SEEDING FELS IN THE SOFT X RAY REGION OF THE SPECTRUM

L. Giannessi, M. Quattromini, C. Ronsivalle, ENEA, Frascati Italy
P. Musumeci, J.B. Rosenzweig, University of California, Los Angeles, USA
G. Sansone, S. Stagira, M. Nisoli e S. De Silvestri, Politecnico di Milano, Milano, Italy
M. Ferrario, C. Vaccarezza INFN-LNF, Frascati, Italy
L. Poletto, CNR-INFM, Laboratorio LUXOR & Dip. di Ing. dell'Informazione, Padova, Italy

FEL Frontiers 07
International Workshop on
Frontiers in FEL Physics and Related Topics

E

Outline

- Introduction
- FEL amplifier and shot noise
- Seed requirements
- SPARX examples of seeded operation
- SPARX configuration in SASE mode

Seeded FELs & Stability

- A seeded FEL is not affected by intrinsic fluctuations as SASE

BUT

Any change in the input parameters as seed power, beam energy, current, beam quality, alignment, time jitters, induces output fluctuations (beam characteristics have to be “stable” at the cooperation length scale

Resonant process

$$\lambda_0 = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

$$\lambda_0 \cong \lambda_{seed}$$

Stability

- The “parameter” mismatch may be “local” along the electron bunch
  - Coherence degradation
  - Local “early” saturation -> superradiance
  - -> Spectral broadening … spiking … as in SASE
- “Parameters” stability has to be ensured down to the scale of a cooperation length
- Stability becomes more & more critical with the number of stages of the cascade

The trade for short wavelengths

- Long wavelength seeding (200-300nm) – Solid state lasers

Large seed energy
but
multiple stage cascade

↔

Single stage cascade
but
Low seed energy and shot noise

- Short wavelength seeding (10-30 nm) – High Harmonics generated in gas (HHG)

Seeding at short wavelength

- Issues:
  - The seed power required to overcome the shot noise scale with the inverse of the wavelength: Shot noise "equivalent power" *(e.g. Giannessi FEL 2004)*

$$P_0 \approx \frac{4}{5}\rho^2\omega_0 E_{beam}$$

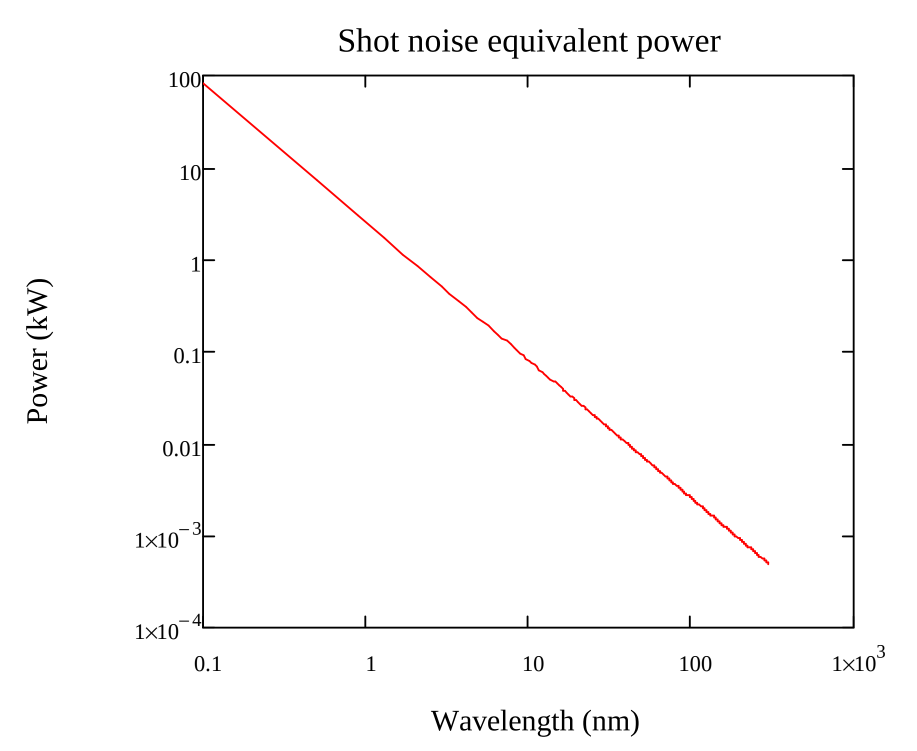
  - Transverse coherence
  - Longitudinal coherence
    - Structure of the pulse
    - Coherence length of the seed pulse
  - Stability

Shot noise equivalent power vs. wavelength

Statistics of radiation from a seeded FEL amplifier

$$P_0 \approx \frac{4}{5}\rho^2\omega_0 E_{beam}$$

@ constant K, λ, ρ



Case label	***A***	***B***	***C***
Wavelength (nm)	50	15	5
Undulator K (peak)	2.2	2.2	2.2
Energy (MeV)	500	900	1550
En. spread (MeV)	0.4	0.4	0.4
I_{peak}(A)	500	800	1500
N. emitt.(mm-mrad)	1	1	1
Σ_b (mm^2)	3.2×10^{-2}	1.8×10^{-2}	1.04×10^{-2}
Pierce parameter ρ	2.86×10^{-3}	2.26×10^{-3}	1.94×10^{-3}
I_0, (W/cm^2)	4.4×10^4	2.9×10^5	1.9×10^6
Sim. window (µm)	250	200	200
Sampl. period (µm)	0.625	0.5	0.5
Sim. bandwidth	4%	1.5%	0.52%

Statistics of radiation from a seeded FEL amplifier

First order correlation function

$$g_1(\tau) = \frac{\langle \tilde{E}(t)\tilde{E}^*(t+\tau)\rangle}{\sqrt{\langle |\tilde{E}(t)|^2\rangle\langle |\tilde{E}(t+\tau)|^2\rangle}}$$

Temporal coherence

$$z_c = c\int_{-\infty}^{+\infty} |g_1(\tau)|^2 d\tau$$

MAXIMIZED along the UM

Second order correlation function

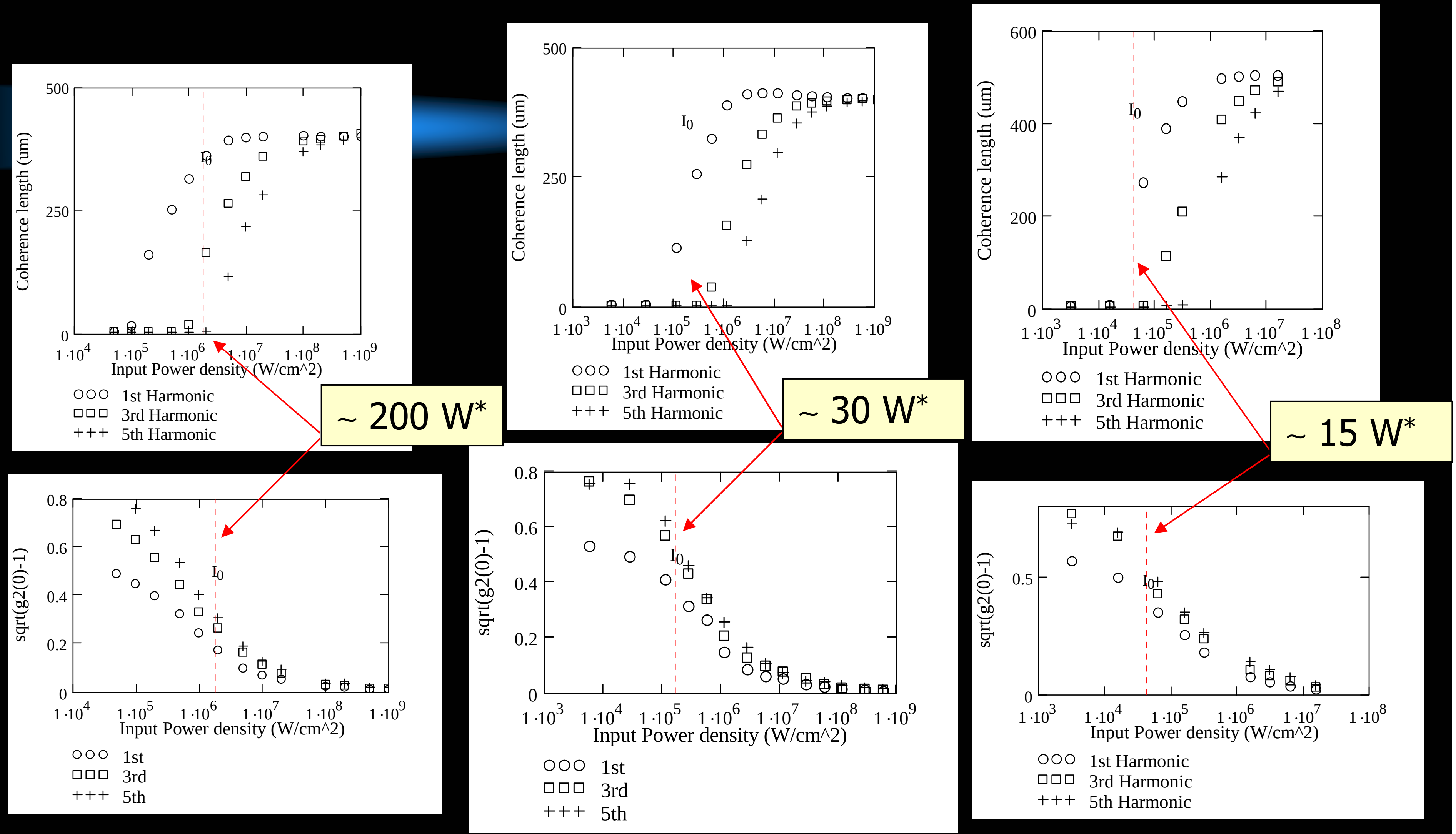
$$g_2(\tau) = \frac{\langle |\tilde{E}(t)|^2 |\tilde{E}(t+\tau)|^2\rangle}{\langle |\tilde{E}(t)|^2\rangle\langle |\tilde{E}(t+\tau)|^2\rangle}$$

Intensity fluctuations

$$\sqrt{g_2(0)-1} = [I/\langle I\rangle]_{RMS}$$

MINIMIZED along the UM

Effect of seeding on 1° and 2° correlation functions



5 nm

15 nm

50 nm

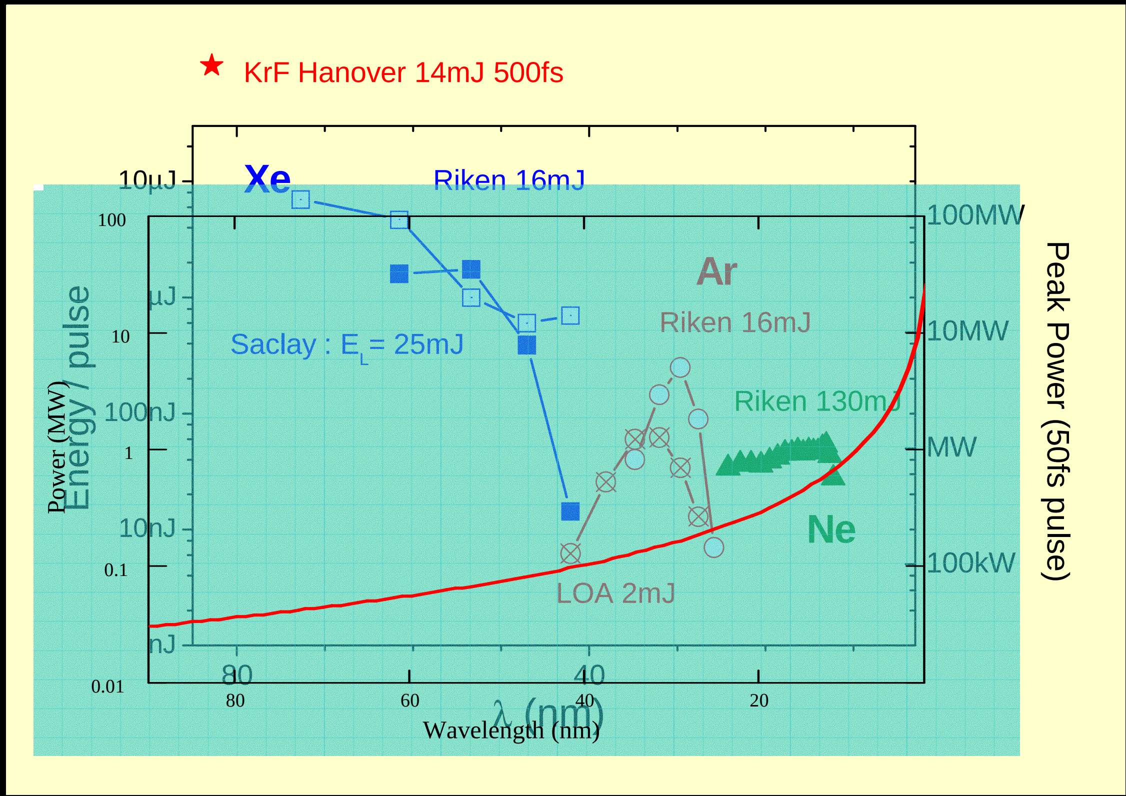
*Power corresponding to perfect matching with e-beam size

Other requirements

- Contrast ratio - S/N ratio ($x10^2$ – $x10^3$)
- Transport optics to the beam (x5)
- Transverse matching: Shot noise calculated in a simplified 1D picture, the power is the fraction really coupled with the electrons (x2-3)
- Frequency matching (Harmonics spectrum broader than ρ …(x10) or of the desired seed bandwidth ($x10^2$-10^3)

Factor: $x10^4$ ($x10^5$ - $x10^6$)

Harmonics generated in gas



Shot noise equivalent power ***x 10⁴***

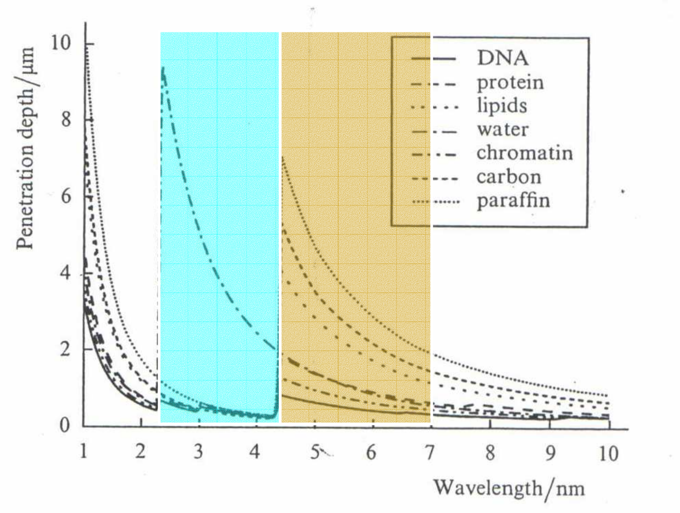
SPARX 1-15nm

- Input from SPARX workshops:

  Wavelength range down to the water window (~ 2.5 – 4.5 nm) and below …

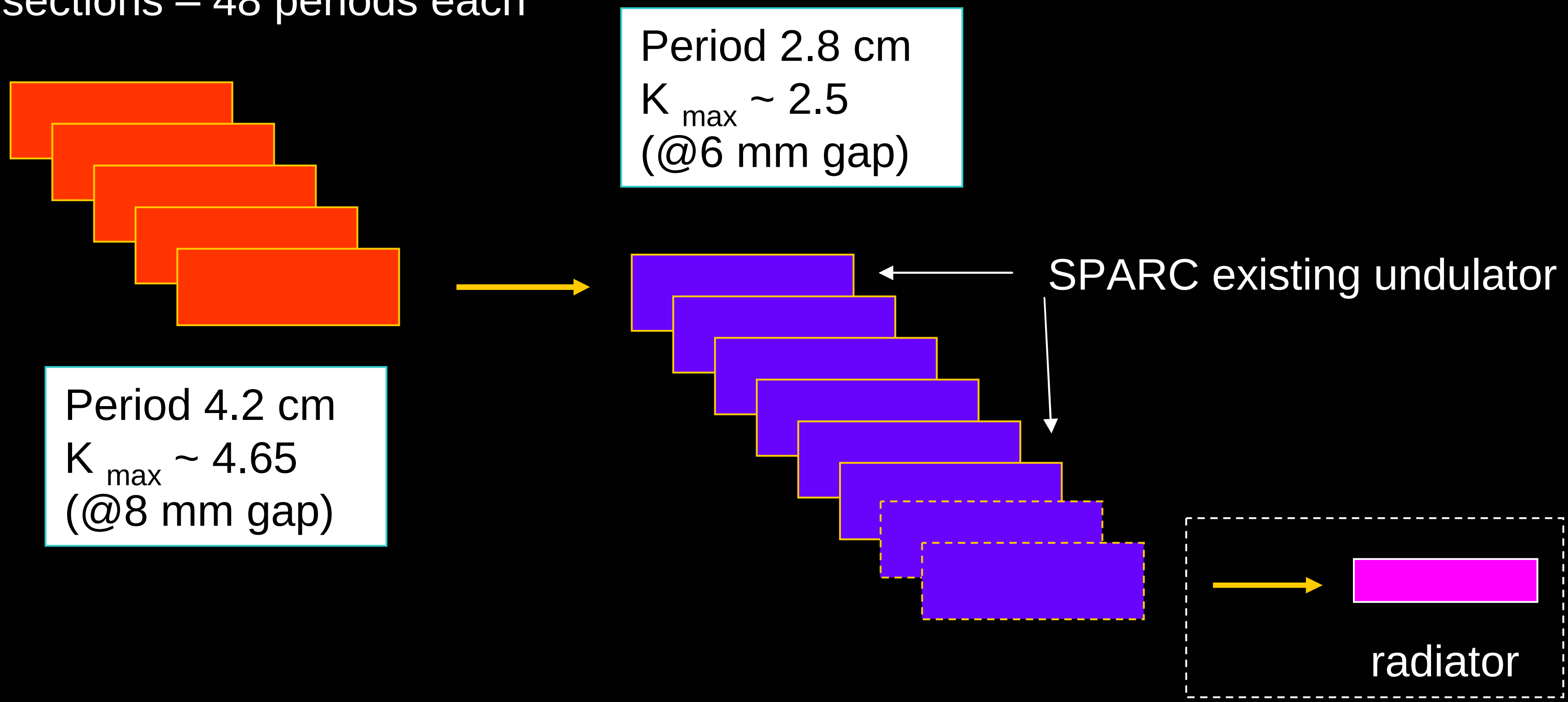
- Flexible design:

  SASE & Seeded configurations
  - Improve coherence length
  - Short pulses (fs range)
  - Increase wavelength operation range



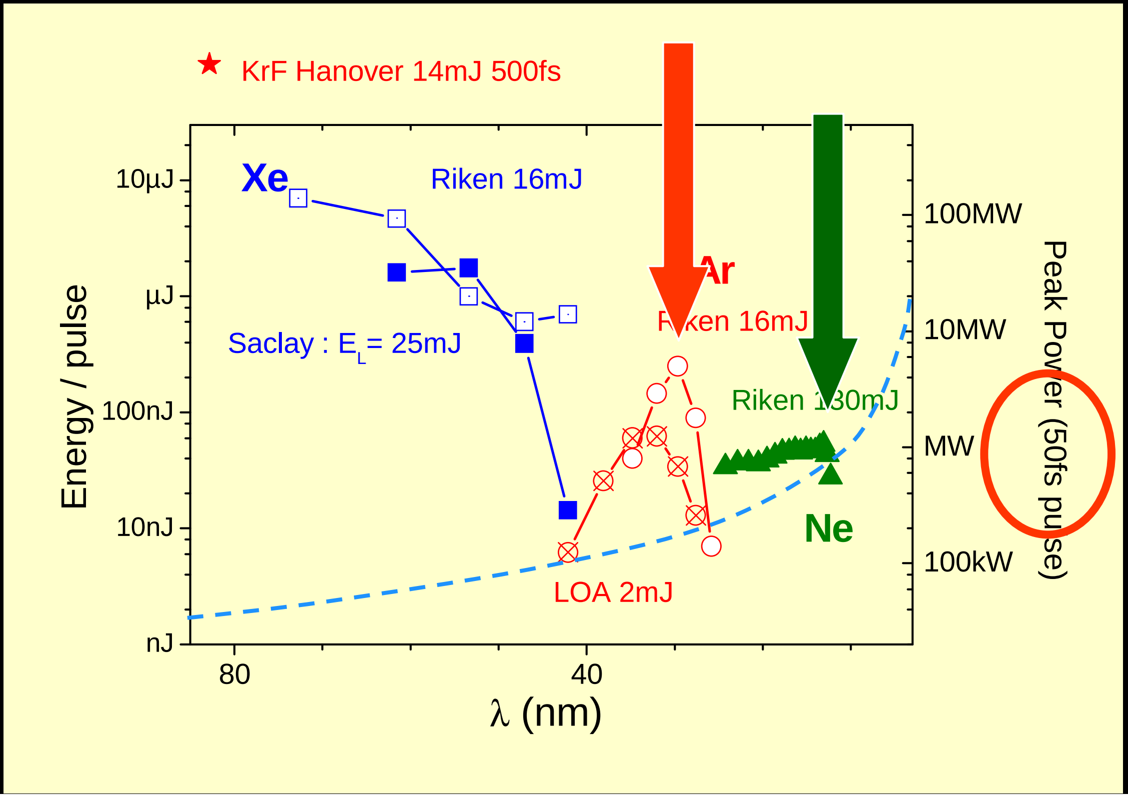
SPARX undulator option

5 sections – 48 periods each



Seeded SPARX *examples*

Seeded SPARX



- Ne
  - Short pulse seeding
  - Low harmonic multiplication factor (x3 and x6)
- Ar
  - Monochromator
  - "Long" pulse seeding
  - Higher harmonic multiplication factor (x6 and x8)

Seeding with Ne @ 13.5 nm

Ne (after matching to the e-beam)

$\lambda \sim 13.5$ nm
E ~ 2 nJ
P ~ 35 kW
$\delta t \sim 50$ fs ~ 6 μm

X 3 X 2

→ UM1 MOD. → UM2 (SPARC) → UM3 (SPARC)

UM1 MOD.
$\lambda_u = 4.2$ cm
K = 3
5 UM
48 periods each
$\lambda_{res} \sim 13.5$ nm

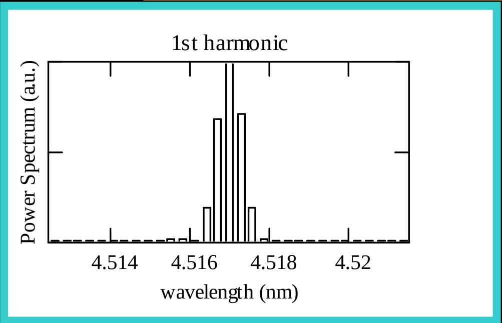
UM2 (SPARC)
$\lambda_u = 2.8$ cm
K = 1.887
2 UM 77 periods each
$\lambda_{res} \sim 4.5$ nm

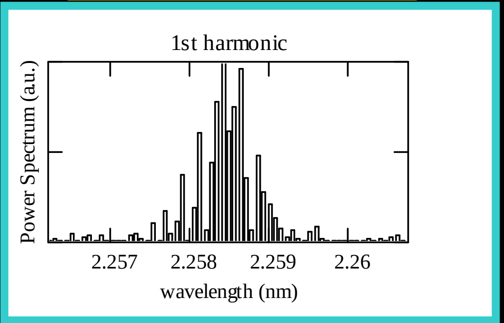
Energy	100 μJ
N ph.	2.5×10^{12}
Linewidth	1.5×10^{-4}
Coher. Len.	16 μm

UM3 (SPARC)
$\lambda_u = 2.8$ cm
K = 0.88
4 UM 77 periods each
$\lambda_{res} \sim 2.26$ nm

Energy	4 μJ
N ph.	5×10^{10}
Linewidth	3×10^{-4}
Coher.len.	5 μm

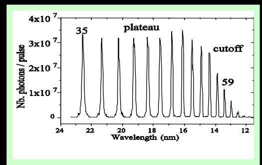
Beam Energy	1. 5 GeV
Peak Current	1.5 kA
Slice en. spread	$< 2\ 10^{-4}$
Slice emittance	< 1 mm-mrad



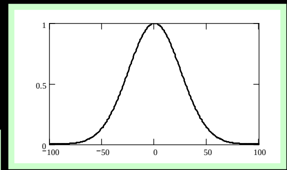


Seeding to increase longitudinal coherence: HHG in Ar (30nm) + Monochromator

Ar
$\lambda \sim 30$ nm
$E \sim 0.4\ \mu J$
$P \sim 8$ MW
$\delta t \sim 50$ fs $\sim 6\ \mu m$



→ Monochromator →



$\lambda \sim 30$ nm
$E_f = \eta_m E_i \sim 0.6$ nJ
$P_f \sim 3$ kW
$c\delta t_f \sim 60\ \mu m$

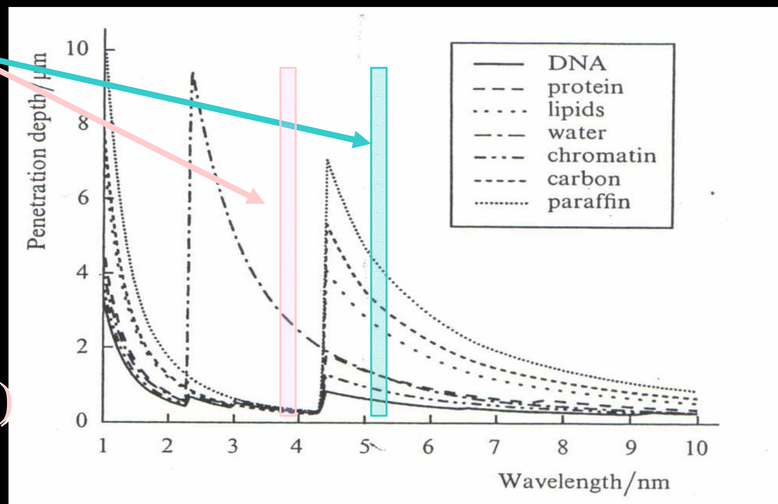
$\eta_m = 0.08 \times 0.5 \times 0.25 \times \delta t_i/\delta t_f$

X 6 (X8)

UM1 → UM2 (SPARC)

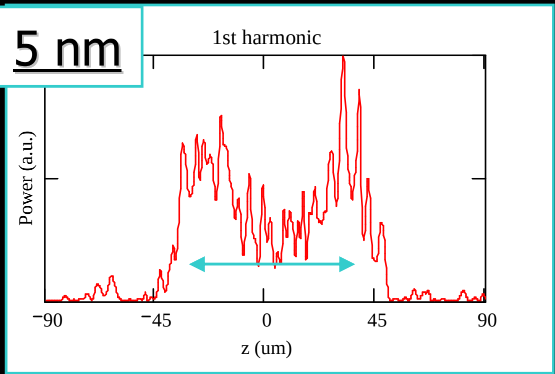
UM1:
$\lambda_u = 4.2$ cm
K = 3.89
5 UM
48 periods each
$\lambda_{res} \sim 30$ nm

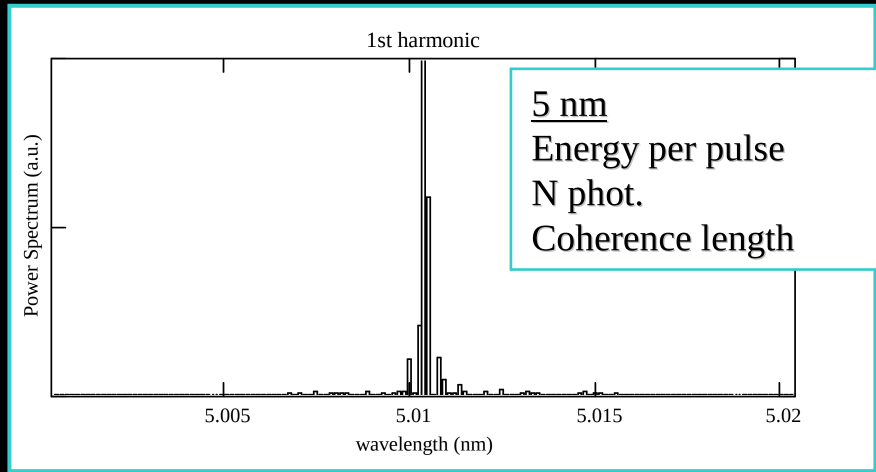
UM2 (SPARC):
$\lambda_u = 2.8$ cm
K = 1.51
6 UM
77 periods each
$\lambda_{res} \sim 5$ nm (3.75 nm)



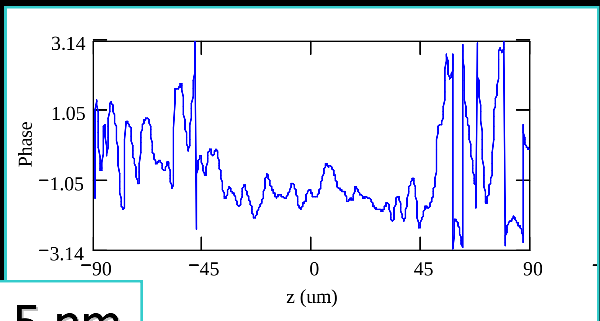
HHG in Ar + monochromator cont.

5 nm

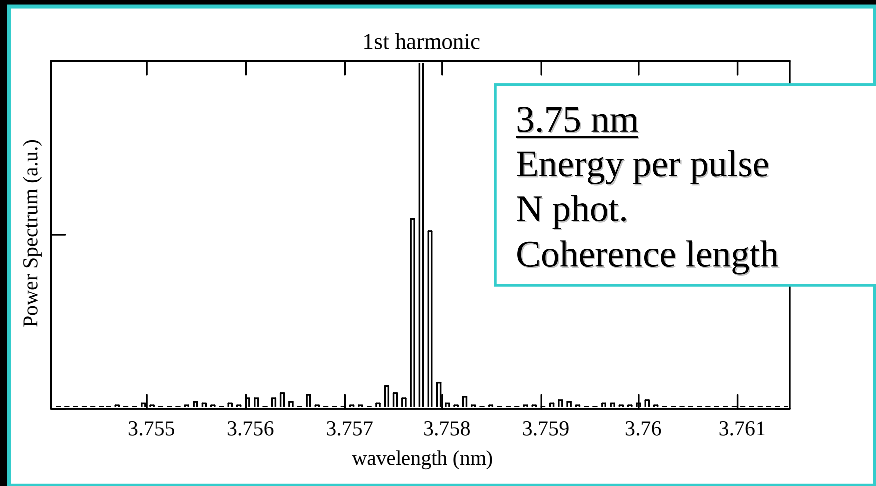




5 nm
Energy per pulse ~ 100 μJ
N phot. ~ $2x10^{12}$
Coherence length ~ 45 μm



5 nm



3.75 nm
Energy per pulse ~ 10 μJ
N phot. ~ $1x10^{11}$
Coherence length ~ 30 μm

FEL 2006 - “Start to end” SIMULATION from the FIELDS point of view

1

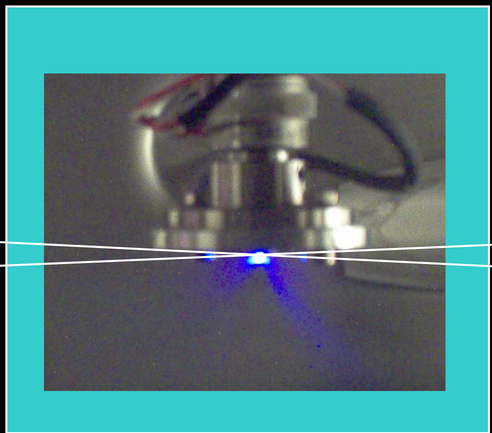
Harmonic generation

2

Matching to the FEL
- Optically
- “Numerically”

3

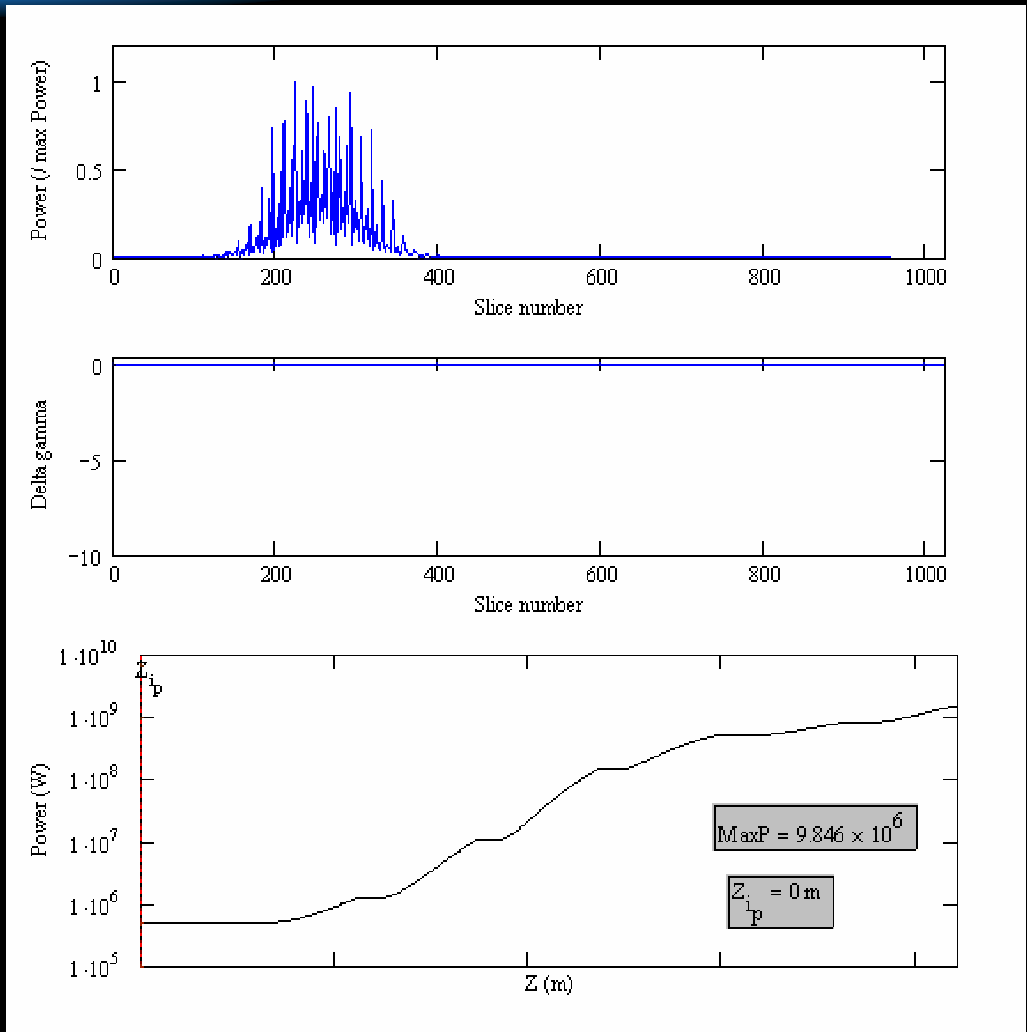
FEL Amplification
with GENESIS 1.3



SINGLE PASS FEL

Picture taken at CEA during preliminary tests of the SPARC HHG chamber

Genesis 1.3 Time dependent Simulation

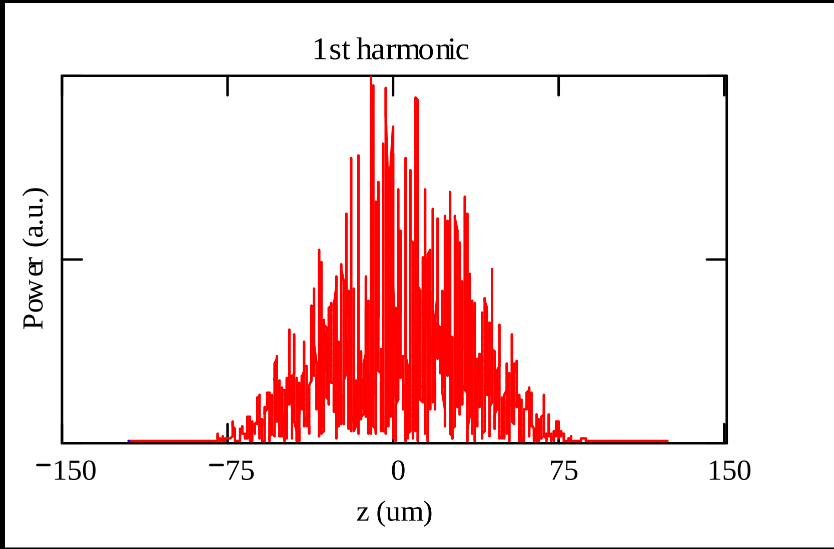


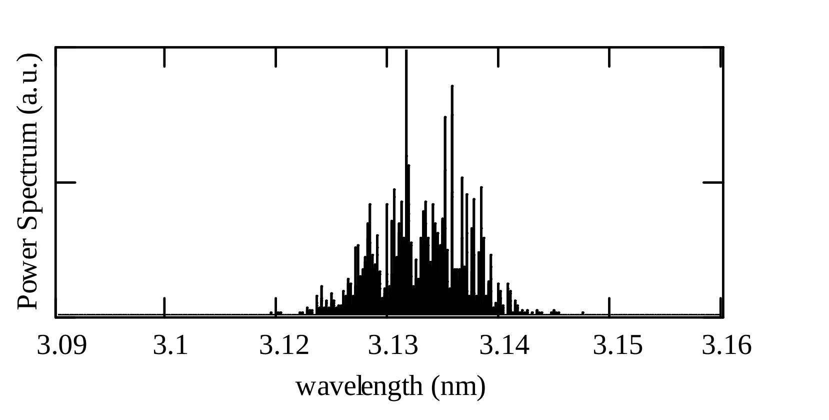
SASE – 1 nC “Long Puse”

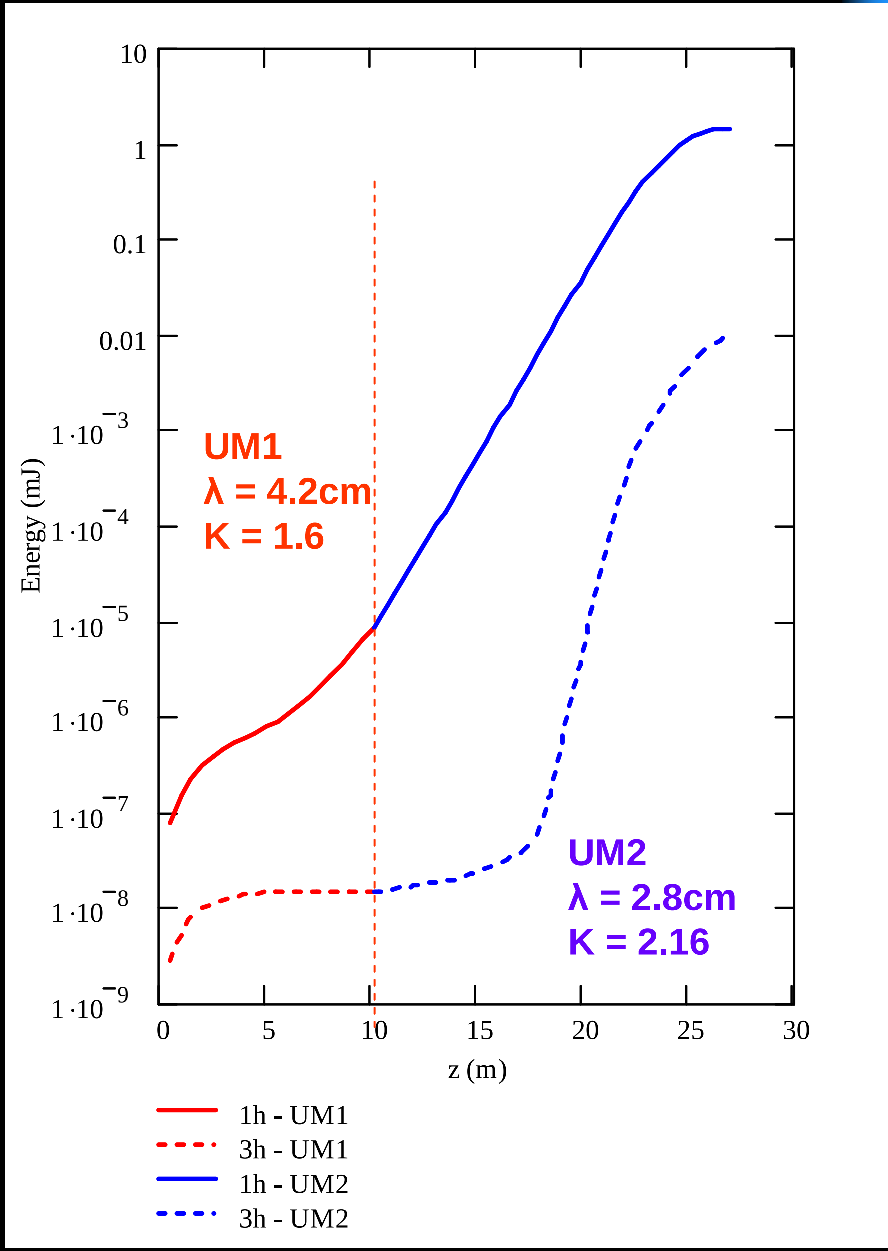
- UM periods of 4.2 cm - 2.8 cm (SPARC UM) allows tuning the whole undulator at the same resonance

Energy (GeV)	2
Peak current	1.5 kA
Charge	0.75 nC
Energy Spread (%)	$2\ 10^{-4}$
Slice Emittance (mm-mrad)	1
Period UM1 (cm)	4.2
Period UM2 (cm)	2.8
K1	1.6
K2	2.16

SPARX SASE 3 nm



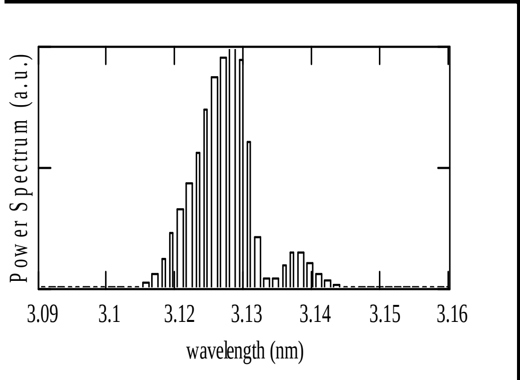


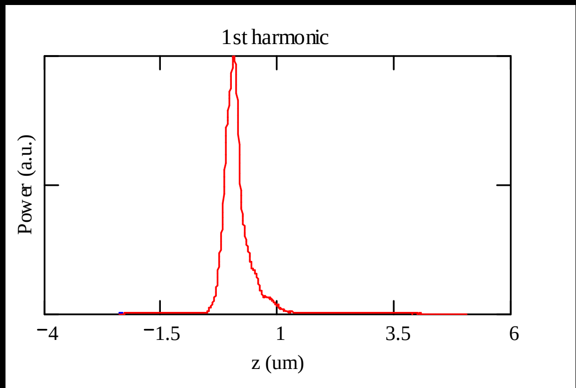


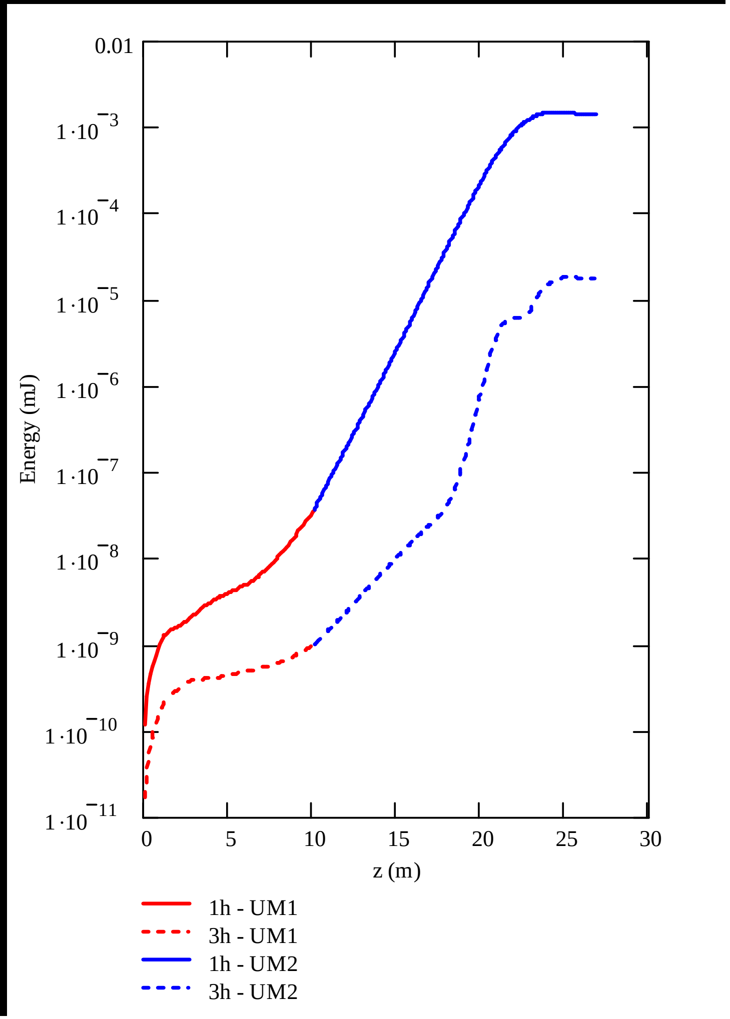
Low charge operation

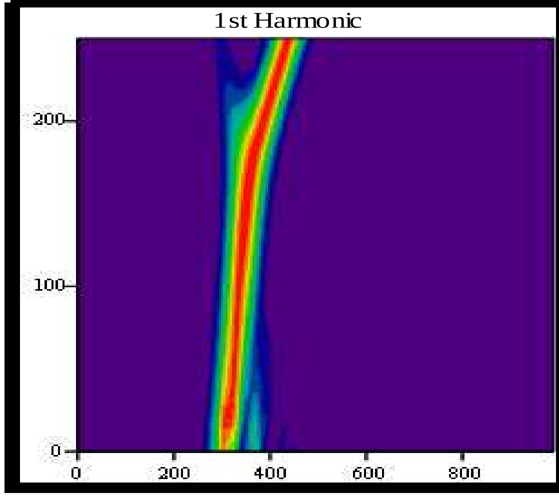
@same wavelength
(work in colaboration with
J. B. Rosenzweig, S. Reiche, C. Pellegrini …
more on S. Reiche talk …)

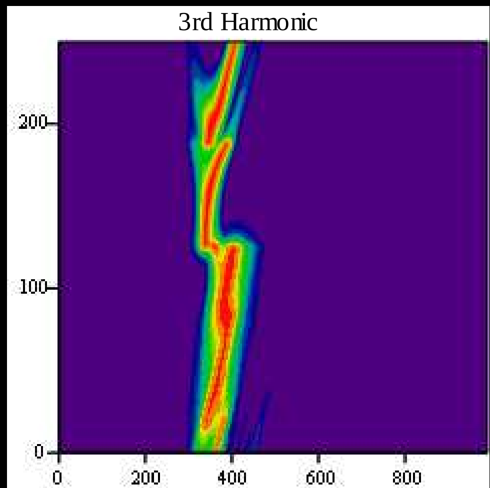
Peak current	0.25 kA
Charge	0.97 pC
Energy Spread (%)	2.4 10^{-4}
Emittance (mm-mrad)	0.062





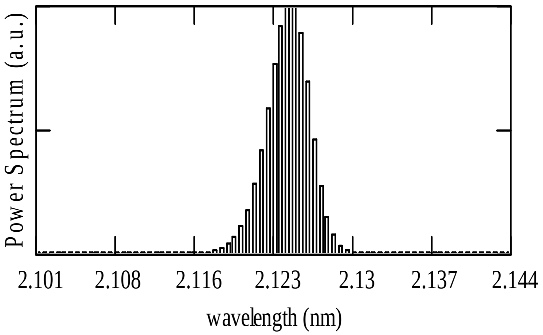


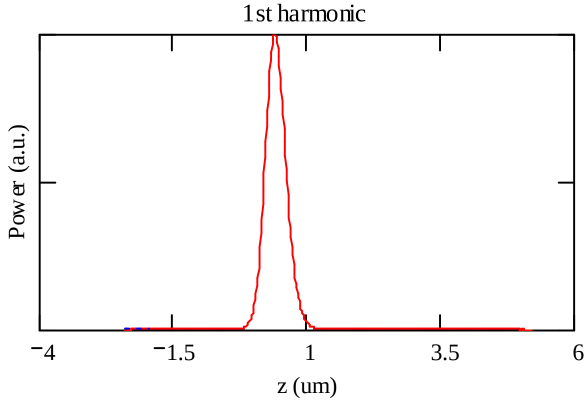


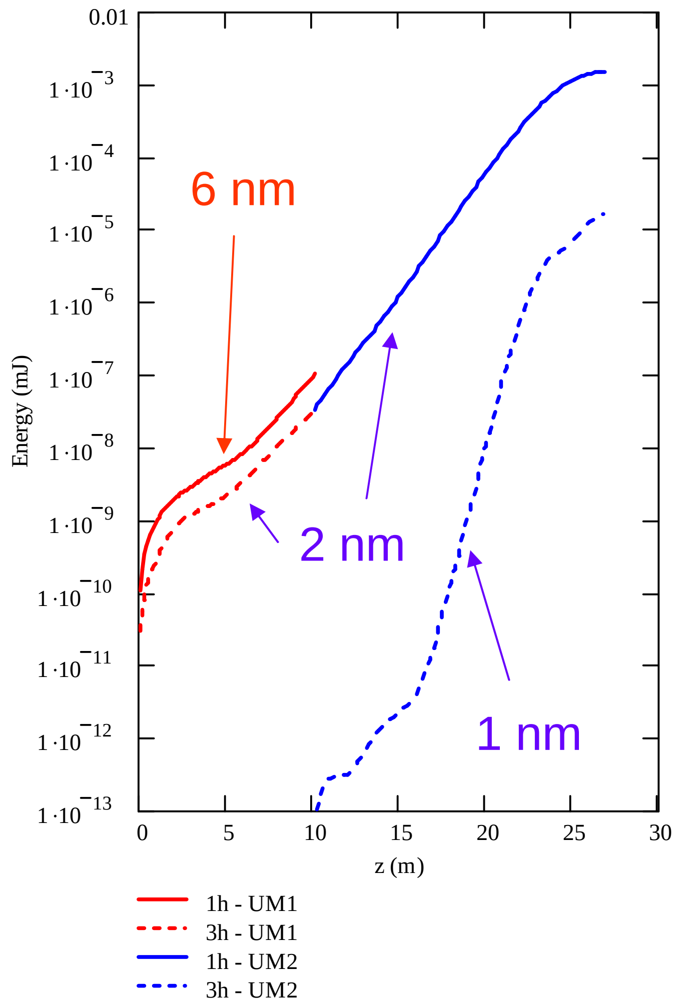


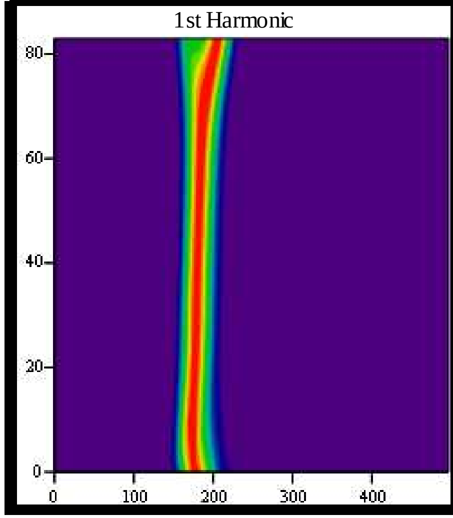
Low charge operation & cascade 6 nm→ 2 nm → 1 nm

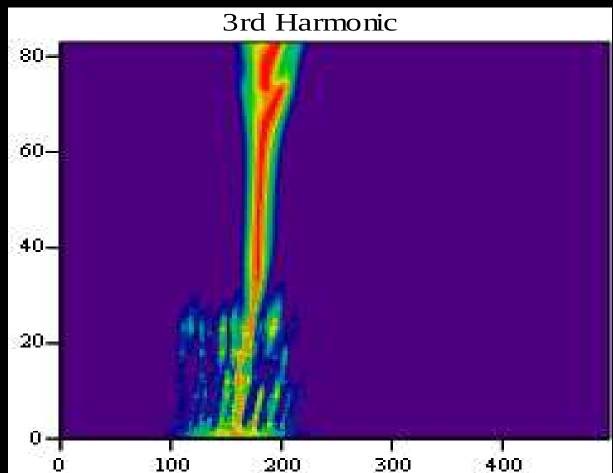
Peak current	0.25 kA
Charge	0.97 pC
Energy Spread (%)	$2.4\ 10^{-4}$
Emittance (mm-mrad)	0.062











Conclusions

- Availabe sources with harmonics in gas should be sufficient to seed FEL cascades operating in the water window
- Larger pulse energy is required for seeding @ shorter wavelegths
- A flexible design allowing both SASE and seeded operation, as the one proposed, is advised for SPARX
- Small charge operation opens interesting possibilities for very short pulses production at extremely short wavelength