Short Wavelength
Regenerative Amplifier FELs (RAFELs)

Neil Thompson, David Dunning
ASTeC, Daresbury Laboratory, Warrington UK

Magnetics and Radiation Sources Group

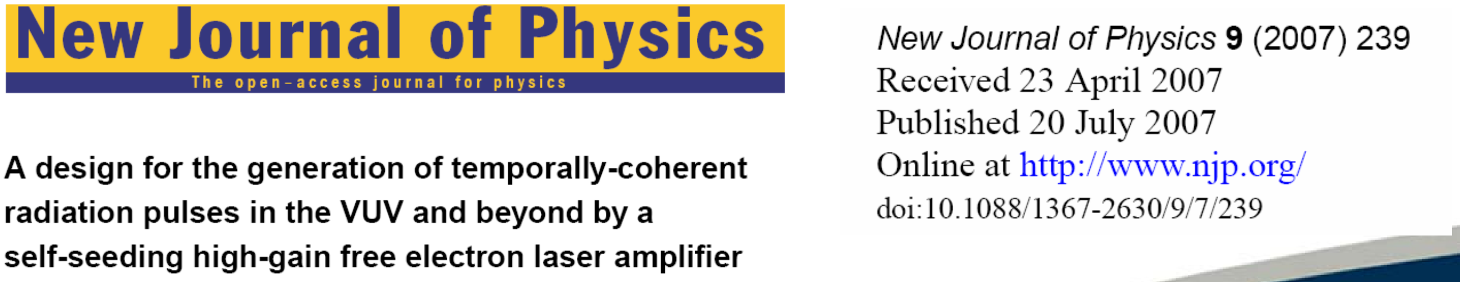
Brian McNeil
Strathclyde University, Glasgow, UK

Jaap Karssenberg & Peter van der Slot
University of Twente, Enschede, The Netherlands

Contents

- What is a RAFEL?
- 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?

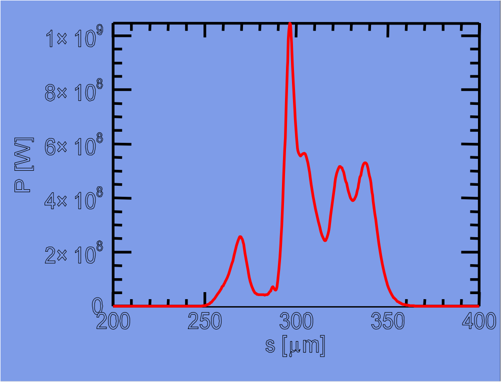
- A high-gain low feedback resonator FEL
  - Reaches saturation in a few passes
  - The resonator is high loss, or low feedback (or Low Q)
  - Low required feedback makes RAFEL candidate for short wavelengths
- Properties of resonator
  - Radiation not stored over many passes
  - Radiation does not propagate freely, but is gain guided
  - Cavity provides small seed field for next pass

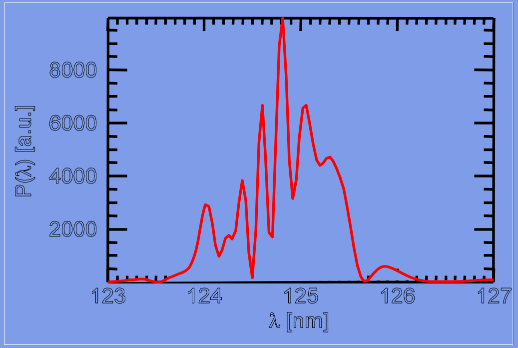
Also called SELF-SEEDING HIGH GAIN AMPLIFIER or LOW-Q CAVITY FEL

- Expected advantages of RAFEL
  - Performance should be less sensitive to mirror degradation
  - Small number of passes to saturation should relax longitudinal alignment tolerances
  - Feedback gives shorter undulator than SASE
  - Feedback averages out electron beam shot noise, improving temporal coherence

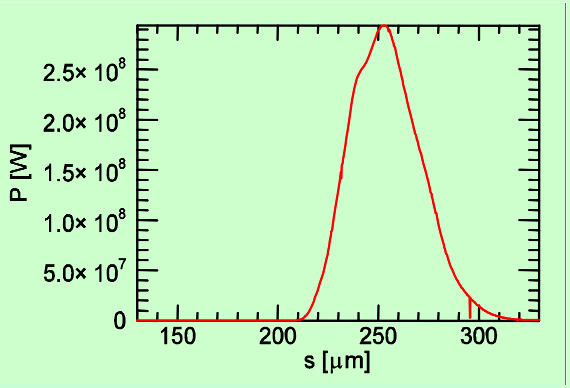
RAFEL Compared to SASE

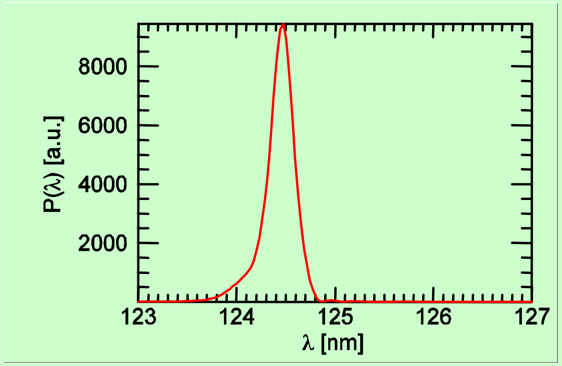
SASE





RAFEL





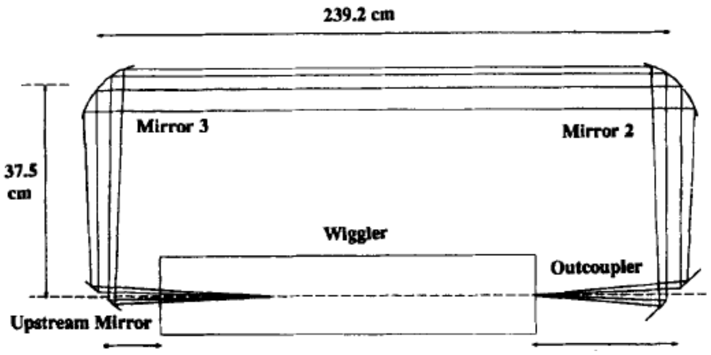
Previous RAFEL Experiments and Other Proposals

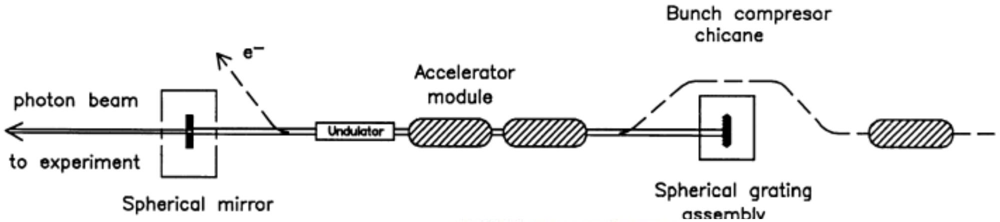
- High Gain Low Feedback concept
  McNeil B W J 1990 *IEEE J. Quantum Electron.* **26** 1124

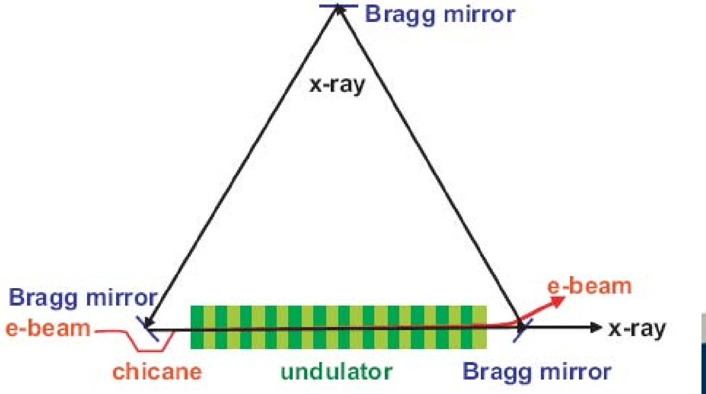
- Los Alamos IR-RAFEL
  Nguyen D C, Sheffield R L, Fortgang C M, Goldstein J C, Kinross-Wright J M and Ebrahim N A 1999 *Nucl. Instrum. Methods Phys. Res.* A **429** 125–30

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







Science & Technology
Facilities Council

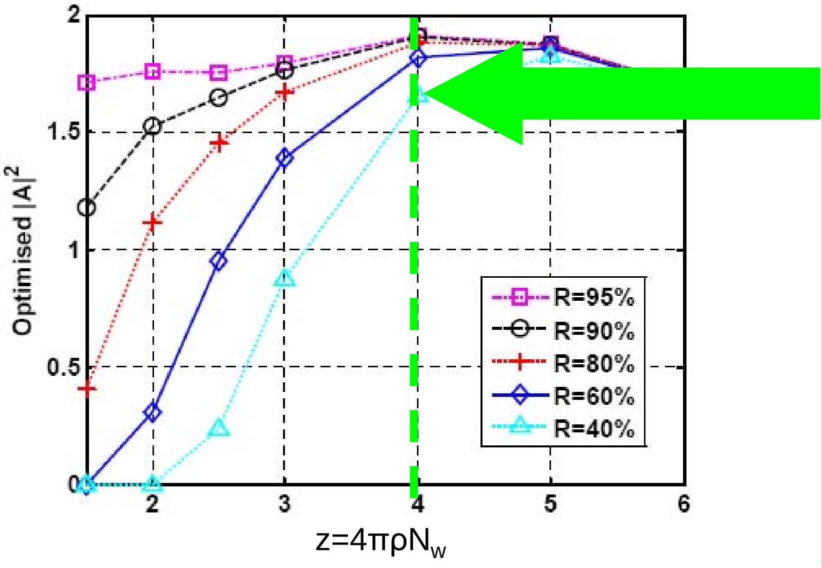
4GLS VUV-FEL:
An example of a current RAFEL proposal

Why we chose a RAFEL for 4GLS

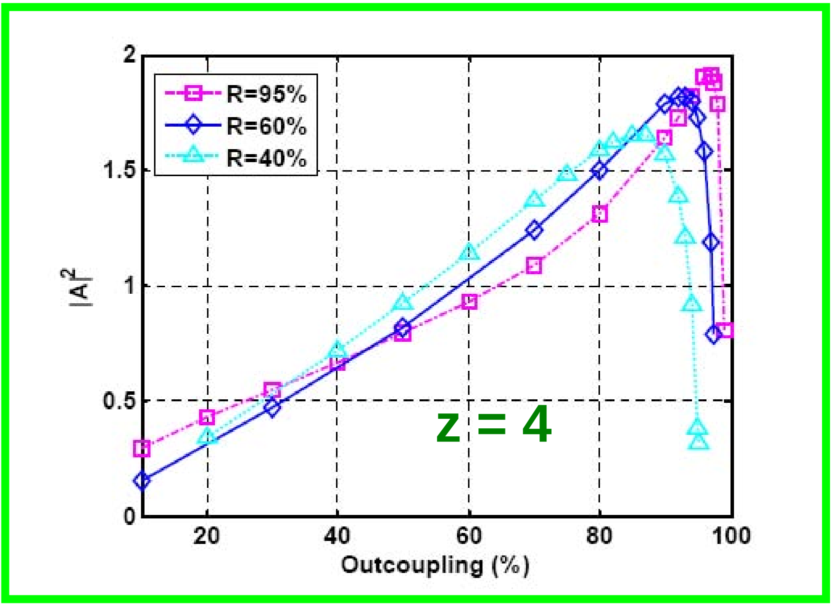
- The Output Requirements of the VUV-FEL, from the **4GLS Science Case**
  - 3-10eV photons
    - *Rules out High-Q oscillator: no high reflectivity broadband optics at 10eV*
  - Temporal coherence and pulse-to-pulse stability (rms variations < 10%)
    - *Rules out SASE FEL*
  - High Repetition Rate (MHz) to match spontaneous sources on ERL
    - *Rules out external seeding*
- But, all these requirements can be met by ***A RAFEL***

How we determined Required Gain and Reflectivity

Analysis of cavity FEL via 1D simulations



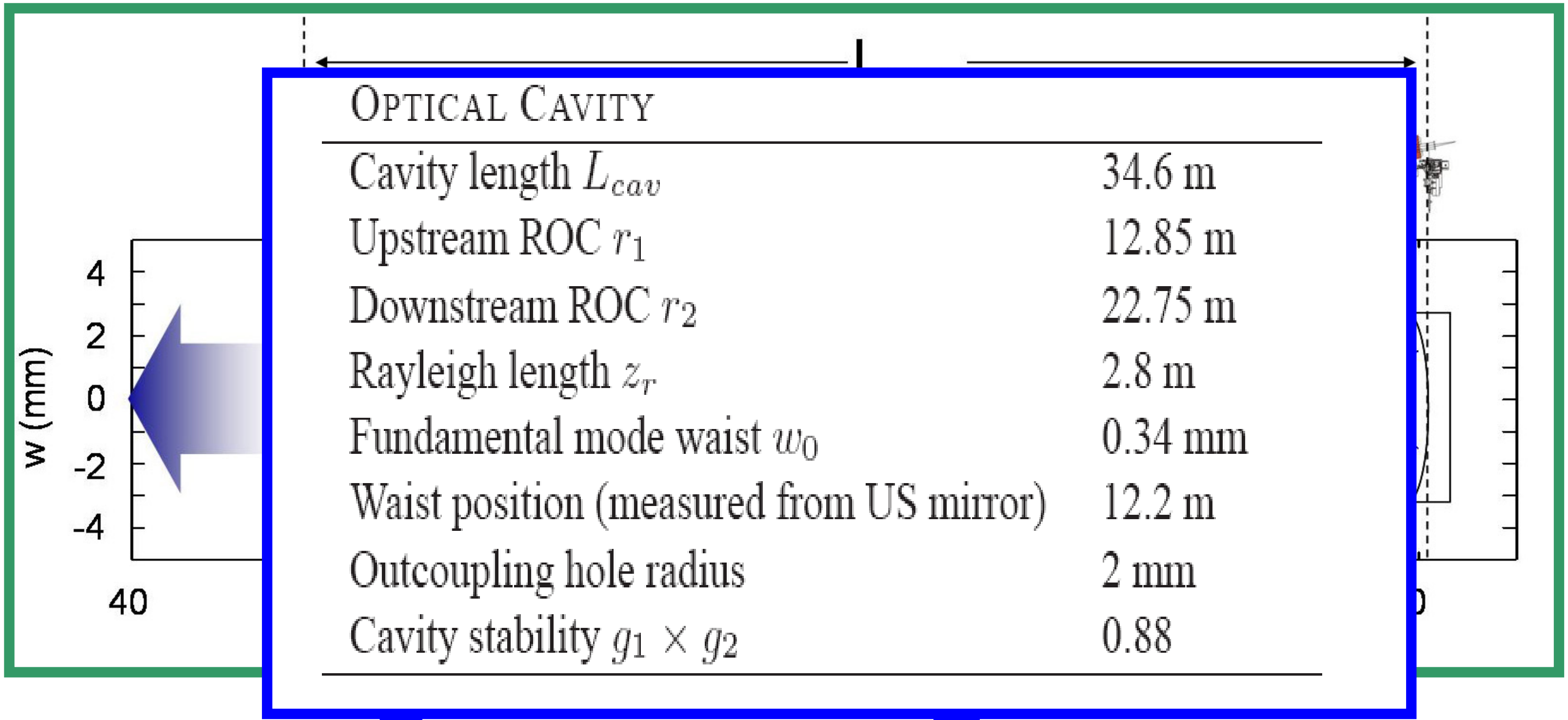
$z=4\pi\rho N_w$



- Assuming G = 4, higher reflectivity gives higher max output power, but more sensitivity to outcoupling fraction

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

How to achieve 75% outcoupling

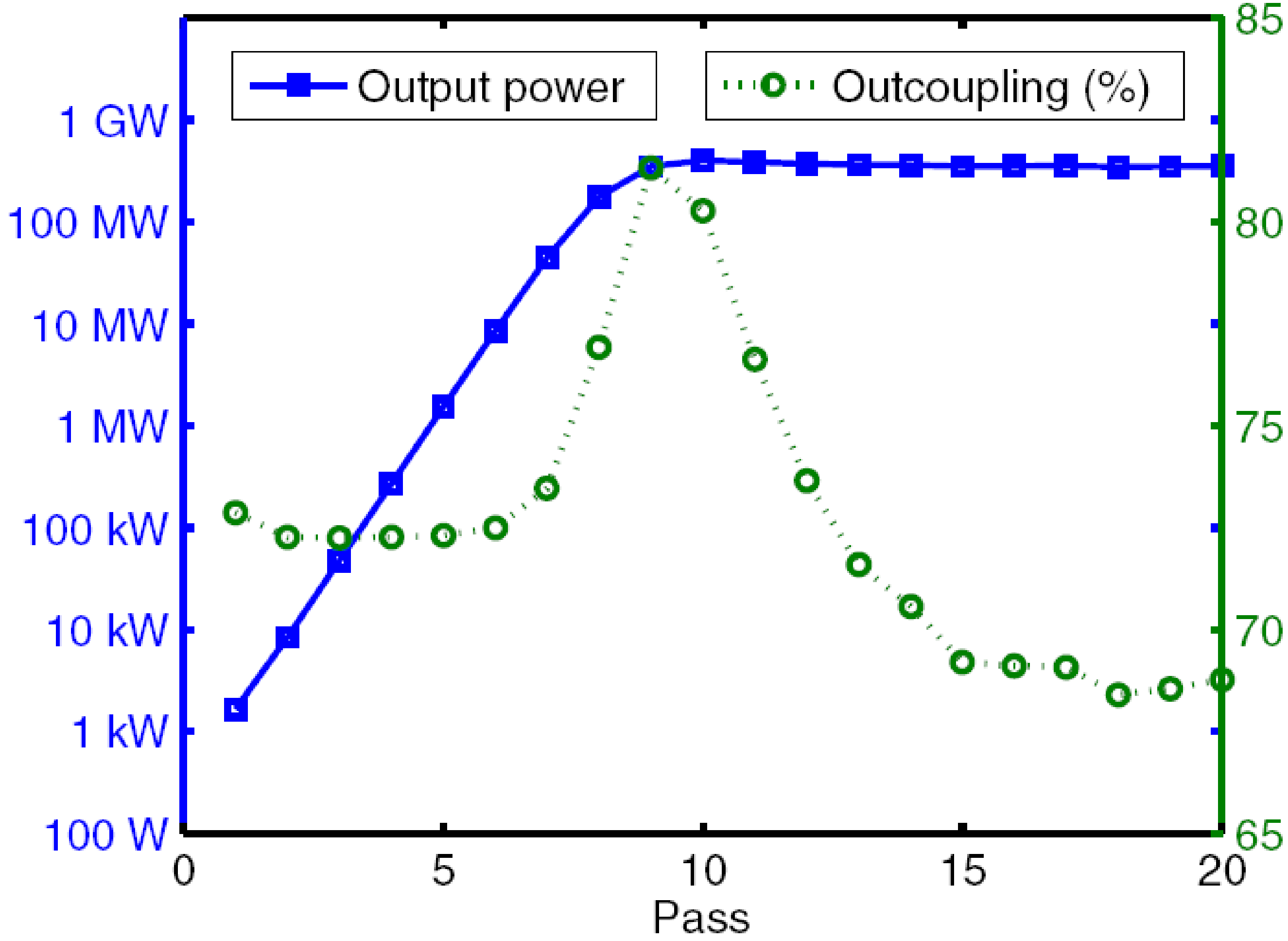


OPTICAL CAVITY	
Cavity length L_{cav}	34.6 m
Upstream ROC r_1	12.85 m
Downstream ROC r_2	22.75 m
Rayleigh length z_r	2.8 m
Fundamental mode waist w_0	0.34 mm
Waist position (measured from US mirror)	12.2 m
Outcoupling hole radius	2 mm
Cavity stability $g_1 \times g_2$	0.88

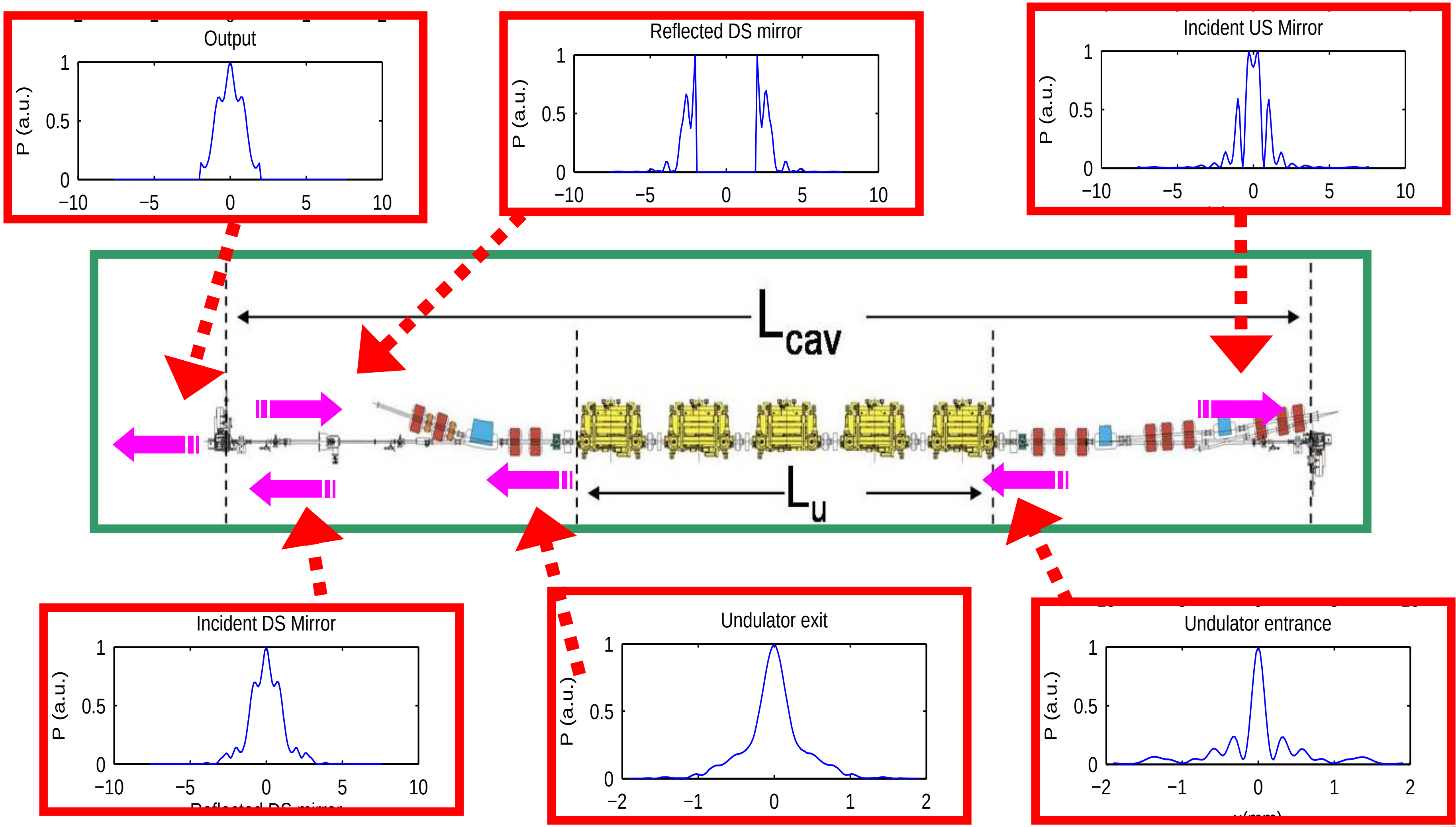
Hole radius set to outcouple ~75% of SR on first pass.
Rayleigh length set to give ~75% outcoupling for TEM_{00}.

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

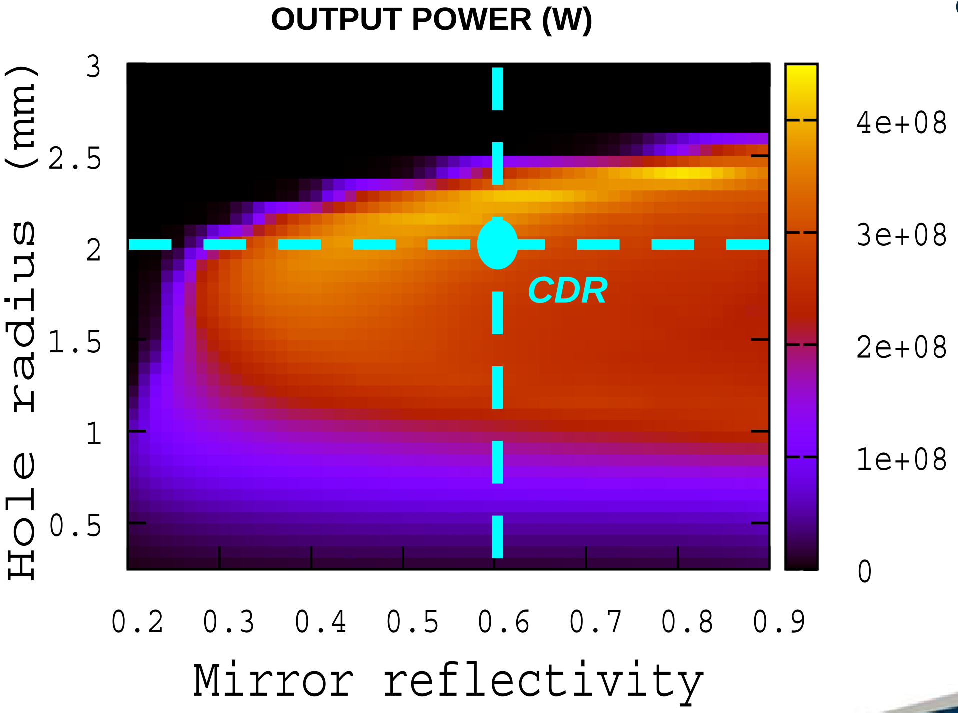


Transverse cross sections at Saturation: Genesis/OPC



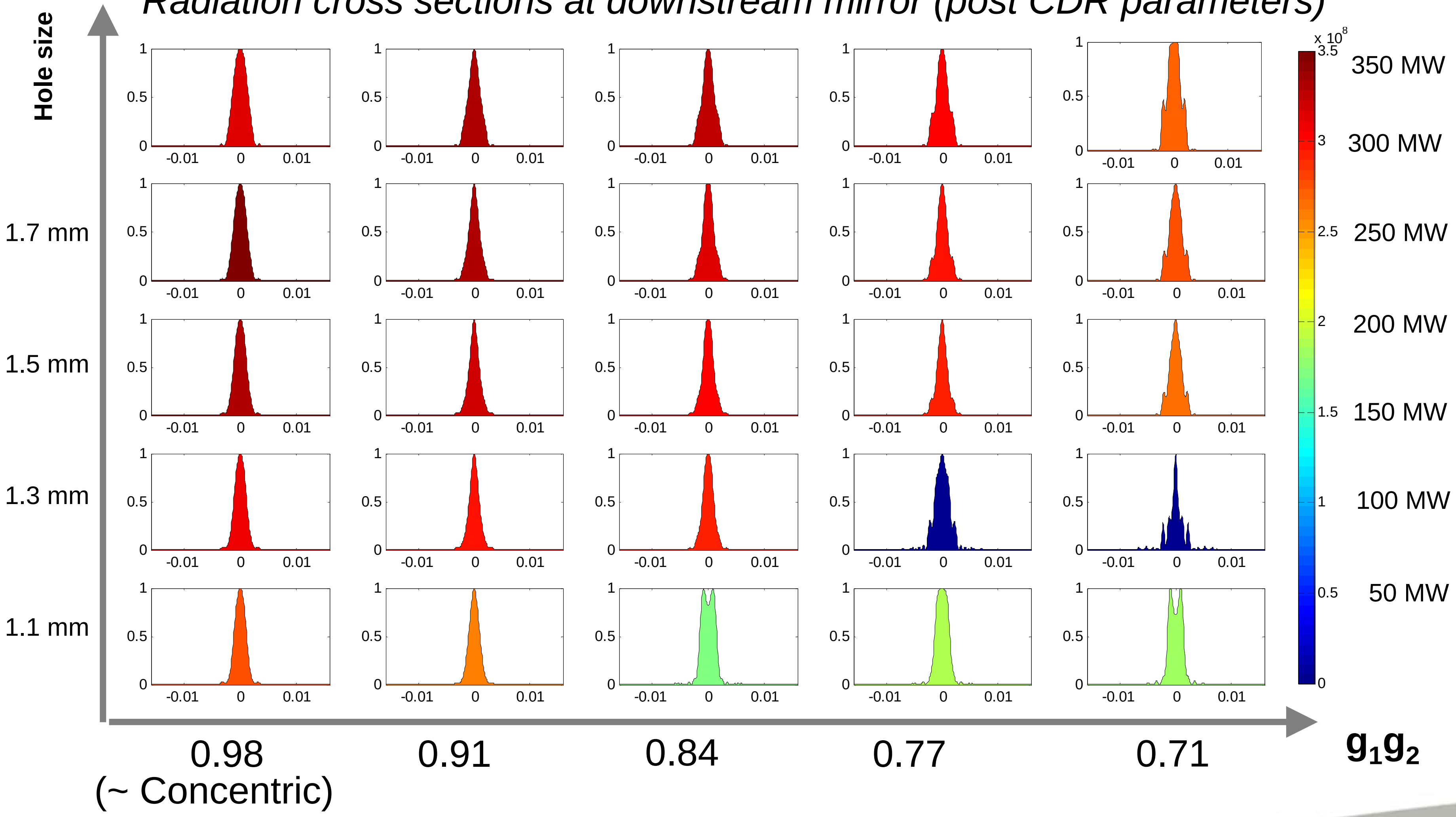
Optimisation of CDR Cavity Parameters

- 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).



- *Example: Hole Radius vs Reflectivity:*
  - Output power relatively INSENSITIVE to reflectivity
  - Reflectivity REDUCTION gives small power INCREASE
  - Consistent with 1D simulations

RAFEL Sensitivity to Cavity Geometry

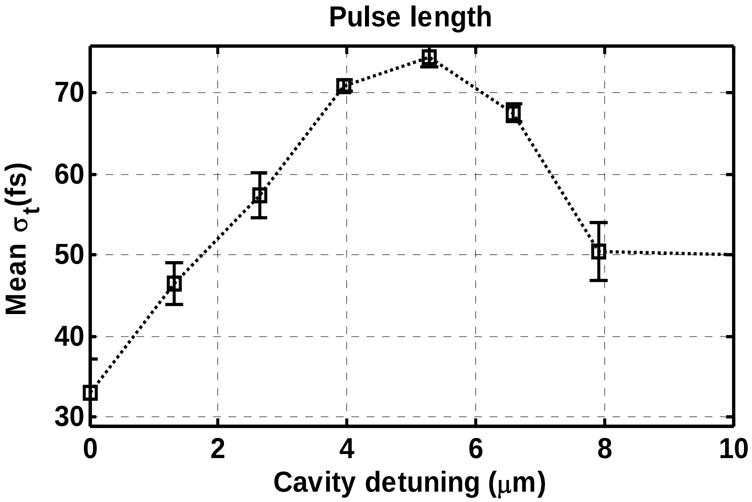

Radiation cross sections at downstream mirror (post CDR parameters)

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

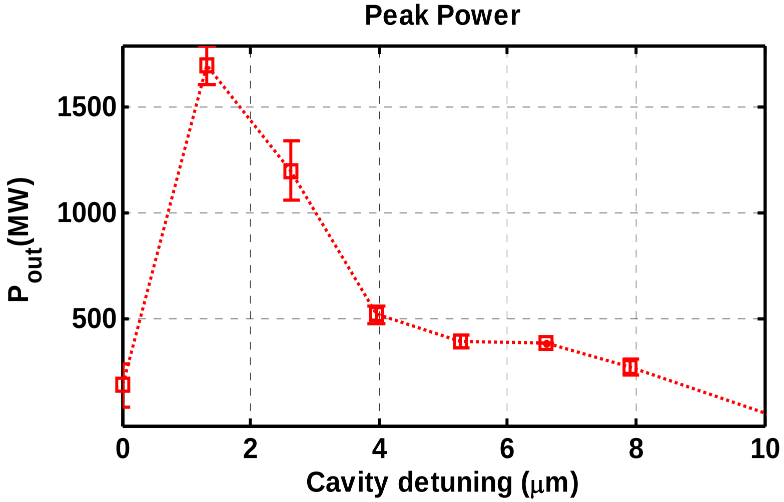
Cavity detuning curves: 10eV Planar Polarisation

Pulse length (fs)

Pulse length



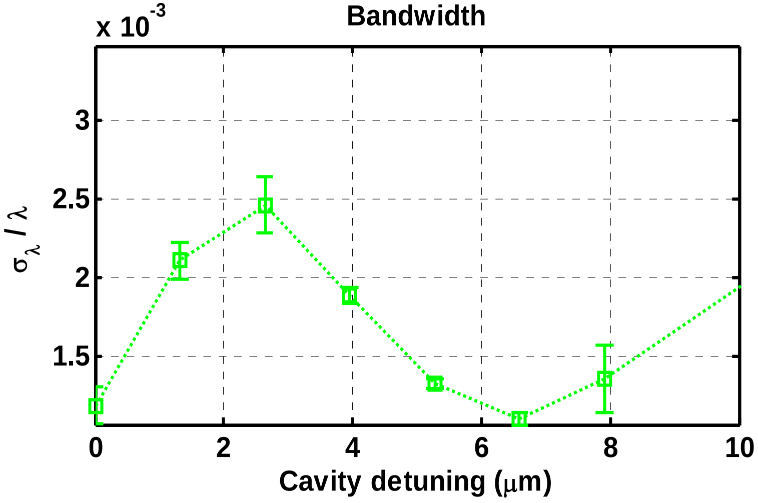
Peak Power



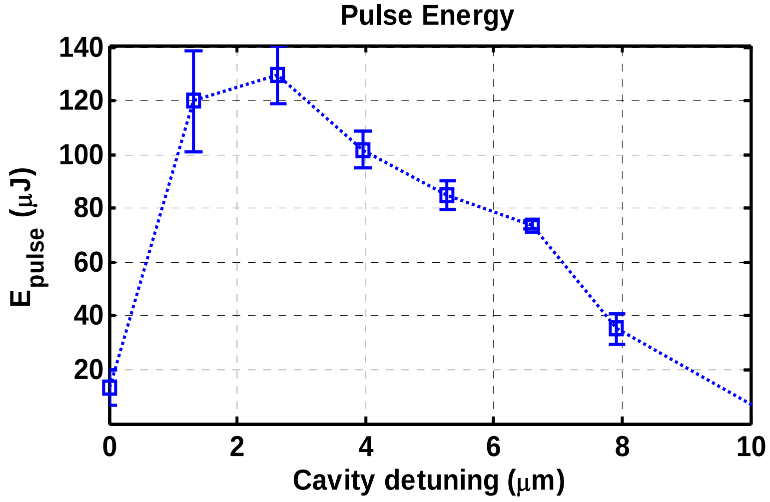
Peak Power (MW)

Bandwidth

Bandwidth



Pulse Energy

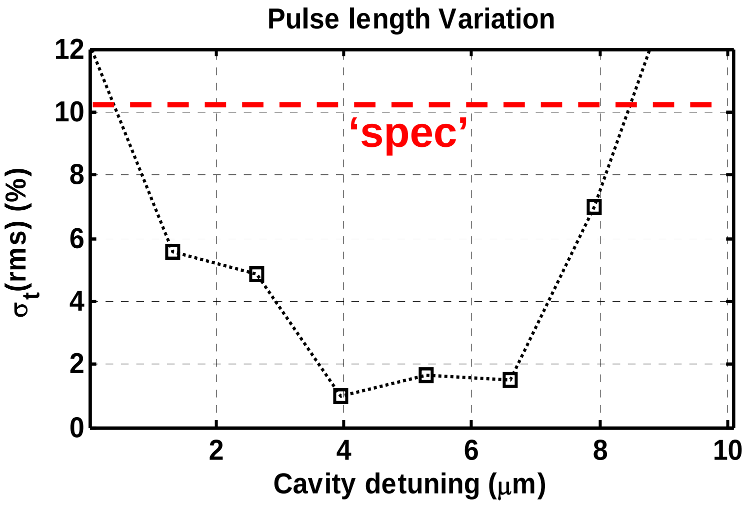


Pulse Energy (μJ)

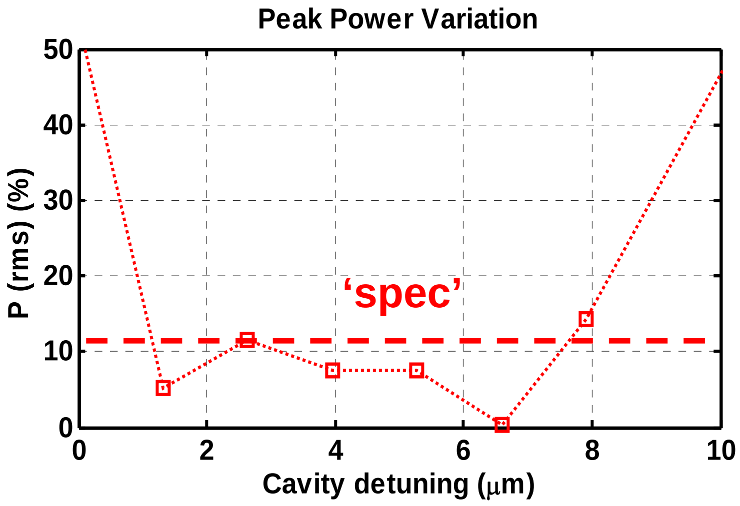
Science & Technology
Facilities Council

Stability rms Variation: 10eV Planar Polarisation

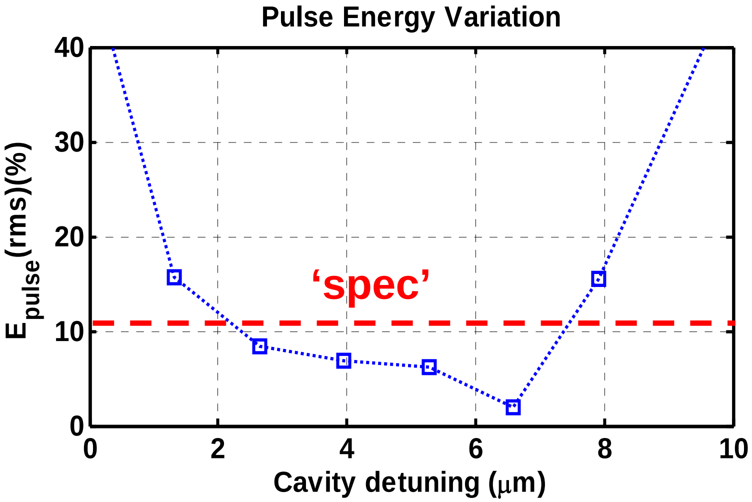
Pulse length



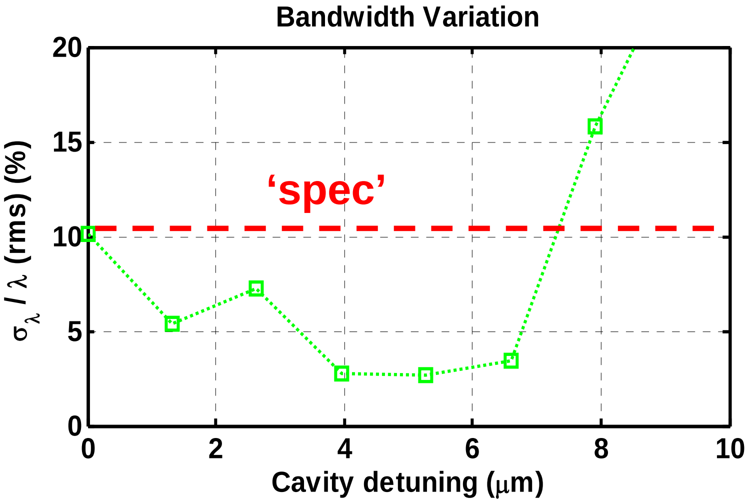
Peak Power



Pulse Energy

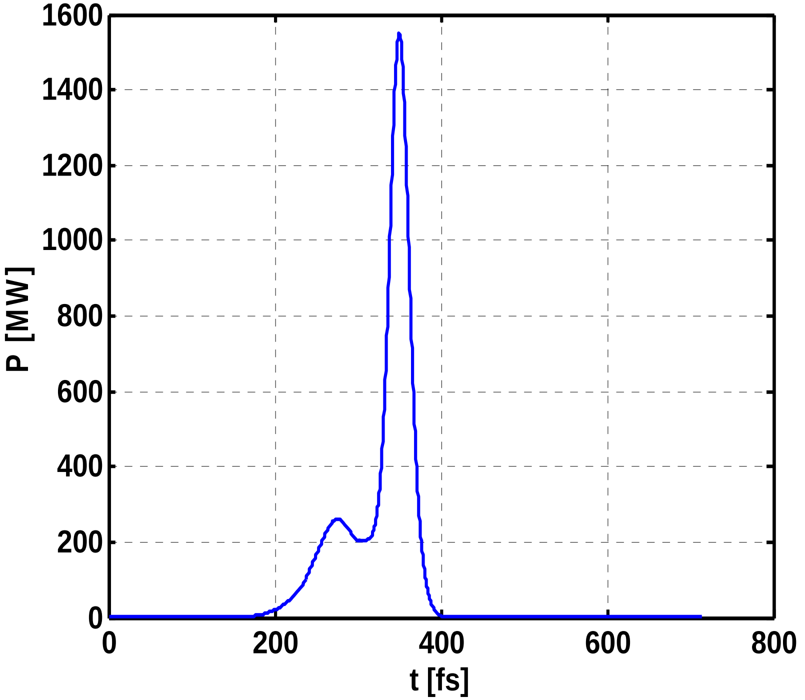


Bandwidth

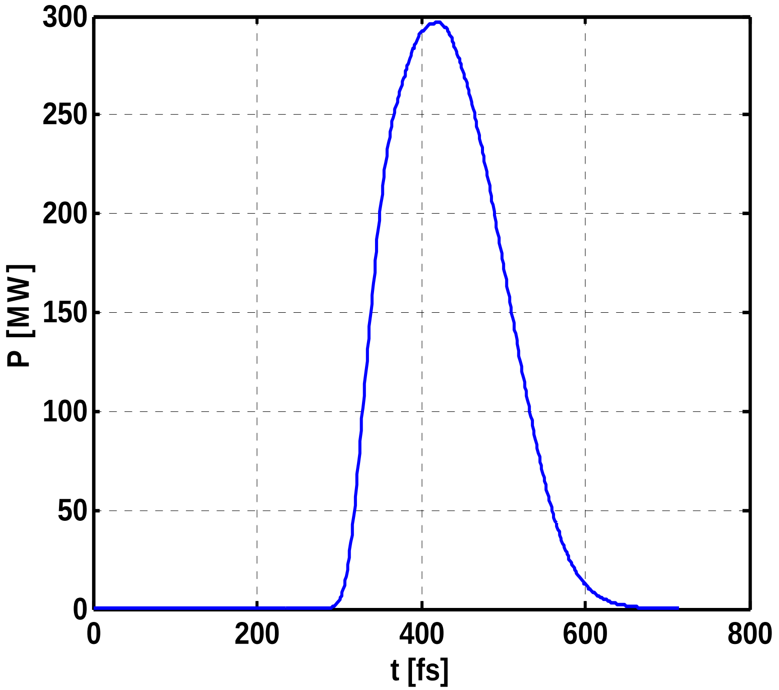


1D time-dependent simulations: Typical Pulses

Near-Synchronous Optical Cavity
‘superradiant’

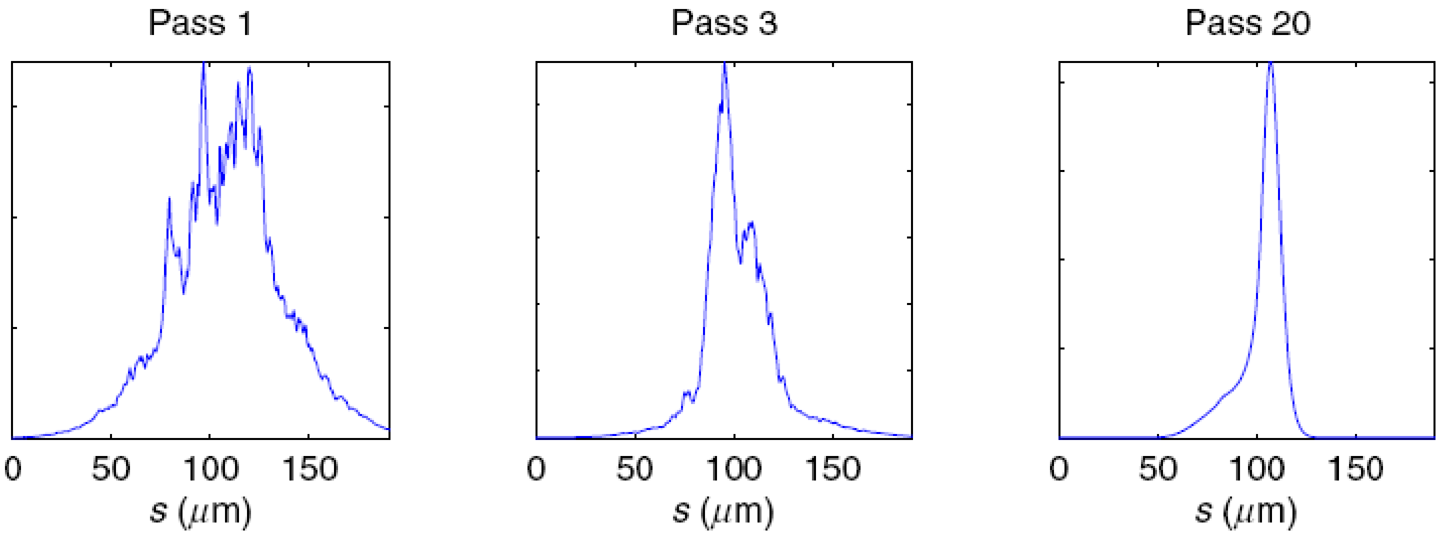


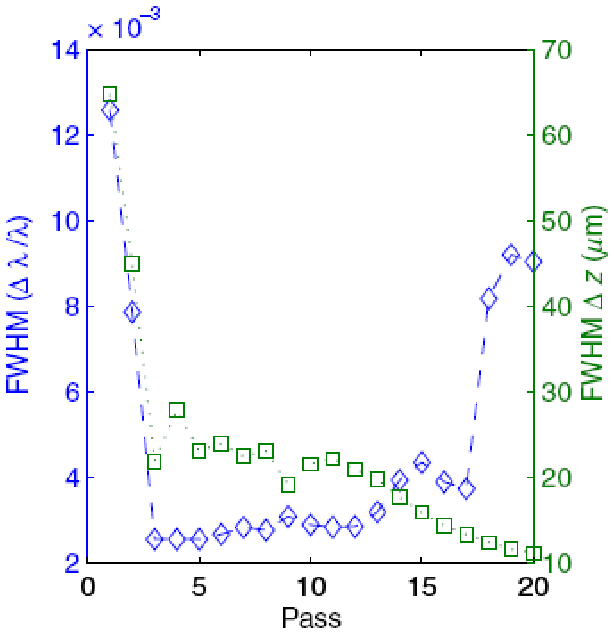
Detuned Optical Cavity
‘steady state’

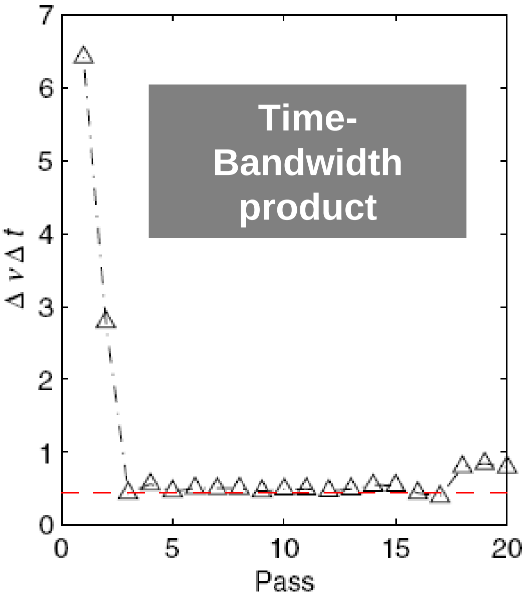


Science & Technology Facilities Council

3D Time Dependent Simulations: Genesis/OPC







Time-Bandwidth product

Science & Technology
Facilities Council

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 $F \sim 1\times10^{-5}$ (***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

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

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**

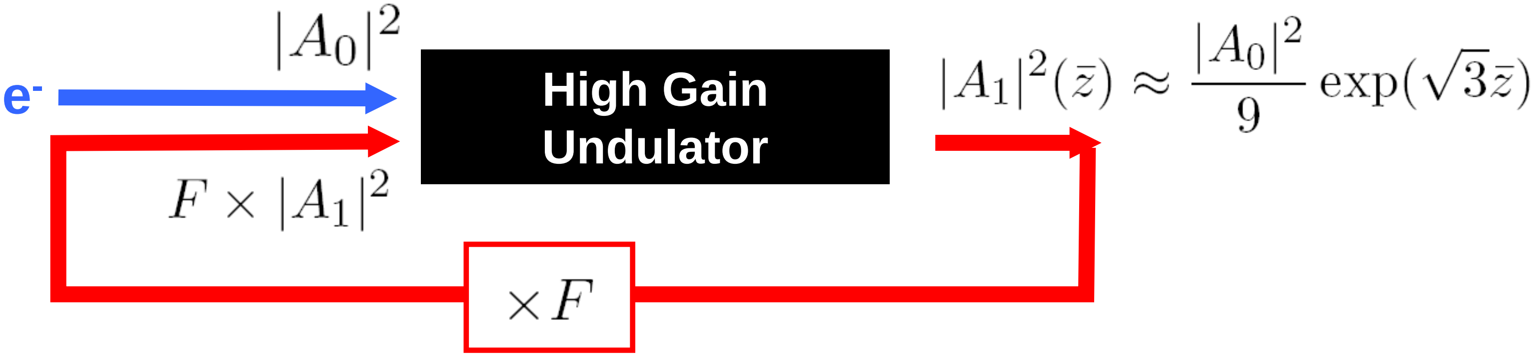
$\bar{z}_1$ **= Particle position in units of cooperation length**

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

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

Science & Technology
Facilities Council

Feedback Required to Dominate Shot Noise at Start-up



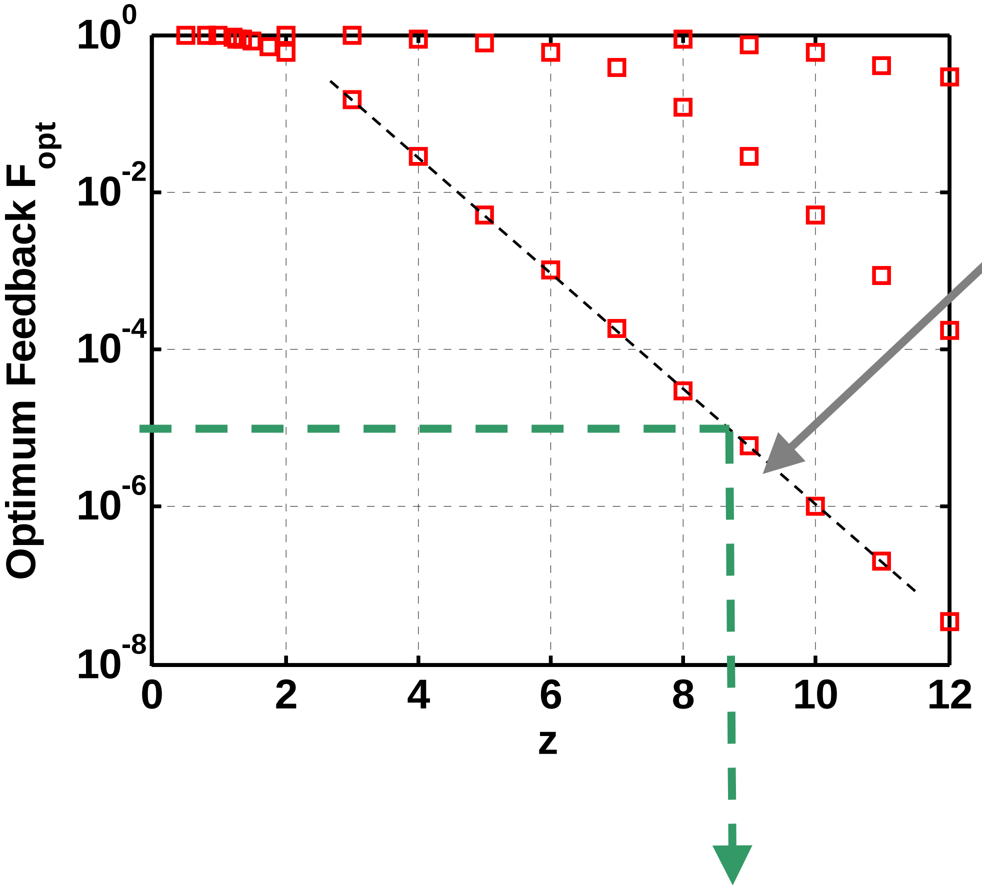
Condition for radiation fed back to start of undulator to dominate electron beam shot noise:

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

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:

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

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:

$$\bar{z} = 8.67$$

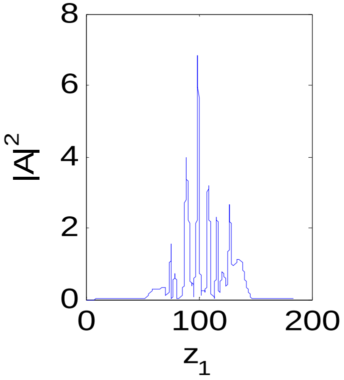
1D Simulation Code and Parameters

- 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
- $z_{bar} = 8.67$
- Gaussian electron bunch
- Varied **feedback** from 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.

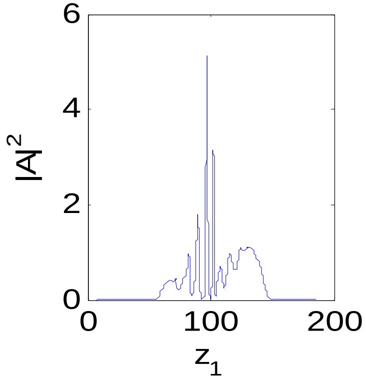
1D Time Dependent Simulations: z = 8.67, detuned cavity

T-BW Product > SASE

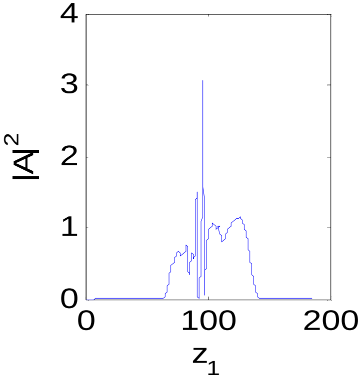
T-BW Product = SASE



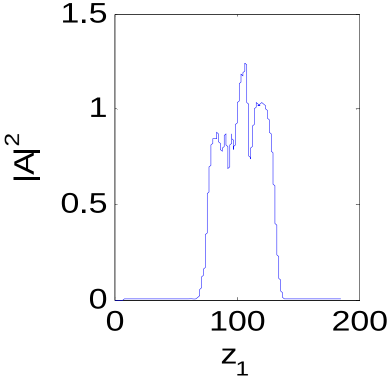
F = 1×10^{-3}



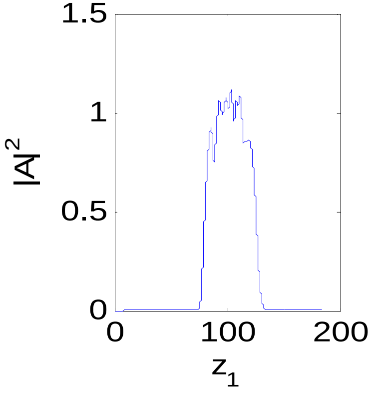
F = 5×10^{-4}



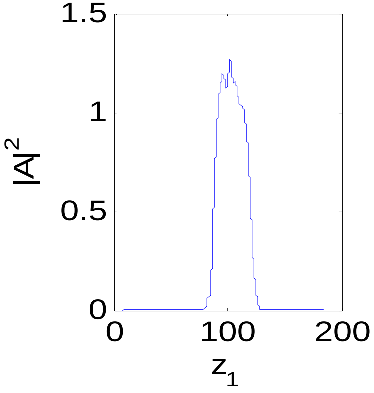
F = 1×10^{-4}



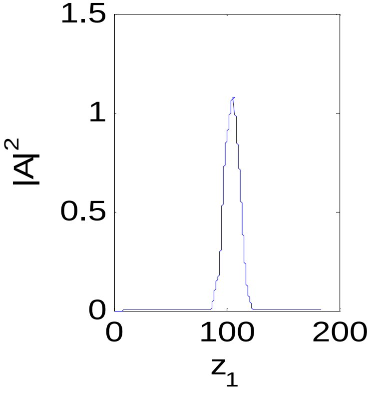
F = 5×10^{-5}



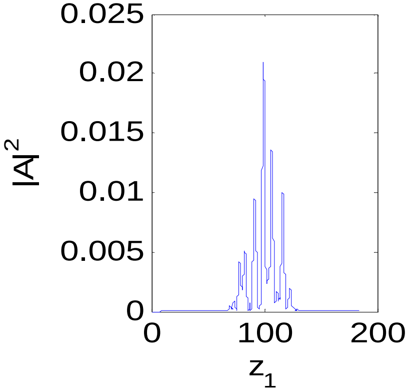
F = 2×10^{-5}



F = 1×10^{-5}



F = 5×10^{-6}

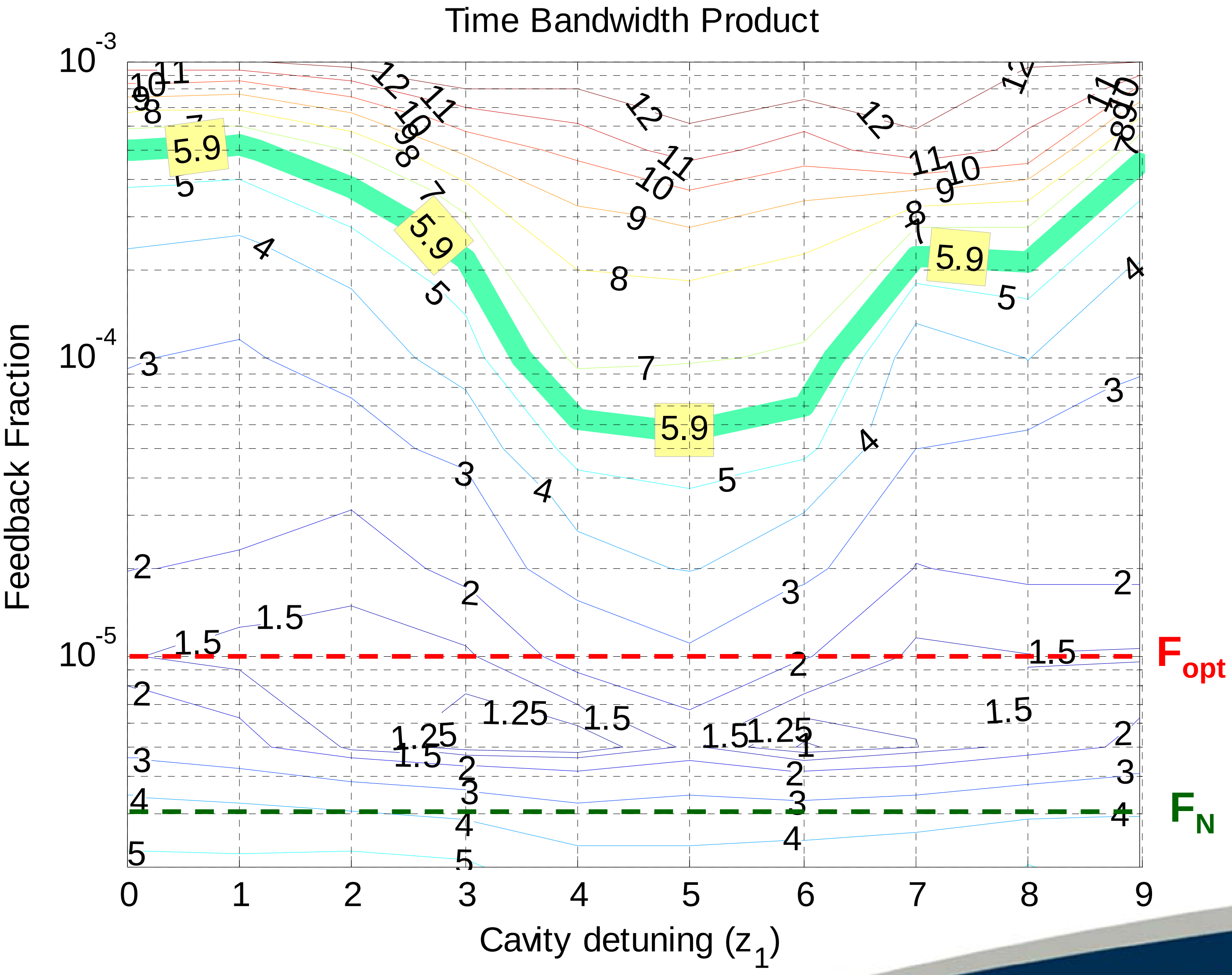


F = 2×10^{-6}

T-BW Product < SASE

T-BW Product = SASE

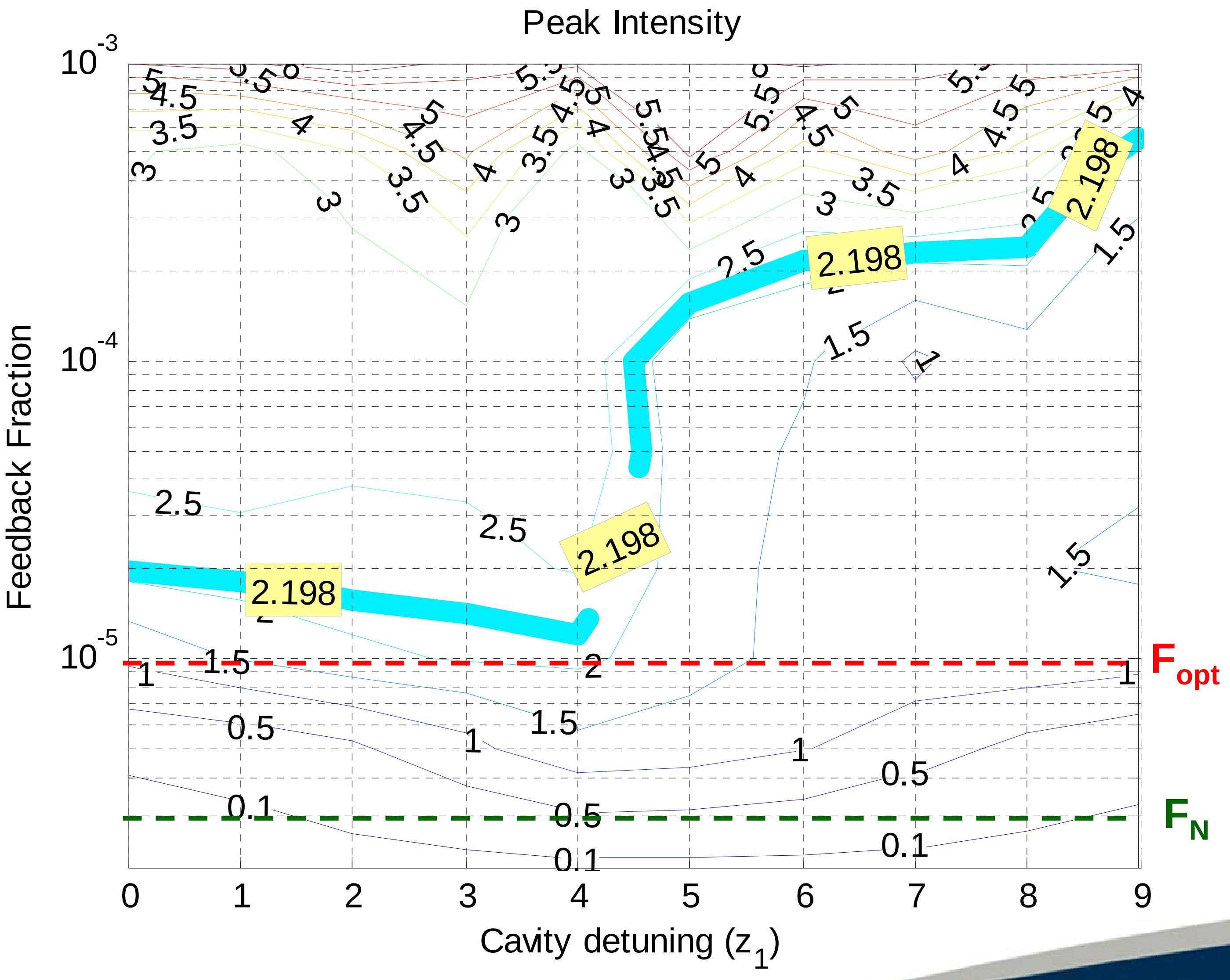
Time Bandwidth Product (averaged over 200 passes)



BOLD CONTOUR = SASE

Science & Technology Facilities Council

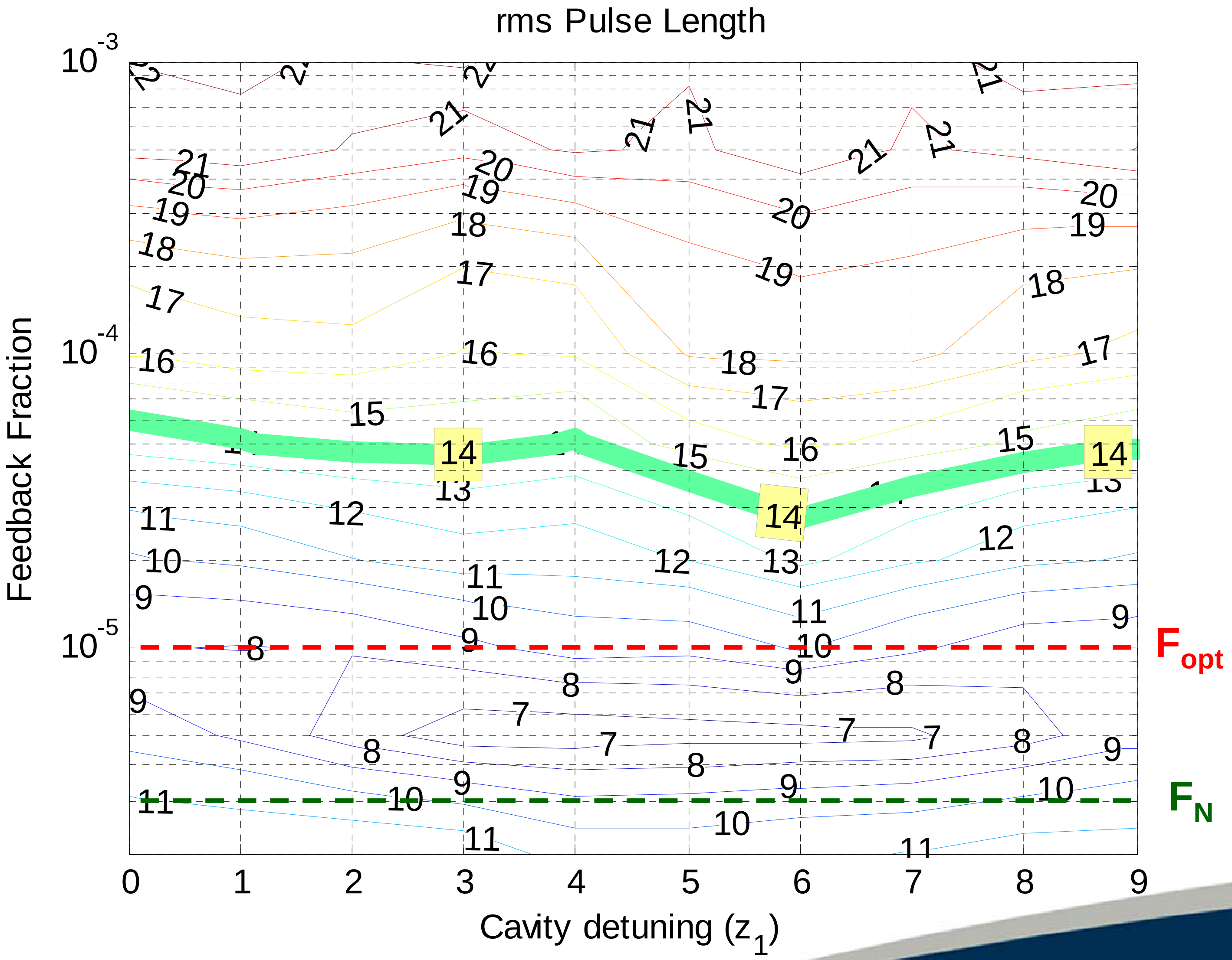
Peak Intensity (averaged over 200 passes)



BOLD CONTOUR = SASE

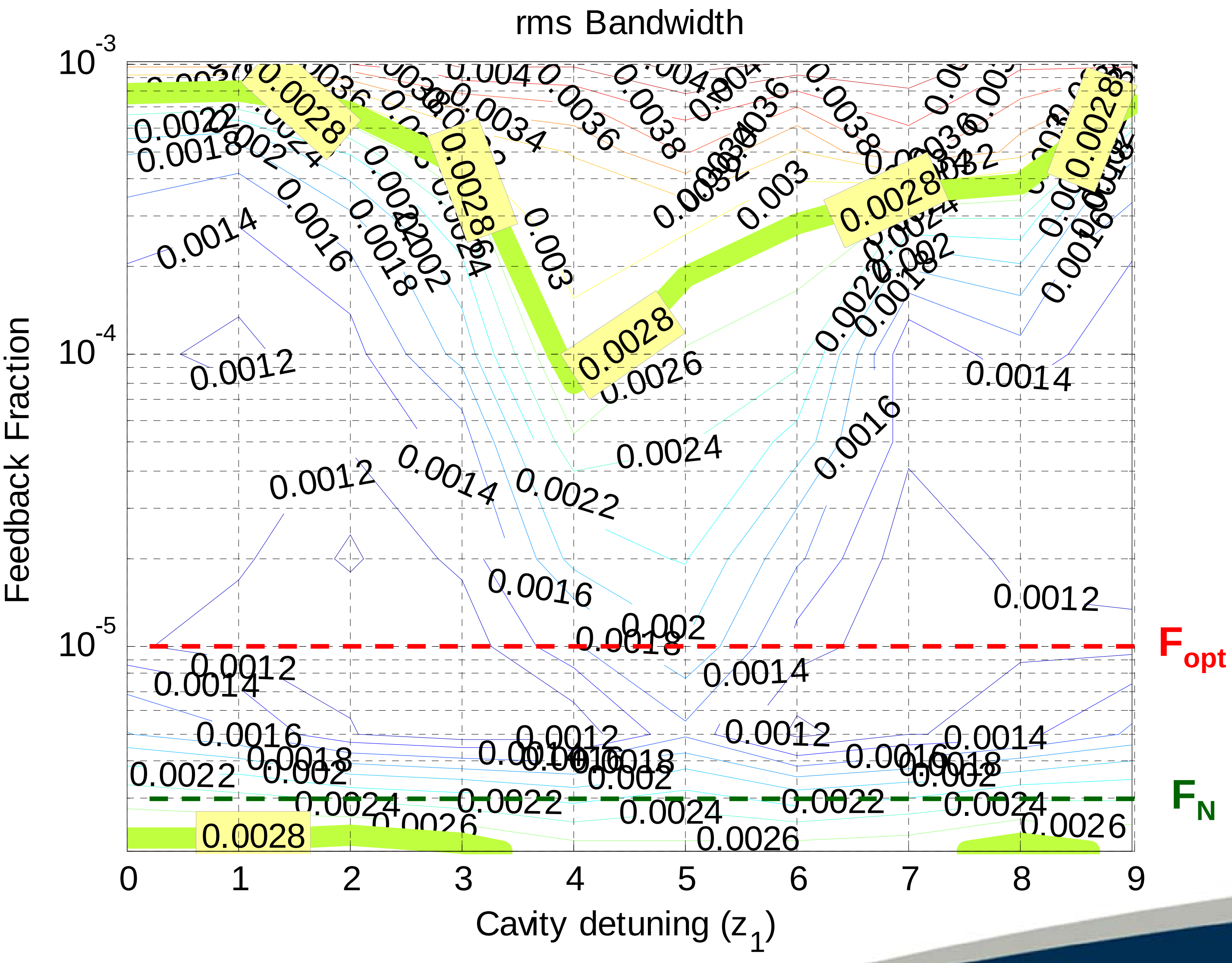
Science & Technology Facilities Council

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: see Peter van der Slot's talk Tuesday in High Power FELs session.
- 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?

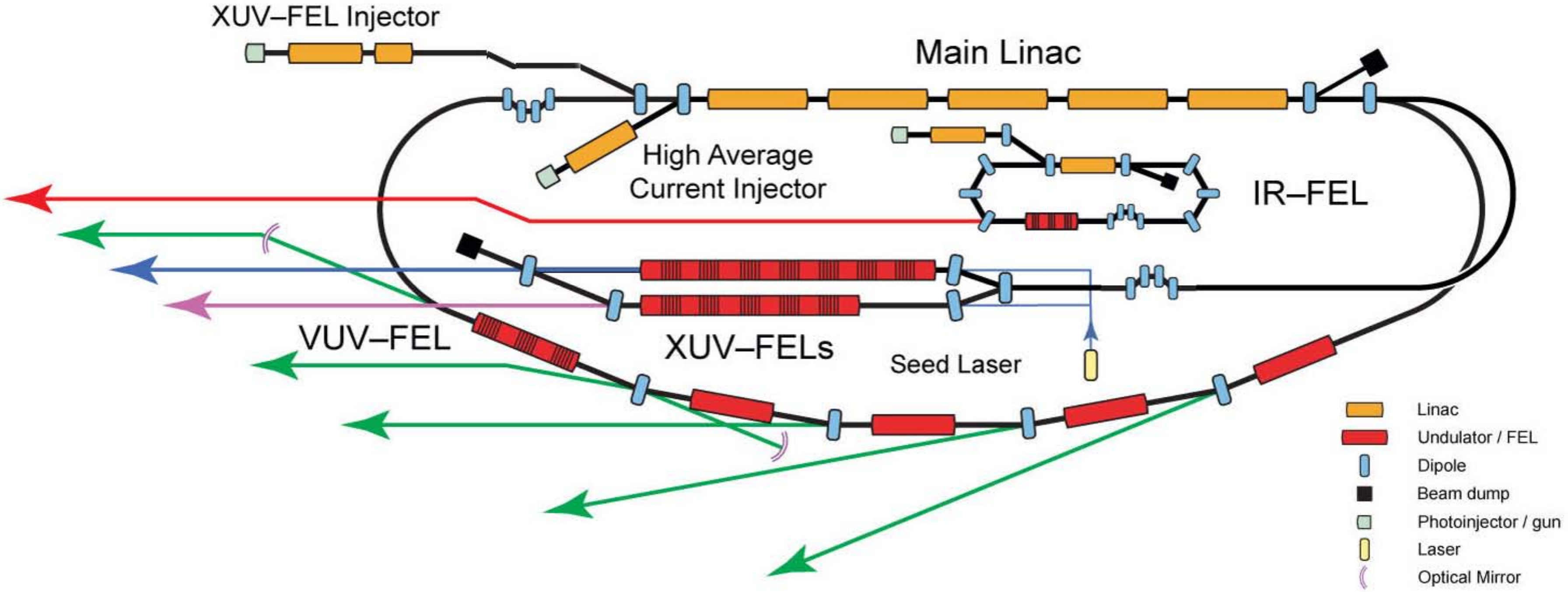
Science & Technology
Facilities Council

The End

Science & Technology
Facilities Council

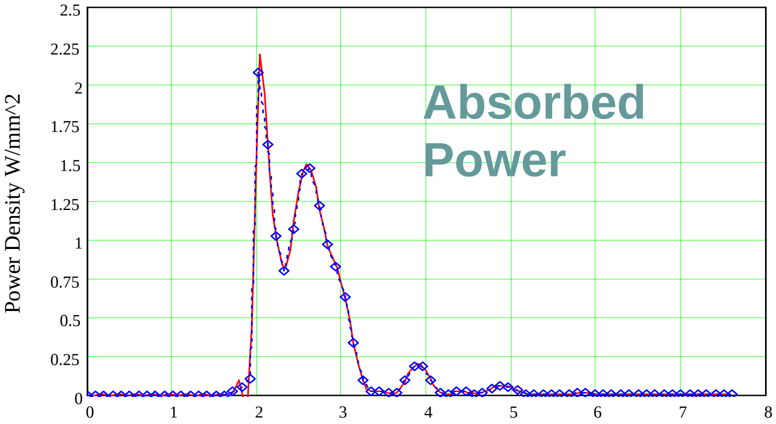
Extra Material………

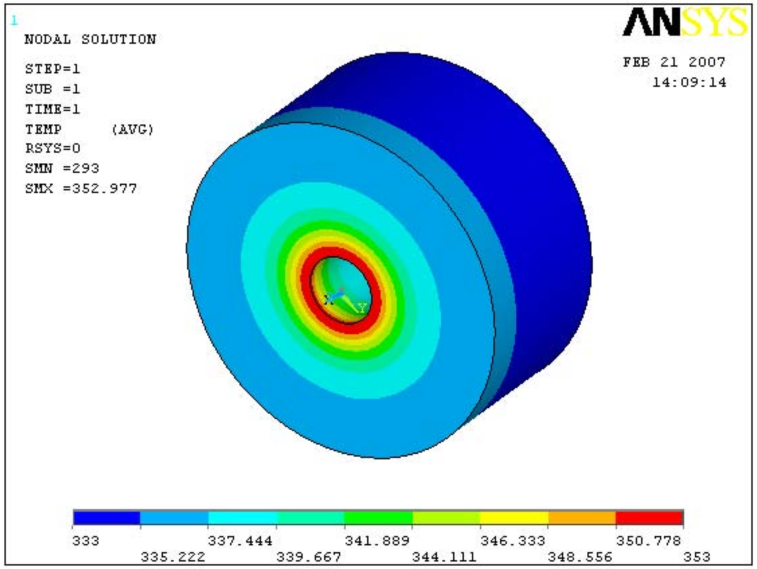
4GLS Layout


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

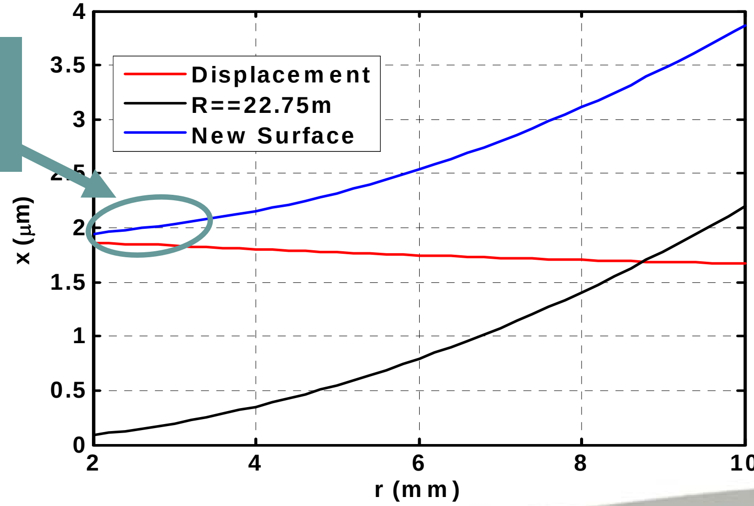
Thermal Loading: FEA Analysis of Outcoupler

- **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



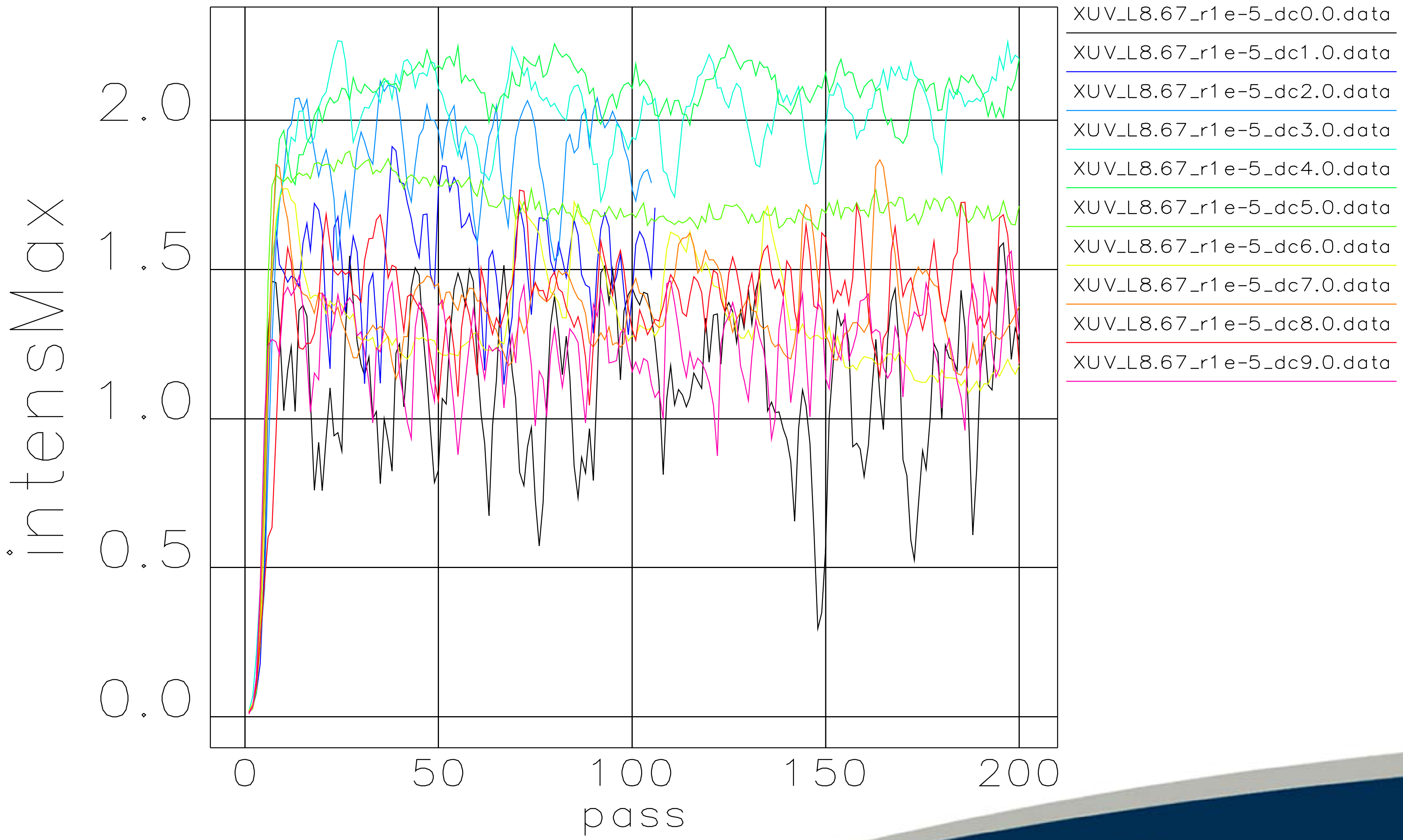
Thermal Loading: Possible Solutions

- Adaptive optics
  - a deformable outcoupler allowing adjustable ROC
- *Cryo-cooling outcoupler*
  - *At -149 °C coefficient of thermal expansion for silicon 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*
- *????...*

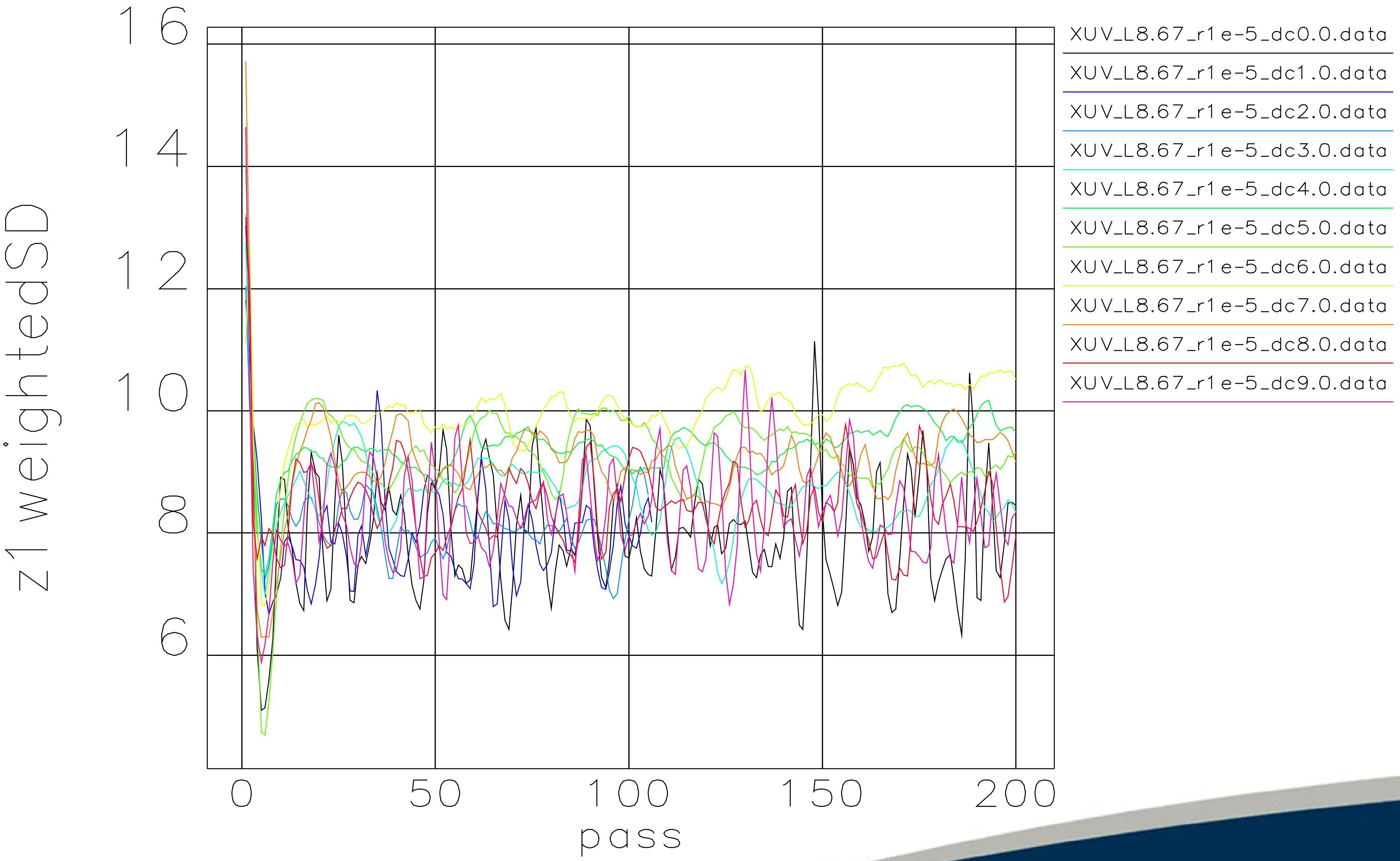
Summary of Possible Output

	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

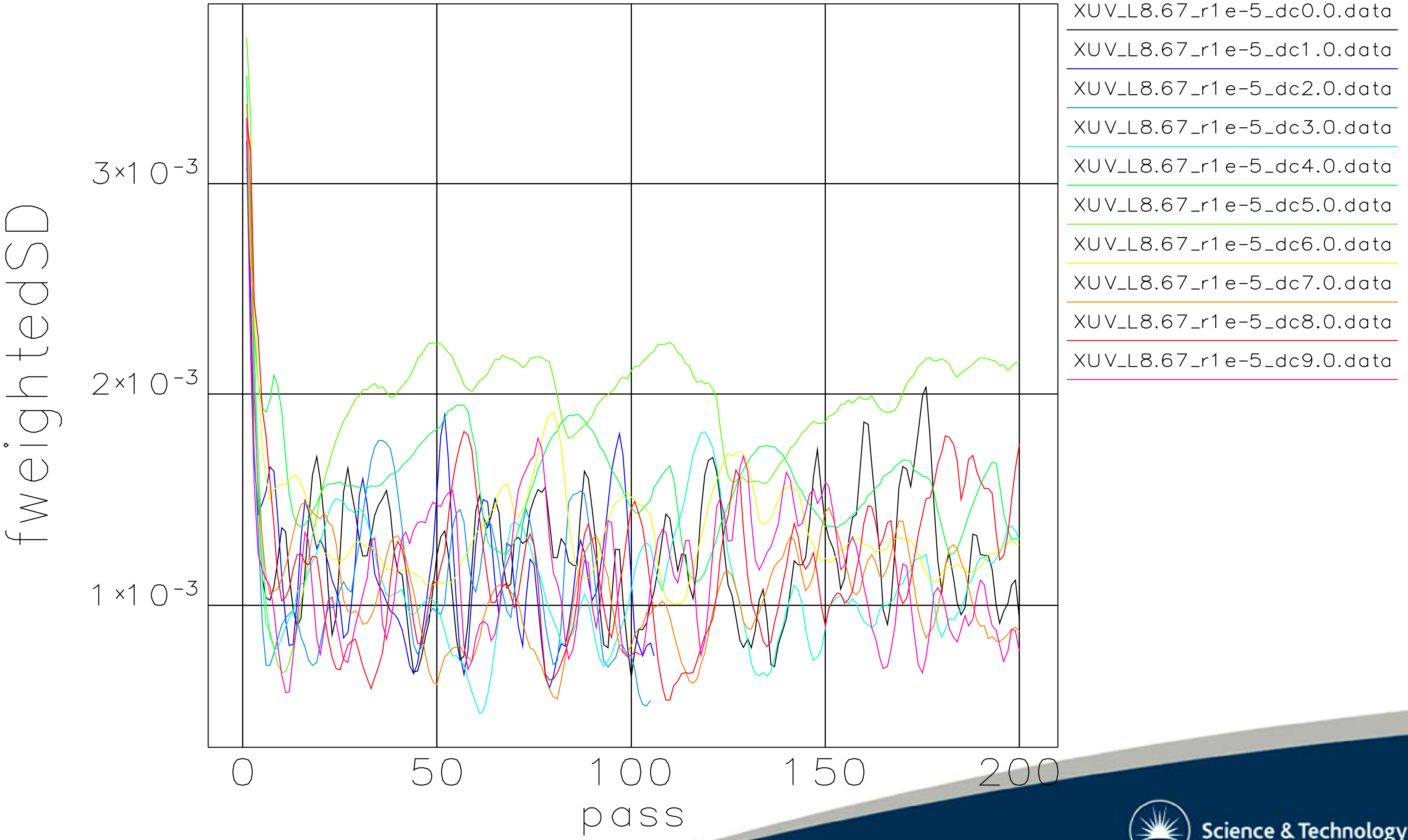
Peak Intensity (evolution over 200 passes): F = 1×10^{-5}



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}