John Adams Institute for Accelerator Science

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Royal Holloway University of London

UNIVERSITY OF OXFORD

Work Packages for FET Open on HiFLUX: High repetition rate Fibre-Laser-plasma accelerators for Ultrabright X-rays

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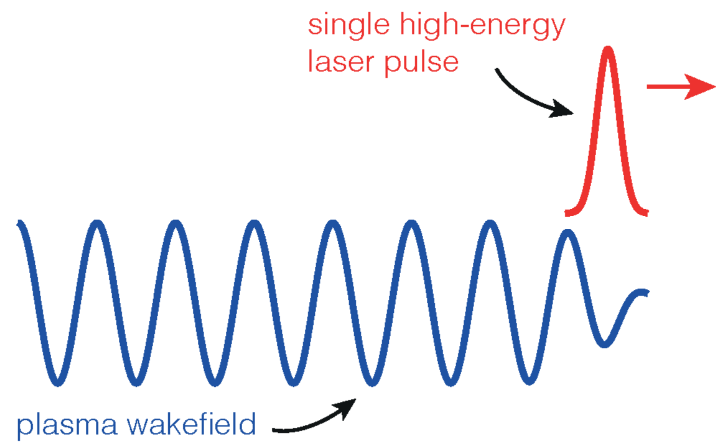
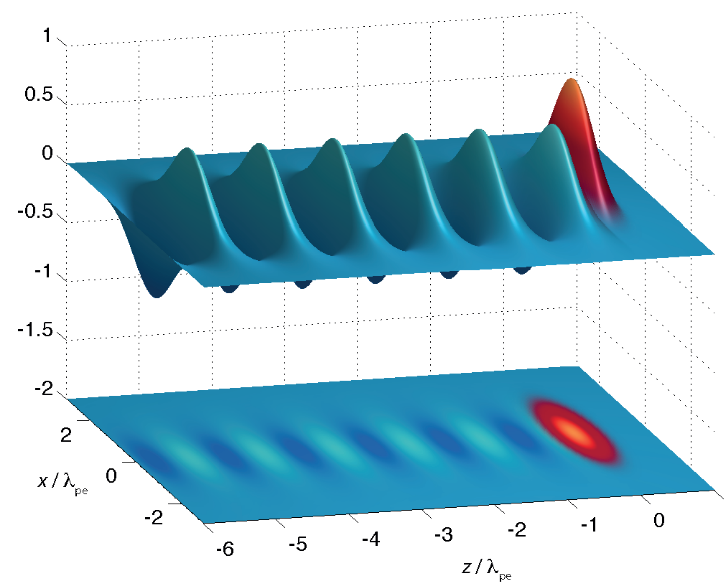
  - MP-LWFA presented to ESGARD on 24 March 2014

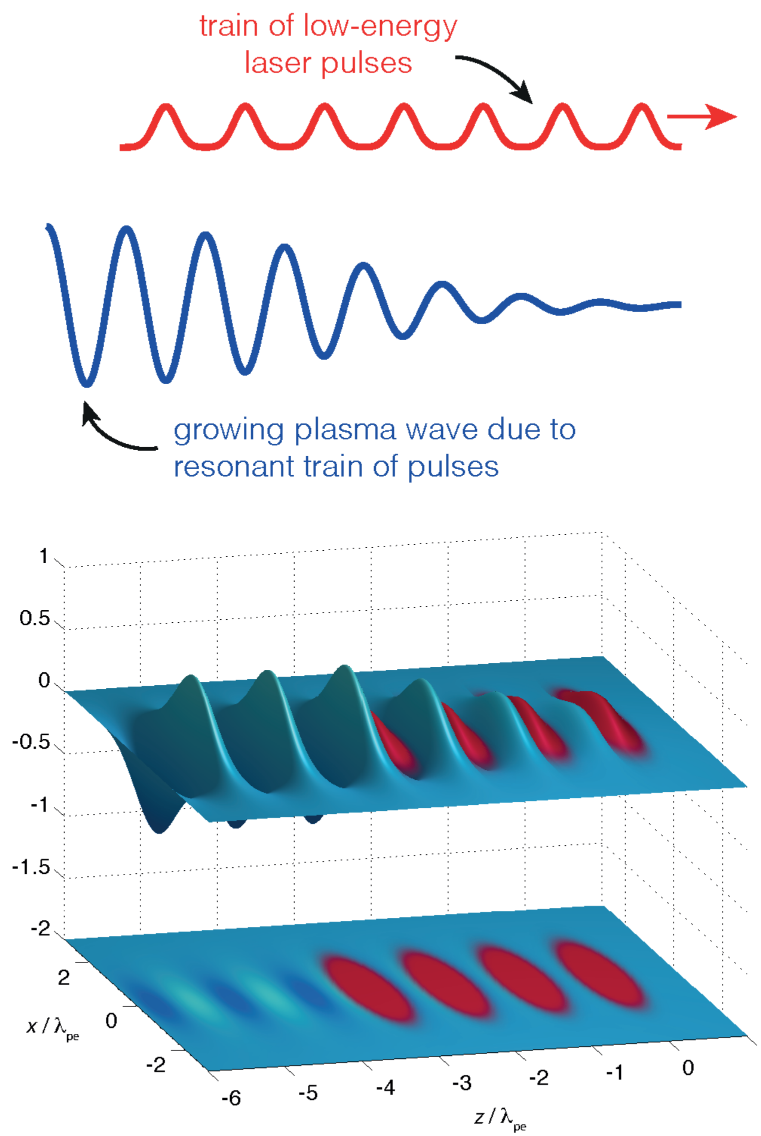
- Almost all laser-driven plasma accelerators today use a single driving pulse
  - Rep. rate typically < 10 Hz
  - Wall-plug efficiency <0.1%



- But, many potential applications require much higher:
  - Rep rate (e.g. > 1 kHz for radiation sources)
  - Wall-plug efficiency (important for radiation sources, vital for future particle colliders)



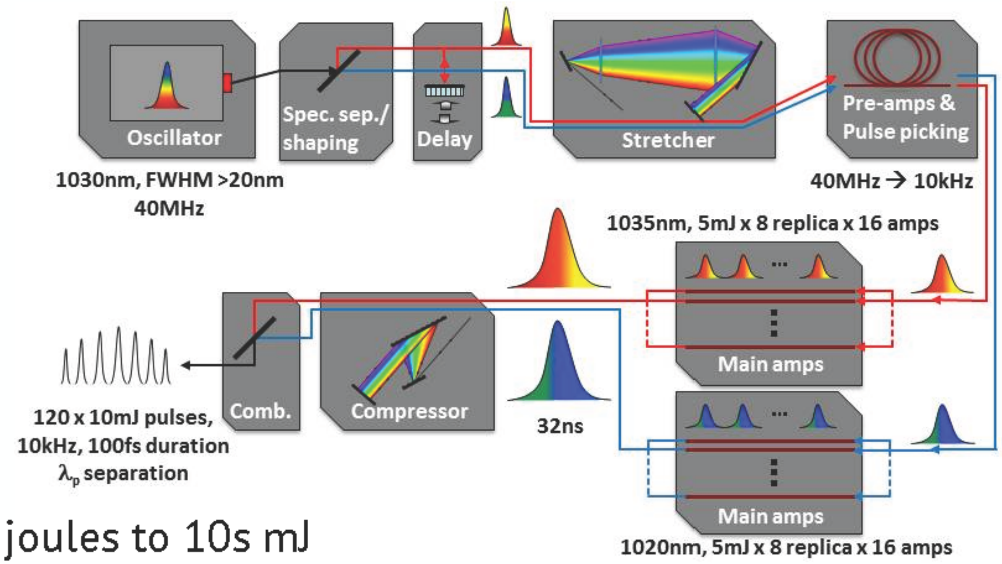
- Our aim is to develop new ways of driving plasma accelerators at multi-kilohertz repetition rates
  - Immediate application to driving radiation sources with high peak and high mean flux
  - In longer term could be important for HED physics
- Our approach is to use a train of pulses separated by plasma period to resonantly excite wakefield
  - Energy stored efficiently in plasma wave
- For details see: http://arxiv.org/abs/1401.7874v1



Advantages of MP-LWFA

S.M. Hooker *et al.* http://arxiv.org/abs/1401.7874v1

Fibre laser system able to generate train of 120 x 10 mJ x 100 fs pulses at 10kHz

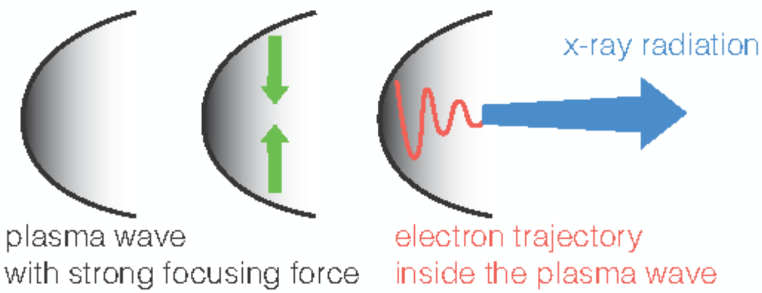


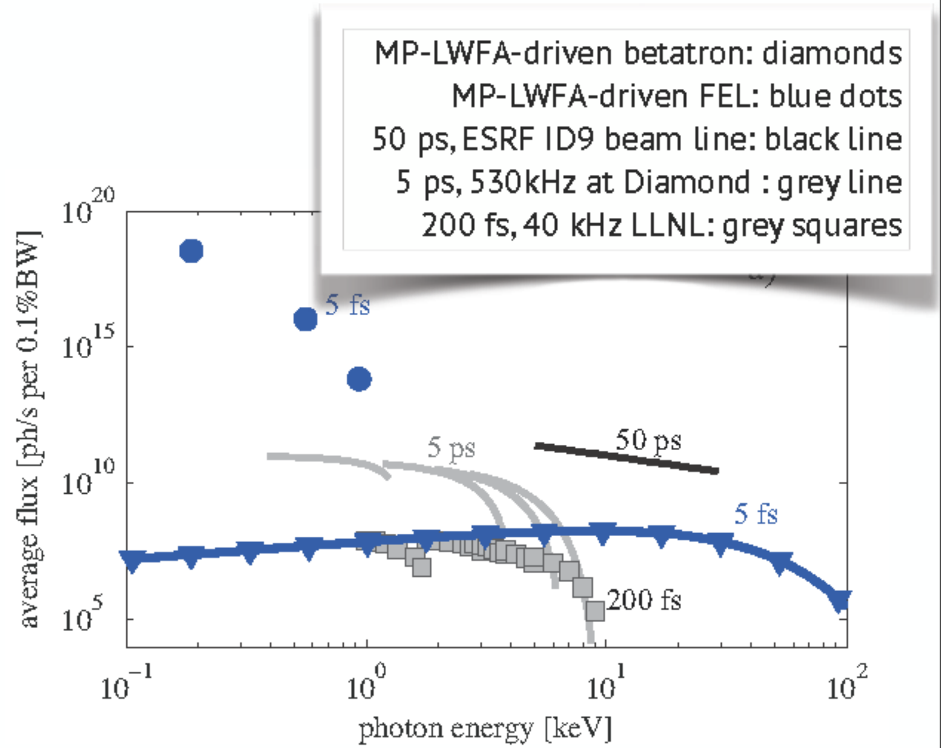
- Energy per laser pulse reduced from joules to 10s mJ
  - Enables use of fibre lasers
  - Already demonstrated 2 mJ, < 500 fs pulses at > 10 kHz rep rate
  - Demonstrated wall-plug efficiency > 20%
- Lower peak intensity on optics
  - Reduced optical damage - especially important at high rep. rate
  - Allows short focal length optics - reduces "dead space" between plasma stages
- Avoid dark current by avoiding laser self-focusing and electron self-injection

MP-LWFA-driven radiation sources

S.M. Hooker *et al.* http://arxiv.org/abs/1401.7874v1

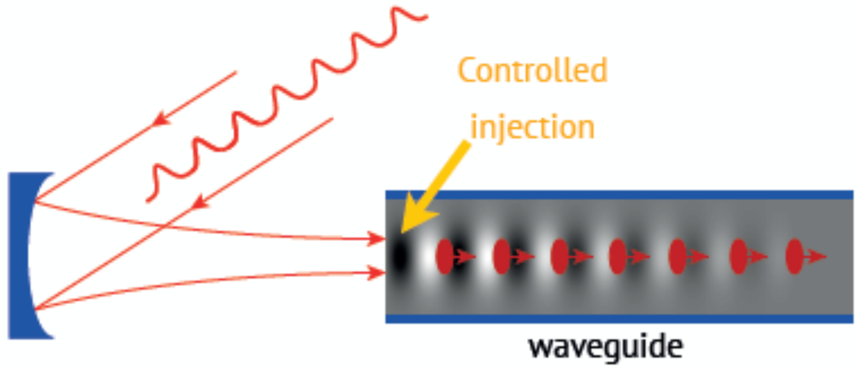
- Betatron radiation
  - At 10 keV photon energy **average** flux is ≈ 2×10^8 photons s^{-1}, per 0.1% BW
  - Greater than existing short-pulse 3rd gen sources - but with **100 x** better temporal resolution
- FELs
  - Simulations show SASE saturation reached in soft X-ray range (λ_{FEL} = 6.9 nm) in 4 m long transverse-gradient undulator
  - Peak FEL power exceeds 1 GW
- Other
  - Compton sources could also be operated at high rep. rate



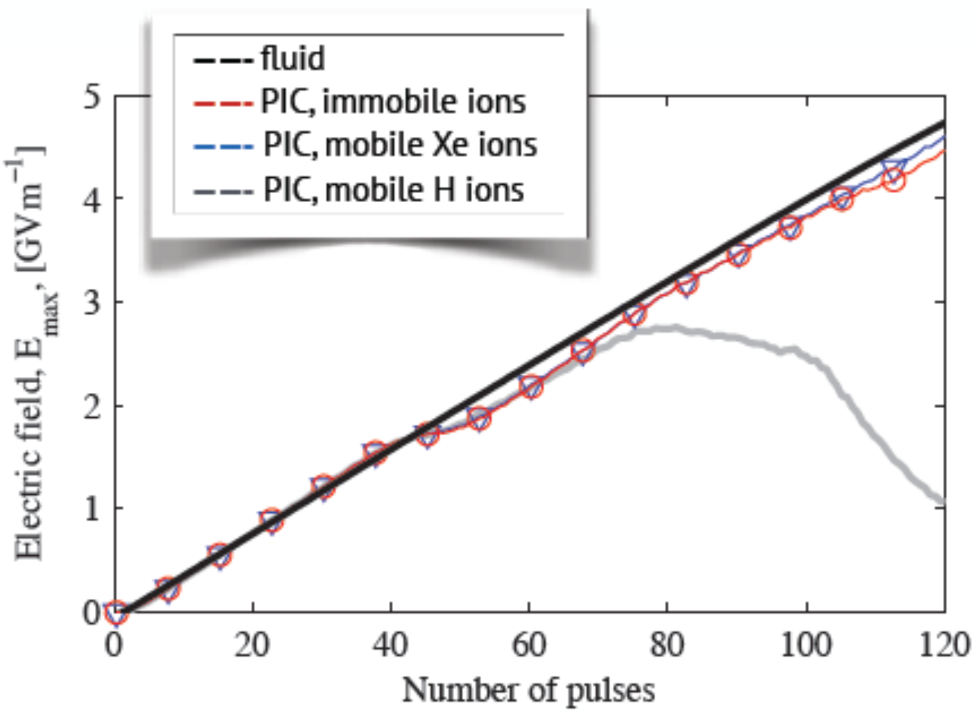


Fluid & PIC simulations

S.M. Hooker *et al.* http://arxiv.org/abs/1401.7874v1



- Fluid and PIC simulations show gradients of 4.7 GV/m for train of 100 pulses
- For $L_{acc} = L_{dep}/2$ = 260mm energy gain is 0.75 GeV
- Pulse trains of up to ~ 100 pulses can be used before ion motion damps plasma wave



Laser-plasma parameters
E = 10 mJ / pulse
τ = 100fs
w_0 = 40 µm
a_0 = 0.05
$n_e = 1.75 \times 10^{17}$ cm^{-3}

Summary

- MP-LWFA could provide **efficient**, **high-rep-rate** plasma accelerators able to drive radiation sources with both **high peak and high average brightness**
- The HiFLUX project was proposed for ERC Synergy funding and passed Step 2A, corresponding to **top 12% of Synergy proposals**
- We are now assessing best ways to fund this project. We would highly value "moral support" from ESGARD for this research programme

Background – WP organization

- MP-LWFA is our central research direction
  - Endorsed by JAI Advisory Board
  - Endorsed by STFC Accelerator Strategy Board
  - Endorsed by JAI affiliate Universities
- Significant part of our efforts directed to MP-LWFA
- Therefore, it is necessary to look at the entire structure of Work Packages of MP-LWFA which includes FET Open
  - The importance of self-consistency and completeness of FET Open is appreciated – we are looking forward for your comments – specific questions on the following slides

Background - physics

- Physics of MP-LWFA is a new territory
- Our studies so far shows the promise of feasibility*
- Several key questions that are usually asked and our answers are shown on the next two slides
- These and other questions will be studied in detail in course of the project
  - It is necessary to balance what is included in FET Open and what we plan to do within our core funding

*) http://arxiv.org/abs/1401.7874

Background – physics -1

Target plasma:

- Ion motion will limit pulse train length.
- Use of heavy ions increases this limit – not clear if necessary though.
- Preliminary (non-optimised) results – H plasma gives 0.5GeV beam @ 10kHz.
- This is straightforward, given suitable guiding mechanism.
- Our other (non-FET) research will concentrate on assessing need for heavy ion plasma and how this could be generated.

Target plasma ionization:

- H plasma easily ionised (laser/discharge).
- Heavy ion plasma more difficult – ionise with leading laser pulse of train?
- Need to avoid exciting wake with ionisation pulse – more research required.

Background – physics -2

Electron injection:

- Issue for *all* LWFA so active area of research across whole field.
- We want to inject in quasi-linear regime - not all proposed solutions suitable.
- Our "2PII" [*] might work, needs experimental confirmation of simulations.
- Other approaches to be researched: counter-propagating pulse, density ramp, external injection from bubble LWFA/conventional accelerator etc.

Hosing:

- Analysis shows hosing controlled by careful pulse spacing in train and/or waveguide.
- Further (non-FET) research required to extend analysis to practical situations given laser jitter etc.

Not all issues relevant only to MP-LWFA so work applicable to LWFA in general.

New laser technology beneficial to *all* areas of LWFA – especially high rep. rate.

Application of (MP) LWFA to e.g. medical science hugely important – cannot rely on applications in HEP only.

[*] Bourgeois, N, Cowley, J & Hooker, SM. Two-Pulse Ionization Injection into Quasilinear Laser Wakefields. PRL 111, 155004 (2013).

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MP-LWFA Work Packages

- **WP1: Physics of MP-LWFAs**
  - **Partially own funding & interface to FET open and selected key physics questions**
- **WP2: Development of lasers**
  - **FET Open**
- **WP3: Medical applications of MP-LWFAs**
  - **FET Open**
- **WP4: Applications of betatron radiation**
  - **Own funding**
- **WP5: Controlled injection, waveguides and staging**
  - **Own funding**

There is a need to balance the FET Open WPs, therefore only key physics questions can be included in FET Open WP. We appreciate your comments on the questions and the balance.

- **Own funding correspond to JAI core funding as well as other research grants we obtain from UK and other sources which is our normal practice**
  - **We in particular planning to use JAI core funds, ERC Consolidator and Advances grants, UK EPSRC funds and Fraunhofer funds**

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FET Open partners

- **Partners in HiFLUX-FET Open:**
  - **UK: (Oxford, Imperial),**
  - **Germany: (Jena),**
  - **One-more-country – TBA (to be announced) –**
    - **we are working on identified promising connections with lead European centres and plan to announce the results soon**

WP1 (own funds and part FET Open): Physics of MP-LWFAs (joint Oxford and Imperial leads)

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- **The physics of MP-LWFAs is a rich scientific area, much of which remains to be explored. There is strong overlap with wakefields driven by self-modulated particle beams (e.g. AWAKE), and we expect significant synergies to be realized by comparing results with groups working on that approach.**

- We plan to undertake studies on:
- ion motion and how this limits the length of the pulse train.
- development of new plasma targets.
- hosing of the pulses and its stabilisation.
- pump depletion/beam loading.

- Experimental tests of these simulations at Oxford/Imperial and the Central Laser Facility at the Rutherford Lab.

- The ultimate objective of this WP is a set of realistic design parameters for the laser pulse train and the target plasma for a MP-LWFA system and its expected performance parameters.

WP2 (HiFLUX-FET Open): Development of lasers (Jena lead)

- **Development of high repetition-rate, high energy PCF fibre lasers for high-flux photon sources driven by MP-LWFAs.**

- Ultrafast fibre amplifiers can already efficiently generate high-average powers, but do not yet achieve the necessary peak powers required for LWFA. Thus, the scaling techniques of temporally and spatially separated amplification and subsequent coherent combination are pursued within this WP.

- Also large-mode-area fibres based on PCF technology are investigated as a promising concept for increasing achievable energies.

- Finally, techniques for generating the pulse train (both prior and after amplification), which is required for MP-LWFA, are investigated.

- The development of such laser sources that can drive wakefield accelerators at kHz repetition rates addresses one of the major disadvantages of current systems (~ Hz) and would completely change the potential scientific, medical and industrial applications of wakefield acceleration.

WP3 (HiFLUX-FET Open): Medical applications (lead TBA)

- **Development of potential applications of high-flux photon sources driven by MP-LWFAs, particularly in medical science.**

- FETopen1 must be: **“Interdisciplinary: the proposed collaborations must be interdisciplinary in the sense that they go beyond current mainstream collaboration configurations in joint science- and technology research, and that they aim to advance different scientific and technological disciplines together and in synergy towards a breakthrough.”**

- Hospitals/universities with kHz/fs electron accelerators would mean new opportunities for research, treatment and diagnostics – such accelerators could be used as coherent/ incoherent light sources.
- .In assessing potential applications in medical science the priority is given to applications which would make real difference to what is available currently at conventional light sources like DIAMOND or ESRF; bringing affordable accelerators to users (patients) instead of bringing users (patients) to accelerators.
- We will also develop a conceptual design of a light source for a hospital taking into account hospital requirements like safety, radiation illumination area, quick variation of X-ray direction for scanning applications and the stability of relevant parameters.

WP3 (HiFLUX-FET Open): Medical applications (lead TBA)

- **X-ray phase contrast imaging.**

- Based on our current expertise of using conventionally produced X-rays and established connections with hospitals, we will consider a range of applications but the leading direction will be X-ray imaging using phase contrast technique; maximizing image contrast and minimizing radiation dose.
- We will calculate parameters of the X-ray broad band betatron radiation (up to 100 keV) to be used in modelling images for most promising applications in medical diagnostics.
- The most advanced technics of phase contrast imaging, like edge-illumination will be exploited and hopefully pushed further to achieve higher resolution and sensitivity.
- We also foresee experiments using plasma driven by a low rep rate Ti:sapp laser supporting outcomes of the modelling and comparisons to existing technology using conventional accelerators like ESRF.
- We will also work on diagnostics and X-ray detectors/cameras to be able to operate at up to 10 kHz rep rate.

WP3 (HiFLUX-FET Open): Medical applications (lead TBA)

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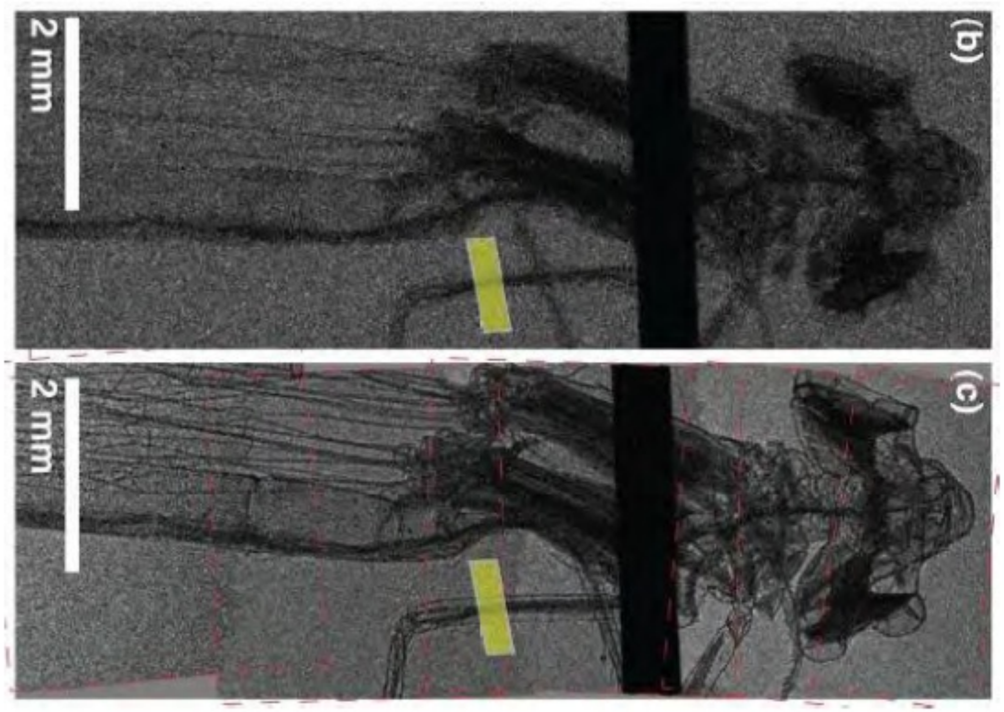

Absorption contrast

Phase contrast

S. Kneip, et al. App. Phys. Lett. 99, 093701 (2010)

WP4 (own funds): Applications of betatron radiation (Imperial lead)

- **Applications of betatron radiation for a probe of extreme states of matter including theory and modelling of betatron radiation by high rep rate MP-LWFAs.**

- WP4 main challenge: development of plasma wigglers for applications. We have recently demonstrated x-ray phase contrast imaging, which can be used for medical applications such as detection of breast cancer and micro-tomography.

- We will demonstrate the efficacy of kHz plasma wiggler radiation for medical applications by thoroughly characterising their imaging capabilities using appropriate phantom objects. This will open up the potential for further clinical and pre-clinical research.

- The established strong collaboration with a team of cancer specialists at Imperial will be expanded for joint work with the team leading WP3. Close interaction with this interdisciplinary team will ensure that developments in plasma wiggler radiation properties and characterisation are closely matched with the requirements for medical imaging.

- We will also investigate the use of plasma wigglers in experiments that fully utilise their unique properties, i.e. bright, broadband radiation of femtosecond duration, in particular in measurements of plasma opacity and ionization rates (needed to understand stellar evolution), and as an ultrafast imaging tool, performing time resolved imaging of laser driven shocks that will further the understanding of materials under extreme conditions.

WP5 (own funds): Controlled injection, Waveguides & staging (Oxford lead)

- **Development of techniques for electron injection, laser guiding and staging for MP-LWFAs.**

- MP-LWFAs will operate in a quasi-linear regime - self-guiding by relativistic effects not sufficient to guide the pulse train over a dephasing or pump-depletion length.
- Therefore necessary to develop techniques to guide pulse train in low density plasma (~ 10^{17} cm^{-3}) over many Rayleigh ranges. Results of WP3 will be an important input in determining the required density and ion species of the plasma; results of WP1 and WP3 will determine the parameters of the laser pulse train.
- Quasi-linear operation also means electrons will have to be injected into the plasma wakefield, (not self-trapped). We will study techniques for controlling the injection of electrons into the plasma wakefield generated within MP-LWFAs via simulations and experiments.
- An important aspect of this WP will also be to maintain an overview of all aspects of the operation and design of MP-LWFAs, and their applications, and to ensure that the promise of this exciting approach is communicated to the wider community of accelerator scientists and potential users.

Summary

- The proposal is exciting
- The team is ready
  - Three countries in partners
  - (announcement of recently joined partner is within days)
- The team is looking forward for preparing and submitting FET Open application in the first call