Science & Technology Facilities Council

Next Generation Light Sources

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ASTeC

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The Cockcroft Institute of Accelerator Science and Technology

OPAC

Motivation

- **3rd generation light sources (3GLS) provide scientists with access to intense, stable, tuneable, monochromatic, light across a very broad spectral range (THz to X-ray)**
- The science that has become possible since 3GLS came on stream is ***dazzling*** in its breadth and reach
- **The impact of this science is clear simply by counting the Nobel prizes that have been awarded …**

The Impact of X-Rays on Science

21 Nobel Prizes so far for X-rays

1901 Rontgen (Physics)

1914 von Laue (Physics)

1915 Bragg and Bragg (Physics)

1917 Barkla (Physics)

1924 Siegbahn (Physics)

1927 Compton (Physics)

1936 Debye (Chemistry)

1946 Muller (Medicine)

1962 Crick, Watson & Wilkins (Medicine)

1962 Perutz and Kendrew (Chemistry)

1964 Hodgkin (Chemistry)

1976 Lipscomb (Chemistry)

1979 Cormack and Hounsfield (Medicine)

1981 Siegbahn (Physics)

1985 Hauptman and Karle (Chemistry)

1988 Deisenhofer, Huber & Michel (Chemistry)

1997 Boyer and **Walker** (Chemistry)

2003 Agre and Mackinnon (Chemistry)

2006 Kornberg (Chemistry)

2009 Yonath, Steitz & **Ramakrishnan** (Chemistry)

2012 Lefkowitz and Kobilka (Chemistry)

These last 5 all used synchrotron radiation,
2 of them used the SRS at Daresbury

4^{th} Generation Light Sources

- **Since 3GLS are so successful, what more could a 4GLS possibly offer?**
- The most significant feature of 4GLS is the increase in the intensity of the light – more photons on the sample!
- *This enables scientists to attempt experiments on samples which would otherwise not give a usable signal – maybe they are too dilute or too small*
- Typically
  - **3GLS ~ 10^6 photons per pulse**
  - **4GLS ~ 10^{12} photons per pulse**
- Can take a diffraction pattern in a single shot, for example
- The second major advantage is the reduced duration of the photon pulses
- Typically
  - **3GLS ~ 10 ps (sub-ps in special operating modes)**
  - **4GLS ~ 10 fs already demonstrated but in principle schemes already exist for <100 as for single pulses of even sub-as for pulse trains (zeptoseconds!)**
- *This enables scientists to attempt experiments which have previously been impossible – watching the fastest of chemical reactions, for example (molecular movies!)*

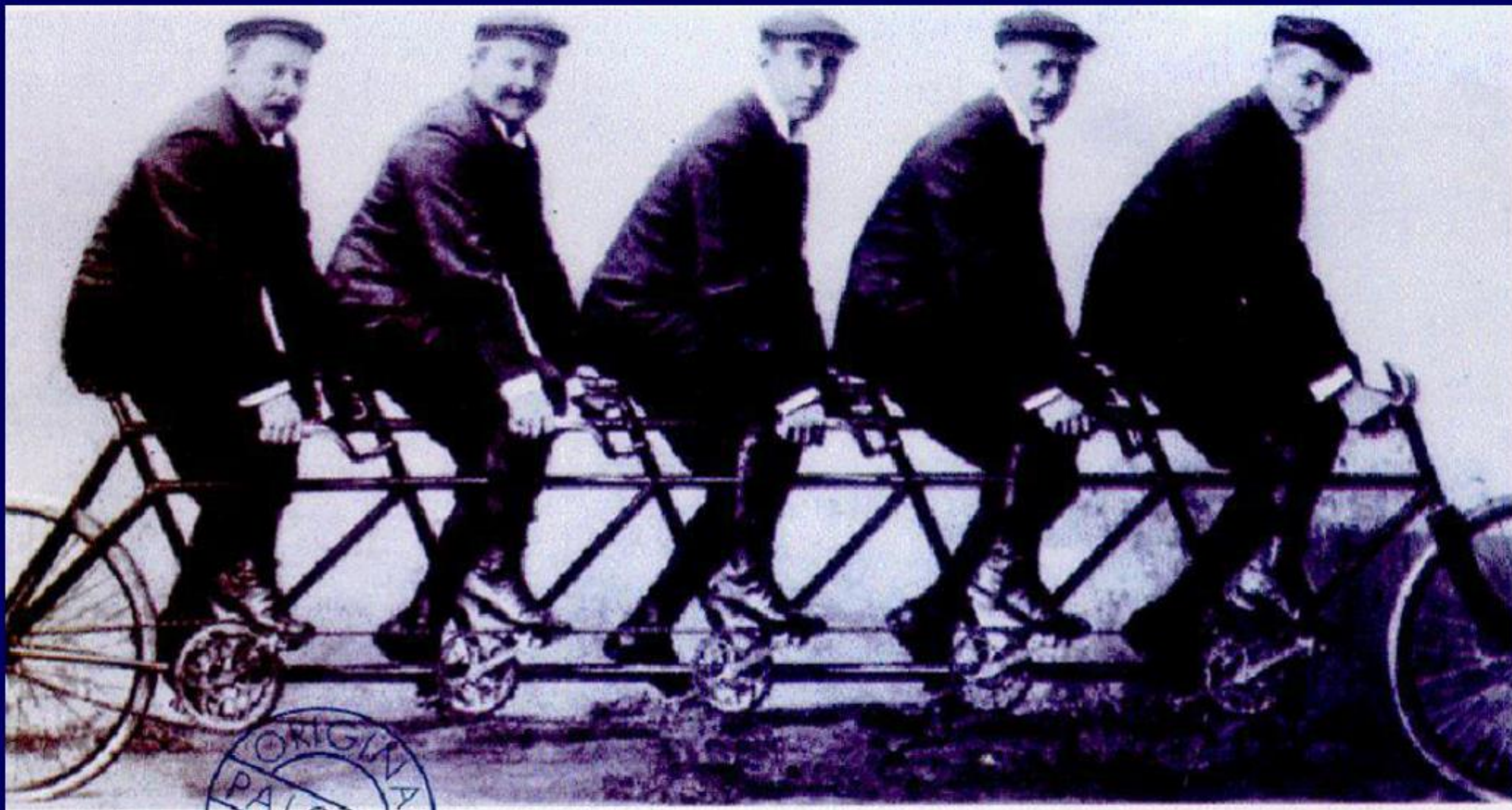
Free Electron Lasers

- 4th generation light sources are based upon **free electron lasers** (FELs)
  - These are devices which use relativistic electron beams and undulators similar to 3GLS
  - But, they are able to make the light emitted ***COHERENT*** – the output is proportional to the **square** of the number of electrons
  - They have the advantage over conventional lasers of being able to emit at any wavelength like 3GLS – including X-rays!

Coherent Emission

- If the emitting electron bunch is shorter in length than the wavelength emitted then the output intensity is proportional to the number of electrons **SQUARED**
- In a 3GLS this condition is not met (except at very long millimetre wavelengths) since electron bunches are typically 10 ps long
- If you want to emit coherently at say 12 keV (~0.1nm) then need electron bunch to be shorter than 0.3 attoseconds!
- It is not possible to generate such short relativistic bunches in an accelerator directly but it is possible to **generate them indirectly** – this is what the FEL does
- The FEL takes an electron bunch and manipulates it such that it forms discrete periodic **microbunches** within it that are shorter than the wavelength emitted and are separated by that wavelength

Coherent action is what counts …



What is an FEL?

A beam of relativistic electrons

co-propagating with

an optical field

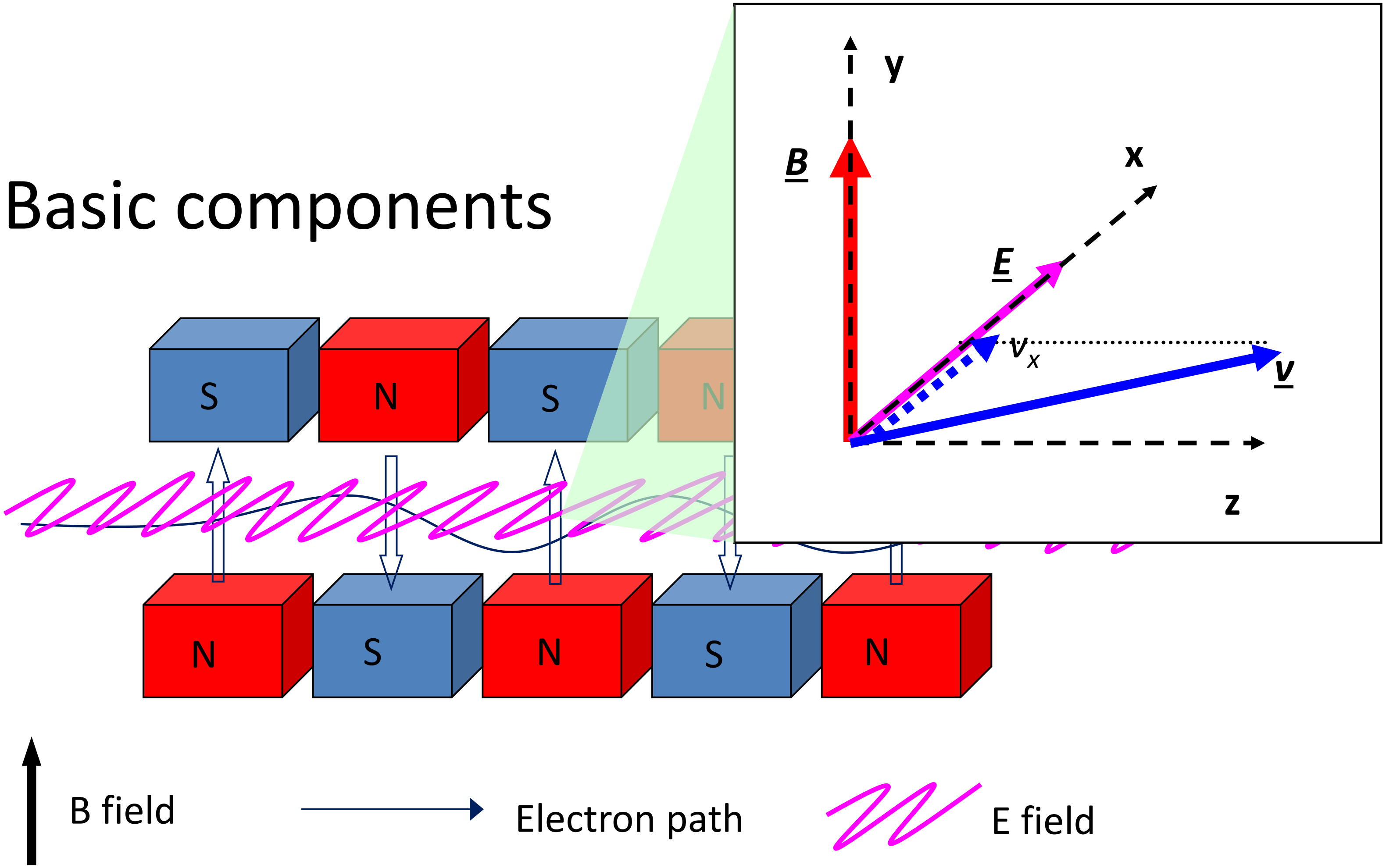
through

a spatially periodic magnetic field

- Undulator causes transverse electron oscillations
- Transverse e-velocity couples to E-component (transverse) of optical field giving energy transfer.
- Interaction between electron beam and optical field causes microbunching of electron beam on scale of radiation wavelength leading to coherent emission

How does an FEL work?

- Basic components



How does an FEL work?

– **Basic physics: Work = Force x Distance**
  - **Sufficient to understand basic FEL mechanism**
  - **Electric field of light wave gives a force on electron and work is done!**

$$\triangle W = -e \int \mathbf{E} \cdot \mathrm{ds} = -e \int \mathbf{v} \cdot \mathbf{E} \mathrm{d}t$$

– **No undulator = No energy transfer**
  i.e. If electron velocity is entirely longitudinal then v.E = 0

– Basic mechanism very simple!!

How does an FEL work?

- Basic mechanism described explains energy transfer between SINGLE electron and an optical field.

But in practice need to create right conditions for:

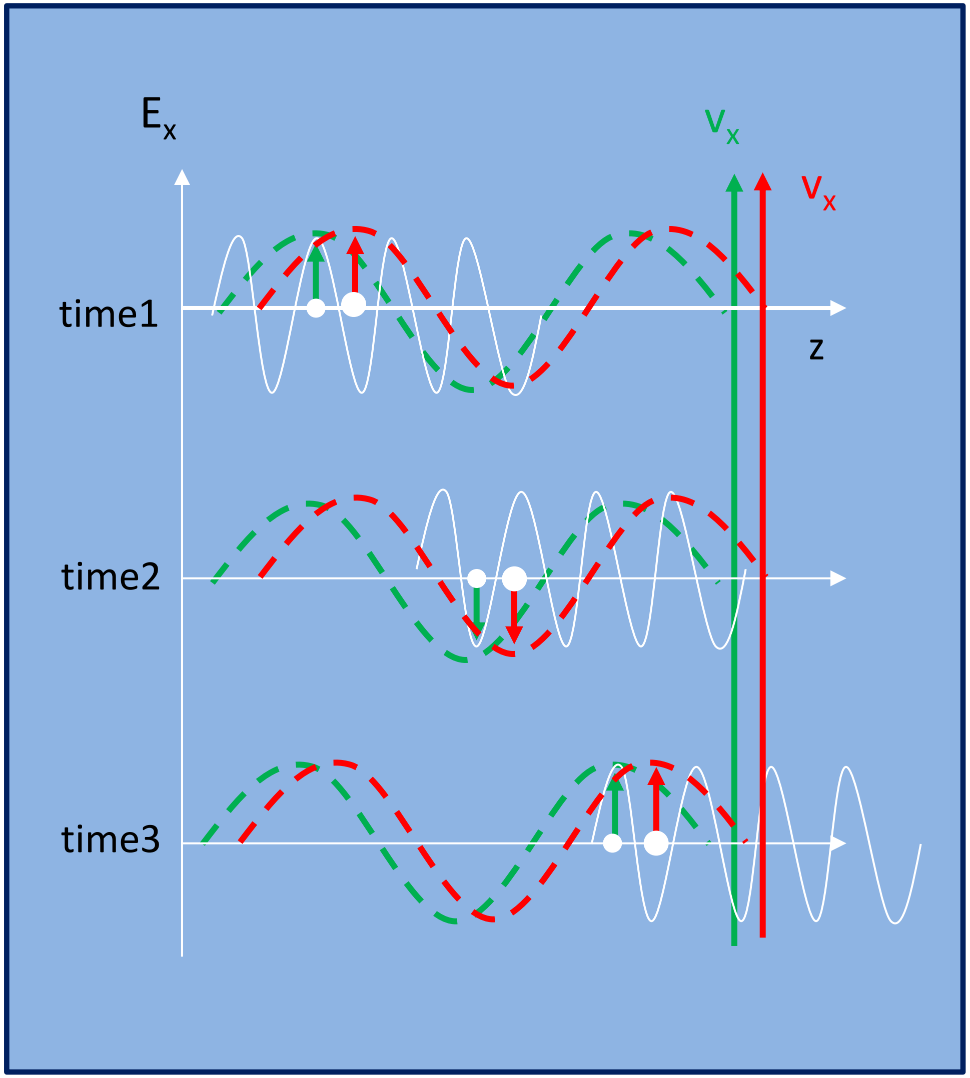
CONTINUOUS energy transfer

in the **RIGHT DIRECTION**

with a **REAL ELECTRON BEAM**

How does an FEL work?

- **Q**. Which way does the energy flow?
- **A**. Depends on electron phase
  - Depending on phase, electron either:
    - Loses energy to optical field and decelerates: **GAIN**
    - Takes energy from optical field and accelerates: **ABSORPTION**



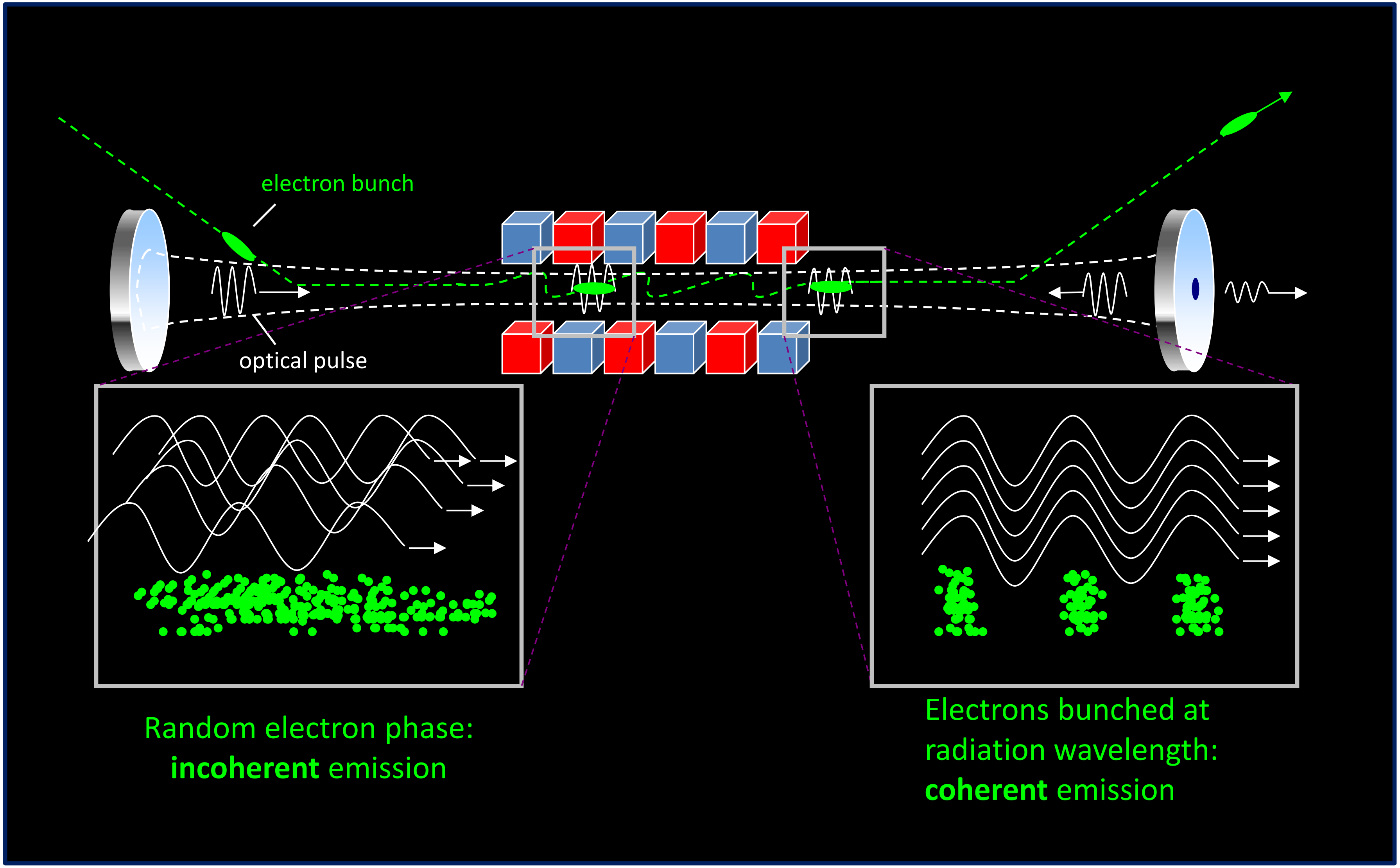
Types of FEL

- **AMPLIFIER (HIGH GAIN) FEL**
  - Commonly called Self Amplified Spontaneous Emission (**SASE**)
  - Long undulator
  - Spontaneous emission from start of undulator interacts with electron beam.
  - Interaction between light and electrons grows giving microbunching
  - Increasing intensity gives stronger bunching giving stronger emission
  - >>> High optical intensity achieved in **single pass**
  - Note, SASE is basic mechanism, there are numerous enhancements applied to improve output (e.g. seeding, harmonic jumping, HB-SASE, …)

- **OSCILLATOR (LOW GAIN) FEL**
  - Short undulator
  - Spontaneous emission trapped in an optical cavity
  - Trapped light interacts with successive electron bunches leading to microbunching and coherent emission
  - >>> High optical intensity achieved over **many passes**

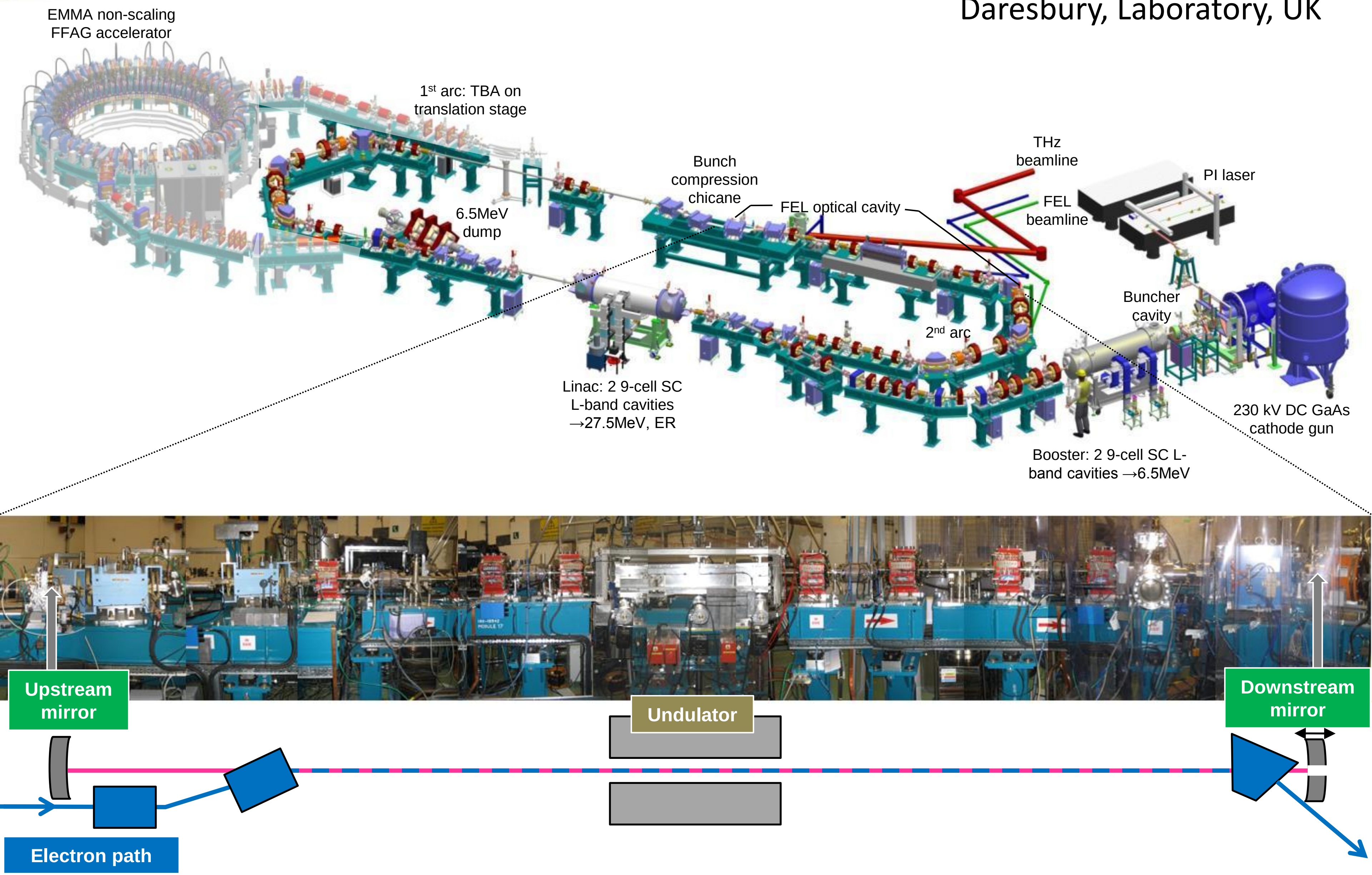
The Oscillator FEL

First demonstrated in 1977 at Stanford

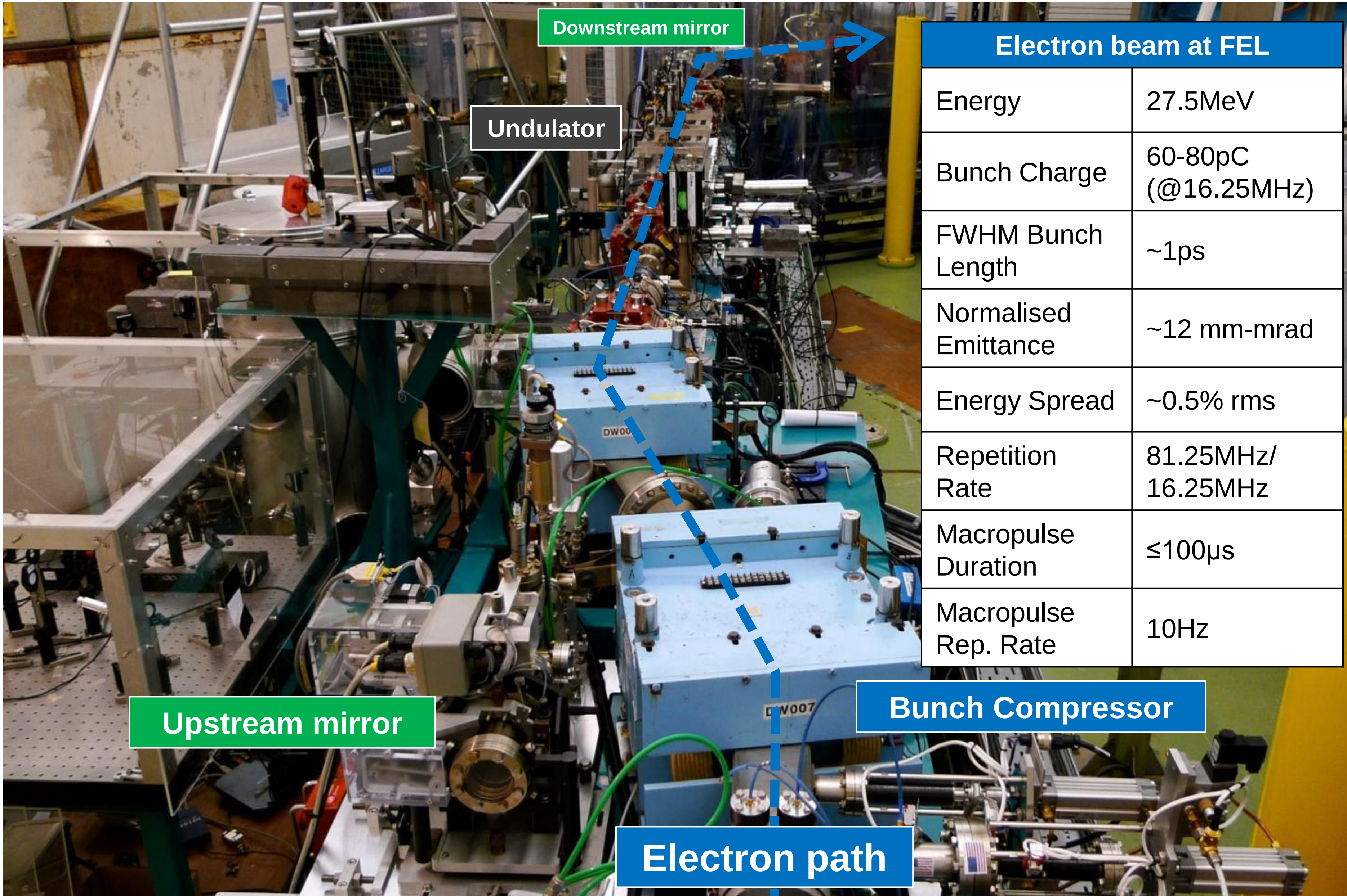


Example: ALICE accelerator and FEL

Daresbury, Laboratory, UK



Electron Beam

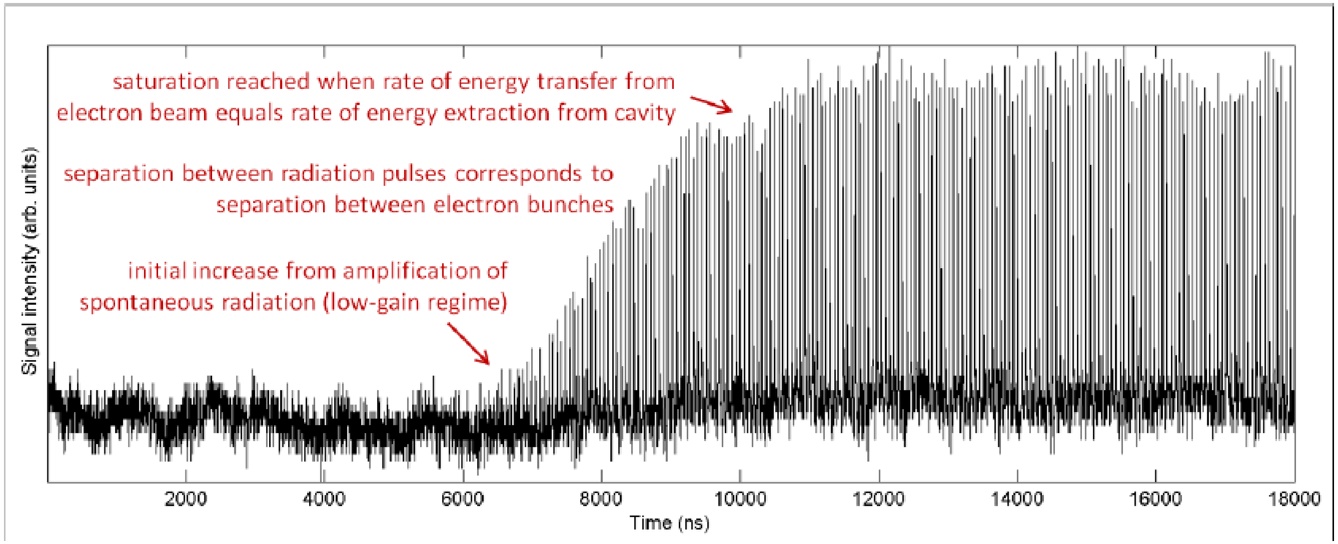


Electron beam at FEL	
Energy	27.5MeV
Bunch Charge	60-80pC (@16.25MHz)
FWHM Bunch Length	~1ps
Normalised Emittance	~12 mm-mrad
Energy Spread	~0.5% rms
Repetition Rate	81.25MHz/ 16.25MHz
Macropulse Duration	≤100μs
Macropulse Rep. Rate	10Hz

How the FEL Ouput Builds Up in ALICE

The time structure of the FEL output can be observed using a fast detector.

Each machine pulse of 100 μs contains 1625 bunches.



By fitting the exponential rise in intensity, it is possible to estimate the gain.

FEL emits over wavelength range ~6 to ~12 μm (infra- red) – user chooses wavelength

The Oscillator FEL

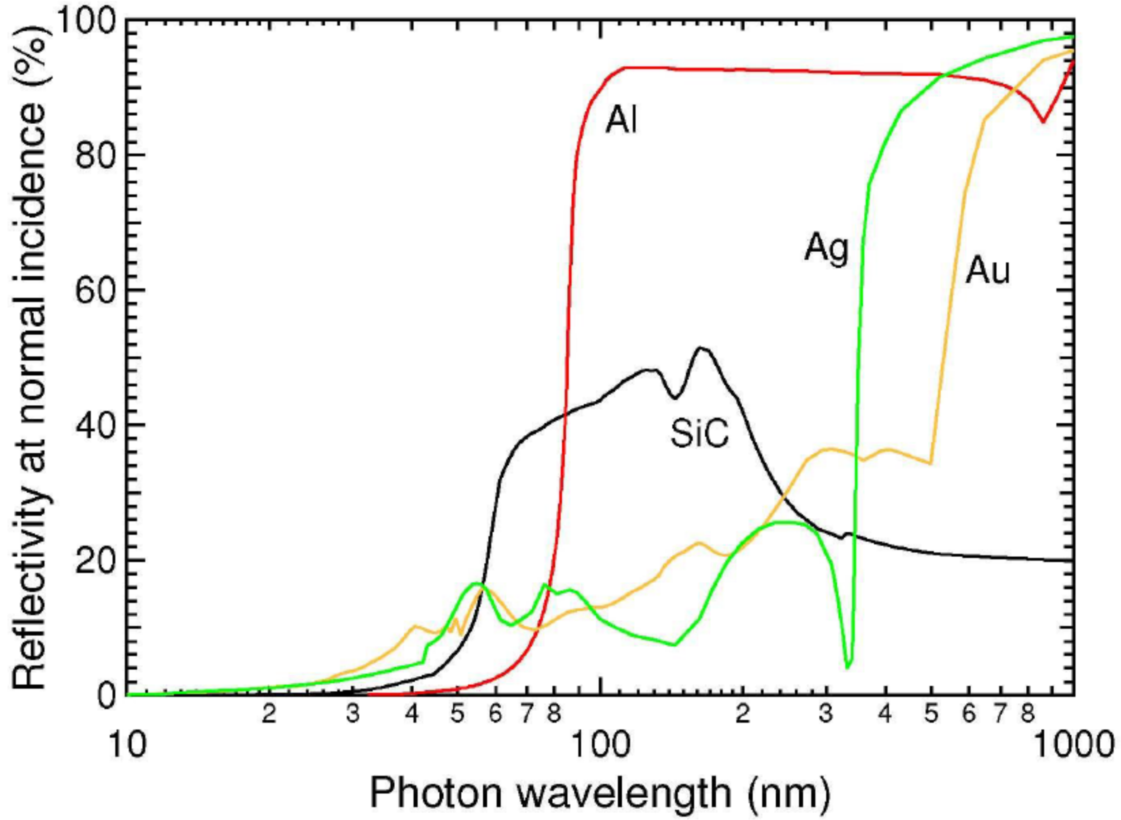
- For oscillator FEL the single pass gain is small.
- The emitted radiation is contained in a resonator to produce a FEEDBACK system
- Each pass the radiation is further amplified
- Some radiation extracted, most radiation reflected
- **Increasing** cavity intensity **strengthens interaction** leading to **exponential growth**:

$$\triangle W = -e\int \mathbf{E}\cdot \mathrm{d}\mathbf{s} = -e\int \mathbf{v}\cdot \mathbf{E}\mathrm{d}t$$

Energy transfer depends on **cavity intensity**

Oscillator FELs Need Mirrors !

An optical cavity is no longer possible for wavelengths below 100 nm



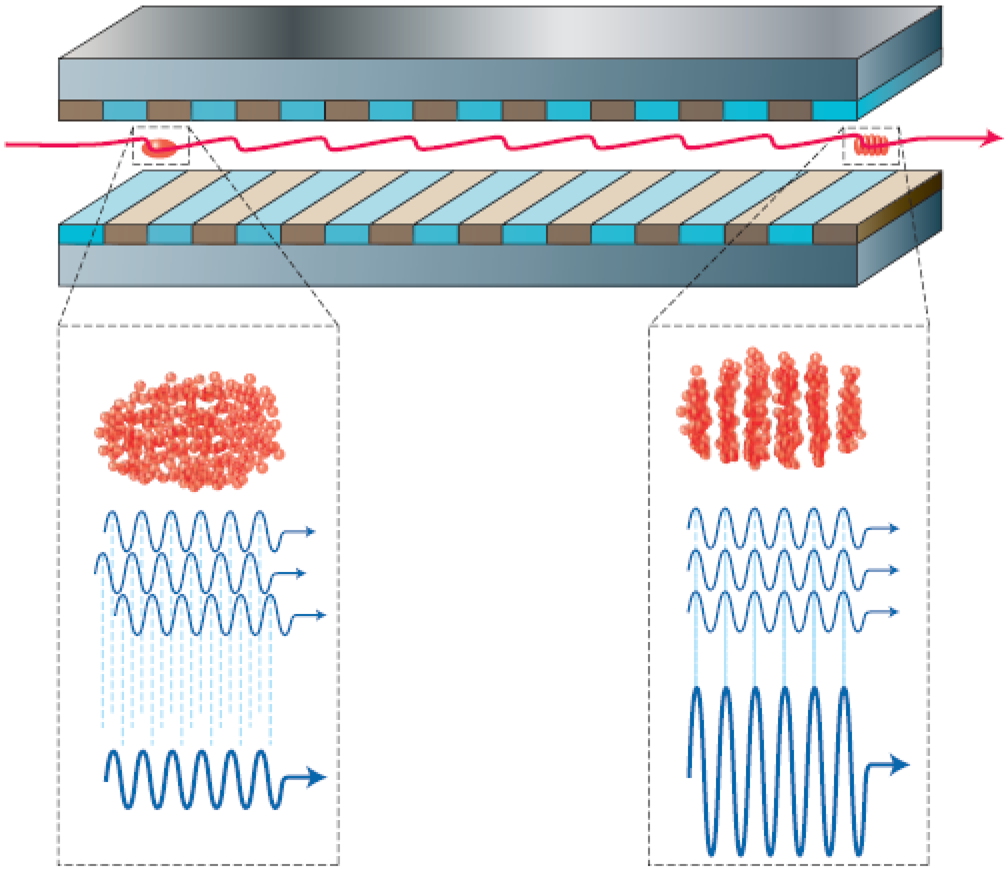
High Gain (Amplifier) FEL

- No optical cavity / feedback
- Relies on growth of microbunching from shot noise
- Requires very long undulator(s)
- Essential for short-wavelength FELs (XFELs)
- Need to have ultra-precise control of electron beam emittance, size and position

X-Ray FELs Are Big !

Undulators Are Long !

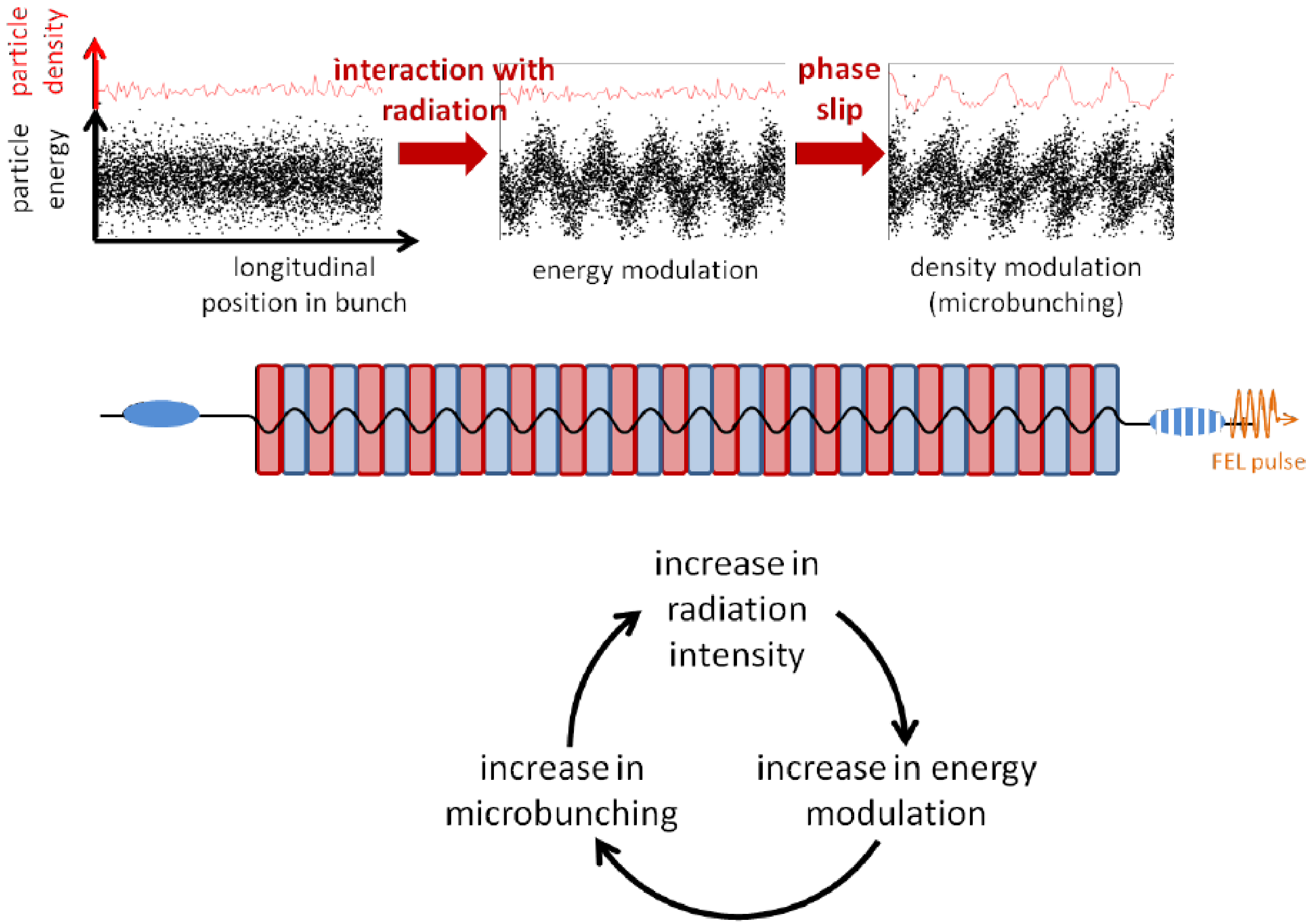
FEL Process (SASE)



Incoherent emission:
electrons randomly phased

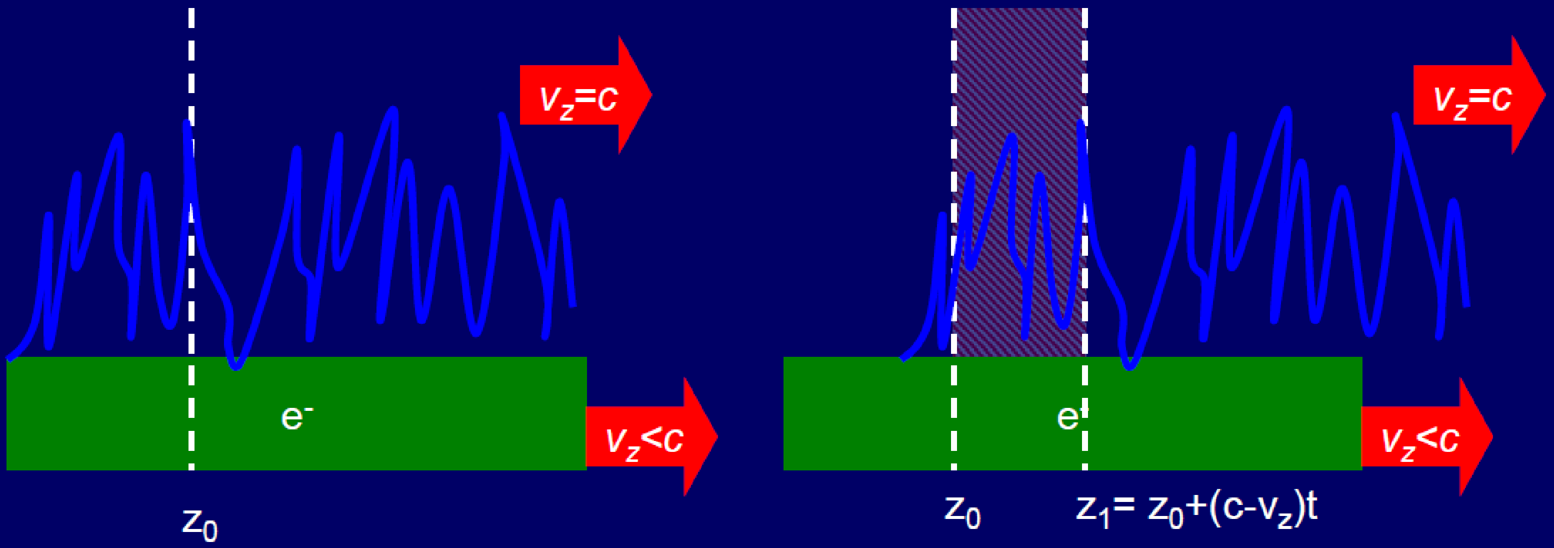
Coherent emission:
electrons bunched at
radiation wavelength

FEL Process (SASE)



Coherence Length

FEL pulses starting from noise in a High-Gain amplifier (SASE)



Many regions of radiation pulse evolve independently from other regions

SASE FEL Output Is Noisy

Self Amplified Spontaneous Emission (SASE) in the X-ray regime

SASE Power output | **SASE spectrum**

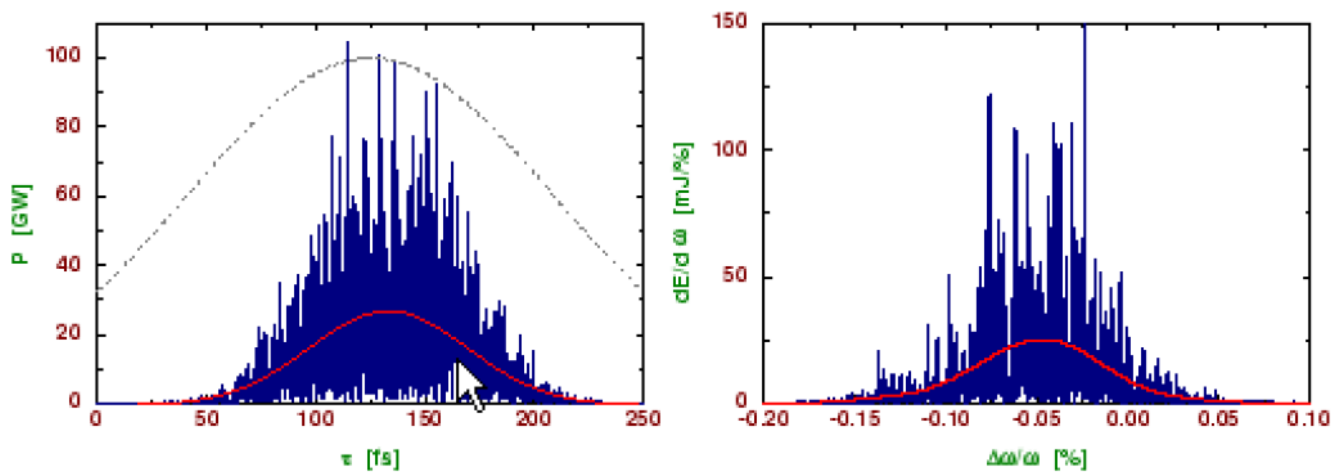
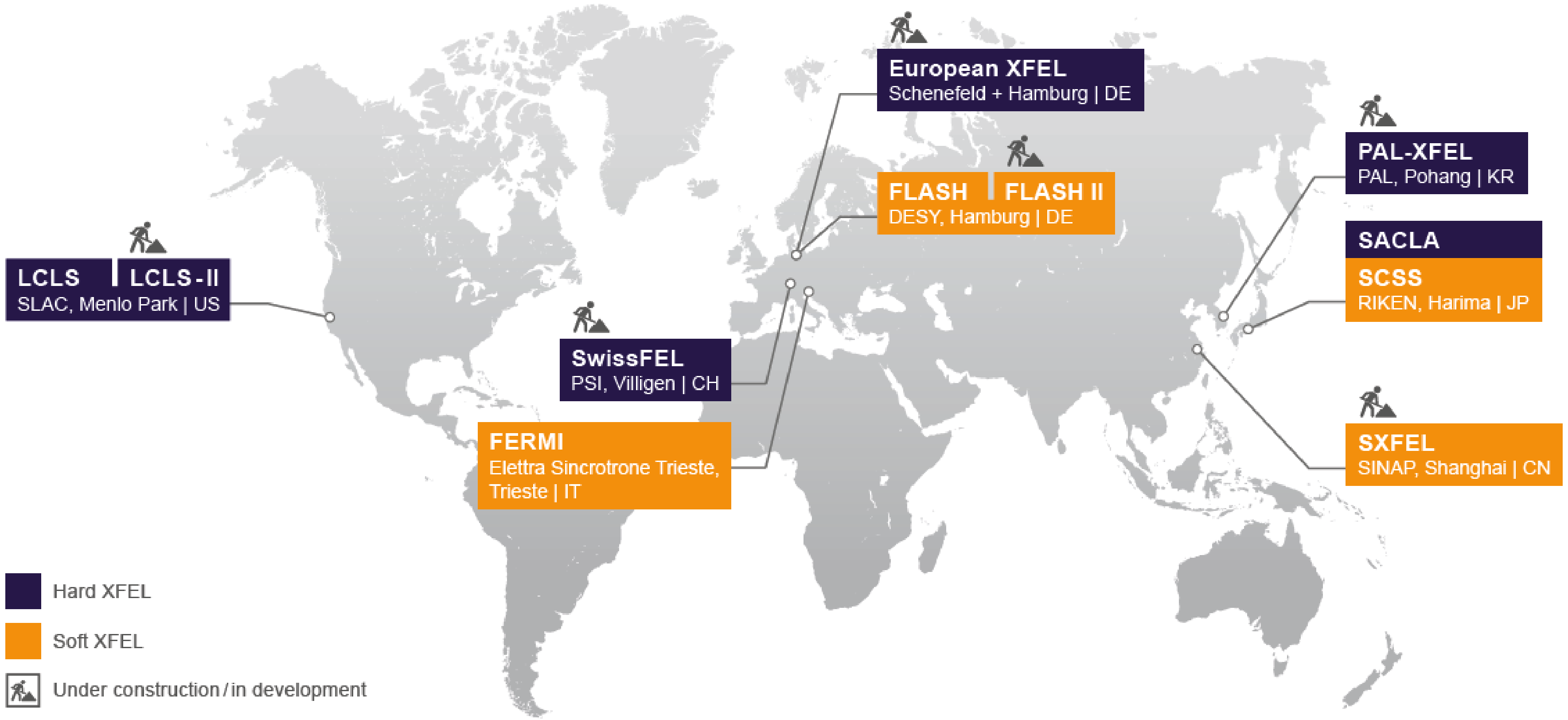


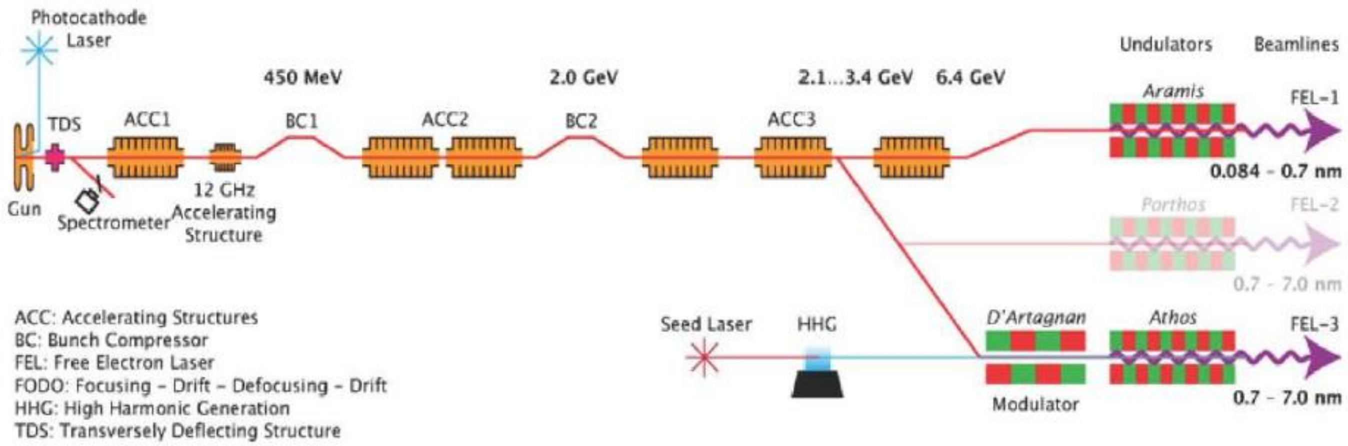
Figure 5: Typical temporal (left) and spectral (right) structure of the radiation pulse from a SASE XFEL at a wavelength of 1Å. The red lines correspond to averaged values. The dashed line represents the axial density profile of the electron bunch. Note that the growth rate in the electron bunch tail is reduced due to the reduced current. Therefore, the radiation pulse length of 100fs (FWHM) is about a factor of two shorter than the electron bunch.

SASE FELs Around the World

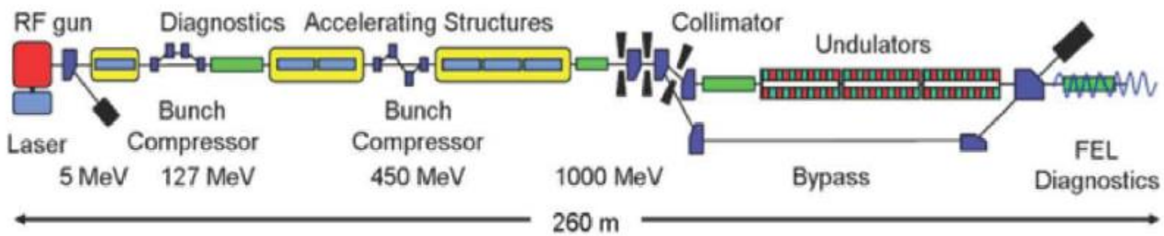


Schematic SASE FEL Layouts – Always Based on Linacs

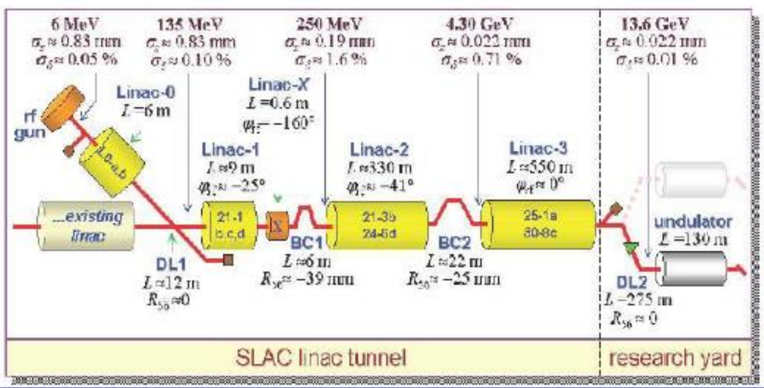
- SwissFEL



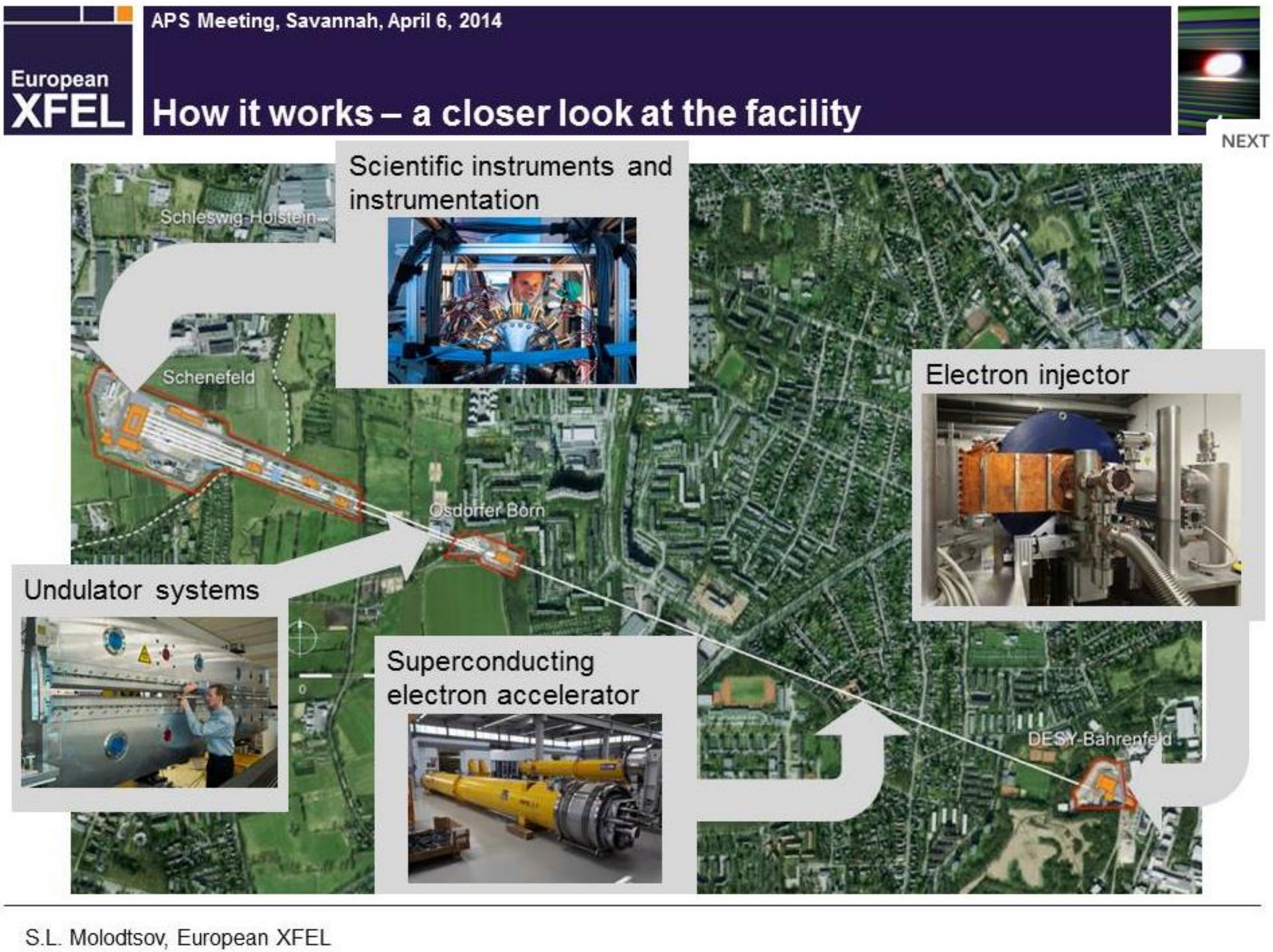
- FLASH



- LCLS

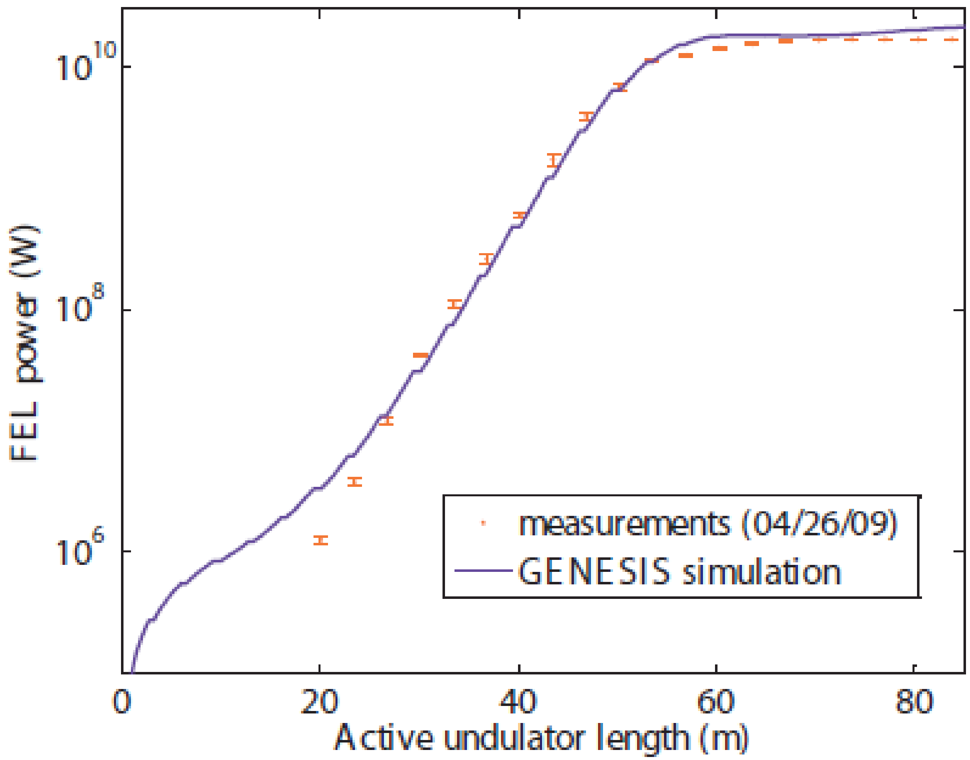


European XFEL



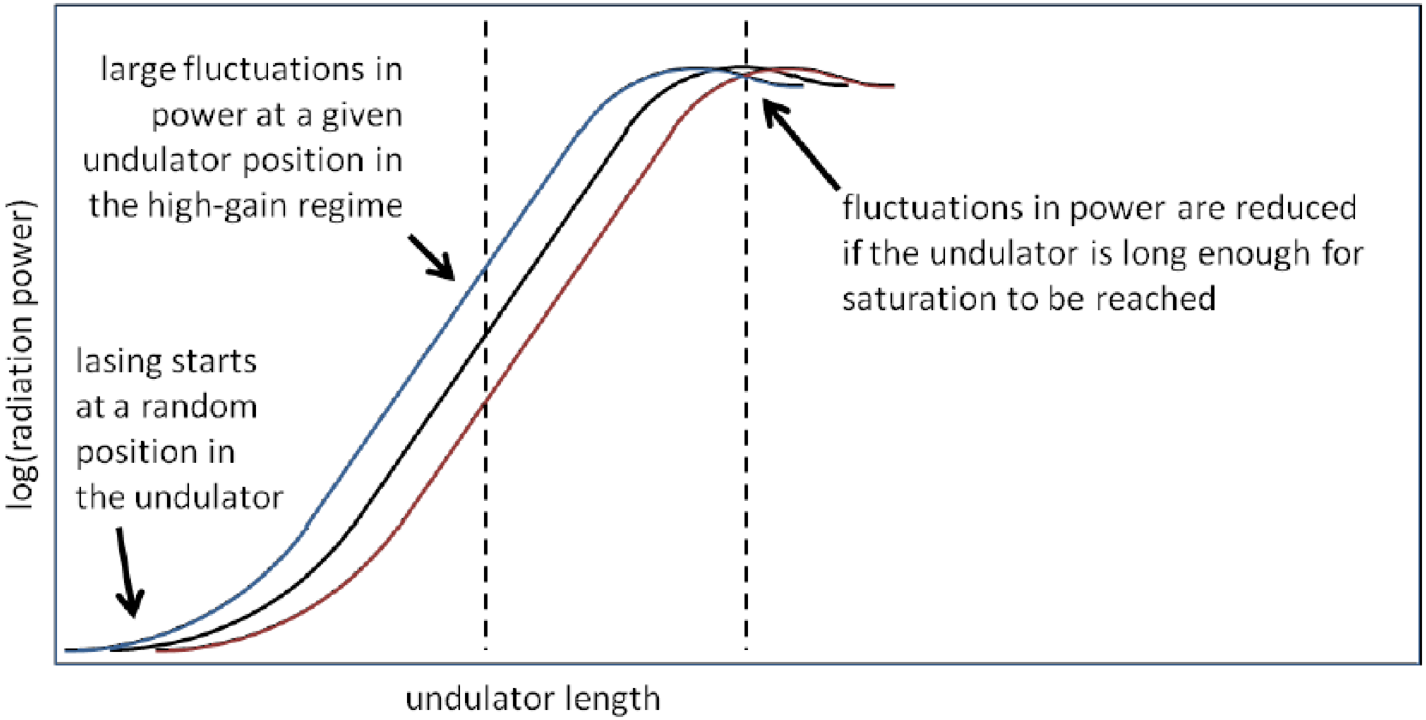
LCLS Power vs FEL Length

- ***Measured*** FEL power vs Undulator Length (log scale)



Saturation

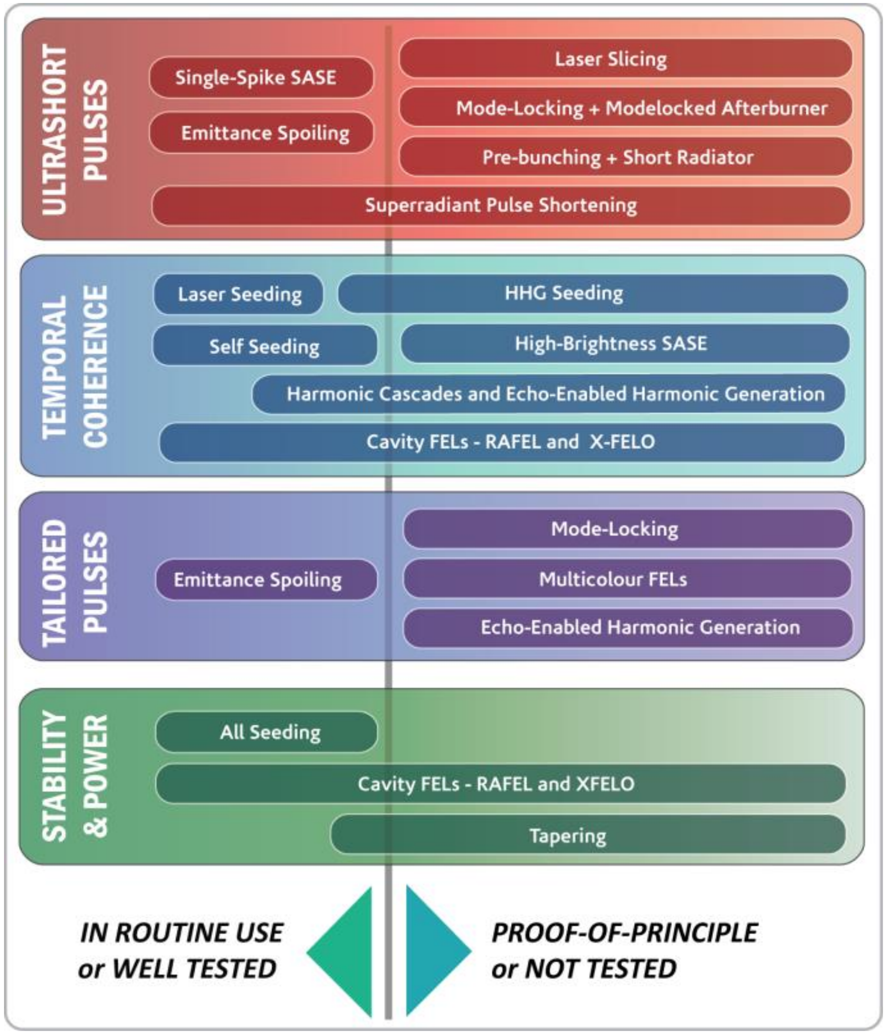
Since the radiation in a SASE FEL grows from random fluctuations in the beam density, it is difficult to control the point in the undulator at which the beam enters the high-gain regime. This means that to minimise fluctuations in output power, it necessary to build the undulator long enough for the power to reach saturation – and no shorter!



FELs – What Next?

- **FELs have made huge advances in the past few years**
  - First X-ray FEL in 2009 (LCLS) then SACLA in 2011
  - More X-ray facilities are under construction
  - Advanced soft X-ray facilities are also now operating routinely for users as well (SCSS, FLASH & FERMI)
- **The potential for improvements is enormous**
  - Better temporal coherence (monochromaticity)
  - Better wavelength stability
  - Increased power
  - Better intensity stability
  - Much shorter pulses of light
  - Two-colour or Multi-colour output
  - …

The Case for an FEL Test Facility

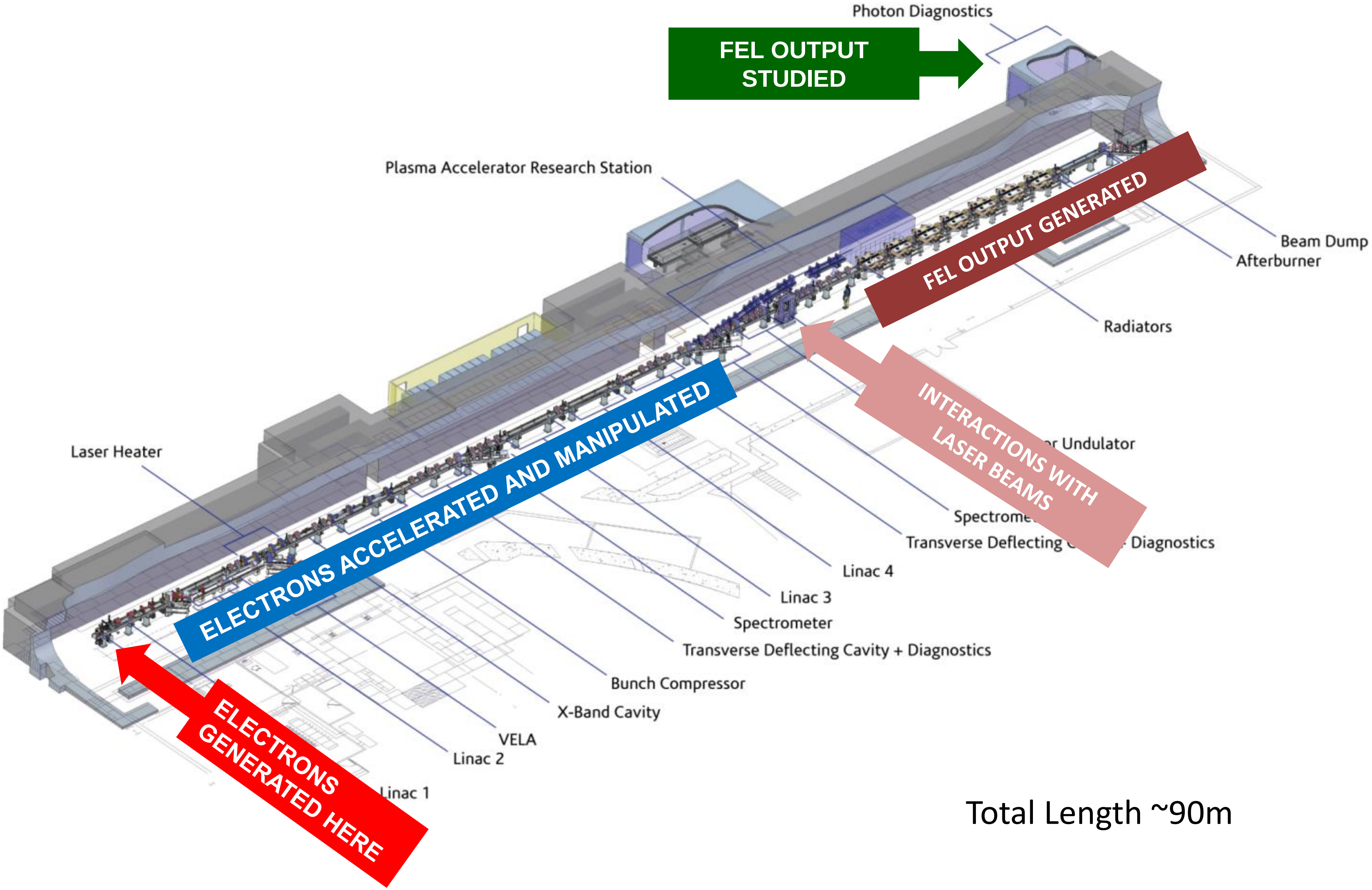


- FELs are remarkable scientific tools
- There are still many ways their output could be improved:
  - ***Shorter Pulses***
  - ***Improved Temporal Coherence***
  - ***Tailored Pulse Structures***
  - ***Stability & Power***
- There are many ideas for achieving these aims, ***but many of these ideas are untested***
- Most FELs have users and little time for R&D – too much demand from users !

CLARA

- **The UK accelerator & light source community has proposed that Daresbury hosts a new dedicated flexible FEL Test Facility**
  - Capable of testing the most promising new schemes
- **CLARA is strategically targetted at ultra short pulse generation**
  - We are looking at the longer term capabilities of FELs, not short term incremental improvements
  - Taking FELs into a new regime
  - By demonstrating this goal we will have to tackle all the challenges currently faced by state of the art FELs (and a few more!)

CLARA Layout



Total Length ~90m

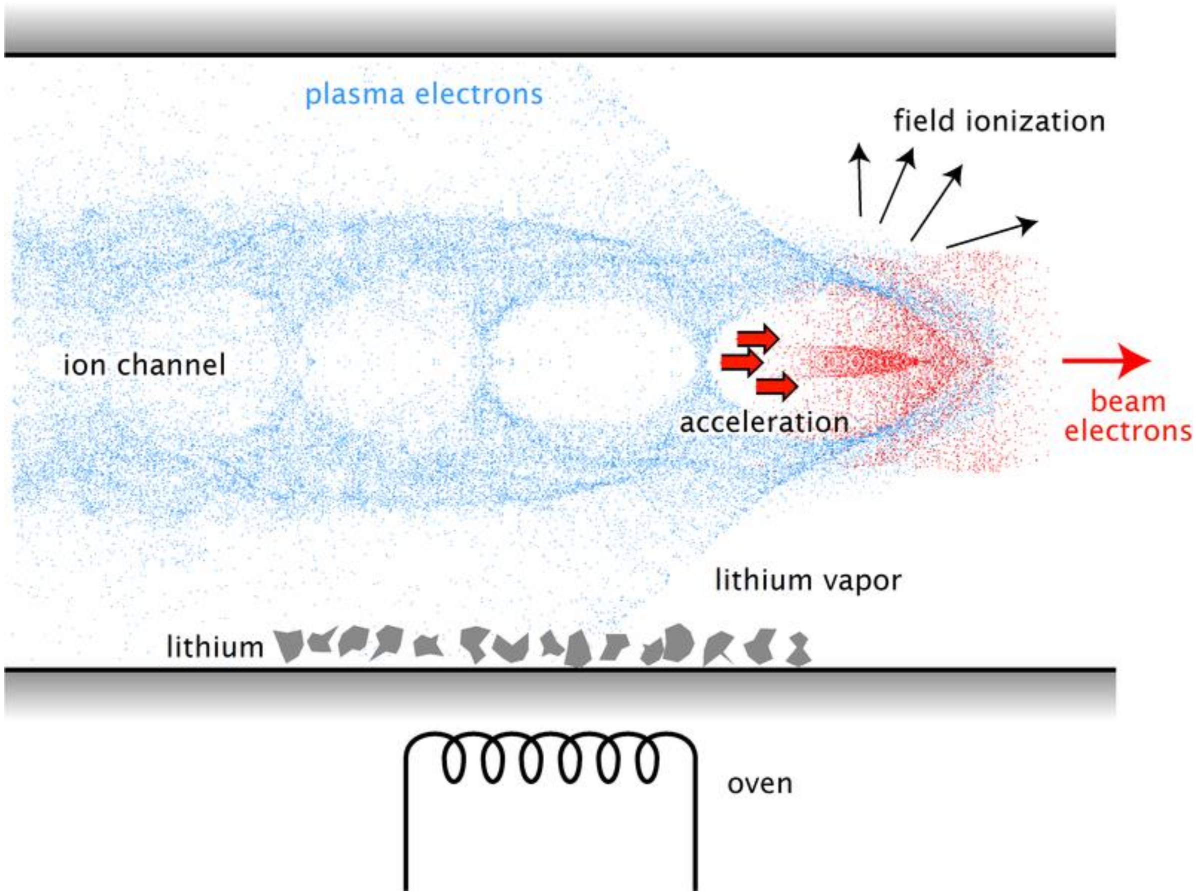
Beyond 4GLS

- The next major change in light source technology (5GLS?) looks more likely to come from a shift in **accelerator technology** rather than a new method of light production
- There are several novel methods under investigation for accelerating charged particle beams **without the need for RF cavities**
- The trick is to transfer energy from the ‘source’ to the ‘beam’ efficiently
- The ‘source’ of the future could be an **intense laser** or another **beam of particles** rather than an RF power source and accelerating cavity

Acceleration with a Laser

- The alternative accelerator which has received the most attention so far is driven by a laser – **Laser Wakefield Accelerator (LWFA)**
- Another option is similar but instead of using a bunch of photons it uses a bunch of electrons (or even protons) - **PWFA**
- The long term motivation for LWFA is generally for high energy physics, such as a future TeV scale lepton collider but it is recognised that they may be applicable to FELs in the short term

How does LWFA work?



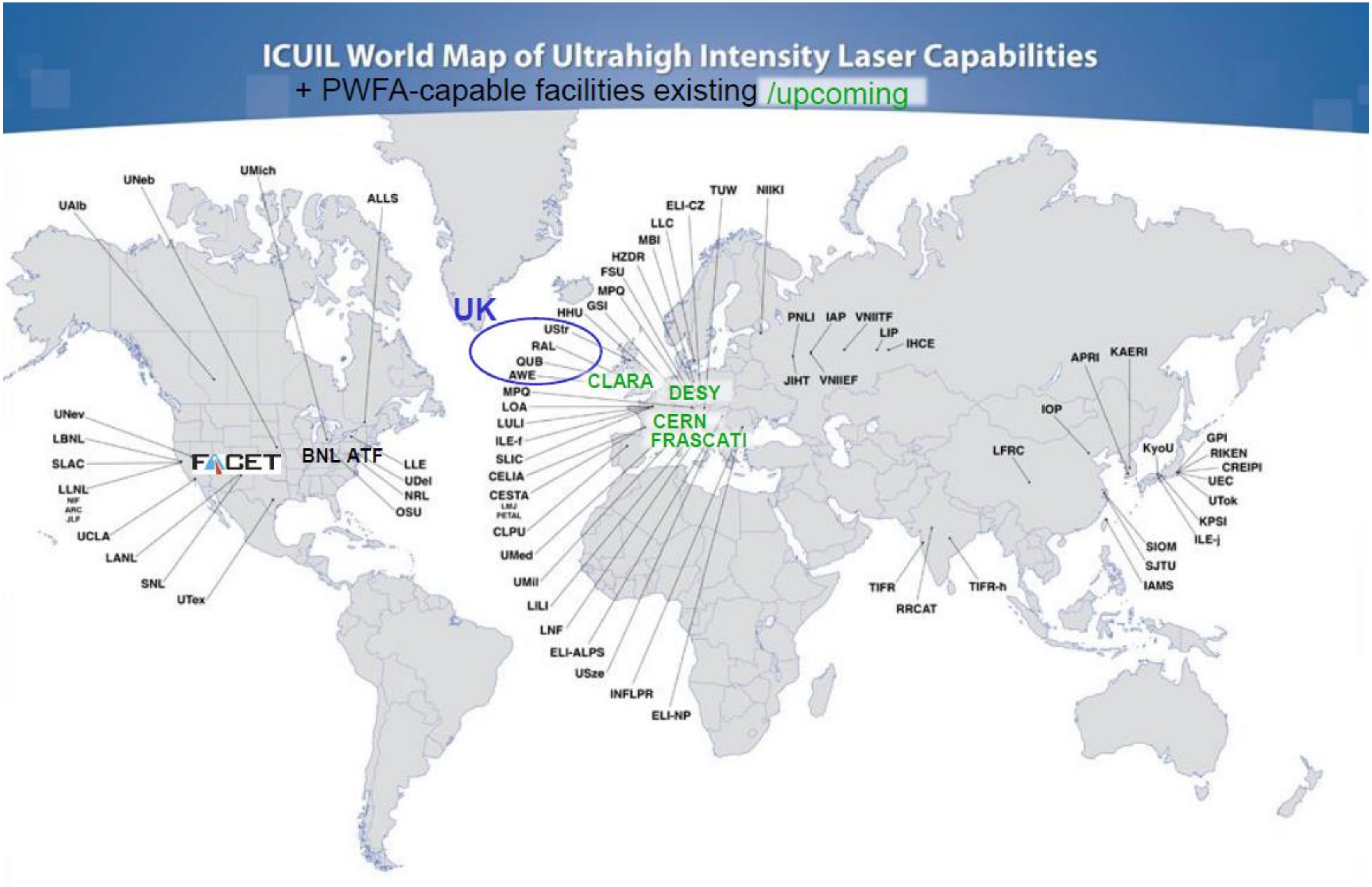
Electric fields of **~50GeV/m** achieved

1. Plasma with ions and electrons but macroscopically charge neutral
2. Strong transverse EM laser field separates electrons (**light**) and ions (**heavy**)
3. Waves of very high charge separation propagate through the plasma similar to the traveling-wave concept in a conventional accelerator
4. Plasma electrons experience a massive attractive force back to the center of the wake by the positive plasma ions
5. This forms a full wake of an extremely high longitudinal (accelerating) and transverse (focusing) electric field.
6. **(Some) Plasma electrons are trapped and accelerated (surfing the wave!)**

Can LWFA be used as an FEL Driver?

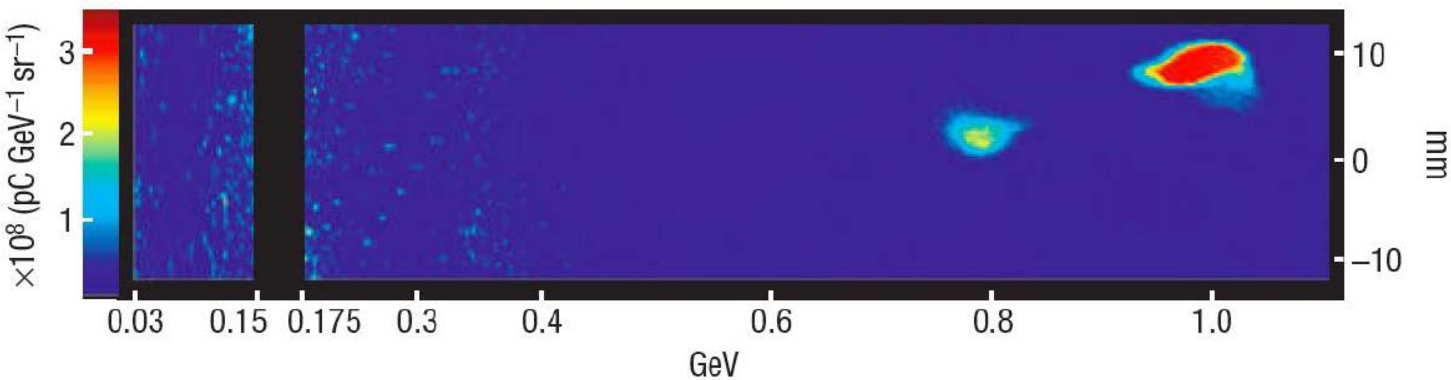
- It is hoped that an LWFA would be cheaper and much smaller than a conventional accelerator and so make FELs more affordable and more widely available
- **But**, the electron beam quality for a FEL is very demanding
- LWFA beams can be several **GeV** from a single laser pulse so **energy** is enough, the **emittance** appears to be good enough but the **energy spread is always much larger than required** and the **pulse lengths may be too short**
- If these can be fixed by LWFA experts then FEL should be ok
- **Alternatively, there might be a clever FEL design that is more tolerant to large energy spread & the short bunches**
- Another approach is to manipulate the beam after the plasma to reduce energy spread and lengthen pulse – this may make a FEL possible but the manipulation takes a lot of space so maybe the advantage of LWFA will be lost?
- Another big drawback is the **shot to shot variation** – it might be possible in the future to generate coherent light but LWFA is not currently predictable/repeatable in terms of energy (and so wavelength) – this will also need to be solved before they can be considered as potential **user facilities**

LWFA (& PWFA) Worldwide



GeV Beams Possible

Plasma Acceleration Works: Here e- Beam Result 2006



LETTERS

GeV electron beams from a centimetre-scale accelerator

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nature physics | VOL 2 | OCTOBER 2006

A breakthrough result → UK community involved!

Present status:
Beam not used. Method pushed to 4.2 GeV e- beam.

DESY

Real LWFA Output – Not a FEL

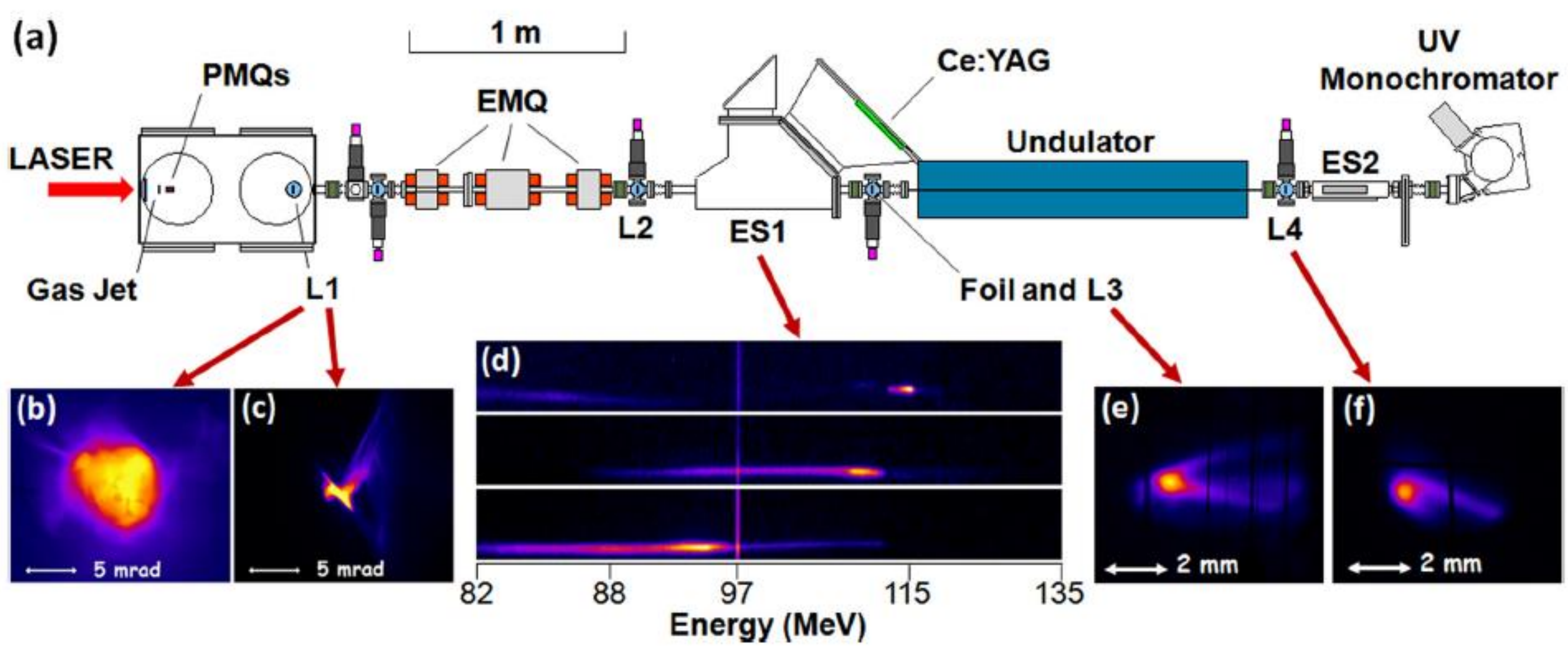

FIG. 2. (a) Plan view of the ALPHA-X LWFA beam line, false color images of the electron beam profile at (b) L1 without PMQs, (c) L1 with PMQs in-line, (e) L3 and (f) L4 and (d) three examples of ES1 spectra with main peak central energy and charge of 115, 109, 95 MeV and 0.4, 0.8, 1.3 pC, respectively.

APPLIED PHYSICS LETTERS **104**, 264102 (2014)

CrossMark

An ultrashort pulse ultra-violet radiation undulator source driven by a laser plasma wakefield accelerator

M. P. Anania,[1,2] E. Brunetti,[1] S. M. Wiggins,[1] D. W. Grant,[1] G. H. Welsh,[1] R. C. Issac,[1] S. Cipiccia,[1] R. P. Shanks,[1] G. G. Manahan,[1] C. Aniculaesei,[1] S. B. van der Geer,[3] M. J. de Loos,[3] M. W. Poole,[4] B. J. A. Shepherd,[4] J. A. Clarke,[4] W. A. Gillespie,[5] A. M. MacLeod,[6] and D. A. Jaroszynski[1,a)]
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ALPHA-X facility at Strathclyde University, Glasgow

Real LWFA Output – Not a FEL

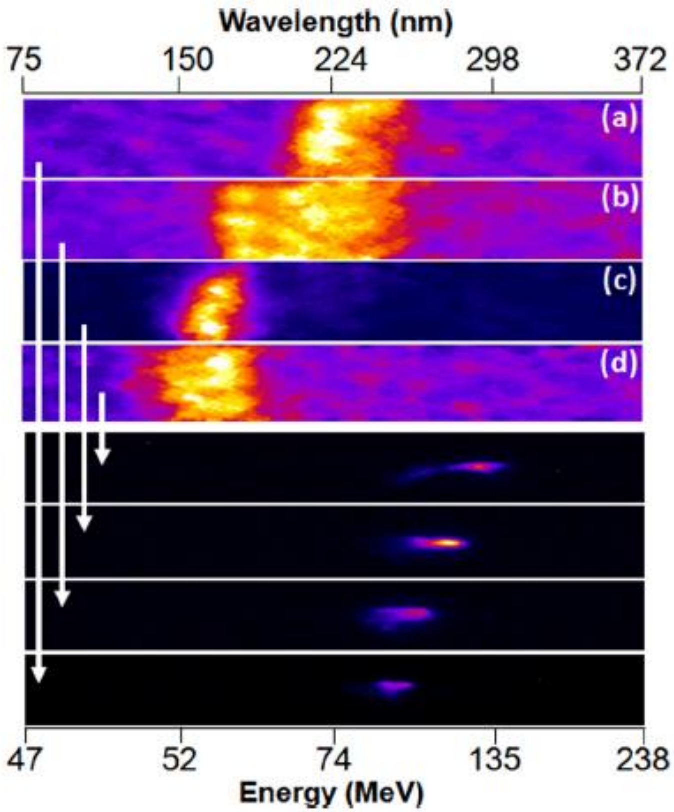

FIG. 3. False color images of four unprocessed undulator radiation spectra with corresponding ES2 electron spectra indicated. Respective values for number of detected photons (after processing for toroidal mirror, grating, and camera response), electron beam charge, and central energy are (a) 1.2×10^6, 0.9 pC, and 92 MeV, (b) 7.7×10^6, 1.6 pC, and 95 MeV, (c) 6.1×10^6, 2.0 pC, and 108 MeV and (d) 4.0×10^6, 1.3 pC, and 122 MeV.

- Large shot to shot energy variation and energy spread variation
- Output wavelength not constant
- Beam qualilty not sufficient for FEL interaction

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Is there hope for 5GLS?

- LWFA has made great progress in terms of absolute energy (4.2 GeV has been achieved) but progress seems to have stalled at reducing energy spread below the % level.
- New types of (more tolerant) undulators have been proposed to make FEL possible – **plenty of room for new ideas!**
- Active experimental programmes in several locations
- Alternative plasma acceleration based upon electron beam may give better quality beams?
- Schemes which **combine laser & electron** driver or **LWFA with injected high quality electron bunch** also being actively considered – **again plenty of room for new ideas!**

Summary

- 4th Generation Light Sources exist now and are based upon **free electron lasers**
- Several XFELs are under construction and more are planned
- The basic mechanism is relatively simple but the electron beam conditions that are required to sustain the interaction between the electrons and light beam are very demanding and has required **years of sustained development**
- High gain FELs are needed for wavelengths shorter than ~100nm
- These FELs are still **immature** and there is plenty of scope for improvements.
- What comes after 4GLS is not yet clear
- Could be a change in accelerator technology rather than a new light source mechanism
- Acceleration by lasers (or electron beams) is a reality but will take years of effort to displace RF based acceleration
- Major breakthroughs are required to bring plasma accelerators into mainstream use

Acknowledgements

- Many of the slides I have used have been taken from excellent presentations by the following very nice people. I'm sorry I didn't ask permission before using them!

- **Neil Thompson**
- **Dave Dunning**
- **Brian McNeil**
- **Allan Gillespie**
- **Andy Wolski**
- **Ralph Assmann**
- **S Molodtsov**
- **Bernhard Hidding**