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


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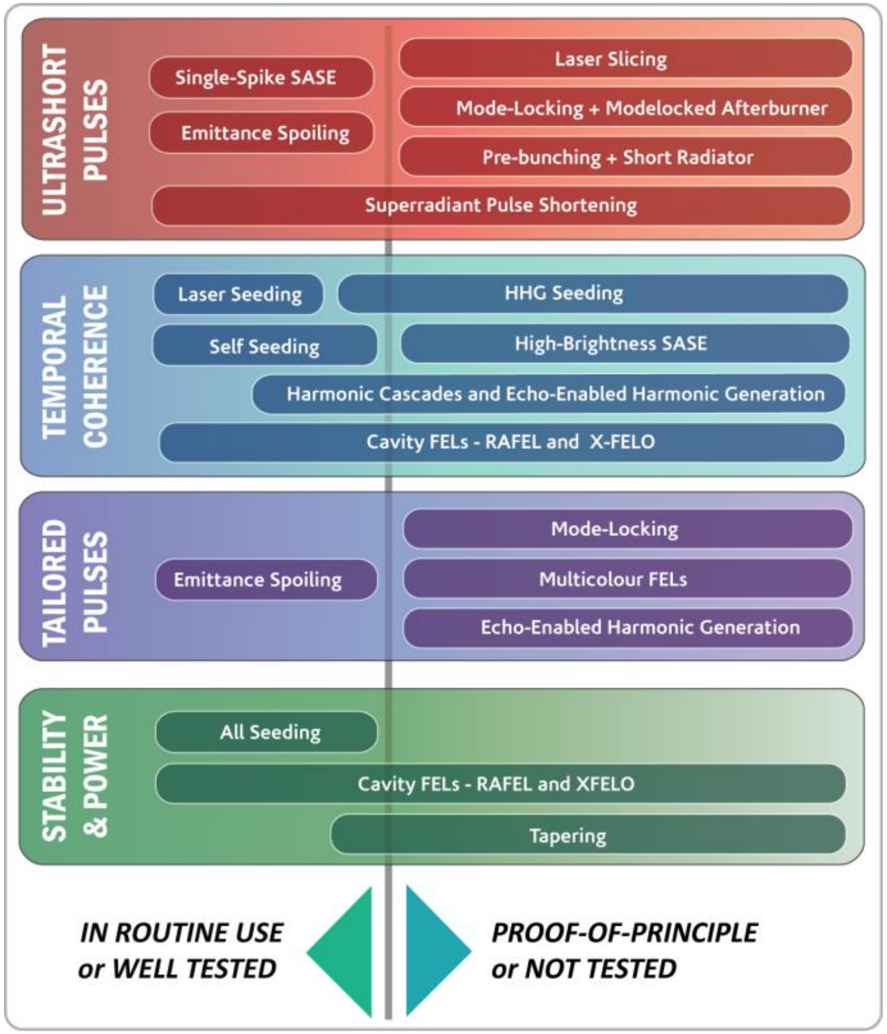
***on behalf of the CLARA & VELA Project Teams***


***CLIC Workshop 2015***

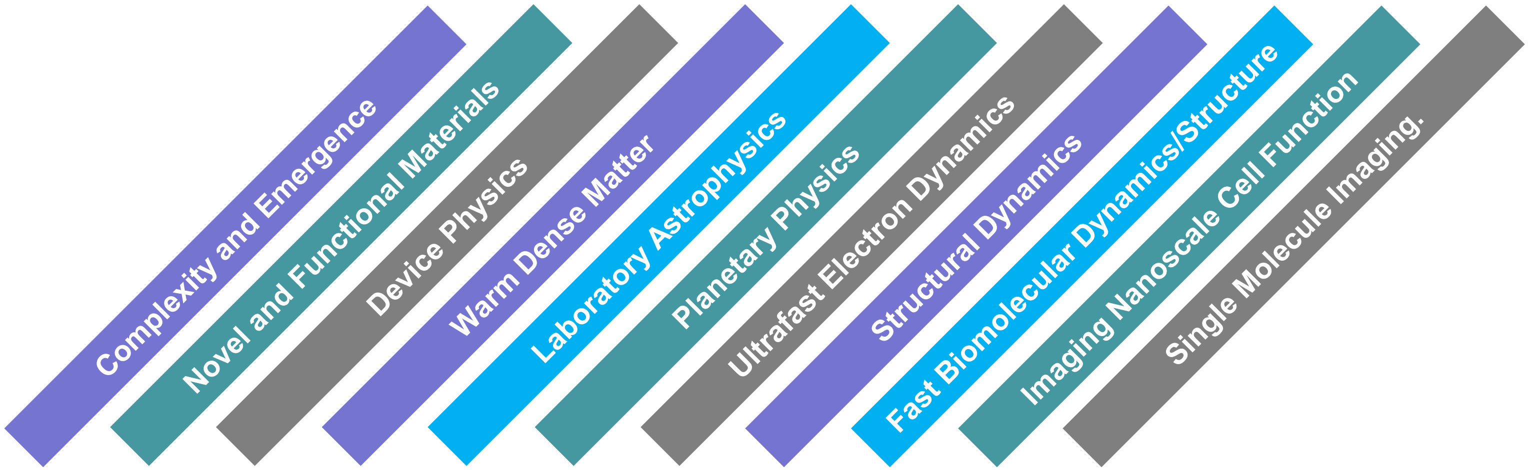
# The 'FEL Case' for an FEL Test Facility




- 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***

# *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 Linear Accelerator for Research and Applications*

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

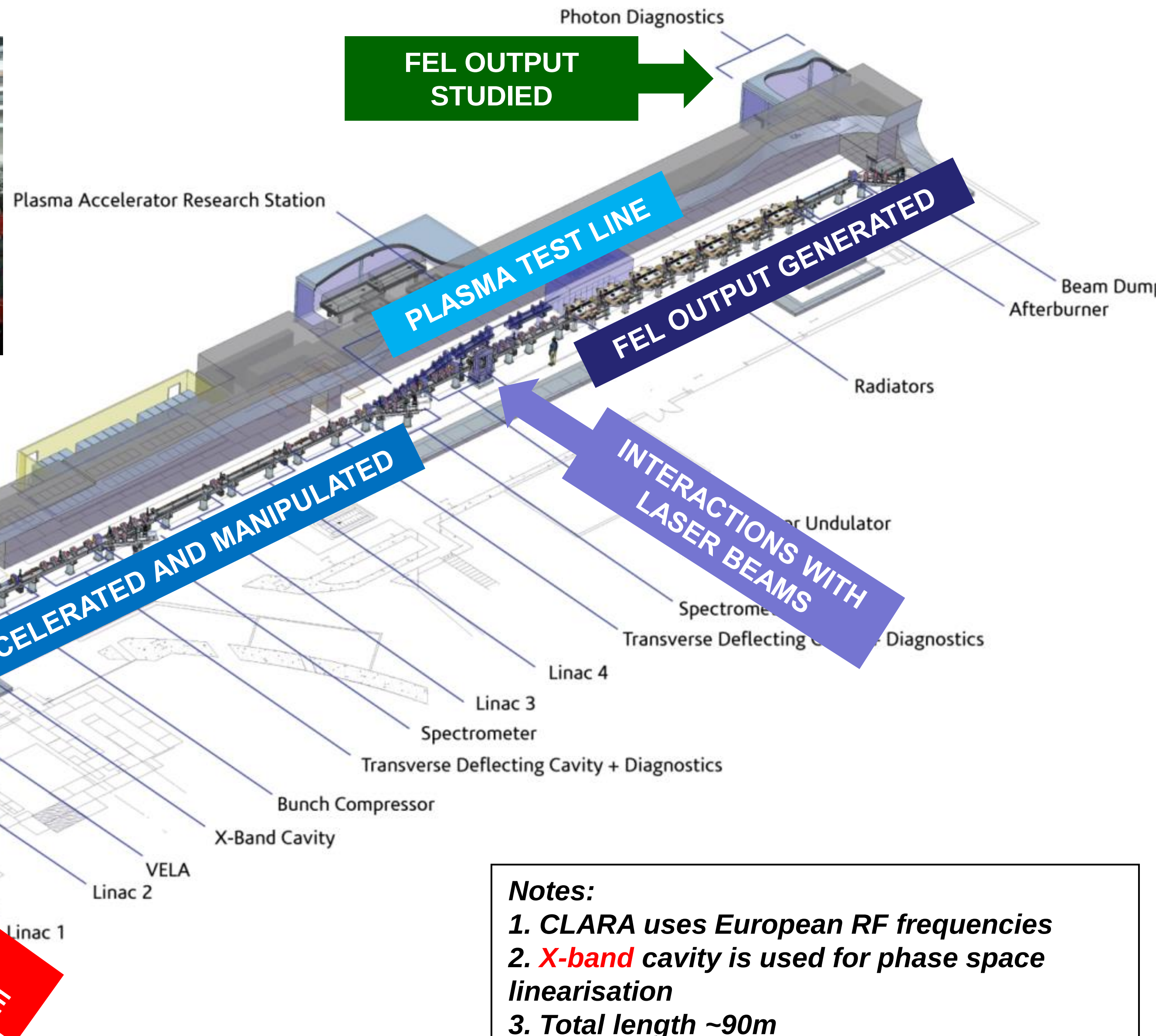
***Proof-of-principle demonstrations of novel FEL concepts***

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

Strathclyde
INFN Frascati
SwissFEL
DLS
Oxford
Liverpool
Imperial

# CLARA Layout

***The existing VELA RF Photoinjector Facility***

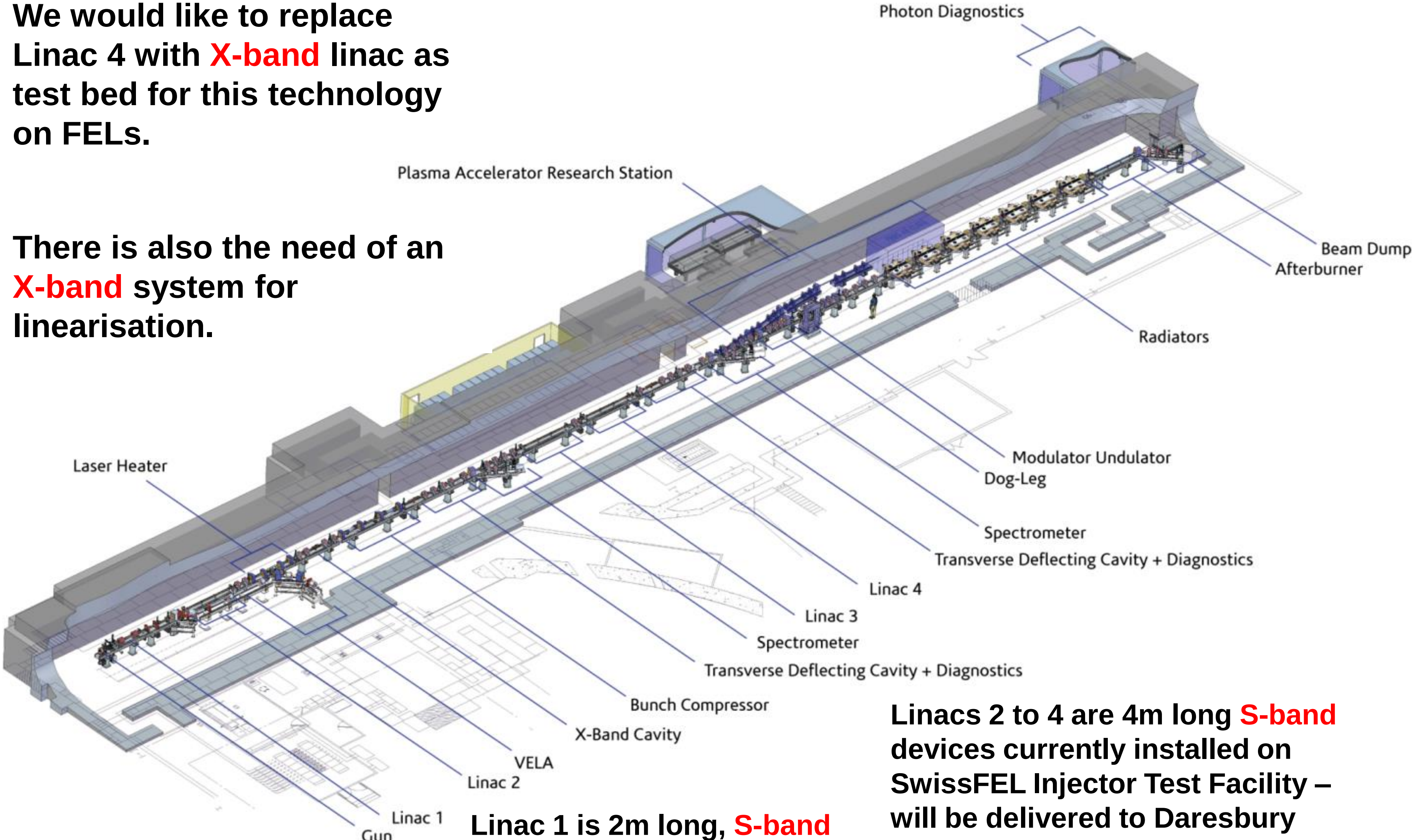



***Notes:***
***1. CLARA uses European RF frequencies***
***2. X-band cavity is used for phase space linearisation***
***3. Total length ~90m***

# CLARA Layout

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

**There is also the need of an X-band system for linearisation.**




**Linac 1 is 2m long, S-band on order from Research Instruments**

**Linacs 2 to 4 are 4m long S-band devices currently installed on SwissFEL Injector Test Facility – will be delivered to Daresbury later this year**

# 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

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

- 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:

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

ASTeC
RHUL
Oxford

**COMPTON SCATTERING FOR GAMMA BEAMS**

**PLASMA ACCELERATOR RESEARCH**

ASTeC
Strathclyde
Manchester
INFN Frascati

**ULTRAFAST ELECTRON DIFFRACTION**

ASTeC
York
Swansea
UCL

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

ASTeC
RHUL
Liverpool
Lancaster
Manchester
Oxford

**NOVEL TYPES OF STORAGE RING**

# *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

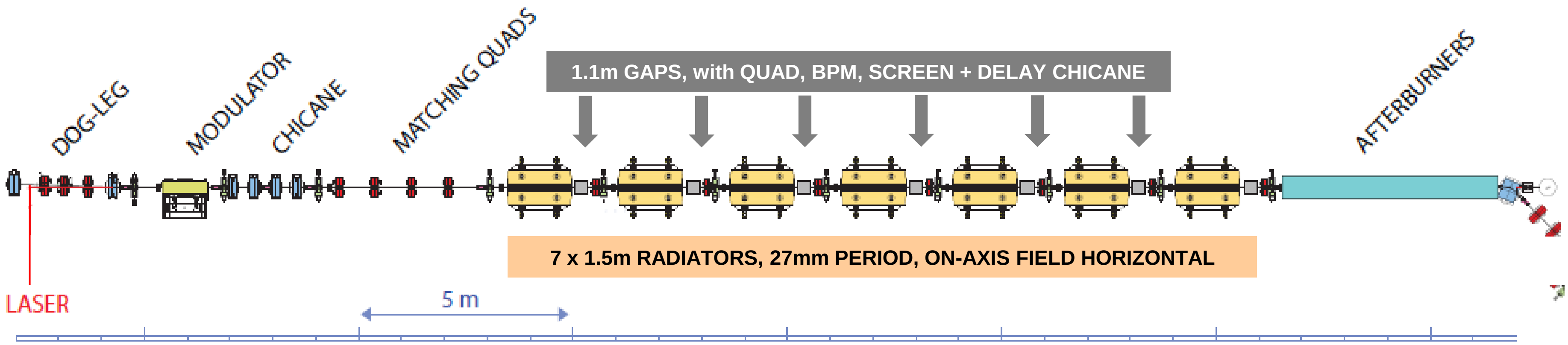
Parameters have been generated to cover **4 different operating modes**.

| | *Operating Modes* | | | |
|---|---|---|---|---|
| **Parameter** | **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 | $\sim$1000 | 25 |
| Bunch length (fs) | 850–250 (flat-top) | 250 (rms) | $<$25 (rms) | 300 (rms) |
| Norm. Emittance (mm-mrad) | $\leq 1$ | $\leq 1$ | $\leq 1$ | $\leq 1$ |
| 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$^{\circ}$

# FEL Layout + Operating Modes




| Parameter | Seeding | SASE | Ultra-short | Multibunch |
|---|---|---|---|---|
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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)

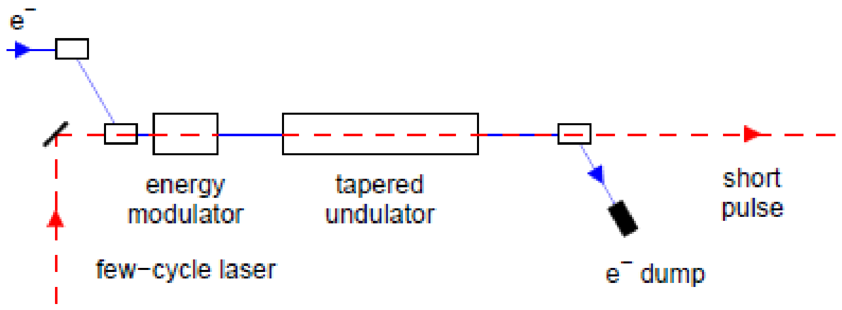
# *Short Pulse Scheme Example: Sliced Chirped Beam + Taper**

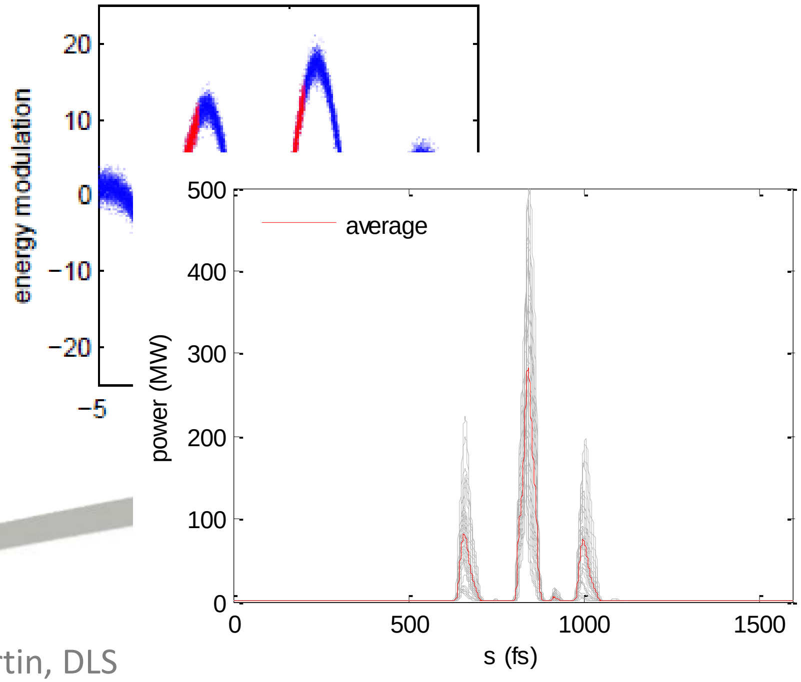
***Principle of scheme***

- 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



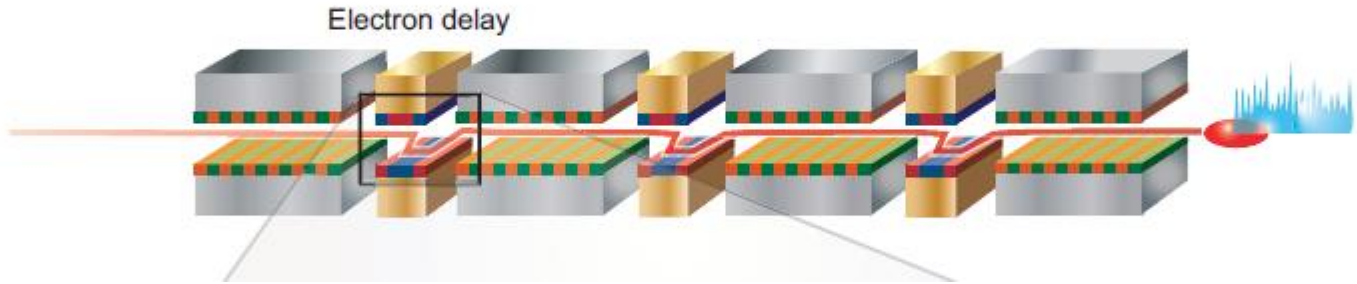




* E. Saldin et al., **PRST-AB**. 9, 050702, (2006)

Slide courtesy Ian Martin, DLS

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

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

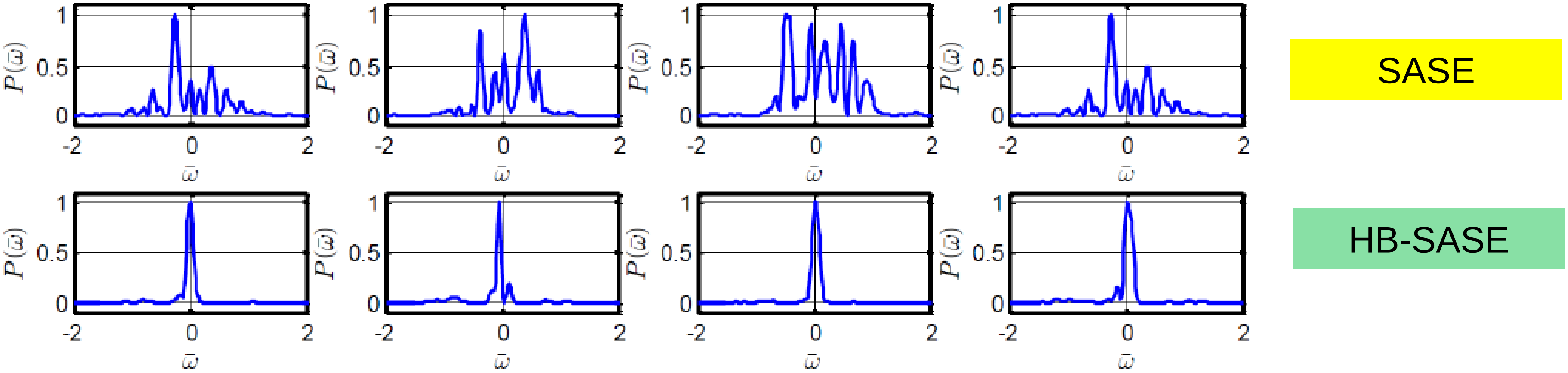



- Each delay is ***different*** to prohibit growth of modes
- ***Increased slippage gives increased communication length*** between radiation and electrons, delocalising the collective FEL interaction and allowing ***coherence length to grow exponentially*** by up to 2 orders of magnitude (compared to 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



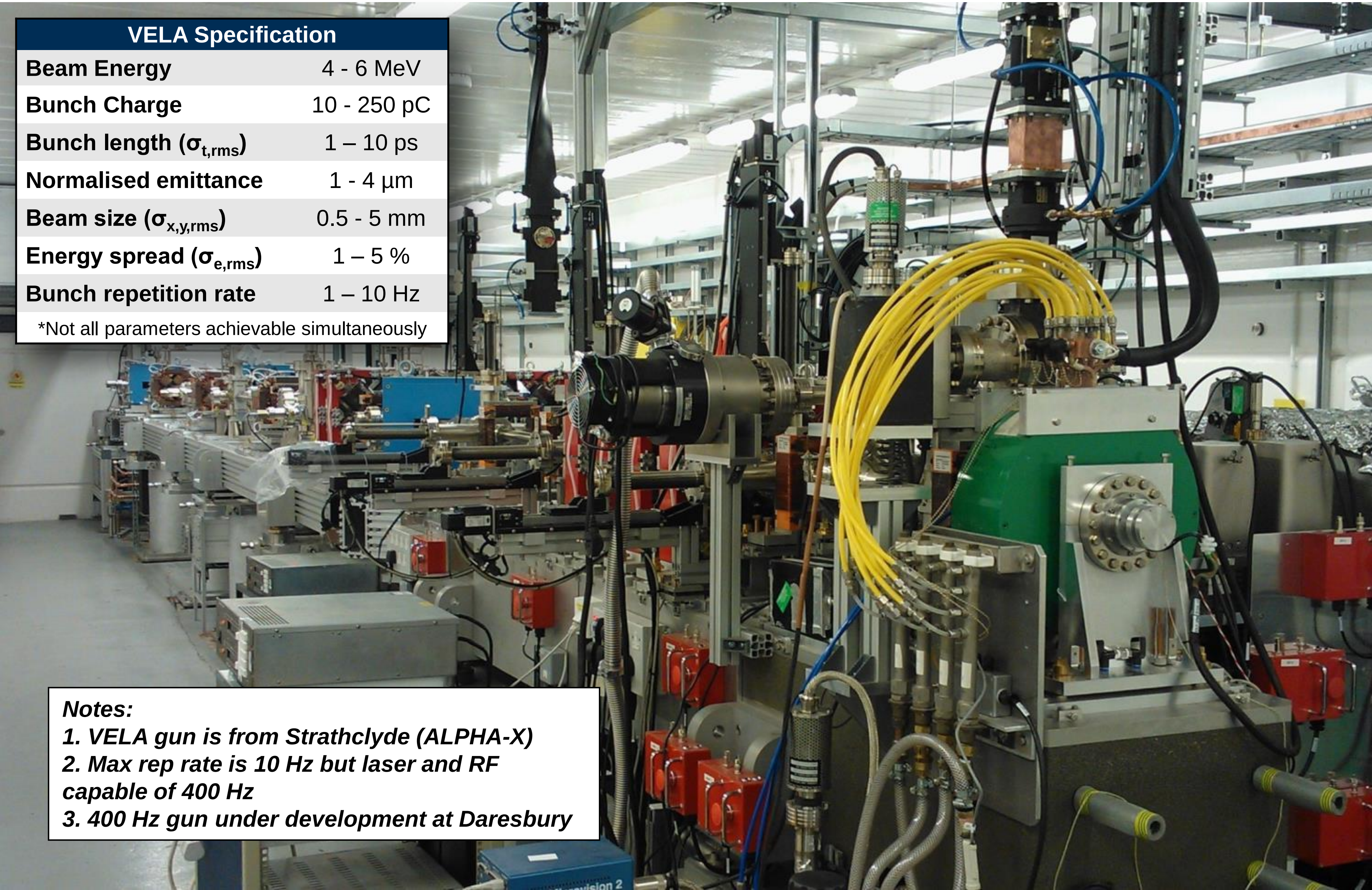

Four different shots on CLARA demonstrate variability of SASE & advantage of HB-SASE

# *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 |

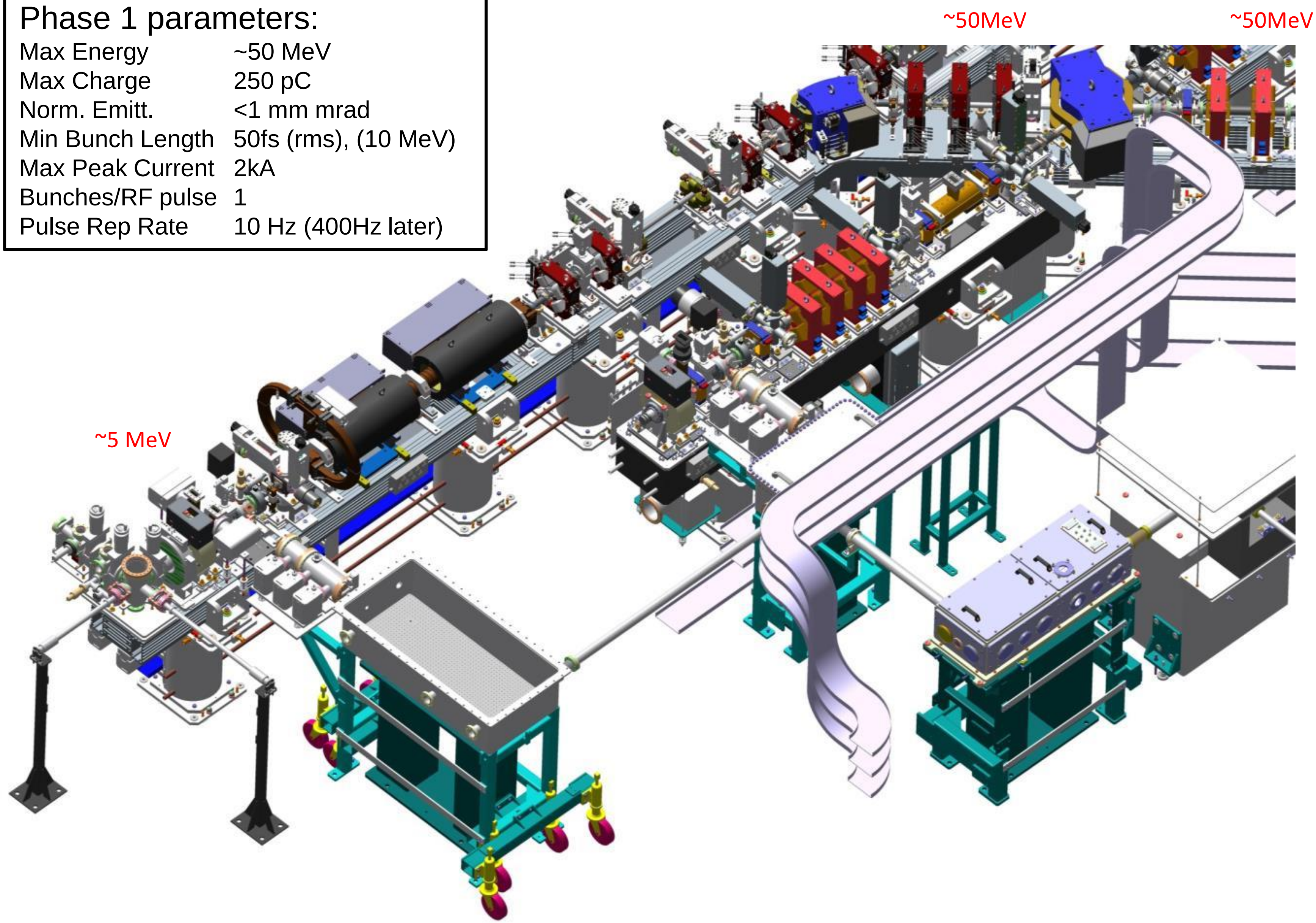
*Not all parameters achievable simultaneously

***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**

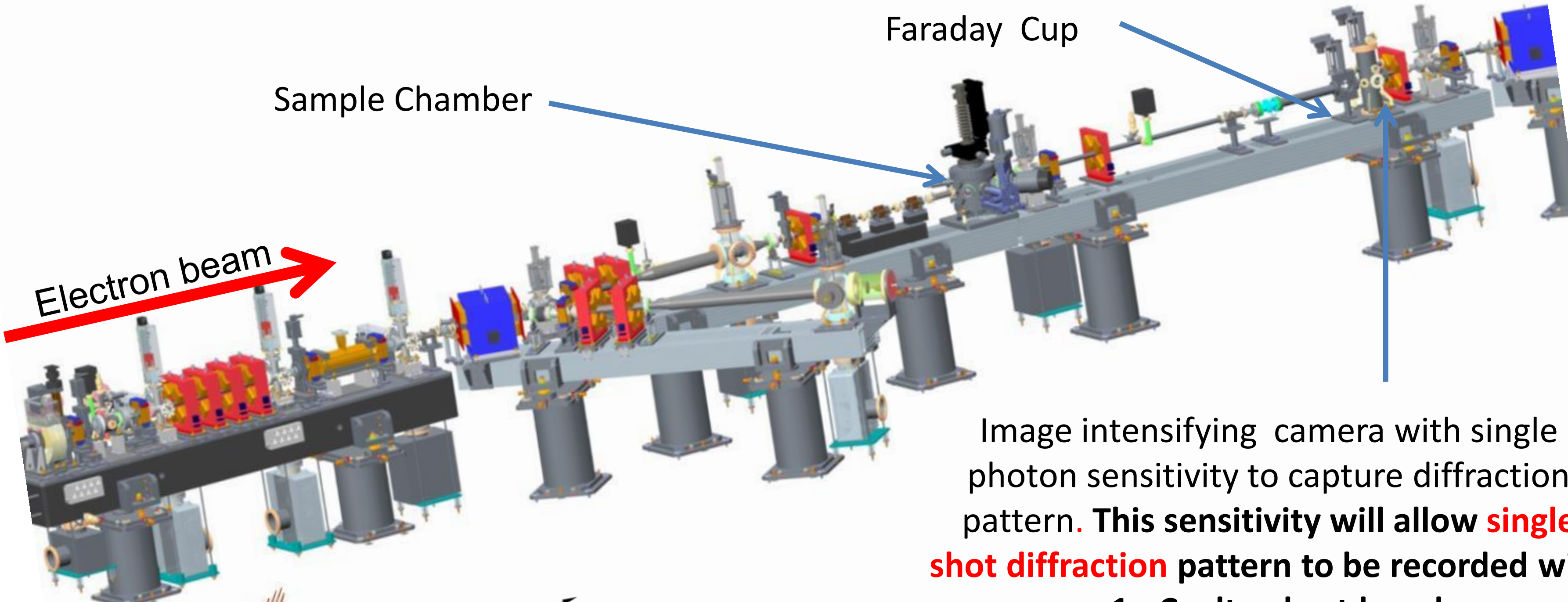
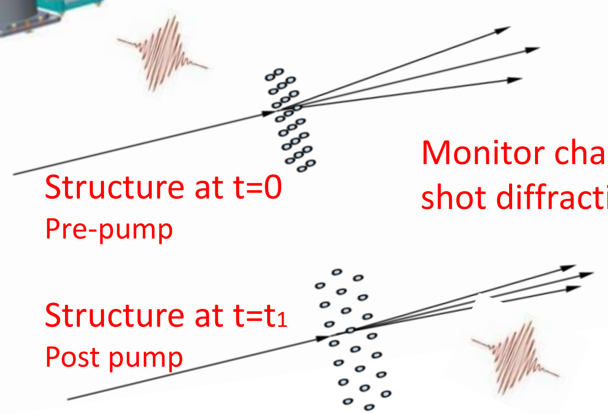


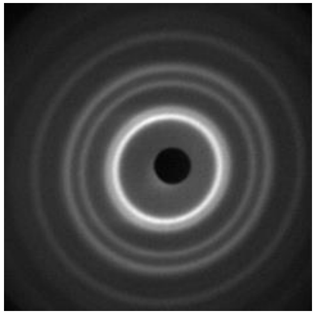

Image intensifying camera with single photon sensitivity to capture diffraction pattern. **This sensitivity will allow single shot diffraction pattern to be recorded with a 1 pC ultrashort bunch**



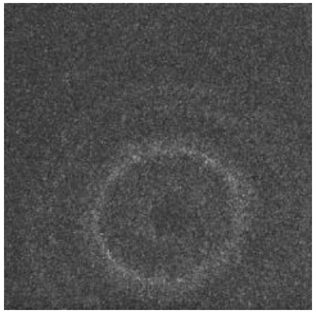

Faraday Cup chamber and Lanex screen detection chamber. Screen located 3.4 m downstream of sample

First Results: September 2014

Charge at detector <<1 pC



Au sample
1000 shots

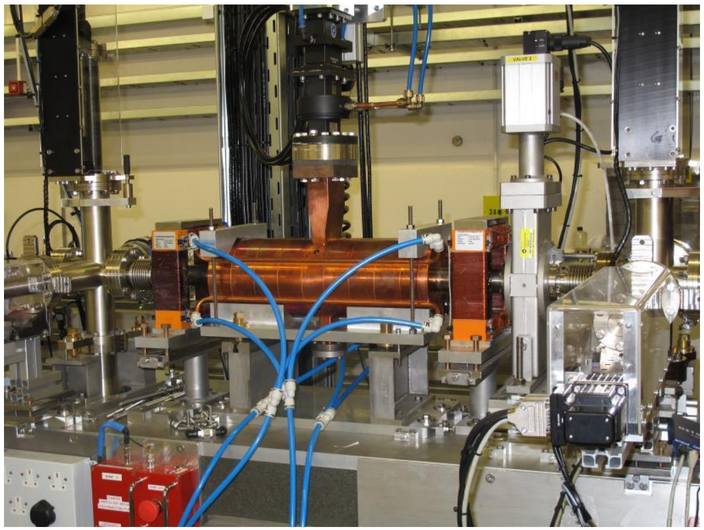


Pt sample
Single shot

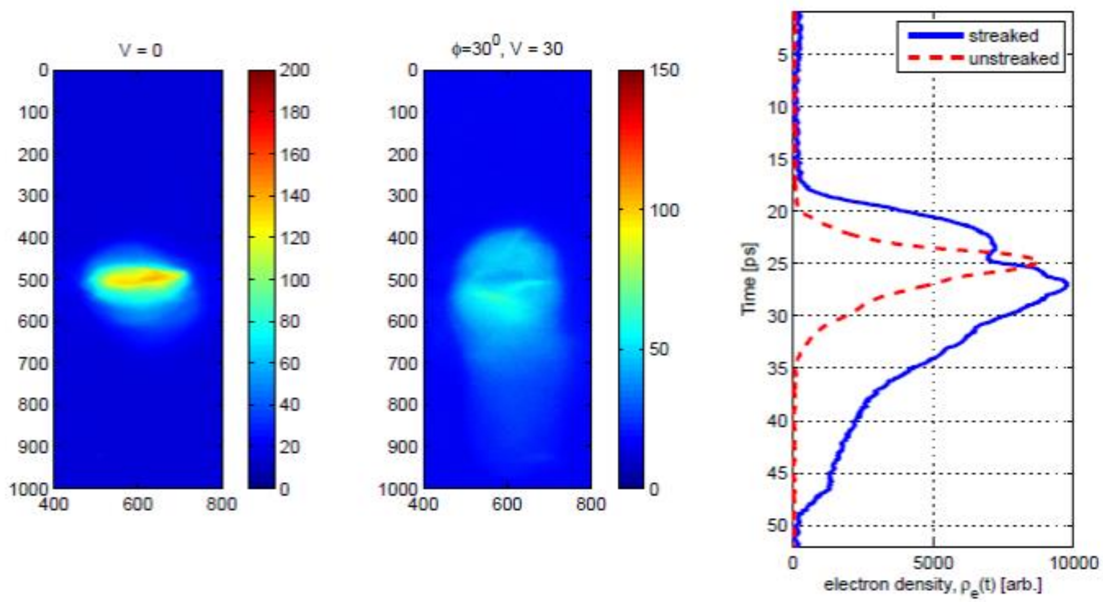
Reconfiguring VELA in future will allow <100 fs time resolution.

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

# *TDC @ VELA*



- S-band Transverse Deflecting Cavity designed by Lancaster University and ASTeC installed at VELA.
- 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 deing 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*

- We are very interested in the development of X-band accelerating structures & sources by CERN & others for the potential application towards a UK X-ray FEL
- Development of accelerating structures (and linearising structures) applicable to FELs is crucial
- 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
- A major issue for the application of X-band for FELs currently appears to be the capital cost

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. Bartolini[1], C. Christou, J.-H. Han, Diamond Light Source, Oxfordshire, UK
[1]and John Adams Institute, University of Oxford, UK

  - "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."

# *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)