RUEDI

(Relativistic Ultrafast Electron Diffraction & Imaging) Future UK Facility

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STFC Daresbury Laboratory

SLAC FUSE Workshop
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Engineering and Physical Sciences Research Council
Science and Technology Facilities Council
University of Liverpool
The Rosalind Franklin Institute
Swansea University Prifysgol Abertawe
University of Leeds

Contents

- Facility overview and status
- Design Evolution
- Imaging/Microscopy Line
- **Ultrafast Diffraction Line**
- Laser Systems
- Digital Twin
- Environmental Sustainability
- Conclusions

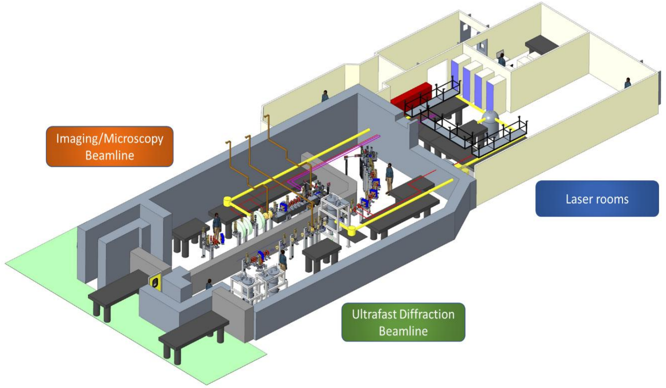
The RUEDI Facility Proposal

- **R**elativistic **U**ltrafast **E**lectron **D**iffraction & **I**maging
- A new UK National User Facility at Daresbury Laboratory
- For time-resolved pump-probe experiments

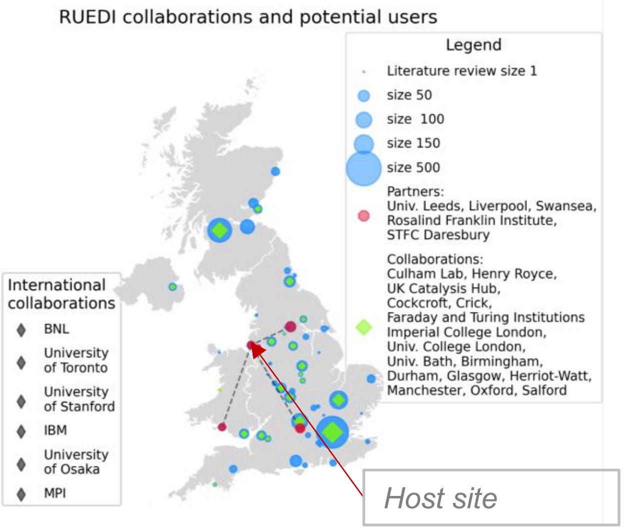
UED	UEM
Ultrafast Electron **Diffraction**	Ultrafast Electron **Microscopy**
Reciprocal space	Real space imaging
Structural determination	Direct observation

- 2020 - Funding bid
- 2022 - Design stage
- 2025 – Business Case
- 2026 - Construction
- 2032 - User facility

- With a wide variety of **pumps** and sample **environments**
  - UV-IR-THz
  - <10fs, *(TW, ions)*
  - Solid/liquid/gas
  - Cryo(mK)
- To enable a wide range of science:
  - Dynamics of Chemical Change
  - Quantum Materials & Processes
  - Biosciences
  - Materials in Extremes
  - Energy Generation, Conservation, and storage



The RUEDI Project



UKRI project through EPSRC, funded by UKRI Infrastructure Fund

Engineering and Physical Sciences Research Council

UK Research and Innovation

Science Team

UNIVERSITY OF LIVERPOOL

The Materials Innovation Factory

Imaging Line

The Rosalind Franklin Institute

Harwell Campus Hub

Diffraction Line

Science and Technology Facilities Council

Daresbury Laboratory

Cockcroft Institute

Facilities & Infrastructure

Science and Technology Facilities Council

Daresbury Laboratory

Daresbury Electron Hall

Other science theme leads:

Swansea University Prifysgol Abertawe

UNIVERSITY OF LEEDS

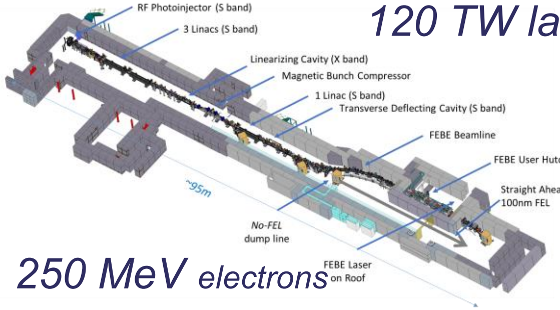
RUEDI

Leveraging Daresbury Experience

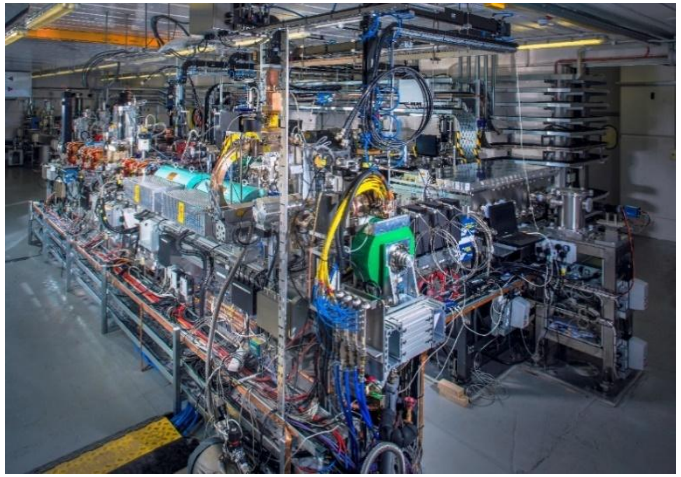
Design, build, and operation of particle accelerator facilities

CLARA

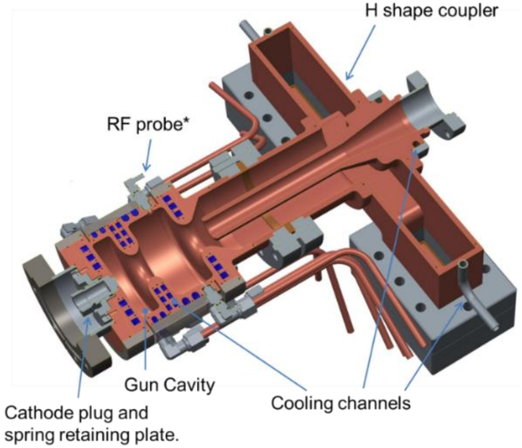
120 TW laser

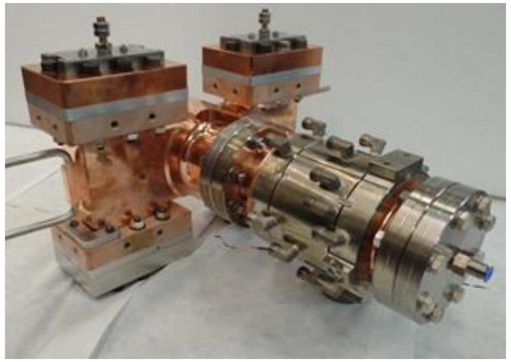


250 MeV electrons

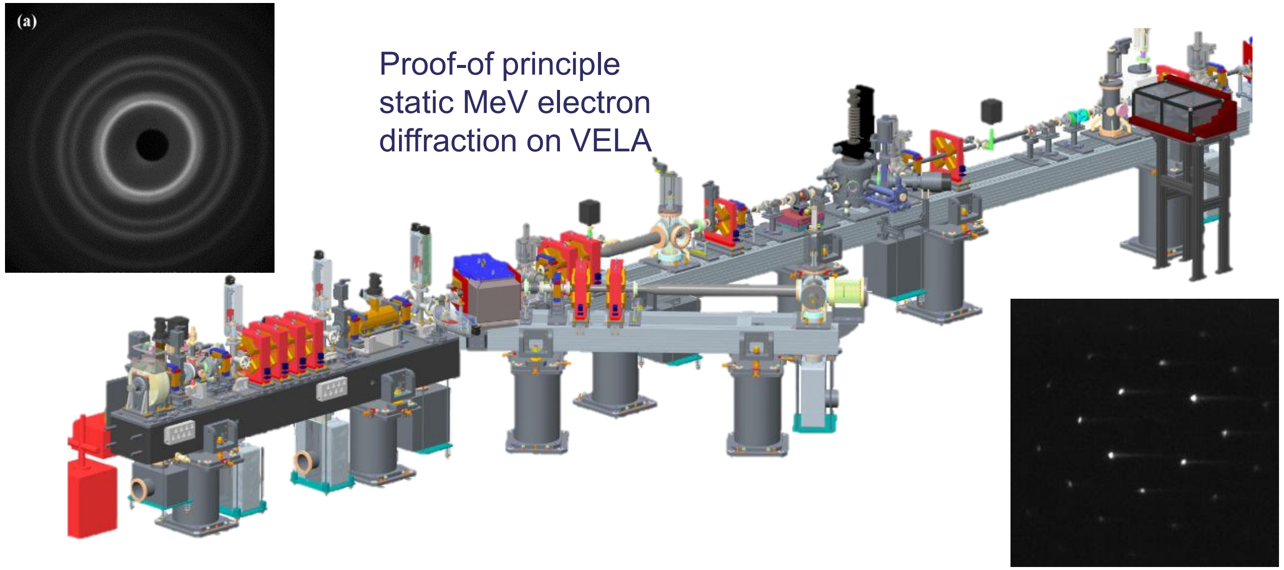


Femtosecond photoinjector development





MeV UED Experience



Proof-of principle static MeV electron diffraction on VELA

Measurement of dynamics of relativistic electrons with laser-driven THz sources, and high power TW lasers

Project Status

- Technical Design Report completed March 2024
- Full project approval announced March 2024

https://www.ukri.org/news/major-research-and-innovation-infrastructure-investment-announced/

- £124.4 million from UKRI Infrastructure Fund from ~2026:
  - 6 years construction, commissioning, and initial science experiments
  - Subject to full business case approval
- Handover to a user facility ~2032
  - 5 year operation + upgrade cycles
  - Guaranteed 2 x 5 year cycles

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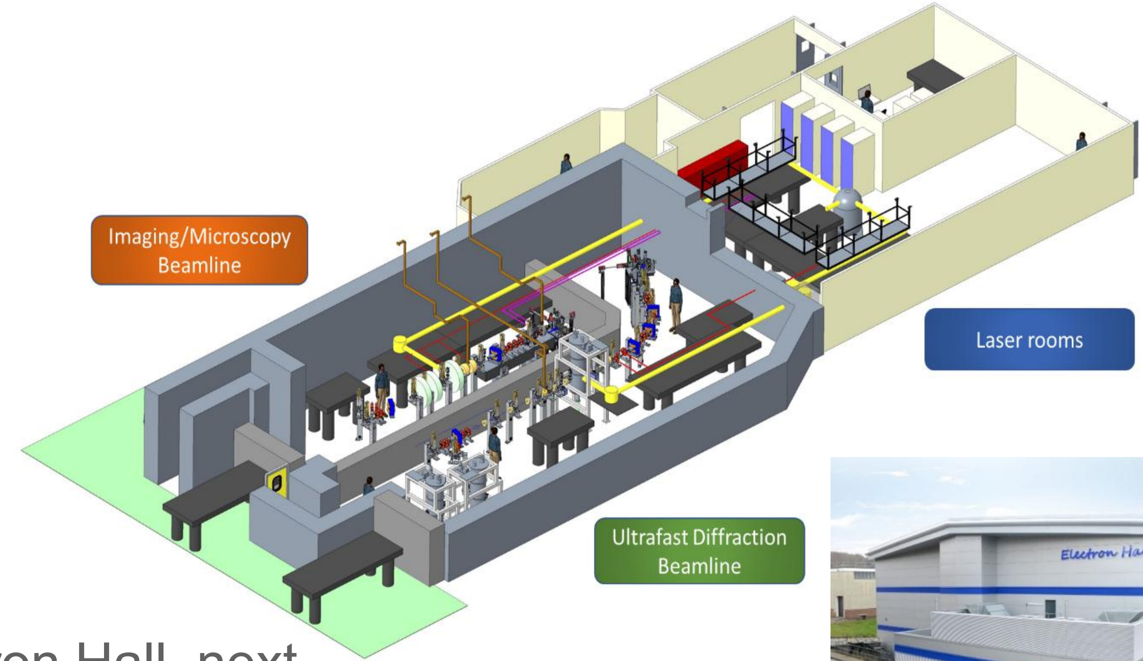


- To be sited at Daresbury Laboratory in the Electron Hall, next to existing CLARA facility
  - (S-band photoinjector, 250 MeV linac, 120 TW laser)

RUEDI

Science Themes Overview

Dynamics of Chemical Change

Chemical complexity across scales
Hydrogen bonding
Pulse radiolysis
Heterogenous catalysis

Wide array of sample environments and triggers
Stroboscopic diffraction
<10fs to 100fs resolution

Quantum Materials & Processes

Ultrafast low-energy optical switching
Magnetic textures & skyrmions
Topological superconductors
Thermoelectric energy harvesting

Cryogenic, mK temperatures
Stroboscopic diffraction
THz & wide optical triggers
<10fs to 100fs resolution

Biosciences

Photosynthesis & energy transfer
Cardiac disease related dynamics
Virology & infection
Biological self-assembly/toxicity

Live cells, liquid environment
Single-shot imaging
0.8nm resolution
<1μs resolution

Materials In Extremes

Astrophysics & warm dense matter
Advanced manufacturing
Nuclear fission/fusion/space
Response to shocks

TW laser >10^{18} W.cm^2
Single shot imaging
10-100nm
1-100ps

Energy Generation, Conversion and Storage

Photocatalysis & induced electro-chemistry
Defect kinetics in solar cells
Ion solvation kinetics in batteries
Kinetics of glasses

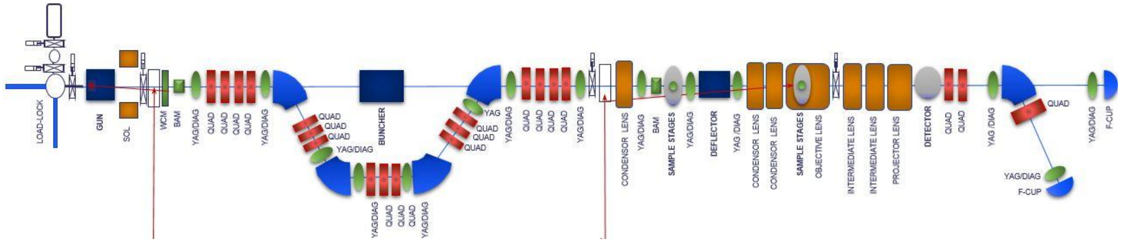
Wide array of laser pumps
NIR to UV
Single-shot / stroboscopic
1nm resolution
<1μs

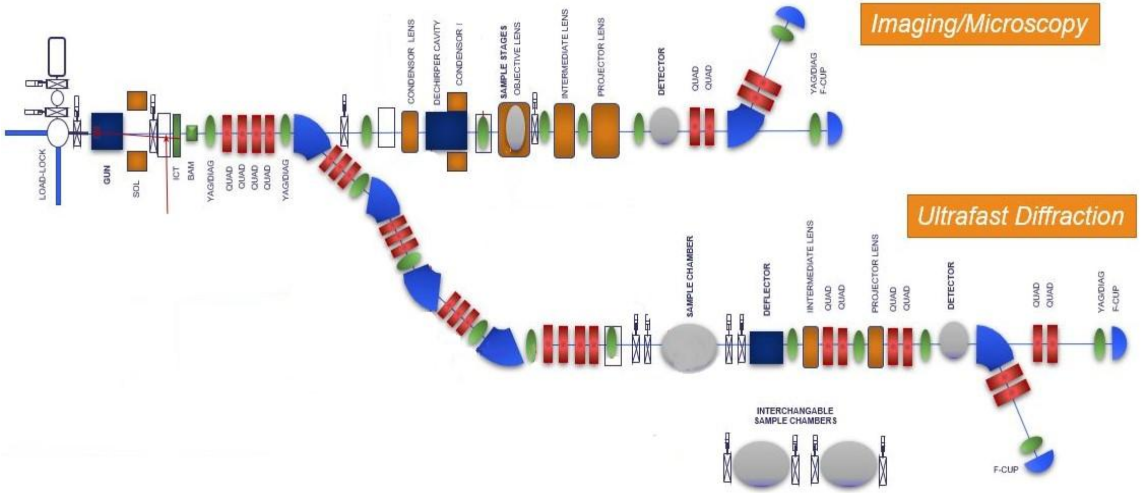
- First round of town halls (user meetings) in 2022
- Further town halls 2025: April - September
- Key to continue close alignment between science priorities and machine design

RUEDI

Instrument Design Evolution 1

- **Initial concept**: 1 beamline for both UED/UEM
- Magnetic or RF bunch compression
- Two sample / beam interaction points
- Issue: different sample locations, beam parameters, and bunch compression on target

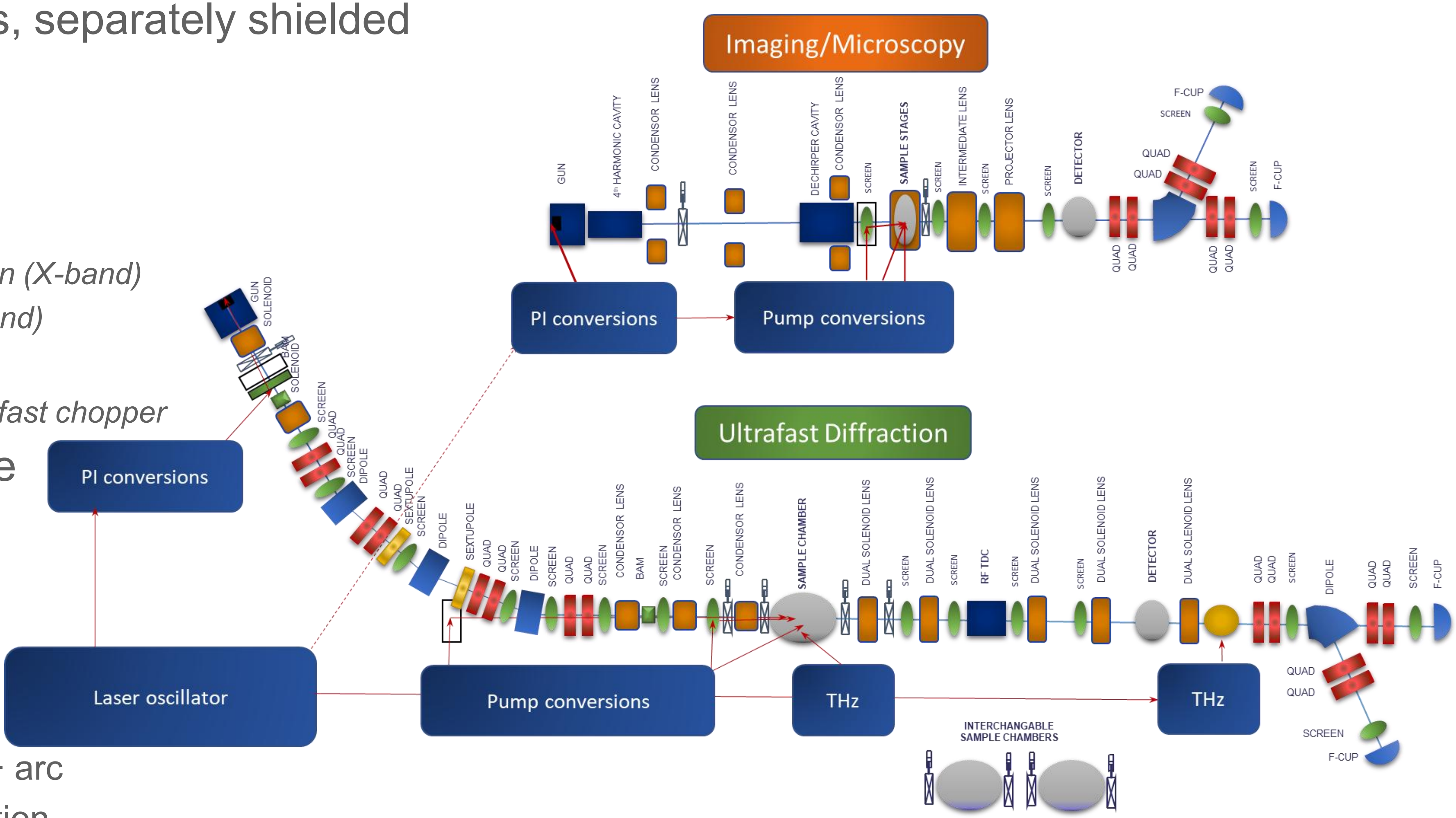




- **CDR** - 1 gun to 2 beamlines
- Magnetic compressor geometry modified to give separation between beamlines
- More space for interchangeable sample chambers
- Still compromises performance, especially of imaging line
- Photoinjector optimisation for two different beam modes

Instrument Design Evolution 2

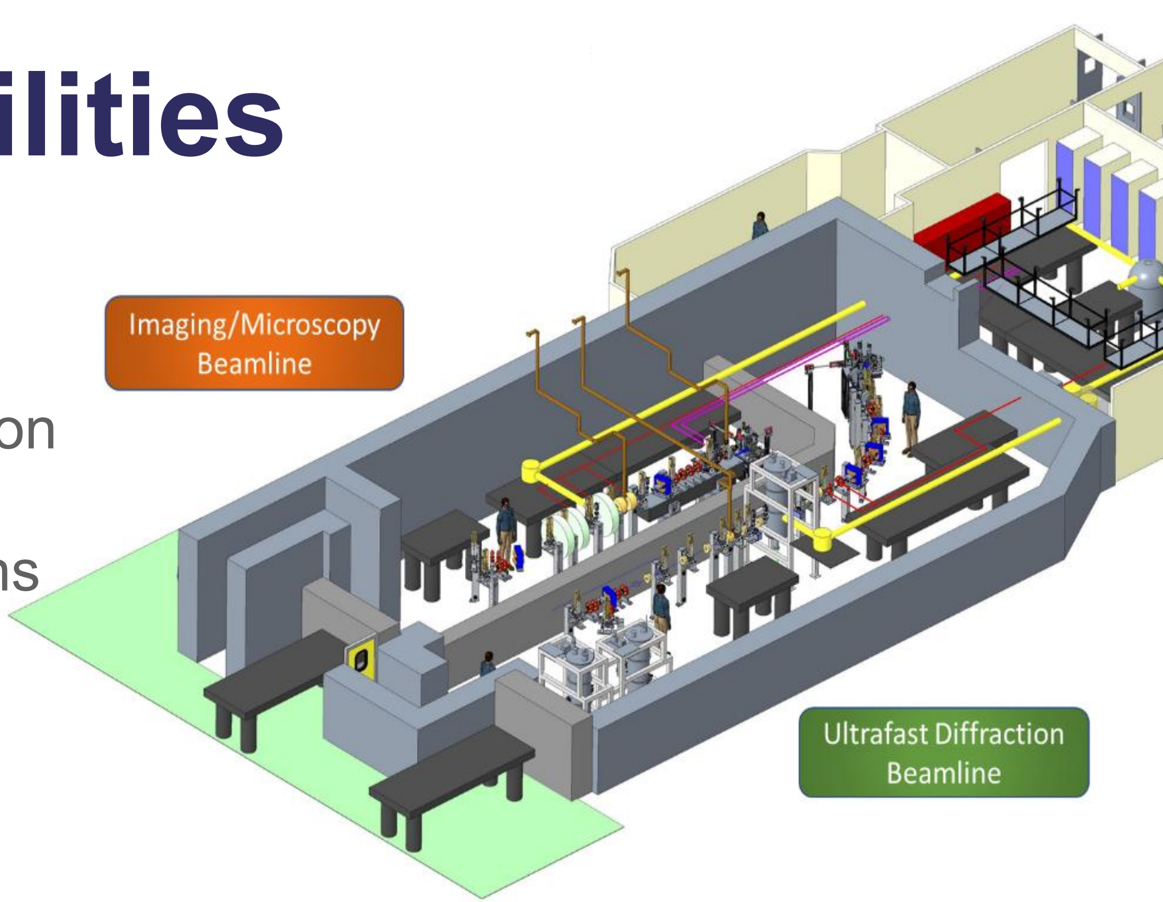
- **TDR**
  - 2 fully separate beamlines, separately shielded
  - 2 options for Imaging line
    - RF option
      - *3xRF cavity*
      - *Photoinjector (S-band)*
        Lossless monochromation (X-band)
        Dechirp/decelerate (S-band)
    - DC option
      - *Fully DC gun (1-2 MeV), fast chopper*
  - Redesigned diffraction line
- **Post-TDR**
  - Imaging line
    - DC option favoured
  - Diffraction line
    - Iterations of photoinjector + arc
    - Diffraction optics simplification



RUEDI

RUEDI Capabilities

- **UED beamline**
  - ≤4 MeV
  - <10 fs temporal resolution
  - $\Delta Q \;\; 0.17 - 0.02 \text{ Å}^{-1}$
  - <7 nm coherance lengths
  - Single-shot capable

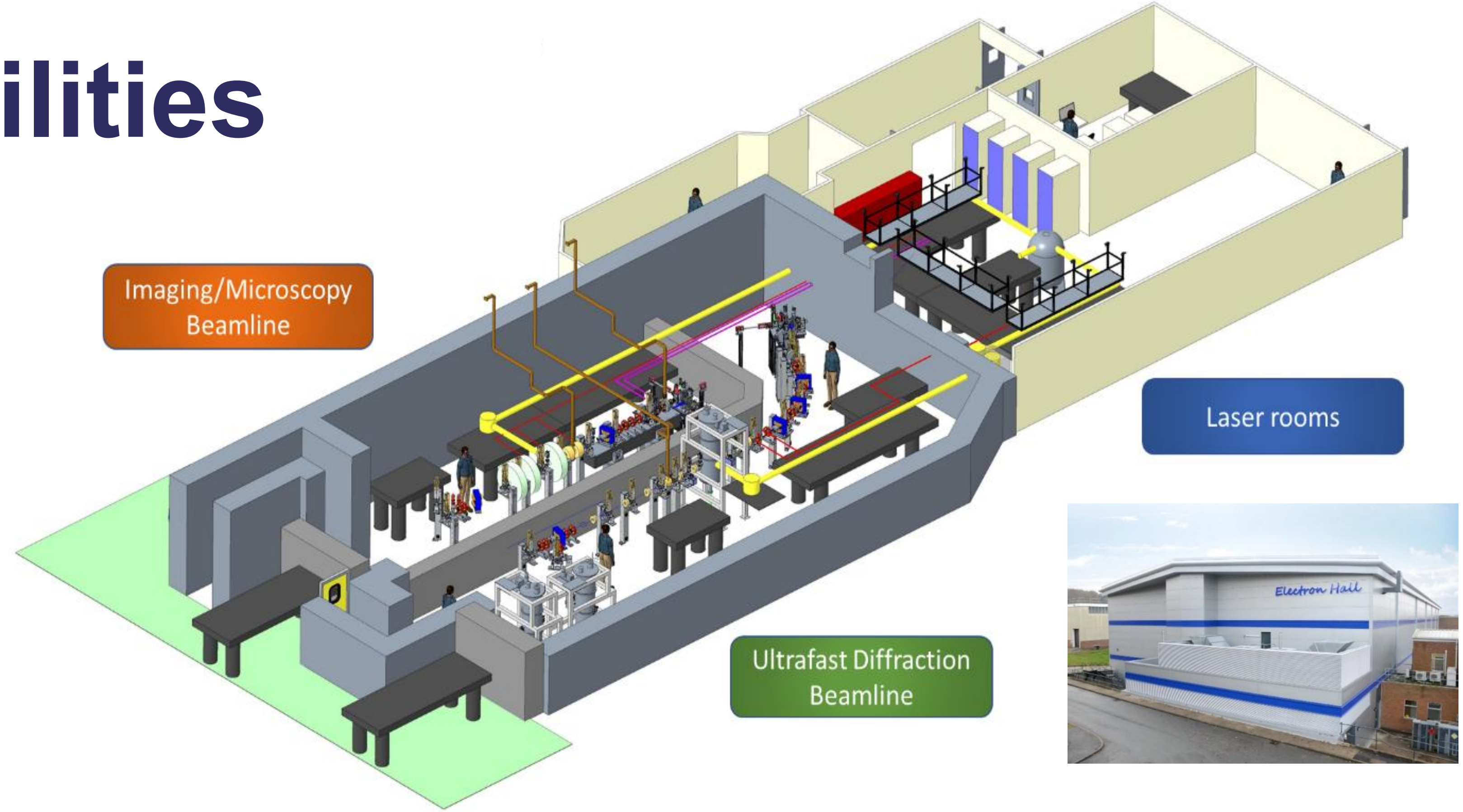


- **UEM beamline**
  - <2 MeV
  - µs-scale temporal resolution
  - 0.8 - 10 nm spatial resolution
  - Spatiotemporal resolution 10^{-15} - 10^{-18} m.s
  - Single-shot capable

- **Laser pumps**
  - UV-IR-THz wavelengths
  - HCF for <10 fs pulse lengths
  - *High intensity TW (>10^{18} W.cm^{-2})*

RUEDI

RUEDI Capabilities



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The Rosalind Franklin Institute

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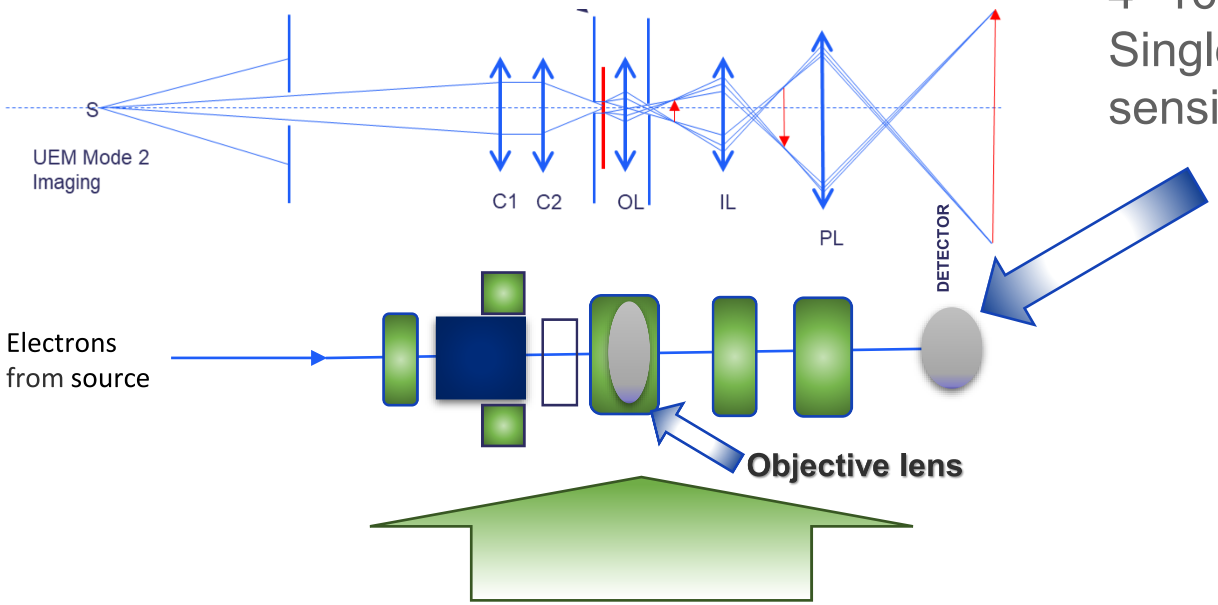
Imaging Beamline

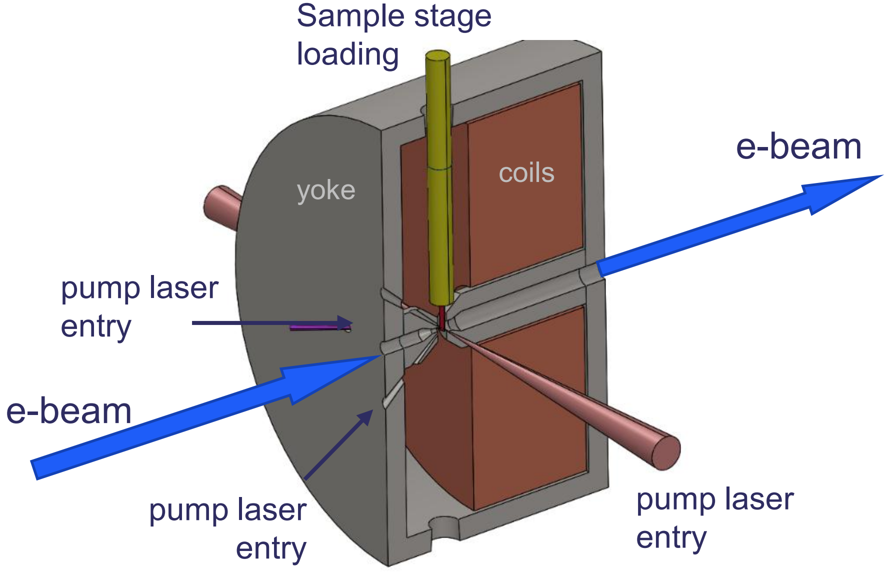


Detector
4- 16 MP MAPS
Single electron sensitive

Imaging lens system
Series of magnetic solenoid lenses

- Energy limited by objective lens to ~ 2 MeV
  - Aberrations from quadrupole options too high
- Need large number of electrons
  - (10^8 for single-shot images, compared to 10^6 for diffraction)
  - Requires very low energy spread (10^-6) due to chromatic aberrations, and 10^-6 energy stability

Objective lens
The *key* to the whole system



- Samples inserted into middle
- Multiple pump laser entry ports
- Compatible with commercial TEM sample stages *(enabling experiments in solid, liquid, cryogenic, heating etc)*

Resolution:

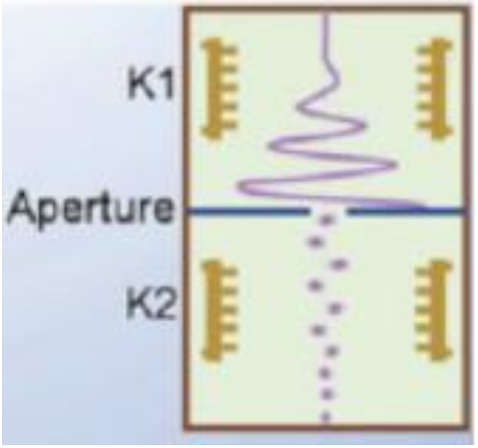
$$\mathcal{R} = \sqrt{\left(C_c \frac{\delta E}{E} \alpha\right)^2 + (C_s \alpha^3)^2}$$

Cs and Cc of lens <10mm

RUEDI

Imaging Source – DC option

- Scale up from proven keV microscopes
- DC accelerator + fast chopper
- Limited manufacturers of MeV-scale DC accelerators
  - Extremely large systems!
  - Excellent energy stability
- RF-based chopper to form short bunches:
  - Good for ms and us-scale
  - Potentially down to ps
  - Cannot reach fs
  - Needs design effort to work at MeV
- Source current not high enough to reach single-shot bunch charges at smaller timescales



RUEDI Capabilities

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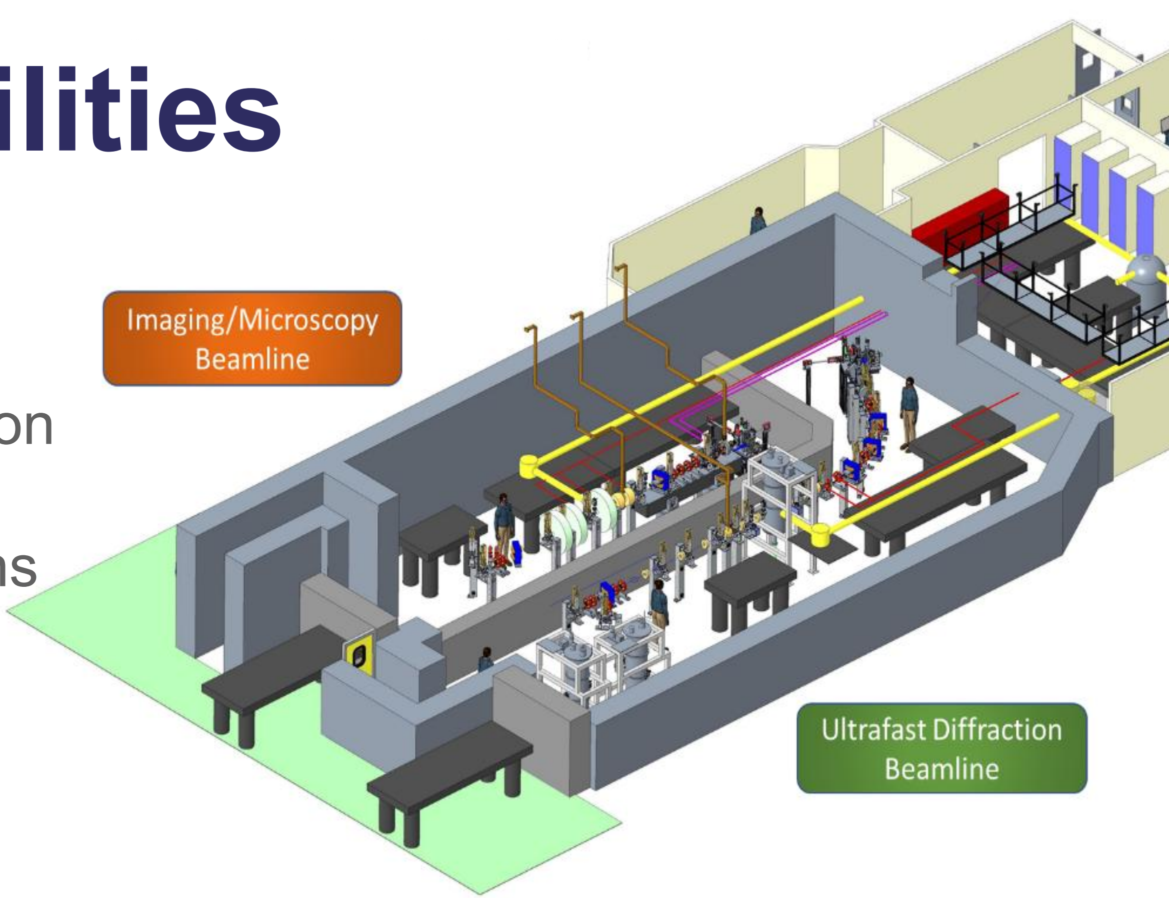
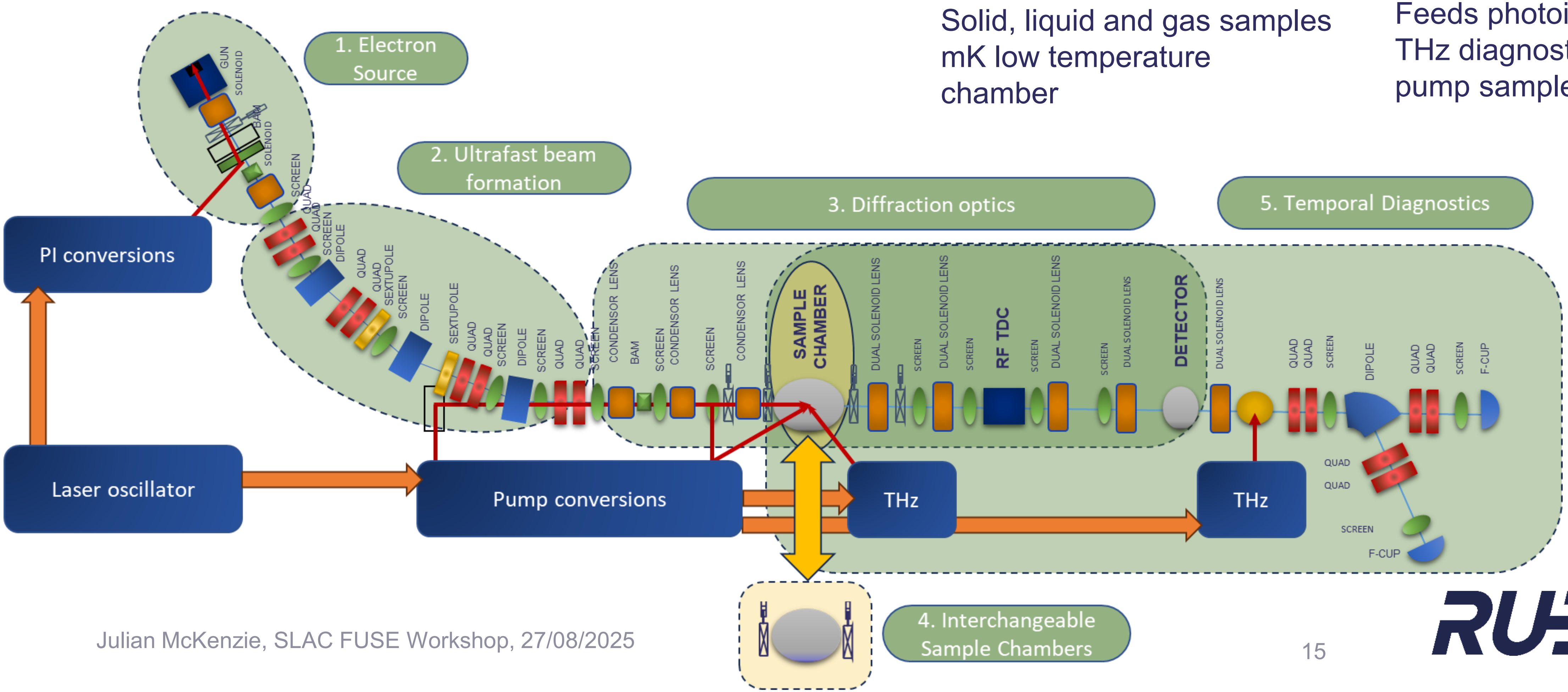
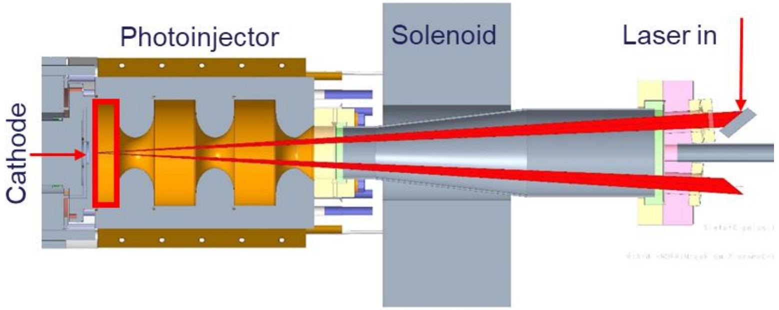


Ultrafast Diffraction Line

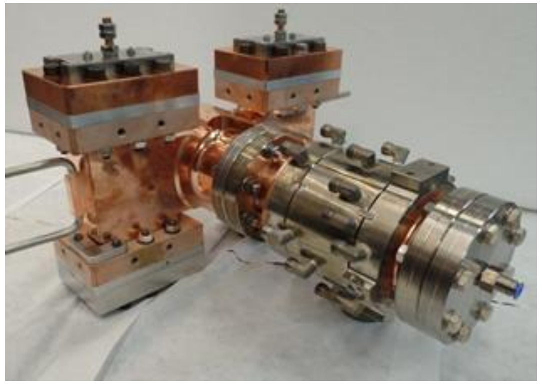
1. **Electron source**
   S-band RF photoinjector
   Creates high brightness, short pulse beams
2. **Ultrafast beam formation**
   Simultaneously compresses bunch length and reduces jitter for overall time resolution
   <10 fs single shot
3. **Diffraction optics**
   Variable magnification + camera length
   Direct electron detector
4. **Chambers**
   Solid, liquid and gas samples
   mK low temperature chamber
5. **Temporal diagnostics**
   Shot-by-shot arrival time and fs bunch length measurements
6. **Lasers**
   Feeds photoinjector, THz diagnostics and pump samples

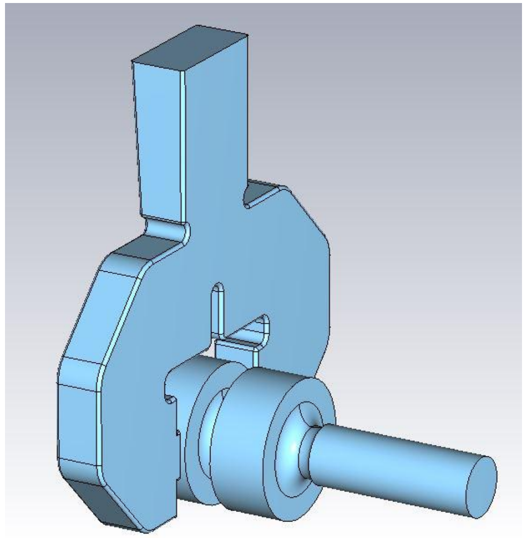


Electron gun overview



- Normal conducting S-band RF gun, *4 MeV, <0.5pC*
- Designed for **low dark current**
- **1 kHz repetition rate**
- 2.X cells
  - Cell lengths*: 0.45 - 0.9 - 1.0*
  - **Optimised for RUEDI magnetic arc design**
- Cathode
  - Copper – backwall of gun
- Over-coupled RF for short pulse lengths *(~1us)*
- Cooling similar to 400 Hz CLARA gun
- Photoinjector laser
  - Front injection
  - Out of vacuum final mirror
  - Blow-out regime – short: *~60 fs pulse duration*
  - Variable laser spot size: *100 um – 400 um diameter*



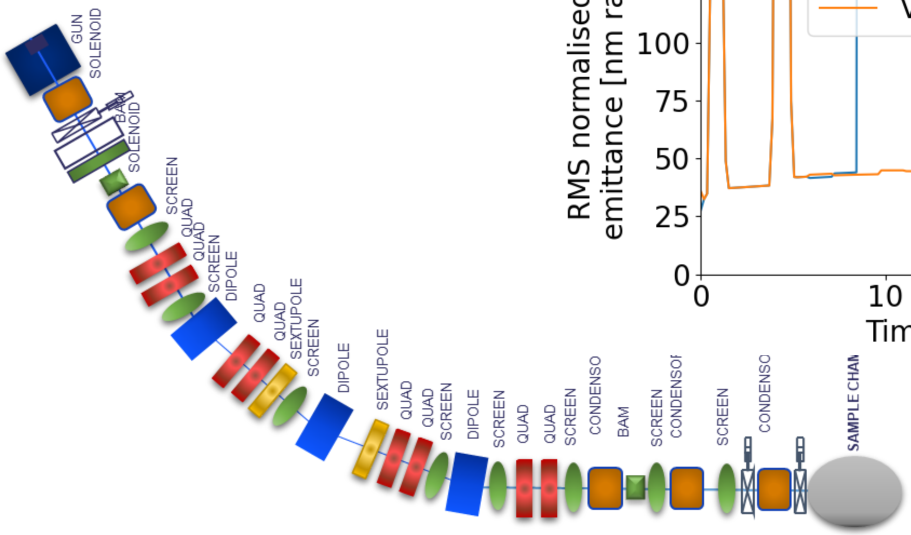


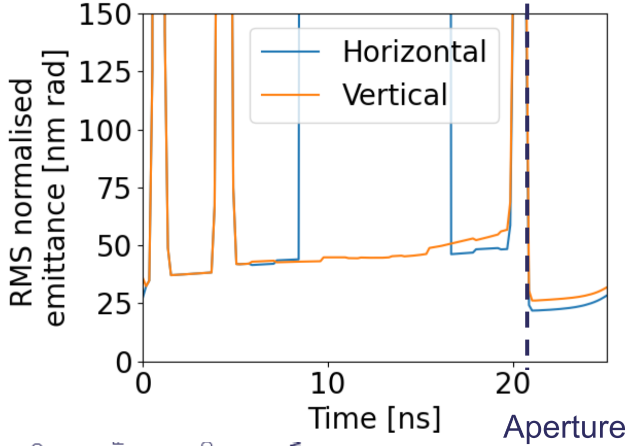
Above: CLARA 400 Hz 1.5 cell
Right: RUEDI 1 kHz 2.4 cell

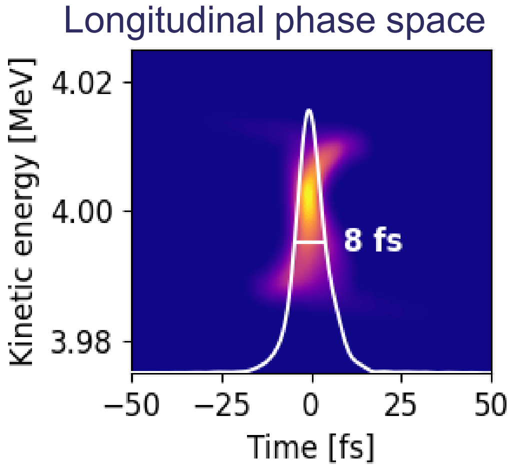
	1.4 Cell	2.4 Cell
RMS bunch length [fs]	148	232
RMS transverse emittance [nm rad]	36	37
Max field on cathode [MV/m]	115	69

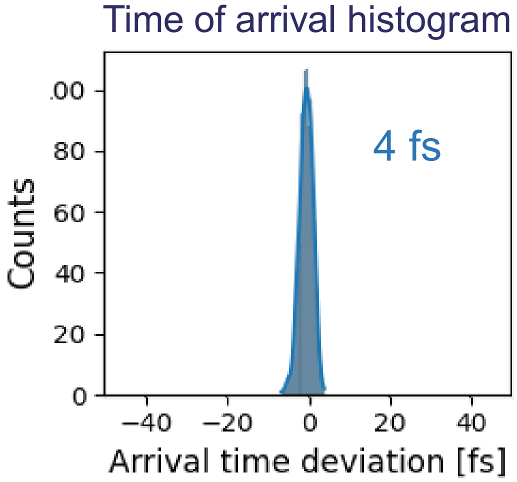
Beam transport arc

- TDR compared no compression, RF compression and range of different magnetic compressors
- Magnetic main advantage is it **removes** photoinjector jitter whilst **simultaneously** compressing the bunch*
- TBA chosen - flexible R56 tuning
- Sextupoles to correct the T566
- Supress space-charge residual dispersion through minimising the spot size in the central dipole
- Separates DC from gun to samples, and gases/liquids etc in sample chamber from gun







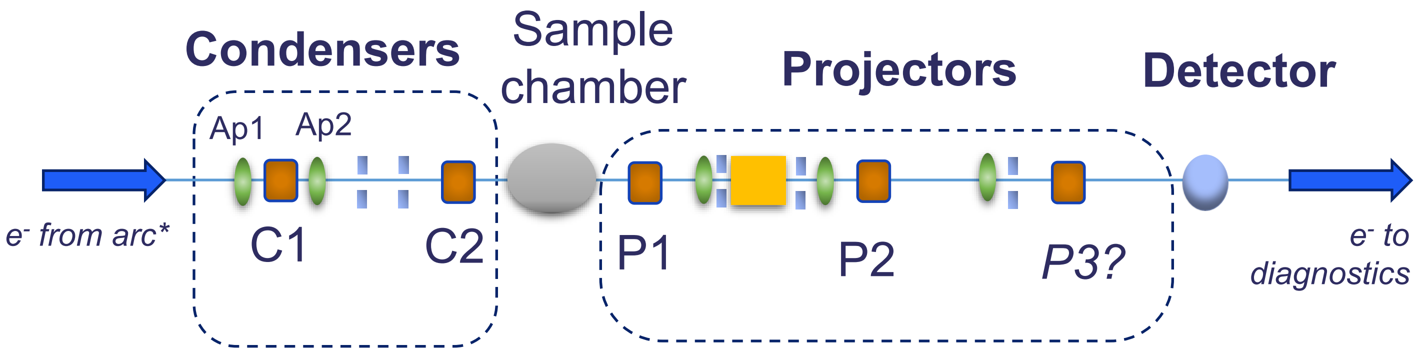


$$\Delta t = \sqrt{\Delta t^2_{Bunch\ length} + \Delta t^2_{Jitter}}$$

*H.W. Kim et al, Nature Photonics 14, p245–249 (2020) https://doi.org/10.1038/s41566-019-0566-4
F. Qi et al, Phys. Rev. Lett. **124**, 134803 (2020) https://doi.org/10.1103/PhysRevLett.124.134803

Diffraction Optics

**Gun, arc, PI laser all fixed for all operational modes*

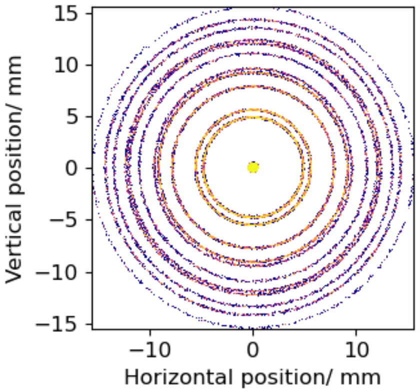


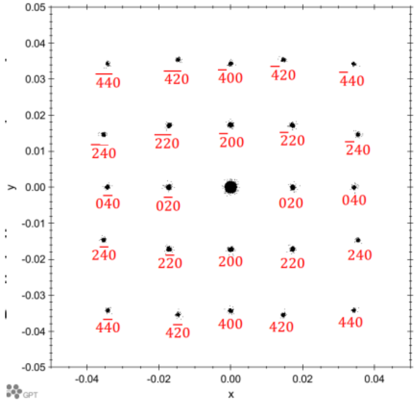
- **Pre-sample optics**
  - 2 **condenser** lens
    2 aperture system
    for flexible illumination
  - Trade-off charge, spot size, coherence length, pulse length

Parameter	Min	Max	Unit
Number of electrons	10^4	10^6	
Spot size *(diameter)*	30	400	um
ΔQ *(FWHM)*	0.04	0.2	Å^{-1}
Bunch length (FWHM)	5	500	fs

**tuning ranges shown, cannot achieve all simultaneously*

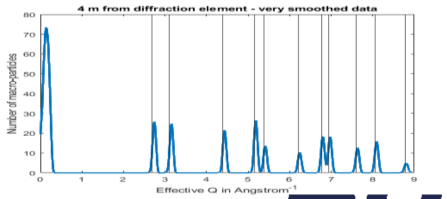
- **Post-sample optics**
  - 2 **projector** lenses
  - Varying de/magnification onto range of potential detectors
  - Tuneable camera length 0.4 – 40 m





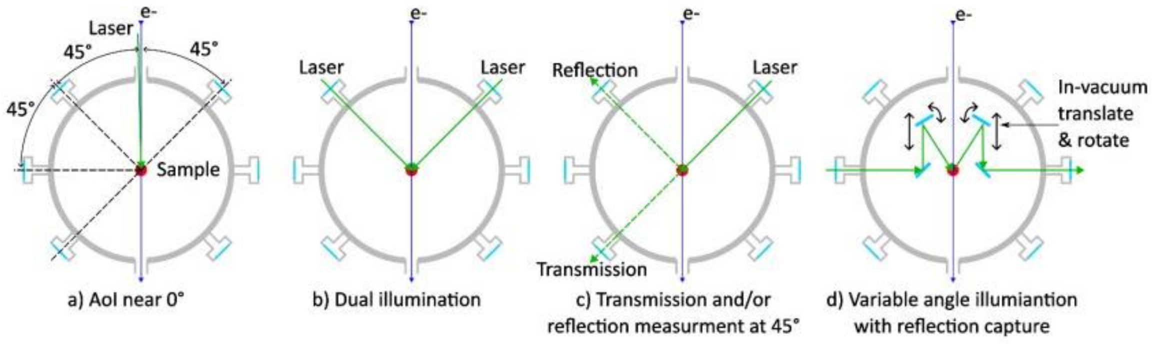
- **Detector**
  - Options analysis underway

Technology	Pixel size	Resolution
MAPS	10-60 um	4 - 16 MP
Hybrid pixel	**50-100 um**	**0.5 – 4 MP**
Scintillator + CCD	~30 um	0.5 – 4 MP

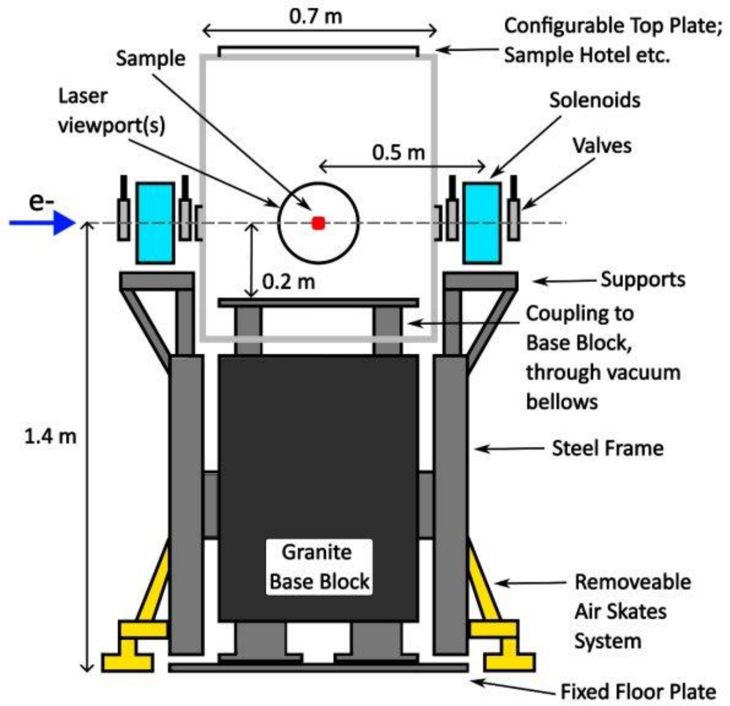


Sample chambers

- Interchangeable sample chambers for different environments
  - eg/ solid samples, liquid jets, gas phase, cryogenic
  - *Initial plan is for 3 chambers*
- In conversation with science team about requirements:
  - Sample control (position, rotation, temperature), laser injection, and diagnostics needed etc



- Potential to be compatible with mK dilution fridge for quantum materials experiments
  - Other solutions for higher temps (sub-K) that can fit in “standard”-style chamber



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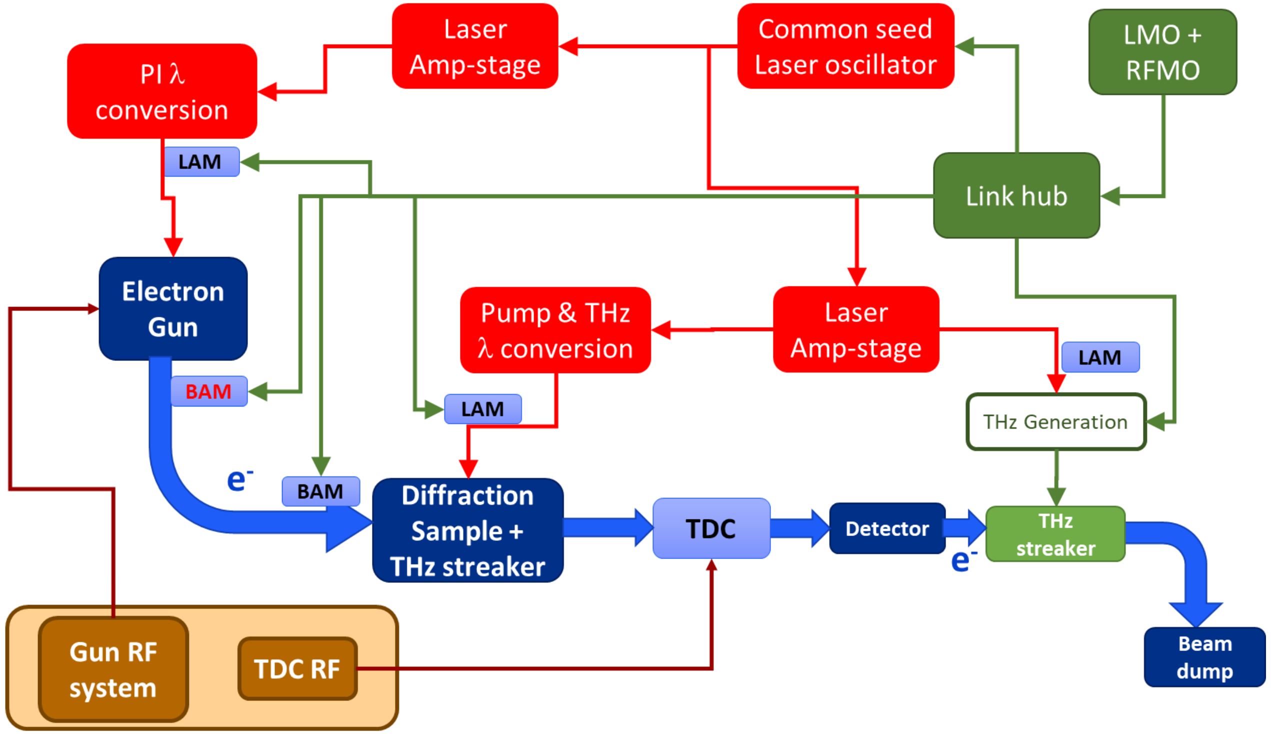
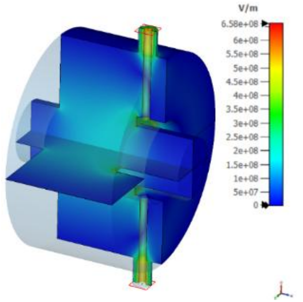
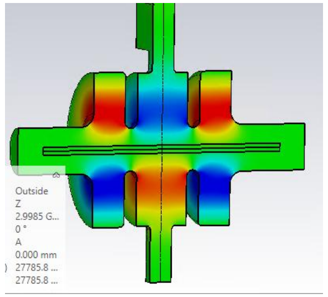
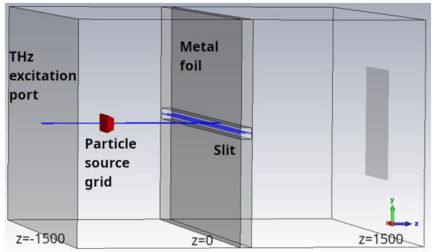
Synchronisation + Longitudinal Diagnostics



- Temporal properties:
  - Time of arrival
  - Bunch length
- Diagnostic suite:
  - RF Beam Arrival Monitors*
  - RF TDC
  - THz at sample position
  - THz post-detector
  - Spectrometer







- Aiming for 10 fs sync between electrons and pump laser
- Full range of options for:
  - Online time-of-arrival measurements
  - Standalone bunch-length measurements

*C.Song et al, Phys. Rev. Accel. Beams **26**, 012803 (2023)

Gap/hole in detector to allow post-detector diagnostics

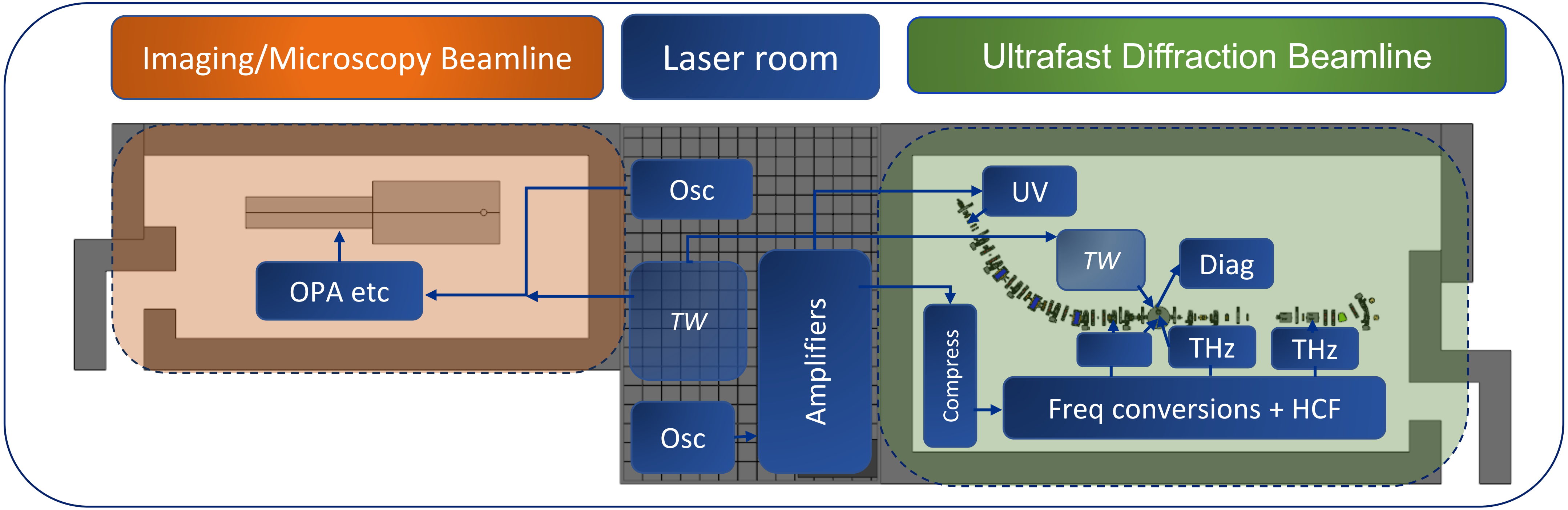
RUEDI

Laser Systems

- One oscillator per beamline
- Ti:Sa vs Yb options
- Multiple amplifiers in diff line chain

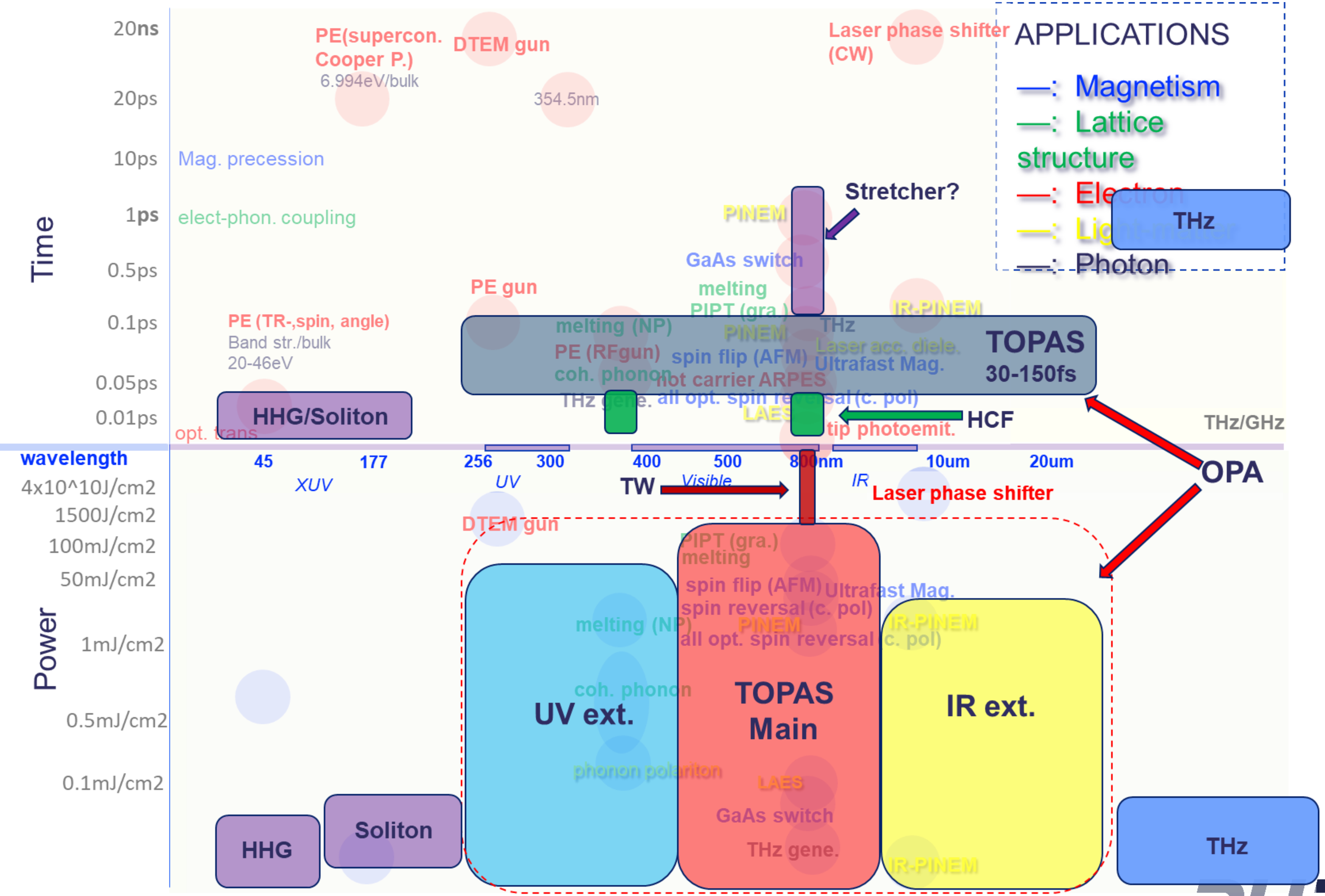
- Diffraction laser simultaneously feeds
  - Electron source
  - Sample pumps
  - fs diagnostics
- Requires specialised synchronisation

- Sample Pumps:
  - UV-IR-THz
    - 200nm – 1mm
    - OPAs + harmonic generation
  - HCF for <10 fs
  - *High intensity TW* *(>10^{18} W.cm^{-2})*
  - *Potential HHG + others*



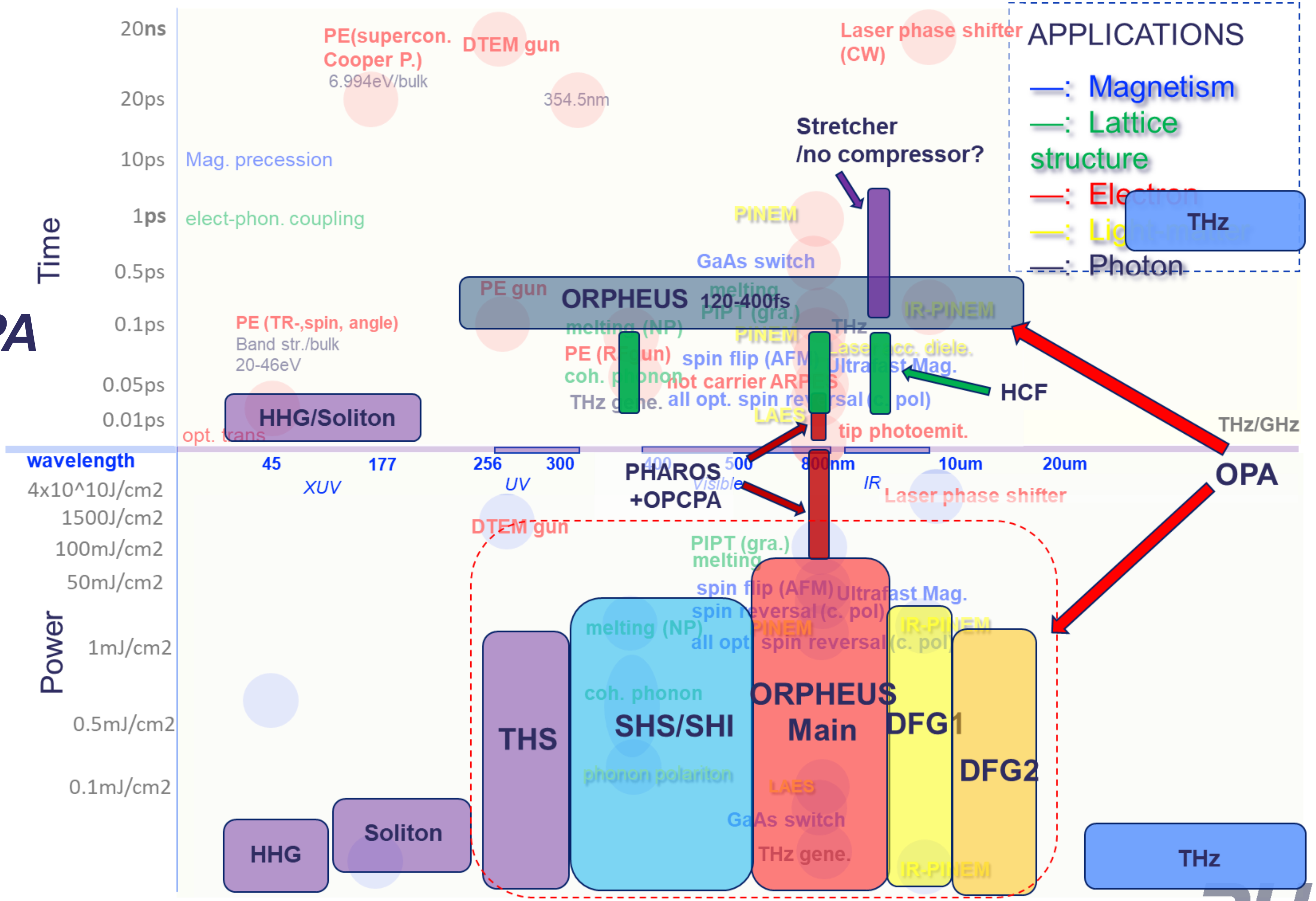
Pump lasers:

Ti:Sa Option

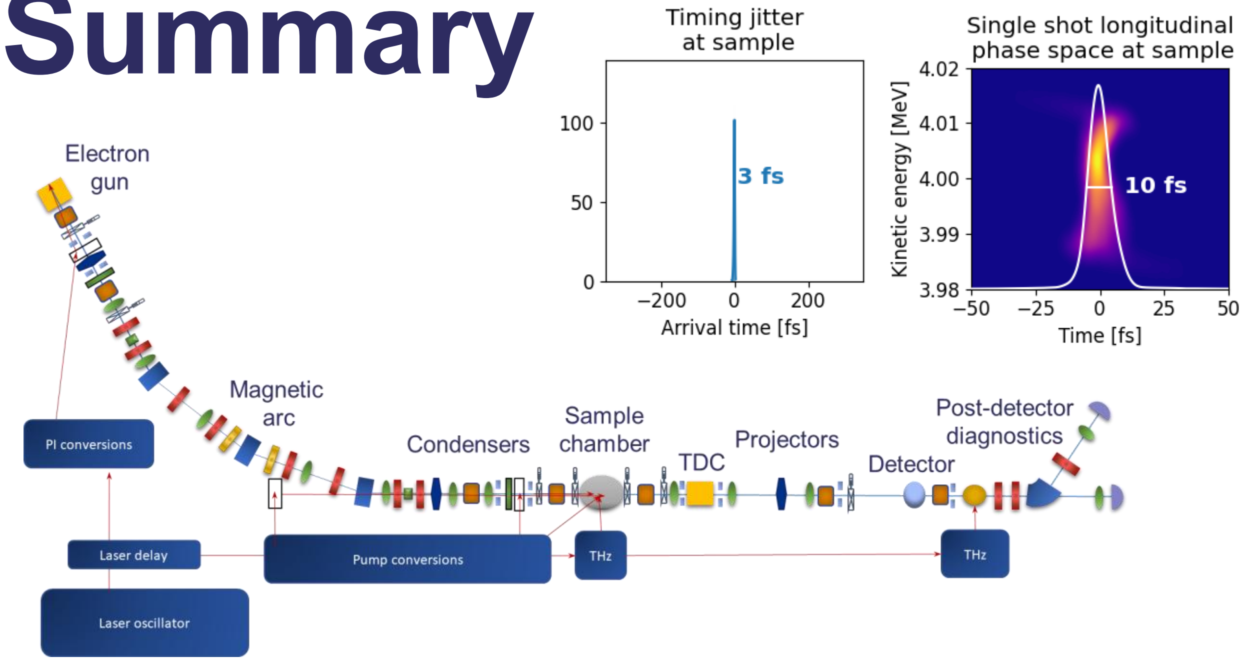


Pump lasers:

Yb/OPCPA Option



Diffraction Beamline Summary



- **Electron beam parameters:**
  - ≤4 MeV
  - <10 fs temporal resolution
  - <7 nm coherence lengths
  - Single-shot capable
  - Tuneable magnification/camera length (0.4 – 40 m)

Parameter	Min	Max	Unit
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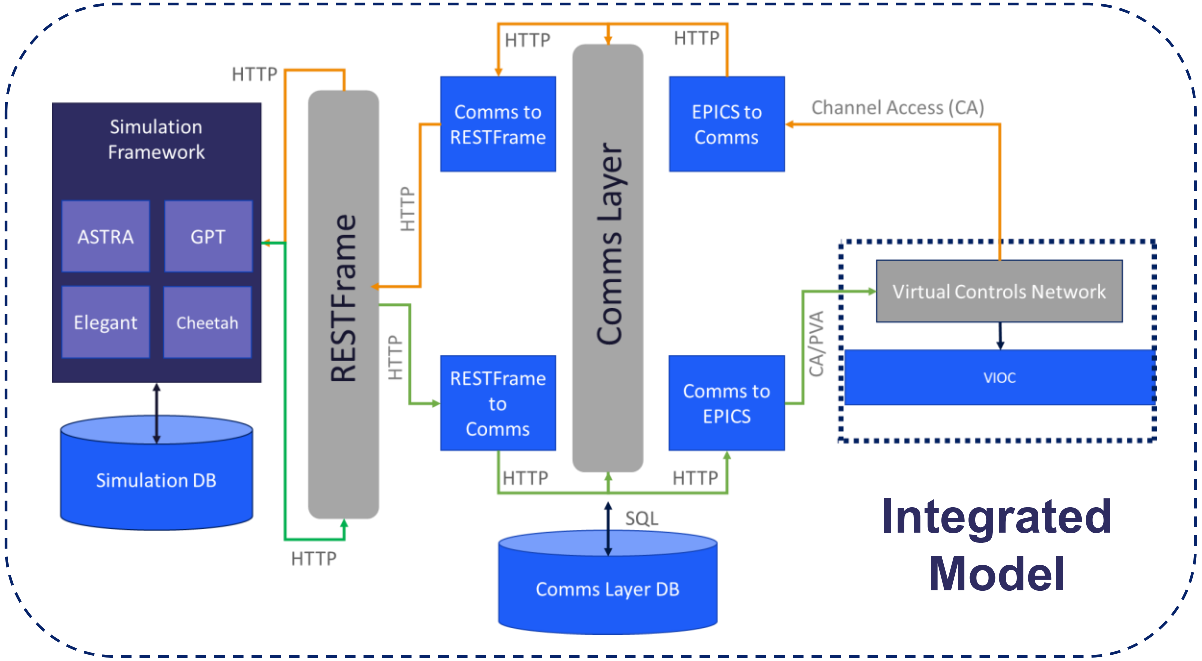
- **Laser pumps**
  - UV-IR-THz wavelengths
  - HCF for <10 fs pulse lengths
  - *High intensity TW (>10^{18} W.cm^{-2})*
- **1 kHz repetition rate**

- **Sample environments:**
  - Solid state
  - Liquid + gas jets
  - Cryogenic temperatures

Digital Twin

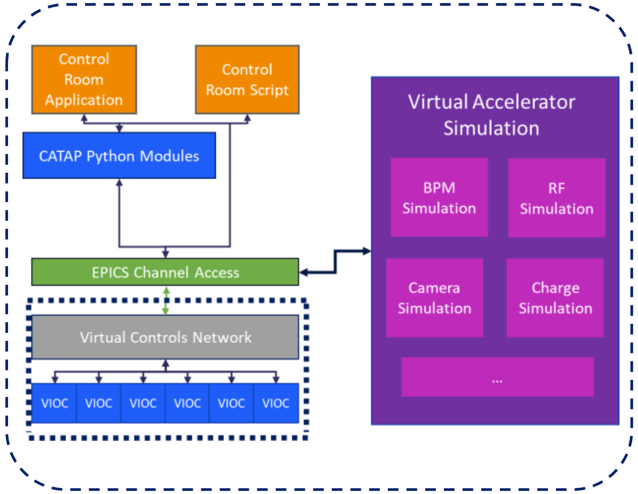
- Interface with virtual machine identically to physical machine via EPICS control system
- Simulation outputs in identical formats to real diagnostics, with artificial noise/jitter
- Builds on developments on CLARA at Daresbury



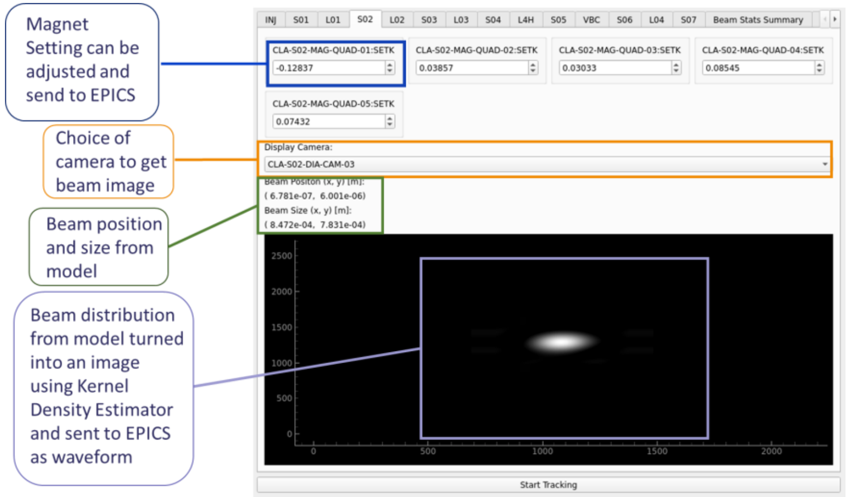
Integrated Model

Benefits:

- Control room software development
- Machine setup characterisation and optimisation
- Operator training
- Virtual Diagnostics
- View "unseeable" beam parameters
- End goal - virtual user experiments



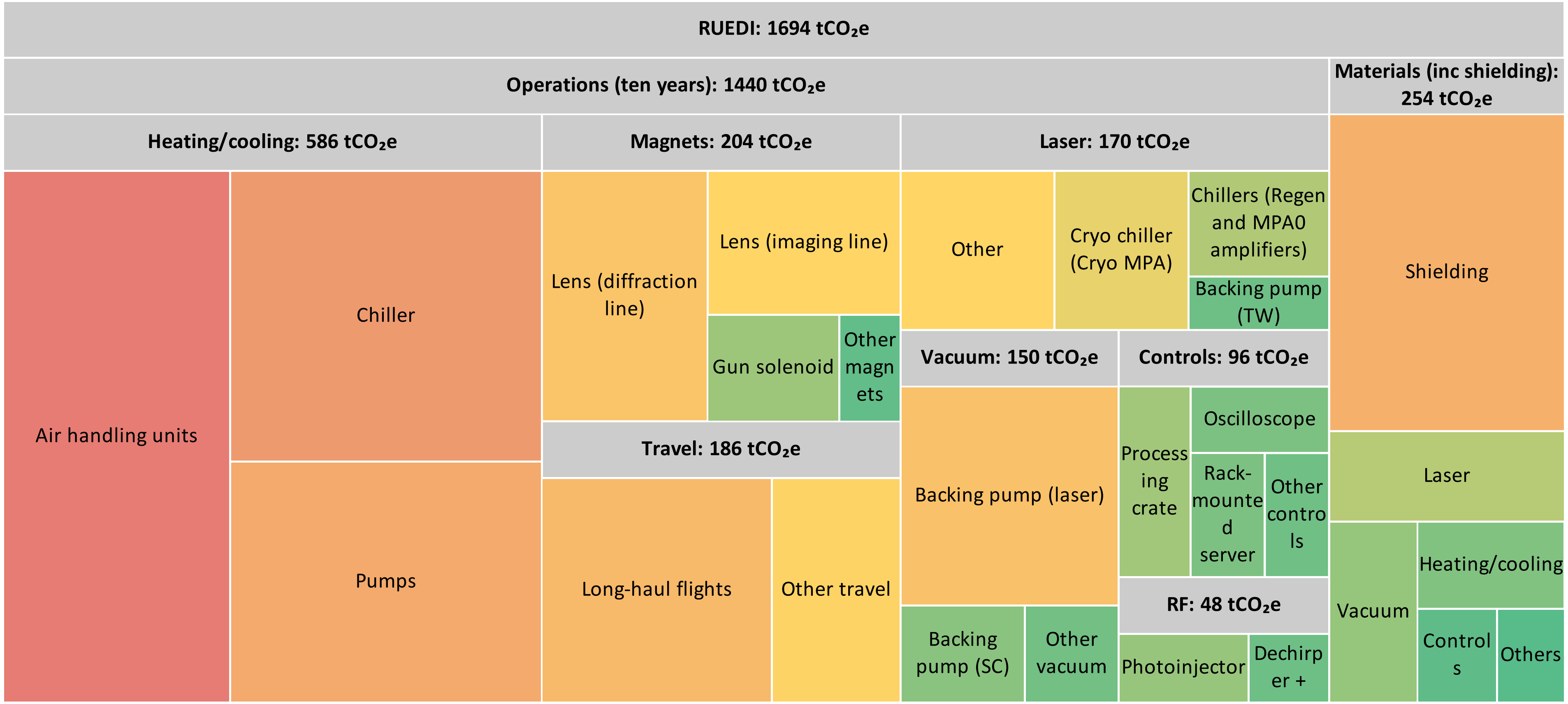
Example app:



RUEDI

Environmental Sustainability

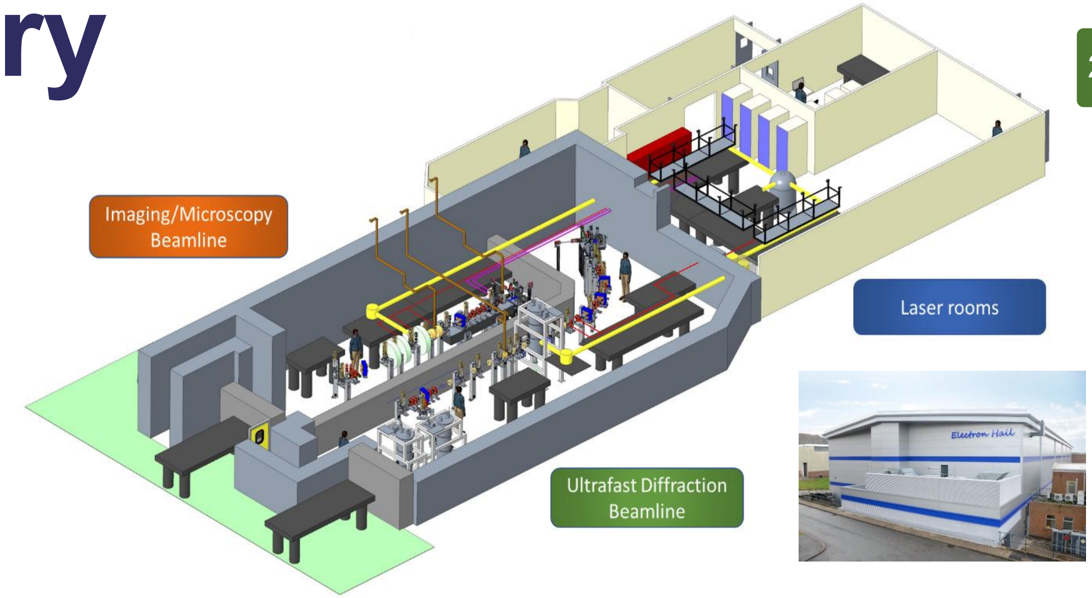
- Lifecycle emissions assessment
- Calculated carbon emissions for manufacture and operations
- 10 year operations
- Investigating options to reduce large contributors



- **Published report Feb 2024**
  - https://www.astec.stfc.ac.uk/Pages/Sustainable-Accelerators-Task-Force-Report-.aspx

RUEDI Summary

- **UED beamline**
  - ≤4 MeV
  - <10 fs temporal resolution
  - $\Delta Q \;\; 0.17 - 0.02 \text{ Å}^{-1}$
  - <7 nm coherance lengths
  - Single-shot capable



- **Timescales**
  - 2020 - Funding bid
  - 2022 - Design stage
  - 2025 – Business Case
  - 2026 - Construction
  - 2032 - User facility

- **UEM beamline**
  - <2 MeV
  - µs-scale temporal resolution
  - 0.8 - 10 nm spatial resolution
  - Spatiotemporal resolution 10^{-15} - 10^{-18} m.s
  - Single-shot capable

- **Laser pumps**
  - UV-IR-THz wavelengths
  - HCF for <10 fs pulse lengths
  - *High intensity TW ($>10^{18}$ W.cm^{-2})*

- **Science Themes**
  - Dynamics of Chemical Change
  - Quantum Materials & Processes
  - Biosciences
  - Materials in Extremes
  - Energy Generation, Conservation, and Storage

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RUEDI