Science & Technology Facilities Council
ASTeC
Accelerators in a new light

Free-Electron Laser R&D in the UK
- steps towards a national X-FEL facility

Neil Thompson, ASTeC, STFC Daresbury Laboratory

The Cockcroft Institute of Accelerator Science and Technology

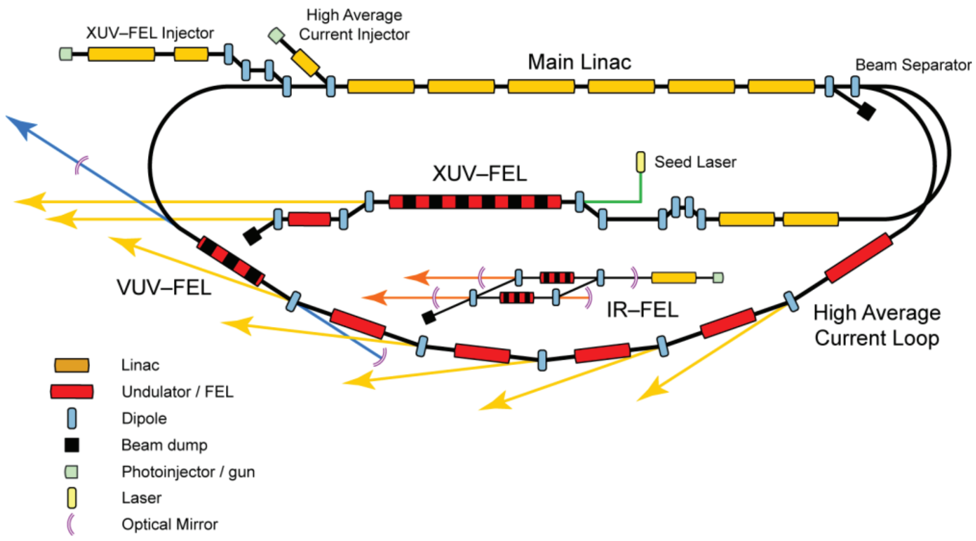
John Adams Institute for Accelerator Science

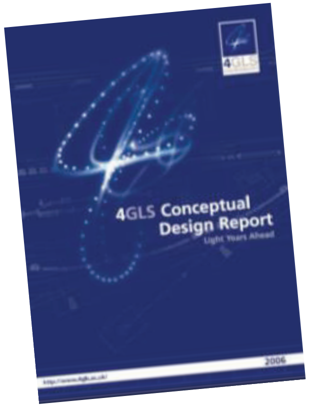
diamond

Outline

- Some history
  - Previous projects
- Where we are now?
  - A UK XFEL within reach (but just over the horizon)
- The CLARA FEL Test Facility
  - Partly constructed, currently commissioning, not quite fully funded
- The UK XFEL R&D Programme
  - Scoping out technologies, new ideas, options.....
- A UK XFEL
  - What might it look like?

Some Recent History





4GLS

600 MeV ERL-based

100eV FEL facility

CDR 2006

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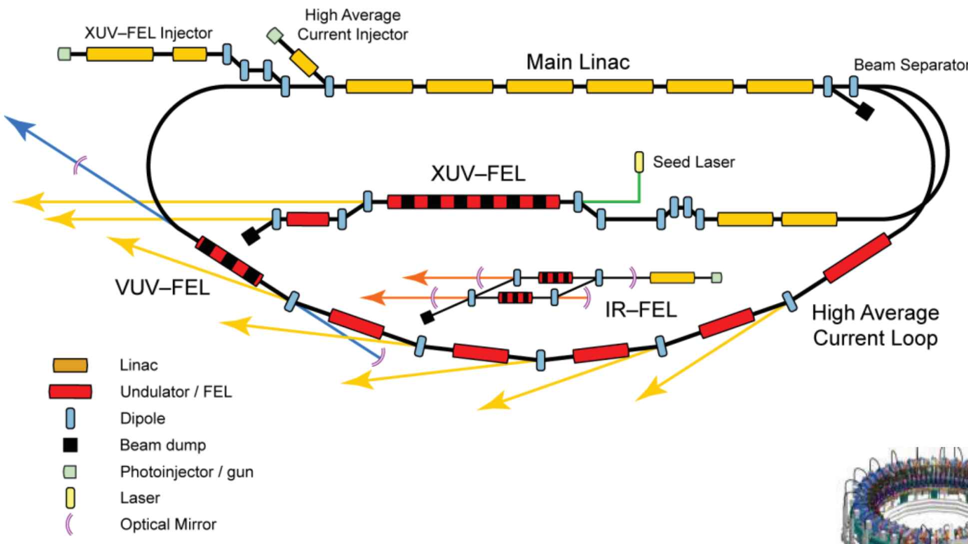

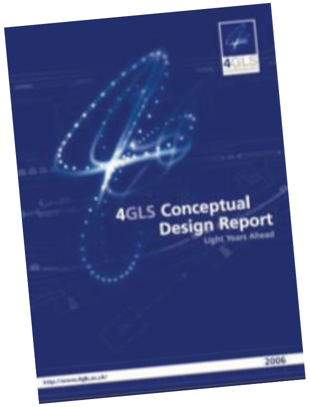

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ERLP/ALICE

35 MeV ERL-based IR FEL

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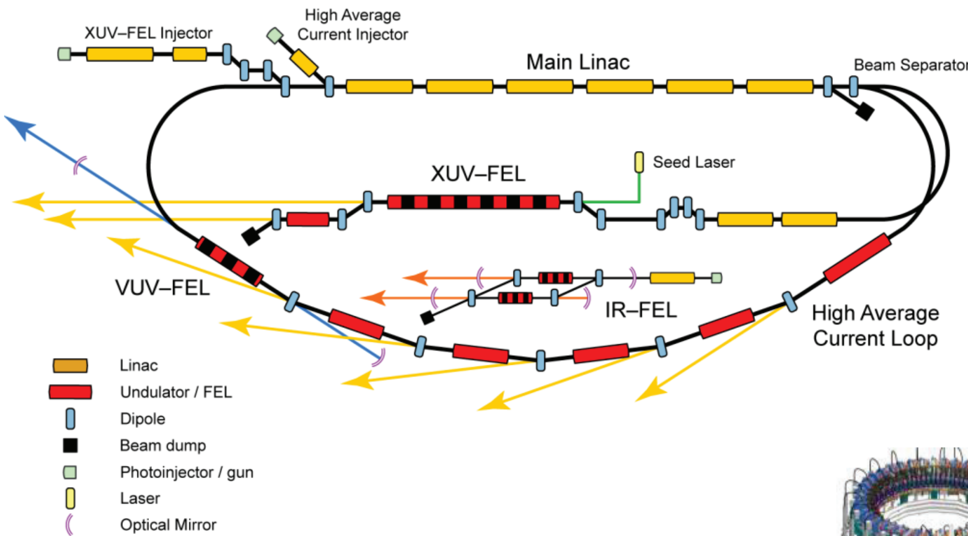

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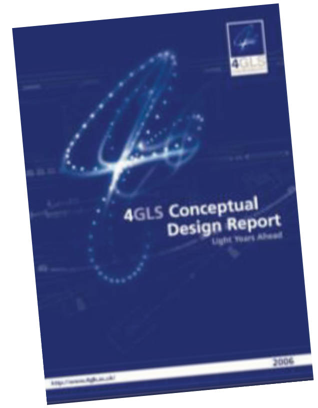

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NLS

2 GeV NC Linac 1keV

FEL facility

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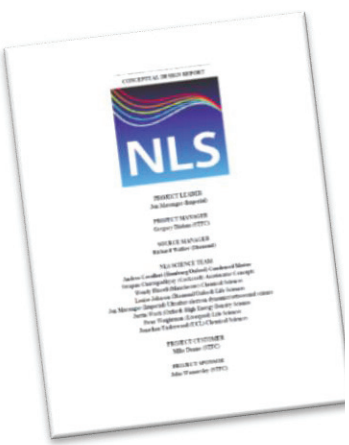
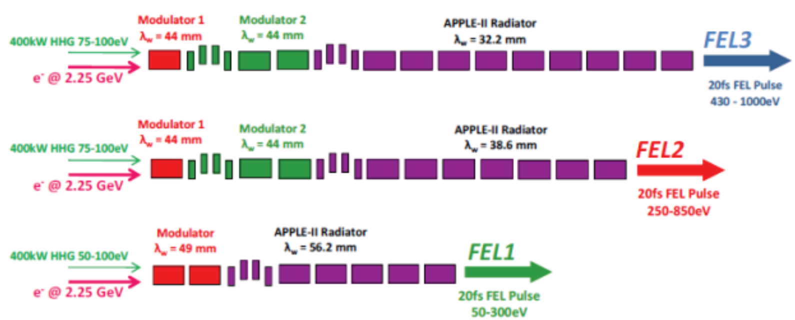
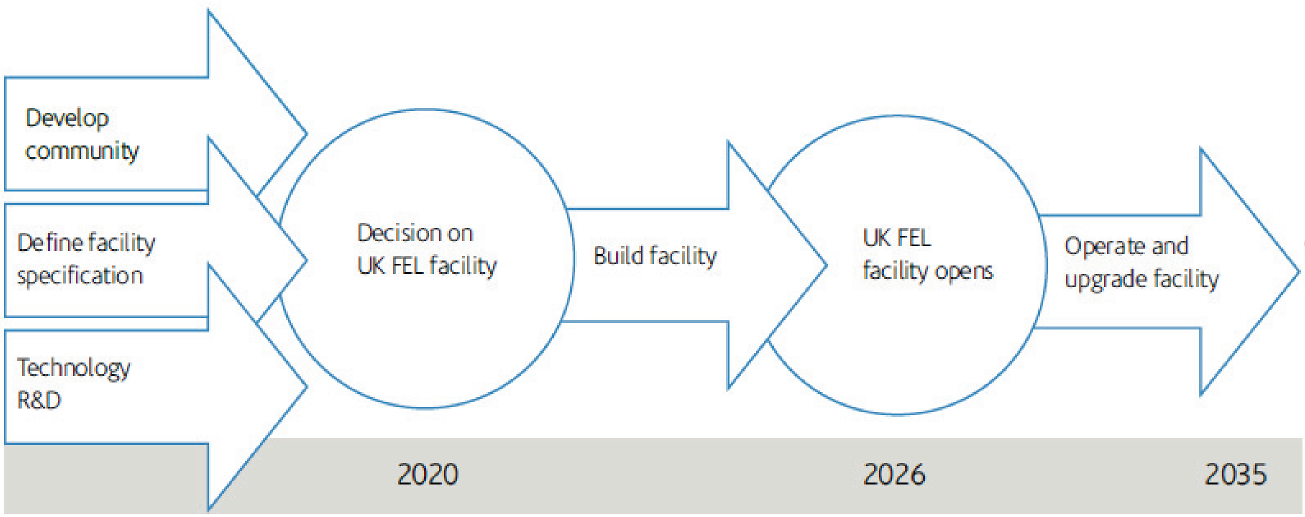




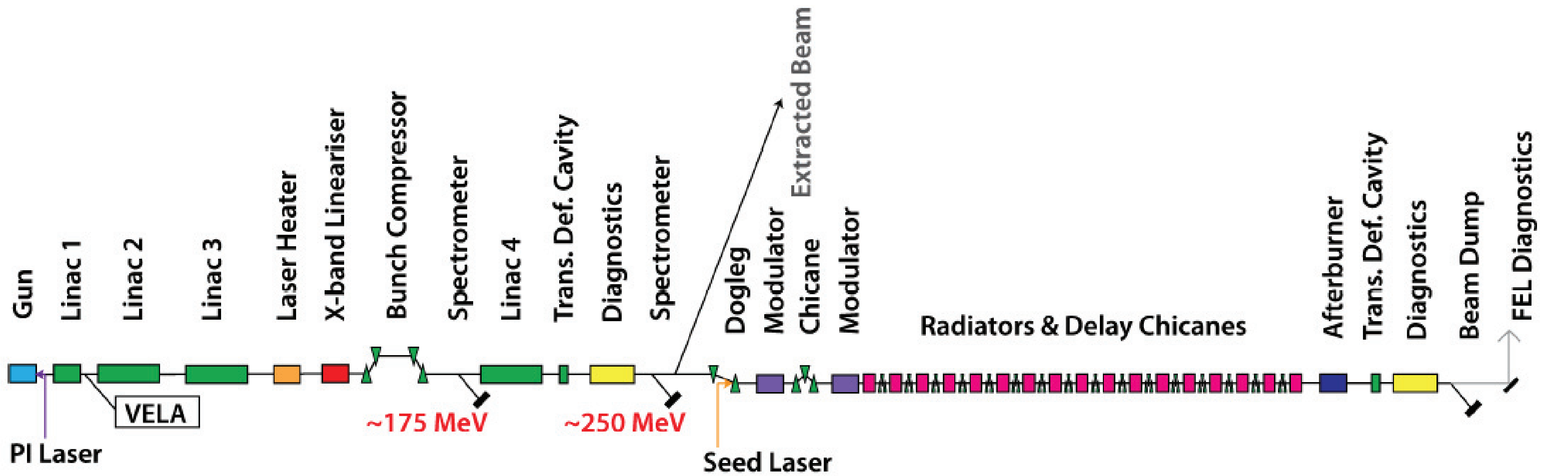
Where are we now?

- In 2011 ASTeC diverted funding from running ALICE to building up a single pass FEL test facility – this is now known as ***CLARA*** – ***C***ompact ***L***inear ***A***ccelerator for ***R***esearch and ***A***pplications
- In 2014-15 STFC (the research council that funds Daresbury) conducted a strategic FEL review and concluded that the UK needs to:
  - Increase engagement with EU XFEL
  - Increase access to other facilities worldwide for UK scientists
  - Further develop the user community
  - Undertake the necessary underpinning R&D for a UK XFEL
  - Construct a UK Facility with a specification designed to meet UK needs.



- The UK accelerator community (ASTeC, CI, JAI, and DLS) responded to the FEL Strategic Review recommendations by developing a coherent four year Underpinning Accelerator & FEL Technology Programme in which CLARA plays a fundamental role.

CLARA: FEL Layout and Status



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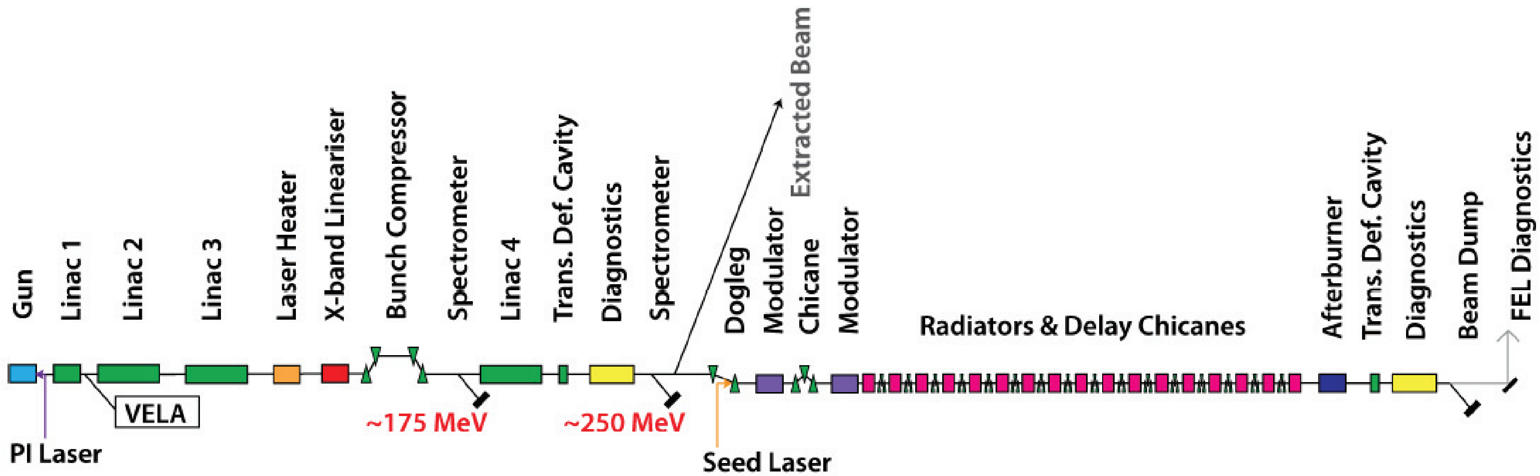

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50 MeV, INSTALLED AND NOW COMMISSIONING

- Have 47 MeV accelerated beam.
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- 2018: Conditioning and characterisation of 400Hz gun

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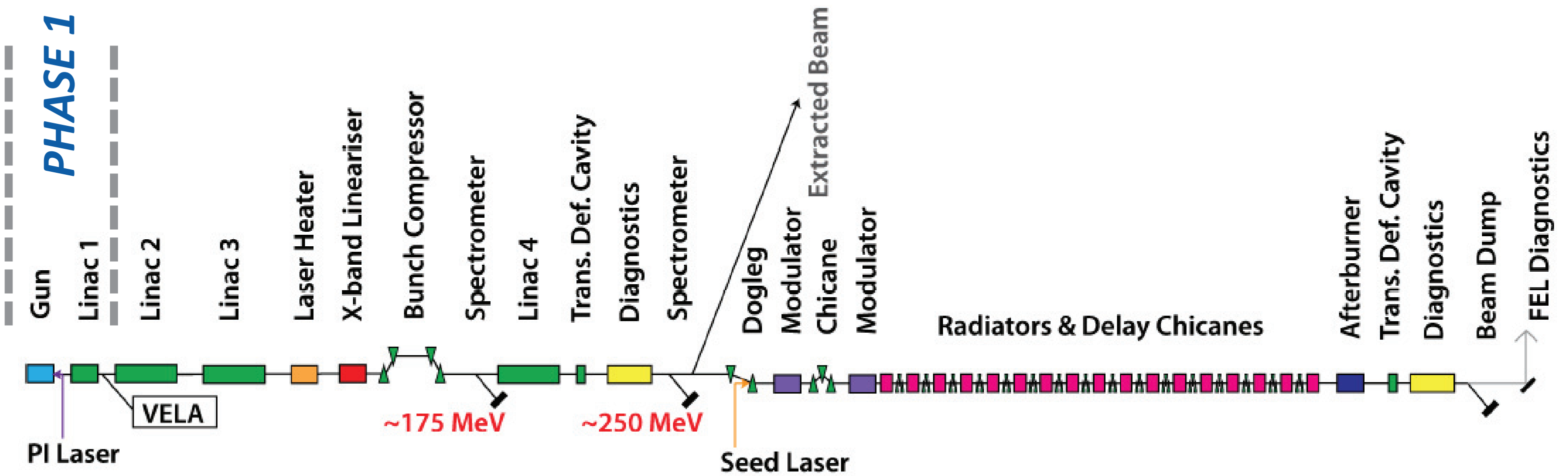

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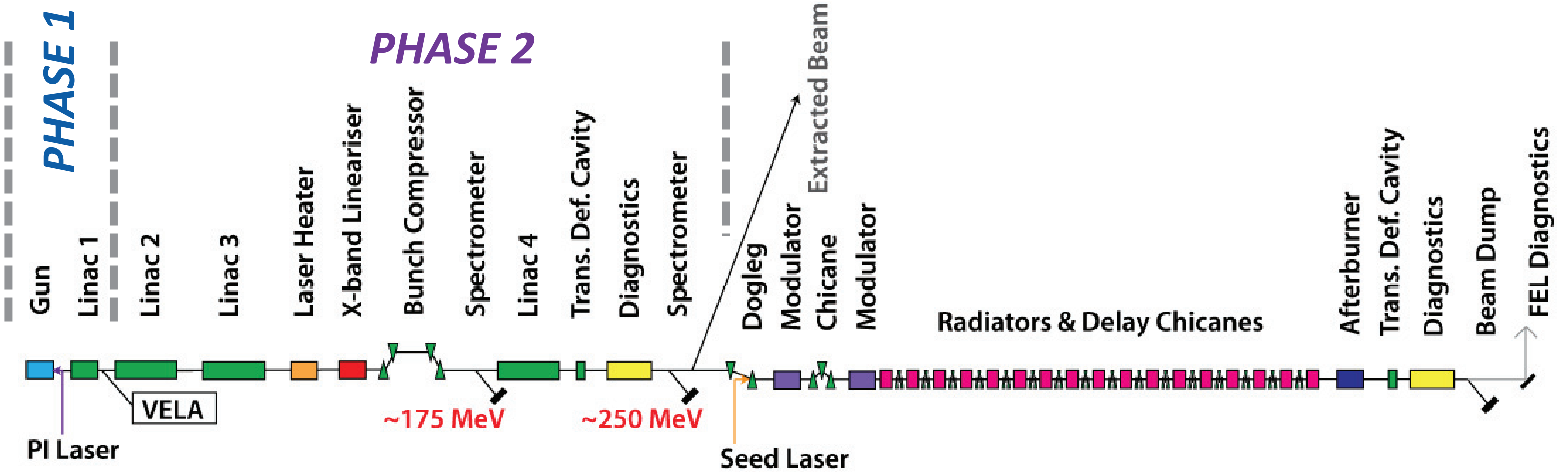

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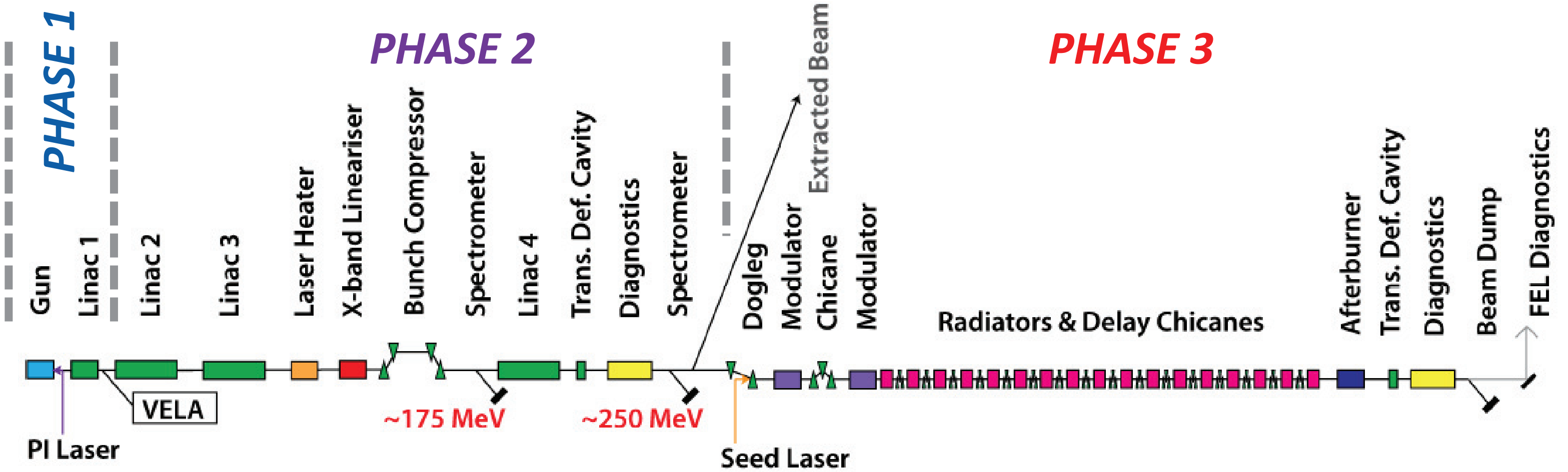

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- 2019: Installation in accelerator

PHASE 3:
100 nm FEL, NOT YET FUNDED

- 2018: Full release of funds…?
- 2021: Installation
- 2022: Lasing!!

CLARA: Refurbished, insulated building

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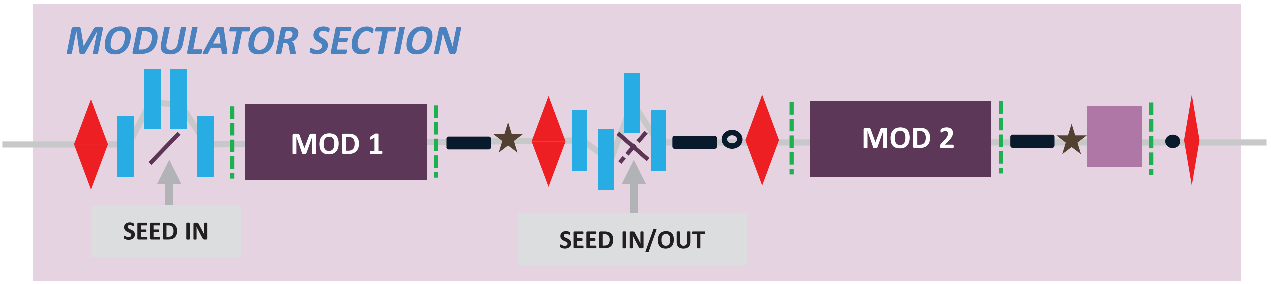
CLARA: Front End Installed

CLARA: Schematic Layout of FEL Section

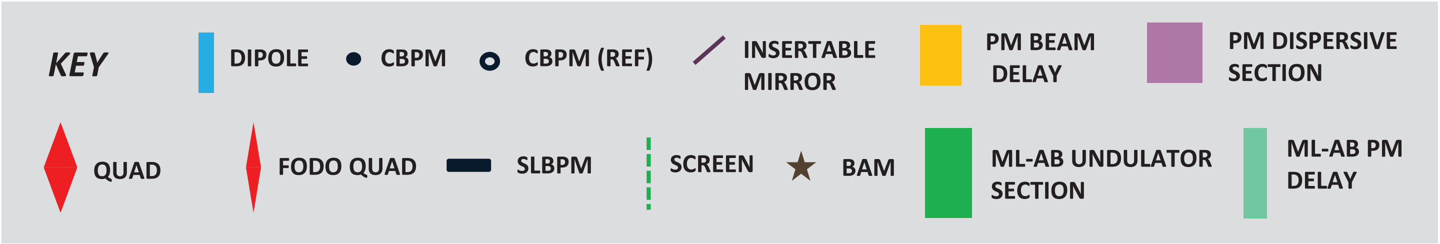


***FEATURES*:**

- 2 Modulator undulators
- 2 seed insertions
- 2 dispersive sections

ENABLING:

- Echo-Enabled Harmonic Generation
- Energy + Current Modulation
- OK effect to increase modulation



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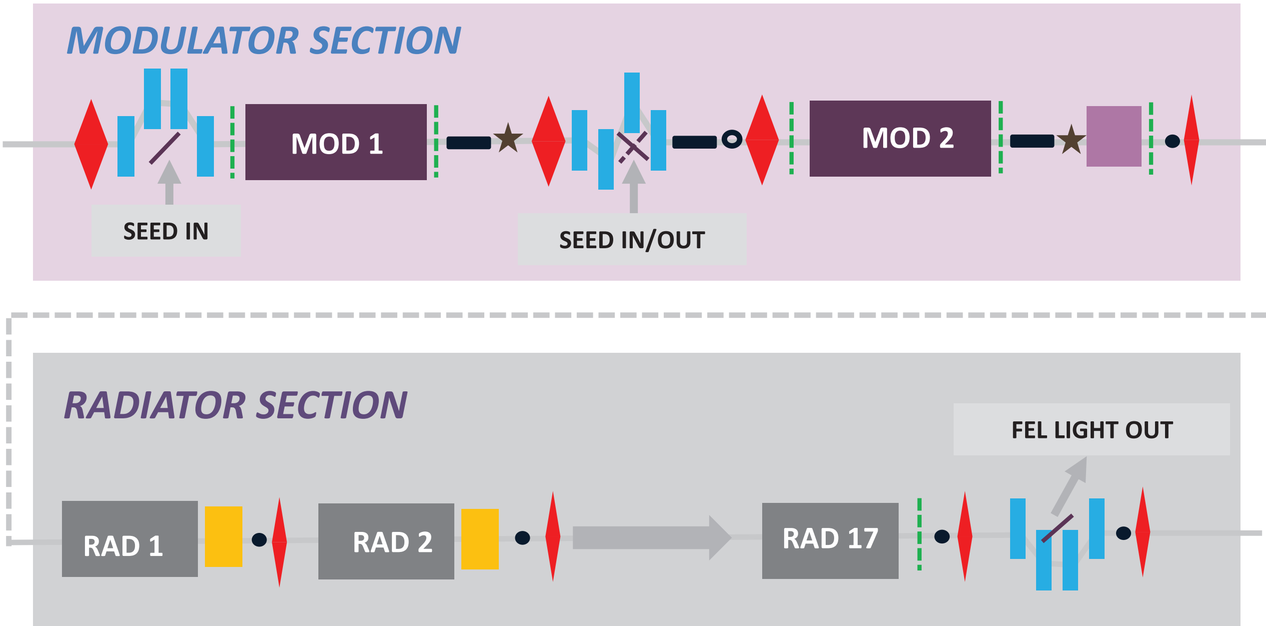

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- Delay chicanes

ENABLING:

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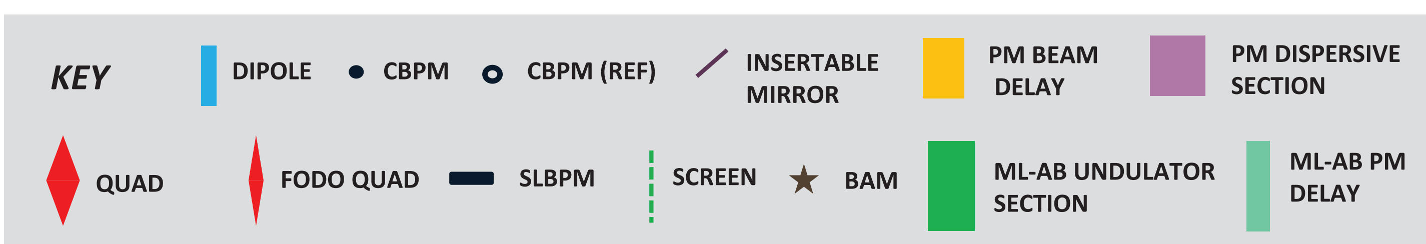
- Fresh bunch for two colour
- OK gain enhancement
- Polarisation control



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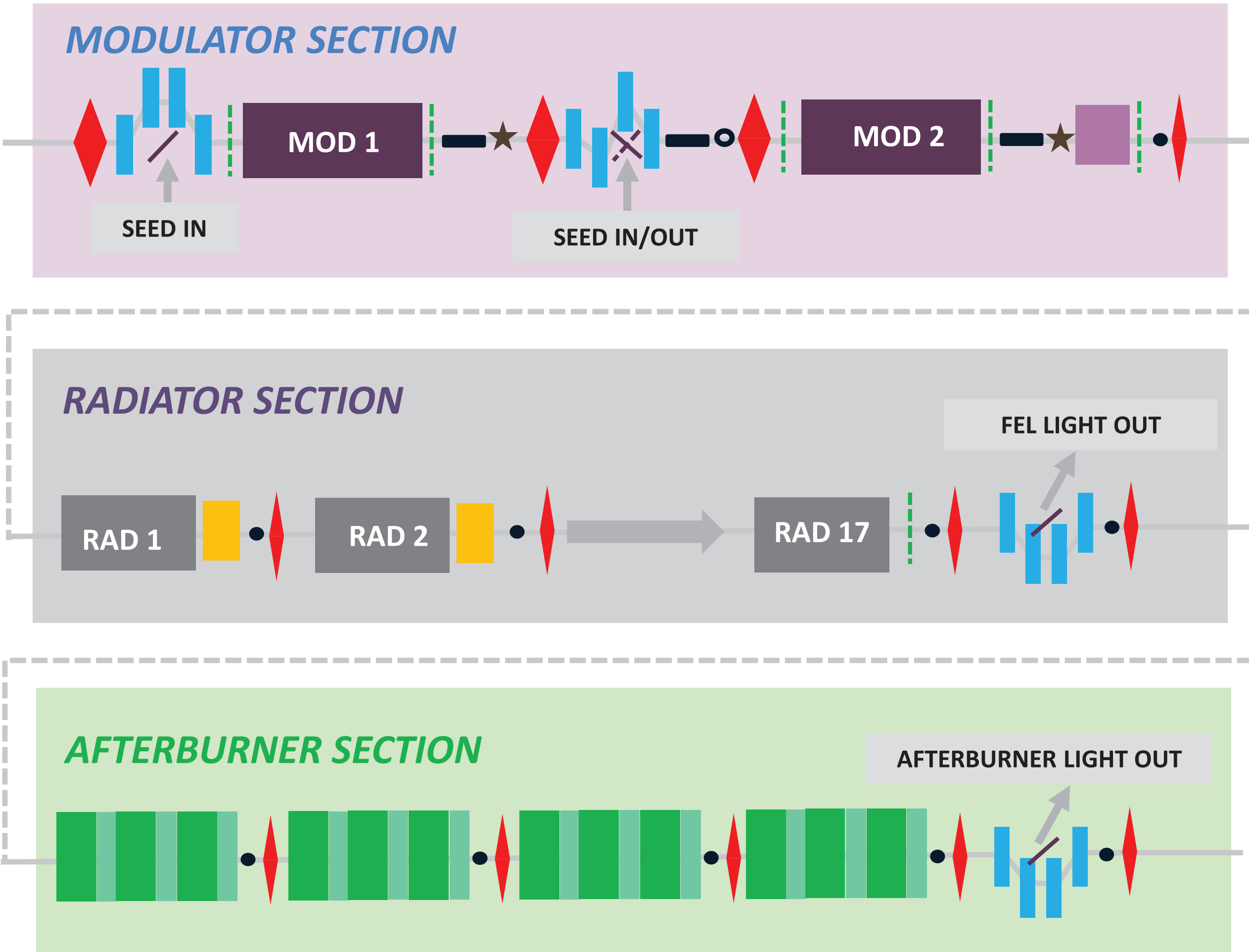

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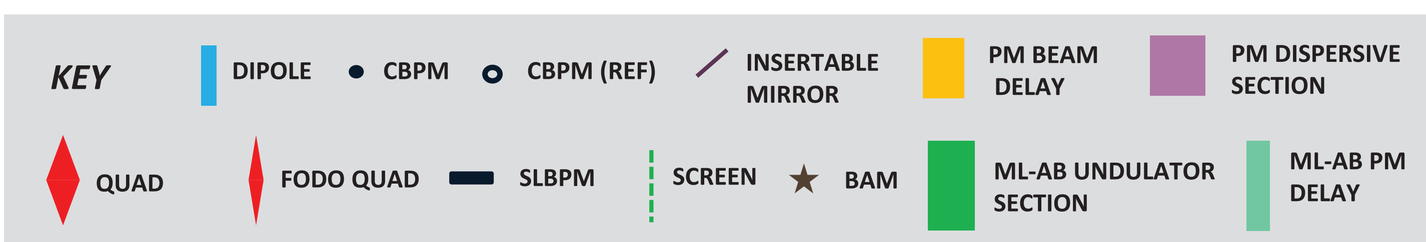
FEATURES:

- 5m space for undulator R&D and future flexibility

ENABLING:

- Mode-Locked Afterburner (shown)
- Undulator tests – RF, SC etc
- NEG tests



UK XFEL: R&D Workpackages

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  - Characterisation of CLARA 400Hz Gun; design study for UK XFEL Gun; telluride photocathode trials; design of laser pulse formation optical system
- **WP2: RF Development** (ASTeC, CI, DLS)
  - Frequency options; LLRF development; modulator technology measurements and improvements
- **WP3: Electron Beam Transport and Optimisation** (ASTeC, CI, DLS, JAI)
  - Strawman NC single pass and high rep rate SC layouts with costing strategy; S2E simulations; alignment and tuning strategies; collective effects; wakefield exploitation
- **WP4: Potential FEL Output Performance Enhancements** (ASTeC, CI, DLS)
  - Stability; flexible pulse structures; ultrashort pulses – mode-locking on CLARA ; transform limited pulses – HB-SASE on CLARA; other potential enhancements.
- **WP5: Beam Instrumentation** (JAI, CI, ASTeC)
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- **WP6: Synchronisation** (ASTeC, CI, JAI)
  - Laser/RF phase noise measurements on CLARA; 400Hz stability and electrical main asynchronous pulsing; optical MO; sub 5-fs electron beam and photon beam arrival diagnostics
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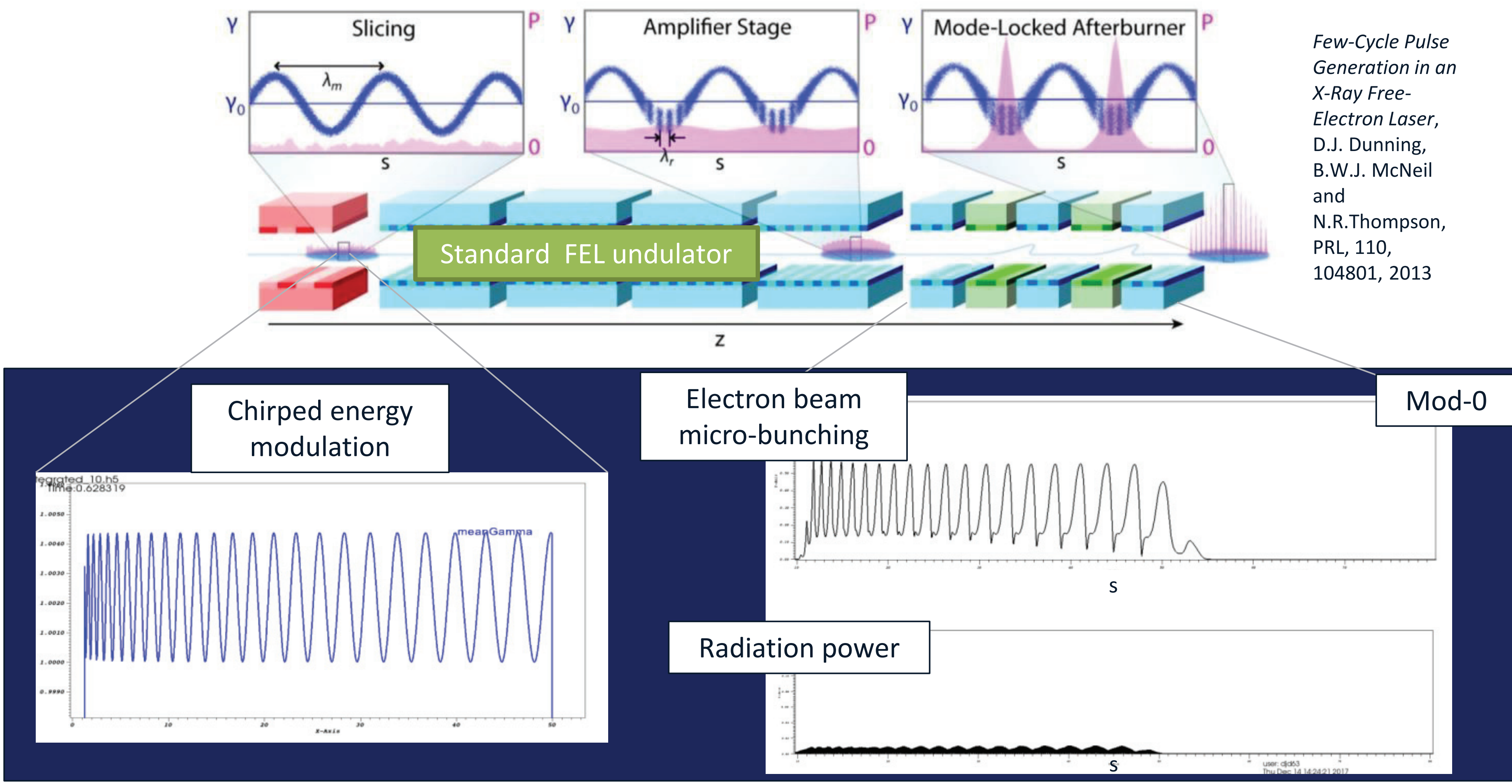

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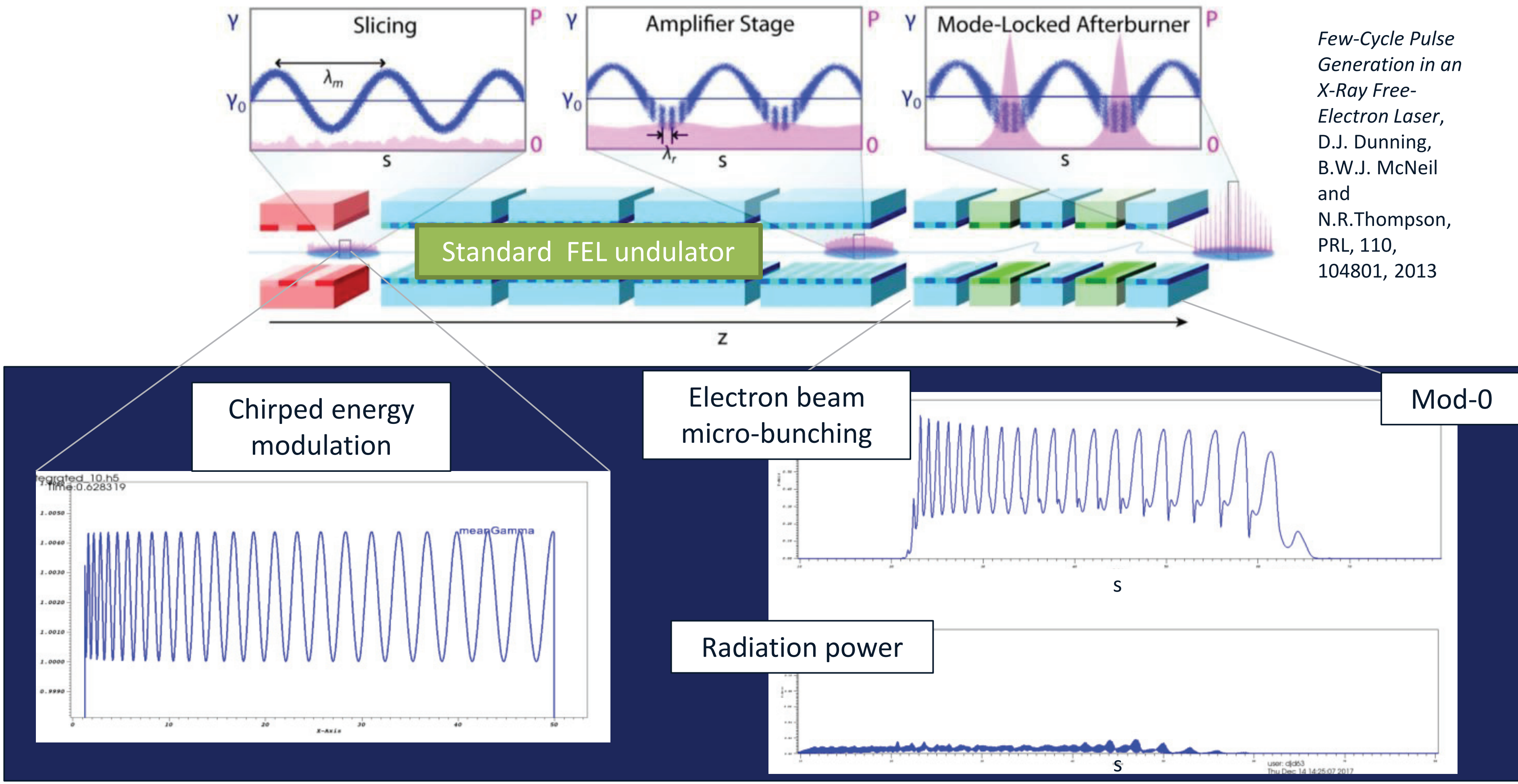

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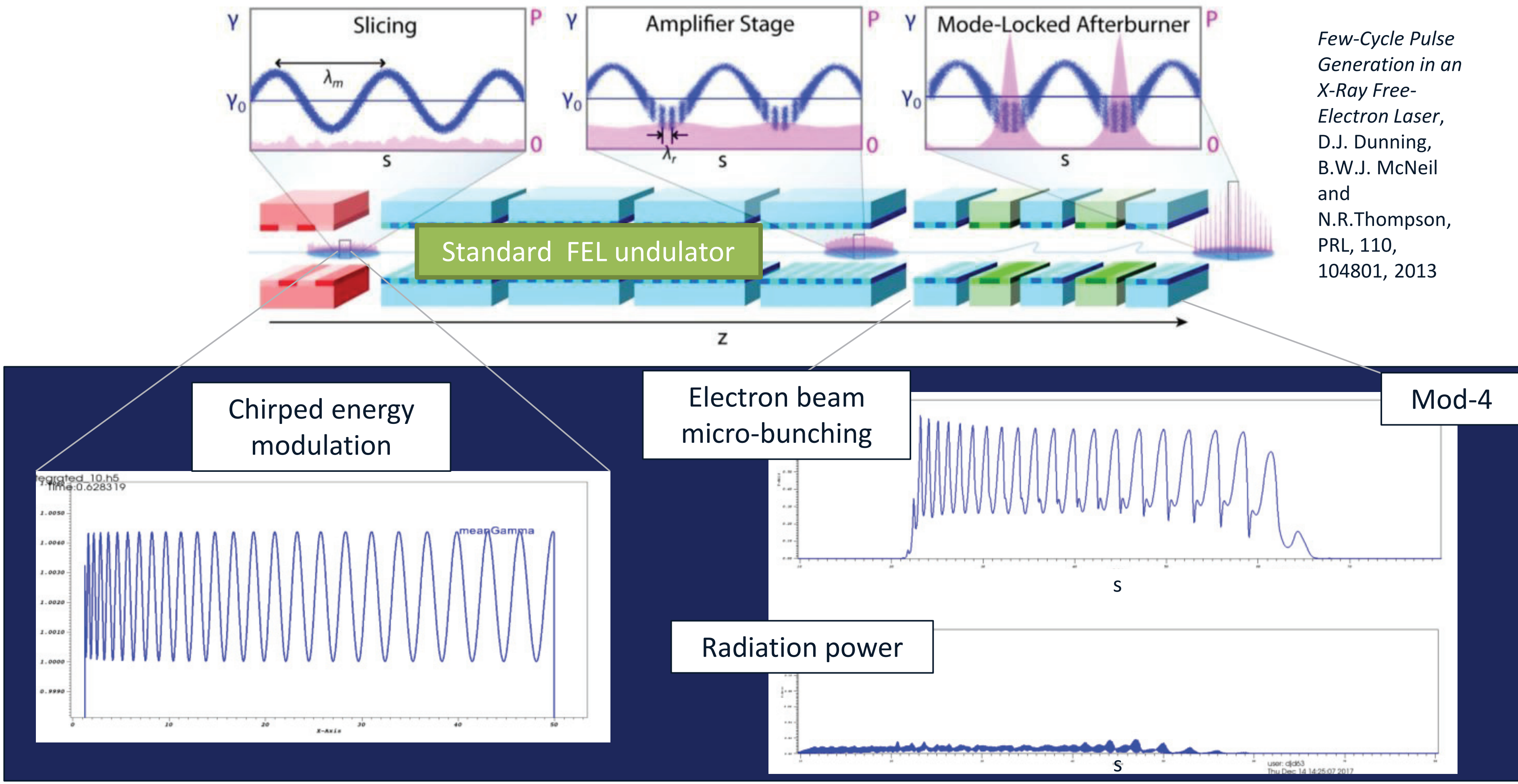

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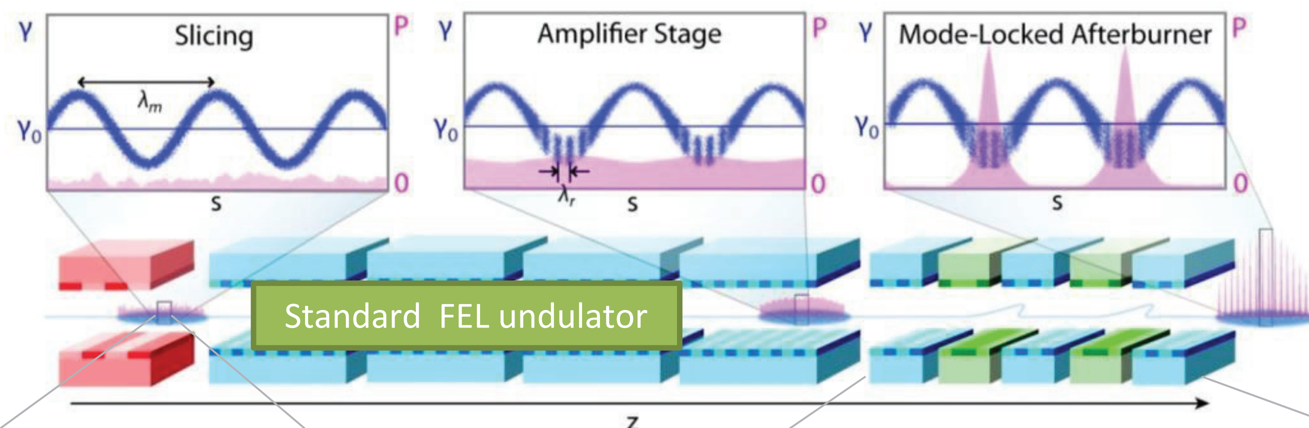

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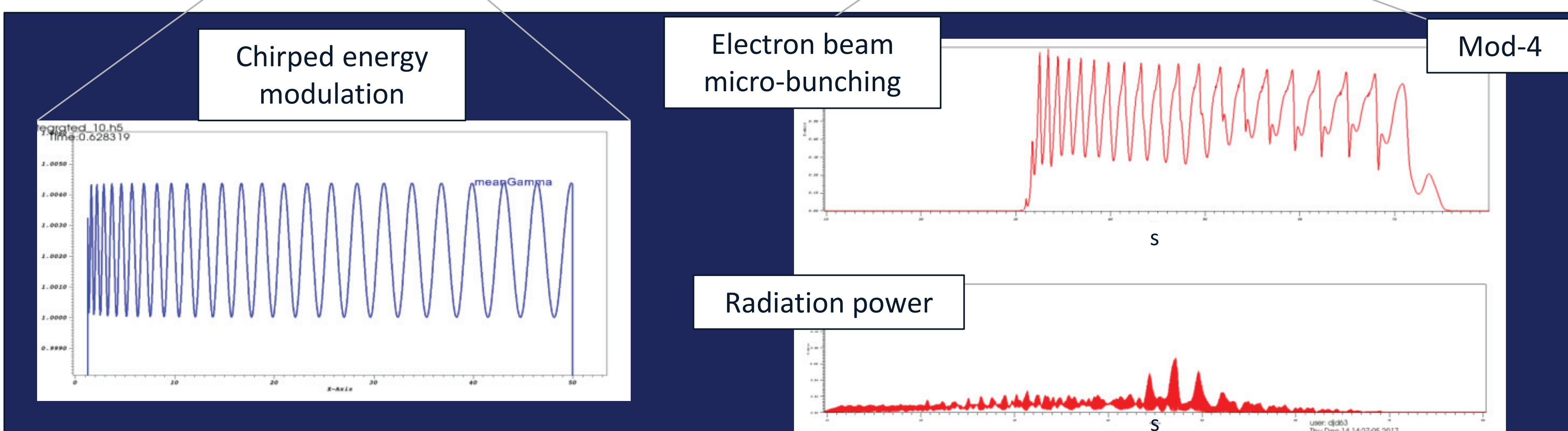

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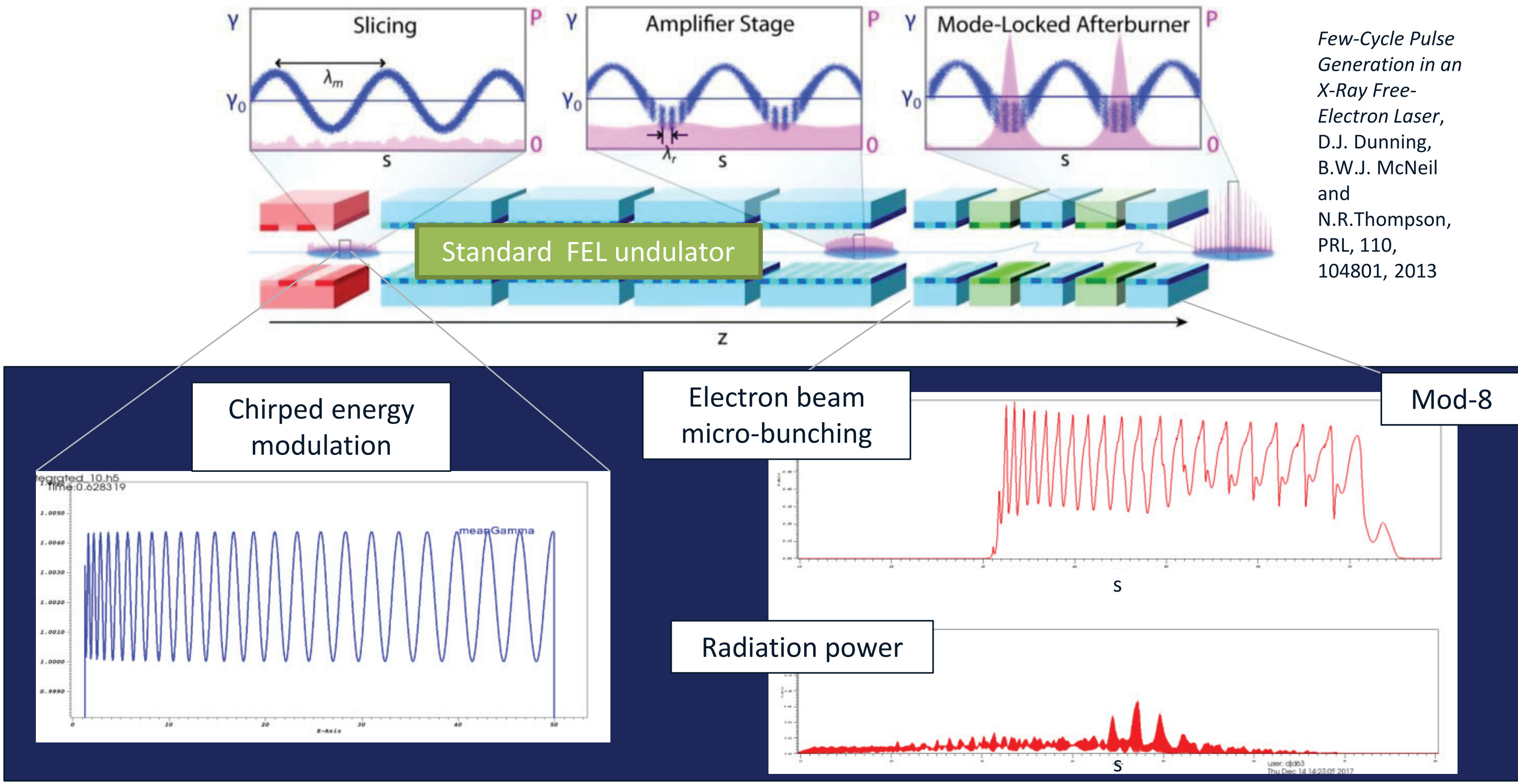

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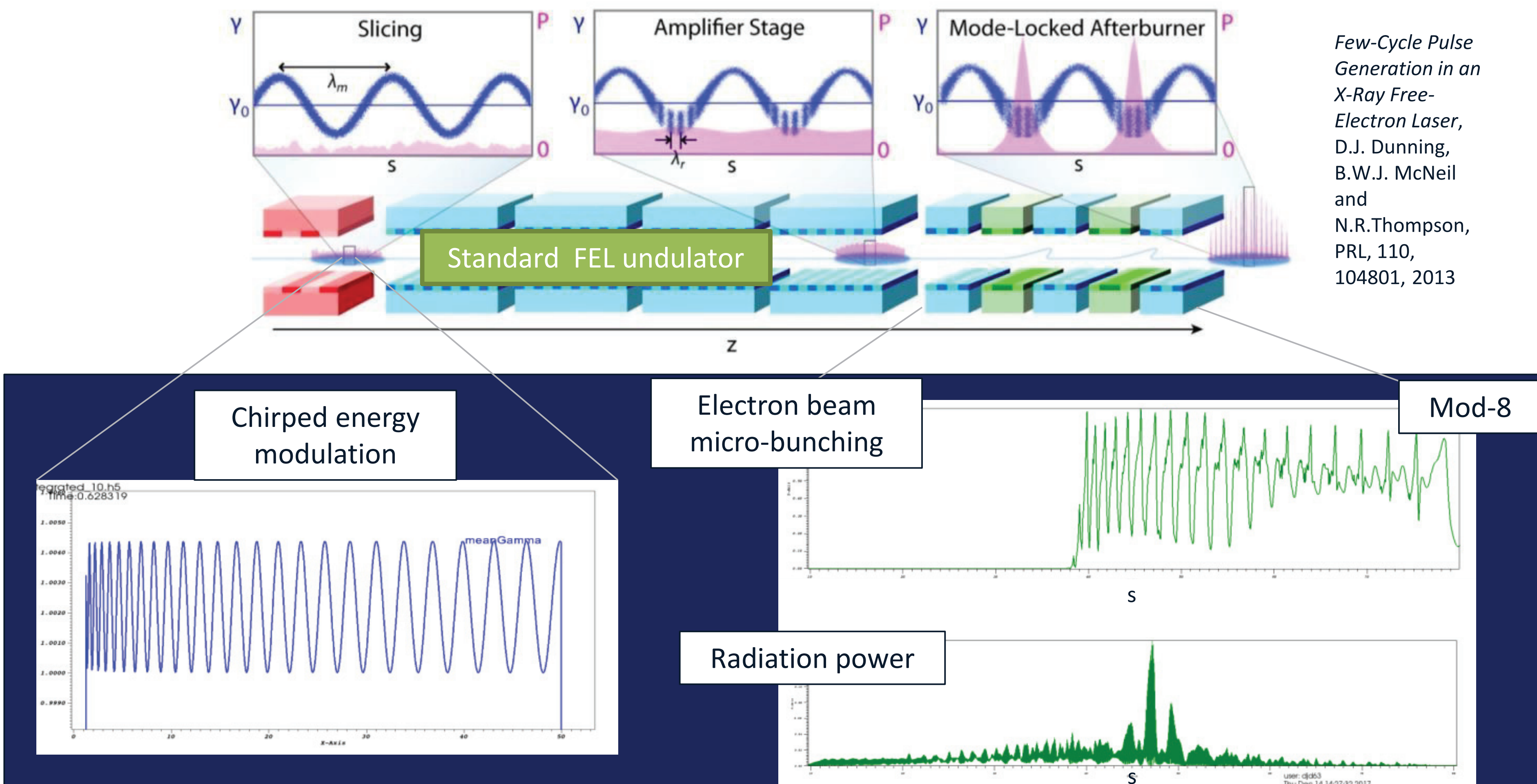

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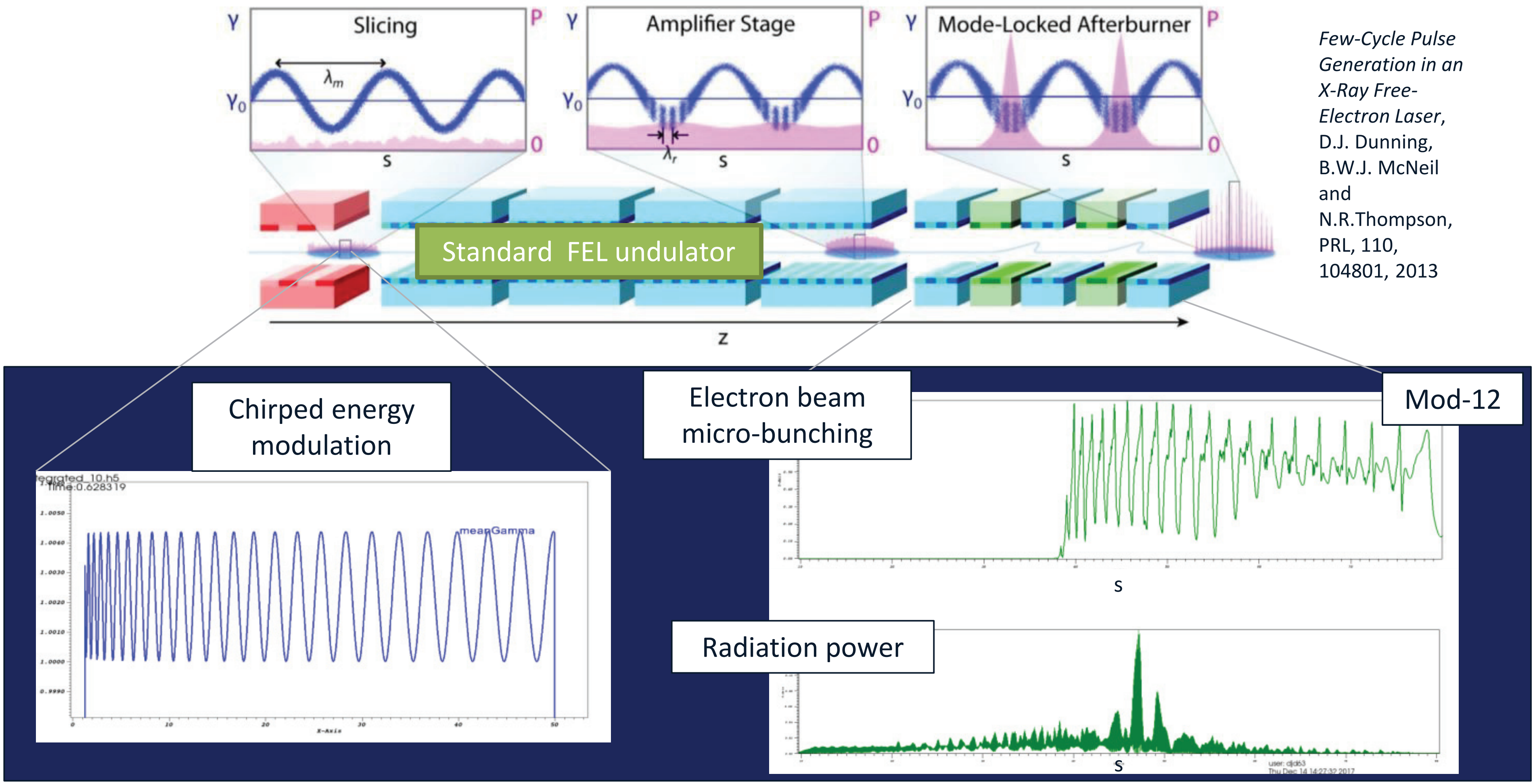

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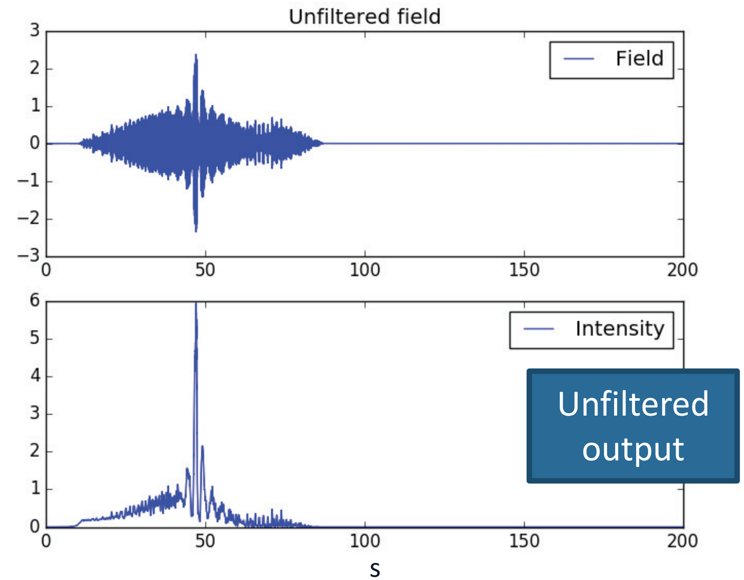
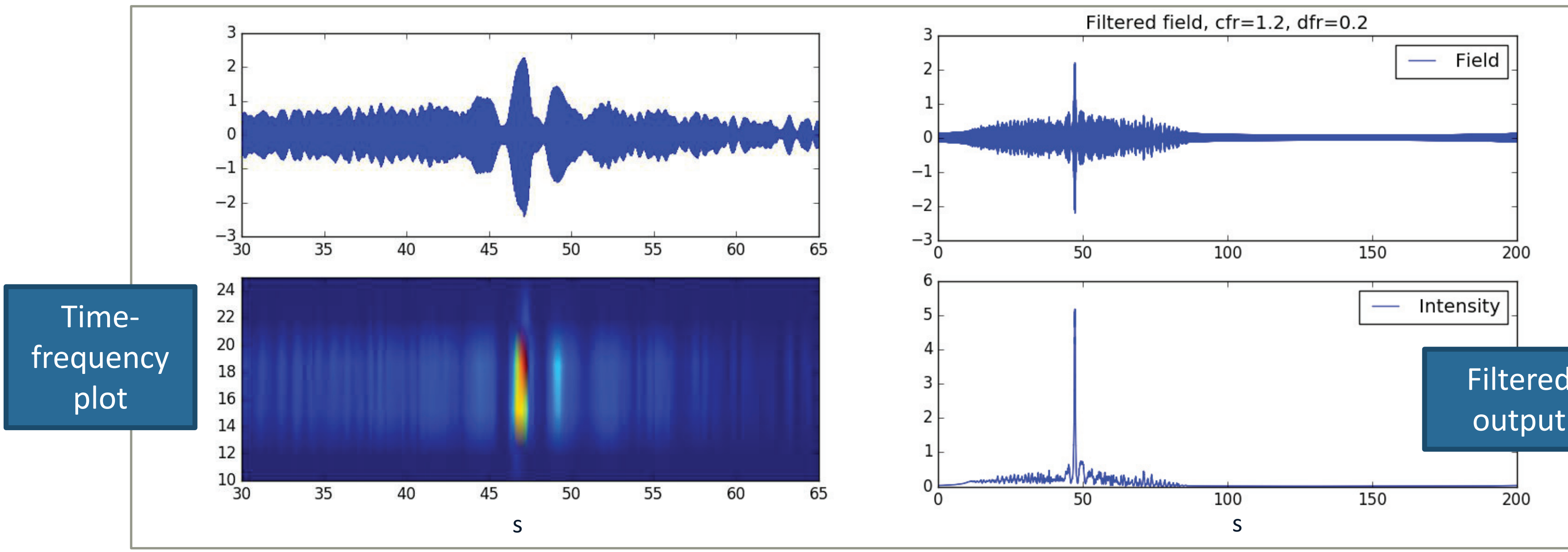
WP4: Modelling isolated few-cycle XFEL pulses

- Simulation studies with the non-averaged PUFFIN code predict a pulse with <u>6 optical cycles FWHM with peak power at normal FEL saturation level</u>
- However there are side-pulses with peak intensity up to 30% of the main pulse.
- One method to improve the contrast ratio is to exploit the fact that the central peak has a frequency shift – a high pass filter removes the background and the side pulses to give an 'isolated' single spike.





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- This technique increases temporal coherence using electron beam delays, with the potential for transform limited XFEL pulses without the use of external seeding or self-seeding.
- For **dipole-only** beam delays the increase in coherence is factor ~ 10. This is being implemented on CLARA and Athos at SwissFEL
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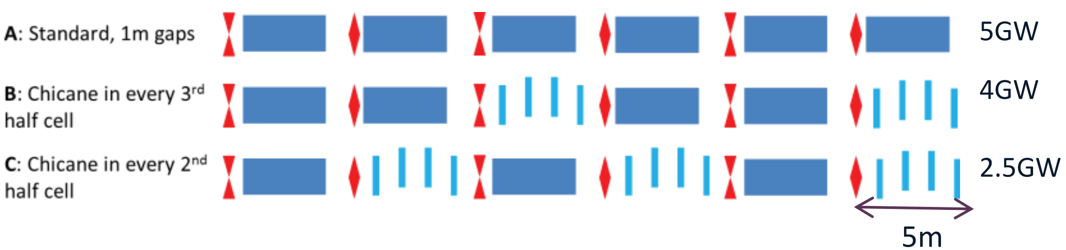
Genesis simulations of 3 Example Scenarios for a 6 GeV 1.24 Angstrom FEL



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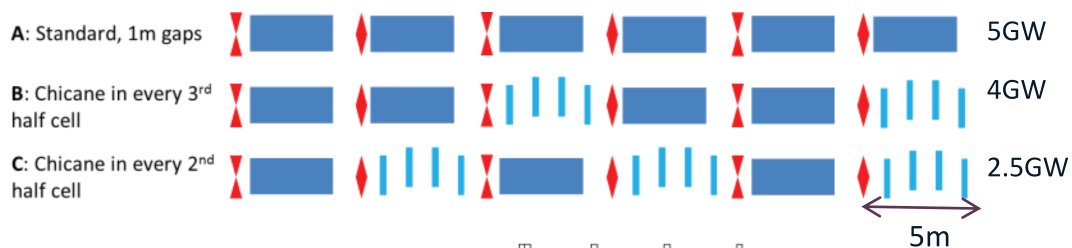

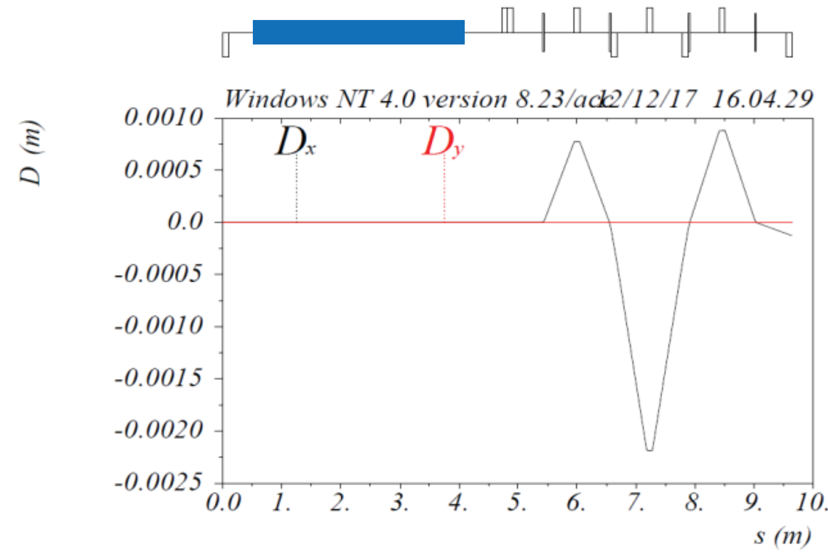

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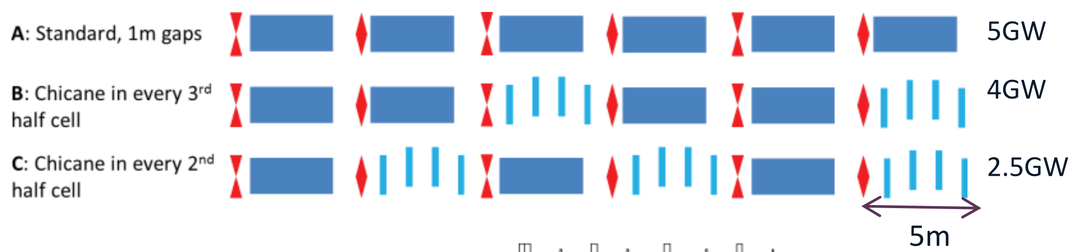
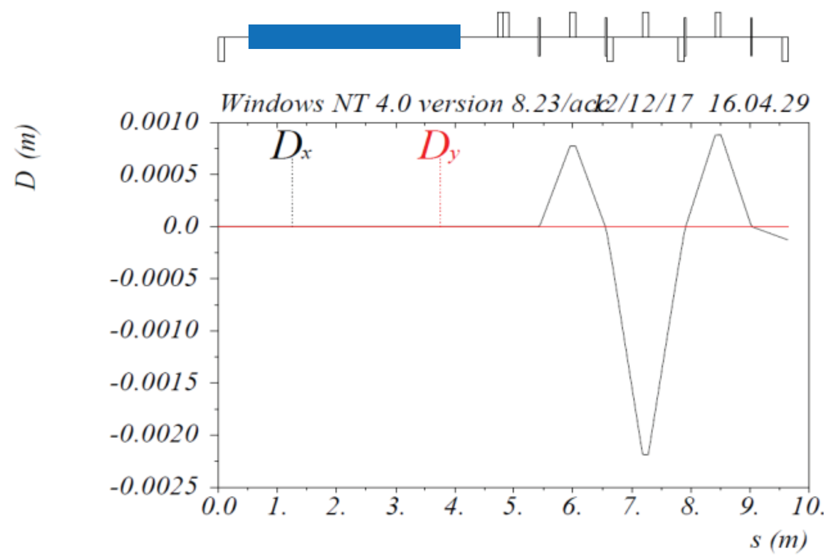
3. Assessing exactly how isochronous the chicanes need to be – ***what residual R_{56} is acceptable?***

Genesis simulations of 3 Example Scenarios for a 6 GeV 1.24 Angstrom FEL

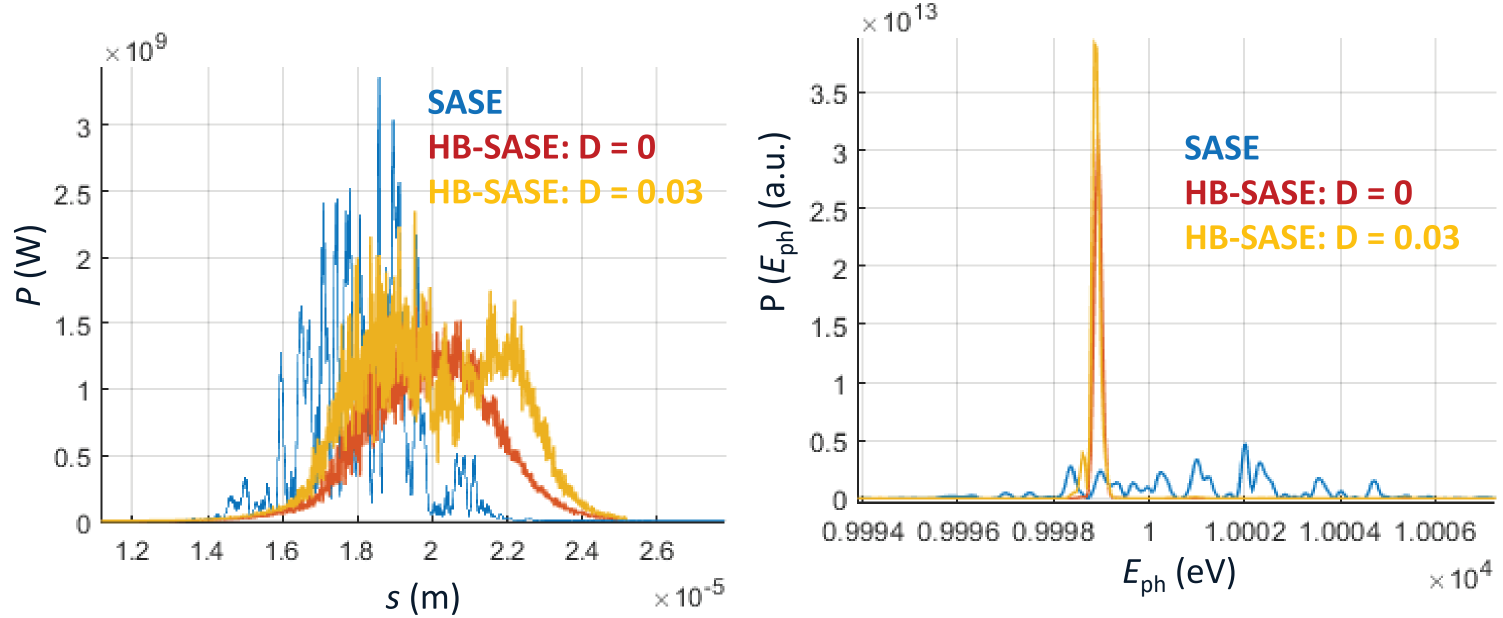




WP4: High-Brightness SASE

Example: 10keV FEL with 6GeV, 50pC, 2kA bunch

D = Ratio of beam delay R_{56} to that of a three-dipole chicane



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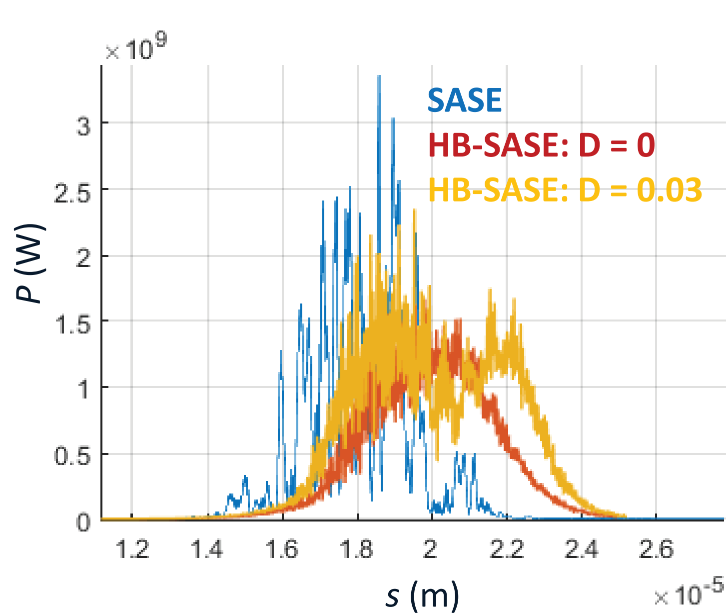

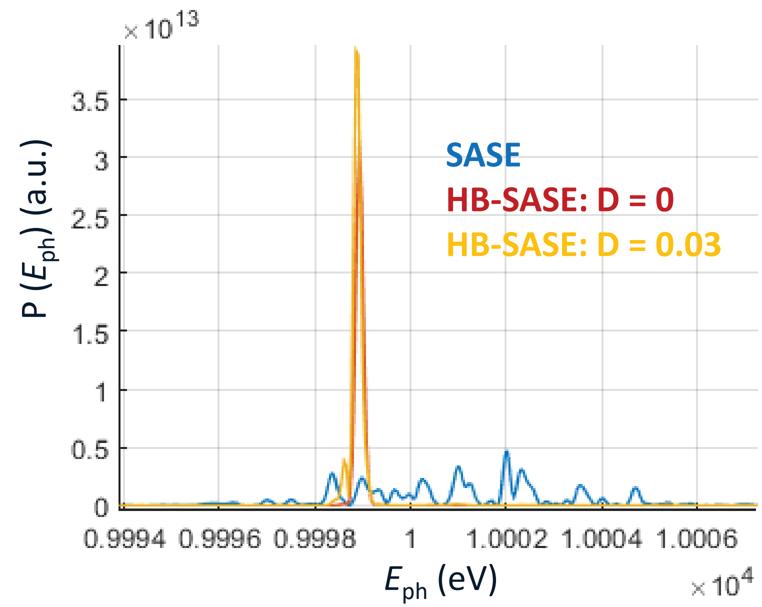

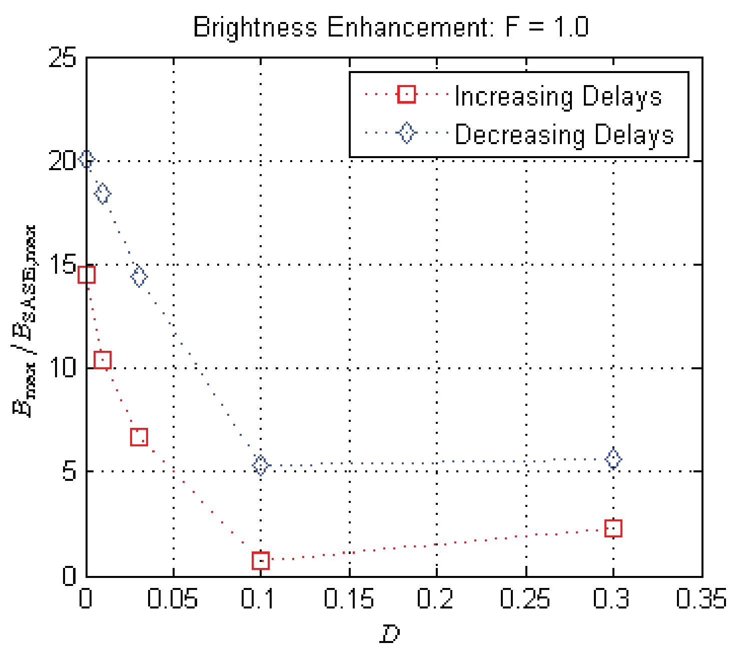

UK XFEL: What might it look like?

- There have been a number of discussions with small groups of UK based XFEL users to determine a likely output specification.
- This is being used as <u>representative only</u> for the R&D programme and is not the final specification for UK XFEL which will evolve over the next years.
- The pragmatic ‘working’ specification is as follows:
  - **Photon energy range 250eV to 25keV** - *This implies at least four separate FEL beamlines at different electron beam energies.*
  - **High repetition rate (MHz) is preferred** - *This implies SCRF but it is not clear if MHz is required at the highest photon energy.*
  - **Pulse energies, at the highest photon energies, of up to 3mJ** - *This implies options for high charge bunches and tapering for maximum efficiency.*
- In addition, we assume
  - **Double pulses with variable separation in time and wavelength** - *We anticipate a factor of two in wavelength separation via gap tuning and a delay of up to ~1ps (i.e. approximately what can be achieved in a 4m delay chicane)*
  - **Options for temporal coherence**
  - **Sub-fs pulses**

Science & Technology Facilities Council

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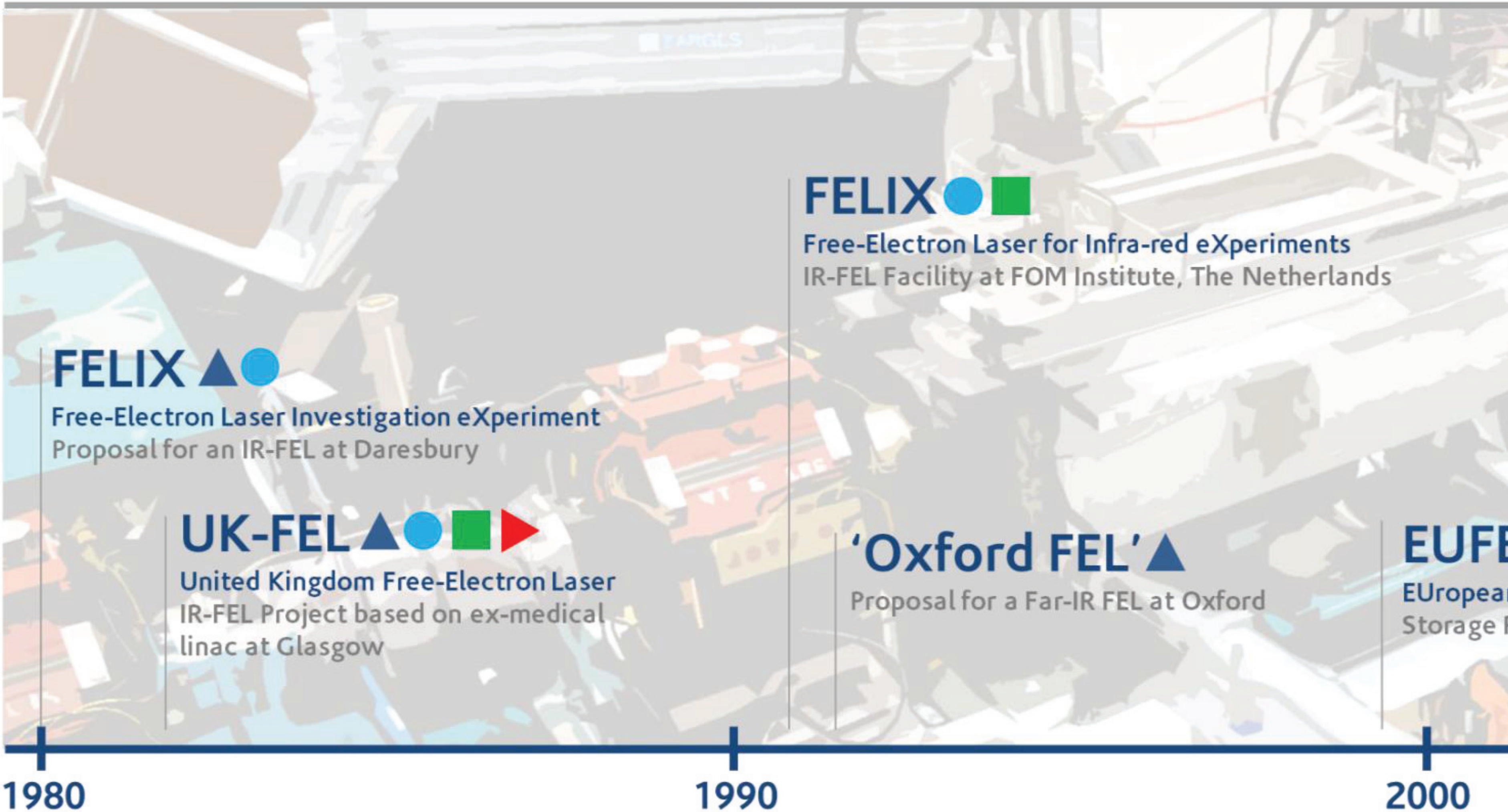
Extra material

Free-Electron Laser Activities at Daresbury

Four Decades of Conception, Design, Construction and Operation



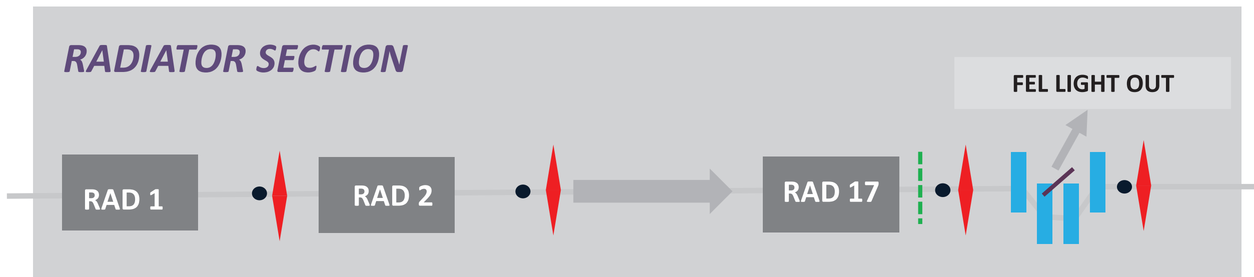
KEY: ▲ Conception ● Design ■ Construction ▶ Operation

CLARA: FEL R&D Topics and Layout Requirements

The selected schemes are listed below in a tentative running order:

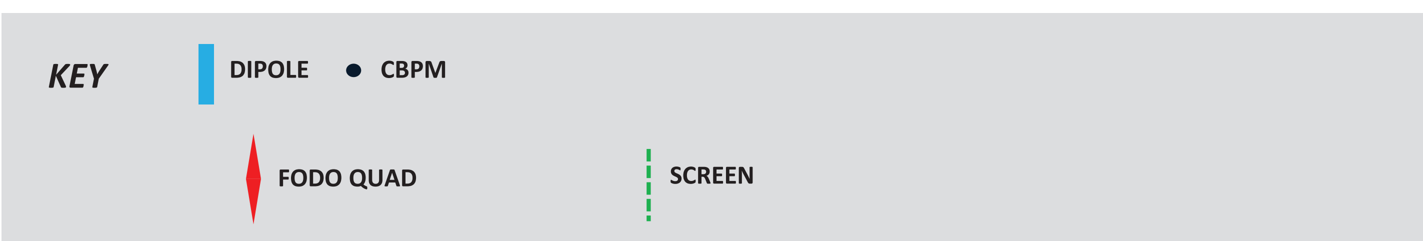
Category	Scheme	Key requirements for FEL	External Laser
Initial projects (relatively quick, no external laser modulation)	**Single-spike SASE**	Standard radiator	N/A
	Tapering	Variable undulator gap	N/A
	2-colour schemes	Variable undulator gap	N/A
	Novel undulators	Space for testing	N/A
Major projects (detailed studies)	**HB-SASE**	Chicane delays in radiator	N/A
	Mode-locked FEL	1 seed + 1 or 2 modulators + chicane delays in radiator	20um laser OR 800nm laser induced beating modulation @ 30-60um
	Mode-locked afterburner	1 seed + 1 modulator + bespoke mode-locked afterburner section	3-8um OPA driven by 800nm
Other potential schemes impacting the layout	**Slicing via energy chirp**	1 seed + 1 modulator + undulator tapering	~70um (alternative via 800nm temporal notch)
	Variable polarisation	Rotatable undulators	N/A
	Echo-enabled harmonic generation (EEHG)	2 seeds + 2 modulators + chicanes after modulators	800nm + 800nm
	Freq. modulation	Tapered radiators	N/A

CLARA: Possible Configurations

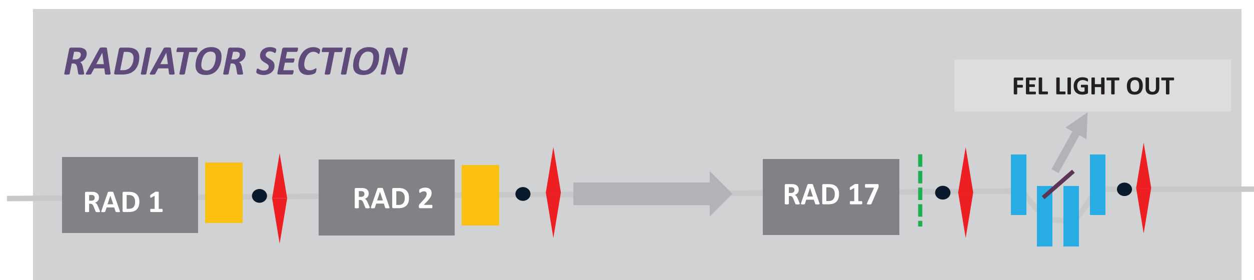


SASE, TAPERING, BASIC 2-COLOUR

Standard variable gap radiator

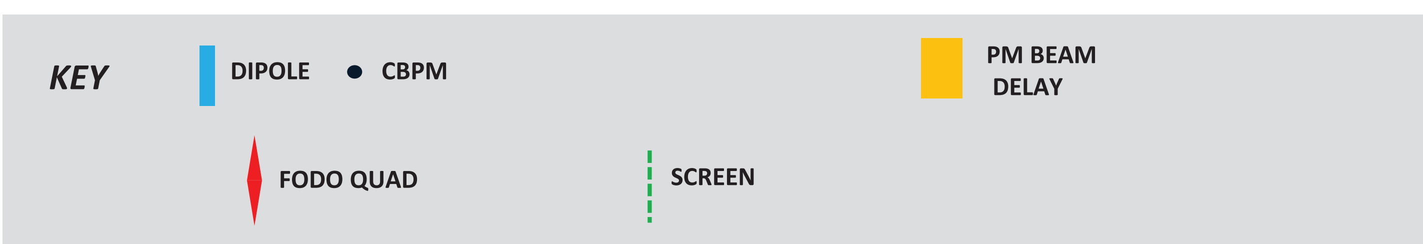


CLARA: Possible Configurations

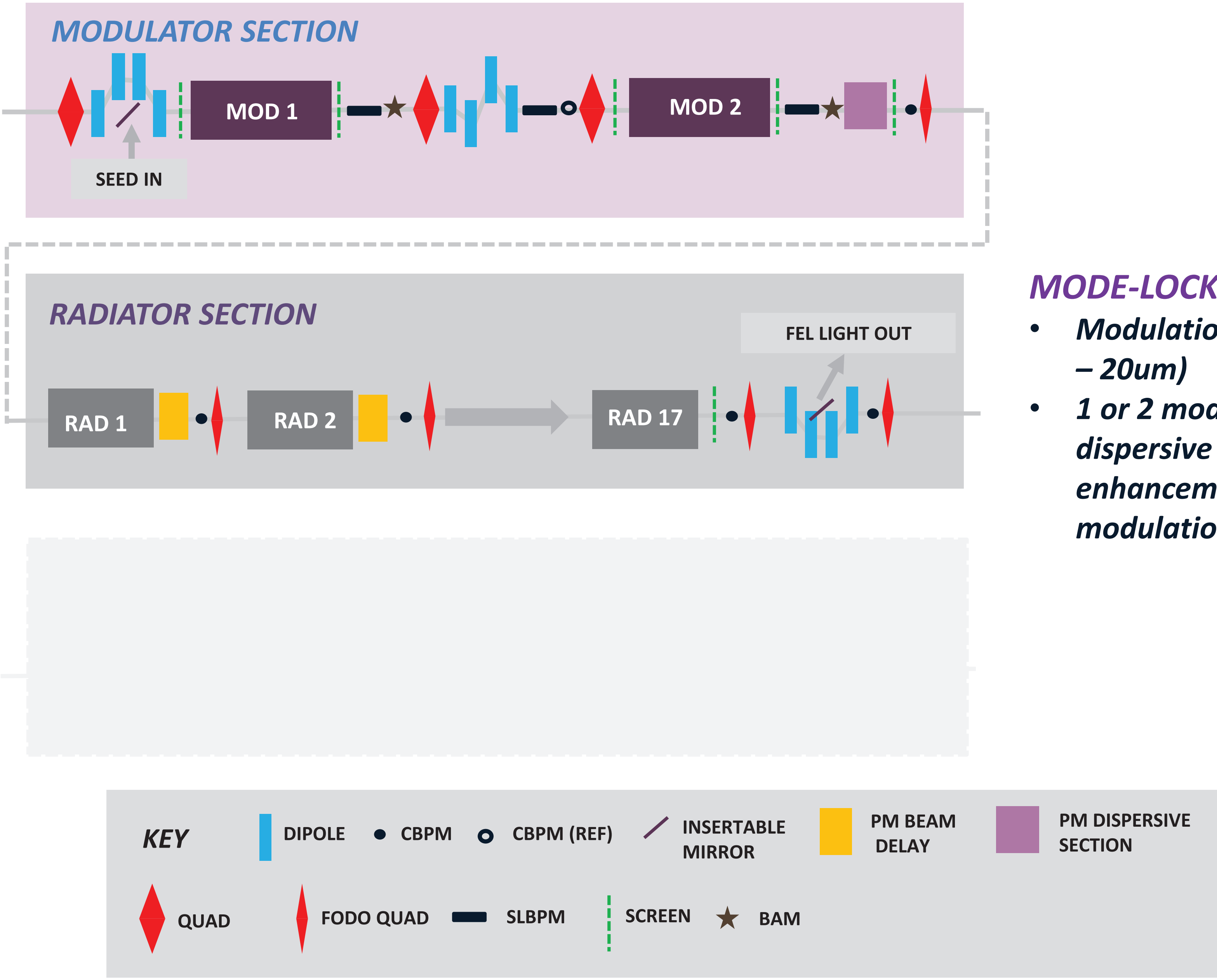


HB-SASE

- ***Permanent magnet beam delays in radiator***



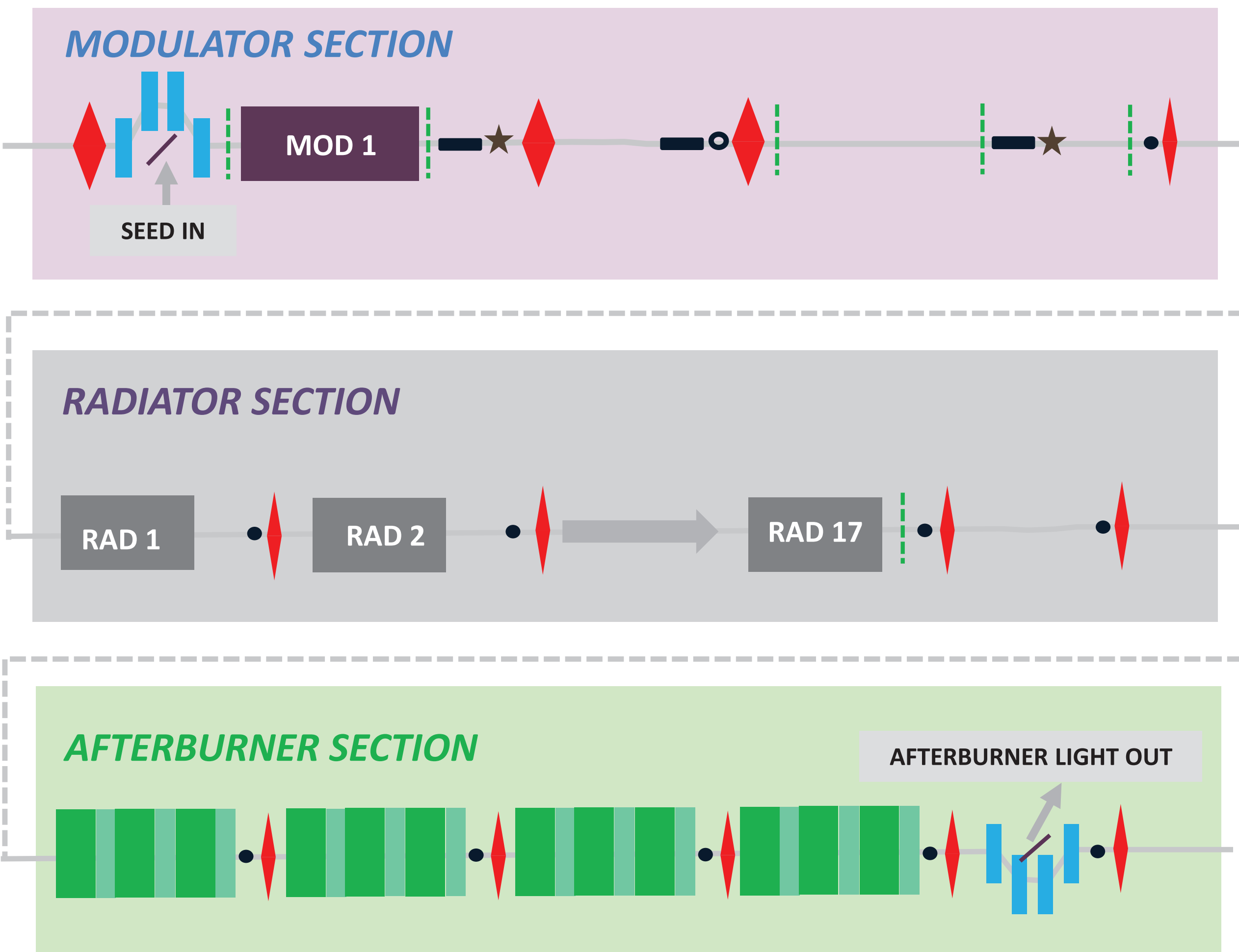
CLARA: Possible Configurations



MODE-LOCKING

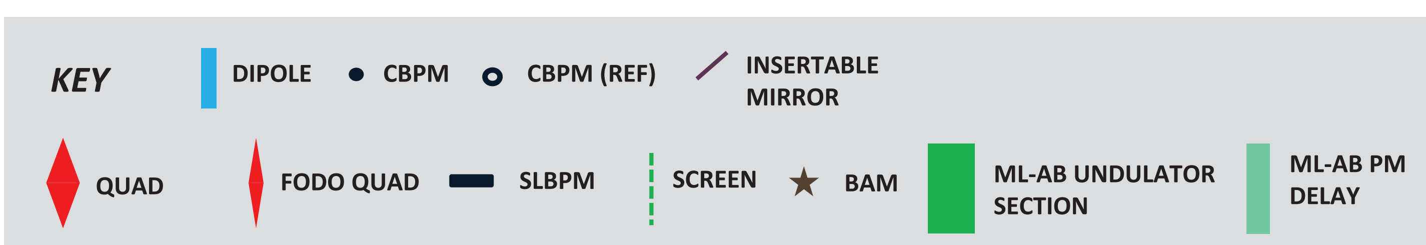
- ***Modulation laser (800nm – 20um)***
- ***1 or 2 modulators plus dispersive sections for OK enhancement or current modulation***

CLARA: Possible Configurations

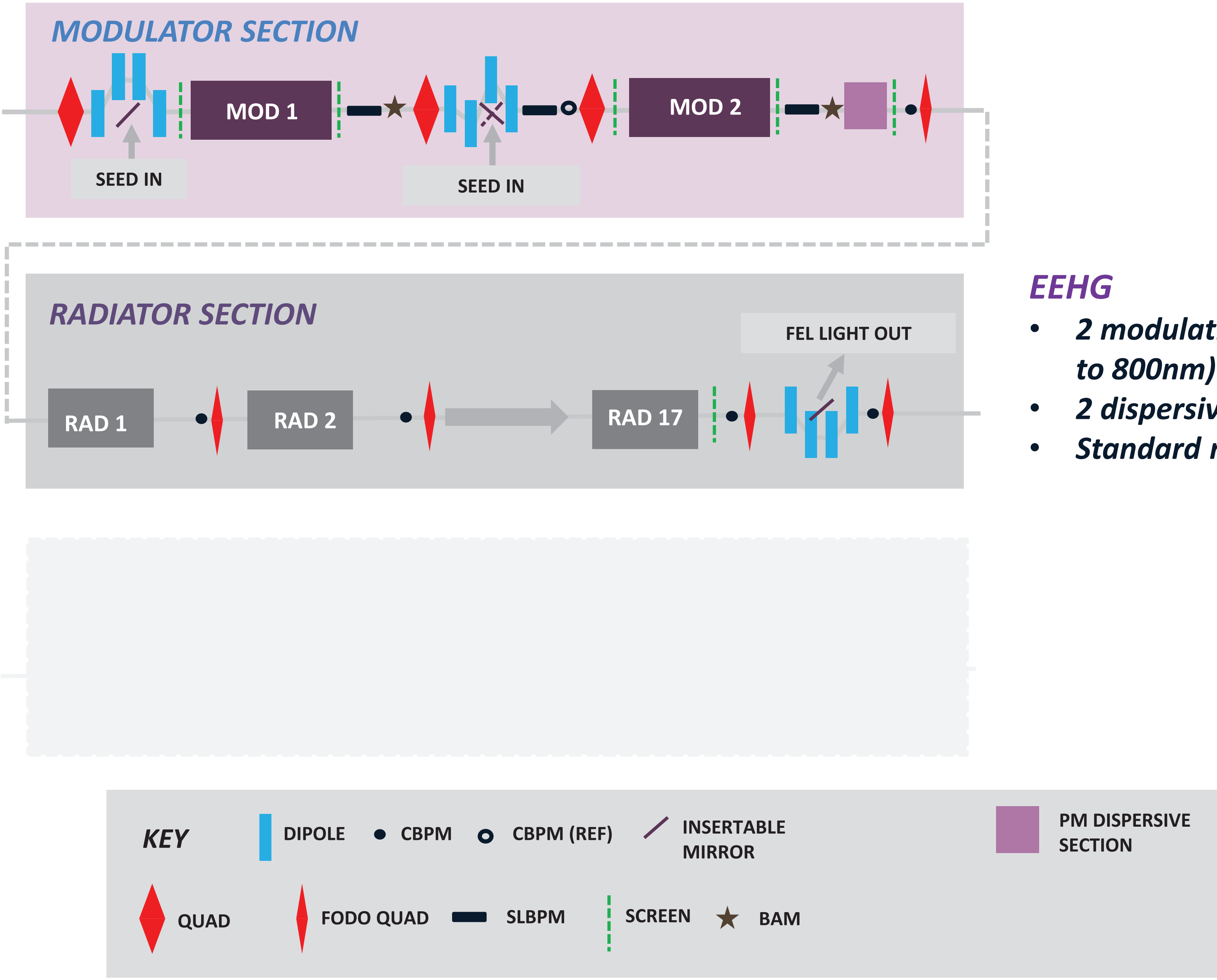


MODE-LOCKED AFTERBURNER

- *Modulation laser (3um – 8um)*
- *Standard radiator*
- *Afterburner*



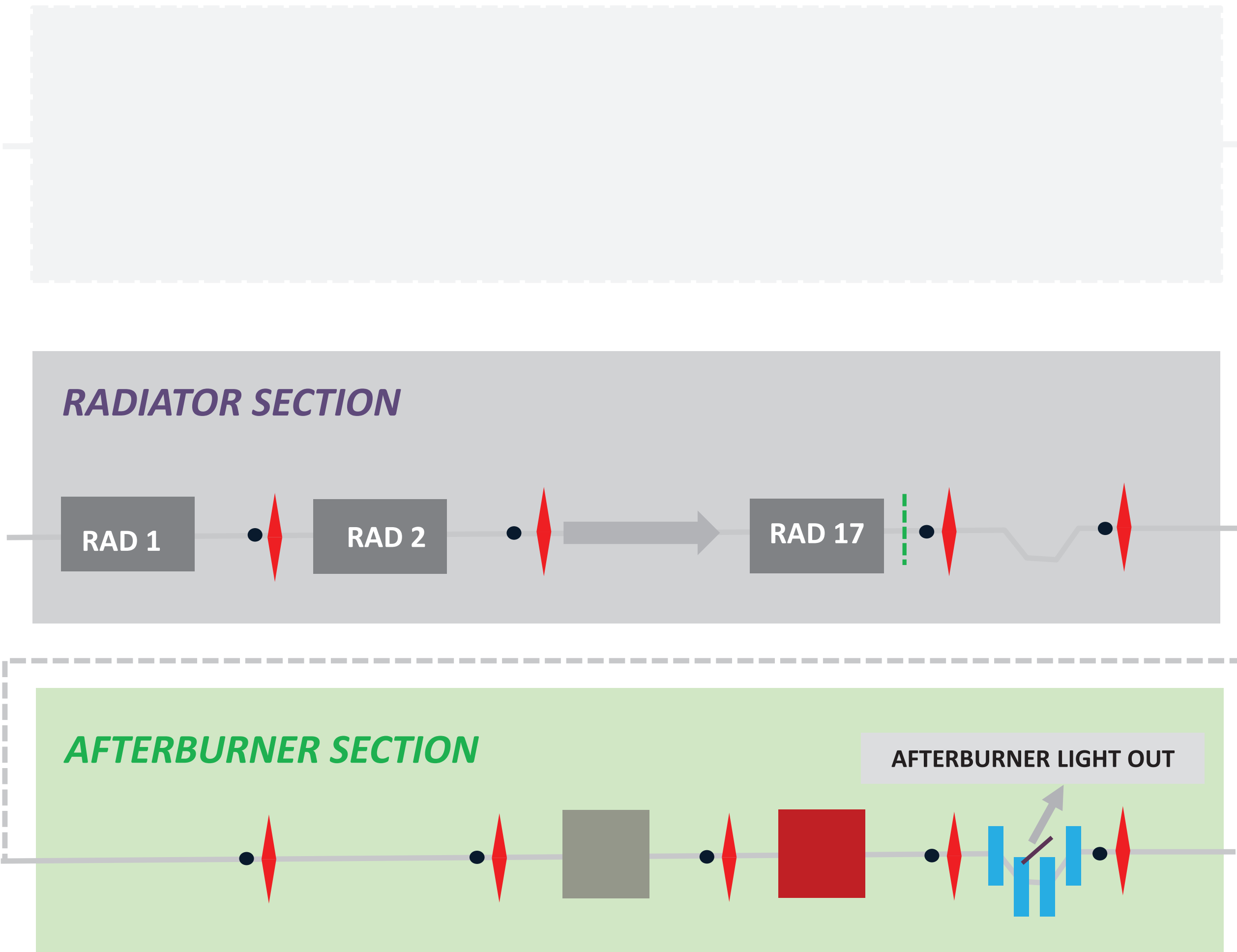
CLARA: Possible Configurations



EEHG

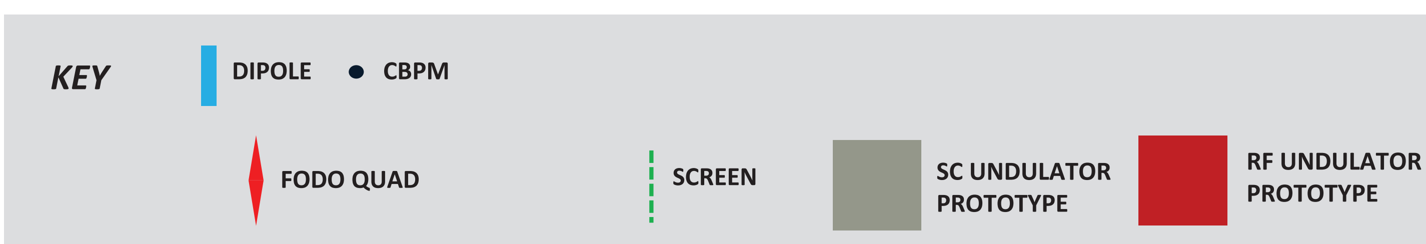
- ***2 modulation lasers (3um to 800nm)***
- ***2 dispersive sections***
- ***Standard radiator***

CLARA: Possible Configurations

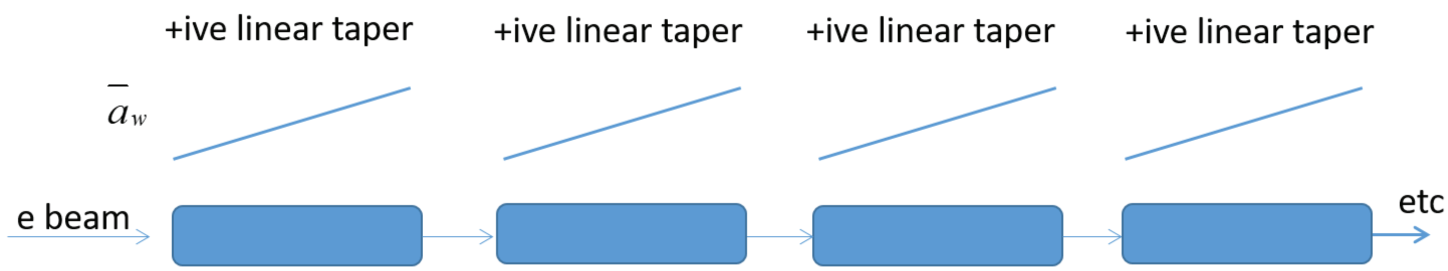


UNDULATOR TECHNOLOGY DEMO

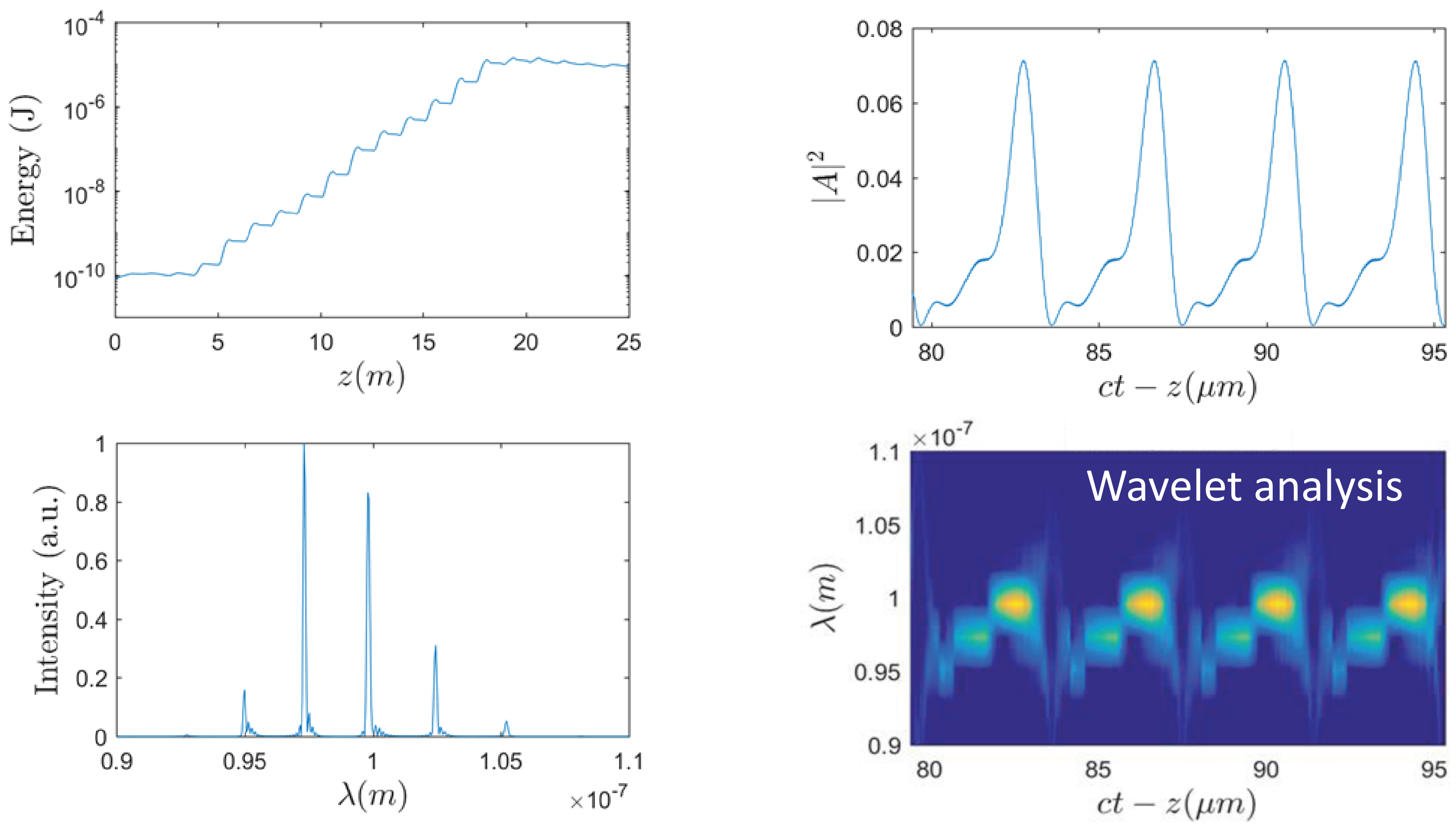
- ***Emission from prebunched beam to test undulator technology***



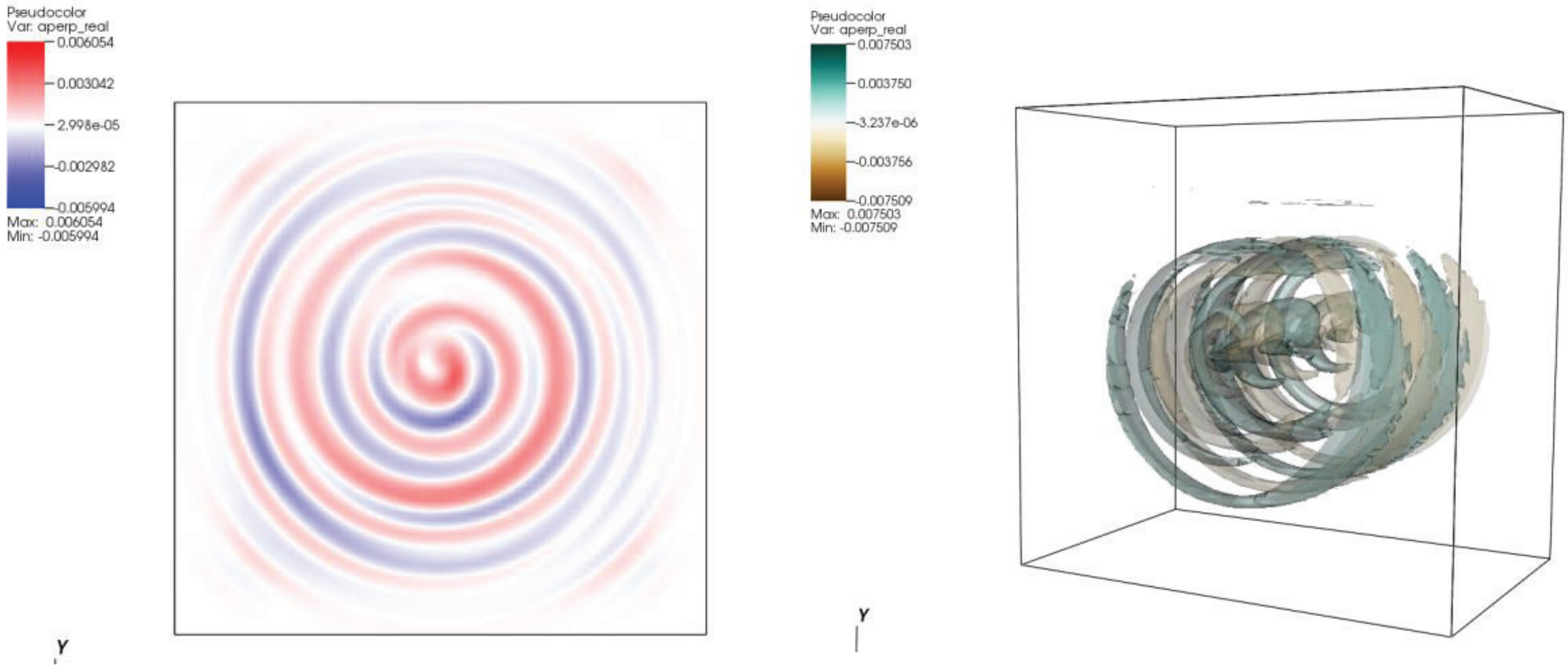
WP4: Frequency Modulated FEL - CLARA



Periodically modulate undulator magnetic field



WP4: Orbital Angular Momentum



2nd Harmonic Radiation Field of CLARA. $l = 1$ mode

These are the first simulations of OAM generation in a FEL

New PhD student, Jenny Morgan, is looking at using orbital angular momentum in FELs for multi-colour, short pulses, OAM mode-locking and more. Involves collaboration with conventional OAM experts at Strathclyde [1] and Stanford University (SLAC).

[1] Alison Yao and Miles Padgett, '*Orbital angular momentum: origins, behaviour and applications.*' Advances in Optics and Photonics, **3** (2011)