Science & Technology Facilities Council
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The VELA and CLARA Test Facilities at Daresbury Laboratory

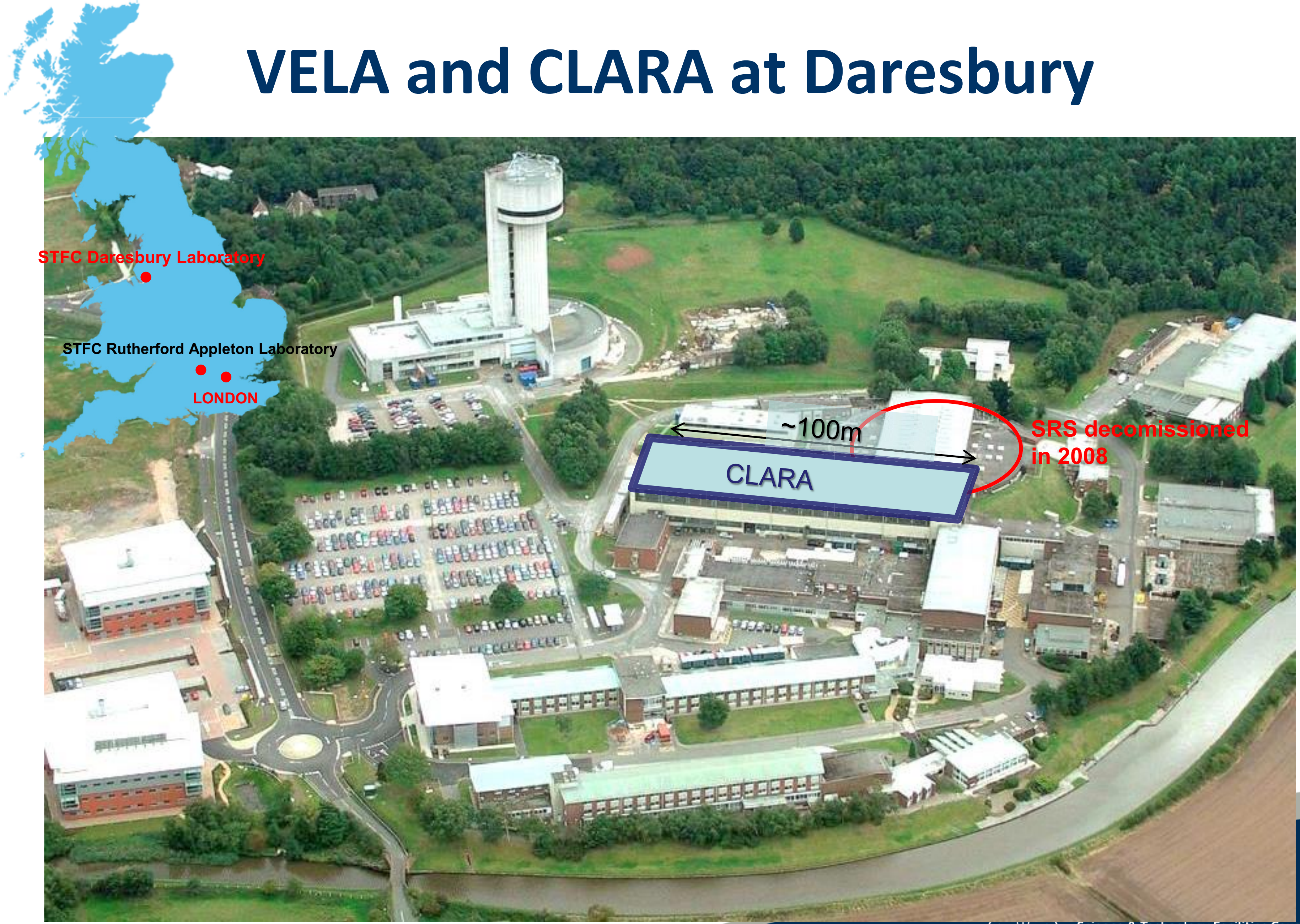
Peter McIntosh, STFC
on behalf of the VELA and CLARA Development Teams

LINAC 16
28TH LINEAR ACCELERATOR CONFERENCE
East Lansing, MI USA
25-30 September

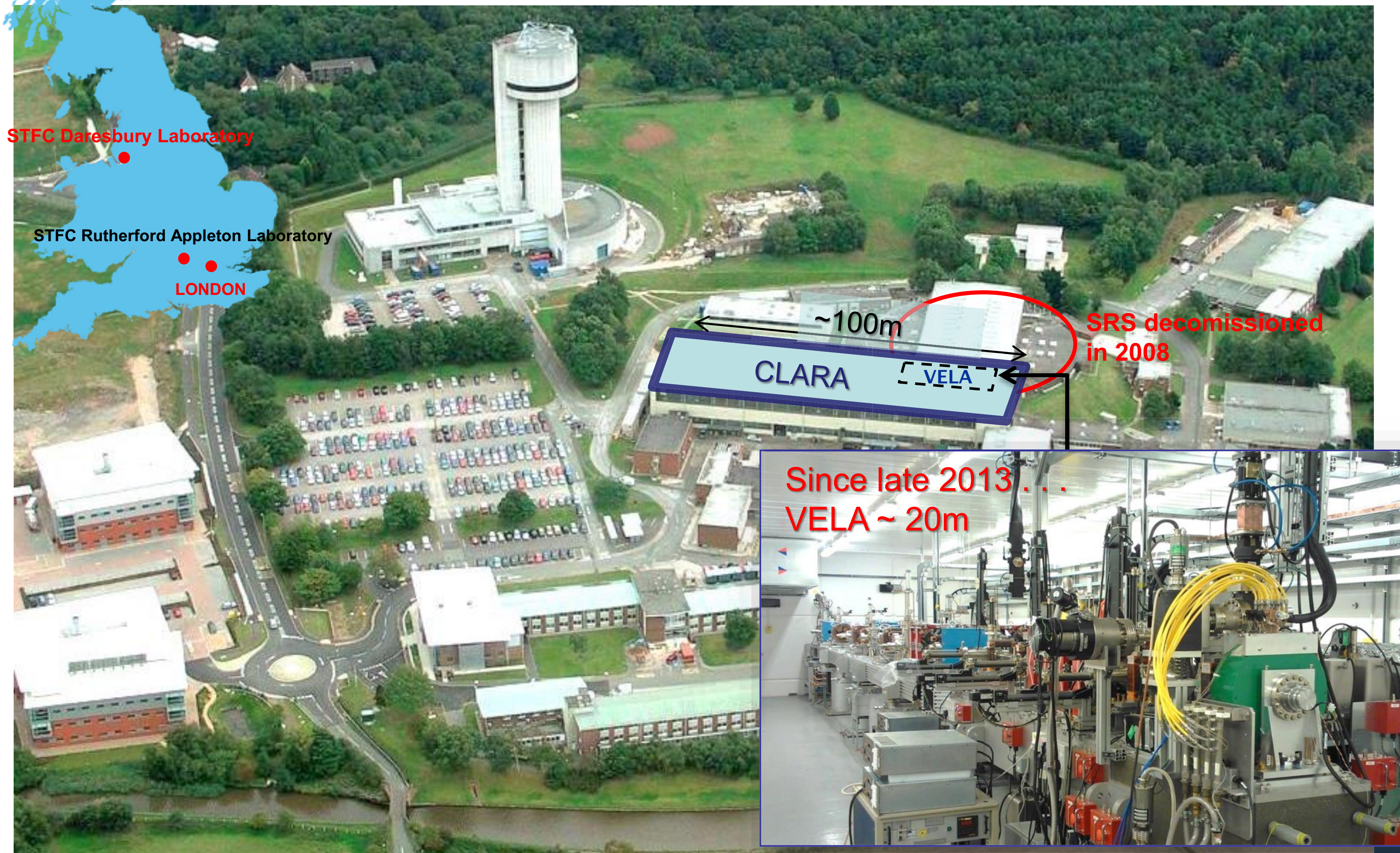
Outline

- *VELA & CLARA Accelerators*
- *VELA Commissioning*
- *VELA Exploitation Activities:*
  - *Electron Diffraction (ED)*
  - *Time of Flight Security Scanning*
  - *New User Area Capabilities*
- *CLARA Design:*
  - *High Repetition Rate Gun*
  - *FEL Research Priorities*
- *VELA & CLARA Future Plans*

VELA and CLARA at Daresbury



VELA and CLARA at Daresbury

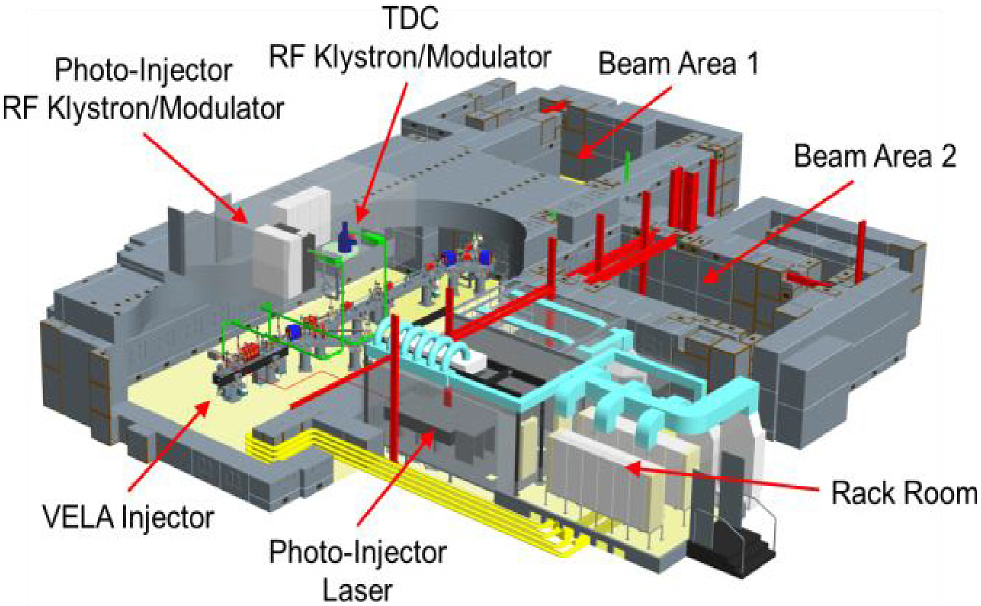


Versatile Electron Linear Accelerator (VELA)

- *High quality, pulsed electron beam source.*
- *Ultra-short pulses, highly stable (position, time, energy etc.), excellent diagnostics, customisable beams.*
- *Two large, flexible, fully shielded experimental areas (BA1 and BA2).*
- *Easy access for industry and academia.*

Can access "both sides of the wall".

- *High performance capability of VELA used to explore fundamental delivery capabilities of future compact FEL sources (CLARA).*



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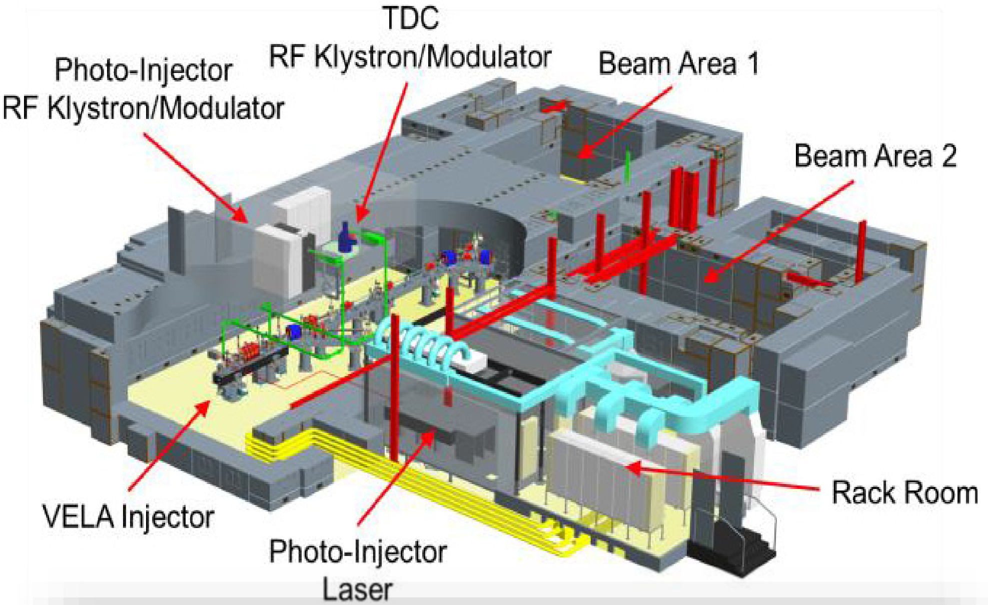

Target Machine Specification	
Beam Energy	4 – 6 MeV (50 MeV with CLARA-FE)
Bunch Charge	0.04 – 250 pC
Bunch length ($\sigma_{t,rms}$)	0.5 – 10 ps
Normalised emittance	1 – 4 μm
Beam size ($\sigma_{x,y,rms}$)	0.5 – 5 mm
Energy spread ($\sigma_{e,rms}$)	1 – 5 %
Bunch repetition rate	1 – 10 Hz (400 Hz with CLARA-FE)

*Not all parameters achievable simultaneously

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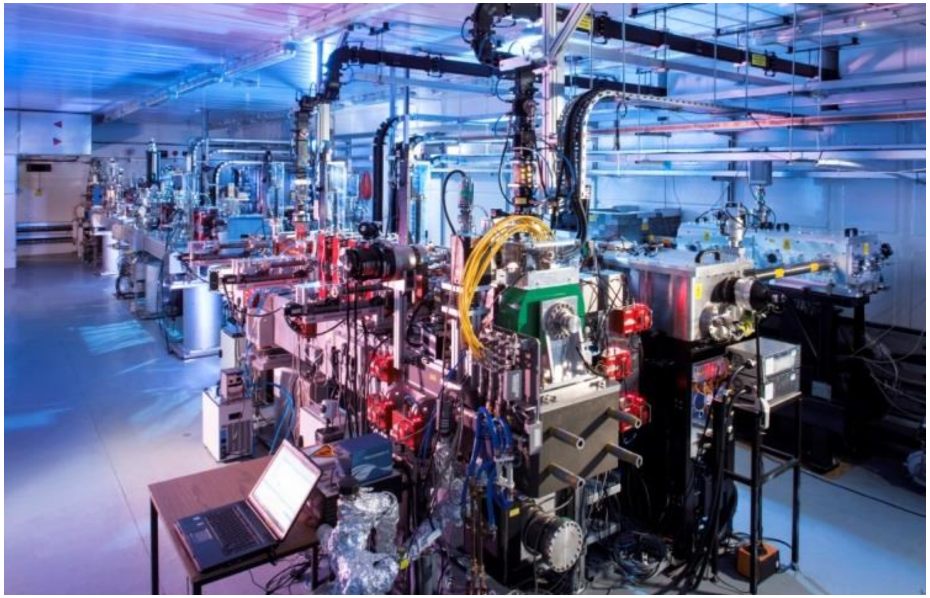
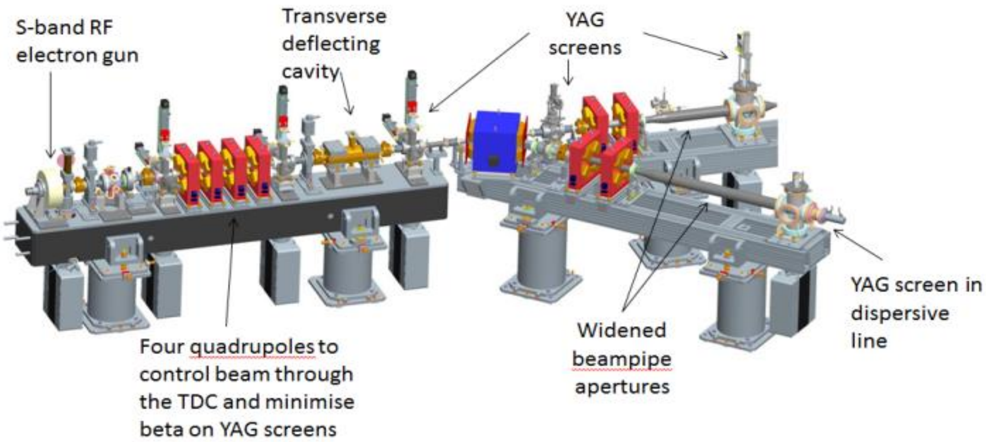


VELA Injector and Diagnostics Line



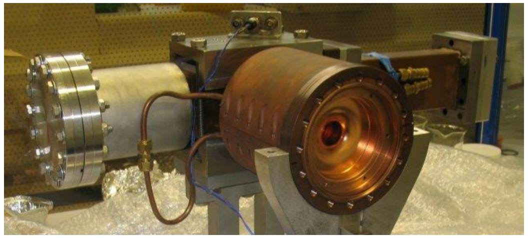
VELA 10 Hz Photocathode RF Gun

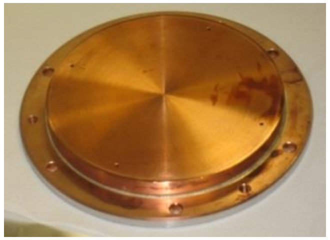
Photo-injector Parameters

Technology	NC RF
Operation frequency, MHz	2998.5
Cavity design	2.5 cell
Maximum Repetition Rate, Hz	10
Maximum cathode field, MV/m	100
Maximum beam energy, MeV	6.5
Maximum RF pulsed power, MW	10
Maximum RF pulse duration, μs	3
Maximum RF pulse repetition rate, Hz	10
Photocathode technology	Metal copper
Maximum bunch charge, pC	250
Beam emittance at maximum bunch charge, mm·mrad	2

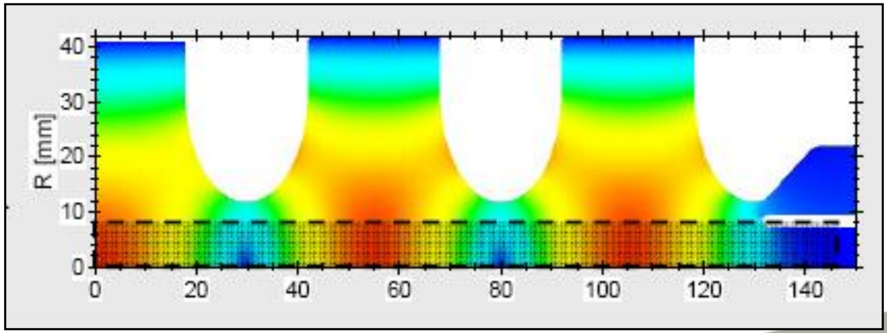
ALPHA-X Gun – on loan from Strathclyde Univ.

VELA photocathode gun





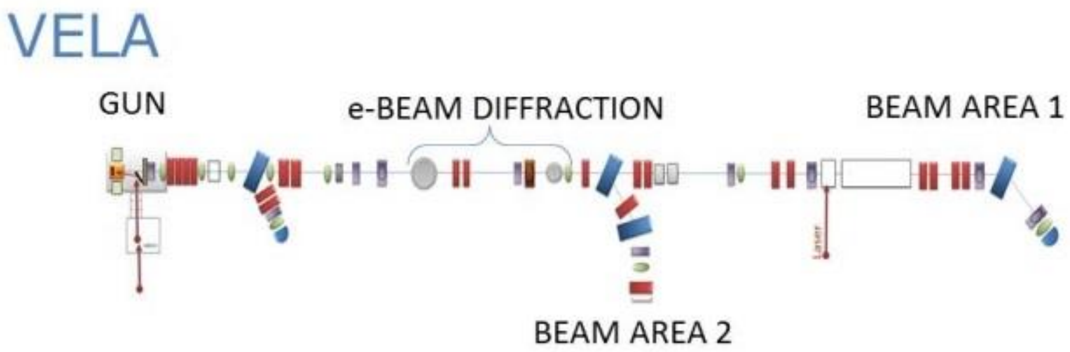
Copper photocathode integrated into the gun as back wall of the cavity, with Qe of 10^{-5} measured.



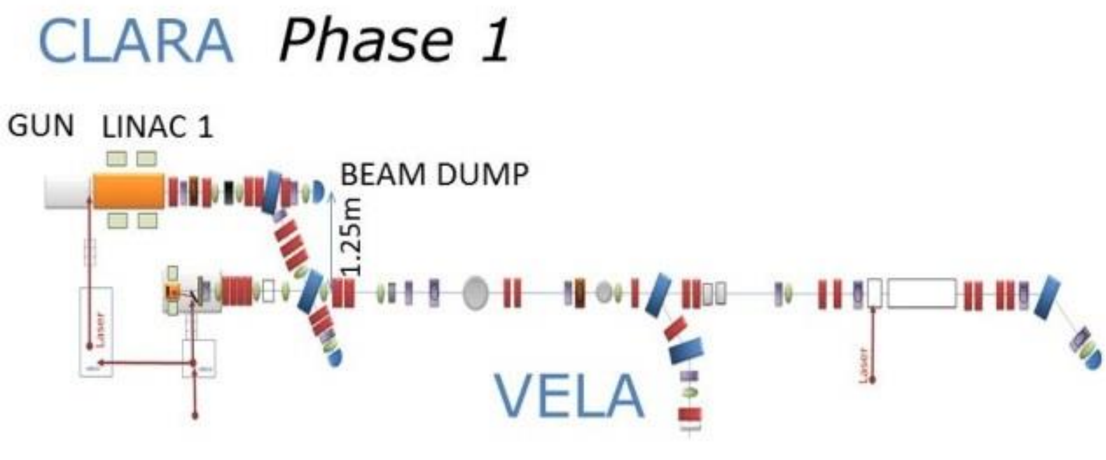
Compact Linear Accelerator for Research and Applications (CLARA)

- *UK-FEL Test facility:*
  - *Capable of testing new FEL techniques.*
  - *Taking FELs into new regime.*
- *Address many scientific and technology challenges for future large scale UK-FEL facility:*
  - Shorter Pulses
  - Improved Temporal Coherence
  - Tailored Pulse Structures
  - Stability & Power
- Key technologies:
  - New photo-injector technologies
  - Novel undulators (short period, superconducting….)
  - New accelerating structures: X-Band etc ...
  - Advanced single bunch diagnostics.

VELA and CLARA



VELA and CLARA



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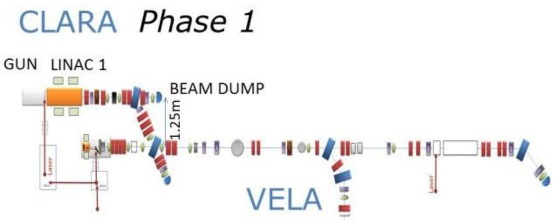

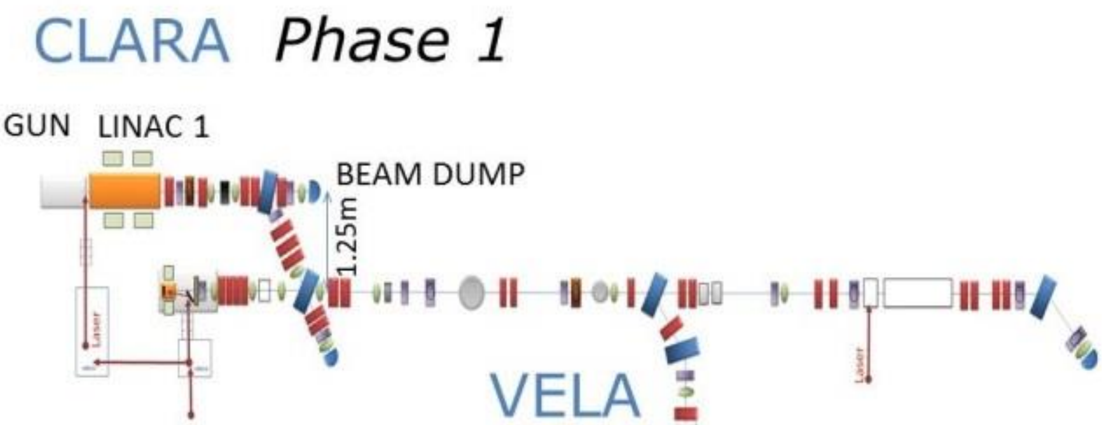

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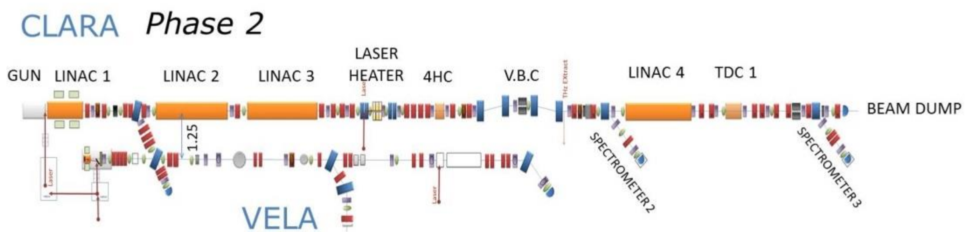

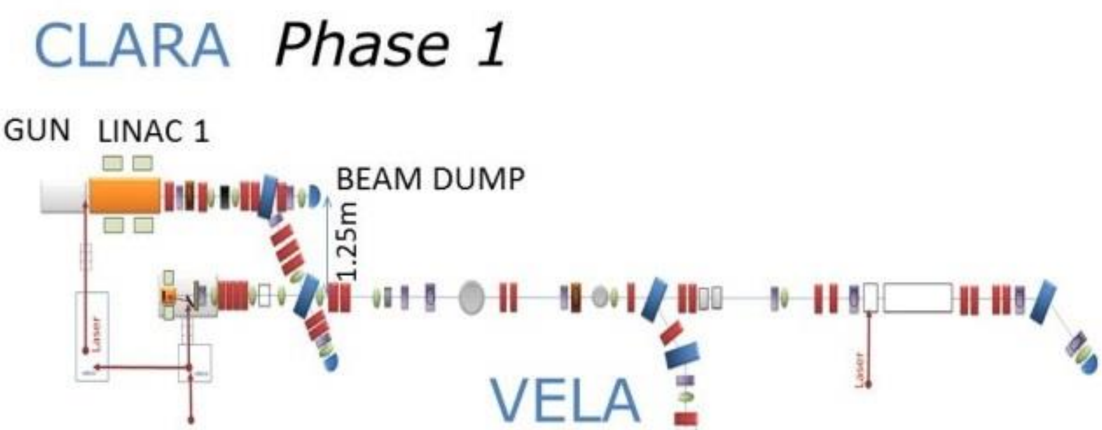

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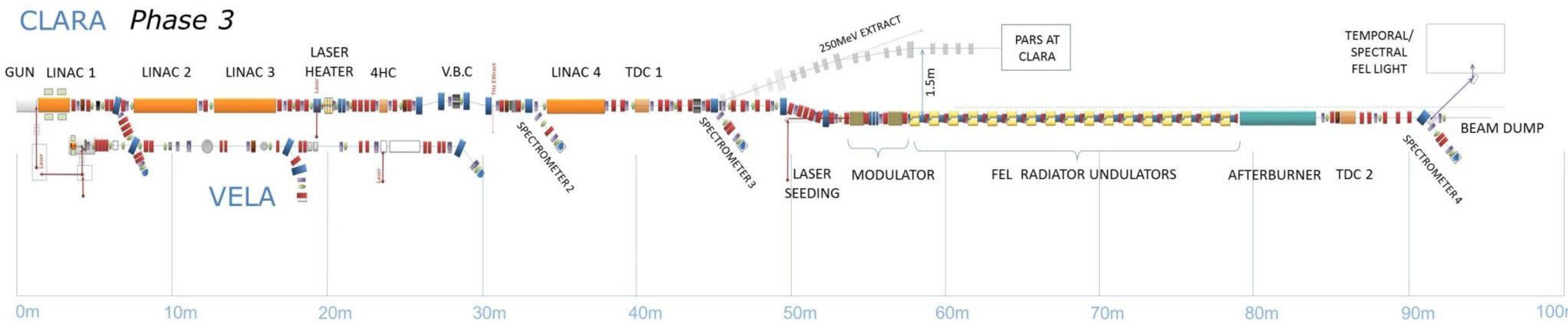

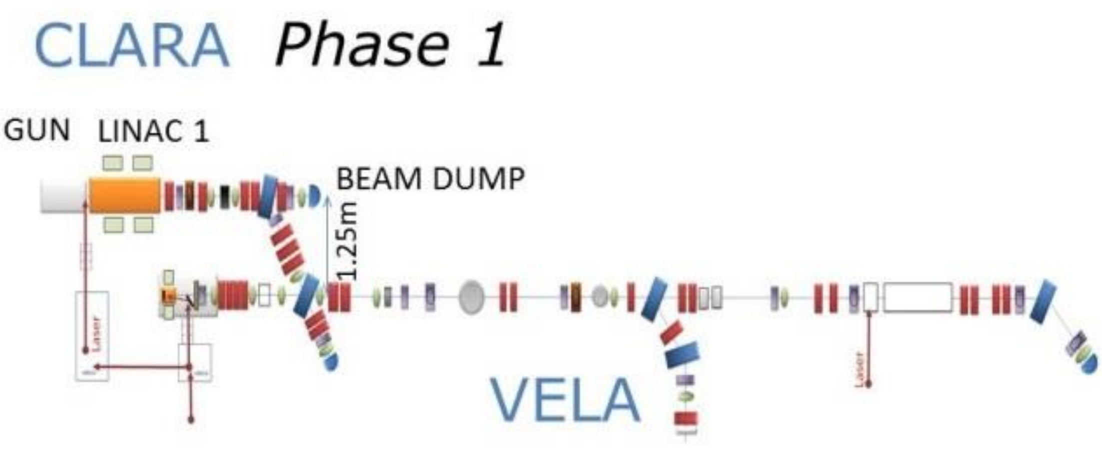

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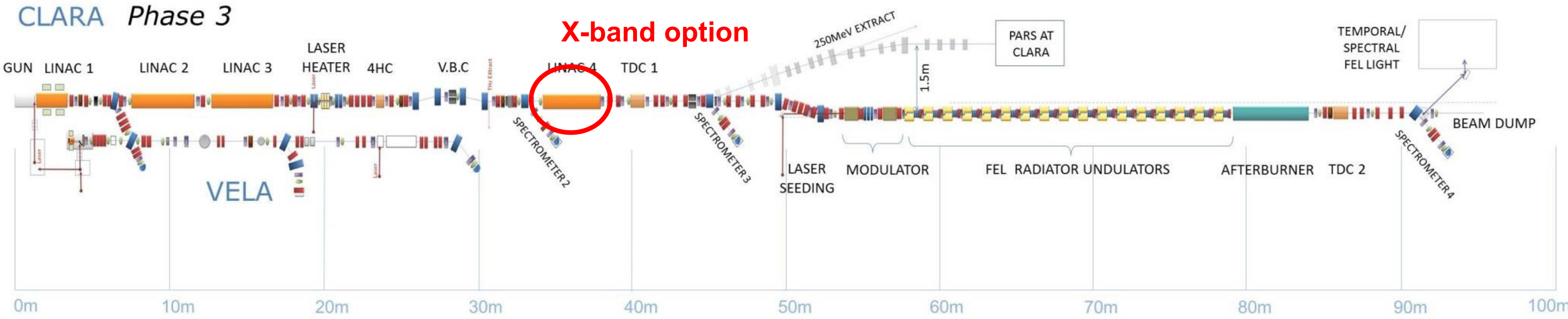
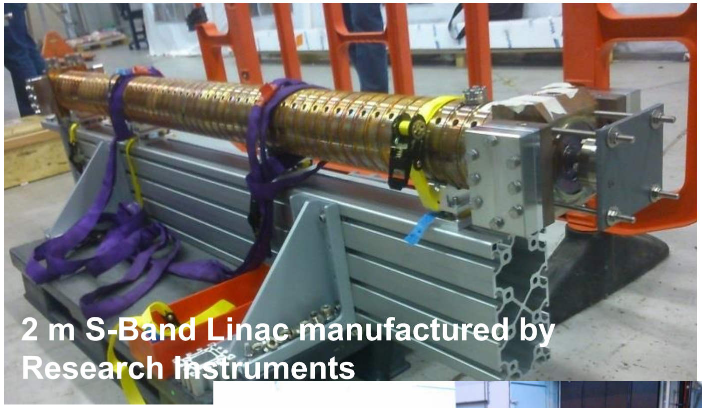


	Linac 1	Linac 2-3	4th Harmonic
Number of cells	*61*	*122*	*72*
Frequency (MHz)	*2998.5*	*2998.5*	*11994*
Nominal RF voltage (MV/m)	**21.4**	**20**	**12**
Maximum RF voltage (MV/m)	*25*	*25*	*16*
Nominal RF power (MW)	*30*	*37*	*6*
Maximum RF power (MW)	*41*	*57*	*29*
Operating Mode	*2π/3*	*2π/3*	*5π/6*
Repetition rate (Hz)	**400**	**100**	**100**
Filling time (μs)	*0.54*	*0.995*	*0.1*
Length Flange to Flange (m)	*2.133*	*4.15*	*0.965*
Active Length (m)	**2.033**	**4.07**	**0.75**
Quality Factor (Q_o)	*~12000*	*~15000*	
Shunt Impedance (MΩ/m)	*54*	*62*	*68*
Nominal operating temp. (°C)	*~30*	*~35*	*~35*

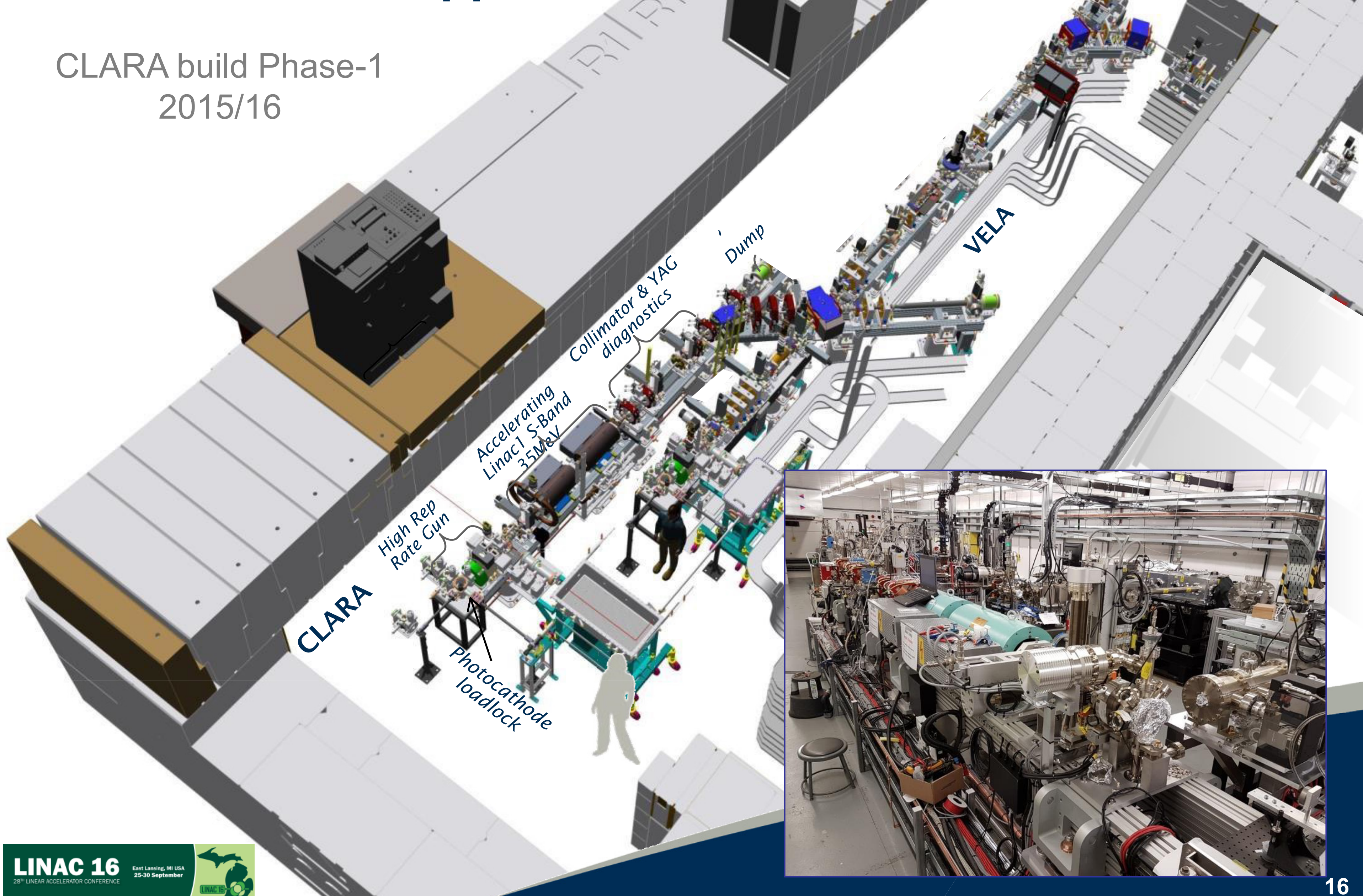


2 m S-Band Linac manufactured by Research Instruments

3 x 4 m S-Band Linacs provided by PSI

Compact Linear Accelerator for Research and Applications

CLARA build Phase-1
2015/16



CLARA

CLARA build Phase-2
2017/19

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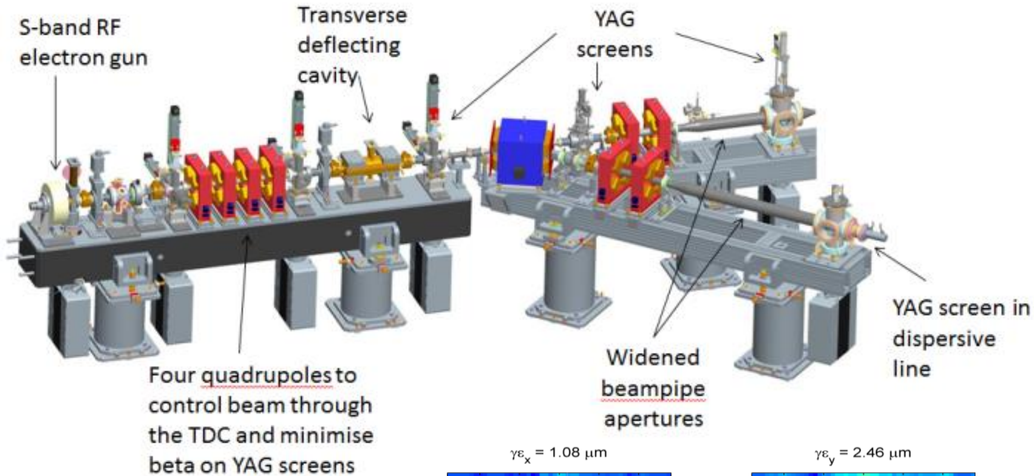
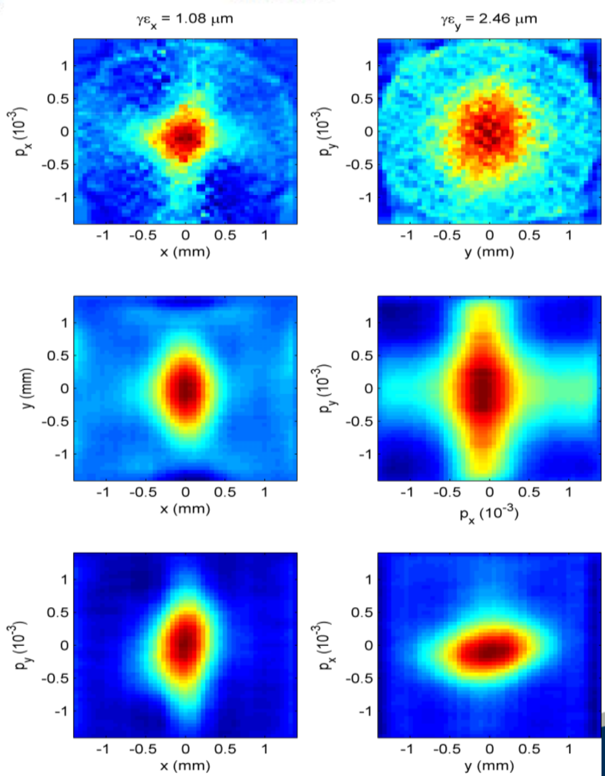
Compact Linear Advanced Research Accelerator

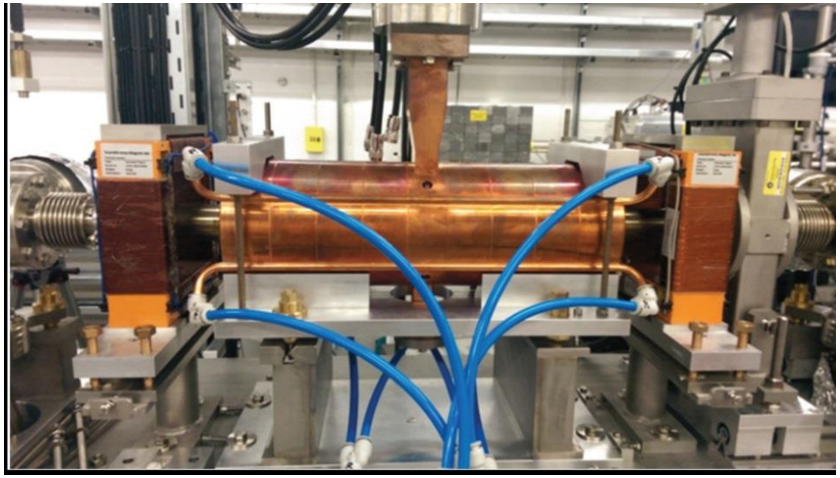
VELA Commissioning

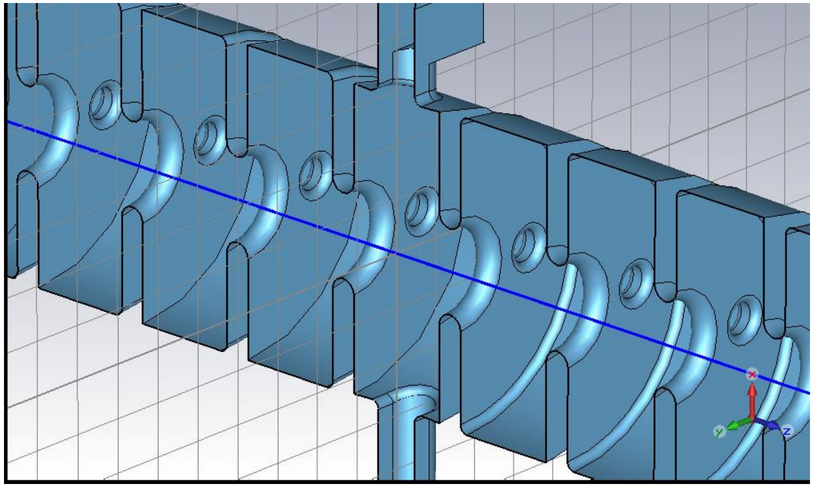




- *Bunch charges from 40 fC (for ED) to 250 pC with peak beam energy of ~5 MeV are reliably achieved.*
- *Dark current, measured with two different cathodes, has shown continual improvement:*
  - *Decreasing from 1.2 nC to 130 pC per 3 μs RF pulse at 70 MV/m.*
- *Long. and Trans. beam qualities characterised through, slit, quad. scans, spectrometer line and TDC measurements.*
- *Micron level beam emittance achieved @ 10 pC.*

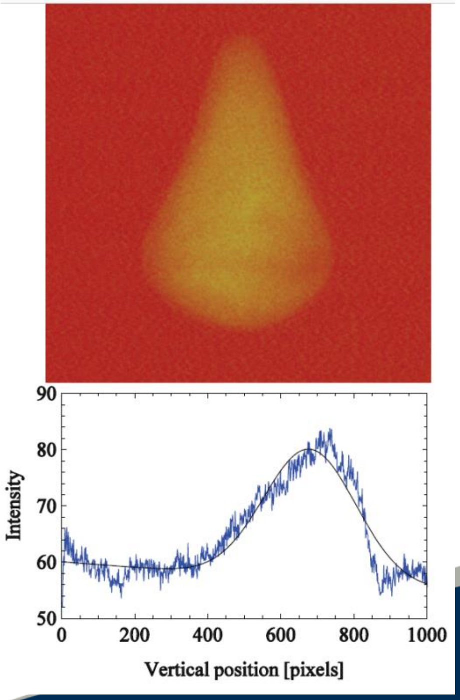
VELA TDC Characterisation

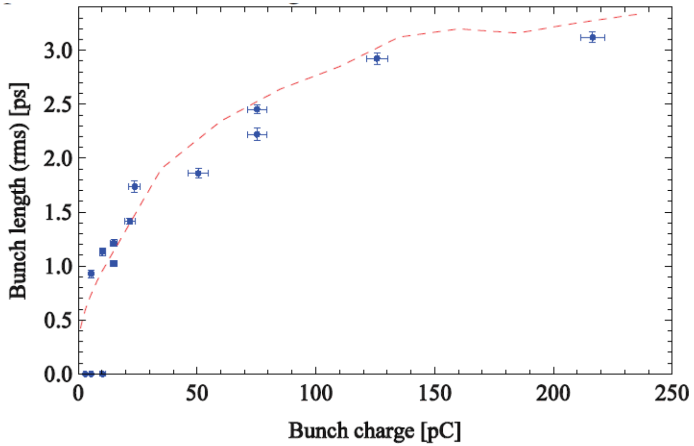




Operating Frequency	2.9985	GHz
Bunch energy	5-6	MeV
Time resolution	10	fs
Phase stability required	0.1	deg
Operating mode	TM110-like	
Nearest mode separation	>5	MHz
Available RF power	5*	MW
Pulse length	3	µs
Repetition rate	10	Hz
Average RF power loss	<150	W

* 6MW klystron power, assume 5MW due to losses in transmission line.





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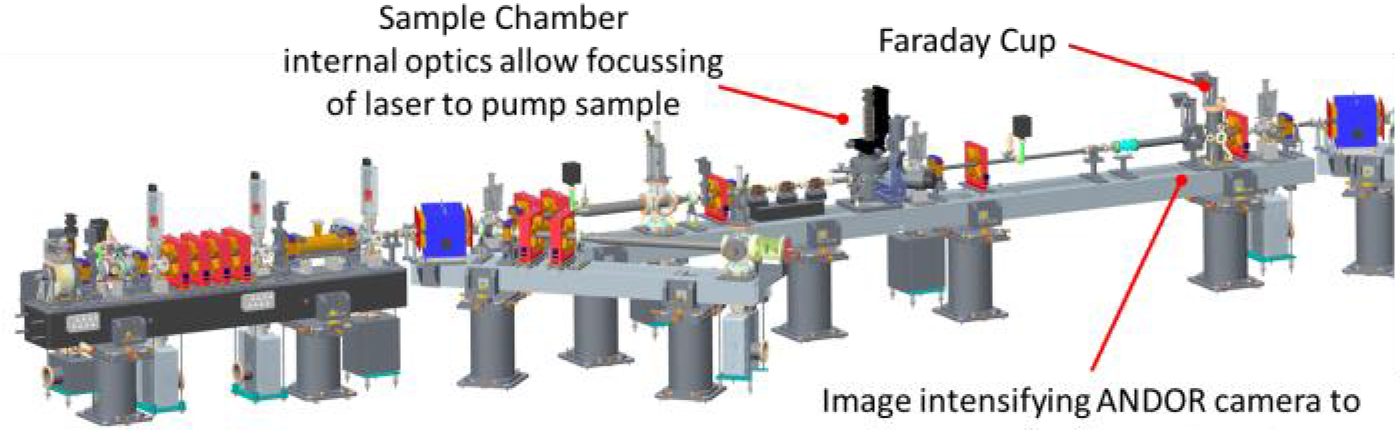
Electron Diffraction on VELA

- *Electron Diffraction enables ultrafast structural analysis of materials.*
- *At a few MeV, able to minimise space charge limitations to obtain short bunches with sufficient charge, to enable high quality diffraction data in a single shot on VELA:*
  - *Complements structural dynamics and fs crystallography with X-ray FELs.*
- *ED advantages:*
  - *Higher scattering cross sections for electrons than X-rays (> 10^4) - smaller samples needed,*
  - *Lower energy transfer per scattering event - less sample damage,*
  - *Smaller and cheaper multi-MeV accelerators, as opposed to multi-GeV accelerators for X-ray FELs.*



UCL

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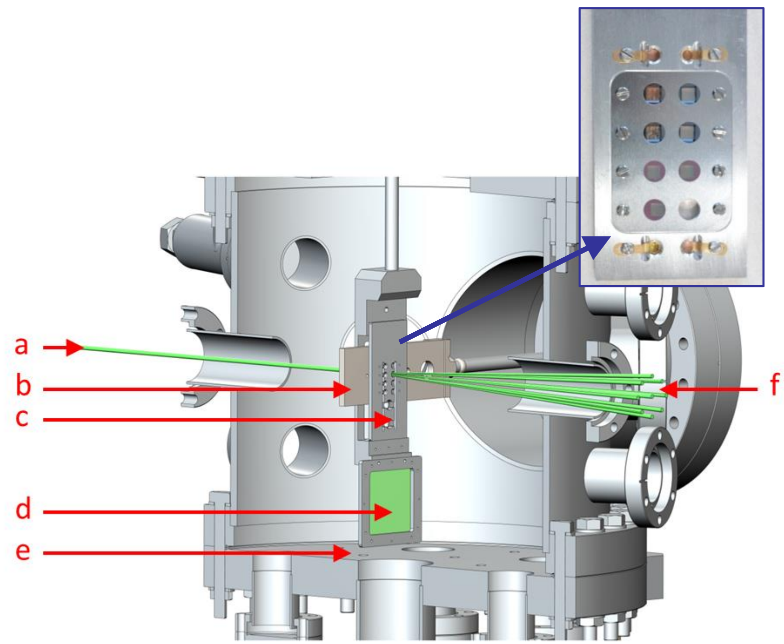
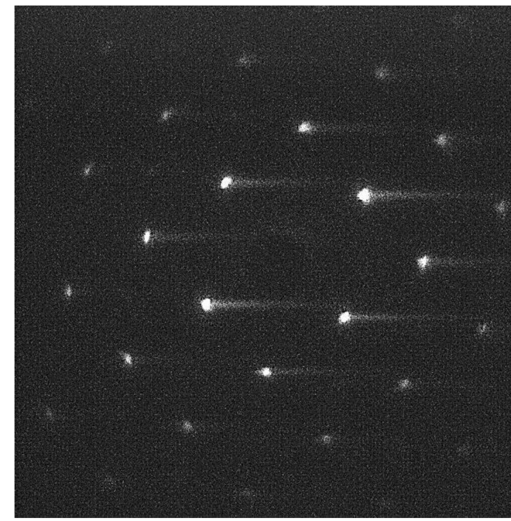
Electron Diffraction Sample Chamber

- *System on VELA allows single shot ED patterns to be obtained with sub-pC bunches from a variety of simple metals and semiconductors.*

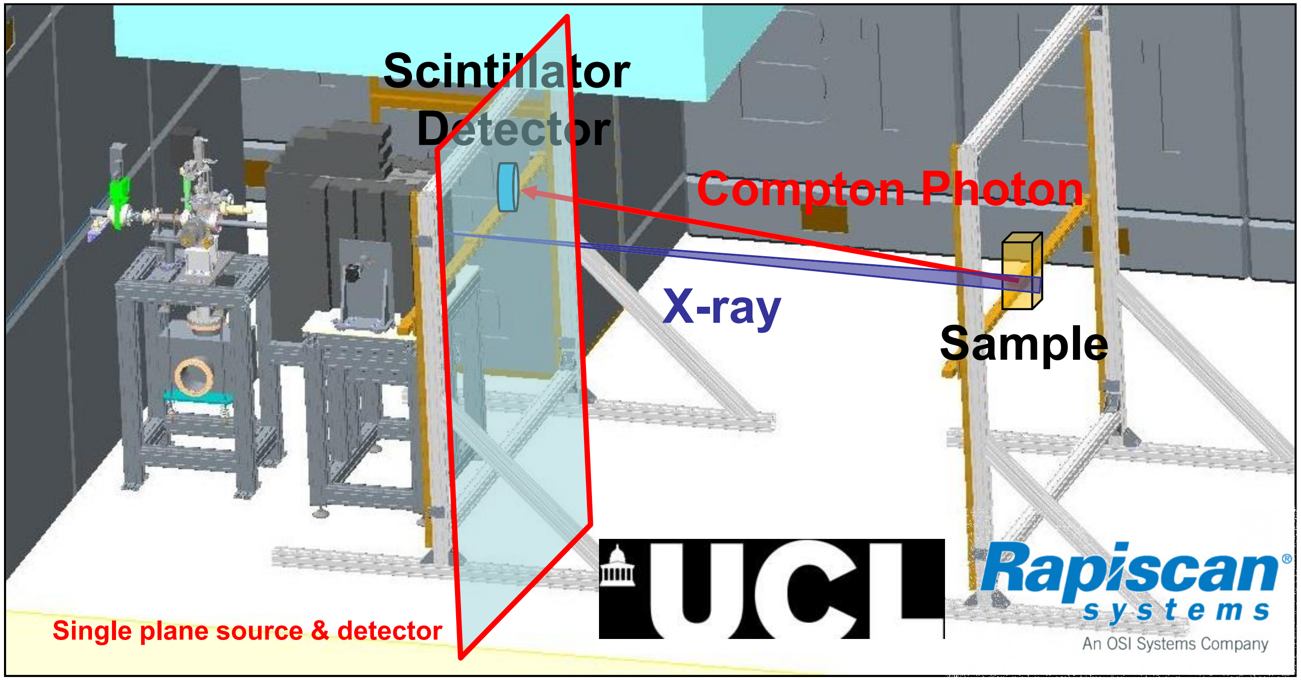




Single gold crystal ED pattern
using single 40 fC VELA electron bunch

a: incident electron beam,
b: shaping apertures
c: sample carousel,
d: screen
e: mounts for focussing optics for laser pump (future programme)
f: diffracted beams

Time-of-Flight Backscatter Security Scanning

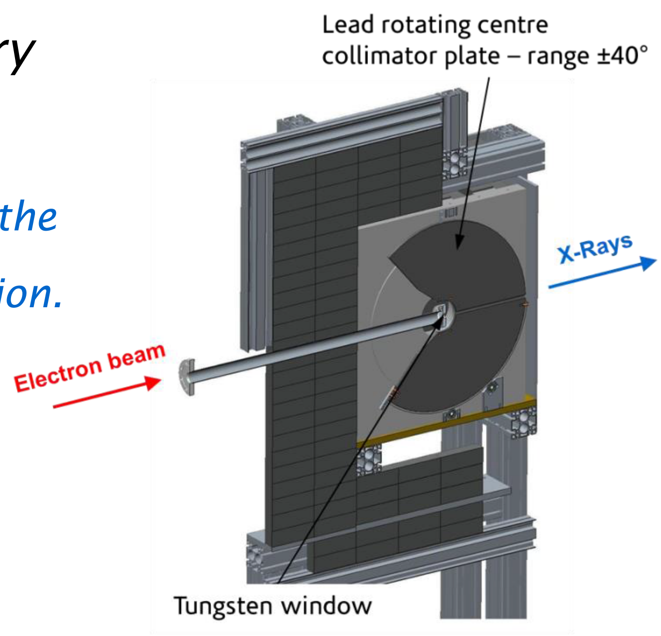


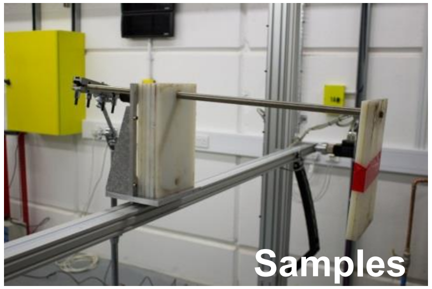
- *Utilising ToF information to create 3D X-Ray Compton Scatter Imaging.*
- *Relationship between the Compton scatter interaction and the photoelectric interaction:*
  - *Amplitude of the returning compton photon represents the density of the material interacted with, its time response identifies its position.*

Allows for the development of a cargo security scanner which can reconstruct '3D' images using a scanner and detector mounted on only one side of the container.

ToF X-Ray Source Requirements

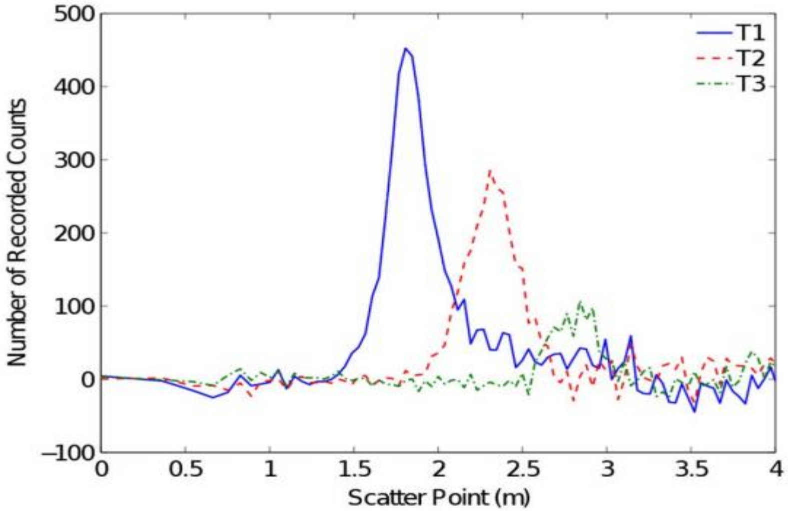
- *Pulsed X-Rays with a very short pulse width (picoseconds):*
  - *Long pulse X-Rays blurs the timing information and reduces depth of resolution.*
- *Collimated source to provide pencil beam geometry:*
  - *Original trajectory to be accurately known.*
- *High energy required to penetrate densely packed cargo for security screening.*
- *Readout electronics with high sampling rate:*
  - *Accurately record the arrival time of each detected photon.*



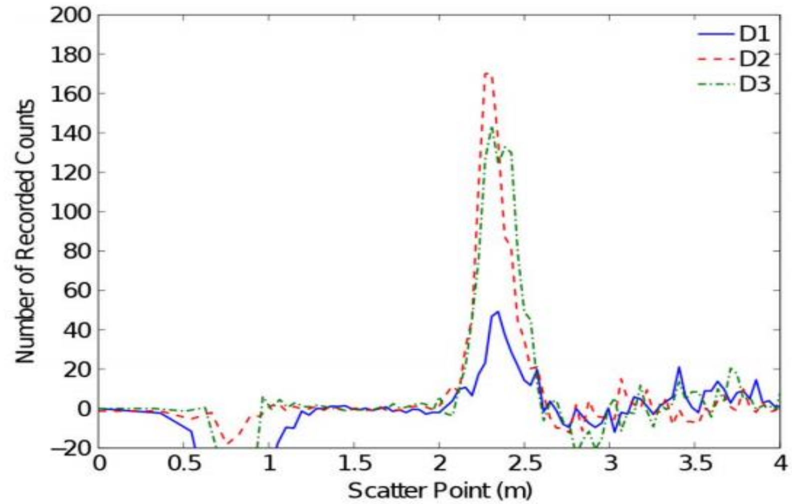


Preliminary Detector Characterisation Results

Timing ⇒ Position



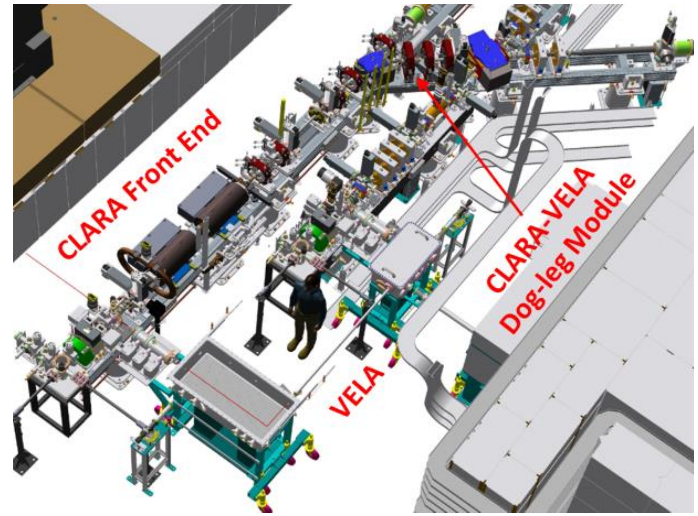
Amplitude ⇒ Density



- *Ability to determine sample position via photon ToF proven over several metres of air with a 10 Hz, 4.5 MeV VELA E-Beam.*
- *Some indication of material determination – further analysis required to improve background suppression and normalisation:*
  - *Data also collected for single and multiple test pieces.*
- *Next step to incorporate multiple detectors and perform first 3D imaging and resolution assessment/refinement.*

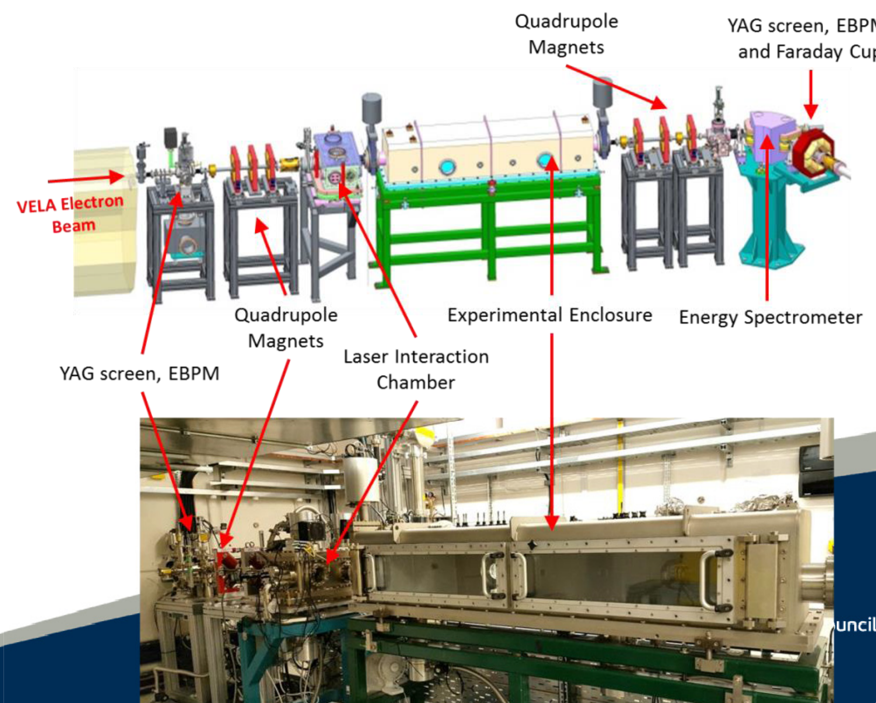
New VELA Beam Area 1 Capability

New BA1 multi-user facility commissioned using ~4 MeV beams from the 10 Hz VELA RF gun in Sept 2015.



2 Beam Sources:

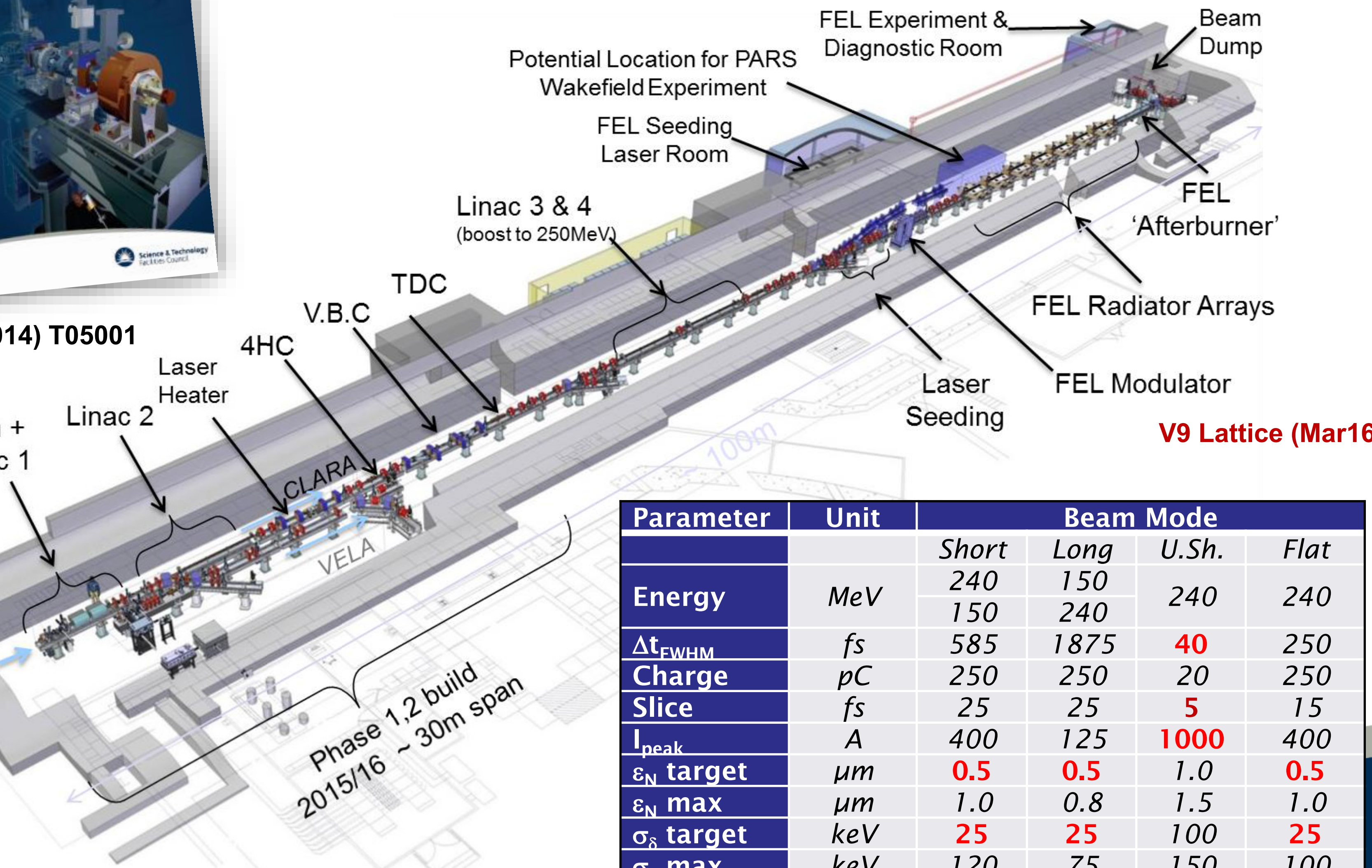
- *New High Repetition Rate Gun (HRRG):*
  - *~4 MeV, >ps long bunches at up to 400 Hz.*
- *New CLARA-FE ~50 MeV, compressed in CLARA - VELA dog-leg, sub-ps at 10 Hz.*
  - *bunch lengths down to 300 fs RMS*
  - *transverse beam sizes of <100 μm RMS at the BA1 interaction point.*
- *High power 802 nm, 16 TW peak power laser, 50 fs pulse duration, 0.8 J pulse energy @ 10 Hz can also be delivered to the BA1 chamber:*
  - **Novel acceleration***: LWFA or electron beam modulation experiments possible.*



See poster: S. Jamison, MOOP019

CLARA Design

JINST 9 (2014) T05001



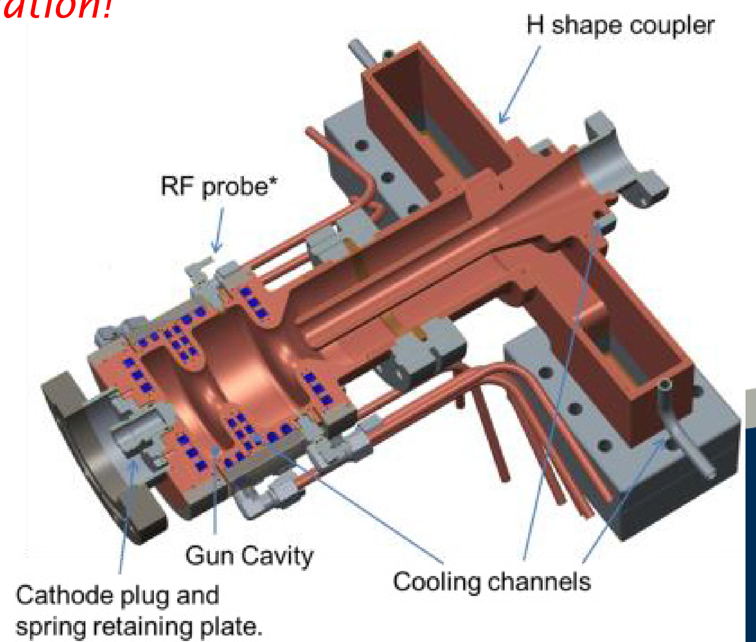
V9 Lattice (Mar16)

Parameter	Unit	Beam Mode			
		Short	*Long*	*U.Sh.*	*Flat*
Energy	*MeV*	*240* / *150*	*150* / *240*	*240*	*240*
Δt_{FWHM}	*fs*	*585*	*1875*	**40**	*250*
Charge	*pC*	*250*	*250*	*20*	*250*
Slice	*fs*	*25*	*25*	**5**	*15*
I_{peak}	*A*	*400*	*125*	**1000**	*400*
ε_N target	*µm*	**0.5**	**0.5**	*1.0*	**0.5**
ε_N max	*µm*	*1.0*	*0.8*	*1.5*	*1.0*
σ_δ target	*keV*	**25**	**25**	*100*	**25**
σ_δ max	*keV*	*120*	*75*	*150*	*100*
E. Chirp	*MeV/ps*	*n/a*	*n/a*	*n/a*	*< 1*
E. Var.	*keV*	*n/a*	*n/a*	*n/a*	*< 240*

CLARA High Repetition Rate Gun

- *Designed in collaboration with:*
  - *Lancaster University, UK*
  - *Institute of Nuclear Research, Moscow*
- *CLARA requirements:*
  - *100 MV/m @ 400 Hz*
  - *120 MV/m @ 100 Hz*
- *Interchangeable copper photocathode illuminated by UV laser.*
- *CLARA stability requires:*
  - *0.1% rms amplitude*
  - *0.1° rms phase*
  - *Necessitates <0.01°C rms temperature regulation!*

Parameter	Value
Frequency (MHz)	*2998.5*
Number of Cells	*1.5*
Q Factor	*>14000*
Maximum Repetition Rate (Hz)	*400*
Maximum Surface Field (MV/m)	*120*
Average RF Power (kW)	*6.8*



Photocathode system development support from: CERN, INFN-LASA (Milano), DESY (Hamburg and Zeuthen) & LBNL

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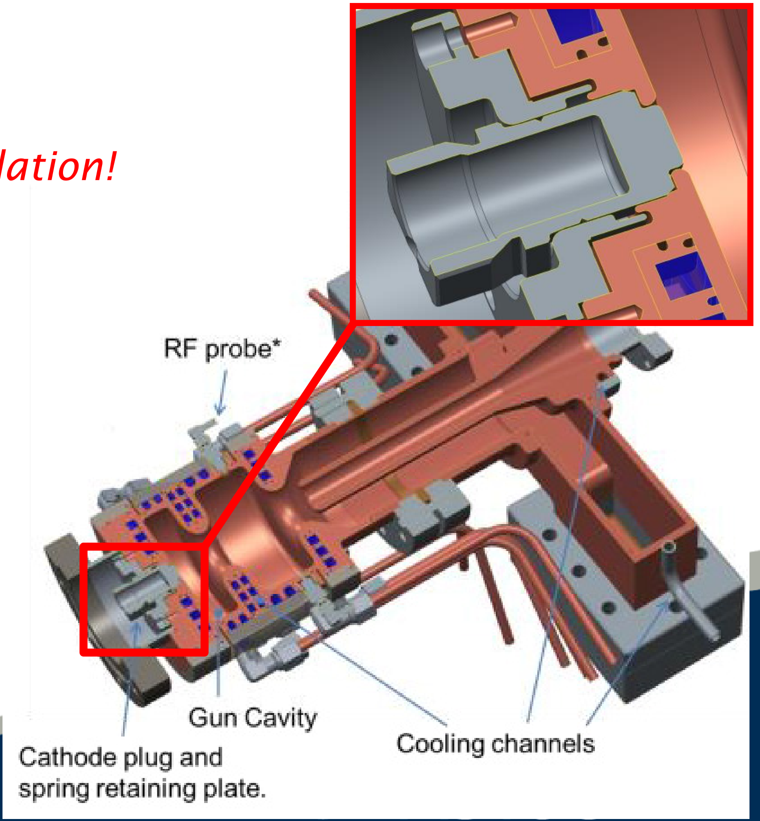

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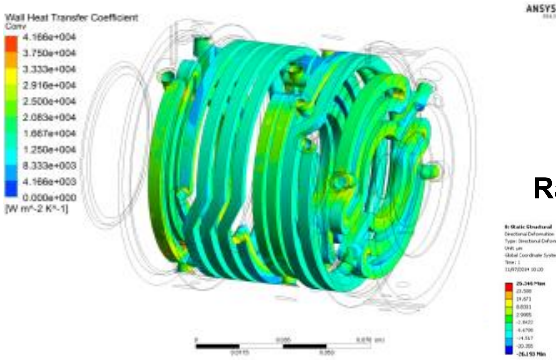
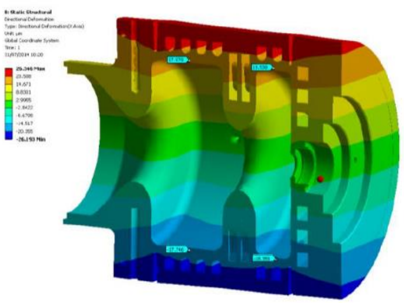
HRRG Thermal Stability

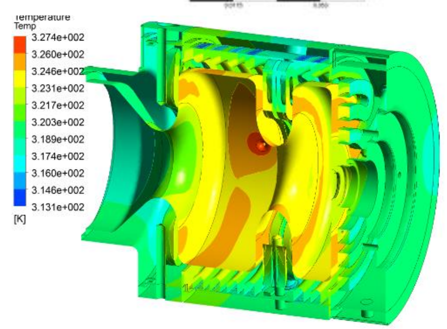
- *Cavity incorporates 9 separate cooling circuits:*
    - *Each circuit optimised for expected localised thermal loads.*
    - *Maximise cooling at RF probe interface.*
- *Simulations utilised:*
    - *CST Microwave Studio – E-M Fields*
    - *ANSYS CFX – Fluid dynamics*
    - *ANSYS Workbench – Displacements, frequency shifts and material stress due to RF heating.*
- *Largest relative temperature rise of +14^{o}C predicted at RF probe interface.*
- *Average power of 6.8 kW for 100 MV/m @ 400 Hz.*
- *Cavity manufactured by Research Instruments.*
- *Operating frequency confirmed at 48 ^{o}C with field flatness of 98 % ± 1%.*

Cooling Channel Pressure

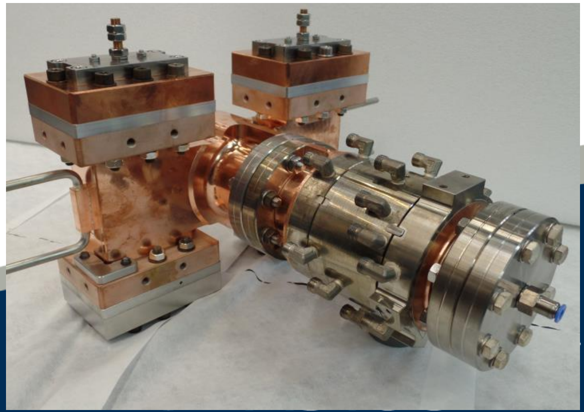


Radial Cell Deformation





Temperature Profile



See posters: B.L. Militsyn, MUPLR016
L. Cowie, TUPRC017

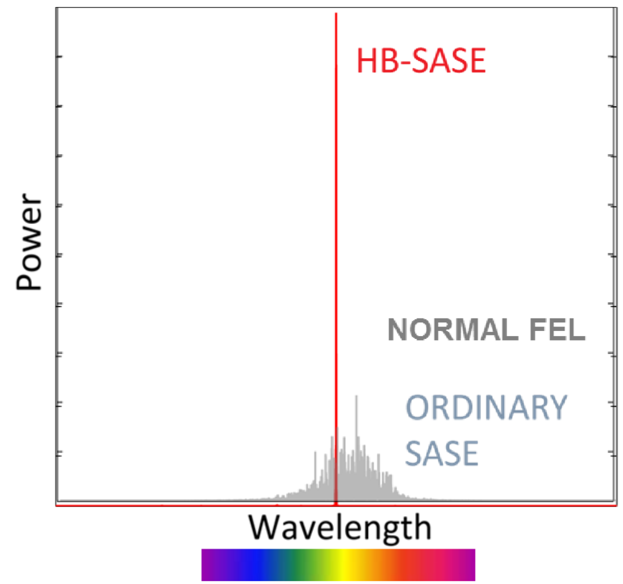
CLARA FEL Research Priorities

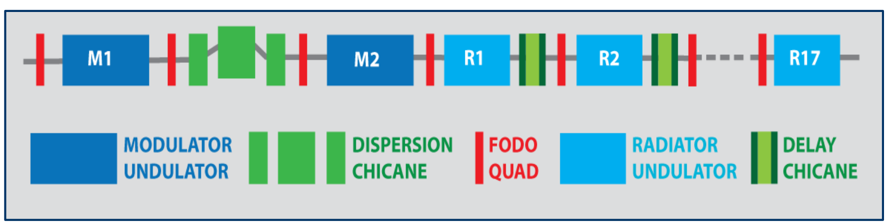
Early stage demonstrations:

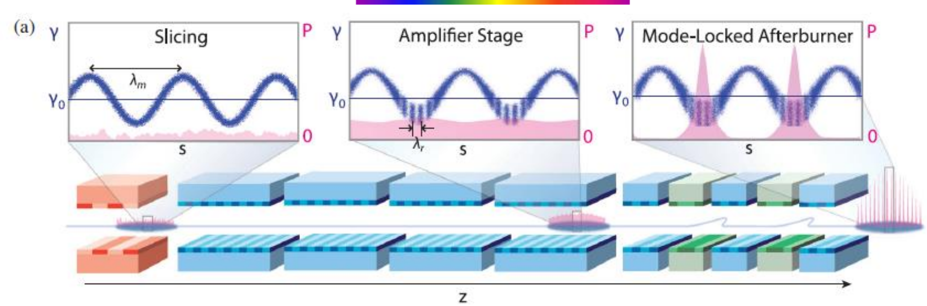
- *Single spike SASE:*
  - *Ultra-short bunches*
- *2-colour Operation:*
  - *Tune undulators for dual λ's.*
- *Tapering:*
  - *At long λ's, early undulator saturation occurs,*
  - *Tapering undulator field post saturation, significantly increased power can be achieved.*

Primary demonstrations:

- *Mode locking*
- *High Brightness SASE*
- *Mode-locked Afterburner*







VELA & CLARA Future Plans

- *CLARA-FE installation expected complete by Jan'17.*
  - *HRRG commissioning on the VELA beamline will start.*
- *Once commissioned, possible to provide VELA with:*
  - *Low energy (4 – 5 MeV) HHRG beam (up to 400 Hz repetition rate),*
  - *High energy (~50 MeV) CLARA-FE beam (10 Hz repetition rate).*
- *Beam characterisation and R&D to establish the design parameters for CLARA will continue alongside some dedicated allocation time for exploitation programme.*
- *Swapping the RF guns possible in early 2018:*
  - *With the HRRG gun installed on the CLARA-FE, it will then be possible to meet CLARA specifications of 100 Hz repetition rate and at the same time provide higher beam power to the VELA beam areas.*
- *CLARA Phase-2 modules ready for commissioning in late 2019.*
- **First FEL lasing on CLARA by end of 2021.**

VELA Trans National Access included in H2020 ARIES Programme – starts 2017!

Collaborators

Berkeley Lab

The Cockcroft Institute of Accelerator Science and Technology

CERN

DESY

FMB Oxford

INFN

JAI John Adams Institute for Accelerator Science

LAL Laboratoire de l'Accélérateur Linéaire

Paul Scherrer Institut PSI

Rapiscan systems An OSI Systems Company

University of Strathclyde Glasgow

UCL

THANK YOU

http://www.stfc.ac.uk/research/accelerator-science/