TU3I1:

Investigating the Transverse Dynamics of Electron Bunches in Laser-Plasma Accelerators

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IBIC 2022, Krakow

Outline

1. Introduction to LWFA
2. Typical setup and diagnostics
3. Betatron decoherence
4. LWFA as a source for x-ray radiation
5. Conclusion and Outlook

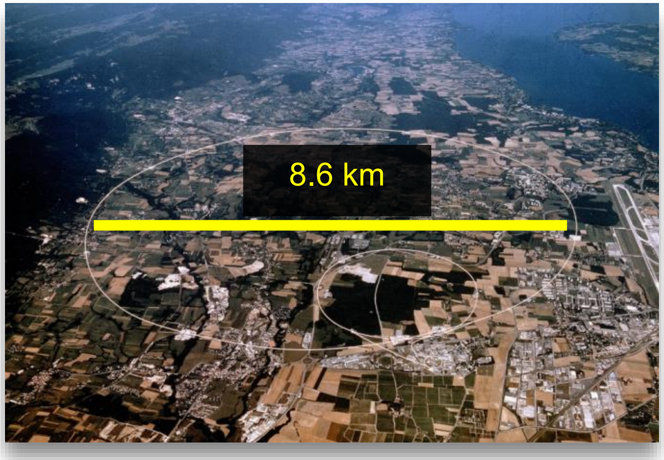
Motivation: typical accelerators

→ Colliders in fundamental science

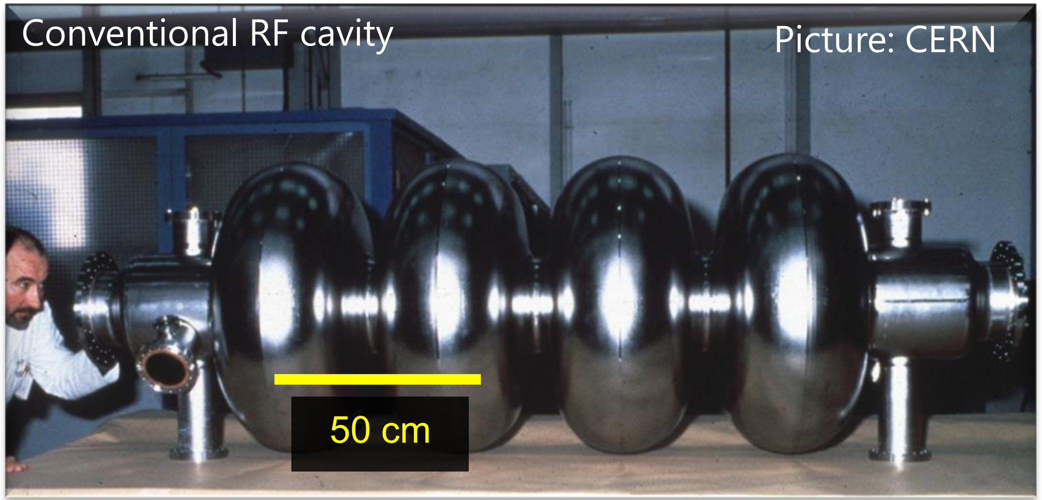
→ Driver for secondary light sources

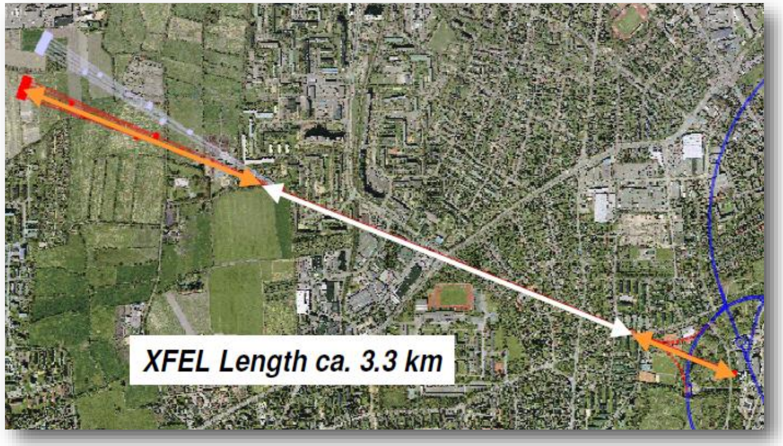
→ Industrial applications

→ But have grown to **enormous sizes**



LHC 2008
CERN



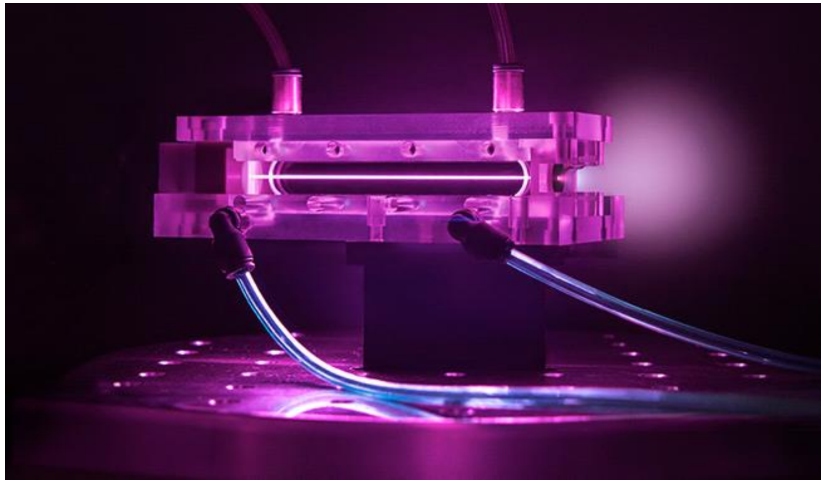


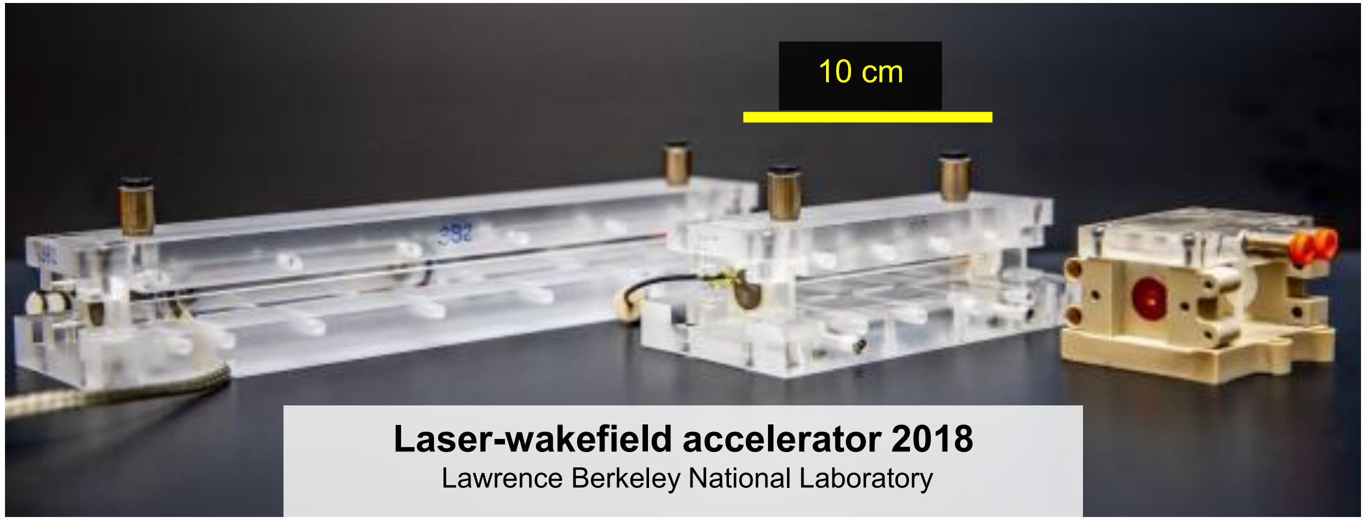
European XFEL 2017

→ Field limited by vacuum breakdown to ~100 MV/m

Compact accelerators with higher energy gain

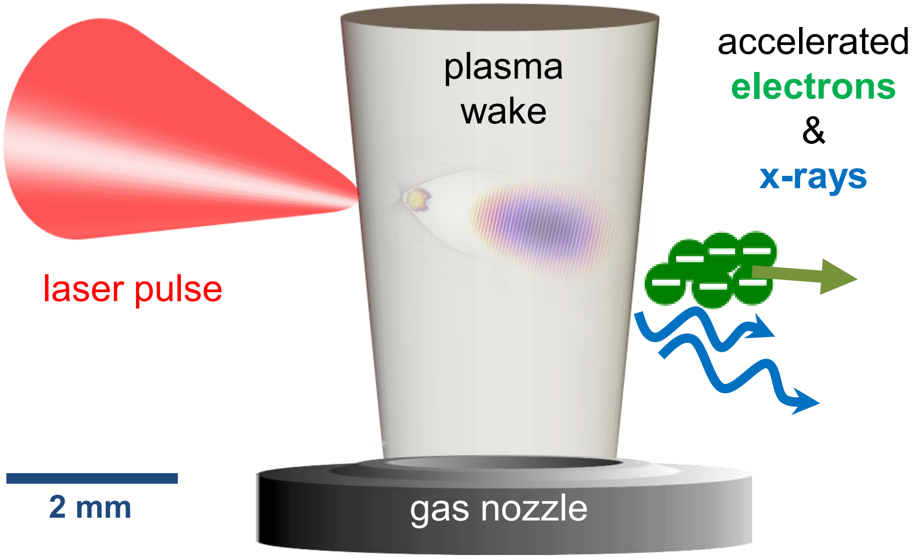
Capillaries





Laser Plasma Accelerator & Wiggler

Gas jets



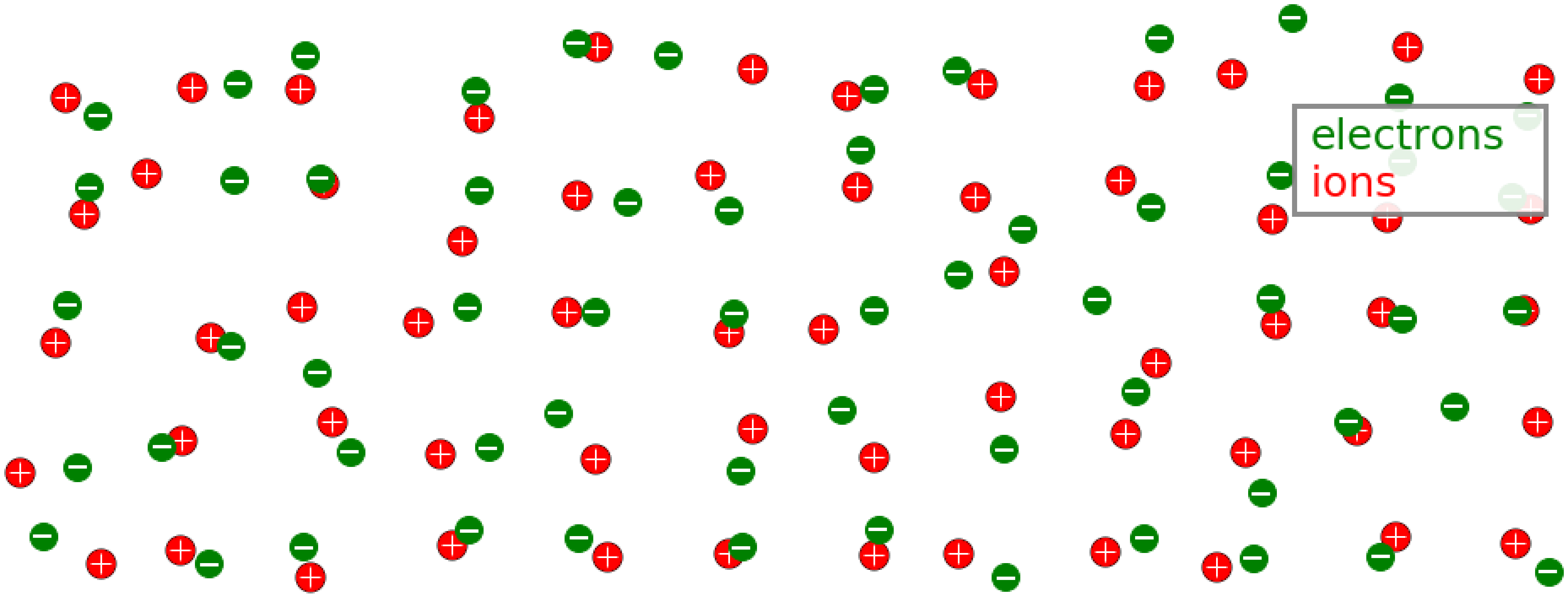
- relativistic energy **electron bunches** within millimeters
- x-ray radiation from electrons (**betatron radiation**)

M. Downer et al. Rev. Mod. Phys. 90 (2018)

Laser-Wakefield Acceleration (LWFA) in a nutshell

- Accelerator medium: Neutral plasma consisting of **ions** and **electrons**
  - Ionized by electrical discharge, preionizing laser or rising laser edge
  - Neutral densities of about 10^19 cm³

$$\omega_P = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}}$$

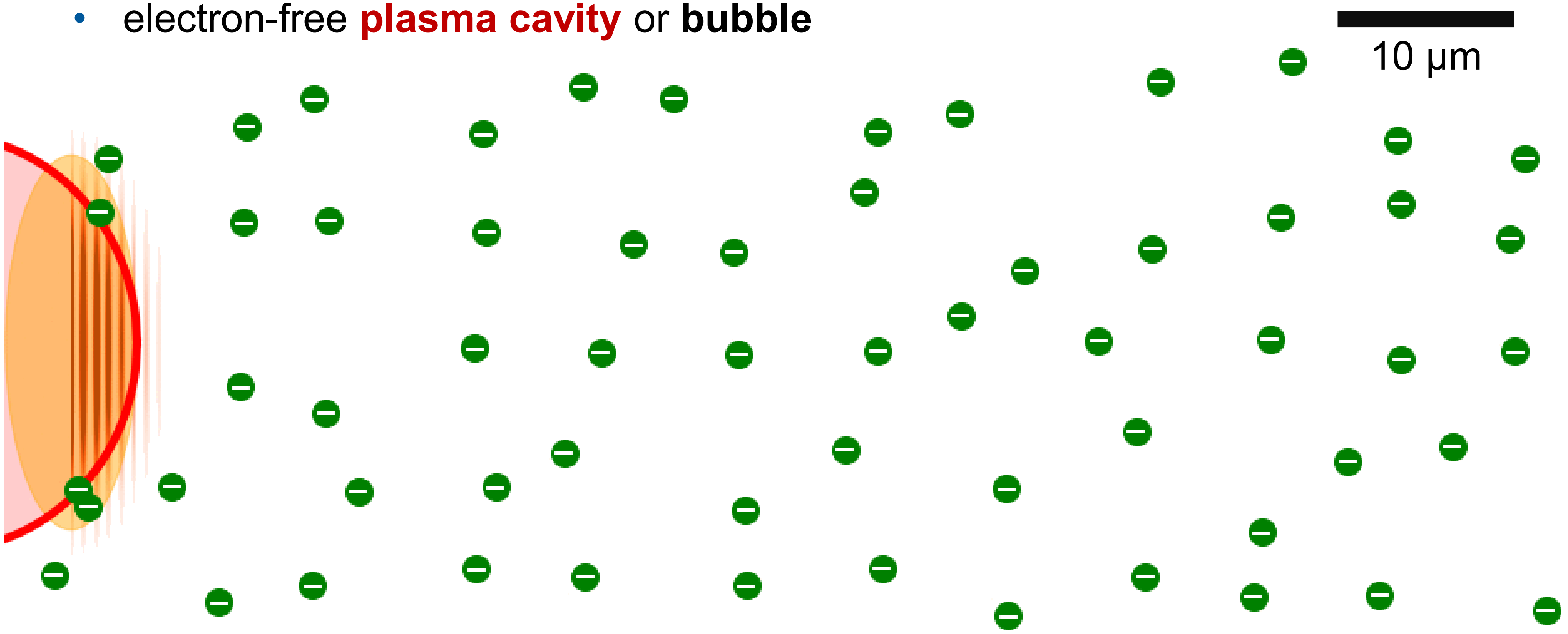


Pukhov & Meyer-ter-Vehn, Appl. Phys. 74, (2002), Lu *et al.*, Phys. Rev. ST Accel. Beams 10, (2007)

Laser-Wakefield Acceleration (LWFA) in a nutshell

- Laser pulse has ponderomotive force F_P proportional to intensity gradient
  -> pushes electrons away from laser pulse
  -> High intense laser pulse excites **plasma waves**
- Non-linear regime: complete electron blow-out
  - electron-free **plasma cavity** or **bubble**

$$\boldsymbol{F_p} = -\frac{e^2}{4 m_e \omega_0^2} \nabla(\boldsymbol{E}^2)$$



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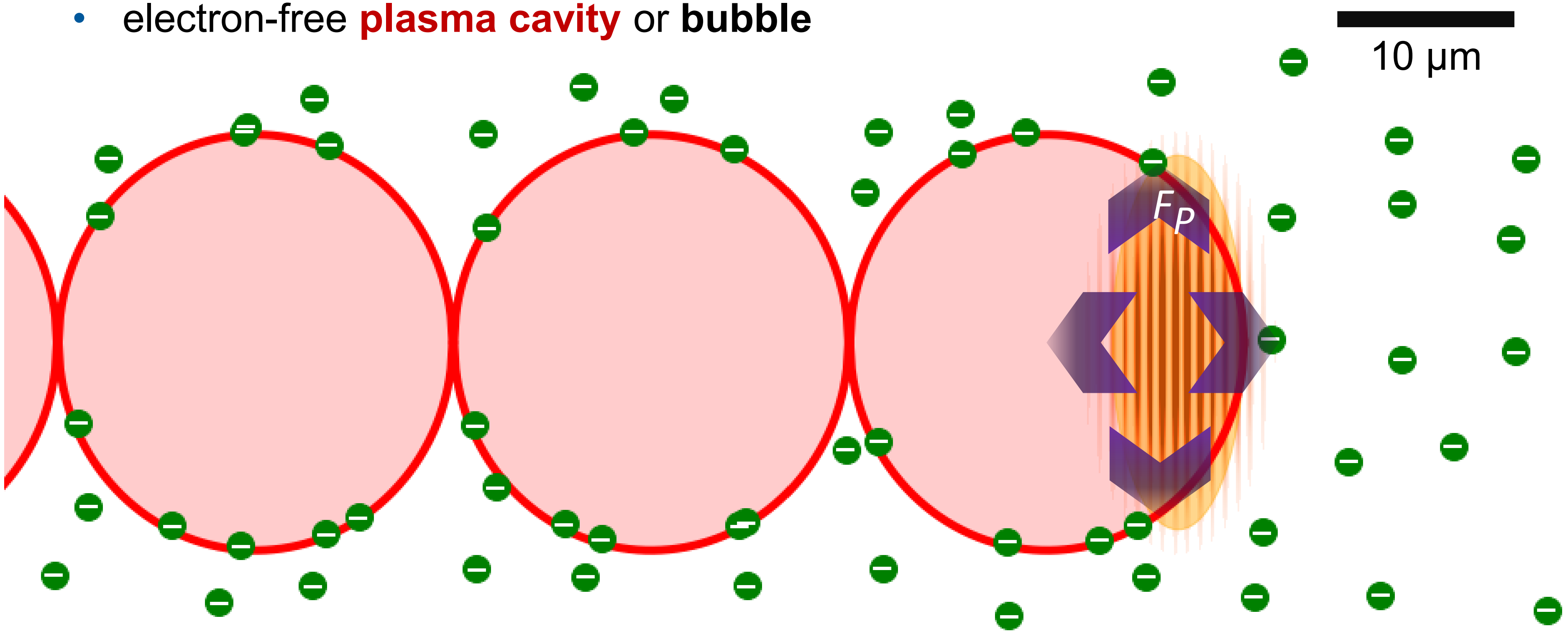

Pukhov & Meyer-ter-Vehn, Appl. Phys. 74, (2002), Lu *et al.*, Phys. Rev. ST Accel. Beams 10, (2007)

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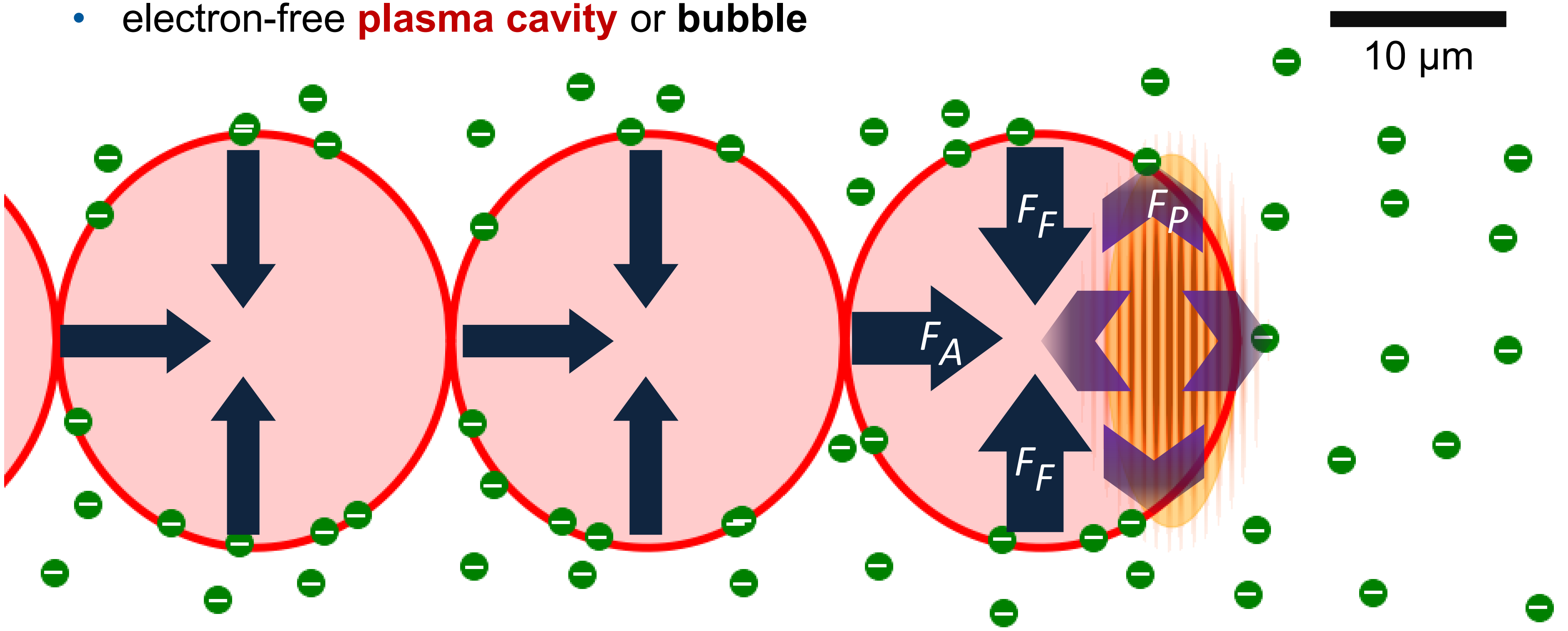
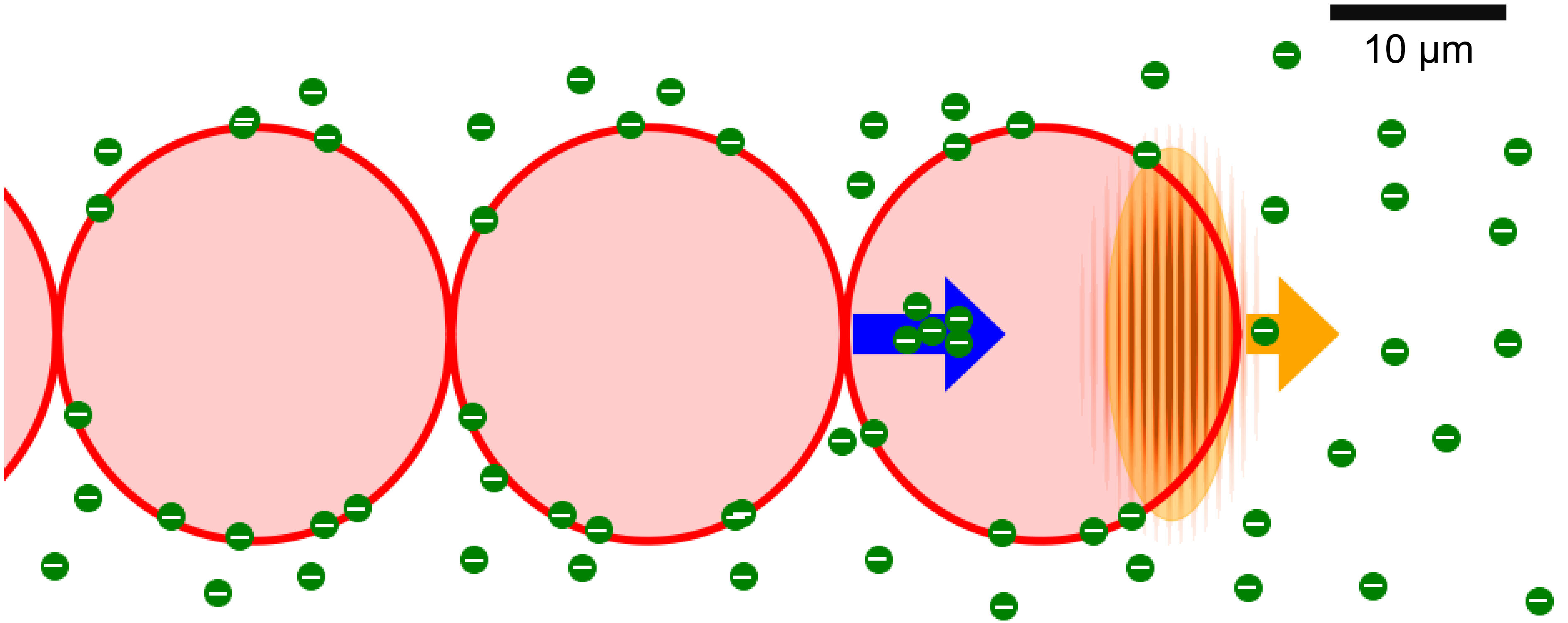


Linear electro-magnetic fields of plasma in cavity:

- Longitudinal: Acceleration (energy gain)
- Transversal: Focusing (betatron oscillations)

Laser-Wakefield Acceleration (LWFA) in a nutshell

- Electron acceleration requires an **injection** of electrons into the cavity
  - Electrons must **copropagate** with laser pulse at (almost) speed of light
  - Successful trapping requires a matching in phase, bunch size & length, time, …
  - Various **injection schemes** (external, wave-breaking, ionization, …)



Injection and acceleration strongly depends on laser pulse and plasma parameters
-> requires **stable** laser systems and reproducible targets

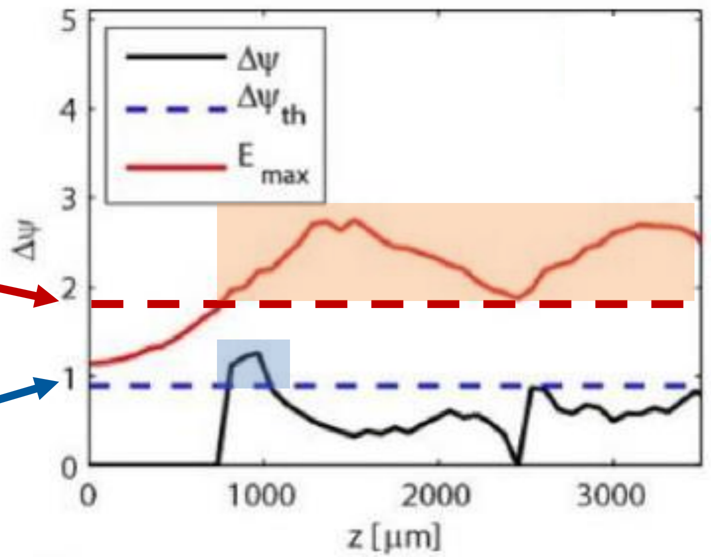
Example: Self-Truncated Ionisation Injection (STII) for short bunches

- Injection during interaction
  -> time must be limited for small energy spread

- Laser pulse and thus wakefield shape evolve during interaction such that injection conditions are only fulfilled for a short period

→ Self-Truncated Ionisation Injection (STII)

- Injection under two conditions:
  - Laser intensity is high enough for ionisation
  - pseudo-potential difference allows trapping



Zeng *et al.* Phys. Plasmas 21, 030701 (2014),
Mirzaie *et al.* Sci. Rep. 5, 14659 (2015),
Irman et al. PPCF, 60(4), 044015 (2018)

Theoretical Limits: The three crucial parameters of LWFA

- **Diffraction** of laser pulse
  - Approx. Rayleigh length
  - External guiding, relativistic self-focusing

$$z_R = \pi \frac{w_0^2}{\lambda_0}$$

- **Depletion** of laser pulse:
  - laser energy transfer to plasma wake

$$L_{pd} \simeq \frac{c}{v_{etch}} c\tau \simeq \left(\frac{\omega_0}{\omega_P} \right)^2 c\tau$$

- **Dephasing** of electrons:
  - entering the decelerating phase

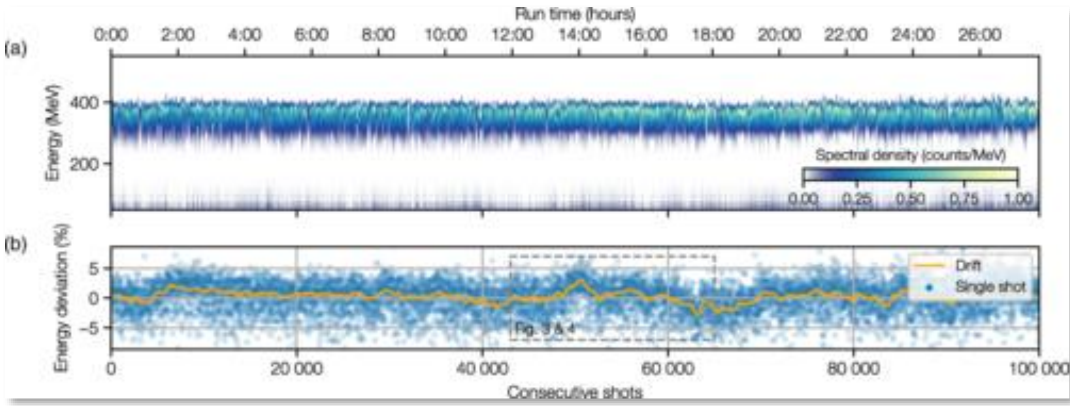
$$L_{deph} \simeq \frac{2\omega_0^2}{3\omega_P^2} R_b \propto \frac{1}{n_p^{3/2}}$$

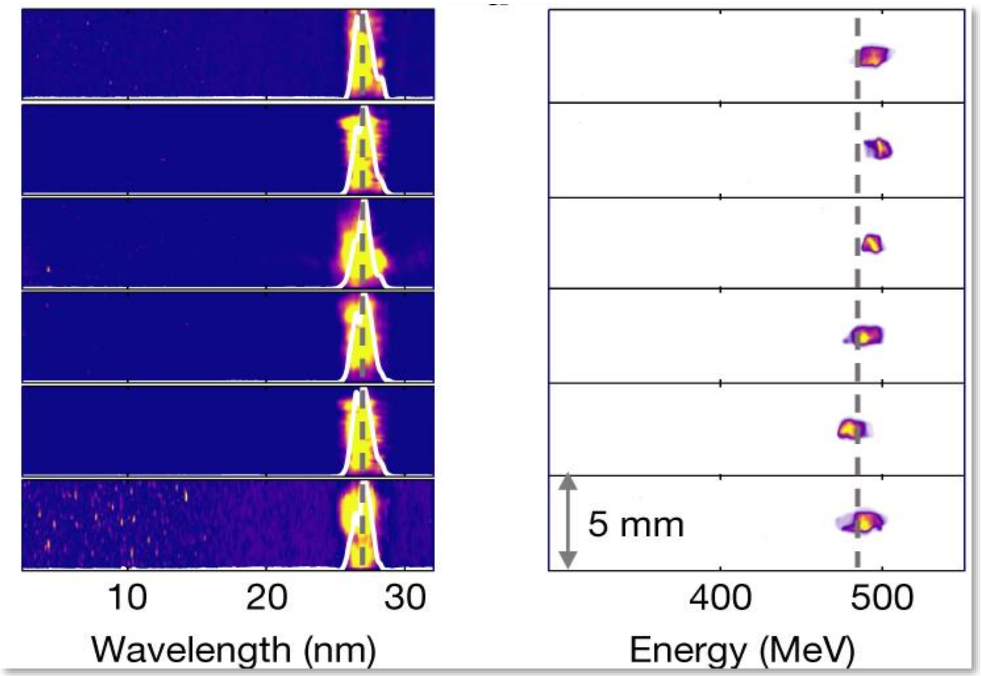
Optimal performing LWFA for

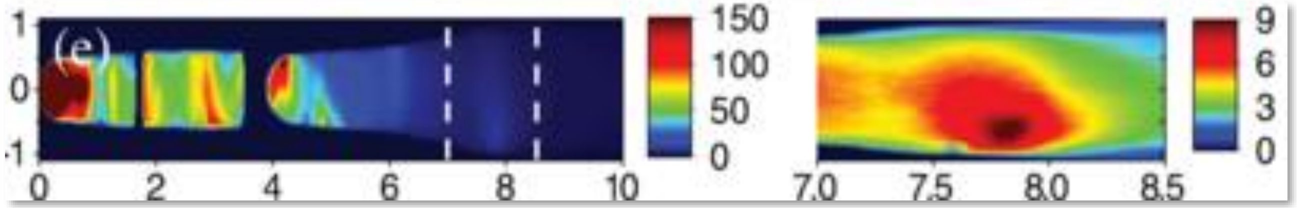
- guiding and
- depletion length ~ dephasing length

State of the Art: Experimentally achieved Beam Parameters

- Up to **8 GeV** bunch energies (Gonsalves *et al.*, PRL 122, 084801(2019))
- High bunch charges of **600 pC** (Li *et al.*, Phys. Plasmas 24, 023108 (2017))
- Low energy spreads of ~1% (Wang *et al.*, PRL 117, 124891(2016))
- Short rms-bunch duration of 10fs (Zarini et al. PRAB 25, 012801 (2022))
- Low emittance of **0.1 mm mrad** (Plateau et al., PRL 109, 64802(2012))
- High shot-to-shot **stability** (Maier et al., PRX, 10, 031039(2020))
- **Free-electron lasing** at 27nm (Wang et al., Nat., 595, 516–520(2021))
- Studies on high charges (Götzfried et al., PRX, 10, 041015(2020))







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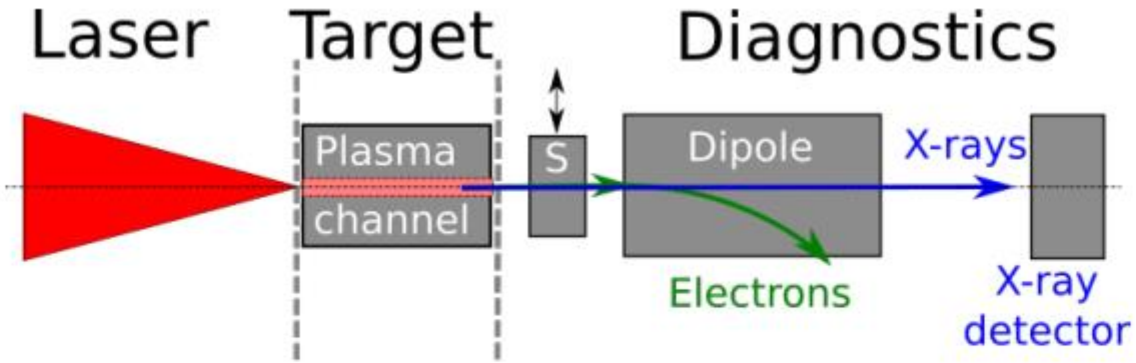
Typical basic setup for LWFA



- Laser
  - 30…100fs (FWHM) pulse width
  - Has several Joules of energy
  - Focussed to 10s µm spot size
  - Critical: Strehl ratio

- Target
  - Low ionization threshold (10^{14}…10^{16} W/cm²)
  - Gas jet from nozzle
  - Gas-filled capillary

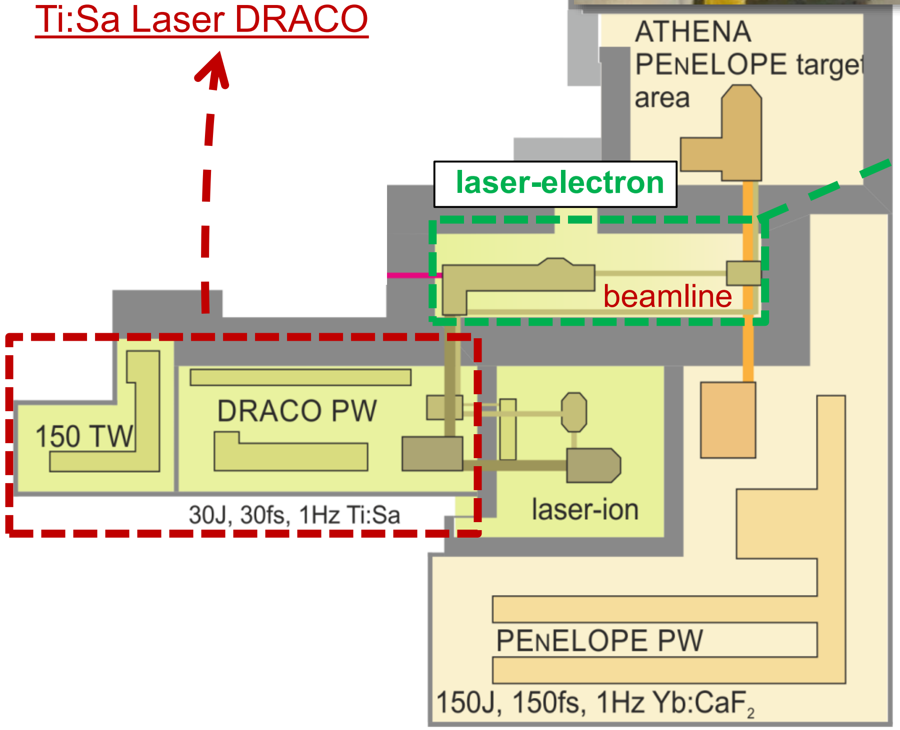
- Diagnostics
  - Charge (ICT, charge-calib. Screen)
  - Electron energy (magn. Dipole)
  - X-ray radiation (SPAE, crystals, scintillators)
  - Transition radiation
  - Transverse probing

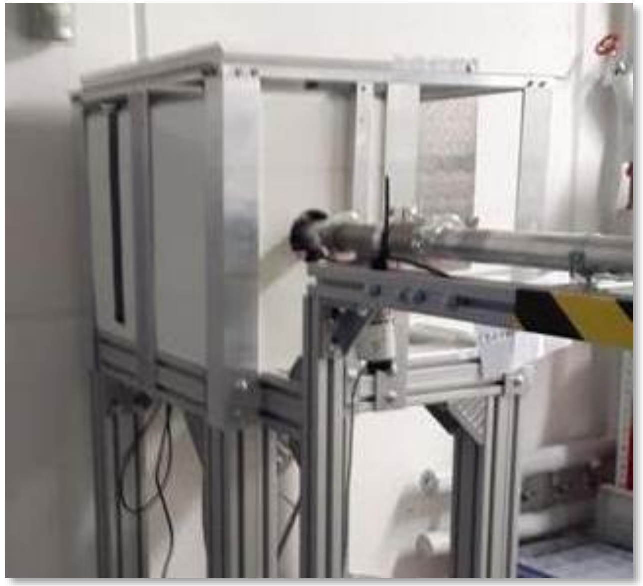
Experimental area at the HZDR

- λ_0 = 800 nm
- up to 4 J on target
- 27 fs pulse width (FWHM)
- Strehl-ratio > 0.9
- 20 µm FWHM

Ti:Sa Laser DRACO

Experimental cave



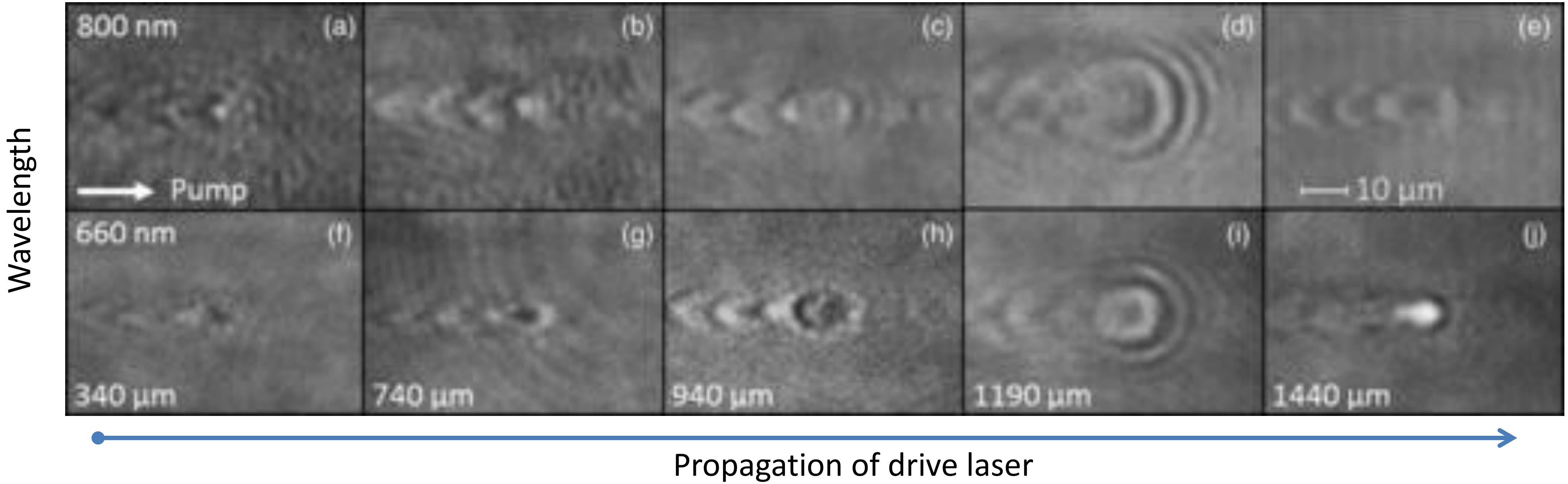


Betatron spectrometer

~12 m distance from source
→ **attenuation** of high x-ray flux

U. Schramm et al. J. Phys. Conf. Ser., 874, 012028 (2017), PhD Thesis A. Köhler (2019)

Transverse probing: Imaging of the plasma cavity



- Same laser source for drive and transverse probe
  -> inherently **synchronized** beams (e.g. pickup)
- Probe is **few-cycle beam** (fraction of main laser pulse duration)
- Taking multiple shots with **different timing** between pulses

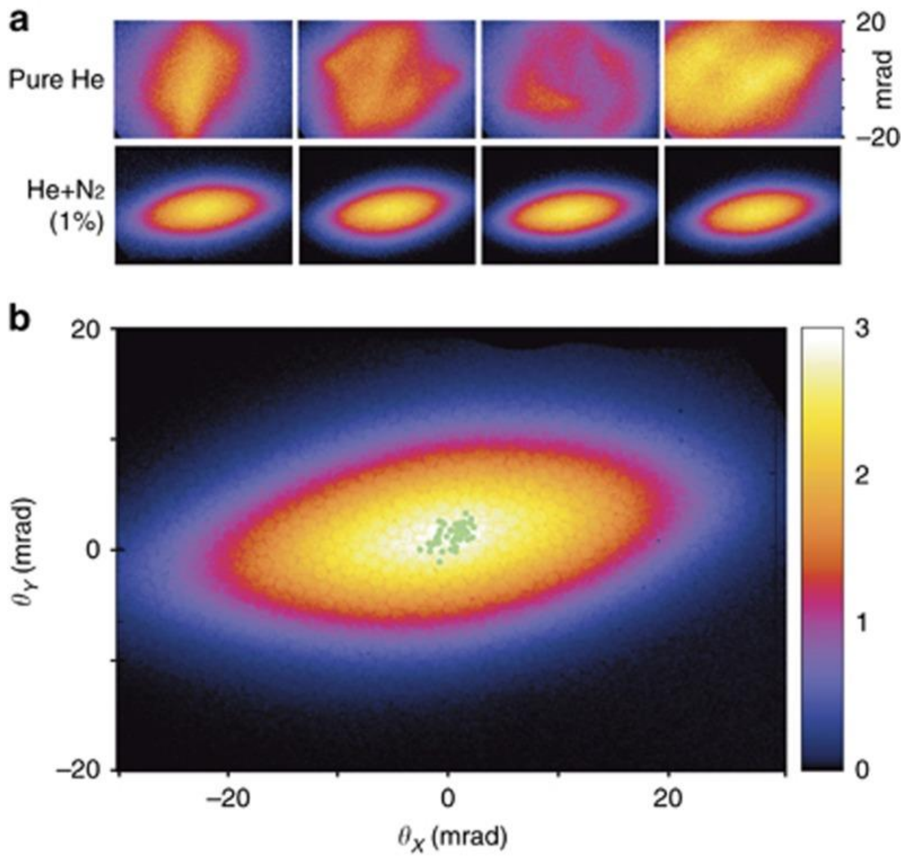
-> Allowing to study the **shape of the cavity**

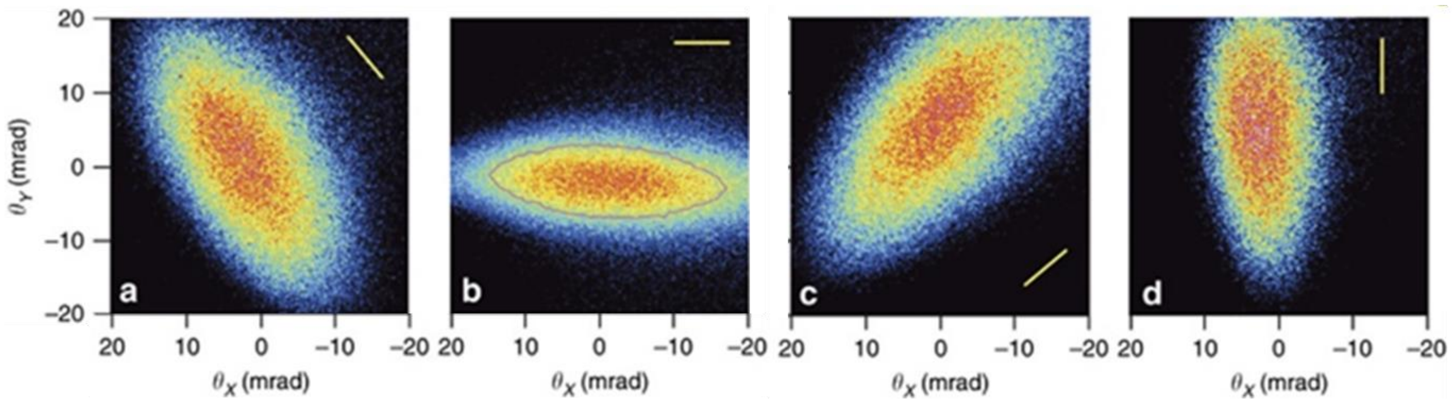
-> Space charge effects can cause reshaping of the cavity

Schwab *et al.*, PRAB 23, 032801(2020),
Schöbel *et al.*, NJP 24, 083034(2022)

Betatron profile indicates orientation of oscillation plane

- **Scintillating screen** (e.g. CsI) on beam axis detects spatial profile of x-rays
- Profile depends on **injection scheme**
- Ionization injection improves shot-to-shot **reproducibility**
- Laser polarization can steer the orientation of the angular profile

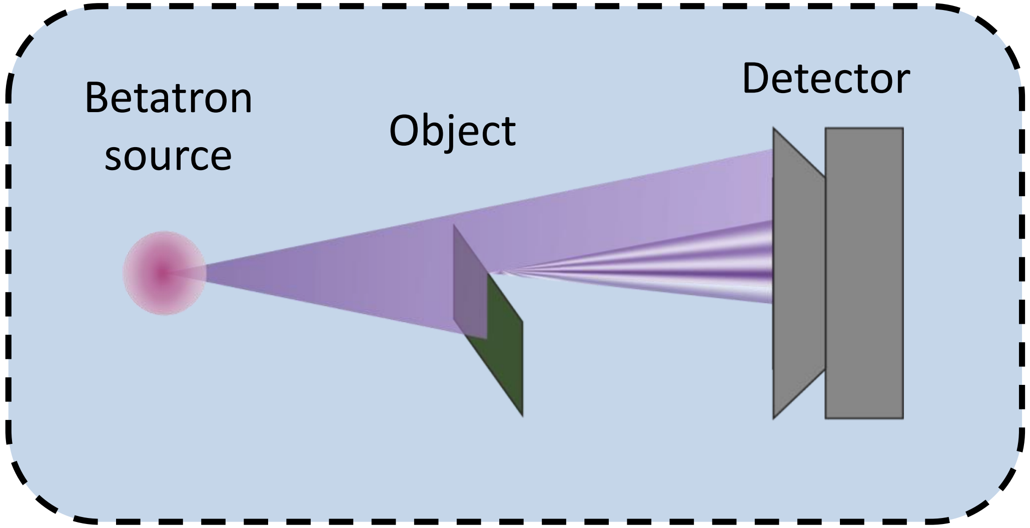


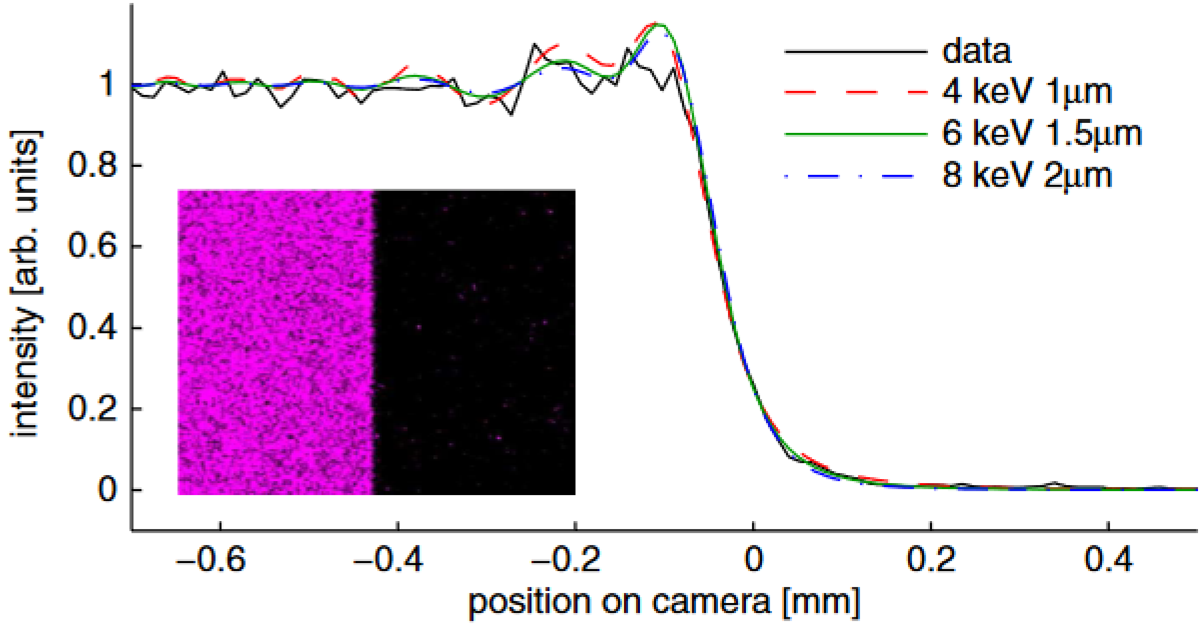


K. Phuoc *et al.*, PRL (2006), Döpp *et al.*, Light Sci Appl 6, e17086 (2017)

Measuring the betatron source size by Frensel diffraction

- Object obstructs betatron beam
- **Fresnel diffraction** at a sharp edge
- Fit on fringes returns the **source size** and critical energy

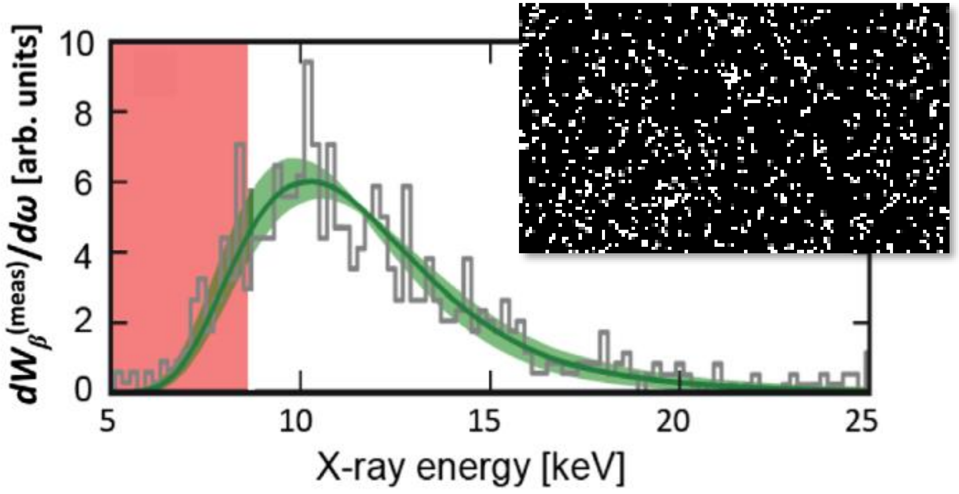




Kneip et al. PRSTAB 15, 021302(2012)

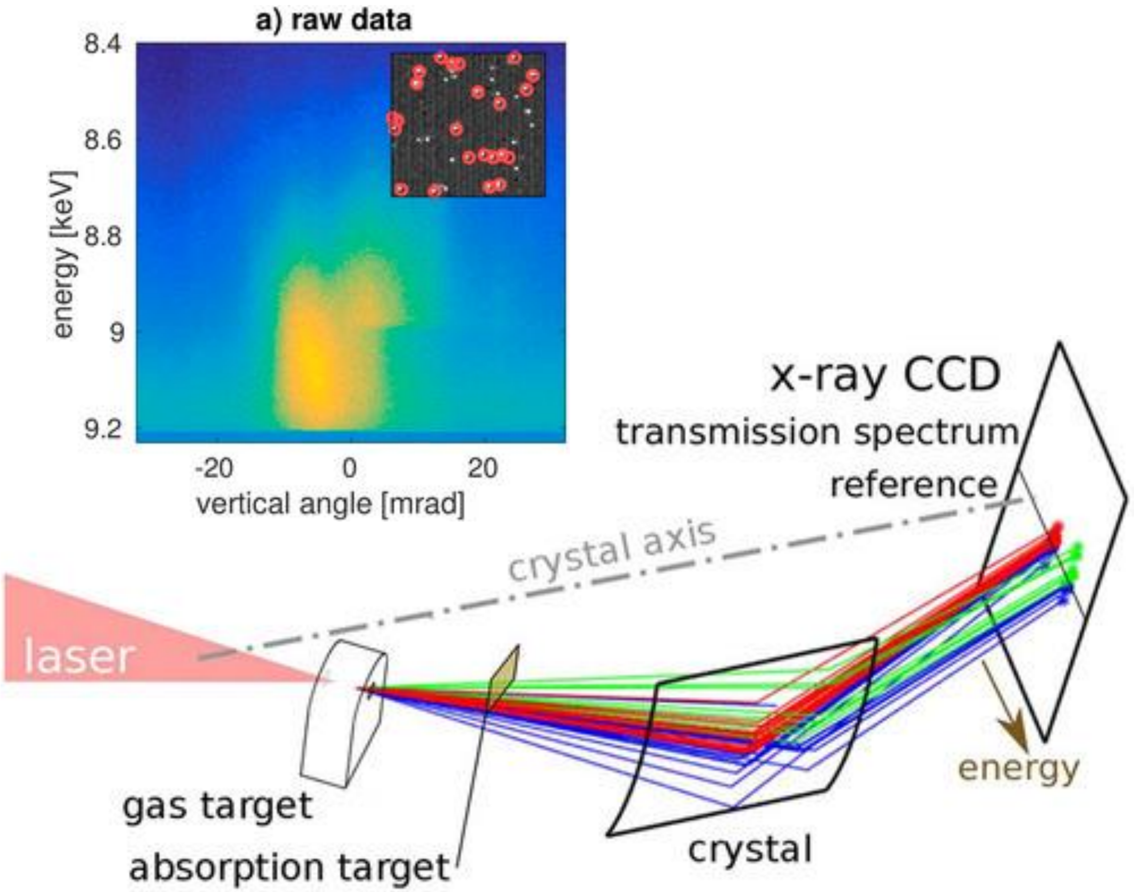
Detection methods for the betatron spectrum

Detection of **single photon events** (SPAE)
-> Photon energy proportional to charge on CCD
-> requires low flux for correct binning



Betatron radius can be deduced from the shape of the **betatron spectrum**
-> Beam size

Crystals for **X-ray diffraction**
-> diffraction angle depends on energy
-> low efficiency is suitable for high flux

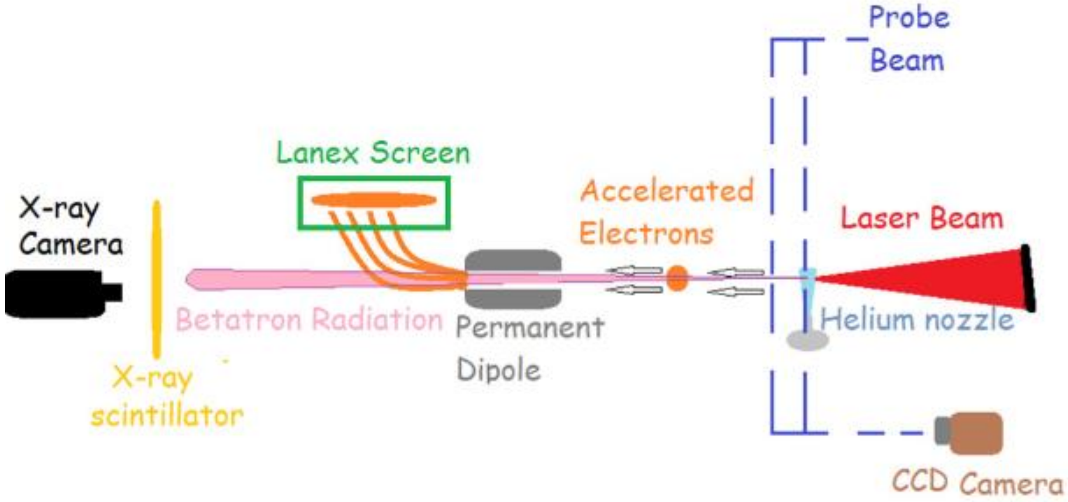


Köhler *et al.,* NIMA 829, 265-269(2016) , Smid *et al.*, Rev.Sci.Instr. 88, 063102(2017), Downer *et al.*, Rev.Mod.Phys. 90(2018)

Reconstructing the trace space of low emittance beams

Simultaneous, single-shot measurements of:

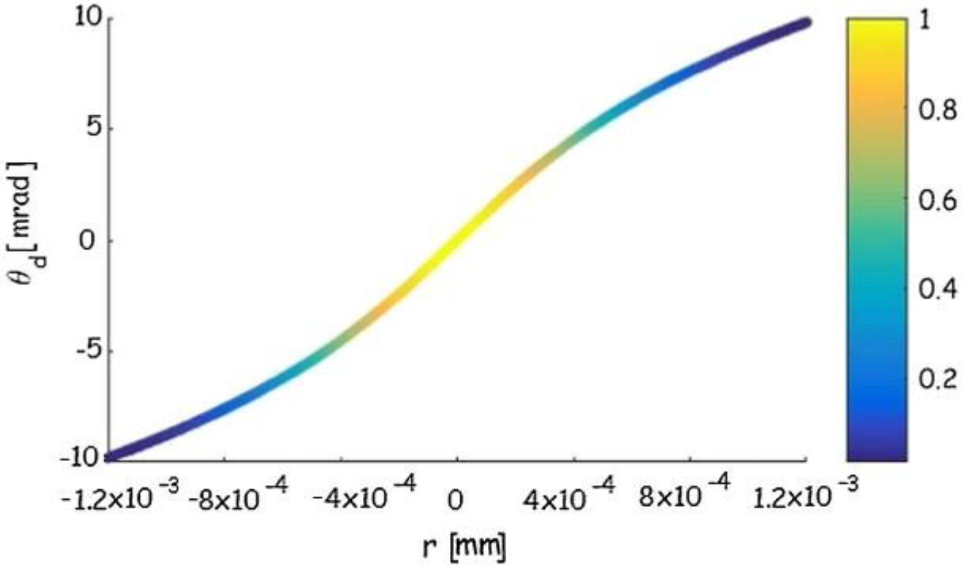
- Electron spectrum,
- Betatron spectrum, and
- Plasma density



A model that including all three quantities could reconstruct:

-> **Trace space** of the bunch

-> **Emittance** with correlation term



Curcio et al., PRAB 20, 012801(2017)

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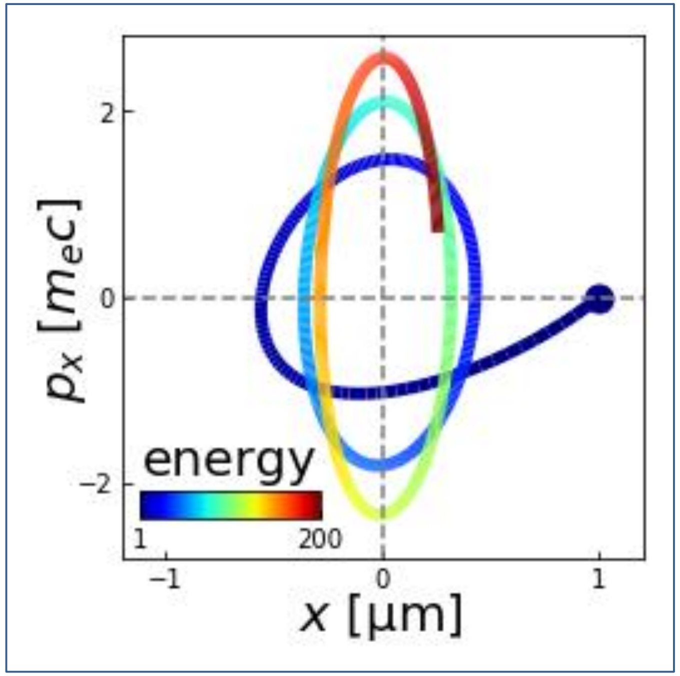
Electron dynamic in the transverse phase space

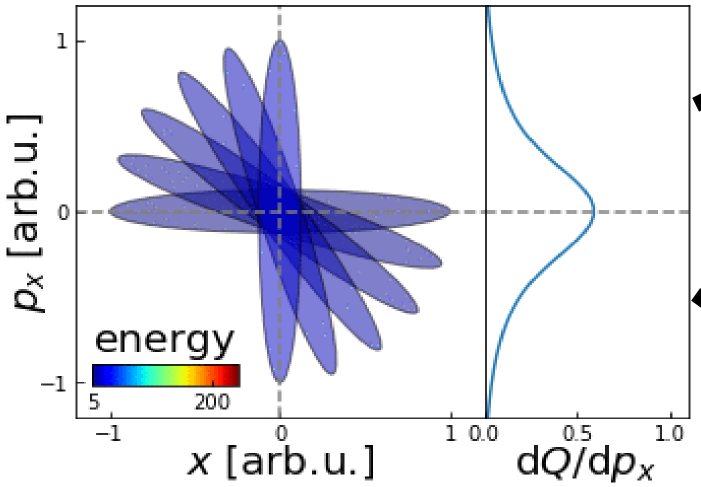
- Transverse phase space represents **possible electron dynamic**
  → transverse position x and momentum p_x
- Electron orbits with **energy-dependent** betatron frequency $\omega_\beta = \frac{\omega_p}{\sqrt{2\gamma(t)}}$



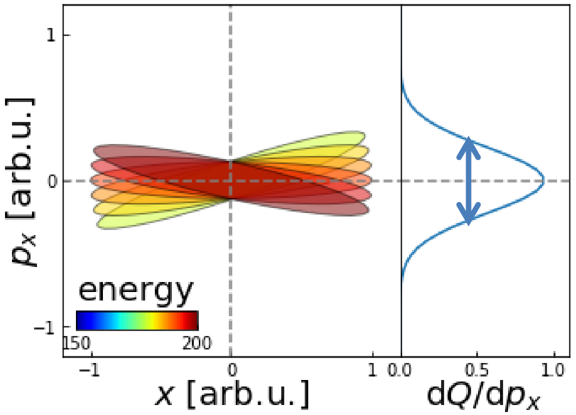
Khachatryan *et al.* PRSTAB (2007)

Coupling of energy spread and phase advance

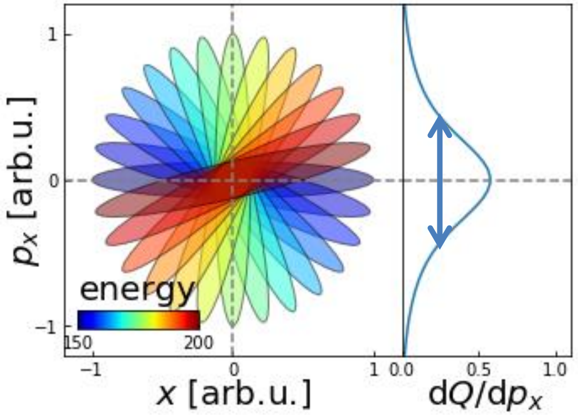
- Bunch has finite **length** and **energy spread**
- **Slices** for each energy



- Small energy sprea → Small divergence possible



- Large energy spread → Full decoherence



→ **energy-dependent** rotation with betatron frequency

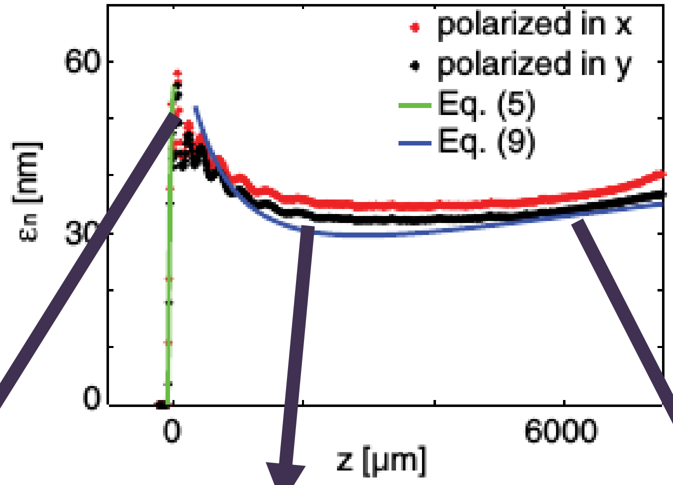
→ **energy spread** causes betatron **phase difference** $\boldsymbol{\Delta\phi}$

Koehler *et al.*, PRAB, 24, 091302(2021)

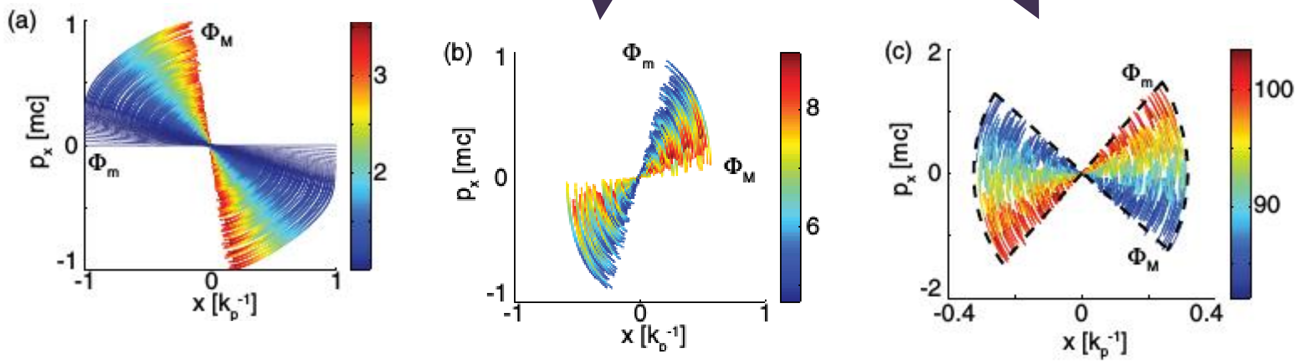
Phase space dynamics in plasma-wakefield accelerators

0) Injection: Emittance rapidly growing
1) End of injection: finite length and energy spread, max. emittance
2) Betatron phase mixing of bunch length and energy spread, emittance decreases again
3) Growing emittance dominated by energy spread
   -> approaching **saturated emittance**

Normalized emittance



$$\epsilon_N \approx \epsilon_{sat} \frac{\Delta\Phi}{\sqrt{3}}$$



$$\Delta\Phi \approx \sqrt{2(E_{zm} z_M + 1)}/E_{zm} - \sqrt{2(E_{zM} z_m + 1)}/E_{zM}$$

X. L. Xu *et al.* PRL 112,035003 (2014)

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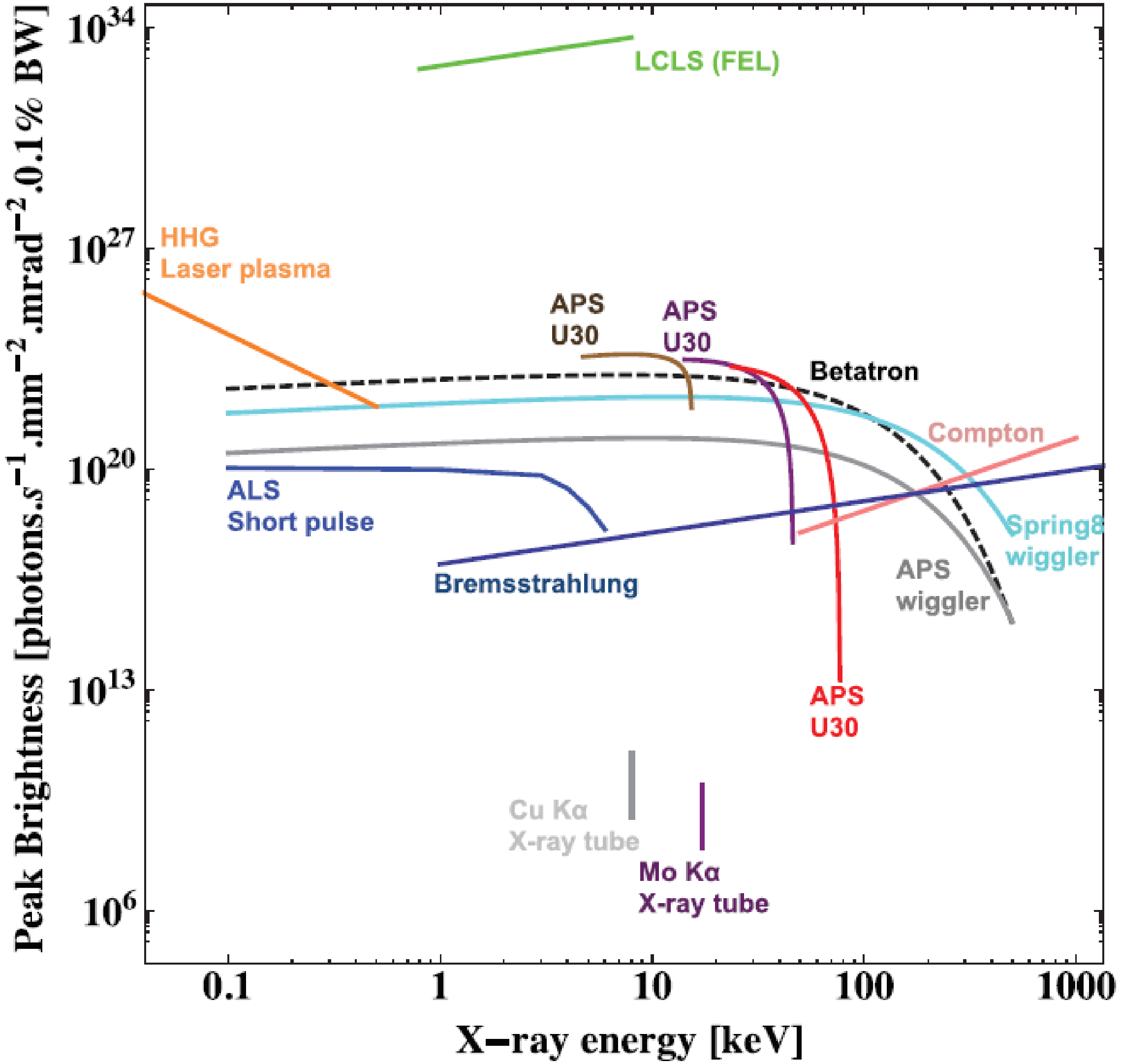
Conventional and plasma-based light sources

Sources driven by LWFA

- FEL
- Undulator, wiggler
- Compton, Thomson
- Betatron
- Bremsstrahlung



F. Abert, A. Thomas, Plasma Phys. Control. Fusion **58** (2016)

Example: Betatron radiation as x-ray source

Property	Typical
Wavelength	1…0.1nm
Spectrum	broadband
Spot size	~ 1µm
Divergence	~ 10mrad
Pulse length	< tens fs

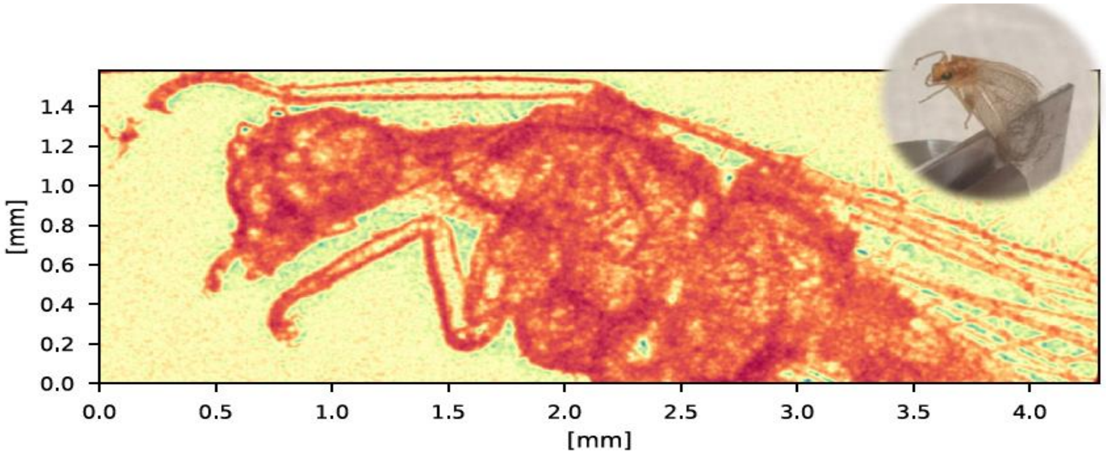
→ X-ray source with high peak flux

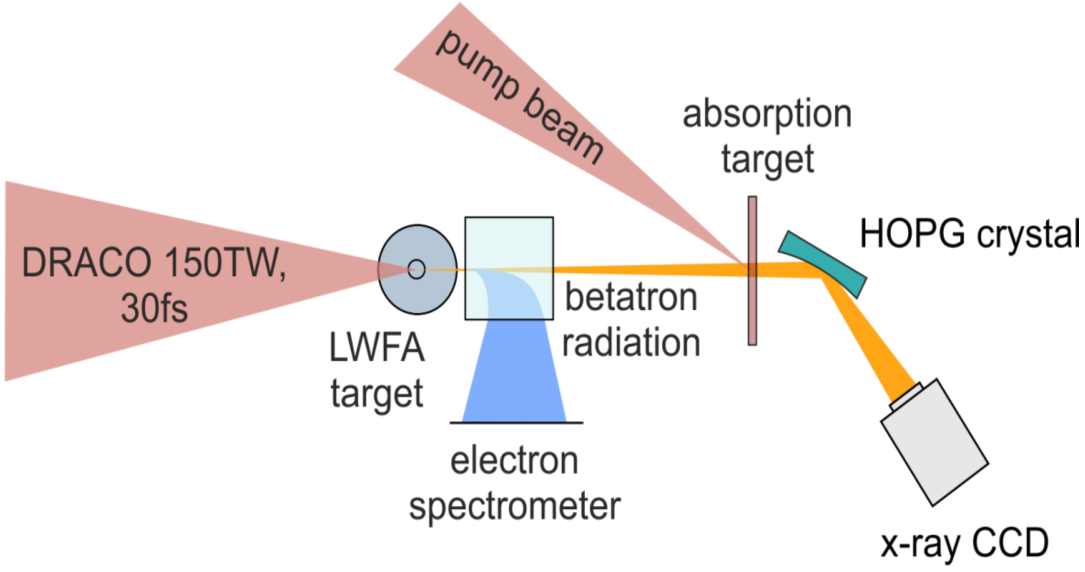
$\sim 10^8 \frac{\text{photons}}{\text{eV mm}^2\text{mrad}^2}$

@ 10 keV

→ Possible applications

- Phase contrast imaging
- Near-edge absorption spectroscopy





Conclusion and Outlook

- LWFA has demonstrated impressive beam parameters
- **Free-electron lasing** has been shown with LWFA and PWFA
- Plasma accelerators require new advanced, single-shot diagnostics

- Plasma accelerators are ready to use as a new driver for light sources and pump-probe experiments

THANK YOU FOR YOUR ATTENTION!