Seeded FELs and Expected Performance

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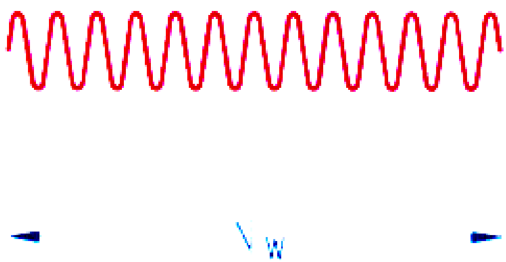
TEMPORAL COHERENCE

$$E(t) = \Sigma_j\, f(t-t_j)$$

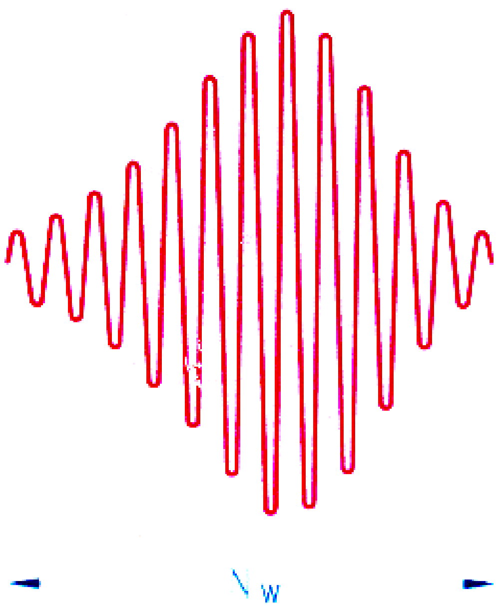
Spontaneous Radiation :

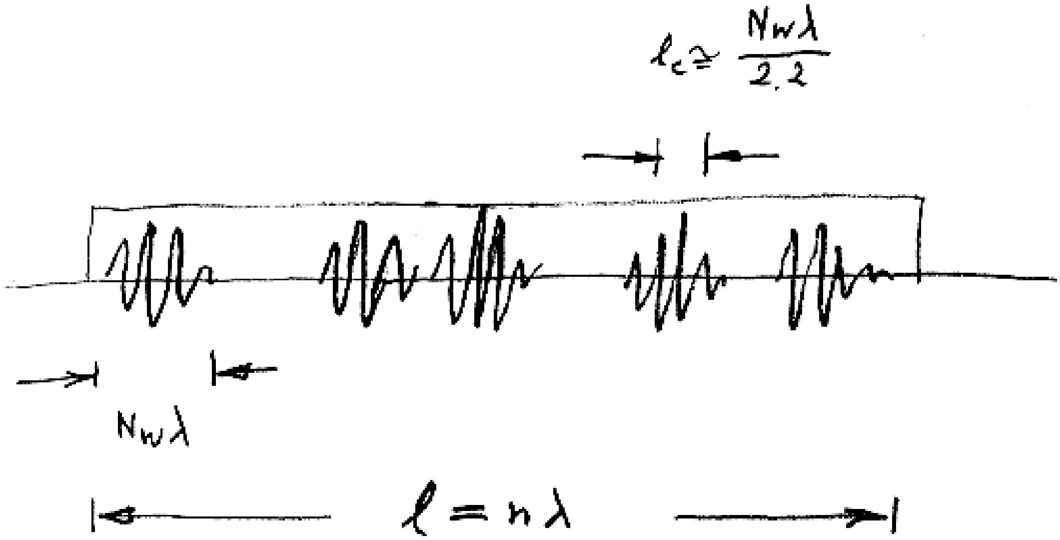
$f_{spont}(t)$:



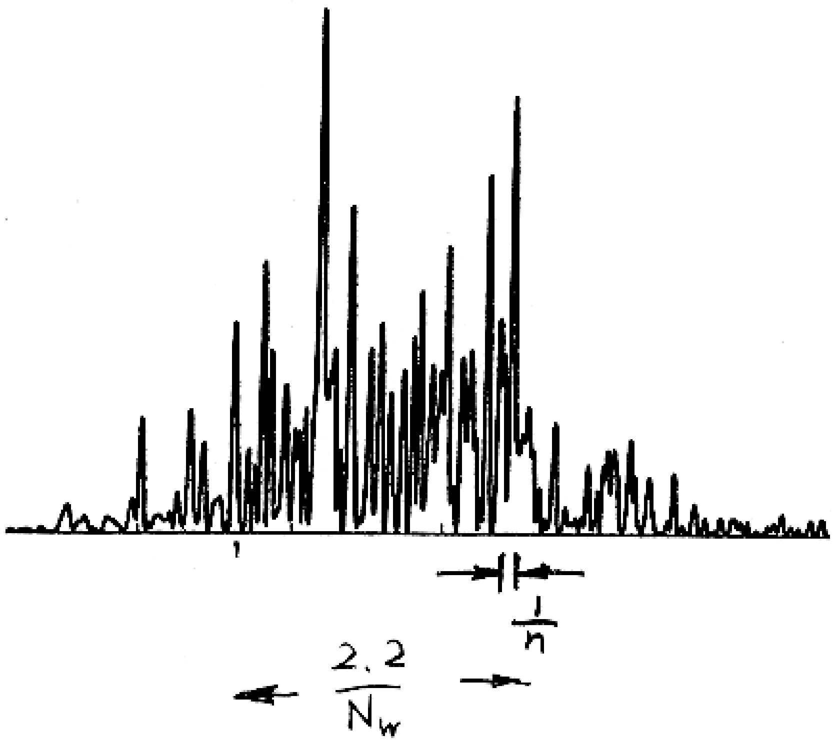
SASE :

$f_{sase}(t)$:





bunch length l, slipage $N_w \lambda$, and coherence length l_c



single shot spectrum

Example : LCLS

$L_W = 100\,m, \quad \lambda_W = 0.03\,m, \quad \ell = 40\,\mu m$

$N_W \cong 3 \times 10^3$

$$\frac{\Delta\lambda}{\lambda} \cong \frac{2.2}{N_W} \cong 6 \times 10^{-4} \quad \text{(bandwidth)}$$

$$n = \frac{\ell}{\lambda} = \frac{40\,\mu m}{1.5 \times 10^{-10}\,m} \cong 3 \times 10^{-5}$$

Fourier transform limit: $\frac{1}{n} \cong 3 \times 10^{-6}$

slippage $\quad N_W \lambda \cong 3 \times 10^3 \times 1.5 \times 10^{-10} \cong 0.5\,\mu m$

lines :

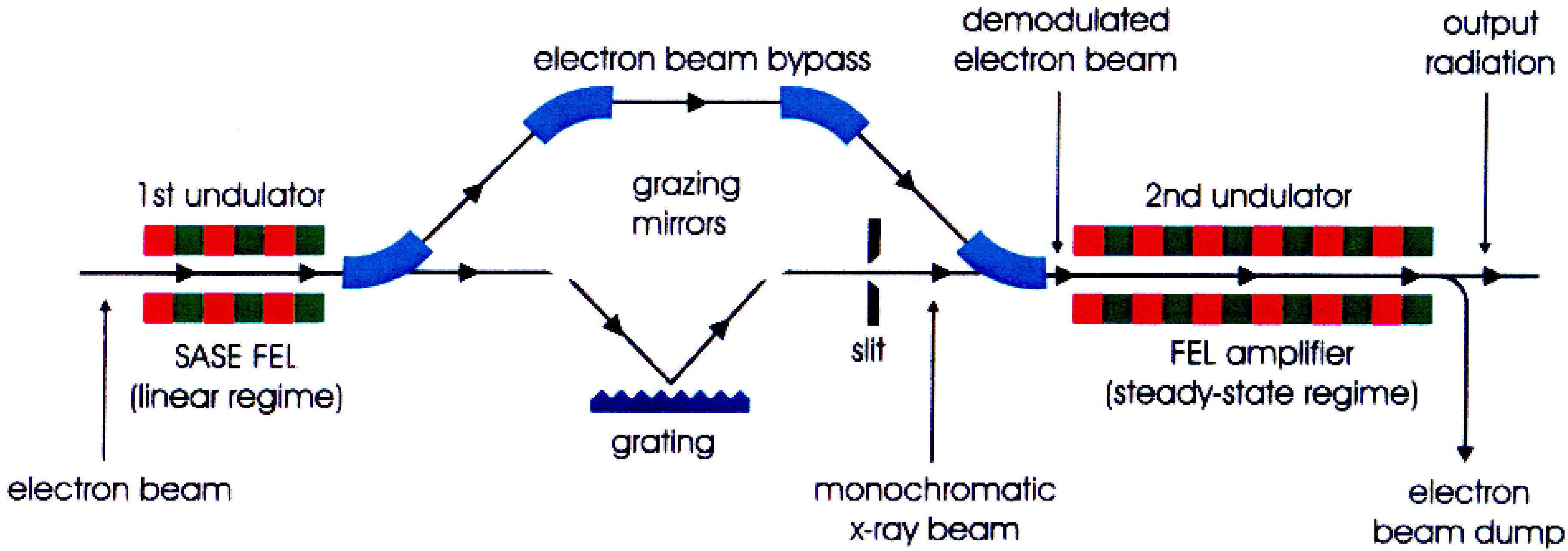
$$\frac{\frac{2.2}{N_W}}{\frac{1}{n}} = 2.2\,\frac{n\lambda}{N_W\lambda} = 2.2\,\frac{\ell}{N_W\lambda}$$

$$= 2.2 \times \frac{40\mu}{0.5\mu} \cong 180$$

Examples of Schemes for Improving the Longitudinal Coherence

- RAFEL (Regenerative Amplifier FEL, LANL)
- 2-Stage-FEL (DESY)
- HGHG (High Gain Harmonic Generation, BNL)

2-stage FEL Scheme (DESY)



TTF FEL (DESY)

For both SASE and 2-Stage FEL

$P_{out} = 5\,GW$, $\lambda = 6.4\,nm$ (200 eV)

bunch length: $\ell = 100\,\mu m$, $\tau = \frac{\ell}{c} \doteq 300\,fs$

pulse energy: $W = 5\,GW \times 300\,fs = 1.5\,mJ$

$$\frac{1.5\,mJ}{200 \times 1.6 \times 10^{-19}\,J} \cong 5 \times 10^{13} \text{ photons}$$

Transverse: diffraction limited

beam size	$90\,\mu m$
divergence	$15\,\mu rad$

Band Width

SASE:

$L_{SASE} = 20\,m, \quad \lambda_w = 2.73\,cm$

$N_w \cong 730$

$$\left(\frac{\Delta\lambda}{\lambda}\right)_{SASE} \cong \frac{2.2}{N_w} \cong 3 \times 10^{-3}$$

2 - Stage

$L_1 = 12\,m, \quad L_2 = 16 - 20\,m$

monochrometer

$$\frac{\Delta\lambda}{\lambda} = 5 \times 10^{-5}$$

Fourier trans. limit:

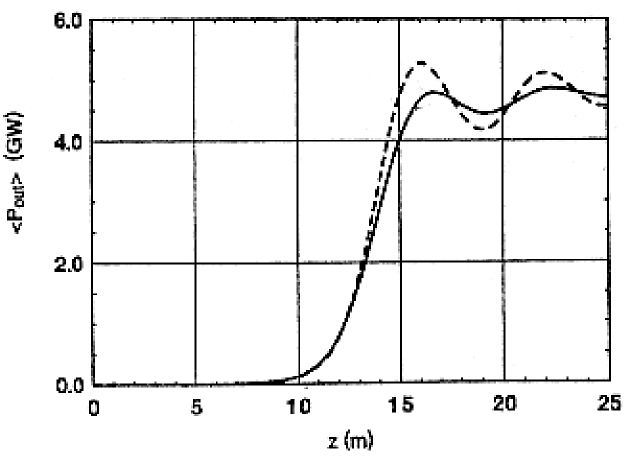
$$\frac{\lambda}{\ell} = \frac{6.4\,nm}{100\,\mu m} \cong 6 \times 10^{-5} \sim \frac{\Delta\lambda}{\lambda}$$

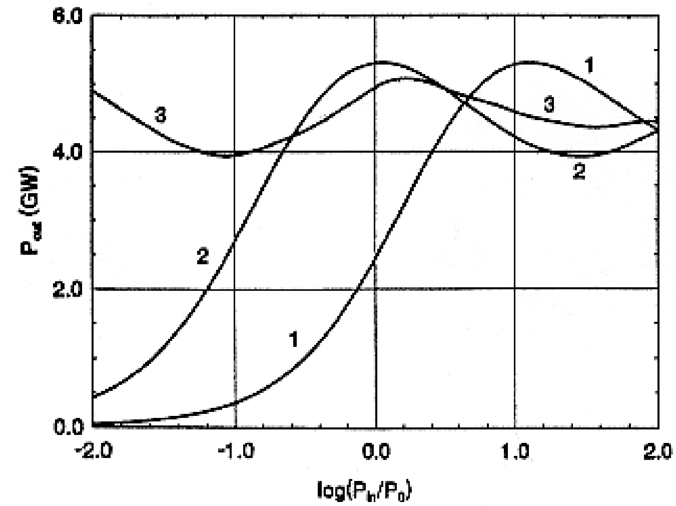
Fluctuation

2-Stage FEL

monochrometer output fluctuation: 100%

Saturation in L_2 is used to reduce fluctuation





$L_2 = 16\ m$ $\qquad \left(\frac{\Delta W}{W}\right)_{rms} = 20\%$ (curve 2)

$L_2 = 20\ m$ $\qquad 10\%$ (curve 3)

Apply to Hard X-ray

LCLS: SASE

$$\left(\frac{\Delta\lambda}{\lambda}\right)_{SASE} \cong 6\times10^{-4}$$

2-stage FEL

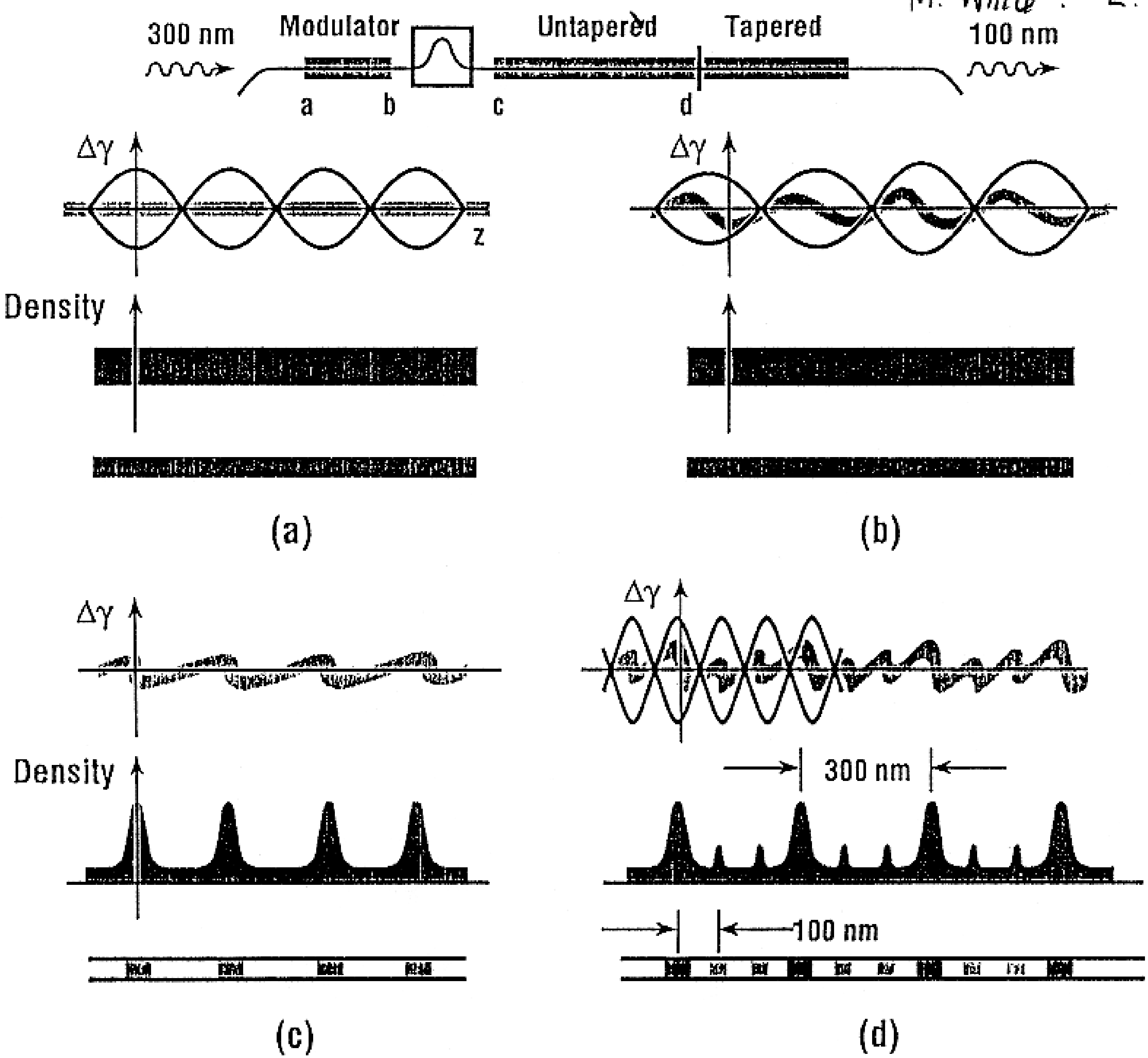
$\frac{\Delta\lambda}{\lambda}$ determined by monochromater

$$\frac{\Delta\lambda}{\lambda} \not\cong 5\times10^{-5}$$

Fourier trans. limit

$$\frac{\lambda}{\ell} \cong 3\times10^{-6}$$

I. Ben-Zvi, L. DiMauro, S. Krinsky,
M. White, L. H. Yu (1990)



UVFEL (100nm, BNL, 1990)

1. $P_{in} = 4$ MW (300nm)

$P_{out} = 200$ MW (100nm)

$L_G = 1.1$ m

modulator 2m

radiator 11m

2. Compare with SASE saturation length

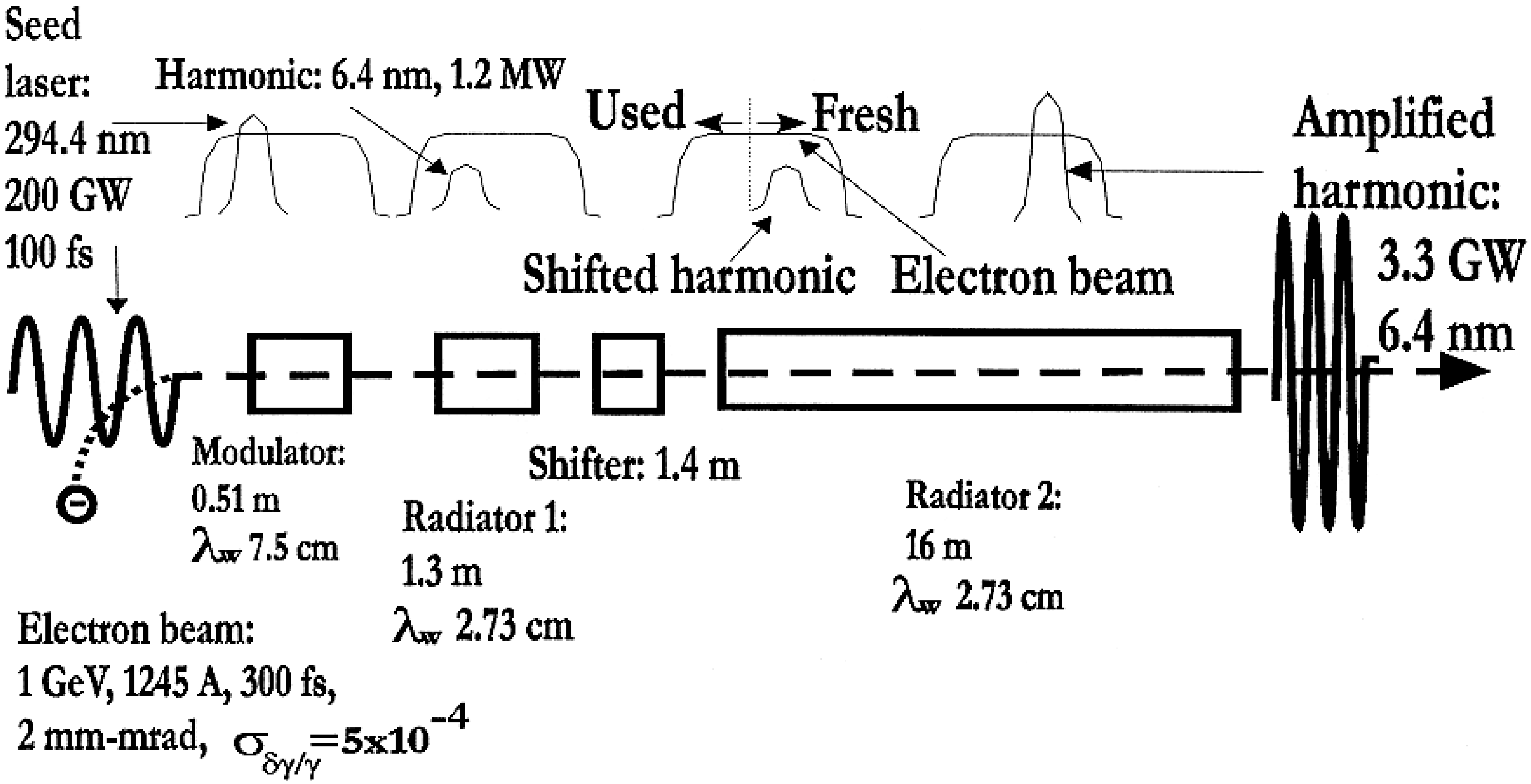
$20 L_G = 22$ m

3. Chirped Pulse Amplification (CPA)

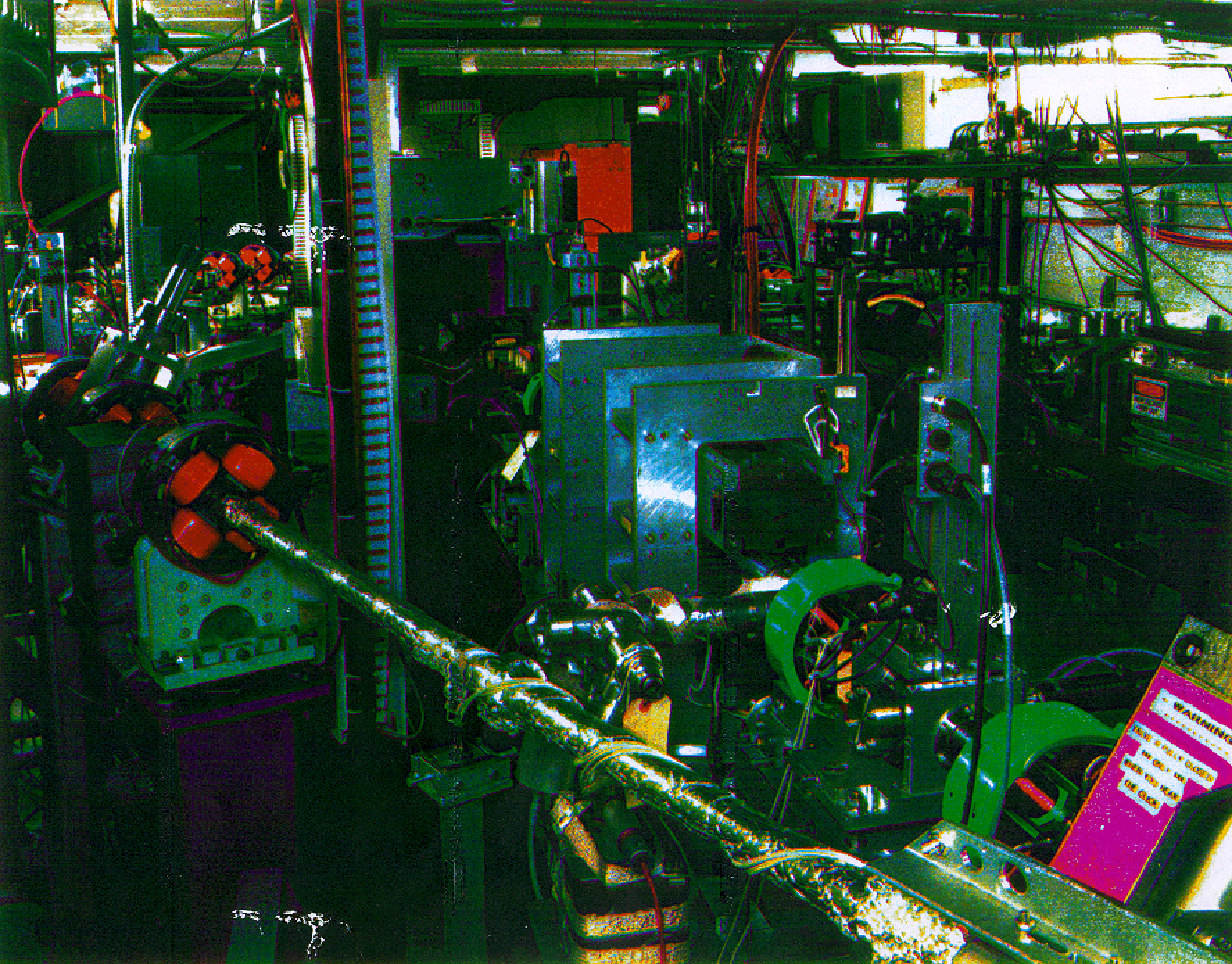
11 fs 264 nm $\longrightarrow$ 4ps, 4.6 MW, 4% bandwidth

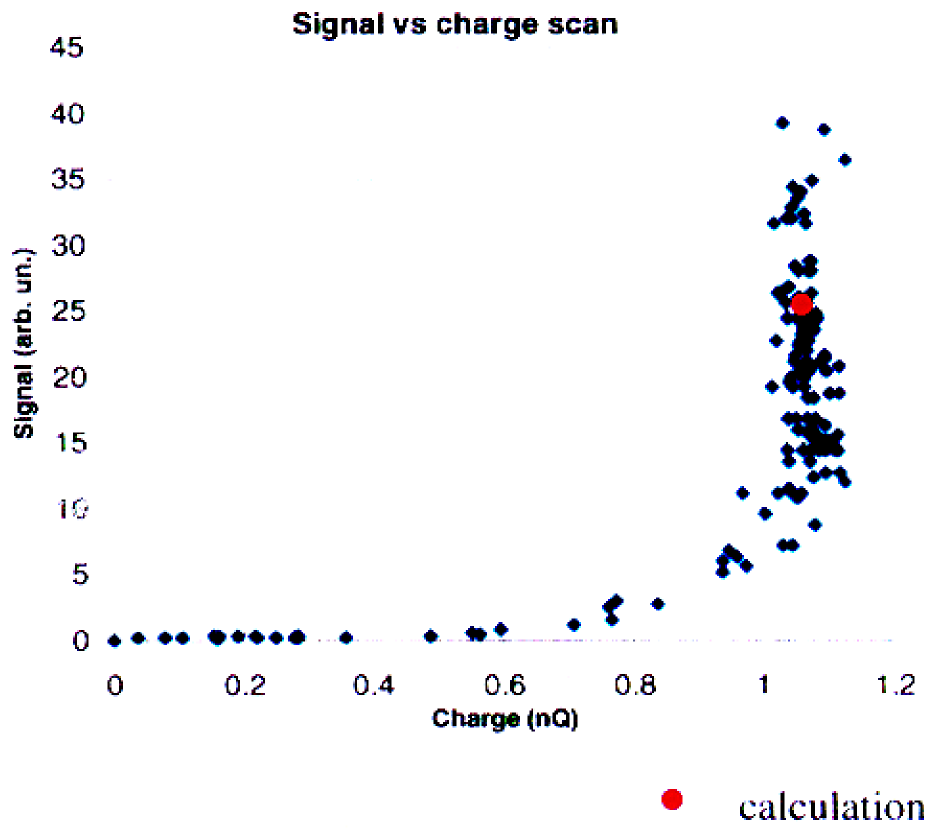
$\xrightarrow{\text{HGHG}}$ 4ps, 150 MW, 3% bandwidth, 88nm

$\longrightarrow$ 5fs, 60 GW 88nm

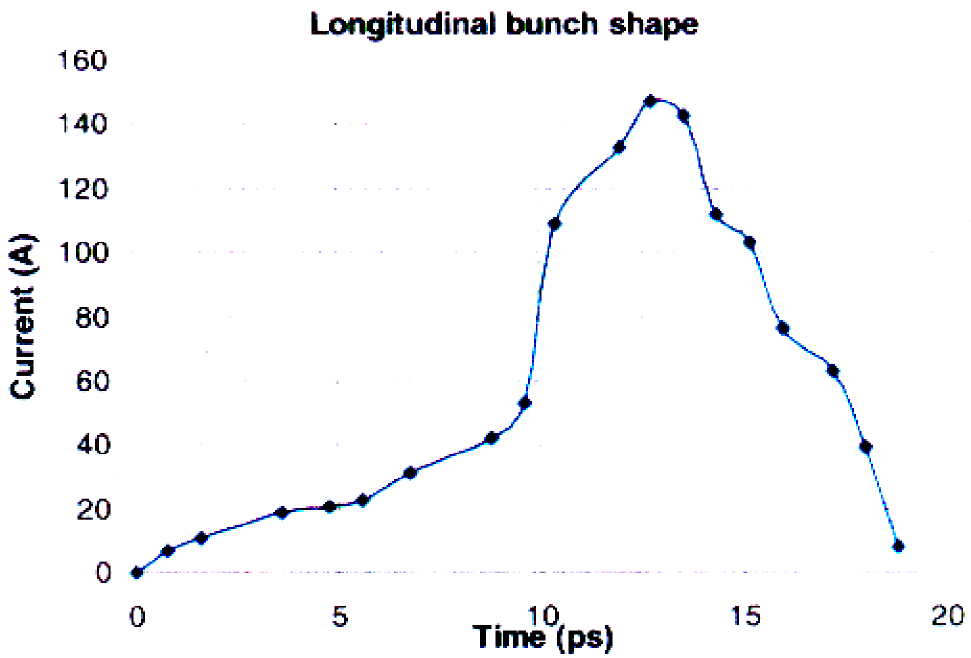


Fresh Bunch Scheme


WARNING



Signal vs charge scan
Signal (arb. un.)
Charge (nQ)
45
40
35
30
25
20
15
10
5
0
0
0.2
0.4
0.6
0.8
1
1.2
calculation



Longitudinal bunch shape
Current (A)
Time (ps)
160
140
120
100
80
60
40
20
0
0
5
10
15
20

Ultrafast Coherent UV and X-ray Sources

Prof. Henry C. Kapteyn
Prof. Margaret Murnane
Prof. Ivan Christov

Andy Rundquist, Charles Durfee, Sterling Backus, Zenghu Chang, Haiwen Wang, Catherine Herne

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University of Michigan

Apply to hard X-rays

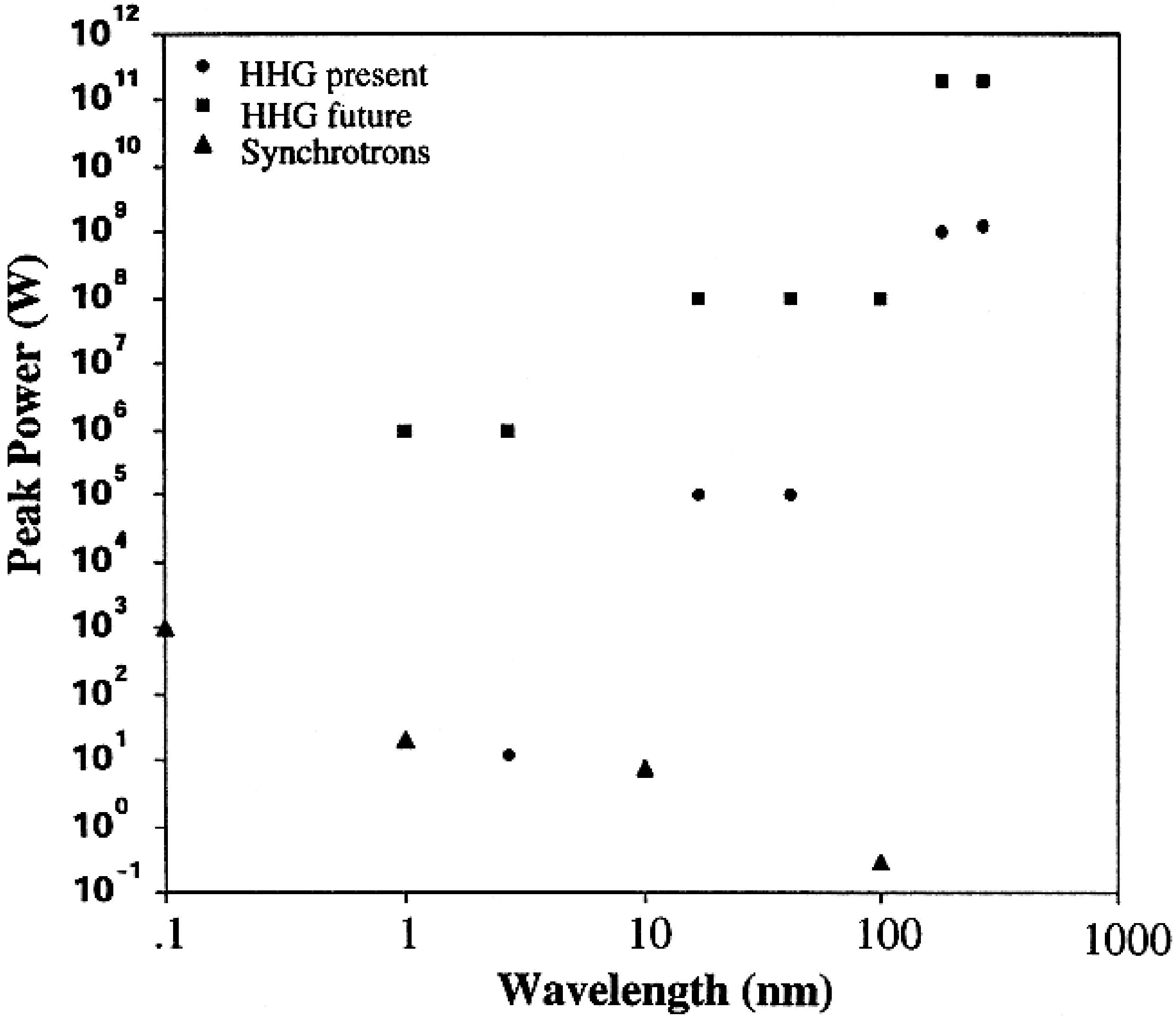
key issues:

- Seed laser power >> input noise

- Equivalent input power of harmonic generation >> noise power in radiator

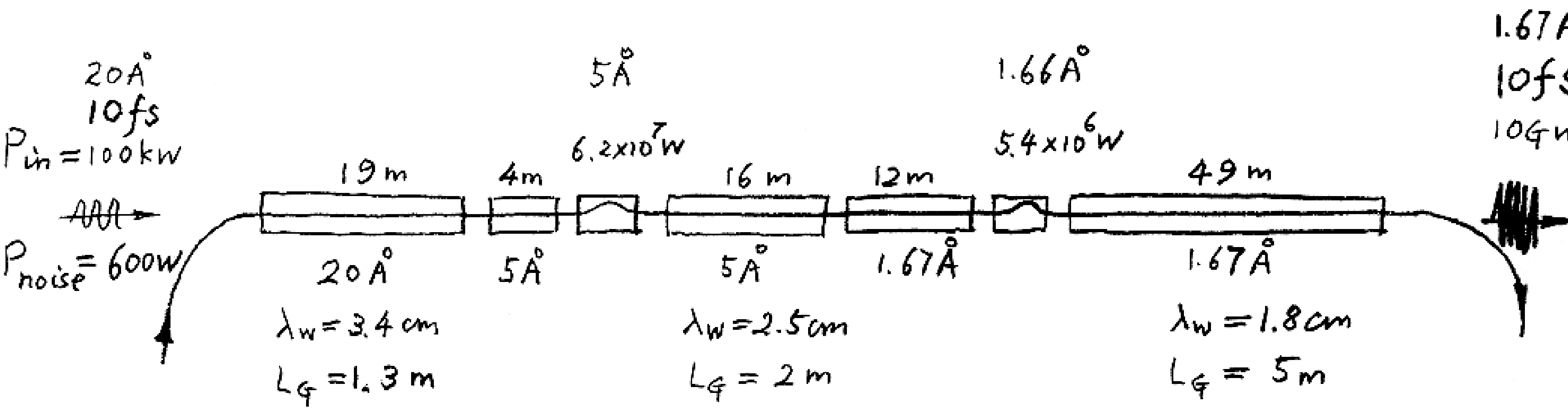
- Whe energy modulation ~ energy spread, use fresh bunch

Peak power:

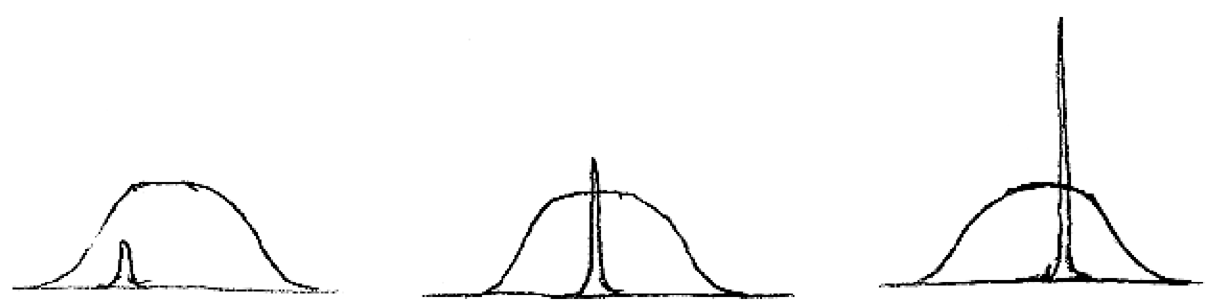


- **HHG radiation has diffraction-limited focusability**

single bunch scheme



e-beam
6GeV
3400 amp
1mm-mrad
100fs



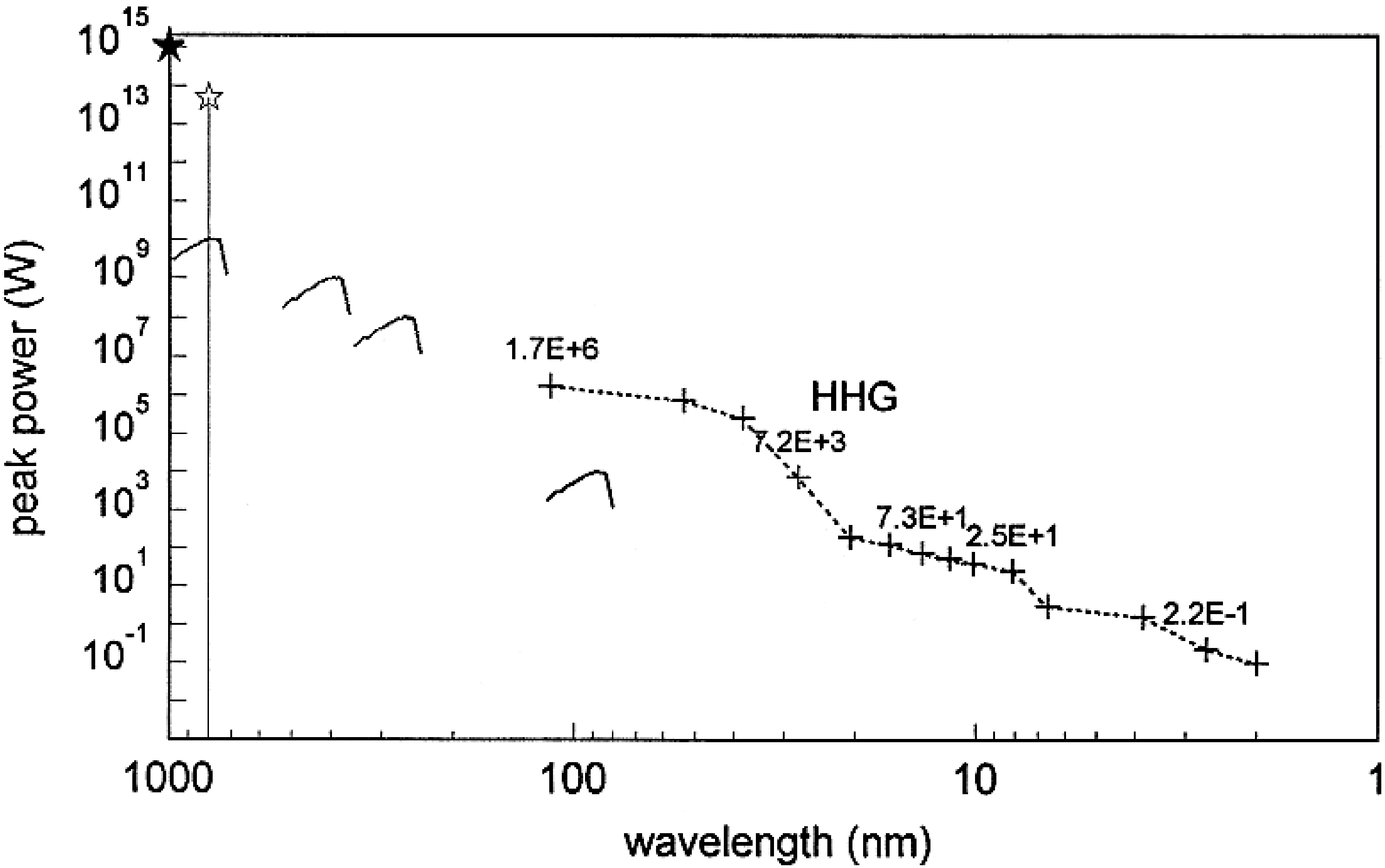
$$\frac{\Delta\lambda}{\lambda} = \frac{\lambda}{\ell} = \frac{1.66\times10^{-10}\,m}{3\,\mu m} = 5\times10^{-5},$$

$W = 10GW \times 10fs = 0.1mJ$
(8×10^{10} photons)

fluctuation $\left(\frac{\Delta W}{W}\right)_{rms} = 5\%$, assuming current fluctuate 10% p-p

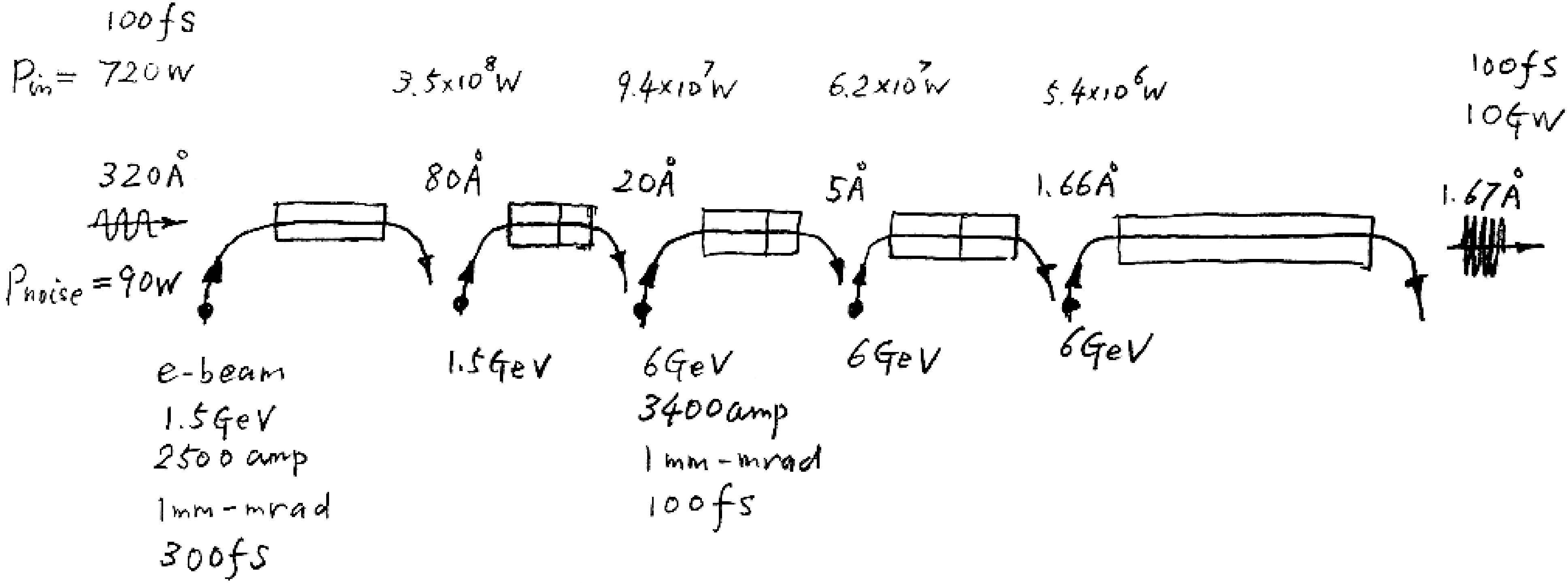
$L_{total} = 100m$

PEAK POWER FOR HHG ASSUMING 10 fs DURATION



Courtesy: L. Di Mauro

5 Bunches Scheme



λ (Å)	320	80	80	20	20	5	5	1.67	1.67
λ_w (cm)	3.6	2.6	2.6	1.8	3.4	2.5	2.5	1.8	1.8
L_w (m)	7	1	2.4	2	10	4	16	12	49
L_G (m)	0.4	0.5	0.5	0.75	1.3	2	2	5	5

$L_{total} = 103\ m$

$$\frac{\Delta\lambda}{\lambda} = \frac{\lambda}{\ell} = \frac{1.67\times10^{-10}\,m}{30\,\mu m} \cong 5\times10^{-6}$$

(Fourier trans. limited)

$$W = 10\,GW \times 100\,fs = 1\,mJ$$

(8×10^{11} photons . 1.67Å)

Summary of the Estimate

	SASE	2-Stage	HGHG single bunch	HGHG 5 bunch
pulse length (fs)	100	100	10	100
band width $\frac{\Delta\lambda}{\lambda}$	4×10^{-4}	5×10^{-5}	5×10^{-5}	5×10^{-6}
Fourier limit	5×10^{-6}	5×10^{-6}	5×10^{-5}	5×10^{-6}
pulse energy (mJ)	1	1	0.1	1
# photons	8×10^{11}	8×10^{11}	8×10^{10}	8×10^{11}
peak power (GW	10	10	10	10
fluctuation	5%	10%-20%	5%	5%
Spon. power in fundamental (GW)	1	–	0.4	0.4
beam size			~30 μm	
divergence			~0.5 μrad	