Echo scheme: Alternative to Slicing in Storage Rings

Frequency mixing scheme: for tunability of seeded FELs

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35^{th} FEL conference

Outline

1. **Echo scheme :** Alternative to Slicing in Storage Rings
   - Introduction : femtosecond radiation in storage rings
   - EEHG on storage rings (SOLEIL case)

2. **Frequency mixing :** increase of tunability in seeded FELs

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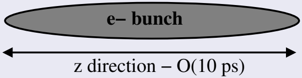
Femtosecond radiation in storage rings

Standard pulse duration

- Pulse light duration ∼ electron-bunch duration



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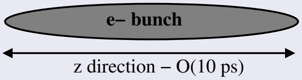

Slicing [A. Zholents et. al., PRL 1996] [R. W. Schoenlein et al., Science 2000][S. Khan et. al, PRL 2008] ...

- Small part of the (incoherent) radiation kept
- **Advantages :** full tunabililty & hard X-rays
- **Drawback :** low peak power

- ALS (USA)
- Bessy II (Germany)
- SLS (Switzerland)
- SOLEIL (France)
- (etc.)

Femtosecond radiation in storage rings

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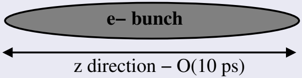

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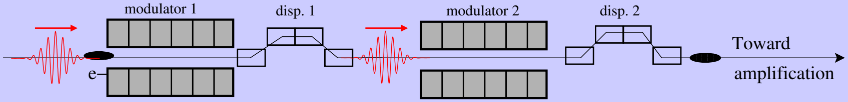
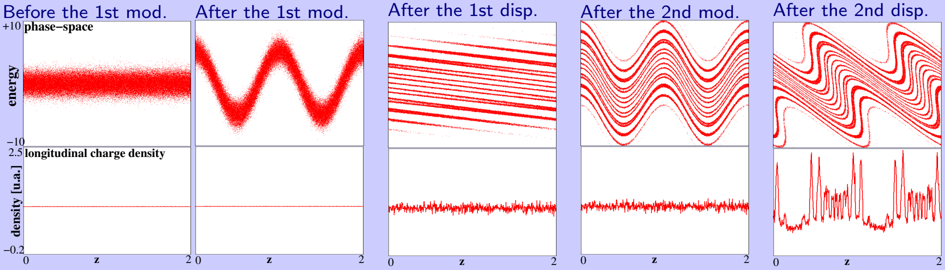
Coherent Harmonic Generation [R. Prazeres et. al., NIMA 1991][V.N. Litvinenko, NIMA 2003] [M.Labat et. al., NIMA 2008] [G. De Ninno et. al., PRL 2008]...

- Coherent radiation at laser harmonics
- **Advantage :** higher photon flux than slicing
- **Drawbacks :** tunability & "long" wavelength

- UVSOR (Japan)
- DELTA (Germany)
- ELETTRA (Italy)
- (etc.)

EEHG scheme [G. Stupakov, PRL 2009][D. Xiang et. al, PRL 2012]...





- Application to storage rings ?
- What type of radiations ?

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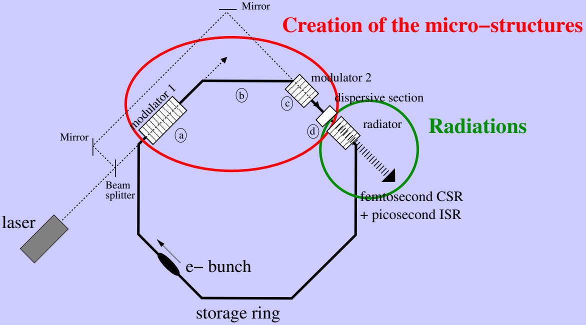
Layout



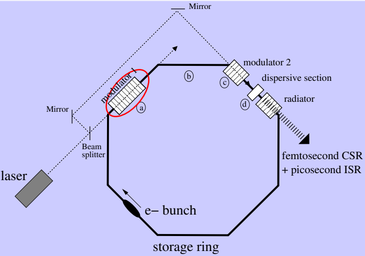
SOLEIL parameters

- $E_0 = 2.75$ GeV
- $\sigma_E = 10^{-3}$
- Peak current $I = 134$ A
- Bunch length $\sigma_z = 10.5$ mm

Studies on the application of EEHG on storage rings :

- SOLEIL : [C. Evain, M.E. Couprie, A. Nadji, A. Loulergue, J.M. Filhol, A.A. Zholents, New J. Phys. 2012]
- DELTA : [R. Molo et. al., this conference - today - WEPS043]
- HEFEI : [H. Li, W. Gao, Q. Jia, L. Wang, IPAC 2013]

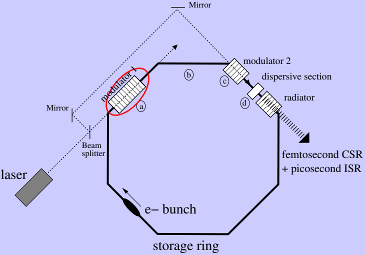
Electron bunch dynamics



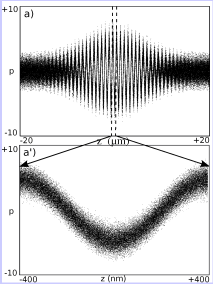
Model

- 6D
- Linear & Non-linear terms for the transport in the magnetic elements
- Energy fluctuation induced by ISR in bending magnets

Electron bunch dynamics



- $p = p + A_1 \times e^{-\frac{z^2}{2(c\sigma_{L1})^2}} \cos(\frac{2\pi}{\lambda_L} z) \times e^{-\frac{x^2+y^2}{w_1^2}}$
- σ_{L1} : rms laser pulse length, w_1 : laser waist
- Parameter values taken :
  - $W_1 = 600\mu$m ($\sigma_x = 147\mu$m), $\lambda_L = 800$ nm
  - $\sigma_{L1} = 43$ fs (100 fs FWHM) , $A_1 = 5$
  - Modulator : 13 periods of length : 150 mm



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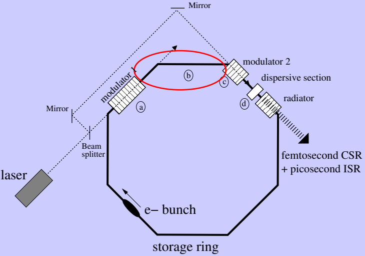
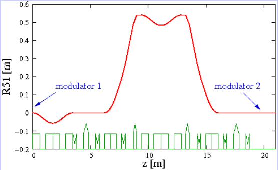
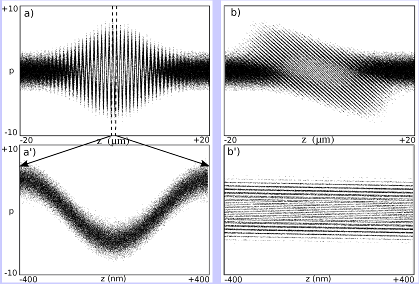
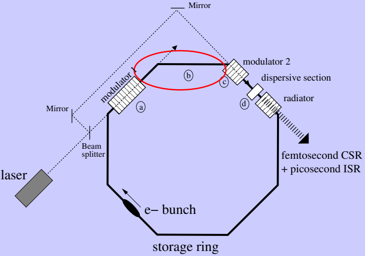


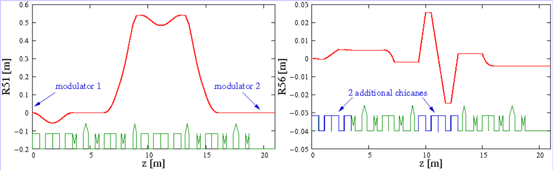


- Chasman-Green lattice ⇒ achromatic lattice

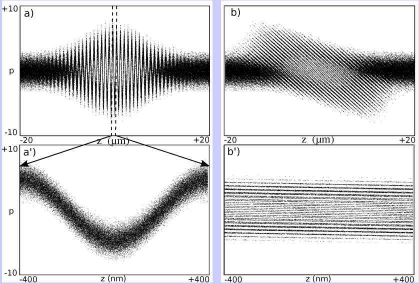


Electron bunch dynamics





- Chasman-Green lattice ⇒ achromatic lattice
- "Small" $R_{56}^{(1)}$ ⇒ additional chicane (here, $R_{56}^{(1)} = -1.5$ mm)



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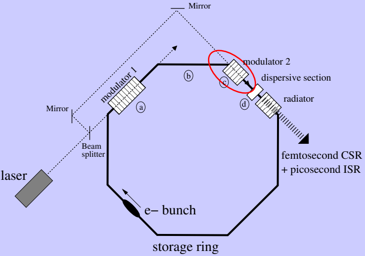
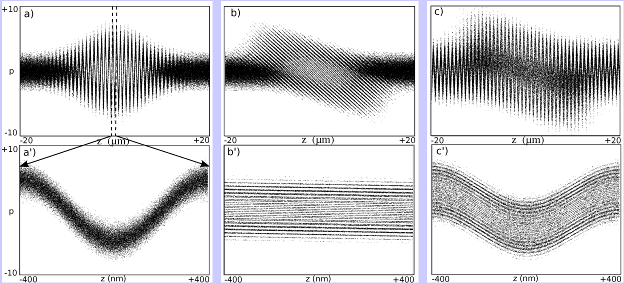
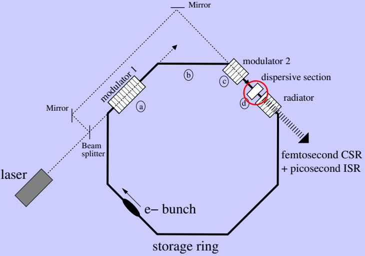


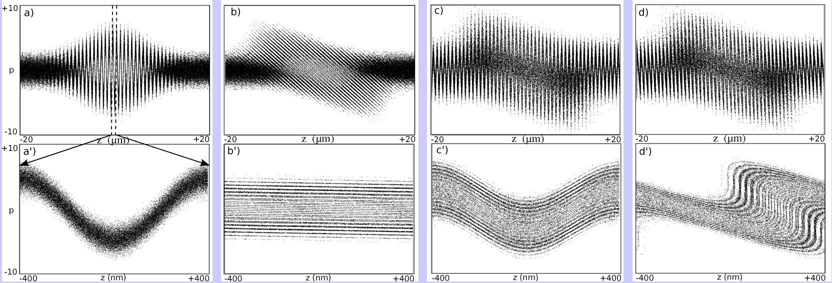
- $p = p + A_2 \times e^{-\frac{z^2}{2(c\sigma_{L2})^2}} \cos(\frac{2\pi}{\lambda_L} z) \times e^{-\frac{x^2+y^2}{w_2^2}}$
- $w_2 = 600\mu m$
- A_2 value depends of the wanted harmonic number (here : $A_2 = 2.95$)



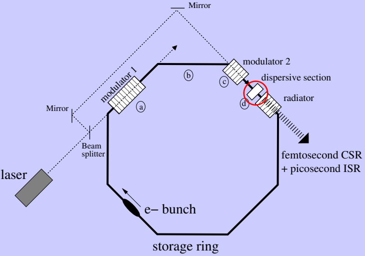
Electron bunch dynamics



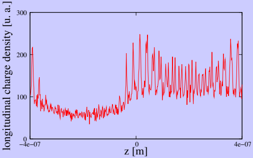
- $z \simeq z + p \times R_{56}^{(2)} \frac{\sigma_E}{E_0}$
- $R_{56}^{(2)}$ value depends of the wanted harmonic number (here : $R_{56}^{(2)} = -48\mu m$)

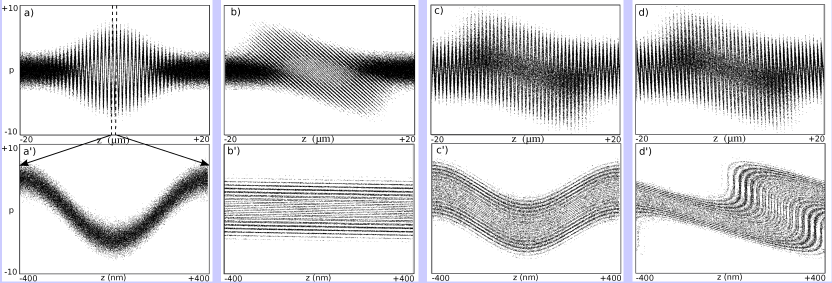


Electron bunch dynamics

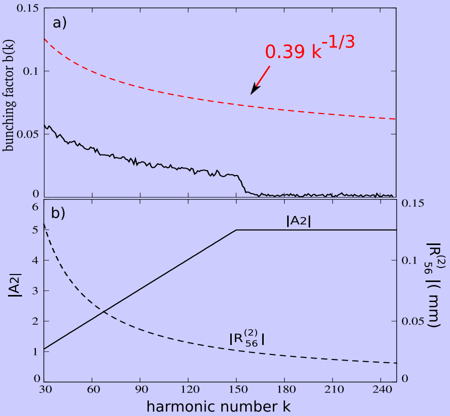


- $z \simeq z + p \times R_{56}^{(2)} \frac{\sigma_E}{E_0}$
- $R_{56}^{(2)}$ value depends of the wanted harmonic number (here : $R_{56}^{(2)} = -48\mu m$)
- Modulation of the longitudinal charge density





Bunching factor vs harmonic number



- $R_{56}^{(1)} = -4$ mm
- $A_1 \simeq 5$
- $\sigma_{L1} = 100$ fs, $\sigma_{L2} = 275$ fs (FWHM)

Analytical formula : [D. Xiang and G. Stupakov, PRSTAB (2010)]

Radiation peak power (TEMPO Beamline : $N_u = 19, \lambda_u = 80$ mm)

- **Analytical formula**

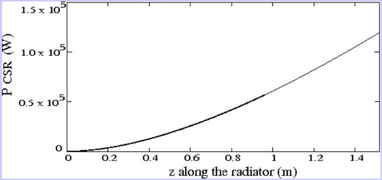
$$P_{CSR} = \pi\alpha\hbar\omega \frac{K^2}{1+K^2/2}[JJ]^2 \frac{I_{\rm peak}}{e} n_e b^2 \sqrt{f_2}.$$

[Z. Huang and K.-J. Kim, PAC'99 p. 2495 (1999)]

- $n_e = \frac{I_{\rm peak}\lambda_r N_u}{ce}$,
- $f_2 = (\sigma_r\sigma_{r'})^2/(\sqrt{\sigma_r^2+\sigma_x^2}\sqrt{\sigma_{r'}^2+\sigma_{x'}^2}\sqrt{\sigma_r^2+\sigma_y^2}\sqrt{\sigma_{r'}^2+\sigma_{y'}^2})$,
- $\sigma_r = \sqrt{2\lambda_r\lambda_u Nu}/4\pi$,
- $\sigma_{r'} = \sqrt{\lambda_r/2\lambda_u N_u}$.

- @ 26.5 nm (800/30 nm) with $b = 5\%$ and $I_{peak} = 138\ A$, $P_{CSR} \simeq 187$ **kW**
- $P_{CSR} > 10^6 P_{slicing}$ (with $\Delta\omega/\omega = 0.05\%$)

- **With GENESIS** (using convharm option) :



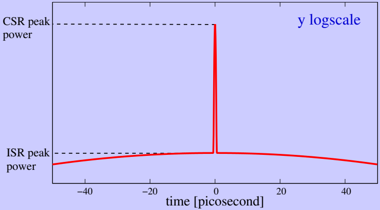
$P'_{CSR} \simeq 120$ **kW**

Signal/noise ratio

- Signal-to-noise ratio S/N

$$S/N = \frac{P_{CSR} \times \sigma_{L1}\ \eta\ c}{P_{ISR} \times \sigma_z} = \frac{n_e b^2 \sqrt{f_2}\sigma_{L1} c}{\sigma_z} N_u \frac{\Delta\omega}{\omega} \simeq 100$$

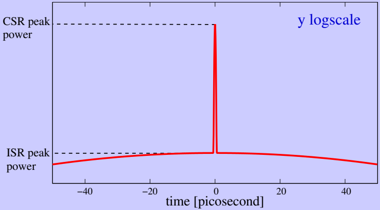
with $\eta = 10\%$ (η : percentage of electrons involved in the fs light pulse)



Signal/noise ratio

- Signal-to-noise ratio S/N

$$
\begin{aligned}
S/N &= \frac{P_{CSR} \times \sigma_{L1}\ \eta\ c}{P_{ISR} \times \sigma_z} \\
&= \frac{n_e b^2 \sqrt{f_2}\sigma_{L1} c}{\sigma_z} N_u \frac{\Delta\omega}{\omega} \\
&\simeq 100
\end{aligned}
$$



with $\eta = 10\%$ (η : percentage of electrons involved in the fs light pulse)

- Conclusion & Perspectives
  - Application of EEHG to storage rings very promising
  - Challenge : technical realization (test facility/user facility) (cf. Z. Zhao & D. Xiang talks)

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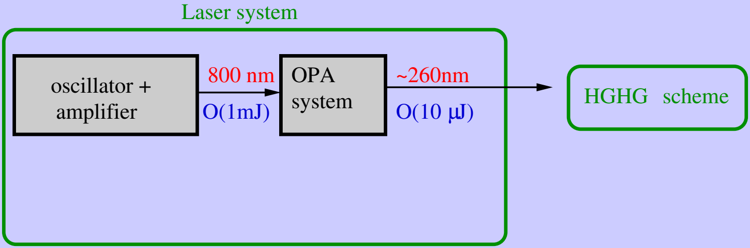
HGHG scheme + tunable seed



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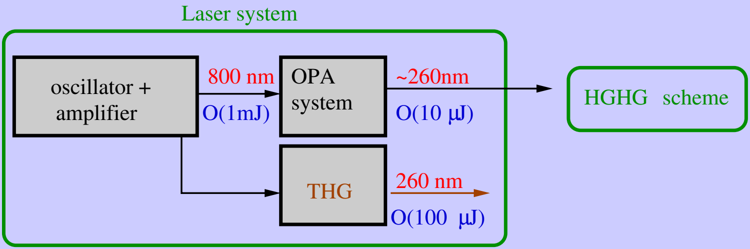
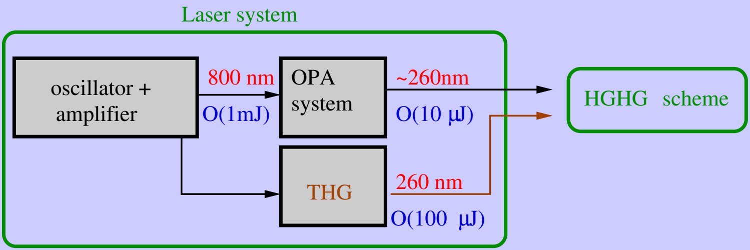
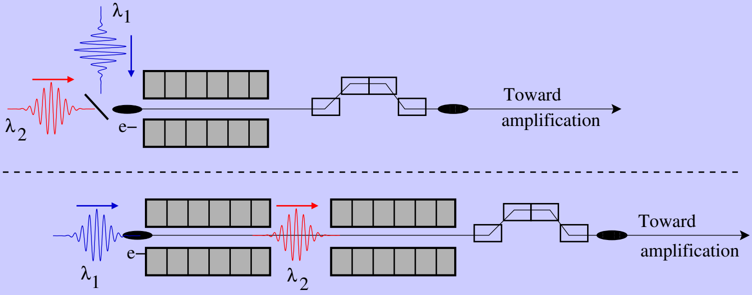


HGHG scheme + tunable seed + 2nd fixed seed

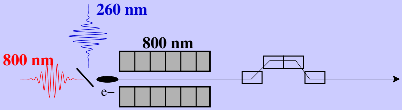


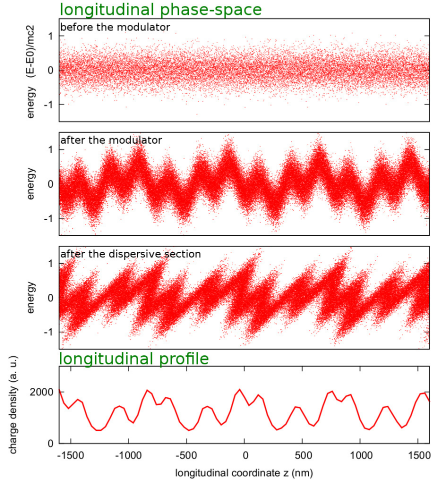
Layout - frequency mixing scheme



- Same layout that in [D. Xiang and G. Stupakov, PRSTAB 2009] for creation of micro-structures in the THz range

Electron dynamics - 1 undulator case & FERMI Parameters



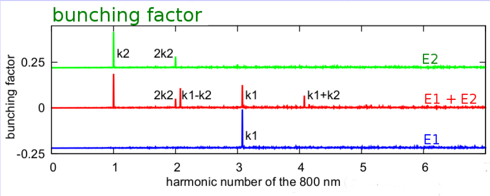


- **Fermi & laser parameters**
  Beam : $E_0 = 1.2$ GeV, $\sigma_E = 150$ KeV
  Modulator : 19 periods, $\lambda_{w1} = 16$ cm, $\lambda_{m1} = 800$ nm
  laser : $\lambda_1 = 260$ nm, $\lambda_2 = 800$ nm, $E_1 \simeq E_2 \simeq 10\ \mu$J

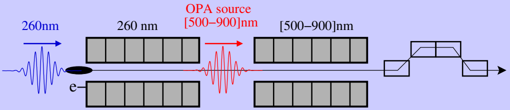
- **Model for the laser/e- interaction**
  see e.g. [A. Zholents, FEL'09]

$$\frac{d\gamma}{dz} = \frac{e}{m_0 c^2} E_x \beta_x , \qquad \beta_x = -\frac{K}{\gamma} \sin\left(\frac{2\pi}{\lambda_{w1}} z\right)$$

$$E_x = \frac{E_1}{\sqrt{1+\left(\frac{z}{z_{r1}}\right)^2}} \sin[k_1(z-ct)] + \frac{E_2}{\sqrt{1+\left(\frac{z}{z_{r2}}\right)^2}} \sin[k_2(z-ct)]$$

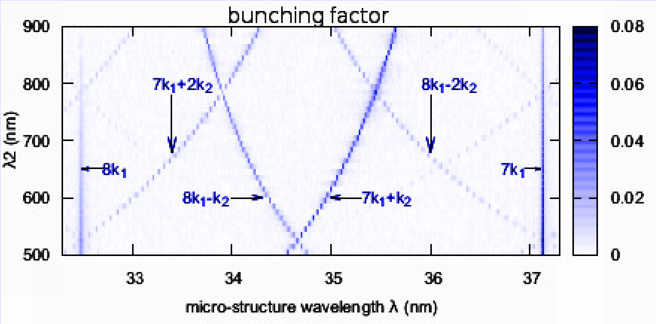


Tunability with an OPA source



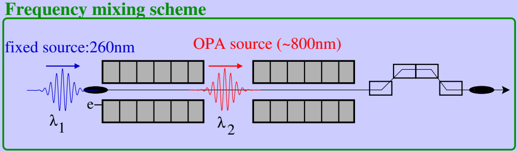
Pulse energy (with 100 fs FWHM) :
(obtainable from 1 mJ pulse @800nm)

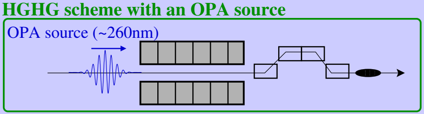
- 260 nm : 130 μJ
- [500-900] nm : 10μJ



Comparison with HGHG with an OPA source

- Analytical formula from : [D. Xiang, G. Stupakov, PRSTAB 2009] (with $B_1 = 0$)





- $k = 7k_1 + k_2 \Rightarrow \lambda_r \simeq 35.5$nm
- $k = 7k_1 + 2k_2 \Rightarrow \lambda_r \simeq 34$ nm
- $A_1 = 5$ (260 nm) $A_2 = 1$ (OPA source @800 nm)

- $k = 7k_1 \Rightarrow \lambda_r \simeq 37$ nm
- $A_2 = 1$ (OPA source @260 nm)

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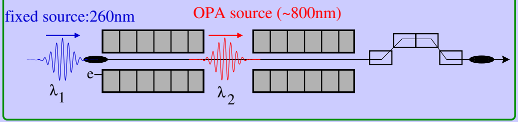
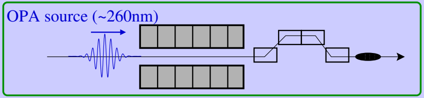
Frequency mixing scheme



HGHG scheme with an OPA source



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- $A_2 = 1$ (OPA source @260 nm)

	fq. mixing (n=7, m=1)	fq. mixing (n=7, m=2)	HGHG (m=7)
Bunching factor	5.1%	2.3%	0.0034%
Ratio with HGHG	$\simeq$ 1500	$\simeq$ 650	

Analytical expression of the bunching factor

- From : [D. Xiang, G. Stupakov, PRSTAB 2009] (with $B_1 = 0$)

$$
\begin{aligned}
k &= nk_1 + mk_2 \qquad \text{with n,m : integer} \\
bf(k) &= \left| e^{-\frac{1}{2}[(Km+n)B_2]^2} \times J_m\left[-(Km+n)A_2 B_2\right] \times J_n\left[-(Km+n)A_1 B_2\right] \right|
\end{aligned}
$$

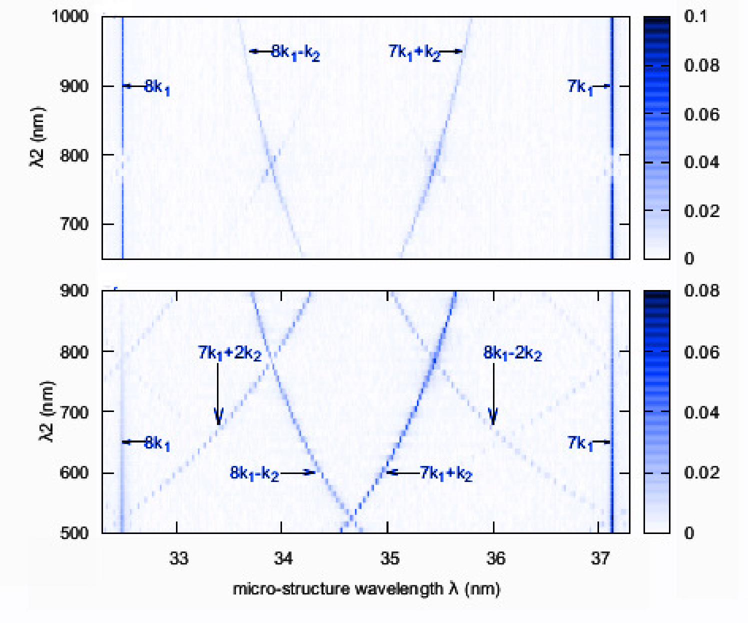
  - A_1, A_2 : energy modulation amplitude (in energy spread unit)
  - B_2 : dispersive strength (normalized)

- if ($A_1 < 1$ & $A_2 < 1$) $\Rightarrow$ $bf_{n,m} \; \alpha \; E_1^n \times E_2^m$ (*since* $A_i \alpha E_i$ [A. Zholents FEL'06])

- Same **power law** that in **non-linear optics :** $P = \chi^{n+m} E_1^n \times E_2^m$
  (P : polarization, χ^{n+m} : susceptibility of the NL material)

Conclusion

- **EEHG on storage rings**
  - Femtosecond coherent synchrotron radiation
  - Promising characteristics (wavelength, peak power, signal/noise)
  - Challenge : technical realization
    (see also application on DELTA storage ring [WEPS043])
- **Frequency mixing scheme**
  - For tunability at "short" wavelengths, it is very efficient to use of an 2nd laser pulse (with higher energy & not tunable), coupled with a tunable source.


1000
900
800
700
λ2 (nm)
8k1-k2
7k1+k2
8k1
7k1
0.1
0.08
0.06
0.04
0.02
0
900
800
700
600
500
λ2 (nm)
7k1+2k2
8k1-2k2
8k1
7k1
8k1-k2
7k1+k2
33
34
35
36
37
micro-structure wavelength λ (nm)
0.08
0.06
0.04
0.02
0

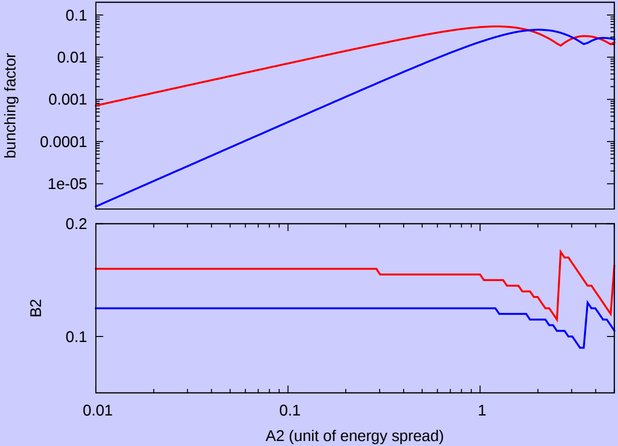
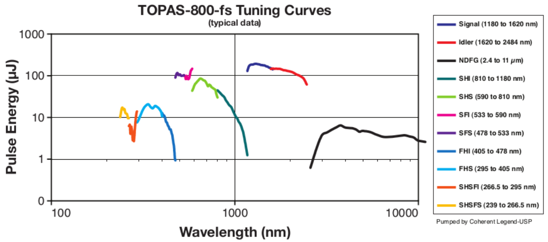


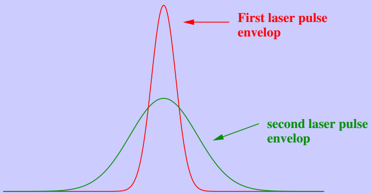
FIGURE: K=3.07, n=7, blue : m=1 and red : m=2. $A_1 = 5$

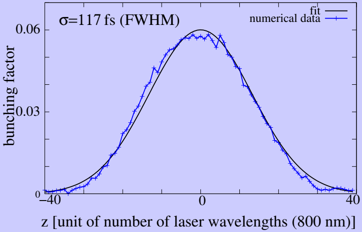
Typical Tuning Curve
(pumped by 1 mJ, <40 fs, 1 kHz, 800 nm Legend)



Duration of the CSR pulse

- value taken : $\sigma_{L1} = 100$ fs (FWHM), $\sigma_{L2} = 275$ fs FWHM

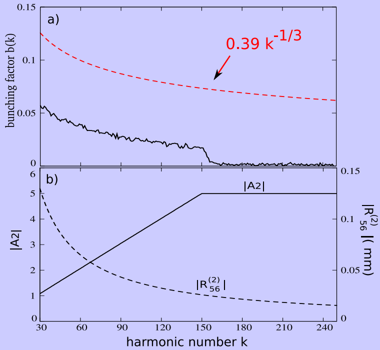




- No transverse dispersion and weak longitudinal one compared to the one in slicing ⇒ shorter pulse that with slicing scheme ($\sigma_{slicing} \simeq 200$ fs FWHM)

bunching factor with non-linear terms in the transport between the two modulators

$R_{56}^{(1)} = 4$ mm - linear transport



$R_{56}^{(1)} = 4$ mm - non-linear transport