Short Wavelength Regenerative Amplifier FELs (RAFELs)

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Contents

- What is a RAFEL? - background
- An example of a short wavelength RAFEL: the 4GLS VUV-FEL proposal
- A Generic ultra-low feedback RAFEL
- Issues / Conclusions ...

see also:

New Journal of Physics
The open-access journal for physics

A design for the generation of temporally-coherent radiation pulses in the VUV and beyond by a self-seeding high-gain free electron laser amplifier

New Journal of Physics **9** (2007) 239
Received 23 April 2007
Published 20 July 2007
Online at http://www.njp.org/
doi:10.1088/1367-2630/9/7/239

What is a RAFEL?

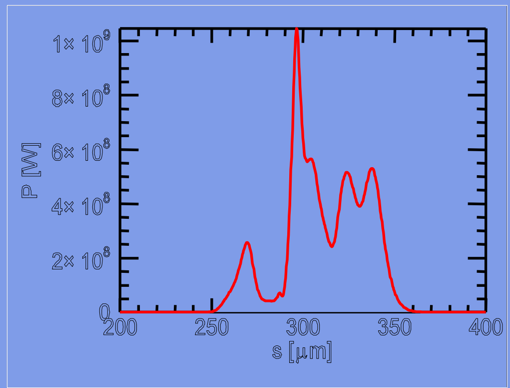
- A high-gain low feedback cavity FEL
  - Reaches saturation in a few passes
  - The resonator is high output coupling, or low feedback (or Low-Q)
  - Low feedback makes RAFEL candidate for short wavelengths

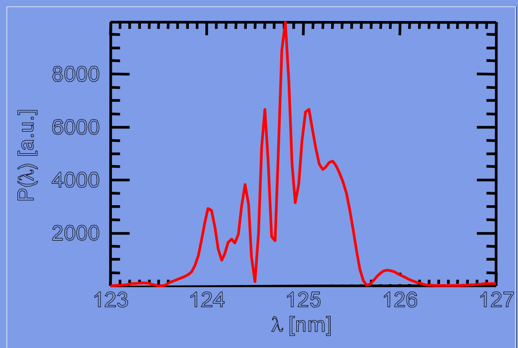
- Properties
  - Radiation not stored over many passes
  - Radiation does not propagate freely, but is gain guided (high gain)
  - Generates small seed field for next pass of high gain system

- Expected advantages of RAFEL
  - Performance should be less sensitive to mirror degradation
  - Feedback gives shorter undulator than SASE system
  - Feedback averages out electron beam shot noise improving temporal coherence

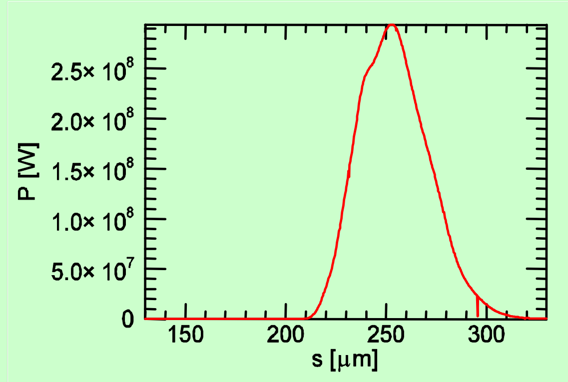
SASE compared to RAFEL : 4GLS VUV   EL

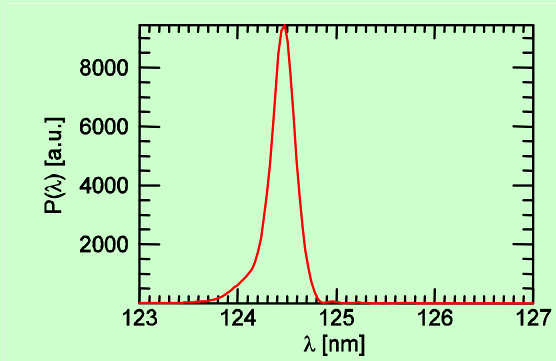
SASE





RAFEL



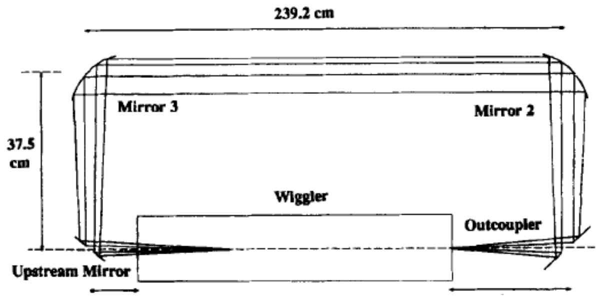


Previous RAFEL Experiments and Other Proposals

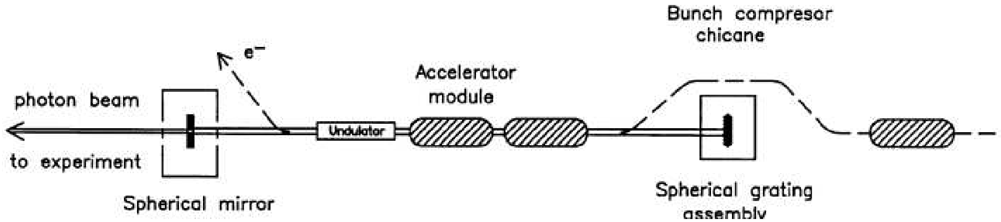
- High Gain Low Feedback concept (Low-Q cavity)
  McNeil B W J 1990 *IEEE J. Quantum Electron.* **26** 1124

As well as these experiments in the infrared region of the spectrum, this high-gain regime of the FEL oscillator is also of interest in FEL designs for the ultraviolet and higher frequencies. The lack of high mirror reflectivities for these frequencies severely restricts the design of low-gain oscillators.

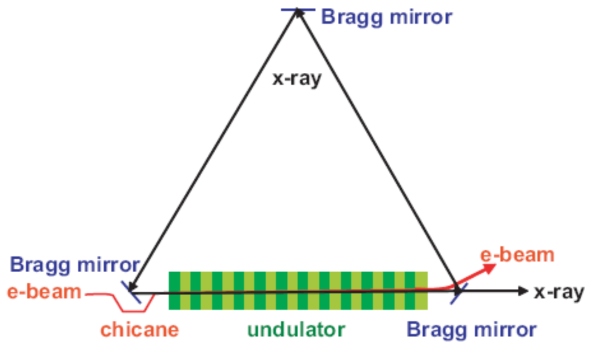
- Los Alamos IR-RAFEL
  Nguyen D C, Sheffield R L, Fortgang C M, Goldstein J C, Kinross-Wright J M and Ebrahim N A 1999 *Nucl. Instrum. Methods Phys. Res.* A **429** 125–30



- TTF VUV-RAFEL
  Faatz B, Feldhaus J, Krzywinski J, Saldin E L, Schneidmiller E A and Yurkov M V 1999 *Nucl. Instrum. Methods Phys. Res.* A **429** 424–8



- LCLS X-RAY RAFEL
  Huang Z and Ruth R D 2006 *Phys. Rev. Lett.* **96** 144801



FEL cavity output Vs Reflectivity (Steady State)

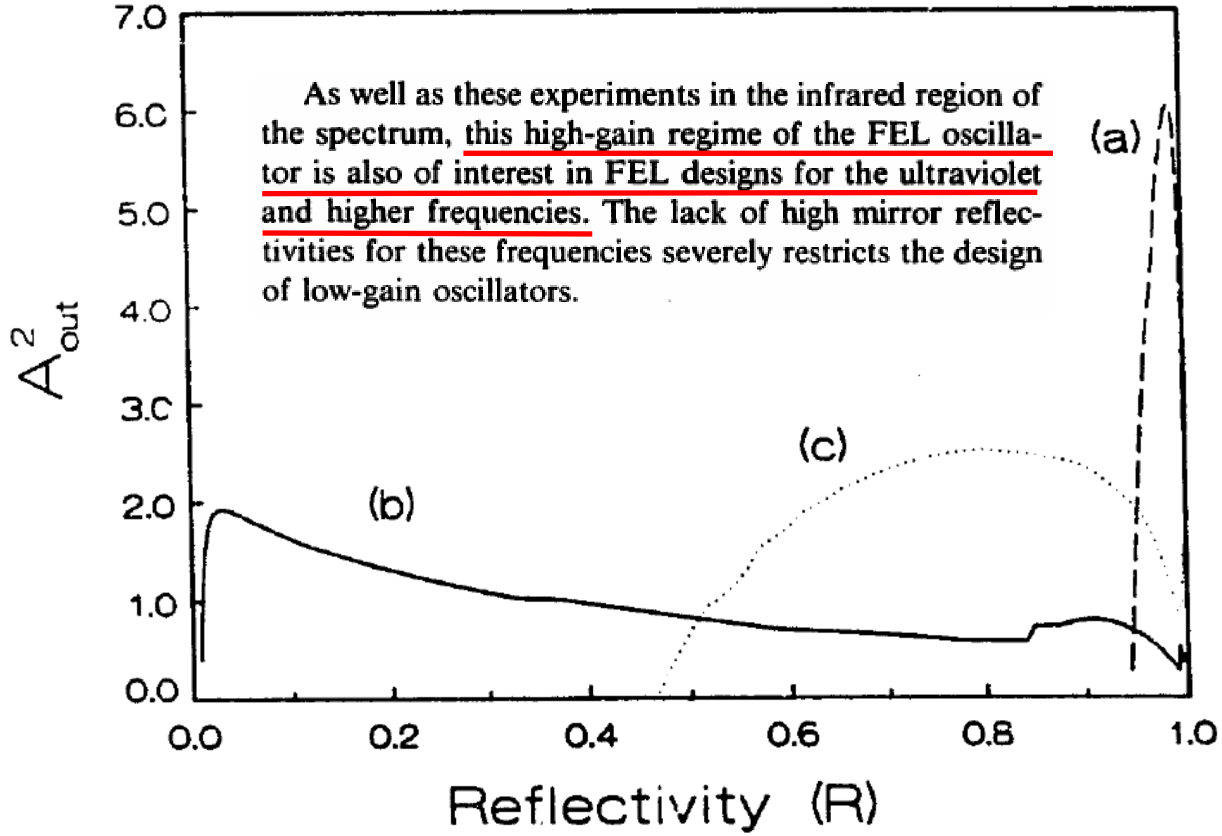
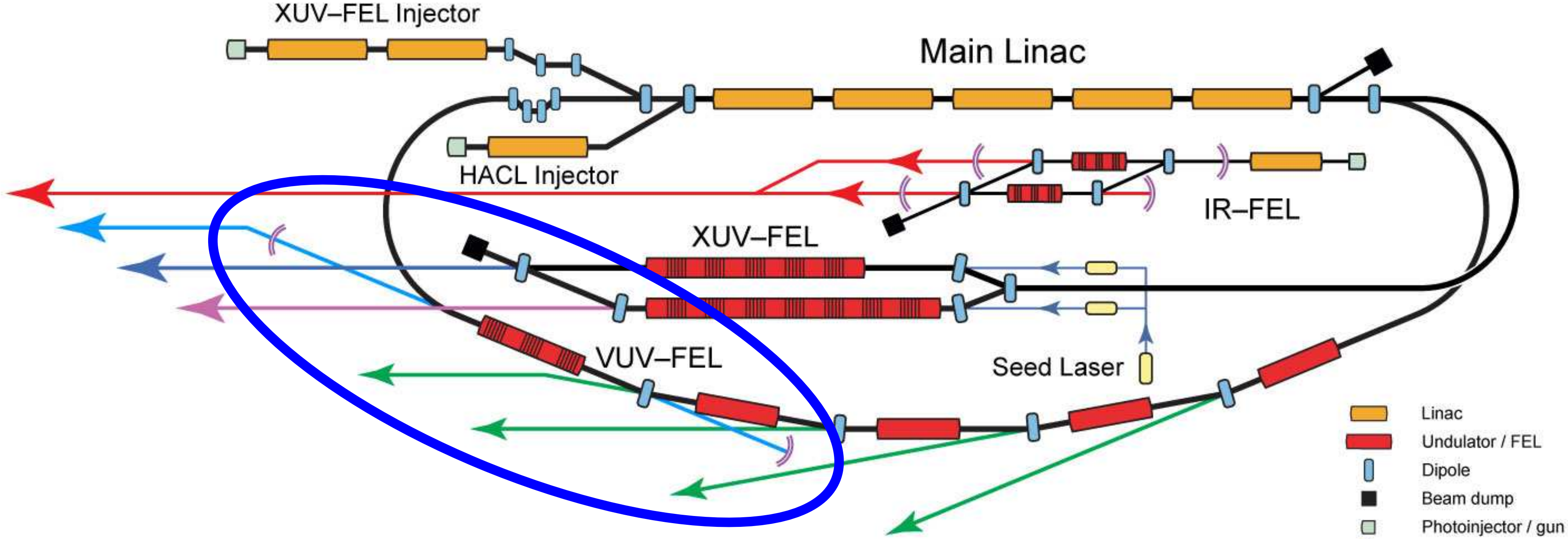


Fig. 5. Steady-state scaled output intensities A^2_{out} from a FEL oscillator as a function of output mirror reflectivity R for (a) $G = 0.6$, (b) $G = 4.0$ and (c) $G = 1.5$.

$G = \bar{z}$

BWJ McNeil, *IEEE J. Quantum Electron.* **26,** 1124 (1990)

4GLS VUV-FEL



XUV–FEL Injector
Main Linac
HACL Injector
IR–FEL
XUV–FEL
VUV–FEL
Seed Laser
Linac
Undulator / FEL
Dipole
Beam dump
Photoinjector / gun
Laser
Optical Mirror

4GLS VUV-FEL:

An example of a current RAFEL proposal

Why we chose a RAFEL for 4GLS

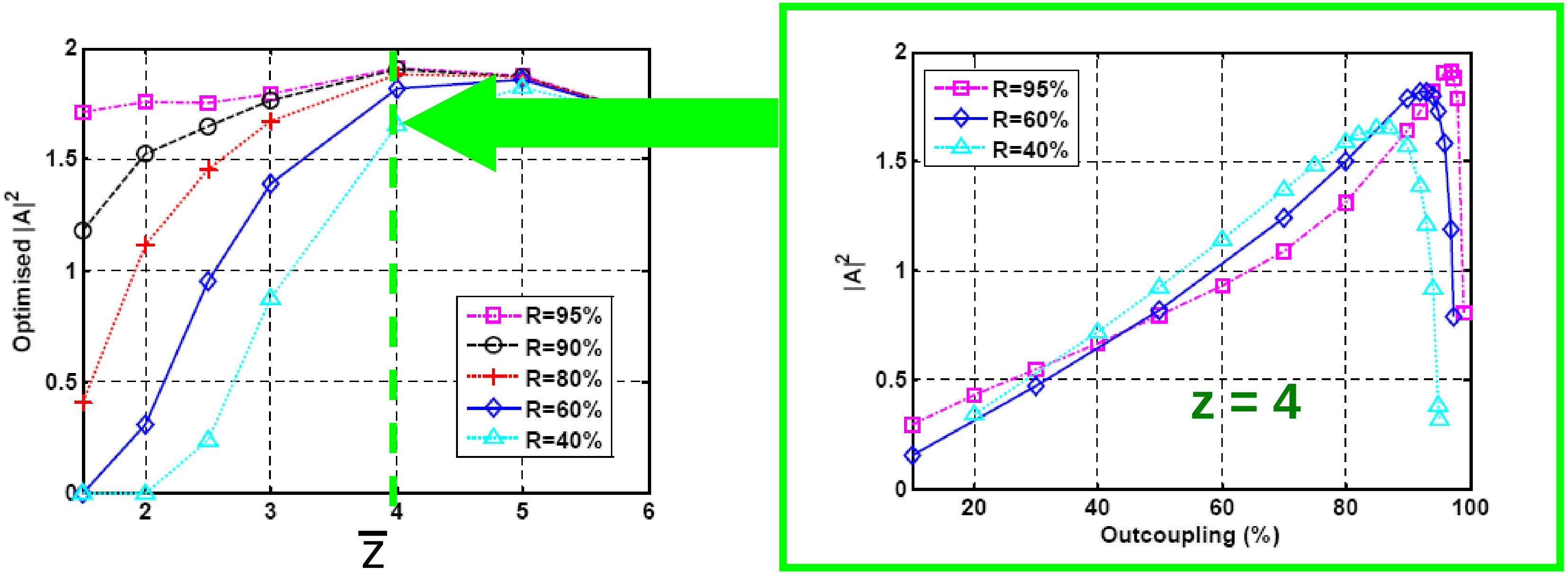
The Output Requirements of the 4GLS VUV-FEL:

- **4GLS Science Case**
  - 3-10eV photons
    - *Rules out High-Q oscillator: no high reflectivity broadband optics at 10eV*
  - Temporal coherence and pulse-to-pulse stability (rms variations < 10%)
    - *Rules out SASE FEL*
  - High Repetition Rate (MHz) to match spontaneous sources on ERL
    - *Rules out external seeding*

- In principle, these requirements can be met by a ***RAFEL***

How we determined Required Gain and Reflectivity

Analysis of cavity FEL via 1D simulations using FELO*

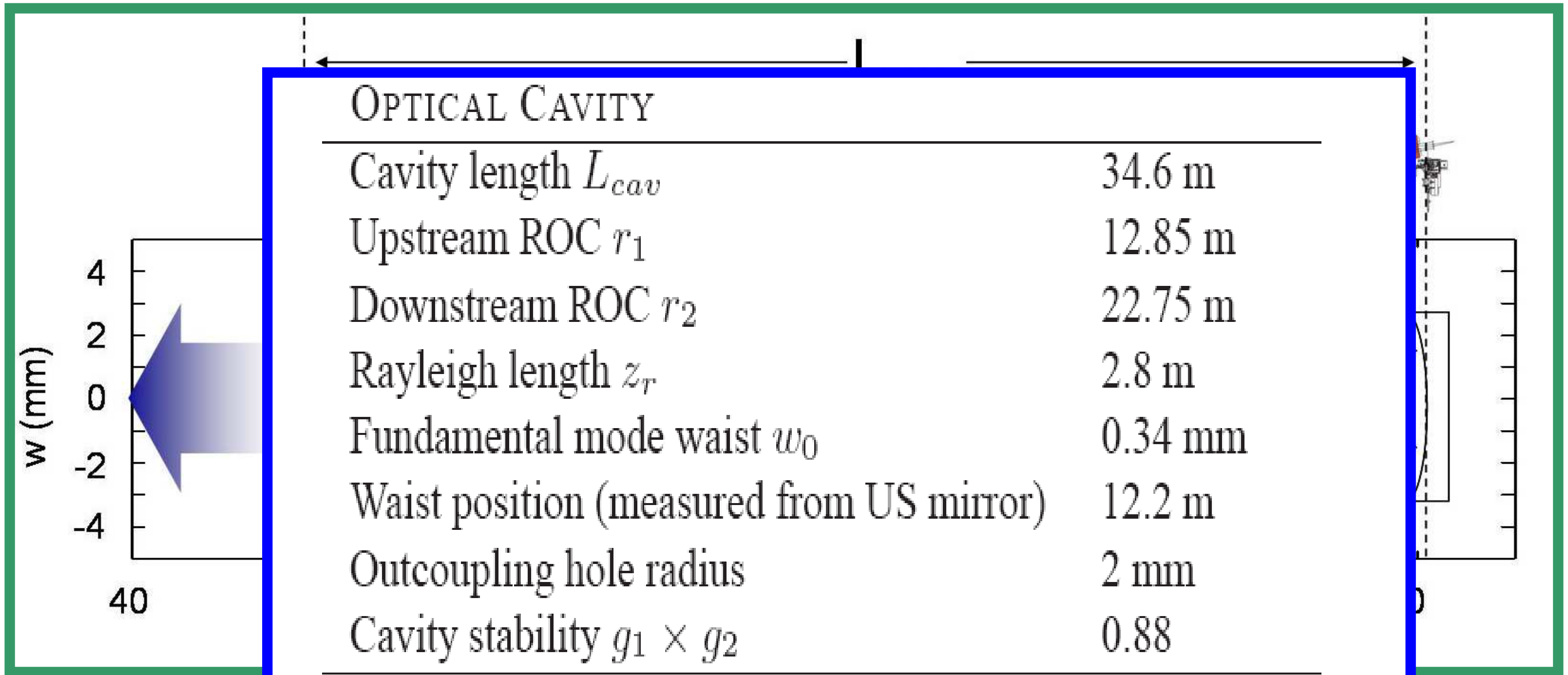


- Assuming $\bar{z}$ = 4, higher reflectivity gives slightly higher max output power, but is more sensitive to outcoupling.

Choose electron beam and undulator parameters to give **z = 4**,
choose **R = 60%** (feasible for 10eV photons with fluoride coated Al),
outcoupling = 75% (stability)

*McNeil B W J, Robb G R M, Dunning D and Thompson N R 2006 *Proc. 28th Int. Free Electron Laser Conf.* (*Berlin, Germany*) pp 59–62 Joint Accelerator Conferences online at http://www.jacow.org

How to achieve 75% outcoupling



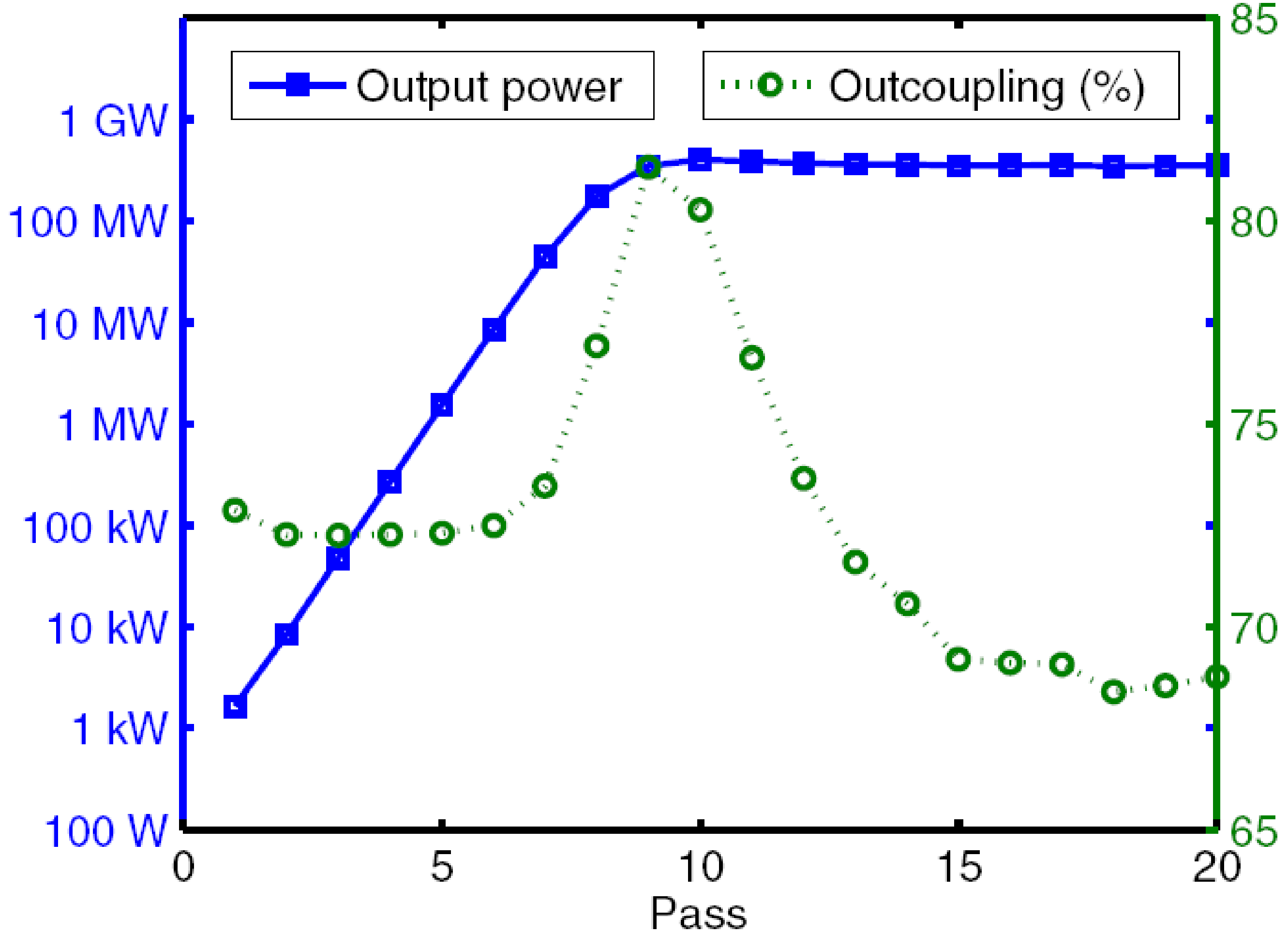
OPTICAL CAVITY	
Cavity length L_{cav}	34.6 m
Upstream ROC r_1	12.85 m
Downstream ROC r_2	22.75 m
Rayleigh length z_r	2.8 m
Fundamental mode waist w_0	0.34 mm
Waist position (measured from US mirror)	12.2 m
Outcoupling hole radius	2 mm
Cavity stability $g_1 \times g_2$	0.88

Hole radius set to outcouple ~75% of SR on first pass.
Rayleigh length set to give ~75% outcoupling for TEM_{00}.

Mirror ROCs set to give cold-cavity mode (TEM_{00}) fundamental waist at end of 1st undulator module (z=12m), maximising overlap over 1st and 2nd modules

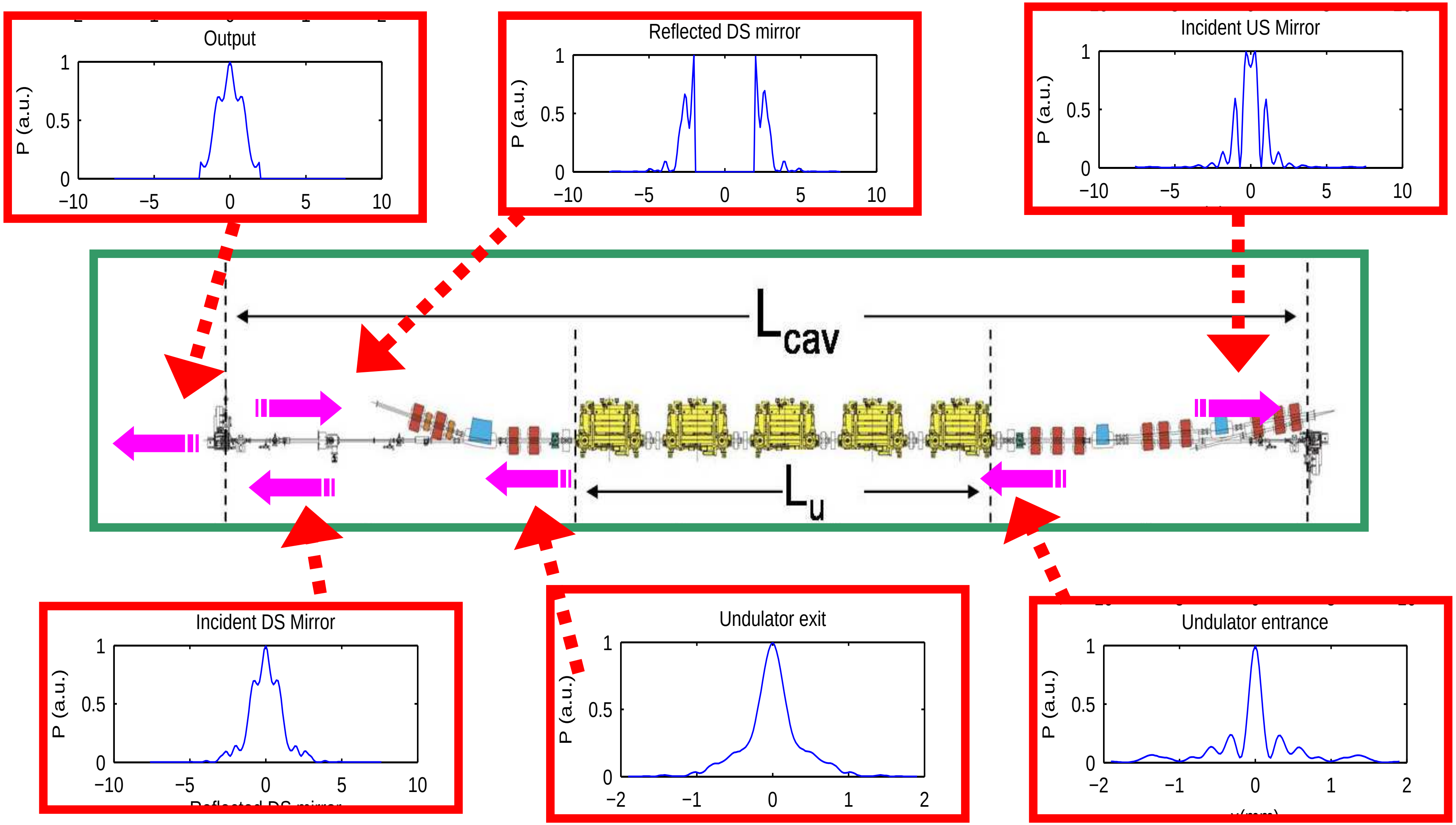
*Power and Outcoupling Evolution: Genesis/OPC**

Translating 1D parameters & cavity design into full 3D simulations:



*Karssenberg J G, van der Slot P J M, Volokhine I V, Verschuur J W J and Boller K-J 2006 *J. Appl. Phys.* **100,** 093106 (2006)

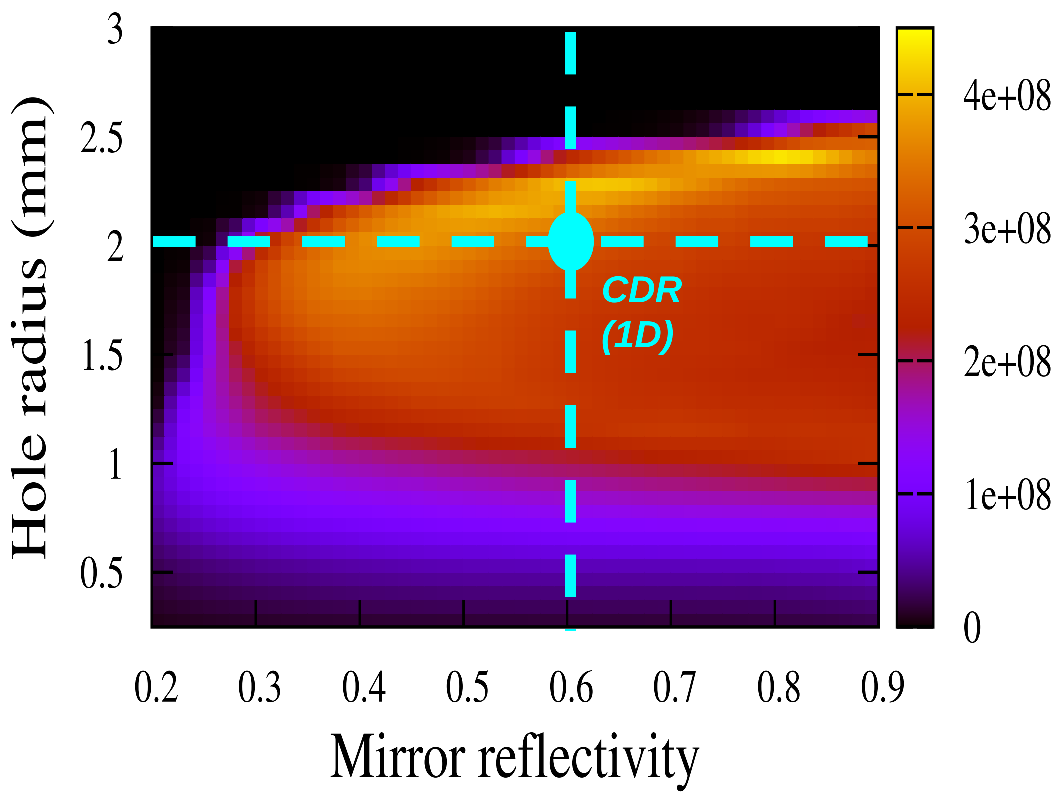
Transverse cross sections at Saturation: Genesis/OPC



Optimisation of CDR Cavity – 1D model = 3D MODEL

- Scans using Genesis/OPC of hole radius, mirror reflectivity and cavity geometry (changing mirror ROC to adjust waist radius and position of fundamental cold cavity mode).

OUTPUT POWER (W)

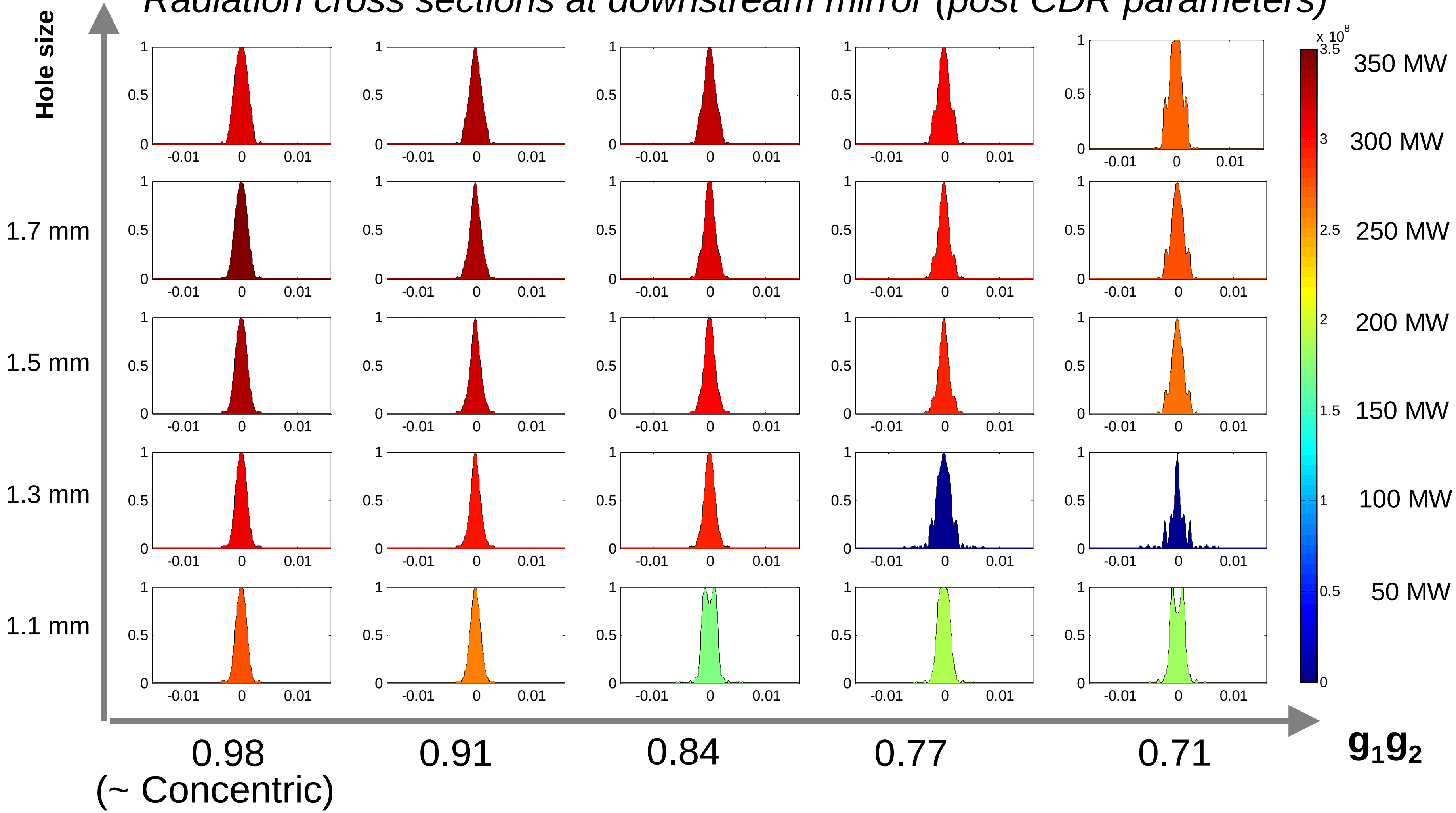


Example: Hole Radius Vs R:

- Output power relatively INSENSITIVE to reflectivity
- Reflectivity REDUCTION gives small power INCREASE
- Consistent with 1D simulations

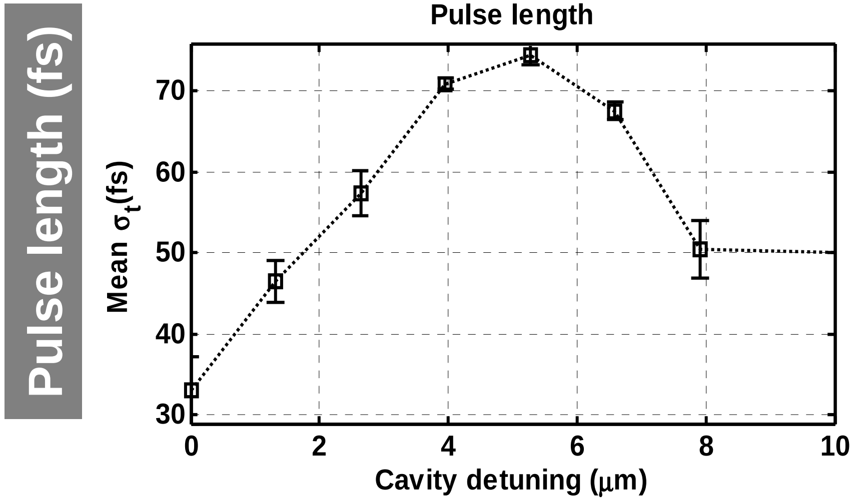
RAFEL Sensitivity to Cavity Geometry – No cold cavity modes

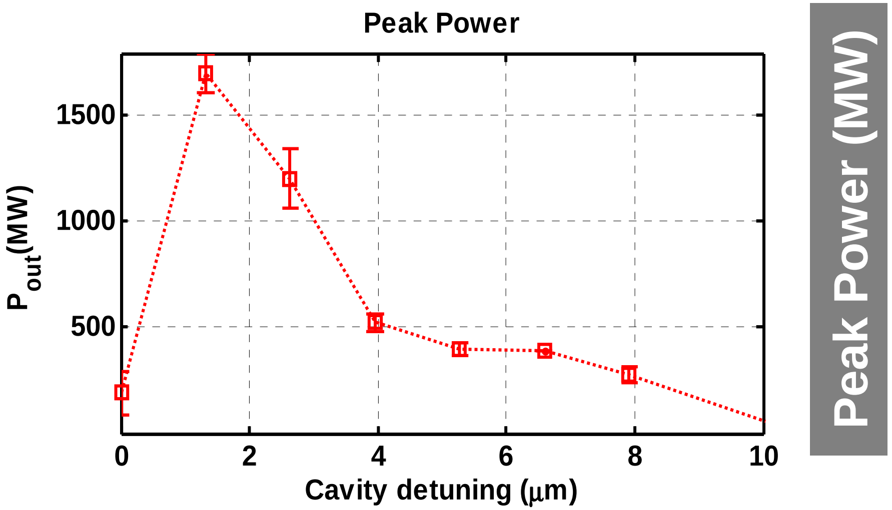
Radiation cross sections at downstream mirror (post CDR parameters)

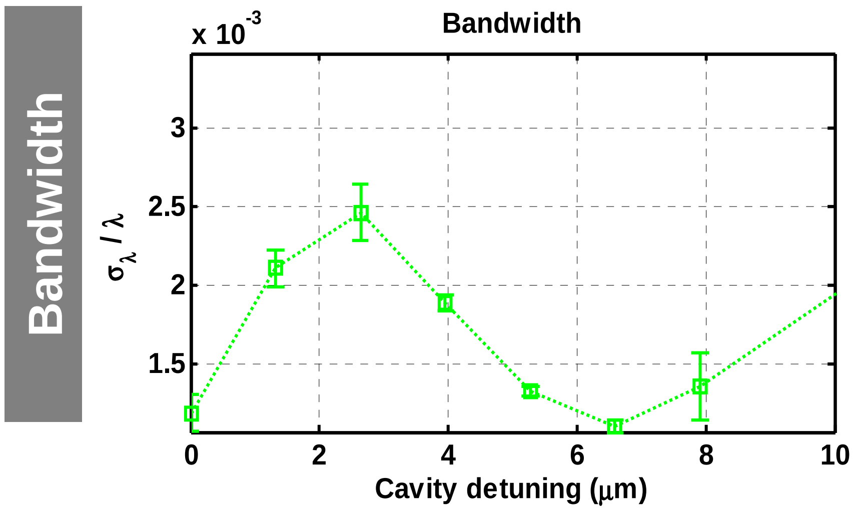


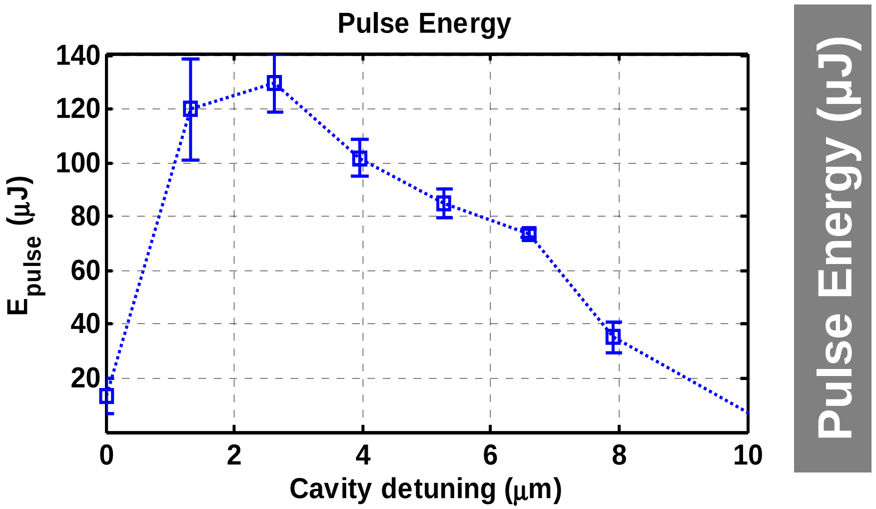
TEM$_{00}$ mode varies by factor > 2 over this range of g_1g_2

Cavity detuning : 10eV Planar Polarisation – 1D model

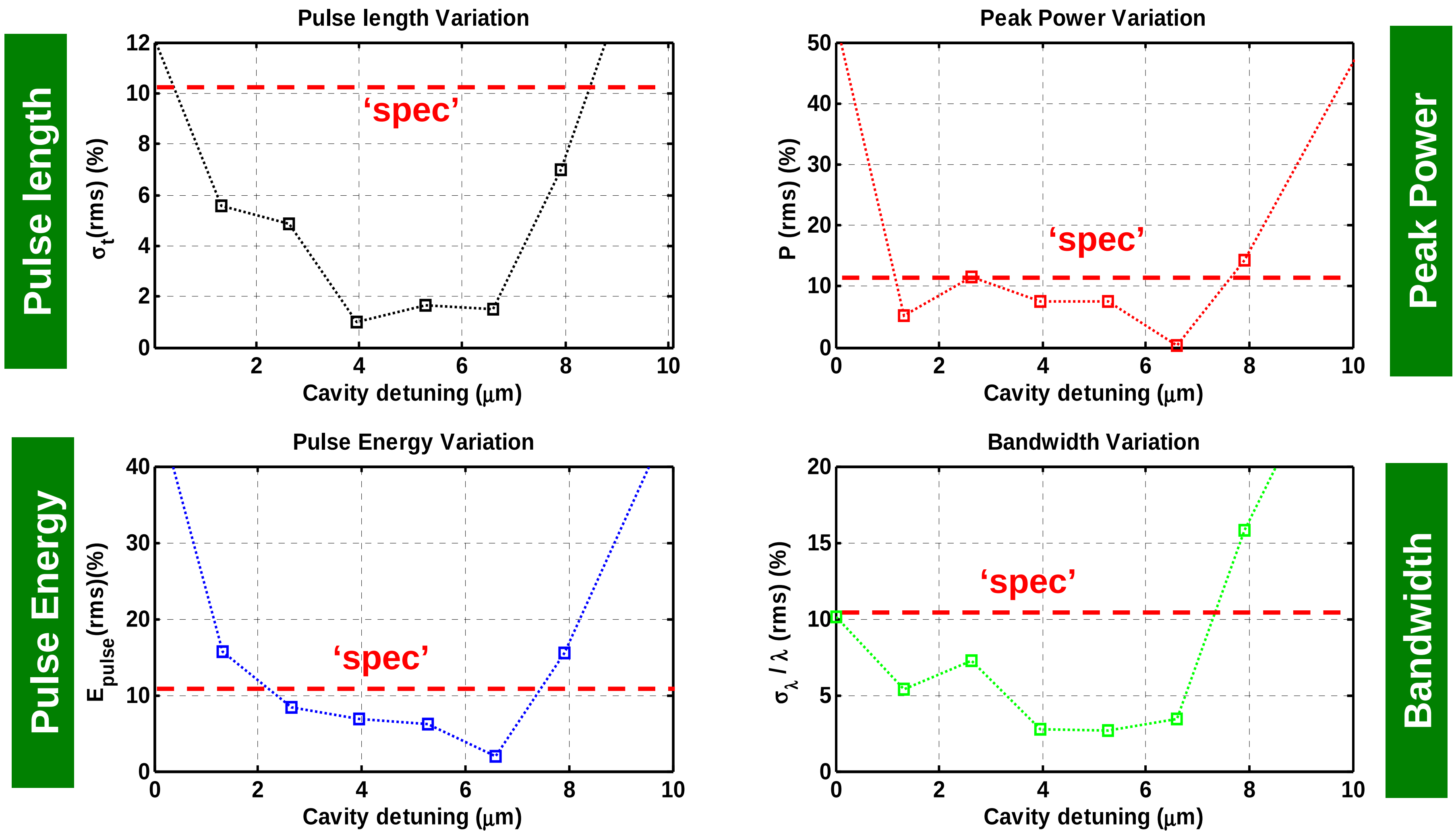








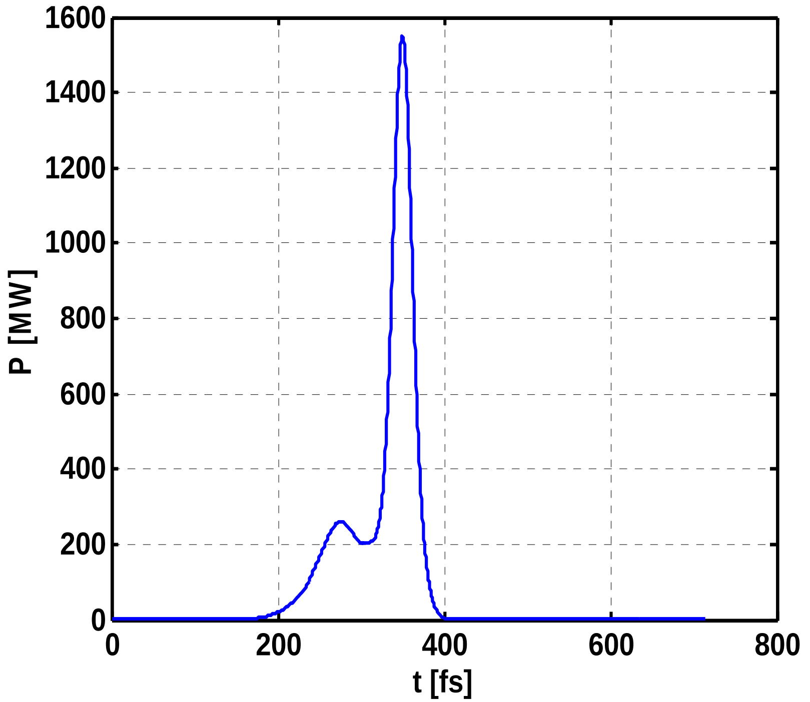
Stability rms Variation: 10eV Planar Polarisation



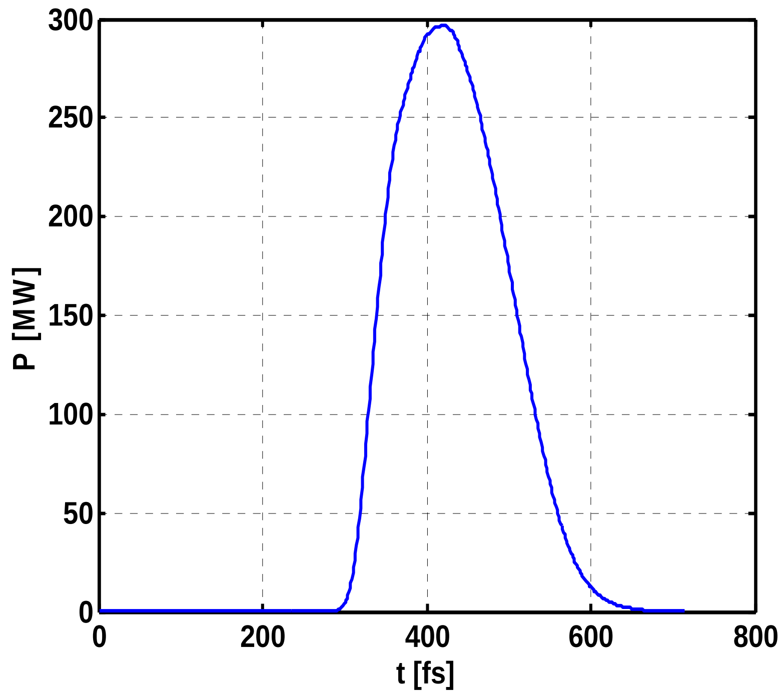
Number in ensemble = 200

1D time dependent simulations: Typical Pulses

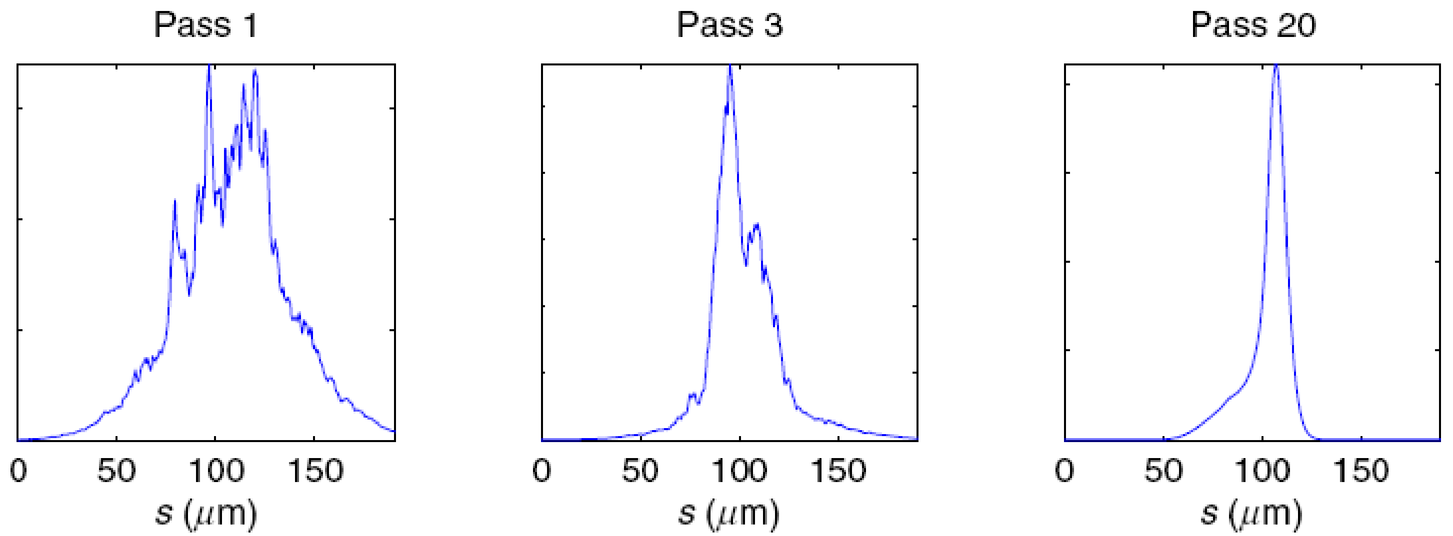
Near-Synchronous Optical Cavity
‘superradiant’

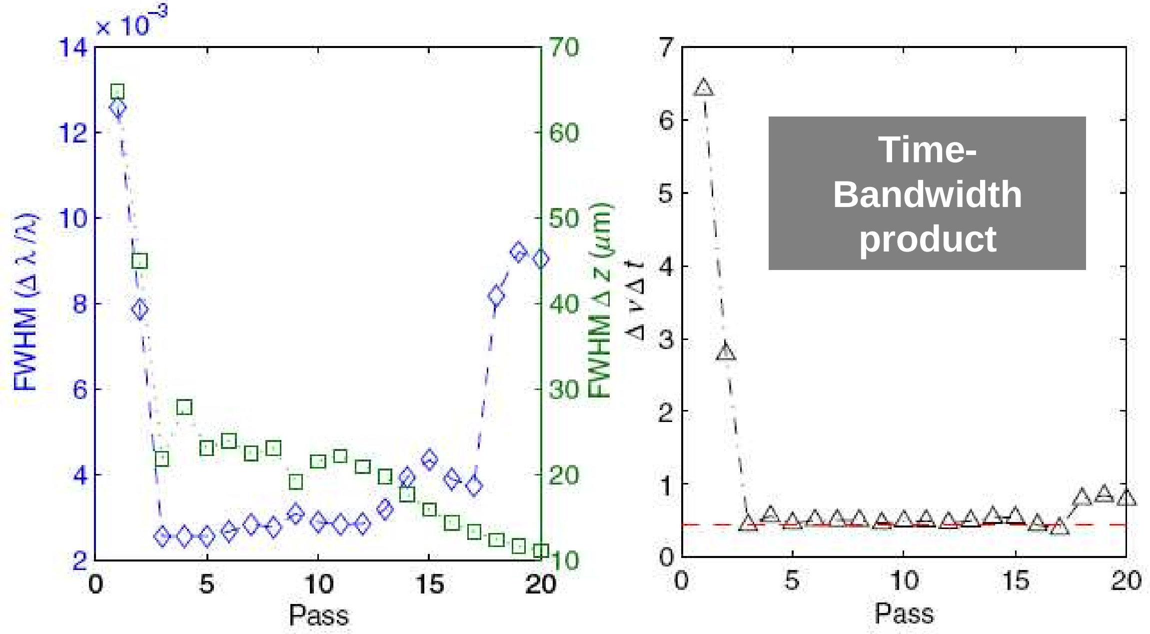


Detuned Optical Cavity
‘steady state’



3D Time Dependent Simulations: Genesis/OPC





Towards Shorter Wavelengths
An Ultra-Low Feedback System

The feasibility of an ultra low feedback system

- Consider a high gain system with ***very low feedback***
- ***Can such a system improve temporal coherence over SASE?***
- *Method*:
  - Simple analysis to find criterion relating **gain** and **feedback fraction** such that shot-noise power is dominated and ***temporal coherence improved***
  - 1D steady state simulations to find criterion relating **gain** and **feedback fraction** such that ***output power is maximised***
  - How do the two criteria compare?
  - Choose a gain such that feedback of F ~ 1×10^{-5} (***4 orders of magnitude less than for 4GLS VUV-FEL***) satisfies criteria and model RAFEL in 1D time dependent code that solves the Universally Scaled FEL equations

FEL Equations in The Universal Scaling

$$\frac{d\theta_j}{d\bar{z}} = p_j,$$
$$\frac{dp_j}{d\bar{z}} = -(A(\bar{z},\bar{z}_1)\exp[i\theta_j] + c.c.)$$
$$\left(\frac{\partial}{\partial\bar{z}} + \frac{\partial}{\partial\bar{z}_1}\right)A(\bar{z},\bar{z}_1) = \chi(\bar{z}_1)\langle\exp[-i\theta]\rangle \equiv b(\bar{z},\bar{z}_1)$$

θ **= Particle phase in ponderomotive bucket**

$p = (\gamma - \gamma_r)/\rho\gamma$ **= Particle energy**

γ_r = Resonant energy in units of electron rest mass

ρ = FEL parameter

A **= Complex field**

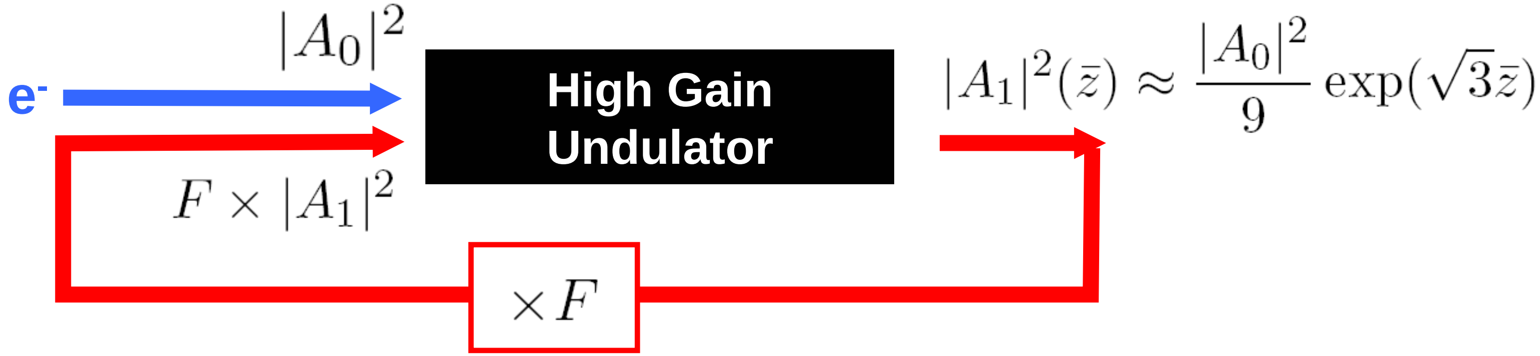
$\bar{z} = 2k_w\rho z$ **= Interaction length**

$\bar{z}_1$ **= Particle position in units of cooperation length**

$$l_c = \lambda_r/4\pi\rho$$

$\chi(\bar{z}_1)$ = Current profile

Feedback Required to Dominate Shot Noise at Start up



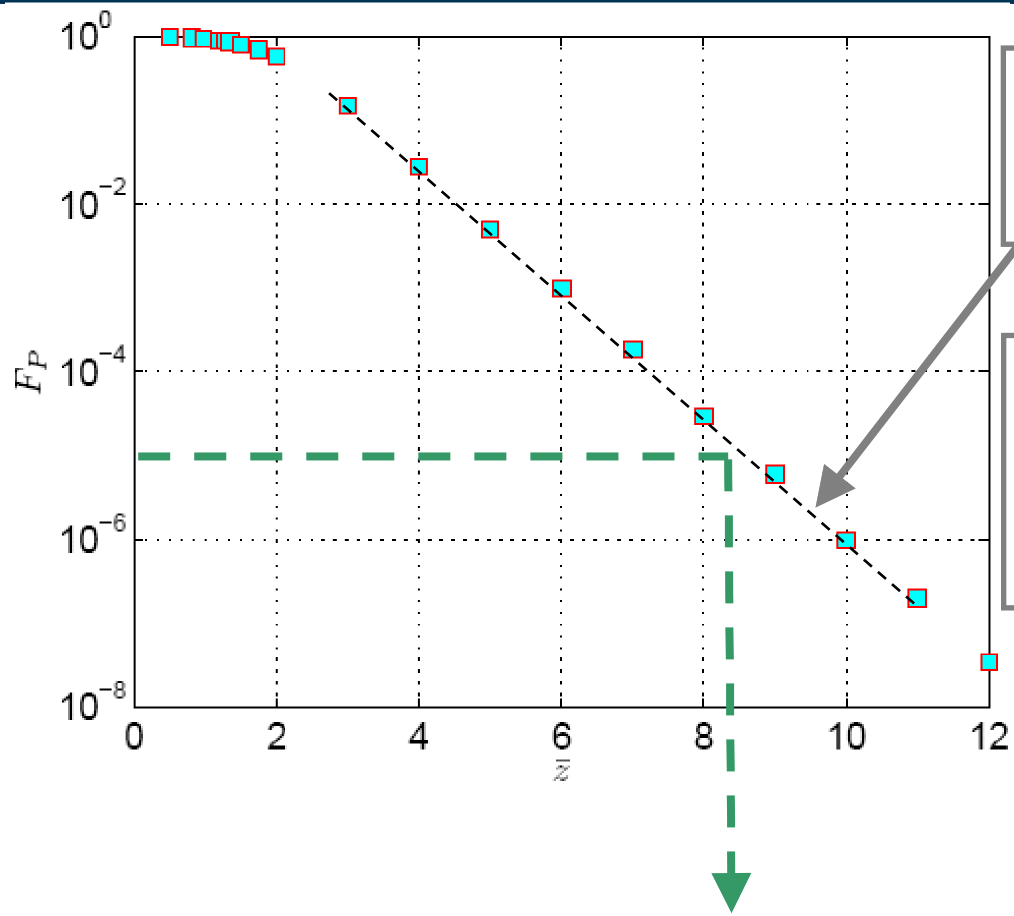
Condition for radiation fed back to start of undulator to dominate electron beam shot noise:

$$F \times |A_1|^2 > |A_0|^2$$

This gives feedback factor to dominate noise:
(also just criteria for growth)

$$\boxed{F_N > 9\exp(-\sqrt{3}\bar{z}).}$$

Feedback Required To Optimise Saturation Output Power



To optimise saturation power:

$$F_{opt} = 25\exp(-1.7\bar{z}), \quad 3 \leq \bar{z} \leq 12$$

To feed back greater than the noise power:

$$F_N > 9\exp(-\sqrt{3}\bar{z}).$$

$$\boxed{F_{opt} \simeq 3F_N}$$

For feedback of 1×10^{-5} need:

$$\bar{z} = 8.67$$

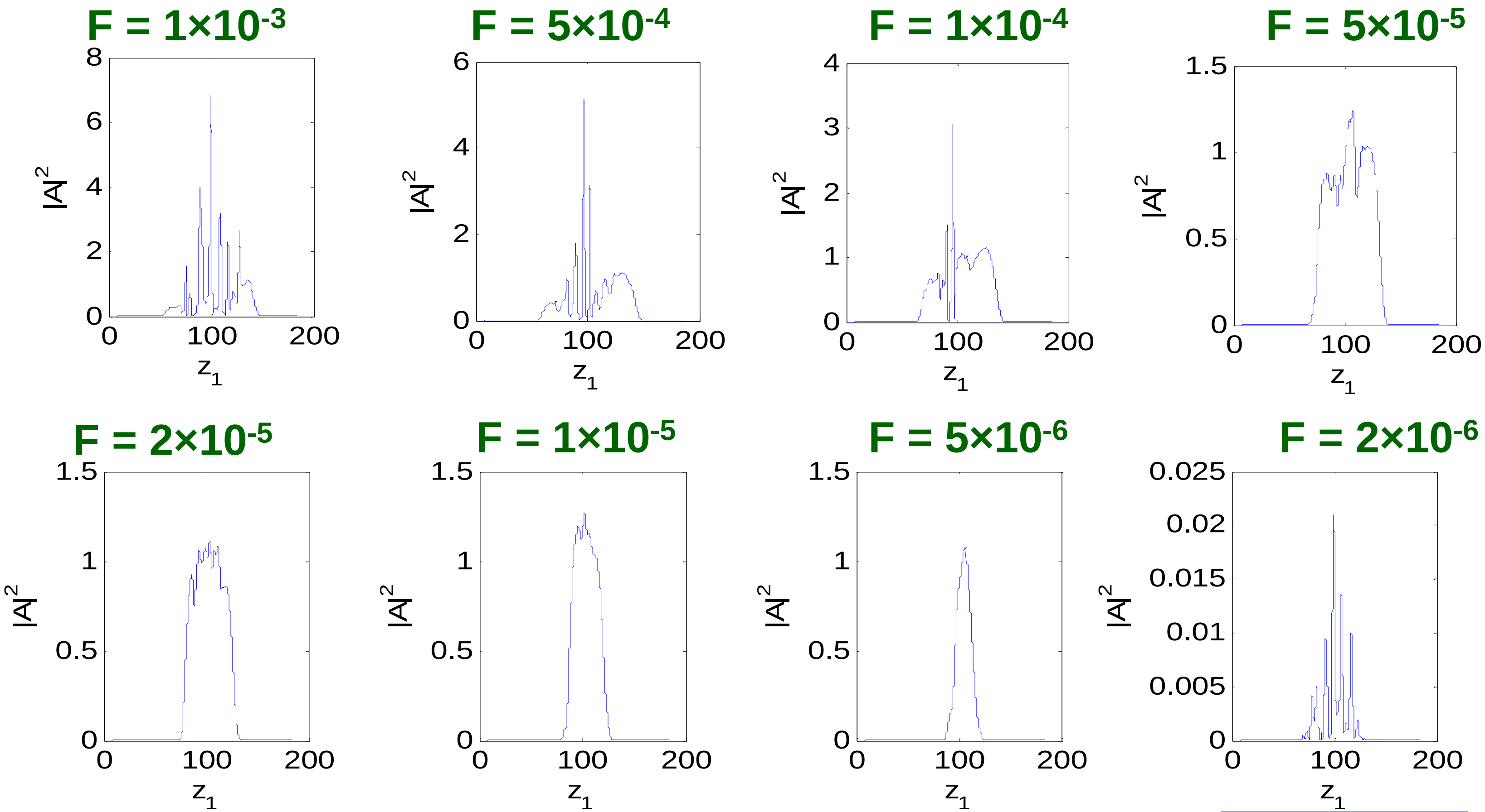
1D Simulation Code and Parameters – ultra low feedback

- Used one-dimensional time-dependent FELO code
    - Shot noise start-up
    - Cavity detuning
    - Temporal jitter
    - SDDS compliant
- FEL parameter $\rho = 2.9\times10^{-3}$, typical for an XUV system
- Gaussian electron bunch
- $z_{bar} = 8.67$ (for $F_{opt} = 10^{-5}$)
- Varied **feedback** from $F = 10^{-3}$ to 2×10^{-6}
- Varied **cavity detuning** from synchronous to detuned by 9 cooperation lengths
- For each parameter set analysed 200 post-saturation pulses
- 200 SASE runs (z_{bar}=14) for comparison.

1D Time Dependent Simulations: z = 8.67, δ_{cav}= 6 l_c

T-BW Product > SASE

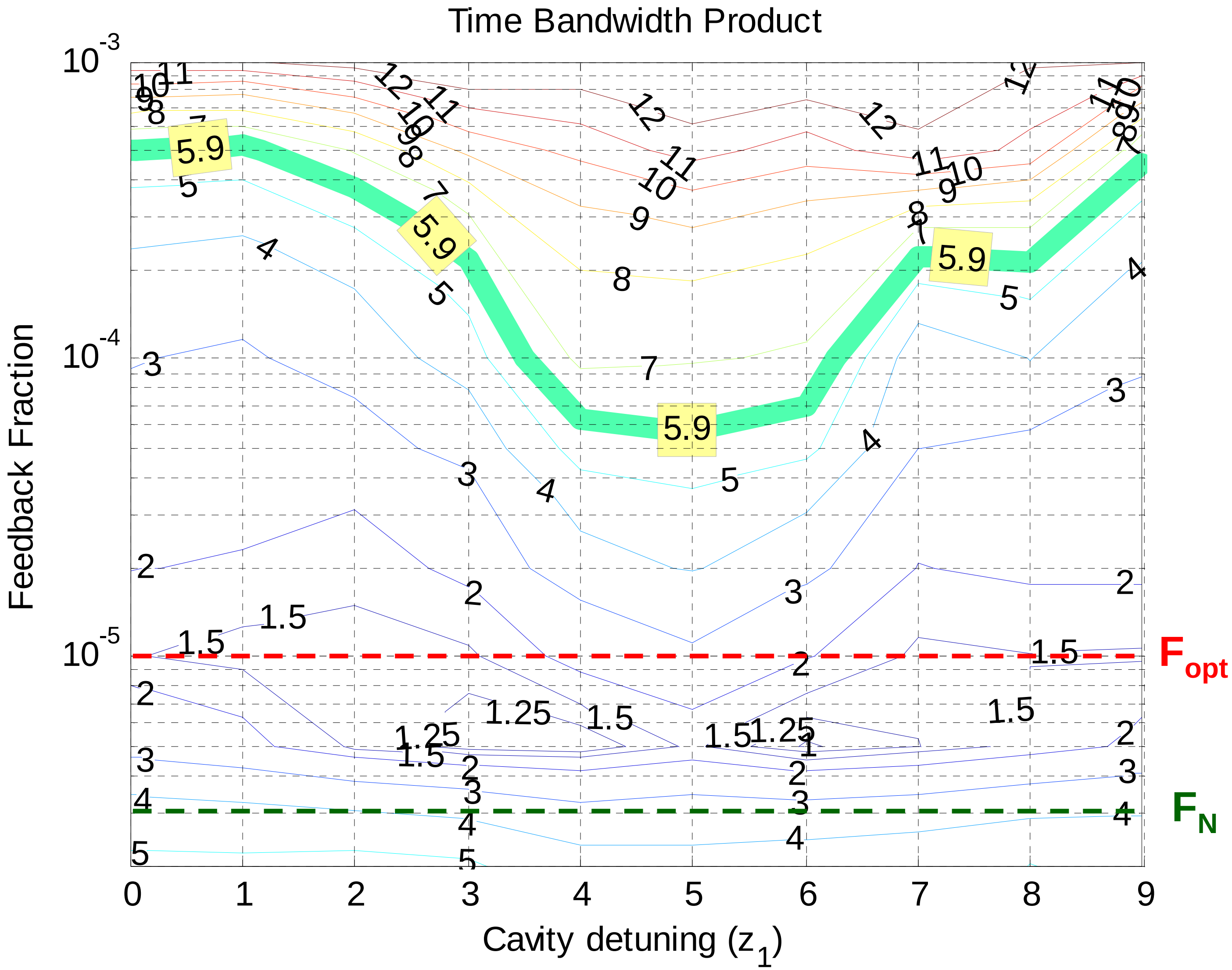
T-BW Product = SASE



T-BW Product < SASE

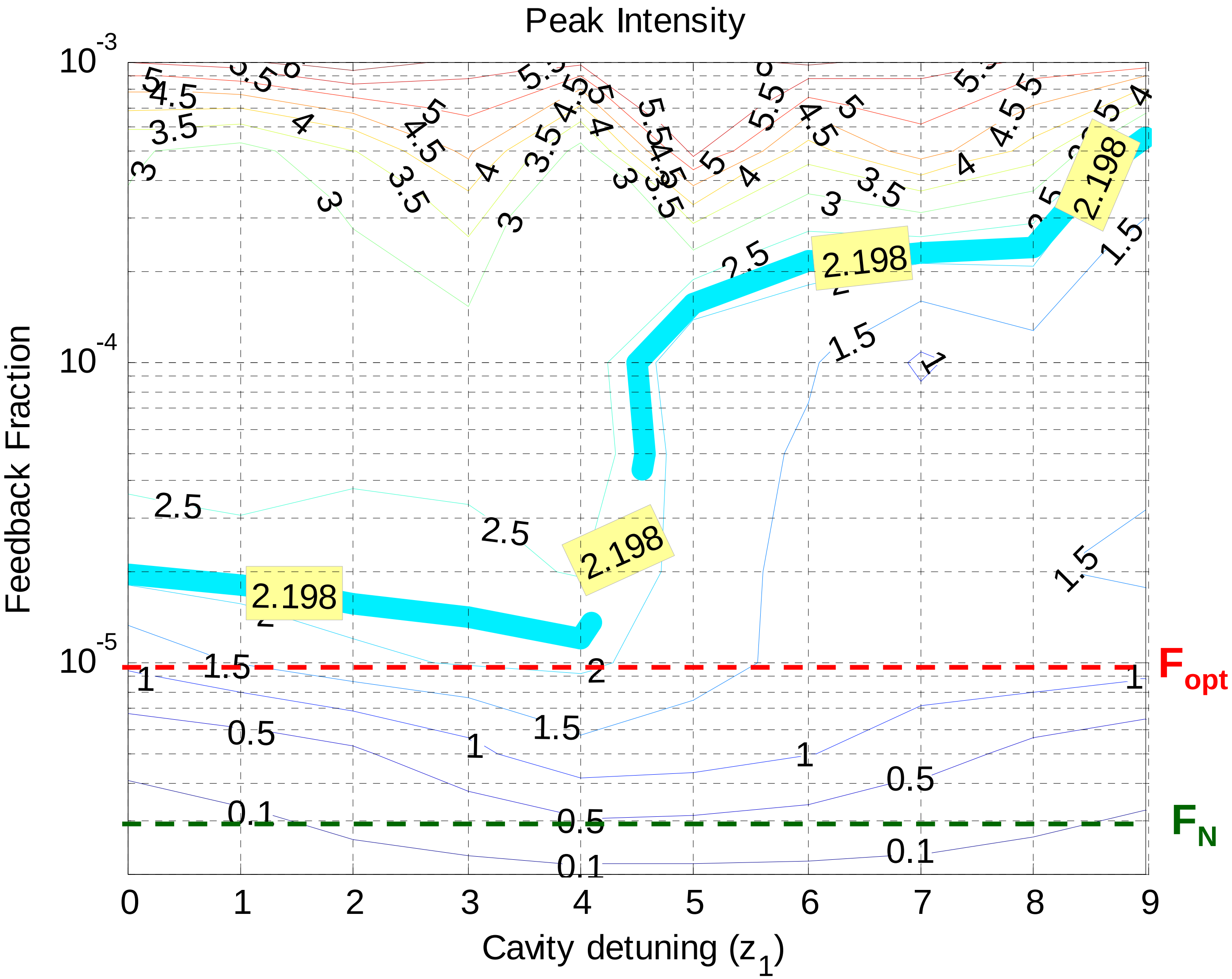
T-BW Product = SASE

Time Bandwidth Product (averaged over 200 saturated passes)



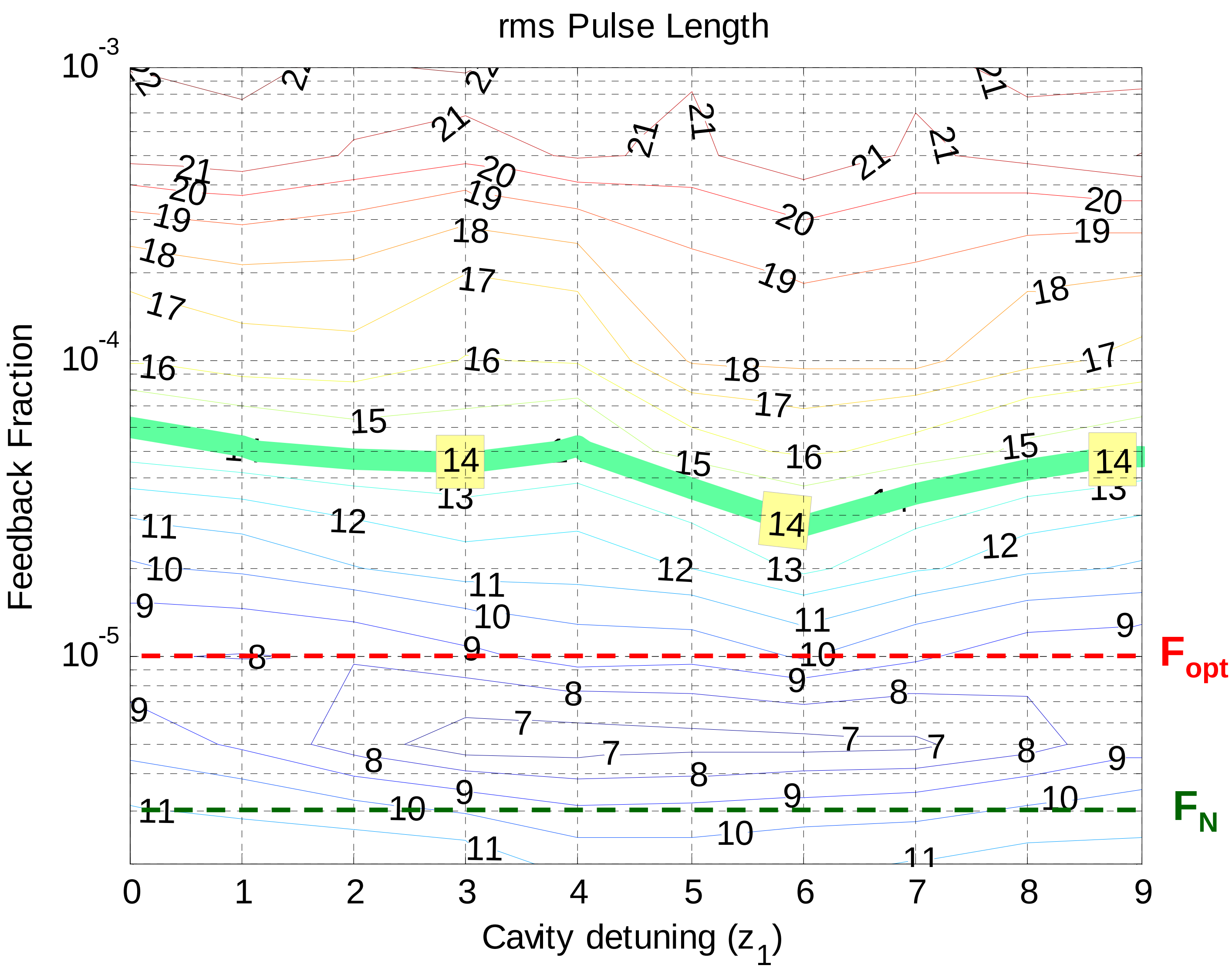
BOLD CONTOUR = SASE

Peak Intensity (averaged over 200 passes)



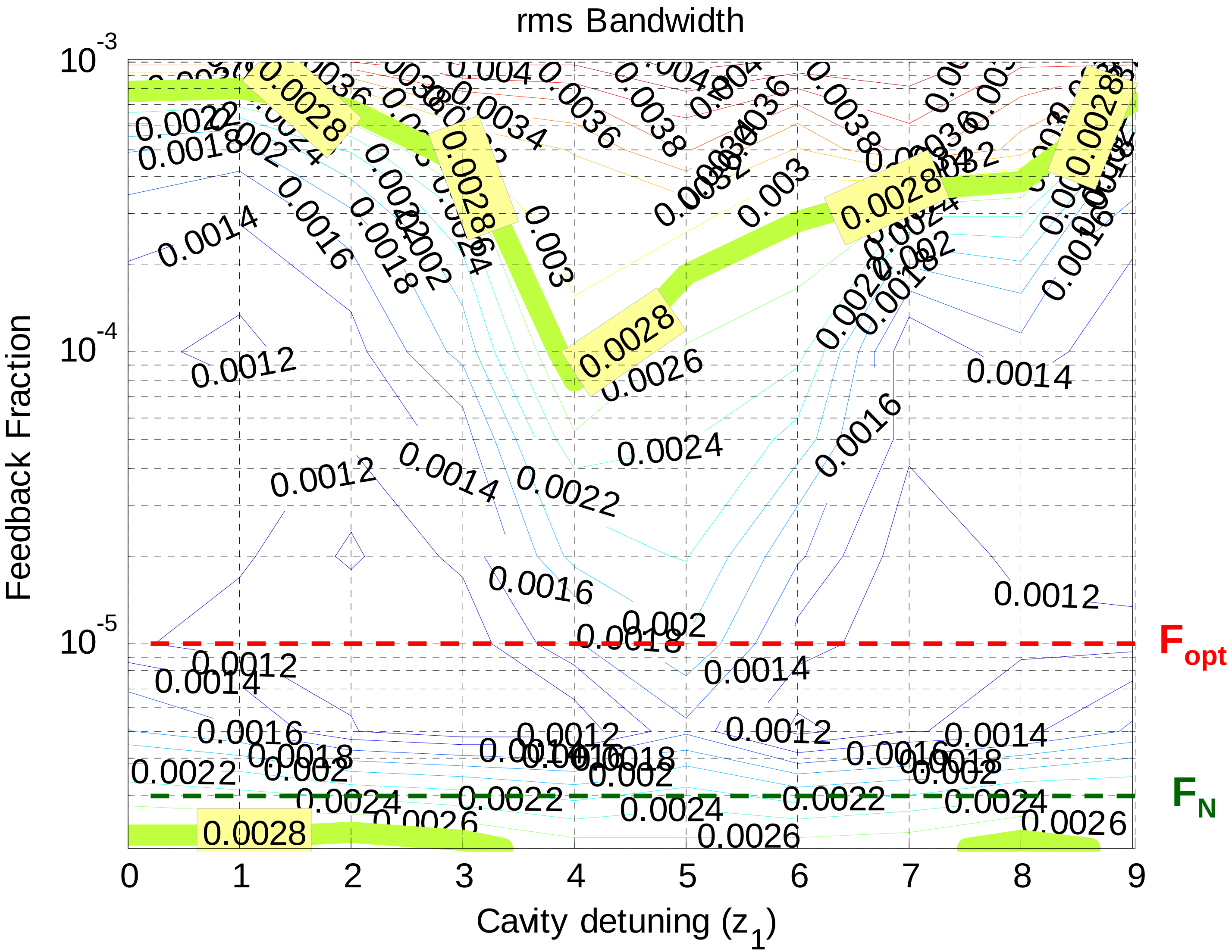
BOLD CONTOUR = SASE

RMS Pulse Length (averaged over 200 passes)



BOLD CONTOUR = SASE

RMS Bandwidth (averaged over 200 passes)



BOLD CONTOUR = SASE

Conclusions and Issues

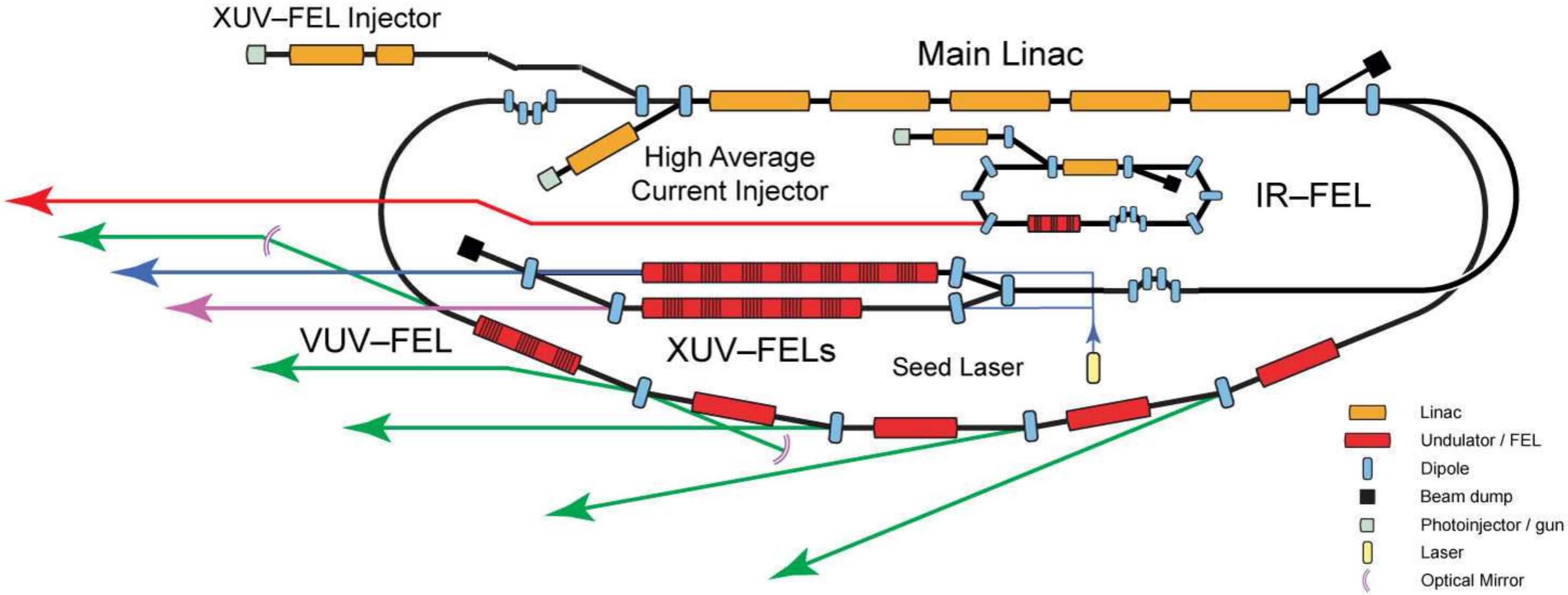
- The properties of the RAFEL have been introduced
- 4GLS VUV-FEL used as an example, to illustrate properties
- Issues for 4GLS VUV-FEL:
  - *Optics!*
    - Degradation of mirror surfaces: currently testing samples
    - Coping with thermal distortion of mirror surfaces:
      - FEA analysis of mirrors underway.
      - Upgrade of OPC code to deal with distorted surfaces in progress
- Shown 1D simulations of generic RAFEL with ultra low feedback producing temporally coherent pulses
  - Potential for short wavelengths: XUV and beyond?
- Issues for ultra low feedback RAFEL:
  - *Optics!*
    - What combinations of materials and geometries can be used to obtain the required feedback fractions in a controllable way?

Science & Technology
Facilities Council

Thank you

Extra Material.........

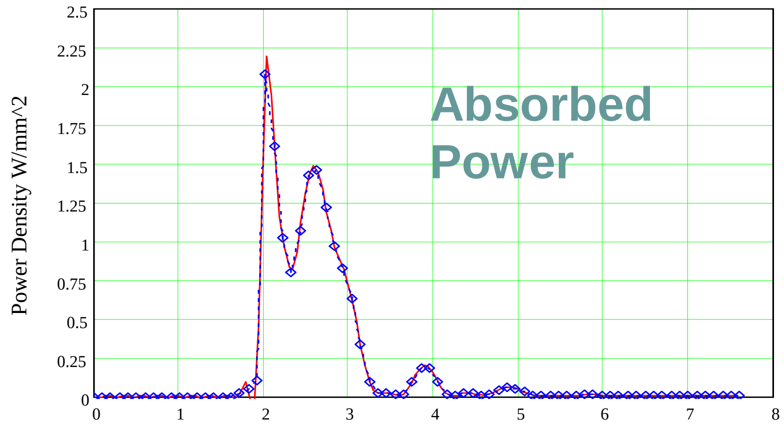
4GLS Layout

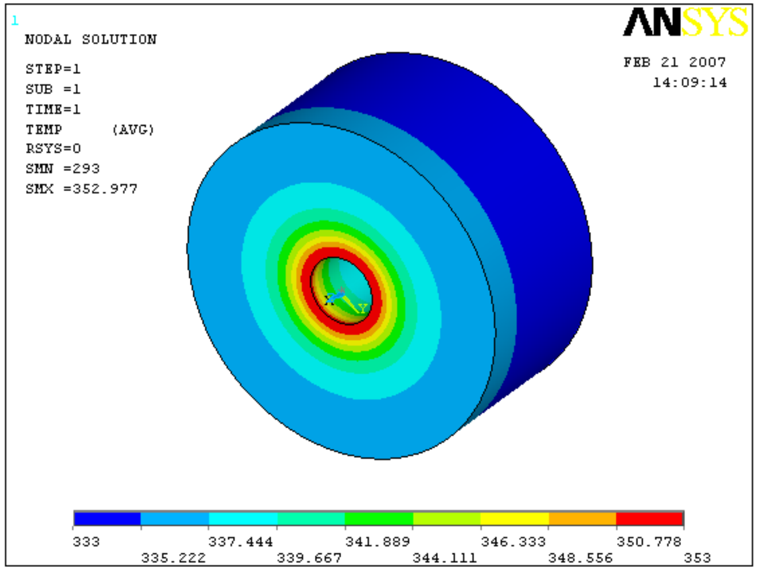


XUV–FEL Injector
Main Linac
High Average
Current Injector
IR–FEL
VUV–FEL
XUV–FELs
Seed Laser
Linac
Undulator / FEL
Dipole
Beam dump
Photoinjector / gun
Laser
Optical Mirror

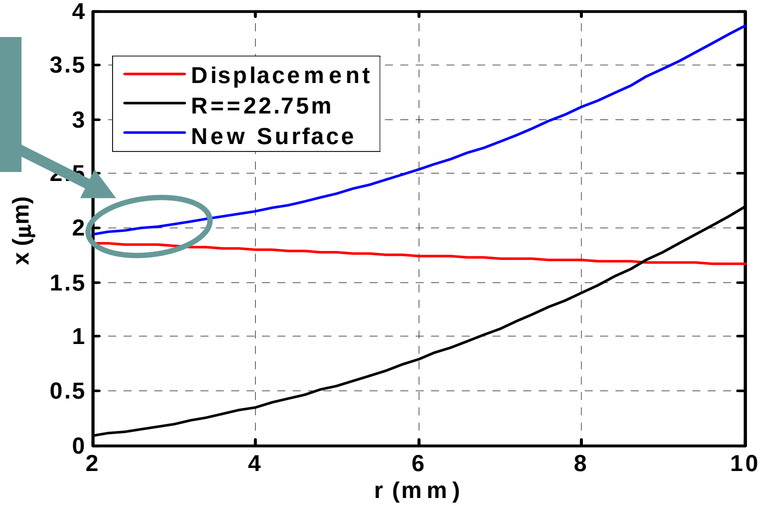
Thermal Loading: FEA Analysis of Outcoupler

- **Average absorbed power = 24W (Doesn't sound much ~ a light bulb)**
  - **Radiative cooling only: ΔT~700K!**
  - **Forced cooling: ΔT~80K**
- **ROC change over 1mm strip around hole: 22.75m to 70m!**





Fitted ROC = 70m



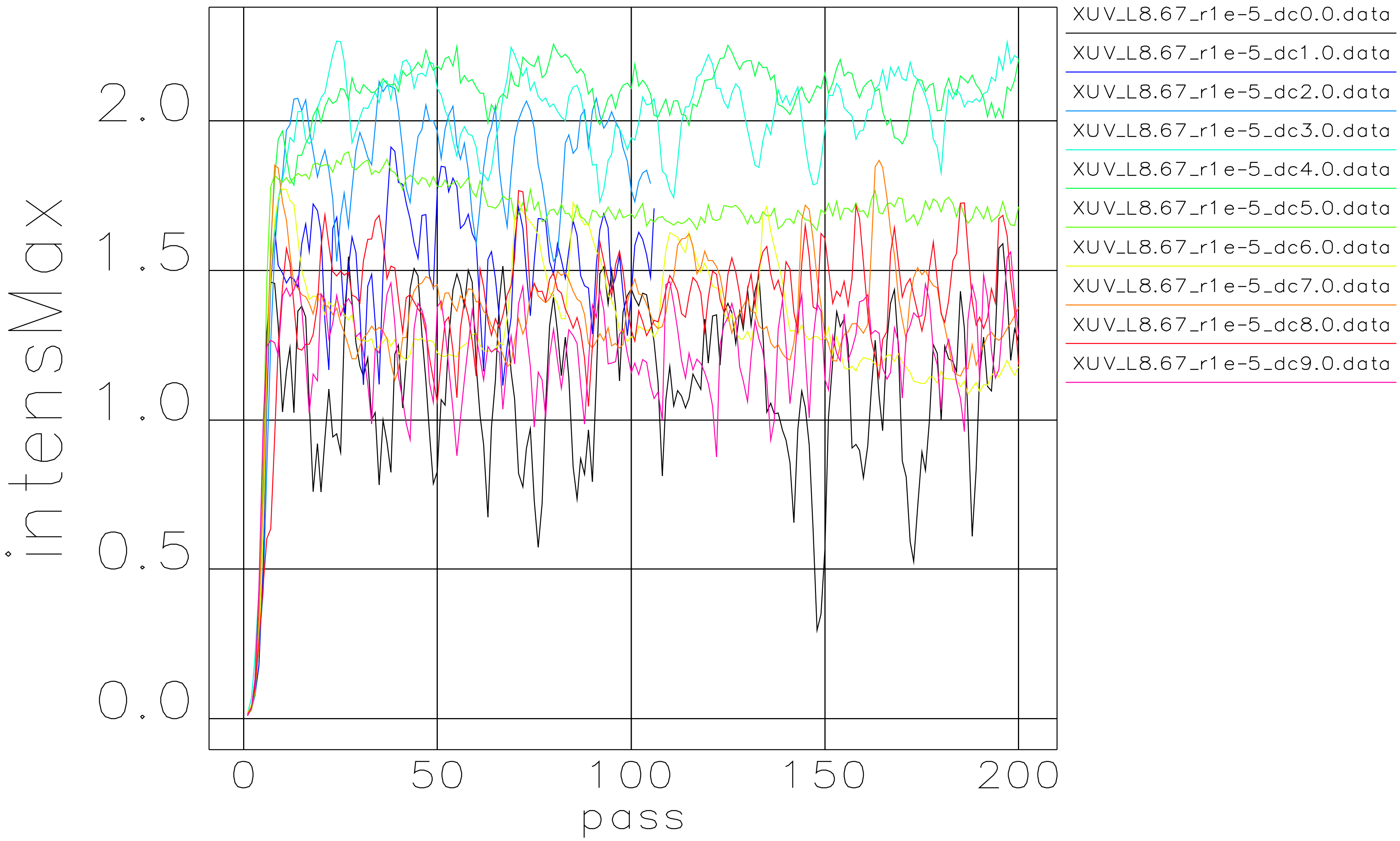
Thermal Loading: Possible Solutions

- Adaptive optics
  - a deformable outcoupler allowing adjustable ROC
- *Cryo-cooling outcoupler*
  - *At -149 ℃ coefficient of thermal expansion for sil icon is zero*
- *Pinch electron beam near end of undulator*
  - *reduced source size gives stronger diffraction hence lower power density on mirror*
- *Compensate for expected distortion by making anti-deformed mirror*
- *????...*

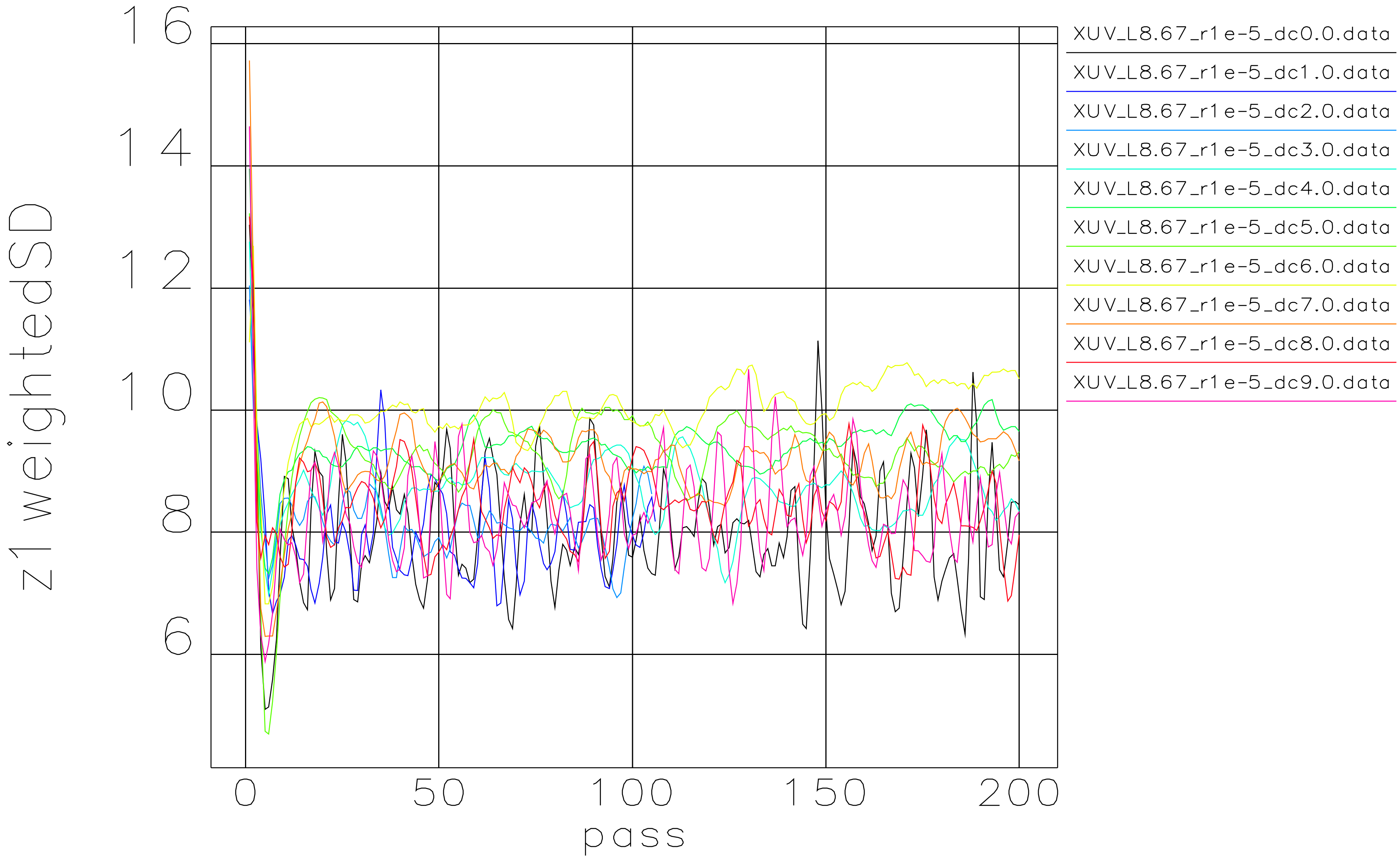
Summary of Possible Output for 4GLS VUV-FEL:

	3 eV	***10 eV***
Peak Power	300 MW – 5 GW	300 MW – 4 GW
Pulse Energy	80 – 250 μJ	40 – 230 μJ
Average Power	350 – 1100 W	175 – 1000 W
Pulse Length (rms)	35 – 75 fs	45 – 100 fs
Bandwidth (rms)	$2 \times 10^{-3} – 1 \times 10^{-2}$	$1 \times 10^{-3} – 5 \times 10^{-3}$
Time Bandwidth Product (gaussian = 0.44)	0.5 – 3.0	0.5 – 6.0

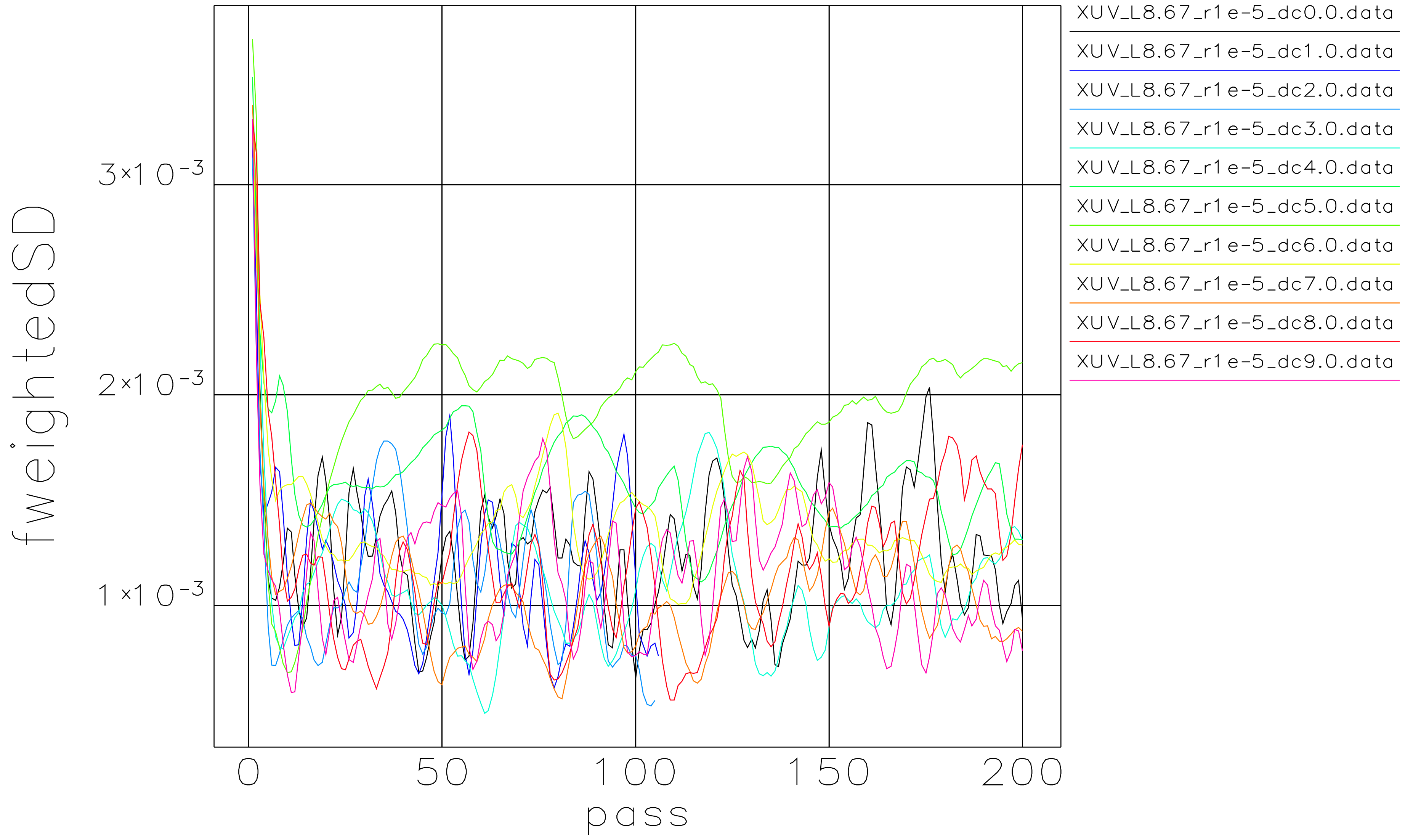
Peak Intensity (evolution over 200 passes): F = 1×10^{-5}



Pulse length (evolution over 200 passes): F = 1×10^{-5}



Bandwidth (evolution over 200 passes): F = 1×10^{-5}



Bandwidth (evolution over 200 passes): F = 1×10⁻⁵