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The Shape of FELs to Come

Jim Clarke, STFC Daresbury Laboratory

UK XFEL Town Meeting

The Royal Society

16th July 2019

Outline

- Potential FEL Output Enhancements
- Progress with Key Enabling Technologies
- UK Accelerator & FEL Capabilities
- Summary

What capability is the science likely to demand?

- Soft to hard x-ray (0.1 – 10 keV), (maybe harder, maybe VUV)
- Short pulse available (< 0.5 fs)
- Two pulse/two colour with delays over sub-fs to ns
- Synchronised or tagged to lasers to high precision (< 5 fs)
- High spectral brightness/narrow bandwidth available (< 50 meV)
- High rep-rate is mandatory for much advanced science (chemical, quantum materials, rare events …) (> 1 kHz maybe > 1 MHz)
- High photon pulse energy (~ 10^{12} photons/pulse, maybe not at full rep-rate)
- Polarisation control (Linear, circular, OAM)
- ………..

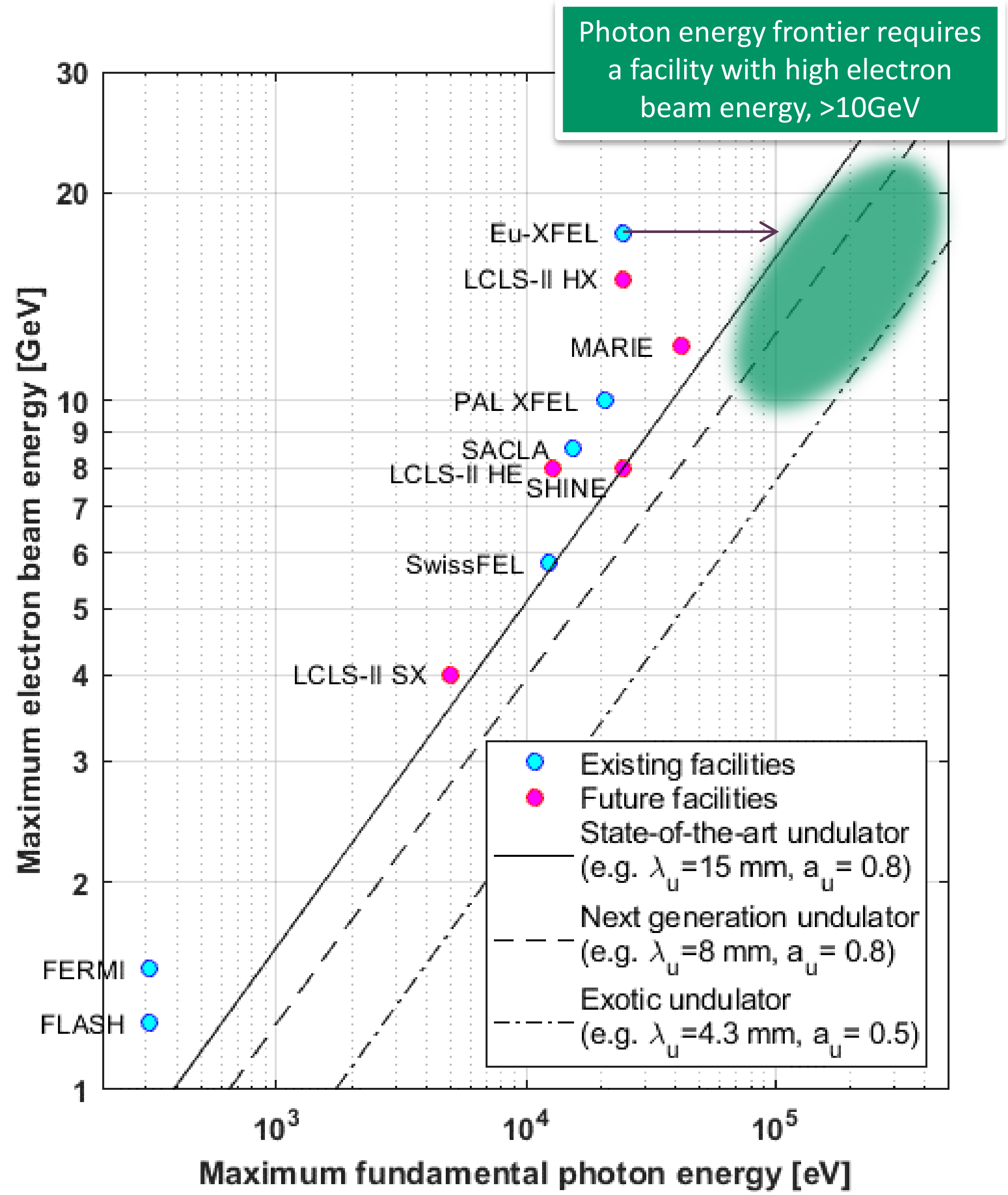
The science case will help define the scientific and therefore the facility technical priorities

Jon Marangos

POTENTIAL FEL OUTPUT ENHANCEMENTS

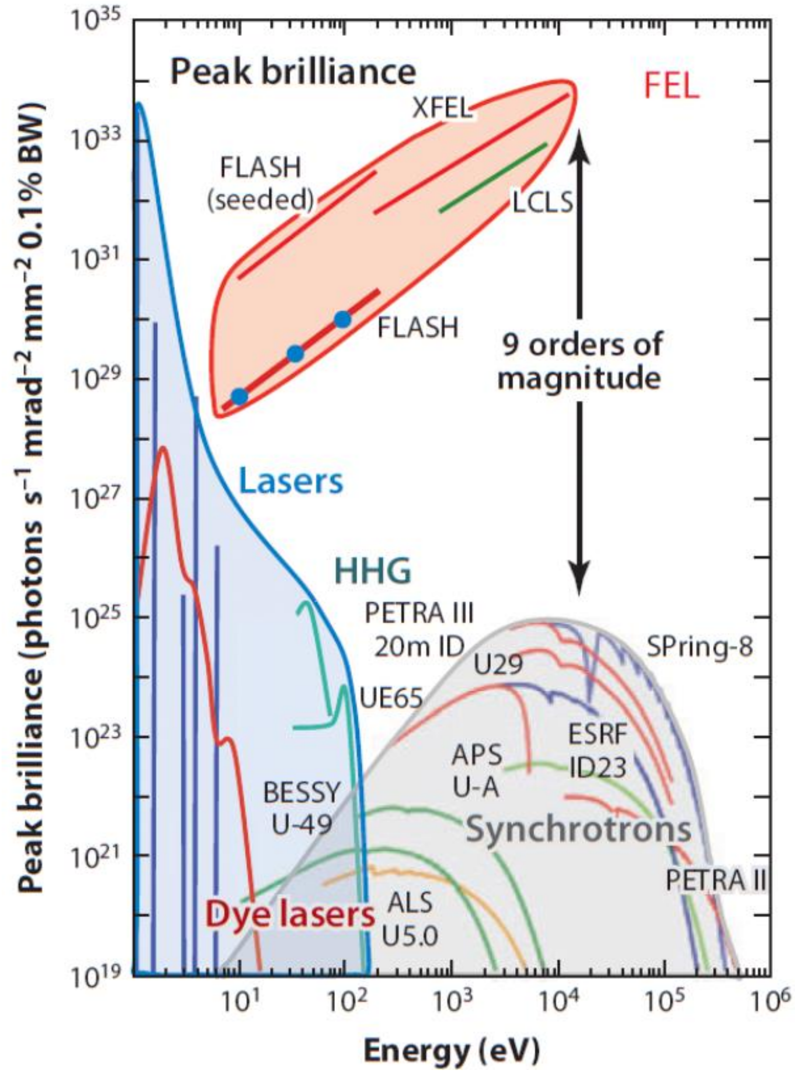
Photon energy

- State-of-the-art:
  - European XFEL: 25 keV (0.05 nm) at the fundamental
  - 100 keV anticipated
- To increase:
  - Shorter period undulators (λ_u)
  - Higher electron beam energy (γ)
  - Harmonic lasing
- Show-stoppers?
  - Electron beam quality, electron recoil -> quantum FEL



Peak Brightness

- State-of-the-art:
  - ~5×10^{33}
- To increase:
  - Larger peak power
    - Stronger undulator field/ longer undulator period and higher electron energy
    - Higher peak current
    - Increased FEL efficiency via undulator tapering
  - Narrower bandwidth (see later slide)
    - Seeding
    - Oscillators



Joachim Ullrich et al. Annual Review of Physical Chemistry 2012 63:1, 635-660

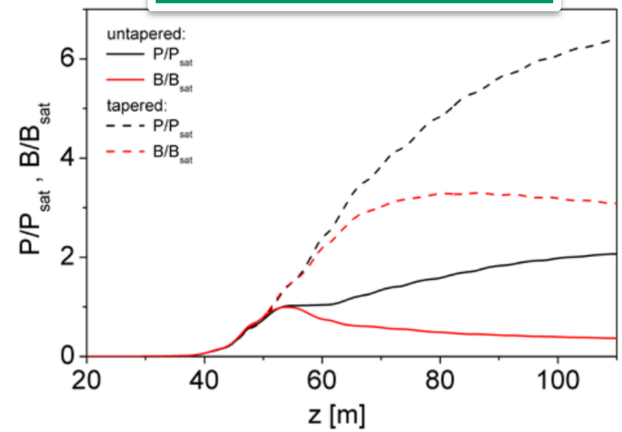
Pulse energy

- State-of-the-art:
  - Soft x-ray: ~10mJ (Eu-XFEL)
  - Hard x-ray: ~5mJ (LCLS, Eu-XFEL)
- To increase:
  - Larger peak power (~10’s GW->TW)
    - Stronger undulator field/longer undulator period/higher electron beam energy (increase in tandem to maintain resonance)
    - Higher peak current
    - Undulator tapering (requires temporal coherence to be most effective)
  - Longer radiation pulse -> requires higher electron bunch charge to maintain peak current.

Show-stoppers?

  - Issues with generating and transporting electron beams with high peak current and high bunch charge

Tapering increases both power and brilliance



E.A. Schneidmiller and M.V. Yurkov, Journal of Modern Optics, Volume 63, 2016 - Issue 4

Tapering works better with seeded FEL

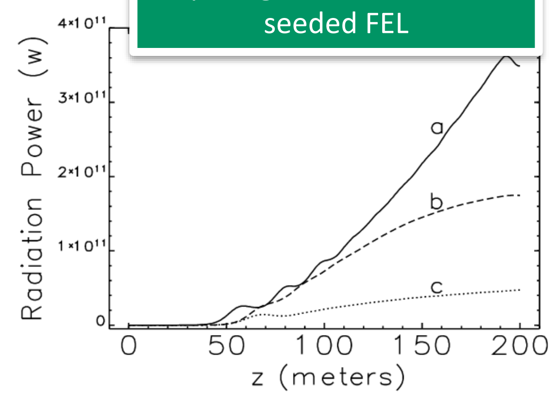
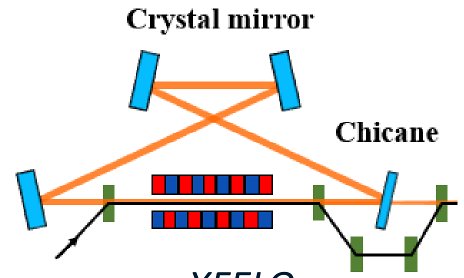


Fig. 4. Comparison of the predicted radiation power for the LCLS: (a) tapered monochromatic amplifier, (b) tapered SASE, and (c) untapered SASE.

W. Fawley et al. NIM A 483, 537, 2002

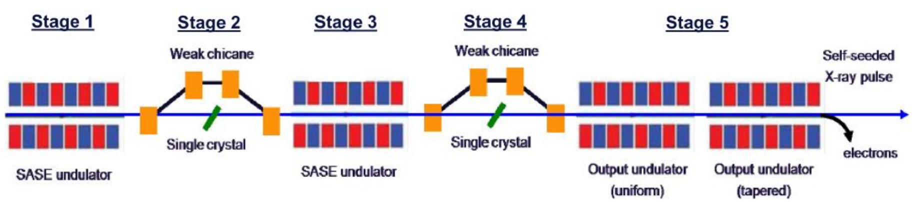
FWHM Bandwidth

- State-of-the-art
  - Soft X-Ray:
    - 1e-3 (Fermi@Elettra – seeded)
    - 2e-4 (LCLS - self seeded)
    - 1e-3 (LCLS – SASE)
  - Hard X-Ray
    - 4e-4 (LCLS – self seeded)
    - 1e-3 (LCLS – SASE)
- To decrease
  - XFELO: potential for 1e-7 – 1e-6
  - HXR Double Self-Seeding (EU-XFEL): potential for 7e-5
  - HB-SASE: potential for 2e-5 – 1e-4
    - No laser/optics required
- To increase
  - Transverse gradient undulator (SwissFEL SXR): potential for 10%



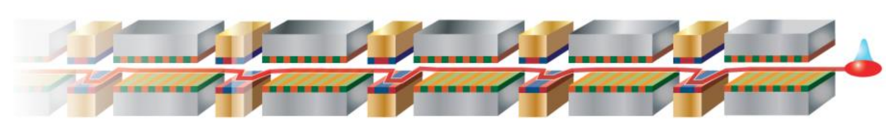
XFELO

K Li et al, PRAB. 21. 10.1103/PhysRevAccelBeams.21.040702.



Double Self-Seeding

X. Dong et al, doi:10.18429/JACoW-FEL2017-MOP008



HB-SASE (High Brightness SASE)

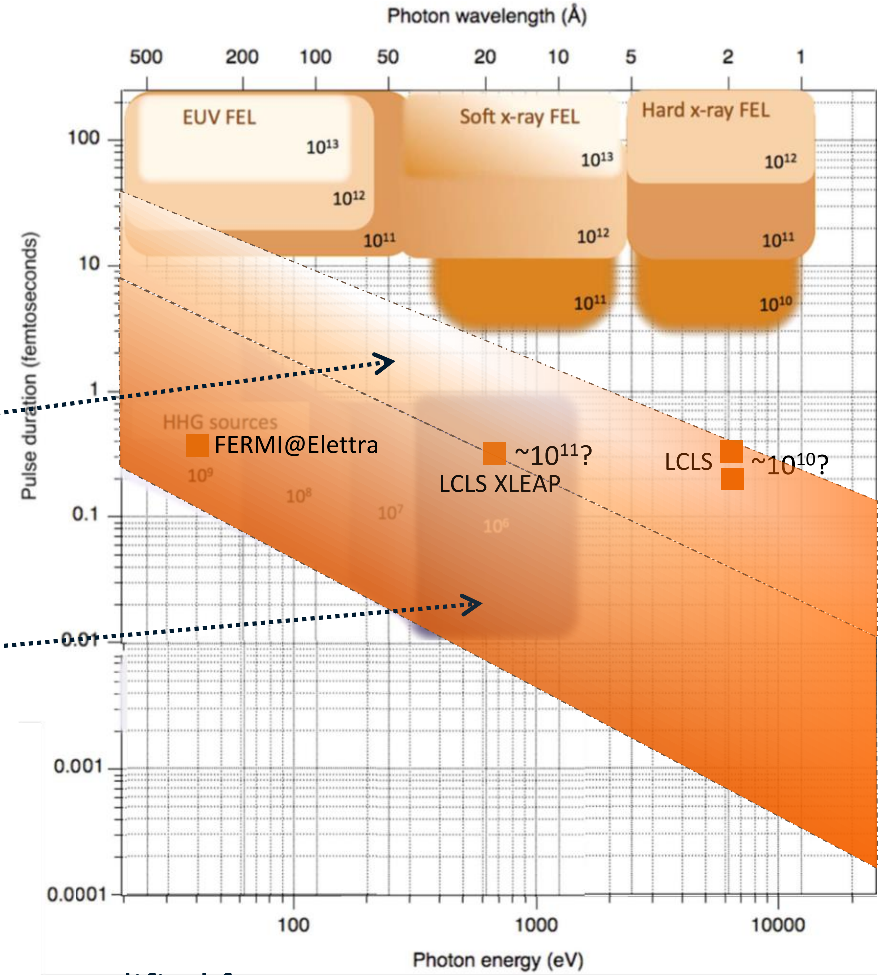
B. W. J. McNeil at al, PRL 110, 134802 (2013)

Stability

- State-of-the-art
  - SASE is intrinsically unstable:
    - Pulse Energy Jitter over full pulse envelope – depends on number of SASE spikes *N* as $1/\sqrt{N}$
      - LCLS ~10% in normal operation and >15% in short pulse modes
      - PAL XFEL ~ 3% (very good electron beam stability)
    - Central wavelength jitter
      - LCLS ~ 0.1%.
      - PAL XFEL ~ 0.03% (very good electron beam stability)
  - Self Seeding pulse energy fluctuations ~50%
  - External Seeding at ~4 nm (Fermi@Elettra) pulse energy 20-40% central wavelength 0.01%
- To improve
  - XFELO ultimate potential is 0.01% pulse energy stability with better than 0.01% wavelength stability (?)
  - RAFEL more stable shot to shot than self-seeding (at MHz)
  - Reduce electron beam energy jitter
  - Reduce complexity of seeding scheme
    - Seed at fundamental
    - Seed length matched to electron bunch length

Ultra-short pulses

- State-of-the-art: ~300 attoseconds
  - EUV: Attosecond pulse train synthesis (FERMI)
  - Soft x-ray: XLEAP (LCLS)
  - Hard x-ray: Single-spike SASE (LCLS)
- To improve:
  - Enhance XLEAP/single-spike SASE
    - ‘Fresh-slice superradiance’ (significant pulse energy increase, >~100 cycles)
  - Sub-co-operation length:
    - Down to single/few-cycle pulses -> zeptosecond scale? (#photons per pulse reduces)
- Showstoppers?:
  - Increased complexity
  - Diagnostics development required hand-in-hand with source development below ~100as



Modified from:

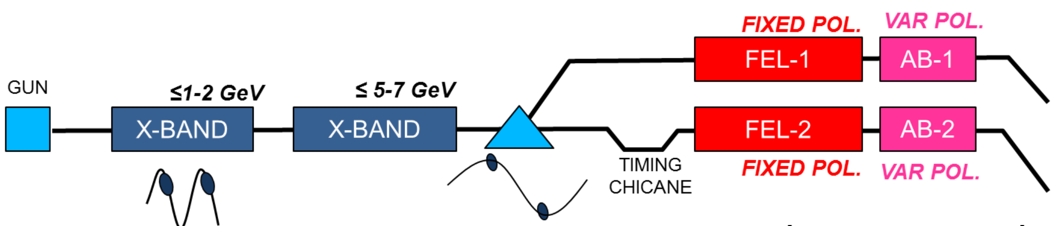
ROADMAP • OPEN ACCESS

Roadmap of ultrafast x-ray atomic and molecular physics

To cite this article: Linda Young *et al* 2018 *J. Phys. B: At. Mol. Opt. Phys.* **51** 032003

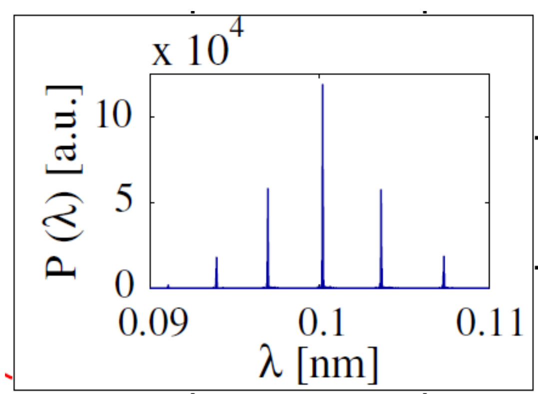
Multi-colour

- State-of-the-art
  - Extensive menu of options at LCLS with continuous pulse separations up to 850fs and photon energy separations up to 2.5%
  - Greater energy separations possible at EU-XFEL and SwissFEL due to variable gap undulators
- To improve
  - Remove correlation between wavelength separation and timing separation
  - Can be done via dedicated double FEL with separate bunch in each branch
    - Full independent control of wavelength, timing separation
    - Independent control of pulse energy, duration, polarisation...

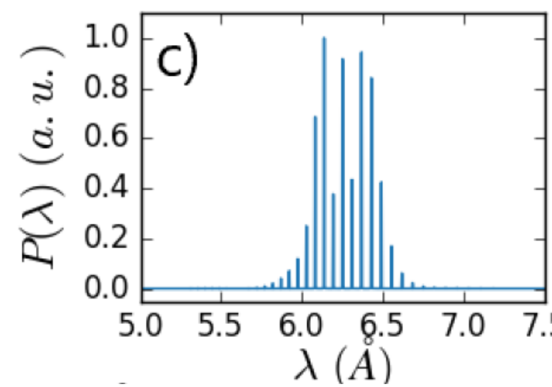


Schematic of CompactLight Double-FEL Proposal

  - Frequency combs via ***Mode-Locked Afterburner*** or ***FM-Modulated FEL***



Mode-Locked Afterburner Frequency Comb
D. J. Dunning et al, PRL 110, 104801 (2013)



FM FEL Frequency Comb
L. T. Campbell and B. W. J. McNeil, Optics Express 27 (6), 8792, (2019)

Multi-colour

- State-of-the-art
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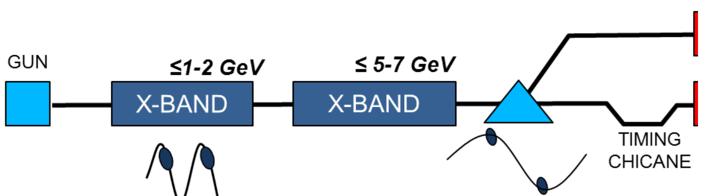


FEL Proposal

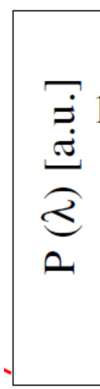
  - Frequency combs via
    Mode-Locked Afterburner
    or ***FM-Modulated FEL***

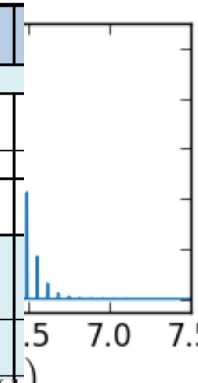
SOFT X-RAYS

Technique	Pulse Separation	Min Pulse Duration	Energy Separation
Fresh Slice			
Two SASE Pulses	~-15 to +850 fs	~5-8 fs	+/-2.5%
Linear SASE + Polarization Controlled SASE	~-15 - +850 fs	~5-8 fs	+/-2.5%
One Pulse Self-Seeded, One SASE	0 - 50 fs	~15-20 fs	+/-2.5%
Three SASE Pulses	0 - 900 fs (1st to 2nd), 0 - 50 fs (2nd to 3rd)	~5-8 fs	2.5% range for all
Split Undulator SASE	0 - 50 fs	40 fs	+/-2.0%
Double Slotted Foil	15 - 70 fs	~ 10 fs	+/-1.5%
Two bucket (ns spacing)	350 ps increments, +/- 120 ns	40 fs	+/-2%
Twin Bunches (fs spacing)	-	-	-

HARD X-RAYS

Technique	Pulse Separation	Min Pulse Duration	Energy Separation
Twin Bunches			
Two SASE Pulses	0 - 125 fs	~ 10 fs	0.2-3%
Twin bunches + V slotted foil	+/- 50 fs	~5-10 fs	~3%
Twin bunches + HXR Self-Seeding	0-100 fs	~ 10 fs	~1 %
Double Slotted Foil	7-20 fs	~ 10 fs	+/-1.5%
Two bucket (ns spacing)	350 ps increments, +/- 120 ns	20 fs	~ 2%



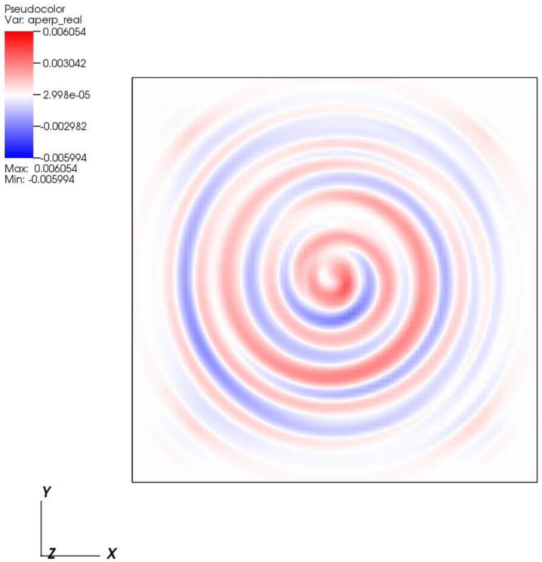


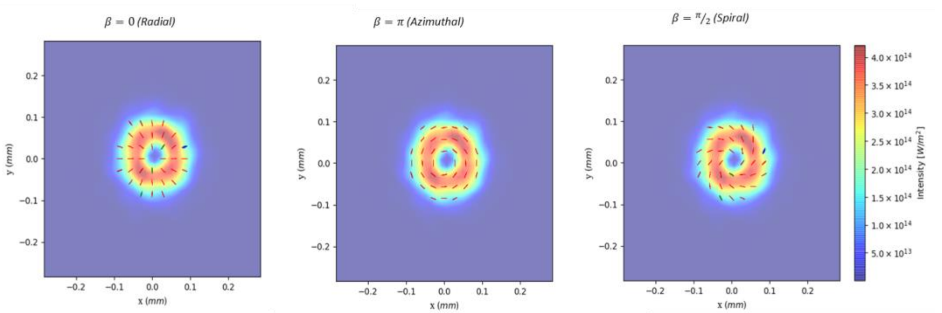
Mode-Locked Afterburner Frequency Comb
D. J. Dunning et al, PRL 110, 104801 (2013)

FM FEL Frequency Comb
L. T. Campbell and B. W. J. McNeil, Optics Express 27 (6), 8792, (2019)

Polarisation, OAM, etc.

- State-of-the-art:
  - Polarisation
    - Variable polarisation control in the full undulator line (FERMI)
    - Variable polarisation control via an afterburner (LCLS)
  - Orbital angular momentum
    - The higher harmonics of a helical undulator carry OAM [1] and pre-bunching the electron beam into a helix can produce OAM at the fundamental [2].
- Next generation:
  - OAM from SASE (B. McNeil et al.)
  - Cylindrical vector beams
    - A helically bunched electron beam is manipulated to create two orthogonal polarized OAM modes. This produces light with a spatially variant polarisation.
  - Arbitrary spatial profiles?





[1] E Hemsing et al, '*First Characterization of Coherent Optical Vortexes from harmonic undulator radiation*', Phys. Rev. Lett **113**, 134803 (2014)

[2] E Hemsing et al, *'Experimental observation of helical microbunching of a relativistic electron beam',* Appl. Phys. Lett, **100**, 091110 (2012)

Trade-offs & Linked Parameters

- Higher photon energy, pulse energy, peak brightness ⇔ Higher cost
  - All else being equal, higher electron beam energy enables higher photon energy, pulse energy, peak brightness – at the expense of higher cost
- Shot-to-shot reproducibility ⇔ Repetition rate
  - No demonstrated external seeding methods beyond ~4nm, self seeding stabilises wavelength but not pulse energy and starts from noise each shot
  - MHz allows more (undemonstrated) options

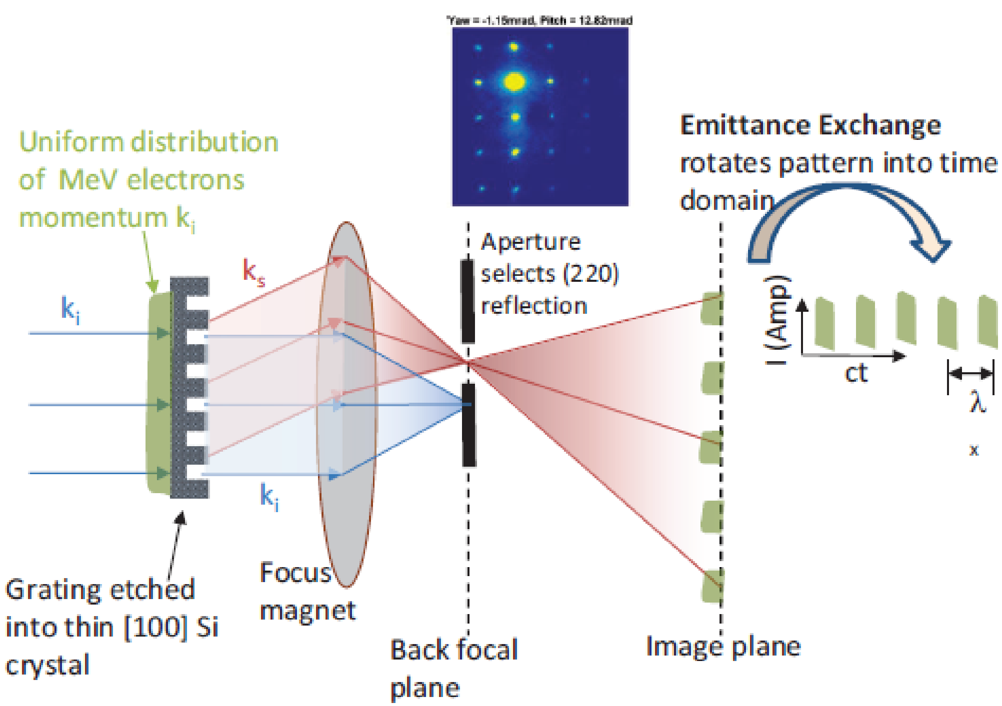
	<1kHz	~MHz
Soft x-ray	• Seeding with external laser and harmonic up-conversion? • Seeding with Compact "XFEL" source (not yet demonstrated)	• XFELO (FELO only demonstrated down to ~200nm) • RAFEL (only demonstrated at 16um) • Seeding with external laser (rep rate???)
Hard x-ray	• Seeding with external laser - harmonic order too high?? • Seeding with Compact "XFEL" source (not yet demonstrated)	• XFELO (FELO only demonstrated down to ~200nm) • RAFEL (only demonstrated at 16um) • Seeding with external laser (rep. rate and harmonic order???)

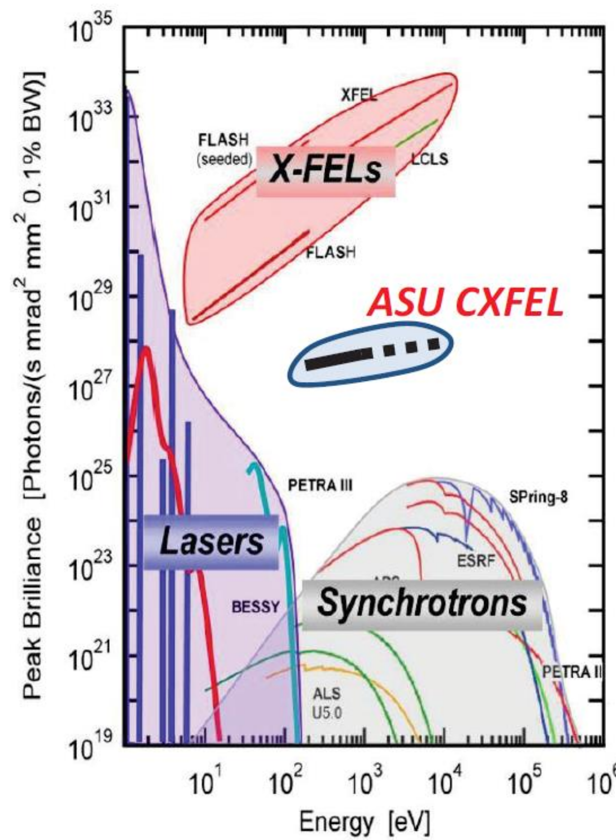
- Ultra-narrow bandwidth ⇔ XFELO ⇔ MHz
  - XFELO is only clear option for meV bandwidths, XFELO requires MHz
- Advanced ultrashort pulse and two colour schemes ⇔ kHz
  - Reliance on high power lasers for advanced schemes

PROGRESS WITH KEY ENABLING TECHNOLOGIES

Direct X-ray Seeding

- A novel Compact "XFEL" concept under active development at Arizona State University
  - Transverse electron diffraction pattern 'transformed' into microbunches at X-ray wavelength
  - Interaction between laser and ~35MeV microbunches (coherent Compton back scattering)
  - Total length ~ 10m
  - Full longitudinal and transverse coherence and **with sufficient power to seed an X-Ray FEL amplifier**
  - Project under construction with tests of beam diffraction ongoing

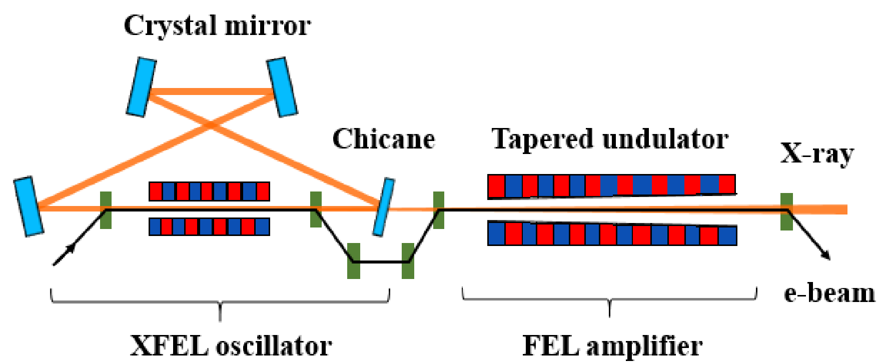




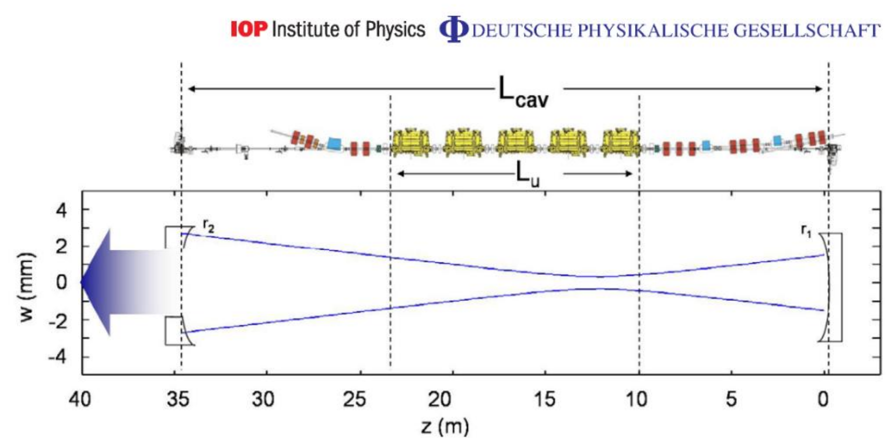
W.S Graves, Proc. of FEL 2017, http://accelconf.web.cern.ch/AccelConf/fel2017/talks/tub03_talk.pdf

X-ray Oscillators: RAFEL and XFELO

- Proposals are being considered for X-ray oscillator FELs – e.g. LCLS II
- Require MHz repetition rates for manageable cavity lengths
- Coherent seed sources for amplifier FEL
- ***XFELO*** is low-gain FEL in a high-Q cavity
  - Cavity comprises 2 – 4 diamond crystal mirrors + focussing (limited tunability)
  - Full transverse and temporal coherence, with ~10-6 – 10-7 bandwidth and excellent shot-to-shot stability
  - Fewer photons/pulse than SASE but similar brightness
- ***RAFEL*** is a high-gain FEL in a low-Q cavity
  - Intracavity power and optics heat loading reduced compared to XFELO
  - Can saturate in ~10 round trips so suitable for short-pulsed RF
  - Full coherence, with 10-4 bandwidth and good stability (not as good as XFELO)
  - SXR tuneable (broadband mirrors) & high pulse energy
  - MHz RAFEL more stable shot to shot than self seeded



Schematic of XFELO seeding an amplifier FEL

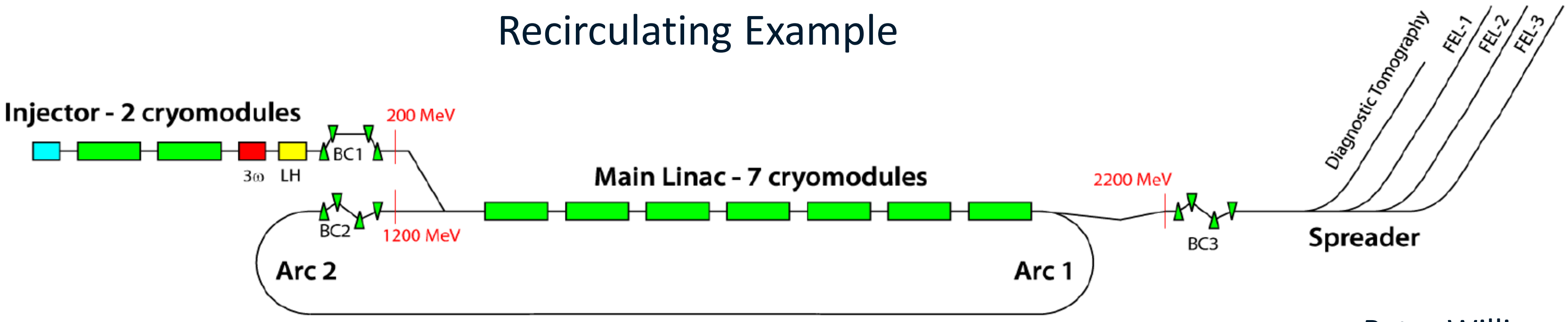


A VUV RAFEL designed for 4GLS

Repetition Rates

- Normal Conducting RF systems typically run at ~100Hz and ~1kHz is looking realistic
  - Lower accelerating gradients to keep average power manageable
- Superconducting RF systems can run CW and so can support ~MHz bunch rates with equally spaced bunches
  - CW operation increases electron energy stability and so timing stability
  - “Recirculation” can also be implemented– passing the beam through the linac more than once – cost effective & easier to extract intermediate energies
- “Energy Recovery” could follow which would allow increased rep rates (~10 MHz) if injector can support that

Recirculating Example



Peter Williams, STFC

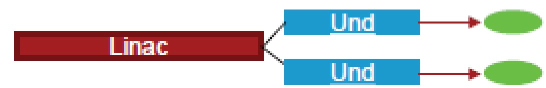
Increasing Facility Capacity

Multiplexing : more than 1 experiment by sharing same linac

SLAC

Performing more than 1 experiment by sharing the same linac

- **Sharing the Electrons**
  - Two undulators in parallel



    - e-beam switching with reduced rep-rate in each undulator

    Tanaka et al : demonstrated successfully at SACLA with BL3, BL2

  - Two undulators in tandem

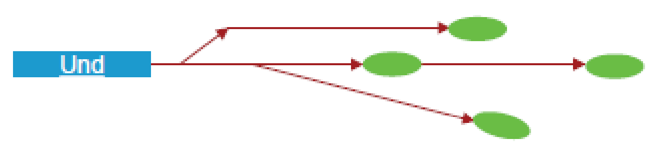
    - e-beam recycling

    Decking et al : demonstrated at Eu-XFEL with SASE 1 and 3

- **Sharing the X-rays**

(i.e. more than 1 experiment at a time from a single undulator)

  - Intermittent splitting & fast switching
  - Recycling the X-rays
  - Splitting
    - Spectral Splitting
    - Spatial Splitting



Robert Aymeric, SLAC, http://fls2018.vrws.de/talks/tha2wa01_talk.pdf

Our aim is to facilitate the widespread development of X-ray FEL facilities across Europe and beyond, by making them more affordable to construct and operate through an optimum combination of emerging and innovative accelerator technologies.

We plan to design a Hard X-ray Facility using the very latest concepts for:

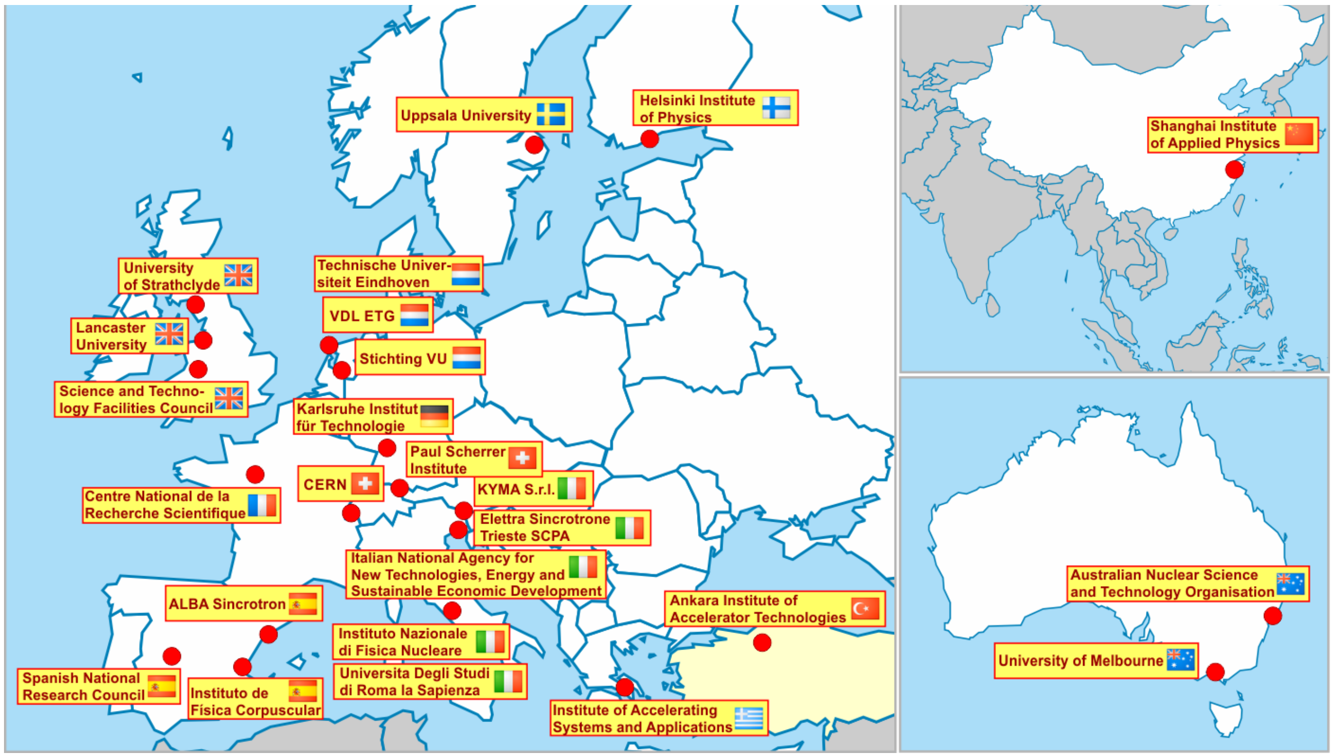
a. ***High brightness electron photoinjectors.***
b. ***Very high gradient accelerating structures.***
c. ***Novel short period undulators.***

The resulting Facility will benefit from:

i. *A **lower electron beam energy** than current facilities, due to the enhanced undulator performance.*
ii. *Will be **significantly more compact due to lower energy and high gradient structures.***
iii. *Will have a **much lower electrical power demand** than current facilities.*
iv. *Will have **much lower construction and running costs.***

Making X-ray FELs more affordable

CompactLight is made up of 24 Partners and it is led by Sincrotrone Trieste/FERMI@Elettra

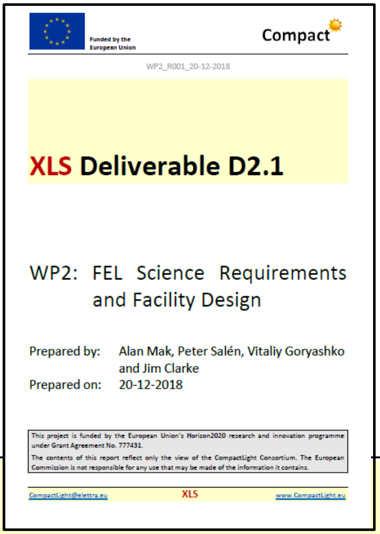


CompactLight is funded by the European Union's Horizon2020 research and innovation programme under Grant Agreement No. 777431.

CompactLight Facility Parameters

Table 1: Main parameters of the CompactLight FEL.

Parameter	Unit	Soft-x-ray FEL	Hard-x-ray FEL
Photon energy	keV	0.25 – 2.0	2.0 – 16.0
Wavelength	nm	5.0 – 0.6	0.6 – 0.08
Repetition rate	Hz	1000	100
Pulse duration	fs	0.1 – 50	1 – 50
Polarization		Variable, selectable	Variable, selectable
Two-pulse delay	fs	±100	±100
Two-colour separation	%	20	10
Synchronization	fs	<10	<10


Funded by the European Union

Compact

WP2_R001_20-12-2018

XLS Deliverable D2.1

WP2: FEL Science Requirements and Facility Design

Prepared by: Alan Mak, Peter Salén, Vitaliy Goryashko and Jim Clarke

Prepared on: 20-12-2018

This project is funded by the European Union's Horizon2020 research and innovation programme under Grant Agreement No. 777431.

The contents of this report reflect only the view of the CompactLight Consortium. The European Commission is not responsible for any use that may be made of the information it contains.

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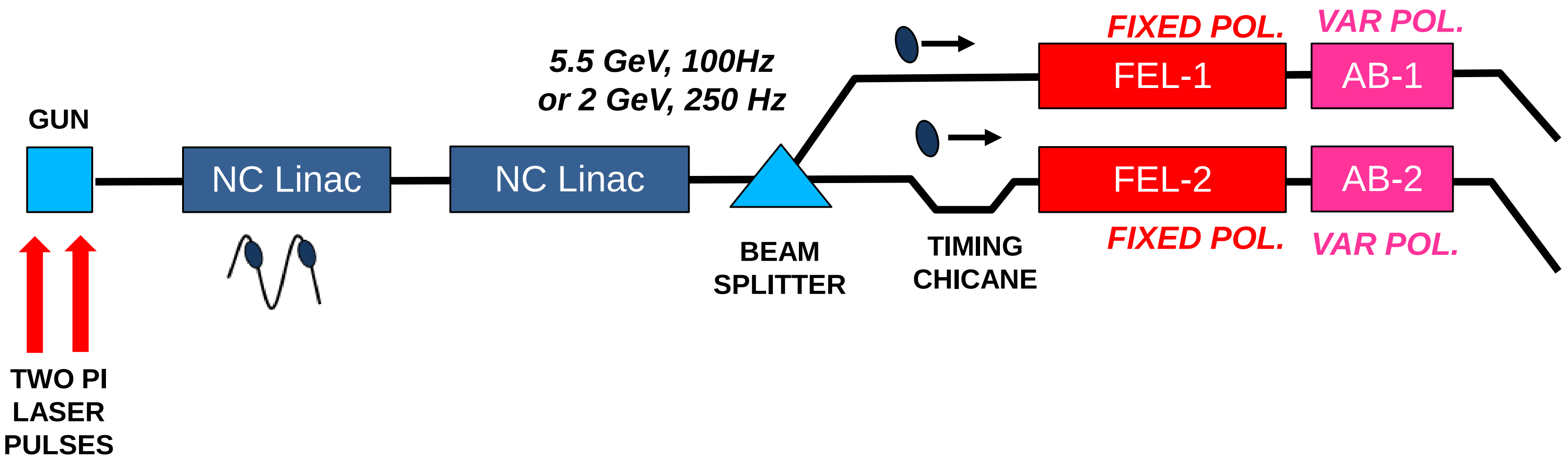
Report summarising facility specification available at http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-374175

CompactLight Core Facility Layout



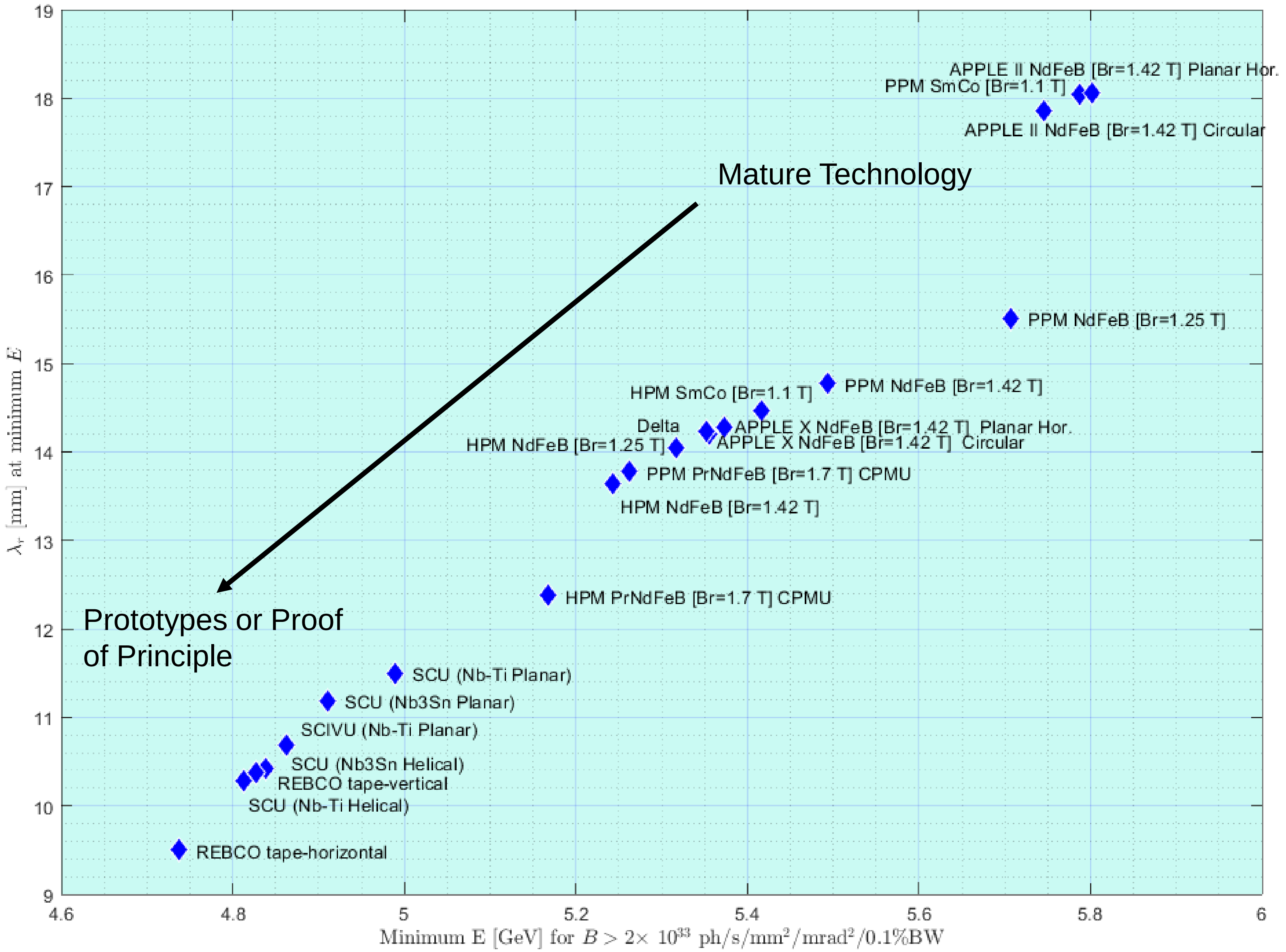
Notes

1. Maximum Energy **5.5 GeV** – lower than SwissFEL but can reach **16keV** cf 12 keV (because of ongoing advances in undulator technologies)
2. Polarisation set by afterburners
3. **Two bunches** per macropulse
4. Dual Mode – **high energy, low rep rate** or **low energy, high rep rate**
5. Can deliver **two hard X-ray pulses at 100Hz** or **two soft X-ray pulses at 250Hz – much greater control of individual pulse properties, wavelength and timing separation**
6. **Easy upgrade path to 1kHz for soft X-ray (up to 2keV) –** could be built in from the start
7. LCLS ~20MV/m linacs and ~110m undulator, CompactLight ~65MV/m linacs and ~30m undulator

Funded by the European Union

Undulator Comparisons

Compact



Plasma Accelerator based FELs?

- EuPRAXIA
  - The largest and most detailed design study yet of the potential for laser or beam driven plasma accelerators to support a FEL
    - Numerous plasma accelerator schemes and combinations have been modelled and compared
    - There is certainly the potential for the electron beam quality to be achieved to support FEL lasing – very challenging!
    - The collaboration is planning to build test facilities (budget 200 - 300MEuro) which will begin operations in 2030 to push this forward
    - If successful, FEL user facilities could possibly follow
- PWFA-FEL
  - A recent STFC grant (PI Bernhard Hidding, Strathclyde) to study if FELs can be made to match plasma accelerator output rather than forcing plasma accelerators to achieve "standard" FEL requirements
- Allow flexibility in future FEL facility designs for plasma accelerator "energy boosters" to higher beam energies and harder X-rays?

EuPRAXIA Objectives

EuPRAXIA is a conceptual design study for a 5 GeV electron plasma accelerator

1. Solve the **quality** problem. Demonstrate first **plasma accelerator technology applications**
2. Demonstrate **benefits in performance, size or cost** versus established RF technology for some applications

Note: EuPRAXIA initially is relatively **low power** and **low wall-plug power efficiency**

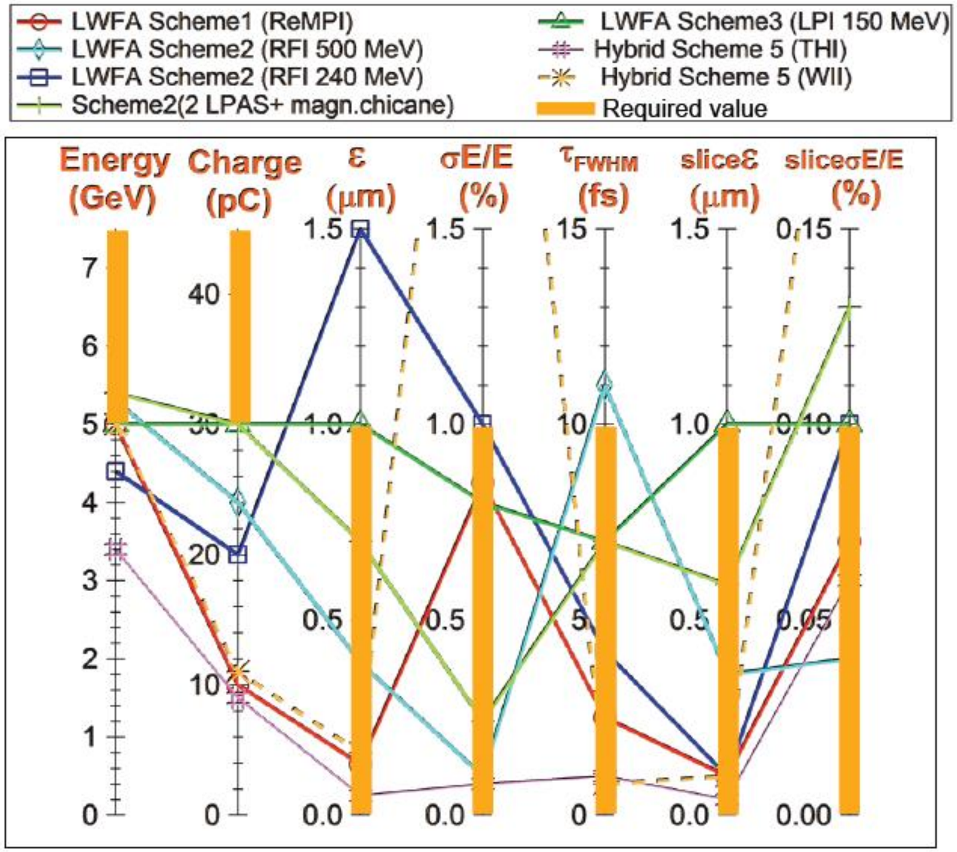
- Baseline (**10 Hz towards 100 Hz**): 10s of Watt average power with e.g. 1 mJ/photon pulse energy in a possible FEL pulse → **higher repetition rate allows high quality** with feedbacks. See e.g. also improvements in stability at LUX (A. Maier, UHH).
- Support **industry and expert laser institutes/projects** to improve rep. rate & efficiency (e.g. fiber-based lasers with 30 % efficiency, IZEST, LLNL approach, ELI, …) → Wim Leemans goals towards high average power lasers

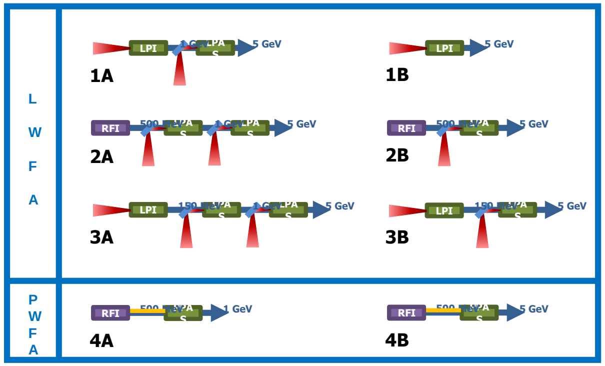
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

EuPRAXIA Project

- EuPRAXIA is a EU design study in its 4th year:
  16 beneficiaries and 25 associated partners (5 joined after start of project)
- **End Date for CDR: 31.10.2019**

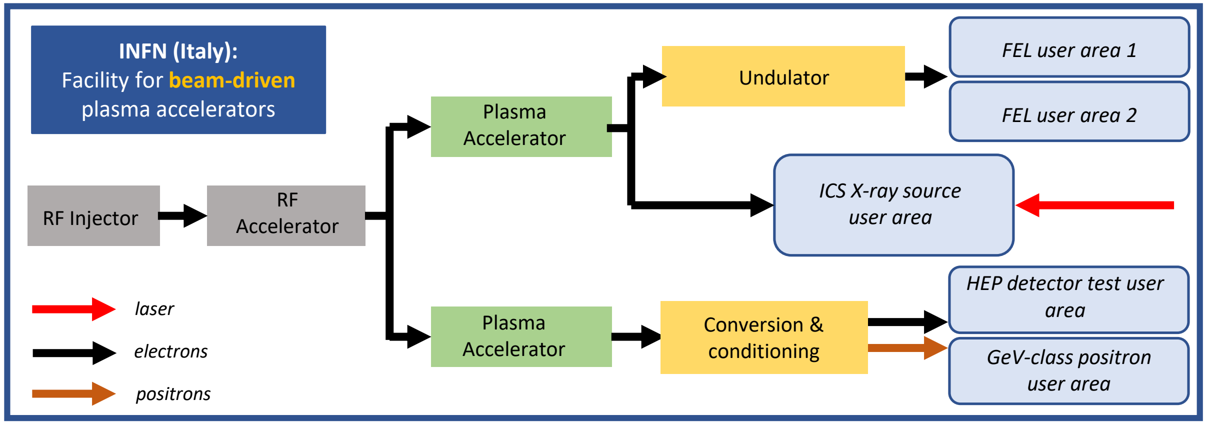
Achieving High Quality (5 GeV)

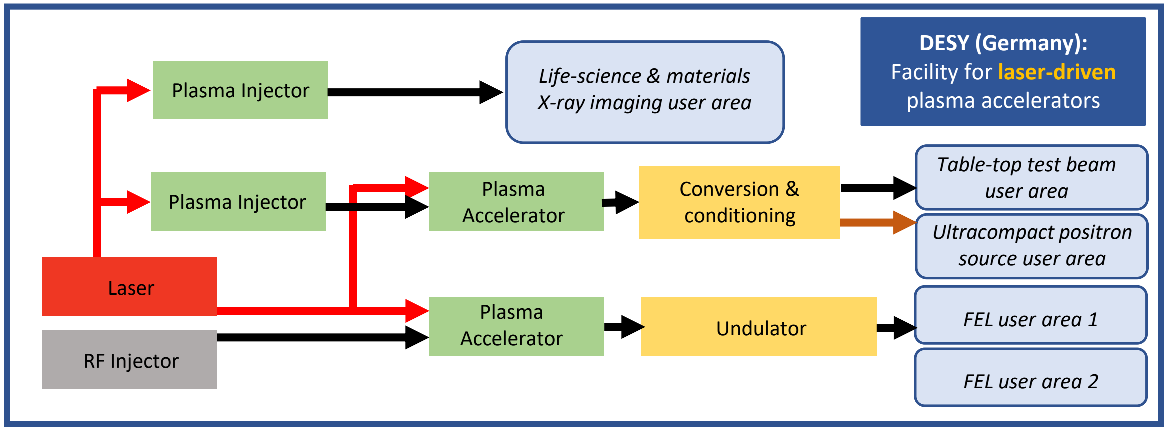




Phi Nghiem et al (WP2)

Beamline Layout and Beam Distribution





Current version of layout for Hamburg and Frascati machine sites

Credit: A. Walker

UK ACCELERATOR & FEL CAPABILITIES

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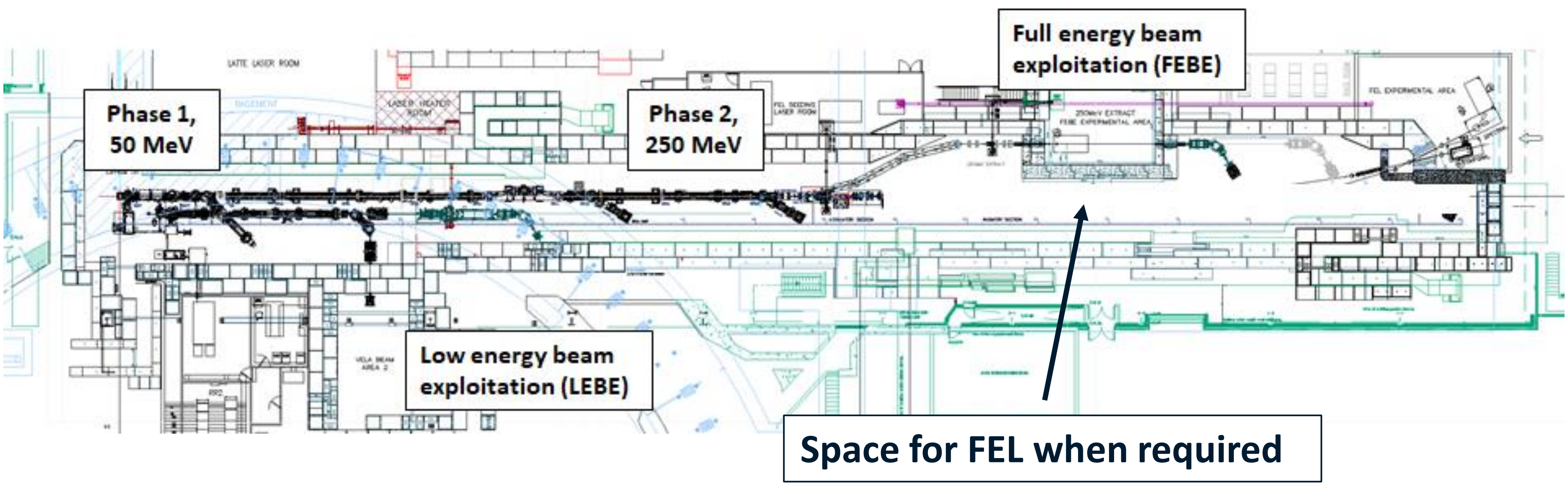
UK Accelerator Skills & Capabilities

- The UK has a very strong accelerator community with all the skills needed to design and build a world leading FEL facility
  - ASTeC, Cockcroft Institute, Diamond, John Adams Institute
- The UK accelerator community has been contributing to the development of FELs for many years and continues to do so
  - SwissFEL, FERMI, LCLS, Shanghai FELs, MAX IV SX FEL, Industrial EUV FEL, …
- We have been working jointly on an Underpinning FEL Programme for past three years
  - Filling skills gaps
  - Addressing generic key technological challenges
  - Developing advanced FEL concepts
- The UK also has a very strong plasma accelerator community so is well placed to benefit from this new technology in the future

CLARA

- CLARA is an "FEL ready" Accelerator Test Facility at Daresbury
  - All the leading FEL projects have built a similar test facility
  - We can rapidly implement an FEL for crucial tests of concepts when needed as part of any UK XFEL project
  - We are already enhancing our skills in key areas
    - Photoinjectors, photocathodes, fs synchronisation, RF stabilisation, single shot diagnostics, full system stability, collective beam effects, X-band RF, ...
  - Phase 1 is operational now
  - Phase 2 will be installed in 2021 – ready for FEL



Summary

- FELs have shown themselves to be extremely flexible in their pulse properties and upgradeability
  - For example, LCLS have implemented numerous science driven improvements since first lasing, achieving outputs that weren't even thought of whilst the facility was being constructed
- There is no sign that the flexibility of FELs has reached any sort of limit as yet
  - There are limits on what can be provided *simultaneously*
  - Any UK XFEL must be flexible by design and have an eye on potential future upgrades
- During this Science Case Exercise it would be extremely helpful to understand your FEL output *priorities* and any requests for, as yet, undemonstrated capabilities
  - This would help stimulate and focus our attention on your "cutting edge"
  - Combining FEL output with other "beams"?
  - Please, don't limit your requests to what you know to be possible!

Acknowledgements

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- Thanks also to Peter Williams and Brian McNeil for their input

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Accelerators in a new light

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ASTeC