THE ARC-EN-CIEL PROJECT

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EUROFEL EU Contract

MOTIVATION AND STRATEGY

FEL History in France :

ACO (1983-87), Super-ACO (1989-2003), CLIO (1992-)
First pump-probe two-color experiments using UV FEL and synchrotron radiation (1994)
Coherent Harmonic generation (100 nm in 1991!)

Aim :

Build a Multi-color radiation with 1 keV FEL source for user applications
High repetition rate => Superconducting accelerator

FEL physics concept :

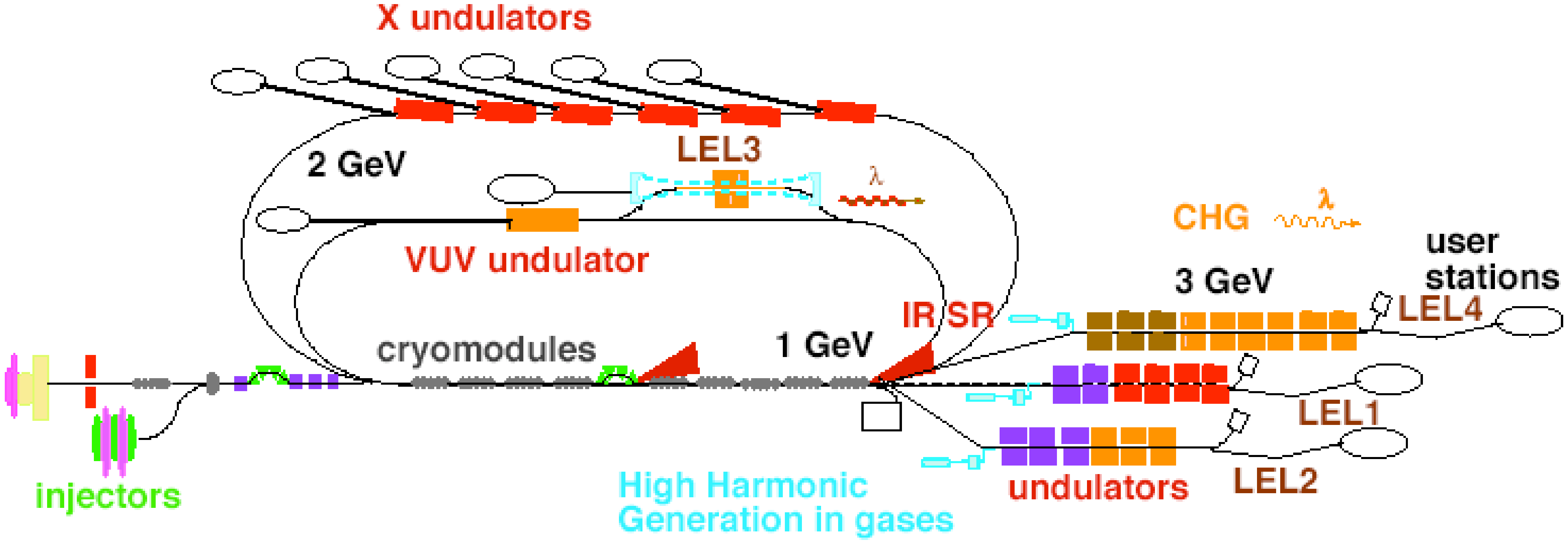
Exploit harmonic generation and seeding schemes
Choice of the seeding source : High Harmonics produced in Gas (HHG)
-> Improved coherence and compactness, reduction of intensity fluctuations
Expertise in France in HHG (CEA-SPAM, LOA, CELIA)
Close synergy between FEL and conventional laser community in the same facility

Strategy :

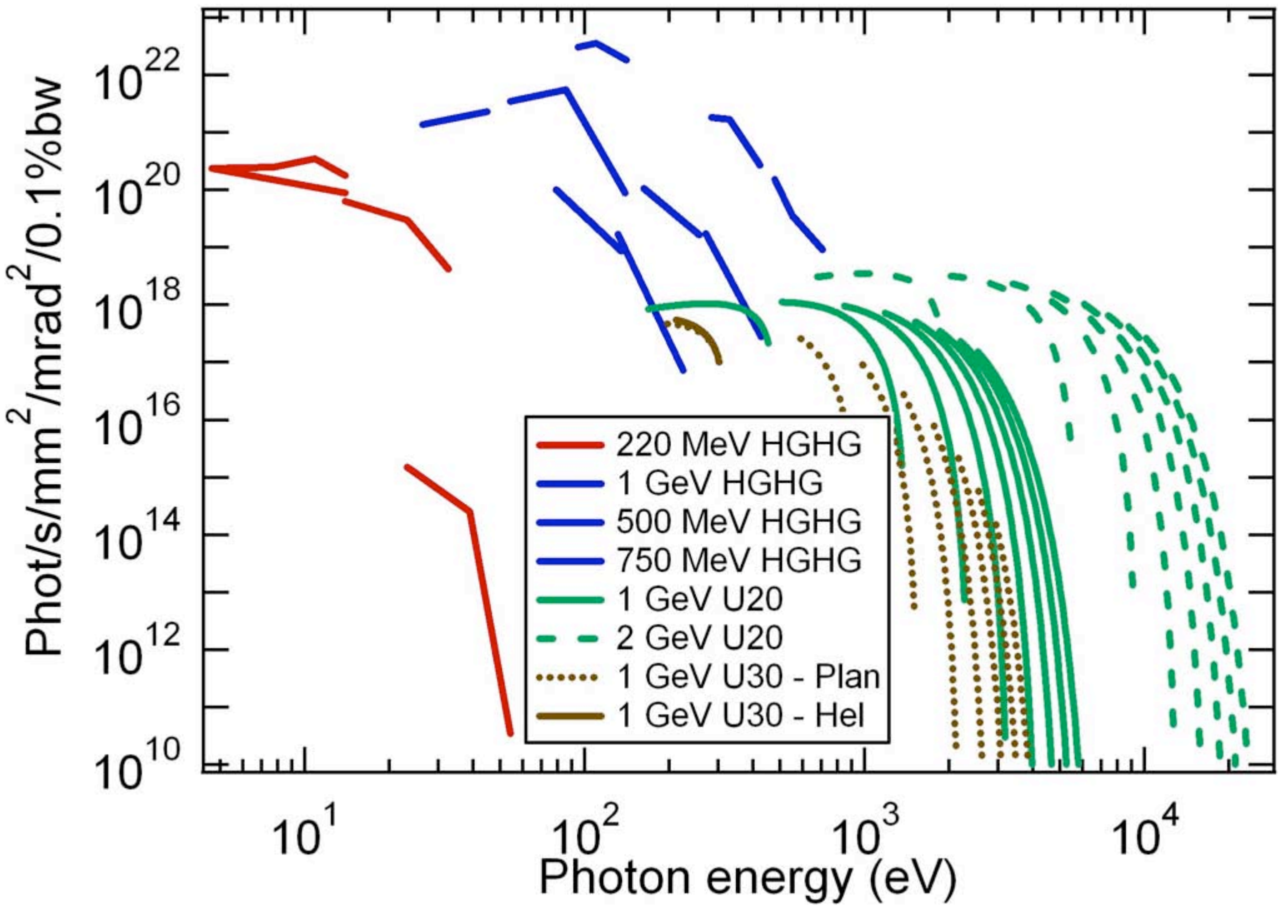
- demonstrate seeding with HHG (coll SCSS, SPARC),
- acquire expertise on seeding with a kHz Ti-Sa laser on a SRFEL odd/even harmonics, planar/ helical undulator (coll. UVSOR)
- modular approach for ARC-EN-CIEL

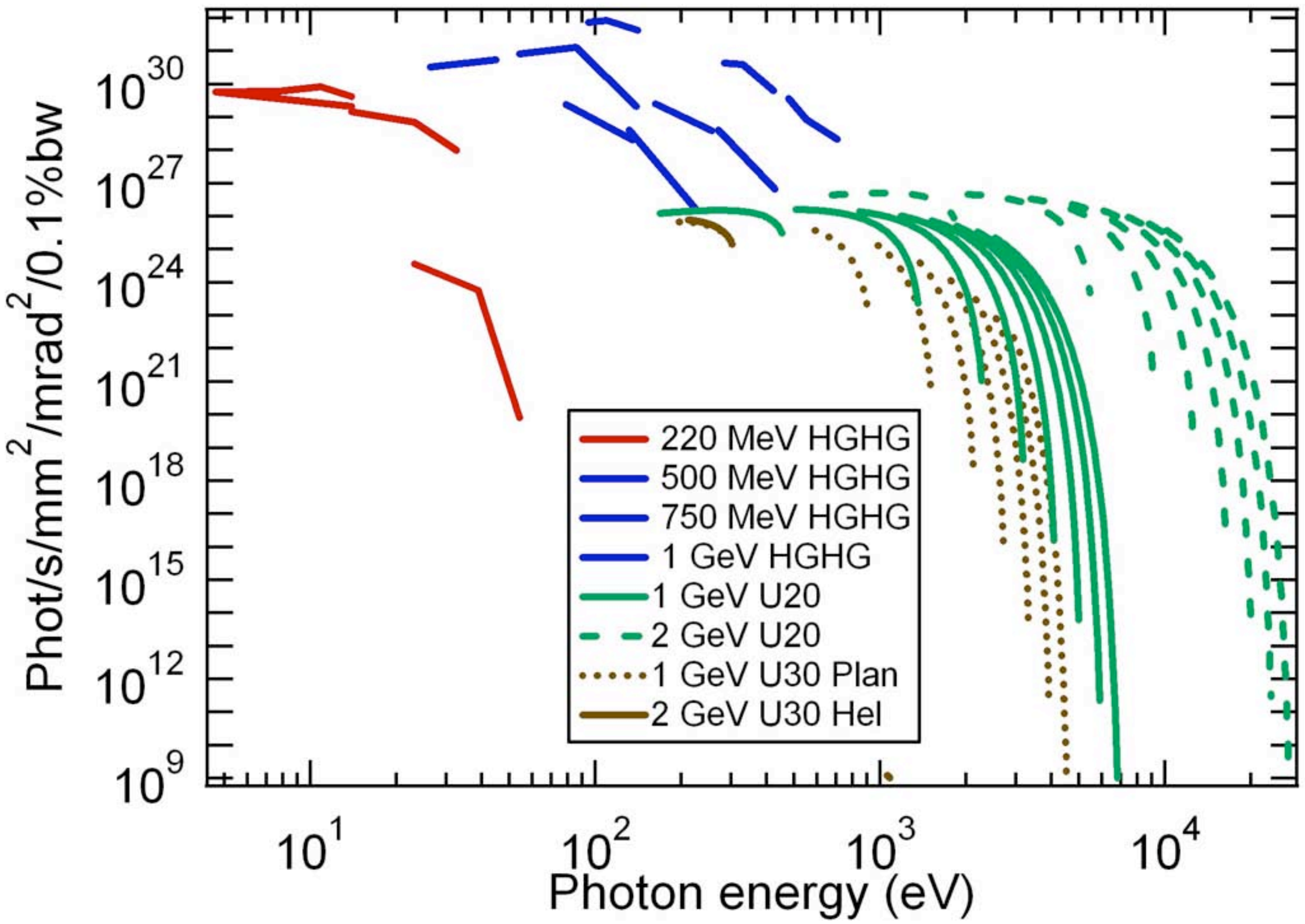
ARC-EN-CIEL

Accelerator Radiation Complex for ENhanced Coherent Intense Extended Light



ARC-EN-CIEL: BRILLANCE

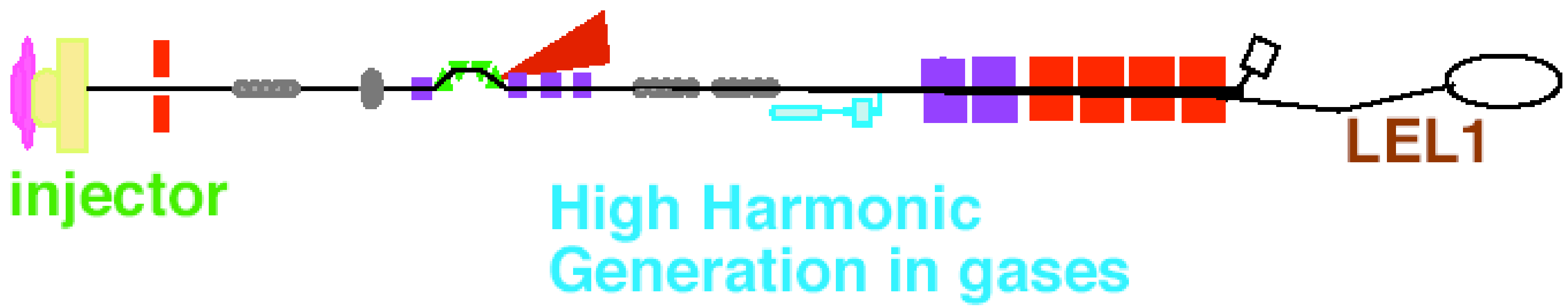




ARC-EN-CIEL PHASES

Phase 1 : 220 MeV,
LEL1, adjustable polarisation : 300-30 nm

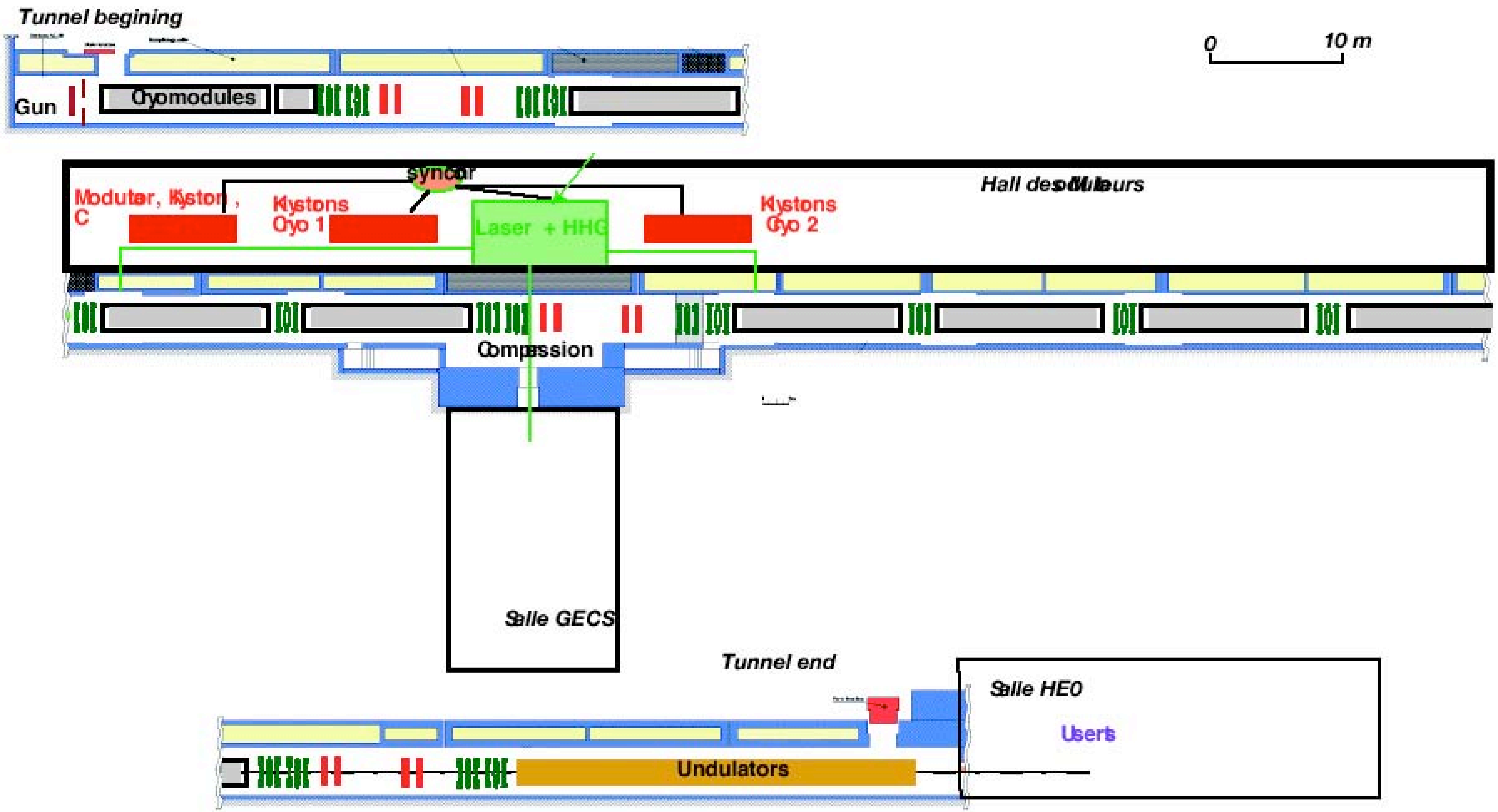
Modulator : U26, N1=200, Radiator : HU30, N2=700



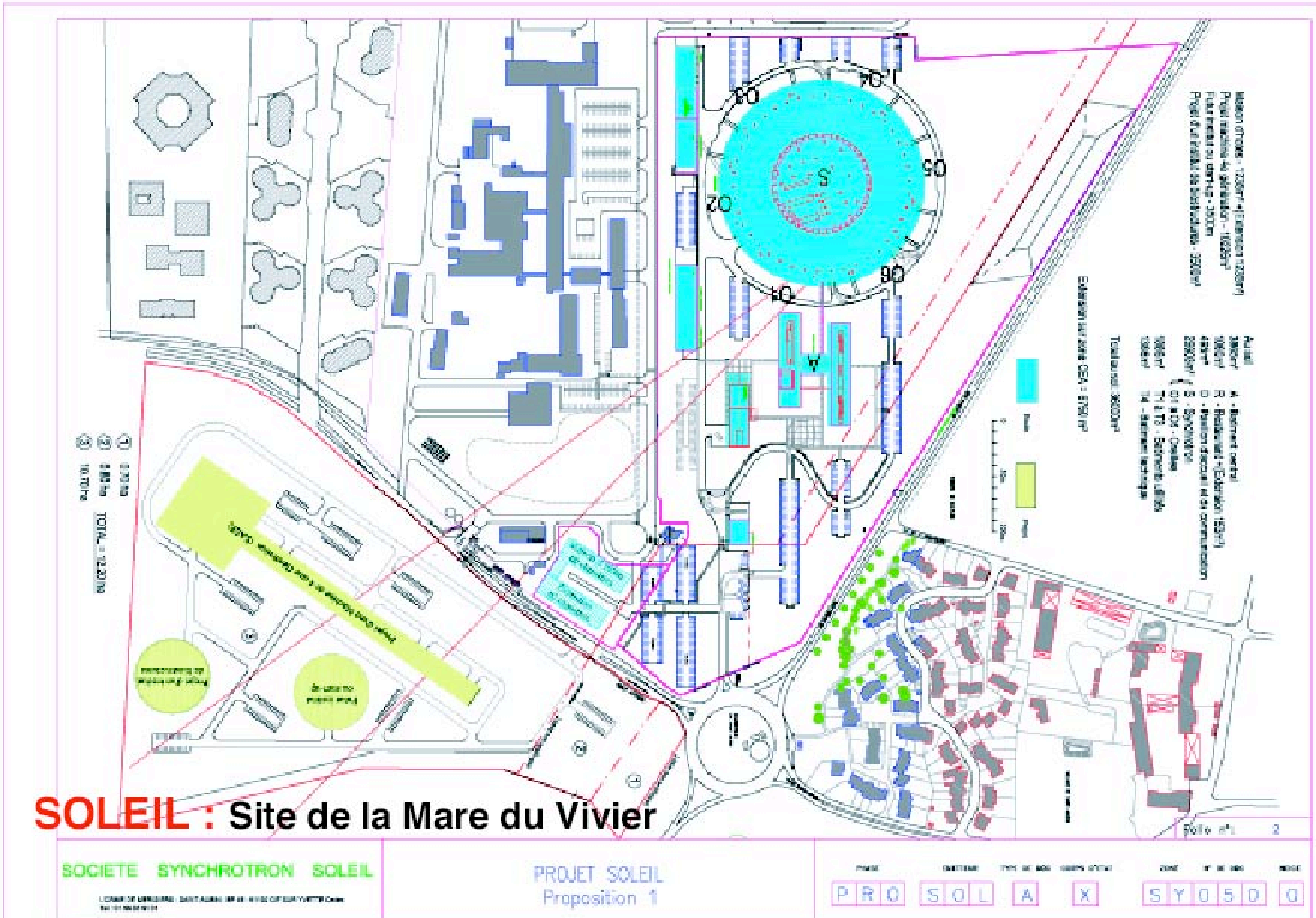
Phase 1' : 800 MeV, LEL1 : 300-3 nm

ARC-EN-CIEL PHASES

Phase 1' : 800 MeV, LEL1 : 300-3 nm



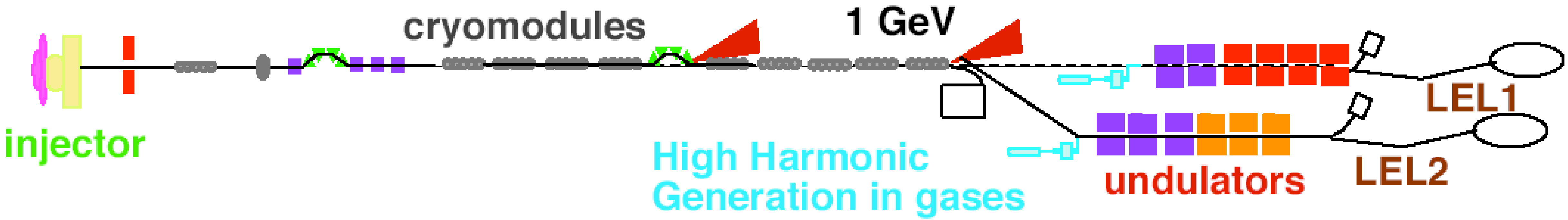
ARC-EN-CIEL PHASES



ARC-EN-CIEL PHASES

Phase 2 :

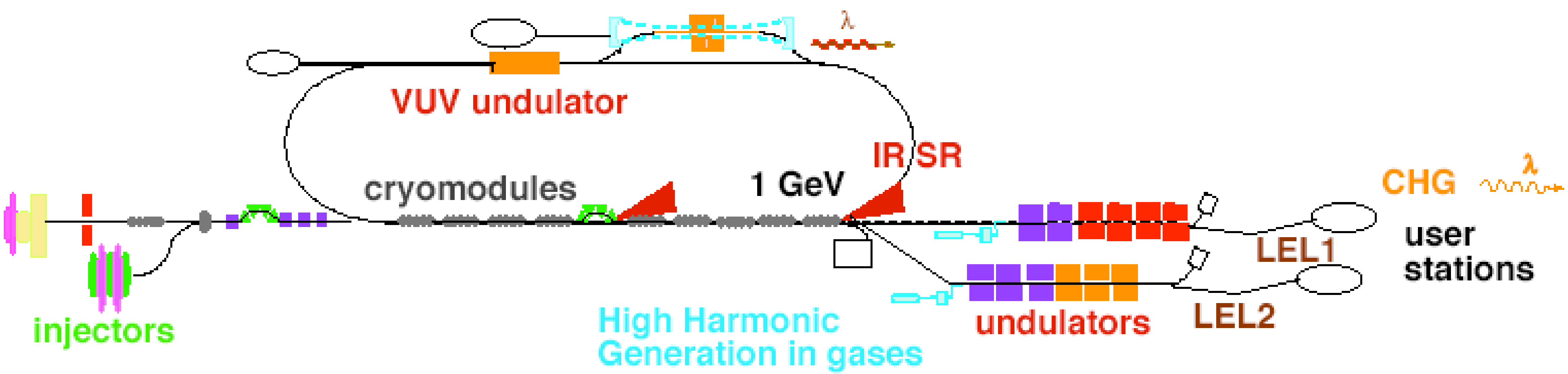
1 GeV, LEL1 : 200-1.5 nm, LEL2 planar pol. : 10-0.5 nm
low average current mode, high peak current operation



Modulator : U26, N1=500, Radiator : U18, N2=1000

ARC-EN-CIEL PHASES

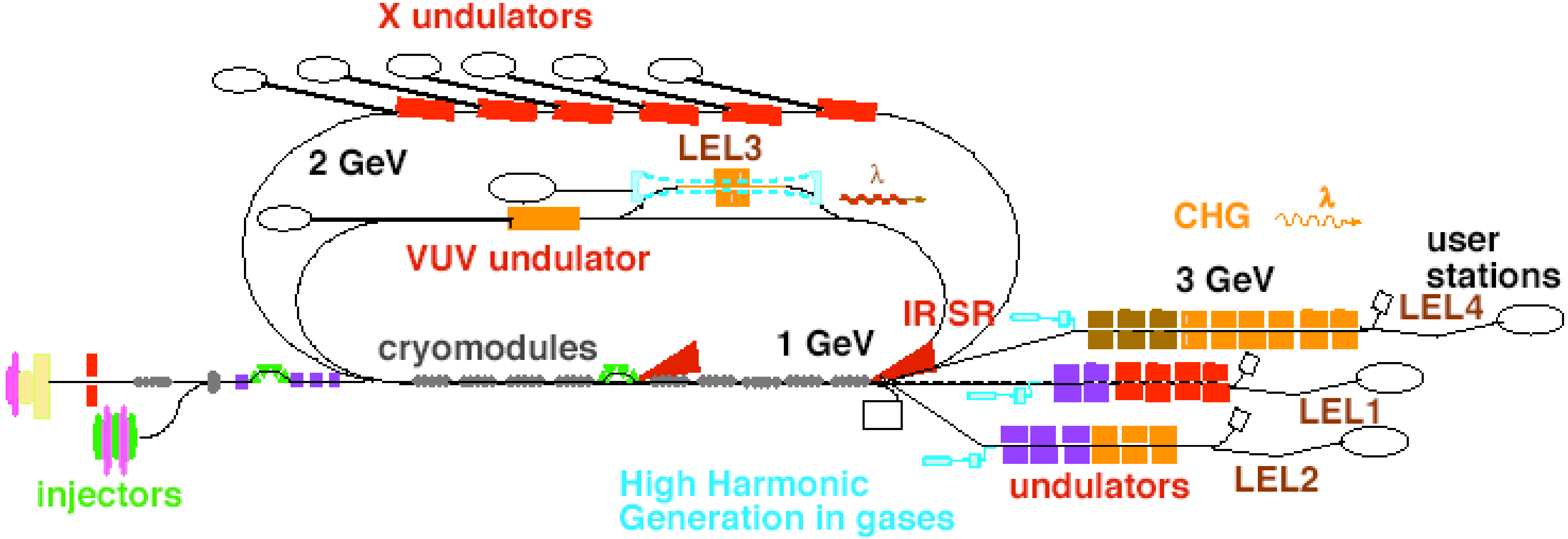
Phase 3B1 : low <I> mode : 1 GeV, LEL1 : 200-1.5 nm, LEL2: 10-0.5 nm
high <I> mode : 1 GeV, LEL3 planar to helical : 40-8 nm, HU30 spontaneous radiator



LEL3 : HU30, N1=350, SpontaneousRadiator : HU30

ARC-EN-CIEL PHASES

Phase 3B2 : low <I> mode : 1 GeV, LEL1 : 200-1.5 nm,
LEL2: 10-0.5 nm, LEL4 : 3 GeV, 2-0.2 nm
high <I> mode :
1 GeV, LEL3 : 40-8 nm, HU30 spontaneous radiator
2 GeV : 6 U20 spontaneous radiators

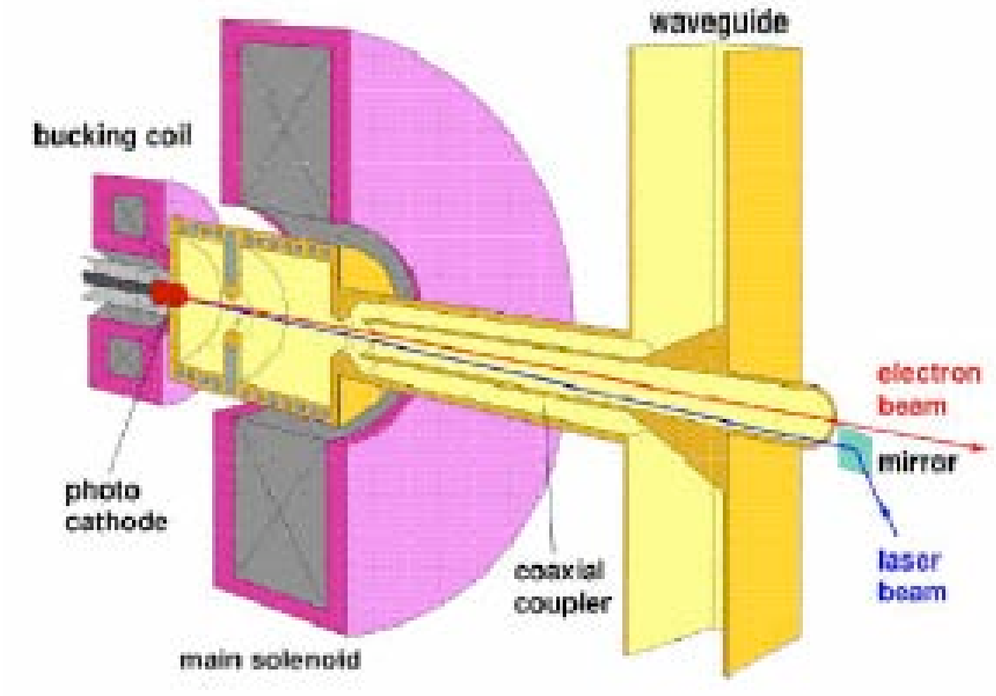


LEL4 : Modulator : U35 cryo, N1=700, Radiator : U18 cryo, N2=1000
Spontaneous radiators : U20

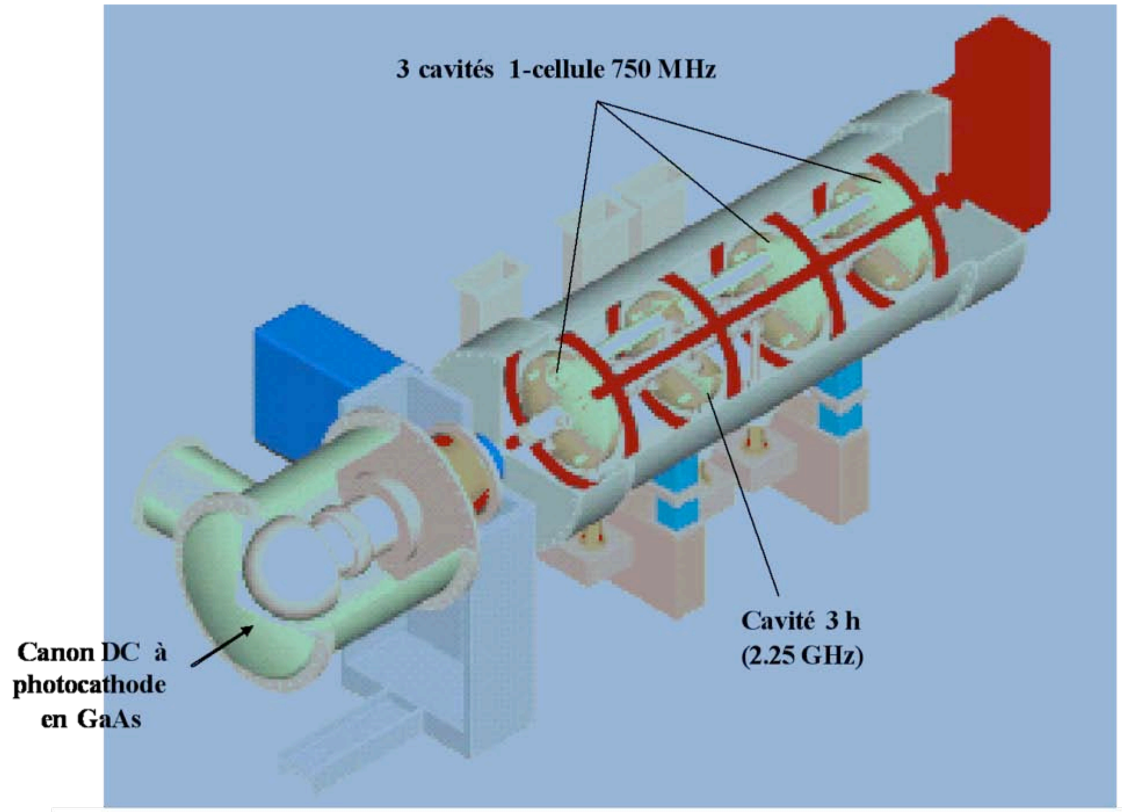
ARC-EN-CIEL: INJECTORS

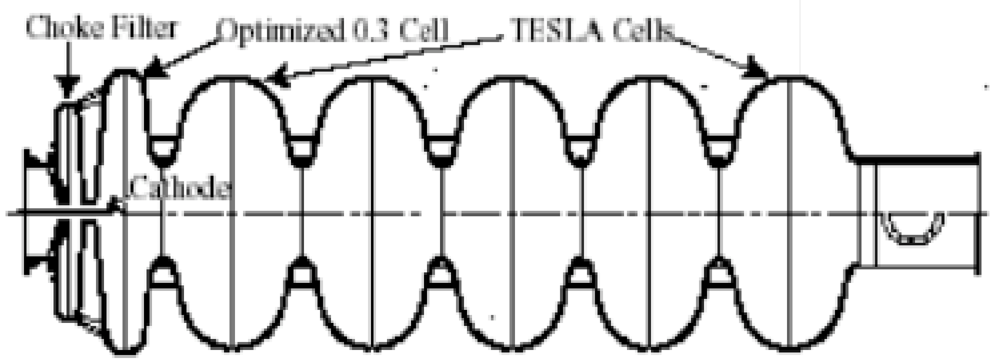
Low average current mode
<I>=1-10 μA, 1 nC, 1-10 kHz

High average current mode
<I>=1-100 mA, 1-1300 MHz, 0.1-1 nC



Modified Zeuthen type gun

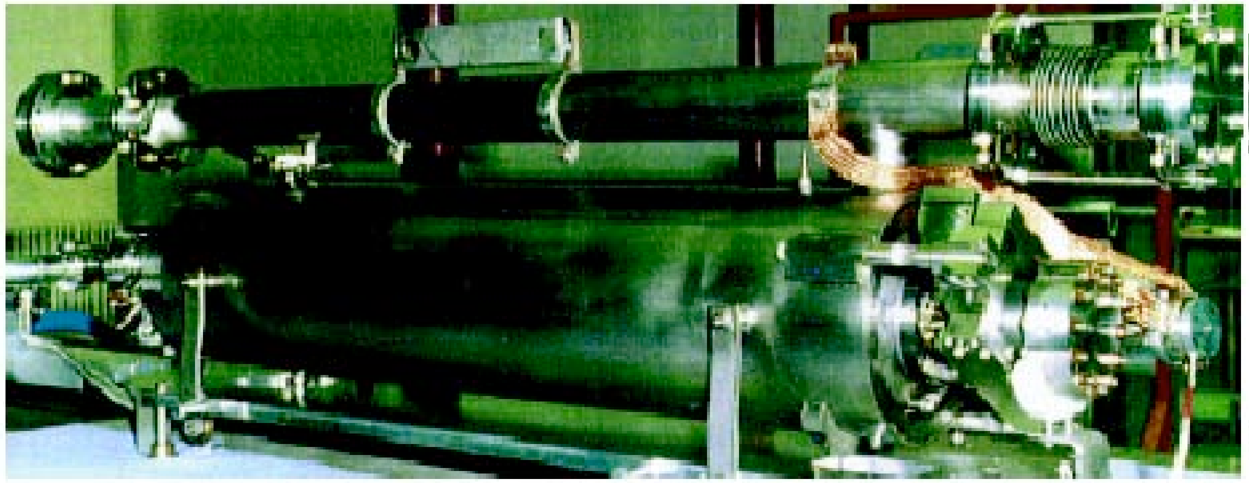




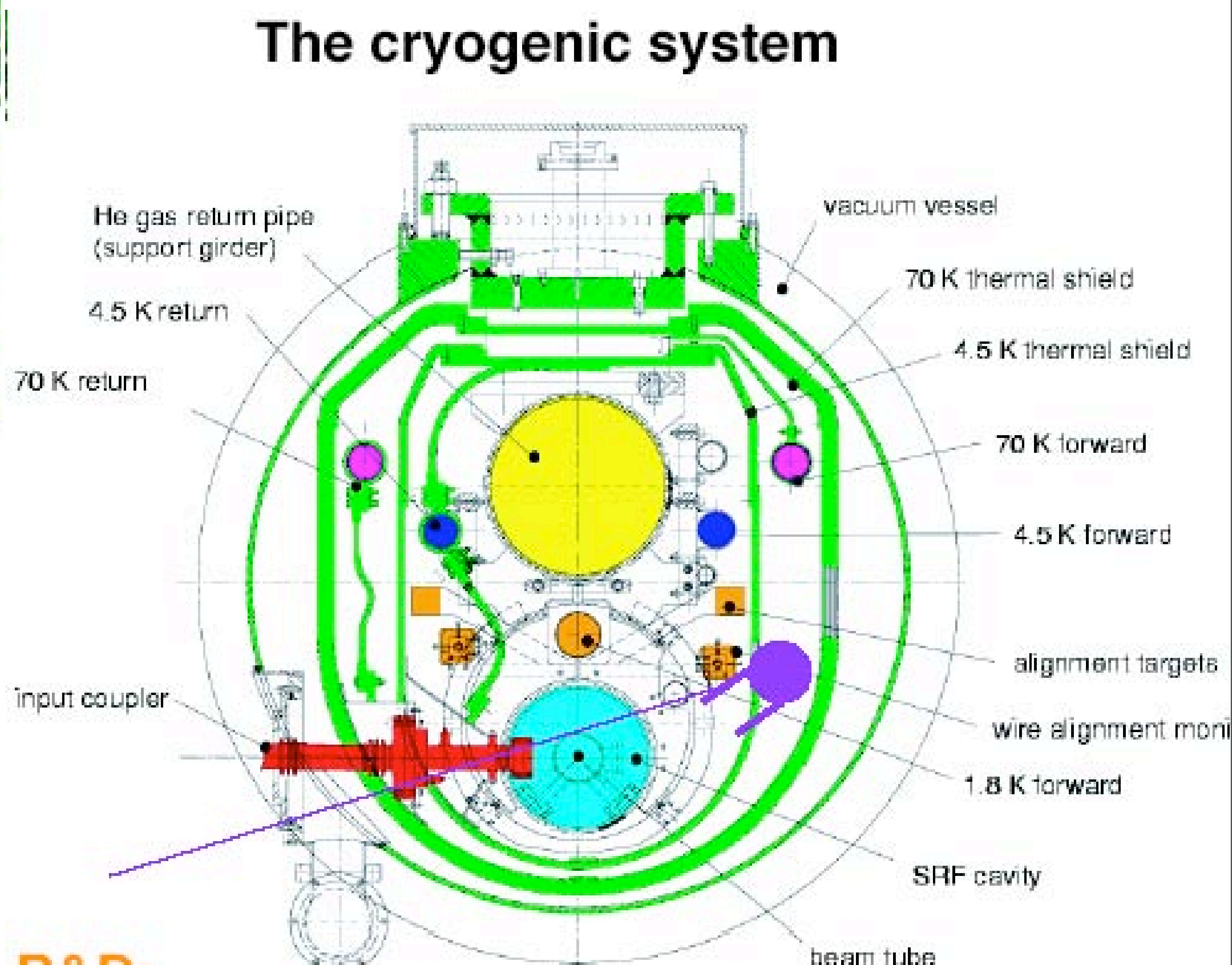
Superconducting gun(Rossendorf)

DC gun (500 kV) type Jlab/AES, GaAs photocathode
7 MeV booster cavity

ARC-EN-CIEL: LINAC



TESLA type,
10 cryomodules
7 cells
12.5 MV/cav, 16 MV/m
cryo consumption :
20 W/cav

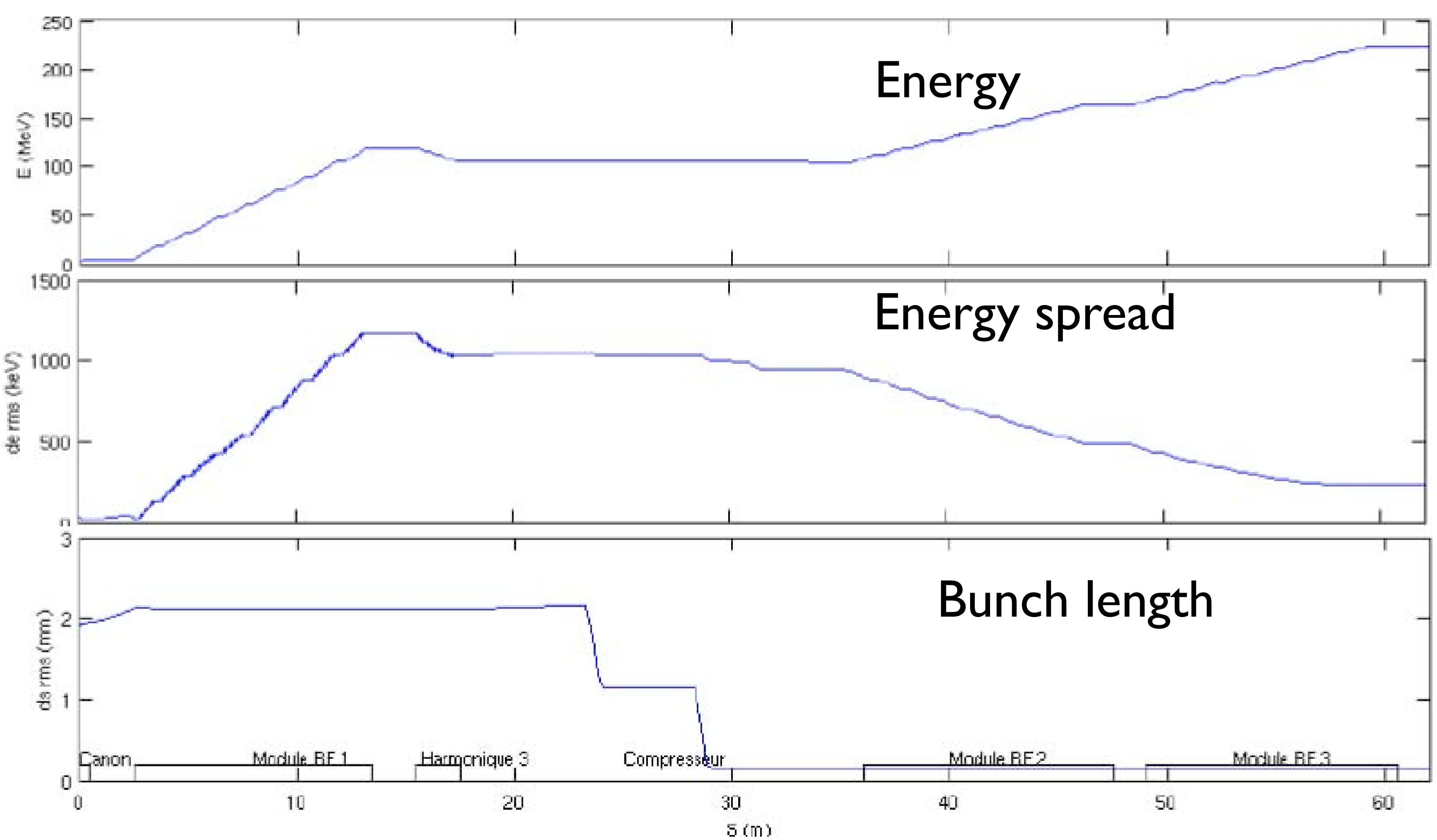


R&D:
- Superconductiong cavities in "cw"regime
- power couplers
- higher order modes couplers
- frequency tuning

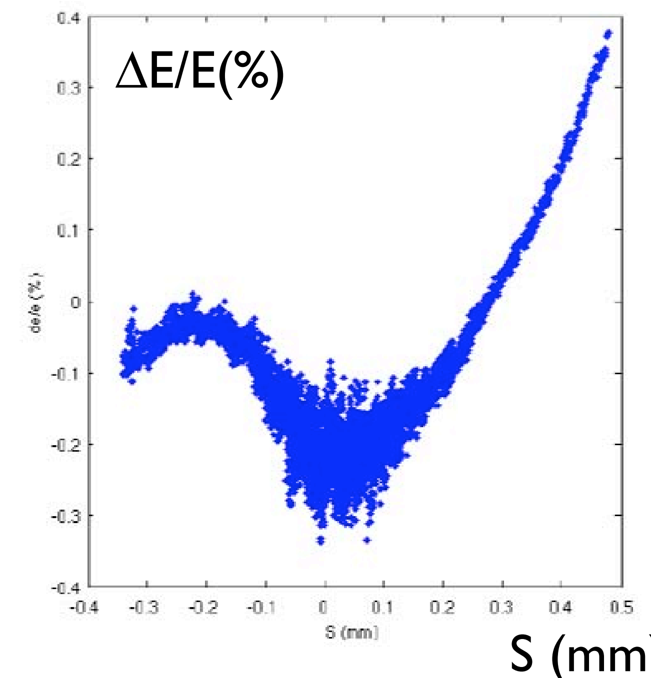
ARC-EN-CIEL: PRE-ACCÉLÉRATION

Laser : spatial and temporal shape
Gun : space charge, RF curvature, emittance compensation, thermal emittance
Cavities : wakefield, RF curvature
Compressor : CRS, optical aberrations

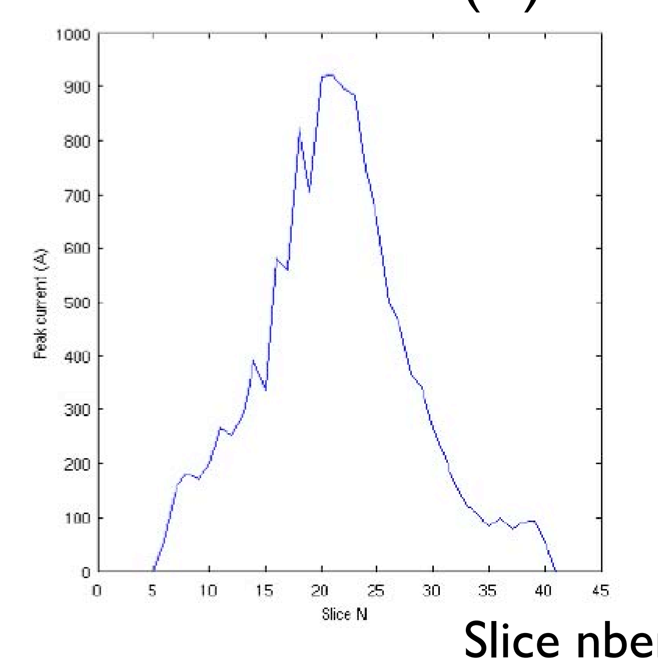
phase 1 : peak current 800 A, slice energy spread : 0.05%, emittance at centre : 1.4 π rms µm.rad, pulse duration 300 µm (600 fs RMS)



Phase space

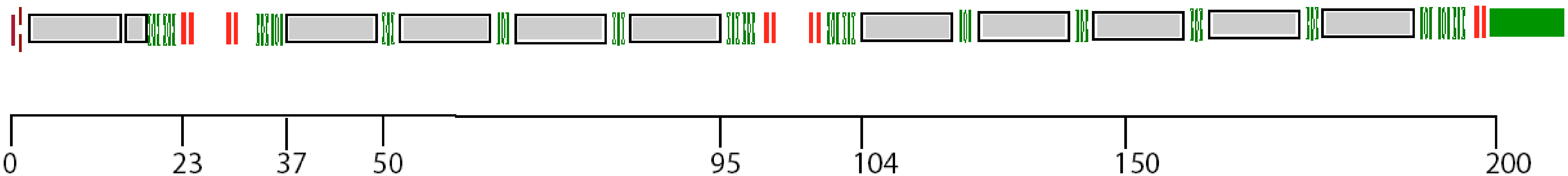


Peak current (A)

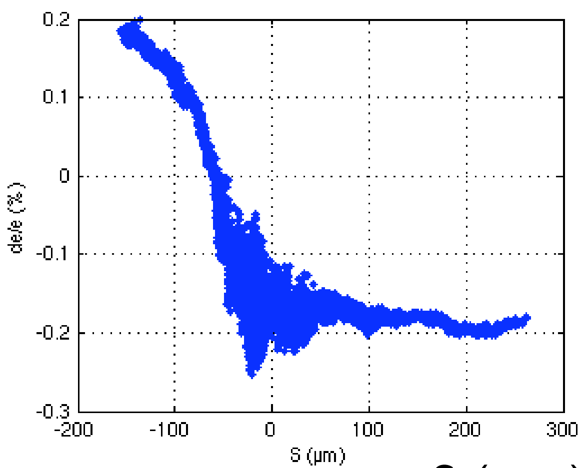


ARC-EN-CIEL: BEAM DYNAMICS

Example : ARC-EN-CIEL Phase 2, 10 cryomodules

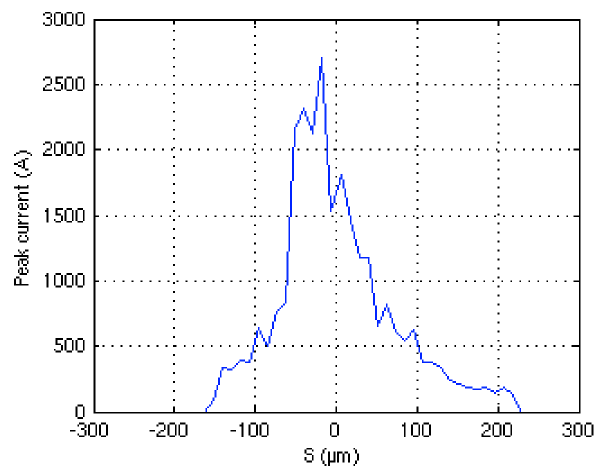


ΔE/E(%)



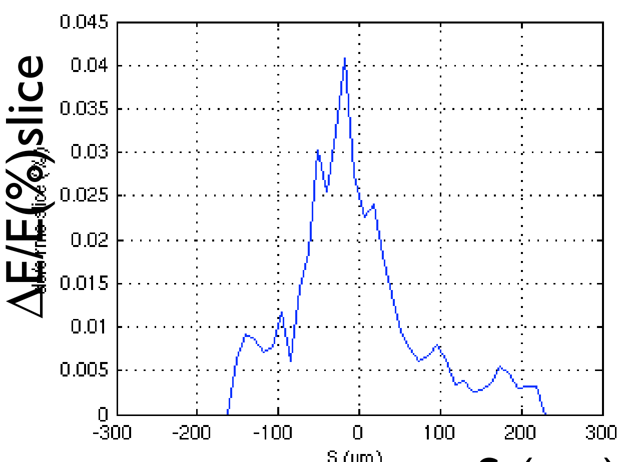
S (mm)

Ip (A)



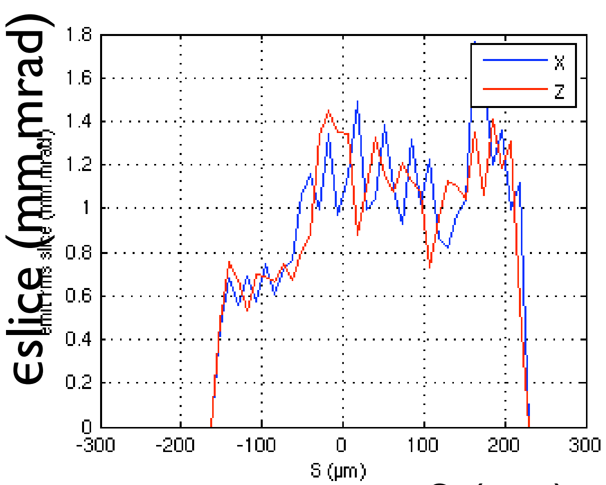
Slice nber

ΔE/E(%)slice

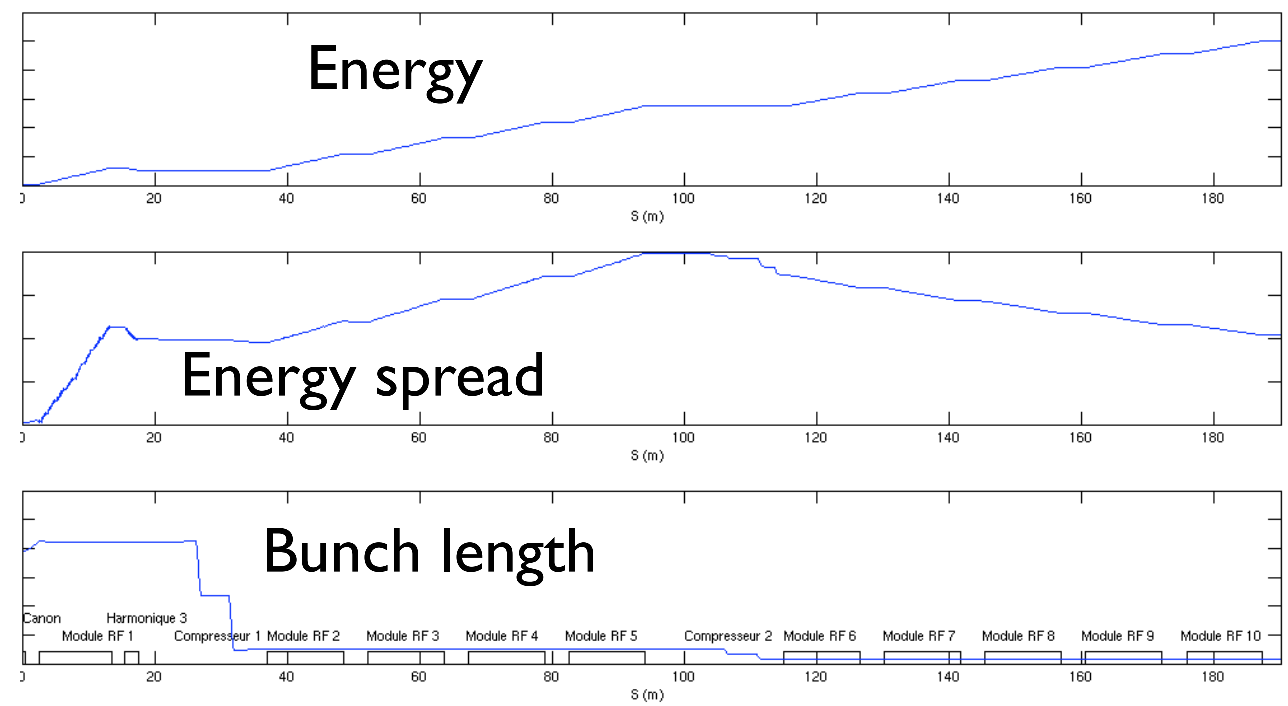


S (μm)

εslice (mm.mrad)



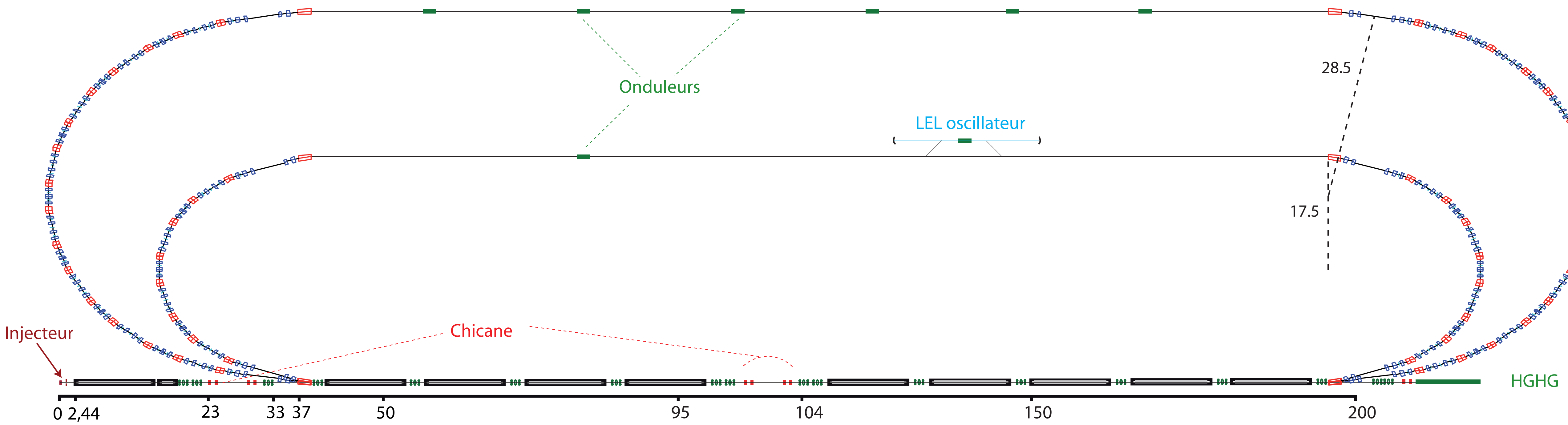
S (μm)



peak current 2000 A, slice energy spread : 0.04%, emittance : 1.2 π rms μm.rad, pulse duration 50 μm (170 fs RMS)

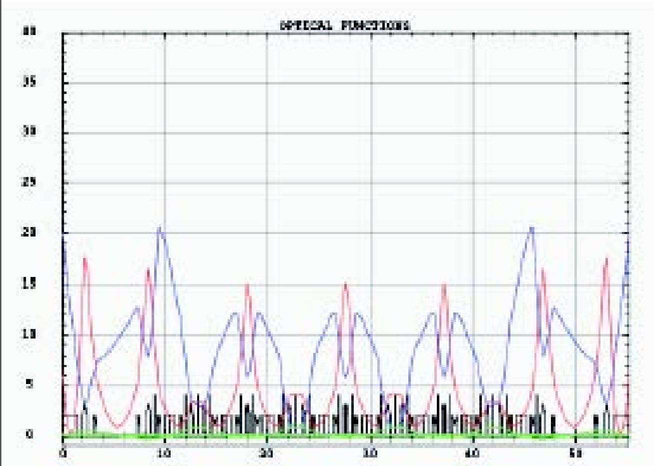
ARC-EN-CIEL: BEAM DYNAMICS

ARC-EN-CIEL Phase 3, ERL loops at 1 and 2 GeV

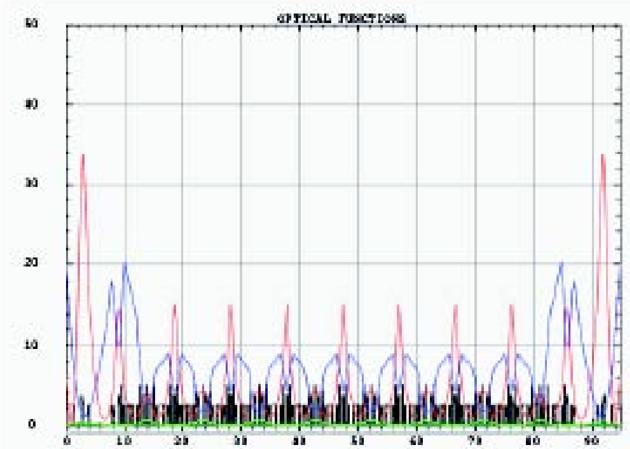


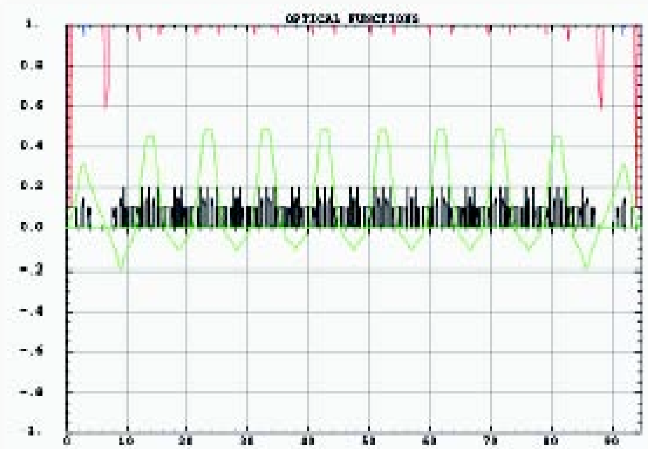
ARC-EN-CIEL: BEAM DYNAMICS

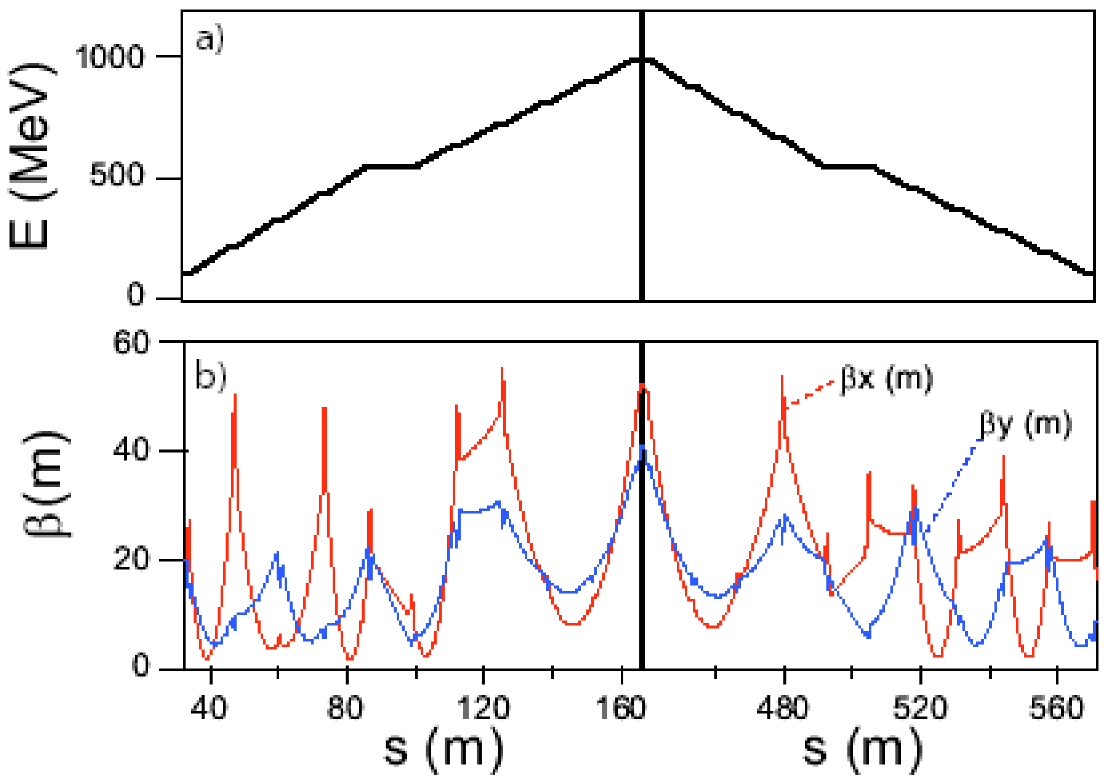
Exemple : ARC-EN-CIEL Phase 3, Loops

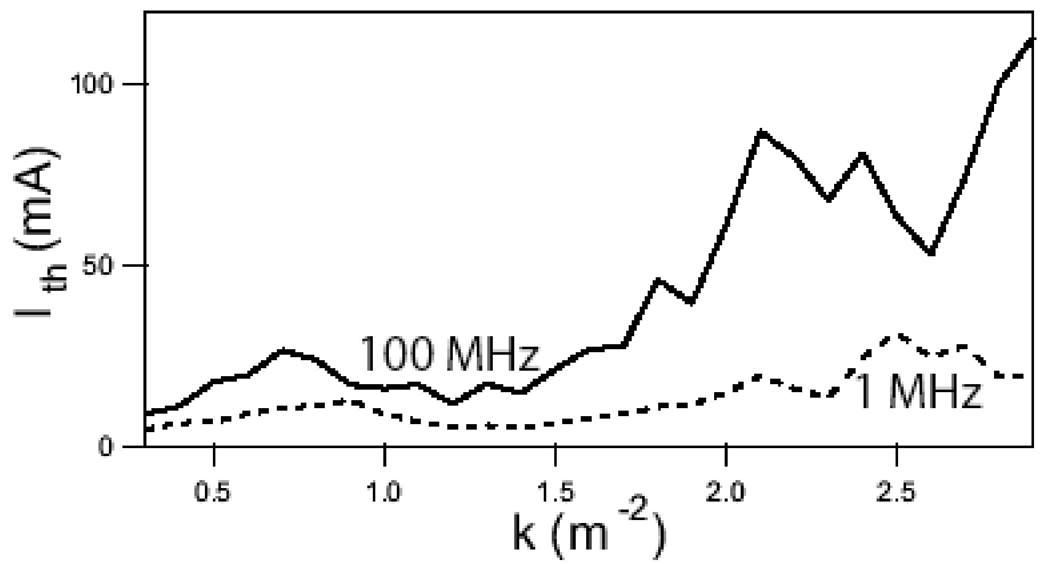

1 GeV, beta function


1 GeV, dispersion


2 GeV, beta function


2 GeV, dispersion





Threshold versus the strength of the quadrupoles

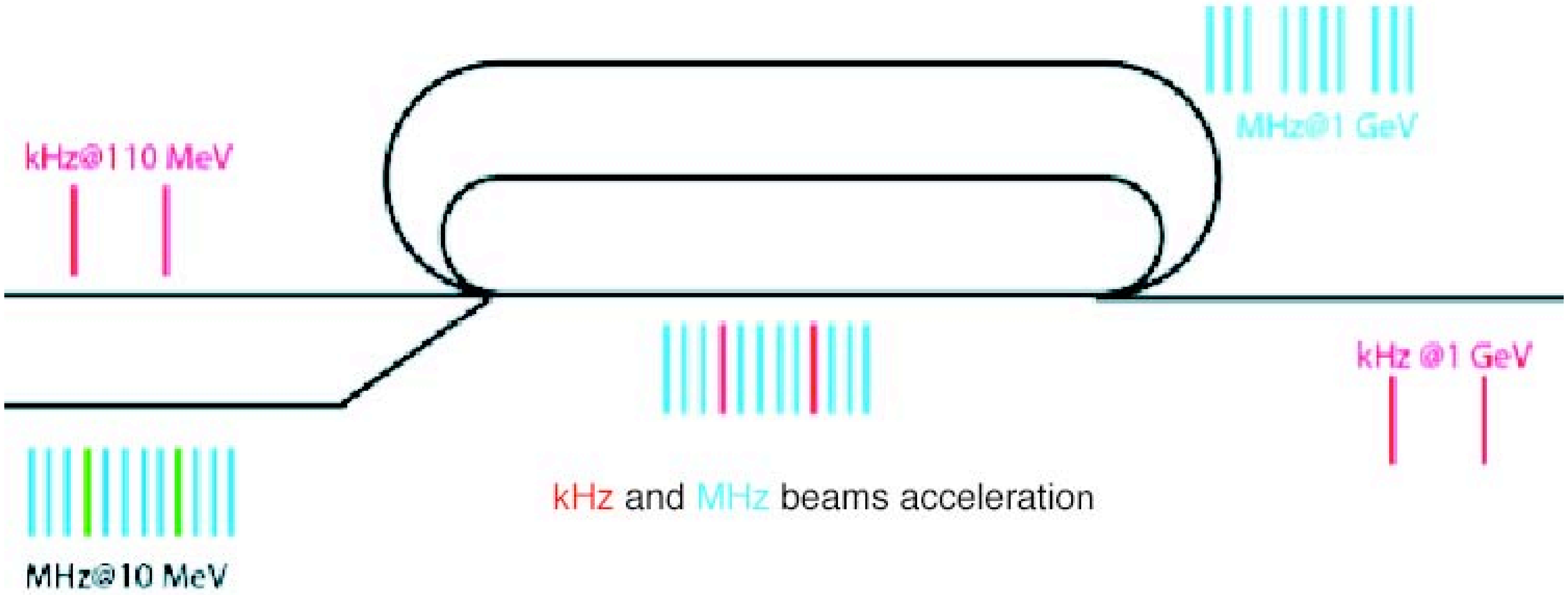
Threshold current (BBU) = 54.4 mA@1MHz

ARC-EN-CIEL: BEAM PARAMETERS

Phase	1	2	3, mode 1	3, mode 2	3
Energy (Gev)	0.2	1	1-2	1-2	3
Rep. rate (kHz)	1-10	1-10	10^3 – 10^5	10^3 – 10^5	1
Charge (nC)	1	1	0.2//1	0.2//1	0.75
ΔT(fs rms)	500-600	200-300	500-600	500-600	200
<I> (μA)	1-10	1-10	10^3-10^5	10^3-10^5	
I_{peak} (kA)	0.8	1.5	0.2	1	
$I_{peak,slice}$(kA)	1	2	1	1	1.5
ε_{tot}(π mm mrad)	2.4	1.6	2	6	
ε_{slice} (π mm mrad)	1	1.2	1	5	1.2
$\sigma_\gamma/\gamma_{tot}$ (%rms)	0.1	0.1	0.1	0.2	
$\sigma_\gamma/\gamma_{slice}$ (%rms)	0.04	0.04	0.04	0.08	0.02

ARC-EN-CIEL: OPERATION MODES

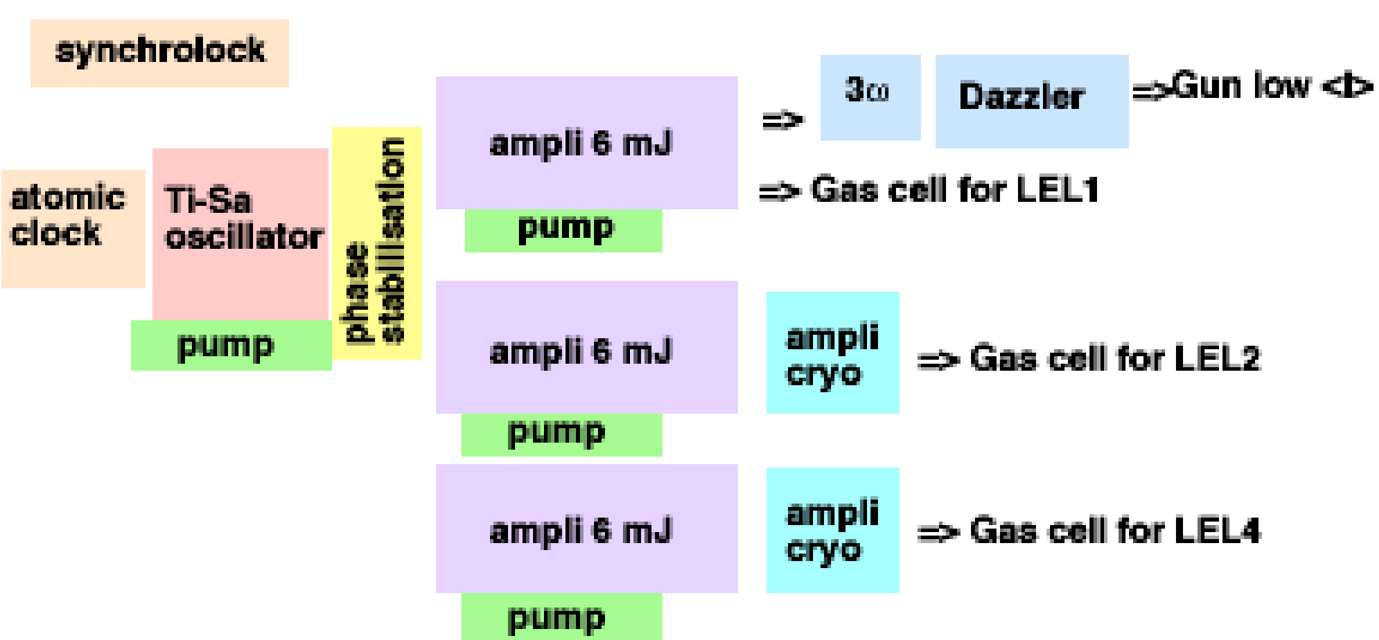
Operation with different beams from the two guns



ARC-EN-CIEL: LASER SYSTEM

Laser for gun 1 and LEL1, LEL2 and LEL4:

• Ti-Sa laser
• Er-crsytal oscillator
• post-shaphing with a UV DAZZLER (Faslite)
• UV regenerative amplifier (Ce:LICAF)



Laser for gun 2:

• Er-fiber oscillator

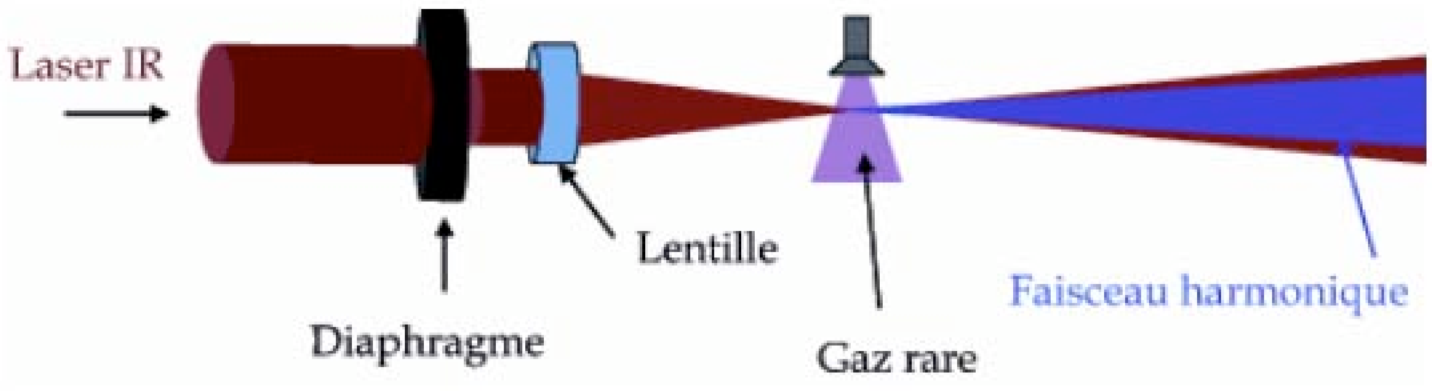
ex FCPA μJEWEL D-400
IMRA Americavaraible rep rate
1045 nm
400 mW average power
rep. rate 0.5 MHz

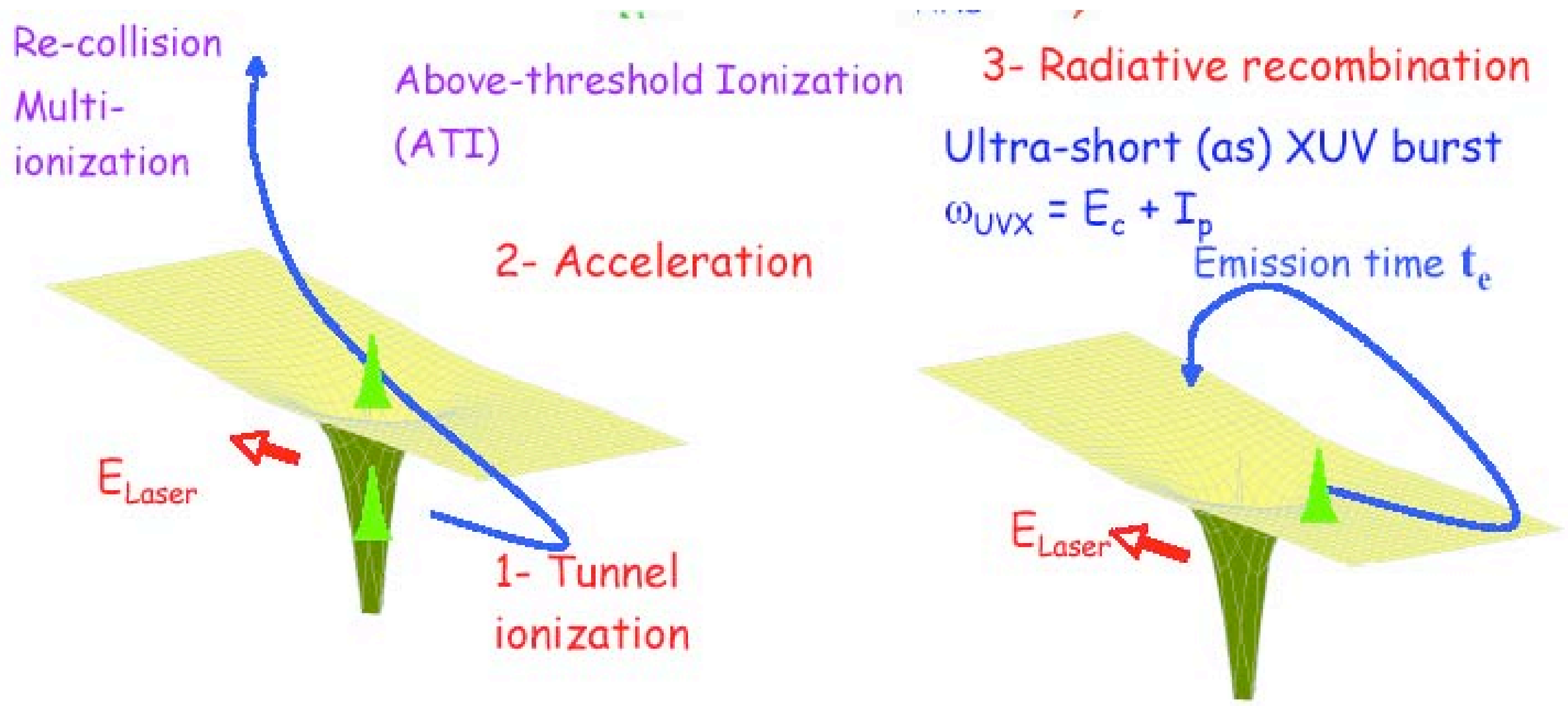
Lab. activity
Phlam
Institut d'Optique (RTRA)

Timing:

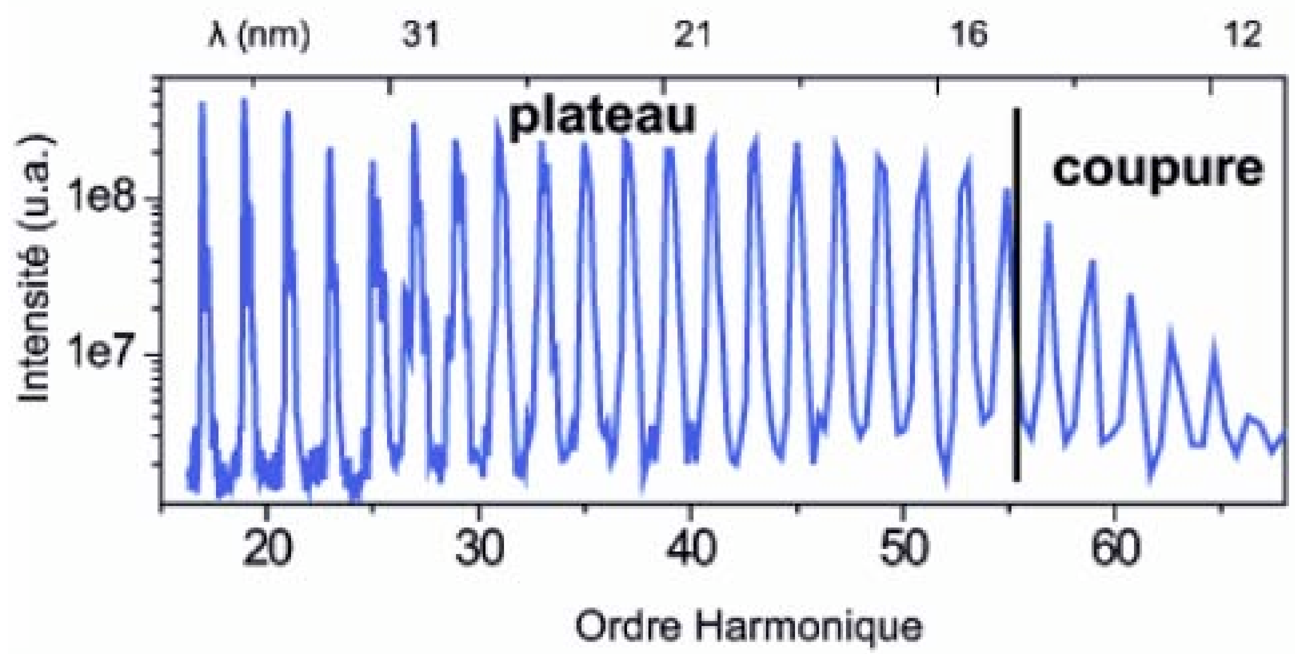
• atomic clock
• transfer of fs timing via fibers

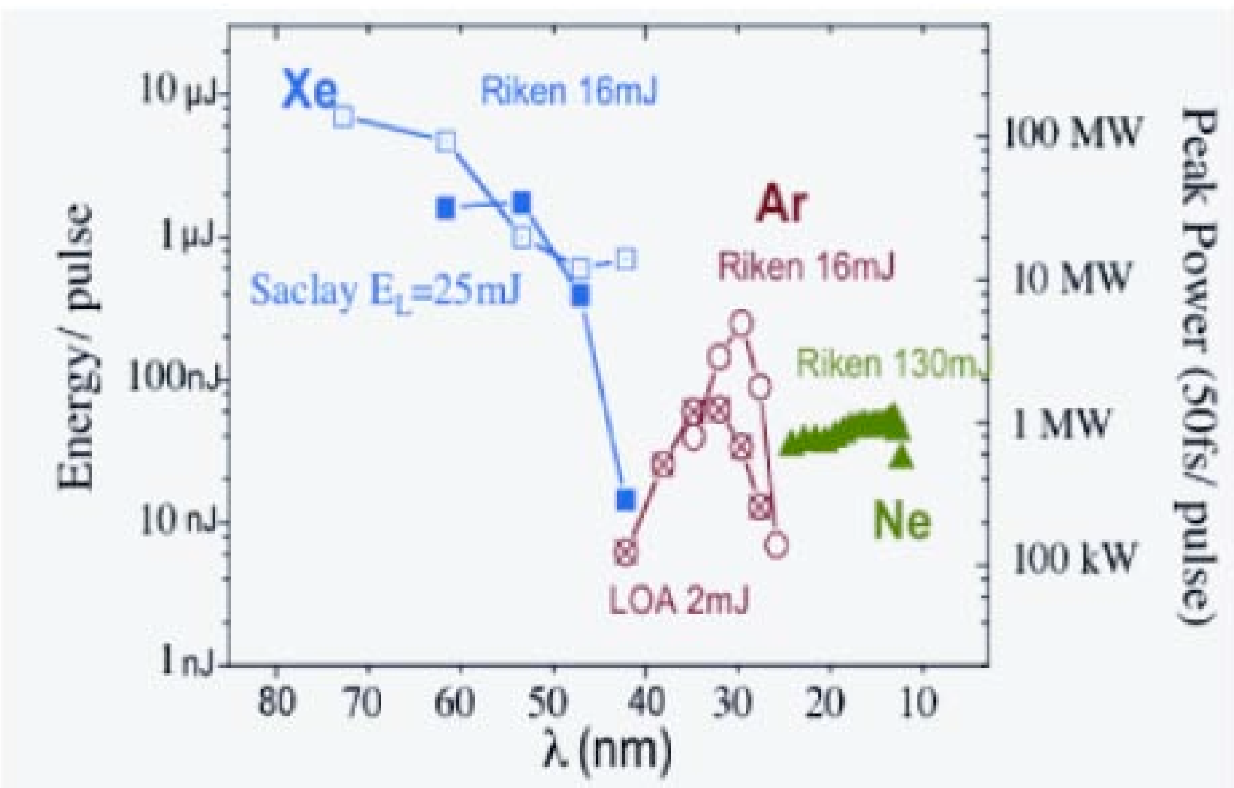
ARC-EN-CIEL: INJECTION WITH HHG

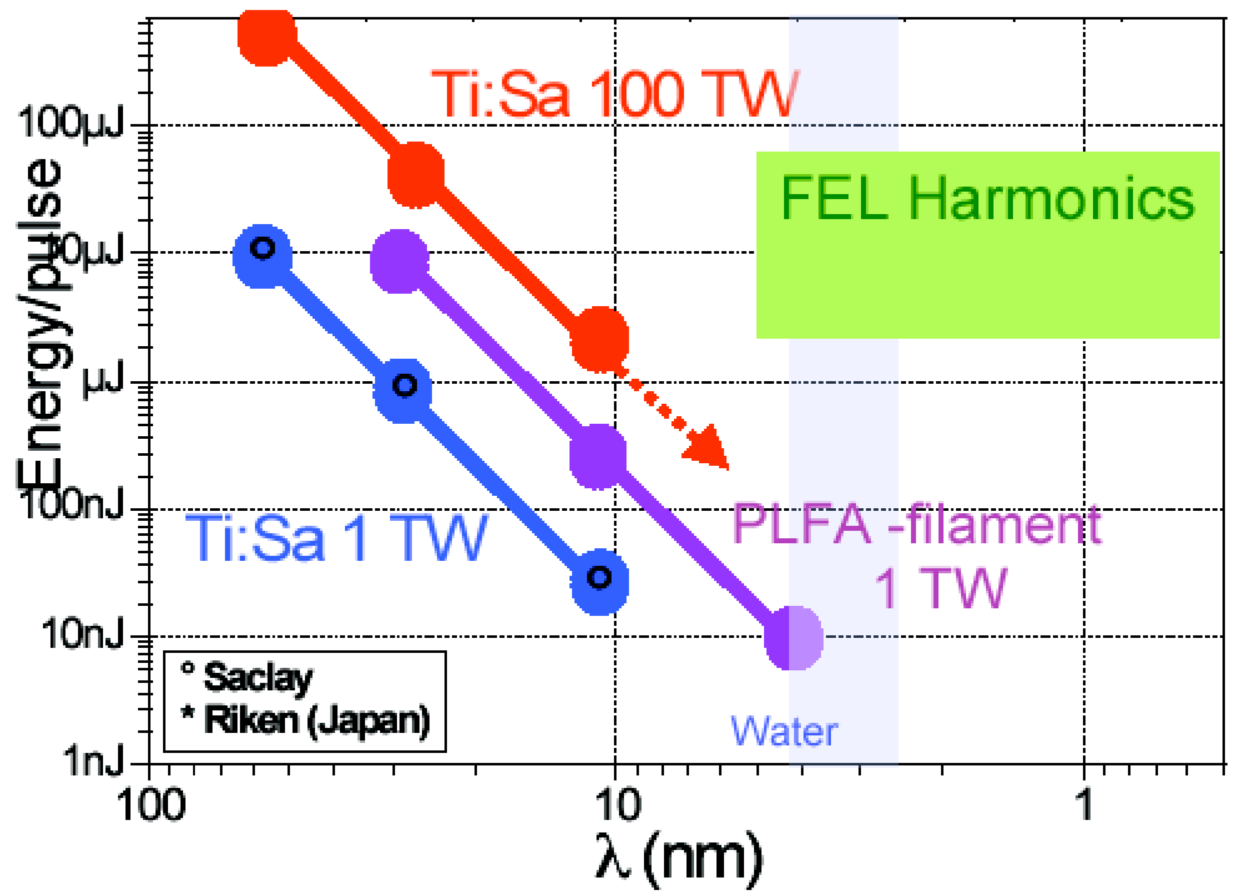




ARC-EN-CIEL: INJECTION WITH HHG







HHG : SPECTRAL RANGE

To the water window :

Ionization potential : atoms (Ne I_p=21.6 eV, He I_p=24.6 eV), => ions

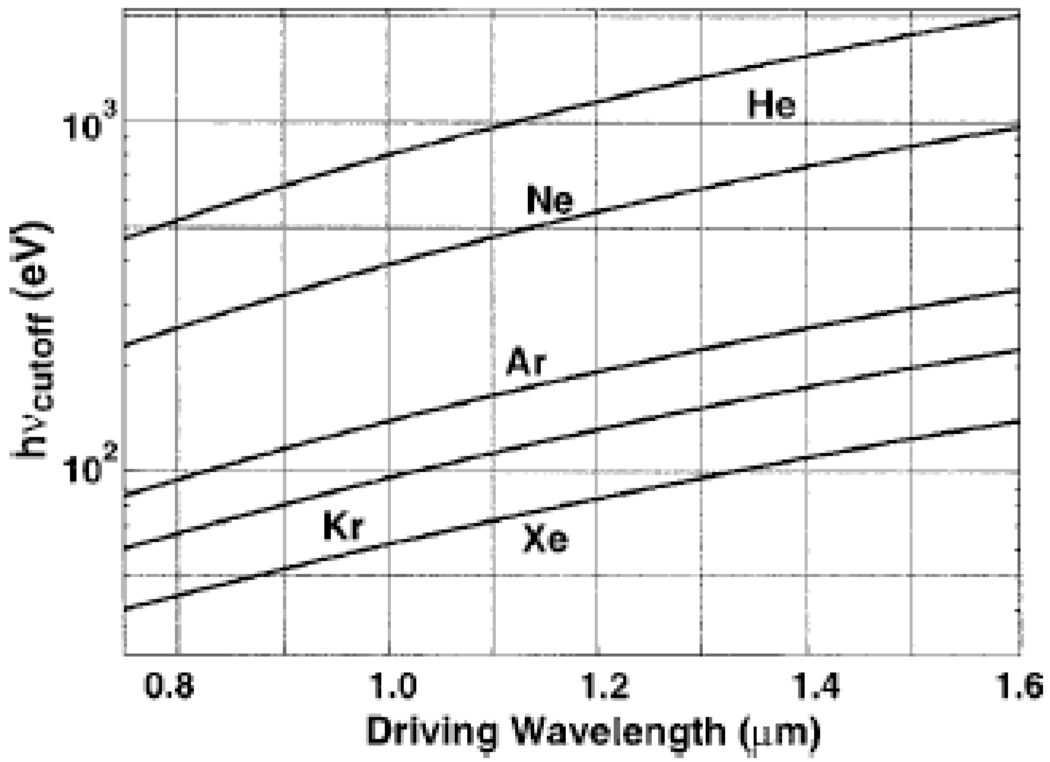
longer wavelength

$$h\nu_{cutoff} = I_p + \frac{0.5 I_p^{3+a}\lambda^2}{\left[\ln \frac{0.86\Delta t\, 3^{2n^*-1} G_{lm} C^2_{n^* l^*} I_p}{-\ln(1-p)}\right]^2}$$

short pulses (5-7 fs: approching the one cycle limit)

l,m orbital and magnetic quantum nber
p ionisation probablility
n* effective principal quantum number

B. Shang et al, PRA 65, 2001, 011804



Z. Chang et al, PRL 79, 1997, 2967
Gibson, Science, 2003. Seres et al, Nature 2005

Water window (Ti:Sa 26 fs, 2.7 nm (460 eV) He, 5.2 nm (239 eV) Ne)

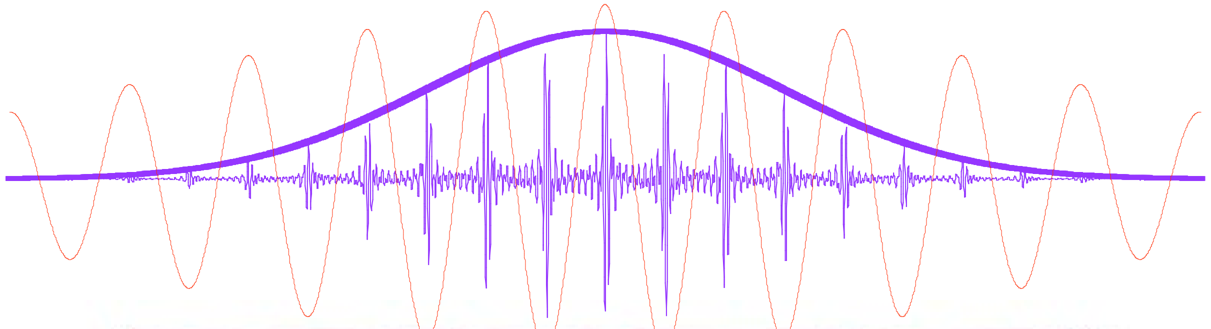
Tuneability :

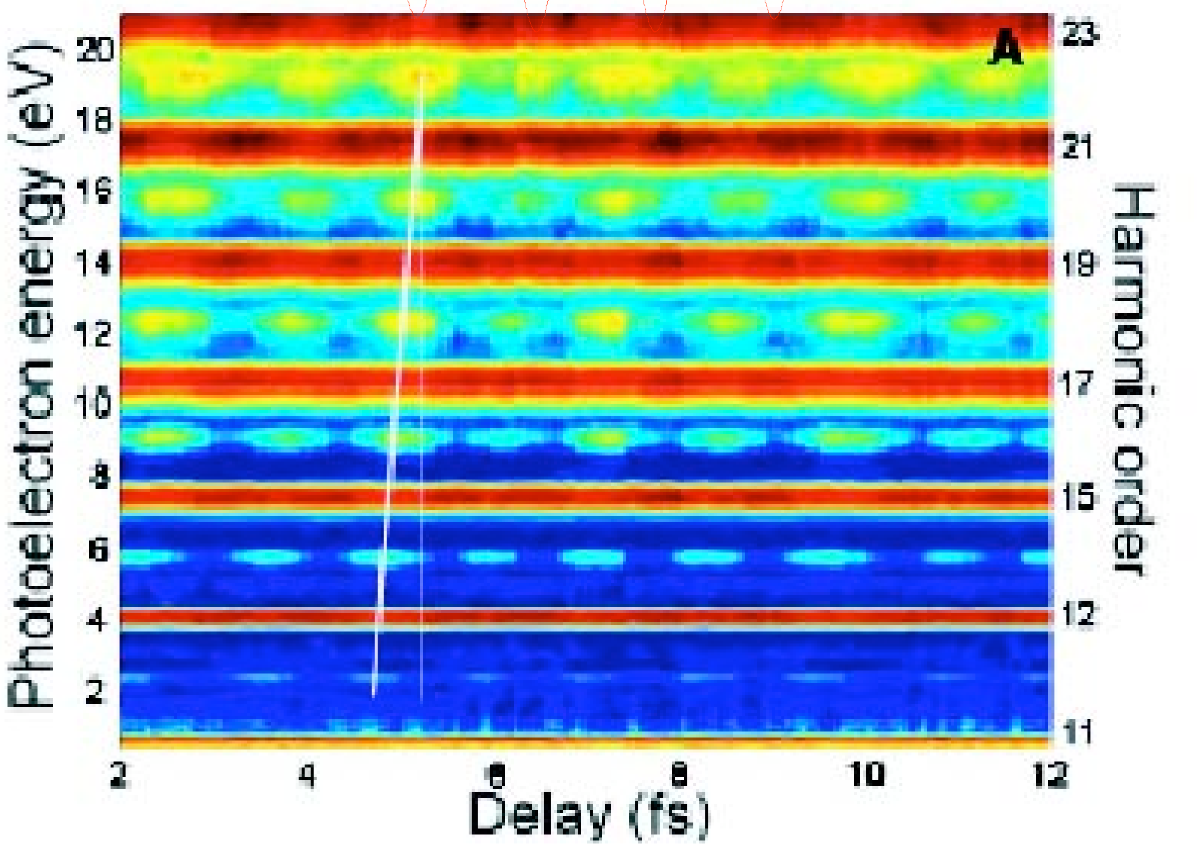
- **Tuning the laser wavelength:**
  - **Ti-Sa tuneability : Δλ/λ=1-0.1%**
  - **Full tunability from 220 nm to 8 nm with 1.1 to 1.6 µm pump (Ti:Sa + OPA)**
  - *Chang et al..Phys. Rev. A 65 (2001)011804*
- **frequency mixing Generating with w_1 fixed and w_2 tunable:**
  - **~70% tunability from 180 to 18 nm with Ti:Sa + OPG** *Gaarde et al., J. Phys B 29, L163 (1996)*
- **Adjusting the laser energy and chirp** ***Kim et al., PRA 67 (2003)***

HHG TEMPORAL COHERENCE

Temporal structure :

as structure in fs envelop

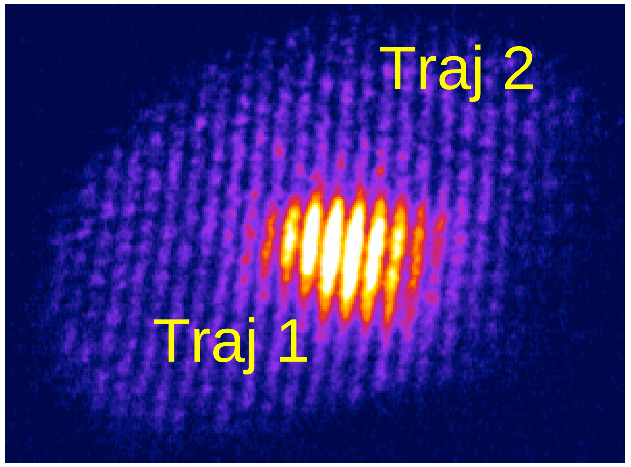




Y. Mairesse et al, Science 302, 1540
Sola et al., Nature Physics (2006)
Baltuska et al Nature 421 (2003)

Spectral domain:

as : harmonic train
fs : single harmonic
quadratic phase

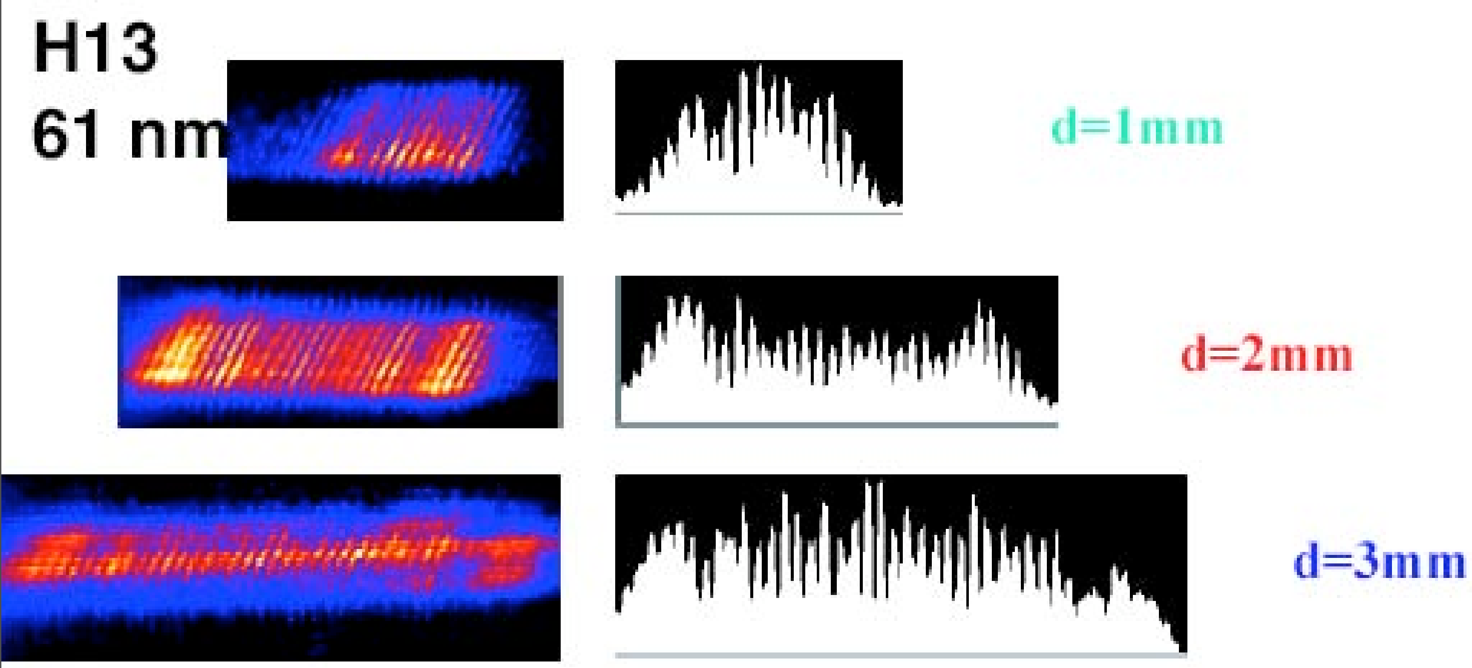


H17 (47 nm)
With 60 fs-1 mJ IR pulse
in Argon

Merdji et al., Phys. Rev. A 74 (2006)

HHG TRANSVERSE COHERENCE

Fresnel bi interferometer

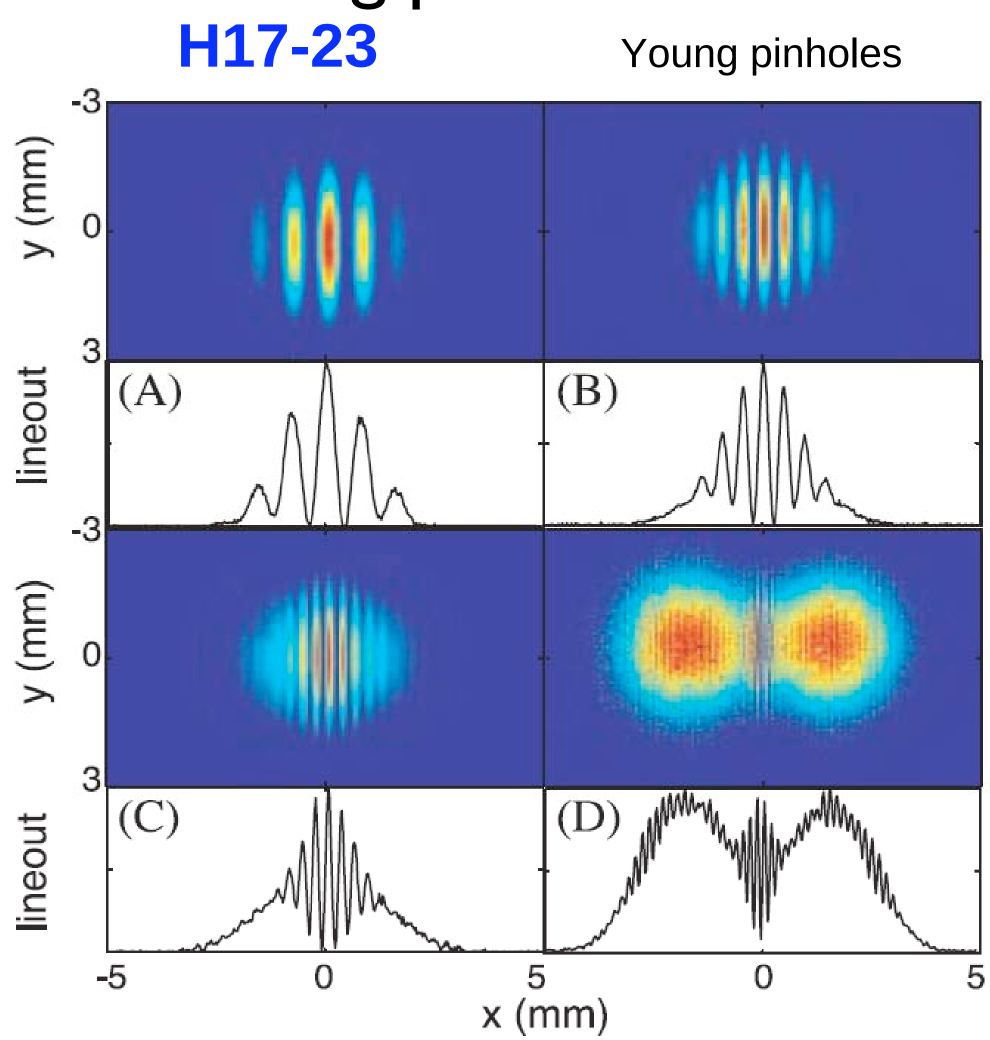


Le Déroff et al., PRA61 (2000) 043802

Ne, 13.5 nm, 25 nJ, DV=0.35 mrad
He, 8.9 nm, 1 nJ, DV=0.3 mrad

E.J.Takahashi et al.,Apply. Phys. Lett 84, 4 (2004)
Opt. Lett. 27, 2000, 1920
Phys. Rev A 68, 2003, 023808
Y.Tamaki et al, JJAP 40, 2001, L1154

Young pineholes



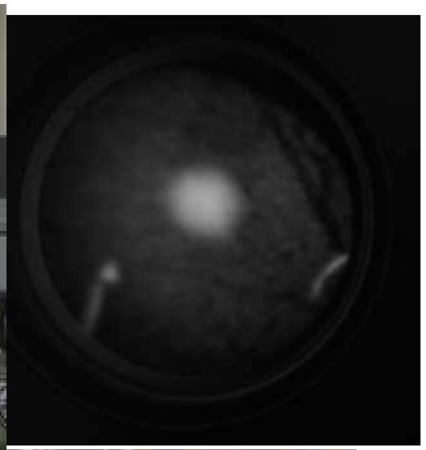
Bartels et al., Science 297,376 (2002)

$1.2 < M^2 < 4$

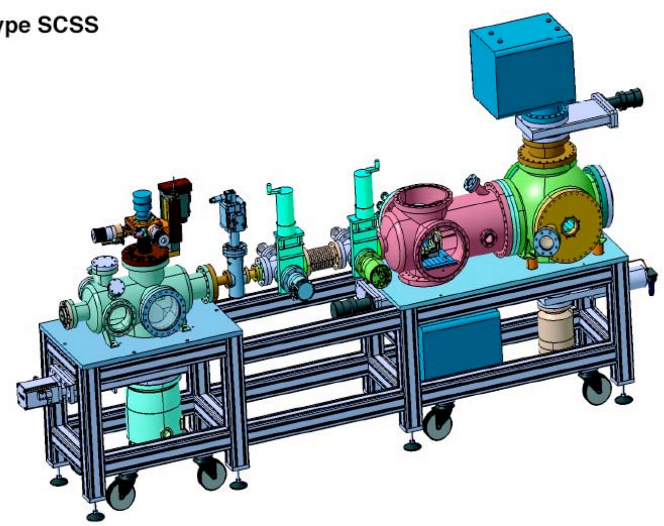
Le Déroff et al., Optics Lett. 23 (1998)

HHG SEEDING DEMONSTRATION EXPERIMENTS

Collaboration SPring-8: seed@60 nm



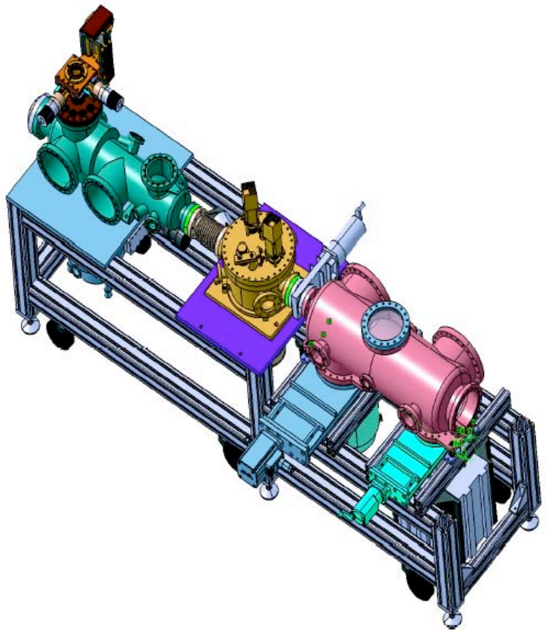
Prototype SCSS



Collaboration SPARC

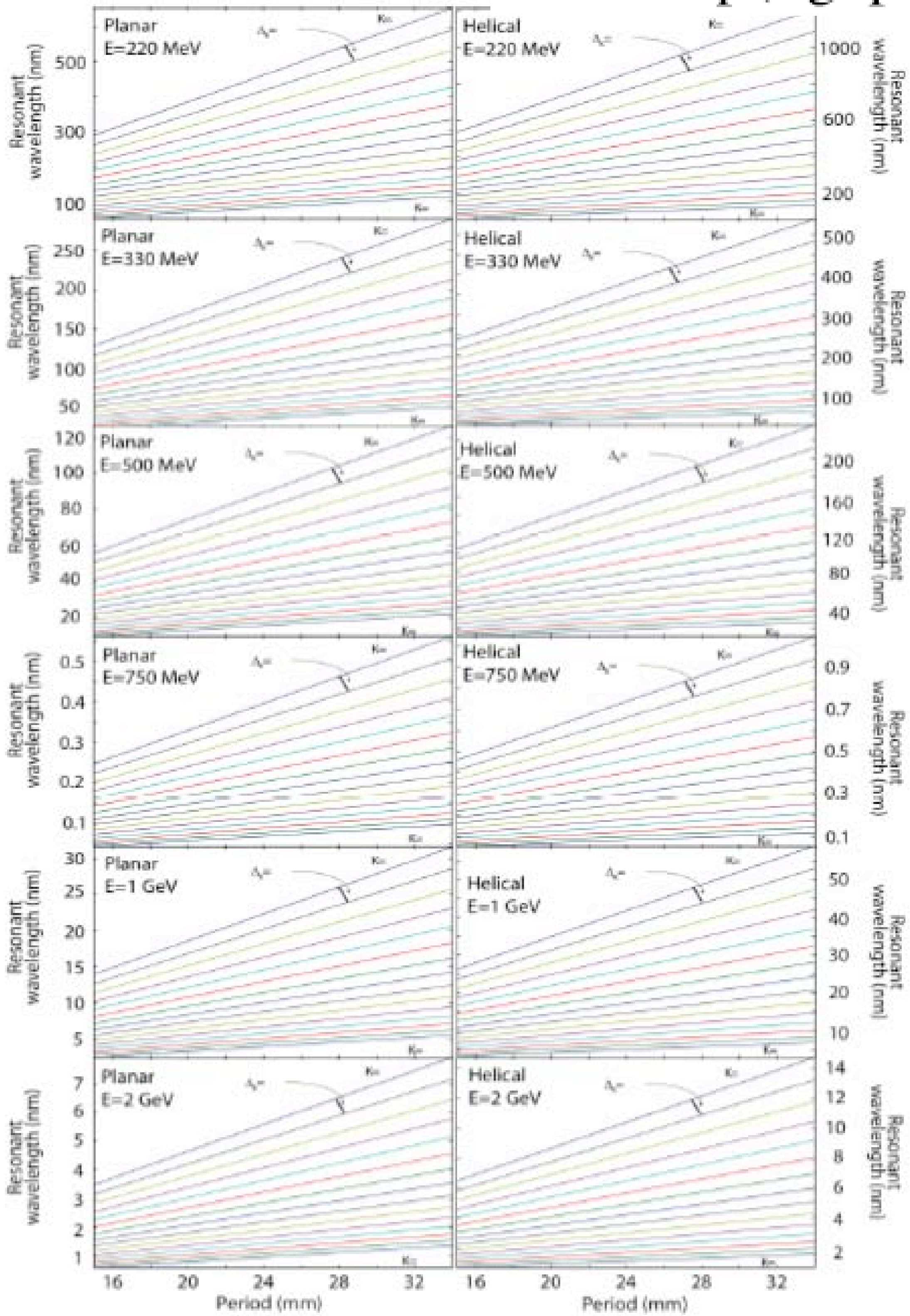
seed@266, 190 nm, HGHG, cascade?
(EUROFEL, DS4)

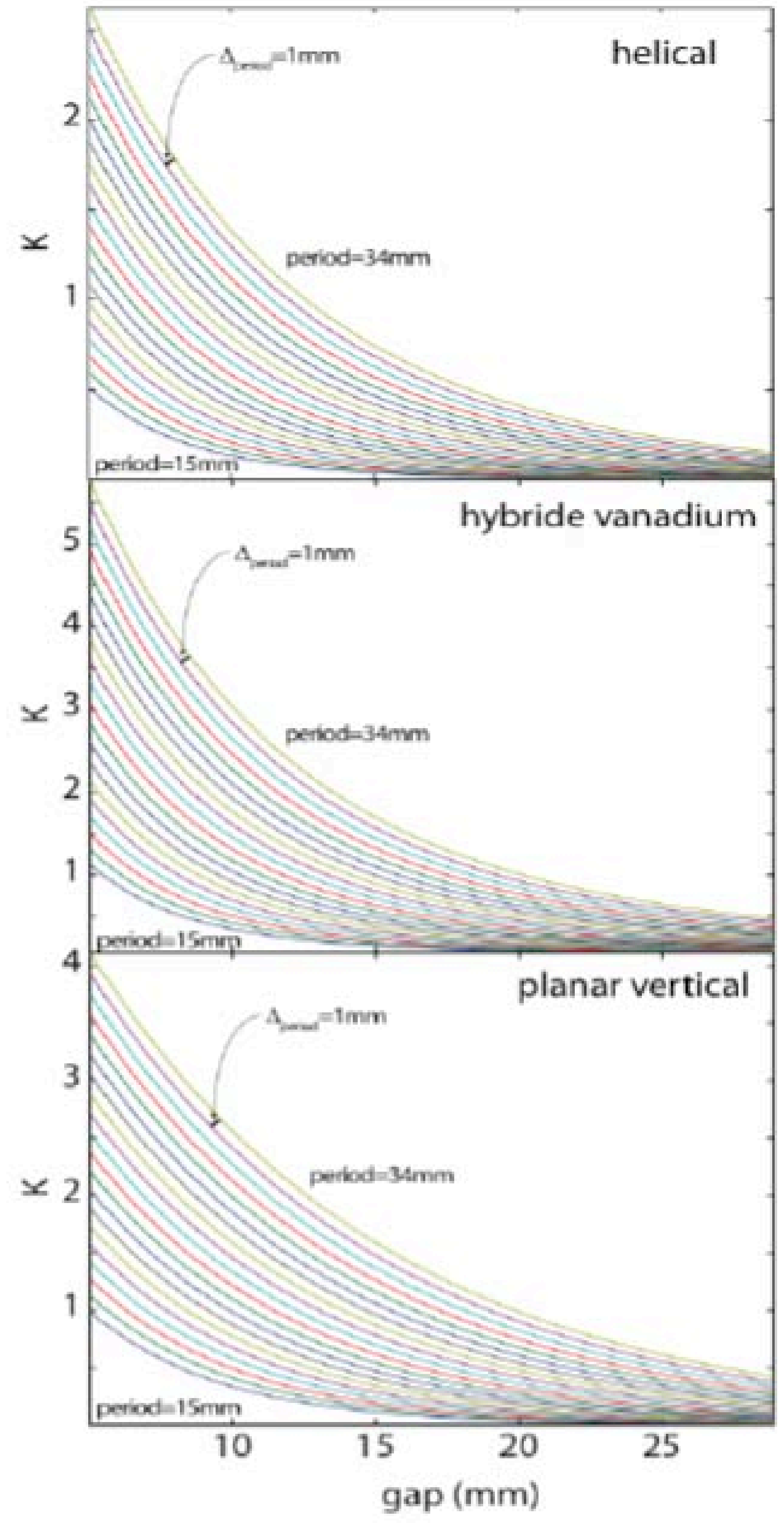
SPARC
(EUROFEL)



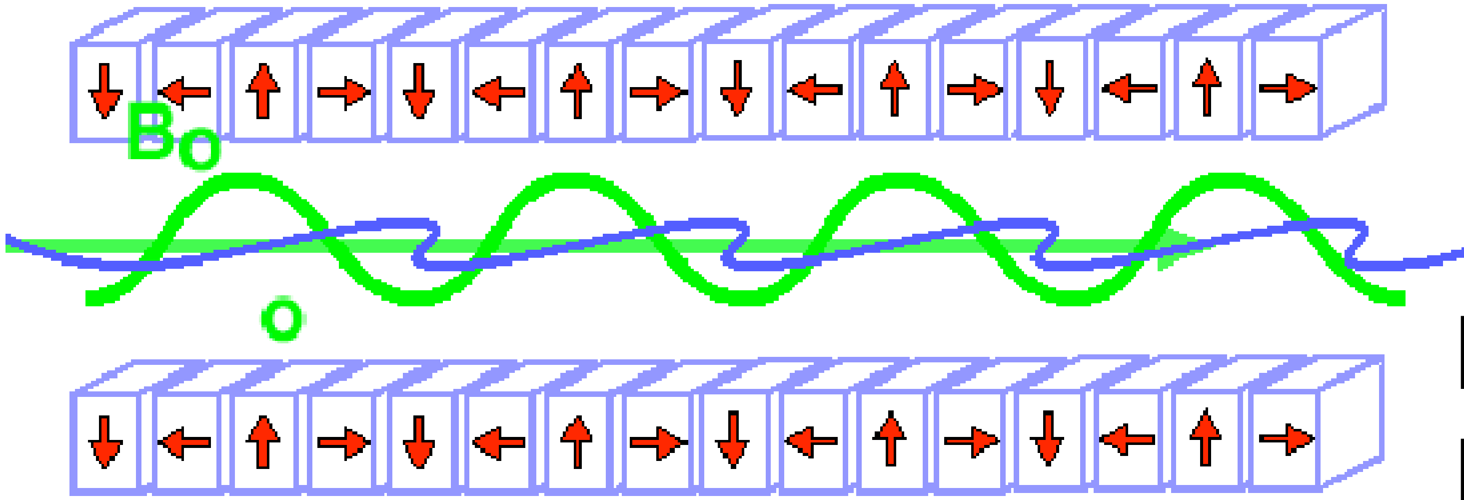
ARC-EN-CIEL: UNDULATORS

$$B=a \ \exp(b\,gap/\lambda_o) + c \ (gap/\ \lambda_o)^2)$$





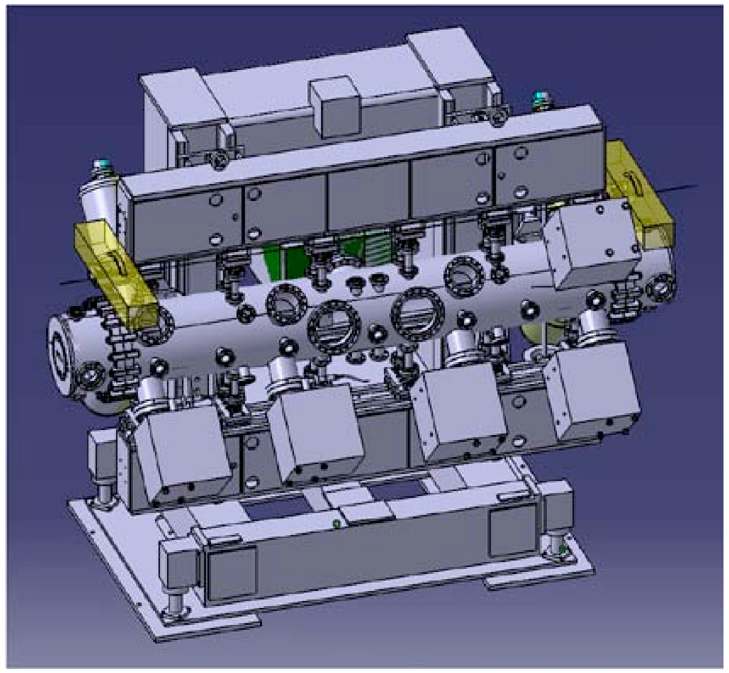
ARC-EN-CIEL: UNDULATORS modulator



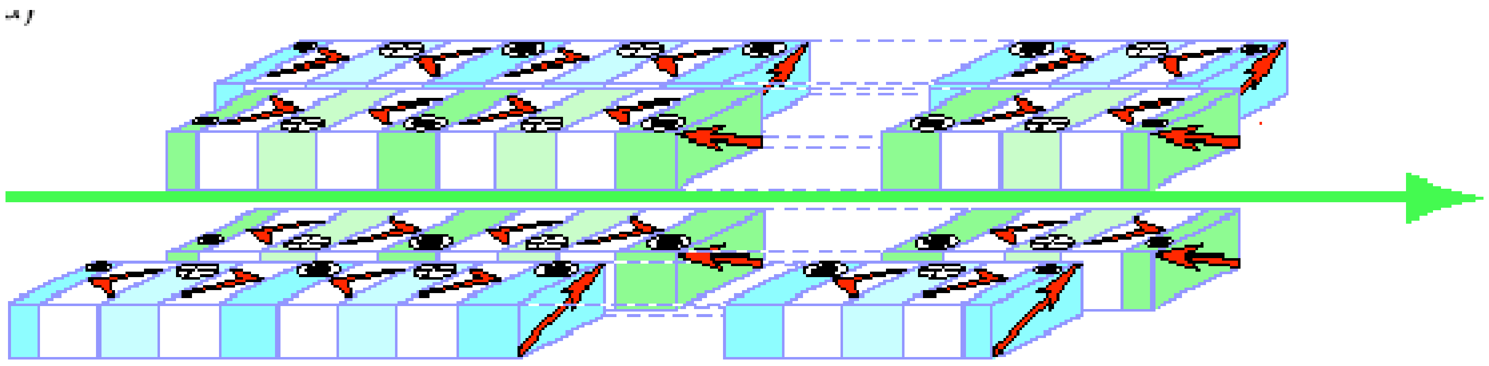
In vacuum U26
Phase 1: 200 périodes
Phase 3: 400 périodes

Hybrid: SM_2CO_{17},
Vanadum Permendur

Gap = 5.5 mm, SmCo17
(50,7.5,30)
VP (33,2.5,22)
Nper = 98
B_0 = 0.96 T
K= 1.8



ARC-EN-CIEL: UNDULATORS
APPLE-II radiator

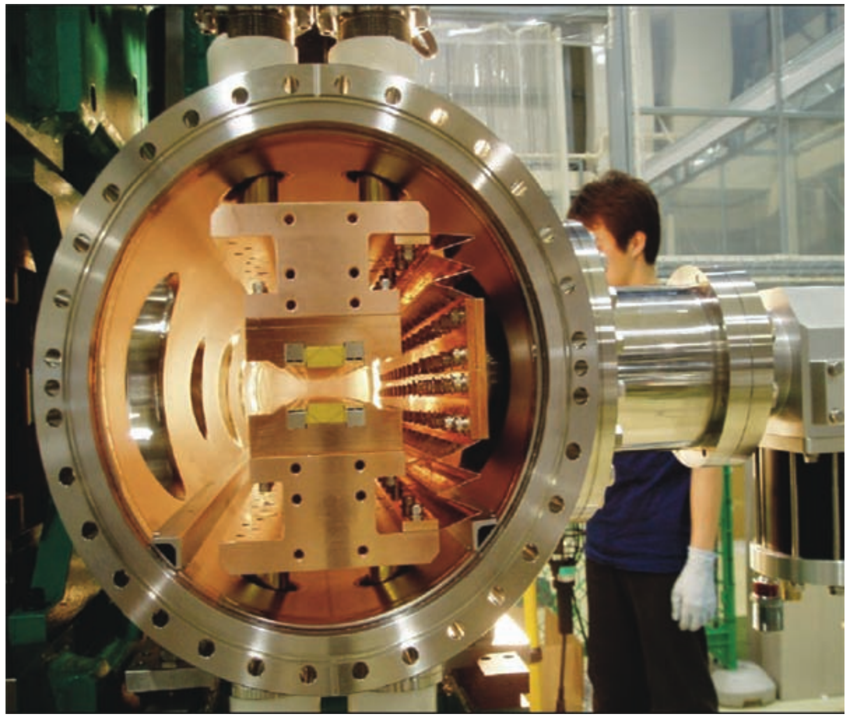


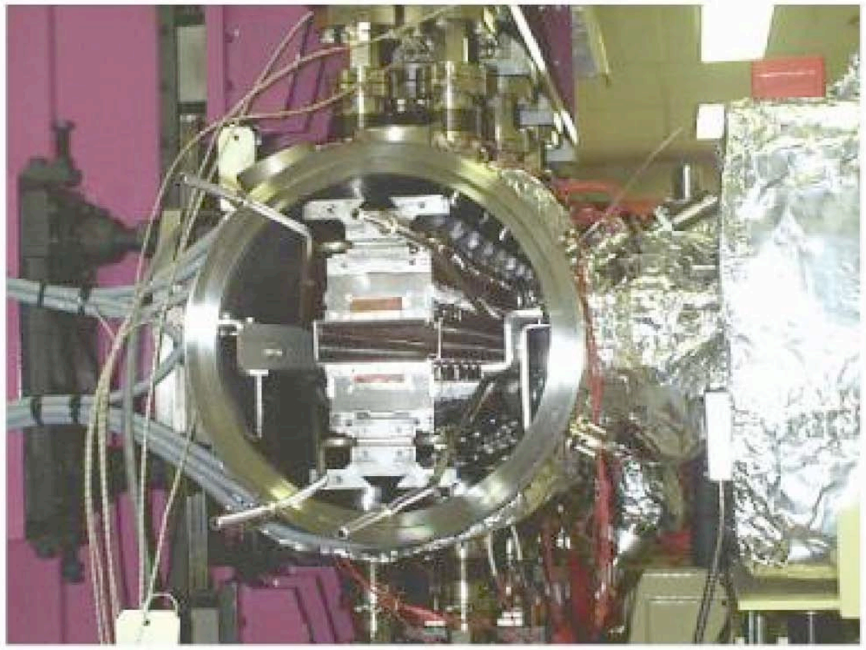
HU30, 9 à 12 m

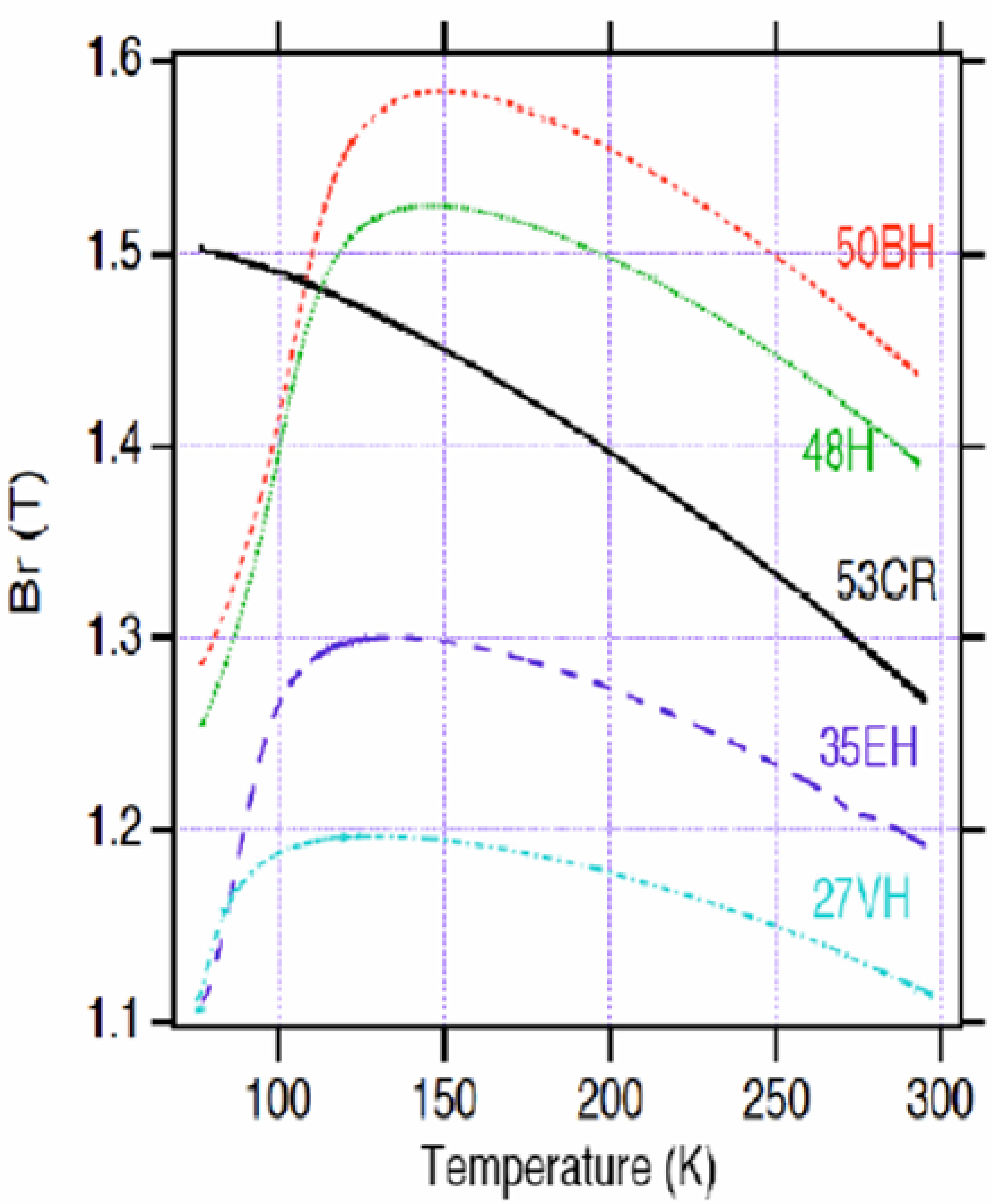
LEL1 : accessible range versus the energy

E (Gev)	U26	Polarisation linéaire Apple II plan HU30	Polarisation circulaire Apple II hél. HU30
220	75-500	100-500	100-600
330	25-220	42-220	50-250
500	15-95	20-80	37-220
750	7-42	8-40	15-55
1000	23-4	3-24	5-30
2000	6-1	1-6	2-7

ARC-EN-CIEL: UNDULATORS
Short period in vac ID







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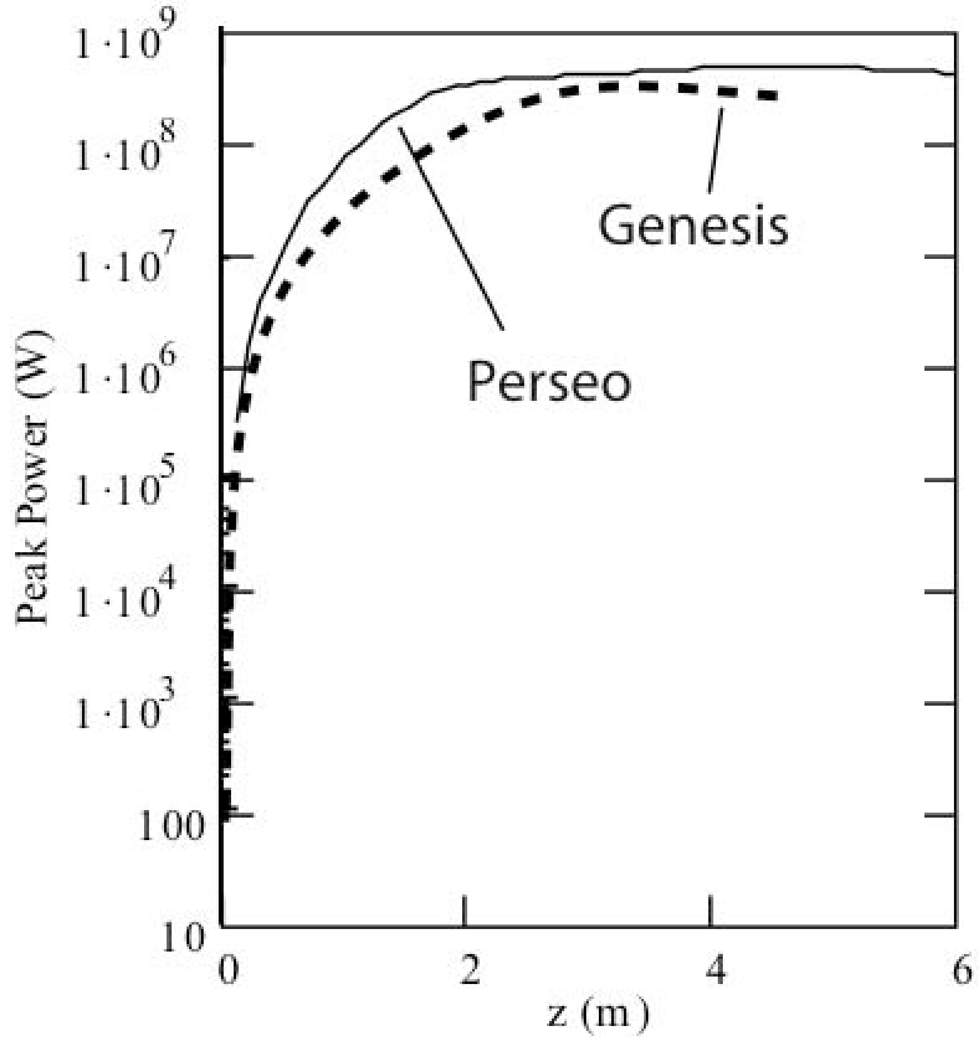
ARC-EN-CIEL: UNDULATORS

FEL	Type	λ_o mm	K_{max}	Gap_{min}	Length (m)
LEL1-M	In vac	26	3.2	3.5	5.2
LEL1-R	Apple-II	30	P:2.16 H:1.5	10 8	21
LEL2-M	In vac	26	3.2	3.5	13
LEL2-R	In vac*	18	3.1*	3.7	9
LEL3	Apple-II	30	P:3.36 H:1.5	6 8	10.5
LEL4-M	In vac *	35	4.8	3.5	24.5
LEL4-R	In vac *	18	3.1*	3.7	18
VUV	Apple-II	30	P:1.1 H:0.7	15.5	2
X	In vac	20	1.9	5.5	2x6

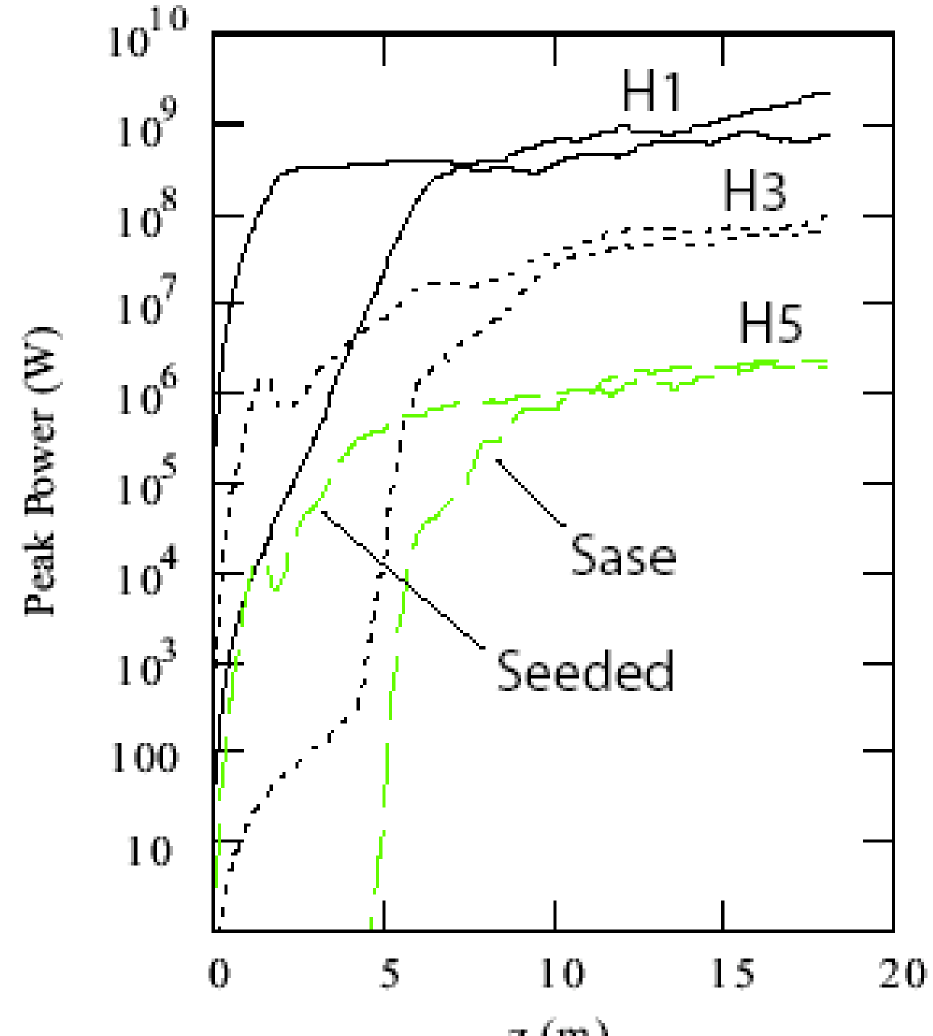
FEL SOURCES CALCULATIONS

PERSEO SS/TD- GENESIS SS-TD coupled to SRW- Ff=0.1

See O. Chubar's talk



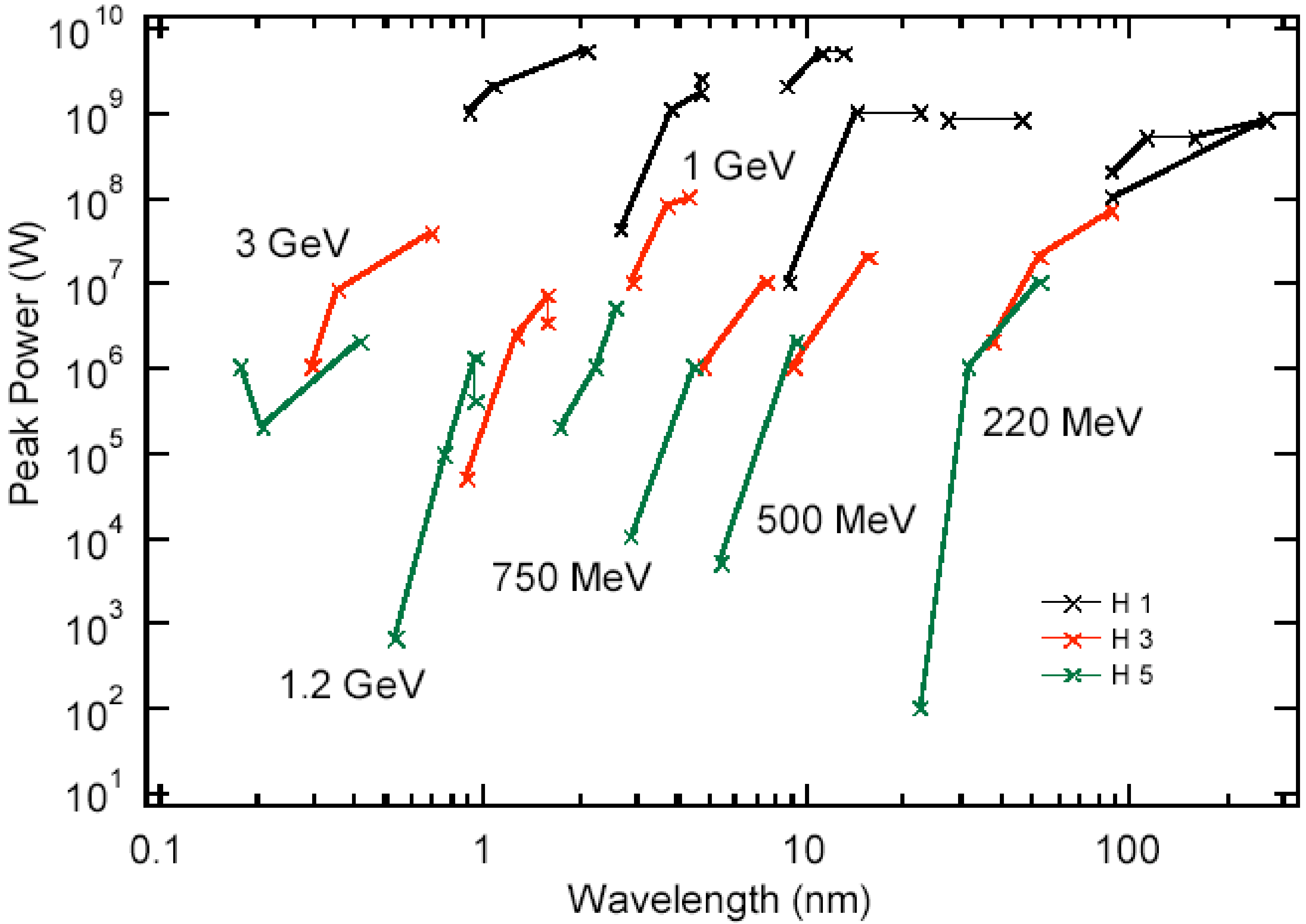
Comparaison simulation PERSEO/ GENESIS inclus dans SRW, cas d'AEC P1



Comparaison seeding/SASE, Perseo, injection at 160 nm pour AEC P1

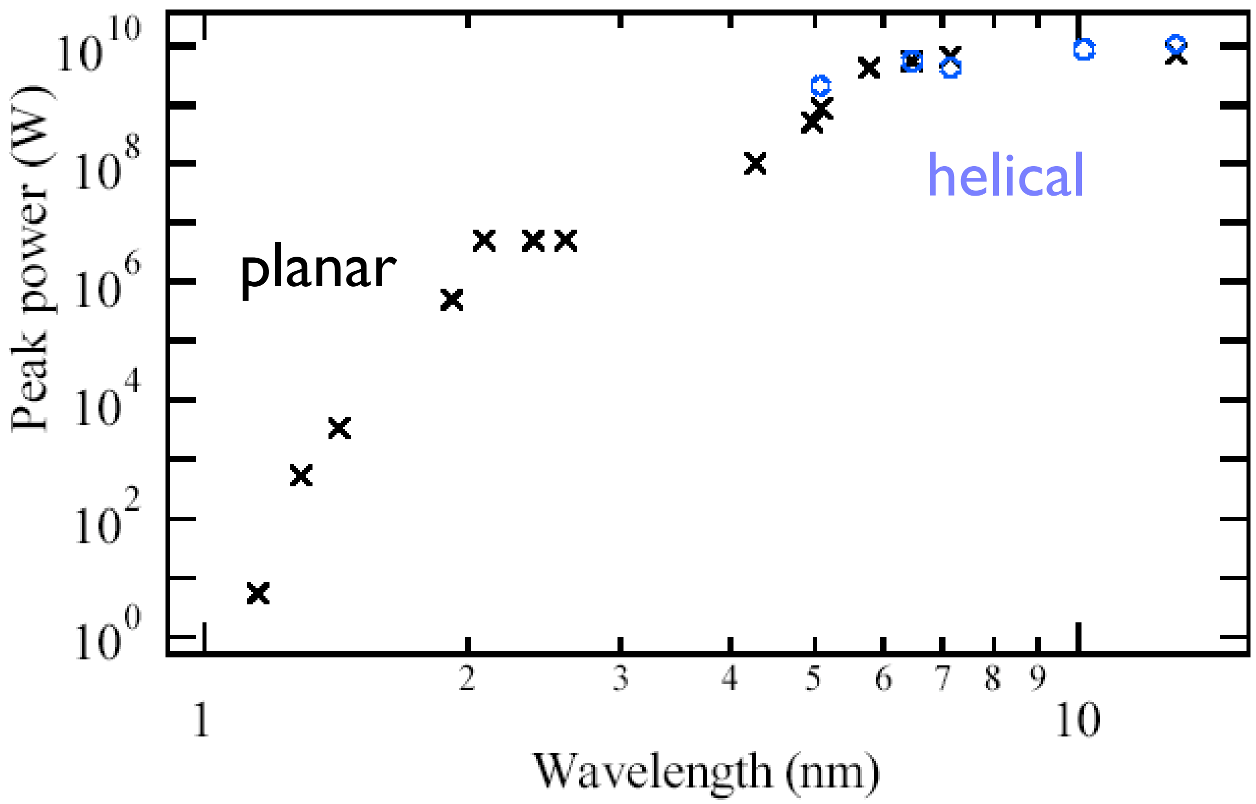
1.5 kA, 1 GeV, 0.04% 1.2 pi, 0.06 mm, 0.75 nC, E=0.5-1 GeV
Und1 : period 2.6 cm, Ff=0.1, Und2 period 3 cm,Config 1-1 and 1-3

SPECTRAL RANGE COVERED BY THE HHH SEEDED LEL1, LEL2, LEL4

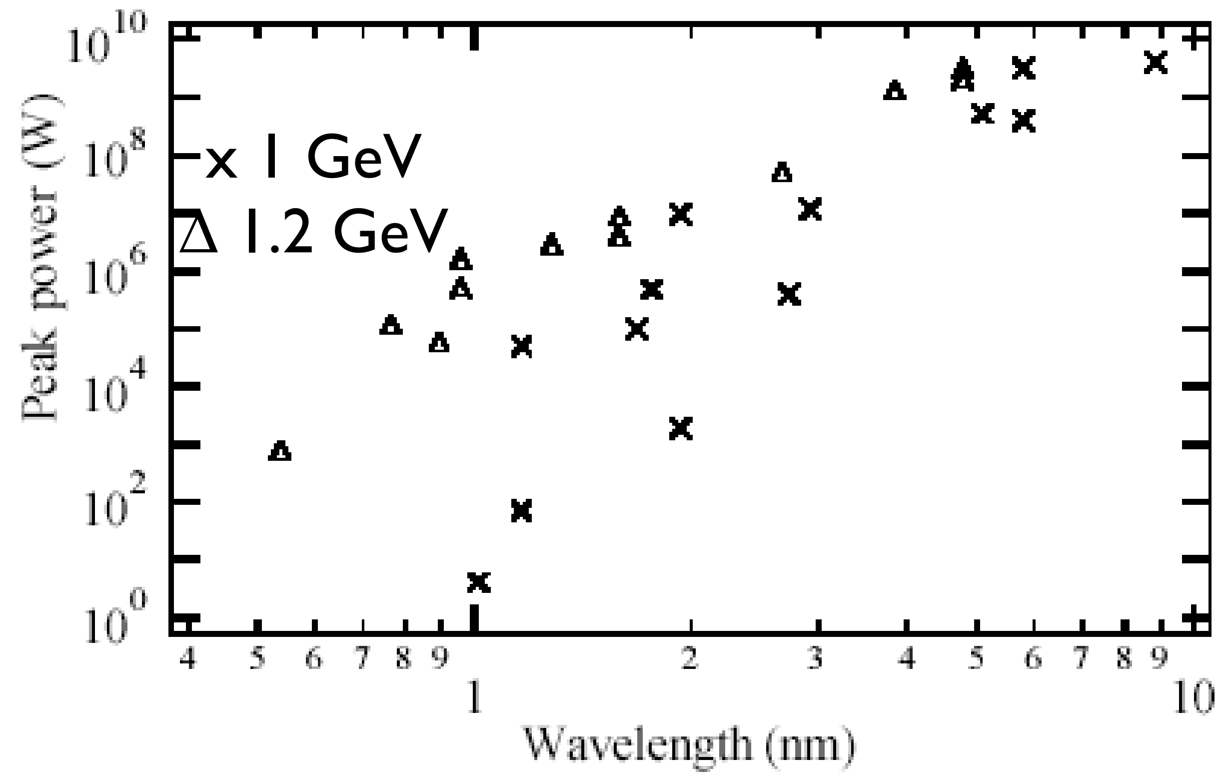


LEL1, LEL2, LEL 4 SPECTRAL RANGE

LEL1 : Seed 50 fs, 30 kW, LEL1@1 GeV (1.5 kA)
U26 : 100 to 200 periods, HU30 : 400-700 periods,
R56=1.5 µm

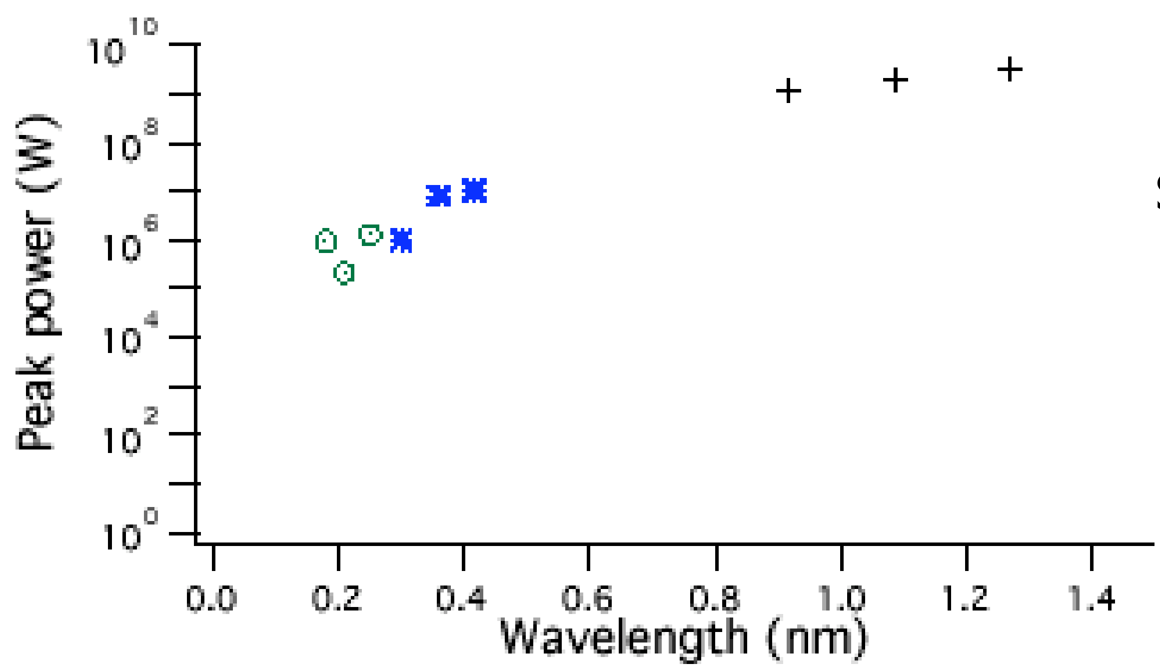


LEL2 : Seed 50 fs, 50 kW, LEL2@1 GeV (1.5 kA)
U26 : 400-500 periods, U18 : 400-500 periods
R56=1.5 µm



LEL4 :

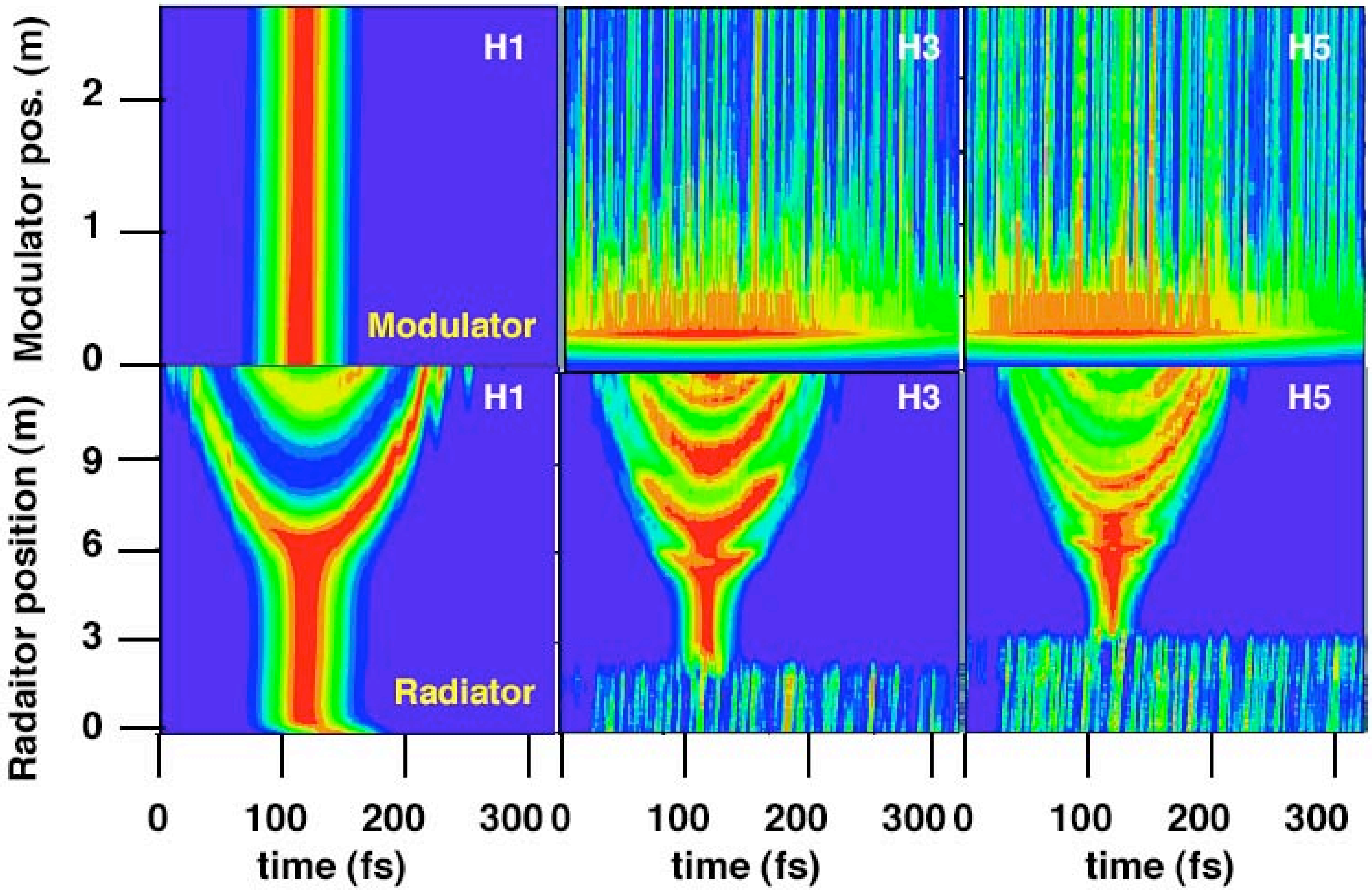
- Much more prospective, using the 2 GeV beam once more accelerated
- Foresees further improvement in the HHG seed
- Cryogenic undulators in series



Seed 50 fs, 50 kW, LEL4@3 GeV
U26 : 400-500 periods
U18 : 400-500 periods
R56=1.5 µm

LONGITUDINAL DYNAMICS

Case LEL1@1 GeV : Seed 12.3 nm, 50fs, 30 kW, conf 1-1, PERSEO TD



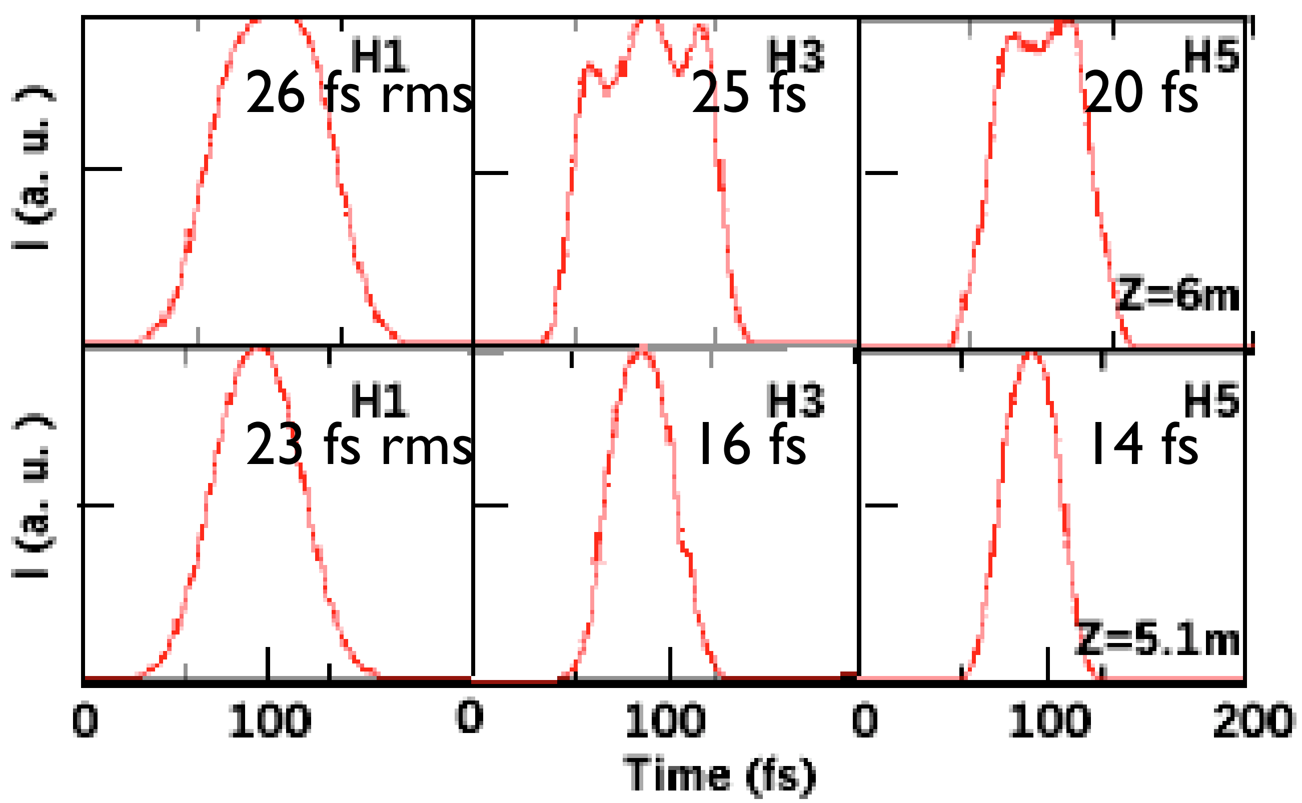
IV-ARC-EN-CIEL light source performances : FELs

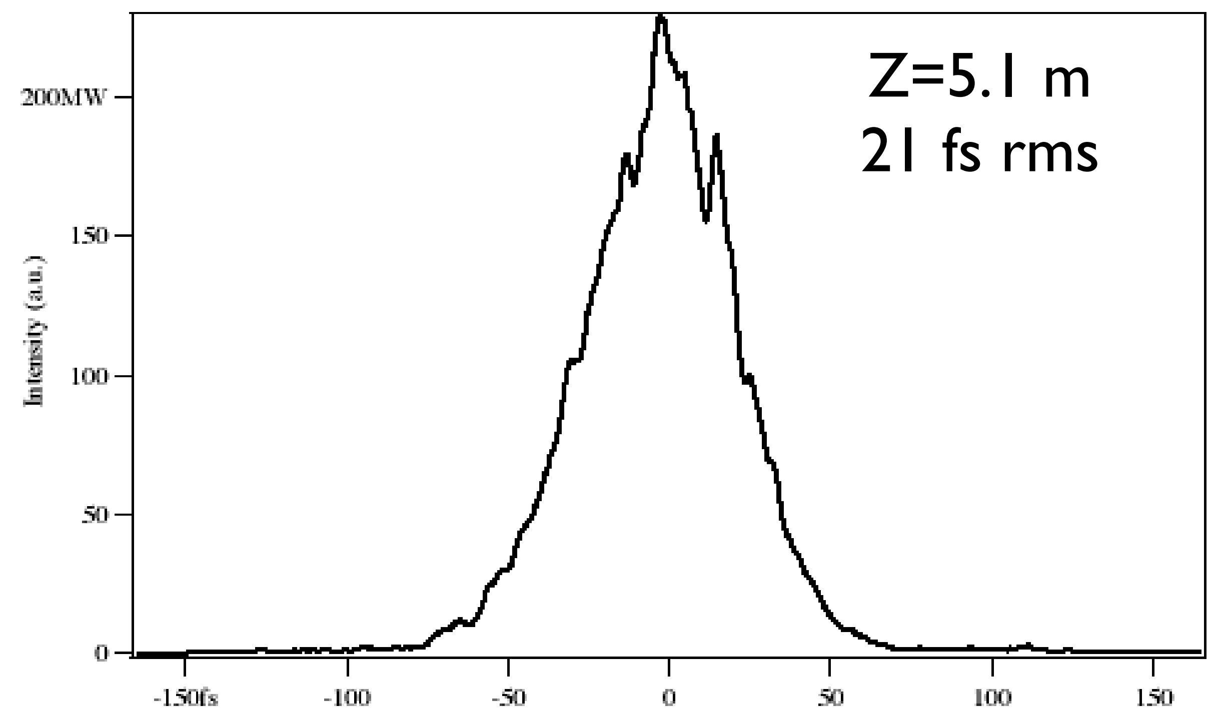
LONGITUDINAL DYNAMICS

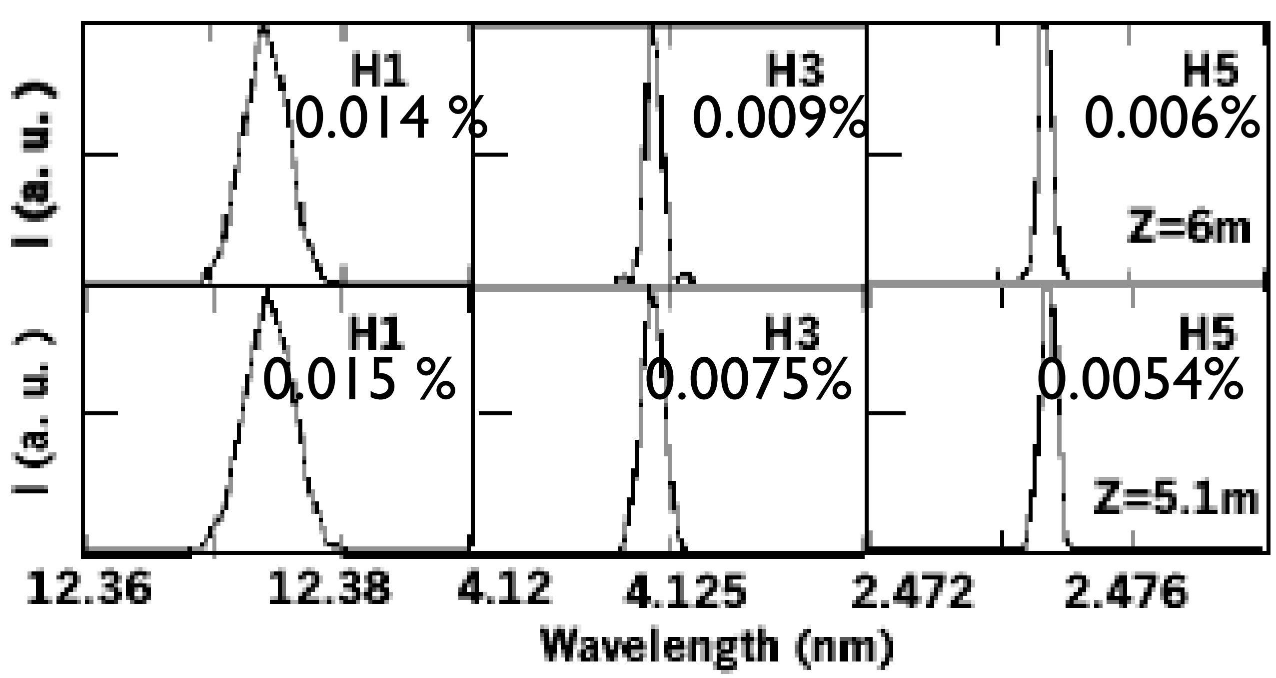
Standard case Case LEL1@1 GeV : Seed 12.3 nm, conf 1-1

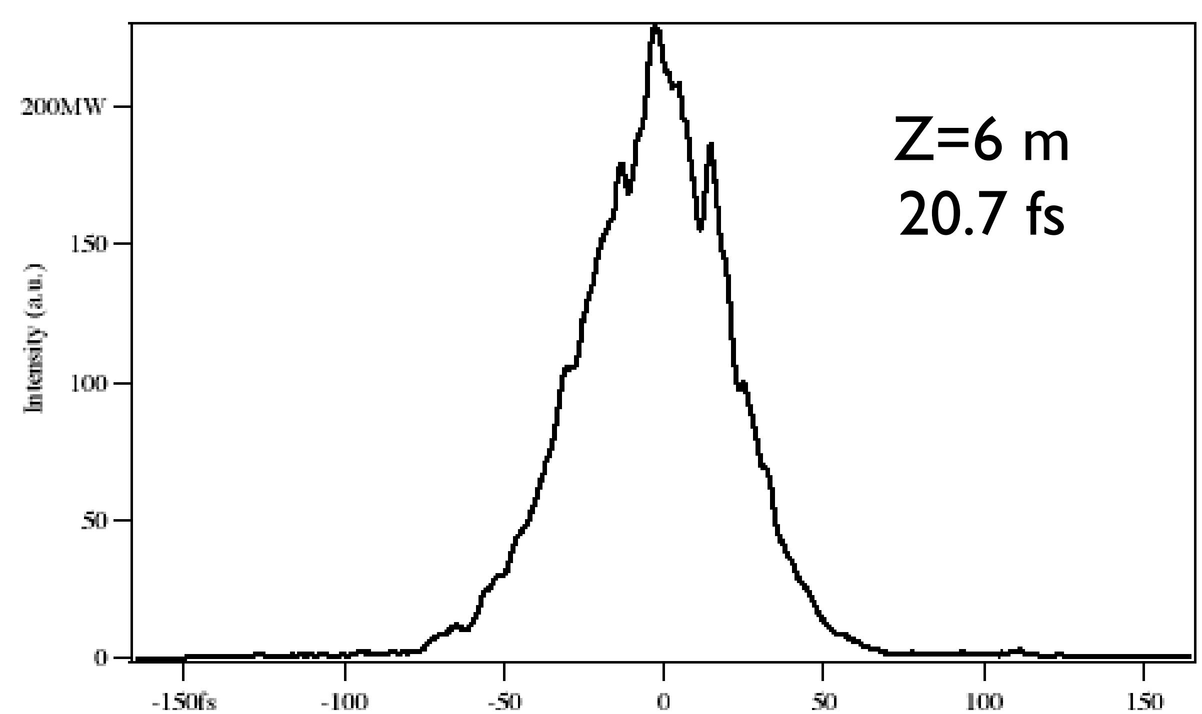
PERSEO TD

GENESIS









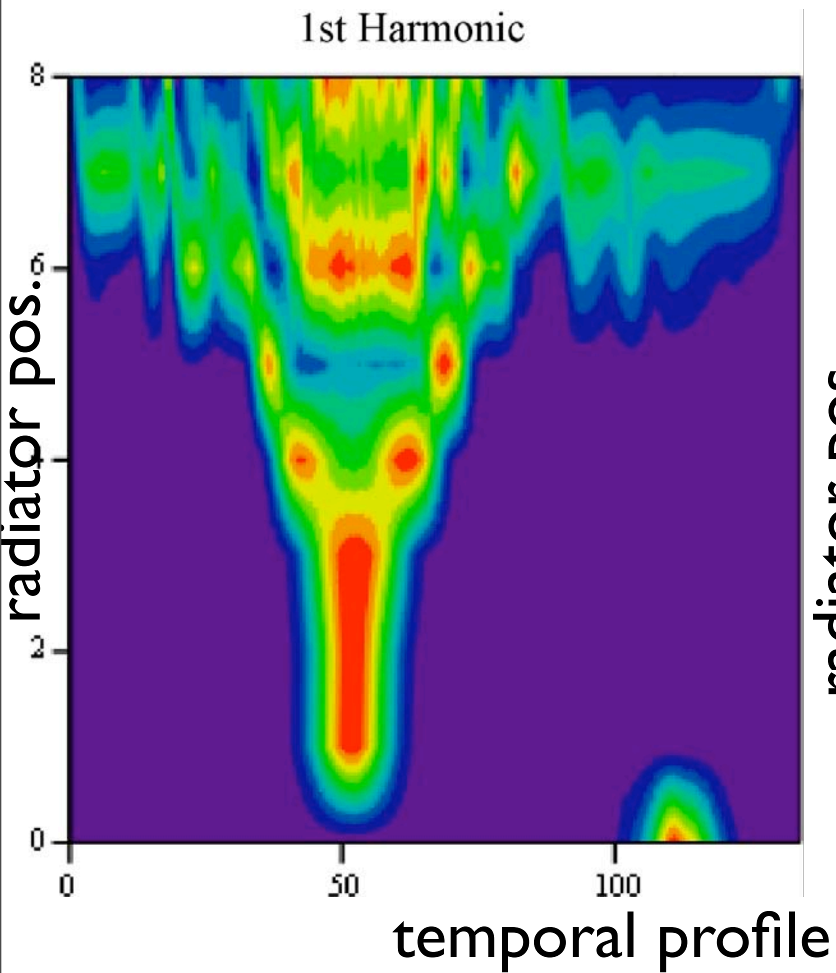
DYNAMICS- LEL2

0.8-1.2 GeV, configuration 1-3, seed 38-10 nm, 50 fs, 50 kW

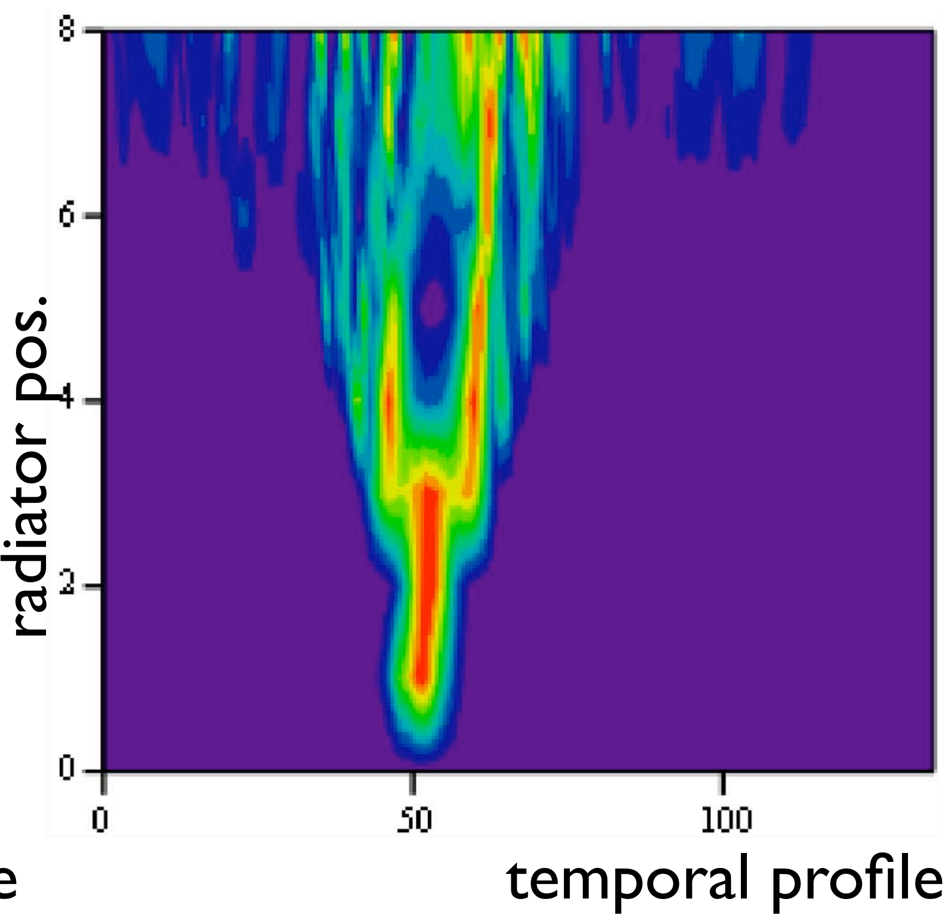
2 kA, 1 GeV, 0.04% 1.2 pi, 0.06 mm, 0.75 nC

Und1 : period 2.6 cm,Und2 period 1.8 cm, Dispersive section R56=1.5 µm, Nd=130

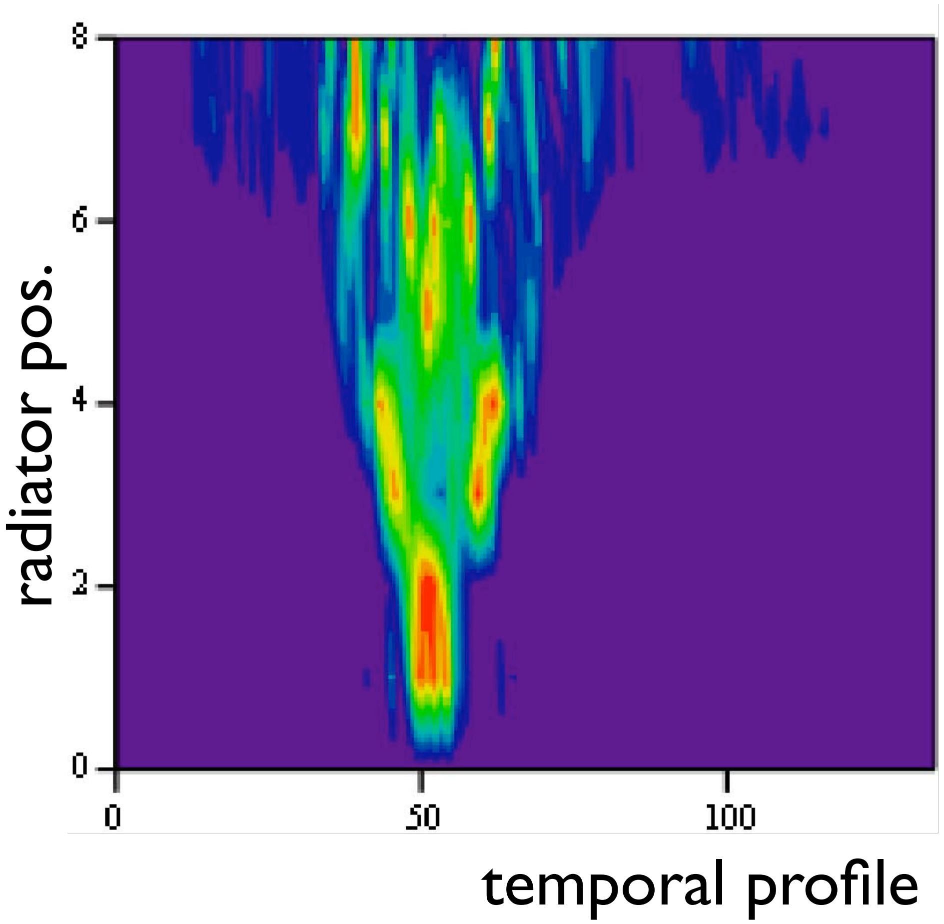
Seed 38 nm



12.6 nm



4.4 nm

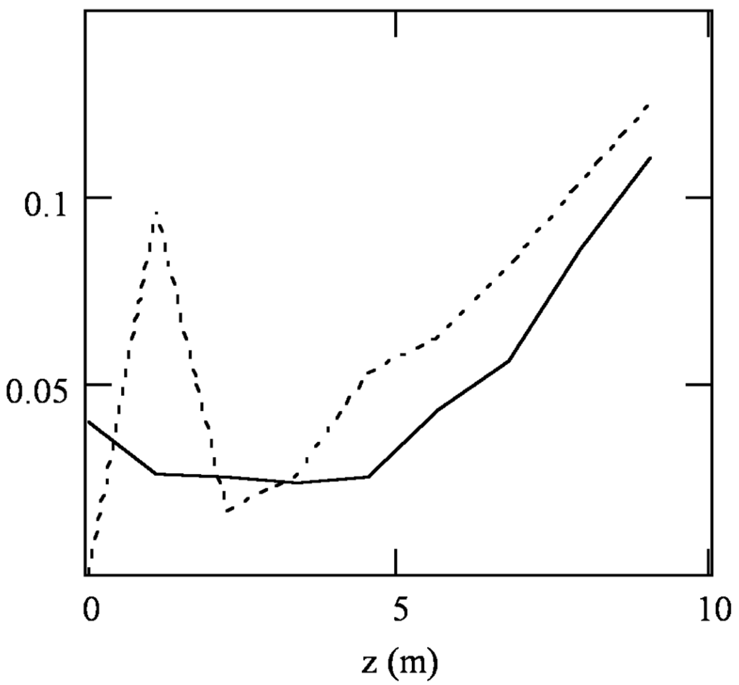


2.5 nm

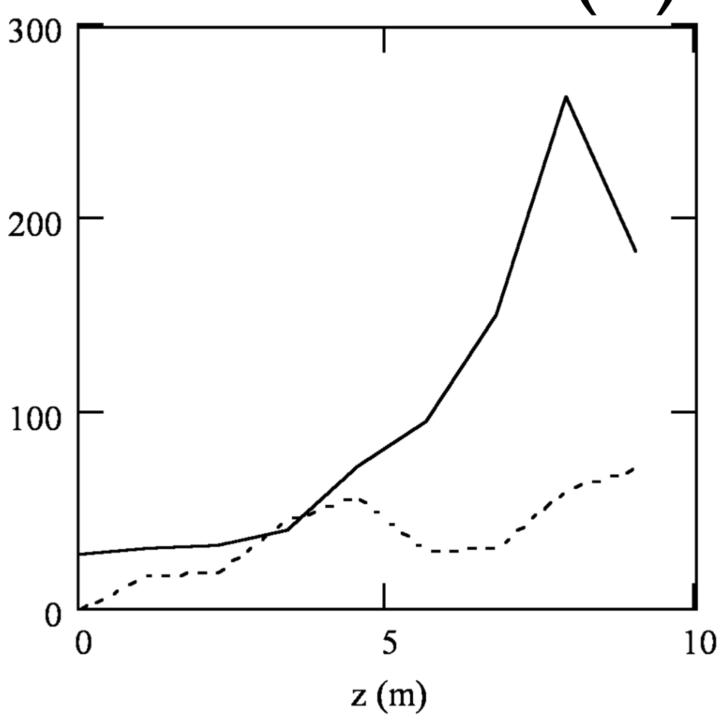
IV-ARC-EN-CIEL light source performances : FELs

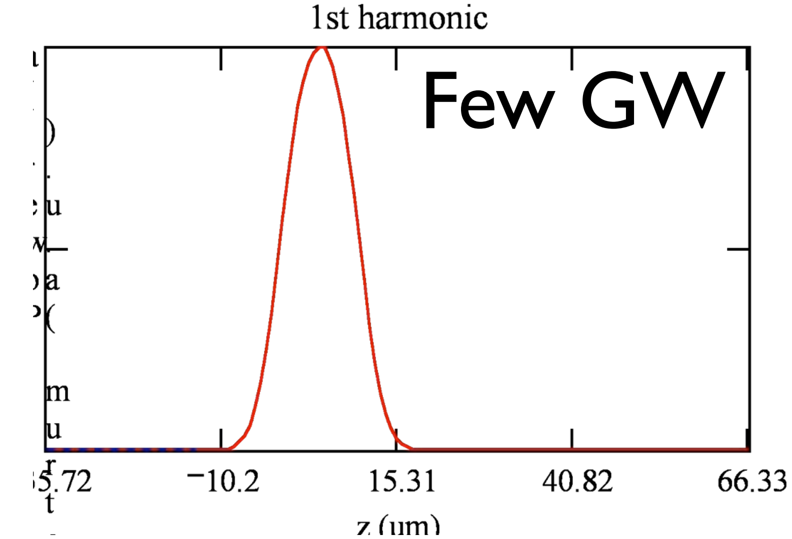
DYNAMICS- LEL2

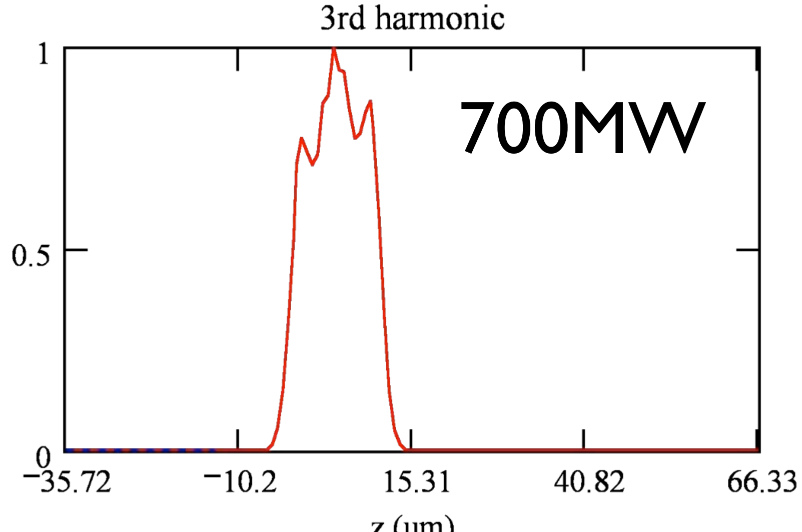
Spectral width (%)

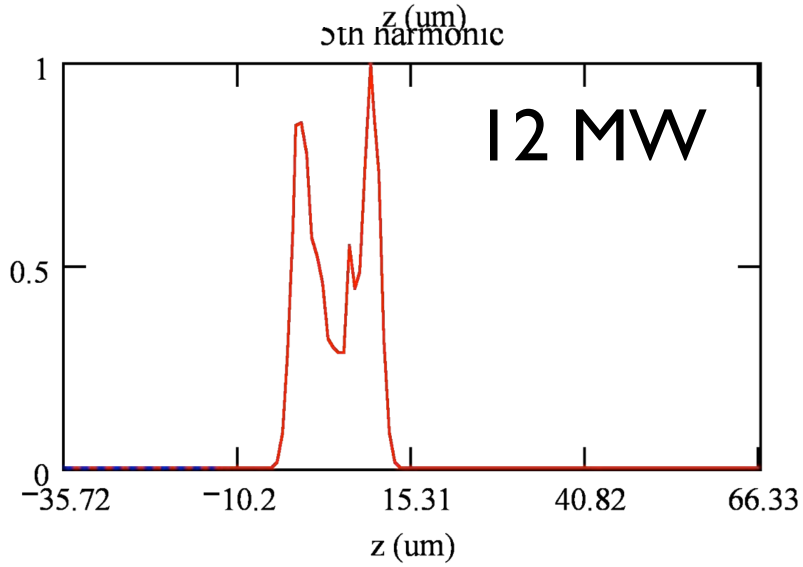


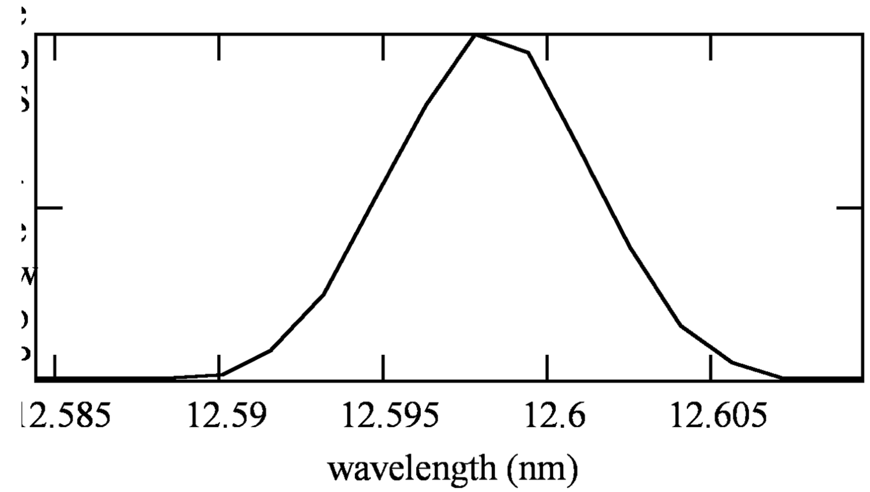
Pulse duration (fs)

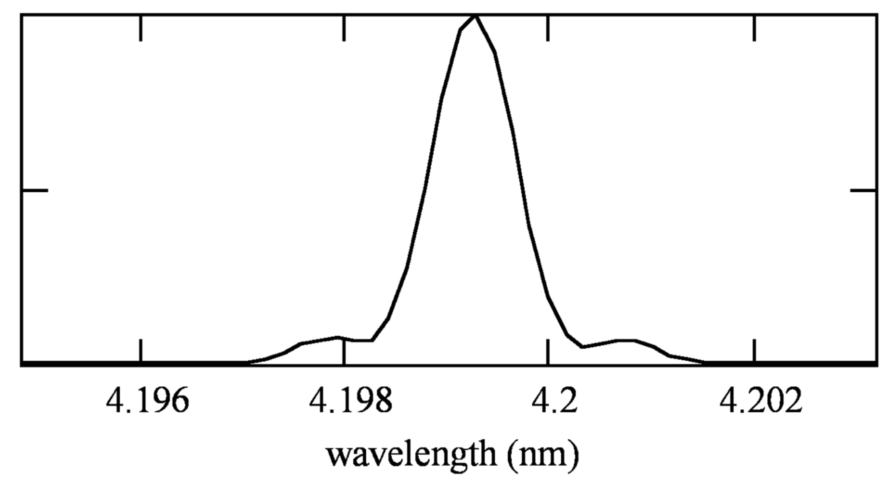


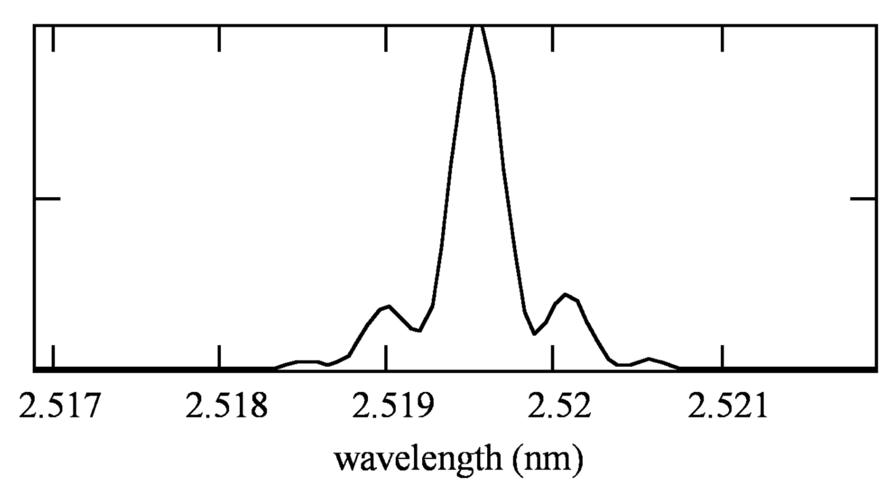










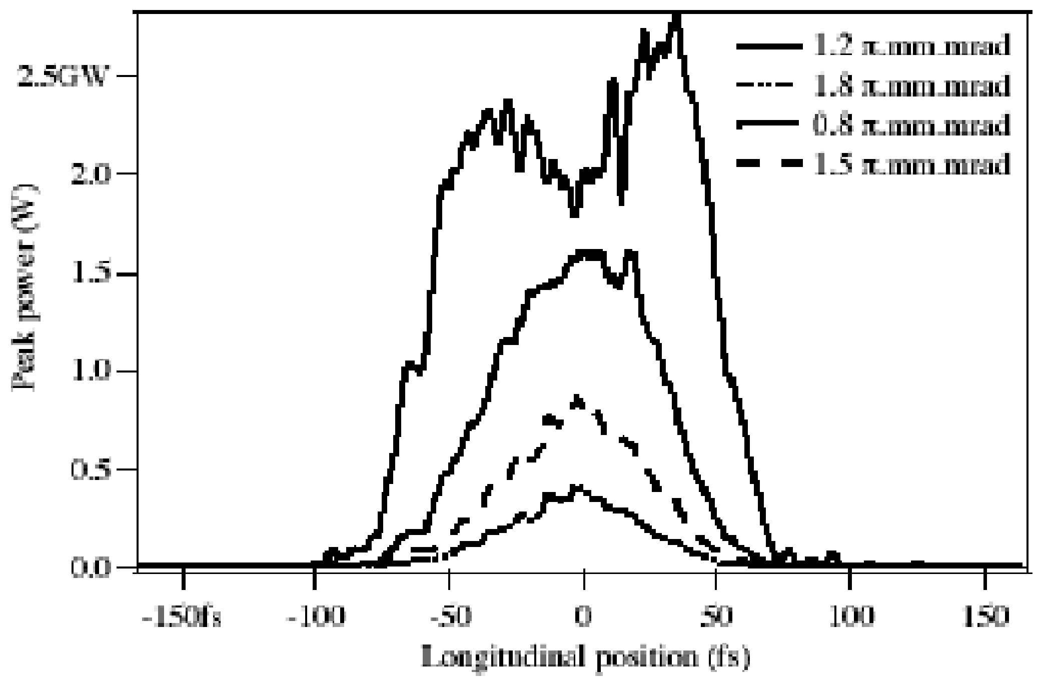


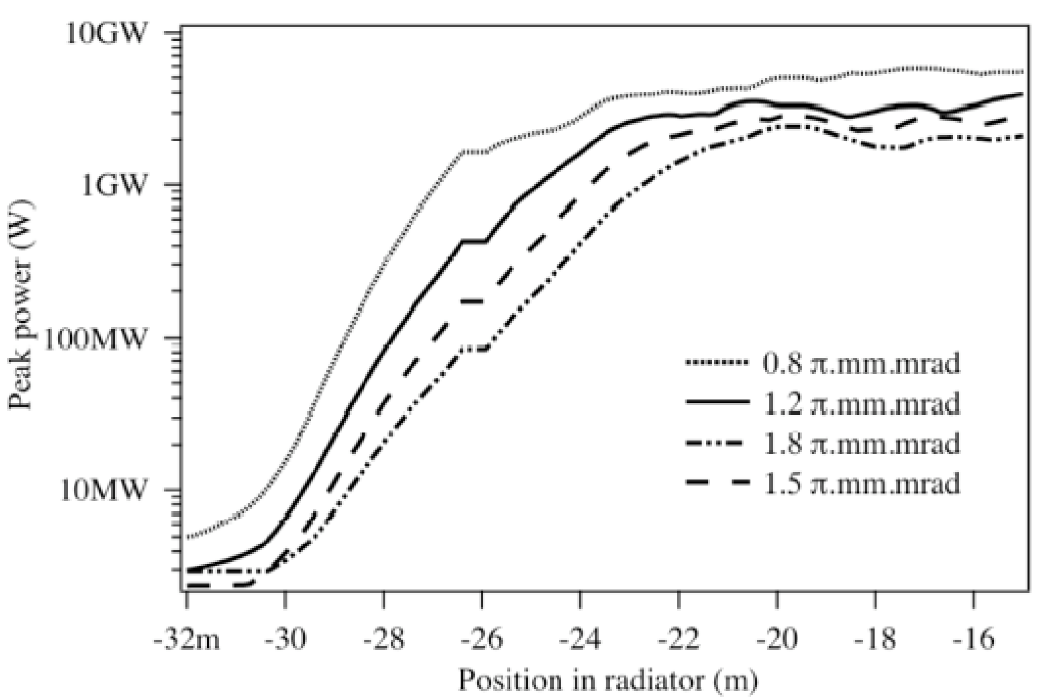
TOLERANCES : SENSITIVITY TO EMITTANCE

LEL1 seed 12.3 nm, conf 1-1

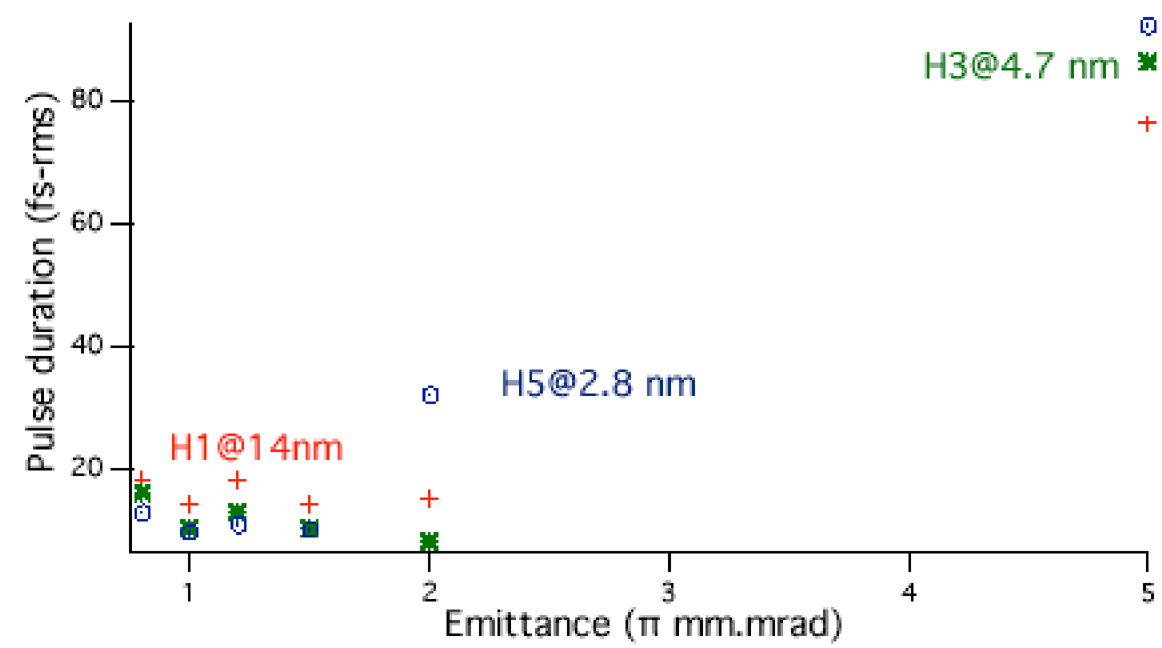
conf 1-3

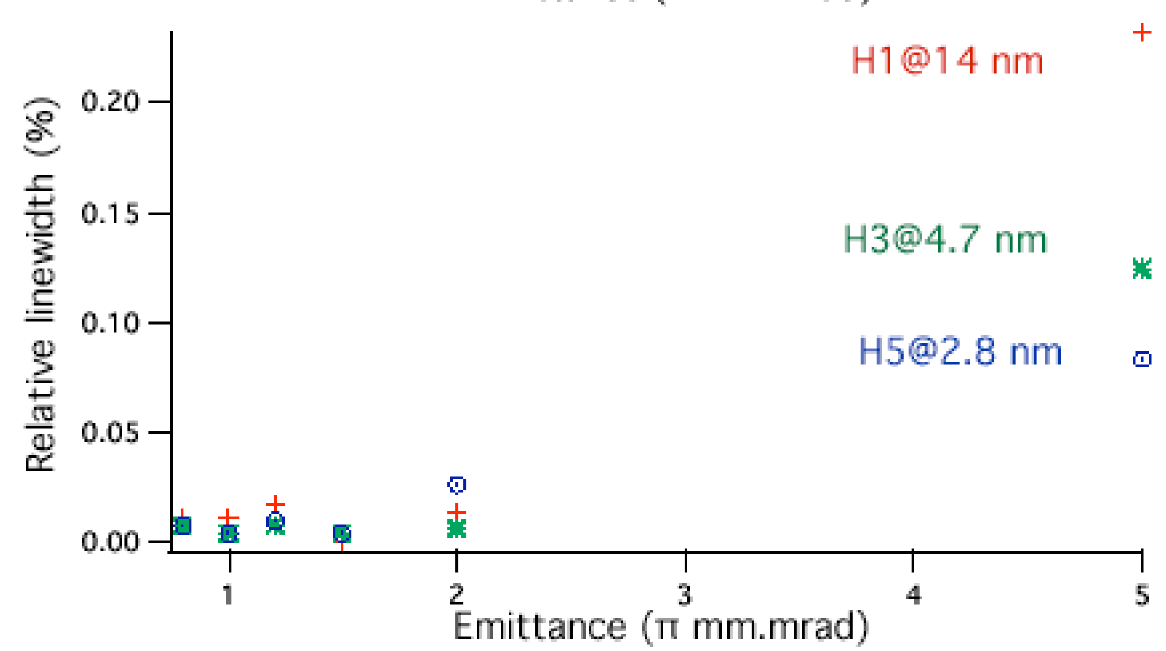
GENESIS



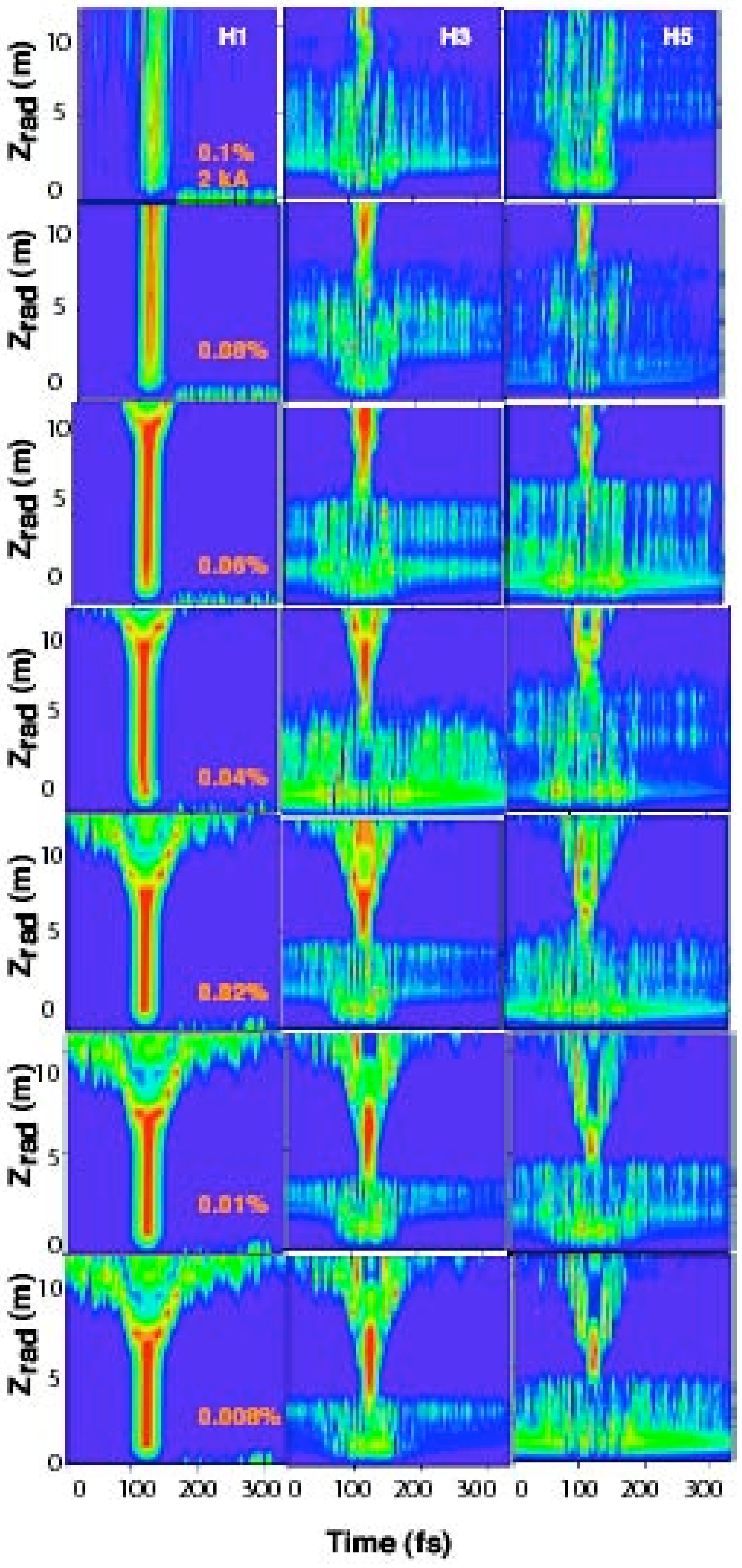


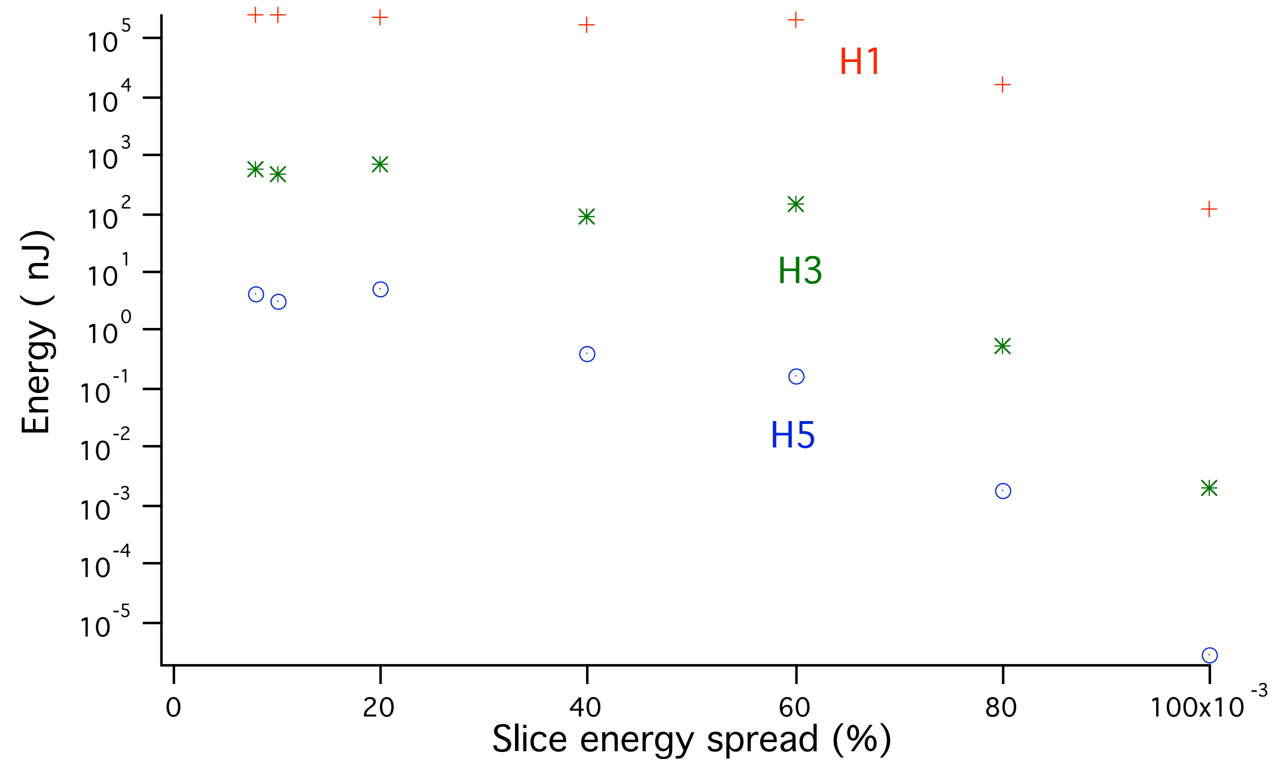
PERSEO TD

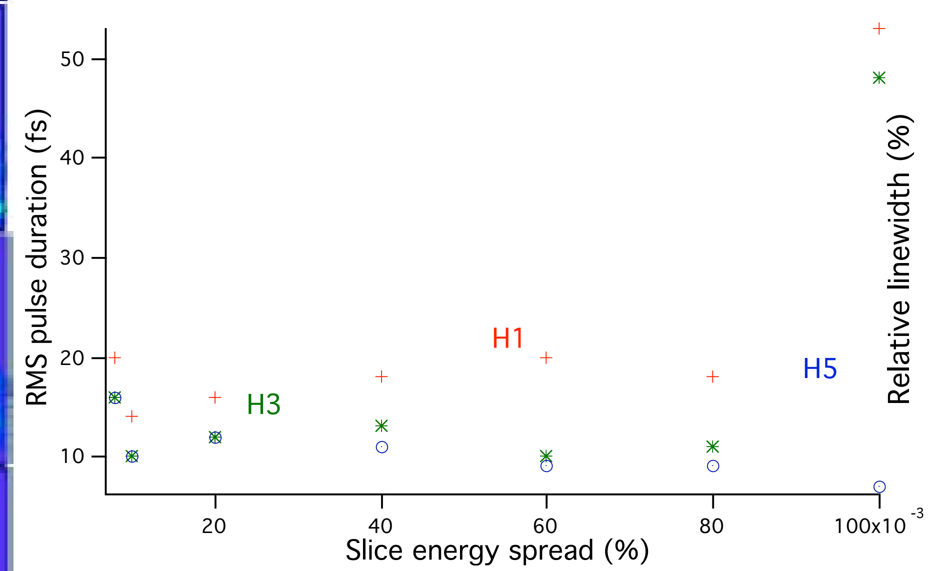


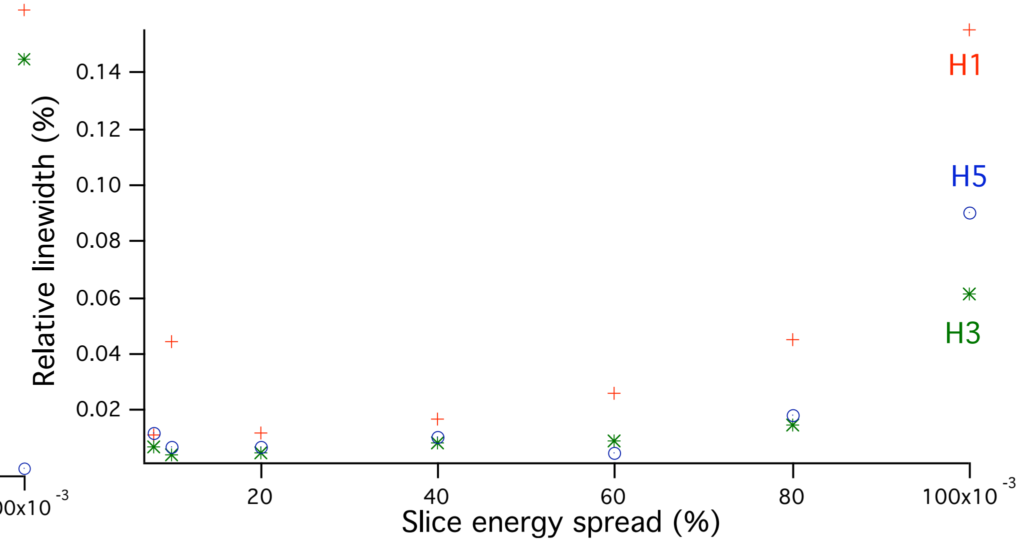


LEL2 config 1-3 : sensitivity to energy spread

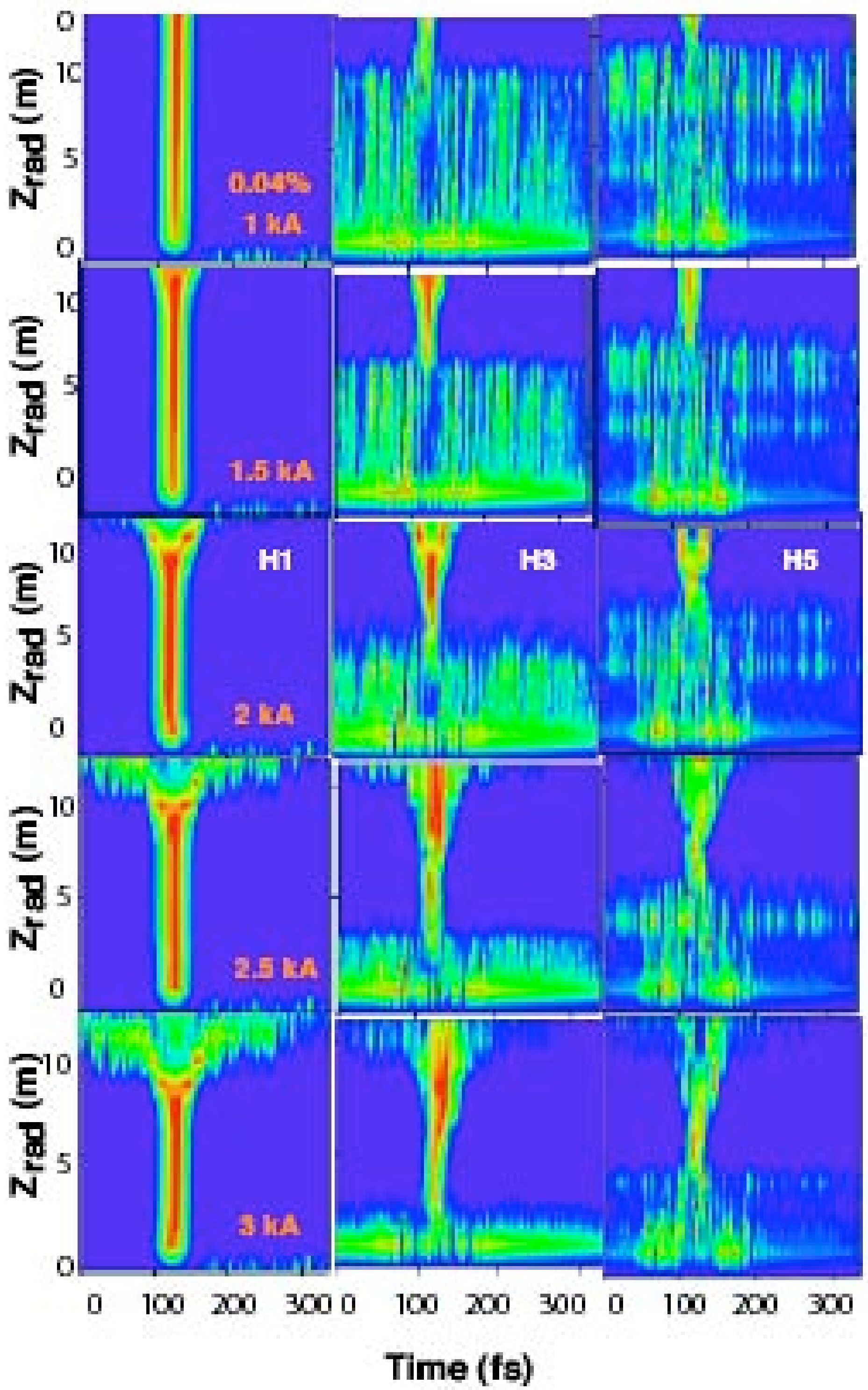


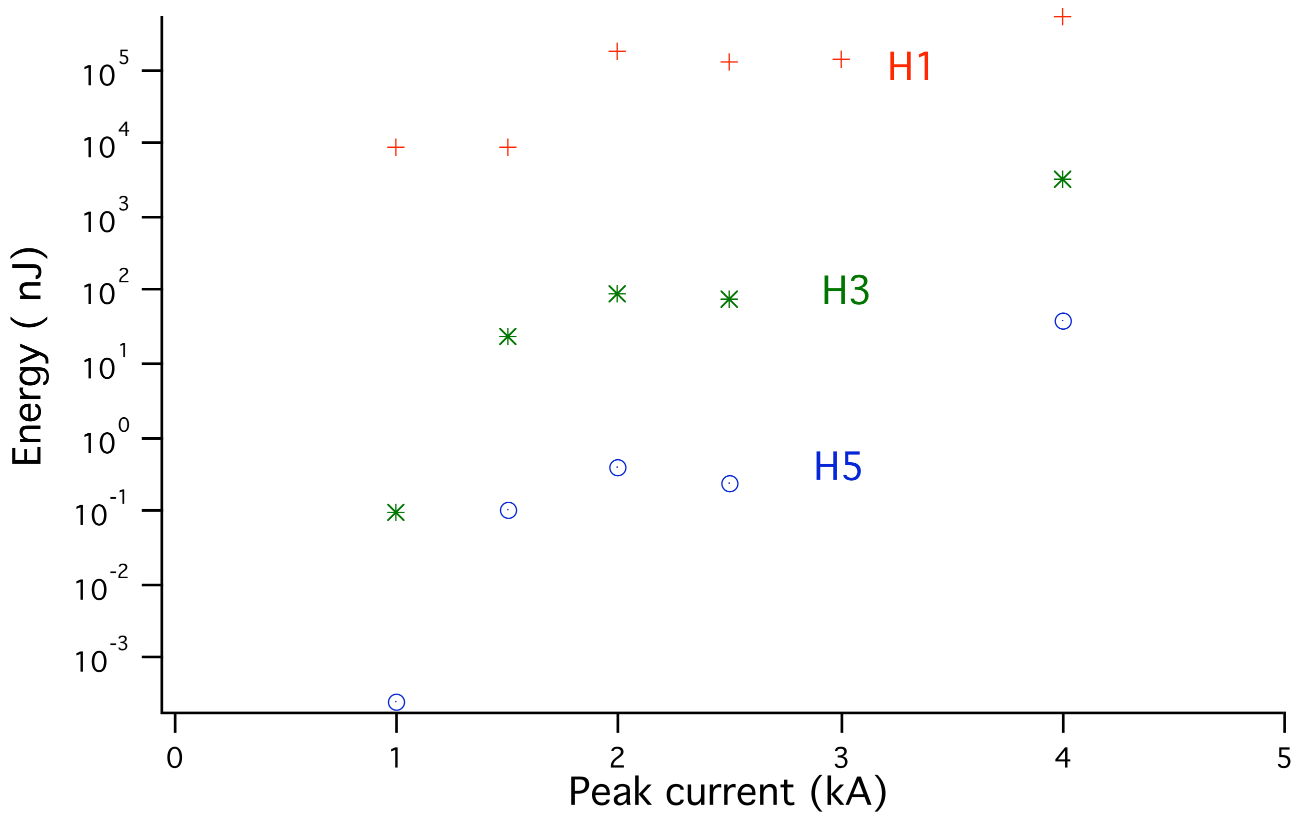


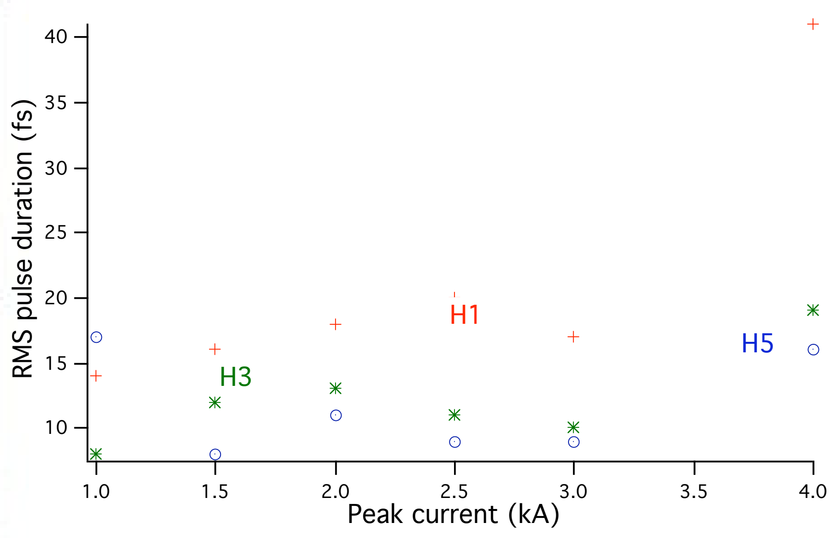


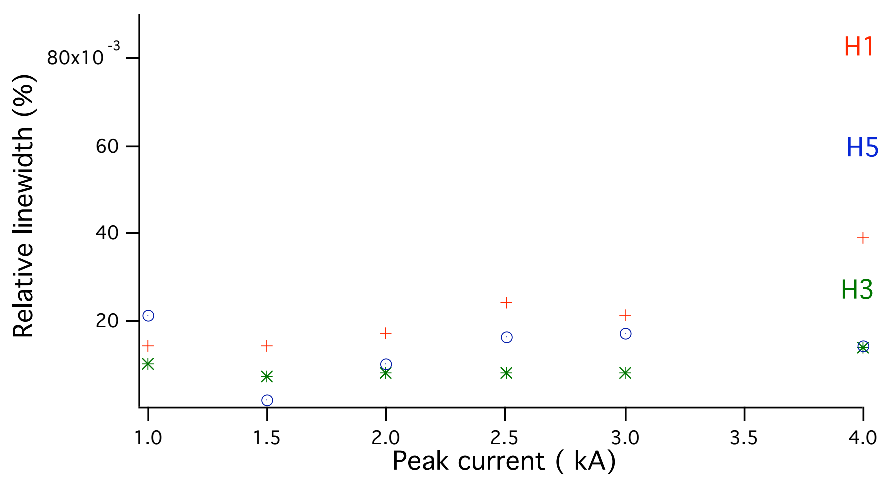


LEL2 config 1-3 : sensitivity to peak current



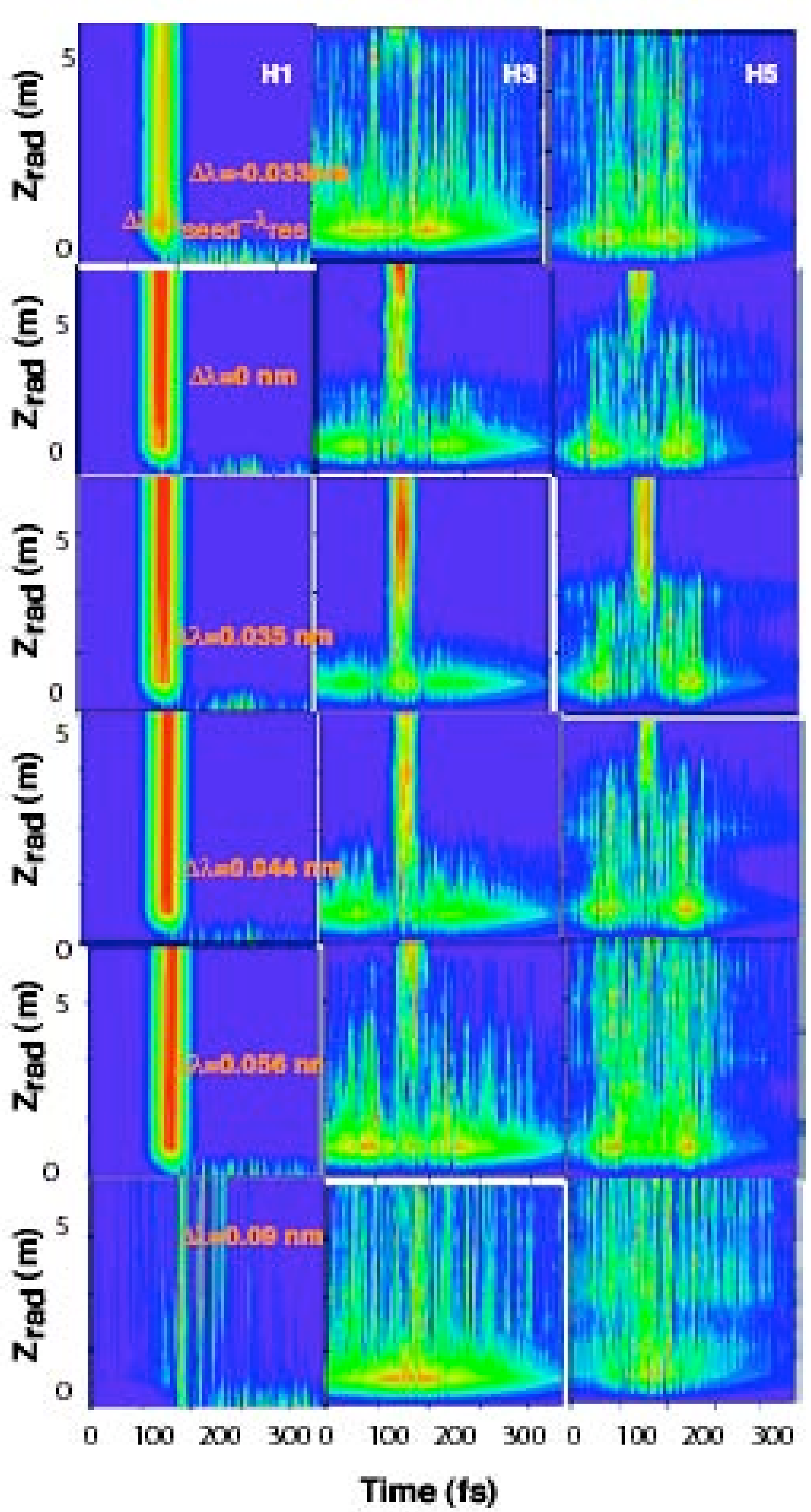




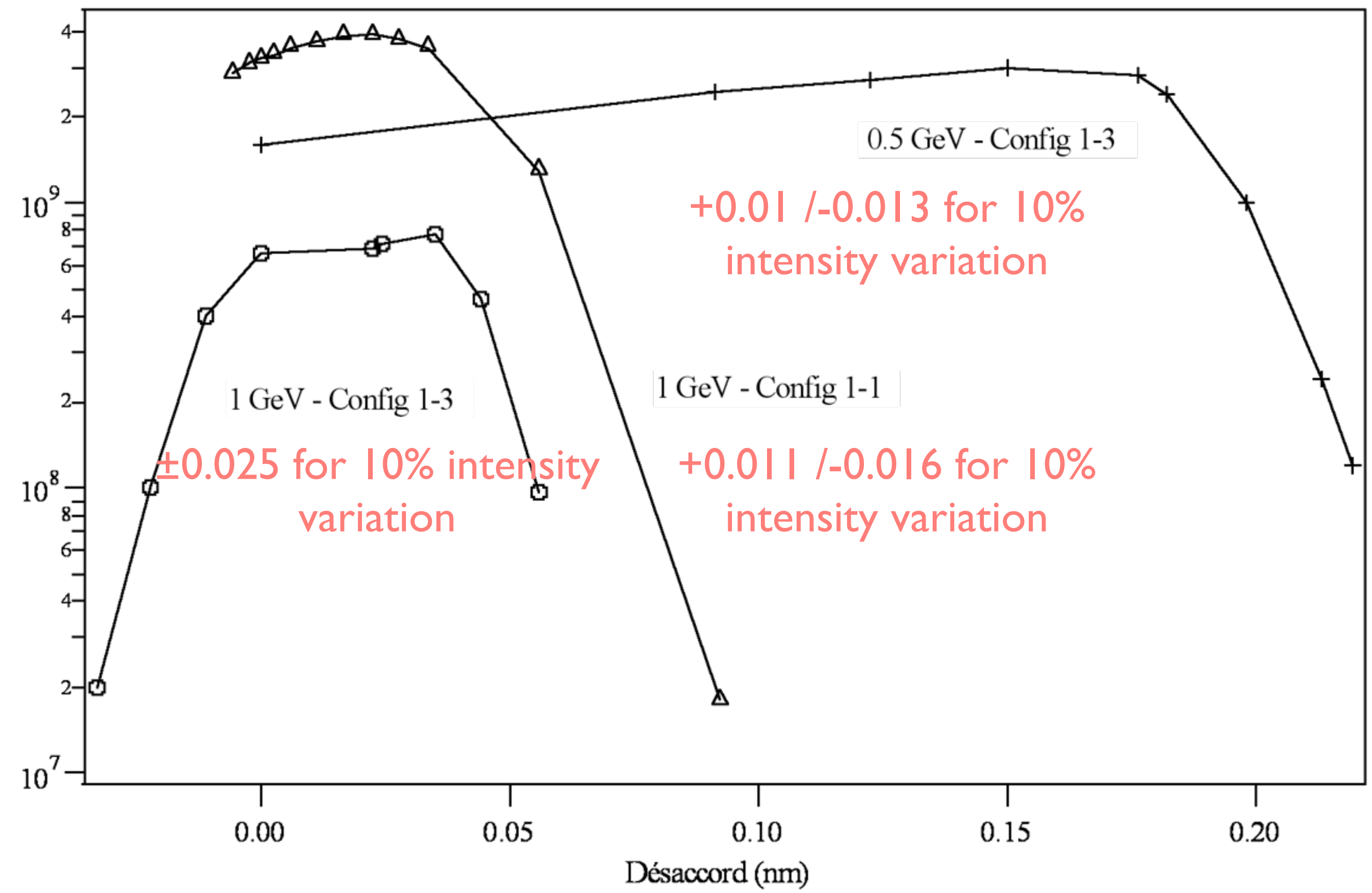


LEL2: study vs spectral tuning

seed 14 nm, 30 kW, config. 1-3



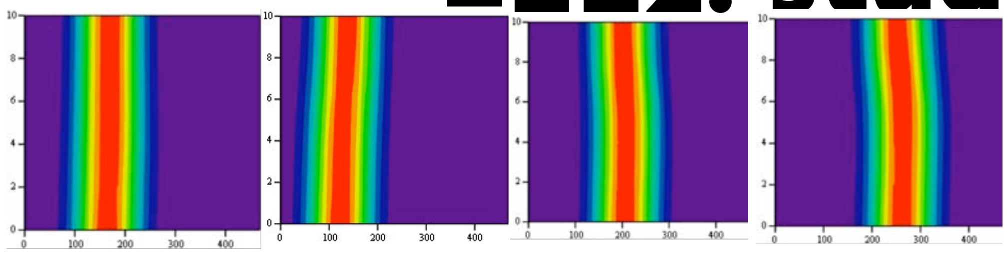
λseed-λres=-0.33 nm, non symetrical
e. start to escape from separatrix (lower energies)



λseed-λres=+0.35 nm
power optimum
(H3x100, H5x10)
slight reduction of pulse widths

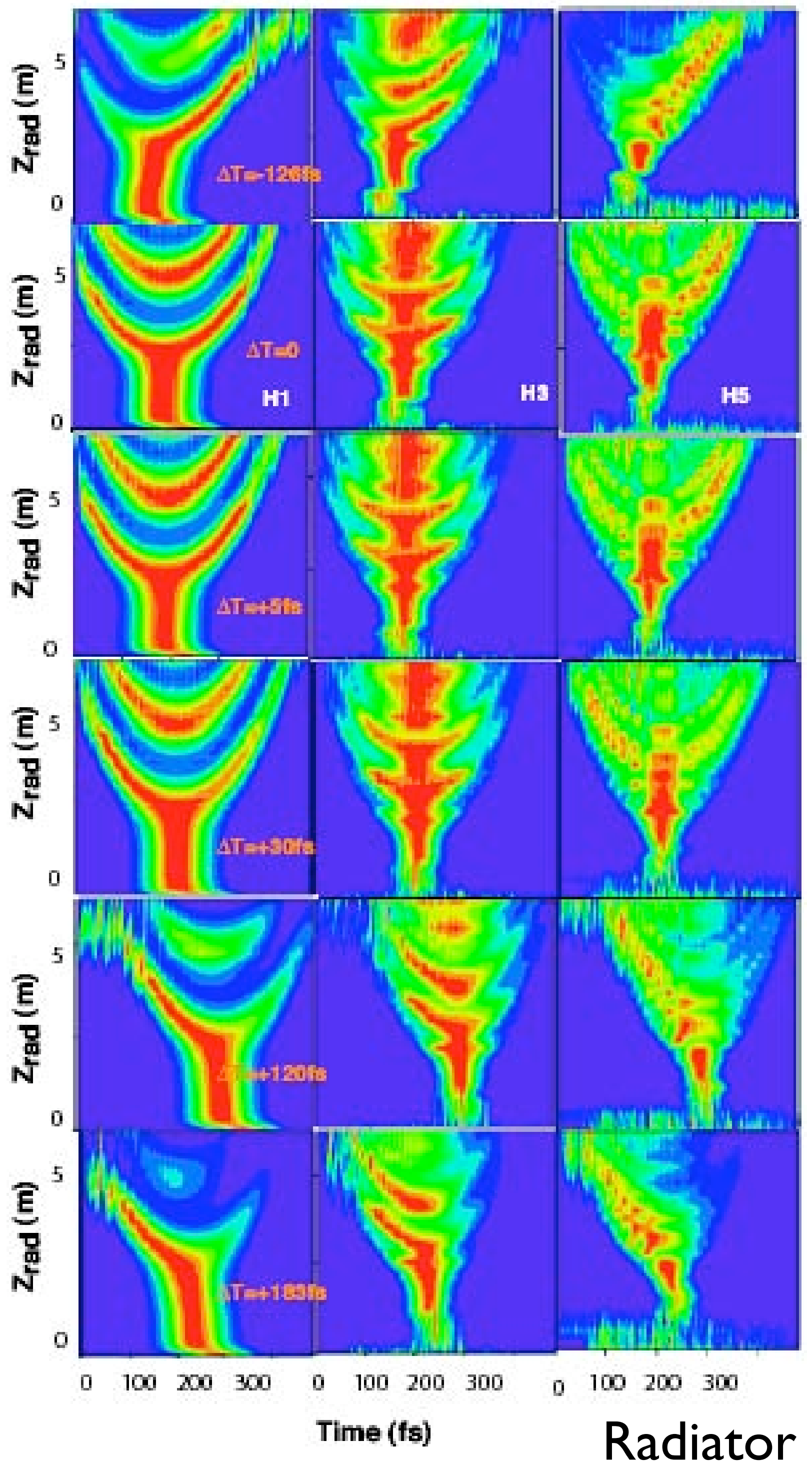
λseed-λres=+0.9 nm
radiation vanishes,
e. escape from speratrix

LEL2: study vs synchronisation

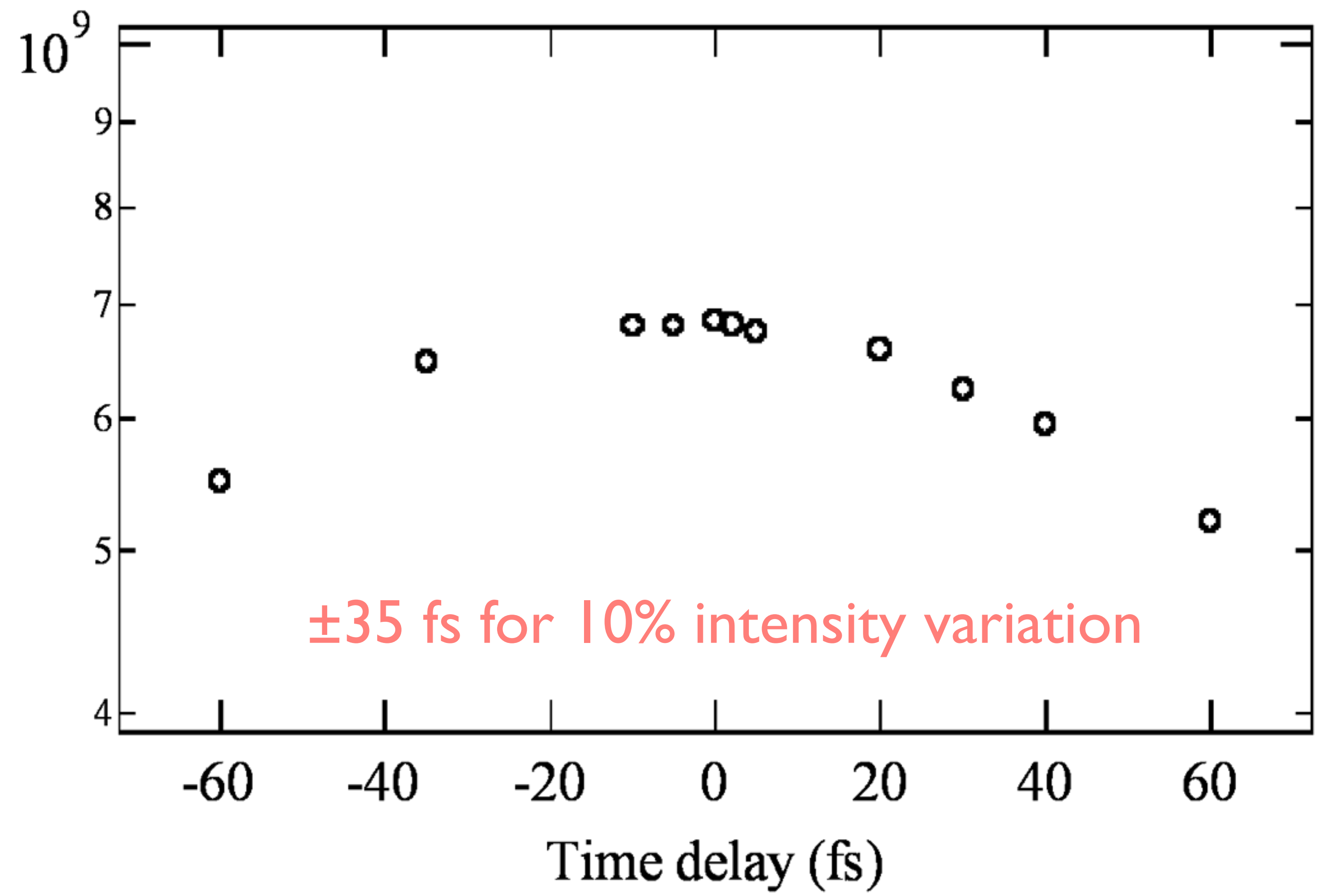


Modulator

Tseed-Telec= 0 fs -126 fs (-38 µm) +126 fs +200 fs



Radiator



ΔT=-126 fs (seed before e.), the pulse moves further forwards

ΔT=30 fs (e. before seed), the pulse moves backwards

ΔT=183 fs, the pulse moves further backwards

e bunch 200fs rms, laser 100 fs FWHM, Seed 14 nm, conf 1-3

ARC-EN-CIEL: RADIATION FROM P3

FEL oscillator

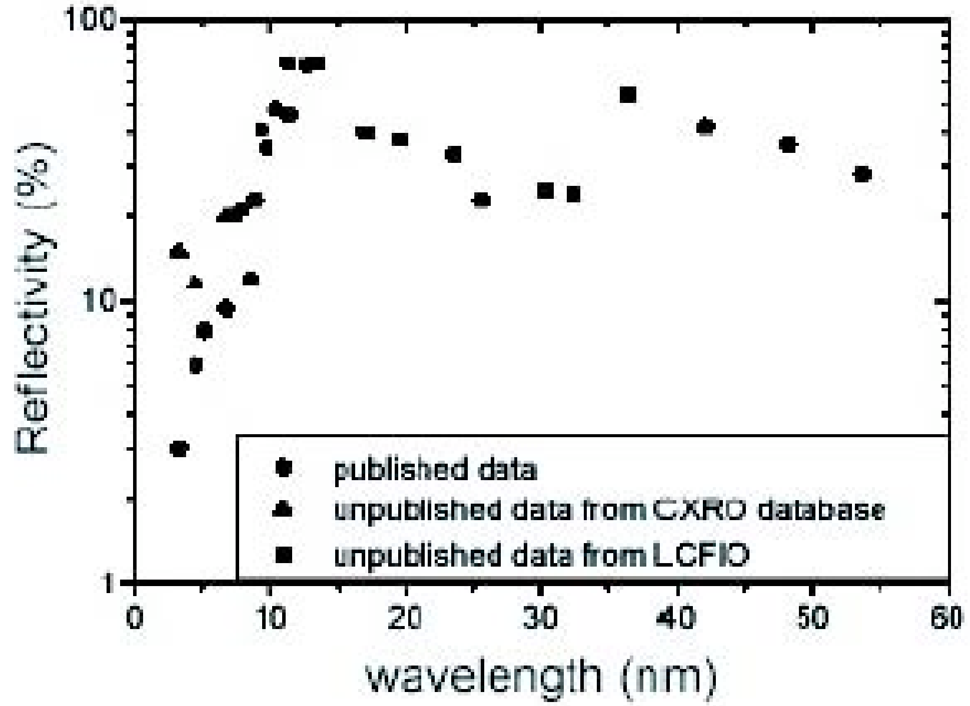
Optical cavity:

- cavity length 32 m, 4.5 MHz
- waist minimizing the mode volume along the interaction

$$\omega_o = \sqrt{L_{ond}\lambda / 2\pi\sqrt{3}}$$

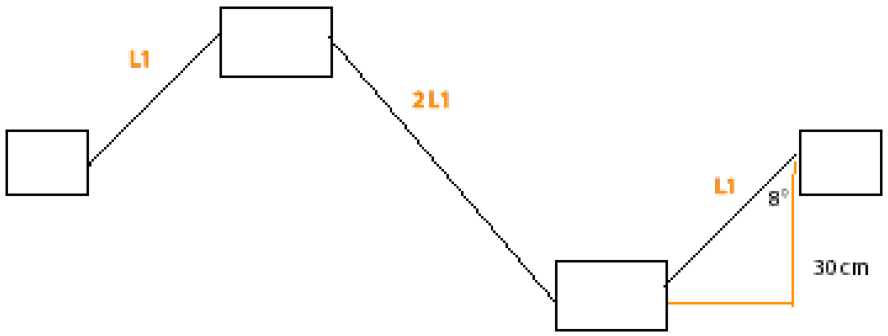
=> cavity length 32 m, 4.5 MHz
- waist minimizing the mode volume along the interaction
Rc= 16 and 20 m taken
- hole extraction : 10 % efficiency
- 2 kW maximum power absorbed
cryogenics cooling (cf SOLEIL beamlines)
- deformable mirror

=> further analysis with a longer resonator model of cooling



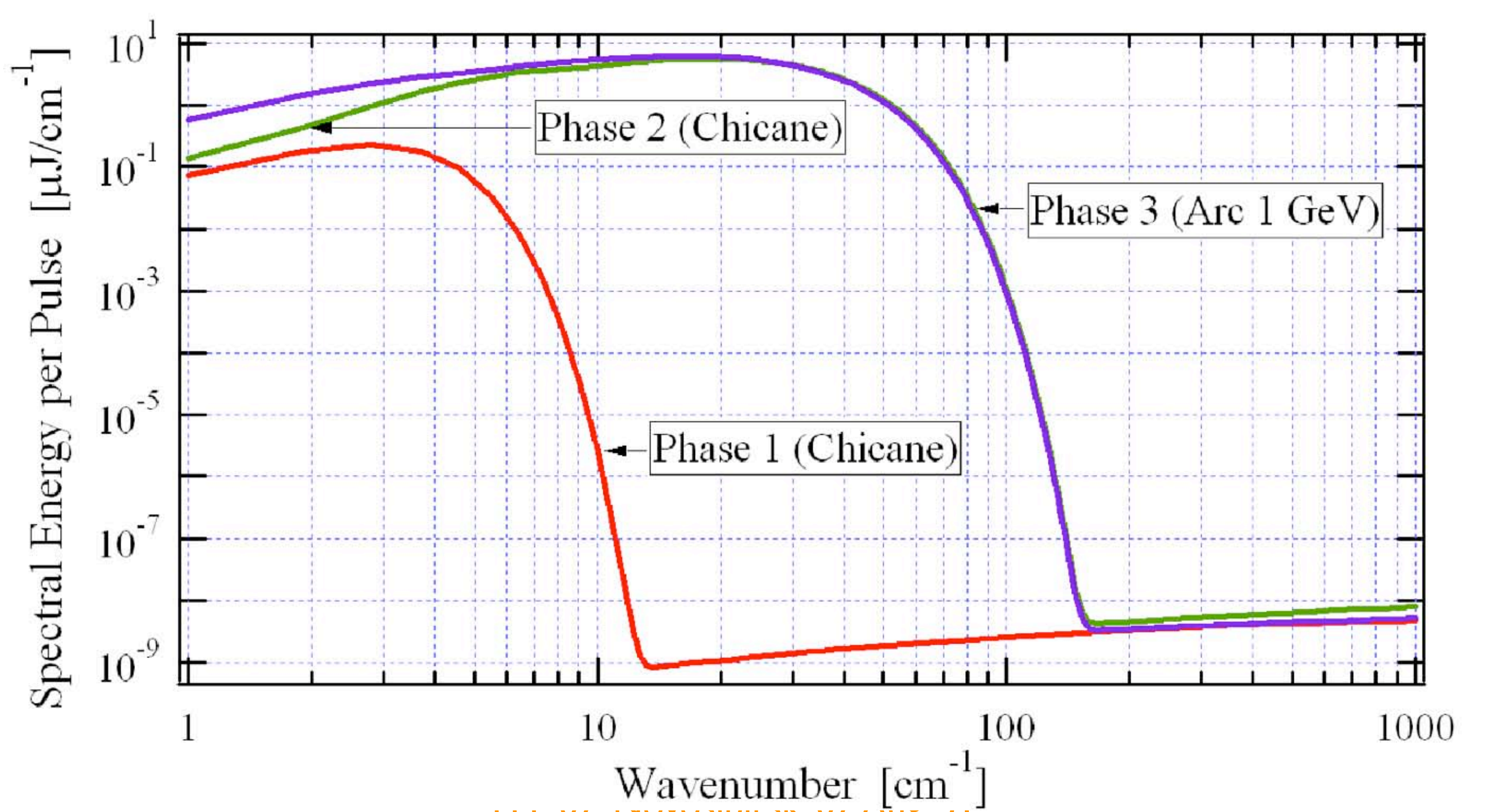
- Planar configuration : 40-26 nm (0.8-1.2 GeV), peak power 15-100 MW, average power 50-150 W (low Q) 200-400 (high Q)
- Helical configuration:13-8 nm, peak power 7-70 MW,/ 20-120 MW average power 30-300 W (low Q) 100-600 (high Q)

ARC-EN-CIEL: RAYONNEMENT THz Radiation



aimant 17°
B=0.165 T
r=2 m
L1 = 2 m

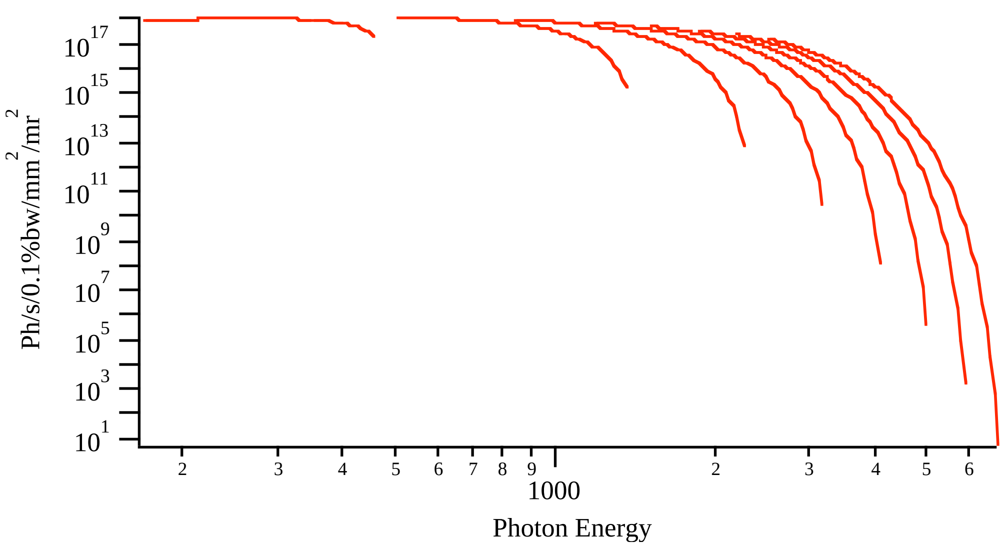
Phase 1 : 1 nC, 1-10 KHz
Phase 2 : 1 nC, 10 kHz
Phase 3 : 20 mA de courant moyen



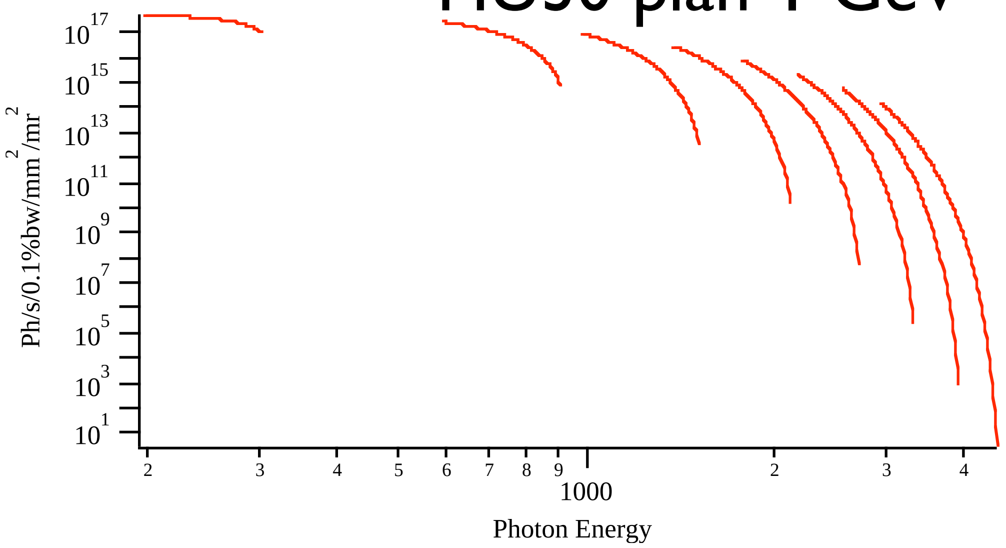
ARC-EN-CIEL: RADIATION FROM P3

Undultaors in spontaneous emission on the ERL loop
pulse duration <1 ps

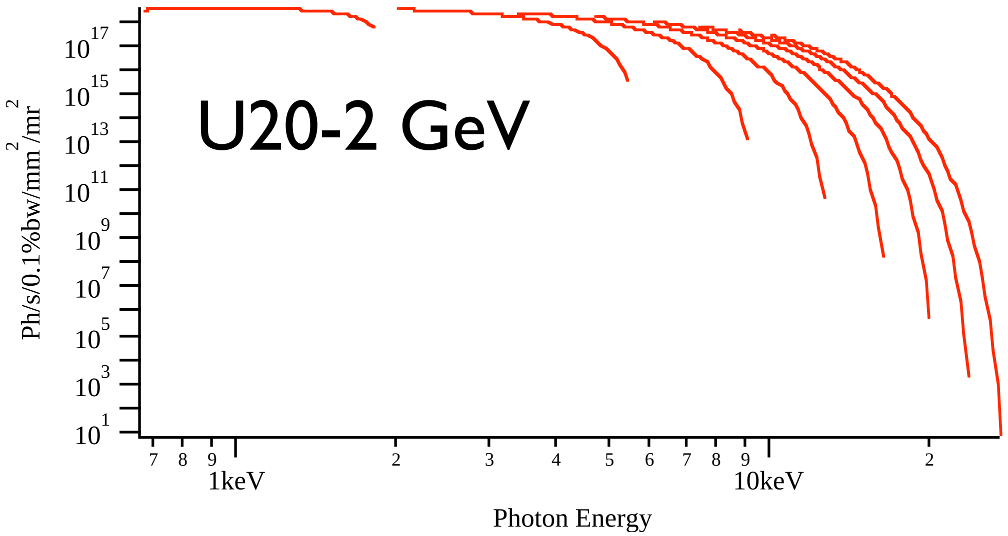
U20-1 GeV



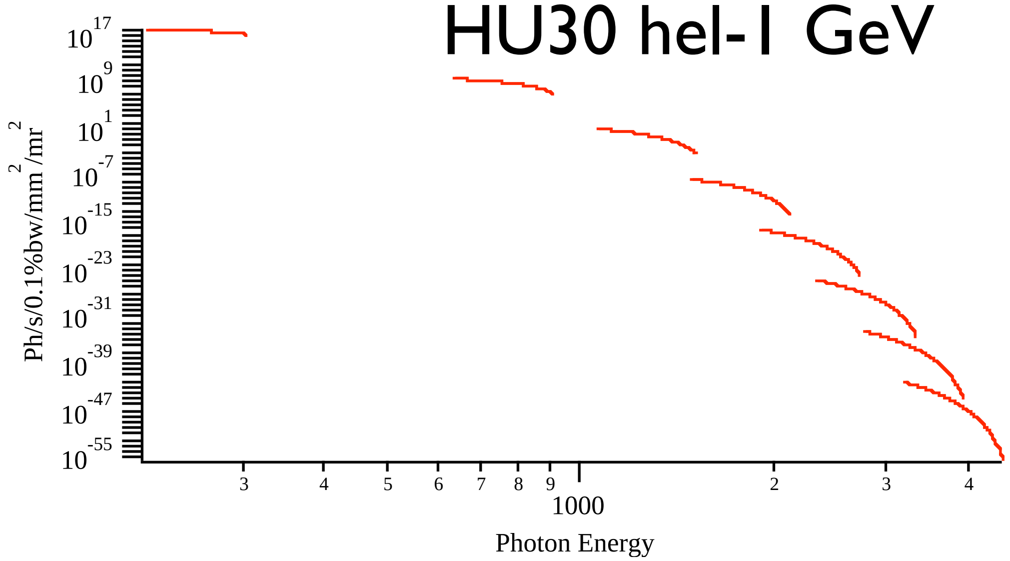
HU30 plan-1 GeV



U20-2 GeV

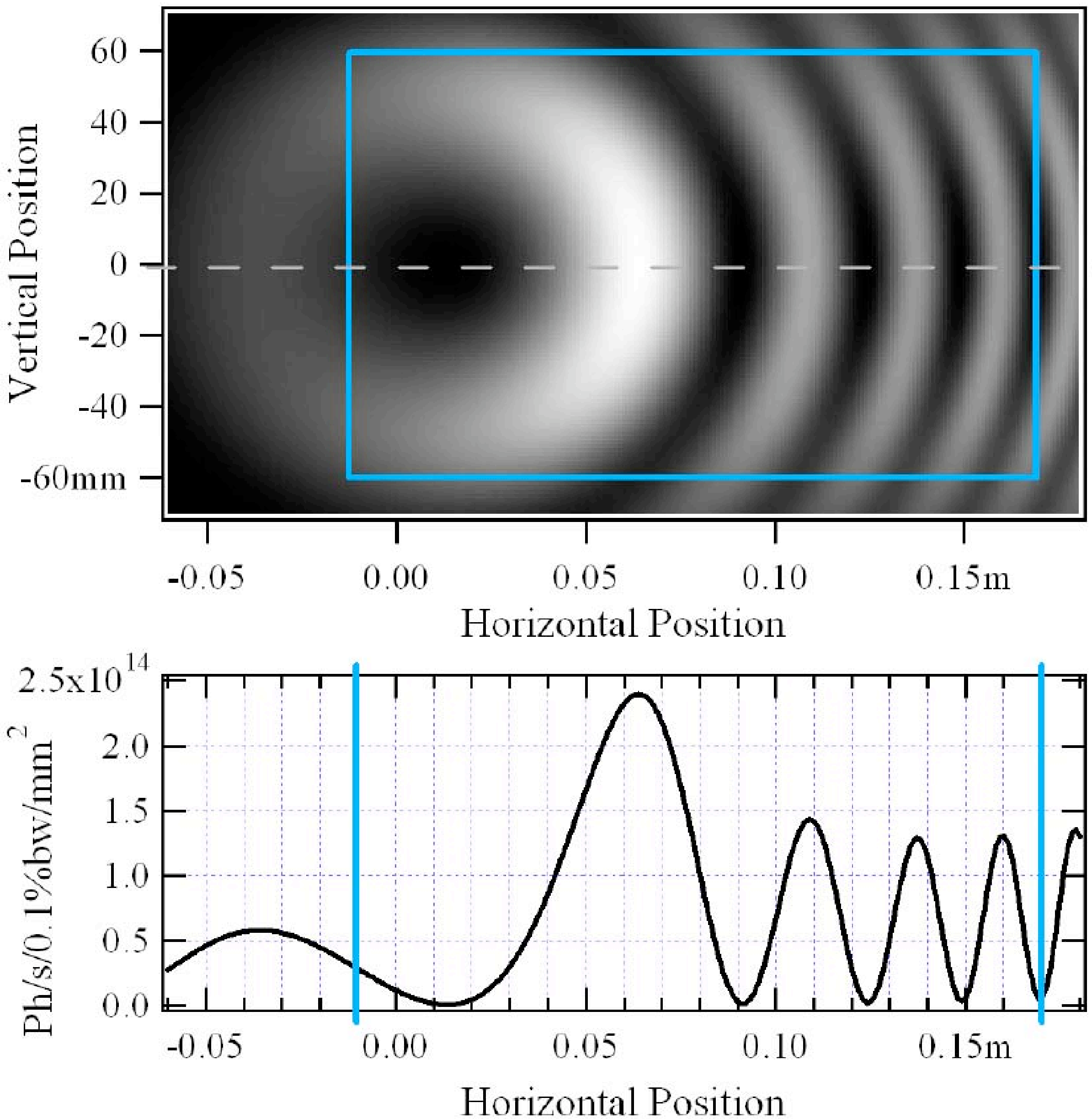


HU30 hel-1 GeV

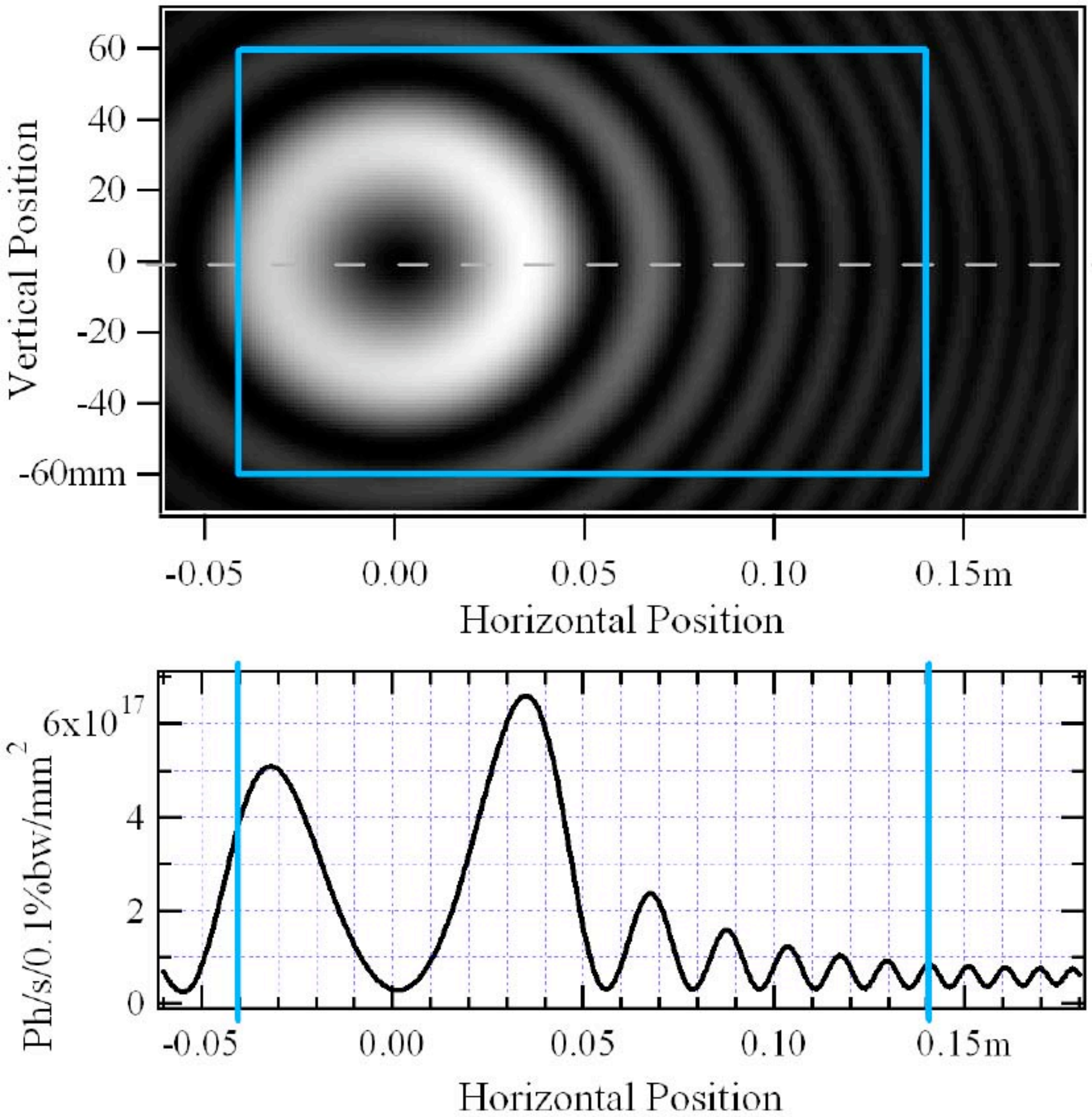


ARC-EN-CIEL: THZ RADIATION

O. Chubar



Phase 2 (edge radiation@1 THz)



Phase 3 (edge radiation@1 THz)

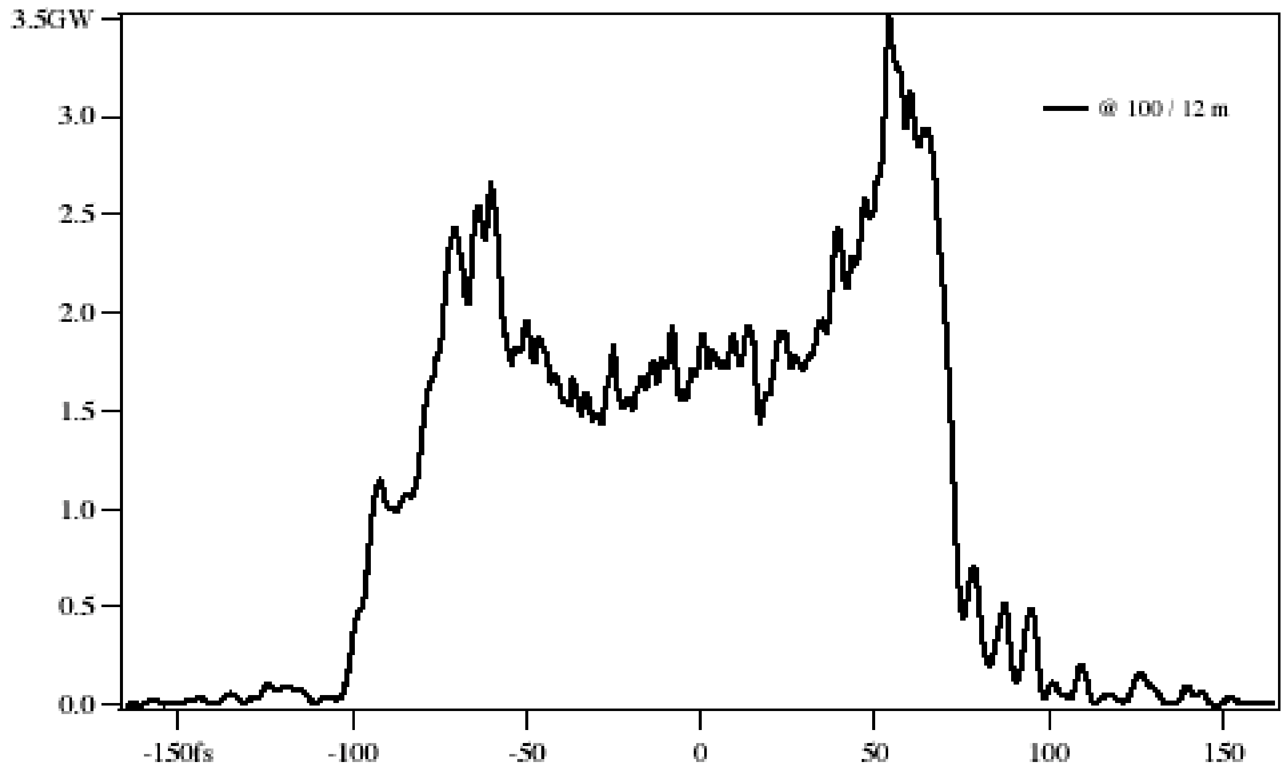
CONCLUSION

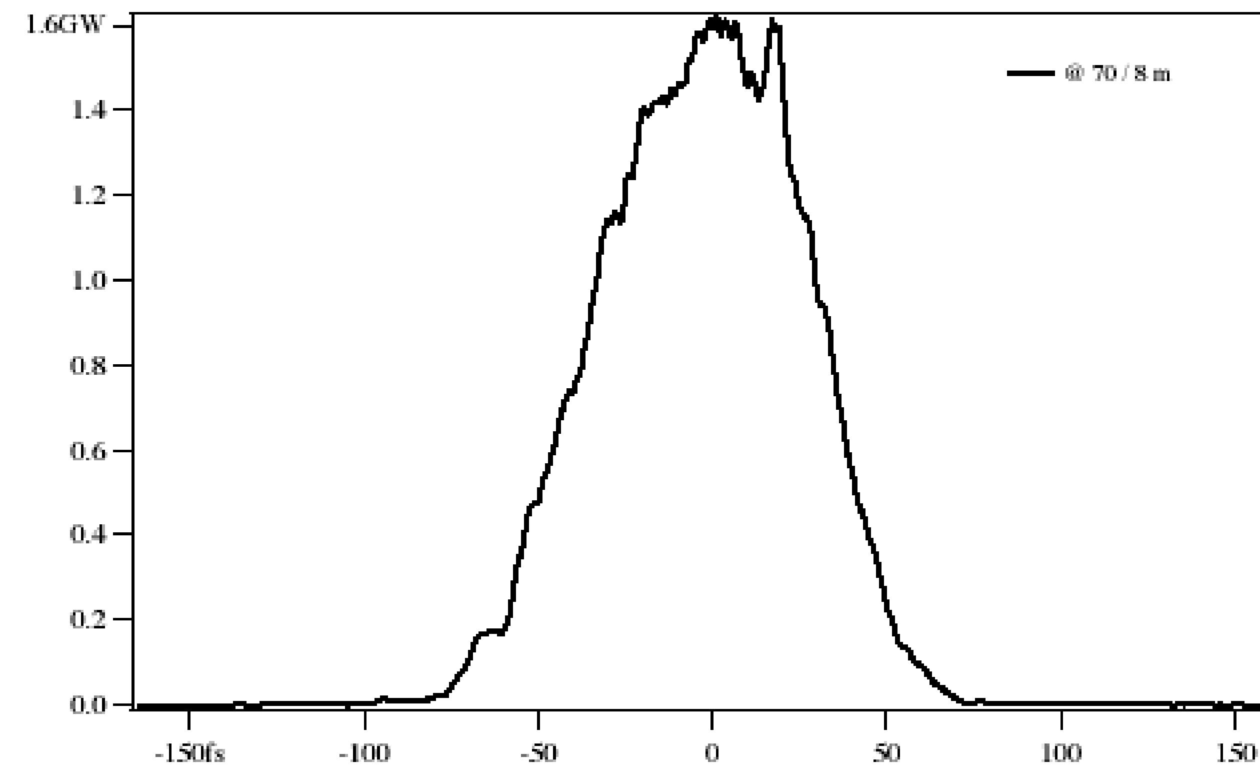
Experimental demonstration od seeding with HHG, in coll with SCSS team
=> confidence in our scheme

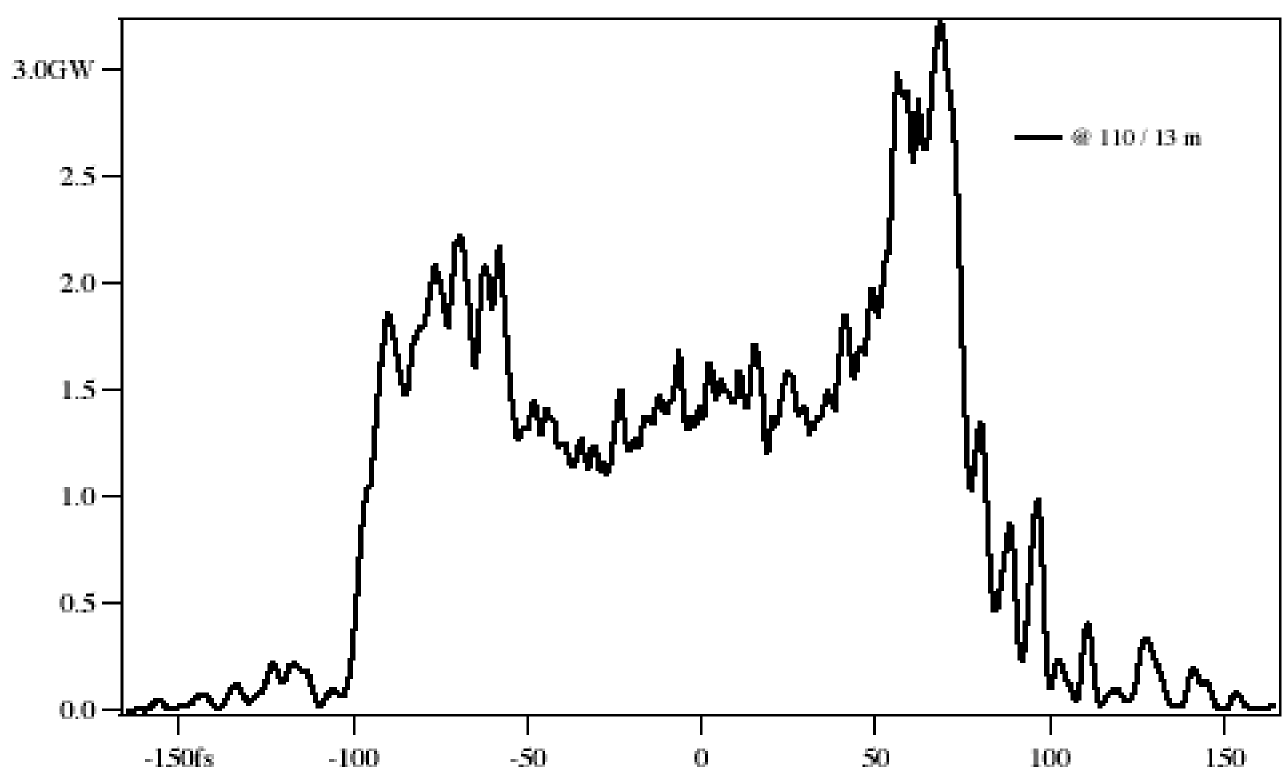
French roadmap on Large Scale Facilities
ARC-EN-CIEL CDR to be submitted

Next step : TDR, according to the result of the French roadmap and R&D in parallel

TEMPORAL PROFILES







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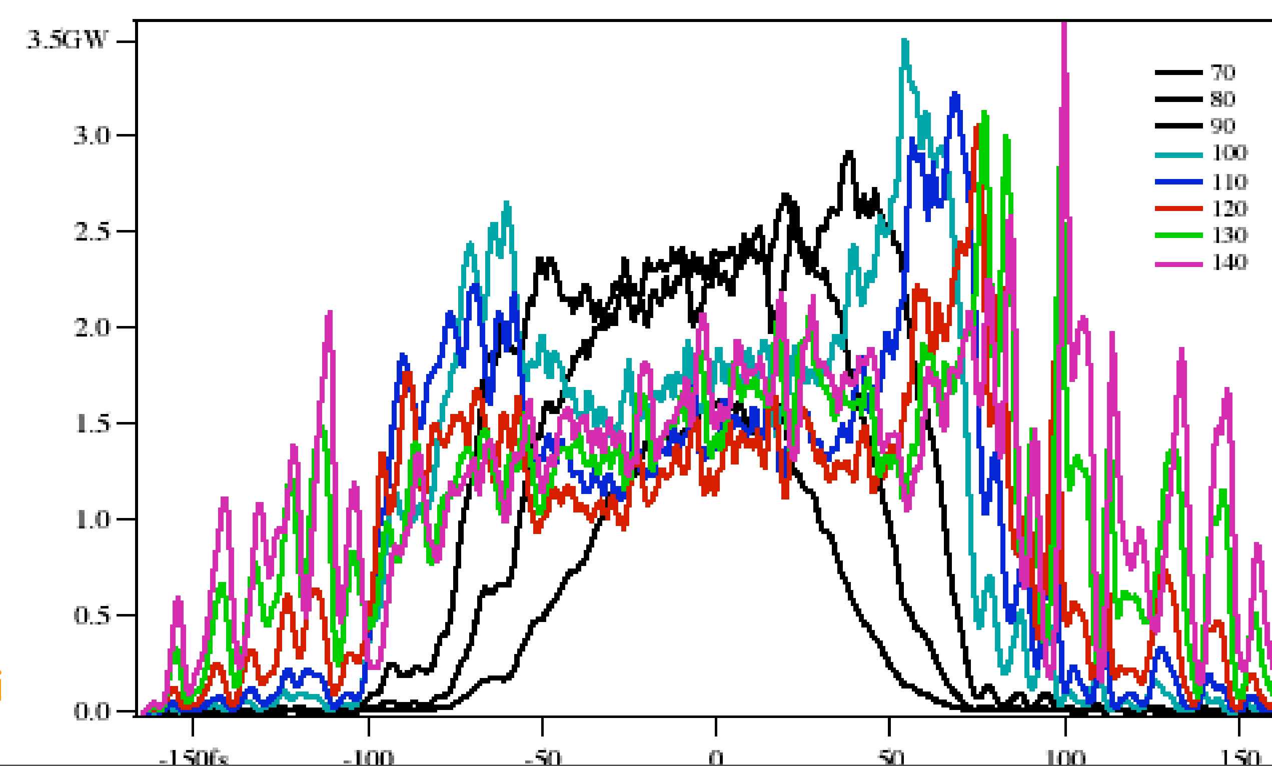
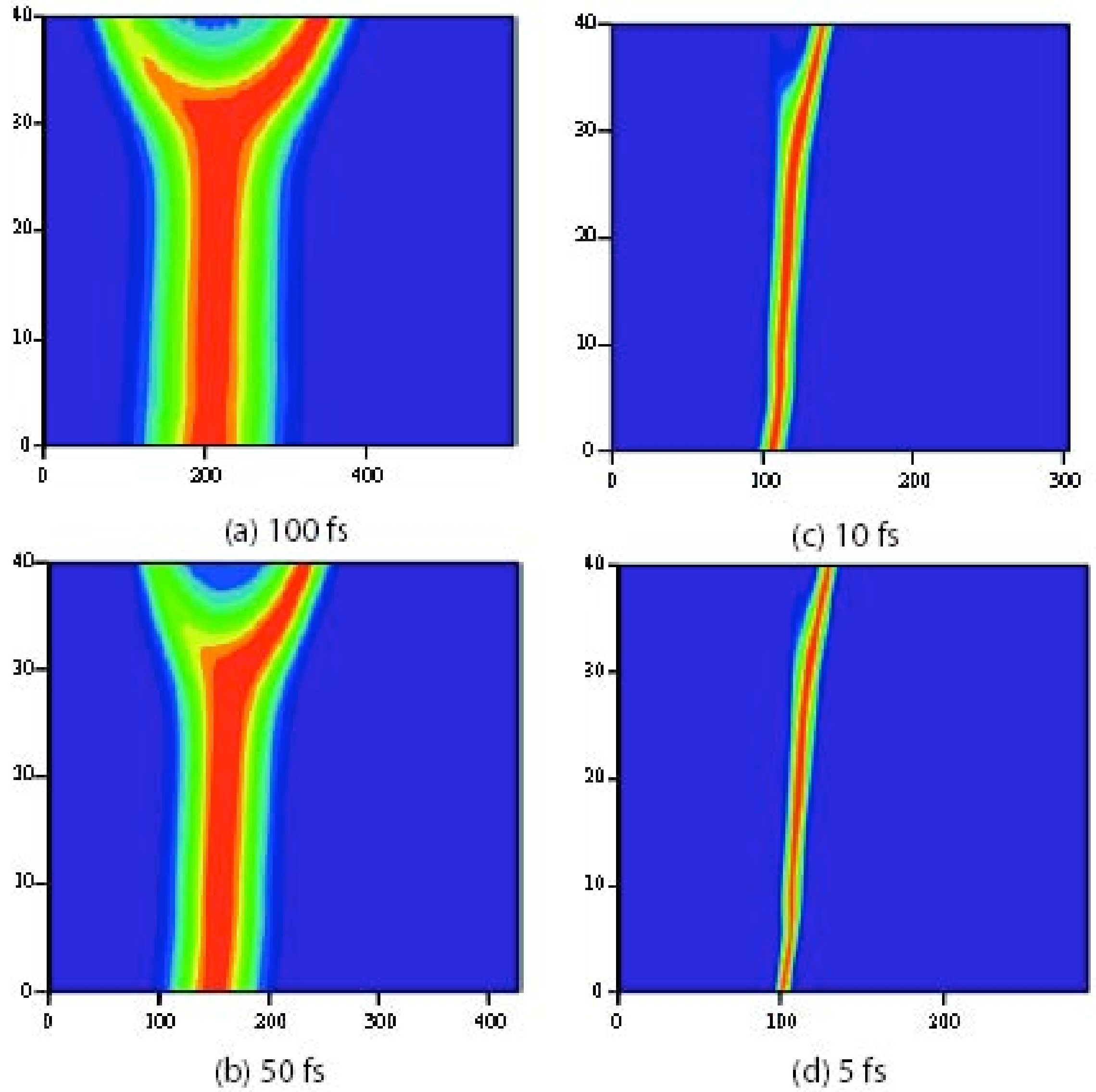


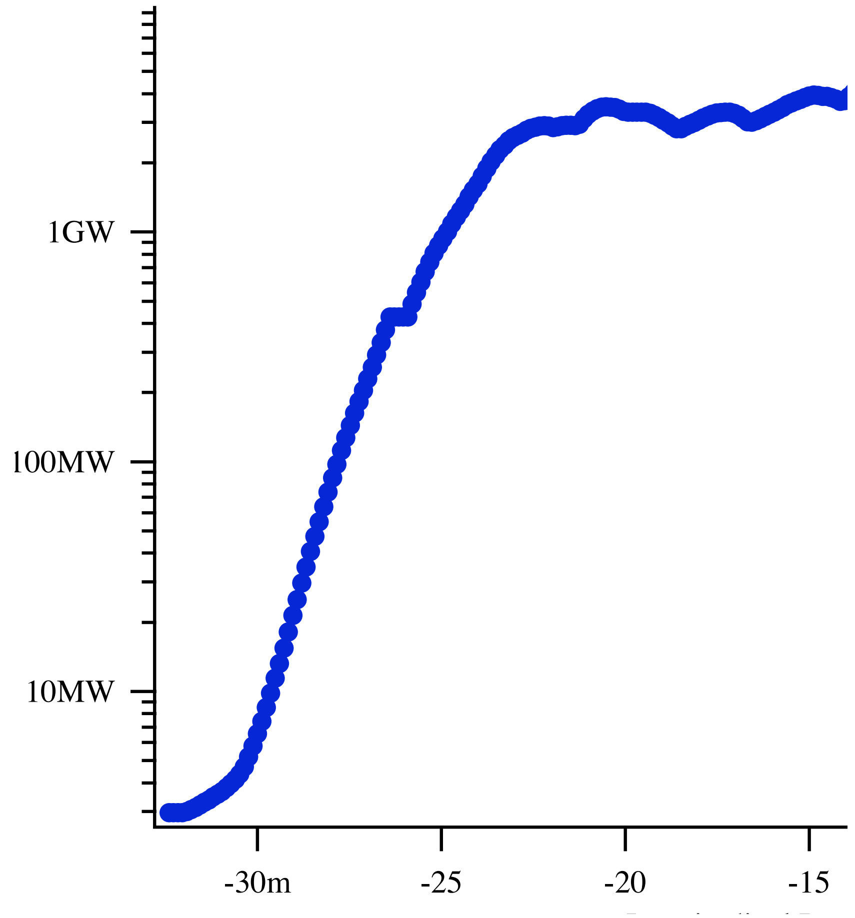
DYNAMICS- LEL2

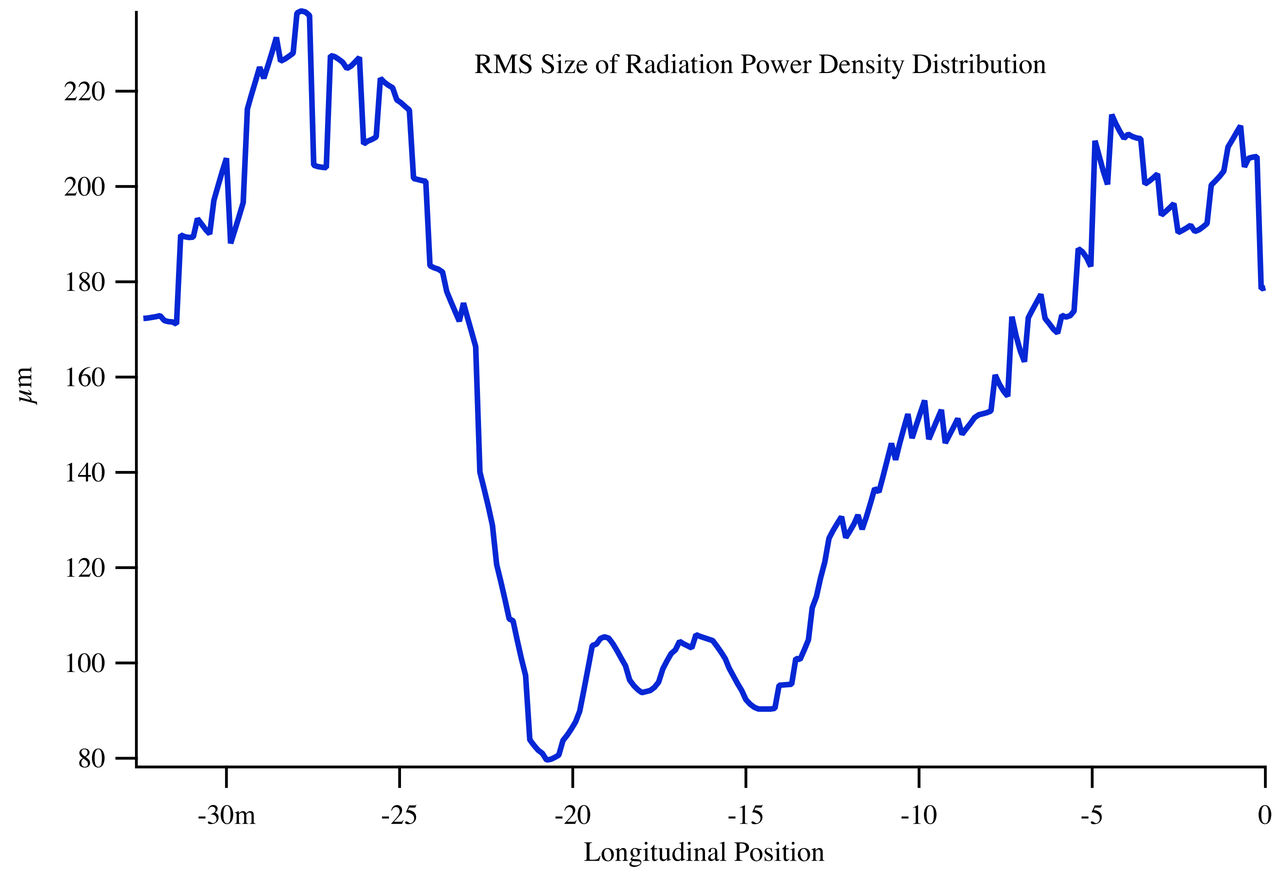
Seed 12 nm, conf 1-1, 50 kW
Dependance versus the pulse seed duration



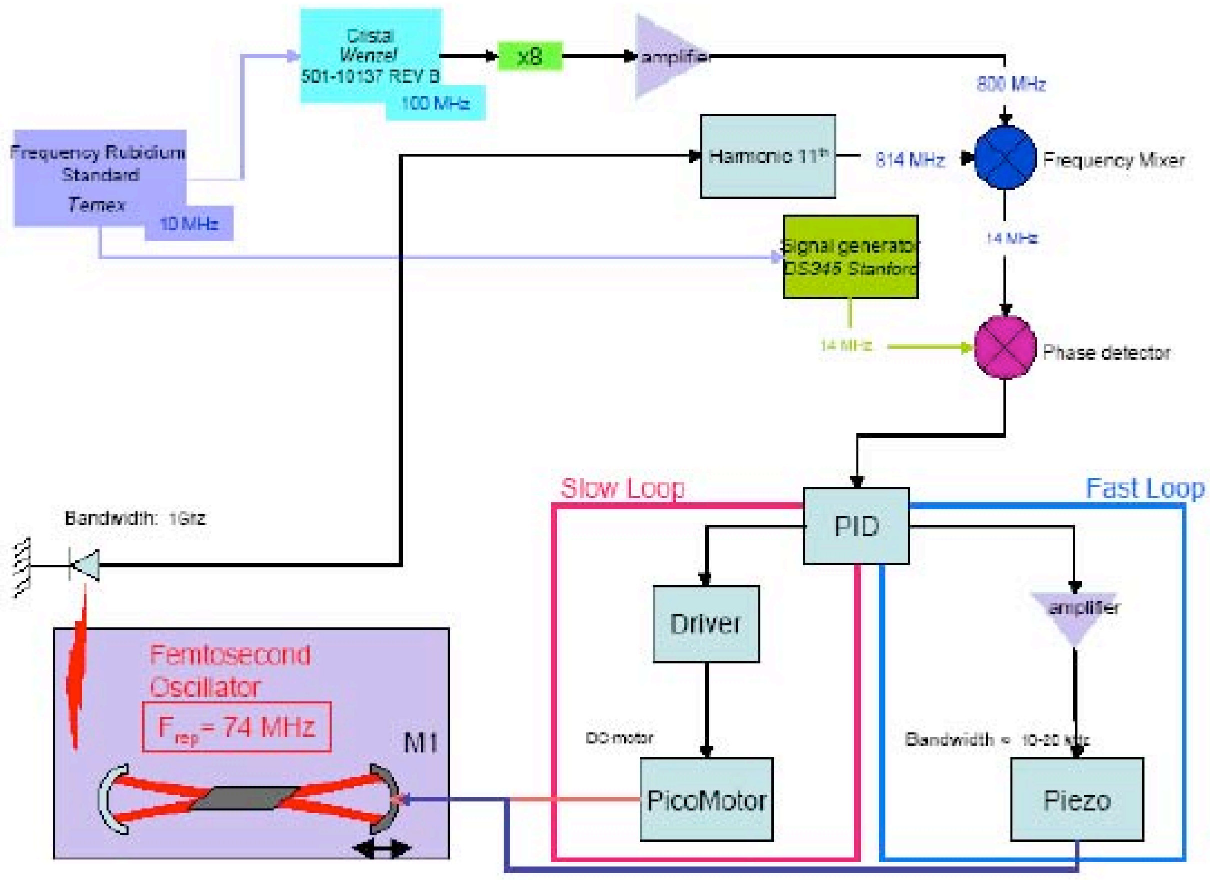
DYNAMICS- GENESIS CALCULATION

Standard case Case LEL1@1 GeV : Seed 12.3 nm, conf 1-1





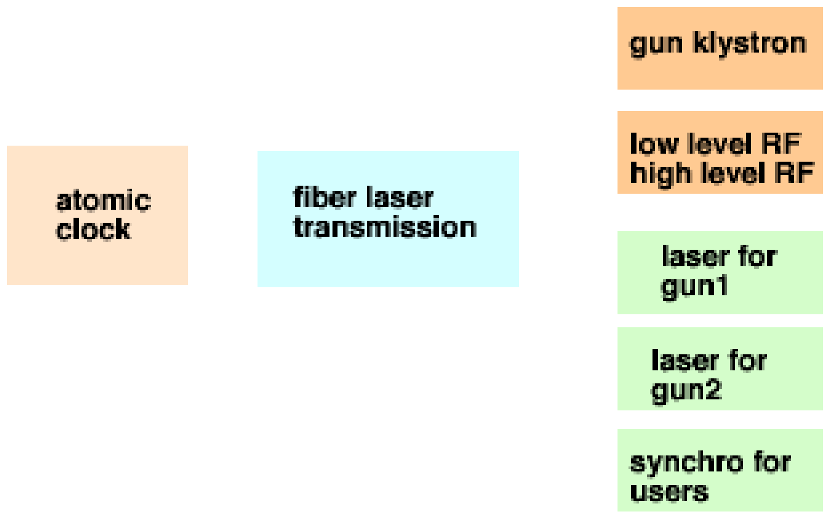
ARC-EN-CIEL: SYNCHRONISATION

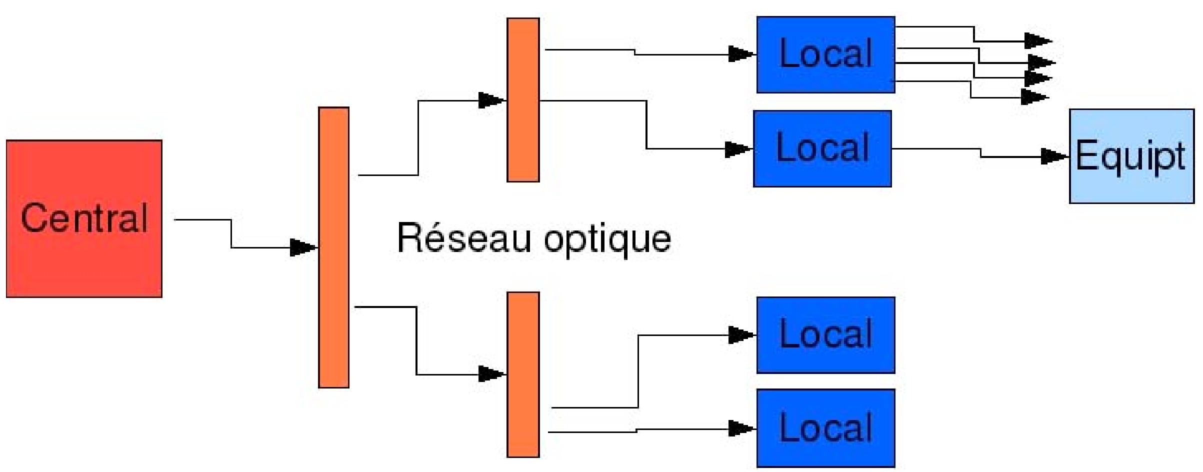


System of frequency stabilisation dof the Ti:Sa oscillator with a reference given from an atomic clock

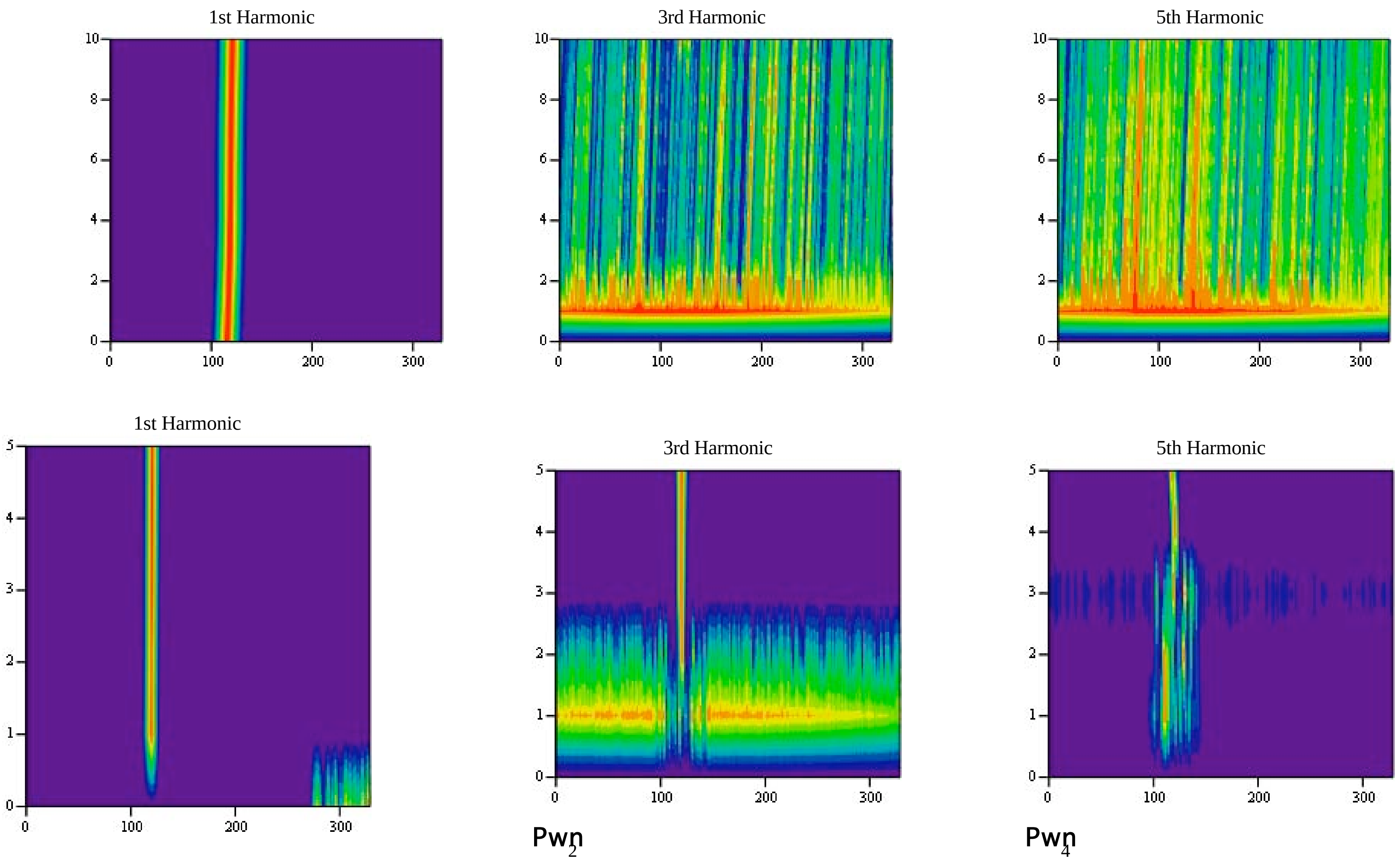
Under study in CEA- EUROFEL
see poster O. Gobert

Fiber transmission





3 GeV BRANCH, seed 4 nm, 100 kW, 10 fs



After Modulator

H1@4 nm, 0.06 μJ,
5 fs rms, 0.028%

After Radiator

H1@0.8 nm, 60 nJ,
5 fs rms
H3@0.26 nm
H5@0.16 nm

Further analysis on transverse coherence

1.5 kA, 3 GeV, 0.02% 1.2 pi, 0.06 mm, 0.75 nC
Und1 : period 3.5 cm, K1=6 (4), N1=200 (seed 10 nm) - 400 (seed 4 nm), Beta =2.6 m,Ff=0.1
Und2 period 1.8 cm, K2=3.6 (2.73), Lambda2=1.9 nm, N2=1000, Beta =2.6 m, Ff=0.1

Config 1_5, Dispersive section R56=5e-4, Nd=130