BESSY

Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung m.b.H.

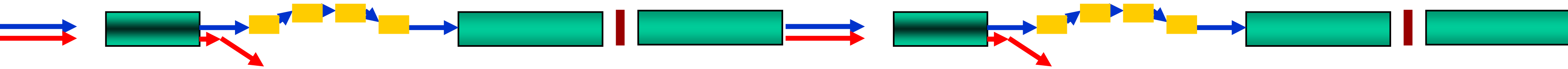
Cascaded HGHG Sources

Bettina Kuske

Workshop on Advanced Photon Sources

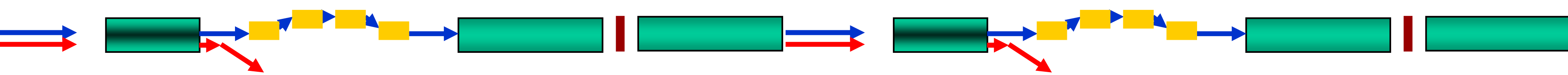
Daresbury Laboratory, June, 3rd-4th, 2008

Leibniz Gemeinschaft

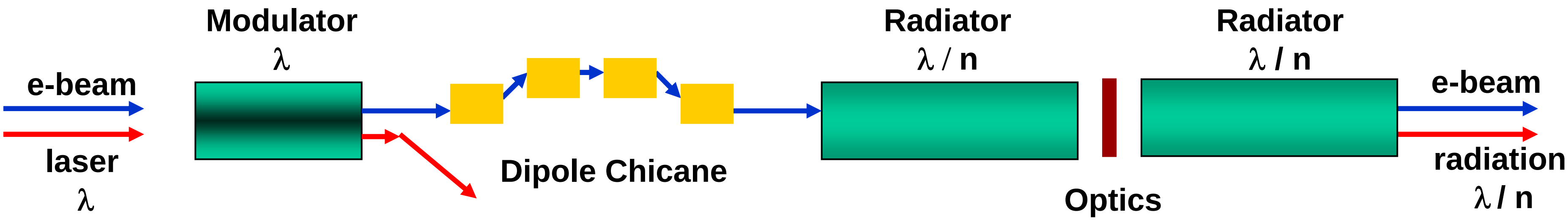


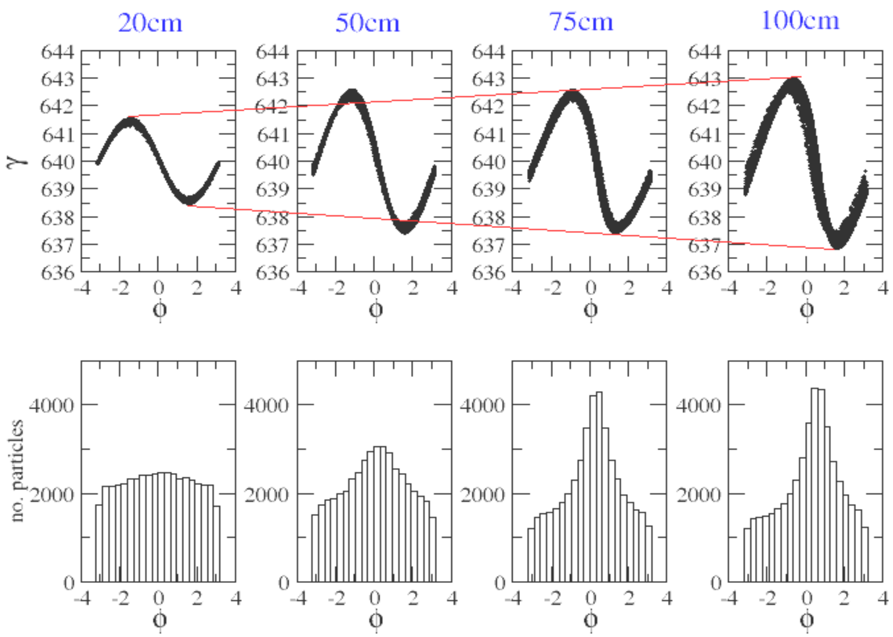
Outline

- Principle of High Gain Harmonic Generation
- Existing hardware – single stage
- Benefits of HGHG
- Facts to “be aware of” in cascading HGHG stages
- Alternatives under discussion



Principle of High Gain Harmonic Generation





Principle of harmonic generation

- Energy modulation due to laser field
- Undulator dispersion causes bunching
- Particle distribution includes higher harmonics that can be amplified in a suitable radiator

No bunching without increased energy spread

- Large energy spread => large long. velocity spread
  => large gain length, reduced bunching/power

Interaction free dispersive section

- Knob to boost certain harmonics
- Diagnostics
- Deflective chicane: eliminate seed radiation

DUVFEL / Source Development Laboratory
Brookhaven National Laboratory, NY, USA

Single stage HGHG

Pioneering Experiments 2002/2003
Li H. Yu et al.

- ***2/2002 Sase***
- ***10/2002 HGHG 5.3μm (CO_2 laser, 2nd harmonic)***
- ***3/2003 266nm (Ti:Sa laser, 3rd harmonic)***

Beam Parameter DUVFEL	
Beam Energy	300 [MeV]
Bunch Charge	300 [pC]
Rep. Rate	2.5 [Hz]
Peak Current	300 [A]
Bunch Length (rms)	1 [ps]
Norm. emittance	3-4 [mm mrad]

Undulator Parameter DUVFEL	
Modulator	10 x 8cm
Dispersion	30cm
Radiator (16 sections)	256 x 3.89cm
Module Length	2.156 [m]
Gap	6-25 [mm]
K	0.38-3.2

Ti:Sa Laser Seed Parameter DUVFEL	
Seed Power	100 [MW]
Seed Wavelength	800/400/266 [nm]
Seed Length	0.1-6 [ps]

DUVFEL - results

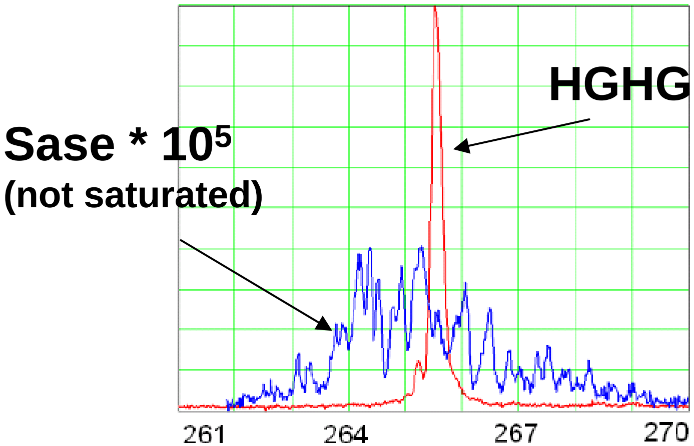


Figure 4: Single-shot HGHG spectrum exhibiting a 0.1% FWHM bandwidth (red curve). Blue curve represents SASE spectrum (magnified by the factor of 10^5). Horizontal axis is scaled in nanometers.

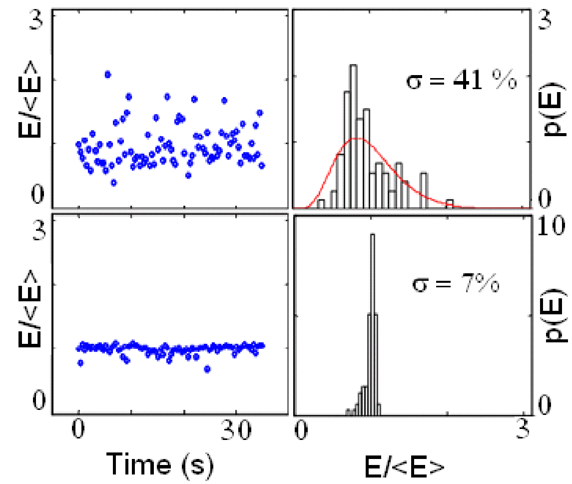


Figure 5: Time dependence and histograms of HGHG and SASE output pulse energies.

Pulse energy:120μJ @ 266nm (fundamental)
1μJ @ 88nm (3rd harmonic)
Pulse energy: stability 7%
Peak intensity / bandwidth fluctuations: 10%
Central wavelength stability < rad. bandwidth

Graphs taken from:
T. Shaftan et al., „Seeded Harmonic Generation Schemes“, Proceedings of APAC 2004, Gyeongju, Korea, pp. 772-776

Many fundamental experiments since then:

-Super radiance demonstrated
-Wavelength tuning by bunch compression
-Experiments concerning degree of long. coherence
-Efficiency enhancement by energy-detuning
-Statistical investigations
-Energy on harmonics, transverse profiles etc.

Further Single Stage HGHG Hardware

EUROFEL
MAX-lab, Lund, Sweden

- *First electrons 12/2007*
- *First overlap laser/beam not yet 5/2008*
- *3rd – 5th harmonic 88/53nm*

Beam Parameters EUROFEL	
Beam Energy	400 MeV
Final bunch Charge	0.1 nC
Rep. Rate	0.5 Hz
Mean Current	300A
Bunch Length (rms)	300 fs
Norm. emittance	4 mm mrad

SDUV-FEL
Shanghai, China

- *Linac commissioning with RF gun 2008*
- *Installation of bunch compressor / undulators 2008*
- *FEL-commissioning 2009*
- *3rd harmonic 88nm*

Beam Parameters SDUV-FEL	
Beam Energy	150 MeV
Bunch Charge	1 nC
Rep. Rate	0.5 Hz
Peak Current	400 A
Norm. emittance	4 mm mrad

FERMI, Trieste & SPARC, Frascati, Italy - later

Benefits of HGHG:

- **Control of output pulse** by seed laser properties
  - *Output pulse length independent from e-bunch length*
  - *Stability determined by timing jitter, e-bunch properties*
  - *Close to Fourier-transform limited*
  - *Pulse shape*
- **Wide wavelength range accessible** by choice of harmonics
- High spectral power
- Good synchronization by coupling seed laser and gun laser (jitter is reduced to bunch arrival time jitter)
- Good synchronization for pump-probe experiments
- No need for monochrometers

Tunability: Different concepts, non thoroughly investigated, few % – 10% detuning range expected

Use broad bandwidth of short seed pulse / Tune seed laser / Tune electron energy / Chirped pulse delay / Dispersion tuning

Quest for shorter wavelength:

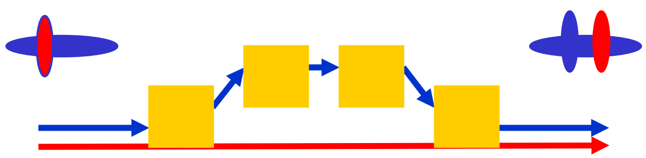
Shorter Seed Wavelength – HHG

Cascaded HGHG stages (has not yet been demonstrated)

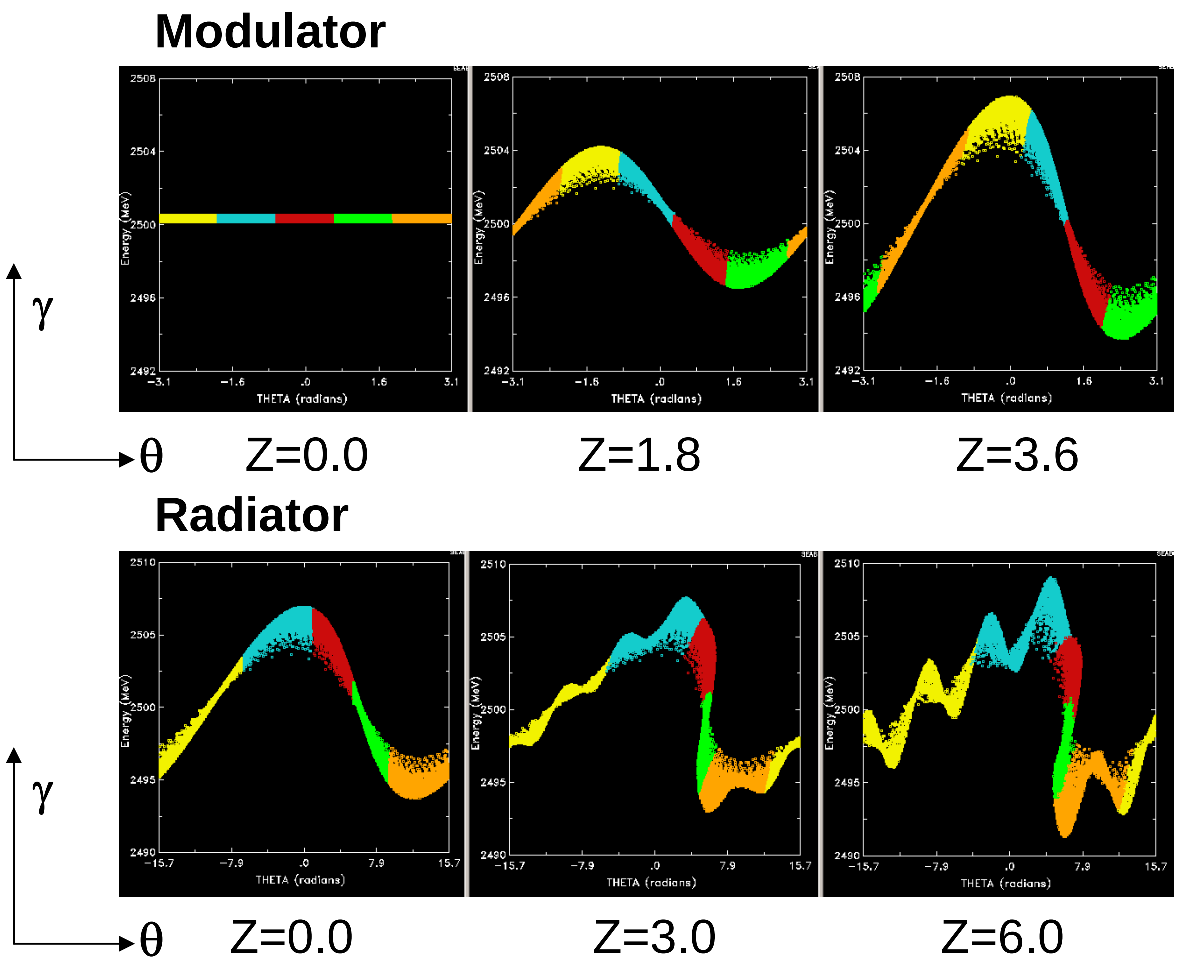
Careful: seeded part of the bunch is too heated for a second seeding

Fresh bunch technique

- **Delay of the e-beam: dipole chicane / dispersive section**
- **Radiation hits the bunch at a 'fresh', unused part**



Bill Fawley:
Calculations for LUX
θ/ γ phase space
at diff. positions



Repeated seeding:

- **loss of peak power**
- **increase of noise**
- **spectral widening**

Picture taken from: William M. Fawley, Workshop on Seeded FELs, 4-5 December 2006, BESSY

Facts to be aware of – no ‘show-stoppers’

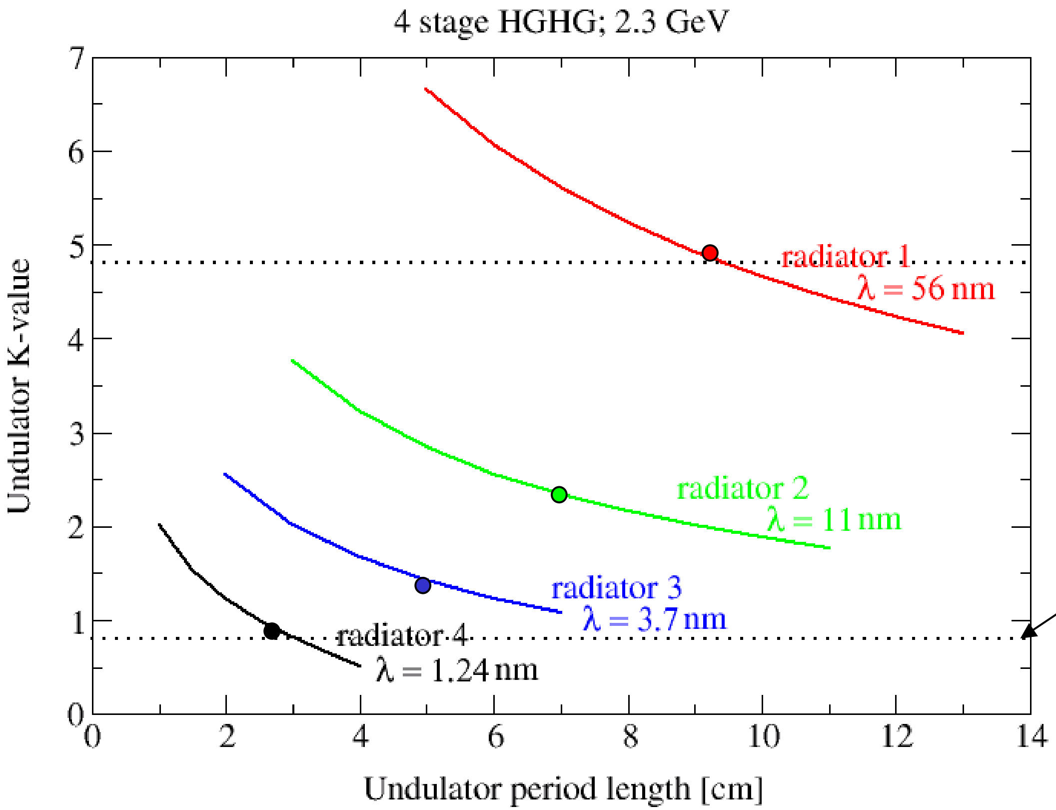
• Single energy for several stages / wavelengths
– compromises on FEL-efficiency in certain stages

• Energy spread increases due to spontaneous emission
• Noise-to-Signal grows with n^2
• Degradation of seed quality

•‘Used’ bunch part still radiates / how to block the seed radiation

• Fresh bunch technique
- bunches are longer
- bunch charge increases
- degradation of bunch purity in gun/linac (SC/CSR)
- bunch properties change along the bunch

Cascade Layout



$$\lambda_{res} = \lambda_u / 2\gamma^2 \text{ sqrt}(1+K^2)$$

Large K-value => large Pierce Parameter
=> small gain length
=> high output power
=> higher content of harmonics

K-value/undulator period becomes too small
- in vacuum undulators
- cryogenic undulators
- superconducting undulators

Facts to be aware of – no ‘show-stoppers’

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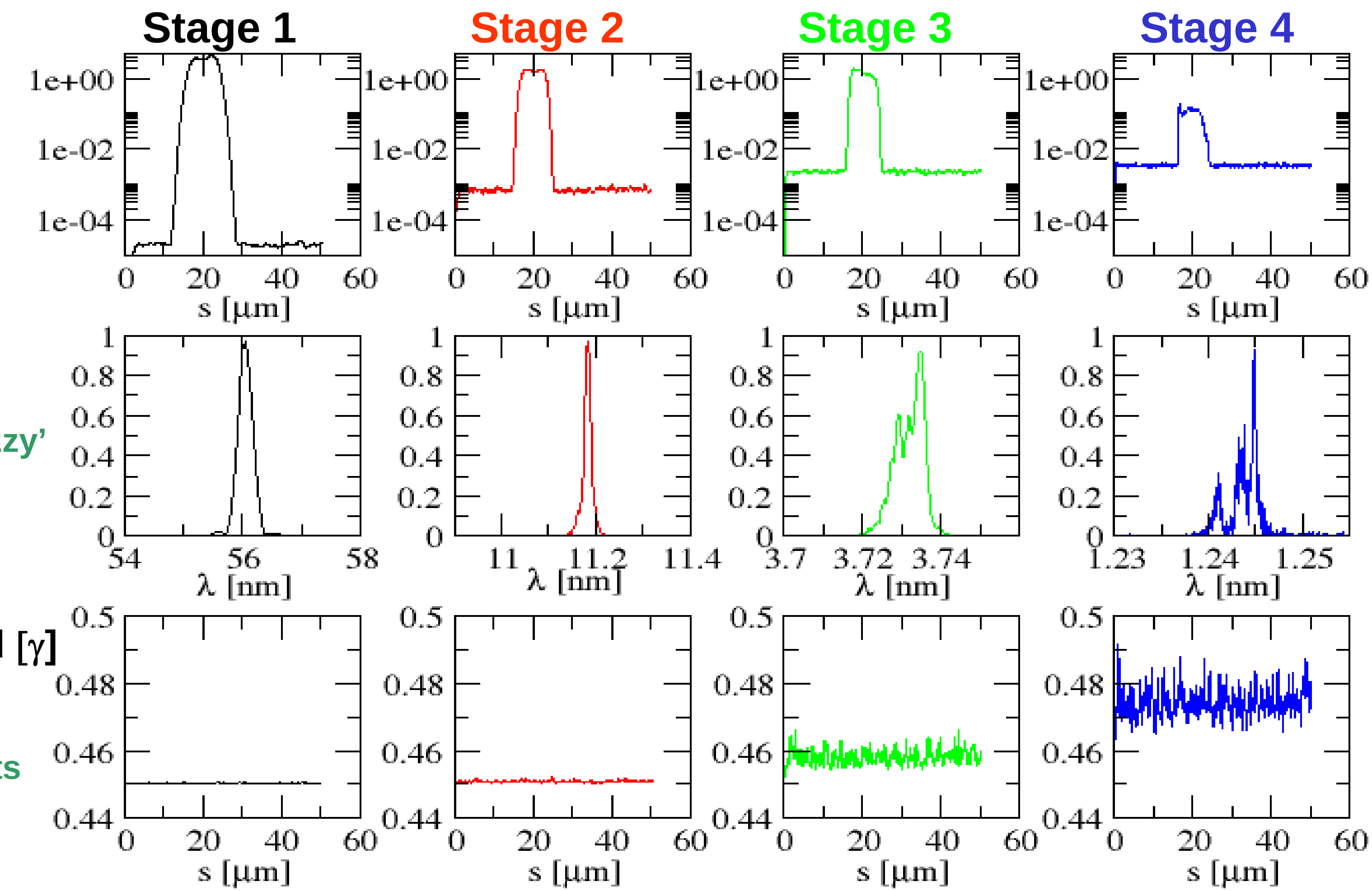
4 stage BESSY FEL Radiator output

Power [GW]
Signal-to-noise ratio degradation

Spectra [a.u.]
degradation due to noise and ‘fuzzy’ energy spread

Energy spread [γ]
grows due to sp. radiation of fresh bunch parts



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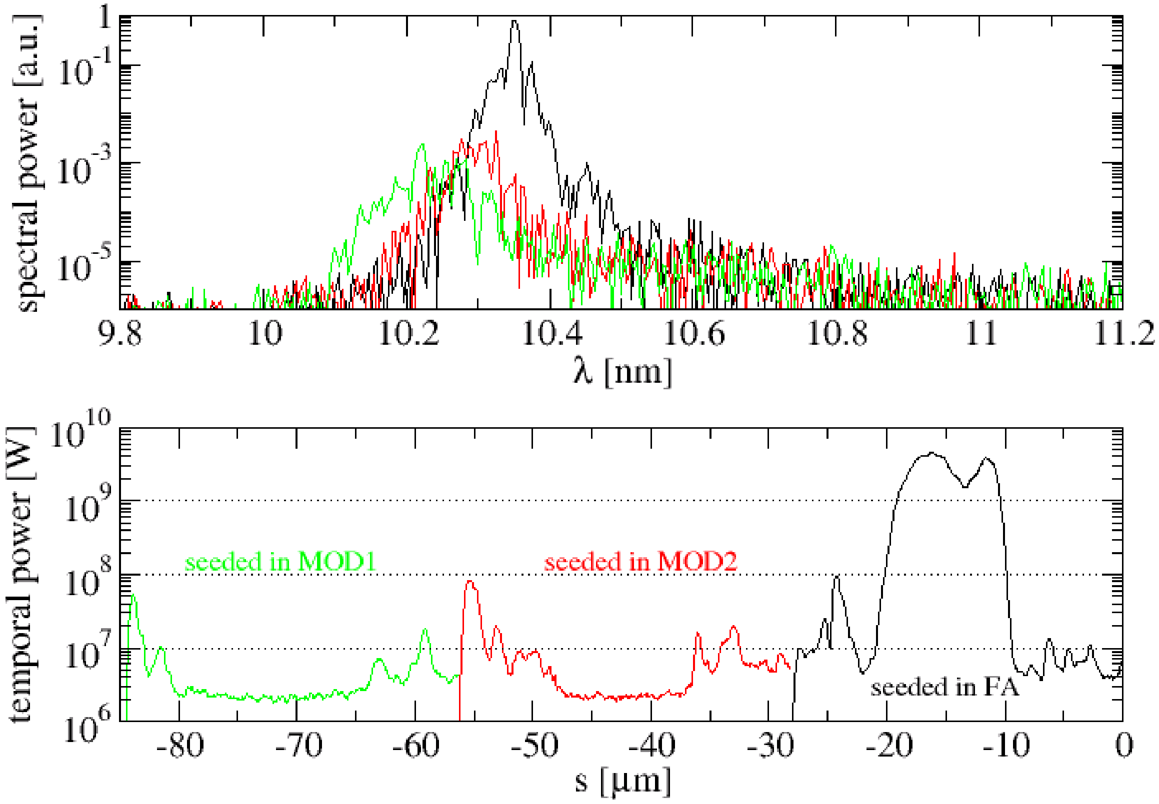
Radiation from upstream bunch parts

Spectrum and temp. power of three consecutively used bunch parts in a two stage HGHG with final amplifier

Be aware:
It is not possible to compute the effects of 'old' seed radiation in upstream stages with available programs



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• Fresh bunch technique
  - bunches are longer
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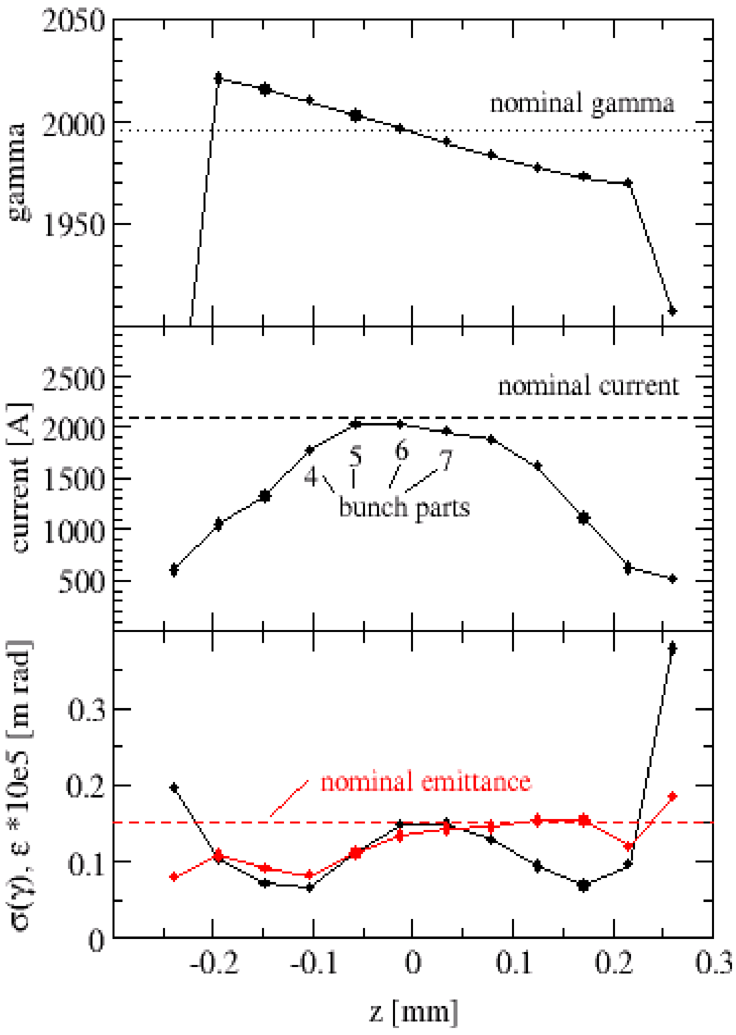
  - bunch properties change along the bunch

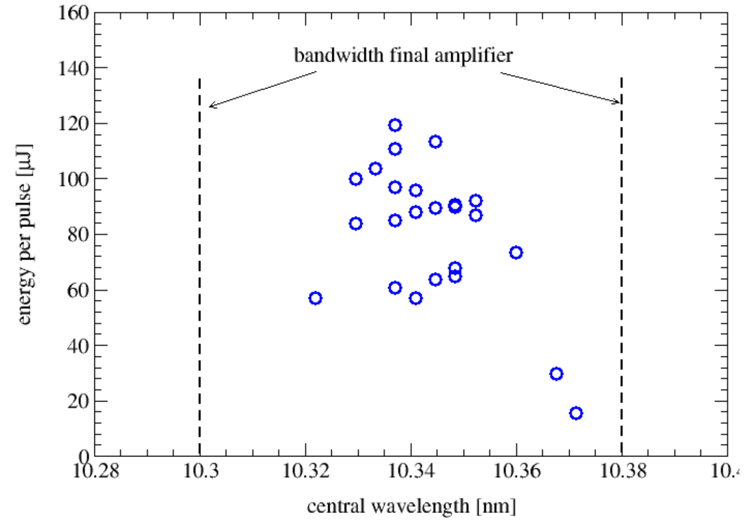
Variation of bunch properties

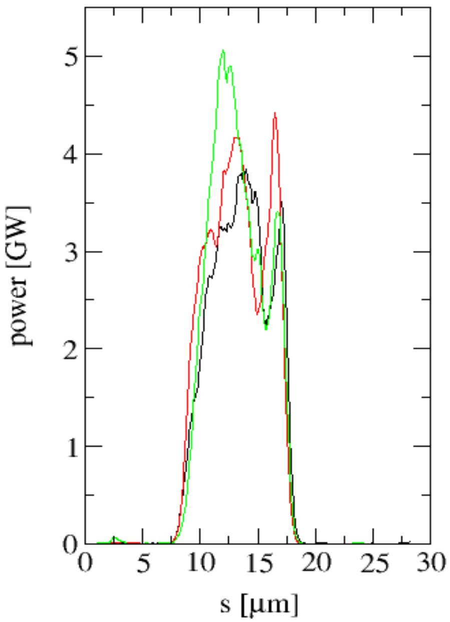
Bunch properties like energy, current, emittance, energy spread, etc., might change significantly along a long, high charge bunch

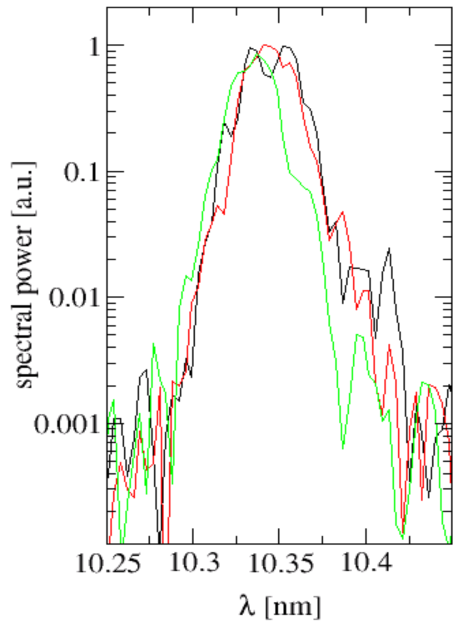


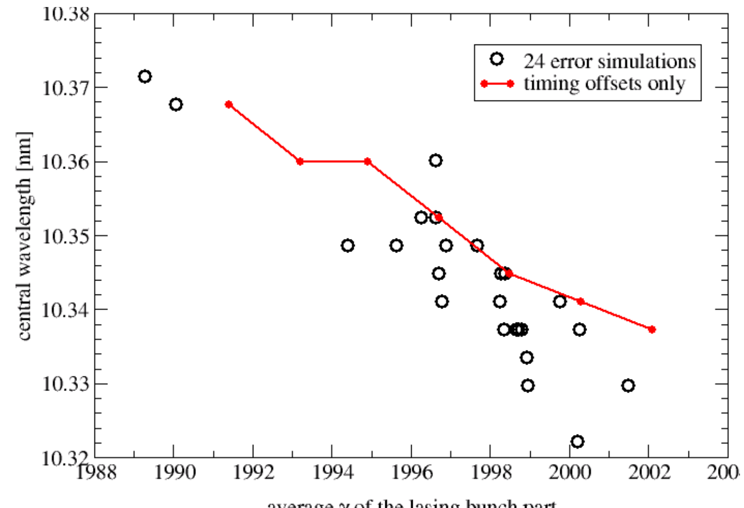
BESSY low energy FEL:
2 stages + final amplifier

24 different bunches
Errors in injector and linac
Dominant contribution: arrival time jitter of e-bunch









B. Kuske et al. "Start-To-End Simulations for the BESSY Low and Medium Energy FEL Line Including Errors"
Proc. FEL conf. 2005, Stanford, CA, USA, pp. 39-42, 2005

Alternatives under discussion

Fermi@Elettra, Trieste, Italy

Create bunching without increasing the energy spread

Sparc, ENEA, Frascati, Italy

Super radiant FEL cascade

WiFEL, Univ. of Wisconsin-Madison, Wisconsin, USA

Modulator cascade / Radiator cascade

FERMI@Elettra
Synchrotrone Trieste, Trieste, Italy

Status:

- Buildings are 'in good shape'
- Gun is installed
- Construction of undulators started
- First photons end of 2009

TDR:

- FEL 1: single stage HGHG, 100-40nm, 5-1GW
- FEL 2: two stage HGHG, 40-10nm, 1-0.3GW

Beam Parameters FERMI	
Beam Energy	1.2 GeV
Bunch Charge	0.7 nC
Rep. Rate	10-50 Hz
Peak Current	800 A
Bunch Length (flat top)	700 ps
Norm. emittance	1.5 mm mrad

Seed Parameters FERMI	
Seed Power	100 MW
Seed Wavelength	240-300 nm
Seed Length	ps

Undulator Parameters FEL1	
Modulator	19 x 16cm
Radiator (6 sections)	36 x 6.5cm
Module Length	2.34 m

New Concept (E. Allaria and G. De Ninno):

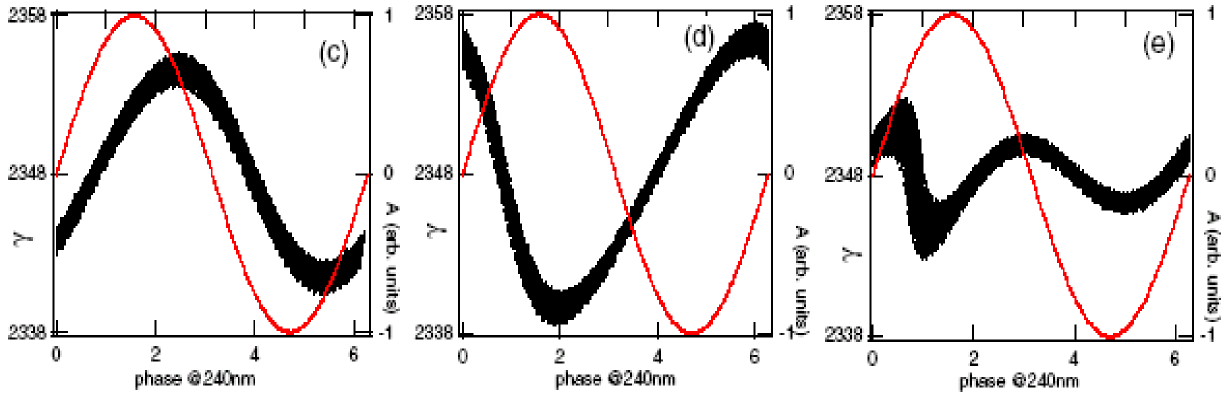
2005: B. W. J. McNeil, G. R. M. Robb, M. W. Pool, N. R. Thompson, "Harmonic Lasing in an FEL Amplifier", Proc. FEL Conference 2005, Stanford, CA, USA, pp. 434-437

- Increase bunching in modulator without increasing the energy spread to access higher harmonics
- Tame the fundamental high gain and let an odd harmonic grow

=> ***Split modulator + 180° phase shifter***

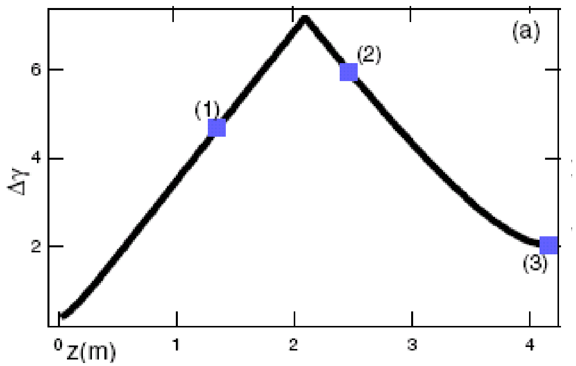
Phase space evolution:

1. Modulator Phase shifter 2. Modulator

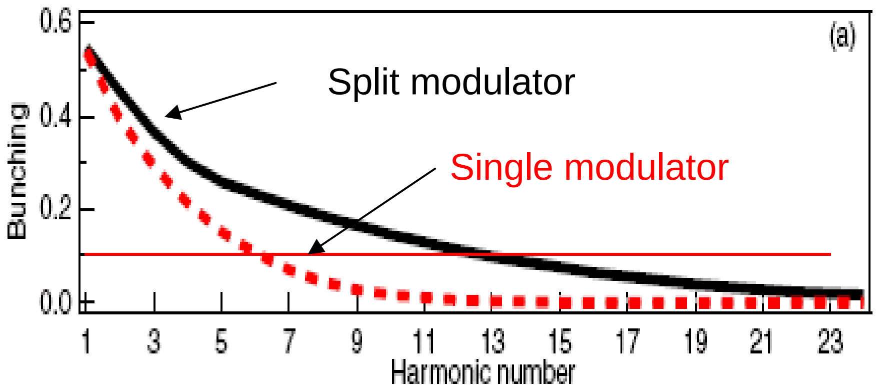


Pictures taken from:
Allaria and De Ninno, Soft-X-Ray Coherent Radiation Using a Single-Cascade Free Electron Laser, PRL 99, 2007

Evolution of energy spread:



Energy spread increase: x 5



- Energy spread increase factor 5 (10% 4-stage HGHG)
  => spectral broadening, larger gain length, less power
- Up to 12th harmonic usable in one cascade
  => current concentrated in λ / 12, many periods needed to smooth current distribution

Pictures taken from:
Allaria and De Ninno, Soft-X-Ray Coherent Radiation Using a Single-Cascade Free Electron Laser, PRL 99, 2007

SPARC-Project
Laboratori Nationali di Frascati, Frascati, Italy

Status:

- Gun works
- SLAC linac modules installed 2007
- Undulators installed in 2007
- Seed laser commissioned Nov. 2007 (clean room)
- HHG chambers commissioned Dec. 2007
- Commissioning has started

Beam Parameters SPARC (uncompr.)	
Beam Energy	155-200 [MeV]
Bunch Charge	1.1 [nC]
Rep. Rate	1-10 [Hz]
Peak Current	100 [A]
Bunch Length (rms)	4 [ps]
Norm. emittance	2 [mm mrad]

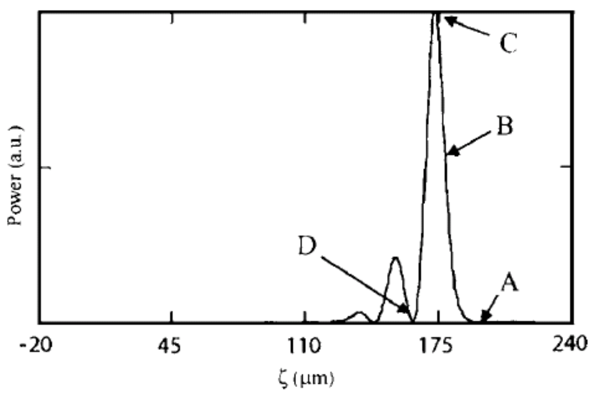
Undulator parameter SPARC	
Undulator Period	2.8 [cm]
No. of Periods	6 x 77
Module Length	2.156 [m]
Gap	6-25 [mm]
K	0.38-3.2

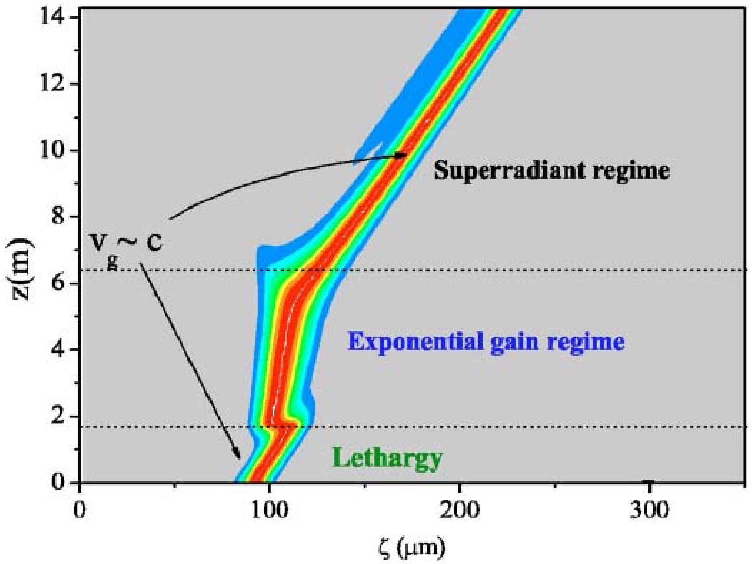
Seed parameters SPARC	
Seed Power	100 [MW]
Seed Wavelength	400 [nm]
Seed Length	100 [fs]

Super radiance (L. Giannessi et al.):

- Use the fast propagation of the super radiant pulse over the e-beam as a permanent fresh bunch feed

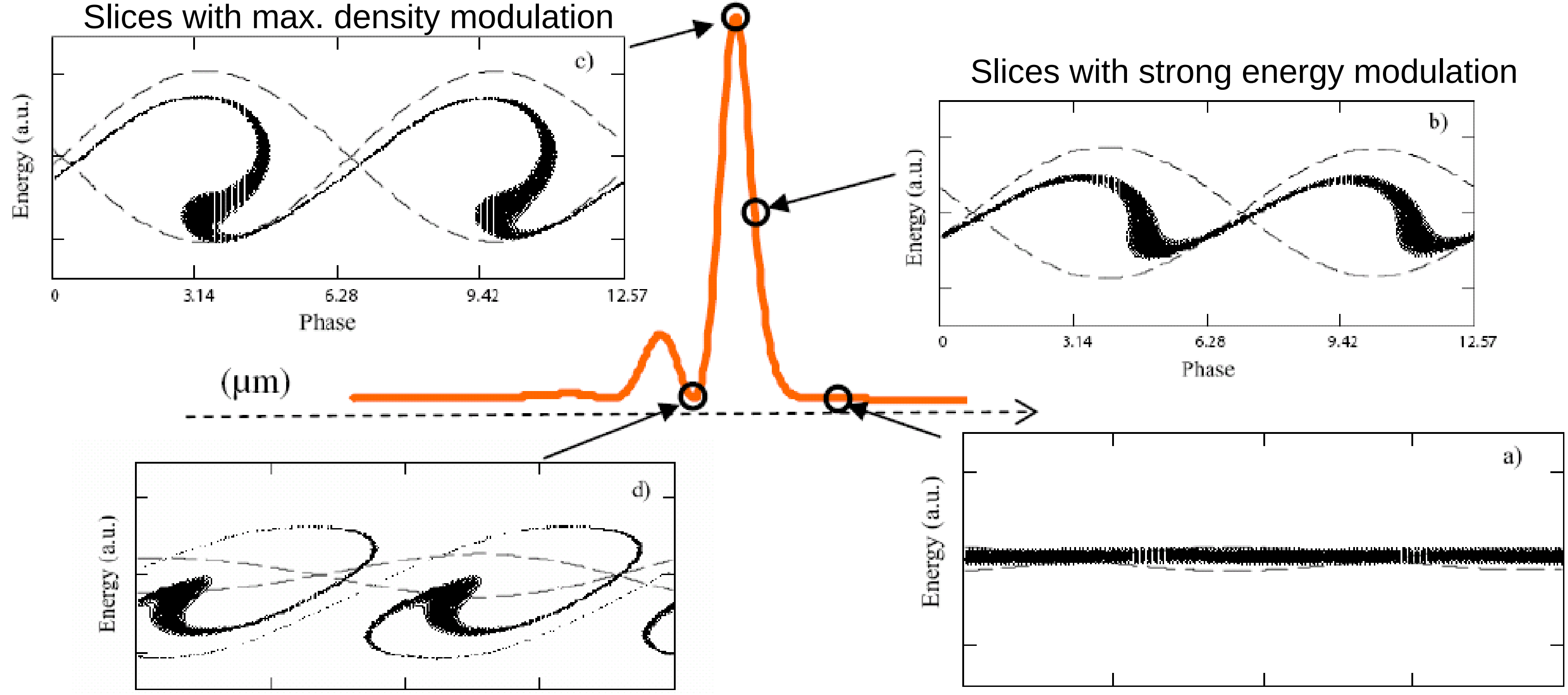
• Super radiance: experimentally characterized at SDL in 2006
• Regime following saturation
• Seed pulse much shorter than e-beam
• 2 typical signatures: pulse shape and pulse propagation





Pictures taken from:
L. Giannessi, S. Spampinati, P. Musumeci: "Non Linear Pulse Evolution in Seeded and Cascaded FELs", J. Appl. Phys. 98, 043110 (2005);

Phase space evolution in a super radiant pulse



Particles gaining energy from the field have reduced the amplitude of the Separatrix and are de-trapped

'Fresh' slices

Pictures taken from:
L. Giannessi, S. Spampinati, P. Musumeci: "Non Linear Pulse Evolution in Seeded and Cascaded FELs", www.Jacow.org, FEL 2005

Super radiant pulse

$\Rightarrow$ Energy modulation, bunching, saturation, de-bunching coexist in one pulse at different slices

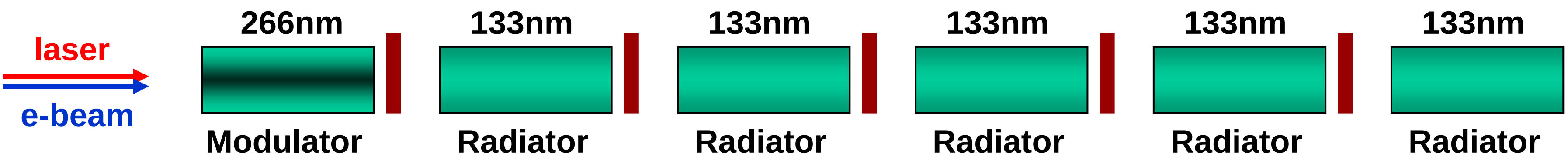
$\Rightarrow$ Maximal bunching on all harmonics permanently present in some part of the bunch

Harmonic multiplication (passage from λ to λ/n):

$\Rightarrow$ Slices with high bunching on suitable harmonic will burst coherent radiation

$\Rightarrow$ Burst triggers new super radiant pulse with λ/n

Single Stage Approach (Test case for super radiant cascade):

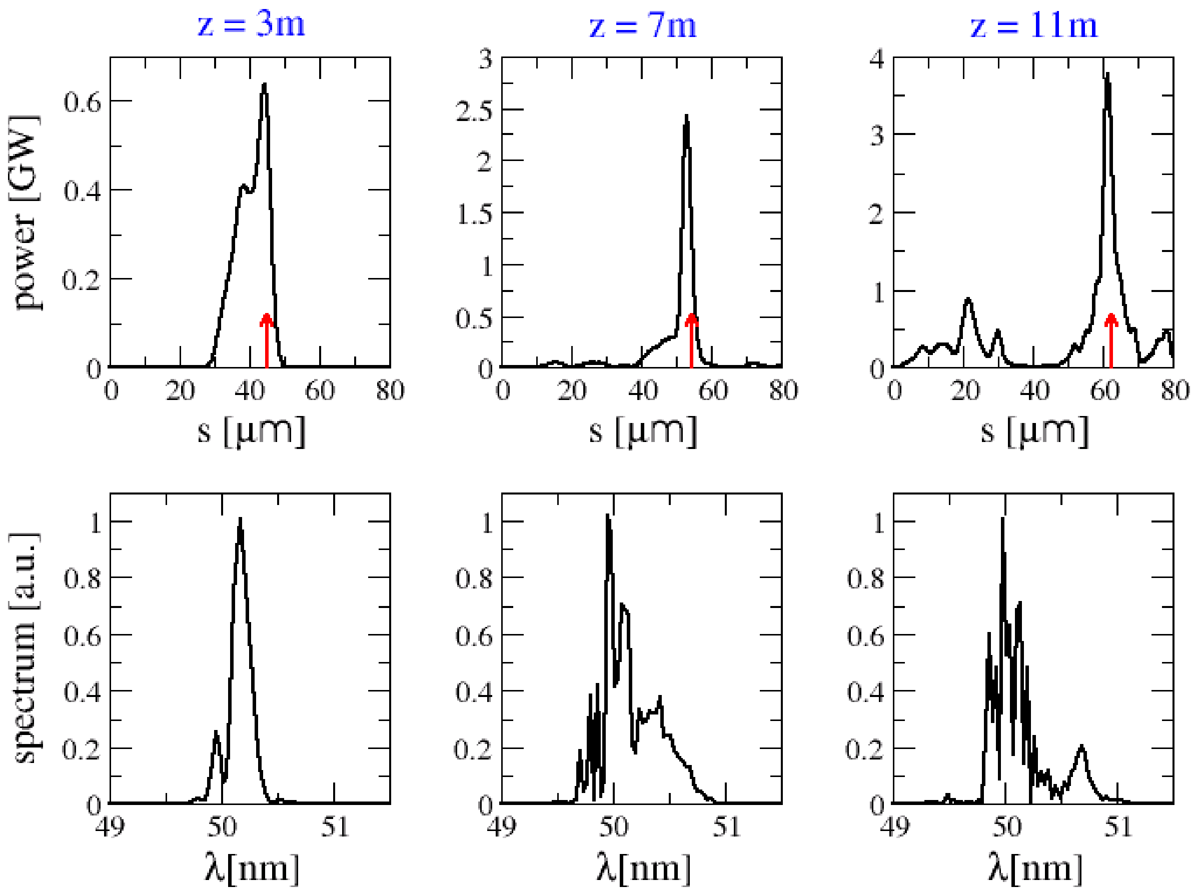


- Intense, short seed pulse
- Reach saturation in first segment
- Amplify the 2nd harmonic in radiator
- Pulse energy > 10μJ

Calculation:

- Repeated switching of harmonics (calc. 3 x 3rd + 1 x 2nd 266nm / 4.9nm)

Loss of spectral purity in a super radiant pulse in STARS (S2E - bunch)



Loss of basic HGHG features

- No pulse property preservation
- No pulse shape control

WiFel-Project
University of Wisconsin-Madison & Massachusetts Institute of Technology, Wisconsin, USA

Concept: Modulator / Radiator cascading
Keep energy spread low by using low harmonics

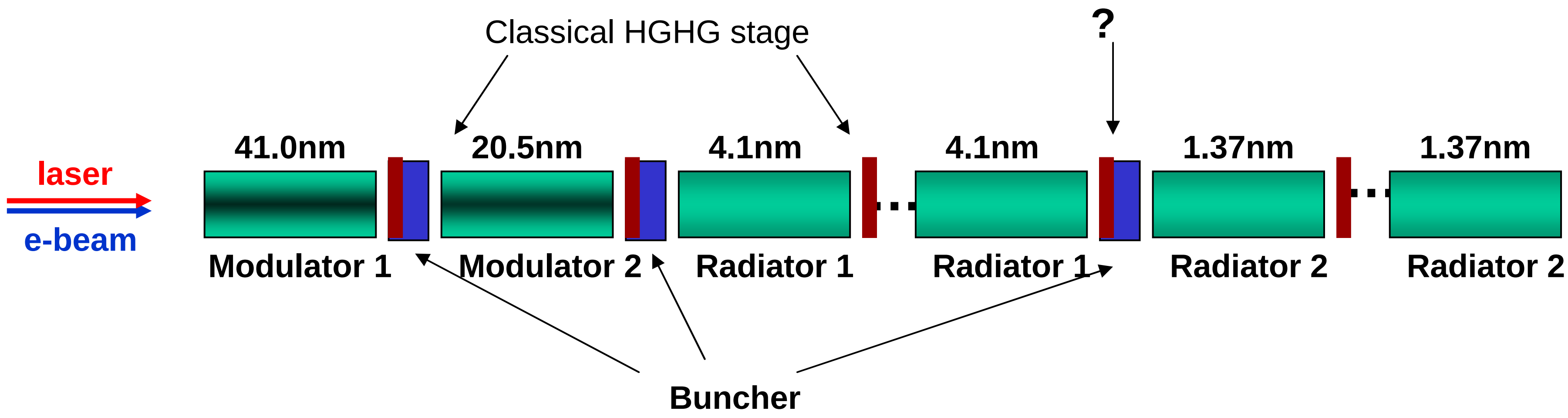
Beam Parameter – Beam Line 6	
Beam Energy	2.2 [GeV]
Bunch Charge	200 [pC]
Rep. Rate	1-10 [Hz]
Peak Current	1 [kA]
Bunch Length (base)	250 [fs]
Norm. emittance	1 [mm mrad]

HHG-Seed	
Seed Power	10 MW
Seed Wavelength	41.33 nm / 30eV
Seed Length	30 fs

Radiator parameter WiFEL	
Undulator Period	3.3 [cm]
No. of Periods	16 x 60
Module Length	1.98 [m]

Beamline 6

- HHG seed 41nm
- Modulator cascade (2 segments) 41nm, 20.5nm, separated by buncher
- Radiator cascade (16 segments) 4.1nm, 1.37nm, separated by buncher



Information taken from:
J. J. Bisognano, D.E. Milton: "Collaborative Reasearch: Conceptual Design Study and R&D for a VUV/Soft X-ray Free Electron Laser Facility", Proposal to the National Sience Foundation, November 2007

Concluding Remarks

? How do the new concepts cope with S2E bunches / tolerances

? How important is spectral purity

Not important: New concepts exist and should be further investigated and tested

Important:
No alternative to classical cascading
My favorite: 2-3 stages in combination with HHG source

! Our simulation tools are still not complete – esp. for cascaded structures

- trajectory correction for several stages
- effect of sub harmonic radiation
- realistic undulator errors (shimming)

Thanks to L. Gianessi, G. DeNinno, T. Shaftan and J. Qika for supplying me with information