



Science and
Technology
Facilities Council

Inverse Compton Scattering at CLARA

Hywel Owen

Nuclear Physics Forum

7th October 2026

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ASTeC: Targeting Global Accelerator Challenges

- Particle Accelerator Science & Technology Centre
- A 'one stop shop' for advanced particle accelerators: simulation, design, technology, system integration, operation, consultancy
- The largest team in the UK dedicated to accelerator R&D: 150+ STFC Daresbury staff plus a further 150+ researchers within the Cockcroft Institute
- Playing a critical role in flagship global projects such as HiLumi (LHC, Geneva), the European Spallation Source (Sweden) and LBNF/DUNE (USA)
- Translating fundamental research to real-world applications: assessed on industrial productivity gains, economic impacts and societal benefits

CLARA: A Leading Electron Test Accelerator

250 MeV ultra-bright electron linear accelerator facility
Daresbury Laboratory in NW England

Ran as 'CLARA Front End'
at 35 MeV 10Hz, with TW-class laser

2 user runs 2018-2022

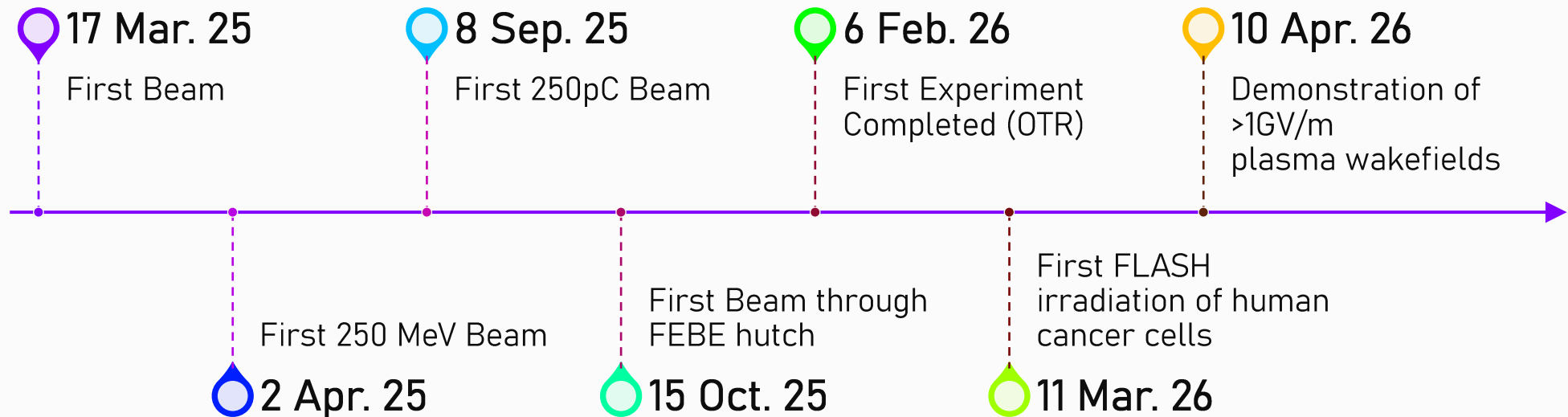
Since 2022 have been building, installing, conditioning and
commissioning...

Achieved 250 MeV, 100Hz beams 2/4/25

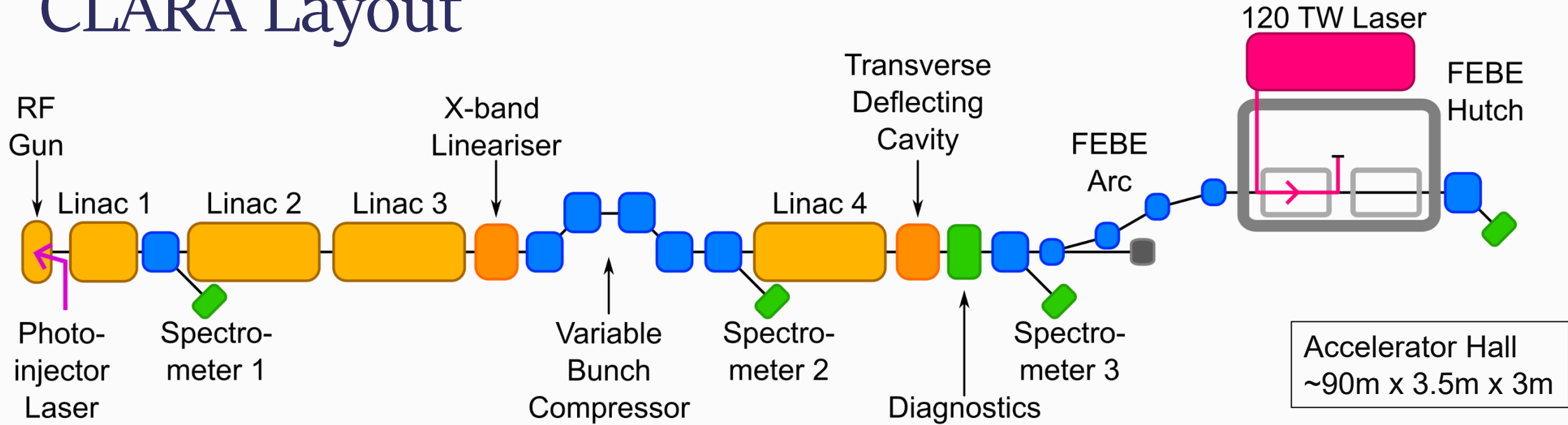
J.A. Clarke *et al.*, JINST 9 T05001 (2014)
D. Angal-Kalinin *et al.*, PRAB 23, 044801 (2020)
E.W. Snedden *et al.*, PRAB 27, 041602 (2024)

CLARA Parameters and Milestones

Parameter	Low Charge	High Charge
Repetition Rate [Hz]	1 - 100	
Bunch charge [pC]	5	250
Bunch length [fs]	50	100
Energy spread [%]	< 1	< 5
Spot Size at IP [μm]	20	100
Norm. Emittance [μm]	2.0	5.0



CLARA Layout

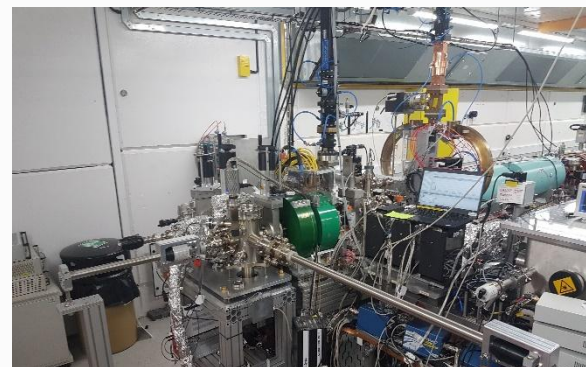


Generate

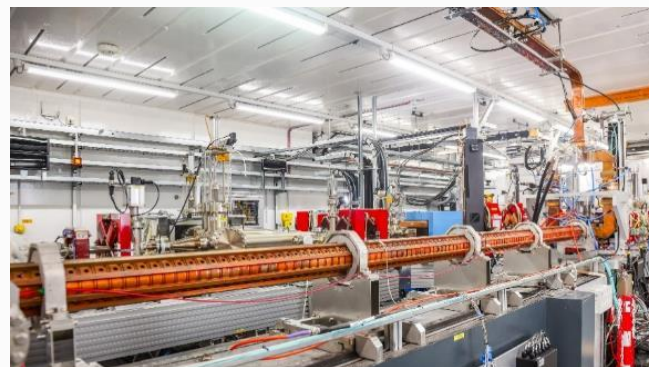
Accelerate + Manipulate + Accelerate

Characterise in 6D

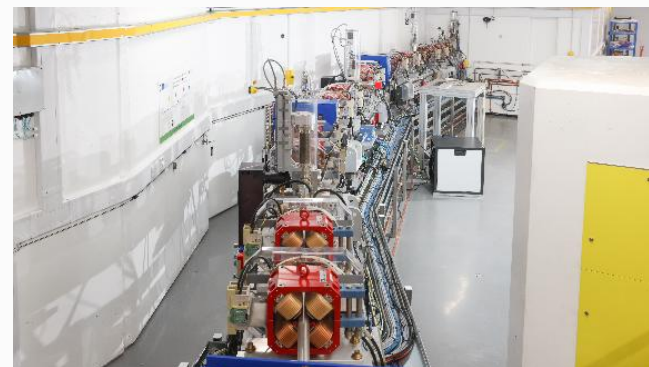
Experiment



CLARA Gun



S-band Linac



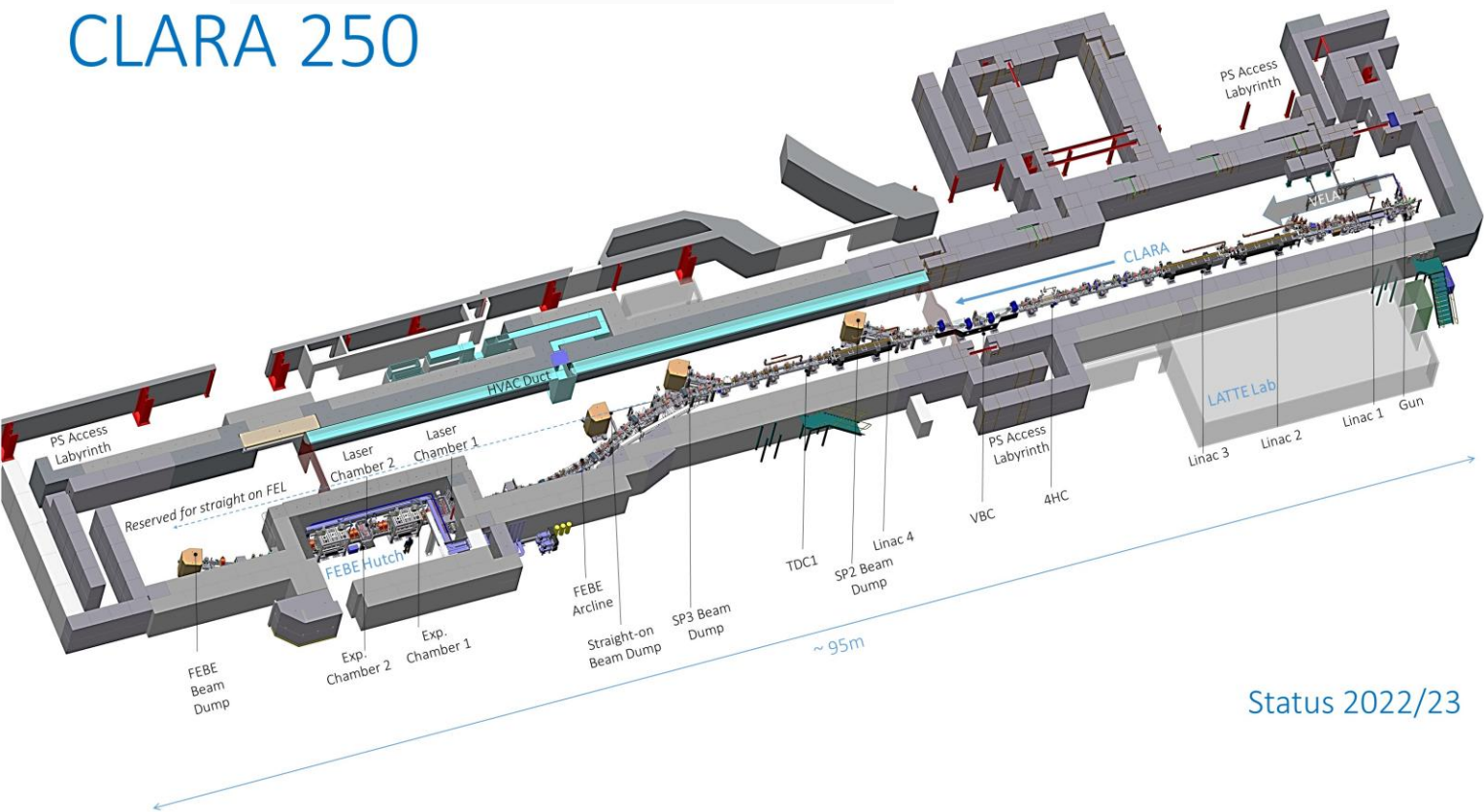
Arc to FEBE hutch



FEBE hutch

CLARA 250 MeV – Accelerator Hall

CLARA 250



Parameter	High charge	Low charge
Energy [MeV]	250	250
Charge [pC]	250	5
RMS t [fs]	100	50
σ_E/E [%]	<5	<1
RMS x [μm]	100	20
RMS y [μm]	100	20
$\epsilon_N x$ @ 250 MeV [μm]	5	2
$\epsilon_N y$ @ 250 MeV [μm]	5	2

User Science Themes



Advanced Diagnostics

Examples:

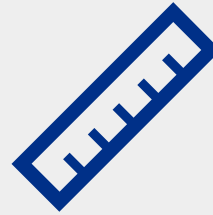
- Optical Transition Radiation (OTR),
- Coherent Transition Radiation (CTR)



Medical Applications

Examples:

- FLASH dosimetry,
- VHEE beam delivery,
- Radiobiology studies



Compact Accelerators

Examples:

- Beam driven plasma acceleration,
- Active plasma lenses



AI for Accelerators

Examples:

- Virtual diagnostics,
- Reinforcement learning optimisation



Laser Based Accelerators

Examples:

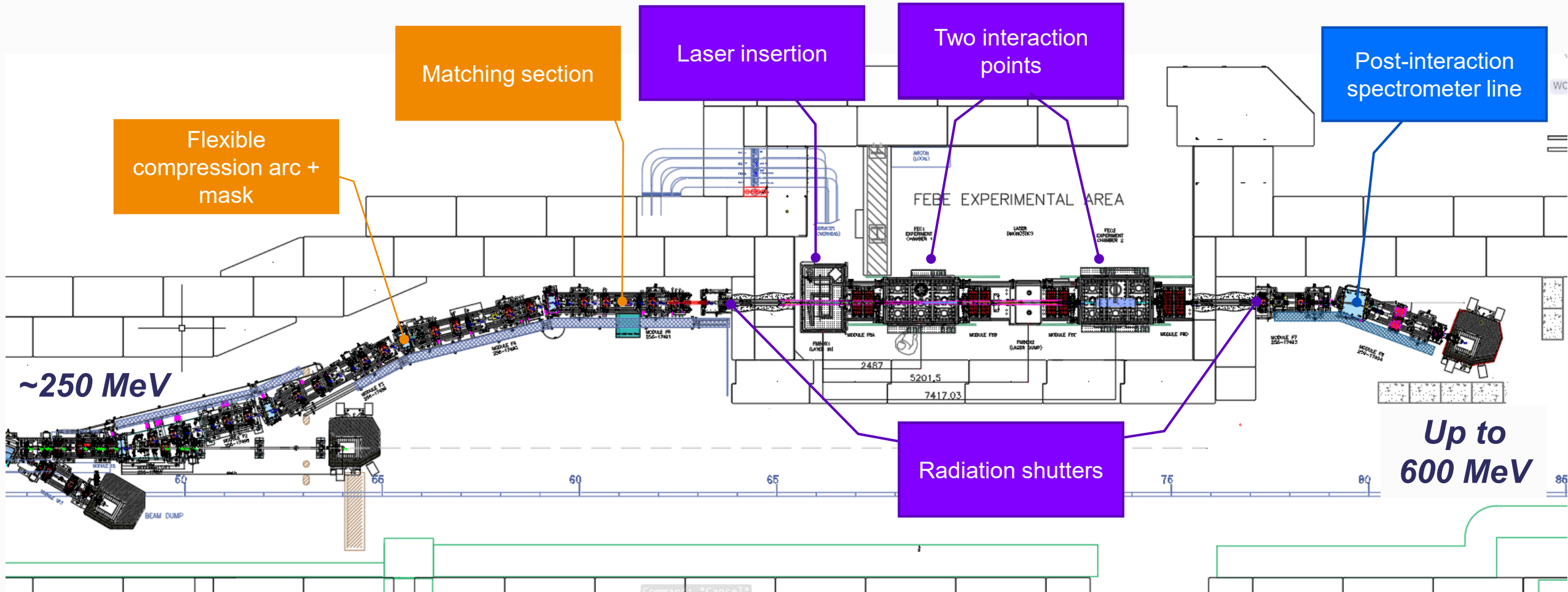
- Laser-plasma acceleration,
- Inverse Compton scattering

First Friendly User Run
(Q1 2026)

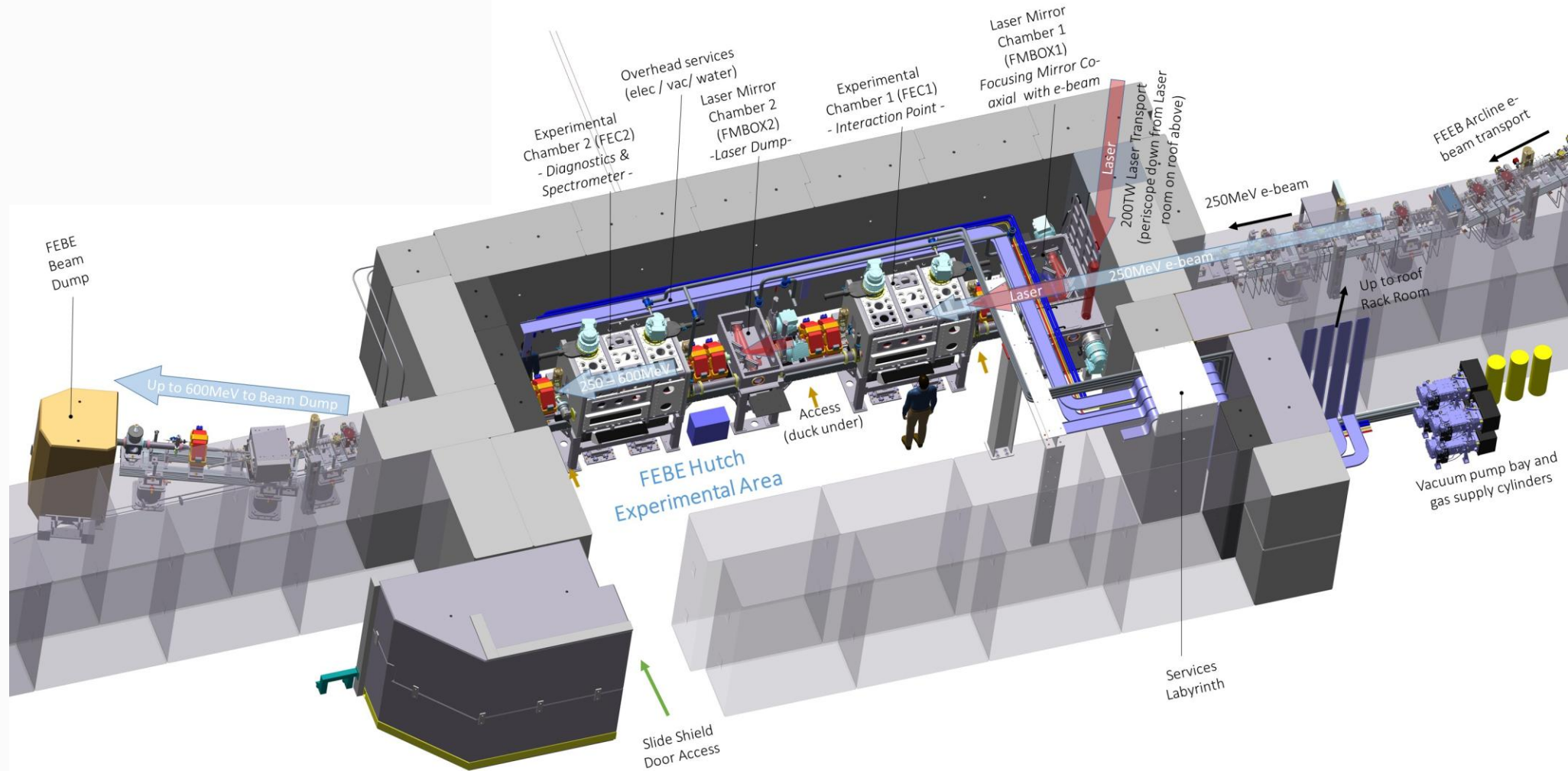
Planned
Friendly User Run
(Q2 2026)

After FEBE Laser
Commissioning
(Q3 2026)

FEBE Design Overview



FEBE Hutch Overview



Two identical chambers: more flexible, provides diagnostic support, and a route towards ambitious interaction/transport/application

Motivation for Inverse Compton Scattering

Inverse Compton Scattering (ICS) is seen as a competitive means to generate X-ray photons

The 3 basic methods:

Synchrotron Radiation: High brightness, stable, expensive, limited to <300 keV

Bremsstrahlung: High flux, compact/cheap, but inherently broadband

Inverse Compton Scattering: high brightness, compact, extends to high photon energy

SR and Bremsstrahlung get worse at higher photon energies

ICS gets better at higher photon energies

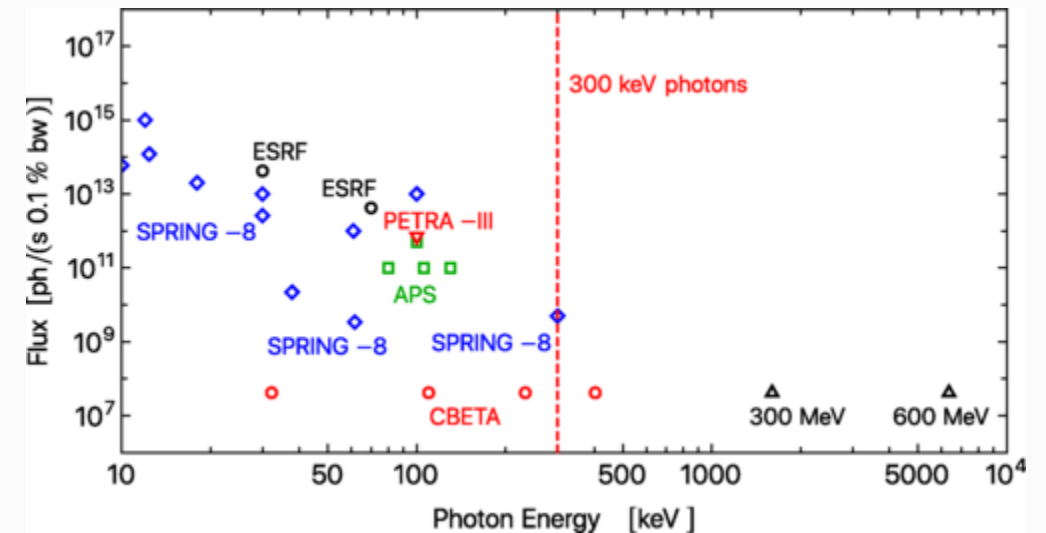
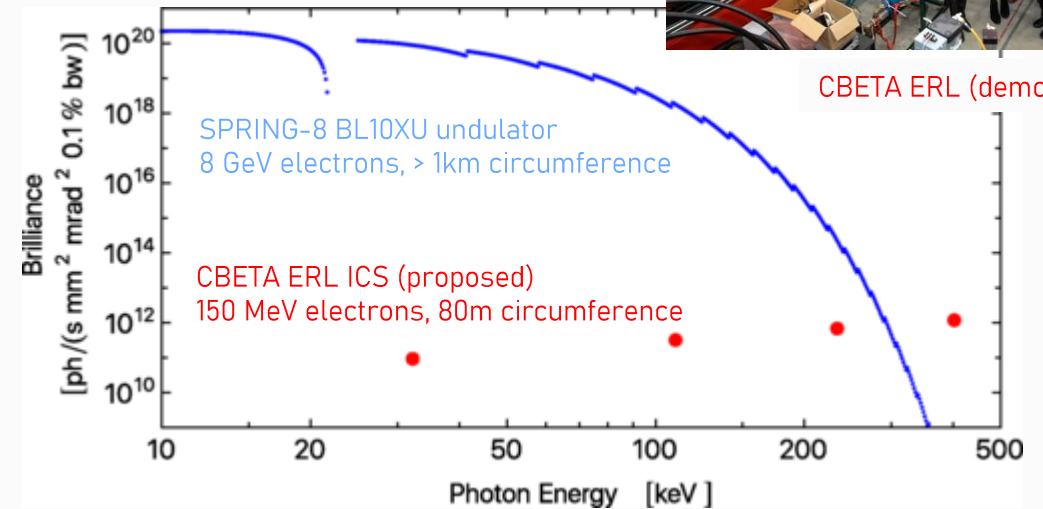
Basic messages:

ICS is better for $E > 1000$ keV

We aim to develop an ICS source for $E > 1000$ keV



CBETA ERL (demonstrated)



ICS Theory (Summary)

ICS is when a photon scatters from an electron and the photon energy **increases**.

The increase in photon energy requires the **electron** to be **moving**, in general **relativistically**.

Linear ICS: single scattering, photons independent of each other

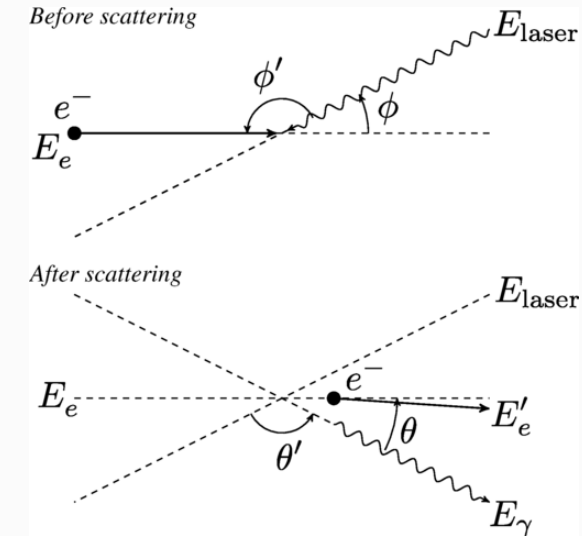
Incoherent ICS: electrons independent of each other

Thomson regime: electron recoil is small

Basic limitation of ICS is small inherent electron-photon scattering cross section of 0.665 barn

$$\sigma_T = \frac{8\pi r_0^2}{3} \simeq 6.6524 \times 10^{-29} \text{m}^2$$

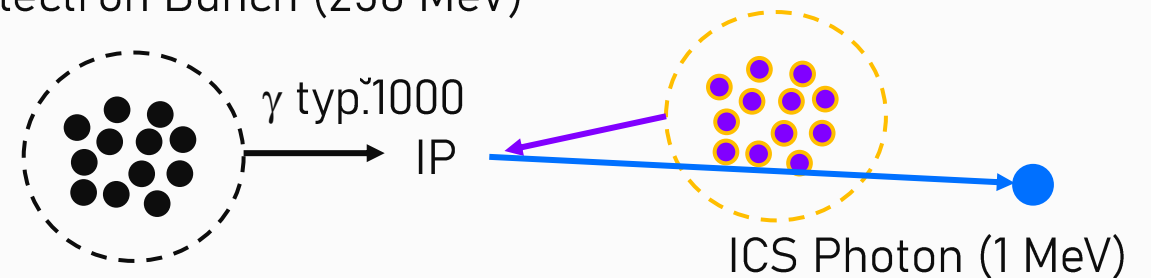
Important ICS property: scattered light has same polarisation as incoming light



$$\sigma_T = \frac{e^4}{6\pi\epsilon_0^2 m^2 c^4}$$

Electron Bunch (250 MeV)

Laser Pulse (1 eV)



'Head-on': $E_\gamma = 4\gamma^2 E_{\text{laser}}$

$$N_\gamma = \sigma_c \frac{N_e N_{\text{laser}} \cos(\phi/2)}{2\pi\sigma_y \sqrt{\sigma_x^2 \cos^2(\phi/2) + \sigma_z^2 \sin^2(\phi/2)}}$$

Do ICS Sources Exist? Yes

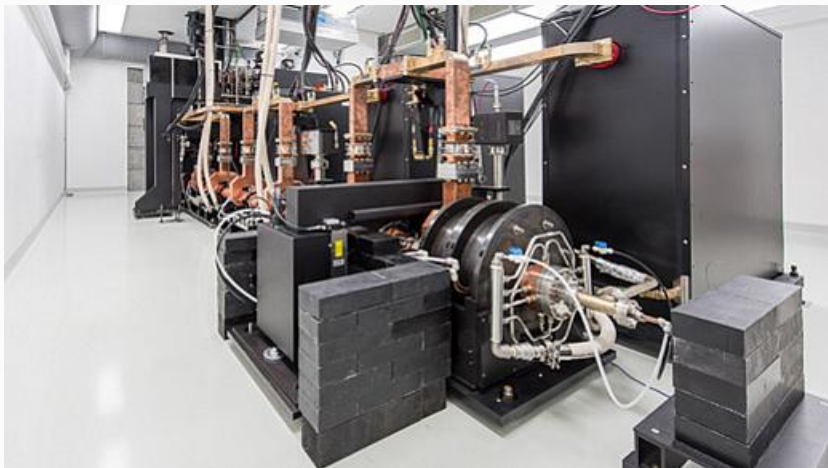
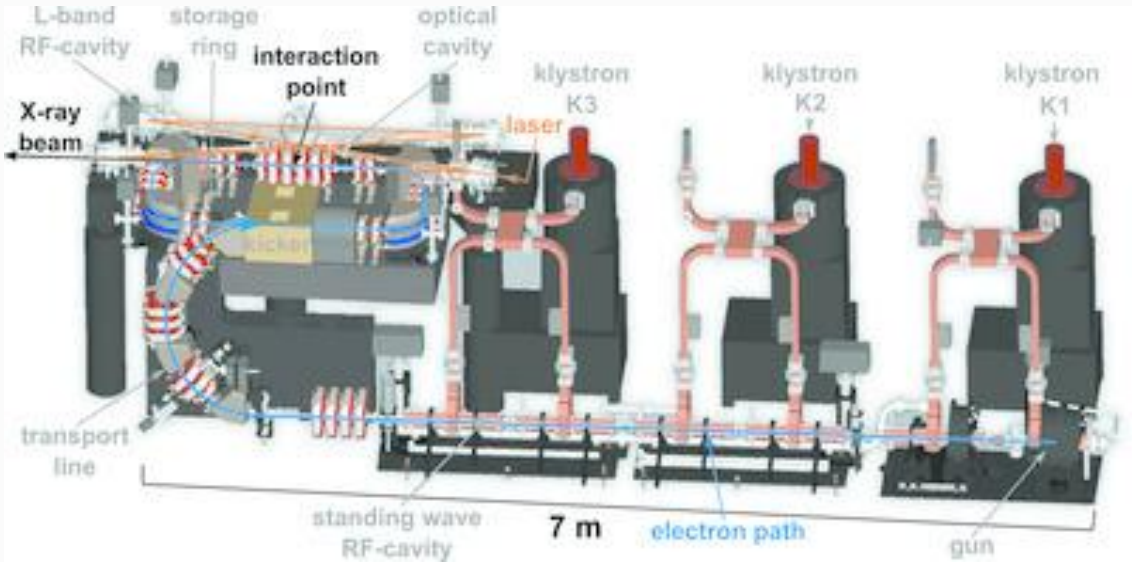


Table 1
Summary of the current operating parameters of the X-ray source of the MuCLS.

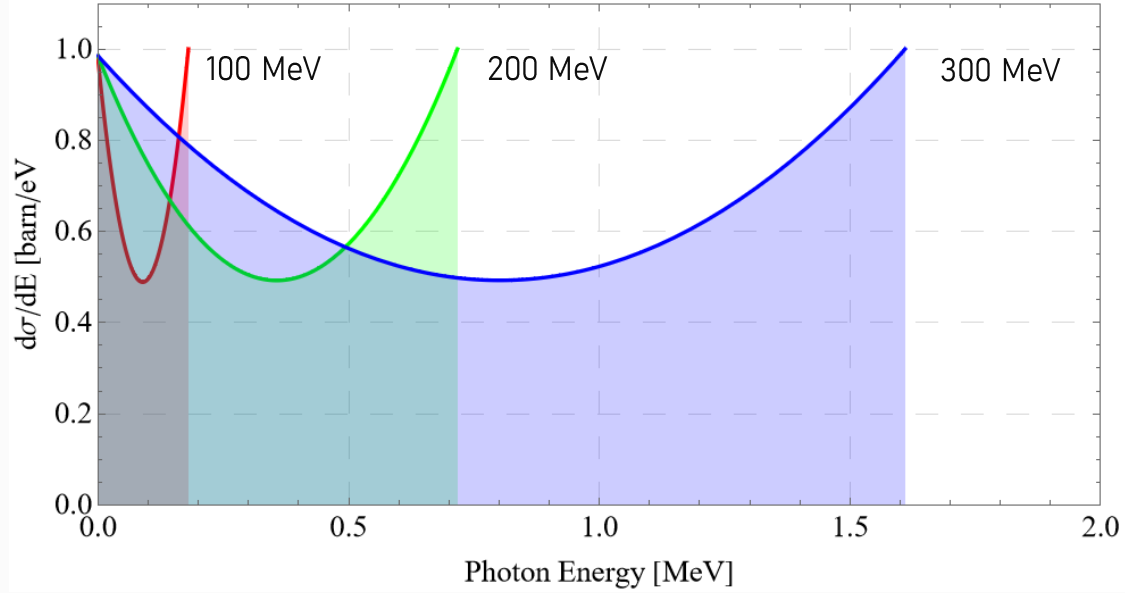
Repetition rate	64.91 MHz
Electron energy	29 MeV to 45 MeV
Storage ring current	16 mA
Electron pulse length	50 ps (Schleede, 2013)
Laser wavelength	1064 nm / 1.17 eV (Nd:YAG)
Laser power (inside the optical cavity)	~ 350 kW
Laser pulse length	26 ps (FWHM)
X-ray energy	15 keV to 35 keV†
X-ray flux	Up to 1.5×10^{10} photons s ⁻¹ (15 keV) Up to 4.5×10^{10} photons s ⁻¹ (35 keV)
X-ray pulse length	60 ps (Feser <i>et al.</i> , 2018)
X-ray divergence	4 mrad
X-ray source size	~ 50 μm (σ-value)
X-ray bandwidth	3% (15 keV) to 5% (35 keV) (FWHM)
X-ray brilliance	1.2×10^{10} photons s ⁻¹ (0.1% bandwidth) ⁻¹ mm ⁻² mrad ⁻²



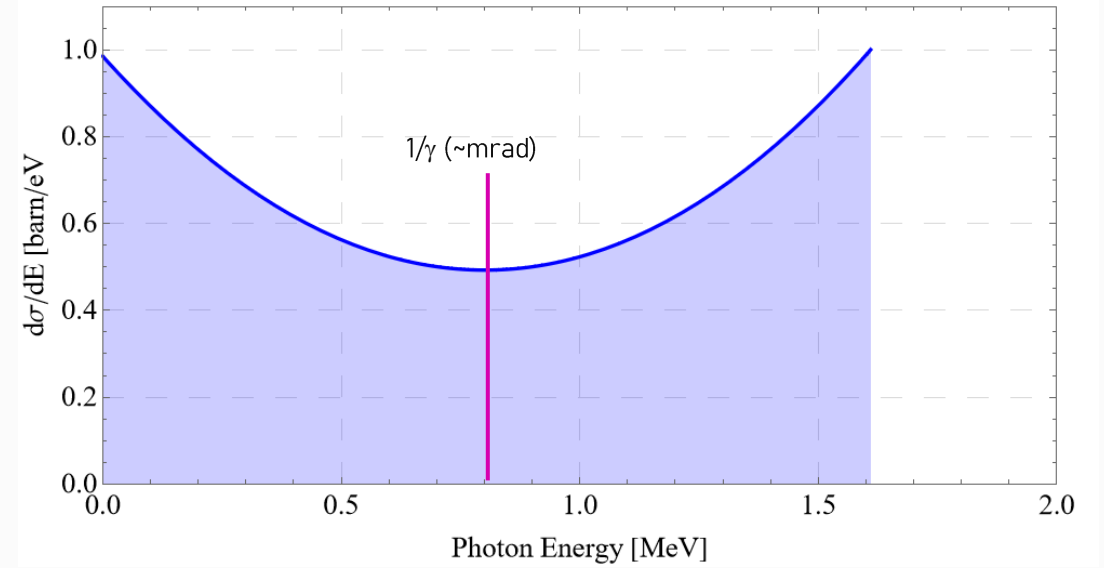
<https://doi.org/10.1107/S1600577520008309>



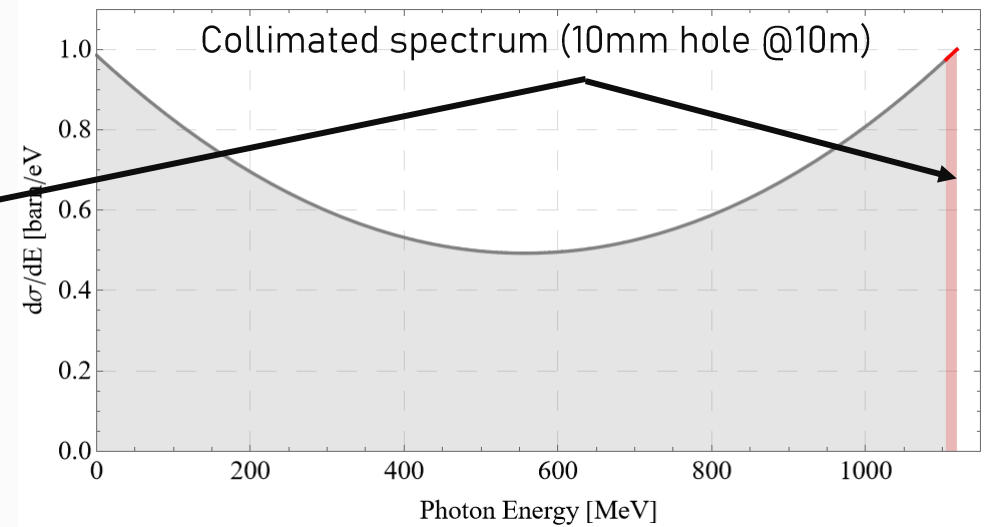
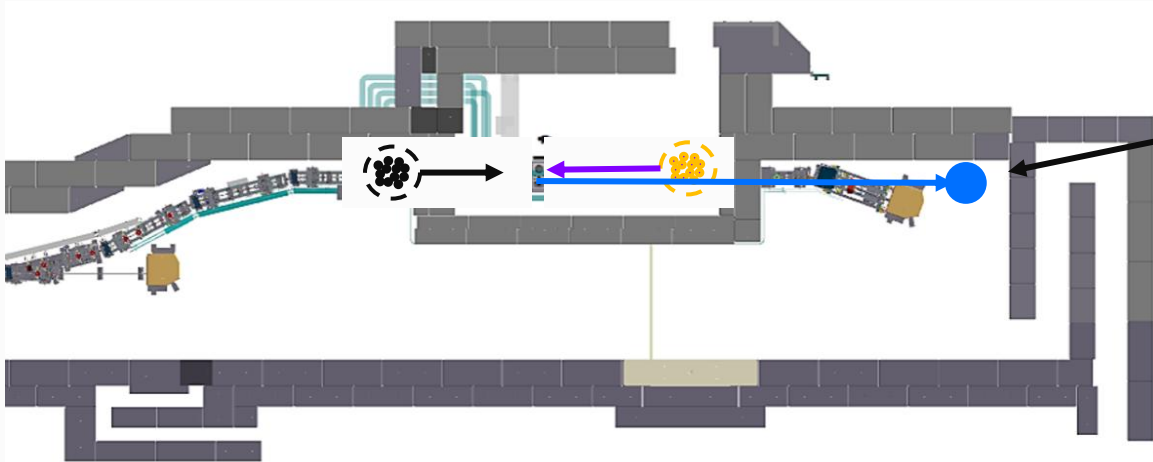
ICS on CLARA



Straight-on



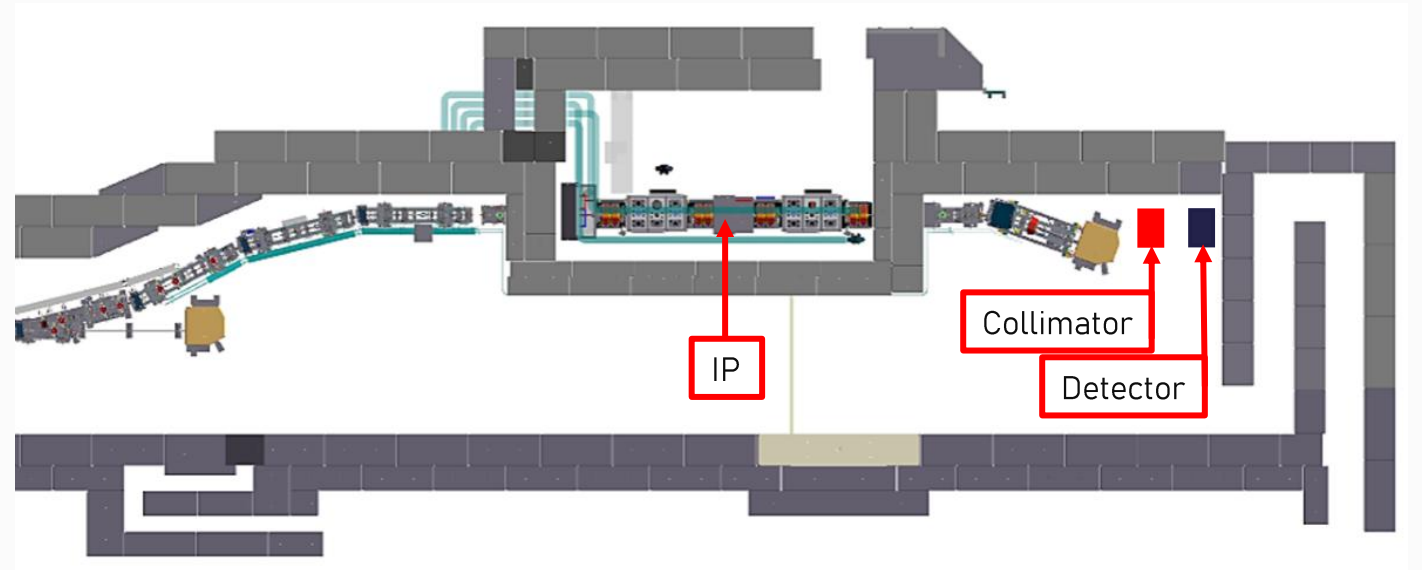
← 'Straight-on'/0 deg 'Backscatter/180 deg' →



First *Proof-of-Principle* Experiment

The first *proof-of-principle* experiment has been designed as a demonstration of the ability to produce, detect and predict the γ -ray spectrum of the FEBE ICS interaction.

To our knowledge, the FEBE ICS experiment would be the highest-flux linac driven ICS generation of γ -rays in Europe. Only the Super-ACO γ -ray experiment, with a demonstrated flux of 5×10^6 ph/s exceeds some FEBE ICS flux predictions.



Schematic of the FEBE experimental area. The electron bunch and laser pulse will be interacted in the first experimental chamber with the resultant γ -rays collimated, then detected beyond the electron beam stop.

ICS Parameters on CLARA

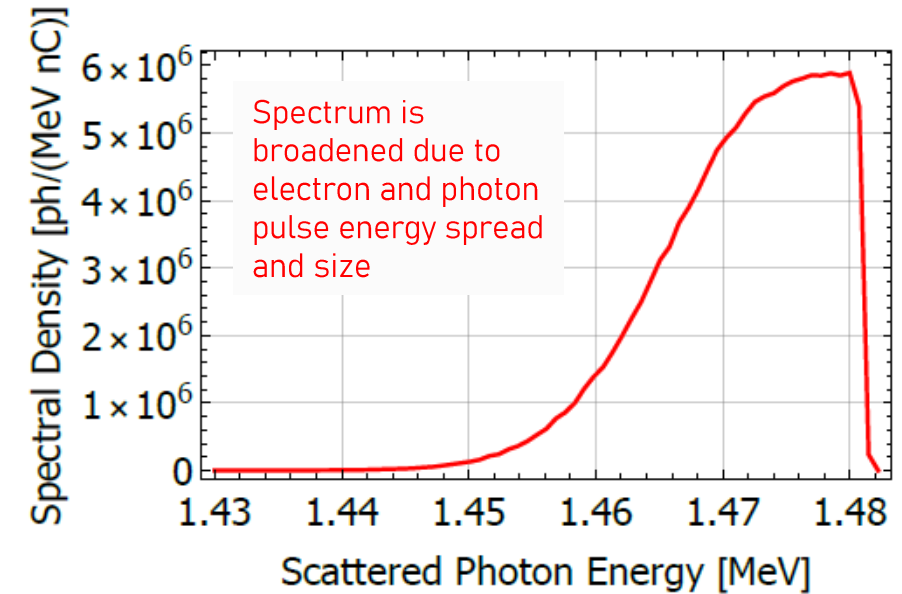
Table 1: Electron Bunch parameters at the IP for the CLARA FEBE ICS experiment.

Parameter	Quantity	Unit
Electron kinetic energy, E_e	150–250	MeV
Repetition rate, f	1–100	Hz
Bunch charge, eN_e	100	pC
Transverse normalised <i>rms</i> emittance, ϵ_N	1–5	mm-mrad
<i>rms</i> bunch length, $\Delta\tau$	0.73 (2.4)	mm (ps)
Absolute energy spread, ΔE_e	20	keV
Relative energy spread, $\Delta E_e/E_e$	$0.13\text{--}8.00 \times 10^{-5}$	
Baseline parameters		
β -function at the IP, β^*	0.15–1.23	m
Electron bunch spot size, σ_{electron}	50	μm

Can increase this

FEBE laser procured and under commissioning

Parameter	Case A	Case B	Case C	Unit
Wavelength, λ_{laser}	800	800	1064	nm
Photon energy, E_{laser}	1.55	1.55	1.17	eV
Pulse energy, E_{pulse}	5.00	0.10	0.06	J
Number of photons, N_{laser}	2.02×10^{19}	4.03×10^{17}	3.21×10^{17}	
Repetition rate, f	1	1	1–10	Hz
<i>Rms</i> Spot size at the IP, σ_{laser}	45	45	45	μm
Crossing angle, ϕ	0	0	0	deg
<i>Rms</i> Pulse length, τ_{laser}	0.01	2.00	21.23	ps
Normalised Laser Vector Potential, a_0	0.83	8.56×10^{-3}	2.71×10^{-3}	
<i>Rms</i> Spectral Bandwidth, $\Delta E_{\text{laser}}/E_{\text{laser}}$	0.03185	0.03185	10^{-4*}	



Case A/B photon output:
Around 500,000 ph/pulse @ 10 Hz
(3 J) in a well-collimated spot

5×10^6 ph/s cf. 5×10^7 at H γ S

Takeaway messages:

Photon energy can be scaled up by increasing electron energy – ‘more linac’

Photon **average** intensity can be scaled up by recirculating the electrons (ring or ERL) and photons (cavity)

Photon **peak energy & intensity** can be scaled up using plasma-based acceleration: EPAC facility at Rutherford Appleton Laboratory

γ -ray Source Comparison

Many ICS sources for production of γ -rays have been designed around the world and several have been operated. The majority of currently operating γ -ray ICS sources are based on existing storage ring facilities – **there are few dedicated ICS based γ -ray sources, with ~3% FWHM bandwidths.** **Narrowband high flux radiation could enable new nuclear photonics experiments + nuclear physics studies.**

The flagship ELI-NP VEGA project – the highest flux (10^{11} ph/s) and narrowest bandwidth (0.5% FWHM) source – is due for first experimentation in 2023.

The DIANA ICS source is designed to match these parameters with an ERL driver – conservative laser parameters mean this could reach fluxes of 10^{12} ph/s with similar narrow bandwidth.

The FEBE ICS experiment would enable flux on the order of other demonstrator projects such as VIGAS at Tsingshua University (~12 m) and NIJI-IV, Japan (~28 m) which are on the lab scale.

Whilst this is a low flux demonstration in comparison to many γ -ray sources, many experiments are still possible with the source.

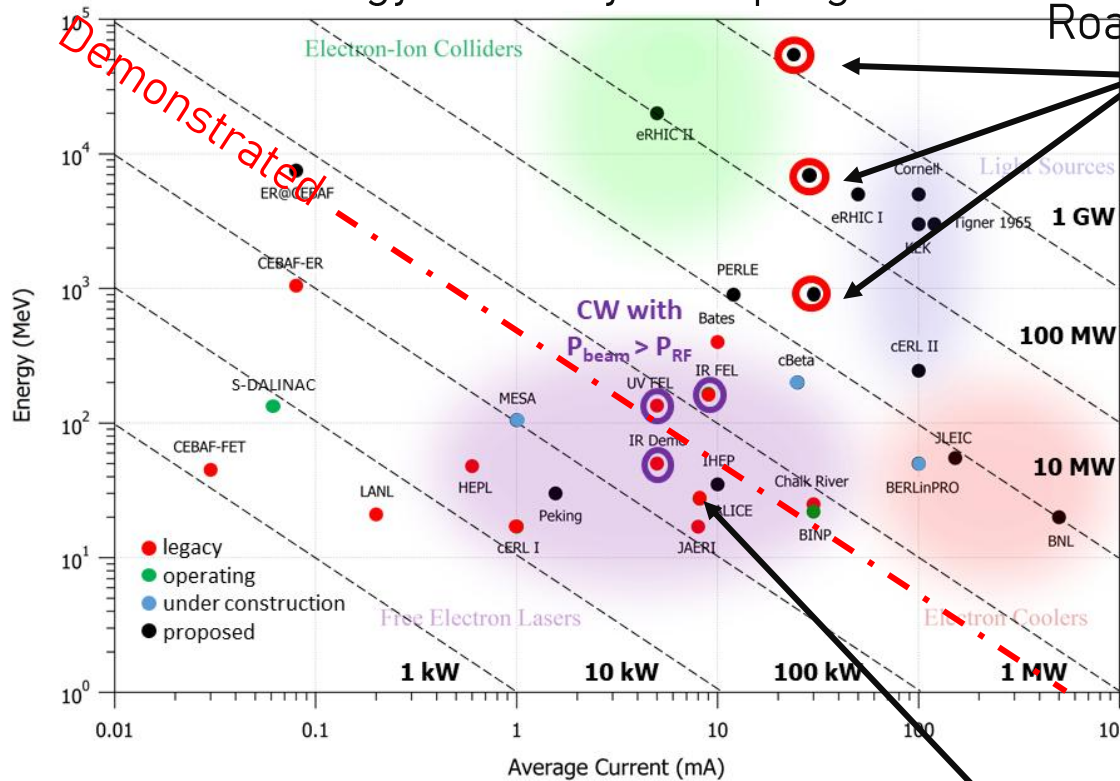
ICS	Accelerator Type	Scattered Photon Energy (MeV)	Flux (ph/s)
DIANA*	ERL	2.33–20.11	$5.77\text{--}6.08 \times 10^{10}$
FEBE Exp.*	Linac	<1.48	$4.63\text{--}5.83 \times 10^5$
NIJI-IV	Storage Ring	1.2	3.1×10^4
VIGAS*	Linac	0.2–4.8	$1\text{--}4 \times 10^8$
ELI-NP-GBS*	Linac	0.2–19.5	3.9×10^9
ELI-NP VEGA*	Storage Ring	1–19.5	1×10^{11}
NewSUBARU	Storage Ring	5–40	3×10^7
Pan et al CBS*	Storage Ring	4–10	$0.14\text{--}3.87 \times 10^{12}$
Super-ACO	Storage Ring	33.4	5×10^6
HI γ S	Storage Ring	1–100	$5 \times 10^7\text{--}5 \times 10^8$

* Denotes design parameters for sources which are not yet demonstrated.

A selection of designed and operating ICS sources in the γ -ray regime. Most currently operated γ -ray ICS sources use large synchrotrons to operate such as HI γ S and NewSUBARU, with some using FELs as drive lasers (NIJI-IV, Super-ACO, HI γ S). Note that an ERL approach has not been pioneered in the γ -ray regime.

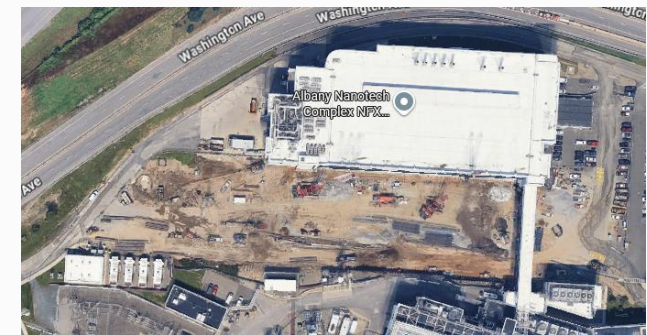
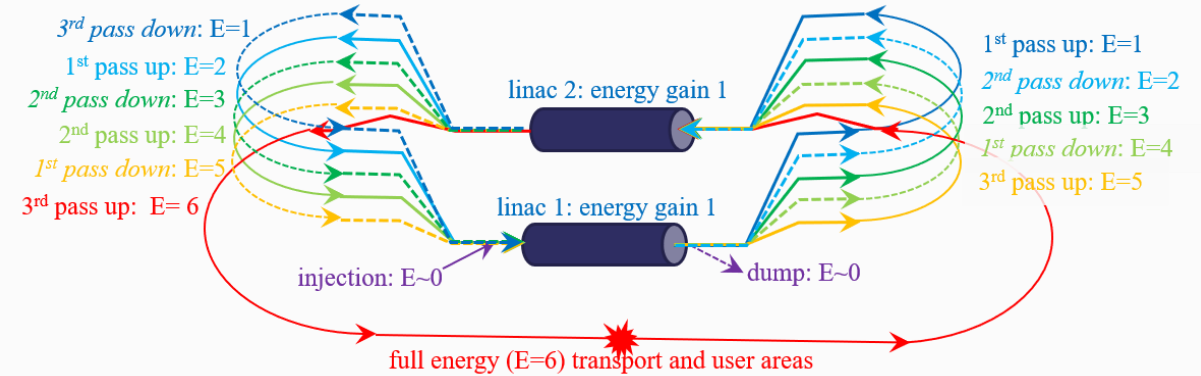
Nuclear Applications and DIANA

Energy-recovery linac progress

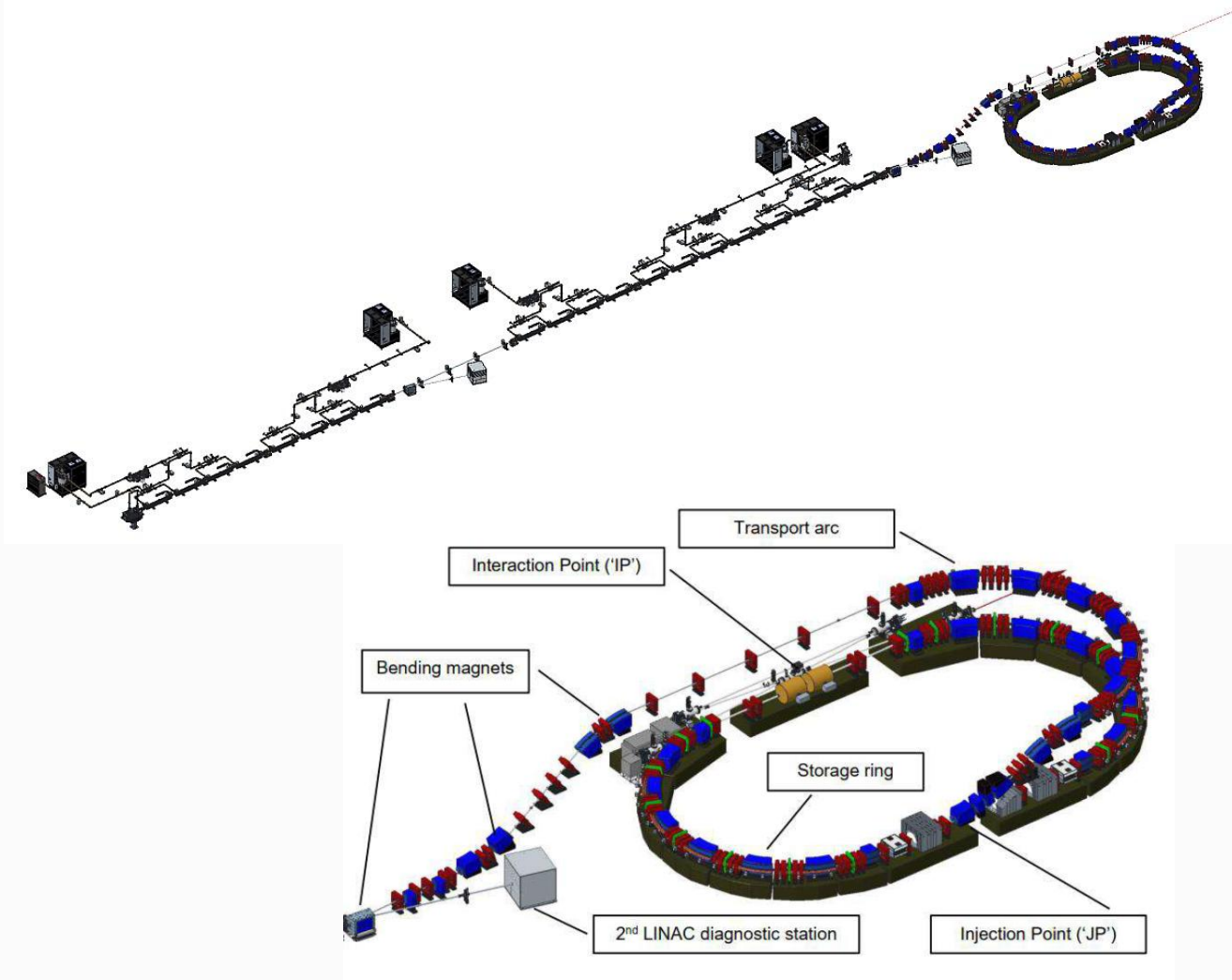


Roadmap

DIANA Concept – 100 mA, 600 MeV ERL



ELI-NP and Lyncean/VEGA



Linac-driven recirculating ring
e- ring 234 – 742 MeV
 γ 1 to 19.5 MeV

Quantity	Unit of measurement	Specification
Maximum Photon Energy	[MeV]	≥ 19.5
Tunability of the Photon Energy		Steplessly variable
Linear Polarization of Gamma-Ray Beam	[%]	≥ 95
Divergence at Full Width Half Maximum (FWHM) of Beam Spot	[rad]	$\leq 1.5 \times 10^{-4}$
Average Relative Bandwidth of Gamma-Ray Beam (FWHM)	[m]	$\leq 5.0 \times 10^{-3}$
Total Photon Flux		$\geq 1.0 \times 10^{11}$
Time-Average Spectral Density at Peak Energy	[1/s]	$\geq 5.0 \times 10^3$
Average Spectral Off-Peak Gamma-Ray Background Density	[1/(s eV)]	$\leq 1.0 \times 10^{-2}$
Angular Spectral Flux Density	[1/(s mrad ² 0.1%W)]	$\geq 1.0 \times 10^9$

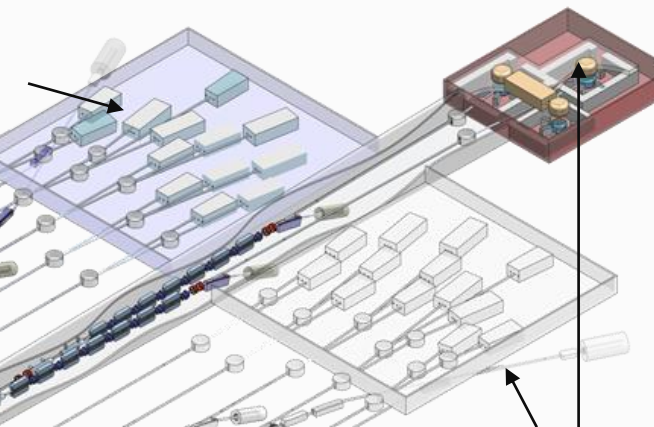
UK-XFEL Project

UK proposal for a national X-ray facility

Primarily operated for free-electron laser based science

Opportunities for plasma acceleration, particle physics and nuclear physics

A world-class array of independently operable instruments, data handling, AI etc.

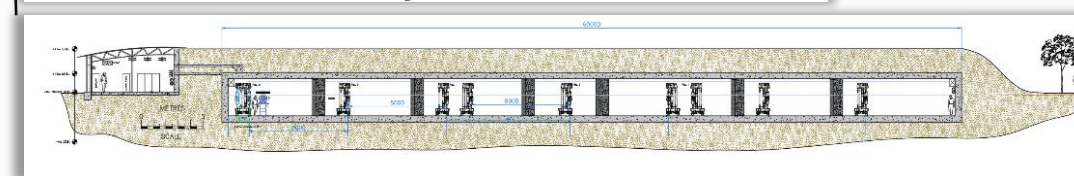
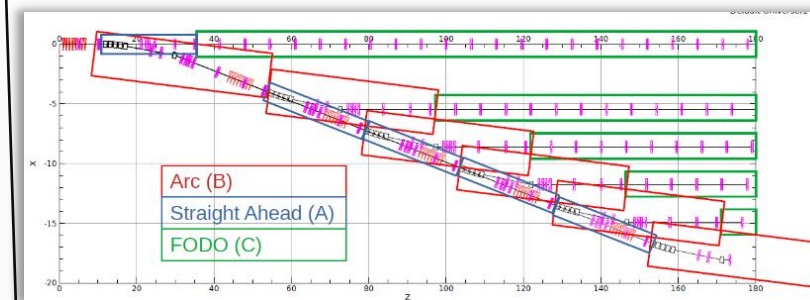


Specialised undulator features per line for near-TL pulses



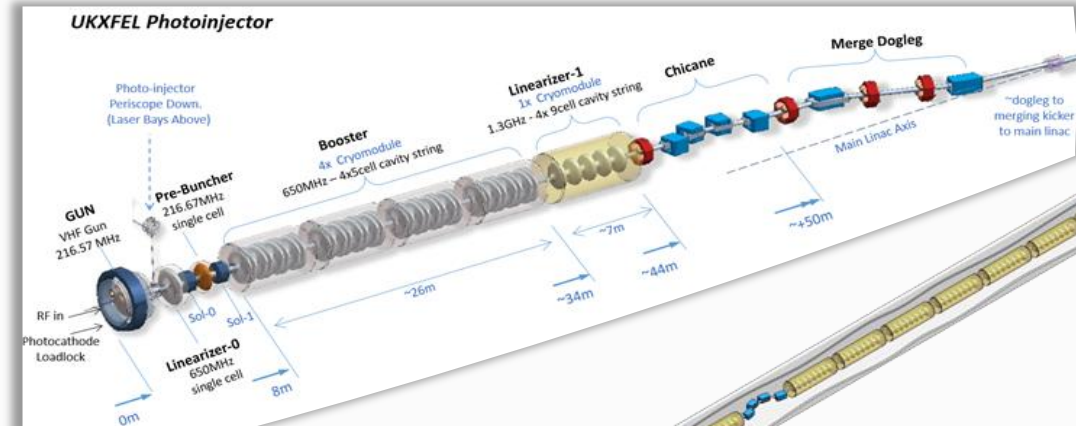
A laser facility as well as an accelerator facility: high rep rate and high power/high pulse energy sources

8 GeV fixed energy and modular beam distribution



Individually shielded undulator lines for independent operation

UKXFEL Photoinjector



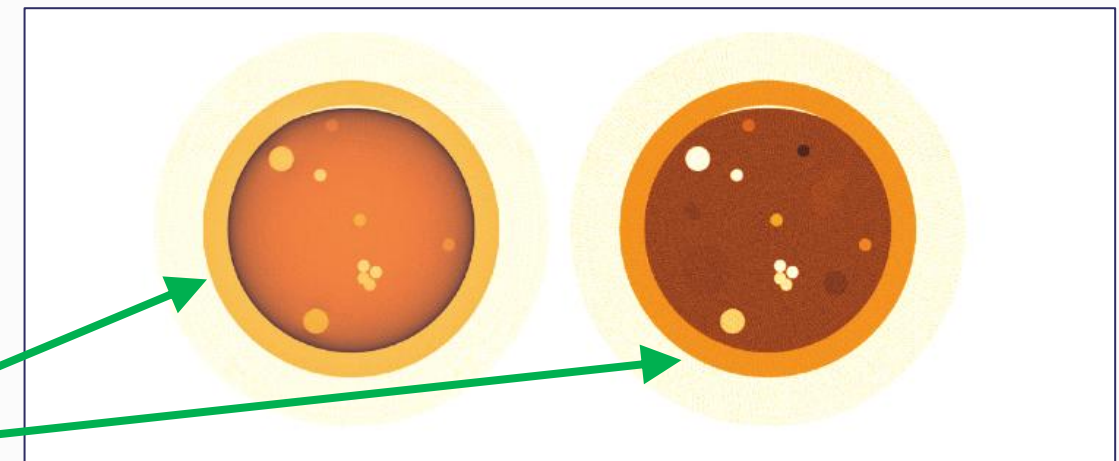
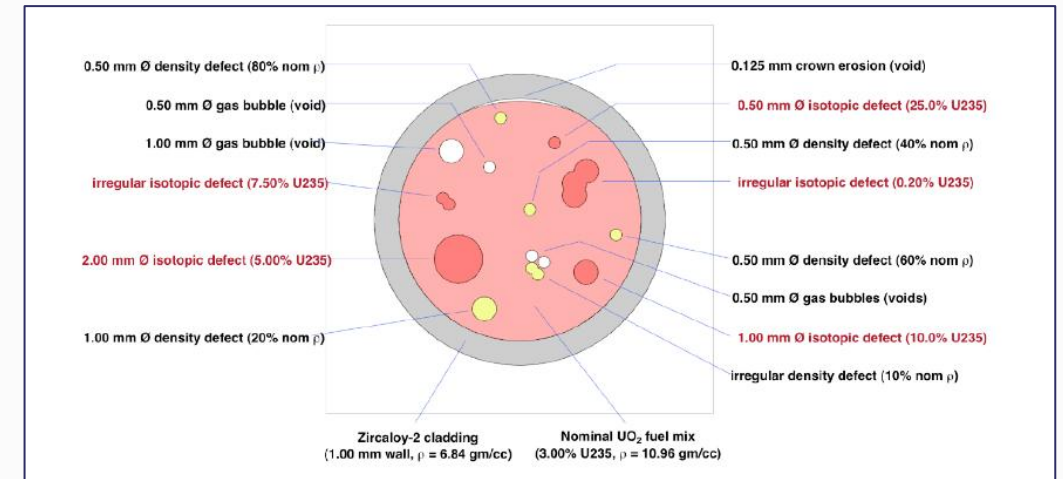
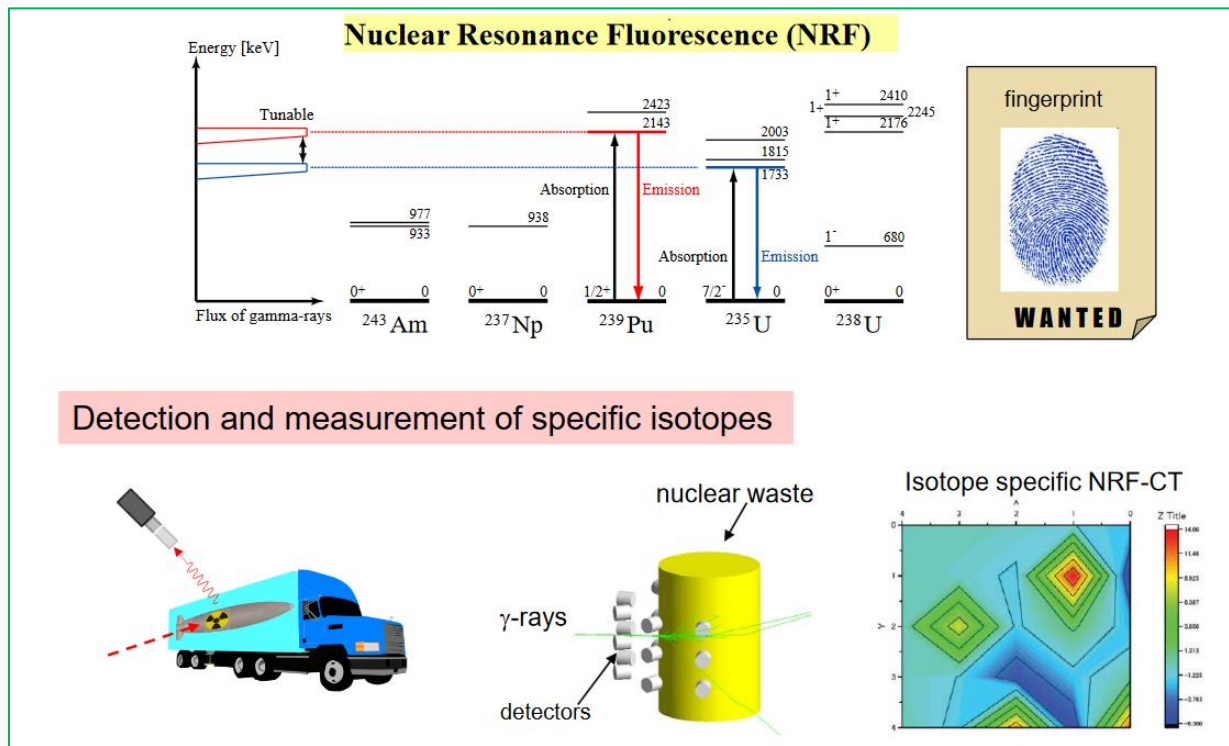
Makes use of established SRF linac technology (with the option to swap in thin-film SRF)



Two VHF-gun-based photoinjectors, with multiple lasers each - for flexibility and redundancy – a key R&D technology

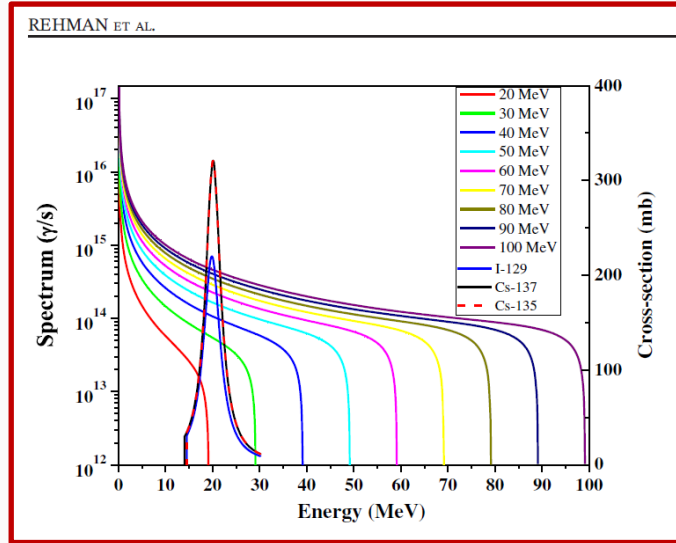
Nuclear Photonics @ 1 – 3 MeV Gammas: Nuclear Resonance Fluorescence

- At 1 – 3 MeV: (γ, γ') = NRF, pencil beam of ICS source ideal for Computed Tomography of: e.g. **detection of clandestine nuclear materials**, defects in fuel assemblies (JAEA & LLNL studies), assay of spent fuels, unknown legacy wastes, ...



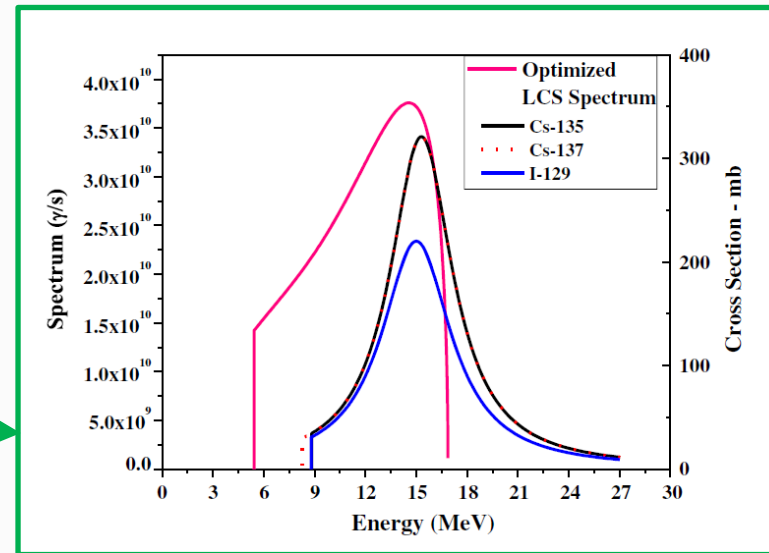
Nuclear Photonics @ 3 - 40 MeV Gammas: Photofission / Transmutation

- At 3 – 40 MeV: (γ, n) , (γ, p) , (γ, f) . Forensic capability as with NRF, but this time by induced decay / fission. But also the broad photonuclear “dipole resonances” of nuclear structure are **not well matched** to bremsstrahlung energy spectrum

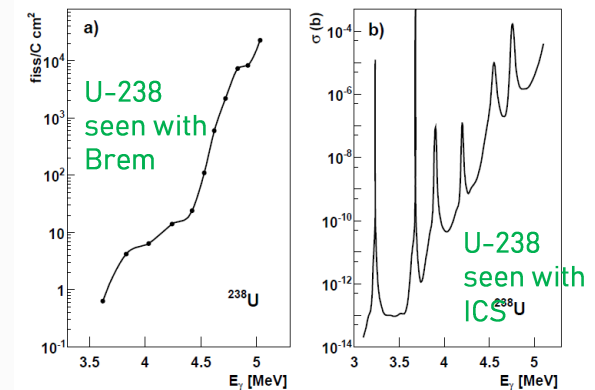


Brem spectra compared to dipole resonances of I-129 and Cs-135/137

ICS spectrum compared to dipole resonances of I-129 and Cs-135/137



Predicted “hidden” resonances in photofission cross sections



- Raw, loosely collimated ICS gamma bandwidth **well matched** to dipole resonance, and flux enabled by ERL more than compensates for lower cross section of ICS vs bremsstrahlung = more efficient transmutation



UK Research
and Innovation