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The CLARA Project - Rationale and Experimental Program of an X-Ray FEL Test Facility

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STFC Daresbury Laboratory and The Cockcroft Institute
on behalf of the CLARA & VELA Project Teams

LCWS14, 9th October 2014



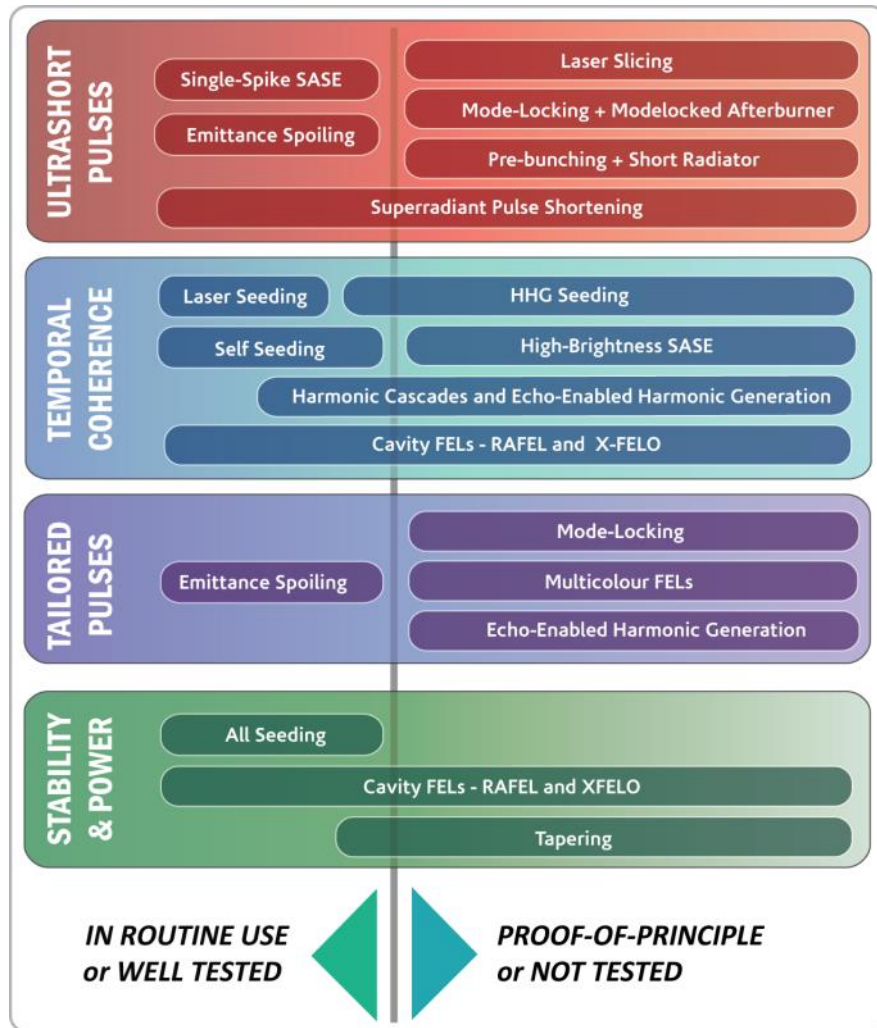
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Free Electron Lasers

- **FELs have made huge advances in the past few years**
 - **First X-ray FEL in 2009 (LCLS) then SACLA in 2011**
 - More X-ray facilities are under construction
 - Advanced soft X-ray facilities are also now operating routinely for users as well (FLASH & FERMI)
- **The potential for improvements is enormous**
 - *Increased temporal coherence*
 - *Increased wavelength stability*
 - *Increased power*
 - *Increased intensity stability*
 - *Ultra-short pulses of light (sub-fs)*
 - *Two-colour or Multi-colour output*
 - ...

The 'FEL Case' for an FEL Test Facility



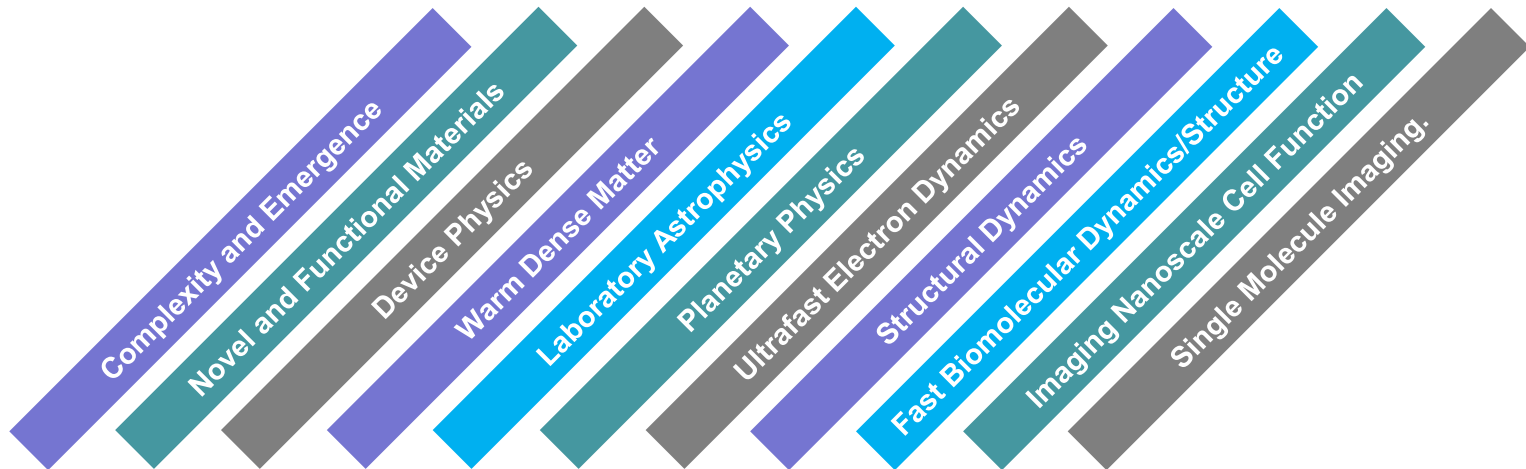
- Free-Electron Lasers (FELs) are remarkable scientific tools
- Short-wavelength FELs are operating for users around the world, for example LCLS (USA), SACLA (Japan), FLASH (Germany) and FERMI@Elettra (Italy).
- There are still many ways their output could be improved:
 - **Shorter Pulses**
 - **Improved Temporal Coherence**
 - **Tailored Pulse Structures**
 - **Stability & Power**
- There are many ideas for achieving these aims, **but many of these ideas are untested**
- **Beamtime on FELs is over subscribed by users and so little time for R&D**

CLARA

- We propose that the UK hosts a new dedicated flexible FEL Test Facility
 - Capable of testing the most promising new schemes
- We have strategically decided to target ultra short pulse generation
 - We are focussing on *the longer term capabilities* of FELs, not short term incremental improvements
 - Taking FELs into a new regime
 - By demonstrating this goal we will have to tackle all the challenges currently faced by state of the art FELs (and a few more!)

The UK Strategic Case

The UK science community has identified that
X-ray FELs are critical to many science challenges



- There is thus a high priority to secure access to an X-Ray FEL
- This may be done initially through engagement in the European XFEL project, or looking further ahead, the ***UK may wish to construct its own X-ray FEL facility***
- R&D activities in support of this need to be put in place.

The CLARA Concept

There are many ways FELs can be improved, but limited scope with existing facilities

UK Scientists need FELs and we want to develop next generation FEL technology towards a possible UK facility



CLARA

*Compact **L**inear **A**ccelerator for **R**esearch and **A**pplications*

An upgrade of the existing VELA Photoinjector Facility at Daresbury Laboratory to a 250MeV Free-Electron Laser Test Facility

Proof-of-principle demonstrations of novel FEL concepts

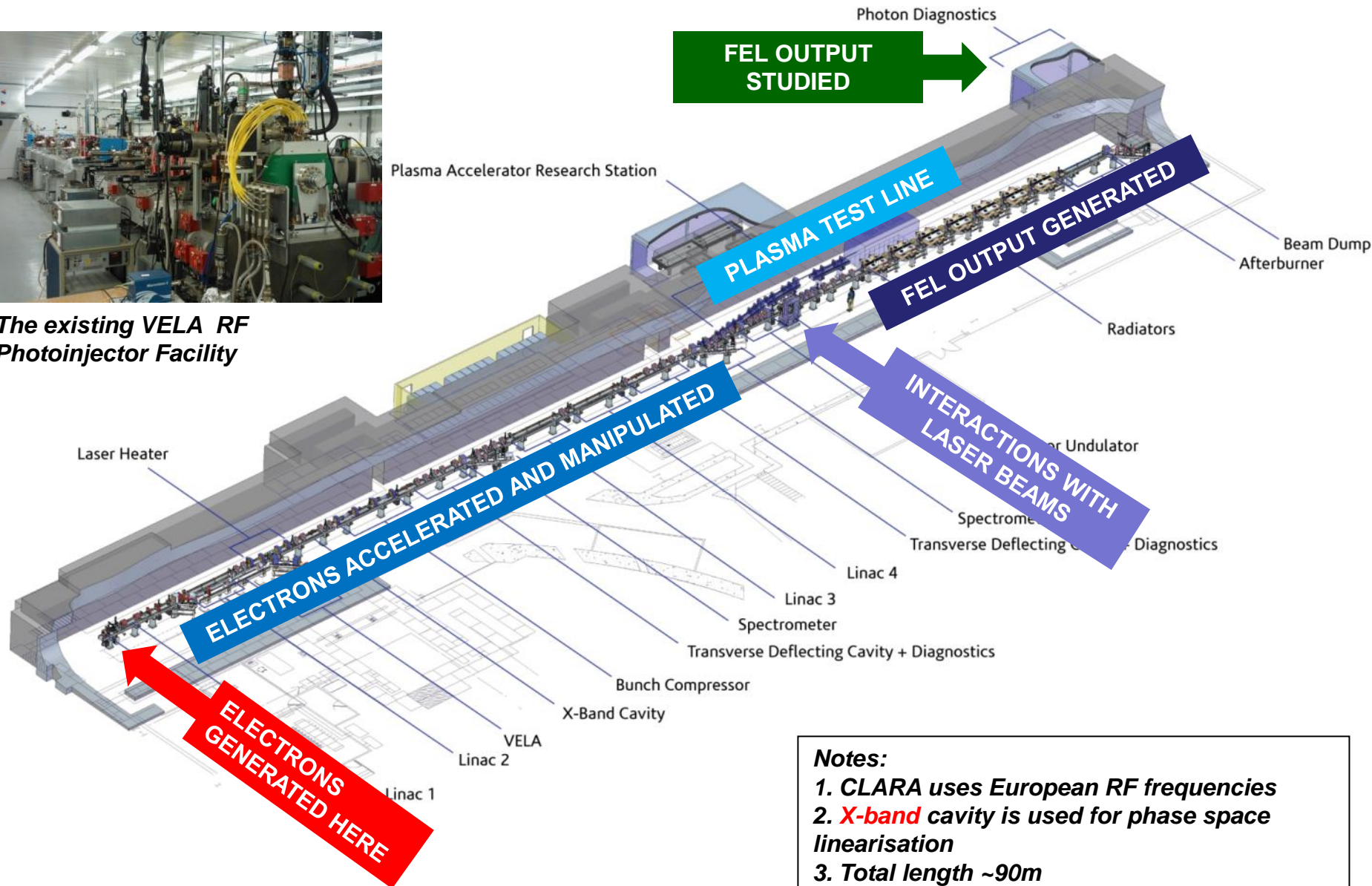
*Emphasis is **ULTRA-SHORT PULSE GENERATION***

Strathclyde
INFN Frascati
SwissFEL
DLS
Oxford
Liverpool
Imperial

CLARA Layout



The existing VELA RF Photoinjector Facility

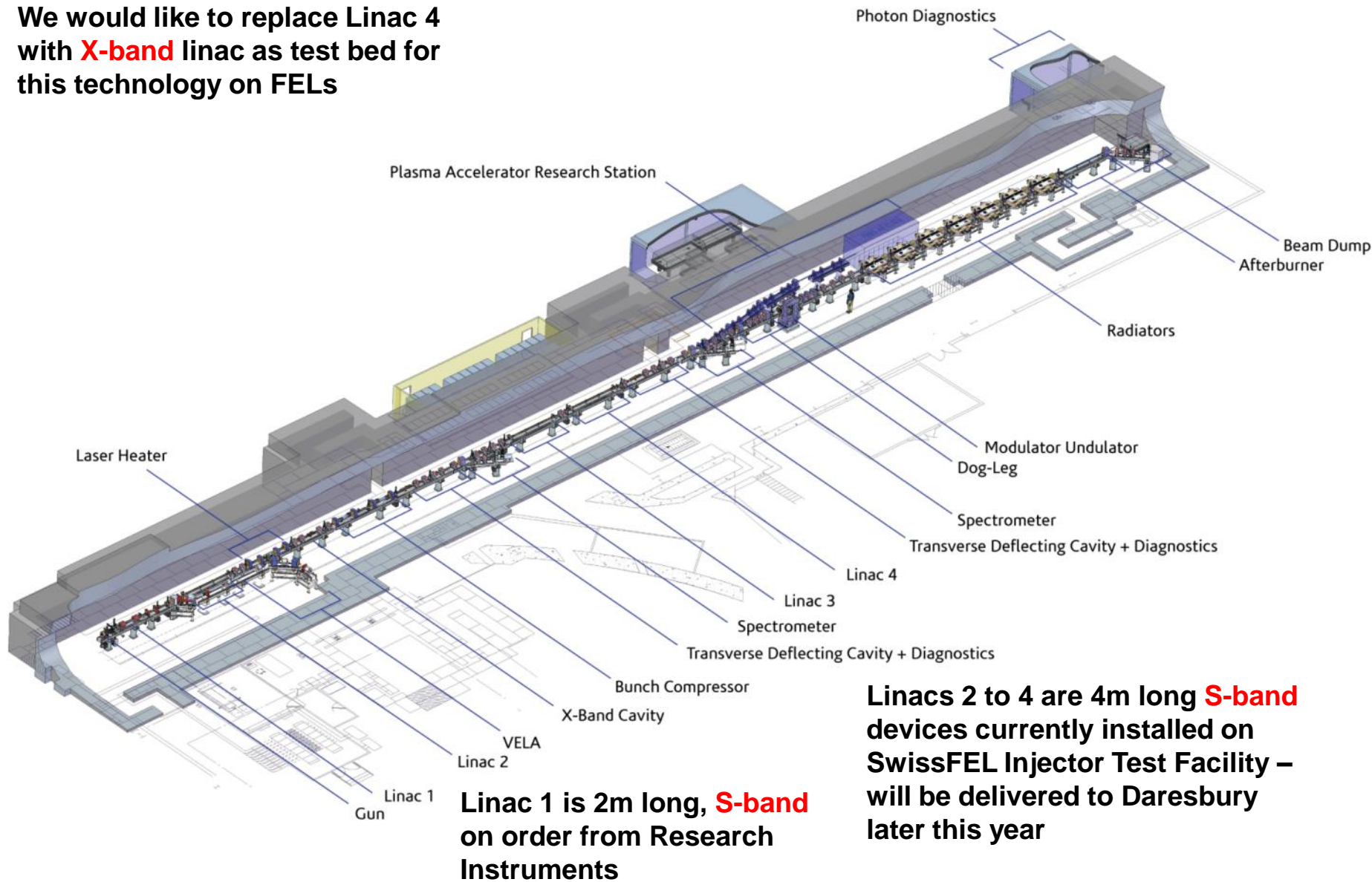


Notes:

1. **CLARA uses European RF frequencies**
2. **X-band** cavity is used for phase space linearisation
3. **Total length ~90m**

CLARA Layout

We would like to replace Linac 4 with **X-band** linac as test bed for this technology on FELs



Other Goals and Benefits of CLARA

- The opportunity for R&D on advanced technologies:
 - New photoinjector technologies
 - Novel undulators (short period, cryogenic, superconducting....)
 - New accelerating structures: X-Band etc...
 - Advanced diagnostics
- The enhancement of VELA beam power and repetition rate, enabling additional industrial applications.
- The possibility to **use the electron beam** for other scientific research applications:

ASTeC
CERN
FERMI@Elettra
RHUL
INFN Frascati
SwissFEL
DLS
Lancaster
INR Moscow

NOVEL PHOTON SOURCES
(CDR, SMITH-PURCELL, ...)

COMPTON SCATTERING
FOR GAMMA BEAMS

PLASMA ACCELERATOR
RESEARCH

ULTRAFAST ELECTRON
DIFFRACTION

NOVEL ACCELERATION
(DWA, DLA, THZ, ...)

NOVEL TYPES OF STORAGE
RING

ASTeC
RHUL
Oxford

ASTeC
Strathclyde
Manchester
INFN Frascati

ASTeC
York
Swansea
UCL

ASTeC
RHUL
Liverpool
Lancaster
Manchester
Oxford

Design Philosophy and Parameters

- CLARA will be a flexible test facility allowing the broad range of accelerator and FEL R&D necessary to ensure a future UK FEL facility is world leading.
- Many of the FEL research topics are in two main areas which are intended to demonstrate improvement of FEL output beyond that available from SASE
 - ***The generation of ultra-short pulses***
 - Our emphasis for the short pulse schemes *is to generate pulses with as few optical cycles as possible* with durations of the order of, or shorter than, the FEL cooperation length.
 - ***For these schemes we will lase at 400–250 nm***, where suitable nonlinear materials for single shot pulse profile characterisation are available.
 - A suitable wavelength range for seed sources to manipulate the electron beam longitudinal phase space is 30 – 120 μm
 - ***Improvement of temporal coherence.***
 - ***For these schemes we will lase at 266-100nm*** because here only spectral characterisation is required.
 - A suitable seed source for harmonic upconversion, if required, is an 800nm Ti:S.
- In all cases, we aim to study the essential physics of the schemes which can often ***be independent of the FEL wavelength.***
- Using a hybrid planar undulator, with minimum gap 6mm, and gap tuning range of 400–100 nm, the required electron beam energy is ~230 MeV.

CLARA Parameters

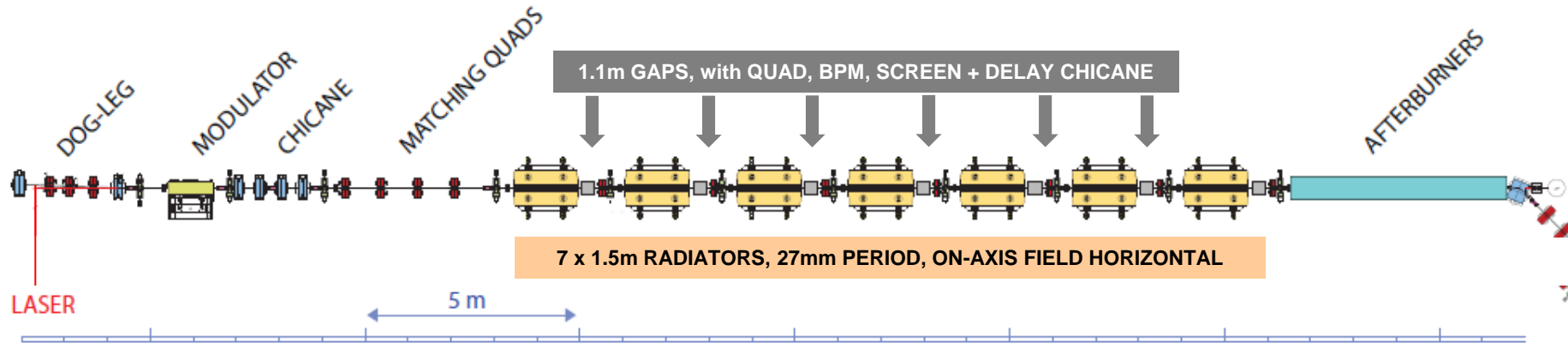
Parameters have been generated to cover **4 different operating modes**.

Parameter	Operating Modes			
	Seeding	SASE	Ultra-short	Multibunch
Max Energy (MeV)	250	250	250	250
Macropulse Rep Rate (Hz)	1–100	1–100	1–100	1–100
Bunches/macropulse	1	1	1	16
Bunch Charge (pC)	250	250	20–100	25
Peak Current (A)	125–400	400	~1000	25
Bunch length (fs)	850–250 (flat-top)	250 (rms)	<25 (rms)	300 (rms)
Norm. Emittance (mm-mrad)	≤ 1	≤ 1	≤ 1	≤ 1
rms Energy Spread (keV)	25	100	150	100
Radiator Period (mm)	27	27	27	27

FEL output wavelengths from 400 nm to 100 nm

- Can make use of 800 nm laser for harmonic generation experiments
- Can use well established laser diagnostics for single shot pulse length measurements
- No need for long photon beamlines, can deflect by 90°

FEL Layout + Operating Modes



Parameter	Operating Modes			
	Seeding	SASE	Ultra-short	Multibunch
Max Energy (MeV)	250	250	250	250
Macropulse Rep Rate (Hz)	1–100	1–100	1–100	1–100
Bunches/macropulse	1	1	1	16
Bunch Charge (pC)	250	250	20–100	25
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Norm. Emittance (mm-mrad)	≤ 1	≤ 1	≤ 1	≤ 1
rms Energy Spread (keV)	25	100	150	100
Radiator Period (mm)	27	27	27	27

Table 3.1: Main parameters for CLARA operating modes.

Seeding Mode is for

Short Pulse Schemes
FEL lasing: 400-250nm
(Seed: 30-120μm)

+

Temporal Coherence Schemes

FEL lasing: 266-100nm
(Seed: 800nm)

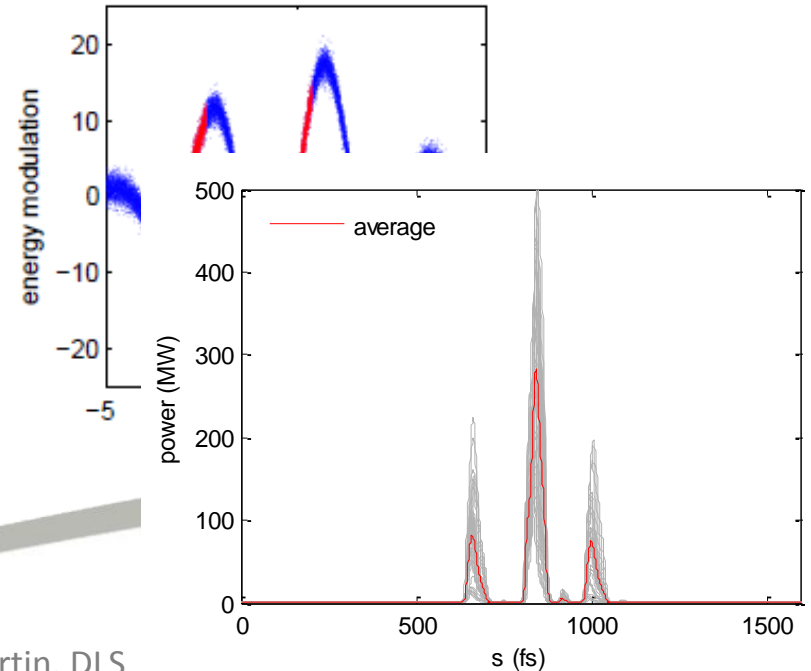
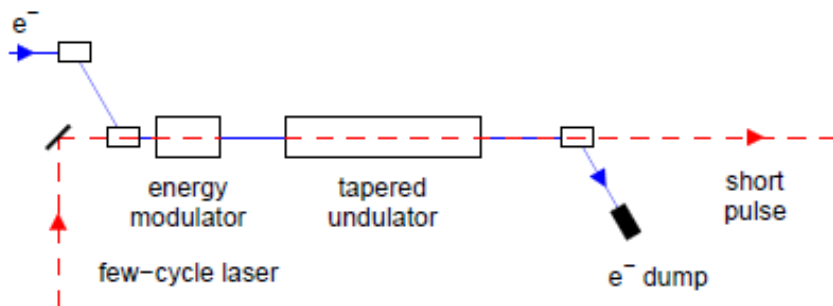
Short Pulse Scheme Example: Sliced Chirped Beam + Taper*

Principle of scheme

- Few-cycle laser interacts with electron beam to generate strong energy chirp in short region of bunch
- Radiator taper is matched to energy chirp to maintain resonance as FEL pulse slips forwards to electrons with different energies
- FEL gain strongly suppressed in remainder of bunch

Constraints

- Length of chirp needs to match cooperation length for single SASE spike to grow
- Amplitude of chirp needs to be greater than natural bandwidth of FEL



* E. Saldin et al., **PRST-AB**. 9, 050702, (2006)

CLARA Short Pulse Schemes: *Predicted Pulse Durations*

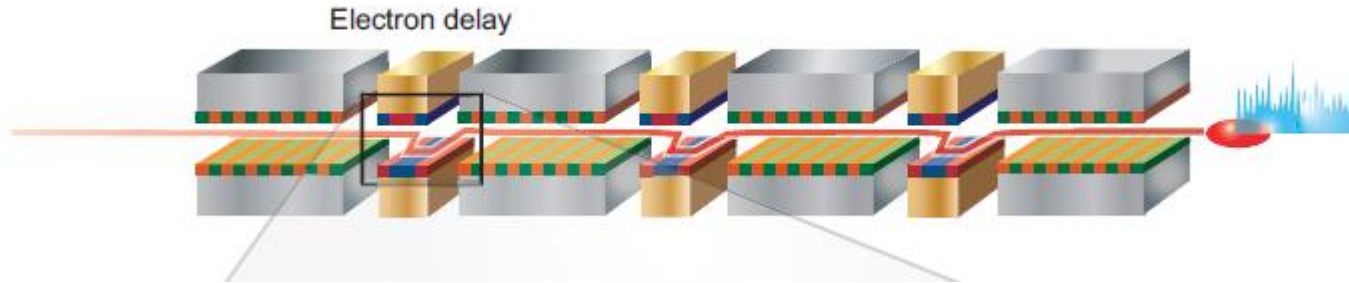
Scheme	Pulse Type	Wavelength (nm)	FWHM Pulse Duration			
			fs	μm	#cycles	# I_c
Slice/Taper	Single	266	50	15	56	2.2
EEHG	Single	100	25	8	75	2.6
Single-Spike SASE	Single	100	23	7	70	2.3
Mode-Locking Phase I	Train	266	43	13	49	1.9
	Train	100	18	5.3	50	1.8
Mode-Locking Phase II	Train	266	17	5.1	20	0.7
	Single	100	14	4.1	41	1.4
Mode-Locked Afterburner	Train	100	1.6	0.5	5	0.16

Table 3.2: Predicted pulse durations for CLARA Short Pulse Schemes.

Typical SASE output is ~100,000 cycles

Temporal Coherence Scheme Example: High-Brightness (HB) SASE*

- As in the mode-coupled FEL, delays are used between undulator modules

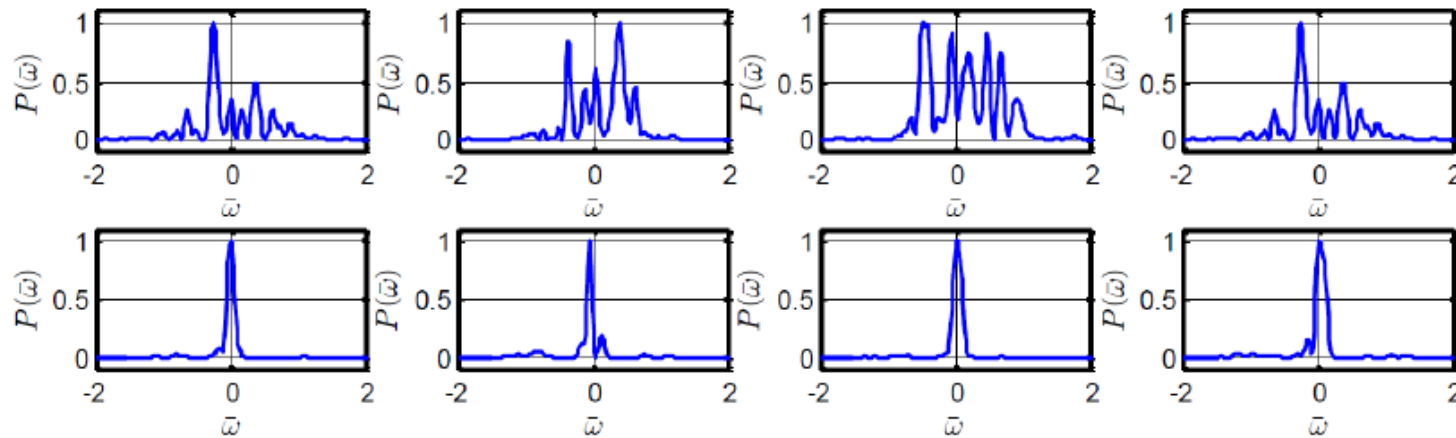


- Each delay is **different** to prohibit growth of modes
- Increased slippage gives increased communication length** between radiation and electrons, delocalising the collective FEL interaction and allowing **coherence length to grow exponentially** by up to 2 orders of magnitude (compared to SASE)
- In contrast to other schemes for improving temporal coherence:
 - No seed laser or photon optics are required
 - It's all done with magnets, and is thus applicable at **Any Repetition Rate** and **Any Wavelength**.
- Was demonstrated (over a limited parameter range) on LCLS, using detuned undulators as delays, and shown to reduce linewidth in inverse proportion to the increased slippage – can't test optimum scheme

* B. W. J. McNeil, N. R. Thompson & D. J. Dunning, *Transform-Limited X-Ray Pulse Generation from a High-Brightness SASE FEL*, PRL 110, 134802 (2013)

Temporal Coherence: HB-SASE

100nm HB-SASE on CLARA, CDR lattice



SASE

HB-SASE

Four different shots on CLARA demonstrate variability of SASE & advantage of HB-SASE

CLARA Status



JINST 9 (2014) T05001

- The CDR was published in July 2013
- SwissFEL are providing required 3 linacs, together with a number of quadrupoles and solenoids (available Q4 2014)
- The project has now been split into **Two Phases**
- **PHASE 1 – Front End, 50 MeV**
 - This is happening now, with procurement progressing, and installation in 2015.
 - Will enable access to bright, short, up to ~50 MeV electron bunches for UK accelerator science and technology community
 - Will enable new high rep rate photoinjector to be characterised with beam whilst VELA/CLARA **Phase 1** still operational (i.e. two guns)
 - Potential for early exploitation of 20 TW laser
- **PHASE 2a – 150 MeV, up to bunch compression section**
 - **Funded, procurement starting this year**
- **PHASE 2b – 250 MeV FEL Test Facility**
 - **Not Yet Funded** – Part of Ongoing UK Capital Consultation Exercise – CLARA is a priority for STFC

VELA

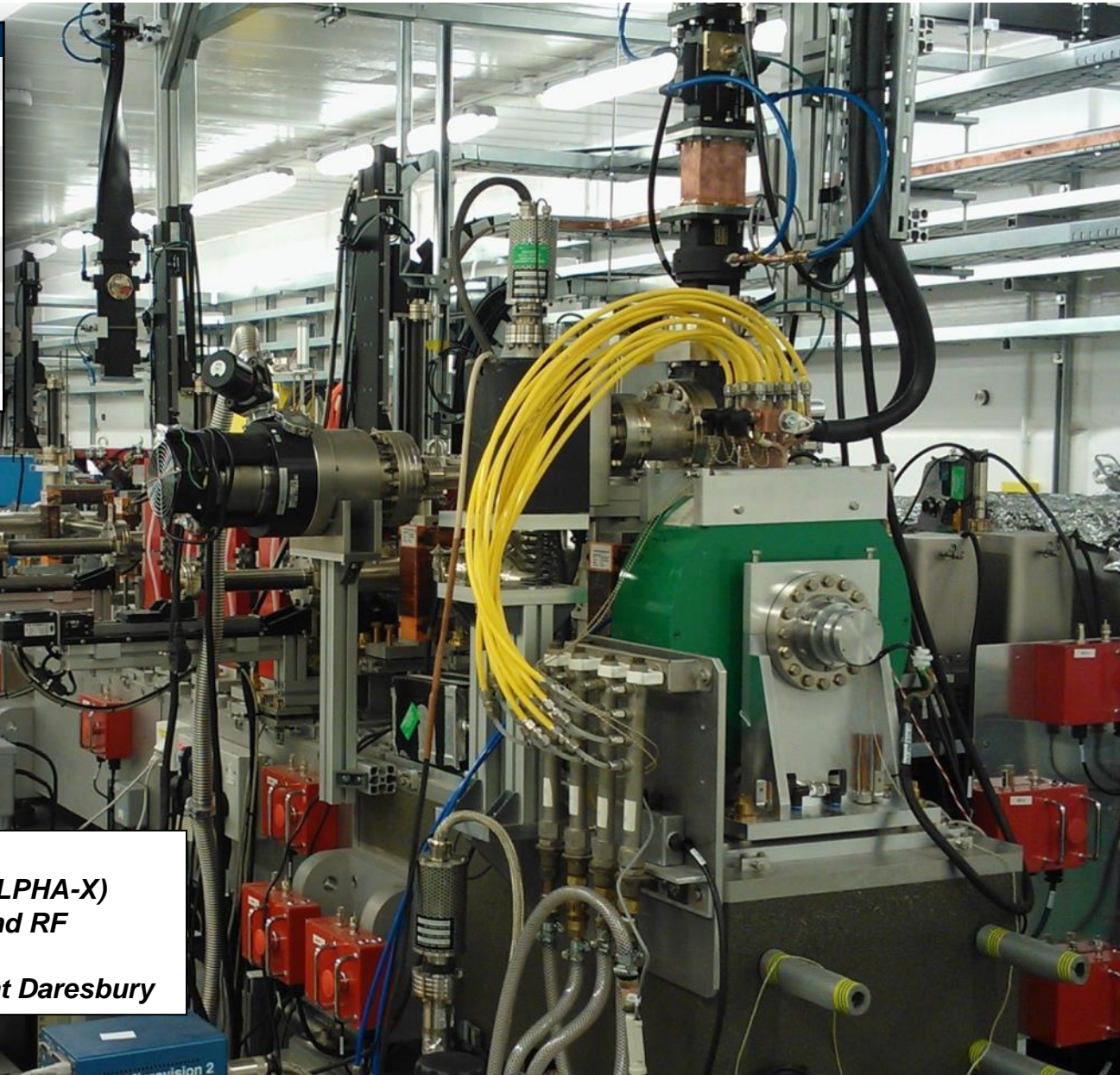
VELA Specification

Beam Energy	4 - 6 MeV
Bunch Charge	10 - 250 pC
Bunch length ($\sigma_{t,rms}$)	1 - 10 ps
Normalised emittance	1 - 4 μm
Beam size ($\sigma_{x,y,rms}$)	0.5 - 5 mm
Energy spread ($\sigma_{e,rms}$)	1 - 5 %
Bunch repetition rate	1 - 10 Hz

*Not all parameters achievable simultaneously

Notes:

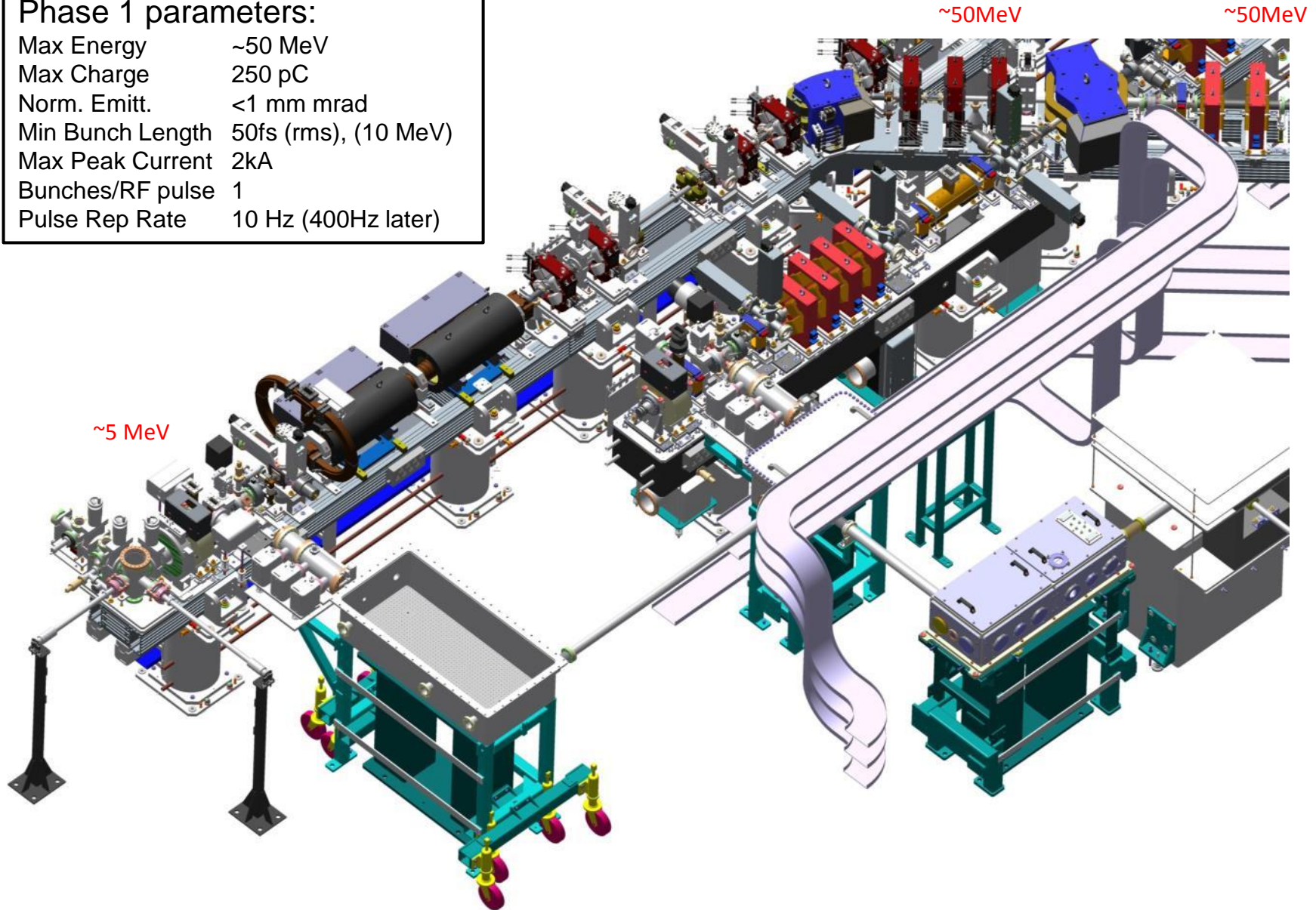
1. VELA gun is from Strathclyde (ALPHA-X)
2. Max rep rate is 10 Hz but laser and RF capable of 400 Hz
3. 400 Hz gun under development at Daresbury



VELA + CLARA Phase 1 (2015)

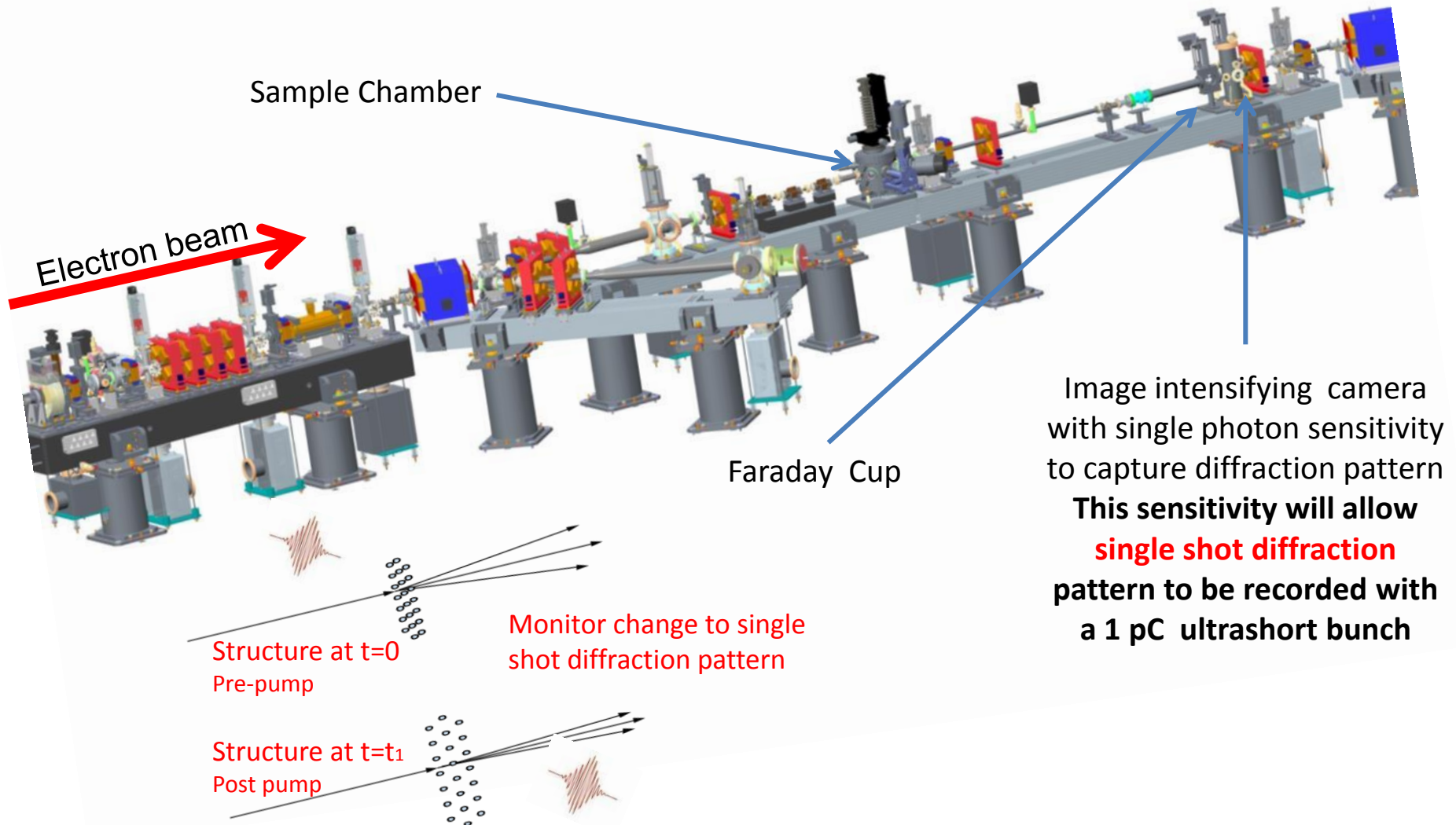
Phase 1 parameters:

Max Energy	~50 MeV
Max Charge	250 pC
Norm. Emitt.	<1 mm mrad
Min Bunch Length	50fs (rms), (10 MeV)
Max Peak Current	2kA
Bunches/RF pulse	1
Pulse Rep Rate	10 Hz (400Hz later)

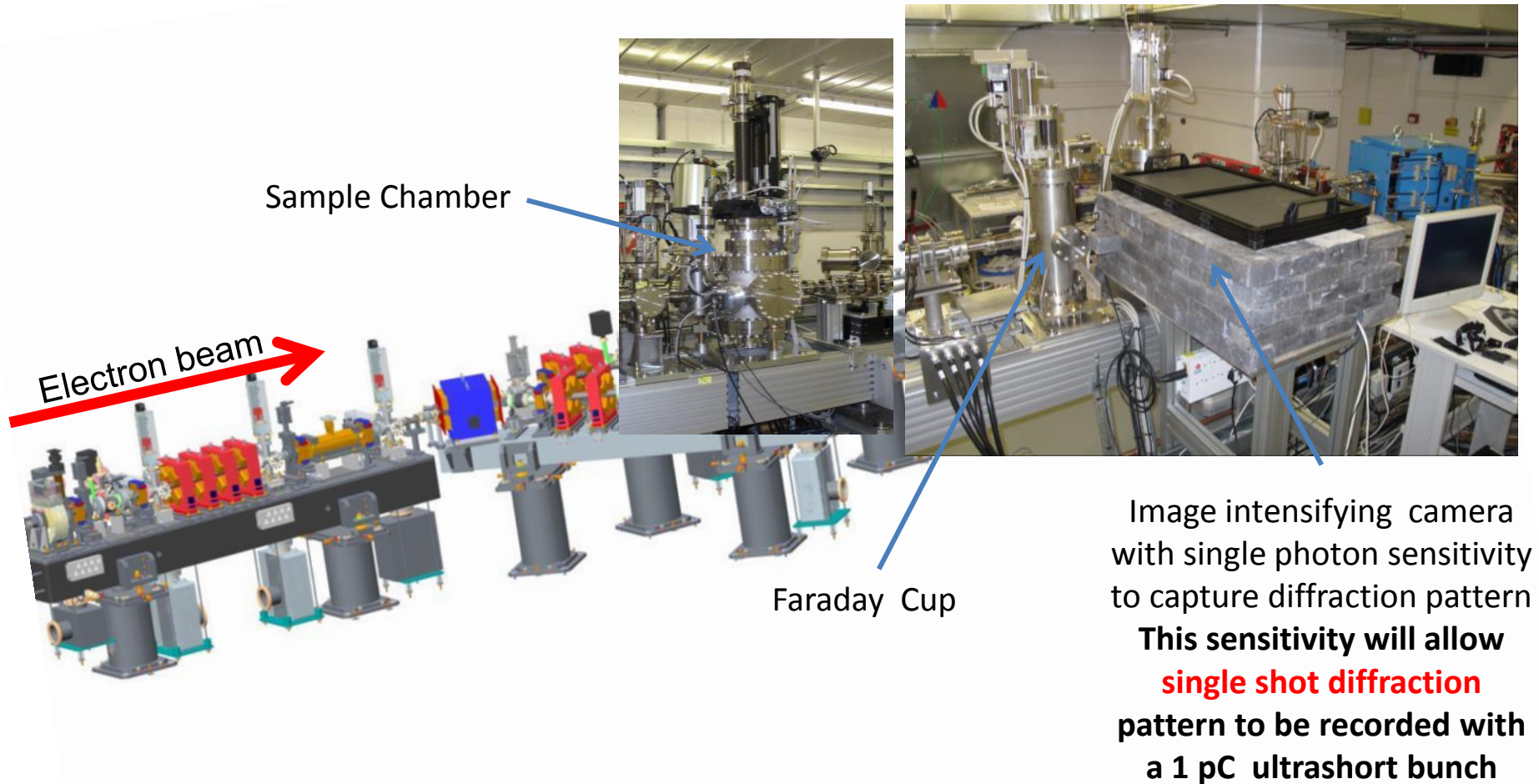


Ultrafast Electron Diffraction

Studying structural evolution in fs regime
Synergy with XFEL Structural Science



Ultrafast Electron Diffraction

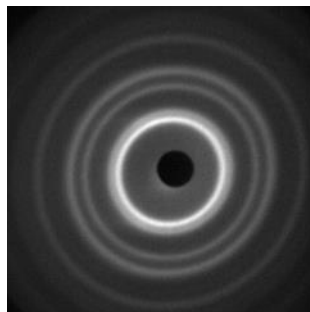




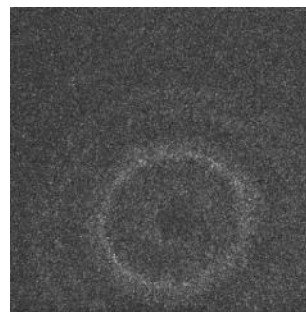
Faraday Cup chamber and Lanex screen detection chamber. Screen located 3.4 m downstream of sample

First Results:
September 2014

Charge at detector
 < 1 pC



Au sample
1000 shots



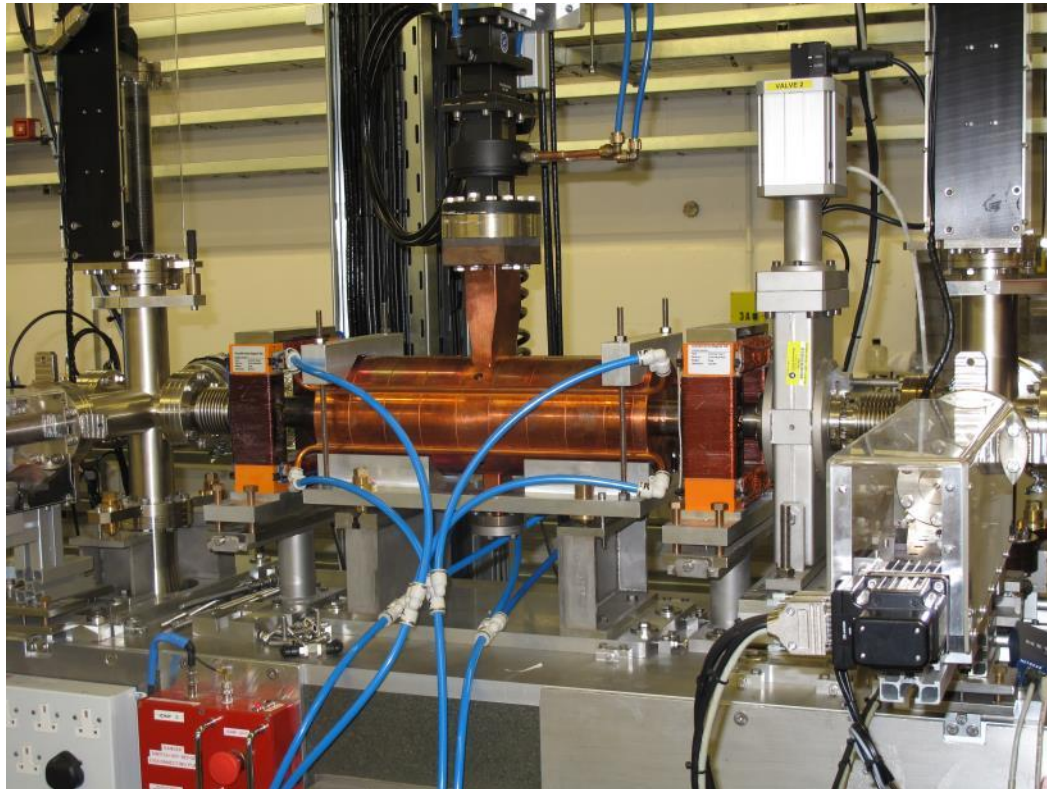
Pt sample
Single shot

Reconfiguring VELA in
future will allow < 100 fs
time resolution.

Already have sufficient information in single shot
to follow sample melting (order – disorder transition)

TDC

- S-band Transverse Deflecting Cavity now installed and ready to be conditioned with RF – scheduled for Nov '14
- Will allow much more detailed diagnosis of bunches (slice properties, bunch length with fs resolution)



UK FEL Aspirations

- Two FEL facility proposals in the UK have been generated
 - **4GLS** (2006), ERL-based accelerator incorporating single pass, seeded, FEL (8 to 100 eV, 1 kHz, 600 MeV electrons)
 - **NLS** (2010), SC Linac-based accelerator with 3 single pass seeded and upconverted FELs after beam spreader (50 to 1000 eV, 1MHz, 2.25 GeV electrons)
- A third proposal is now being actively discussed
 - Results from LCLS especially seem to have convinced the UK life science community that FELs offer new capabilities
 - Implications are that higher photon energies will be required (<100eV to >15 keV) and so higher electron energies (~6 to ~9 GeV)
 - To keep costs manageable this is likely to mean that NC RF will be selected (users will compromise on repetition rate)
 - Hence our interest in the application of X-band accelerating technology

X Band Technology

- STFC is a member of the XbFEL (H2020) bid – our prime contribution would be towards the design of an X-ray FEL based upon X-band technology
- We are therefore very interested in the development of X-band accelerating structures & sources by CERN & others for the potential application towards a UK X-ray FEL
- A major issue for the application of X-band for FELs currently appears to be the capital cost
 - “Comparing S-band and X-band solutions for the particular choice of 1 kHz repetition rate, it appears that S-band would currently be a cheaper option. For X-band to be competitive with S-band, the currently estimated costs of X-band components, *particularly the klystron*, would have to come down significantly.”

Proceedings of FEL2011, Shanghai, China

TUPB

PRELIMINARY STUDIES OF A POSSIBLE NORMAL-CONDUCTING LINAC OPTION FOR THE UK'S NEW LIGHT SOURCE

R. P. Walker, R. Bartolini¹, C. Christou, J.-H. Han, Diamond Light Source, Oxfordshire, UK
¹and John Adams Institute, University of Oxford, UK

X Band Technology

- Development of accelerating structures (and linearising structures) applicable to FELs is crucial
- Development of economic RF sources is just as vital for widespread adoption by the community
- *Progress is required in both these areas*
- Demonstrations with beam (at CERN or CLARA or elsewhere) are also essential to alleviate concerns over possible detrimental wakefield effects
- In the UK (and elsewhere), the operating costs of new facilities are very important – **energy consumption costs money but is also politically sensitive** – increasing the advantage of X-band technology in this area would be very beneficial
 - **The green accelerator technology?**

Summary

- **CLARA** is an FEL Test Facility for the UK Accelerator Community
 - NC RF (up to 400 Hz)
 - Emphasis on ultra short pulse generation
 - Enabling other electron beam applications
 - Major upgrade to VELA
- **VELA** is an RF Photoinjector with two user areas
 - Generating ~4.5 MeV bunches for use by industry and academia
 - First industrial users already
 - Electron diffraction station taking data now
- **CLARA** Phase 1 (50 MeV) will be installed in 2015
 - Phase 2 not yet fully funded
- UK FEL aspiration to hard X-ray makes NC RF very likely and X-band acceleration very interesting
 - CLARA looks well suited to carry out technology tests and could effectively duplicate front section of multi-GeV FEL
- XbFEL (H2020) will enable UK participation in X-ray FEL design with X-band technology and also bring the technology a step closer
- For widespread adoption the capital costs need to decrease or operating costs become more advantageous (or ideally both)