A Comparison of HGHG and Self-Seeding for the Production of Narrow Bandwidth Radiation in a Free Electron Laser

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Introduction

In this talk I will discuss a numerical study on the two main schemes for the production of narrow bandwidth FEL radiation.

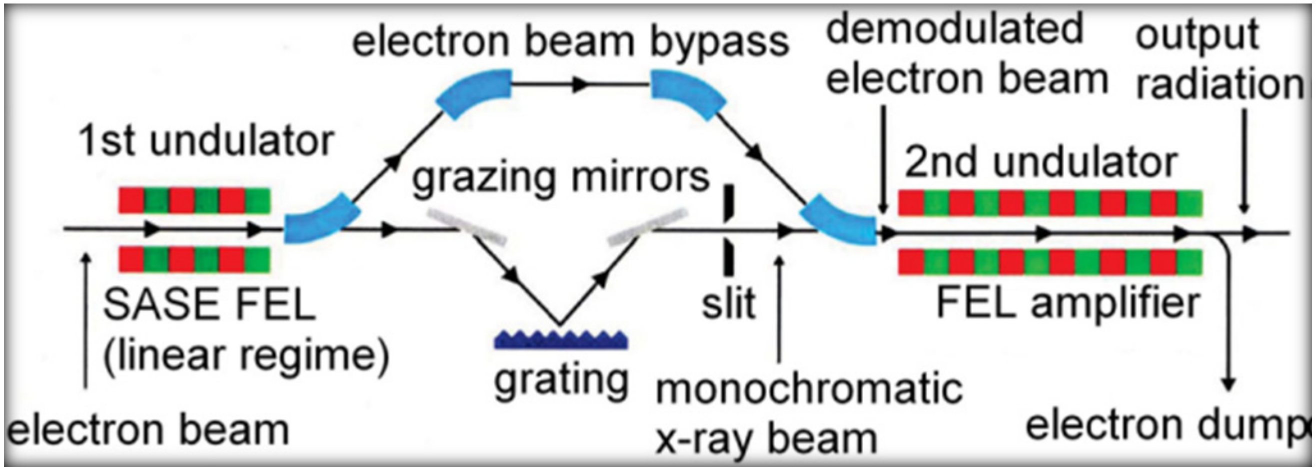
The talk will cover:

-1-D simulations in an idealized case

- Discussion on the non ideal effects that mainly affect the performance of seeded FELs

- 3-D Start to End Simulations for the

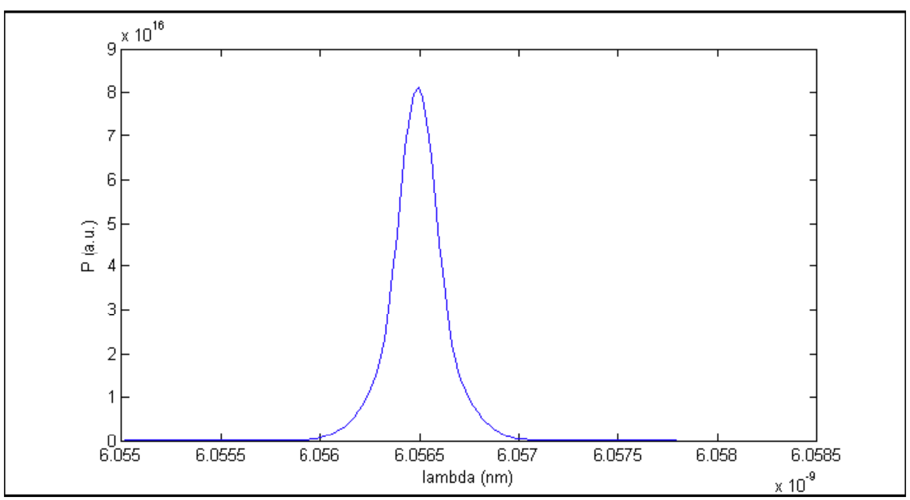
Narrow Bandwidth FELs: Self-Seeding



SASE-FEL process in the first undulator is interrupted well below saturation

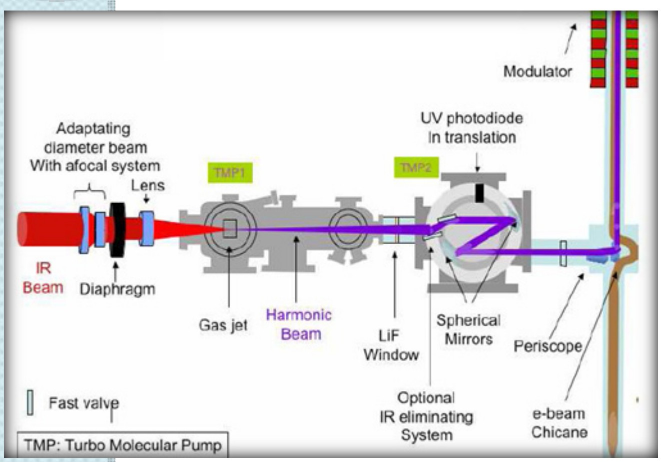
SASE radiation from the first undulator is monochromatized and used as a seed in the second undulator.

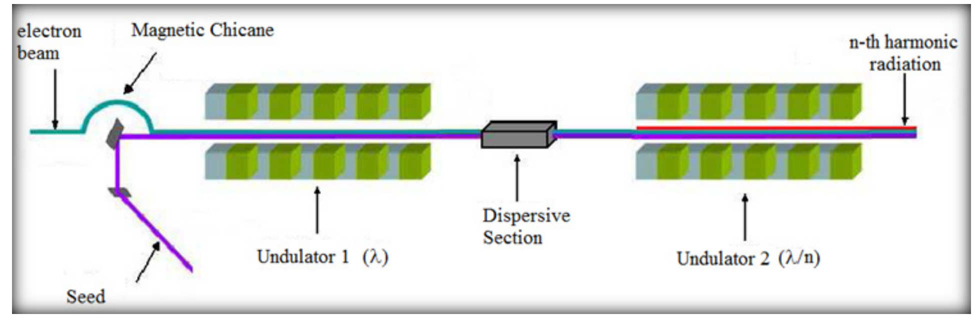
Electron Beam is demodulated by the Magnetic Chicane

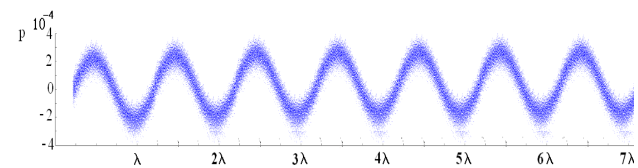


Narrow Bandwidth FELs: High Gain Harmonic Generation

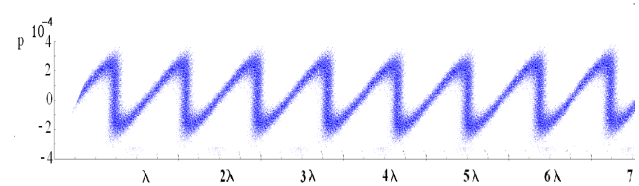
Seeding with HHG in gases

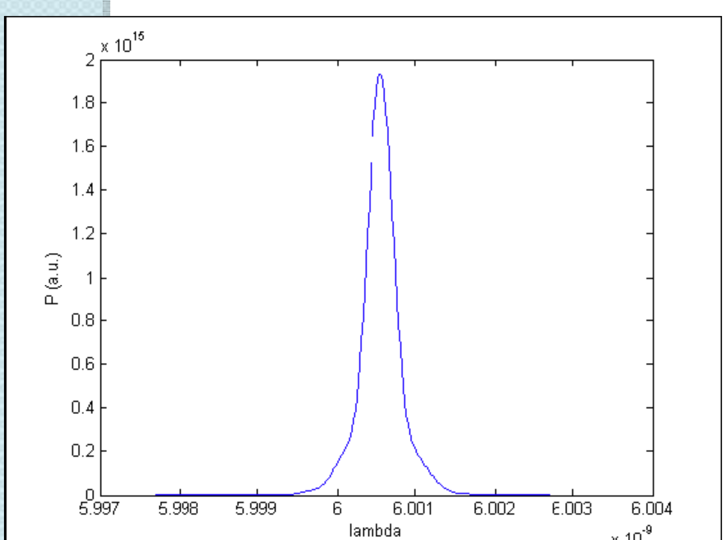






Frequency up-conversion of the FEL process





Narrow Bandwidth FEL radiation

Comparison in an Ideal Case

E=1,5 GeV
I=1,5 kA (Gaussian)
Espread=0,01%
Emittance=1mm*mrad
σ_z=60microns
Beta=5.5m

SELF SEEDING

λ_{rad}=6 nm

First Undulator : L = 2.8*410cm=11.5 m

Monocromator : $d\lambda/\lambda$=3 x 10^{-5}

Demodulator : R56 = 50μm

HGHG

λ_{mod}= 30nm → λ_{rad}=6nm

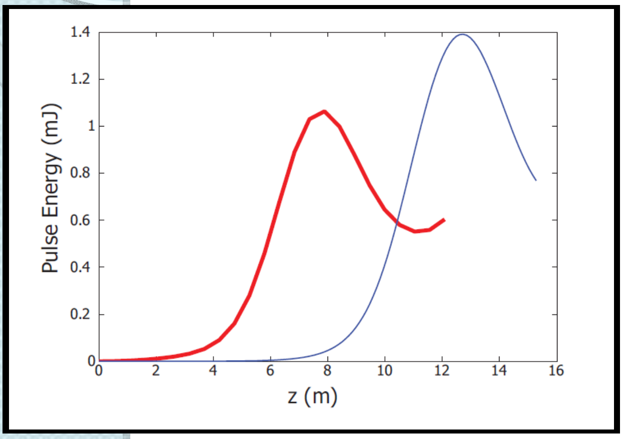
First Undulator : 130*4.2cm=5.5m

Seed Power = 100 kW
(Same duration as the e-beam)

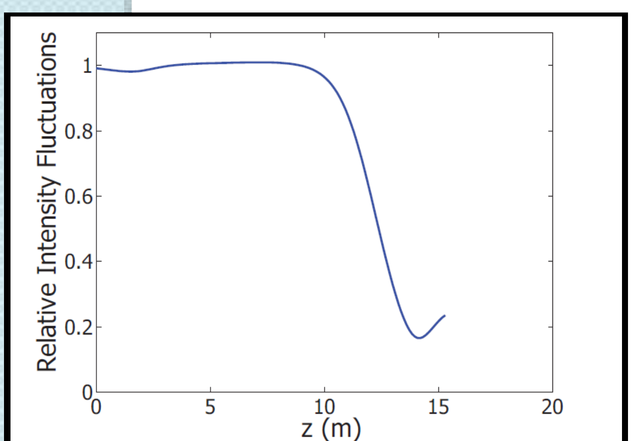
b_5=0.1

Ideal Case: Simulation Results with PERSEO

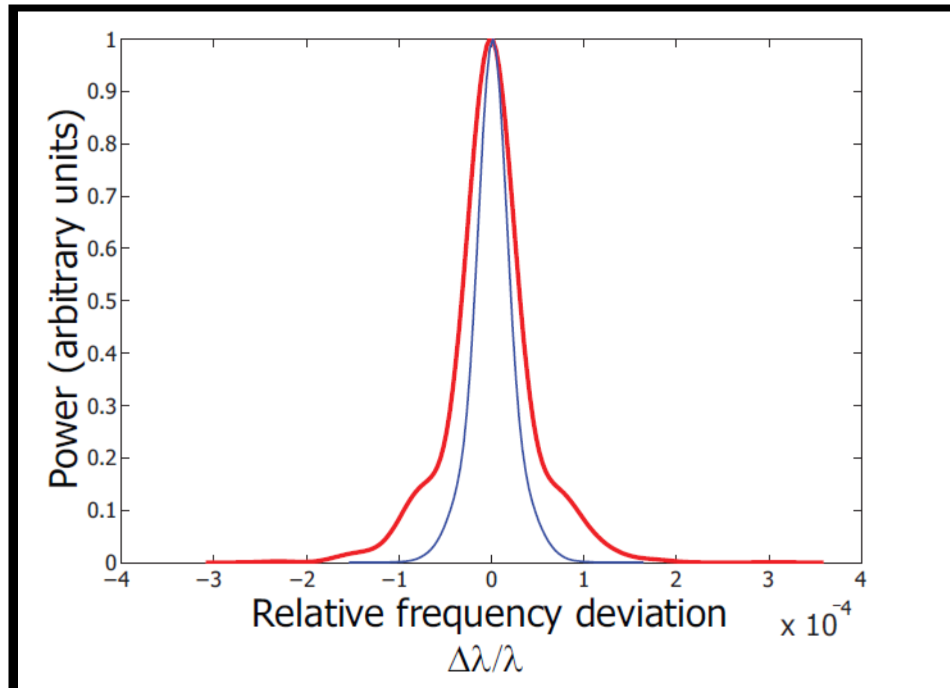
Energy vs z



Saturation energy
Self Seeding: 1.4 mJ
HGHG: 1.1 mJ



Spectrum @ saturation



Bandwidths
Self Seeding: 4.2 x 10^{-5}
HGHG: 6.8 x 10^{-5}

Comparison in the Ideal Case

-The performances of the two schemes are similar in terms of pulse bandwidth and energy.

-Self Seeding suffers from intrinsic intensity fluctuations (100% after monocromator → 10% @ saturation).

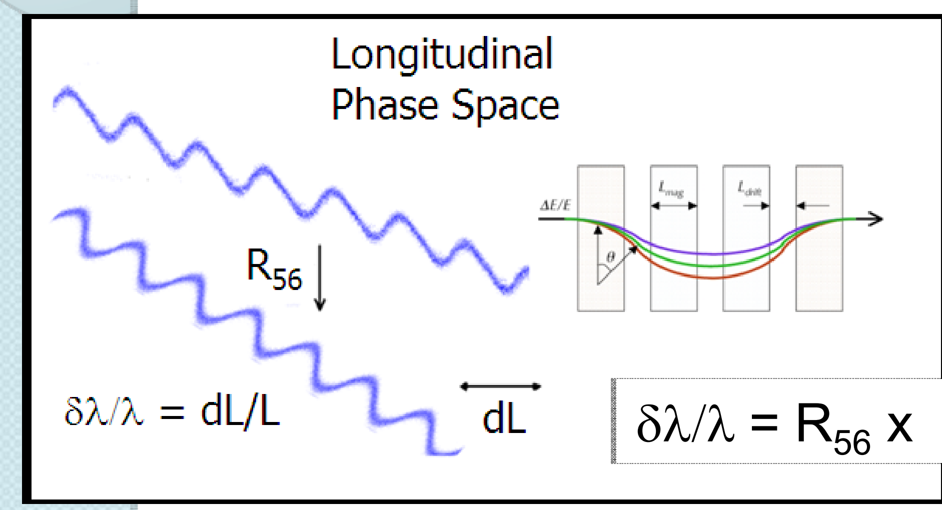
-Total saturation length is much longer in the self seeded case:

Pseed >> $P_{shot\text{-}noise}$ (HGHG) → (5+8 meters)

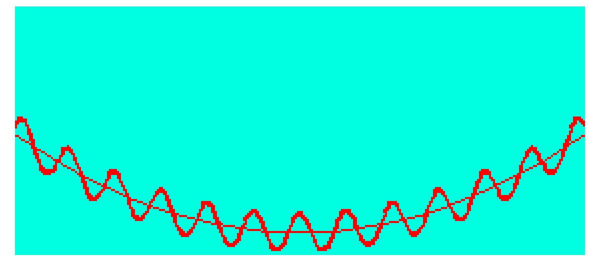
"Equivalent" Pseed << $P_{shot\text{-}noise}$ (Self Seeding) → (11+13 meters)

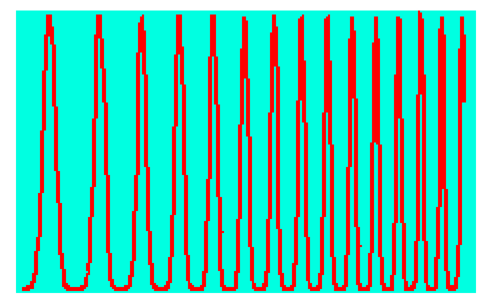
(The effective seed power is less than the shot-noise power since the only part of the SASE spectrum that reaches saturation is the one contained in the monochromator bandwidth)

Effect of Quadratic Energy Chirp: Bandwidth Broadening Through R56



$\delta\lambda/\lambda = R_{56} \times dp/ds$





A linear energy chirp results in a frequency off-set in the bunching factor after the dispersive section

A non-linear chirp results in a frequency modulation -> bigger bandwidth !!

Output Bandwidth Effects in Seeded FELs

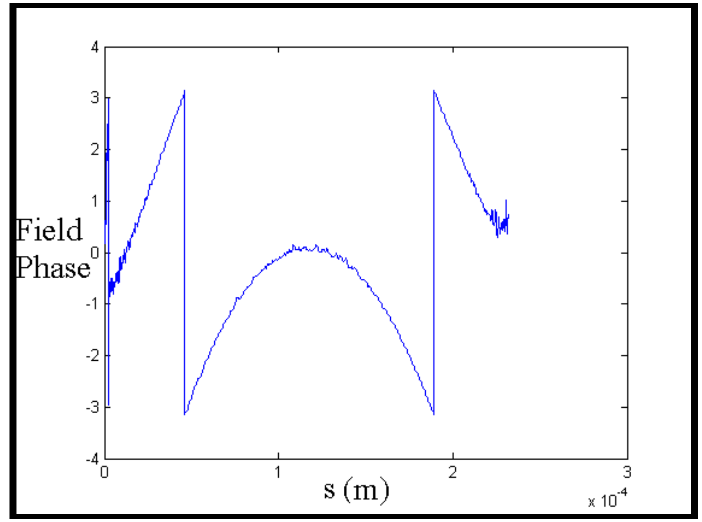
William M. Fawley

fel 06 BERLIN

S. G. Biedron, S.V. Milton, and H.P. Freund, NIM A **475** (2001) 401;
T.Shaftan *et al.*, Phys. Rev. E, **71**, (2005) 046501.

Effect of Quadratic Energy Chirp: Bandwidth Broadening in the Undulators

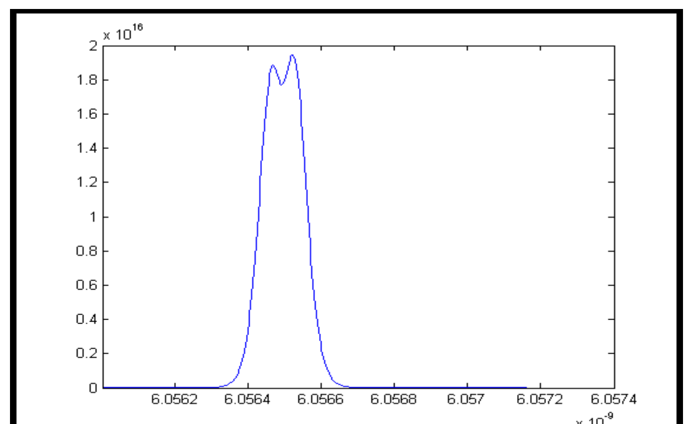
$\Delta\theta$ term due to the equivalent dielectric constant (imaginary part of the gain) varying along the beam with the energy.
The phase chirp is non-inear resulting in a frequency modulation of the output pulse



$$\psi(s) = -2k_w z p(s) + \Re\{\Lambda(p(s))\}2k_w z\rho.$$

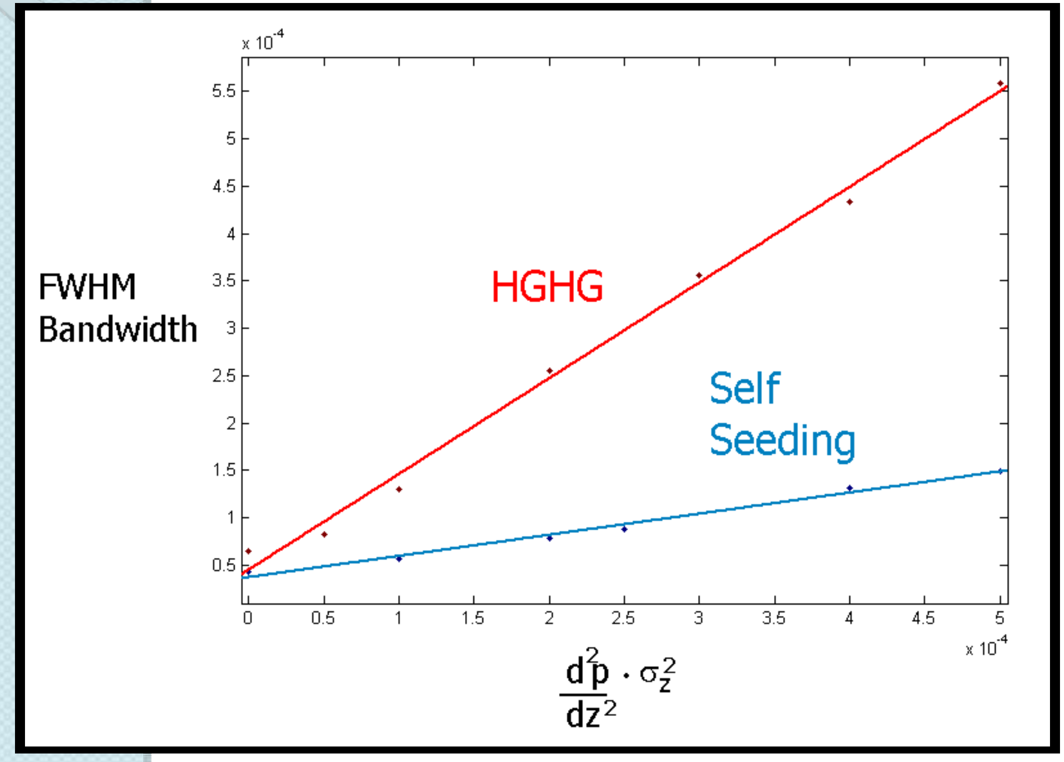
Spectrum @ saturation

$$\frac{\delta\lambda(s)}{\lambda} = 2N_w\lambda\frac{dp}{ds} - \frac{1}{2\pi}\frac{\lambda}{3\rho}\frac{dp}{ds}N_w\lambda_w 2k_w\rho = \frac{4}{3}N_w\lambda\frac{dp}{ds}$$



If $\beta*\sigma_p^2$=5*10^{-4} Bandwidth is 1.4 * 10^{-4}

Effect of Quadratic Energy Chirp: Comparison



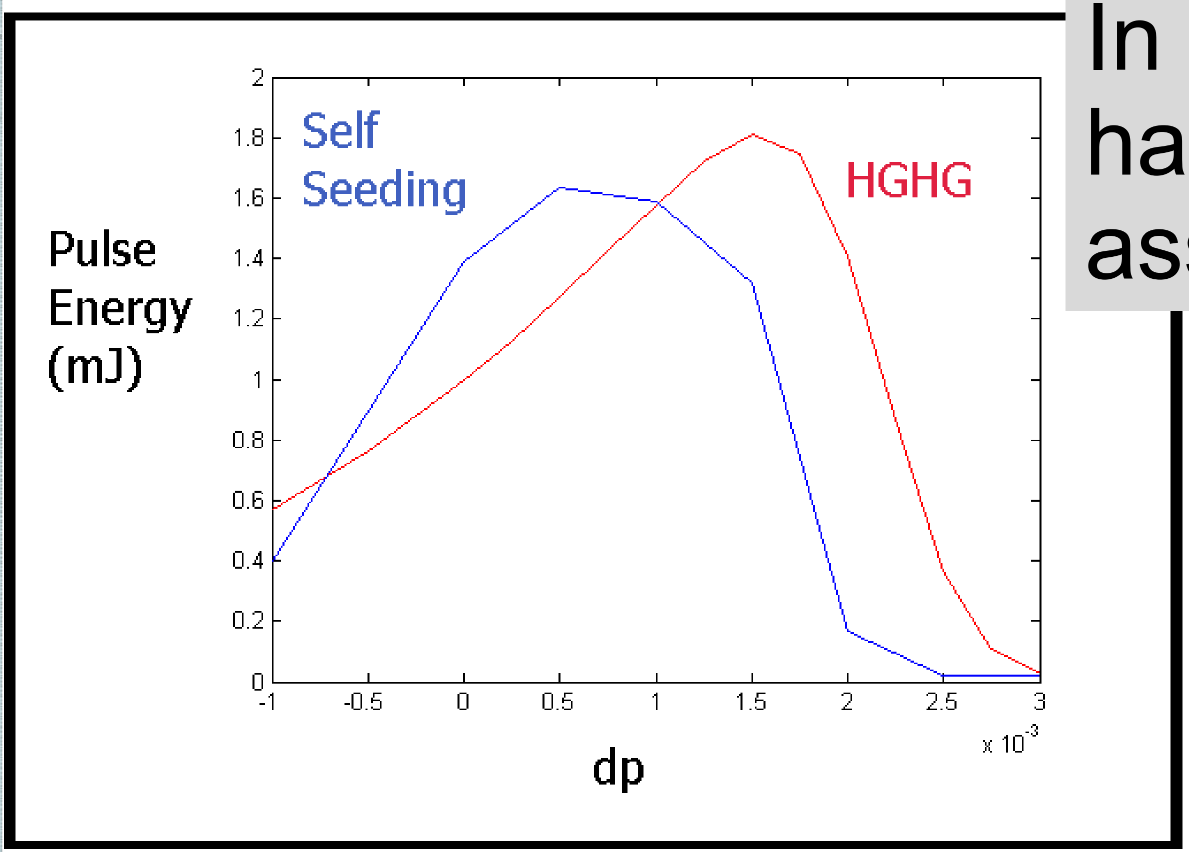
$$\frac{\delta\lambda(s)}{\lambda} = [\frac{4}{3}\lambda(nN_{mod} + N_{rad}) + R_{56}]\frac{dp}{ds}$$

$$\frac{\delta\lambda(s)}{\lambda} = \frac{4}{3}N_w\lambda\frac{dp}{ds}$$

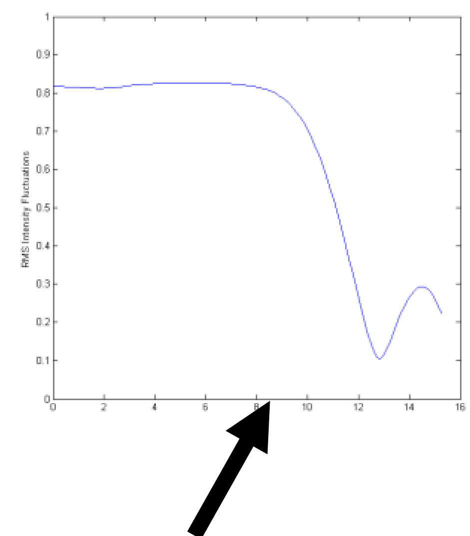
$$R_{56,opt} >> \frac{n\lambda}{2\pi\rho}. \qquad \frac{4}{3}N_w\lambda \sim \frac{\lambda}{\rho}$$

The effect is almost 5 times bigger in the HGHG scheme

Effect of Beam Energy Fluctuations



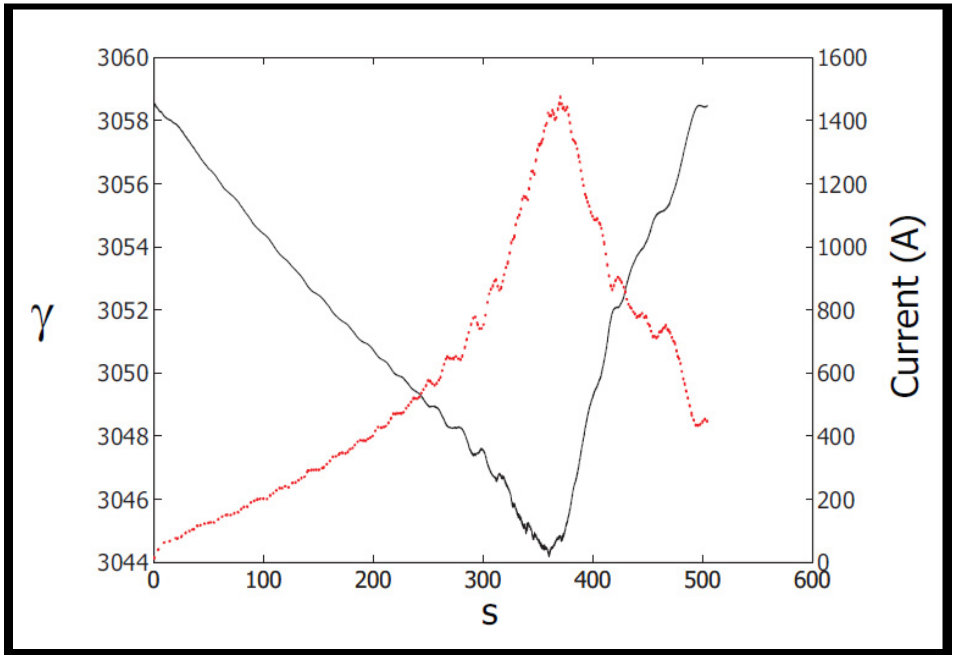
In both cases we have Δ_E=50% assuming Δ_p=10^{-3}



FEL amplifier in the saturation regime is insensitive to the starting value of radiation power or bunching factor!

Since the only difference between the two systems is the trigger of the instability, the performances with respecto to beam energy fluctuations atr comparable!!

3D Start to End Simulations: the 1nC SPARX e-beam



We analyzed the performances of the schemes with the standard 1 nC 1.5GeV working point with two stages of magnetic compression

Emittance = 1mm*mrad
Peak Current = 1.5 kA
Slice E-spread = $2*10^{-4}$

Very non linear longitudinal phase space!

3D Start to End Simulations: Modeling the Seed Source

State of the art for seeding at 30 nm

-λ_{pump} = 800 nm (Ti:Sapphire source)

-τ_{pump} = 35 fs

-gas target : Argon (Cut-off = 20 nm)

-ionization level η = 4%

(S. Stagira and L. Poletto, SPARX TDR)

Seed Pulse After Gas Jet

-Energy 0.02 μJ

-τ_{pulse} = 20 fs

-Fractional Bandwidth: 2% !!!!

A MONOCHROMATOR IS NEEDED

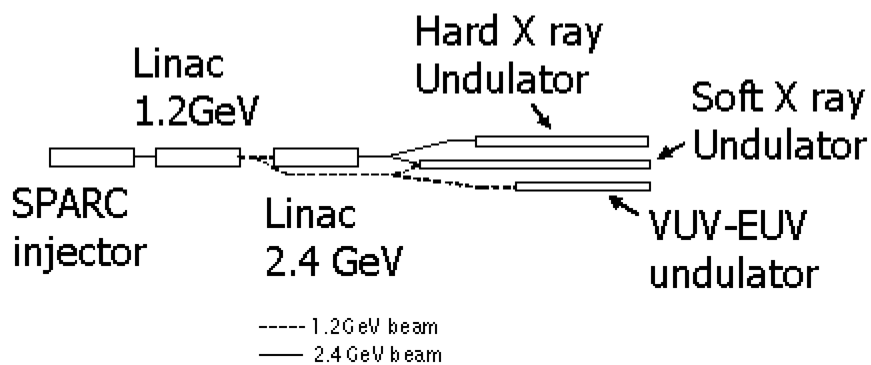
Seed Pulse After Monocromatization

-Fractional Bandwidth: $5*10^{-4}$

-Duration: 100 fs

-Peak Power: 10 kW

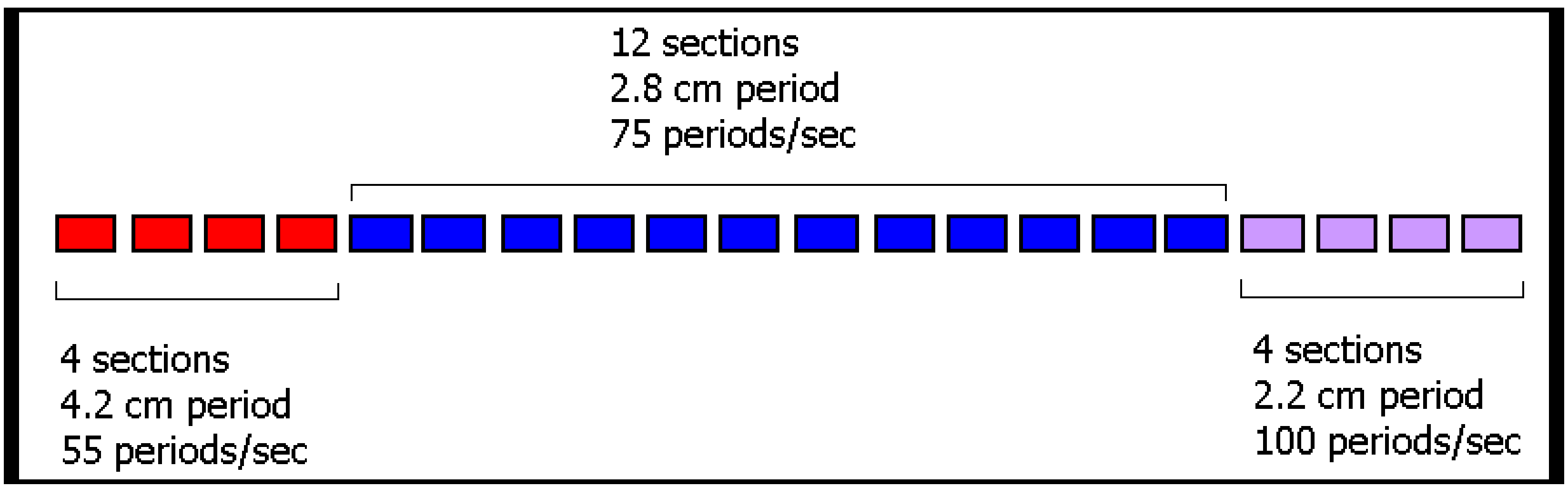
3D Start to End Simulations: the SPARX soft X-ray Undulator



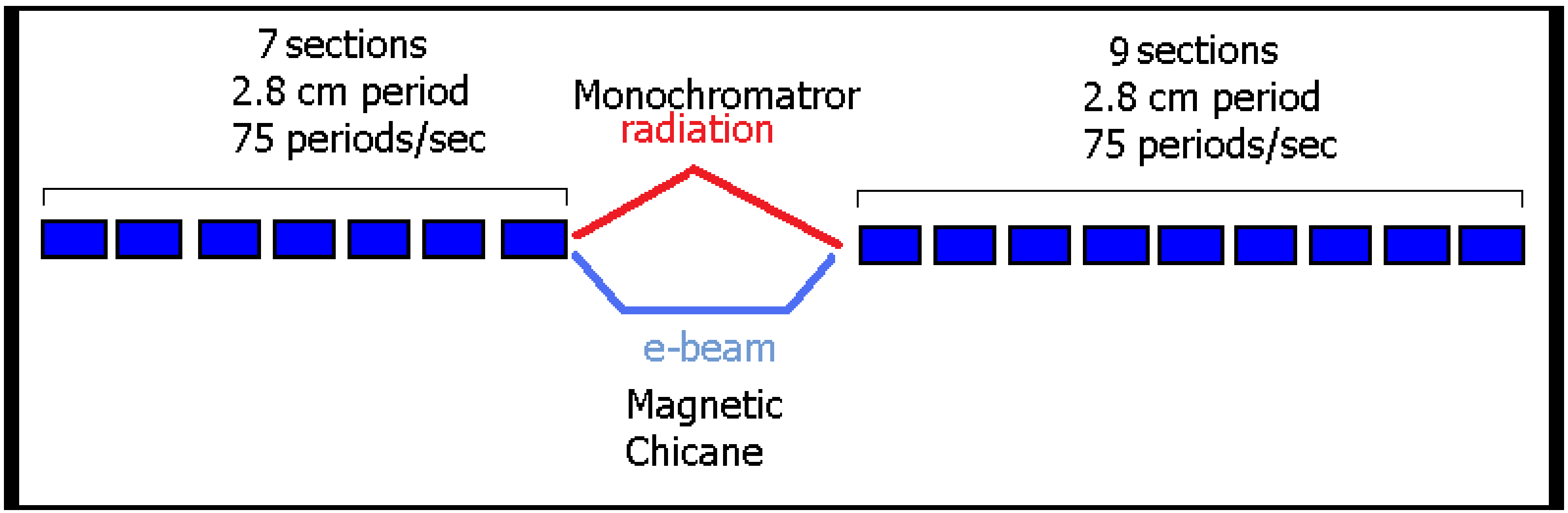
With the assumed seed power :

-Fifth harmonic bunching factor at radiator entrance is 8%

-Induced energy spread is σ_{pi}=8*10^{-4} = 4*σ_p



3D Start to End Simulations: Self-Seeded Scheme

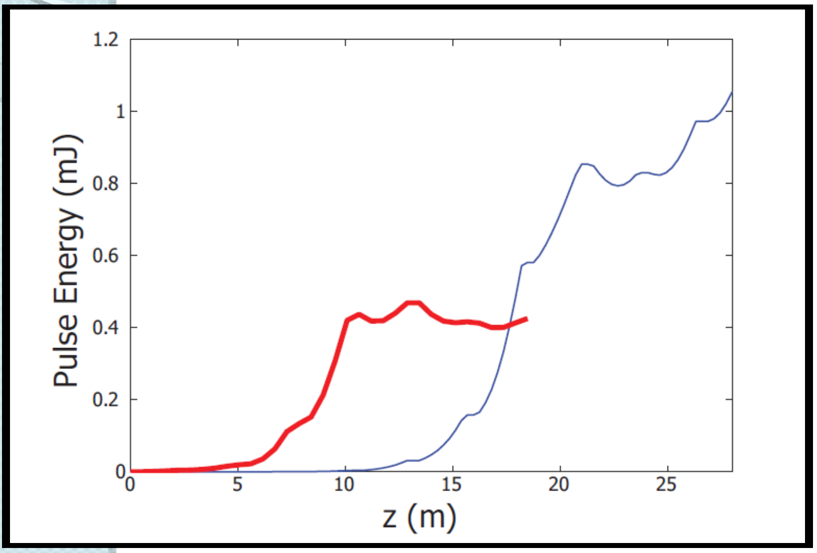


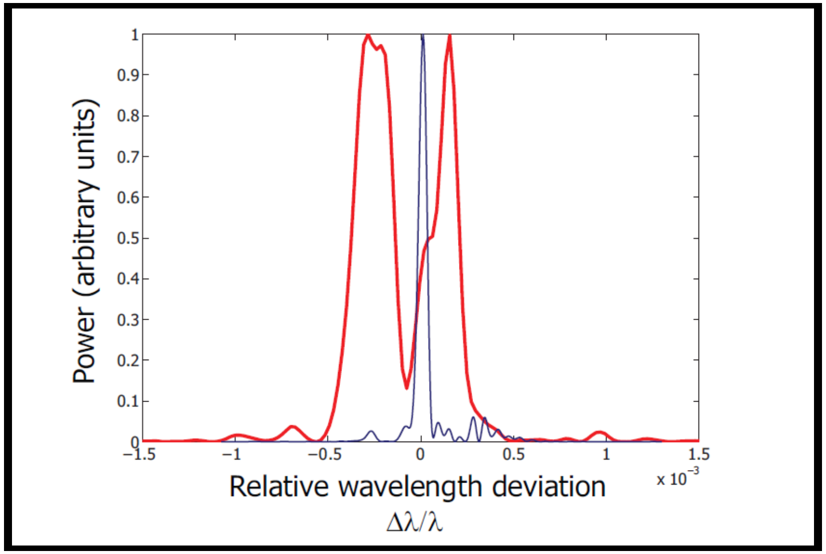
-Monochromator bandwidth is $3*10^{-5}$
-Assumed efficiency of 20%
-Average power at 2nd undulator entrance 60 kW
(Equivalent shot-noise power = 300W)

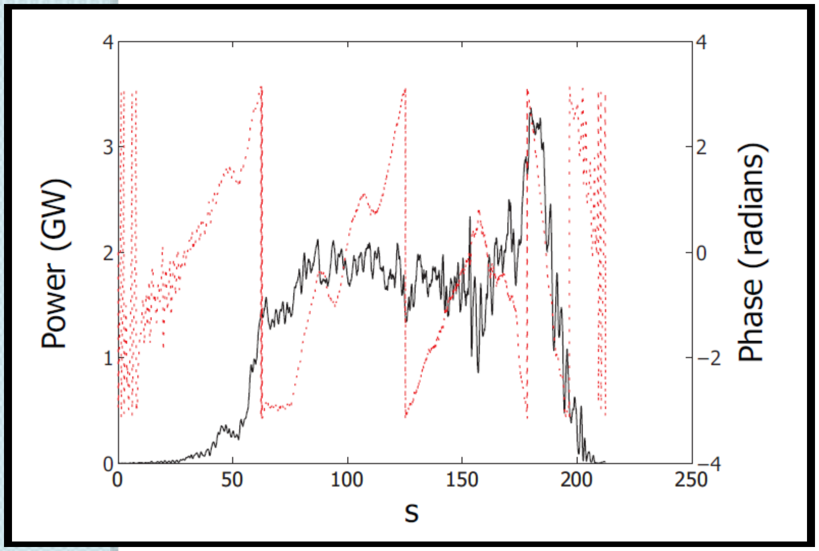
-Magnetic Chicane : R56=100μm

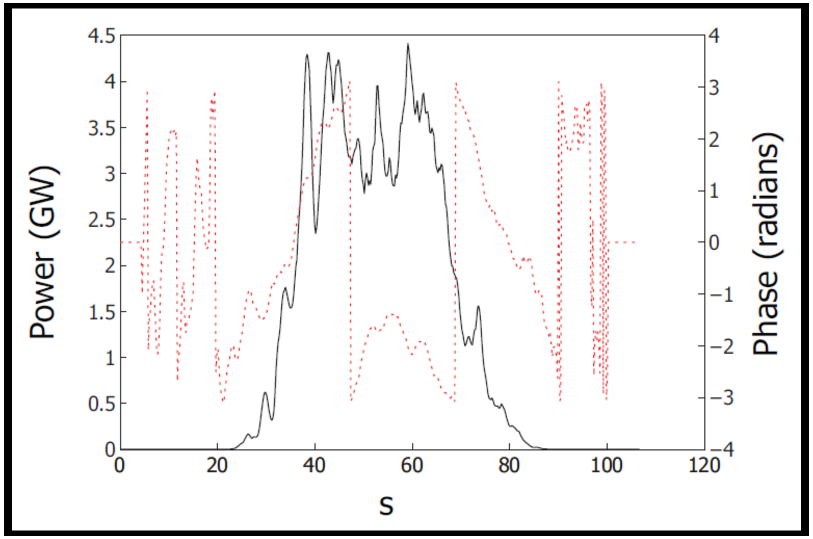
-Total length is 51 m

Start to End Simulations: Results

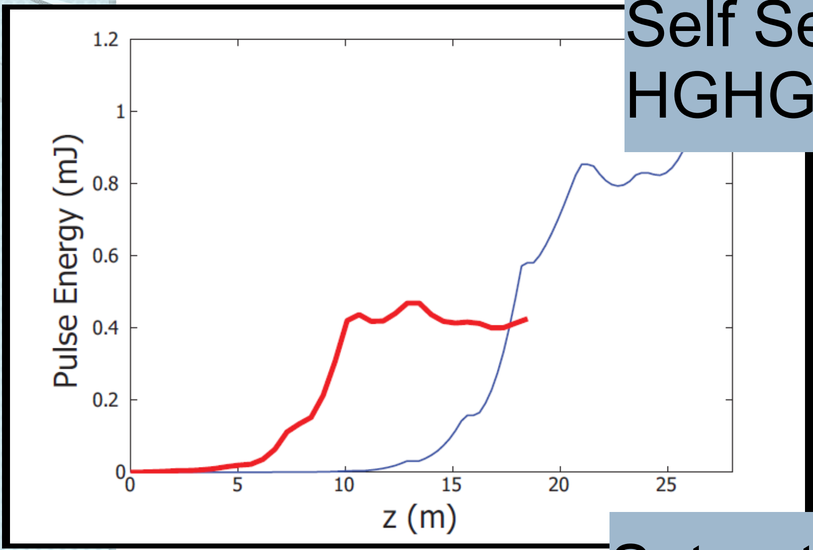


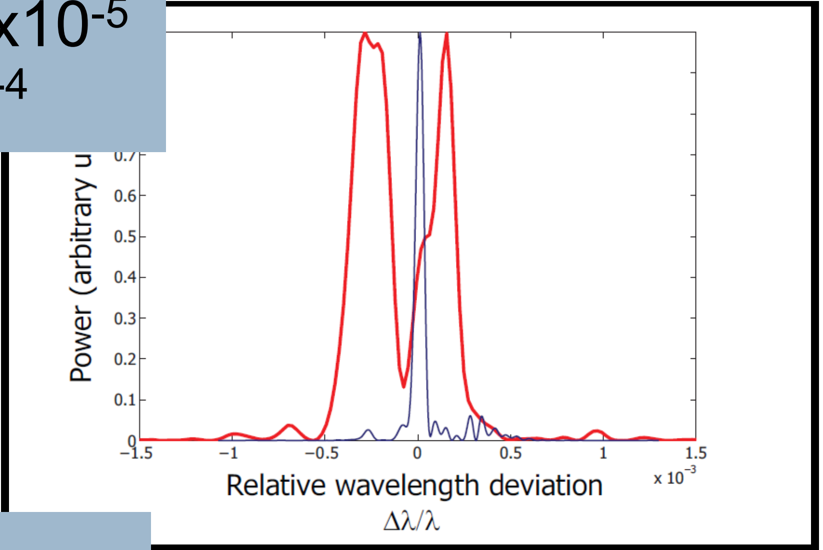




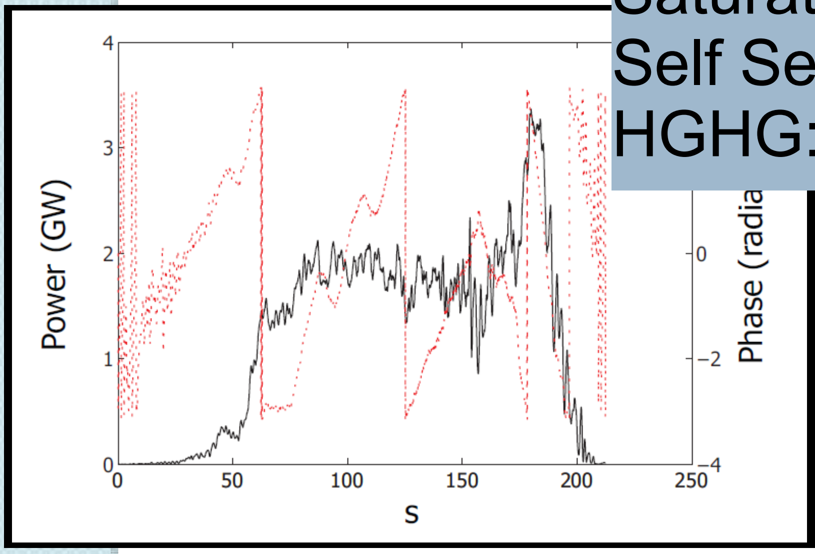


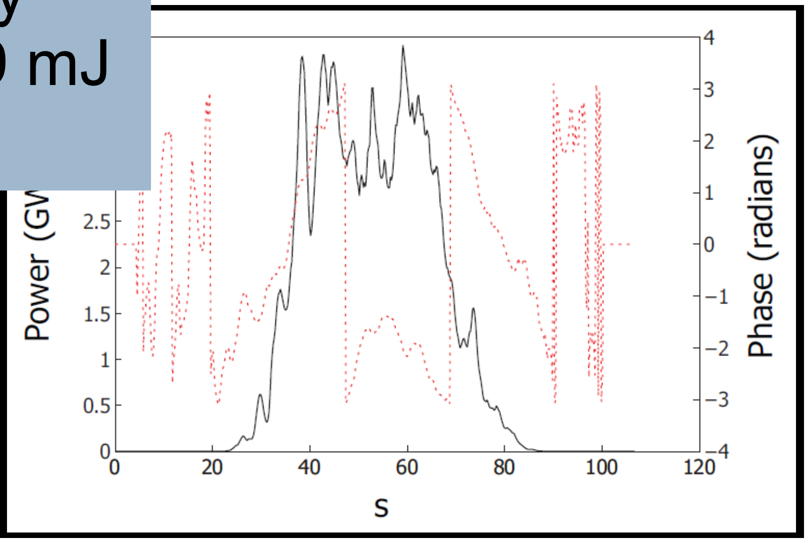
Start to End Simulations: Results





Relative Bandwidth
Self Seeding: 5 x10^{-5}
HGHG: 5.5 x 10^{-4}





Saturation energy
Self Seeding: 0.9 mJ
HGHG: 0.4 mJ

Conclusions

-The performances of the two schemes have been studied taking into account several "real life" effects.

-Self seeded FELs are less sensitive to non linear terms in longitudinal phase space

-Both schemes are equally sensitive to e-beam shot to shot energy fluctuations

-Taking into account state of the art seed sources and realistic electron beams the self seeded scheme performances exceed those of HGHG by a factor 30 in terms of spectral power density due to:

1) Short duration of the seed pulse (improvement in HHG in gas technology could help...)

2) Bandwidth increase due to non linear energy chirp (fundamental problem, requires specific optimization)

Conclusions 2

-This work points out the different sensitivity that these schemes have with respect to deviations from ideal beam conditions: while self-seeding is robust to non-linear beam energy distribution, the HGHG scheme performances suffer greatly from this effect and requires specific optimization and operation with lower current.

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Formation of electron bunches for harmonic cascade x-ray free electron lasers

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(Received 11 August 2006; published 6 December 2006)

Specific requirements for the electron beam in harmonic cascade-free electron lasers, together with means to produce such beams, are presented. All results are illustrated with simulations and particle tracking studies.

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A. Dr. Zholents, Dr. L. Poletto, Dr. S. Stagira and Dr. E. Hemsing.

The authors are also grateful to the SPARC/SPARX team, in particular Dr. C. Vaccarezza, for sharing the results of their start-to-end simulations

3D Start to End Simulations: Self Seeded Scheme, Simulation Technique

You have to trust demodulation in the Chicane!
(All the information on the particle phase is lost)

1 st Undulator
FEL process simulated with GENESIS 1.3 using a 6D particle distribution generated by accelerator codes

Dump and undersample .dpa file extracting from each slice a number of particles proportional to its current

Dump and filter (with FFTW3) the .dfl file and apply losses

More detailed simulations of the monochromator are needed!

Track the particles through the magnetic chicane with Elegant

Simulate the FEL process in the second undulator