Proprieties of FEL radiation at SPARX

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Outline

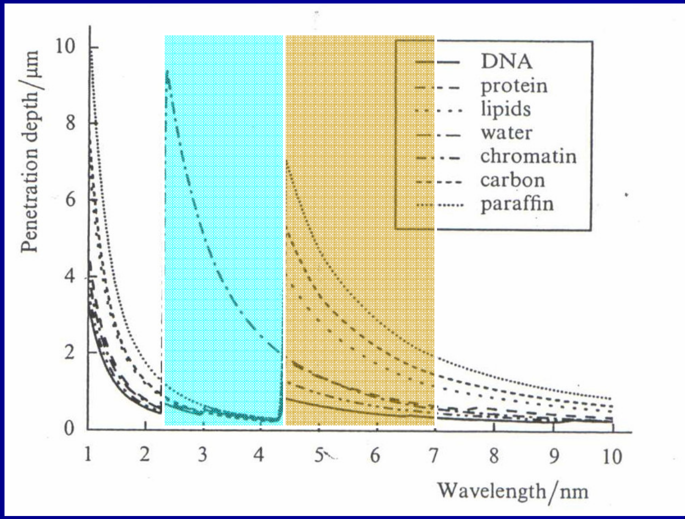
- Objectives & Resources
  - Beam parameters
  - Undulator
- SASE
  - Longitudinal coherence
  - Transverse coherence
  - Main parameters & constraints
- Seeded FEL configurations
  - Seeding with HHG in gas
    - Short pulses
    - Coherence
  - Seeding in “superradiant mode” – generation of fs soft x ray pulses
- Pointing stability
- Conclusions

Objectives

- Input from the last SPARX workshop:

  Wavelength range as close as possible to the water window (~ 2.5 – 4.5 nm)

  … and to the carbon window



- Flexible design:

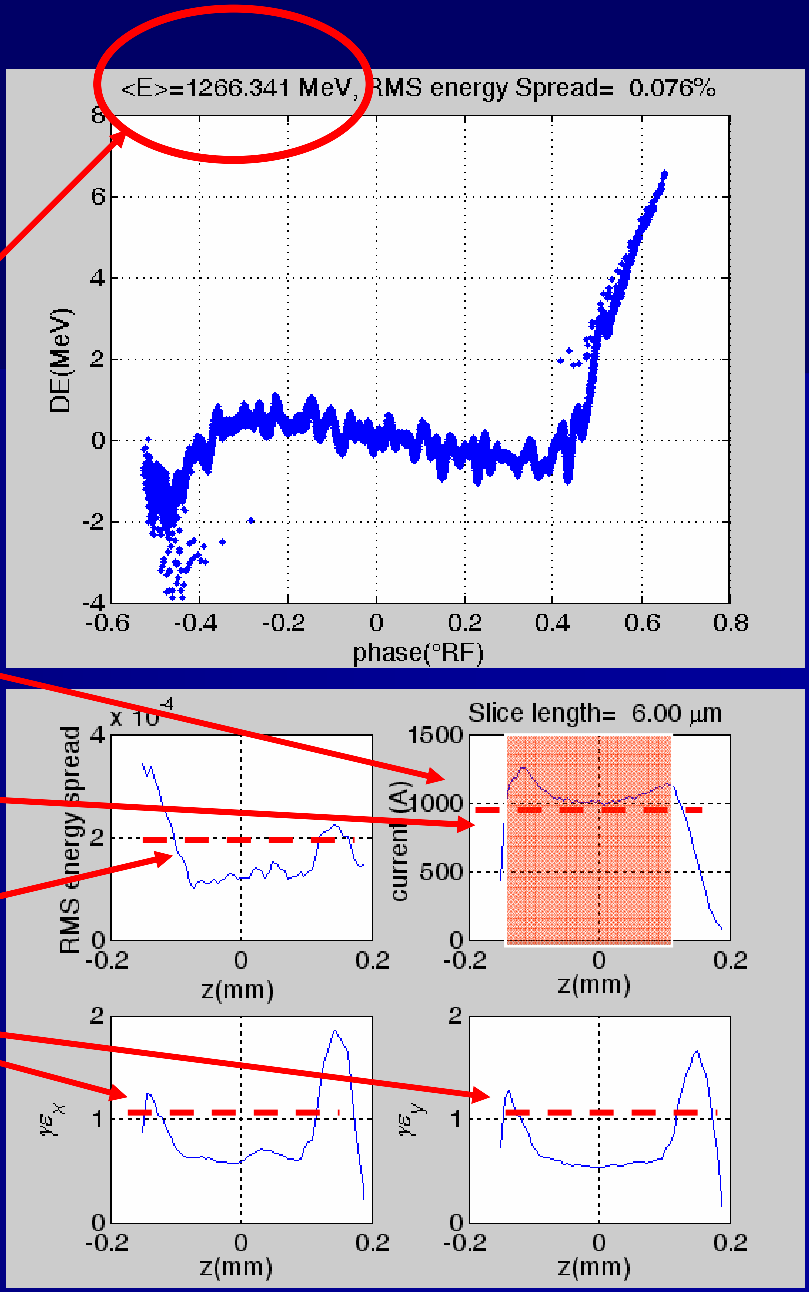
  SASE & Seeded configurations
  - Improve coherence length
  - Short pulses (fs range)
  - Increase wavelength operation range

Resources

- Upgraded DaΦne linac
  - Beam energy 1 – 1.5 GeV (possible extensions to higher energy)
  - State of the art beam brightness
- SPARC Undulator
  - 6 sections 77 periods 2.8 cm

e-beam @ the UM

C. Ronsivalle –
C. Vaccarezza BD 11/4/2005



- Beam energy 1.25 GeV
- Flat longitudinal current profile ~ 1kA
- Pulse Duration ~ 300μm ~ 1 ps
- Slice energy spread < 2 10^{-4}
- Slice emittances < 1 mm-mrad

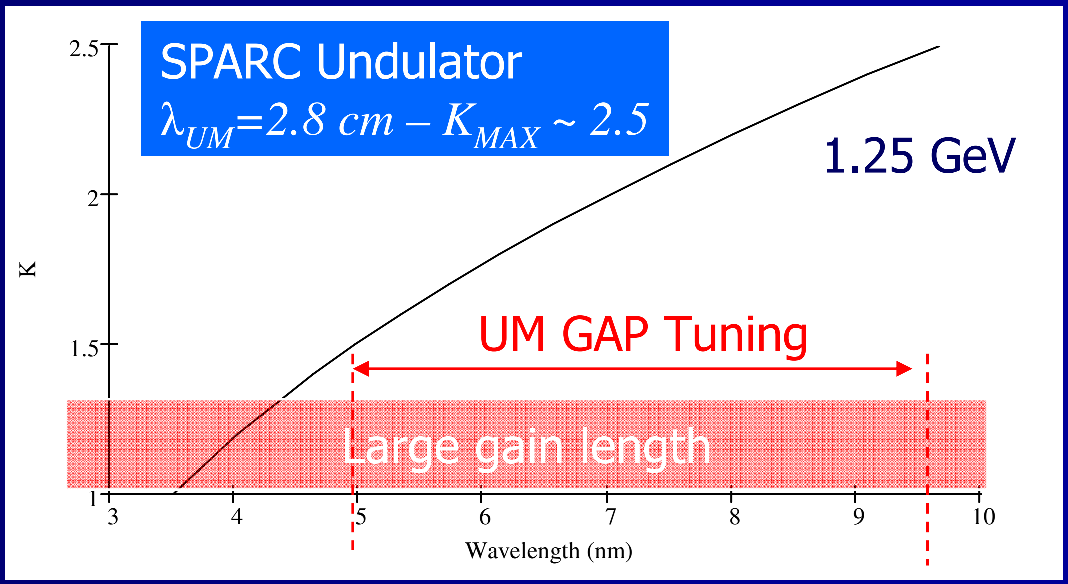
SPARC Undulator 2.8 cm period

Reference:

Beam Energy	1.25 GeV
Peak Current	1 kA
Slice energy spread	$< 2\ 10^{-4}$
Slice emittance	< 1 mm-mrad

Resonance condition

$$\lambda_{FEL} = \frac{\lambda_{UM}}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$



SPARC Undulator 2.8 cm period

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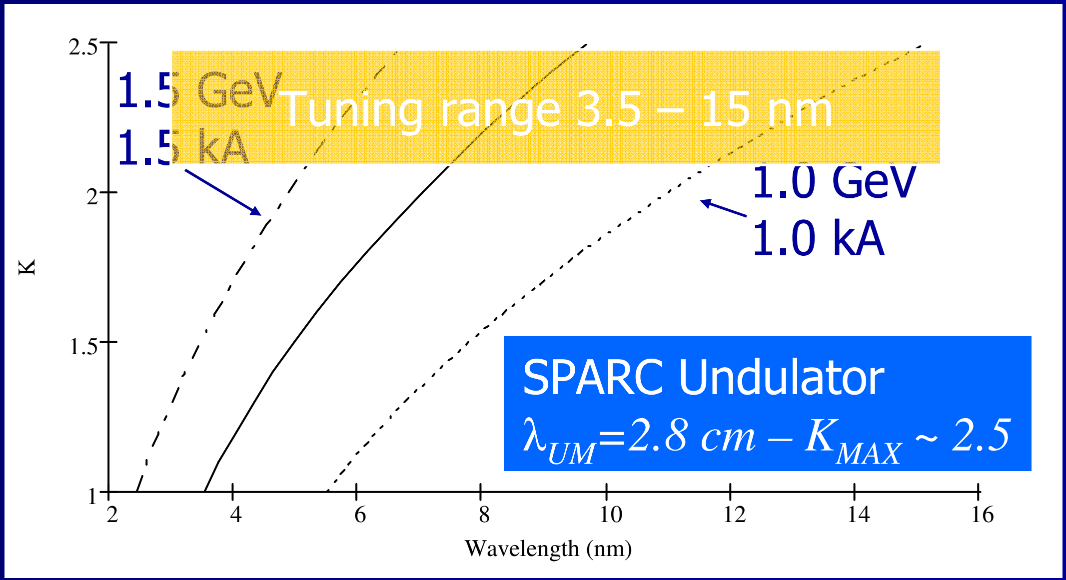
Resonance condition

$$\lambda_{FEL} = \frac{\lambda_{UM}}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

Low Energy : 1.0GeV & 1.0kA

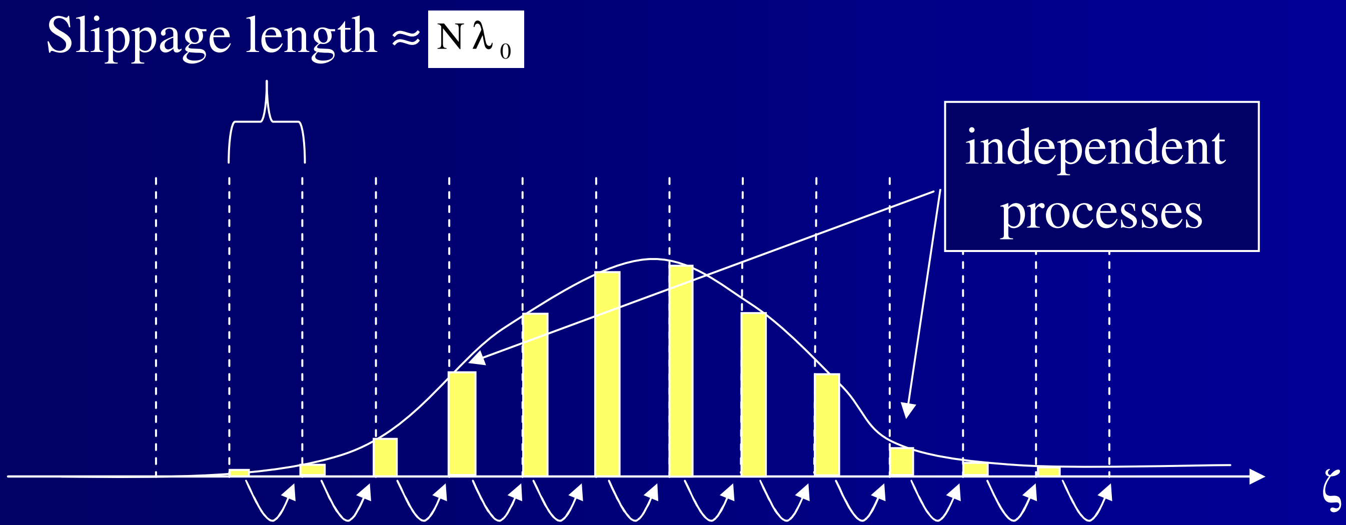
High Energy : 1.5GeV & 1.5kA



Wavelength tuning range - 15 – 4 nm

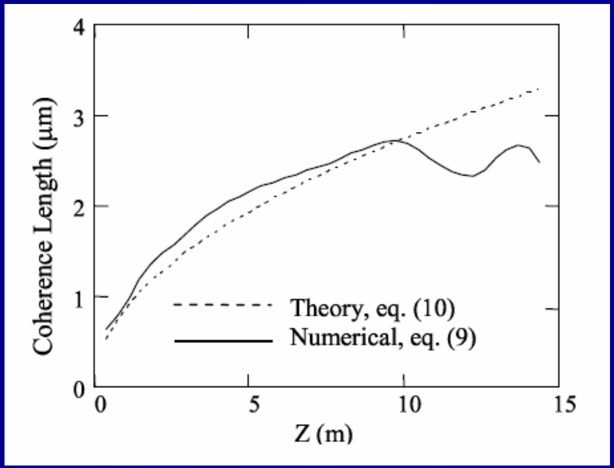
SASE

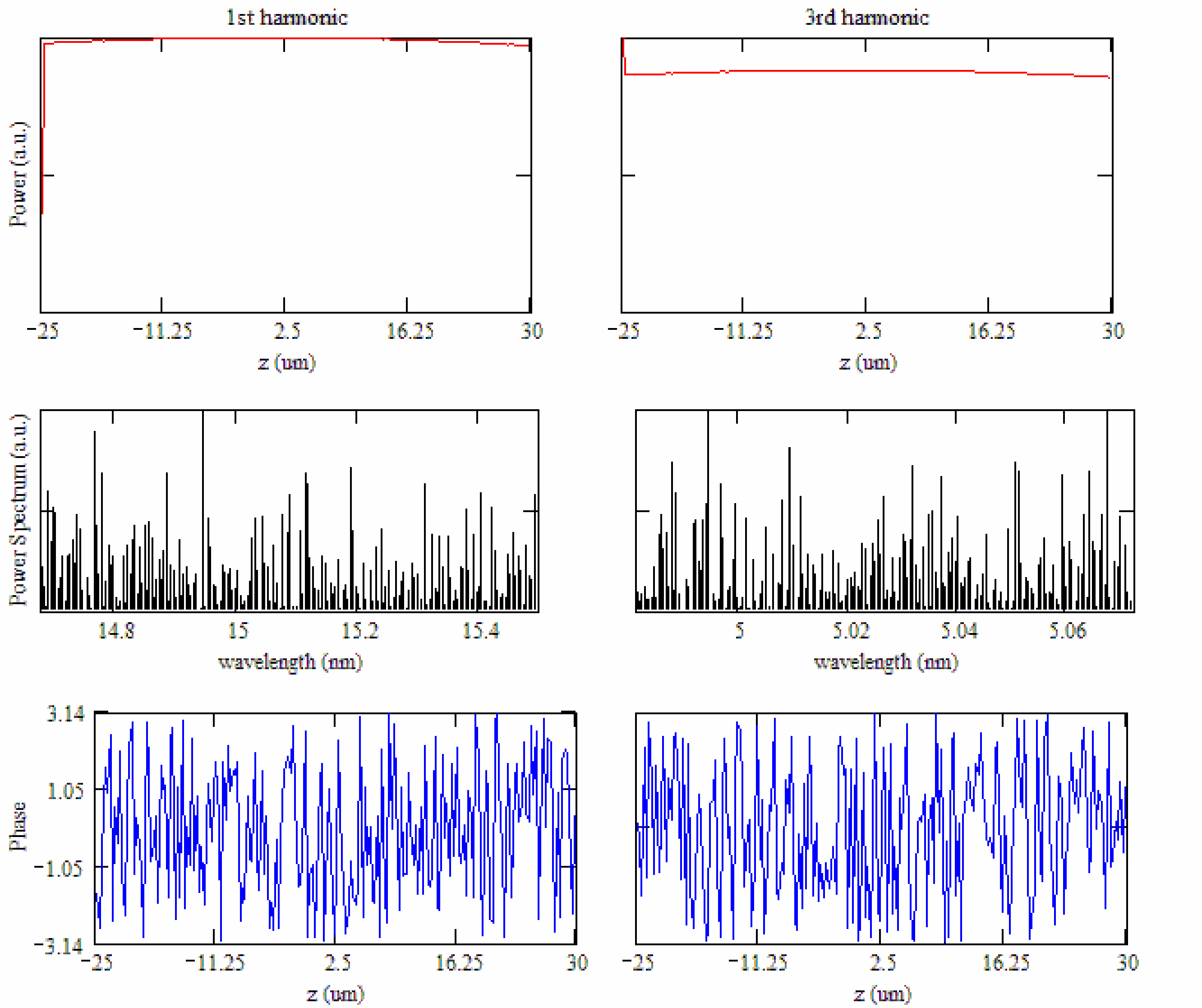
SASE & Spikes

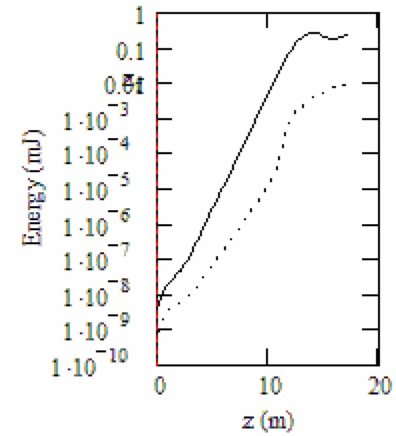


- The radiation "slips" over the electrons for a distance $N\lambda_0$

$$z_c = \frac{1}{6}\frac{\lambda_0}{\rho}\sqrt{\frac{z}{2\pi L_g}}$$







Main parameters at

f = 0 , **or** $z_f = 0\,m$

$P_{in} = 0\,W$

$Energy_{f,0} = 4.684 \times 10^{-9}\,mJ$

$Energy_{f,2} = 8.398 \times 10^{-10}\,mJ$

$\frac{1}{c} \cdot length_{rms_{f,0}} = 0.053\,ps$

$\frac{1}{c} \cdot length_{rms_{f,2}} = 0.053\,ps$

$width_{rms_{f,0}} \cdot \frac{\lambda_{0_{n_u}}}{c} = 1.639\,\%$

$width_{rms_{f,2}} \cdot \frac{\lambda_{0_{n_u}}}{c \cdot 3} = 0.155\,\%$

$dfl_1 = 4.198$

$dfl_3 = 7.55$

Perseo in 1D mode http://www.perseo.enea.it

M longitudinal independent modes

Cooperation length $L_c = \lambda/4\pi\rho$

Number of modes $M \sim L_c / L_b$ (L_b - bunch length)

$\rho \sim 10^{-3}$

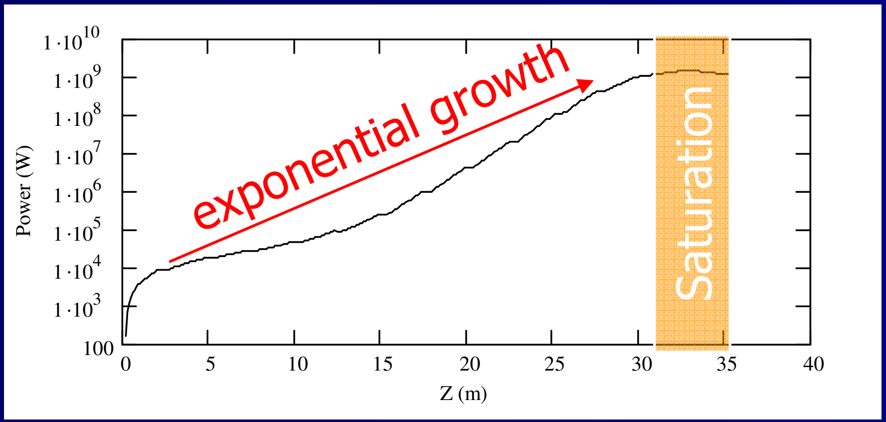
$\lambda \sim 5 - 10$ nm

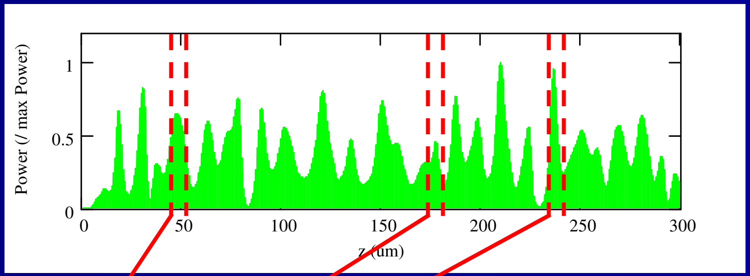
$L_b \sim 0.5 - 1$ ps

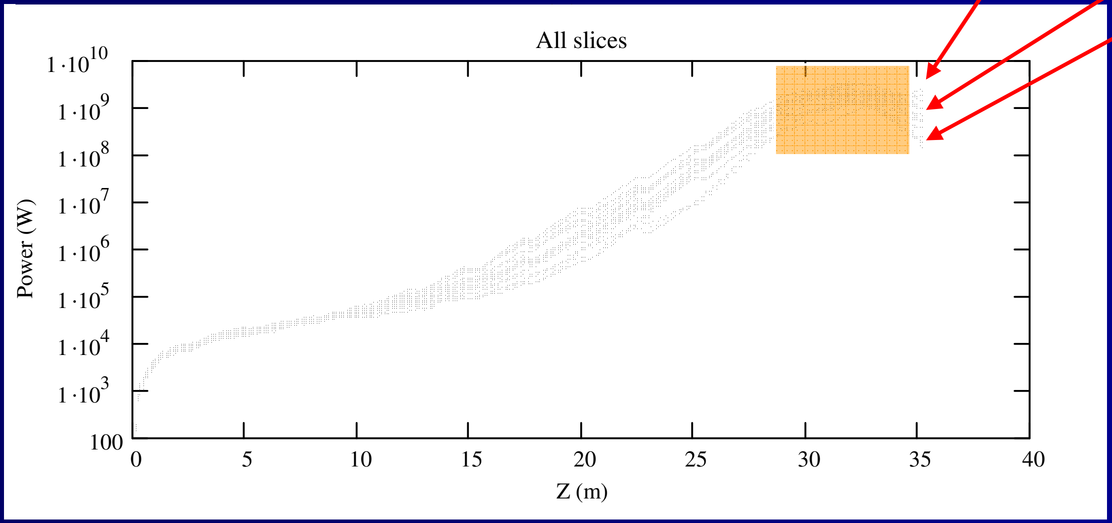
$L_c \sim 100\,\lambda$

Shot to shot fluctuations $\sim 1/\sqrt{M} \approx 5\%$

Saturation of different slices





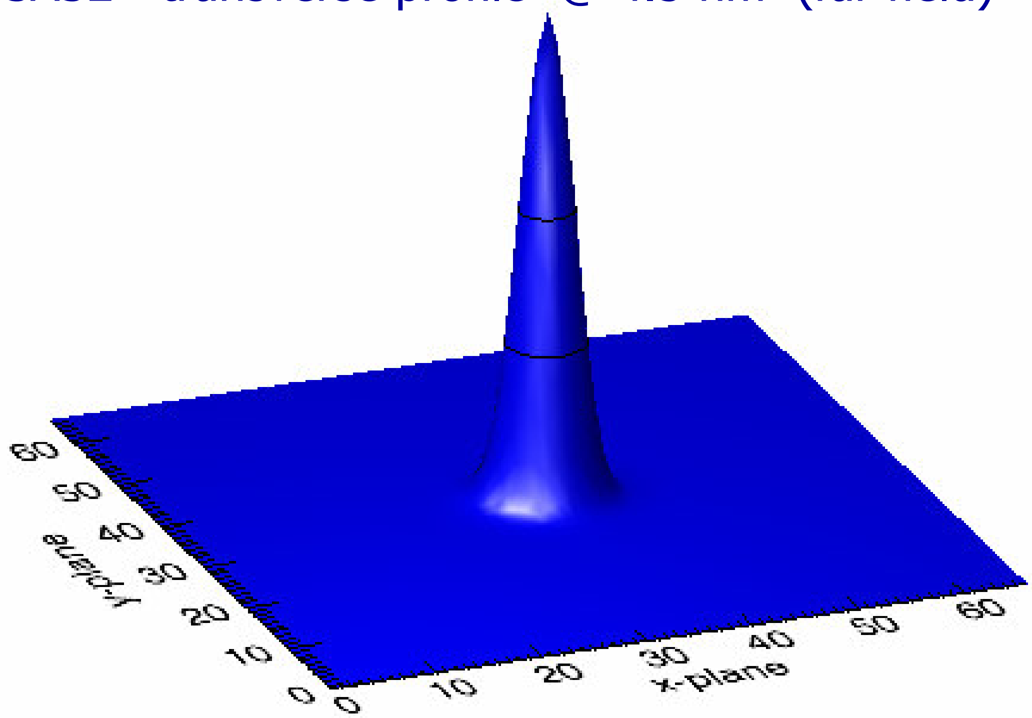


Independent slices saturate at different positions

The integrated source has an increased longitudinal extension

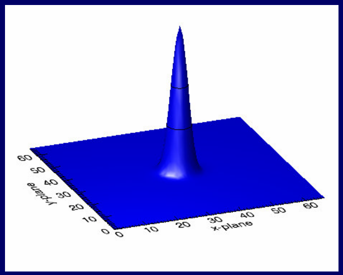
Transverse plane

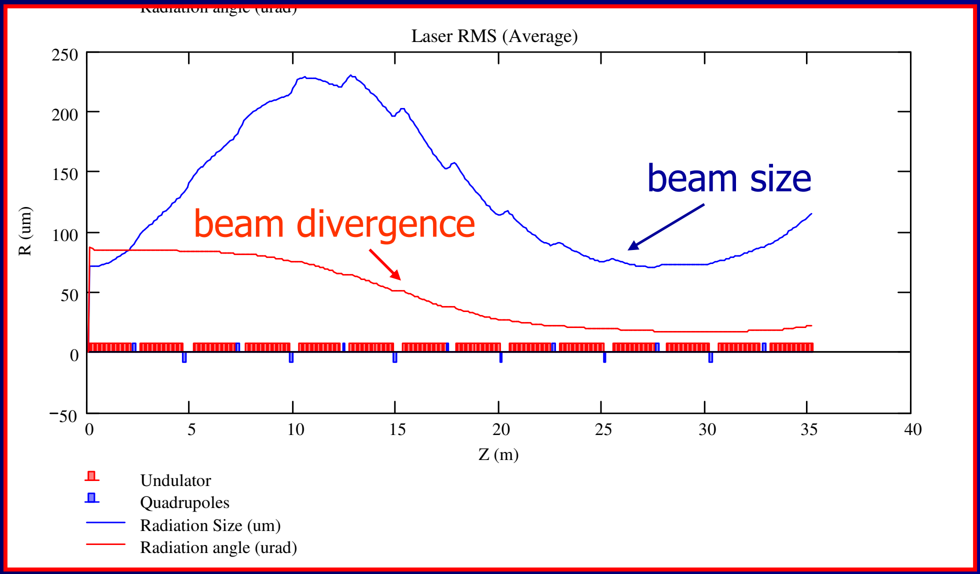
SASE - transverse profile @ 4.5 nm (far field)



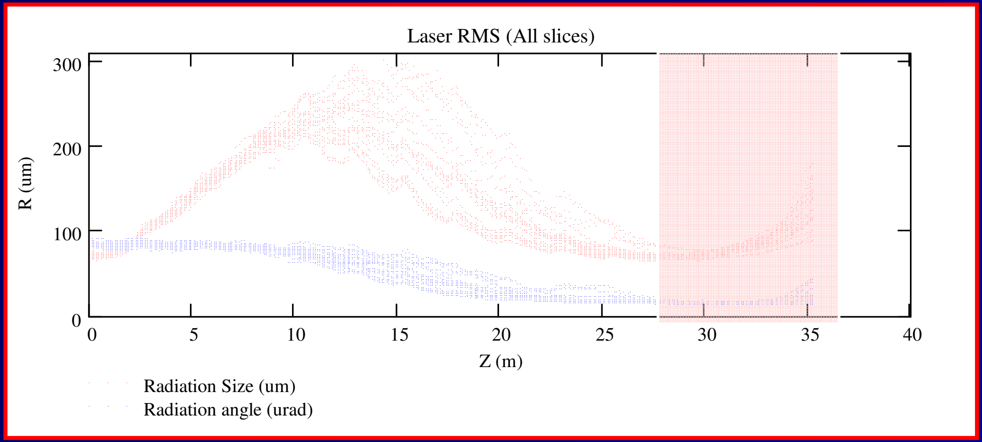
GENESIS 1.3 – Averaged over long. slices at 33 m

Transverse plane





Spiking effects in the transverse plane



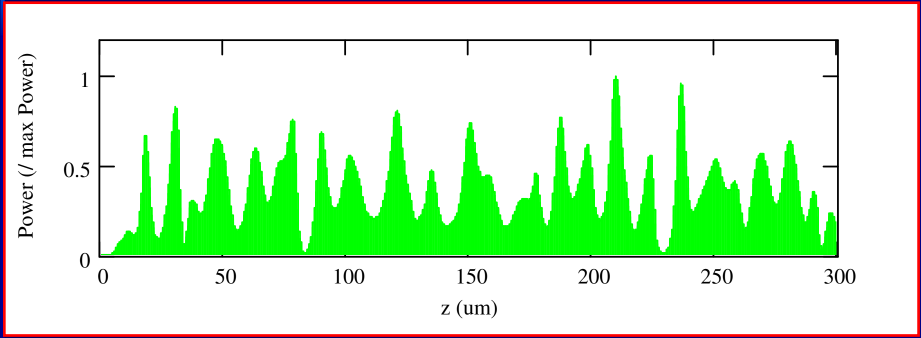
The integrated source has an extension "larger" than the diffraction limit

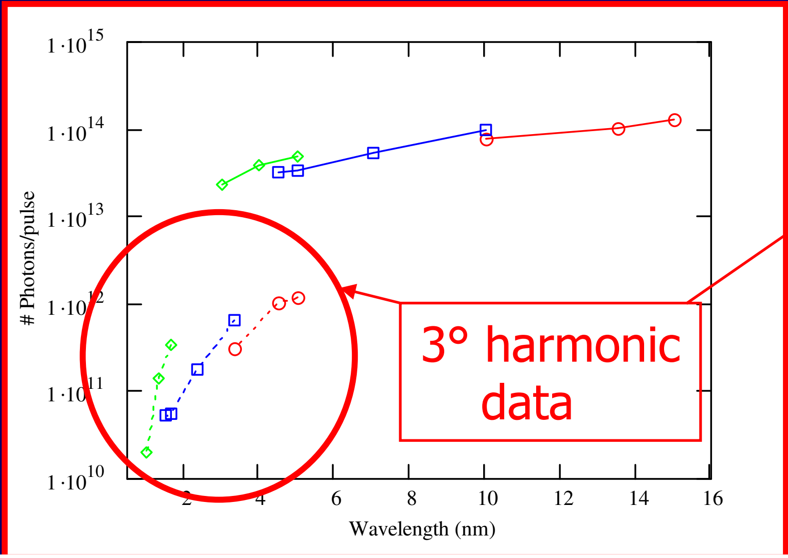
$$\sigma\sigma' = \frac{\lambda}{4\pi}$$

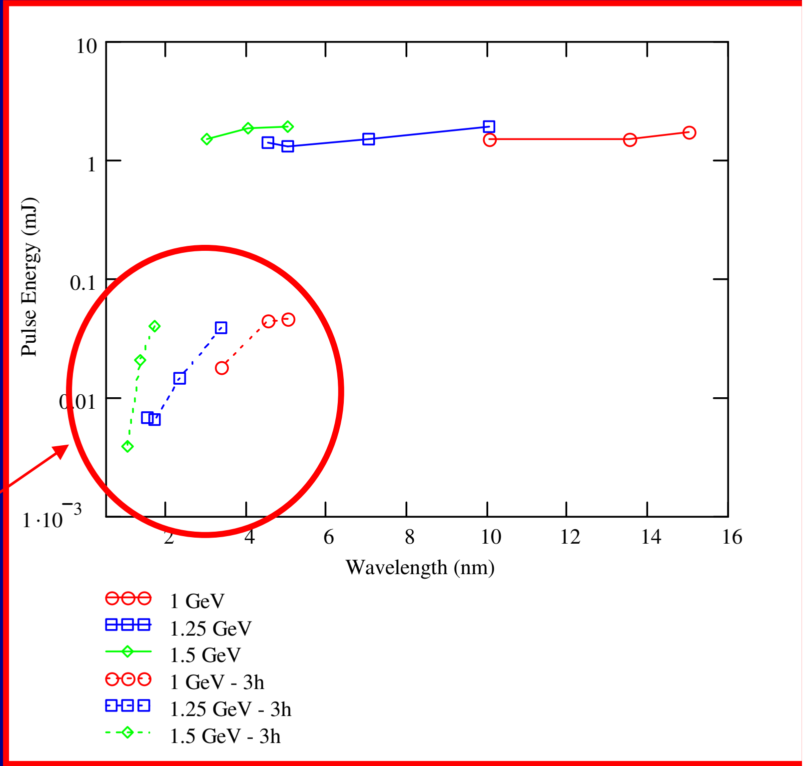
SASE – Performances

Simulations made with GENESIS 1.3 + Perseo for the high order harmonics

SASE PULSE (4.5nm – 33m)

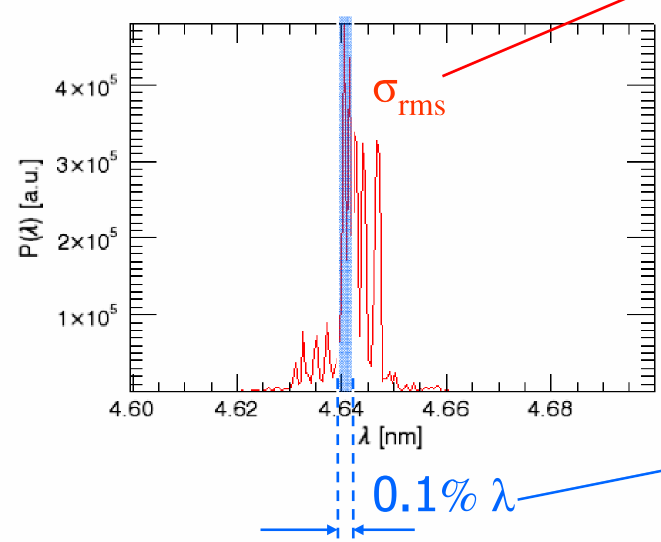


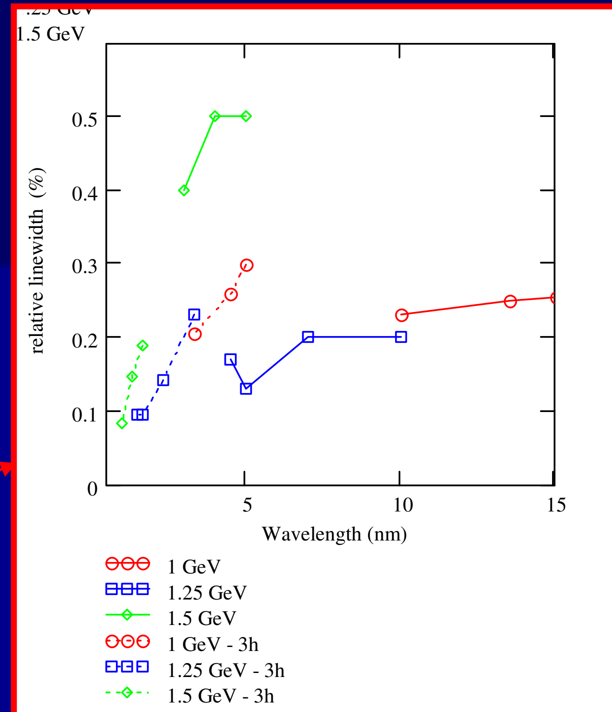


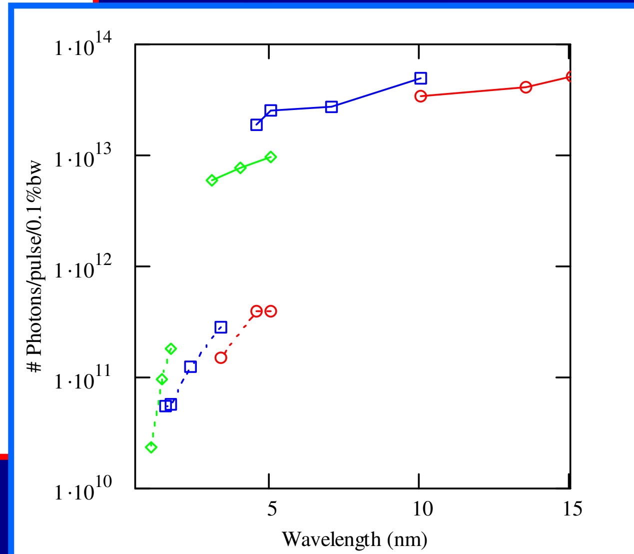


Spectrum

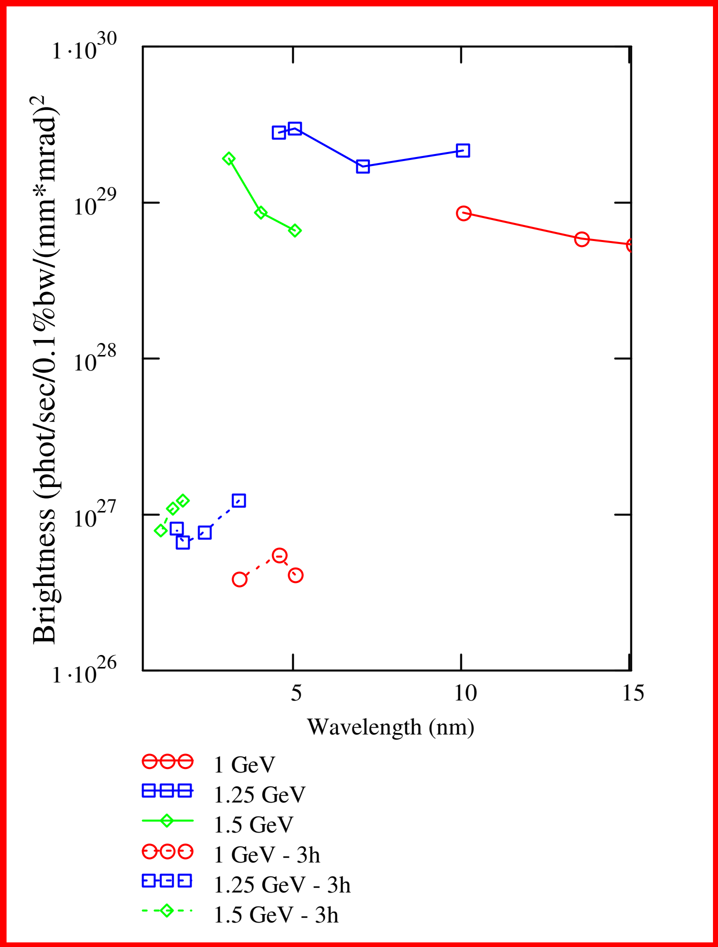
SASE Spectrum @ 4.5 nm – 33m



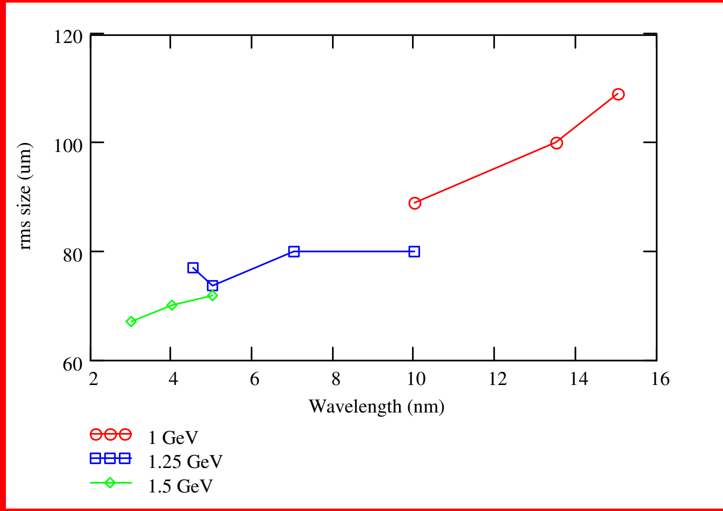




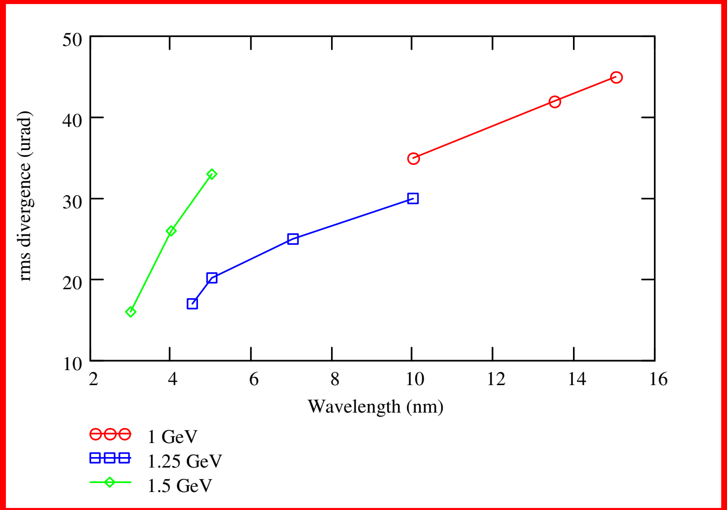
Brightness



1 ·10^30
10^29
10^28
10^27
1 ·10^26
Brightness (phot/sec/0.1%bw/(mm*mrad)^2
5
10
15
Wavelength (nm)
1 GeV
1.25 GeV
1.5 GeV
1 GeV - 3h
1.25 GeV - 3h
1.5 GeV - 3h

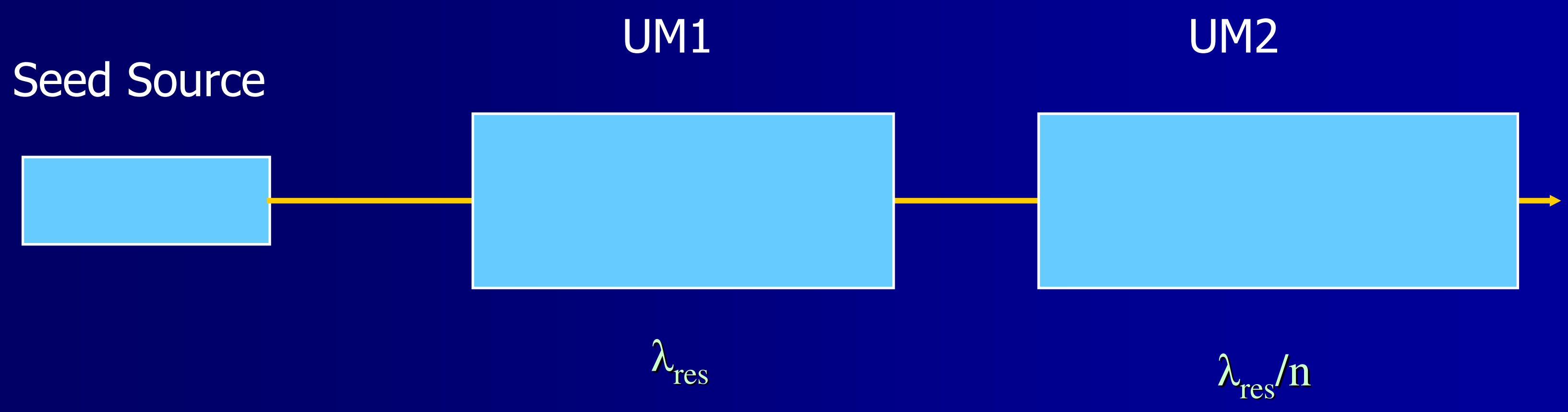


120
100
80
60
rms size (um)
2
4
6
8
10
12
14
16
Wavelength (nm)
1 GeV
1.25 GeV
1.5 GeV



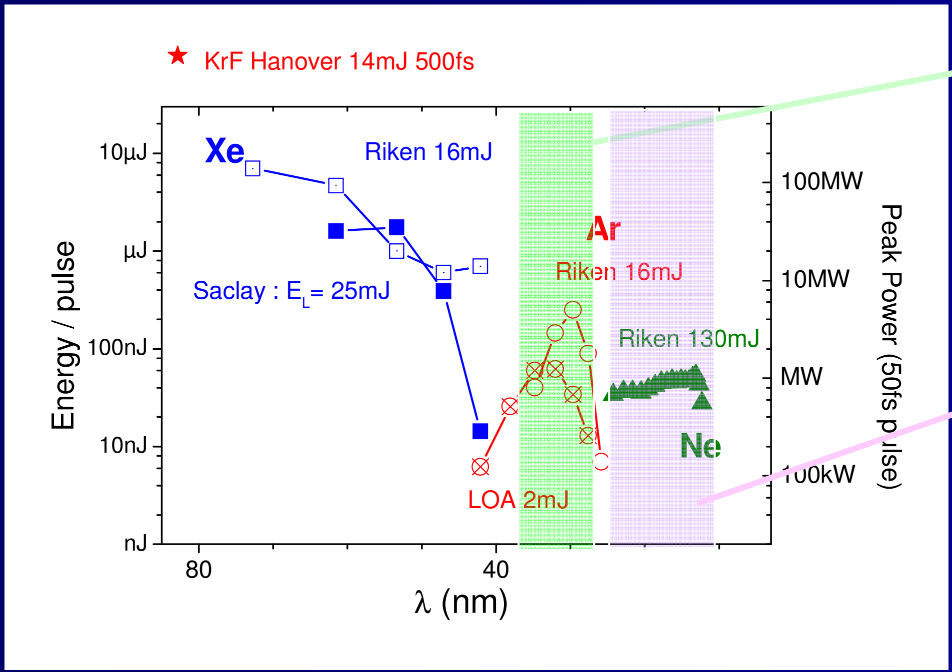
50
40
30
20
10
rms divergence (urad)
2
4
6
8
10
12
14
16
Wavelength (nm)
1 GeV
1.25 GeV
1.5 GeV

SEEDING & Harmonic Gen.



Seed Sources

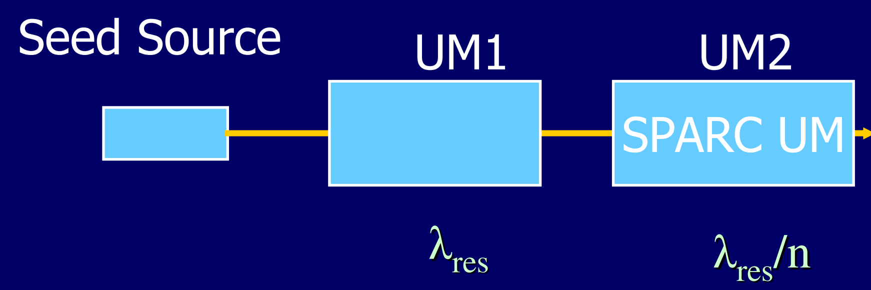
- 3° harm of Ti:Sa 260 (→ 180 nm) + multiple stages cascade
- HHG in gas + cascade

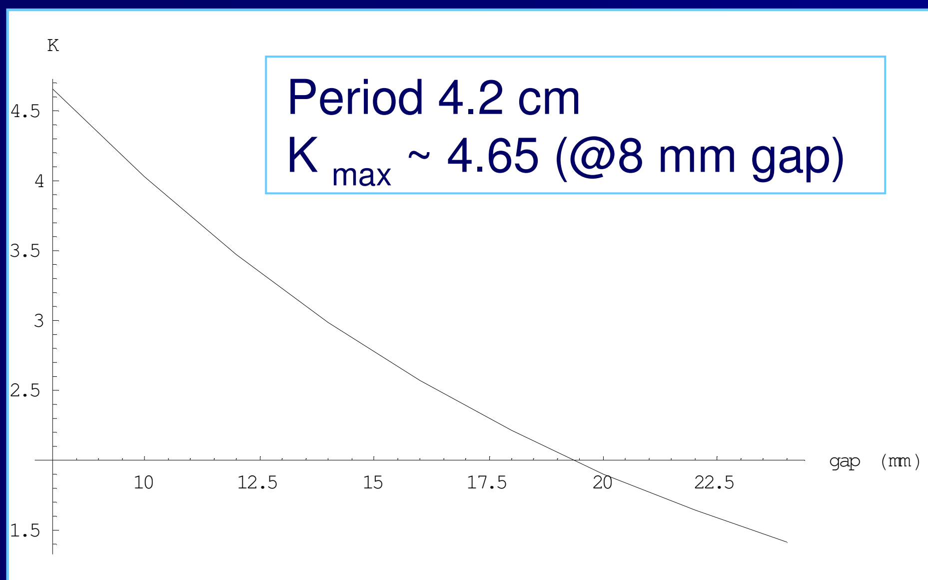


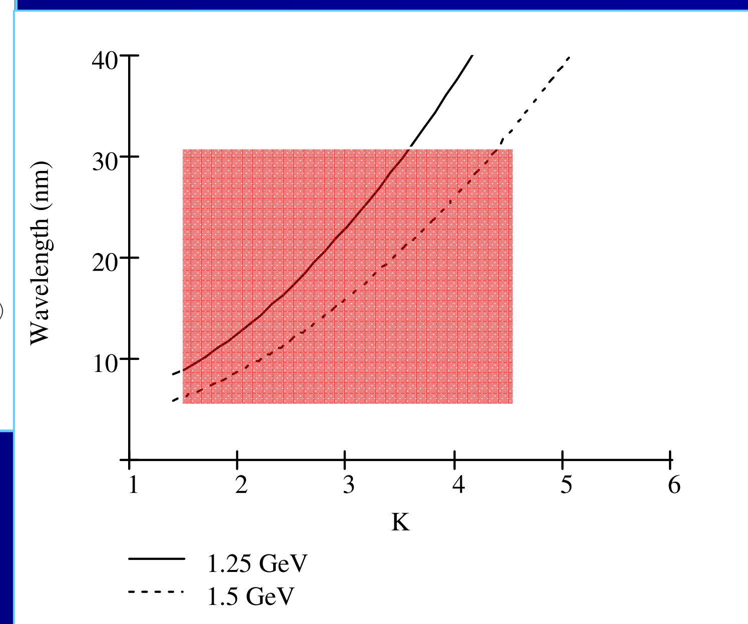
Ar λ ~ 28-32 nm
E ~ 0.3 – 0.4 µJ
P ~ 5-10 MW

Ne: λ ~ 10-15 nm
E ~ 30 nJ
P ~ 1 MW

Modulator







Can be used as :

- a sub-harmonic modulator for the SPARC undulator at large K (seeding)
- an additional undulator to increase the SPARC UM length at small K (SASE)

Seeding with Ne @ 13.5 nm

Ne (after matching to the e-beam)

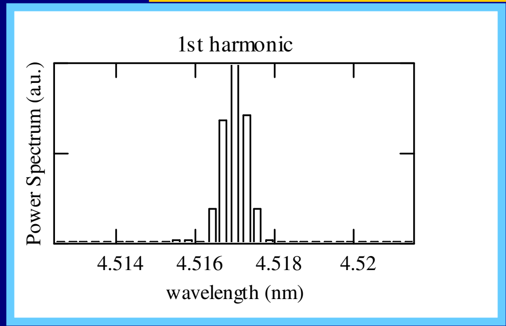
$\lambda \sim 13.5$ nm
E ~ 2 nJ
P ~ 35 kW
$\delta t \sim 50$ fs ~ 6 µm

→ UM1 MOD. → (X 3) UM2 (SPARC) → (X 2) UM3 (SPARC)

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

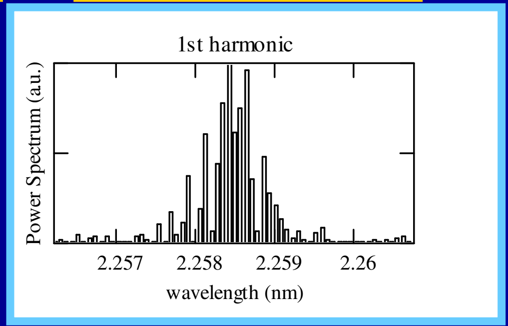
UM2 (SPARC)
$\lambda_u = 2.8$ cm
K = 1.887
2 UM 77 periods each
$\lambda_{res} \sim 4.5$ nm

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

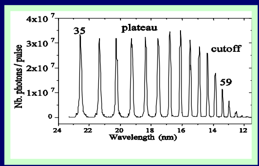
Energy	4 µJ
N ph.	5×10^{10}
Linewidth	3×10^{-4}
Coher.len.	5 µm



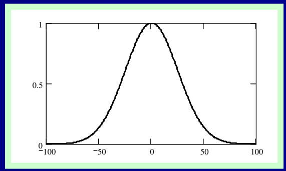
Beam Energy	1. 5 GeV
Peak Current	1.5 kA
Slice en. spread	$< 2\ 10^{-4}$
Slice emittance	< 1 mm-mrad

Seeding to increase longitudinal coherence: HHG in Ar + 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
$c\delta t_f \sim 60\ \mu m$

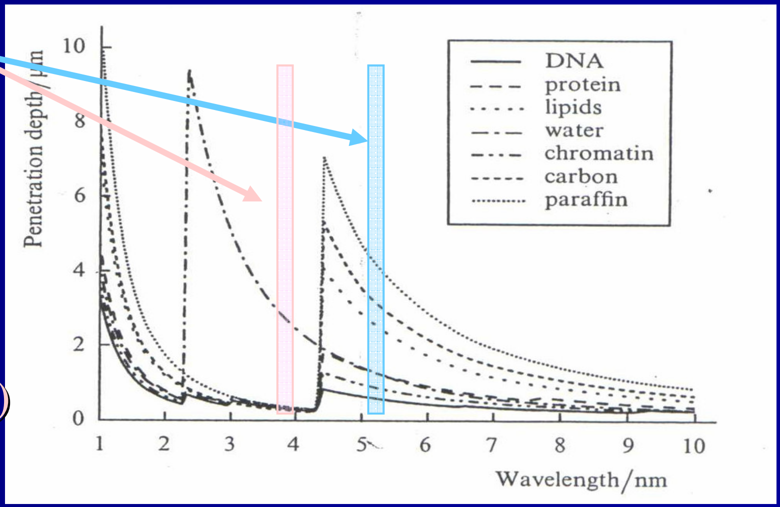
$\eta_m = 0.08 \times 0.5 \times 0.25 \times \delta t_i/\delta t_f$

X 6 (X8)

UM1 → UM2 (SPARC)

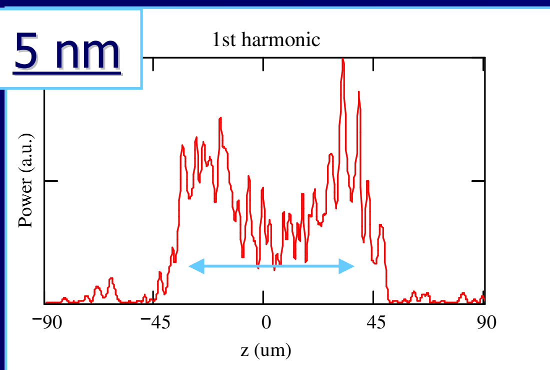
$\lambda_u = 4.2$ cm
$K = 3.89$
5 UM
48 periods each
$\lambda_{res} \sim 30$ nm

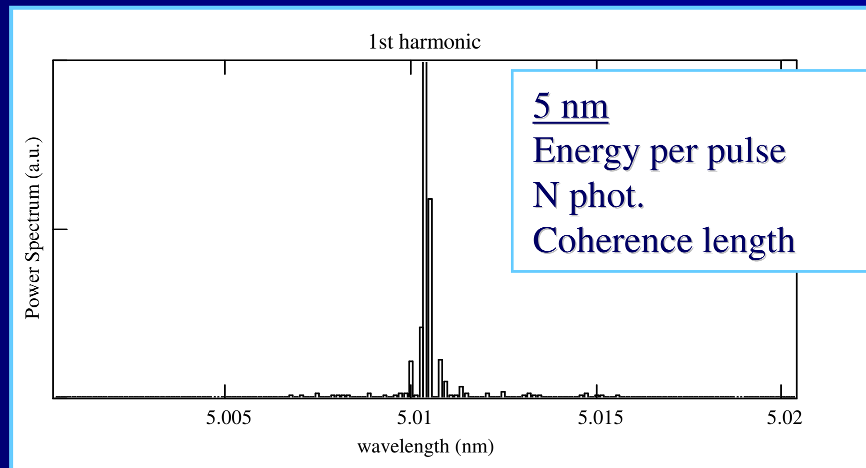
$\lambda_u = 2.8$ cm
$K = 1.51$
6 UM
77 periods each
$\lambda_{res} \sim 5$ nm (3.75 nm)



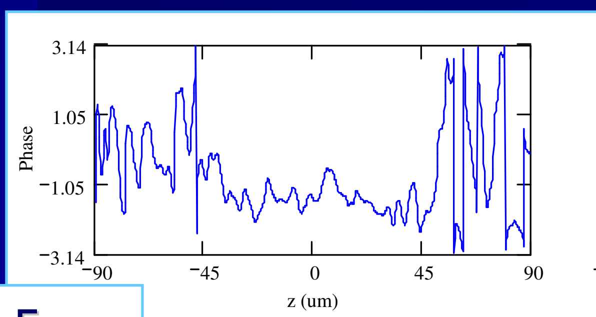
HHG in Ar + monochromator cont.

5 nm

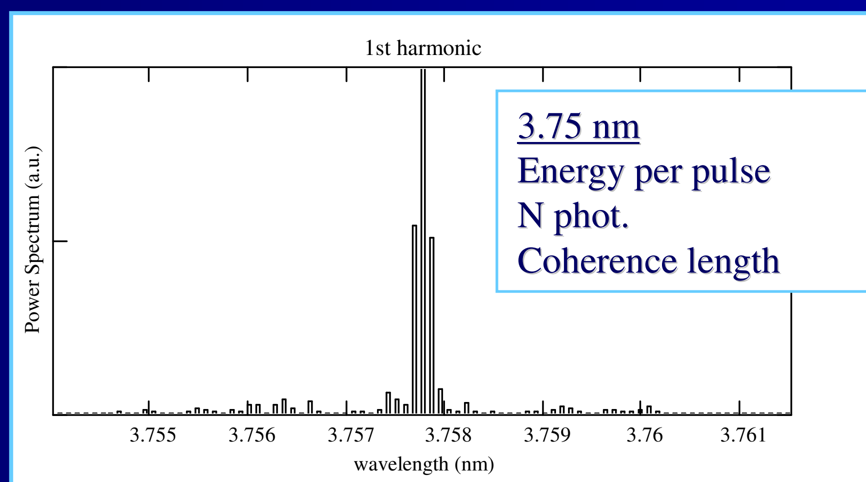




5 nm
Energy per pulse ~ 100 μJ
N phot. ~ $2x10^{12}$
Coherence length ~ 45 μm



5 nm



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

Very short pulse generation

Submitted to Journal of Applied Physics - http://jap.aip.org

Non linear Pulse Evolution in Seeded Free-Electron Laser Amplifiers and in Free-Electron Laser Cascades

L. Giannessi,[1] P. Musumeci,[2] and S. Spampinati[1]

Superradiance + Multiple stages cascaded FEL

- Simpler cascade scheme with many stages (no Fresh bunch required)
- Reduced sensitivity to tolerances and fluctuations
- Pulse shape determined by FEL dynamics
- Sub-fs pulses

Superradiant Cascade

Ti:Sa 3° harm (after matching to the e-beam)

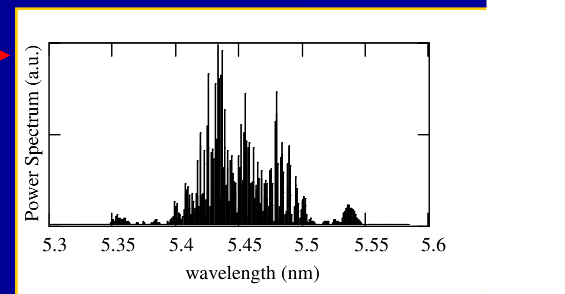
$\lambda \sim 266$ nm
E ~ 3.8 μJ
P ~ 225 MW
$\delta t \sim 16$ fs

→ PRE MOD. → X 8 → UM1 MOD. → X 6 → UM1 MOD. →

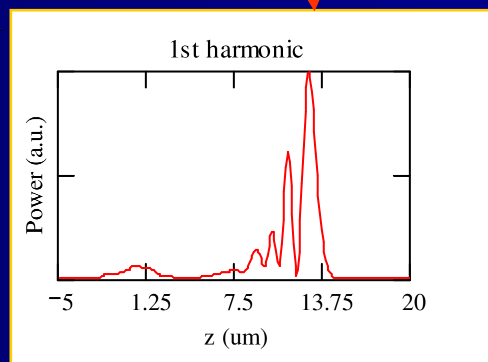
PRE MOD.:
$\lambda_u = 10$ cm
K = 9.5
50 periods
$\lambda_{res} \sim 260$ nm

UM1 MOD. (X 8):
$\lambda_u = 4.2$ cm
K = 4.9
2x48 periods
$\lambda_{res} \sim 35$ nm

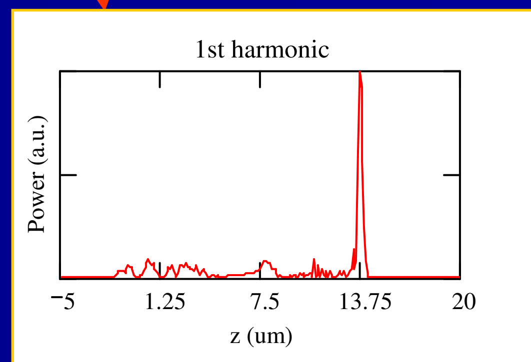
UM1 MOD. (X 6):
$\lambda_u = 4.2$ cm
K = 1.5
3x48 periods
$\lambda_{res} \sim 5$ nm



Beam Energy	1. 5 GeV
Peak Current	1.8 kA
Slice en. spread	$< 1.3 \, 10^{-4}$
Slice emittance	< 1 mm-mrad



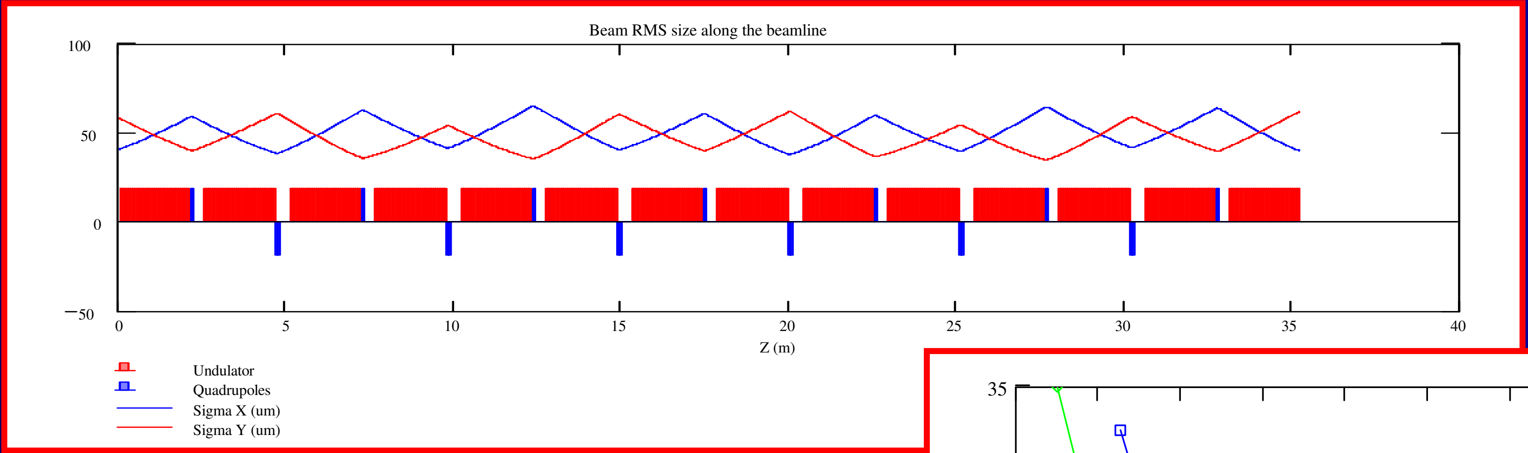
Energy	40 μJ
N ph.	7×10^{12}
Duration	4.3 fs (fwhm)



Energy	1.6 μJ
N ph.	4×10^{10}
Duration	1 fs (fwhm)

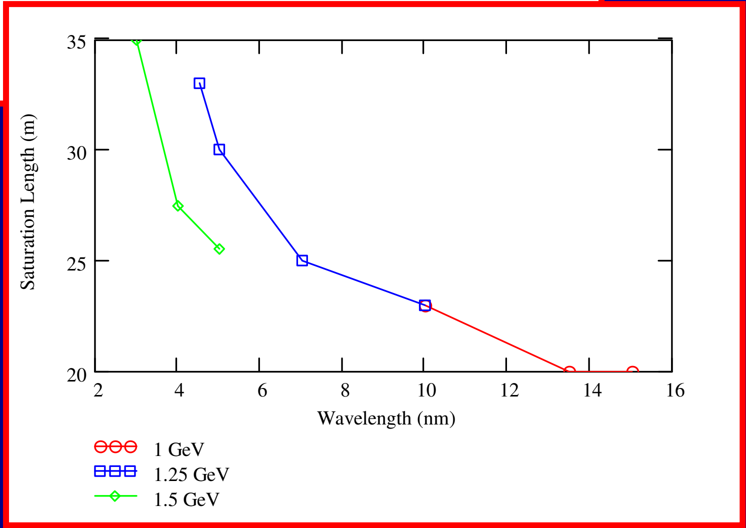
Undulator optics & saturation length

- SPARC Undulator sections 2.156 m + 40 cm gaps



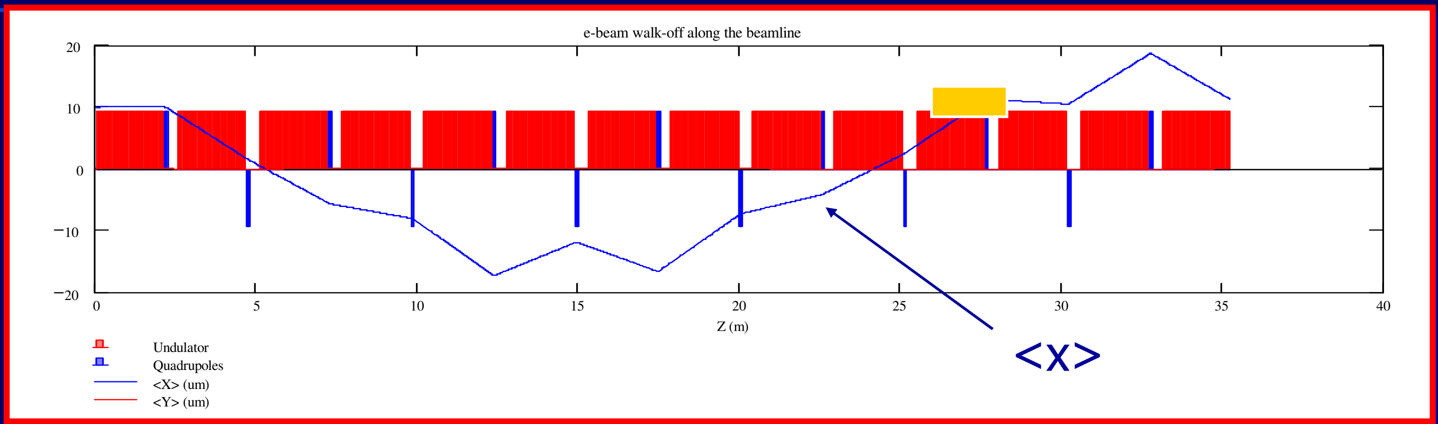
Average beta 6 m

The saturation length with the Modulator + Sparc undulator is 10-20 % larger



Pointing Stability

$\Delta x = 10\ \mu m$

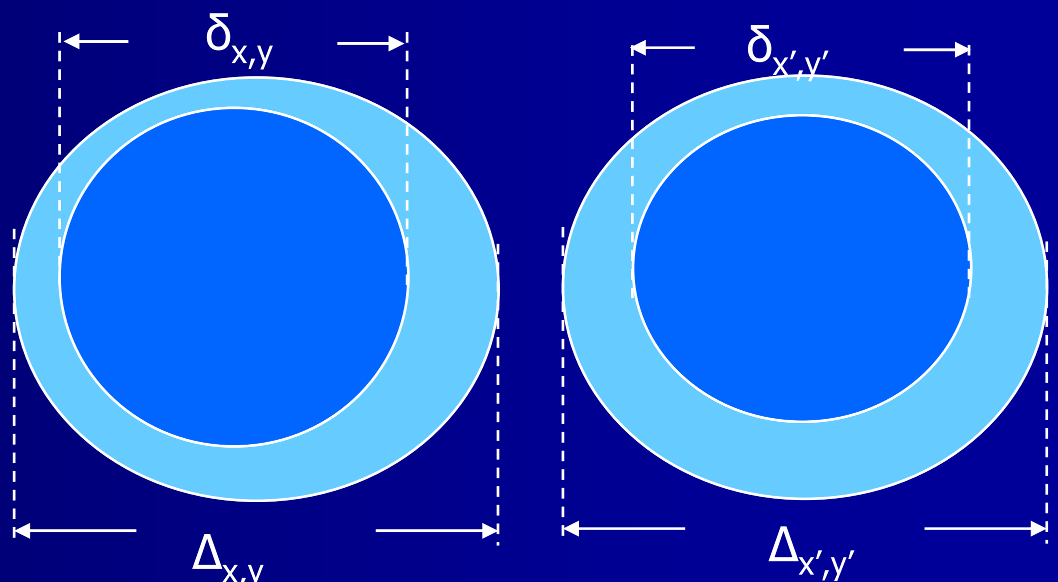


$\delta_{x,y,x',y'}$ = source size

$\Delta_{x,y,x',y'} = [(\delta_{x,y,x',y'})^2 + (J_{x,y,x',y'})^2]^{1/2}$

Beta=6m, $\Delta x = 10\ \mu m$

$J_{x,y} \sim 15\ \mu m$
$J_{x',y'} \sim 4\ \mu rad$

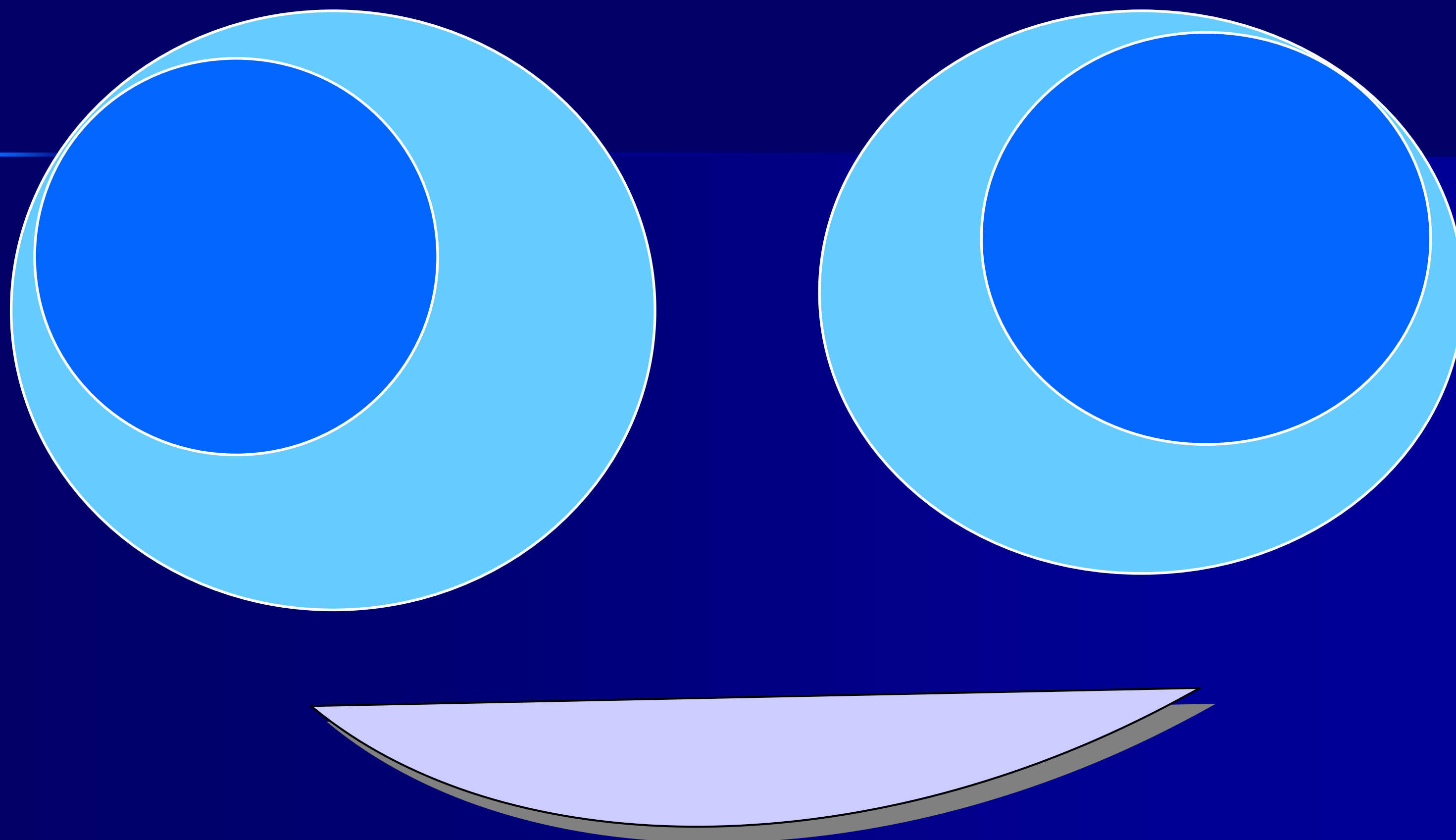


Conclusions

- Several sample configurations have been analysed
  - SASE in the range 3 – 15 nm
  - Seeded with cascade from Ne@13.5nm
  - Seeded with cascade from Ar@30nm+monocheromator
  - Seeded in superradiant mode for very short pulses

- This is a preliminary study
  - The linac configuration is still under study,
  - The simulations parameters have been only partially optimized

- The experience @ SPARC in the UV – VUV is fundamental for testing many of the ideas about seeding and cascaded FEL configurations



... buon lavoro