Soft X-ray HGHG FEL
Team 6

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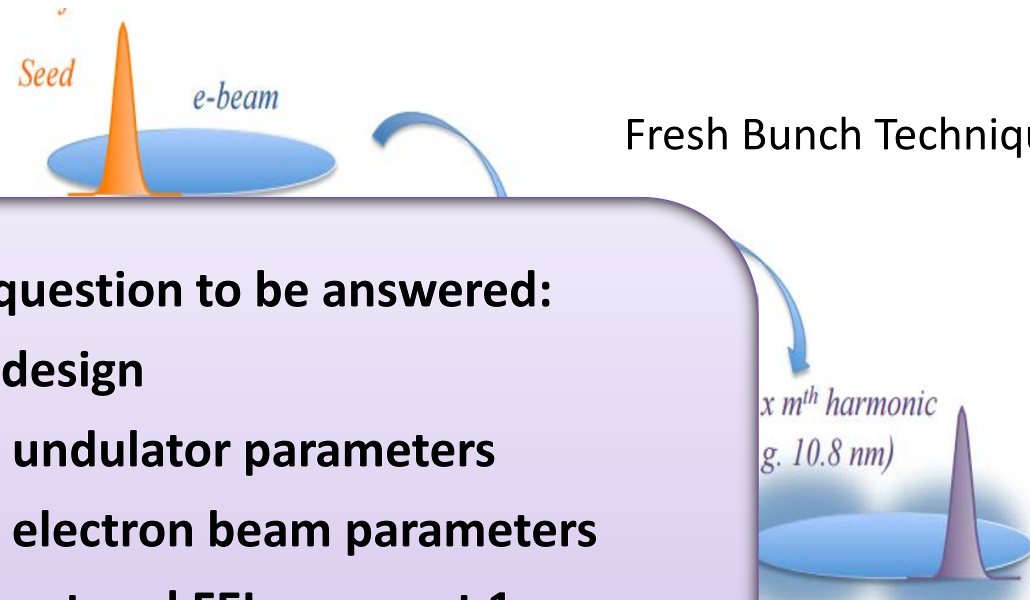
Cascaded HGHG-Seeded FEL



Fresh Bunch Technique

L. Giannessi

Stages: 3 (two fresh

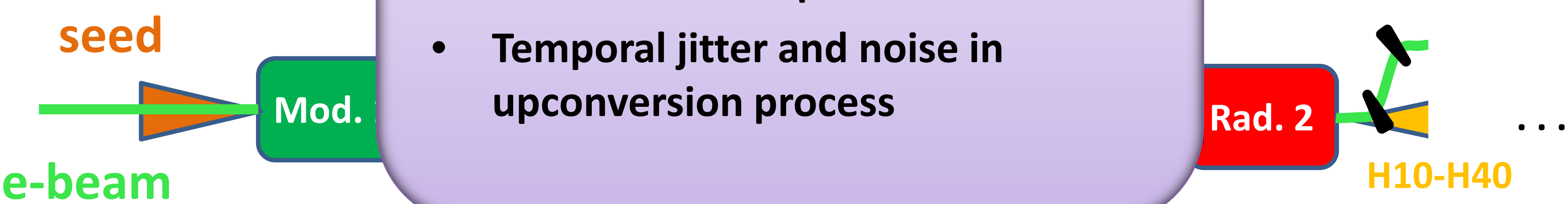
Harmonic per stage

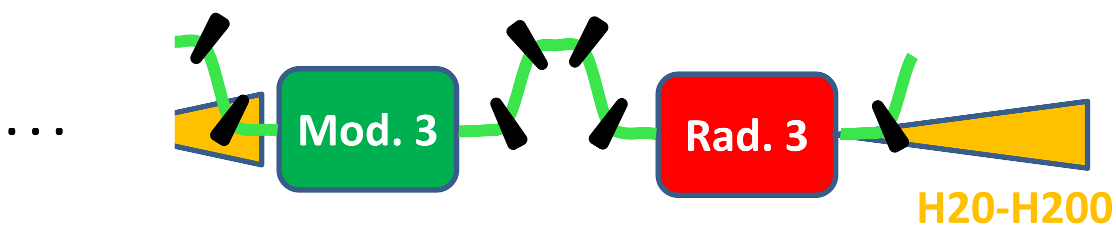
Seed wavelength:

Bunch charge: 1 r

Major question to be answered:

- **FEL design**
  - **undulator parameters**
  - **electron beam parameters**
- **Current and FEL power at 1 nm**
- **Temporal jitter and noise in upconversion process**





continuous tuning from 1 nm to 10 nm

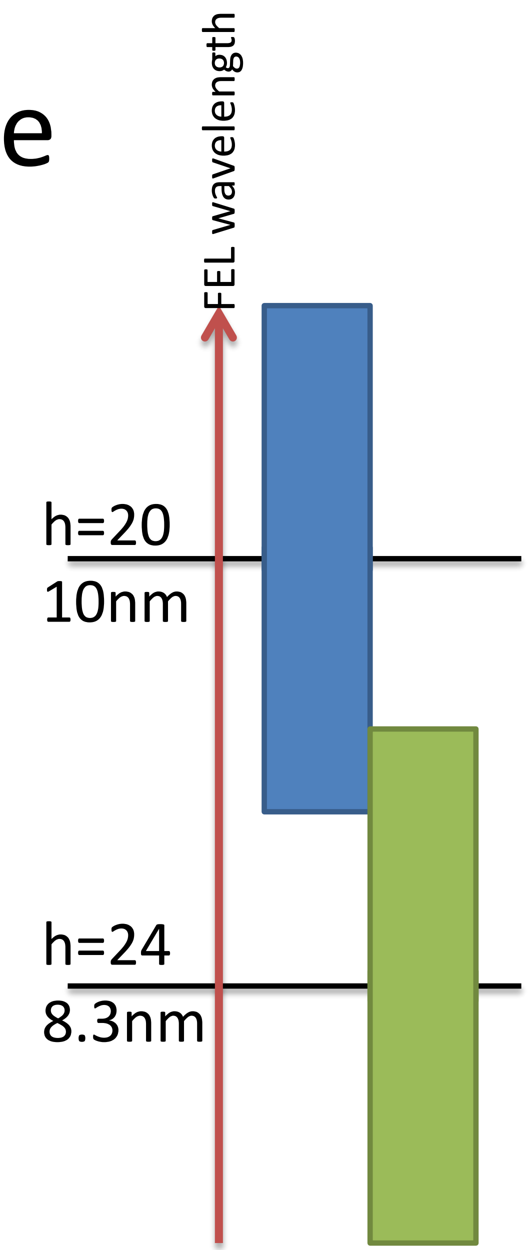
Laser Tuning Range

- Assignment calls for continuous tuning of seeded FEL wavelength
- Scanning of atomic transitions, other AMO applications
- Largest gap between 20^{th} and 24^{th} harmonic
- To close gap, we need:

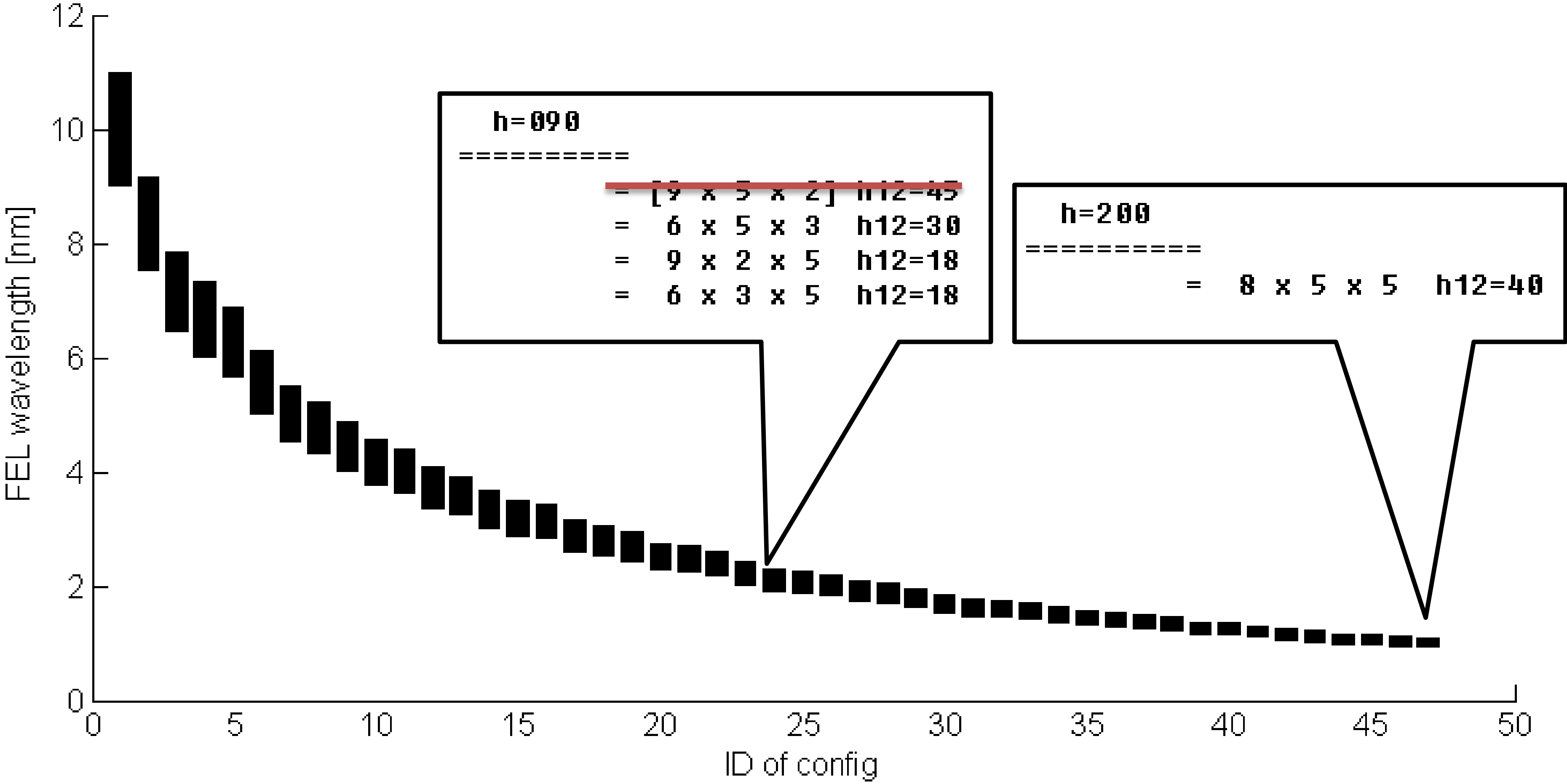
$$\frac{200\,\mathrm{nm} - u}{20} = \frac{200\,\mathrm{nm} + u}{24}$$

- Result u=18.2nm

going for seed wavelengths
<u>180nm..220nm</u>



Possible Upconversion Configurations



Total harmonic factors:
20 24 ~~27~~ 28 30 32 36 40 42 45 48 50 54 56 60 63 64 70 72 75 80 81 84 90 96 98 100 105 108 112 120 125 126 128 135 140 144 147 150 160 162 168 175 180 189 192 196 200

Undulator Parameters

- Three-stage HGHG setup requires 6 undulators with 4 different parameters sets
  - planar, variable-gap undulators (hysteresis-free, tunable)
  - lengths determined by FEL considerations

	period [mm]	**Krms**		**radiation wavelength [nm]**		**Length**
		min	max	min	max	
Mod 1	128	8.45	12.68	180	220	?
Rad 1, Mod 2	80.4	3.45	7.96	20	55	?
Rad 2, Mod 3	59	1.71	5.84	4.5	22	?
Rad 3	37	1.22	3.66	1.0	10	?

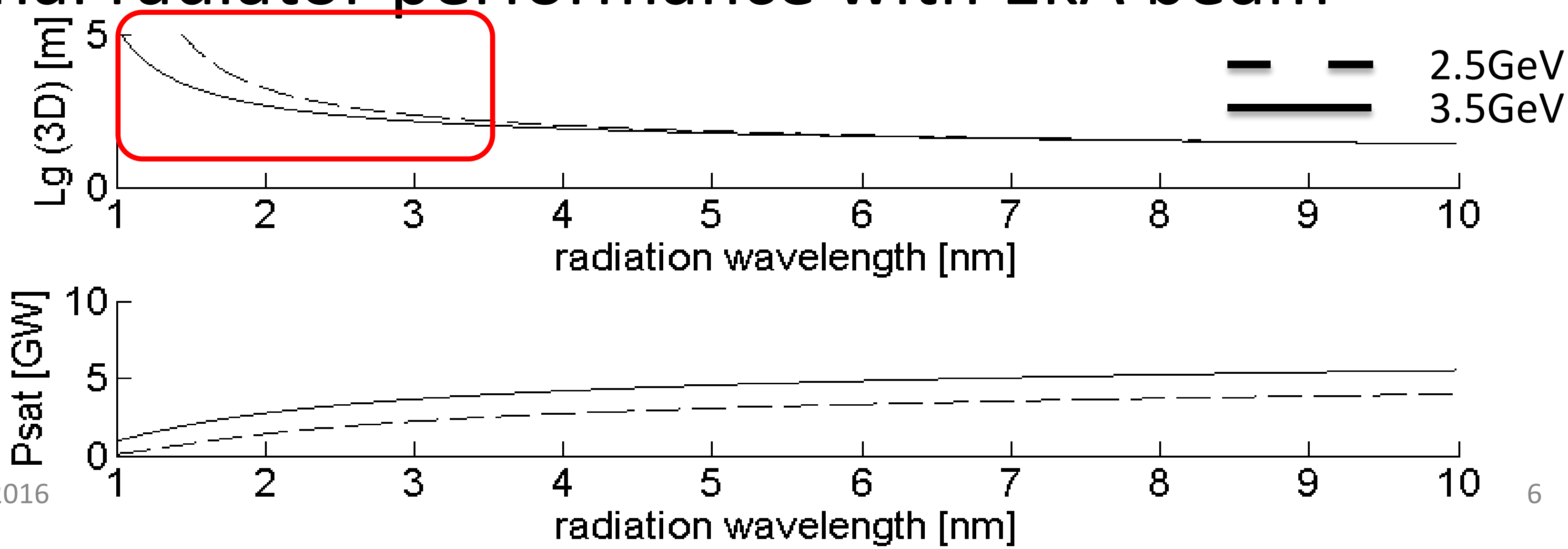
Electron Beam Parameters

- Beam current has strong impact on FEL performance

$$P_{\mathrm{sat}} \propto I^{4/3}$$

- Energy spread is proportional to beam current
  - suppose, laser heater does 10keV slice energy spread at 60A injector current [similar to FERMI@Elettra parameters, see S. Spampinati, et al., PRSTAB 17, 120705 (2014)]
  - for 1kA current after compression, 170keV slice energy spread

Final radiator performance with 1kA beam



Estimation of Seed Power

reasonable energy modulation amplitude

$$\Delta E = h \cdot \sigma_E$$

$$\Delta\gamma = \sqrt{\frac{P}{P_0}}\,\frac{2K_m L_m \mathrm{JJ}}{\gamma_0 w_0}$$

$$\mathrm{JJ} = \mathrm{J}_0(\xi) - \mathrm{J}_1(\xi)$$

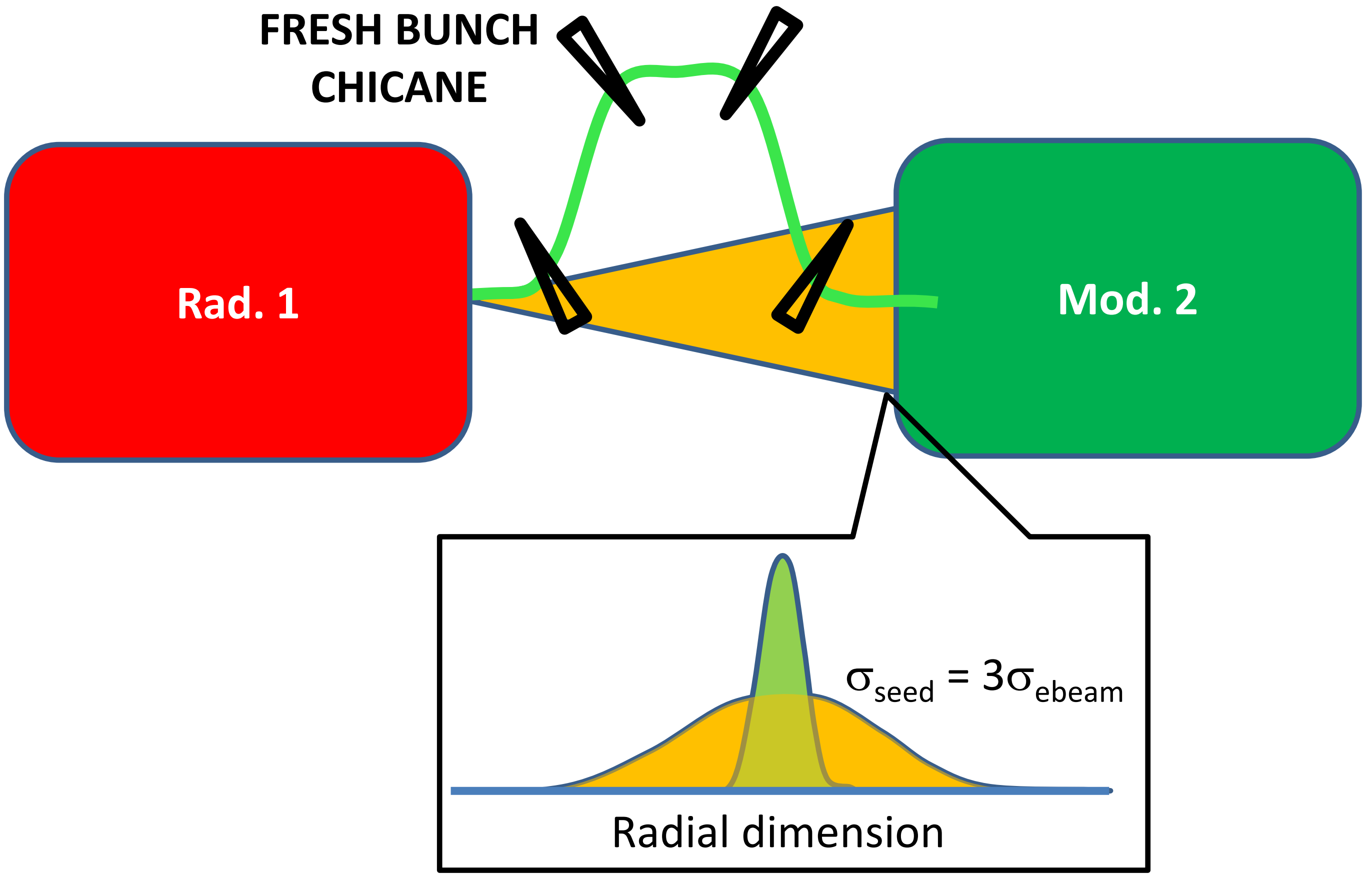
$$\xi = K_m^2/(4 + 2K_m^2)$$

$$P_0 = 8.7\,\mathrm{GW}$$

See e.g. E. Hemsing, et al., Rev. Mod. Phys. 86, 897 (2014)

- Obtained by integrating FEL pendulum equation
- Transverse intensity profile of seed has to be reasonably uniform over electron beam

Diffraction Effect between Radiator and Modulator



$$P(z) = P_{\mathrm{th}} \left[\frac{\frac{1}{3}\left(\frac{z}{L_g}\right)^2}{1 + \frac{1}{3}\left(\frac{z}{L_g}\right)^2} + \frac{\frac{1}{2}\exp\left(\frac{z}{L_g} - \sqrt{3}\right)}{1 + \frac{P_{\mathrm{th}}}{2(P_F - P_{\mathrm{th}})}\exp\left(\frac{z}{L_g} - \sqrt{3}\right)} \right]$$

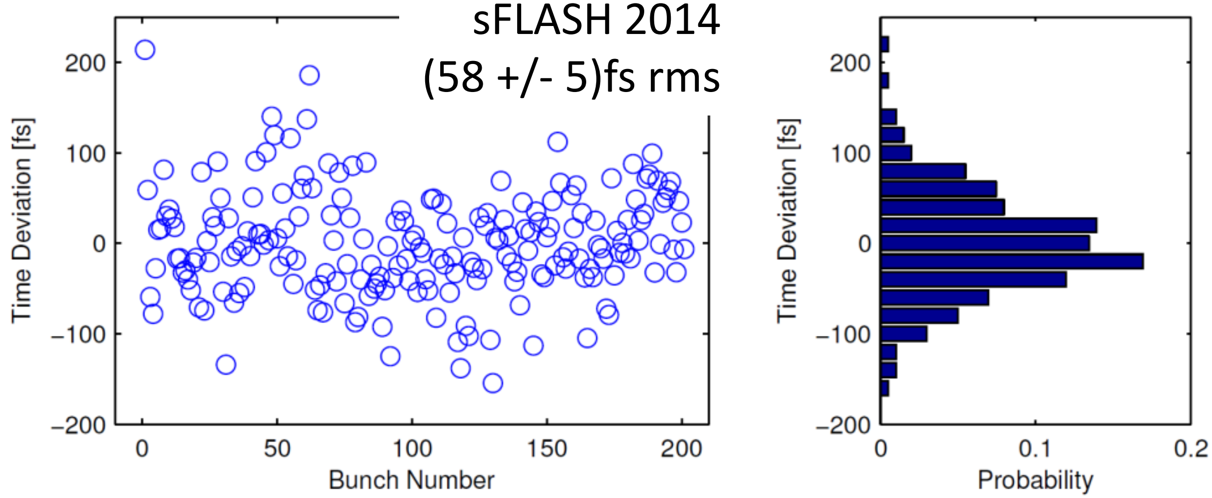
Active Lengths of Undulators

Assume conservative initial bunching b0=.1

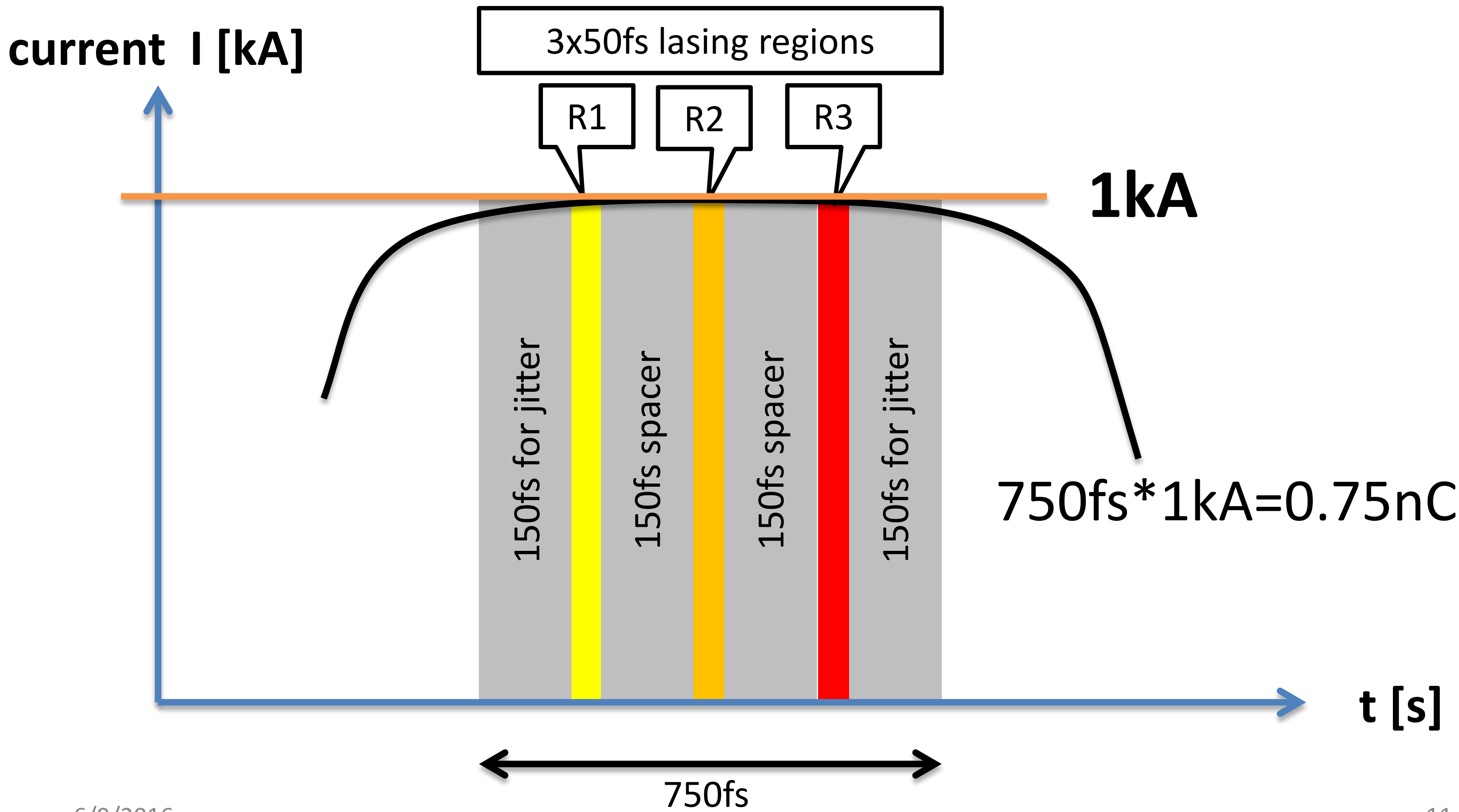
	Length [m]	remarks
Mod 1	3m	200MW seed power gives deltaE=2.6MeV
Rad 1	10m	1GW
Mod 2	3m	1GW seed power gives deltaE=2.3MeV
Rad 2	16m	1GW
Mod 3	4m	1GW seed power gives deltaE=1.7MeV
Rad 3	53m	1GW @1nm
total	89m	active length of undulators

Temporal Jitter

- We need some budget for temporal jitter (and drifts)
- Assume relative laser-electron jitter of **70 fs rms**
- Supported by measurements:
  - (58 +/- 5)fs rms at sFLASH [C. Lechner, et al., Proc. FEL2014, THP076 (2014)]
  - 68fs rms at FERMI@Elettra [E. Allaria, et al., Phys. Rev. ST Accel. Beams 17, 010704 (2014)]



Electron Bunch Allocation
for 70fs rms jitter



Noise in HGHG Seeding

$$\left(\frac{P_s}{P_n}\right)_{\mathrm{out}} = \frac{1}{h_{\mathrm{tot}}^2}\left(\frac{P_s}{P_n}\right)_{\mathrm{in}}$$

Saldin, Schneidmiller, and Yurkov:
Opt. Commun. 202, 169—187 (2002)

- Signal-to-noise ratio degrades in upconversion process (signal: seed laser, noise: shot noise)
- Parameters:
  - Seed power at 200nm: Ps=200MW * 1/9
  - Pn=50W
  - factor 1/9: seed power within electron beam diameter
- <u>Final SNR only 11 with htot=200</u>

Summary

- Designed 3-stage HGHG setup
  - Calculated undulator parameters
  - Defined electron bunch parameters (1kA, 2.5GeV / 3.5GeV for short wavelengths)
  - 200MW @200nm seed FEL with 1GW @1nm
- Shotnoise upconversion obliterates quality of seeded pulses (poor signal-to-noise ratio)
- LCLS soft x-ray self seeding: 500eV—1000eV (2.5nm – 1.25nm)
- (identification of next steps)

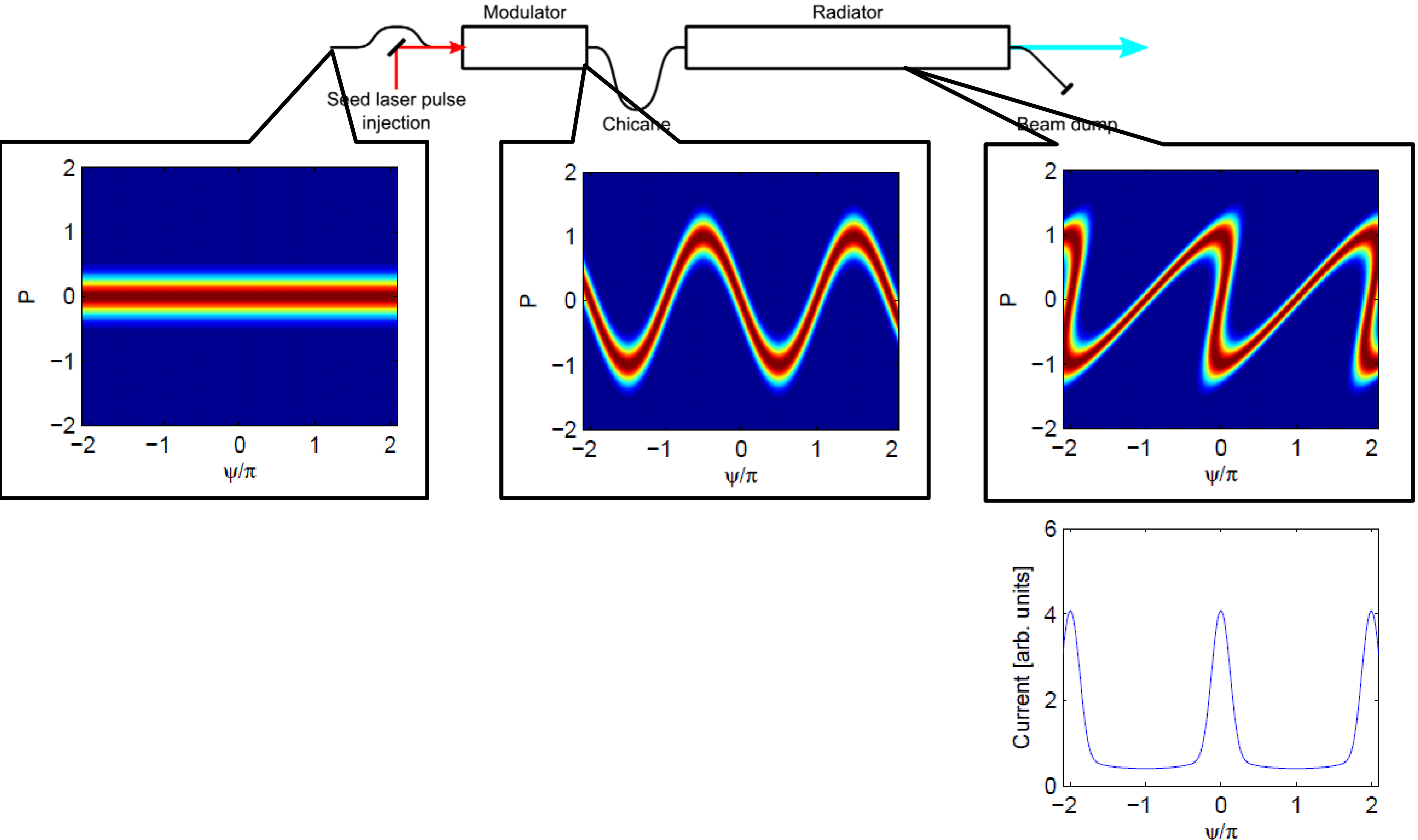
thank you for your attention

The Next Steps …

- Stability analysis to determine
  - distribution of harmonics for given total upconversion
  - electron beam parameters
  - time-dependent simulations
- Consider different (longer) laser wavelengths centered, for instance
  - THG from OPA: 235nm—300nm
  - Or 260nm—310nm, around 100uJ pulse energy
  - Significantly higher laser pulse energies, BUT higher harmonics in FEL upconversions

BACKUP SLIDES

HGHG Seeding Principle



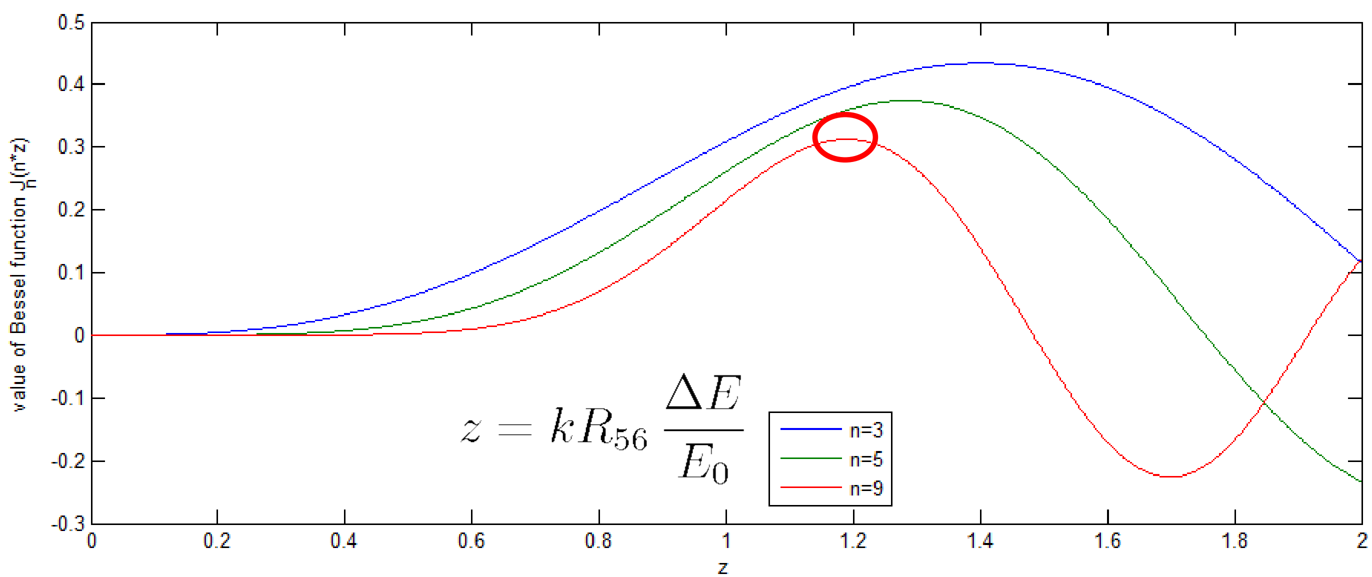
see lecture by L. Giannessi …

Bunching Formula

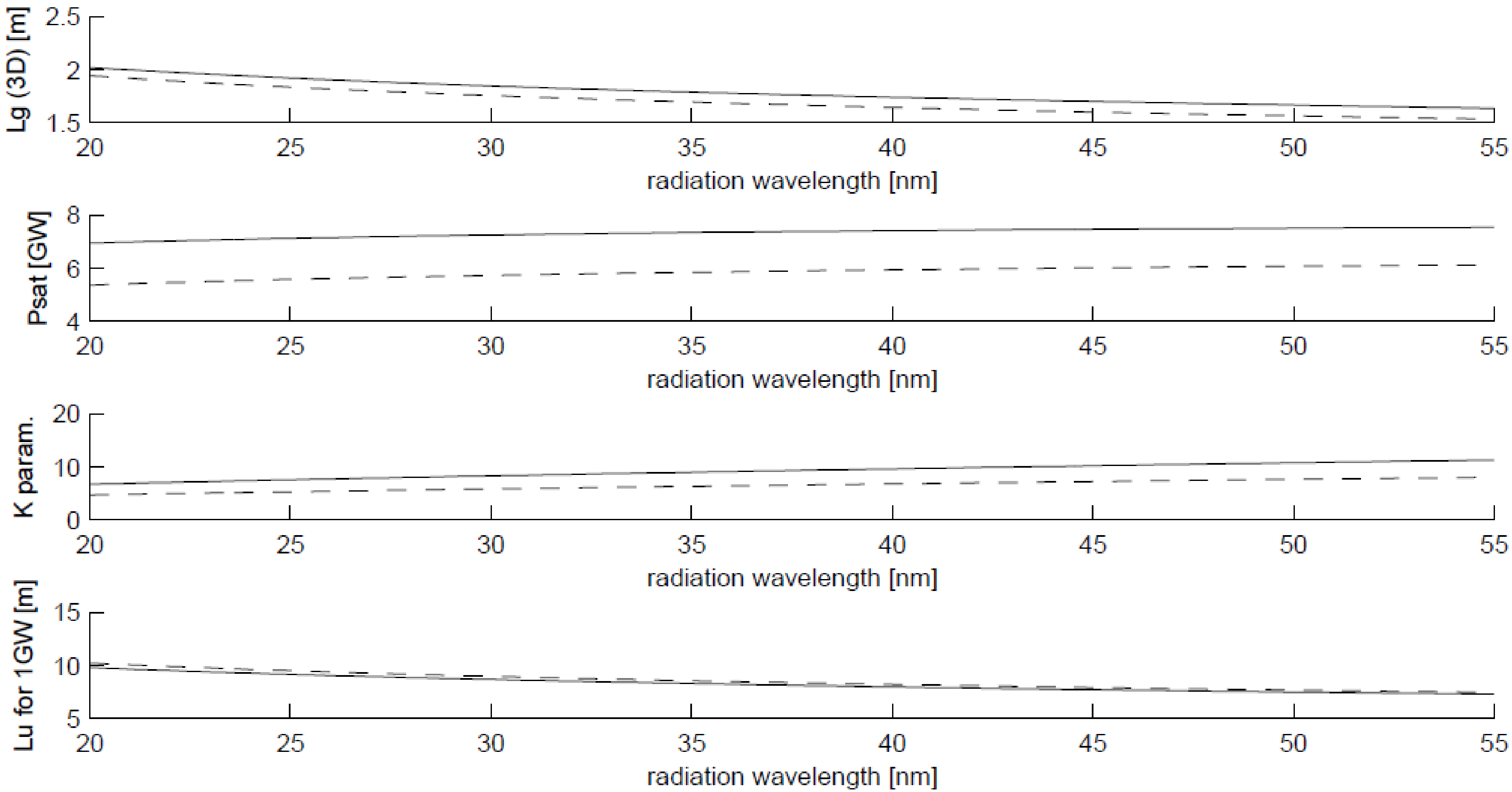
$$b_h = \boxed{J_h\left(hkR_{56}\frac{\Delta E}{E_0}\right)} \exp\left(-\frac{1}{2}\left(hkR_{56}\frac{\sigma_E}{E_0}\right)^2\right)$$

- In all radiator stages, assume conservative b=0.1
- For harmonic h, energy modulation amplitude:

$$\Delta E = h \cdot \sigma_E$$

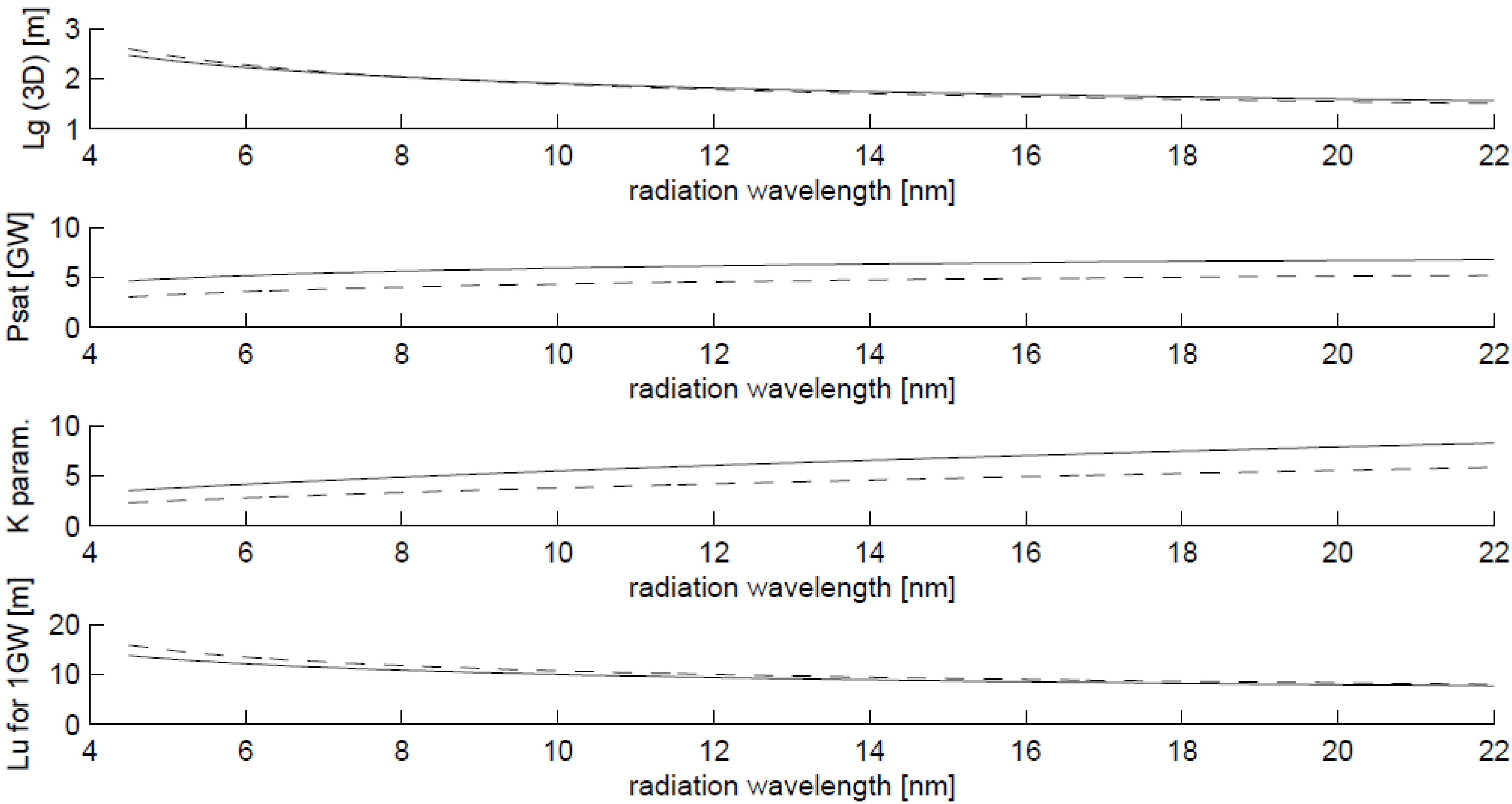


Radiator 1



calculated with 900keV slice energy spread

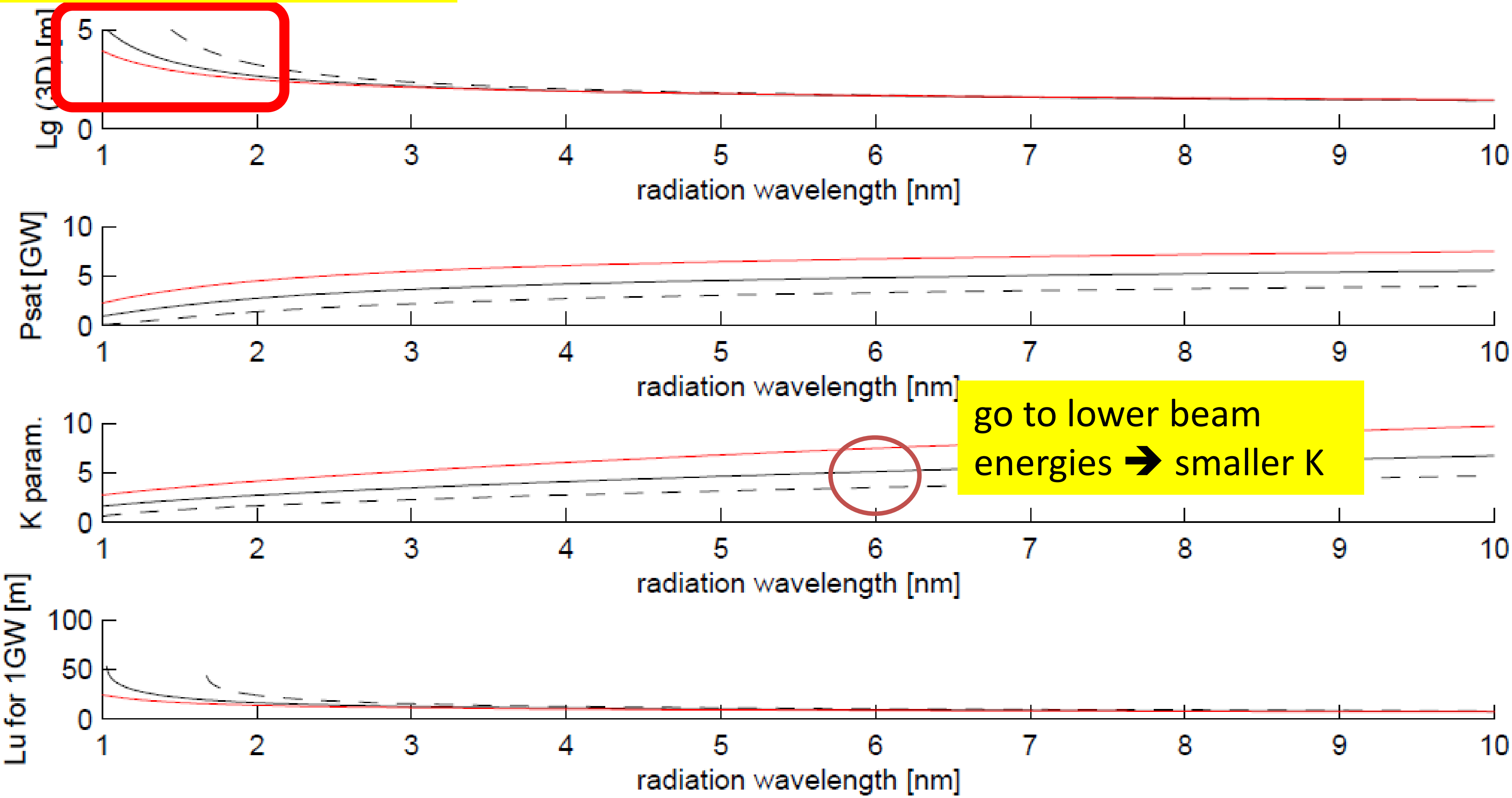
Radiator 2



calculated with 900keV slice energy spread

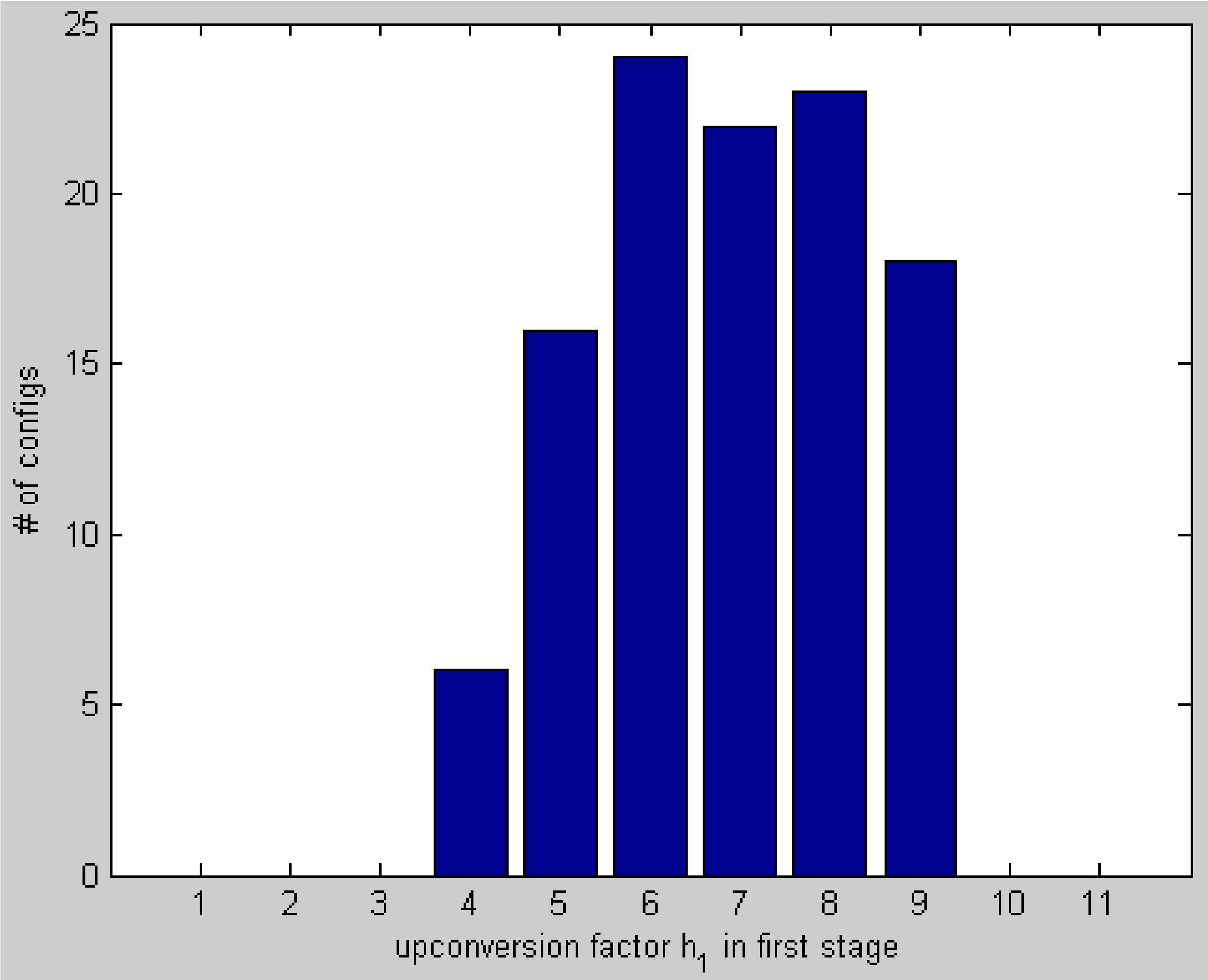
At short wavelengths:
Different performance
With different energies

Radiator 3



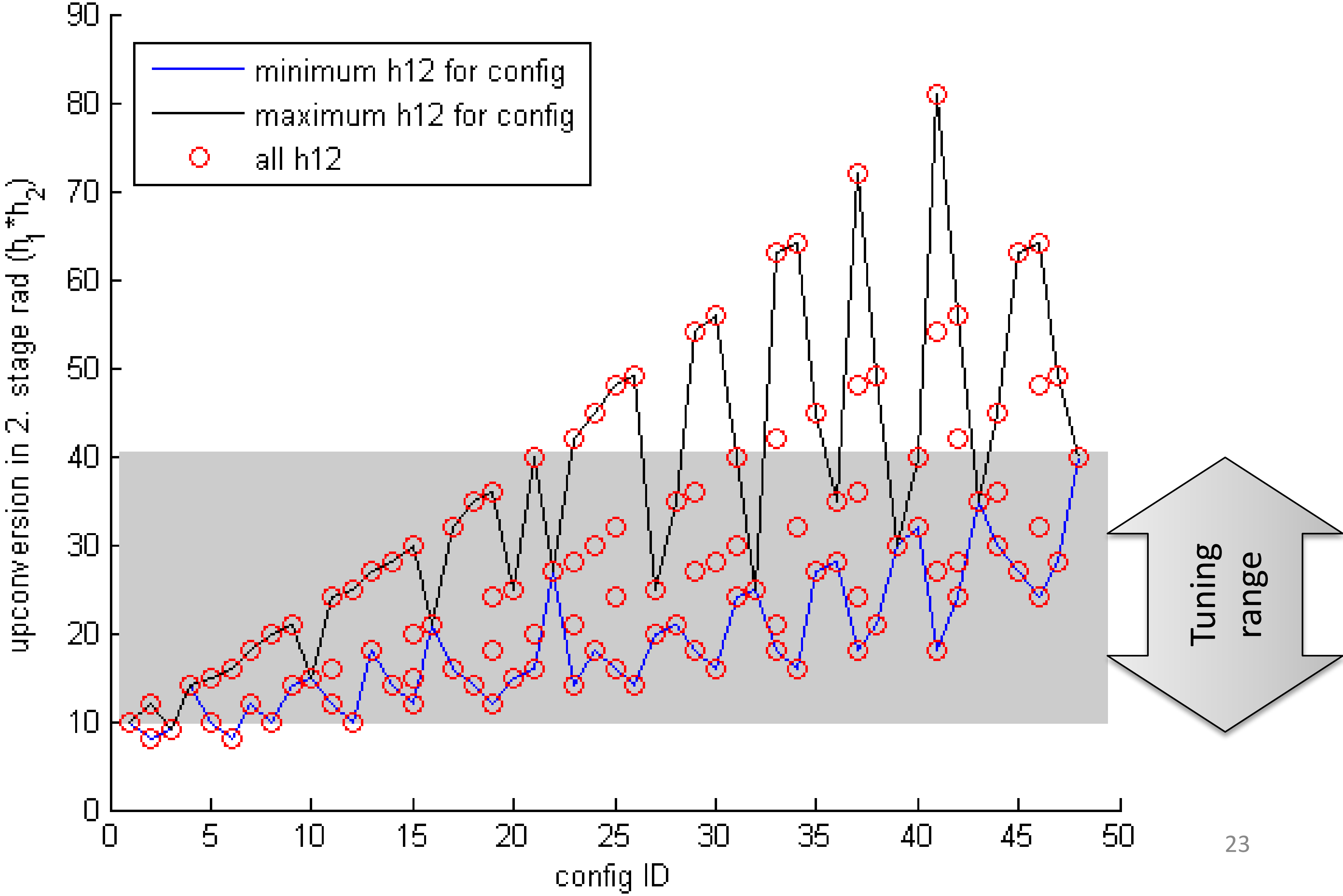
black dashed = 2.5GeV, black solid = 3.5GeV, red solid = 5.0GeV
1kA, sigmaE=900keV (including modulation for h=9), emit_n=1.5e-6

Needed Harmonics in First Stage

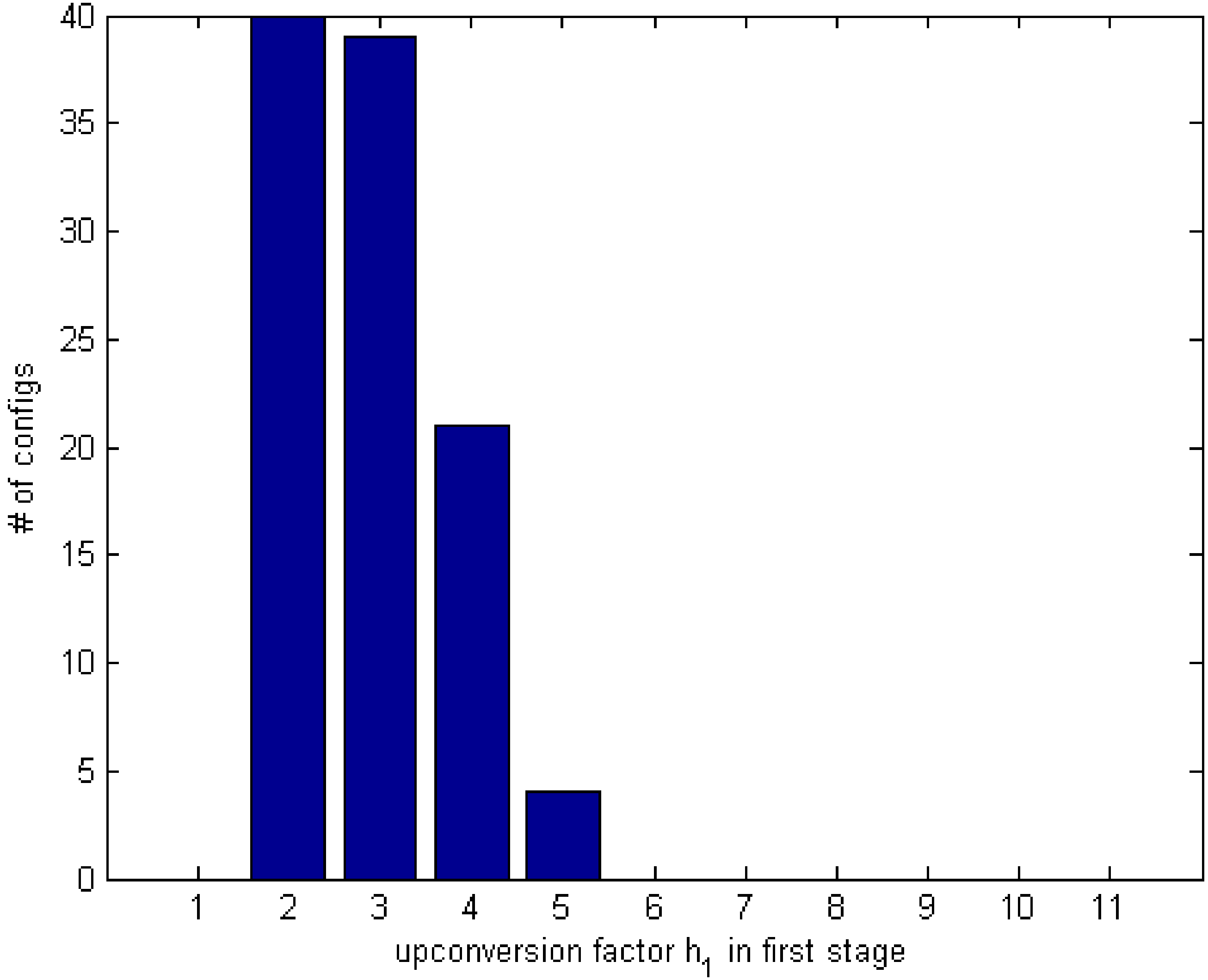


… defines the resonance condition for R1

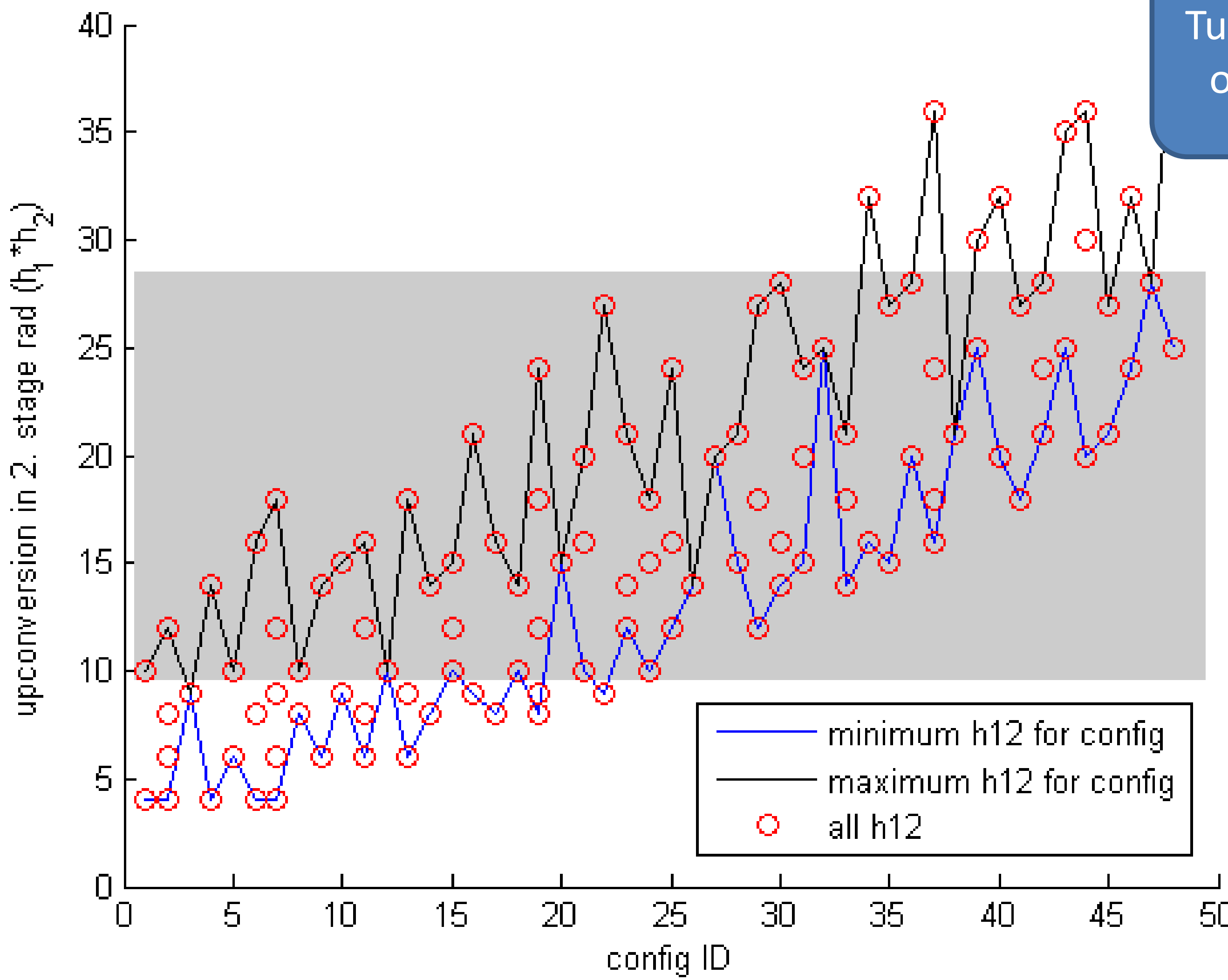
Total Up-Conversion in Radiator of Second Stage (h1*h2)



Lowest Factor First: h1

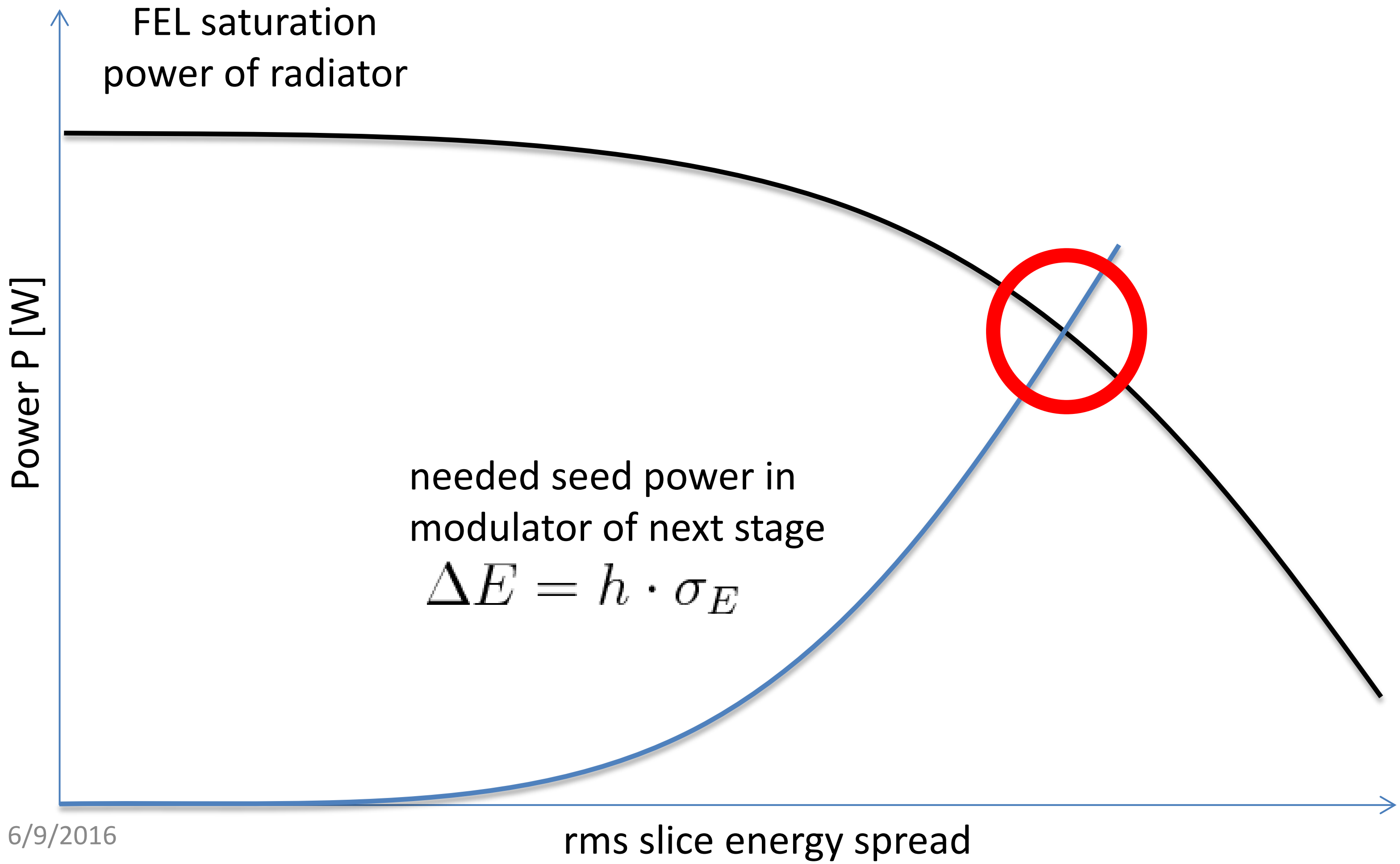


Lowest Factor First: h1*h2



Tune 2nd radiator over h=10…28

Slice Energy Spread can be a Deal Breaker



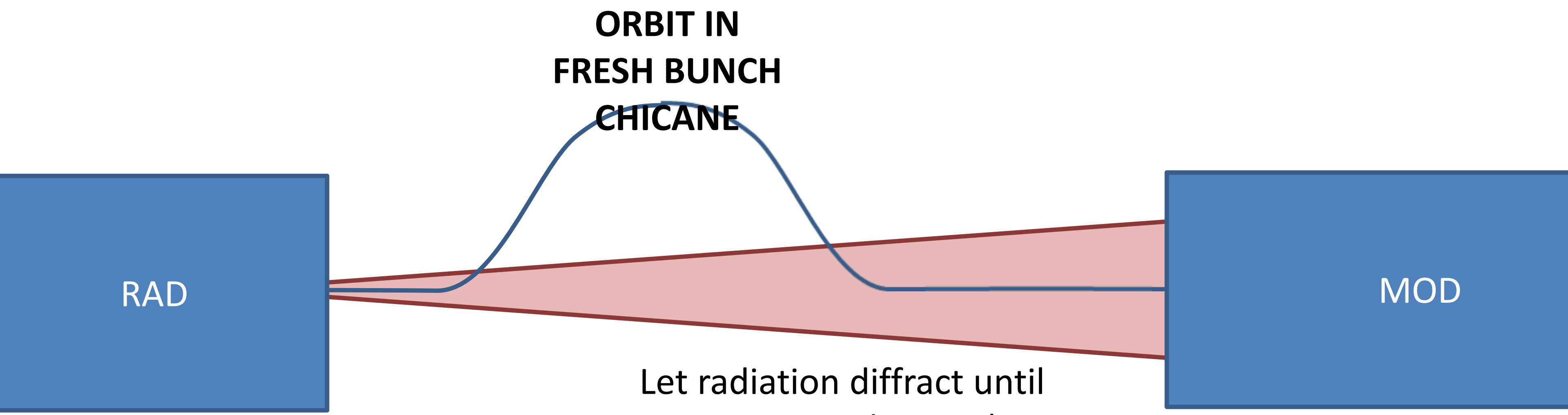
Infos Regarding Beam in Modulator

- FERMI FEL-2 undulator parameters: page 15 of http://www.nature.com/nphoton/journal/v7/n11/extref/nphoton.2013.277-s1.pdf
- FERMI CDR, p. 96 says:
  - 200MW of FEL emission from first stage radiator at FEL-2
  - "Provisionally the fresh bunch delay section is presumed to have a 1.8 m length (necessary in the numerical simulations to include proper diffraction effects)."
- Beam size at E=2.5GeV, emit=1.5mm*mrad, <beta>=10m ➔ sigma_x=55um

Modulator Noise

- http://www.slac.stanford.edu/cgi-wrap/getdoc/slac-pub-12097.pdf

Diffraction Effect between Radiator and Modulator



Let radiation diffract until rms spotsize at least 3*rms ebeam size …

Evolution of FEL power in radiator computed with formula from presentation by L. Giannessi

$$P(z) = P_{\mathrm{th}} \left[\frac{\frac{1}{3}\left(\frac{z}{L_g}\right)^2}{1+\frac{1}{3}\left(\frac{z}{L_g}\right)^2} + \frac{\frac{1}{2}\exp\left(\frac{z}{L_g}-\sqrt{3}\right)}{1+\frac{P_{\mathrm{th}}}{2(P_F-P_{\mathrm{th}})}\exp\left(\frac{z}{L_g}-\sqrt{3}\right)} \right]$$

$$\Delta\gamma = \ldots$$