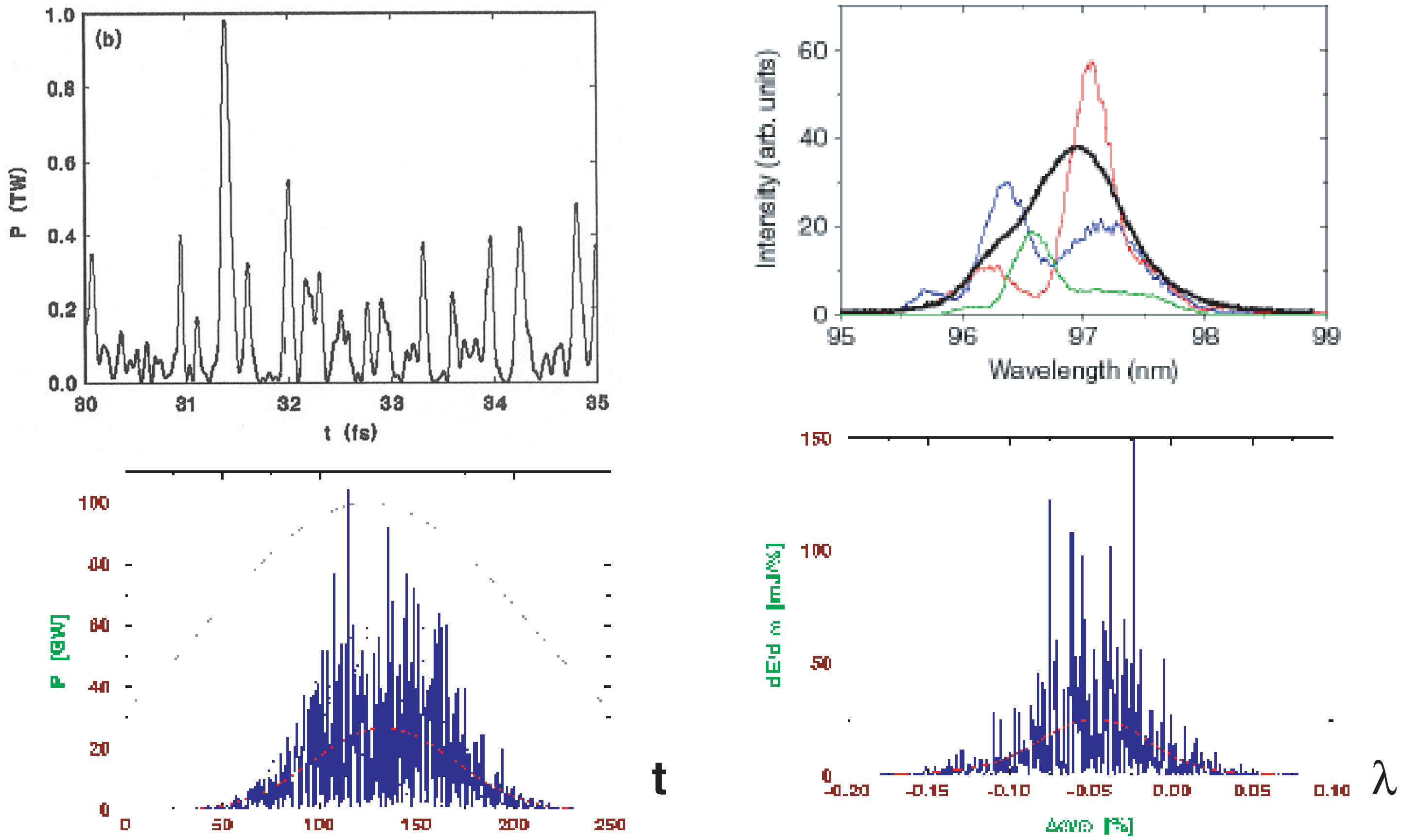
**Temporal coherence: Limited**

- **Start-up from noise: bunching on different sections of the e bunch**
  - **No correlation between the ≠ trains**

**"Spikes"**

**Spectral width**

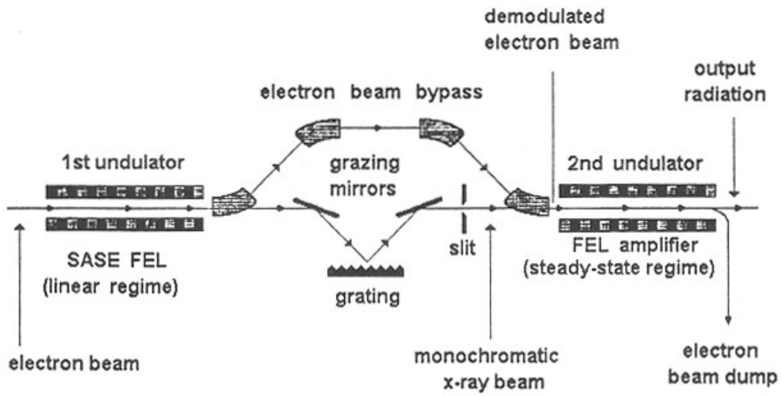
$\Delta\omega/\omega \sim \rho \sim 2\ 10^{-3}$




**Possible Solutions**

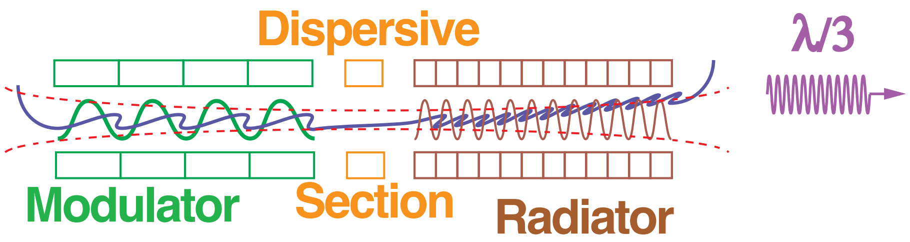
- **seeding**
- **2 stage und.**

**monochromator**



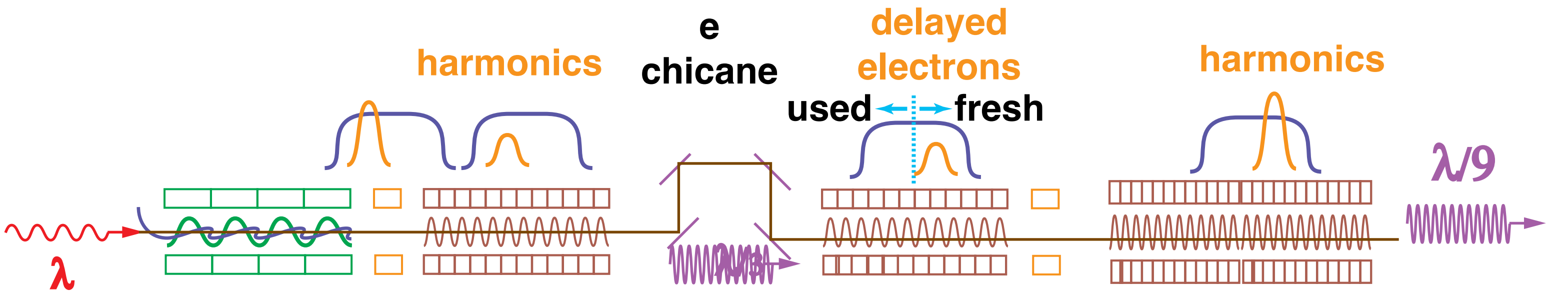
# HIGH GAIN HARMONIC GENERATION

- **HGHG**



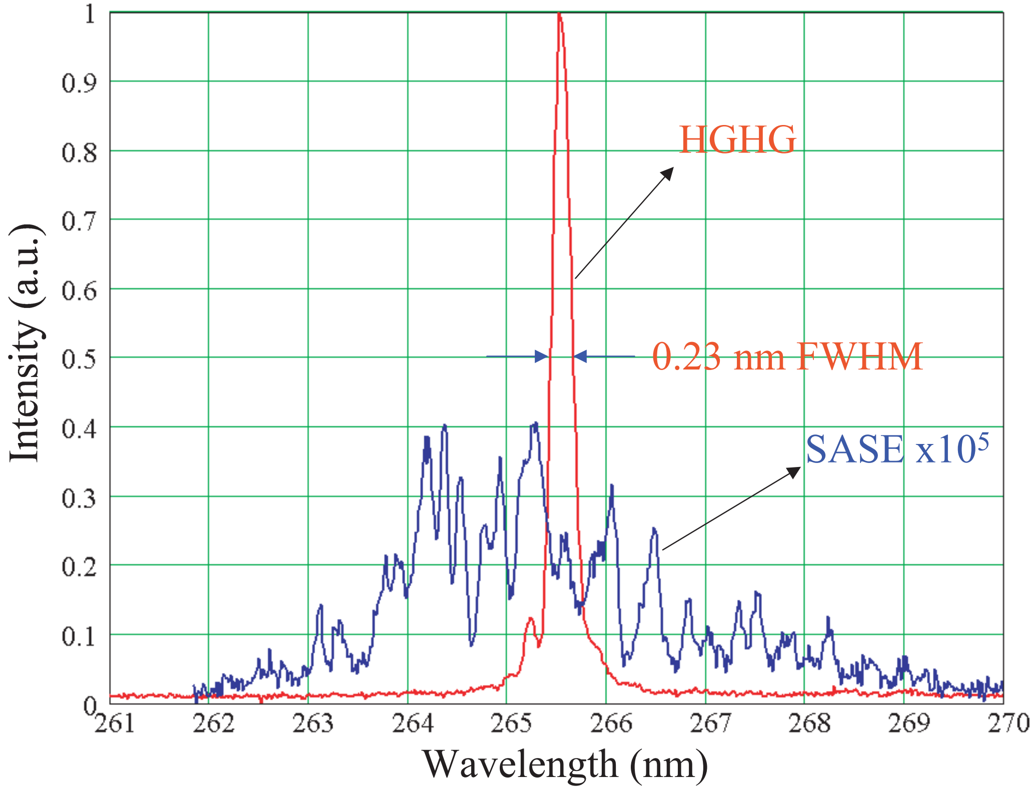

**- reduction of gain length -> compact device**
**- reduction of intensity fluctuations**
**- improved temporal coherence**
**- tuneability with a chirp of the electron bunch and of the laser (T. Shaftan)**

- **Cascading HGHG: fresh bunch technique (L. H. Yu, BNL)**



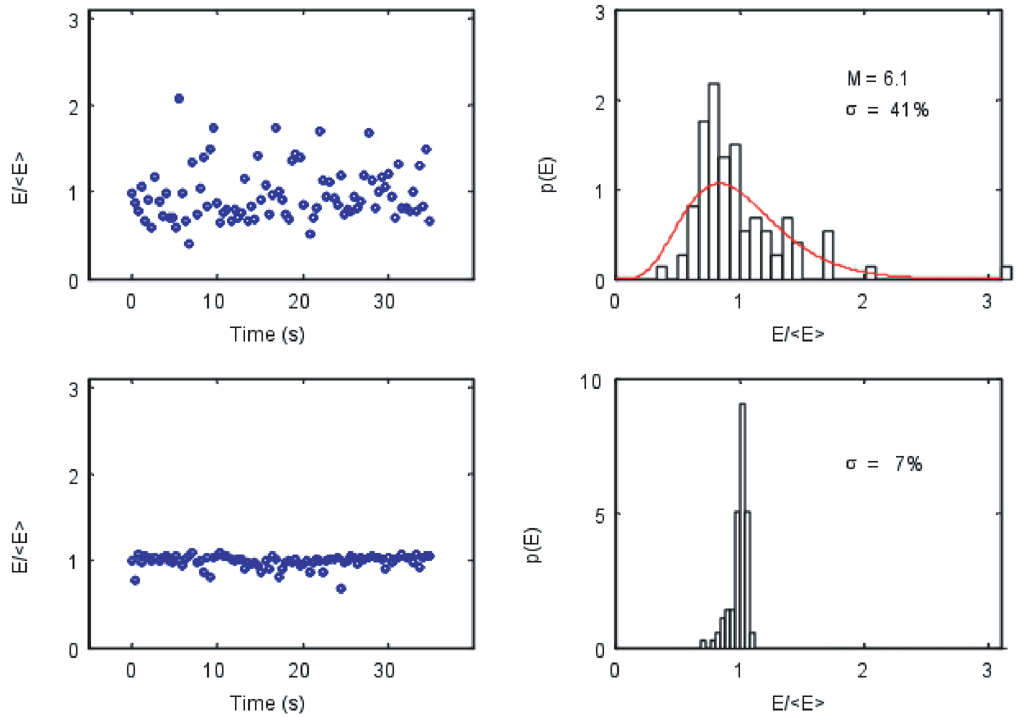
# HIGH GAIN HARMONIC GENERATION

## DUVFEL
## (210 MeV, 30 mJ- 800 nm Ti:Sa laser)



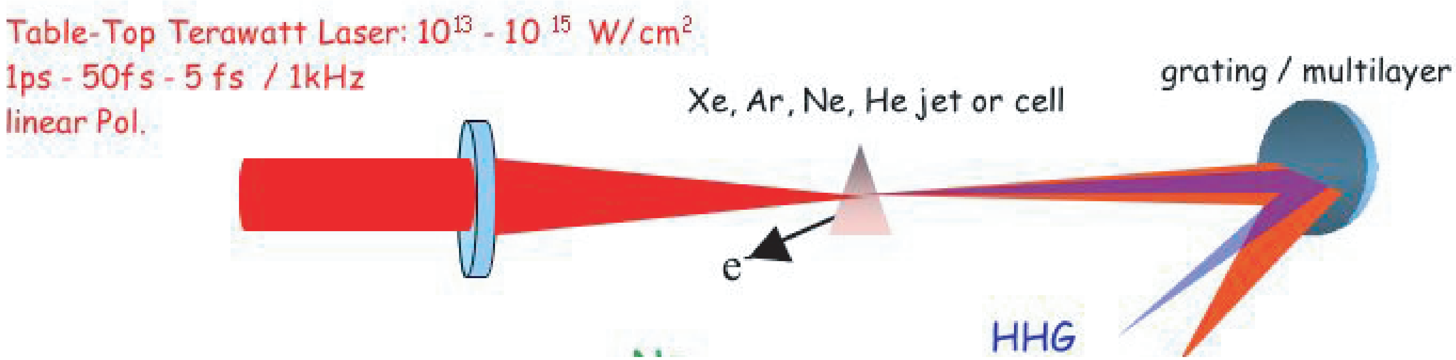

## Shot to Shot Intensity Fluctuation
## Shows High Stability of HGHG output

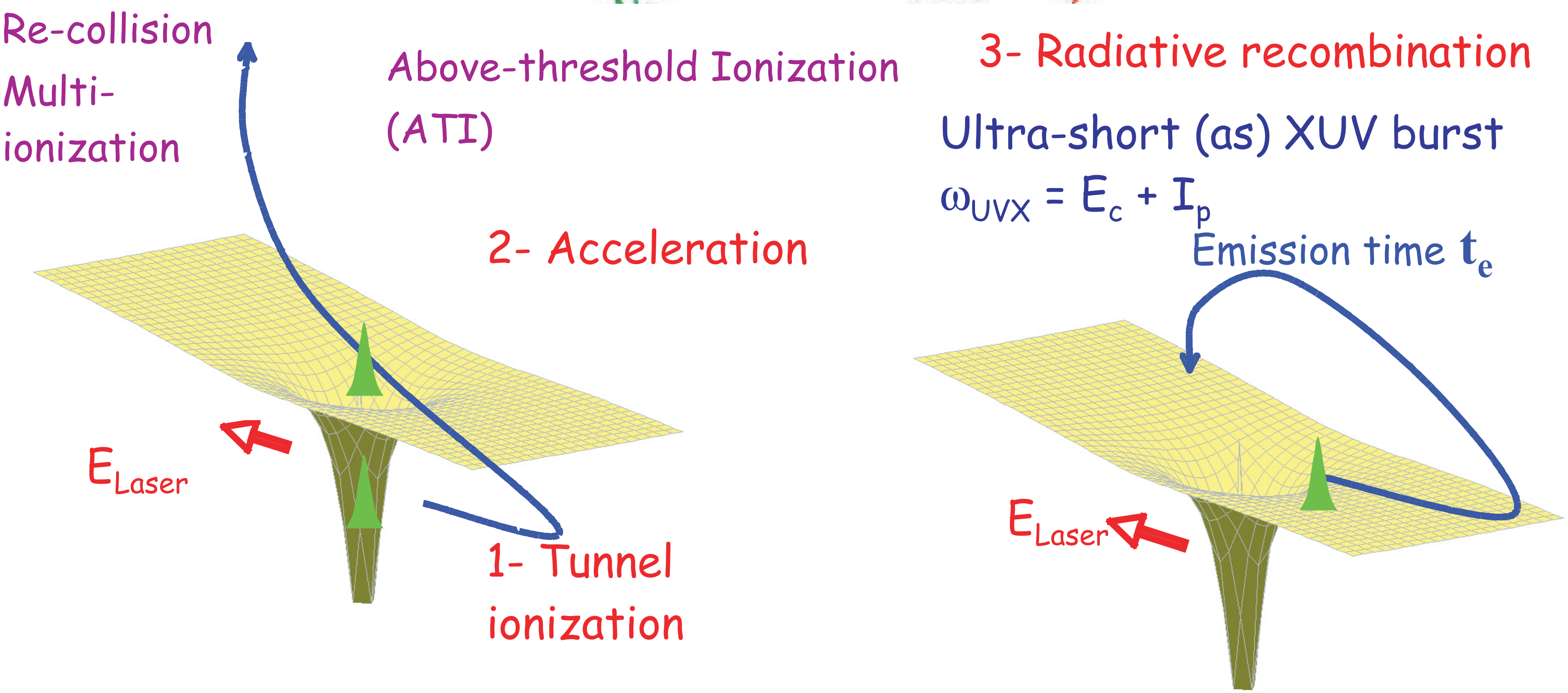
E/<E> ρ(E)



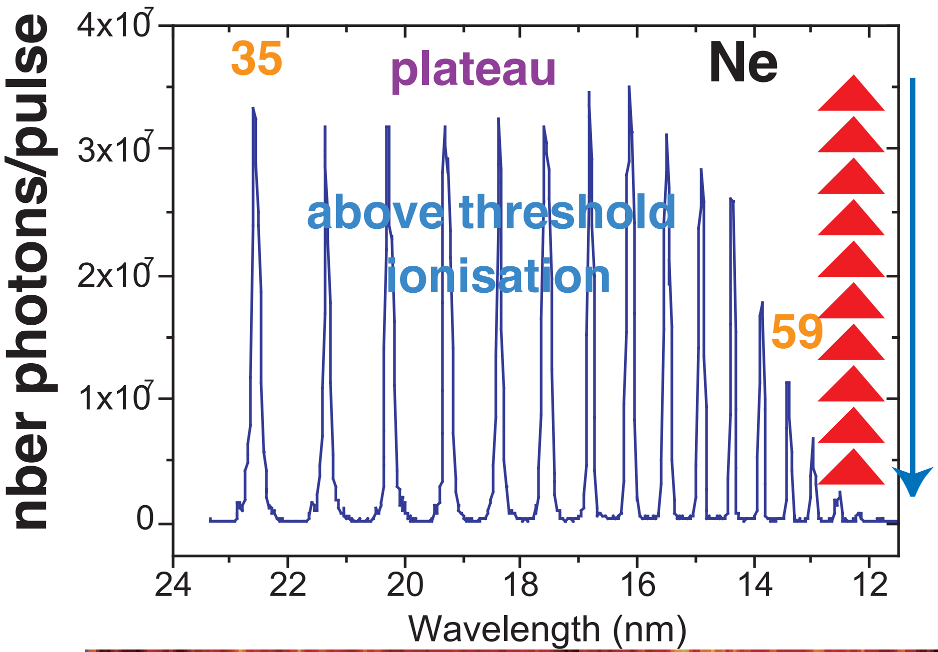

**Courtesy L. H. Yu**

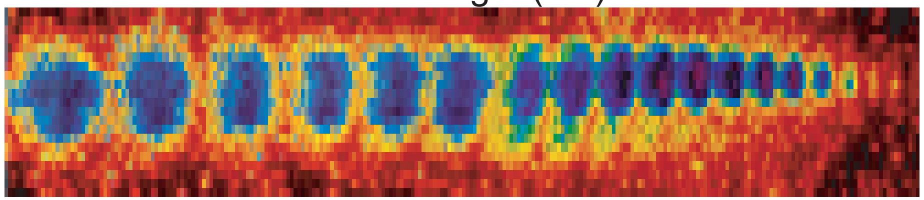
# HIGH HARMONICS IN GAS

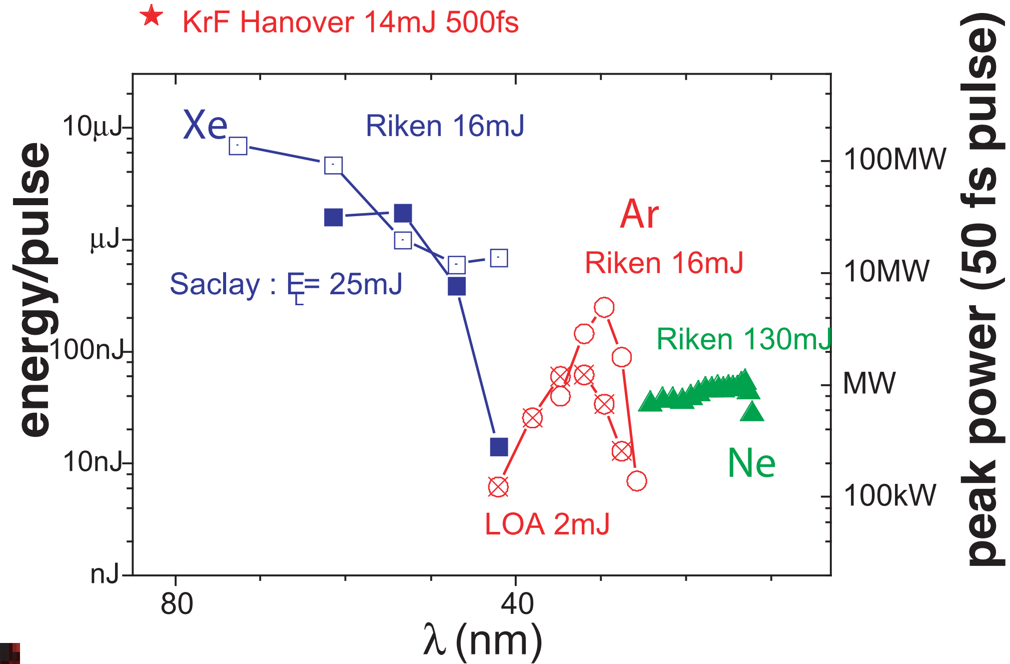


# HIGH HARMONICS IN GAS






**$E_{max} = I_p + 3.2\ U_p$ $I_p$ ionization potential, $U_p$ : ponderomotive potential**

**->Ne, He High $I_p$ lower conversion effeciency than for Xe, Kr, Ar**

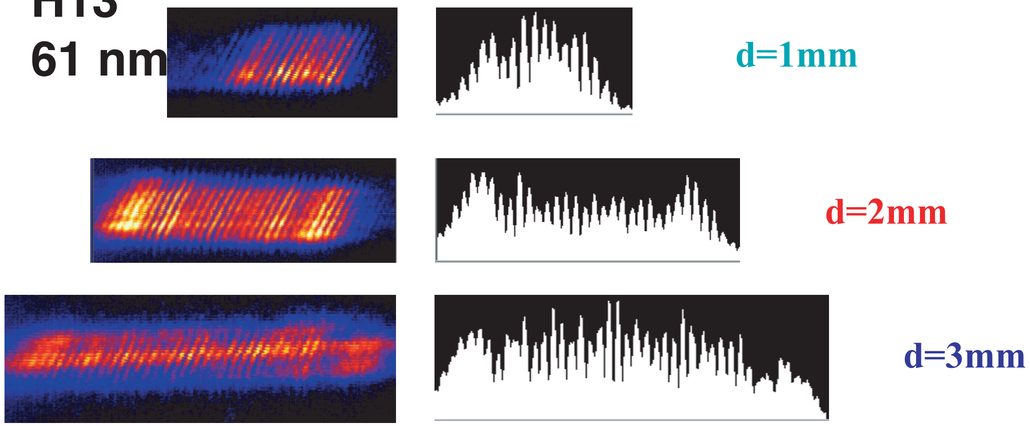
**modification of the chirp of the Ti:Sa laser, chnage of the laser wavelength, molecules**

# HIGH HARMONICS IN GAS

- **spatial and temporal coherence**

**Fresnel bi-mirror interferometer**

**H13**
**61 nm**




Le Déroff et al. PRA 61 (2000) 043802

$w_{0har}=w_{0las}q^{-1/2}$, $div_{har}=div_{las}q$, $M^2_{har}=M^2_{las}q^{1/2}$

**Ne target, 13.5 nm, 25 nJ, DV = 0.35 mrad**

**He target, 8.9 nm, 1 nJ, DV = 0.3 mrad**

**E**. J. Takahashi et al., Appl. Phys. Lett. 84, 4 (2004)
Opt. Lett 27, 1920 (2002), Phys. Rev. A 68, 023808 (2003)
Y. Tamaki et al., JJAP 40, L1154 (2001).

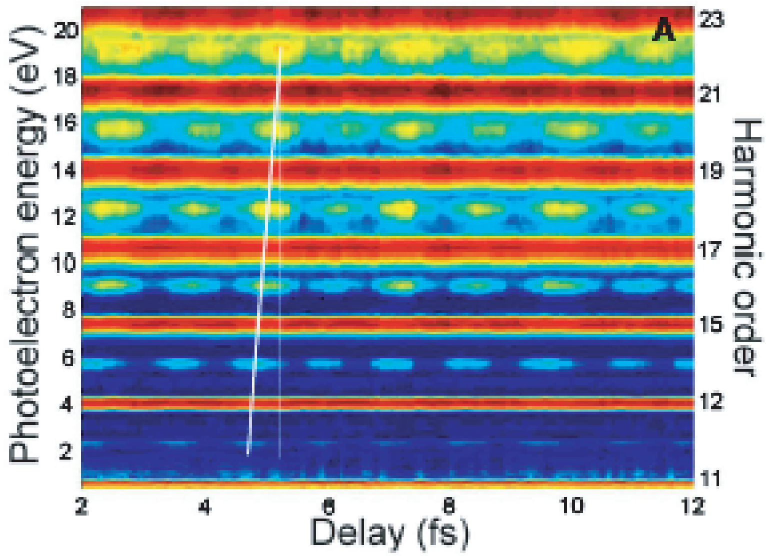
- **tuneability**

**Frequency mixing of the pump laser, Ti:Sa tuneability 760-1100 nm**

$\Delta\lambda/\lambda$=1-0.1%

- **pulse duration : fs, as range**

for $n\geq7$, $n=2q+1$, $\Delta t_{har}=t_{las}q^{-1/2}$,




**Y. Mairesse et al, Science 302, 1540**

- **linear polarisation**

# HHG SEEDING IN AN X-RAY LASER

- in a Collisionally pump X ray amplifier neonlike gallium plasma

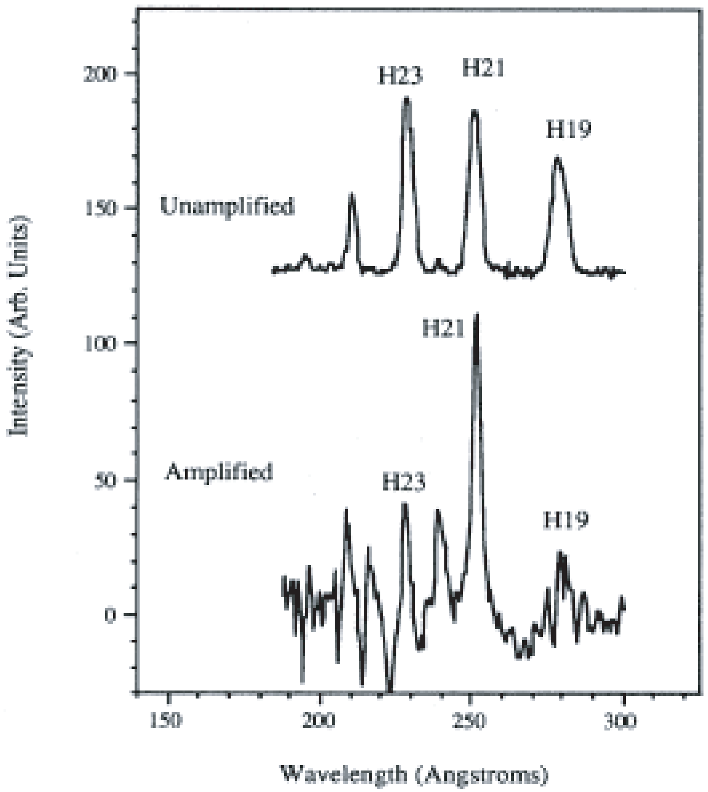
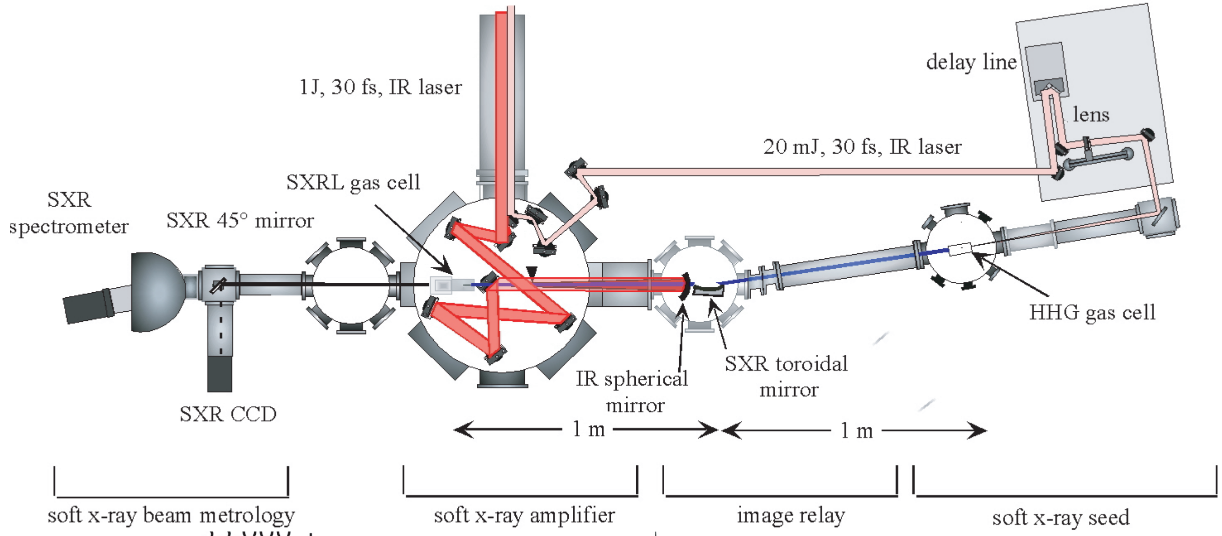
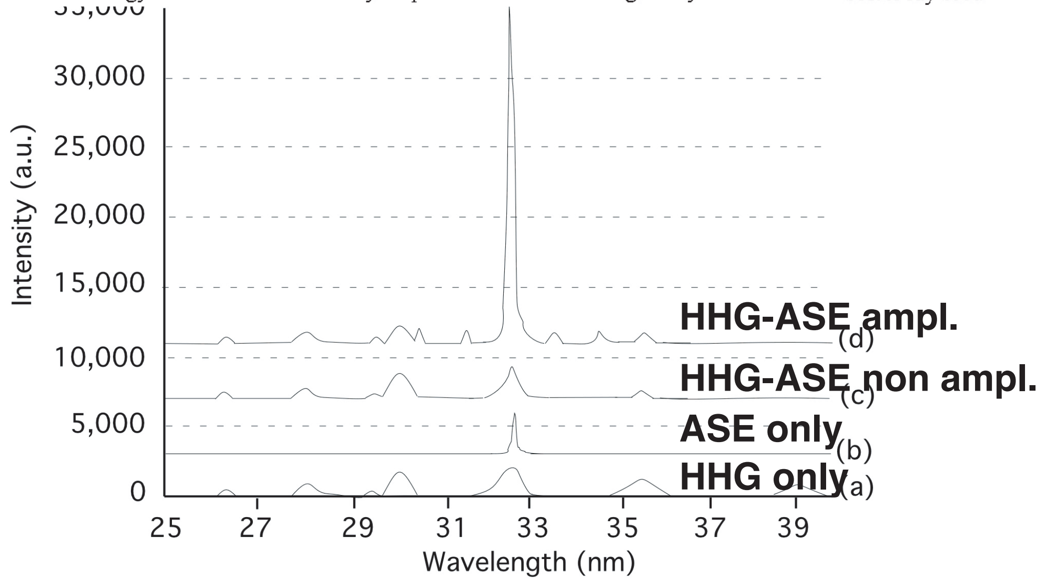



FIG. 5. Comparison of (background subtracted) harmonic spectra with and without a Ga XXII plasma present. Spectral data are integrated over a 30-psec time window and the unamplified spectrum is offset in intensity for ease of comparison.

**T. Ditmire et al., Phys. Rev. A 51 (6), (1995), R4337**

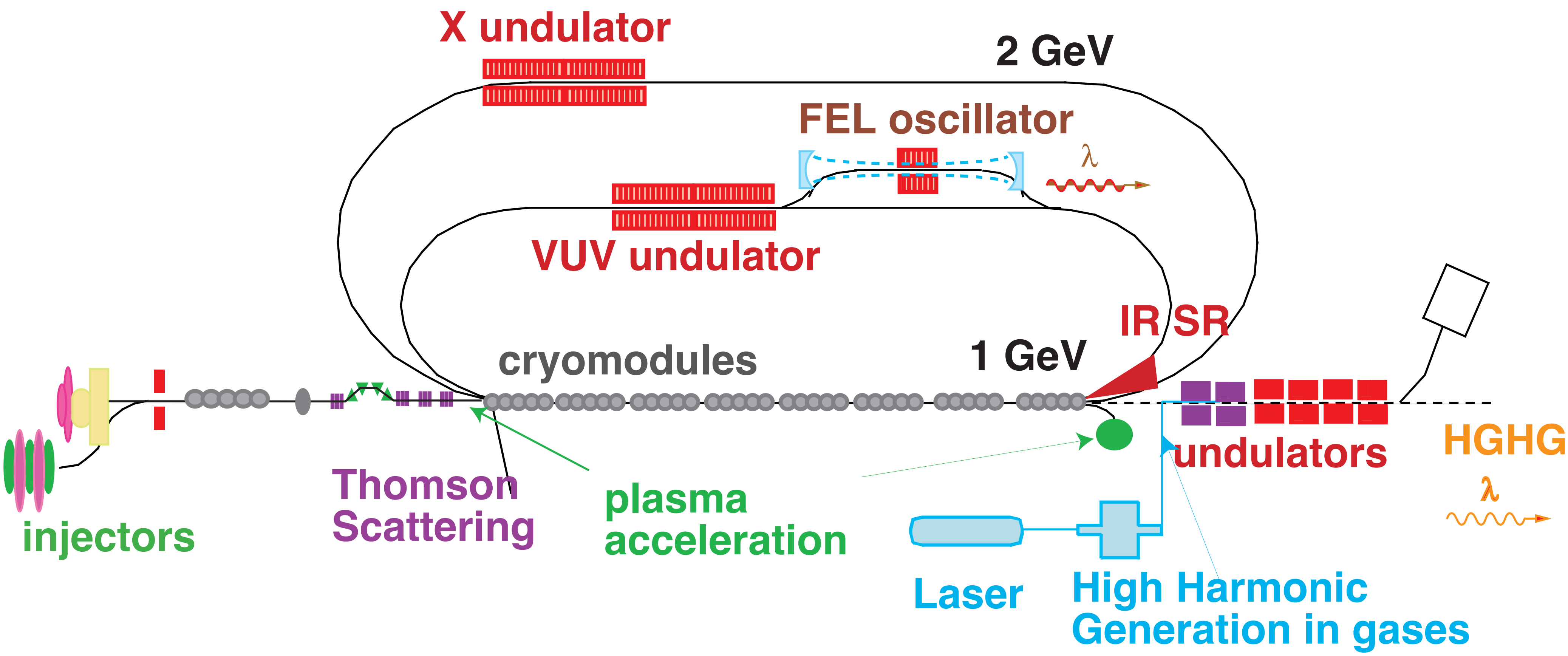
- in an Optical field ionised plasma ($Kr^{8+}$)



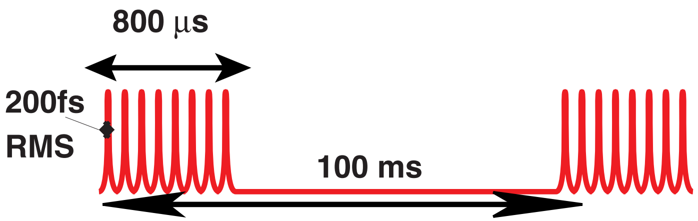

**P. Zeitoun et al., Nature 431, 426 - 429 (23 Sep 2004)**

# SCHEME

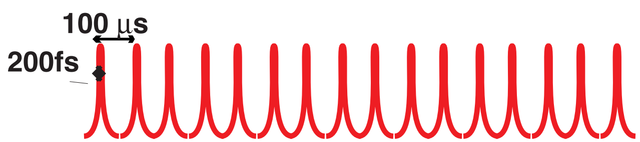

X undulator
2 GeV
FEL oscillator
λ
VUV undulator
IR SR
cryomodules
1 GeV
undulators
HGHG
λ
injectors
Thomson
Scattering
plasma
acceleration
Laser
High Harmonic
Generation in gases

# INJECTORS

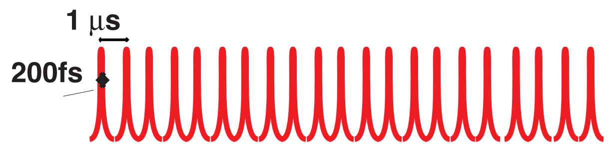
## Injector 1



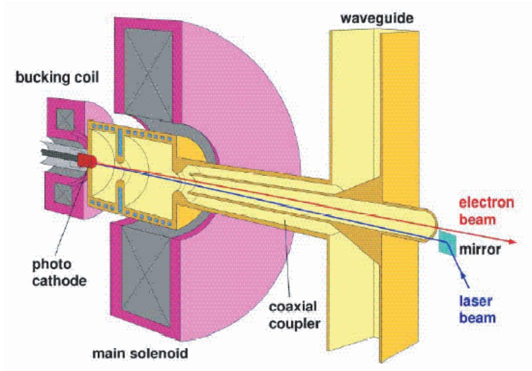

## Injector 2



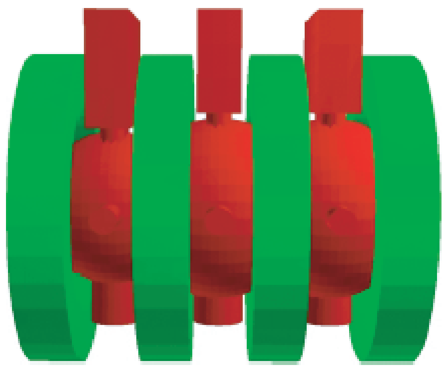

## Injector 2 bis

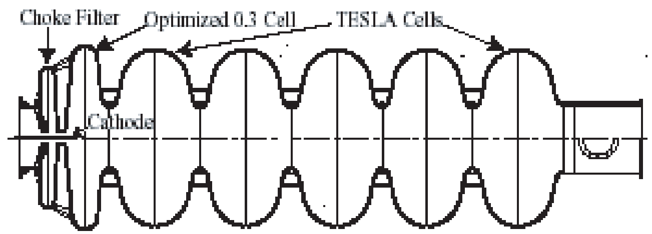



**emittance : 2π mm.mrad, charge : 1nC**




RT pulsed RF gun (TTF 2)





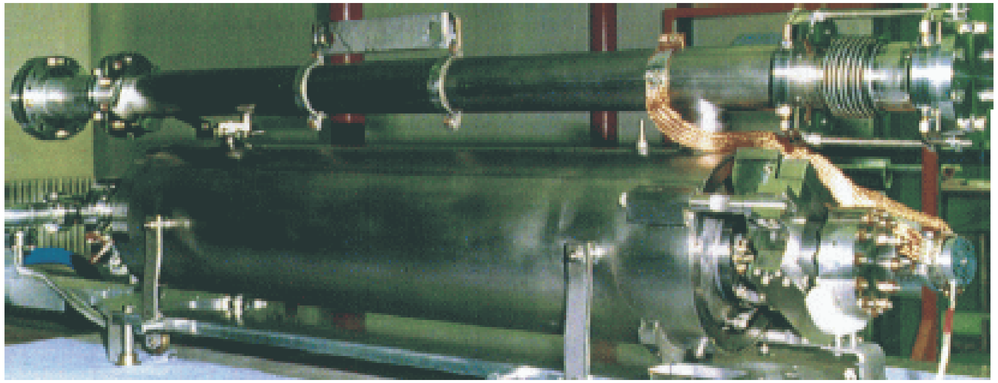

SC RF gun ( Rossendorf)

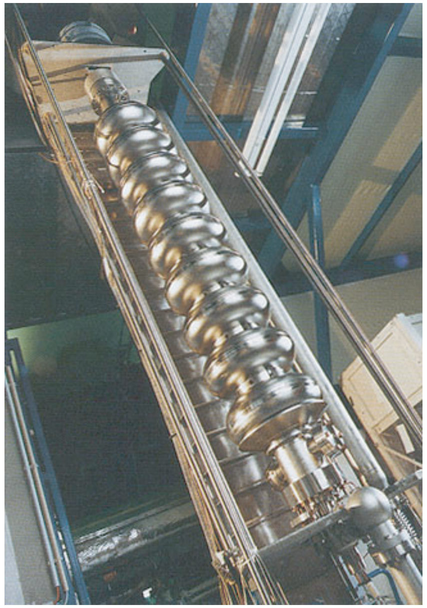
- Coupler modification
- Active removal of the power (phase inversion during fall time)

R&D :

- Emittance compensation
- "cw" operation
- Reliability

# THE LINAC CAVITIES

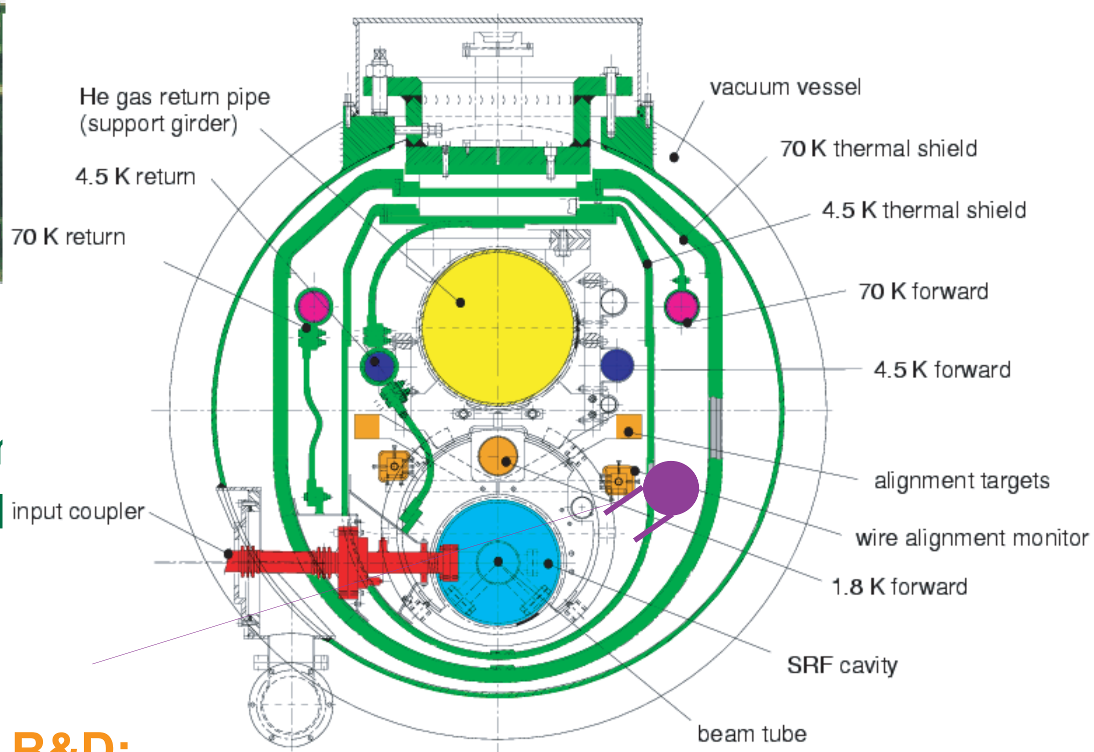




**E=1 GeV**
**I=1mA/pass (ER : 5-10 m**
**emittance : 2π mm.mrad**
**charge : 1nC**
**energy spread : 0.1 %**
**Î=2kA, <I> = 0.1 mA**

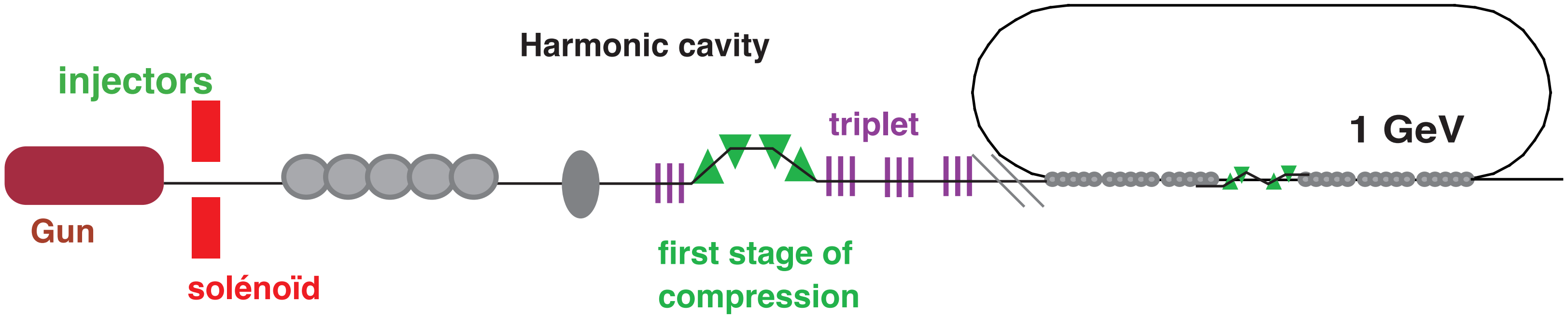
**TESLA type superconductiong accelerator**
**8 cryomodules (1.3 GHz)**

## The cryogenic system

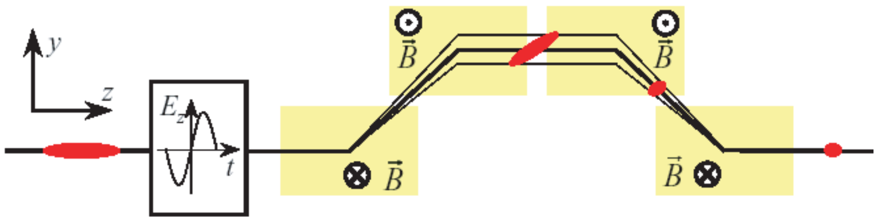


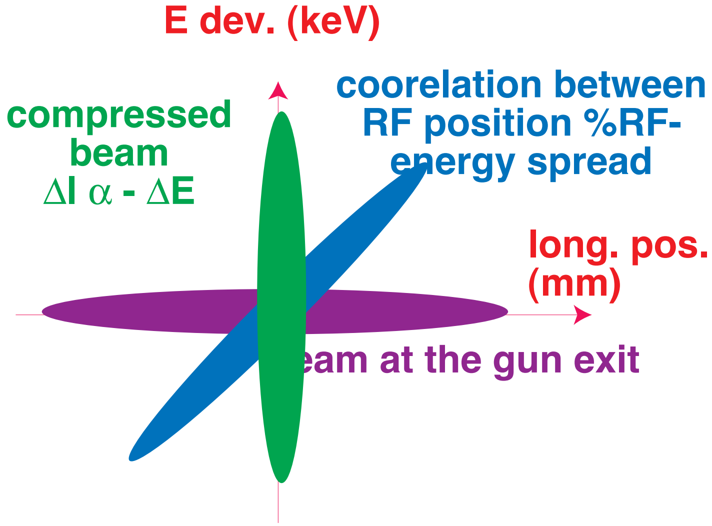

**R&D:**
- **Superconductiong cavities in "cw"regime**
- **power couplers**
- **higher order modes couplers**
- **frequency tuning**

# PRE-ACCELERATION




- Magnetic chicane



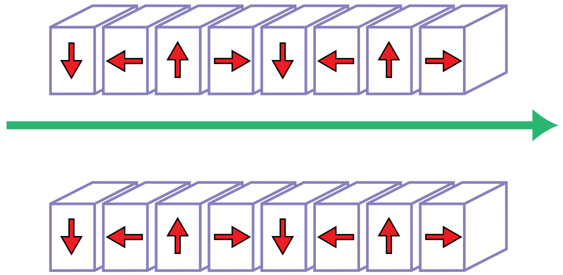



$$R_{56} = \frac{\Delta l}{\frac{\Delta E}{E}}$$

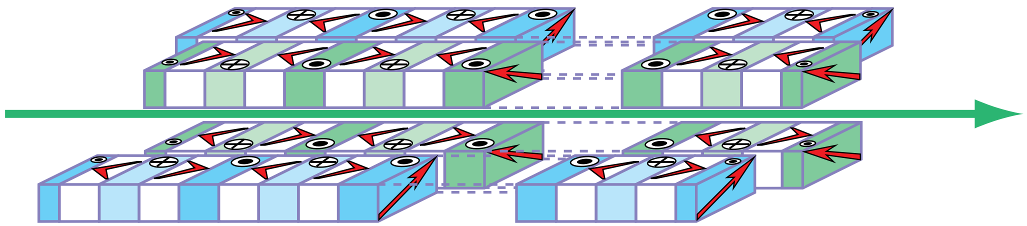
- Harmonic cavity to linearize the phase energy correlation in the bunch

# UNDULATORS

**Planar undulator**

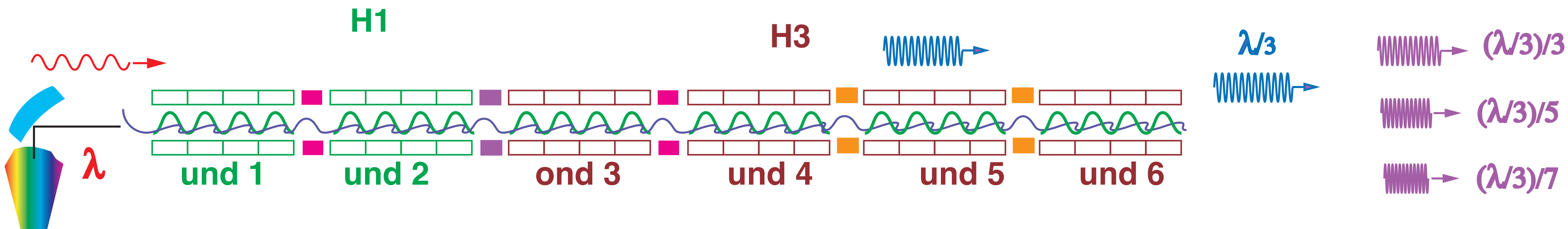


**Planar to helical undulator**



$\lambda_o$= 30 mm, L=4m
ajustable polarisation

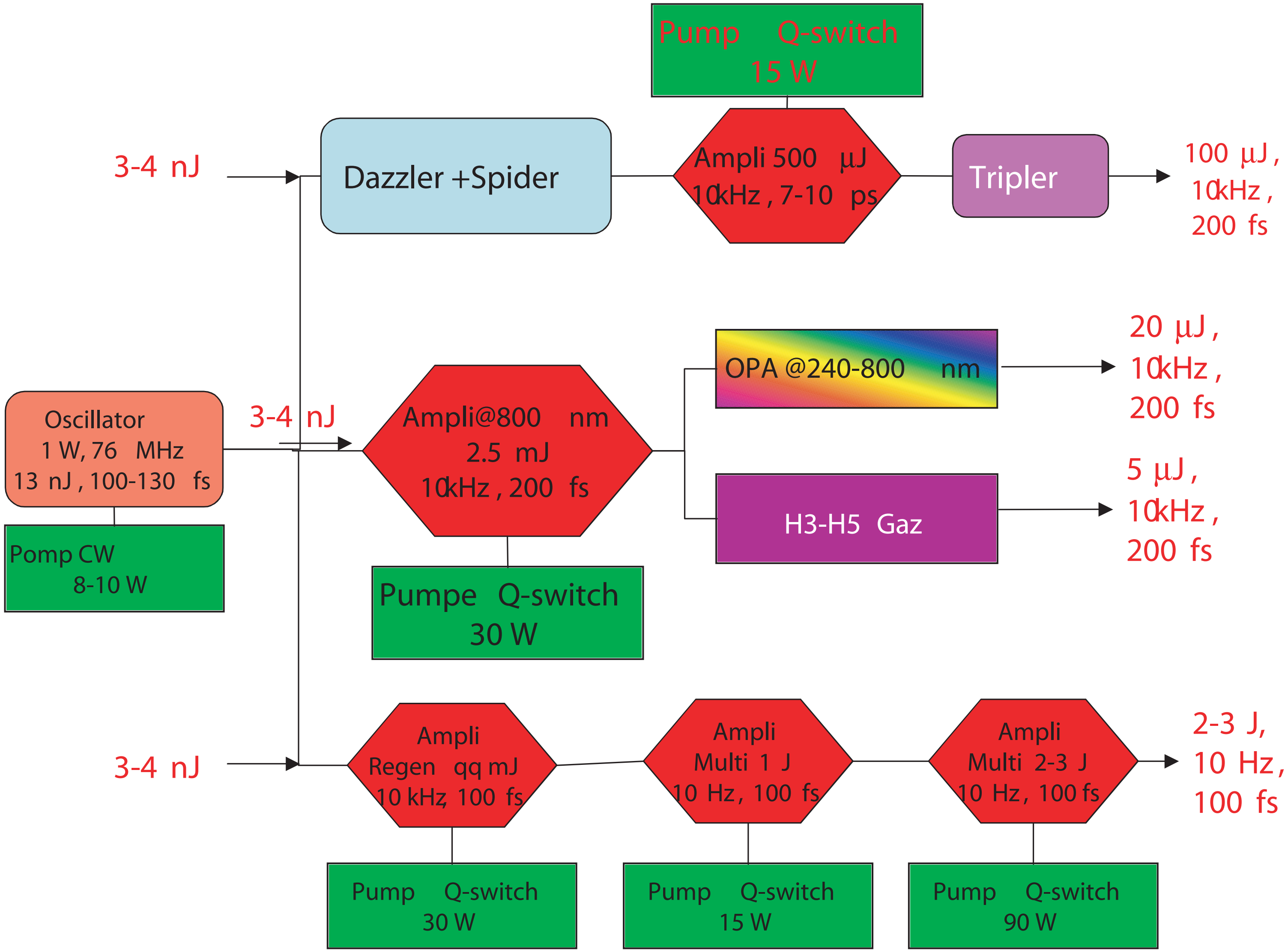
$\lambda_o$= 20 mm, L=4m
ajustable polarisation




seeding : - Ti-Sa, 4ω
- high harmonics generated in gas

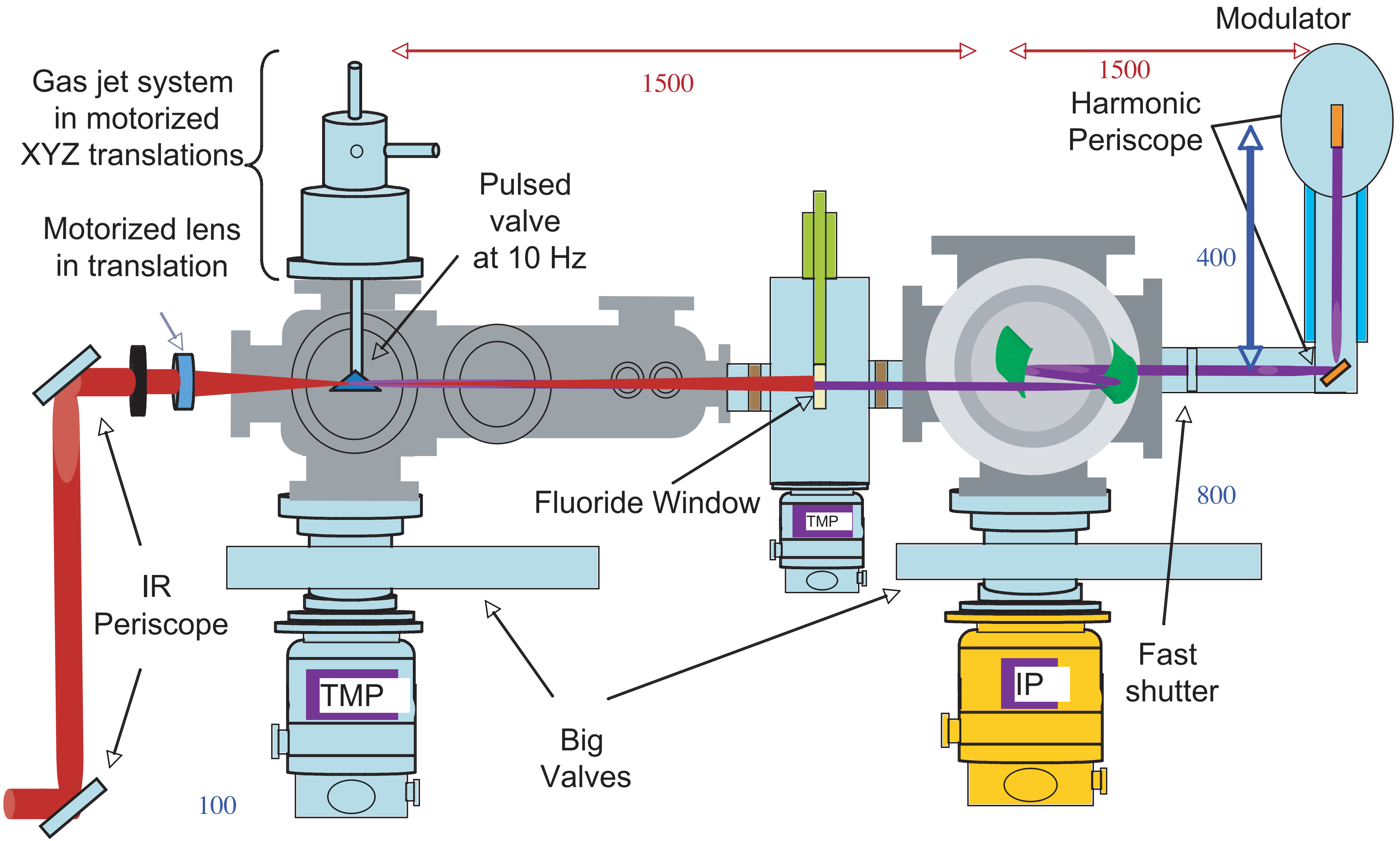
ARC-EN-CIEL : the constituting elements

# THE LASER SYSTEM



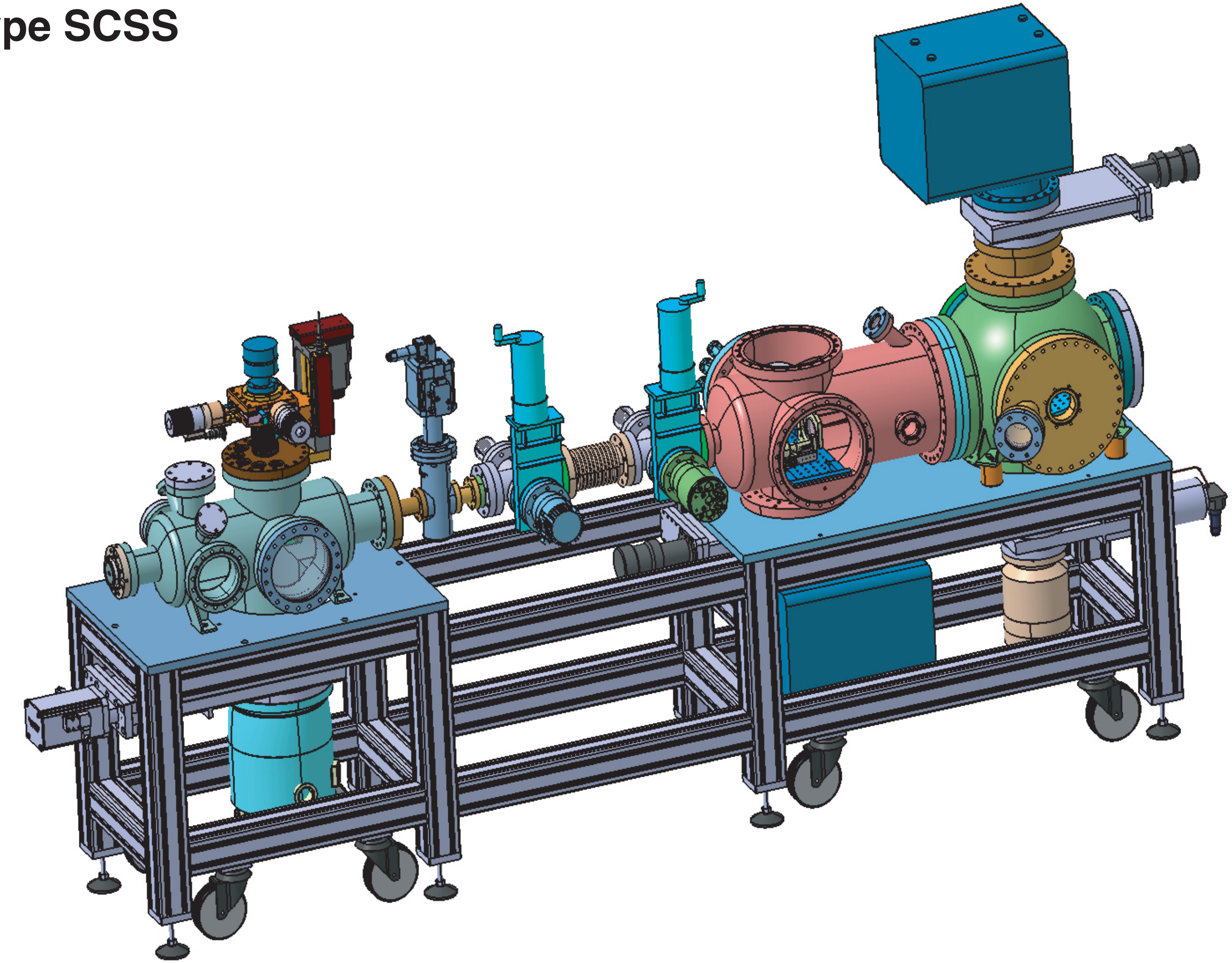
ARC-EN-CIEL : the constituting elements

# THE HARMONIC GENERATION CHAMBER



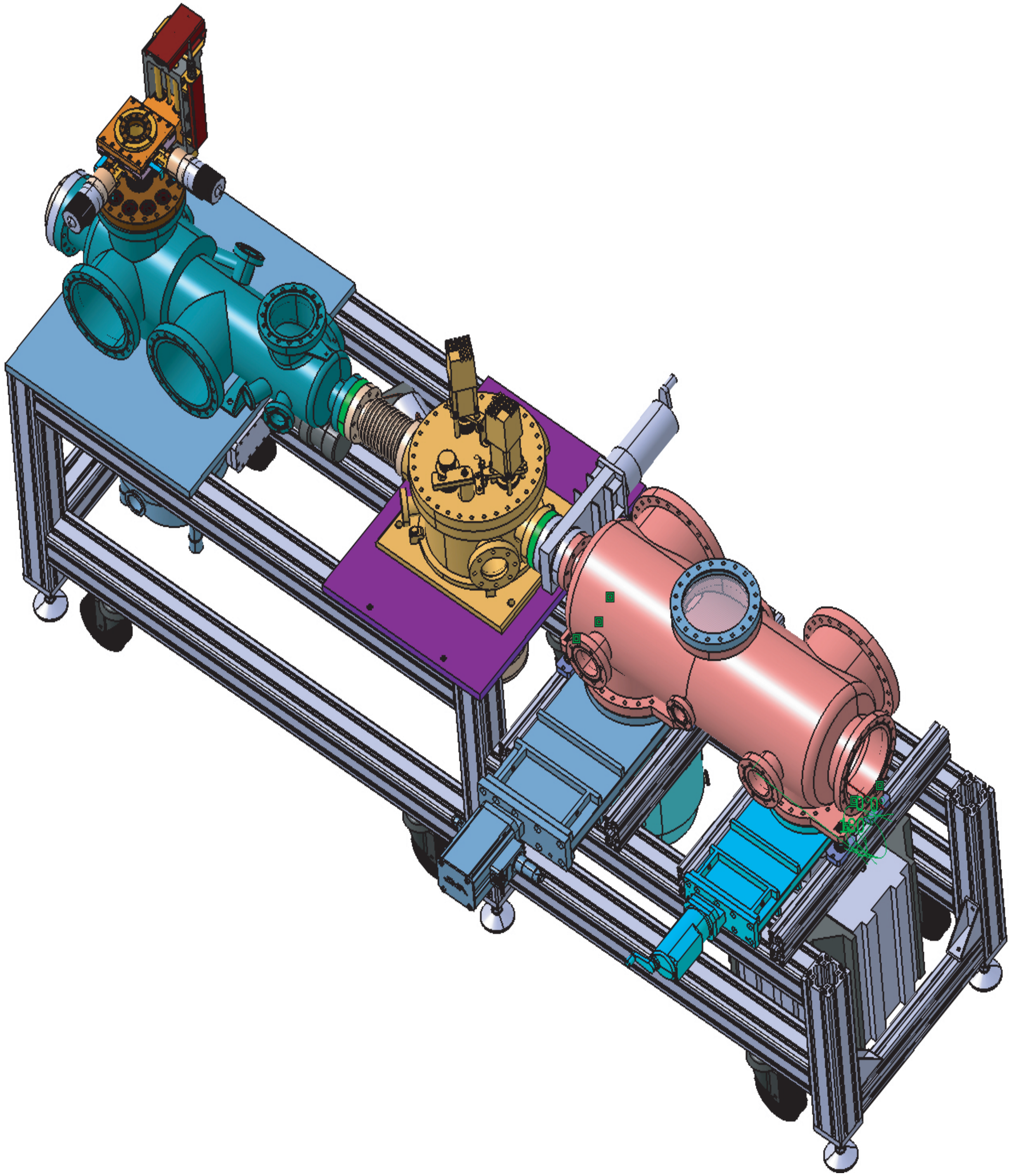
# HIGH HARMONICS CHAMBERS

**Prototype SCSS**



# HIGH HARMONICS CHAMBERS

**SPARC**
**(EUROFEL)**



# HARMONIC GENERATION TRANSPORT

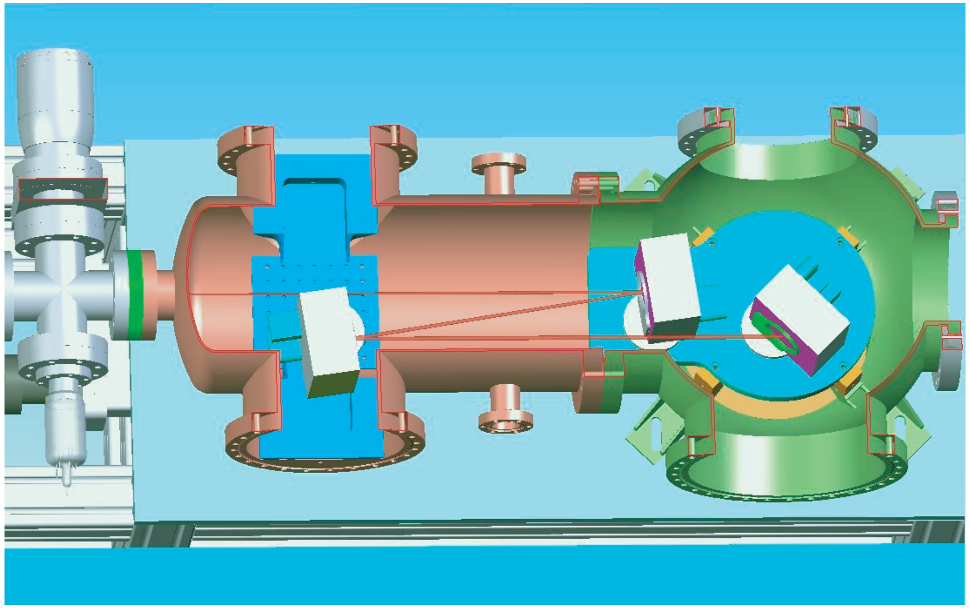
- **2 mirrors for the telescope**

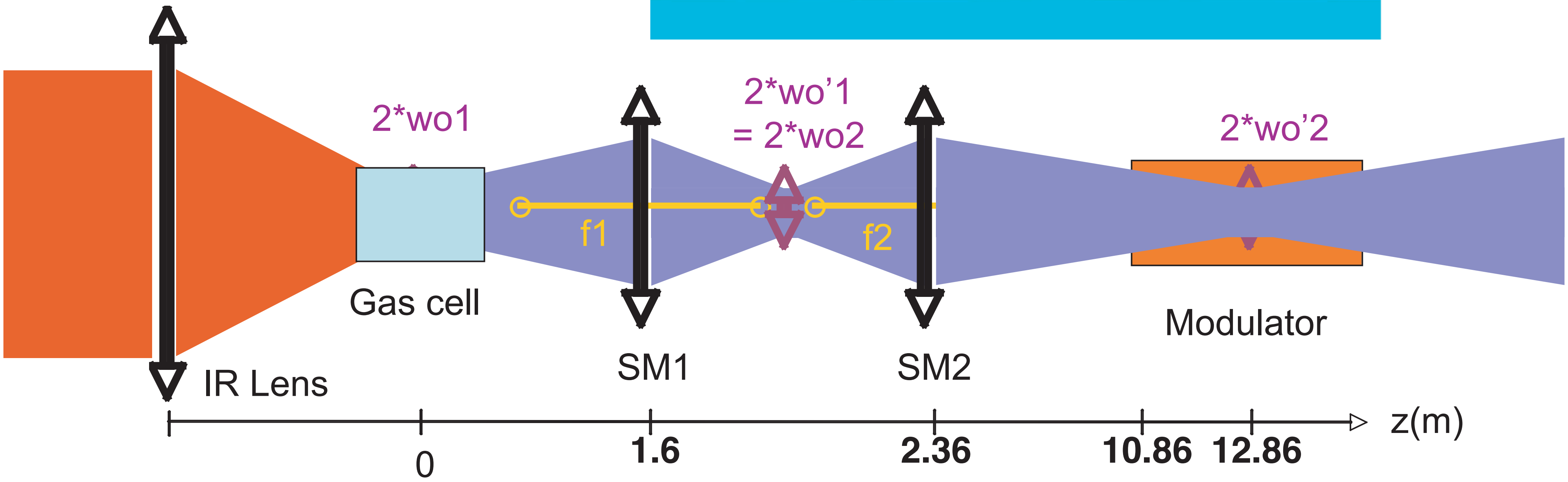
**$f_1$=0.1m, $f_2$=0.55 m**

- **2 mirrors for the periscope**

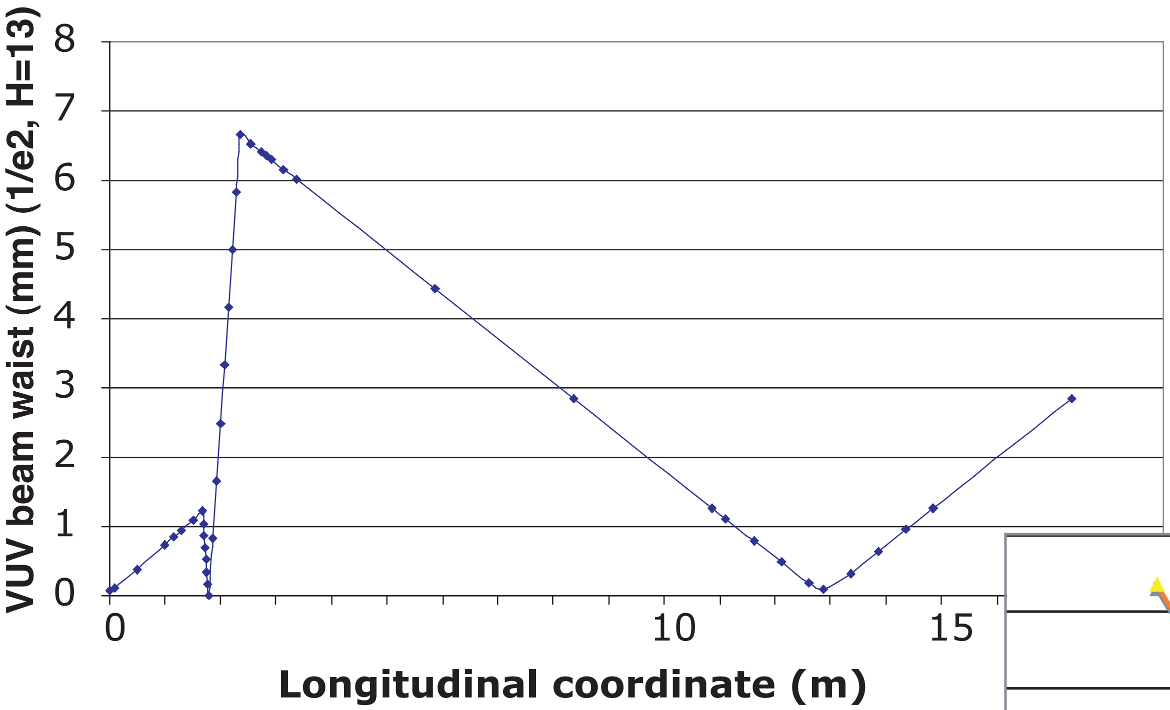
**f=7 m**

**$M^2$=3**

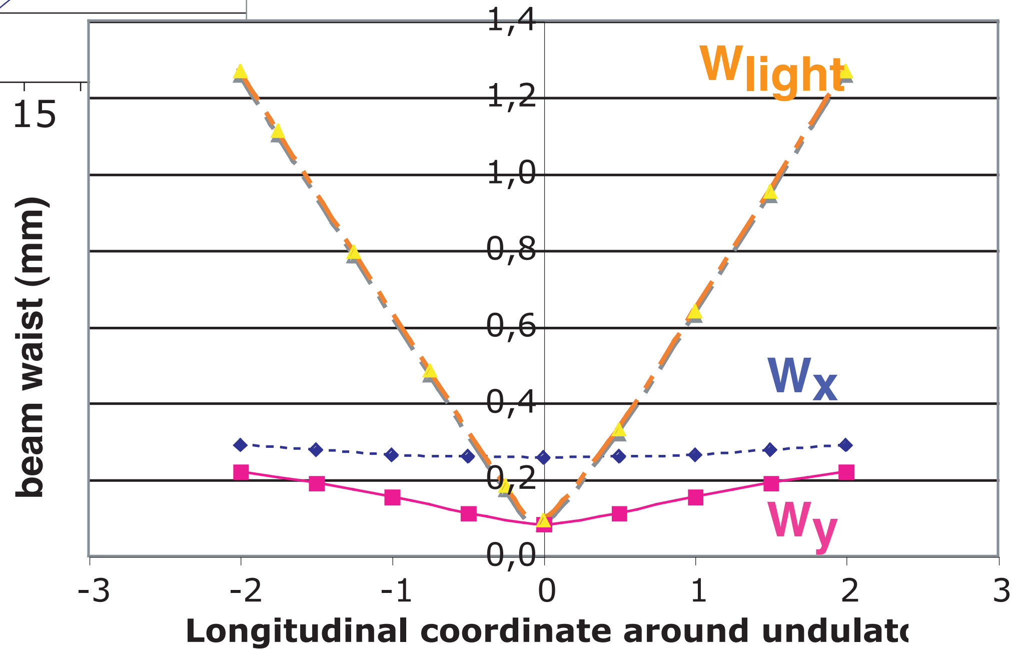




# HARMONIC GENERATION TRANSPORT



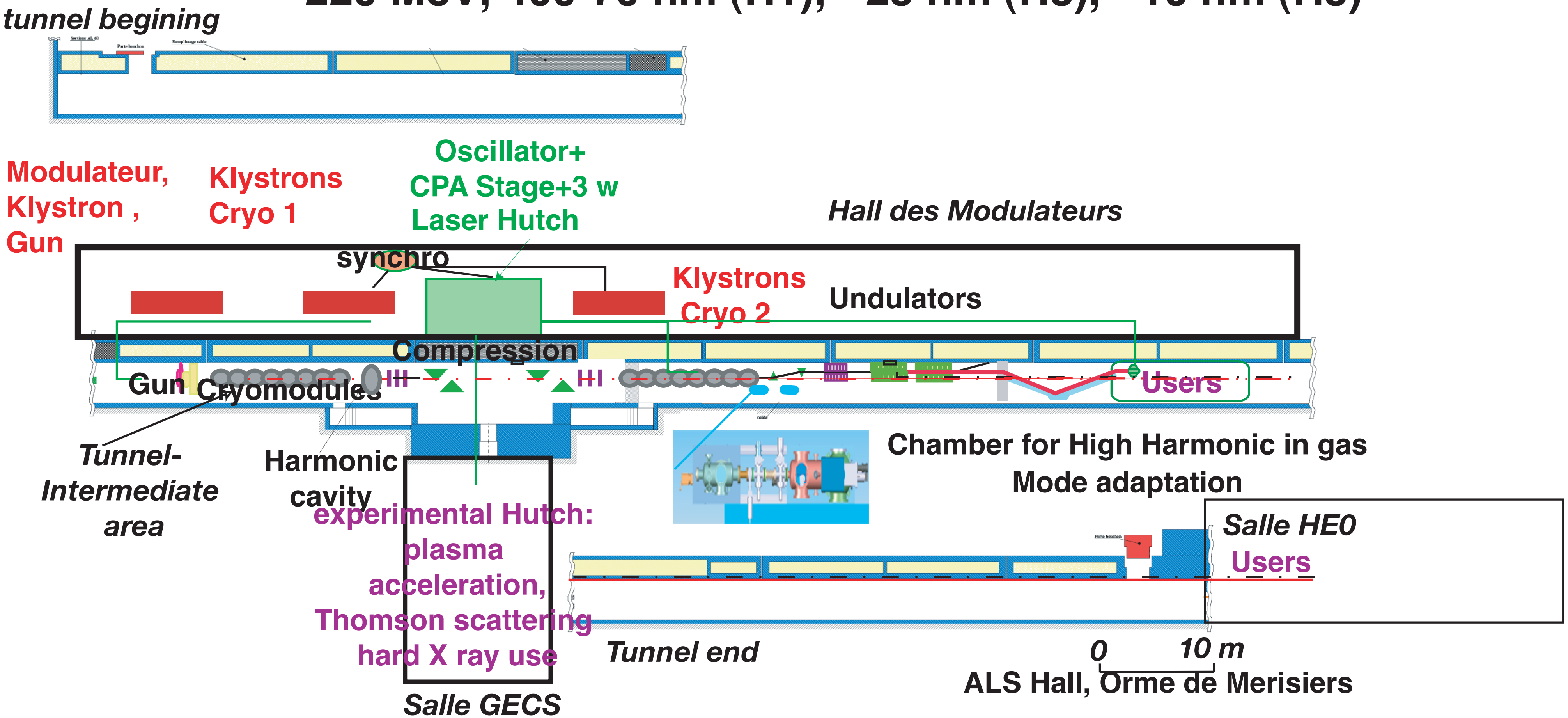

$\beta_x$=4.7 m
$\beta\zeta$=0.5 m




**Filling Factor Ff=0.154**
**Colson Elleaume : Ff=0.036**
**=> gain reduction**

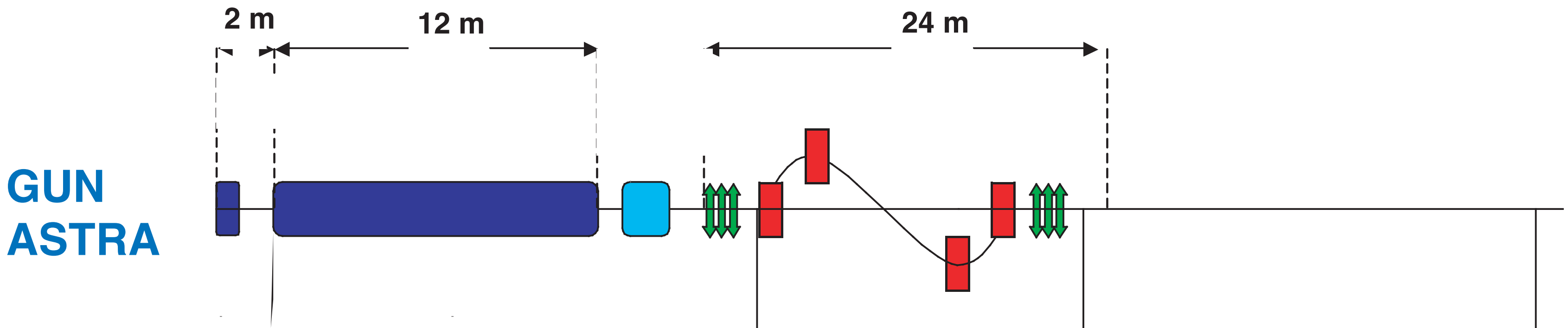
# ARC-EN-CIEL : PHASE 1

## 220 MeV, 400-70 nm (H1), - 25 nm (H3), - 10 nm (H5)



ARC-EN-CIEL : proposed prototype

# S2E SIMULATIONS




**TTF module (15MV/m, space charge, wakefield)**

**S-chicane compressor Trafic 4 (CSR+3D space charge, R56=0.1m)**

**TTF module (15MV/m)**

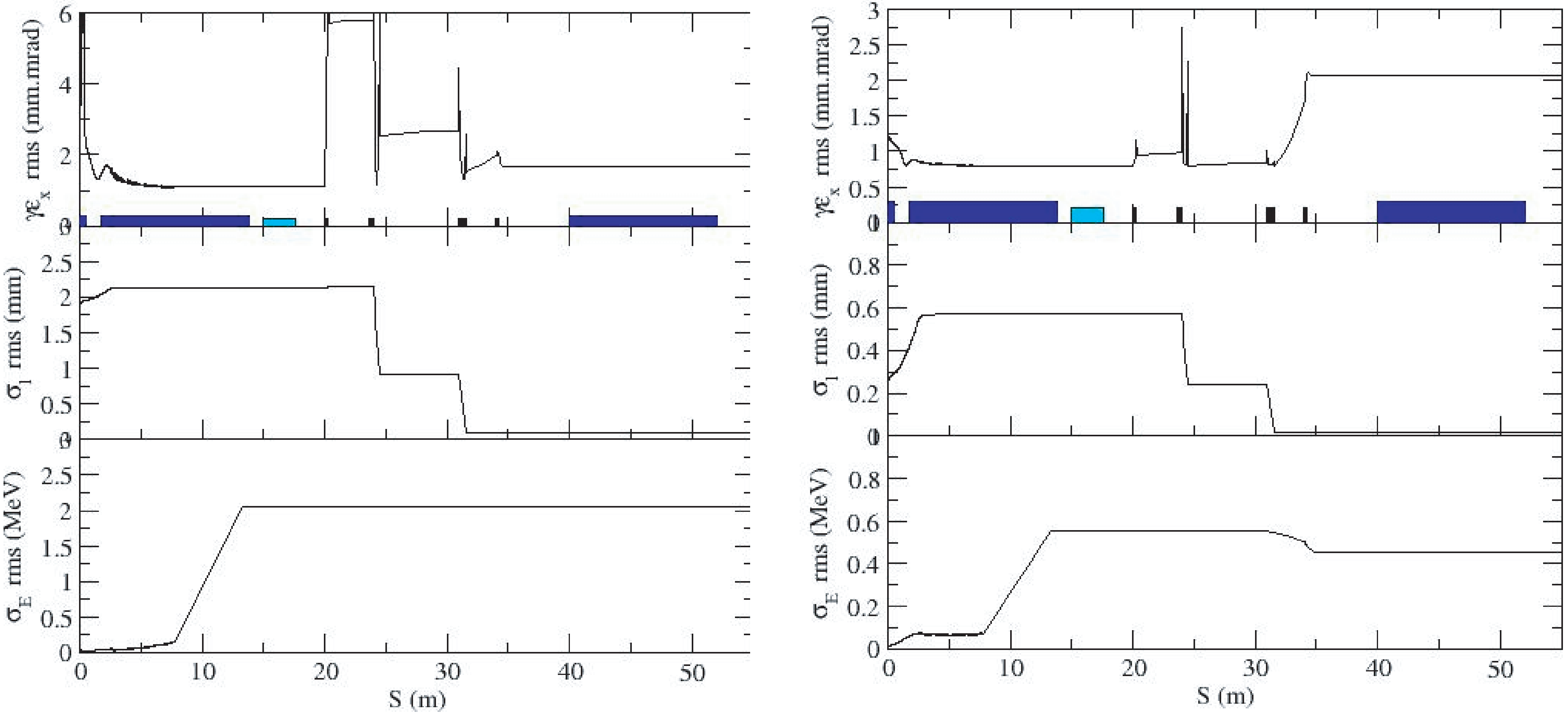
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Q (nC) | 1 | 0.1 | 1 | 0.1 | 1 | 0.1 | 1 | 0.1 |
| E (MeV) | 4 | 4 | 101 | 101 | 101 | 101 | 220 | 220 |
| $\Delta$E (keV rms) | 10 | 5 | 2 | 0.5 | 2 | 0.5 | 2 | 0.5 |
| ds (mm rms) | 2 | 0.6 | 2 | 0.6 | 0.1 | 0.02 | 0.1 | 0.02 |
| ds (fs rms) | 6000 | 2000 | 6000 | 2000 | 300 | 60 | 300 | 60 |
| $\gamma\varepsilon$ ( $\pi$ mm.mrad rms) | 1.1 | 0.8 | 1.1 | 0.8 | 1.7 | 2.1 | 1.7 | 2.1 |

ARC-EN-CIEL : proposed prototype

# S2E SIMULATIONS

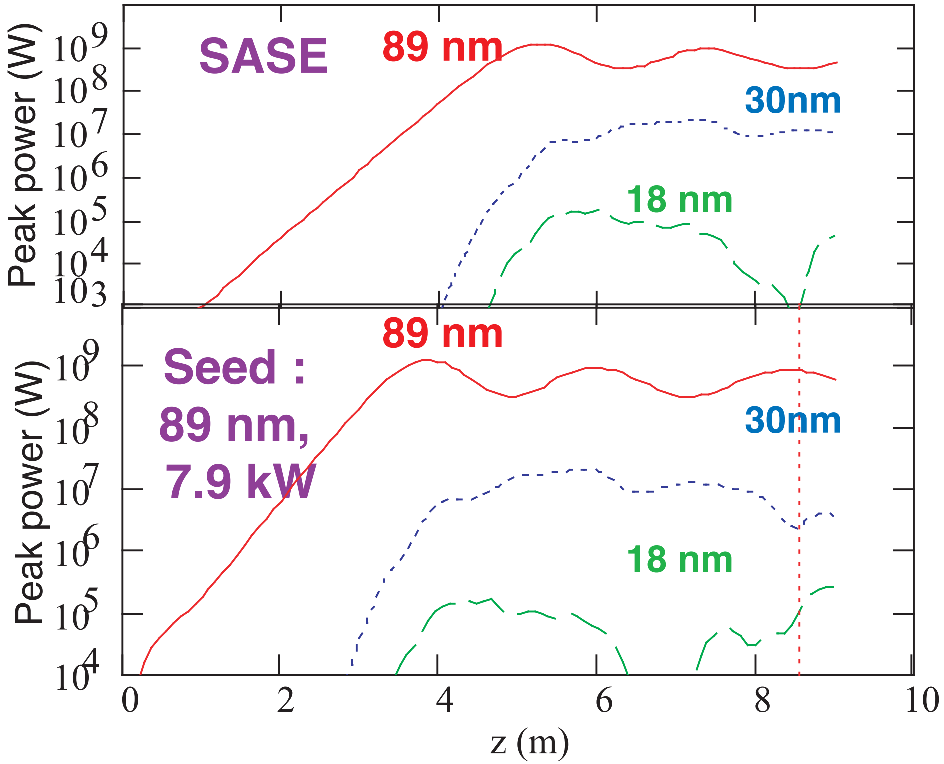
**1 nC, laser 20 ps**
**bunch compressed to 300 fs (100 μm)**

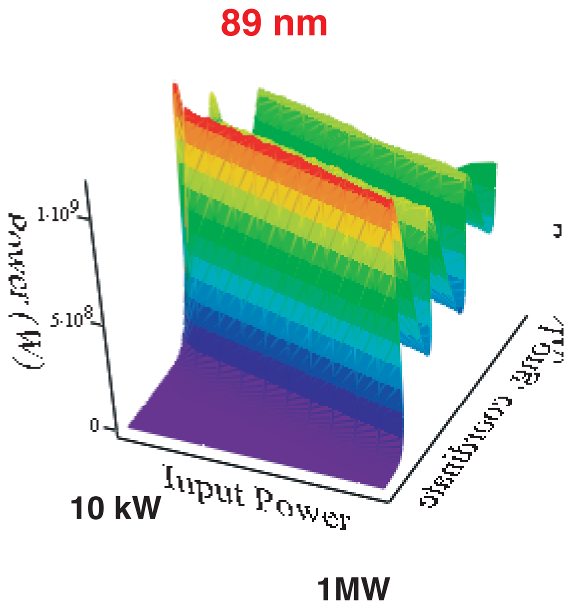
**0.1 nC, laser 2 ps**
**bunch compressed to 60 fs**

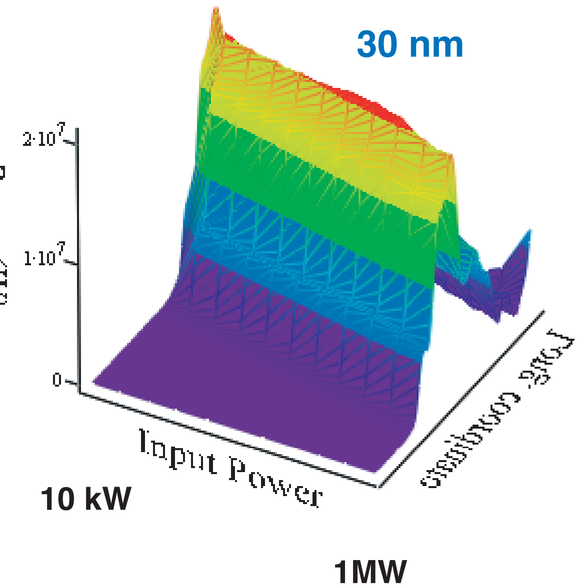


# PERSEO CALCULATIONS

**Und 1: 3 cm x 50 Und. 2 : 2 cm x 450, E = 220 GeV, 1 kA, 1.4 π mm.mrad, 0.015%, 200 fs Ff=0.1**

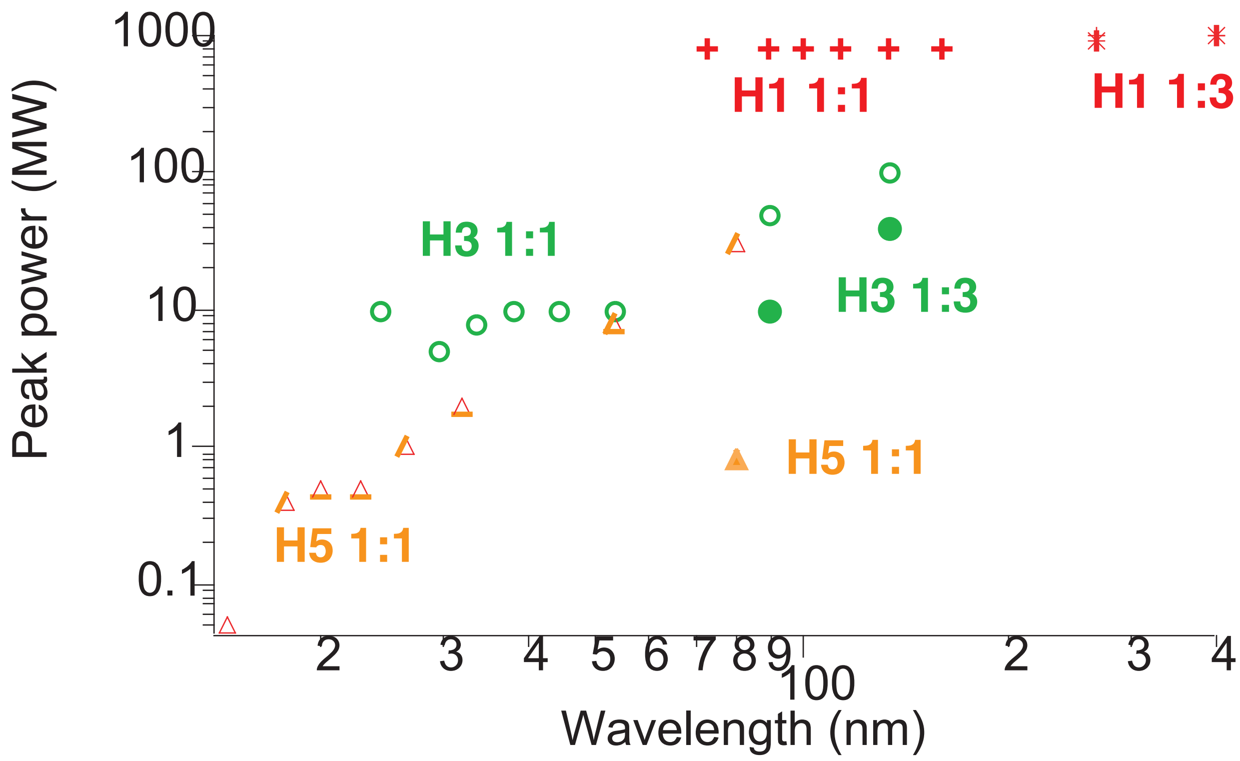


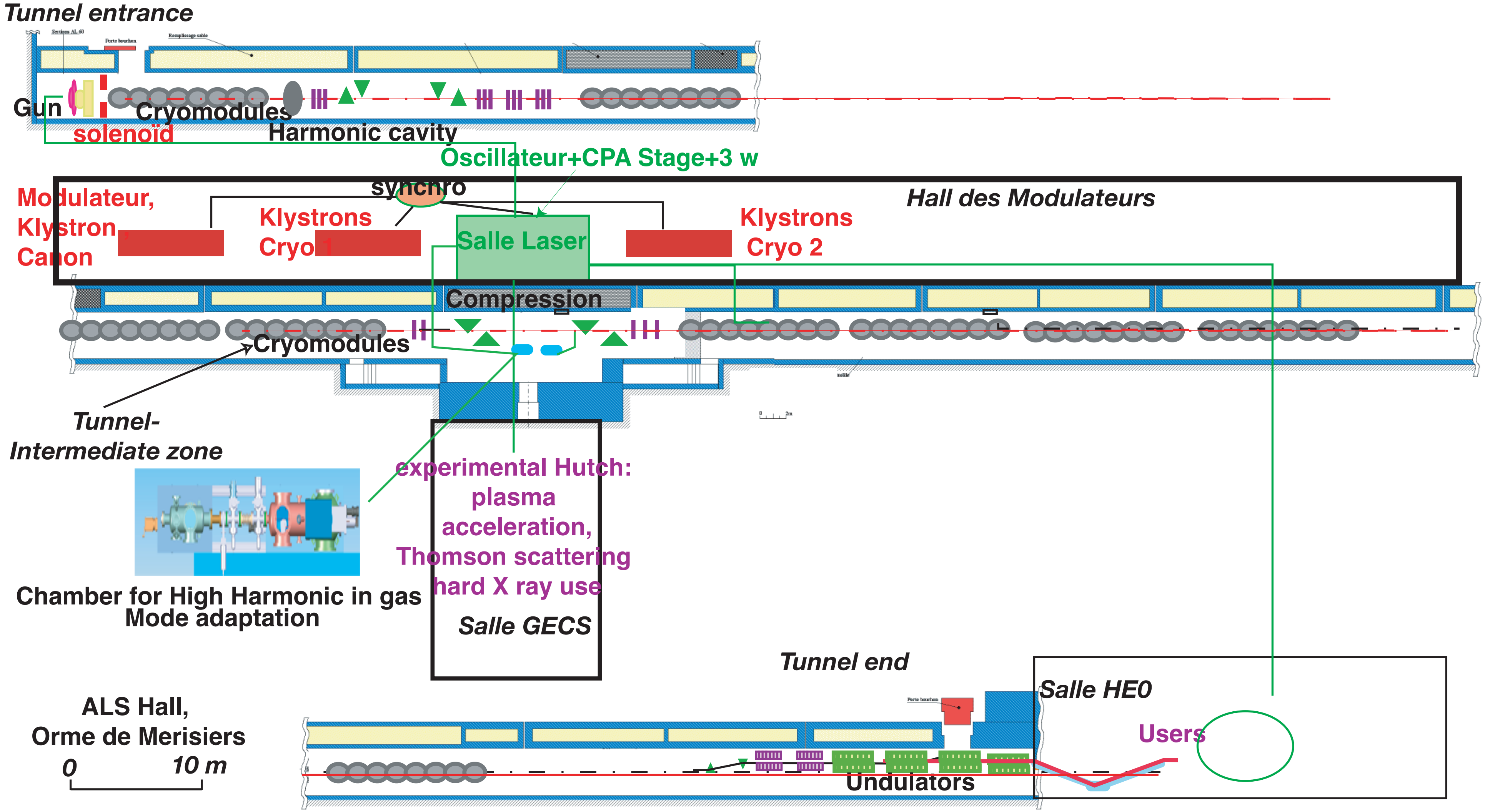

* PerseoMathcadlibrary, available @ http://www.perseo.enea.it

# ARC-EN-CIEL PHASE 1 RADIATION



# ARC-EN-CIEL : PHASE 2

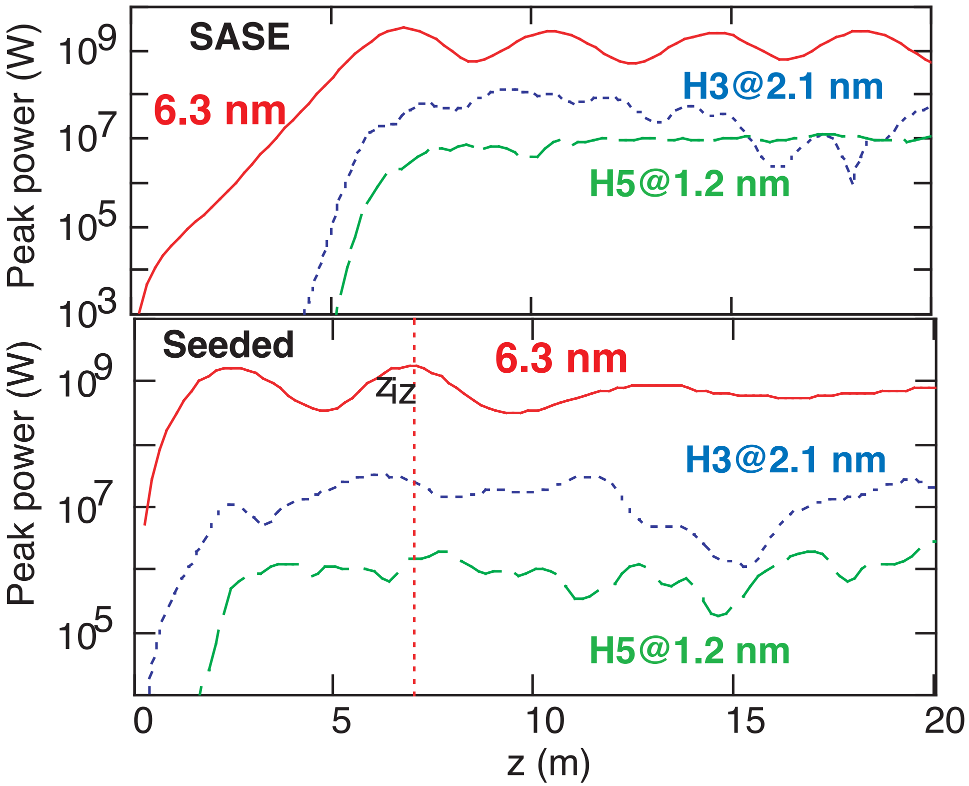
## 1 GeV, HGHG, 400-10 nm (H1), - 4 nm (H3), - 1 nm (H5)

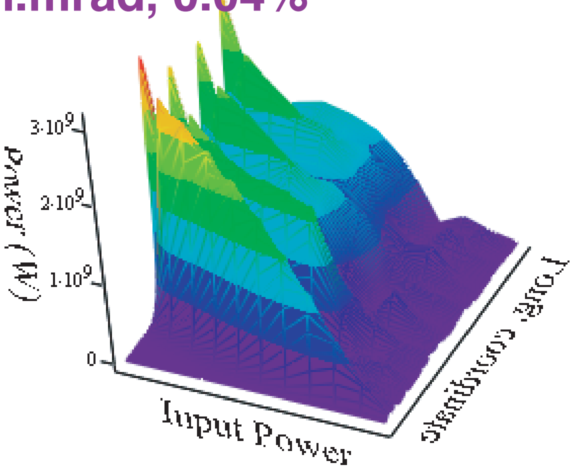


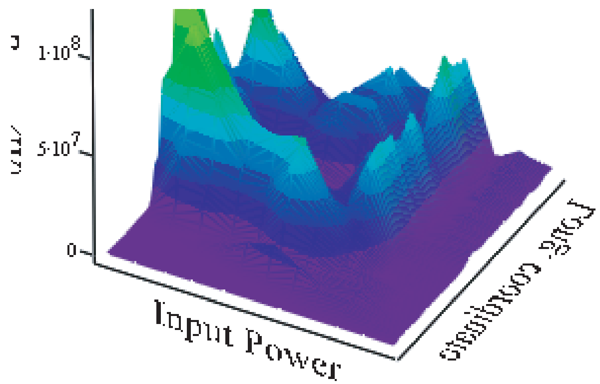
# ARC-EN-CIEL PHASE 2 RADIATION

## Perseo Calculation

**Seed : 19 nm, 16 kW, E = 1 GeV, 1 kA, 1 π mm.mrad, 0.04%**

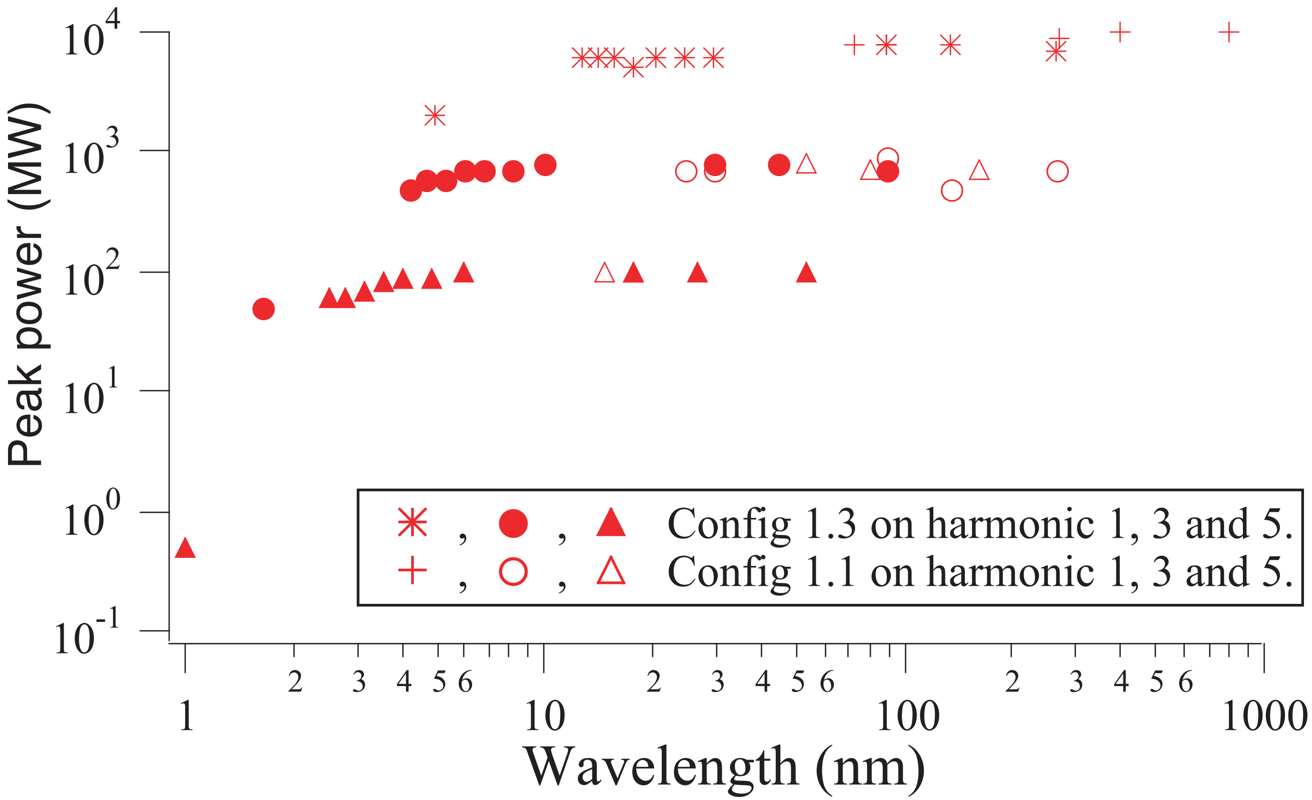


# ARC-EN-CIEL PHASE 2 RADIATION

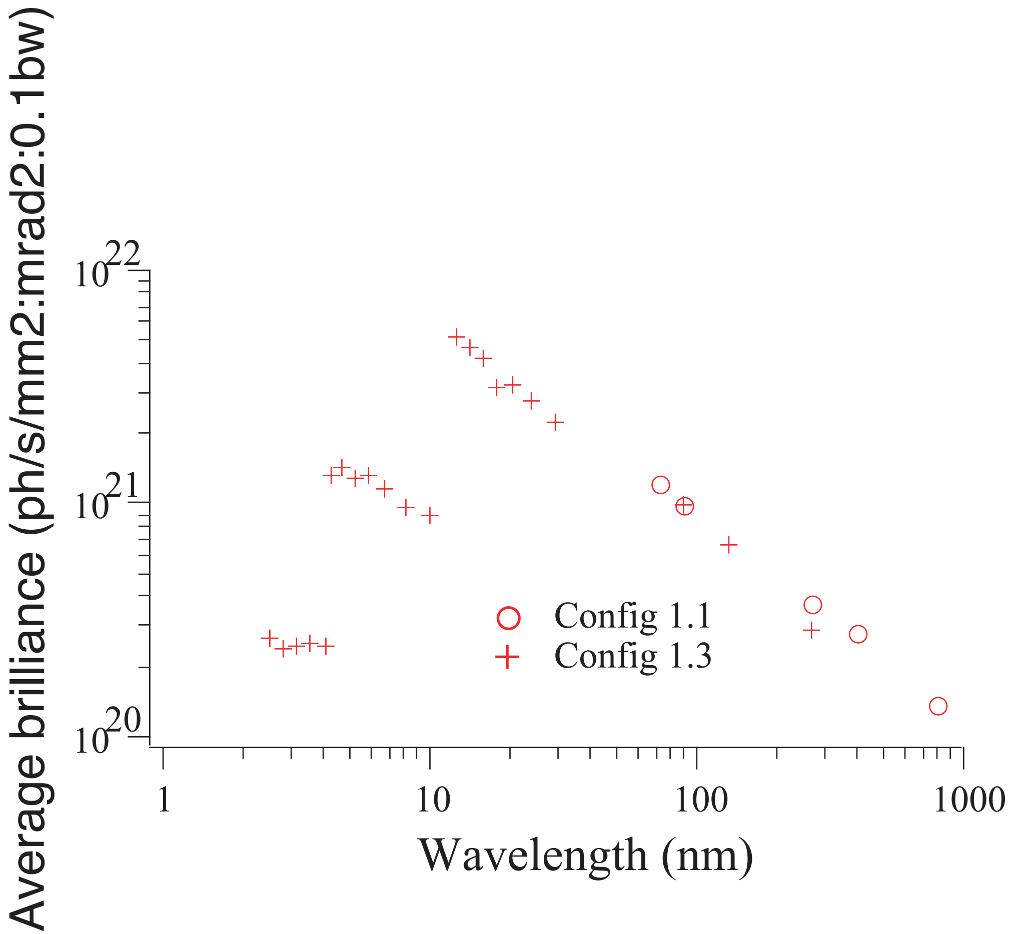
**Und 1: 3 cm x 133 Und. 2 : 2 cm x 450,**
**E = 1 GeV, 1.5 kA, 1.35 π mm.mrad, 0.0004%,**
**200 fs, β=2m, Ff=0.088**

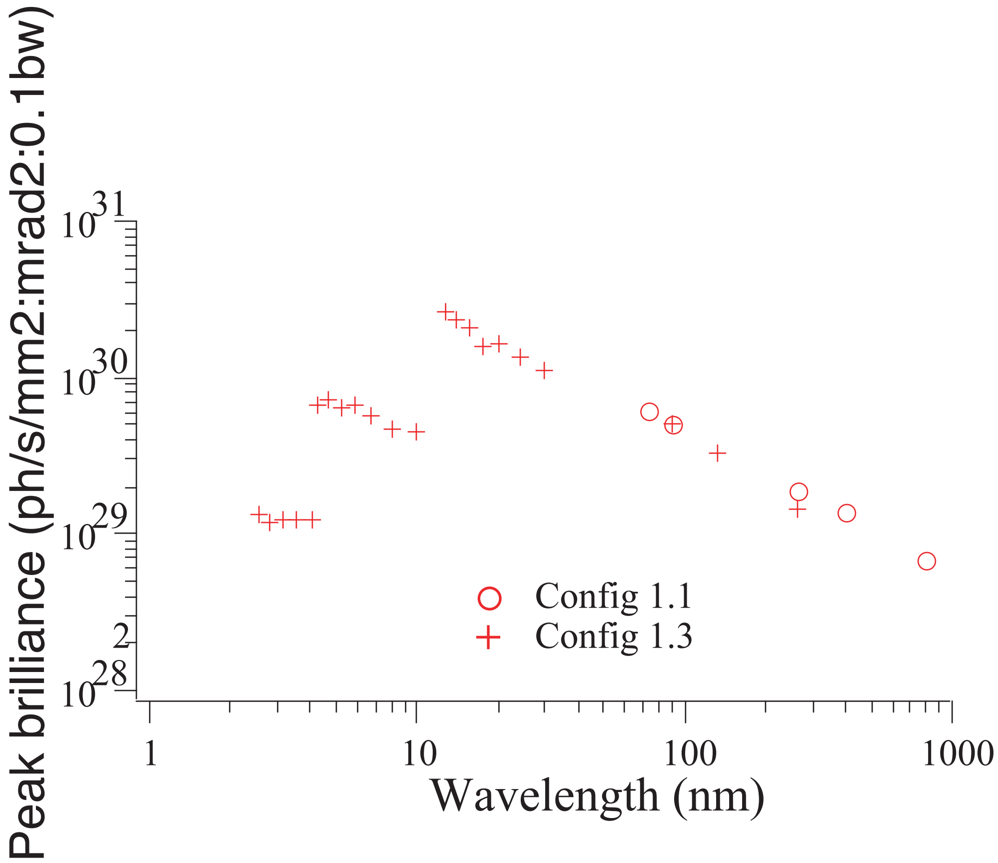


ARC-EN-CIEL : AEC phase 2

# ARC-EN-CIEL PHASE 2 RADIATION

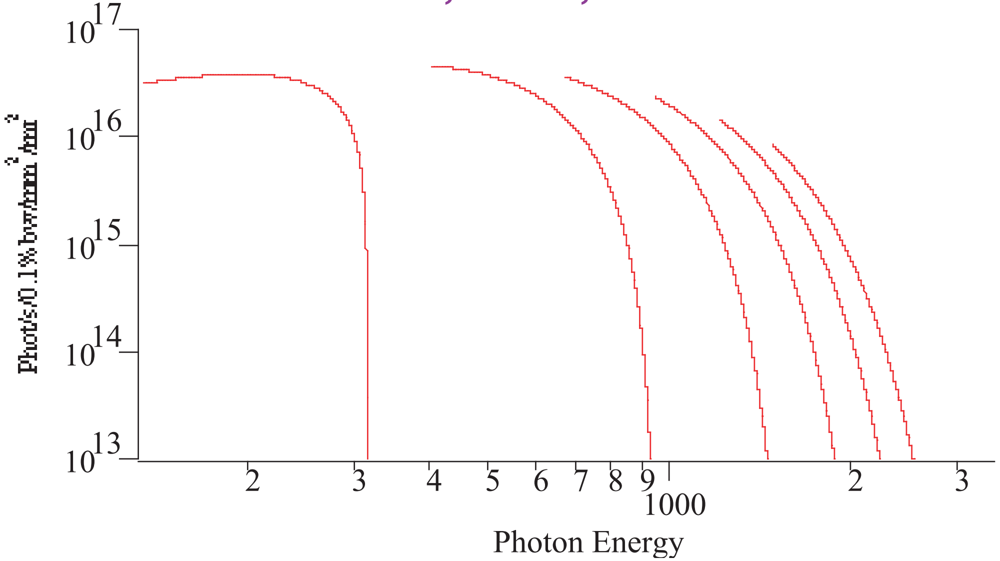
**Und 1: 3 cm x 133 Und. 2 : 2 cm x 450, E = 1 GeV, 1.5 kA, 1.35 π mm.mrad, 0.0004%, 200 fs β=2m, Ff=0.088**



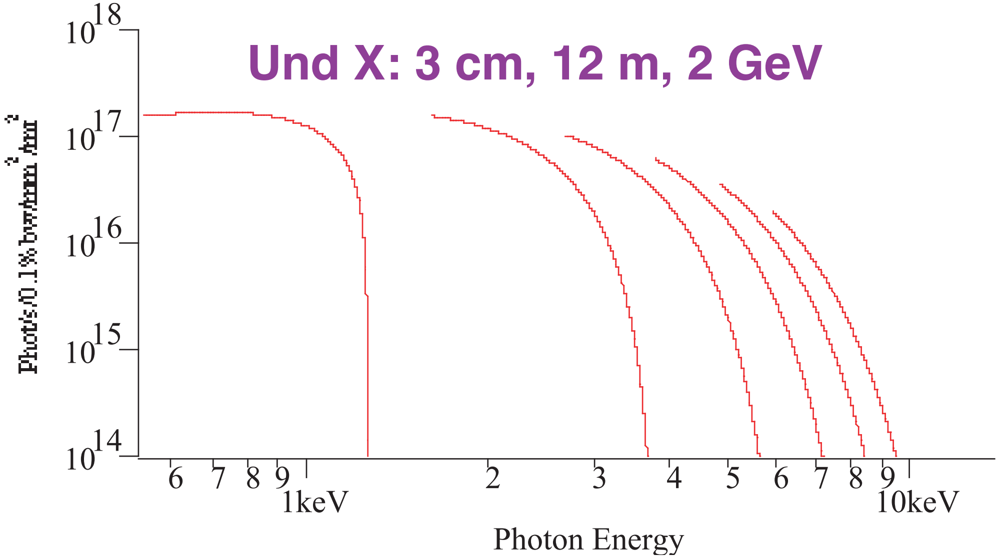



# ARC-EN-CIEL PHASE 3 RADIATION

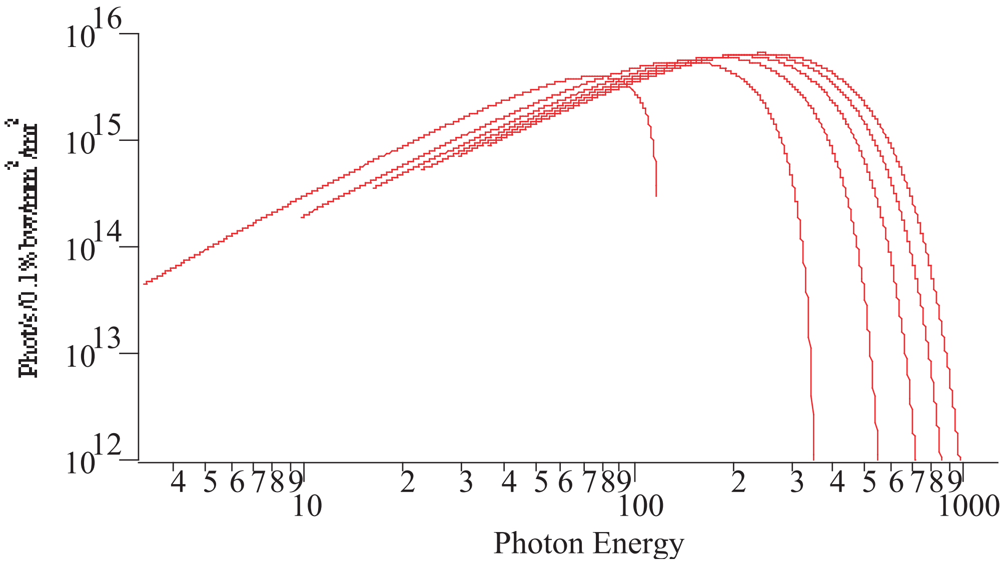
## Und X: 3 cm, 12 m, 1 GeV



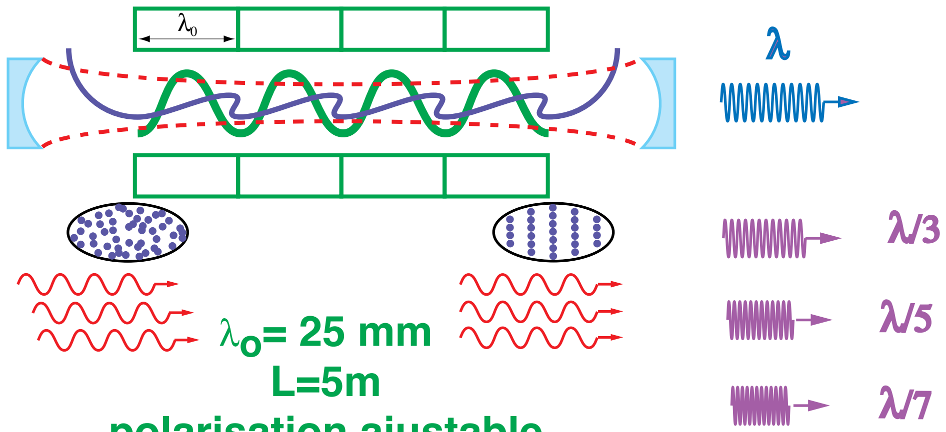

## Und X: 3 cm, 12 m, 2 GeV



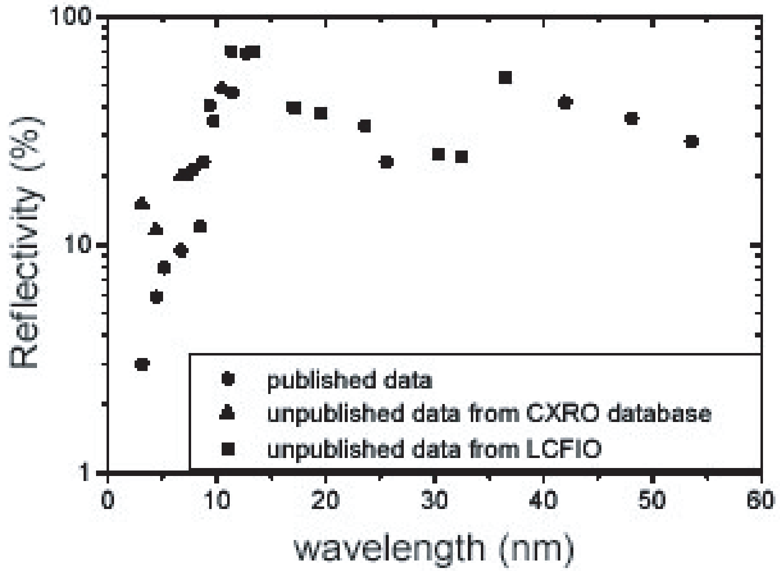

## Und VUV: 8 cm, 12 m, 2 GeV



# THE FEL OSCILLATOR




$\lambda_o$= 25 mm
L=5m
polarisation ajustable
outside vacuum




**130-13 nm**

**<P> = 100W-1kW**

**adjustable polarisation**

# LASER SOURCE

Infra-red Ti:Sa laser system, mJ, 1-10 kHz, frequency conversion

amplification chain : few J, 10 Hz, 30 TW, $10^{20}$W/cm$^2$

## Plasma Acceleration

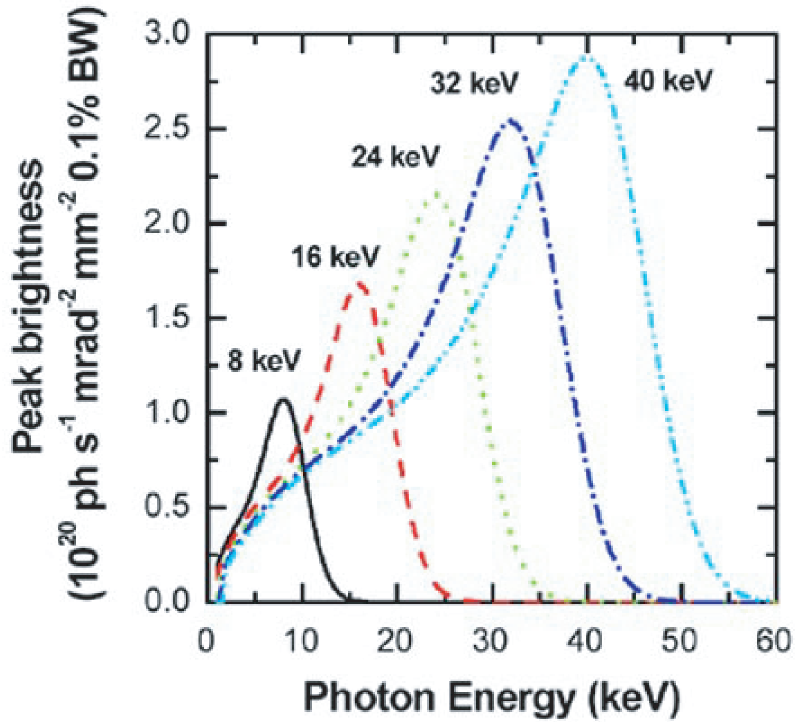
Intense Laser (30 TV/m)

plasma wave

progressive wave
(longitudinal electric field,
velocity close to c)

| $E_{in}$ | $\Delta t$ | emitt | $L_{acc}$ | E | spot | $E_{fin}$ |
|---|---|---|---|---|---|---|
| MeV | fs | mm.mrad | cm | J | µm | GeV |
| 10 | 200 | 1 | 0.5-3 | 1 | 20 | 1.6 |
| 700 | 200 | 1 | 8-32 | 100 | 100 | 1.6 |

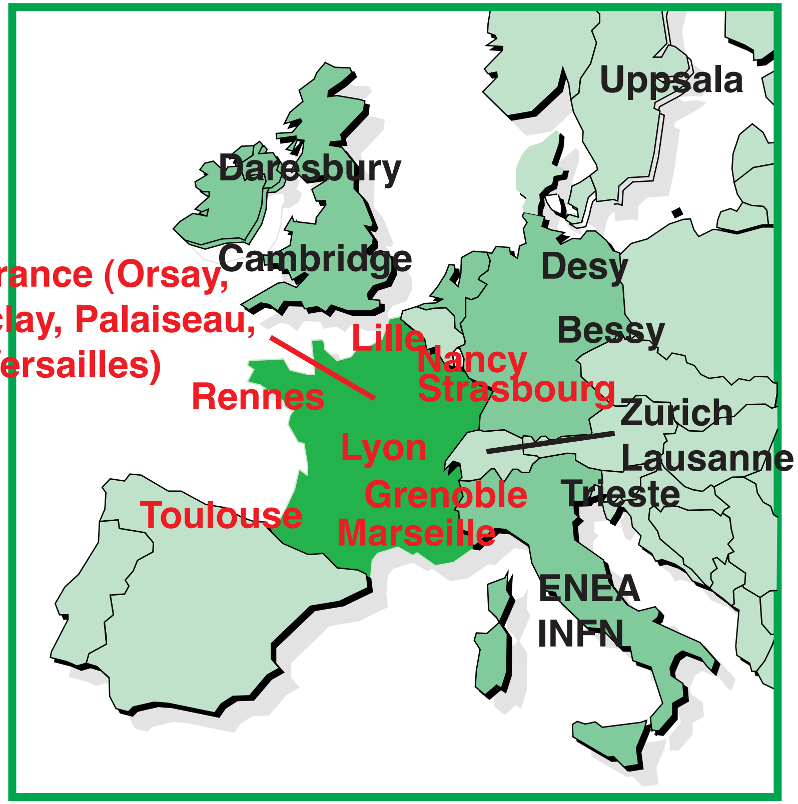
## Thomson Scattering




8-40 keV, 100 fs FWHM
3 $10^7$ph/pulse/0.1%BW
12 mrad, 50 µm

# VUV-X fs SCIENCE USER WORKSHOP

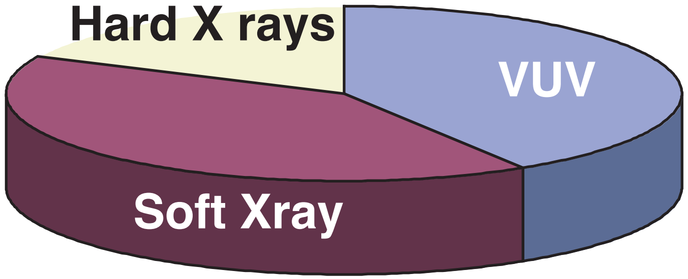

- **154 participants**
  - 136 from France
  - 2 companies
  - from abroad : Belgium (1), Germany (4), Italy (5), Sweden (3), Switzerland (2), UK (2), USA (1)
- **40 different French Laboratories**



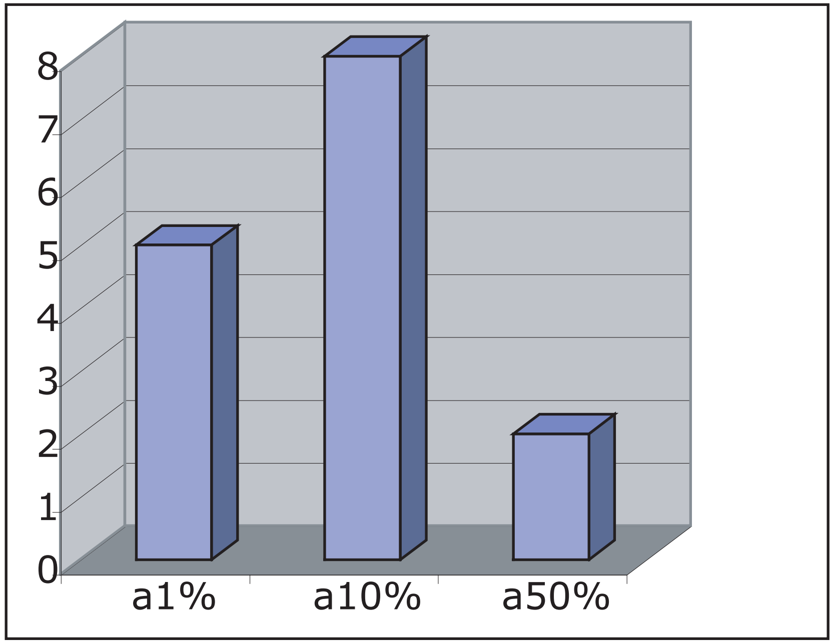
# QUESTIONNAIRE

- **answers from 22 research teams + oral presentations**
  - **11: Material ans surface science + 1 theory**
  - **13 : atomic and molecular physics + 1 theory**
  - **4 : plasma physics**
  - **5 : biology and chemistry + 1 theory**

- **Spectral range**




**Stability**

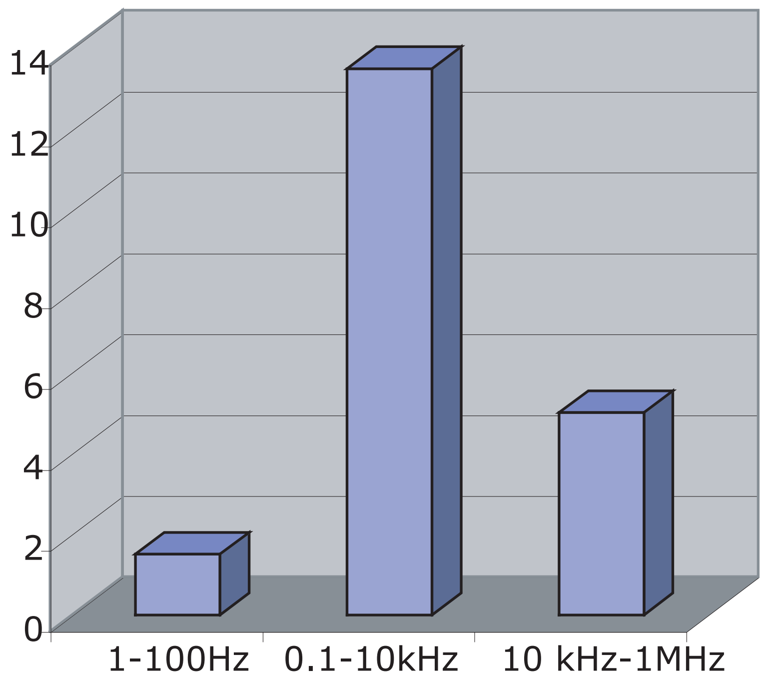



- **Spectral resolution : 1-0.01%**
- **Tuneability : yes**
- **Transverse coherence : yes**
**focalisation on 0.5 µm to 100 µm**
- **Pump-probe experiments : 72 %**
**focalisation on 0.5 µm to 100 µm**
- **Adjustable polarisation: 63 %**

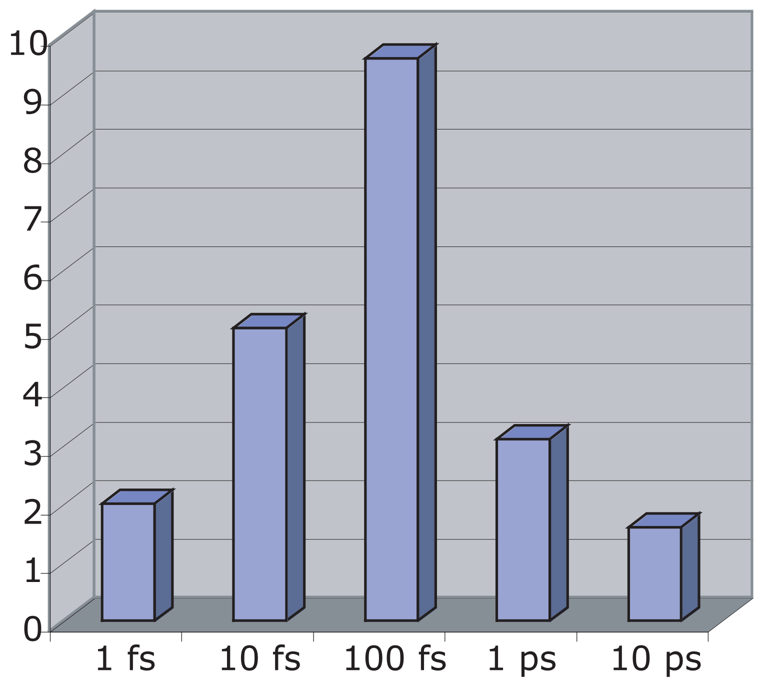
# QUESTIONNAIRE

## Temporal structure

### Repetition rate




### Pulse duration




• **answers**

| | No (%) | Yes | Indifferent |
|---|---|---|---|
| Several micropulses ( few nsrep. rate) in a macropulse at 1 Hz : | 66 | 22 | 11 |
| Spiking structure of the FEL pulse | 55 | 30 | 15 |
| Gaussian distribution | 28 | 61 | 11 |
| Measurement and not control of the pulse temporal start | 59 | 41 | |

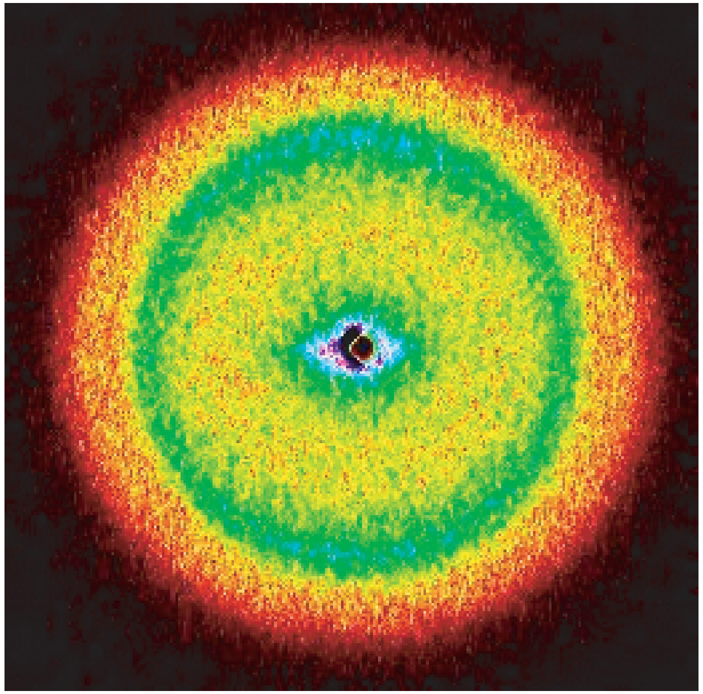
**Accumulation (72 %) vs single shot (28%)**

# GAZ PHASE

## - femto-photochimistry

molecular dynamics in gas phase

Technique : VYV/ XUV photoionisation

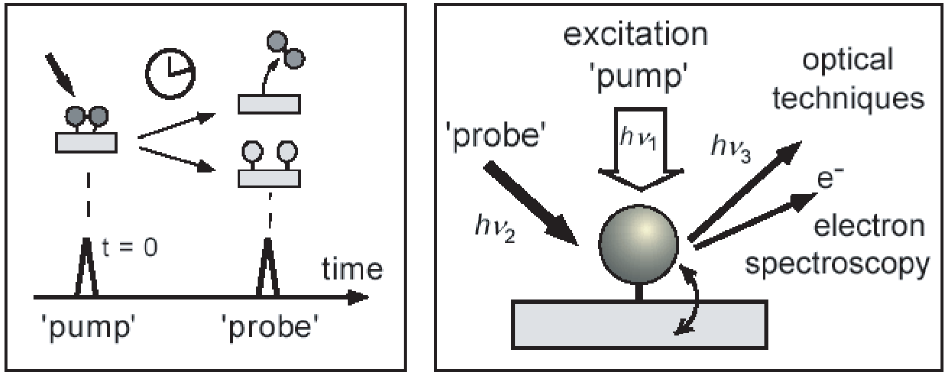


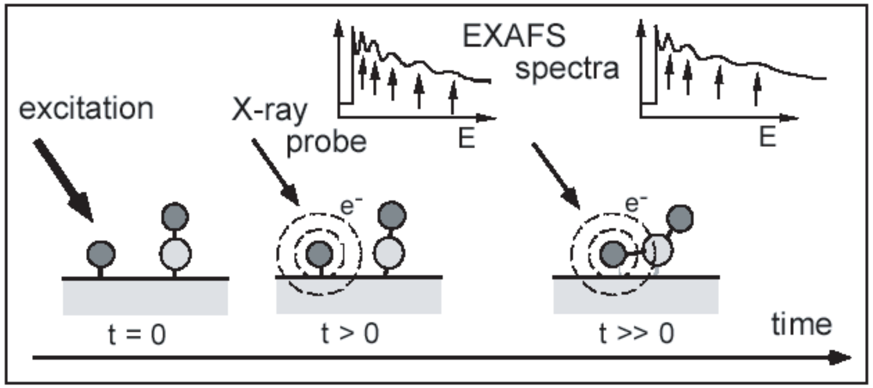
BNL

W. LI and Suits, , PRL (2004)

angle selectrivity, multiple detection (imaging)

## - molecules adsorbed on surface



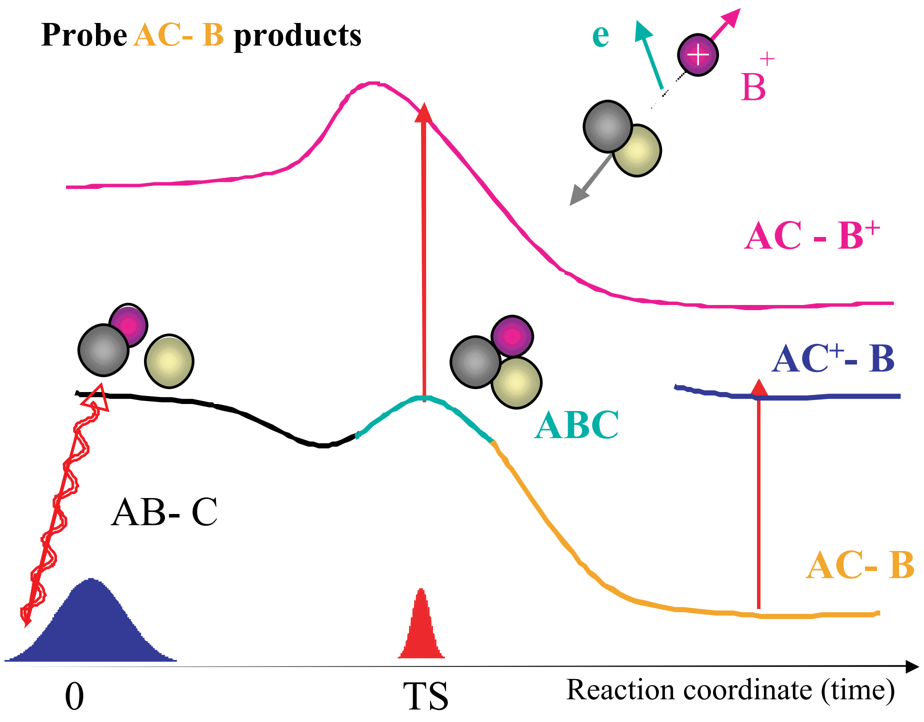



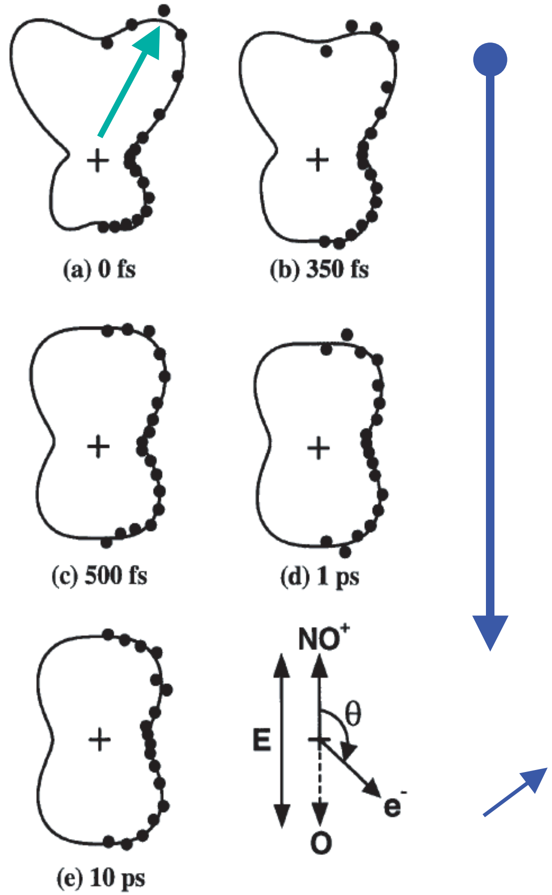

N. Lugent-Glandorf, PRL 87, 193002 (2001

# GAZ PHASE

## - alignment and dynamics of photoionisation

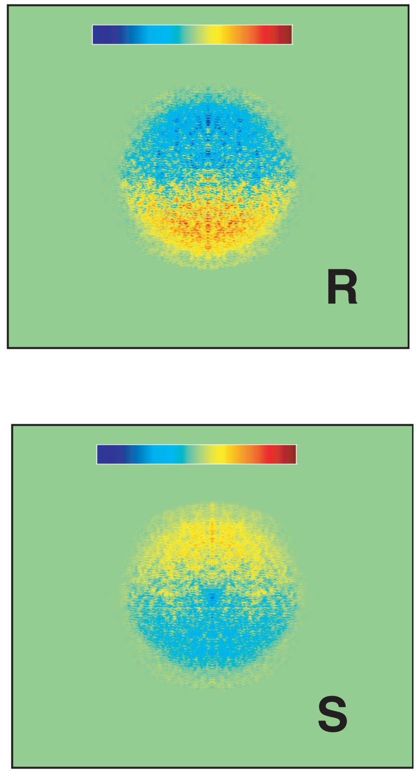
form resonance, internal shell




Davies et al. PRL 84, 5983 (2000)

## dichroïsm of chiral molecules




**Camphre**

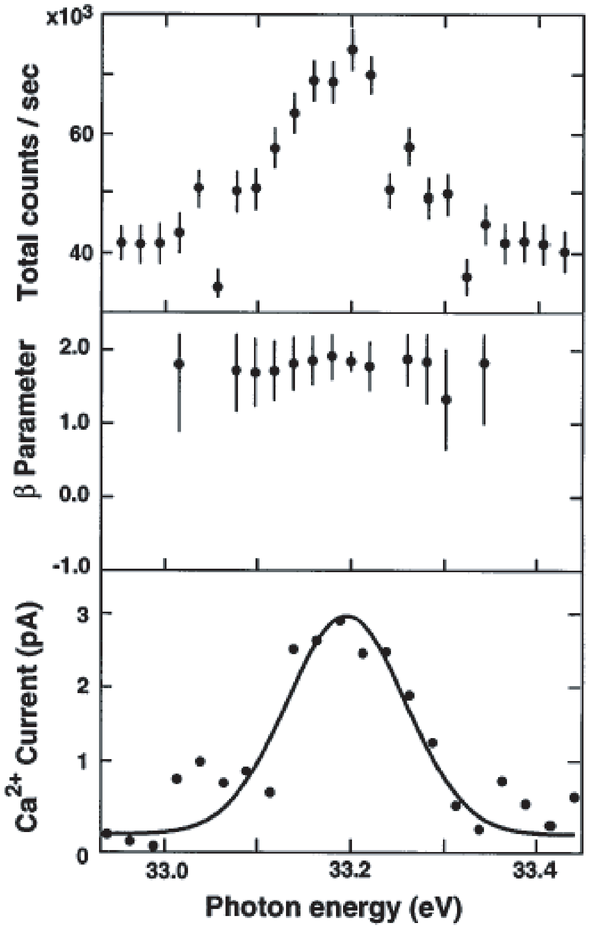
**Garcia et al**

# GAZ PHASE

## - high average flux spectroscopy

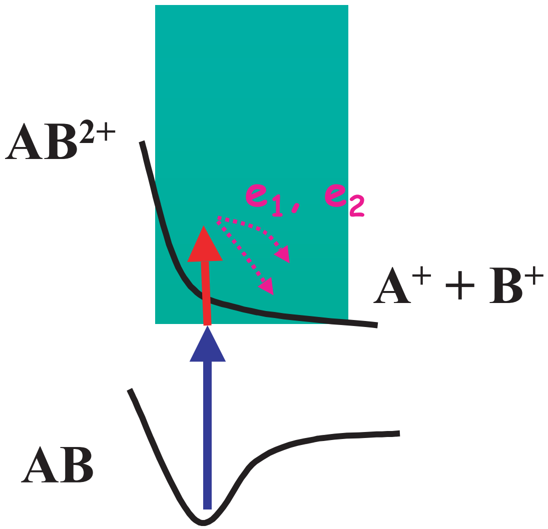
radicals, ions...

3p --> 3d de Ca+



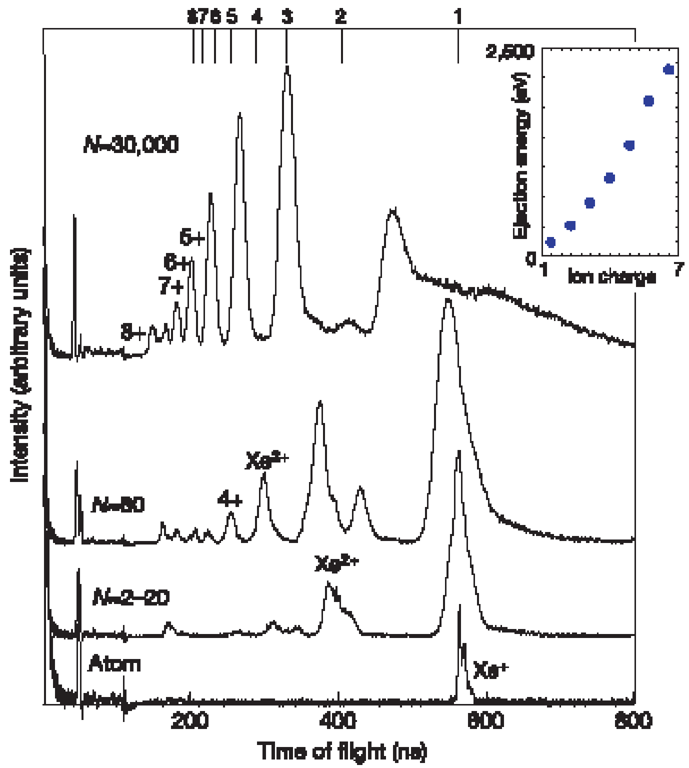

Al Moussalami et al, PRL 76, 4496 (1996)

## - atomic physics in non linear regime




## - agregates under high field

on TESLA-TTF1



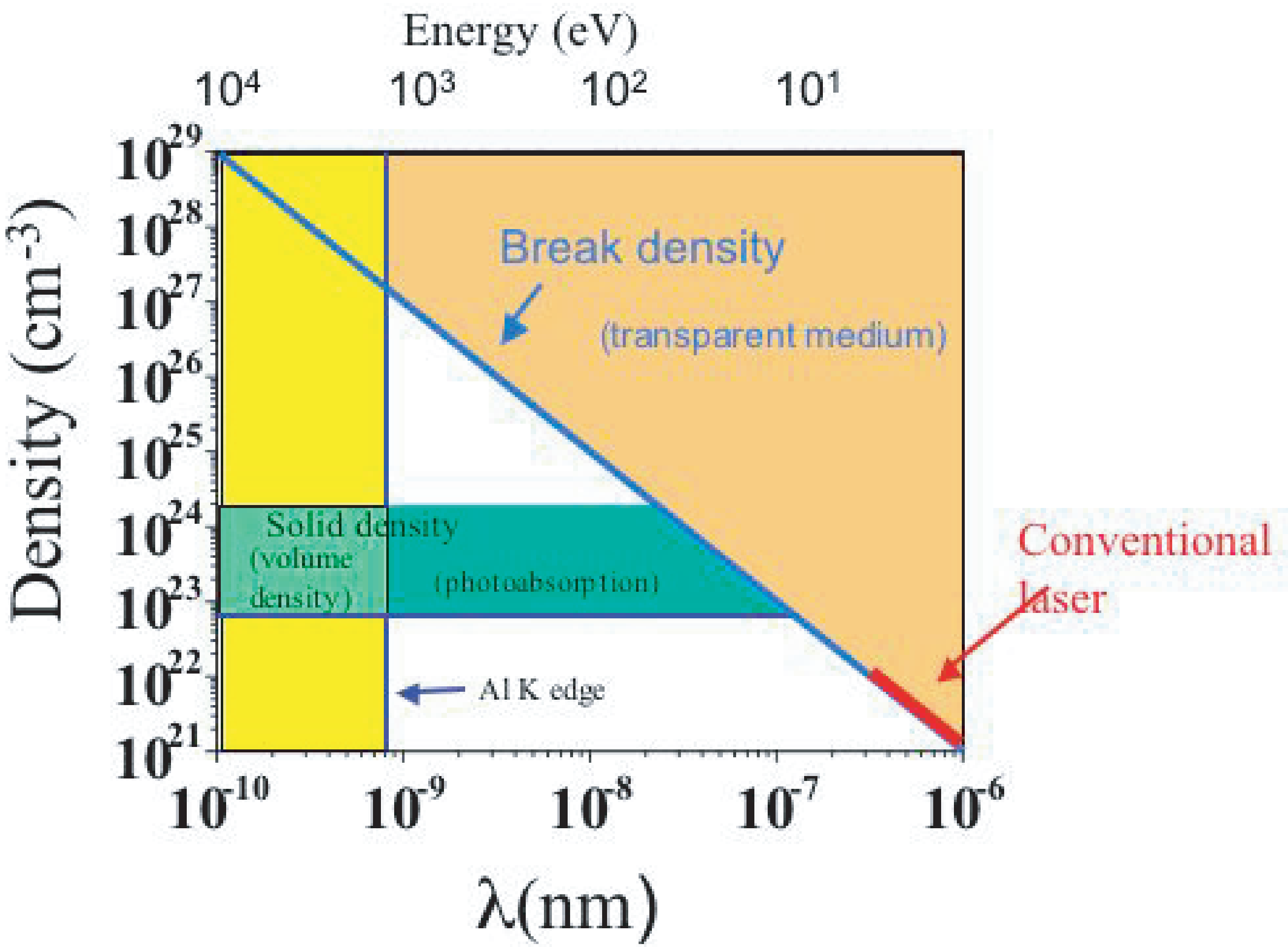

H. Wabnitz et al., Nature 420, 482 (2002)

# PLASMA PHYSICS

- generation of hot dense plasma

- Caracterisation of plasmas at solid density

- plasma acceleration



# GENERATION OF HOT DENSE PLASMAS

1-50 nm => generation of dense plasma,
vol. determined by photo-absorption length in the medium
moderate penetration depth

1 μm -> 100 eV Temperature,
1 nm -> 1 meV, less contribution to the heating of the medium :
energy deposited by photo-absorption-> control of the T medium

• Hot plasmas

interest : inertial fusion, cf stellar plasmas
studies vs densities (tuneability), transition of the energy deposition mechanism
plasma heating and plasma dynamics decoupled (short pulses)
plasmas at solid density

- Degenerated / correlated plasma

high density ionised medium of low T, giant planets
strong Coulomb coupling (thermal energy< electrostatic energy)
degenerated (thermal energy>Fermi energy : De Broglie wavelength> interpart. distance

# PLASMA PROBES

**Plasma temperature : few eV (discharges ) few dizains of keV (fusion)**
**Diagnostics of microscopic parameters (density, T, abondance)**

• **Atomic Physics**

**lifetime of multi-charges ions**
**high opacity**

**plasma generation**
**inertial fusion : focus of high intensity laser on a solid target**
**tokamak plasma : Electron Beam Ion Trap**
**X ray laser Plasma : transient pumping of plasmas with ns pulses on solid targets**

**- Determination of volume properties**

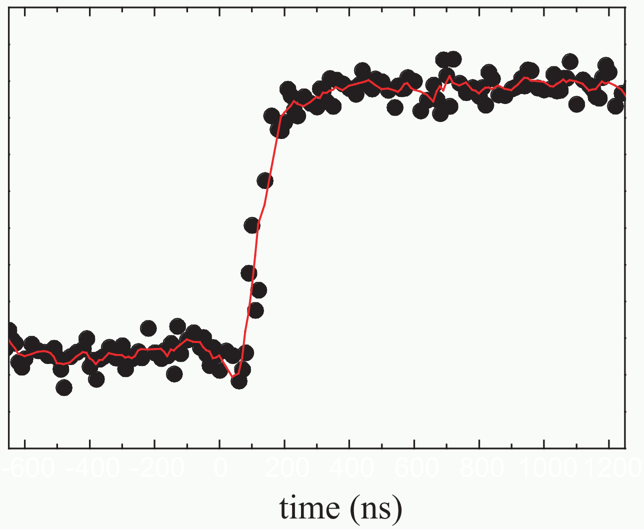
**high charge densities**
**density close to solid**
**Technique : spectral imaging (LIF), interferometry, diffusion**

# MATERIAL-SURFACE SCIENCE

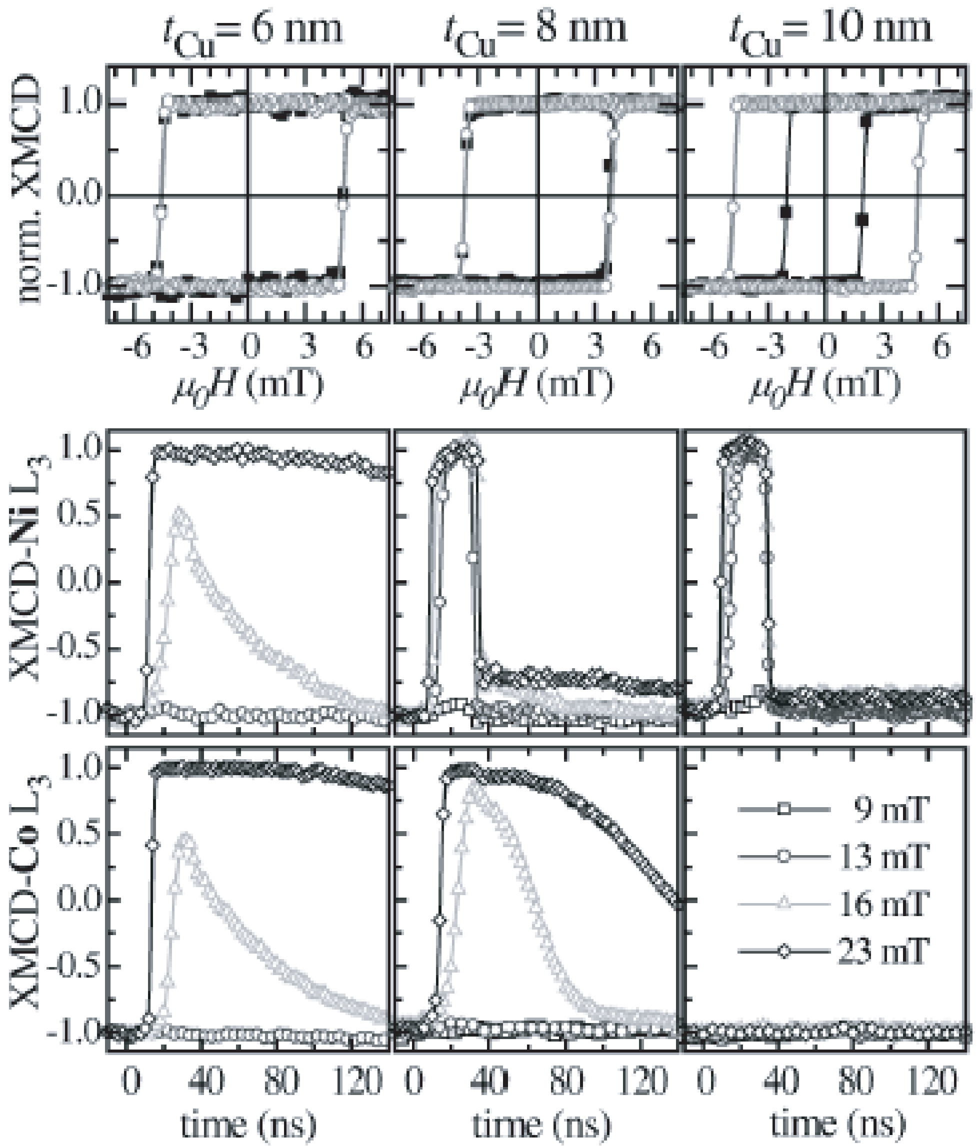
## - spintronics

• magnetization reversal dynamics of thin films complex heterostructure :
(spin valves, tunnel junctions)
Technique : X-ray magnetic circular dichroism

• surface magnetometry
Technique : 1 or 2 photon photo-emission




F.Sirotti PRB 61, (2000) R9221




M.Bonfim et al., Phys. Rev. Lett. 86 (2001) 3646

# MATERIAL-SURFACE SCIENCE

## - surfaces and interfaces

- interface solid/liquid
- surface magnetometry
- adsorbates
- desorption of a polymer layer on a surface

Technique : Non linear regime

## - complex materials

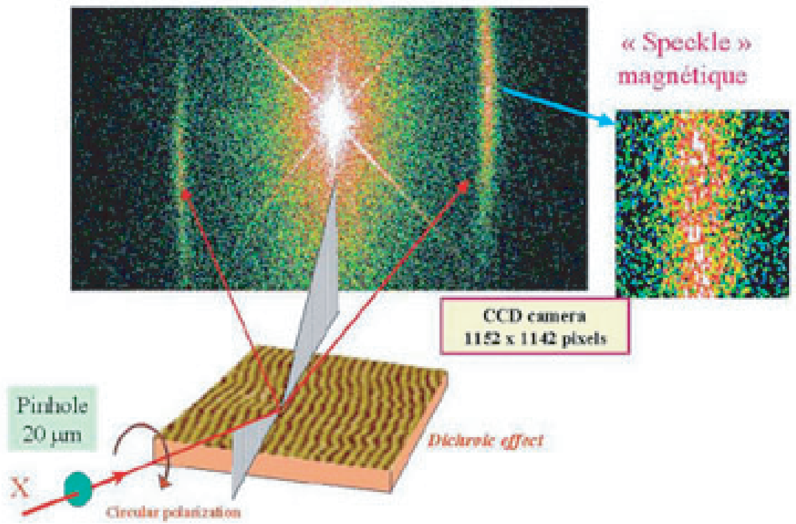
- oxides of transition metals
- phase transition

Technique : Inelastic Scattering

## - Large gap solids, dynamics of excited states

## - Creation of ponctual defects

- dielectrics, collective electronic relaxation



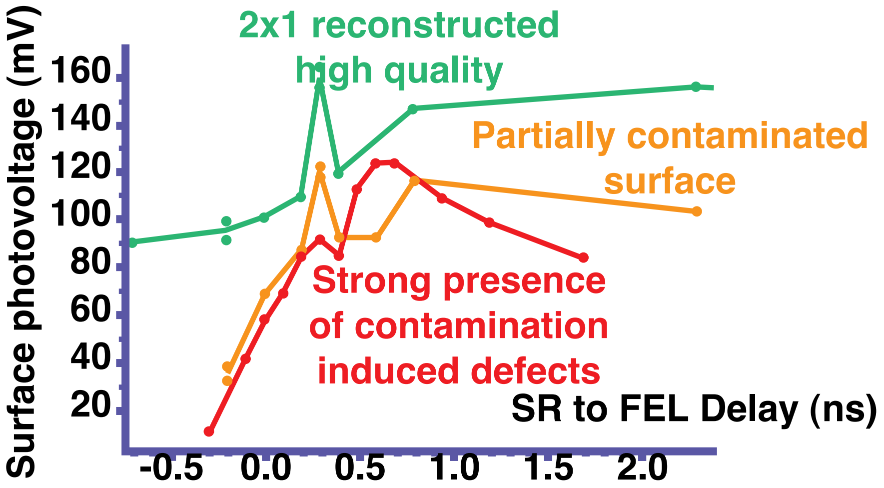
# MATERIAL-SURFACE SCIENCE

## - studies of excited samples

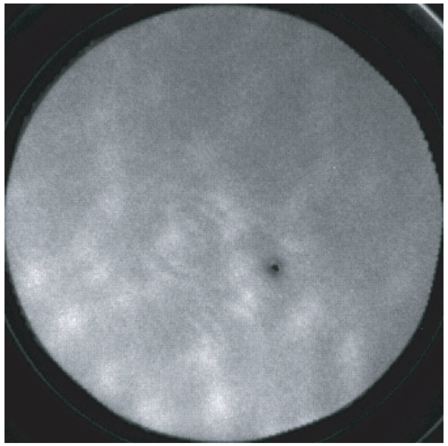
**Transient charge carrier distribution at surfaces and interfaces**

**FEL+SR spectroscopy of unoccupied states in SC and metal**

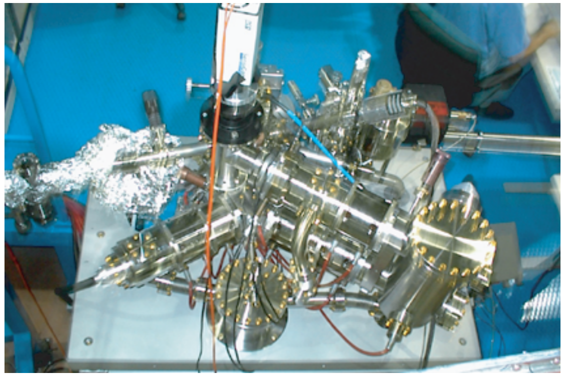
**Technique : transient spectro-microscopy, fluorescence, PES , PEEM, X-ray diffraction**




Surface photovoltage effect
(UV FEL, VUV SR)
GaAs/Ag, Si, Si/Au,
Si/SiO2. M. Marsi, A. Taleb



Pb islands grown
in-situ on W(110)
Work function contrast
seen with 196 nm
FEL light
Field of view: 5 μm

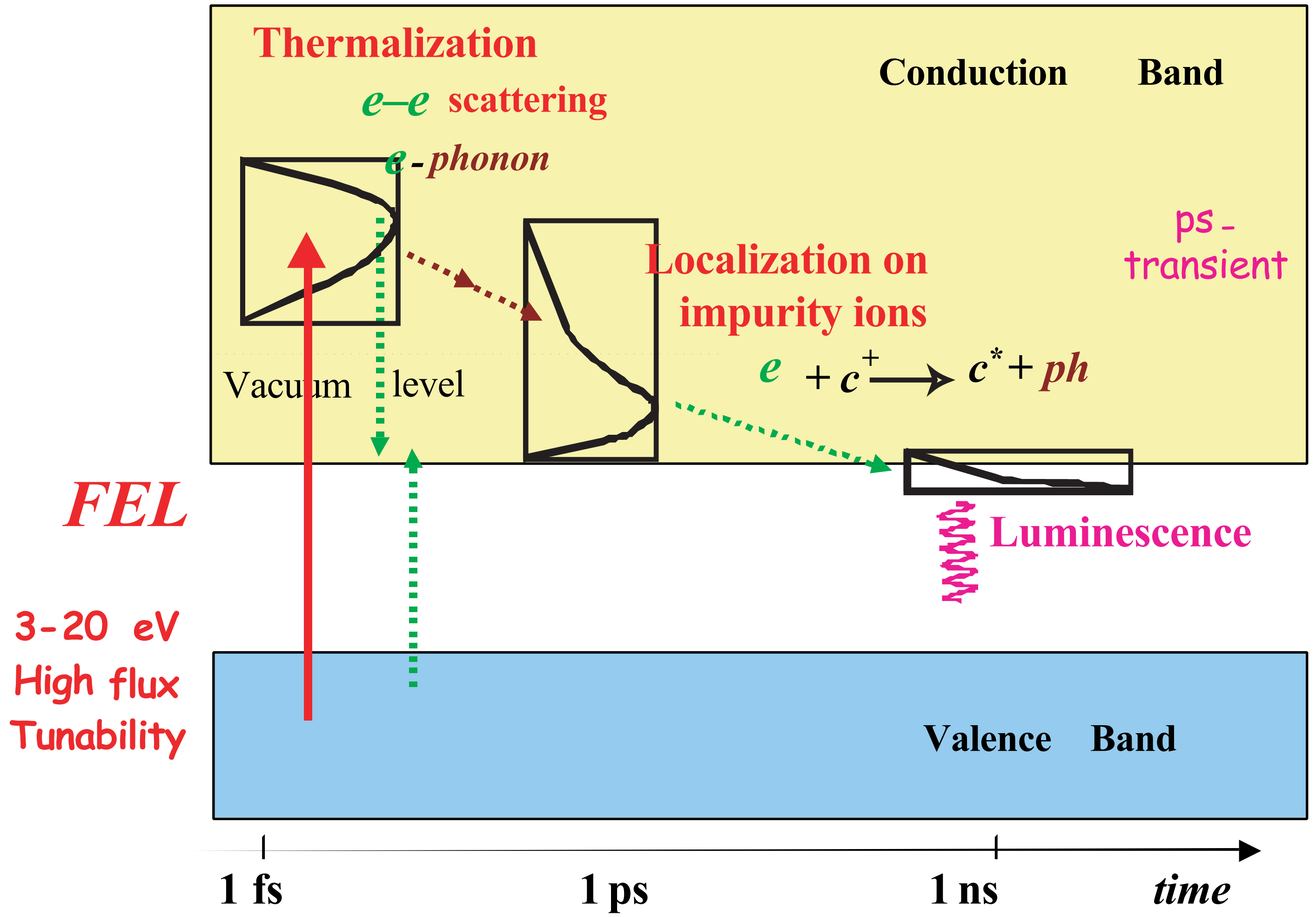


Photoelectron Emission
Microscopy
with the EU FEL
at Elettra

# MATERIAL-SURFACE SCIENCE

## - Creation of pontual defects

• dielectrics, collective electronic relaxation/ energy transfer in large gap dielectrics




luminescence (BaF2, scintillators for imaging)

A. Belski et al,
S. Guizard et al.

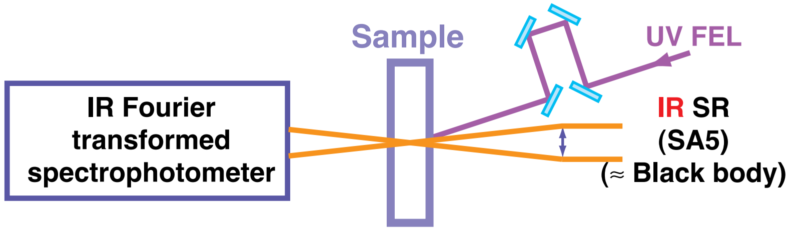
# MATERIAL-SURFACE SCIENCE

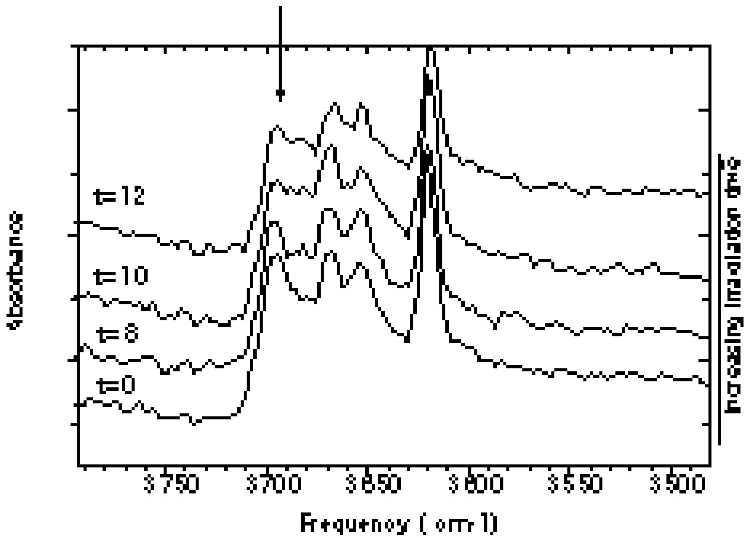
## - vibrational studies of excited states, electron -photon interaction

**Transient charge carrier distribution at surfaces and interfaces**

**FEL+SR spectroscopy of unoccupied states in SC and metal**

**Technique : IR spectromicroscopy coupled to UV-VUV excitation**



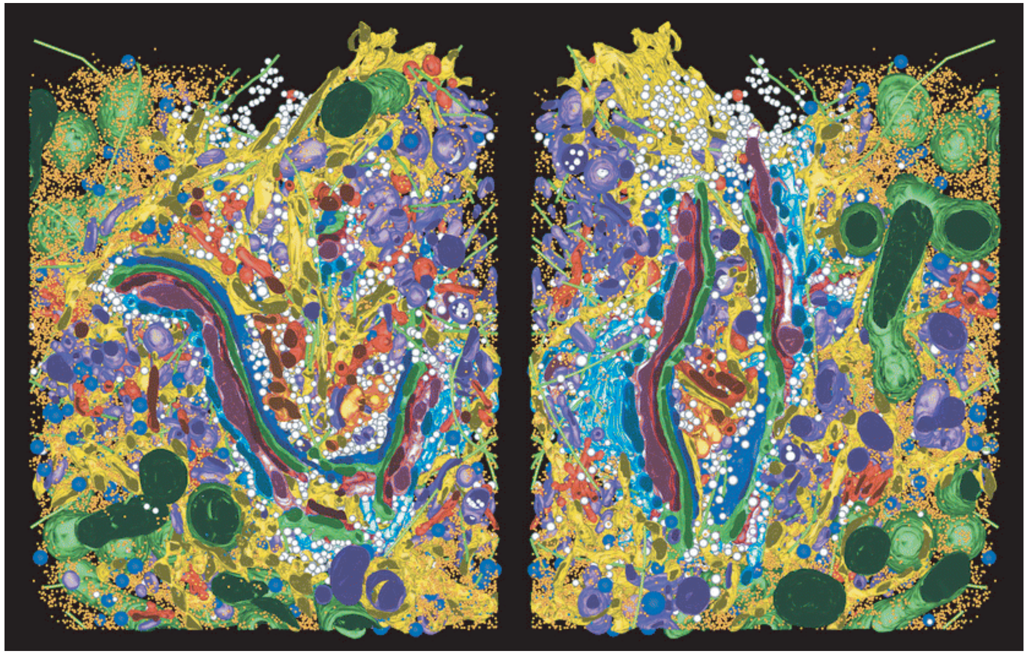




elongation band of the external OH of kaolinite under irradiation

# CHEMISTRY - BIOLOGY

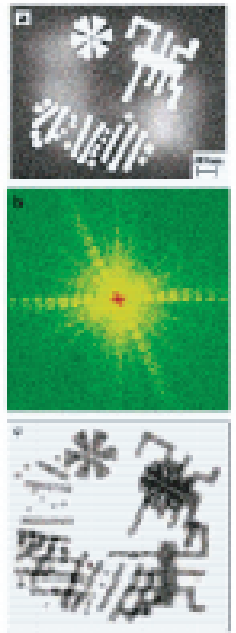
- **Relaxation Dynamics of unknown excited states**

**- Structure and dynamics of multiproteins complexes by X ray microscopy**



**3D Model organisation around the Golgi 3D in pancreatic cells. Two perpendicular views.**
**Derived from electronic tomography (Marsh B.L. et al PNAS, 2001)**

- **Catalysis of complex systems**
- **Electrochemistry**



**Miao J. Phy Rev Lett 2002**

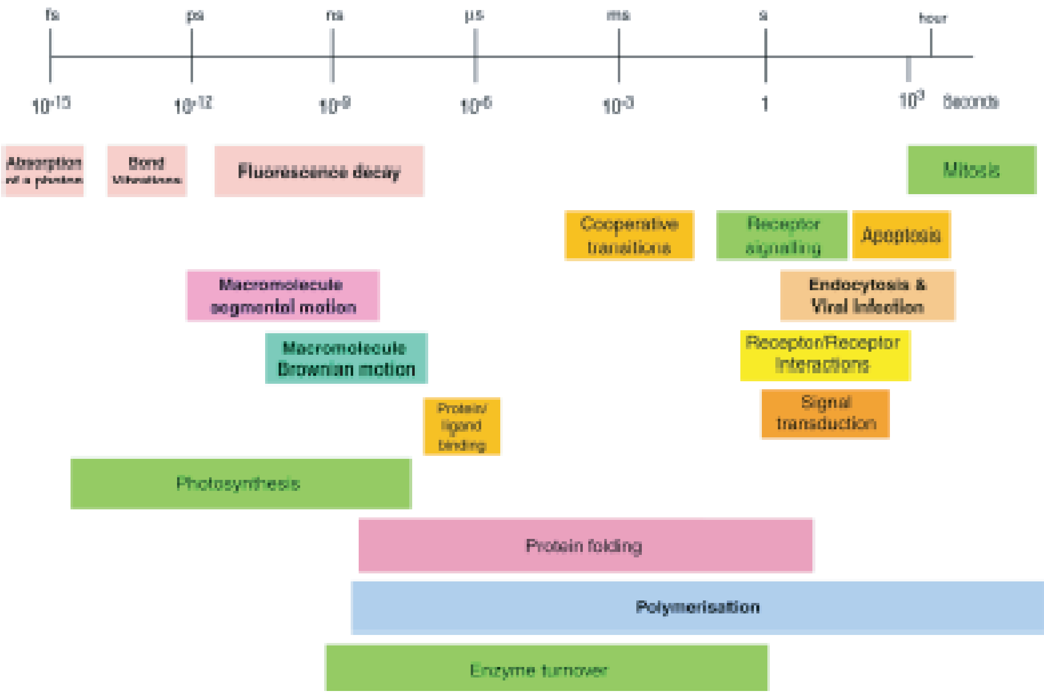
# BIOLOGY

## - Mechanism of protein folding

pathogen fibers in badly folded conformations, neuro-degenerative deseases (prion ...)

study of first steps of secondary structure formation

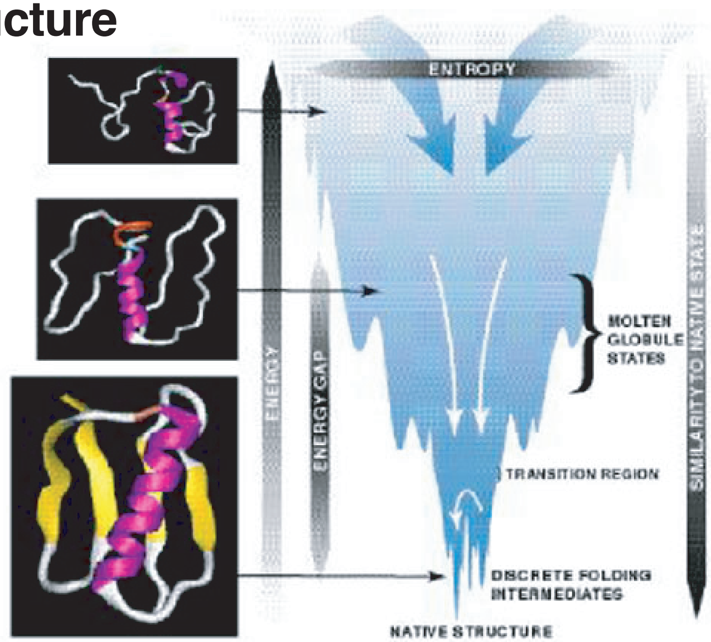
Technique : Circular Dichroim, Raman




ps- ns
partial formation
of 2dary structure

μs-ms
melted
globule

s
native
structure



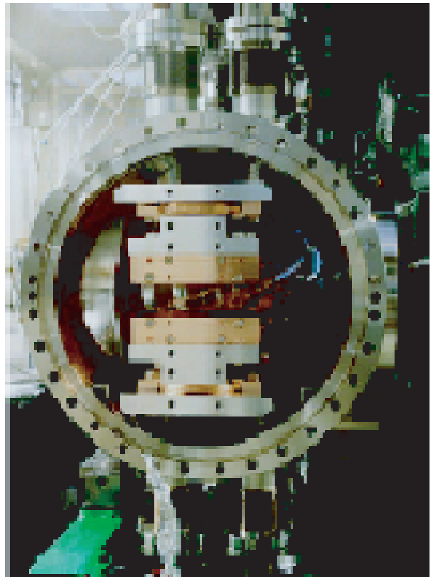
# CONCLUSION

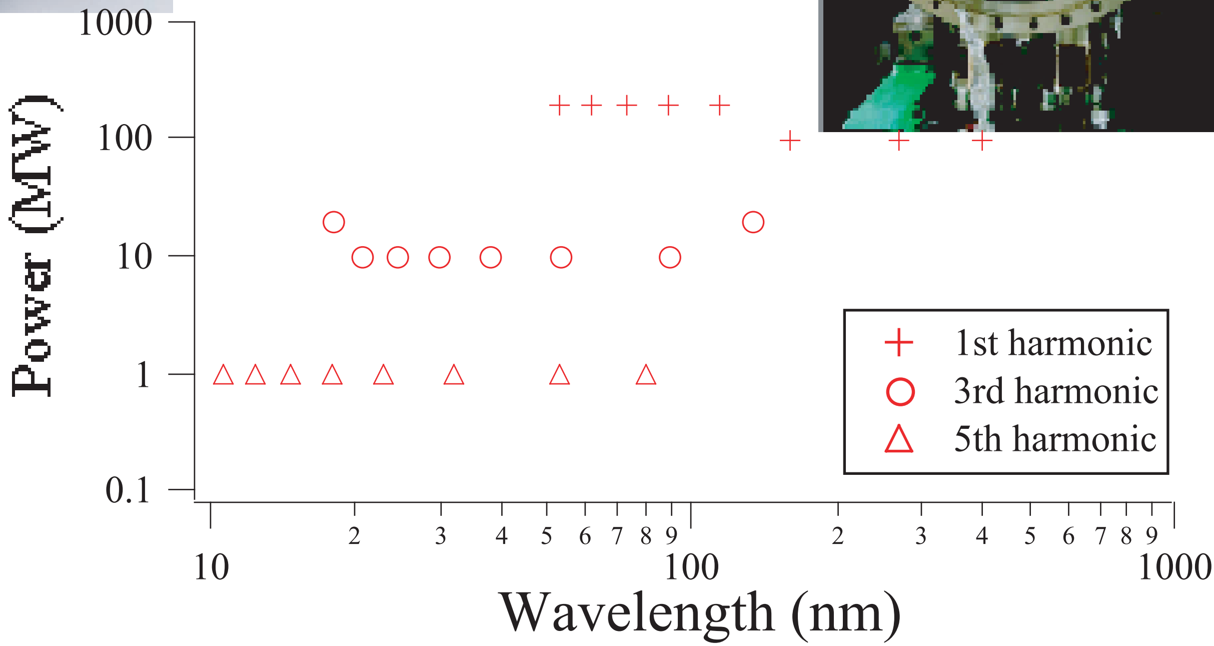
- **2006 :Commissionning of SOLEIL : French 3rd generation light source**

- **2006 : Demonstration experiment on seeding with HHG**

**SCSS prototype (H2-13), SPARC (H3-9, cascading)**

**Thermo-ionic gun CsB6**





# CONCLUSION

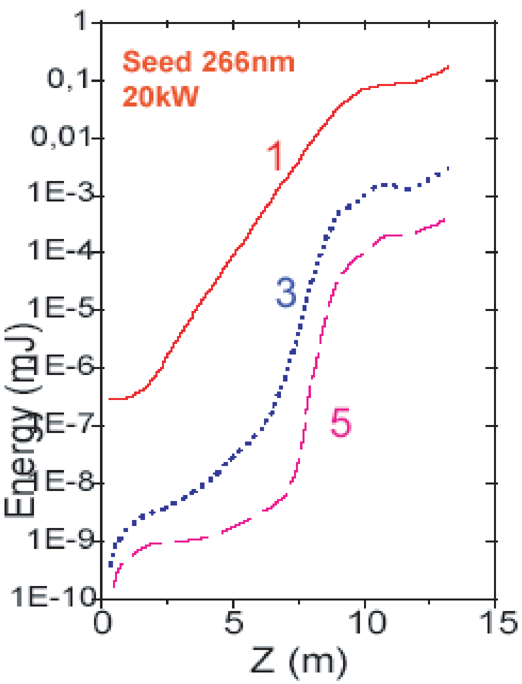
- **ARC-EN-CIEL : under way**

**- detailed calculations (HGHG : new version of SRW, injector and LINAC)**

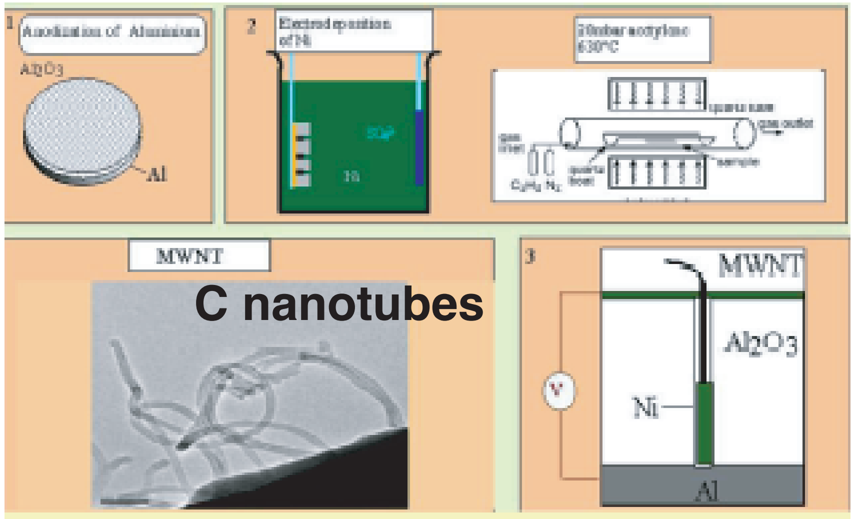
**- gun proto?**

**-EUROFEL**

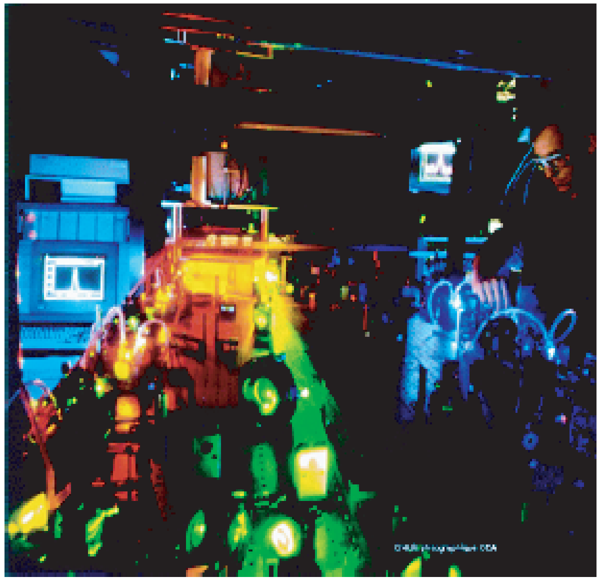
High Gain High harmonics




**seeding@SPARC**




**microphonics vibrations compensation**



**laser longitudinal and spatial shaping for photo-injector**