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Start-to-end modelling for the realization and optimization of plasma-wakefield-accelerator-driven free-electron lasers

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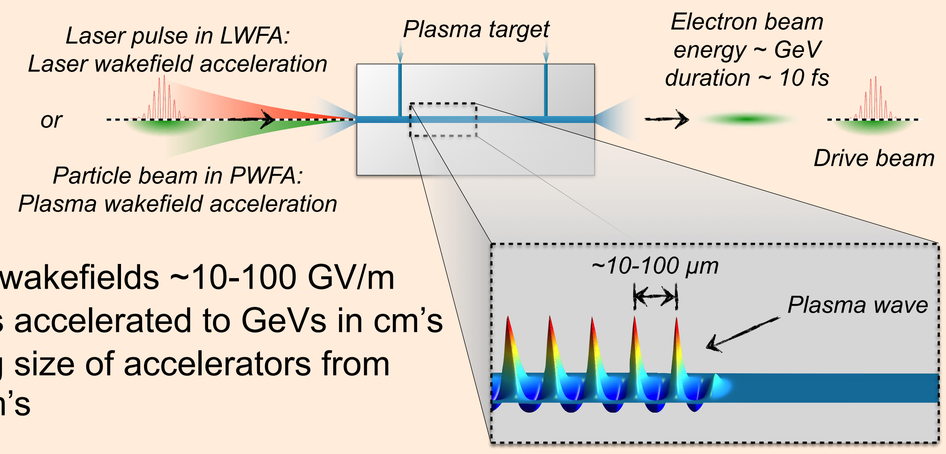
TÉCNICO LISBOA

Plasma-based acceleration

- In plasma-wakefield acceleration (PWFA), short and high-current particle beams generate large amplitude plasma waves.
- 40 GeV energy gain of electrons in meter-scale plasma modules was demonstrated experimentally [1].
- Allows for dramatic miniaturization and reduction of costs of future light sources [2,3] or particle colliders [4,5].



- Extreme wakefields ~10-100 GV/m
- Electrons accelerated to GeVs in cm's
- Shrinking size of accelerators from km's to m's

Free-electron lasers

Free electron lasers (FELs) are deliver
- Spatially and temporally coherent radiation
- with (sub-)nm wavelengths
- pulsed in a few femtoseconds
- ultra-high brightness (~10^33 Photons/(s mm^2 mrad^2 0.1% b.w.))

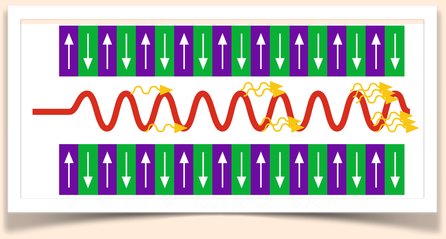


Illustration of the generation of FEL radiation in an undulator [6].

FELs are
- key technology to new insights in medicine, biology, chemistry or materials science
- Today driven by km-scale machines (LCLS, XFEL, SwissFEL)

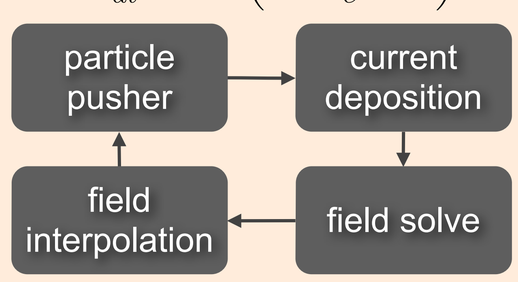
Particle-In-Cell modelling

- Analytic description of phenomena in plasma-based accelerators not possible
- Particle-In-Cell (PIC) methods model kinetic plasma phenomena with affordable computational means
- PIC codes implicitly solve the Maxwell-Vlasov system
- Particle density is discretized with macro-particles
- Macro-particles are advanced along the characteristics of the Vlasov equation
- Fields and currents are defined on a grid

$$\frac{\partial f}{\partial t} + \mathbf{v}\cdot\frac{\partial f}{\partial \mathbf{r}} + q\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right)\cdot\frac{\partial f}{\partial \mathbf{p}} = 0$$

$$f(\mathbf{r},\mathbf{p},t) \approx \sum_{\alpha=1}^{M} N_\alpha\, S(\mathbf{r}-\mathbf{R}_\alpha(t))\,\delta(\mathbf{p}-\mathbf{P}_\alpha(t))$$

$$\frac{d\mathbf{R}_\alpha}{dt} = \mathbf{V}_\alpha \qquad \frac{d\mathbf{P}_\alpha}{dt} = Q_\alpha\left(\mathbf{E} + \frac{\mathbf{V}_\alpha}{c}\times\mathbf{B}\right)$$



Numerical main loop scheme in a PIC code

- OSIRIS [7] is a massively parallel, fully relativistic PIC code
- Developed by UCLA and IST
- Scalability to ~300 K cores
- SIMD hardware optimized
- Tunnel (ADK) and Impact Ionization
- Optimized higher order splines
- Parallel I/O (HDF5)
- Boosted frame in 1/2/3D
- Ponderomotive guiding center

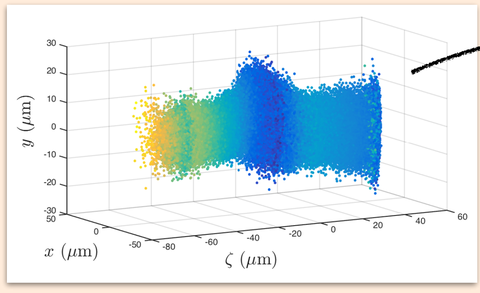
Start-to-end modelling for FLASHForward

FLASHForward▸▸
Future-oriented wakefield-accelerator research and development at FLASH

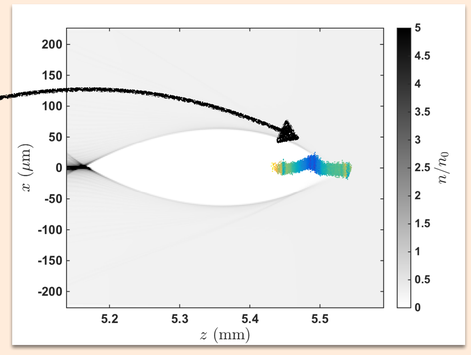
- FLASHForward is a facility using FLASH beams at DESY for PWFA experiments
- The project aims at advancing beam-driven novel-accelerator science
- Simulations so far assumed ideal beam parameters neglecting realistic effects

This project will develop numerical methods for the first time allowing for the study and optimization of PWFA-driven FELs
- These studies are key to successful experiments at FLASHForward
- This has a transformative potential to the field of novel accelerator research
- May allow for small-lab scale high-brilliant X-ray or FEL generation

Spatial beam distribution from a tracking code



Depiction of a realistic beam in a PIC simulation



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