Laser-wakefield accelerators as drivers for undulator-based lightsources

Matthias Fuchs

32nd International FEL Conference
Malmö, 26.08.2010

Co workers

Institute	Name(s)	Task
LMU Ludwig-Maximilians-Universität München, MPQ	R. Weingartner, J. Osterhoff, A. Popp, Zs. Major, **S. Karsch**, **F. Krausz**, **F.Grüner**	FEL team electron acceleration laser development
FZD Forschungszentrum Dresden Rossendorf	U. Schramm	undulator & mini-quad design
PSI	S. Reiche	FEL simulations
DESY	W. Decking, T. Limberg, H. Schlarb, M. Dohlus, K. Flöttmann, C. Gert, B. Schmidt, J. Rossbach	diagnostic, space-charge, wakefields, FEL physics
BESSY	A. Meseck, J. Bahrdt, A. Gaupp	full FEL simulations, cryogenic undulator
Oxford Physics	T. P. Rowlands-Reese, S.M. Hooker	electron acceleration
Berkeley Lab	C. Schroeder, E. Esarey, B. Fawley, W. Leemans	FEL design study staged acceleration

Outline

- Laser-Wakefield Acceleration
  - the basics

- Spontaneous Undulator Source Driven by Laser-Wakefield Accelerated Beams
  - experimental results

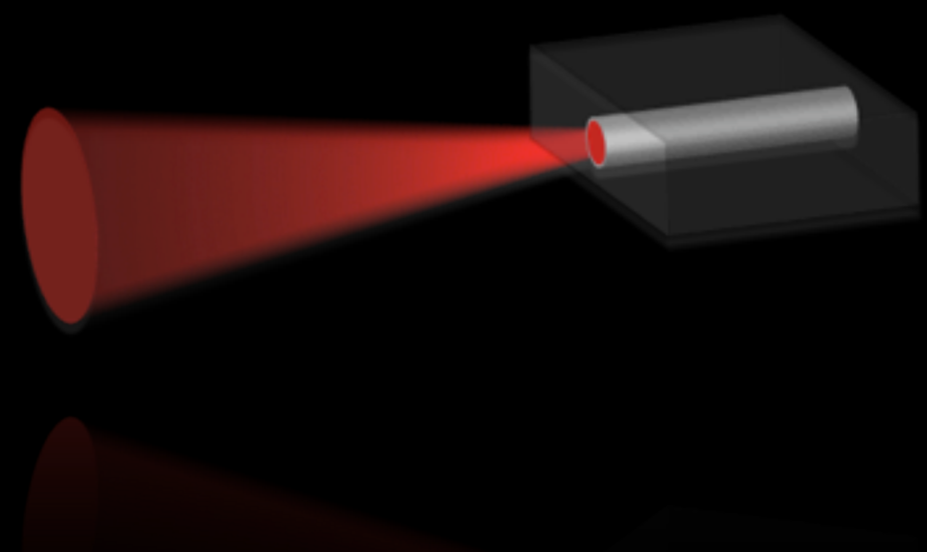
- Laser-wakefield Acceleration
  - the dirty details and problems
  - improvement of the beams

Laser-wakefield acceleration
World-wide Research Activities

Laser-wakefield electron acceleration

laser
power: ~ TW to PW
energy: ~ J
pulse length: ~ 5-50 fs

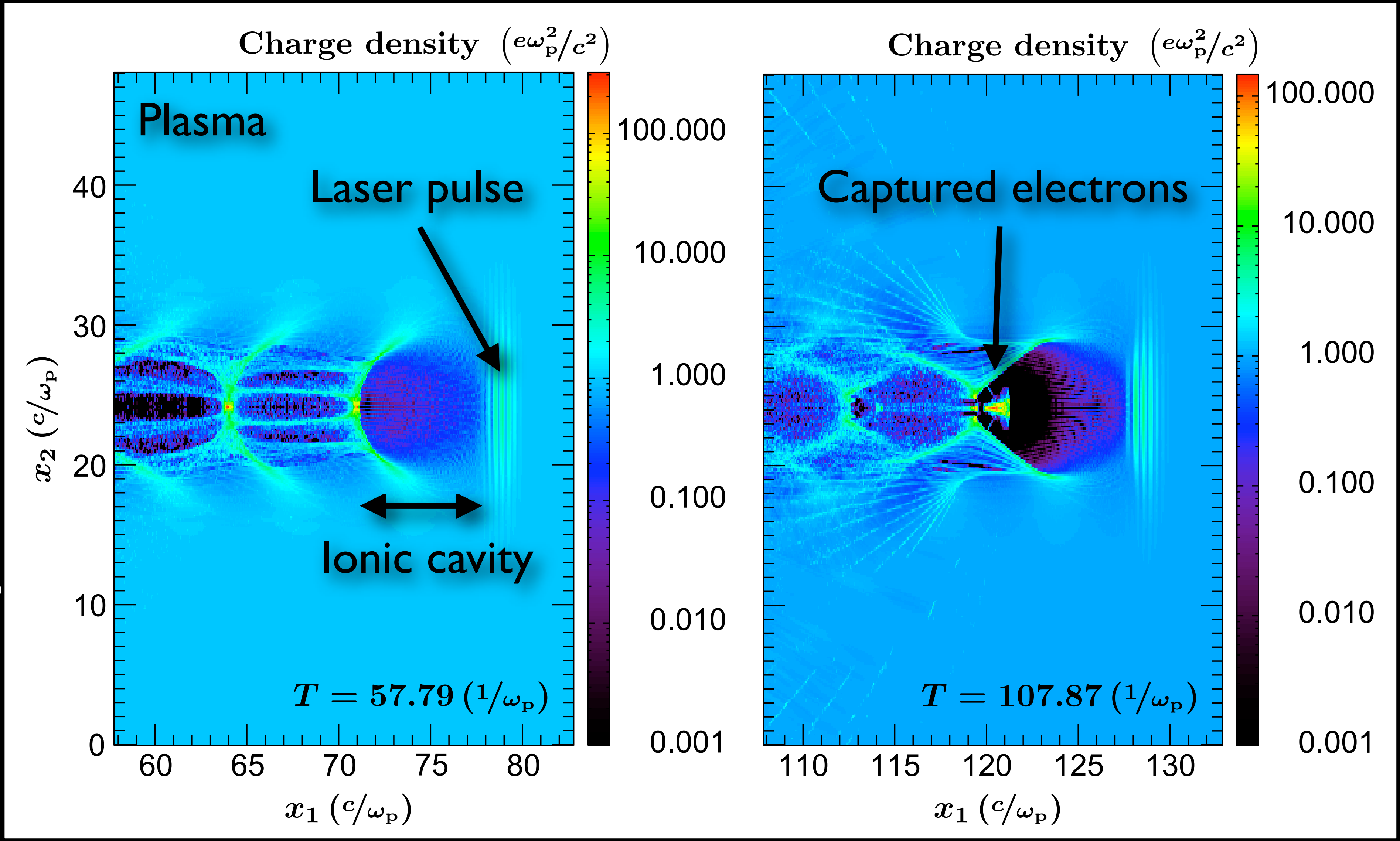
gas jet or **capillary:**
plasma



- **laser ionized atoms as it moves through the gas**

Laser-wakefield electro

Particle-in-Cell Simulation



"Bubble"
Meyer-ter-Vehn, Pukhov
Appl Phys B, 74, 355 (2002)

simulation: courtesy J. Osterhoff

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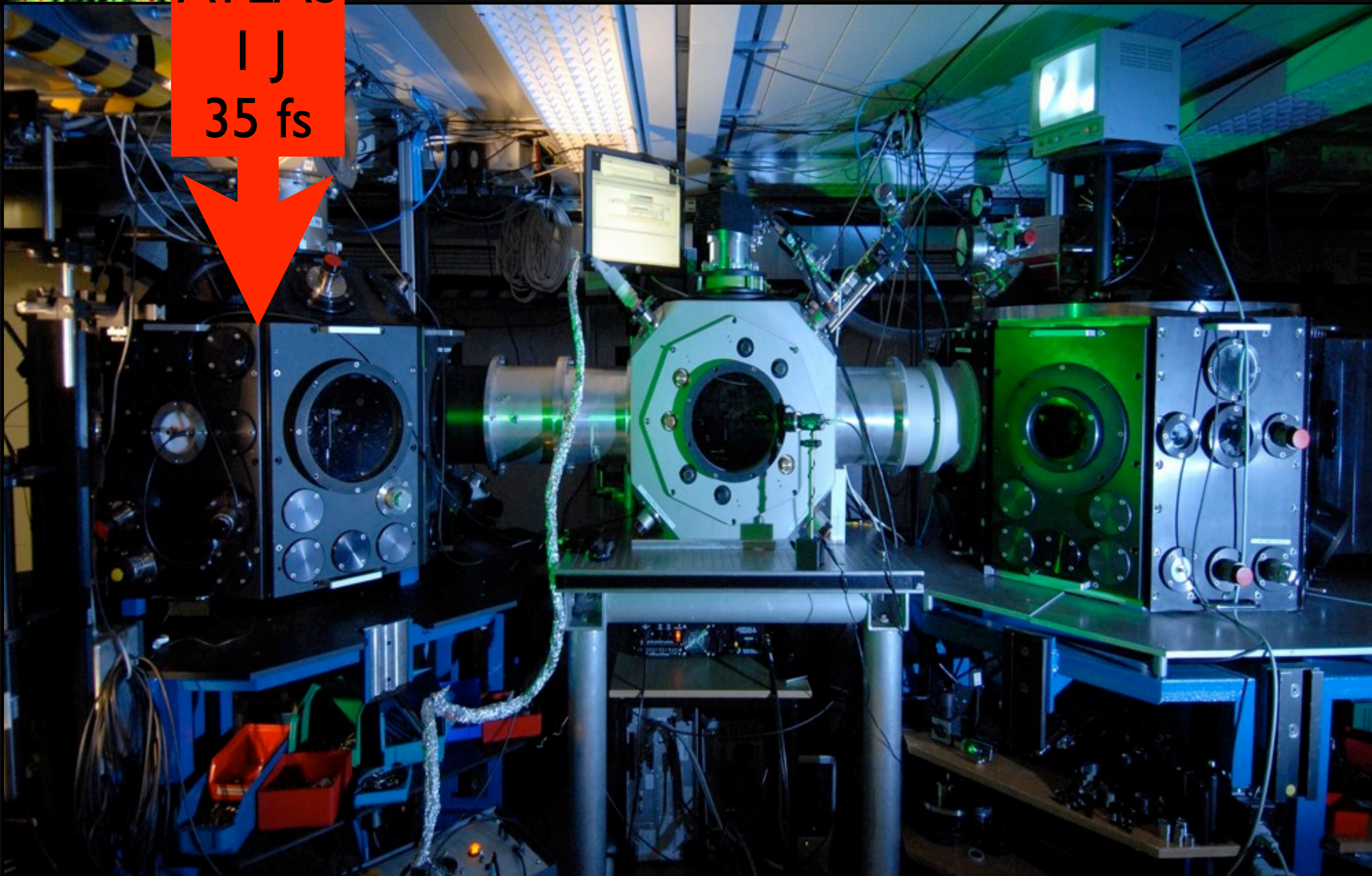
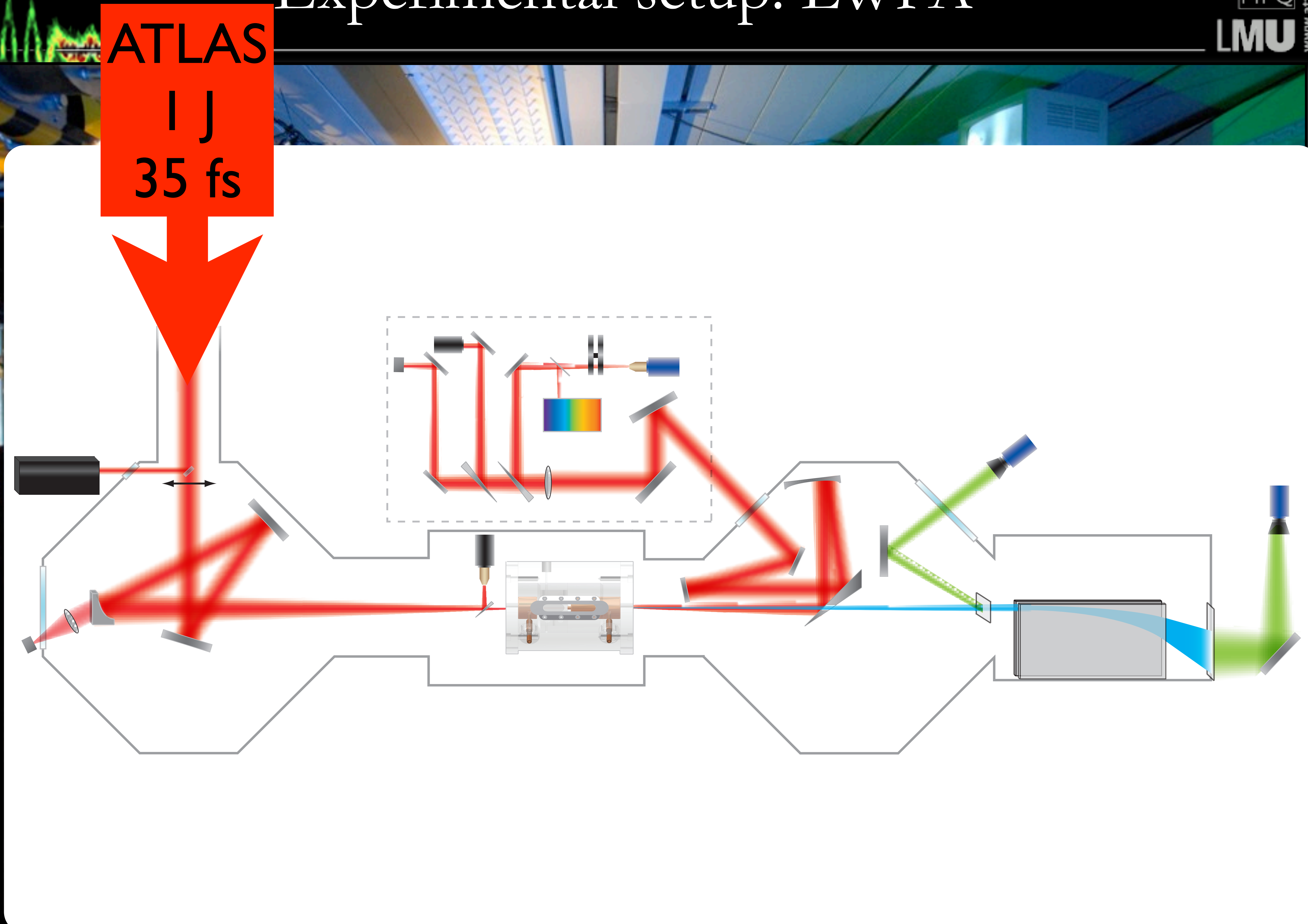
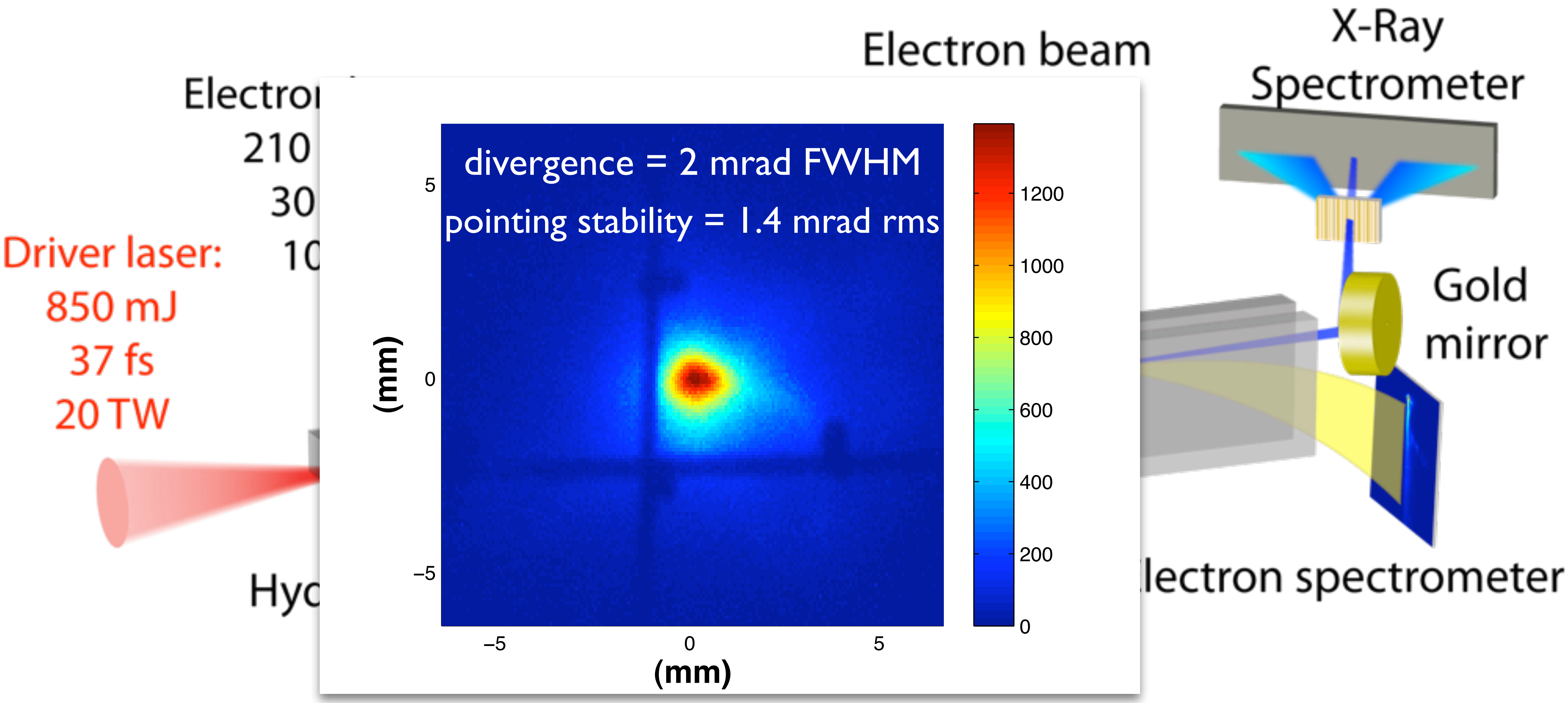
Experimental setup: LWFA



Experimental setup: LWFA

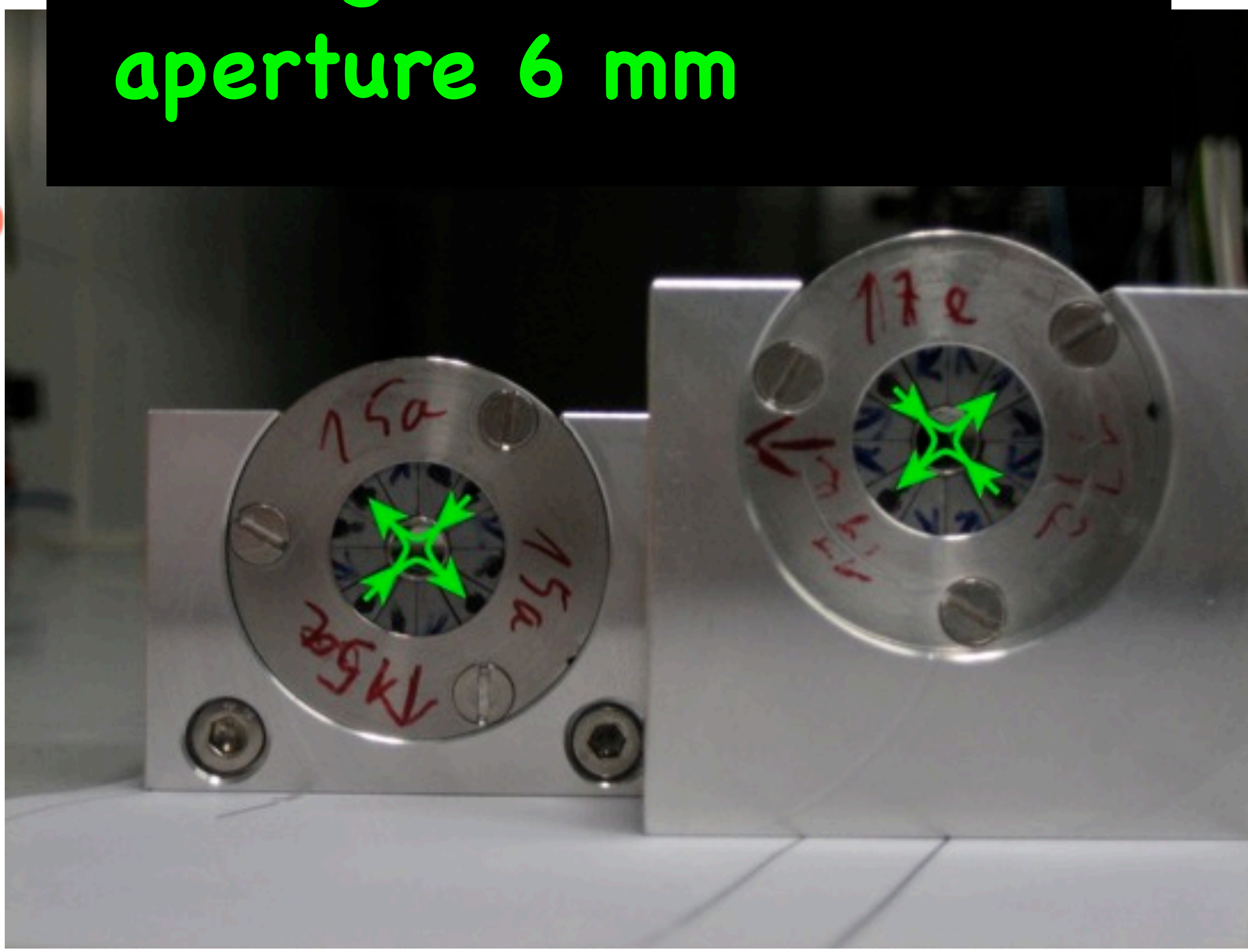


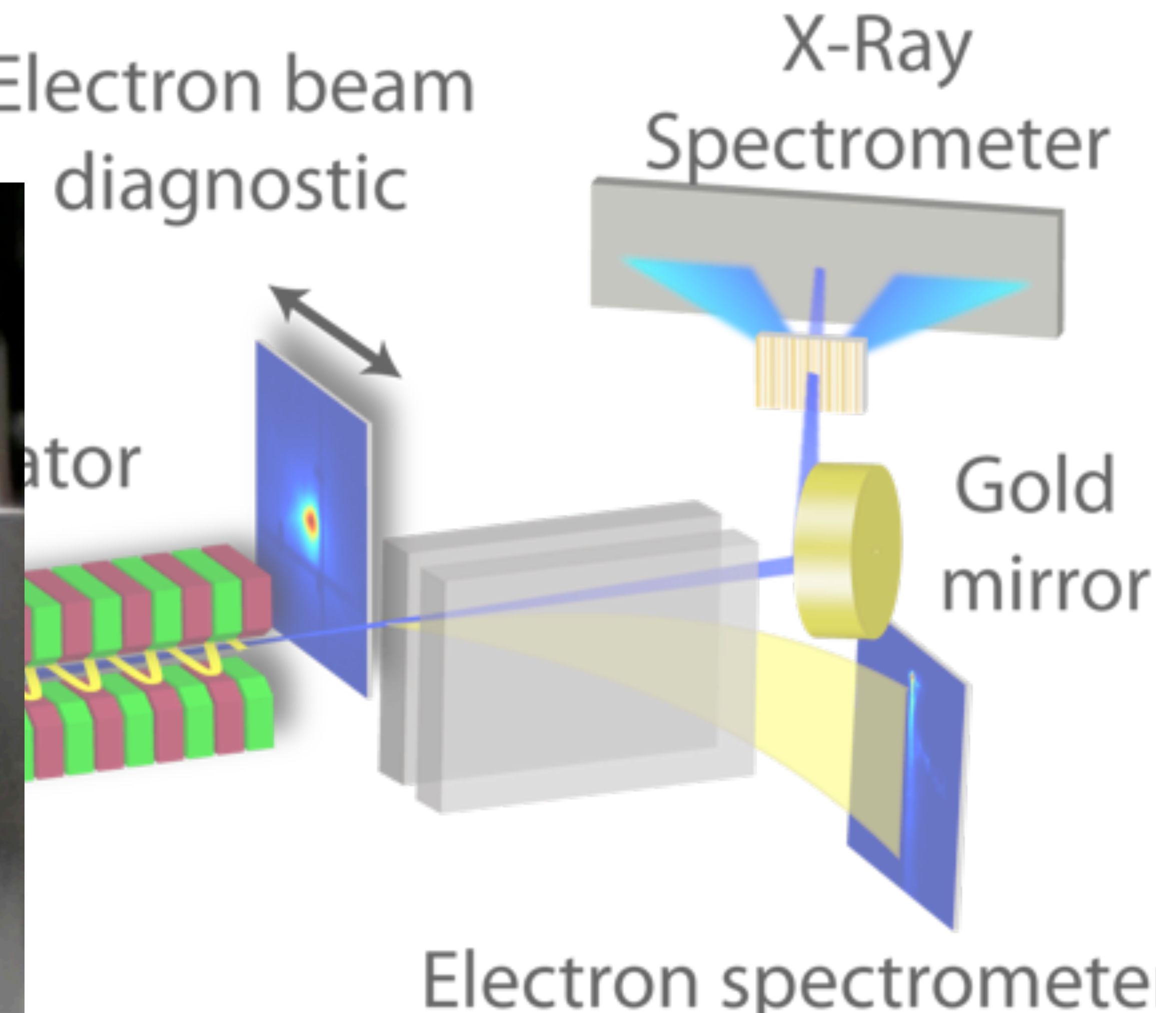
Setup Undulator Radiation



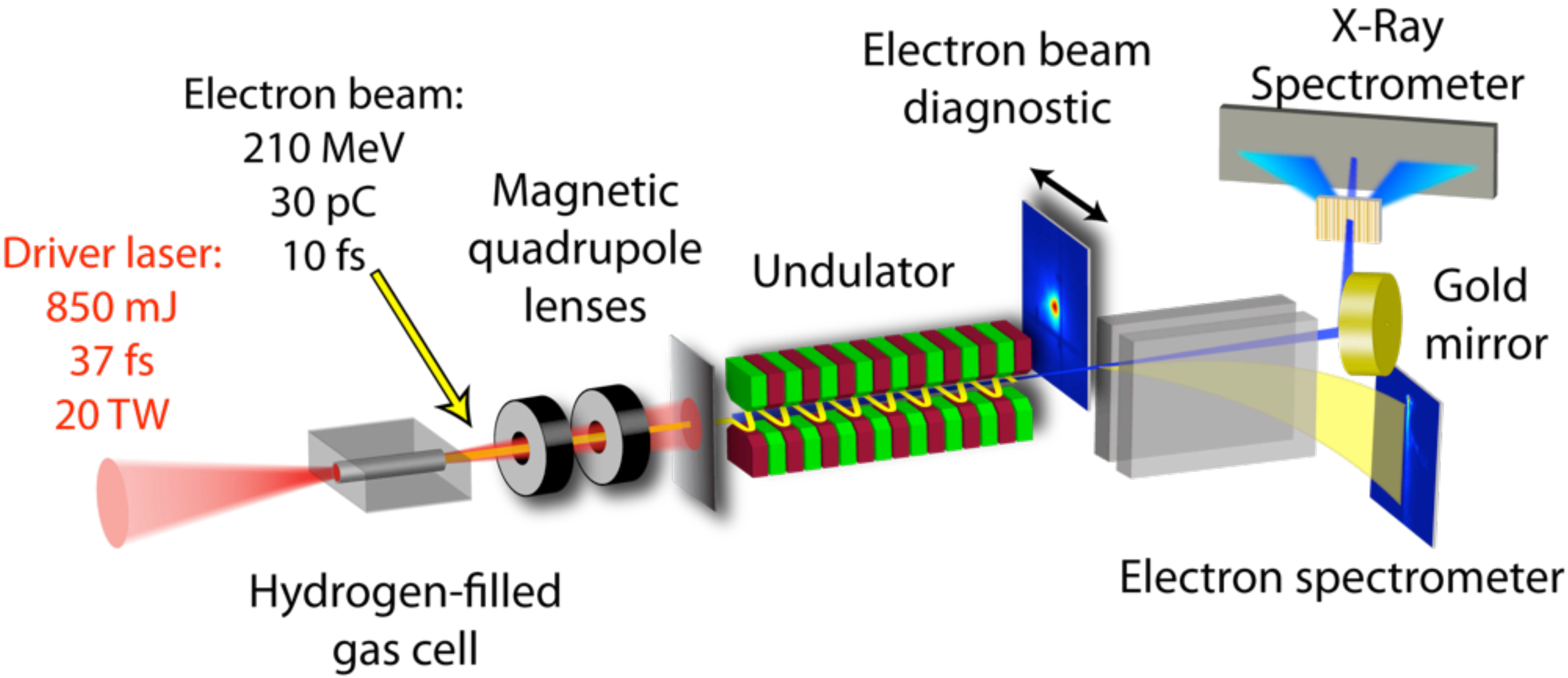
Setup Undulator Radiation

field gradient: 500 T/m
aperture 6 mm

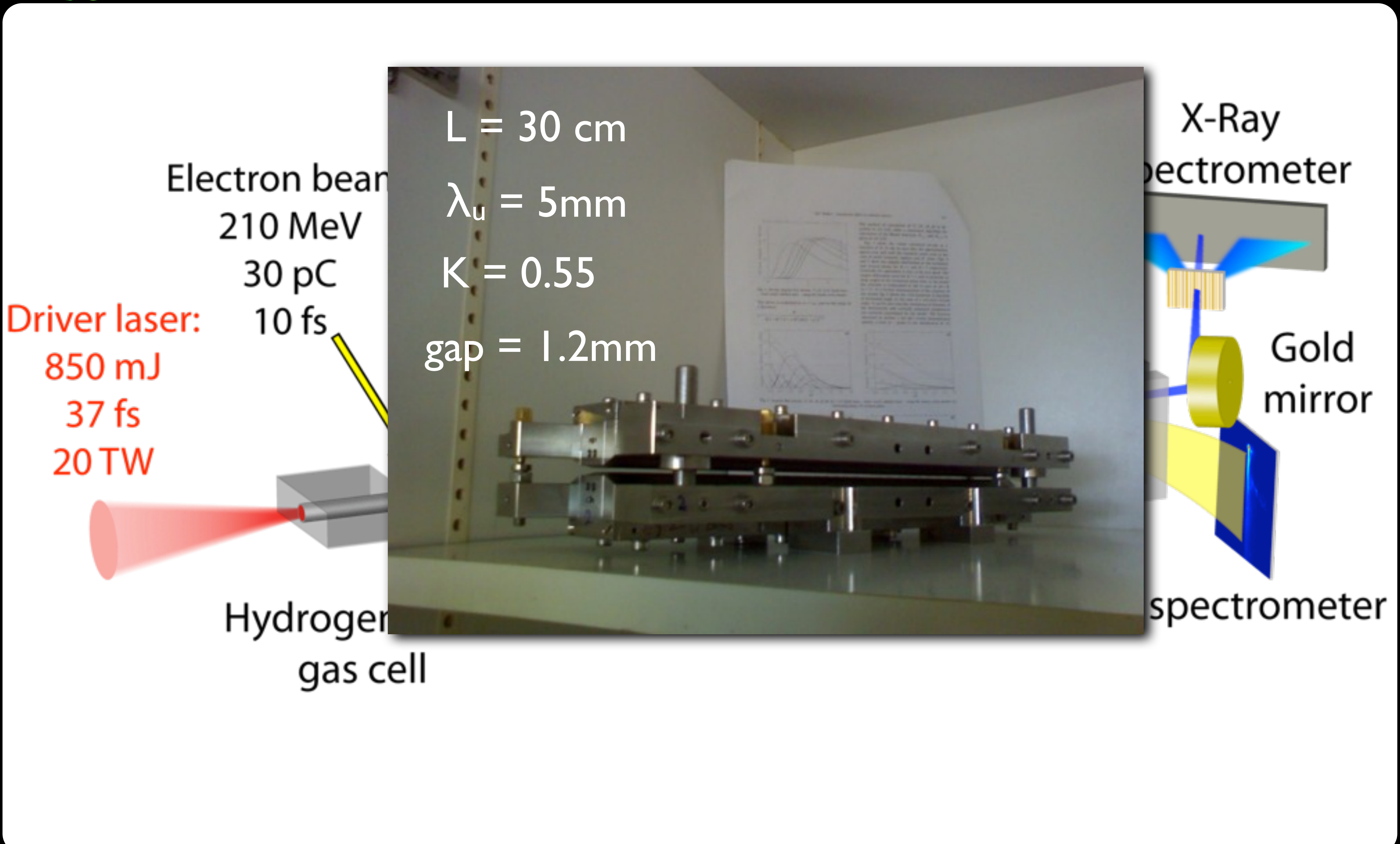




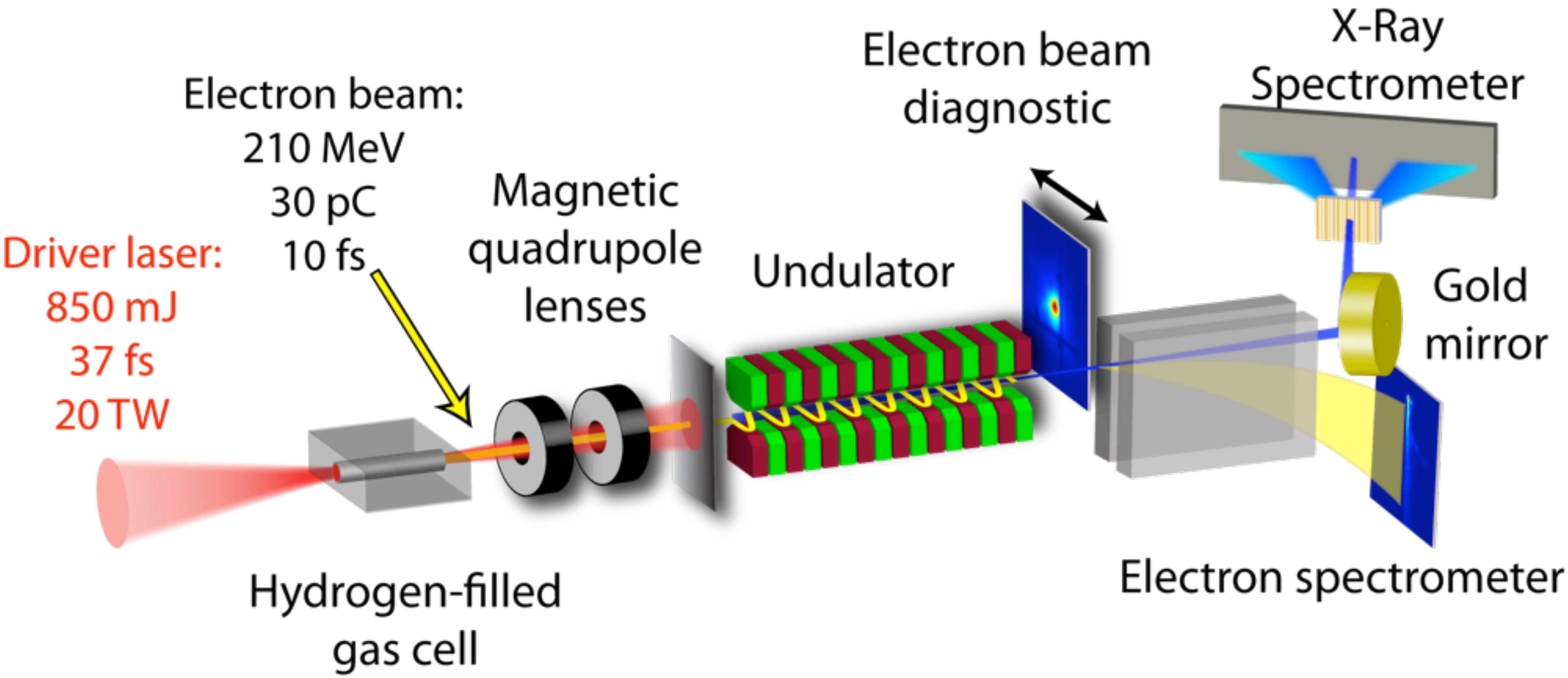
Setup Undulator Radiation



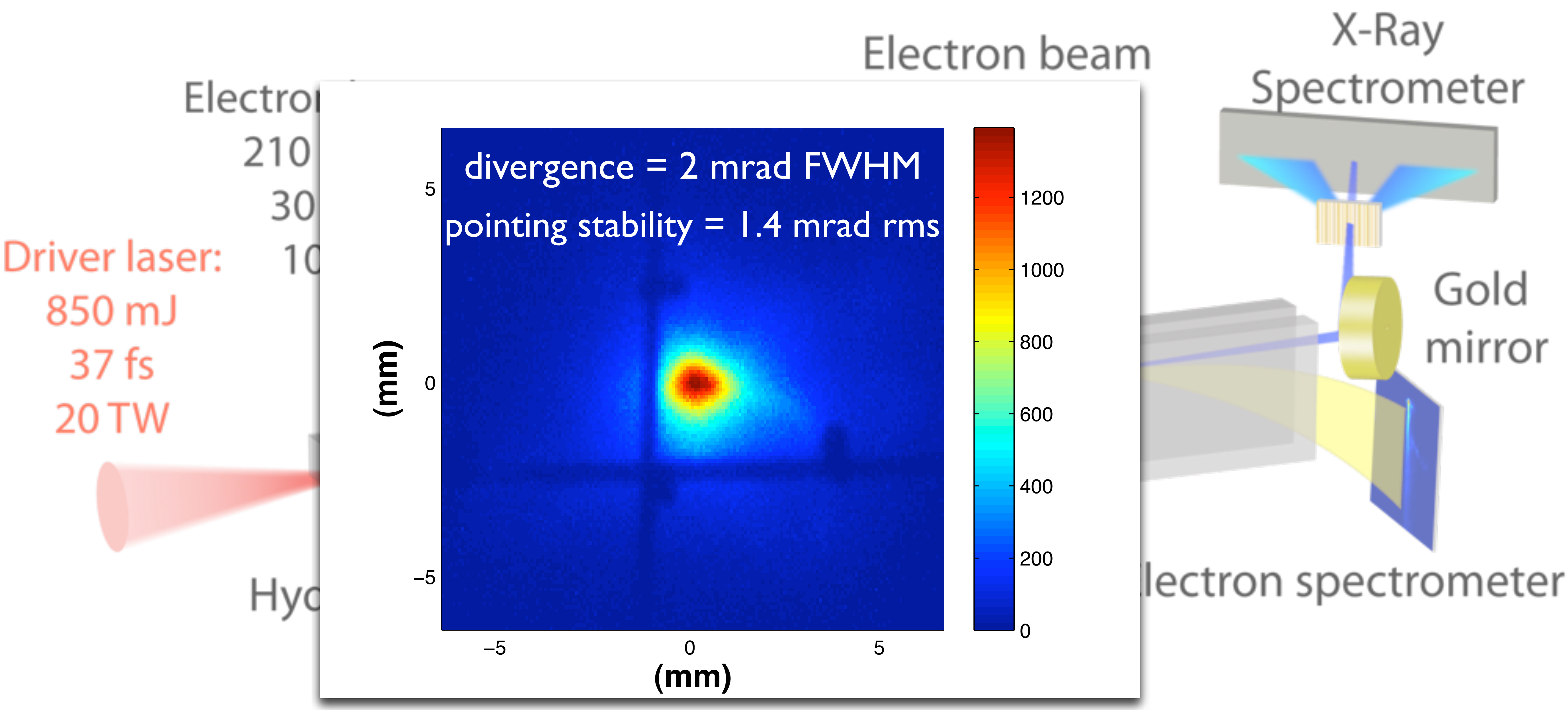
Setup Undulator Radiation



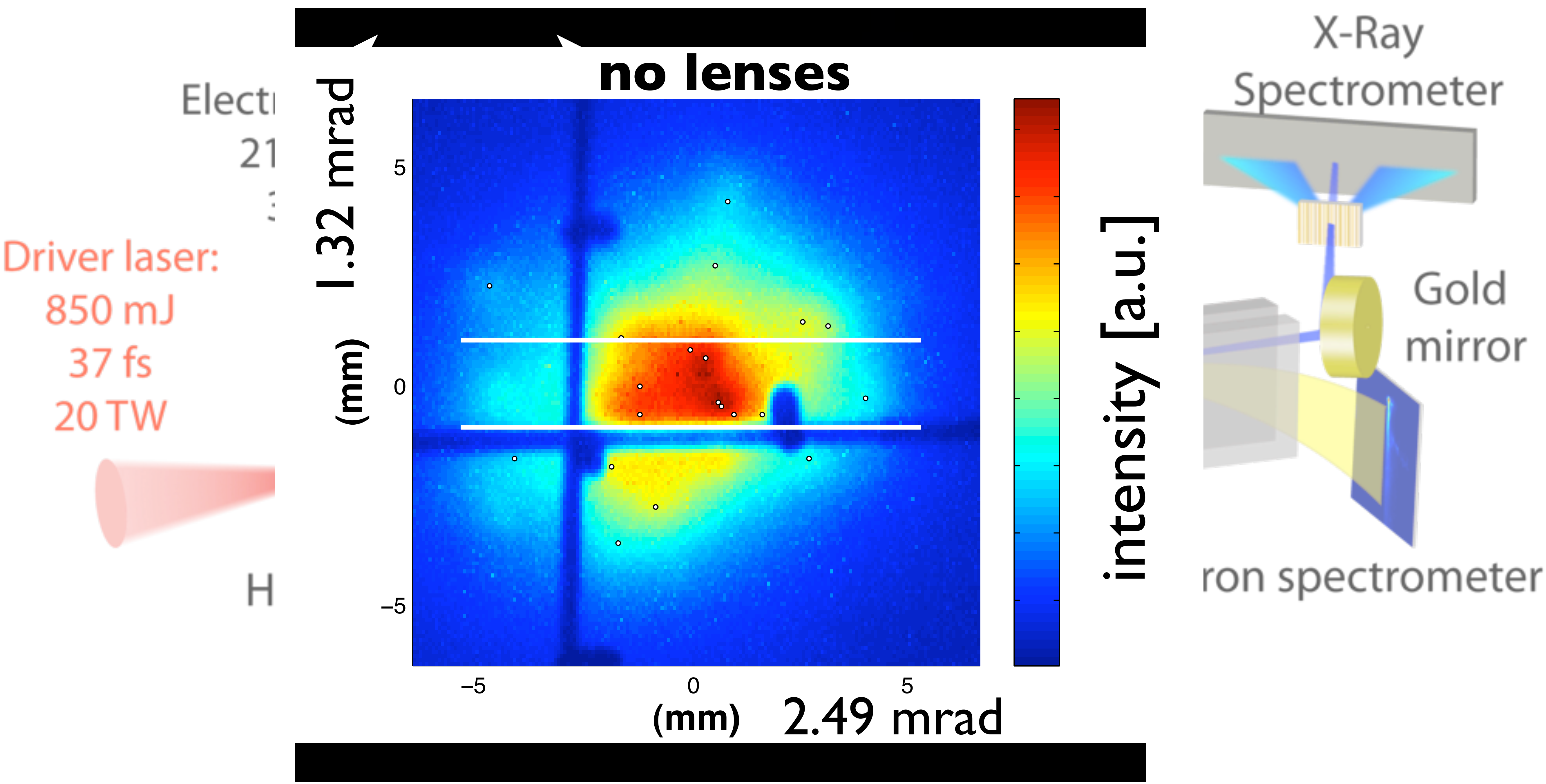
Setup Undulator Radiation



Setup Undulator Radiation

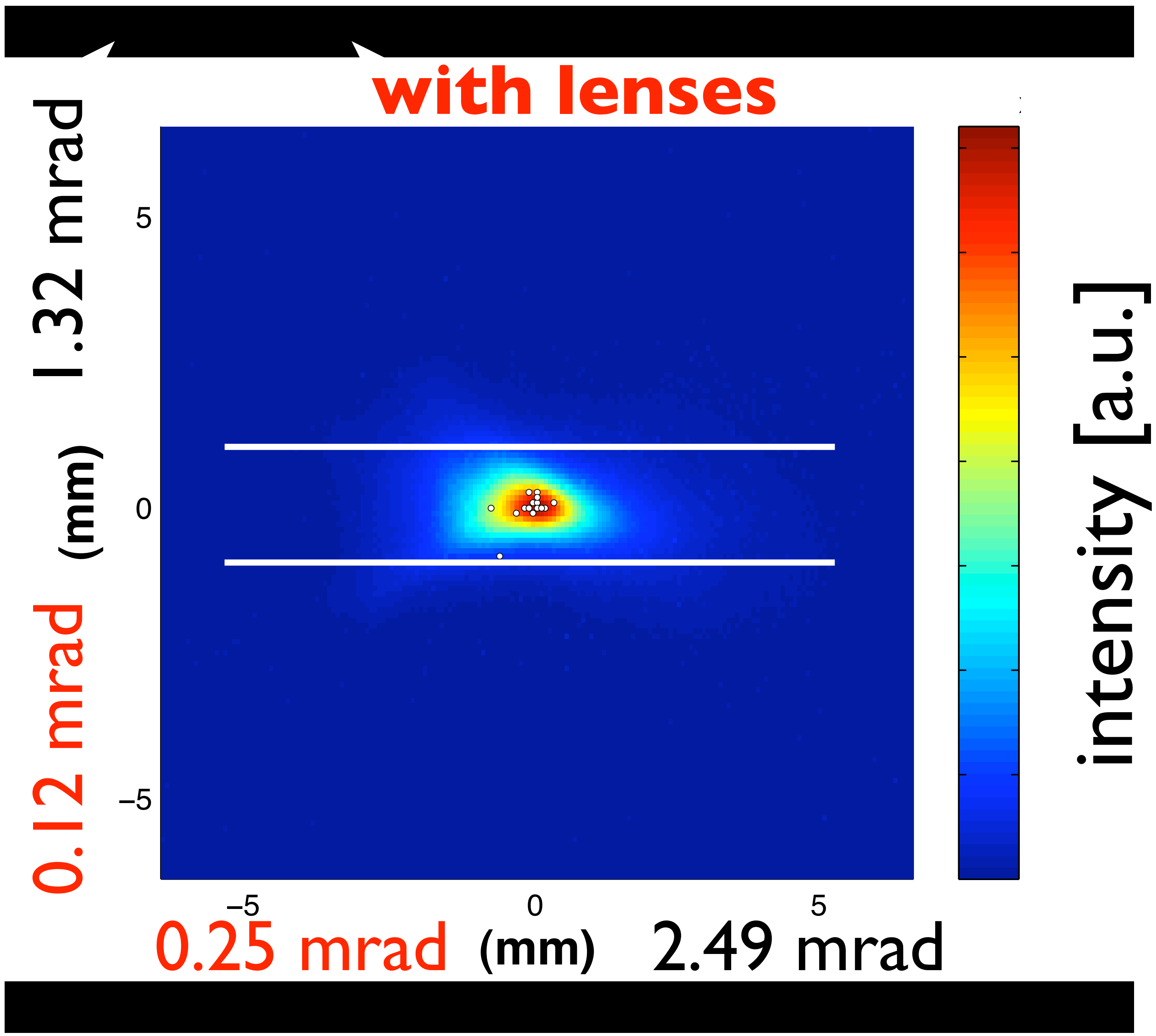


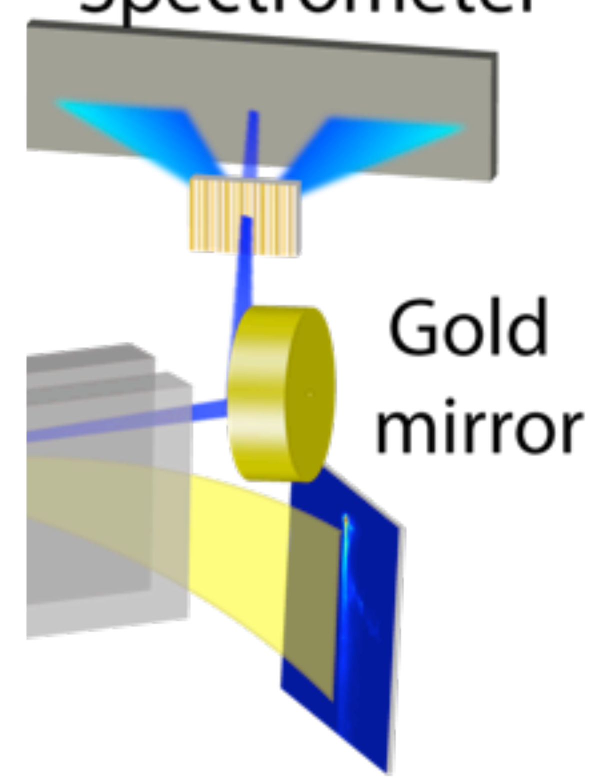
Setup Undulator Radiation



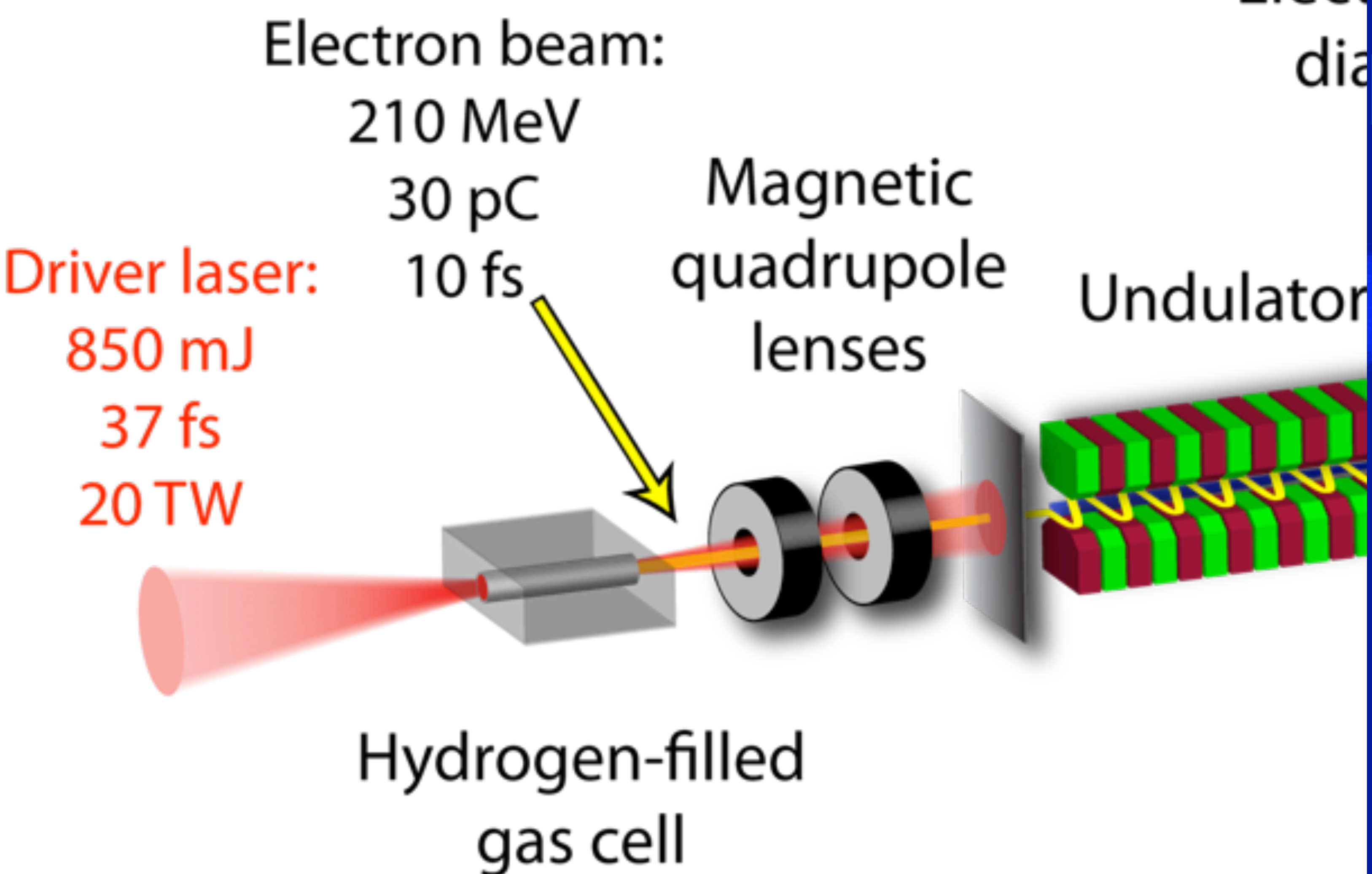
Setup Undulator Radiation

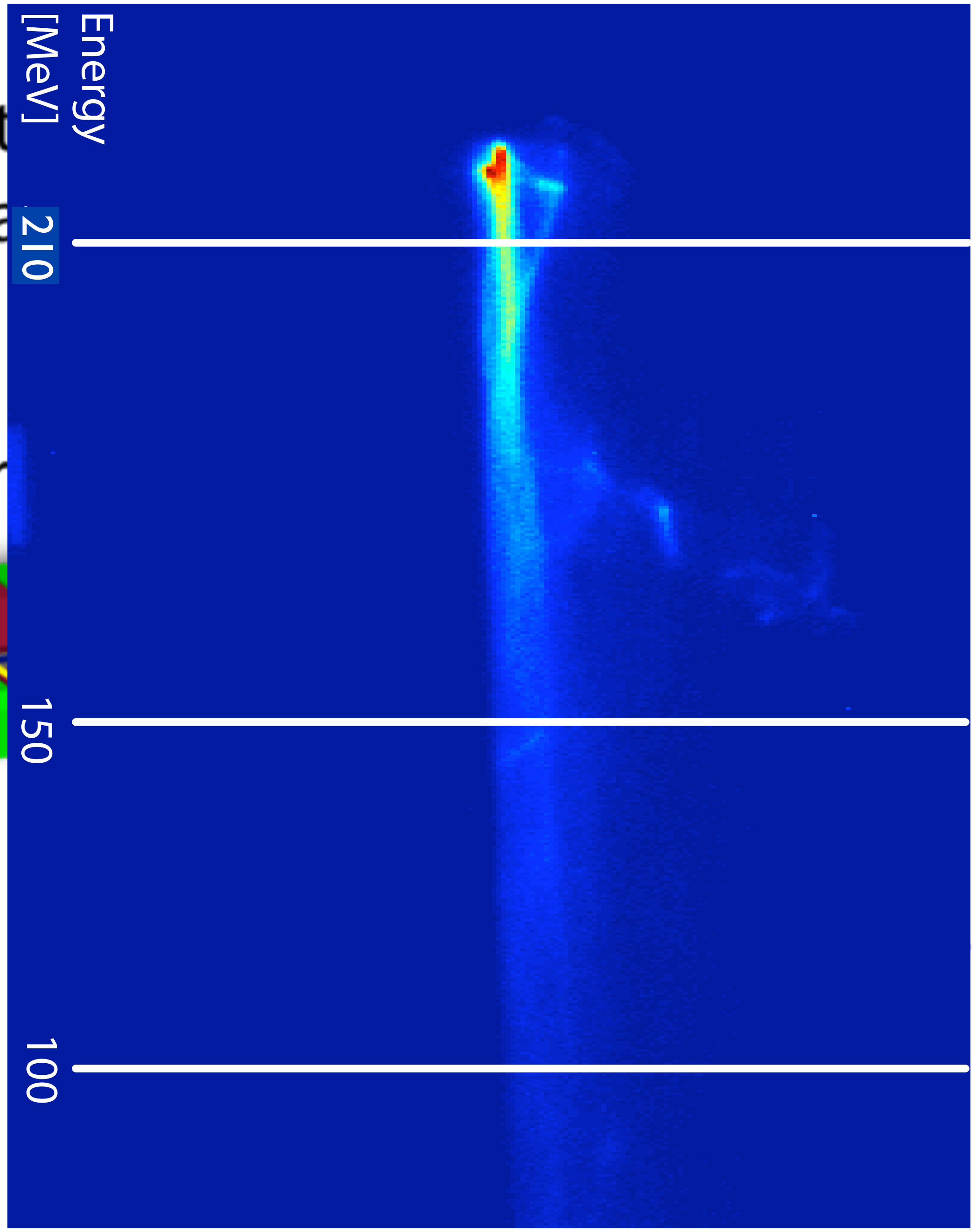
Driver laser:
850 mJ
37 fs
20 TW





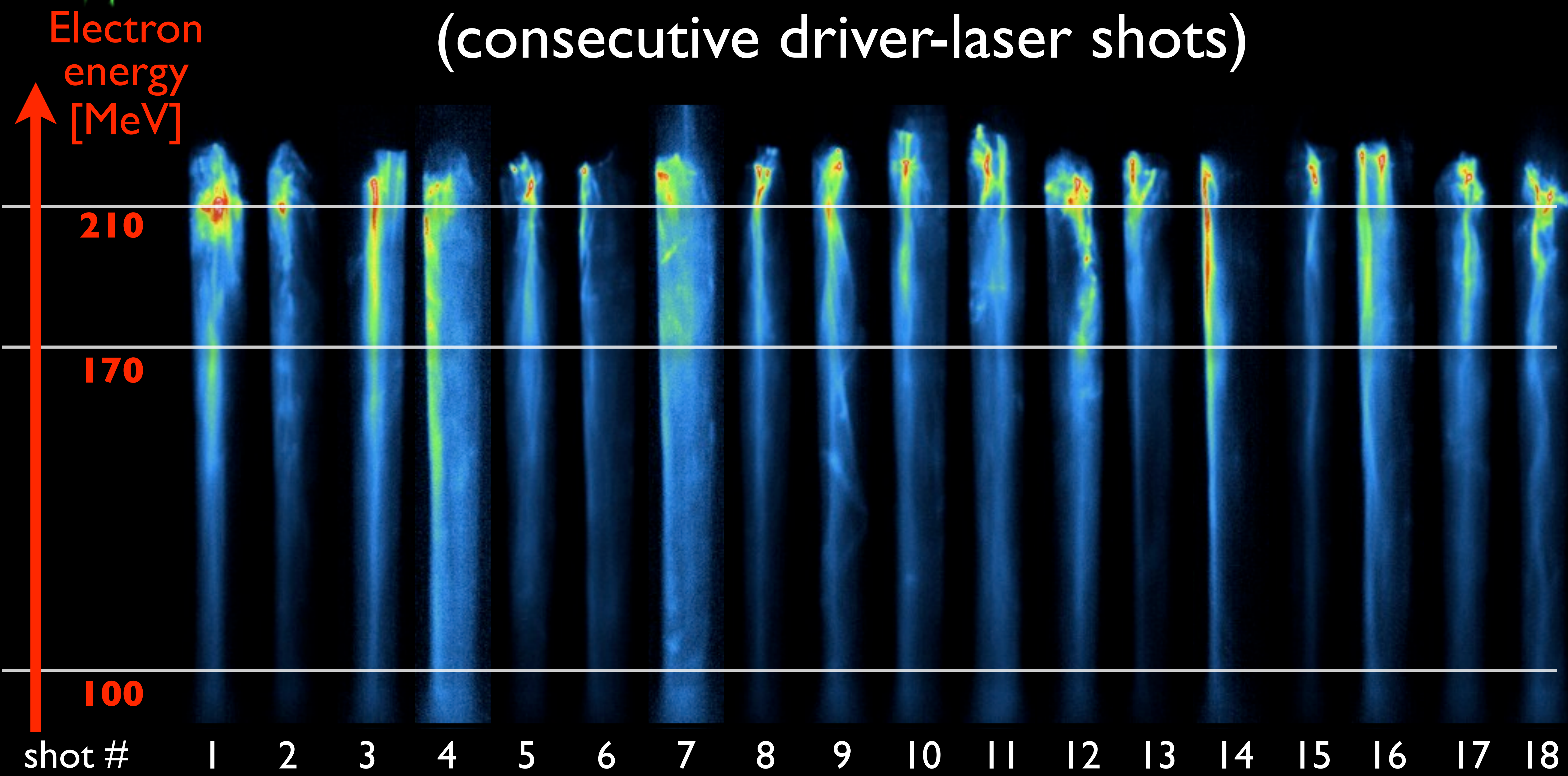
Setup Undulator Radiation





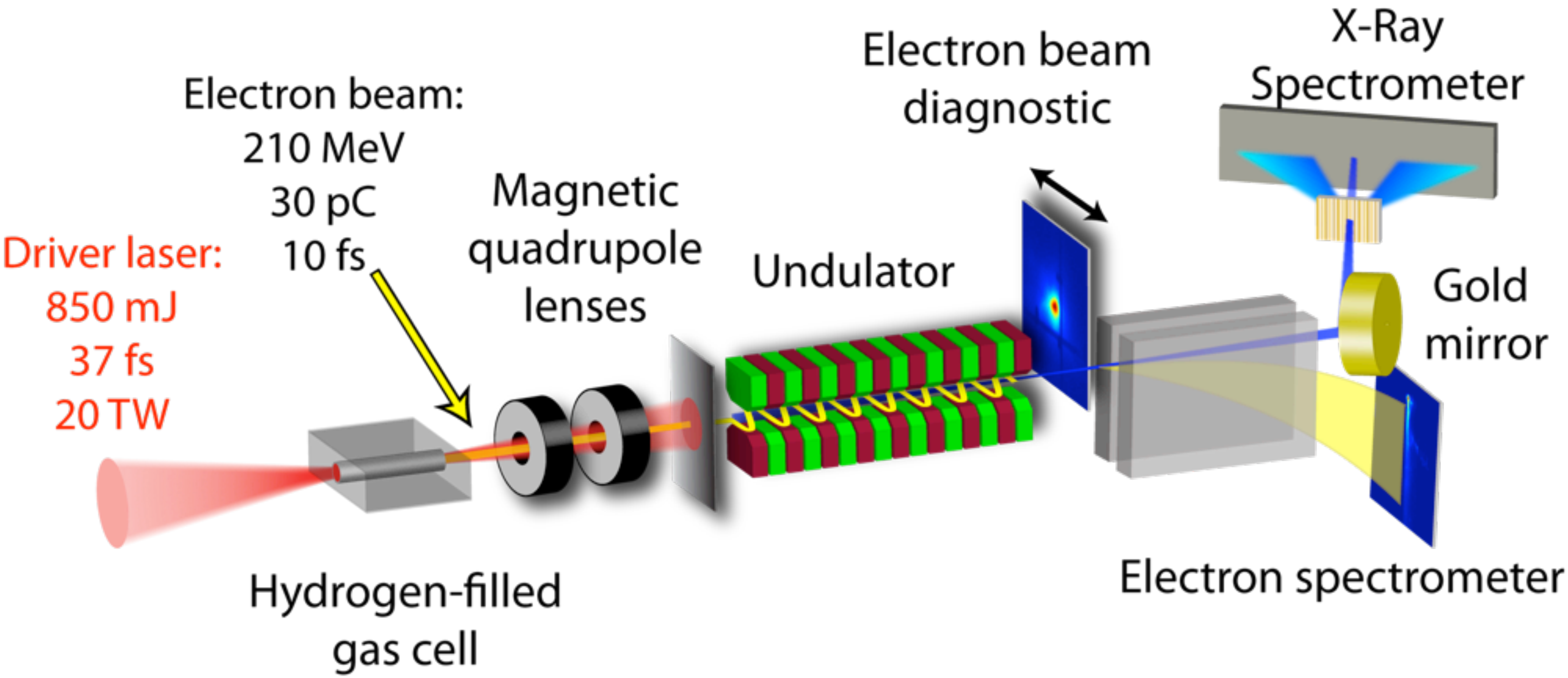
Series of Measured Electron Spectra

(consecutive driver-laser shots)

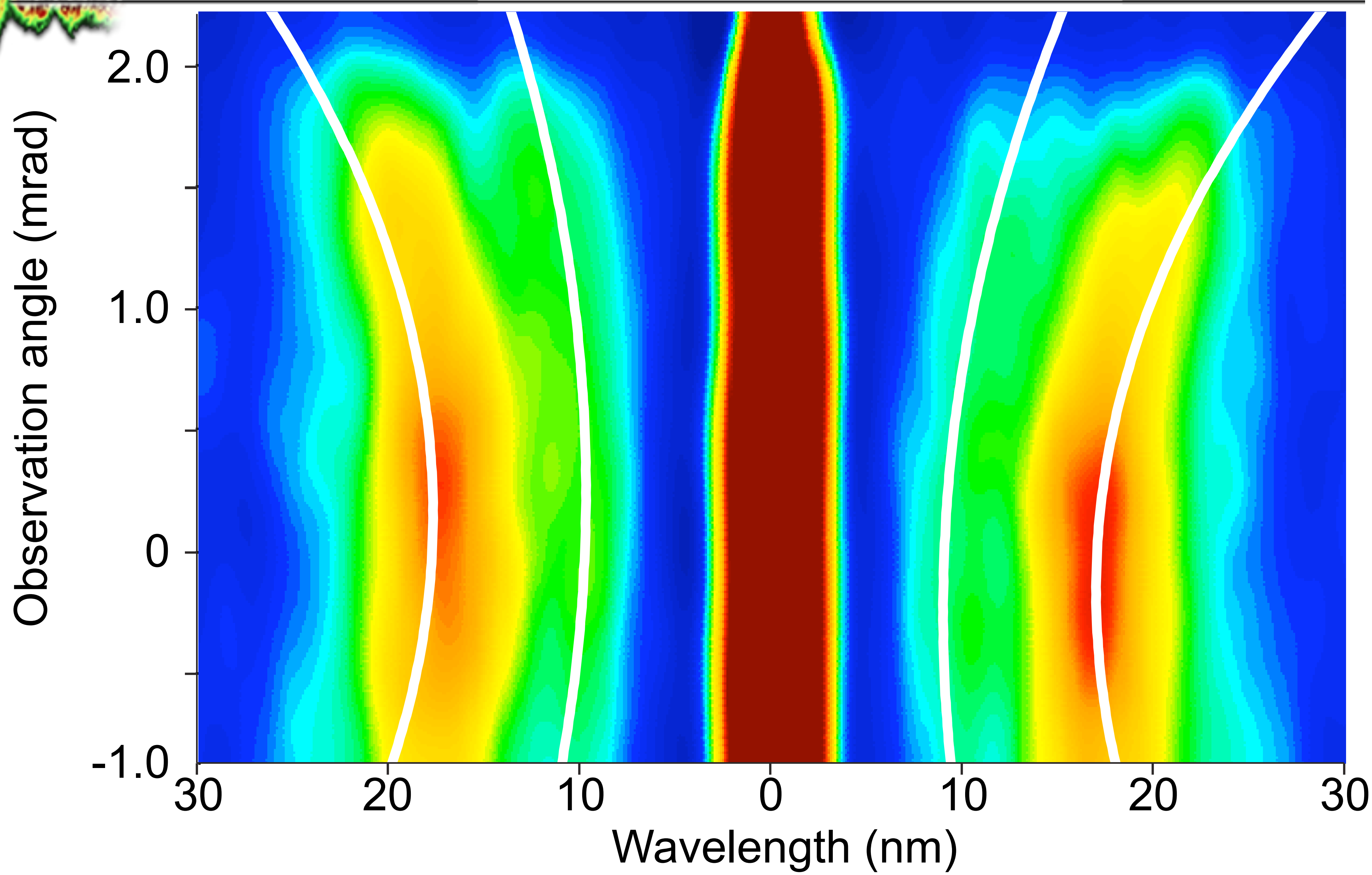


$$n_e = 7.3 \cdot 10^{18}\mathrm{cm}^{-3}$$

Setup Undulator Radiation



Measured Undulator Spectrum

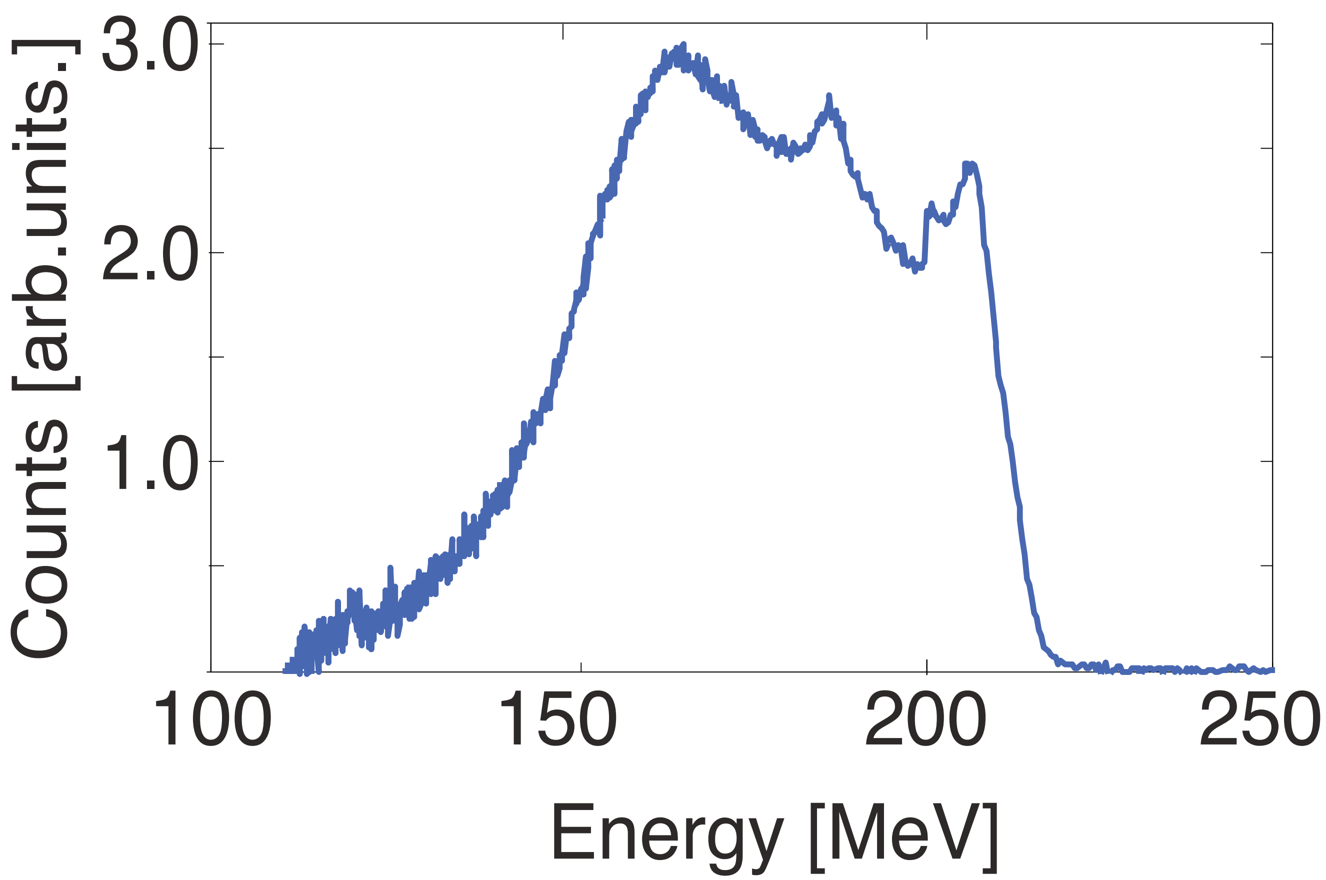


$$\lambda_{\mathrm{res}} = \frac{\lambda_{\mathrm{u}}}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\Theta^2\right)$$

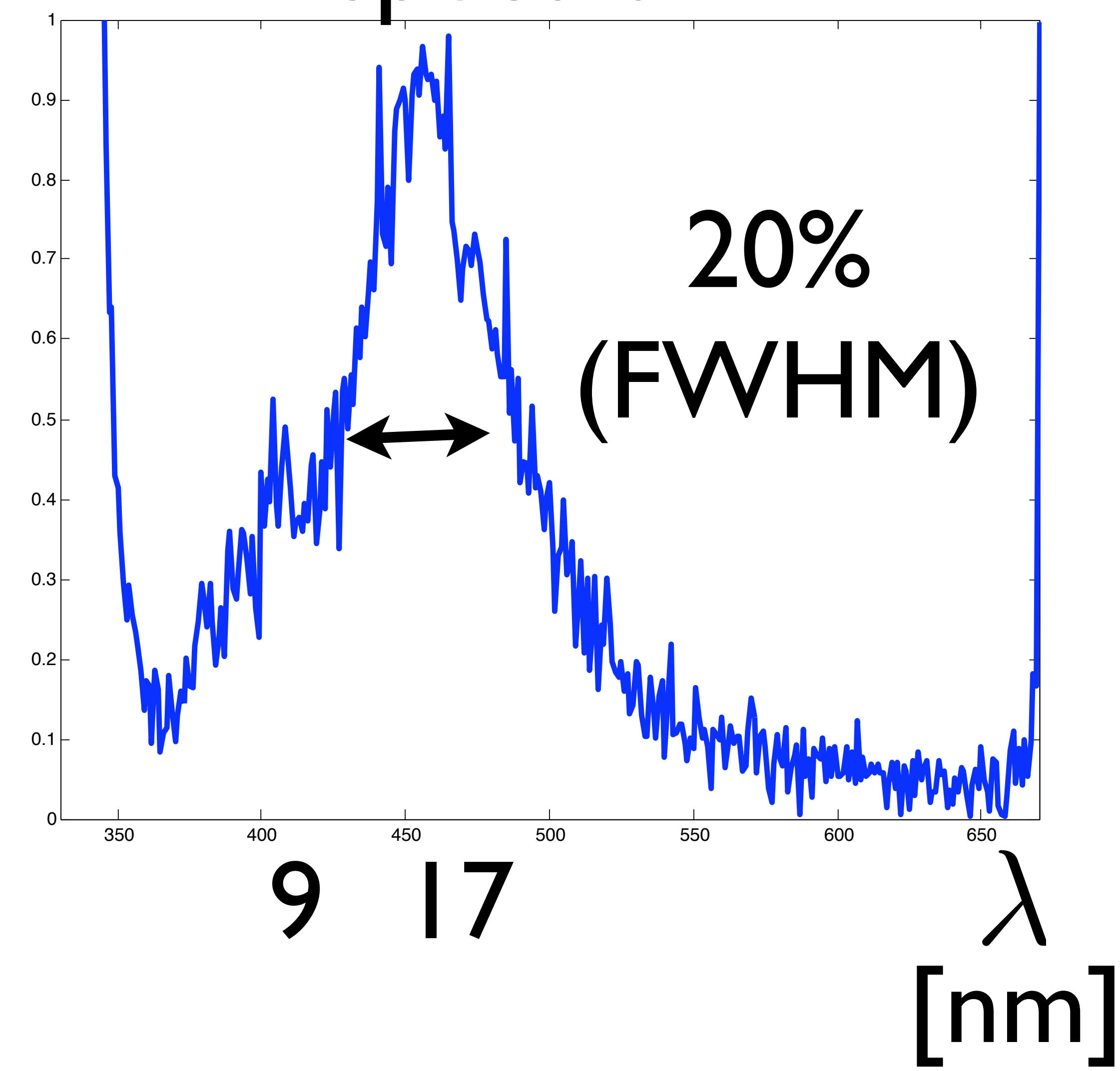
MF et al.,
Nature Phys. **5,** 826 (2009)

Electron- & Undulator Spectrum

Electron spectrum

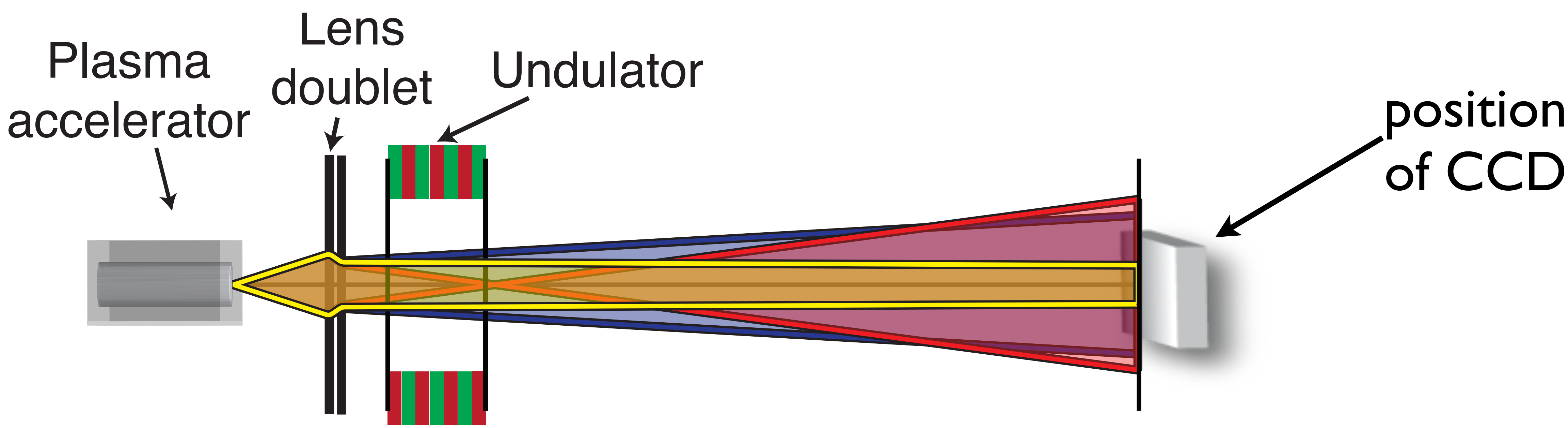


Undulator spectrum



Chromatic effects of the Magnetic Lenses

Electron beam envelopes for different energies



undulator beam size:

$$\Sigma_{\mathrm{und}}(s) = \sqrt{\sigma_{\mathrm{ph}}^2(s) + \sigma_e^2(s)}$$

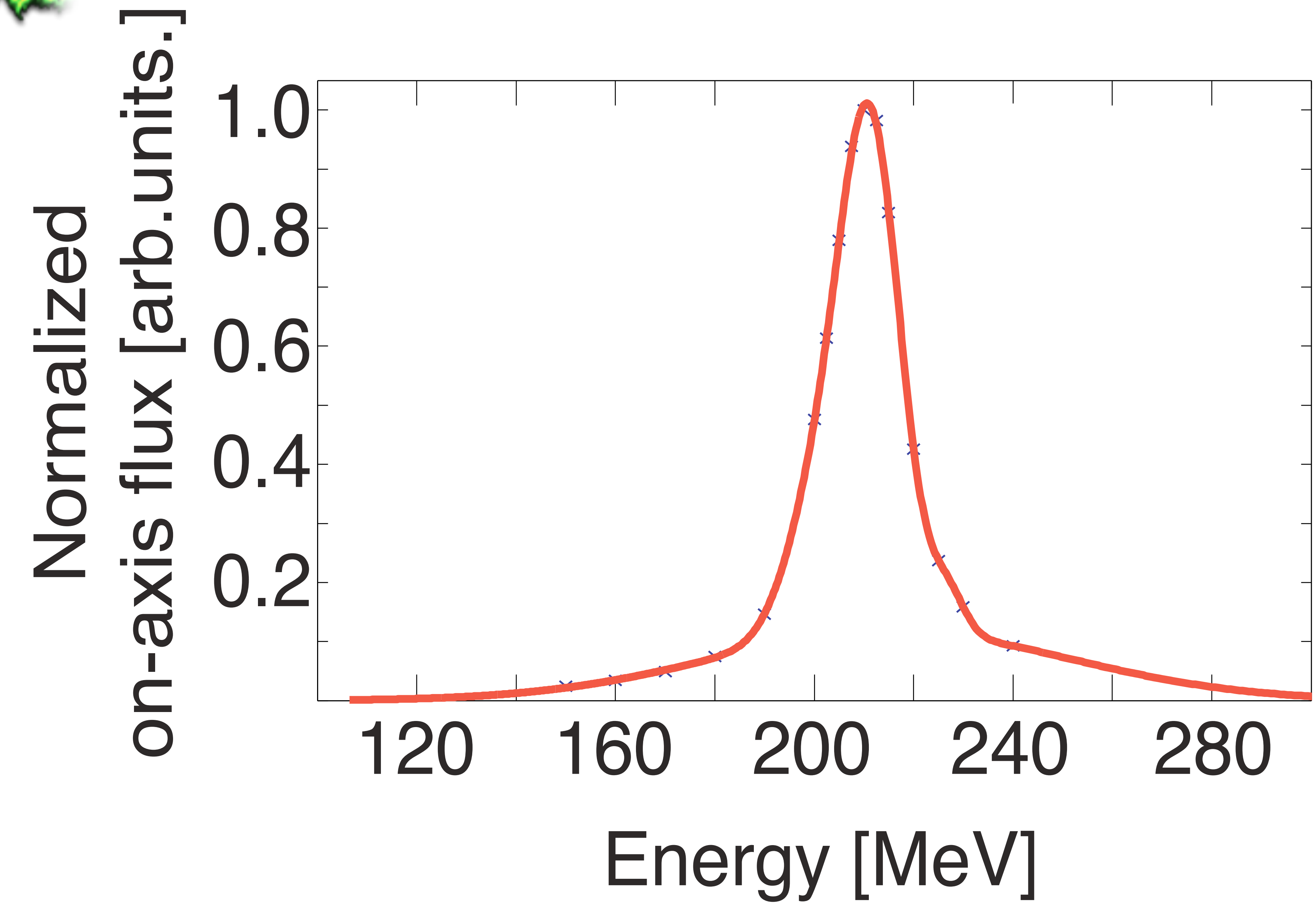
single electron emission

electron beam

on-axis flux:

$$\left.\frac{\mathrm{d}\Phi}{\mathrm{d}\mathcal{S}}\right|_{\vec{x}=0} = \frac{\Phi_n}{2\pi\,\Sigma_x(s)\,\Sigma_y(s)},$$

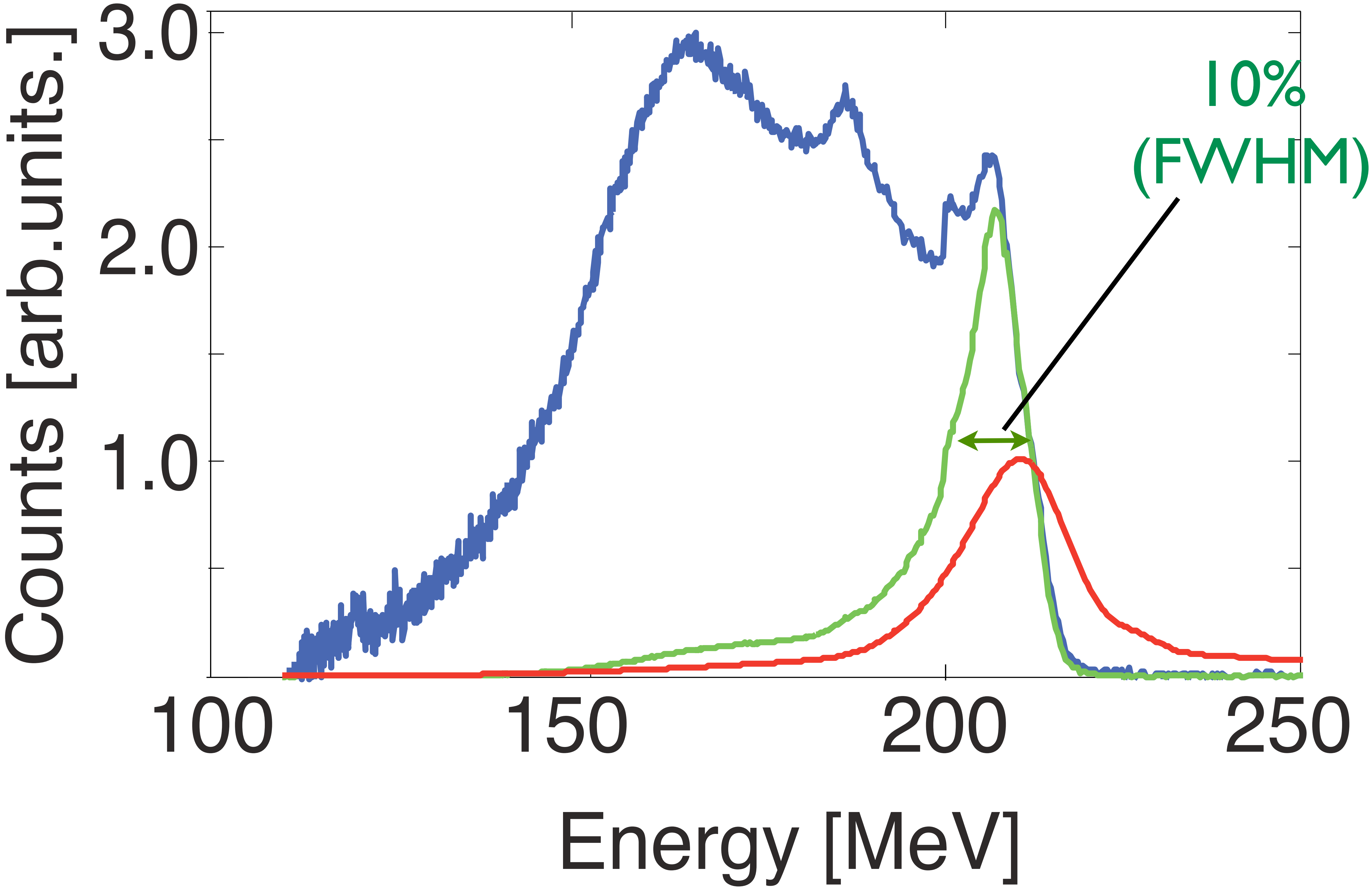
System Response Function



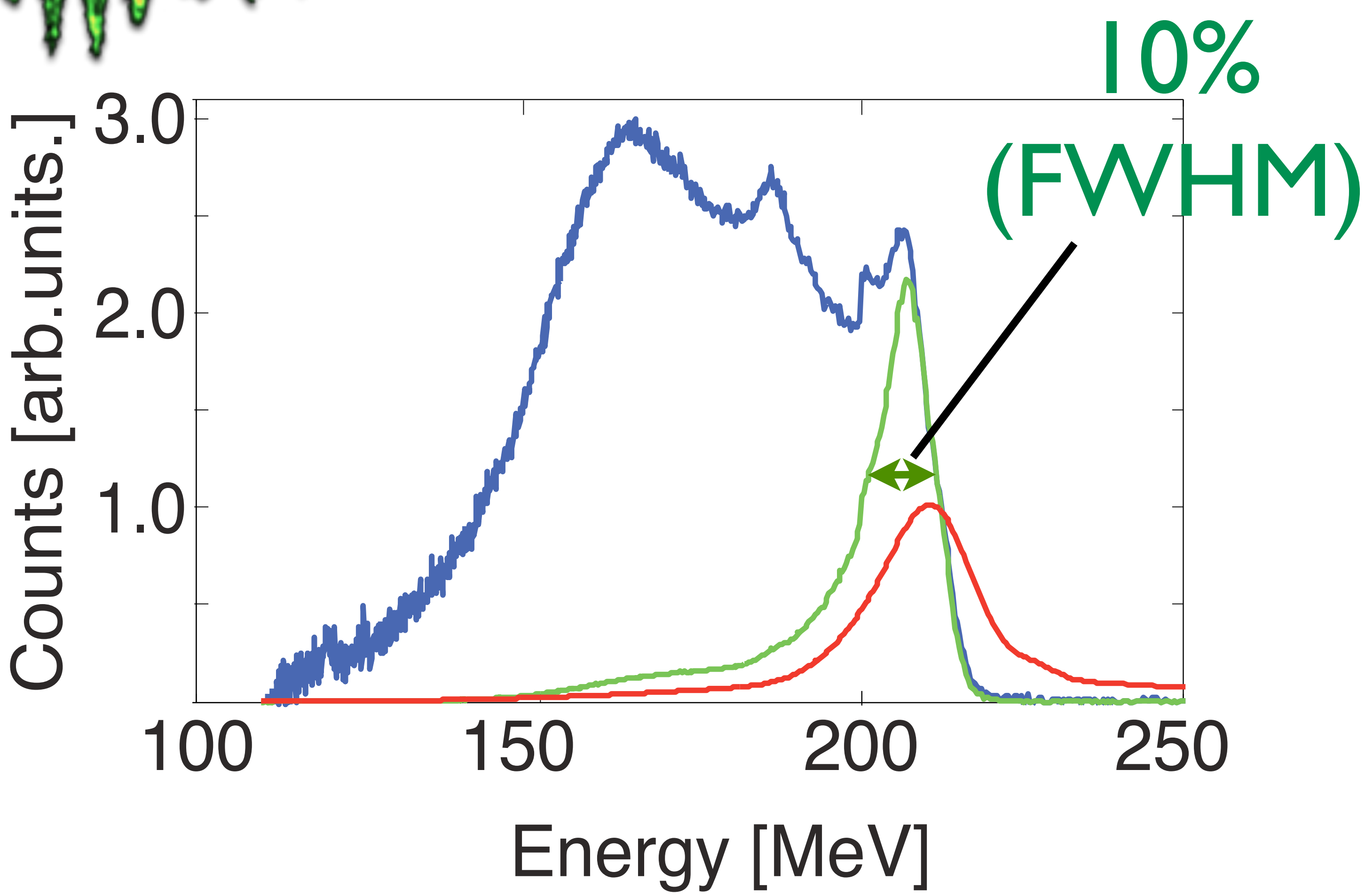
on-axis flux:

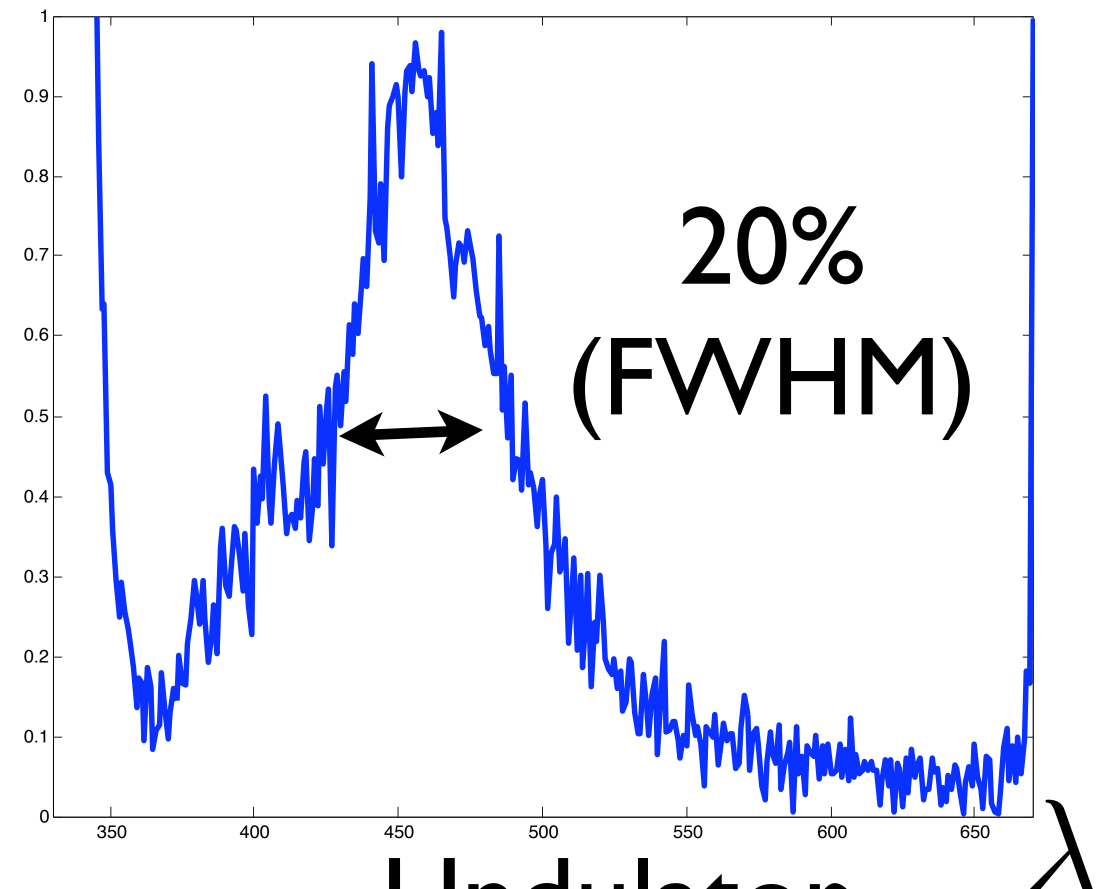
$$\boxed{\left.\frac{\mathrm{d}\Phi}{\mathrm{d}\mathcal{S}}\right|_{\vec{x}=0} = \frac{\Phi_n}{2\pi\,\Sigma_x(s)\;\Sigma_y(s)},}$$

Filtered Electron Spectrum



Filtered Electron Spectrum





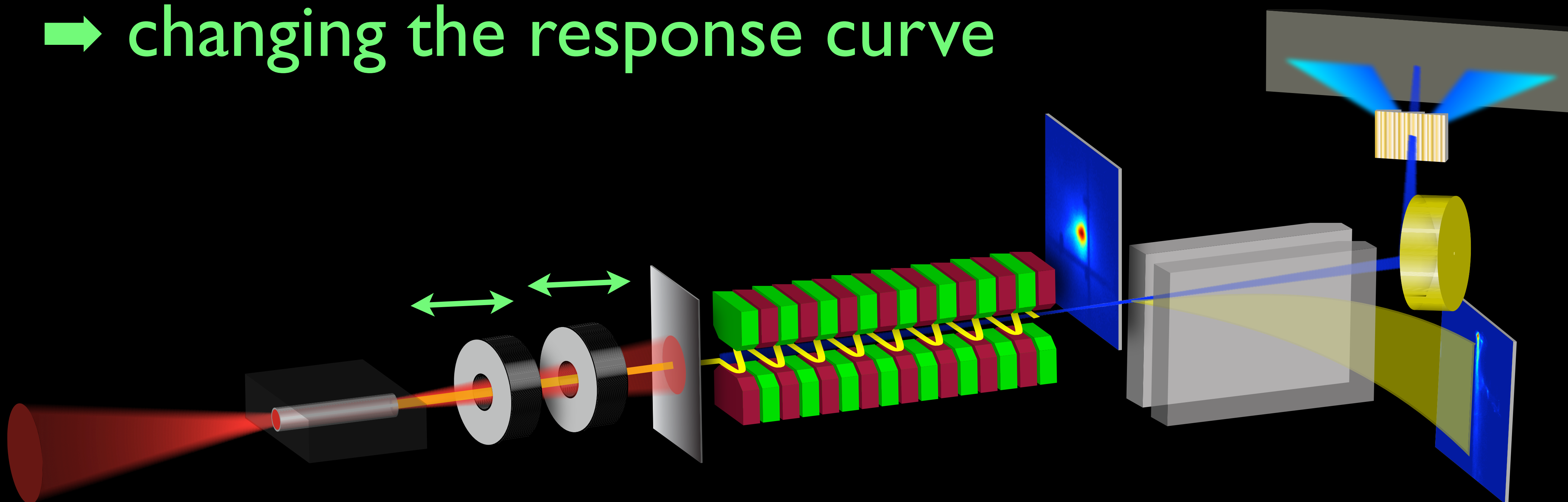
Undulator spectrum

$$\lambda \sim \frac{1}{\gamma^2} \Rightarrow \boxed{\frac{d\lambda}{\lambda} \simeq 2 \cdot \frac{d\gamma}{\gamma}}$$

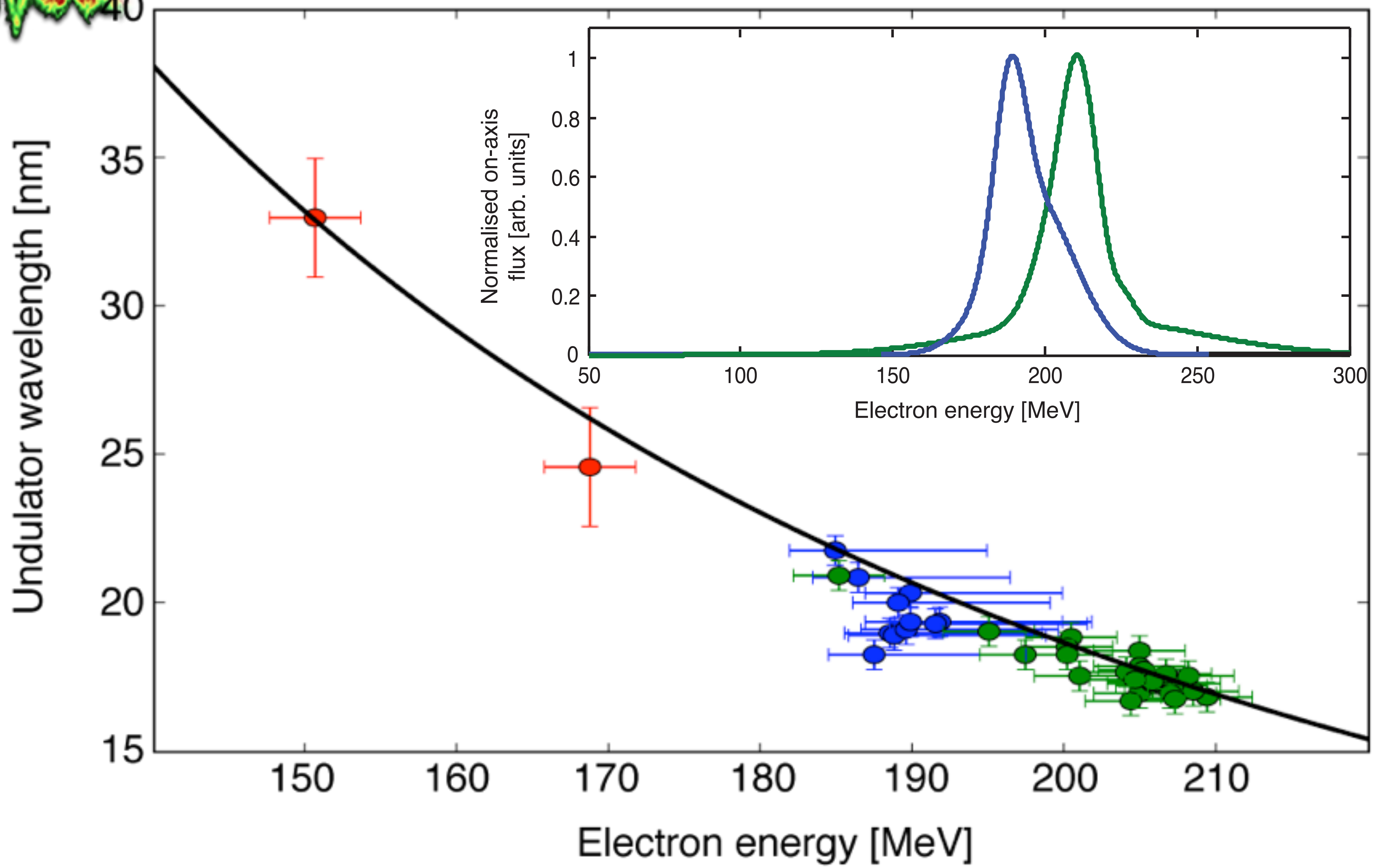
Tuning of the Undulator Radiation

tuning by moving the lens' position:

➡ changing the response curve

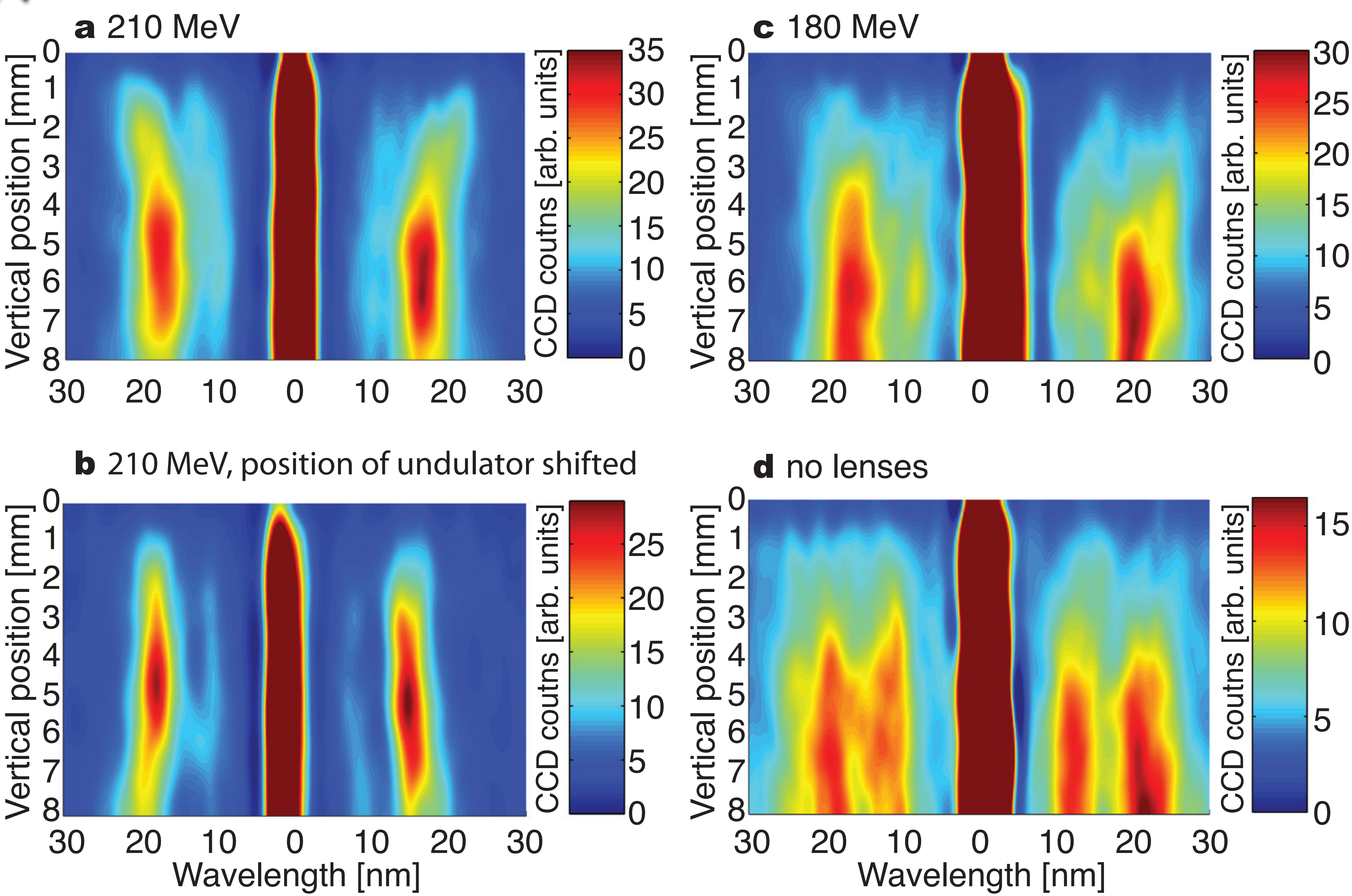


Tunability of the Source

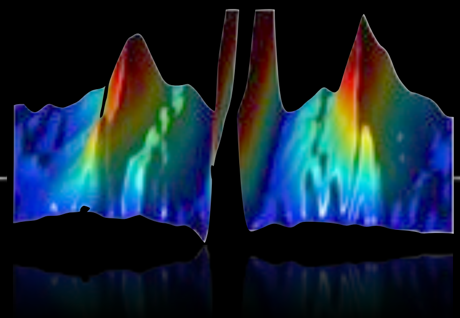


$$\lambda_{\mathrm{res}} = \frac{\lambda_{\mathrm{u}}}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\Theta^2\right)$$

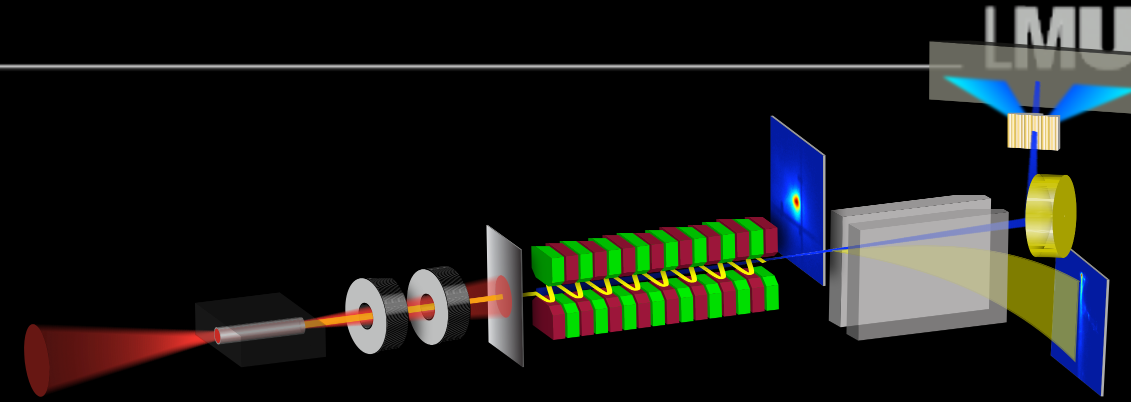
Measured Spectra with Different Setups



M.Fuchs, LWFA-driven lightsources



Properties of the Undulator Source



- stable operation: detected undulator spectra in 70 % of consecutive laser shots
- tunable in wavelength by changing lens' positions
- on-axis peak intensity: 10,000 photons/(shot mrad^2 0.1%b.w.)

  (1 pC charge in effective spectrum)
- pulse duration expected to be few 10 fs
- perfectly synchronized to the laser (pump-probe experiments)

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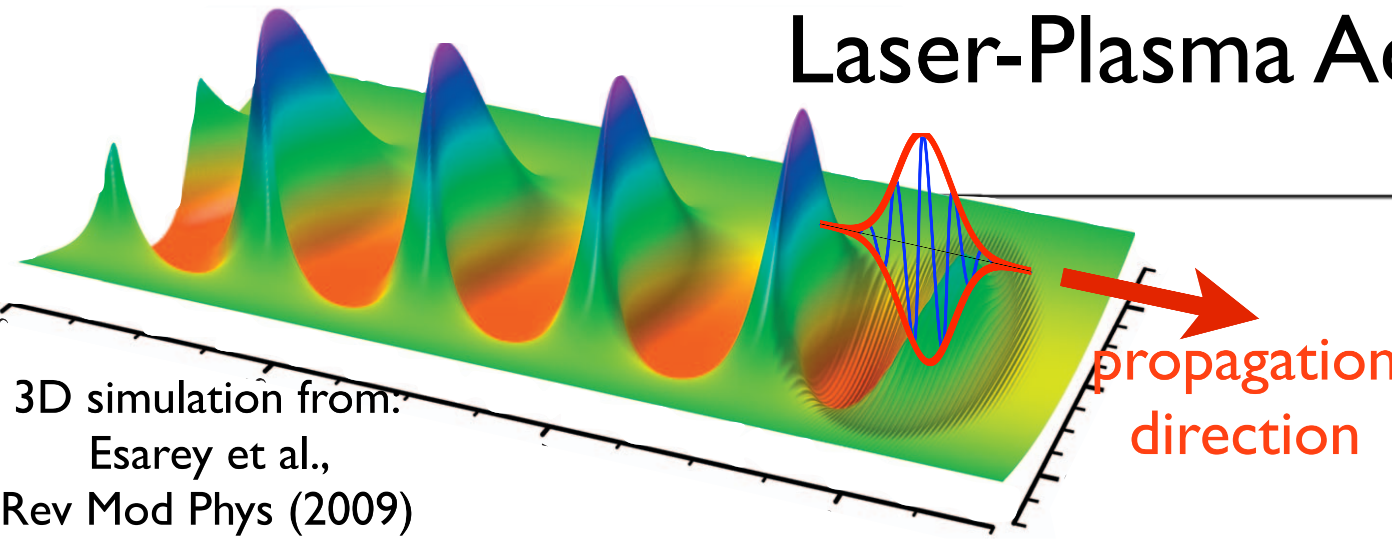
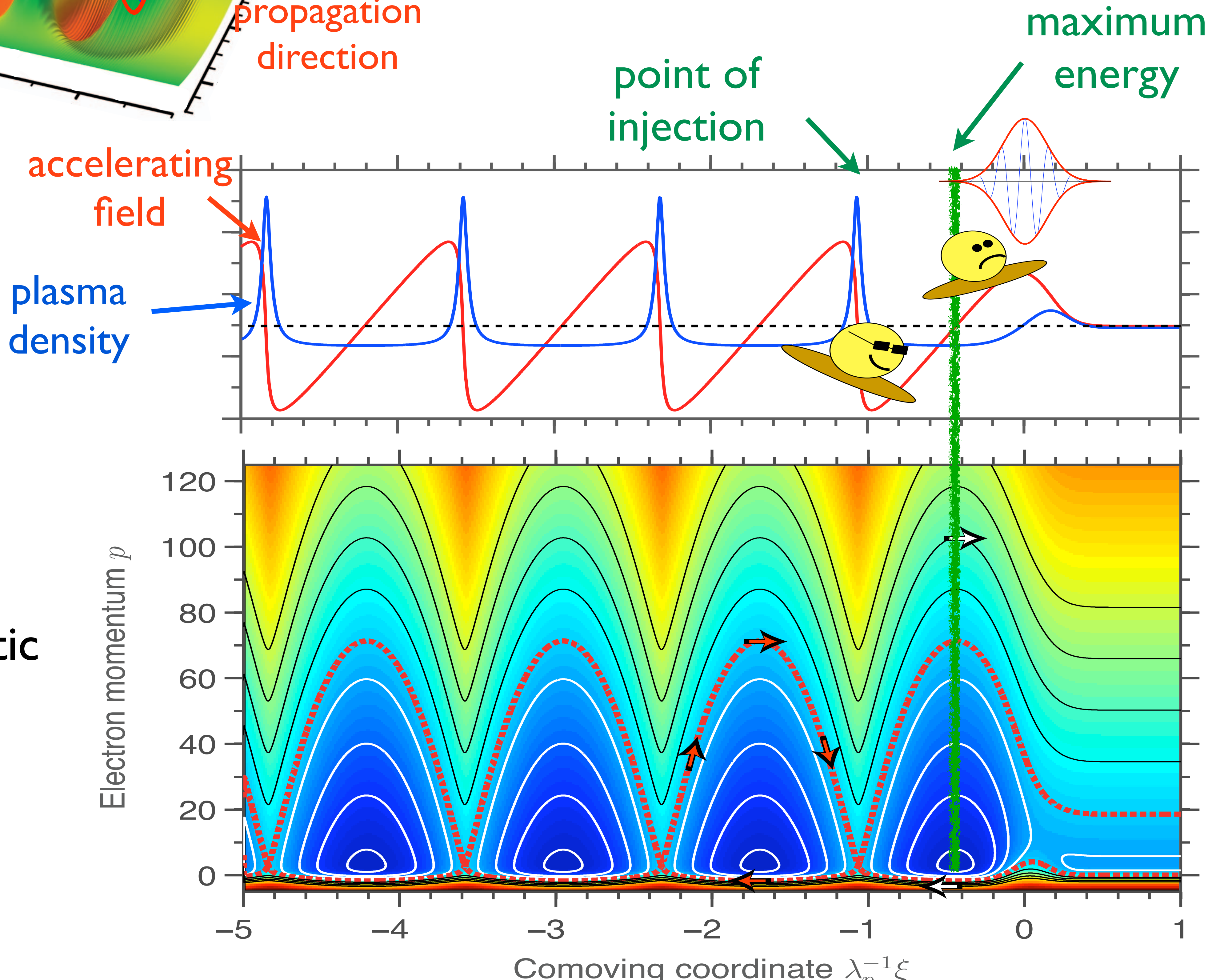
Laser-Plasma Accelerator: Bunch Duration



3D simulation from:
Esarey et al.,
Rev Mod Phys (2009)



- **electron bunch duration**

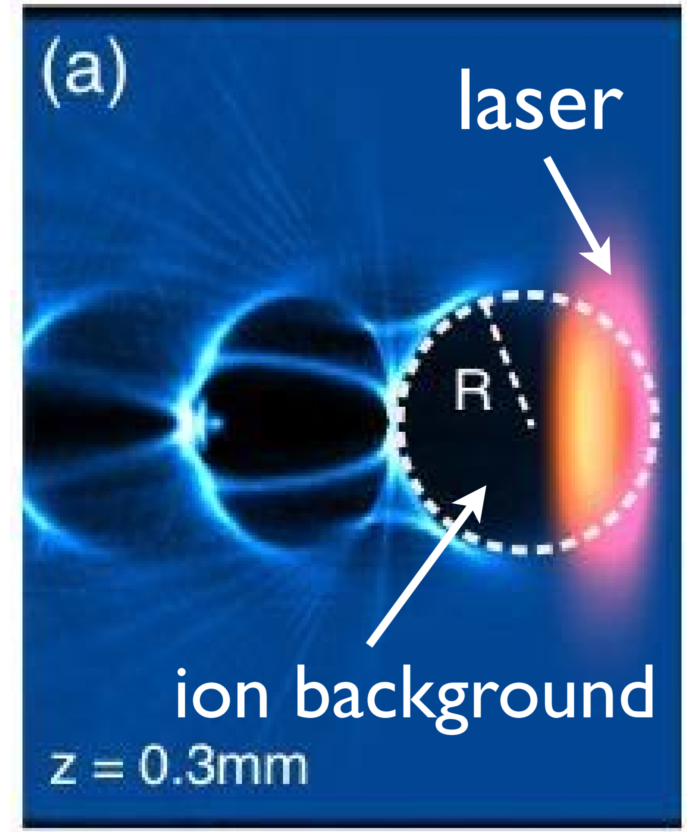
  quasi-monoenergetic peak indicates: fraction of plasma wavelength:
  λ_p = 15 μm (50 fs)

Acceleration in the Bubble Regime: Requirements on the Laser

Typical requirement on laser for bubble regime:
(from theory and PIC simulations)

(plasma density: 10^{18} cm^{-3})

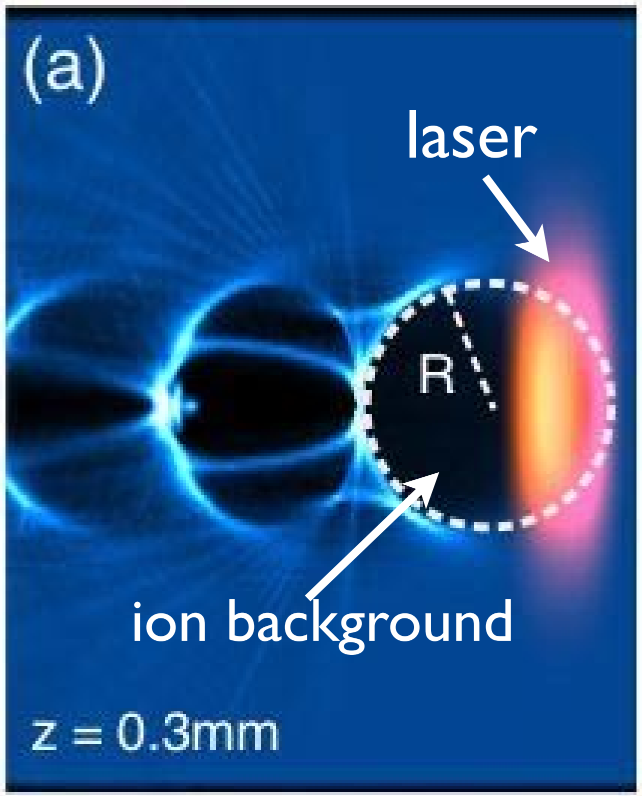
- Laser Power: >200 TW
- PIC simulation: 300 pC with 1.5 GeV
  –> ≈500 mJ energy in electron beam
- Efficiency (laser –> electron beam): 10 - 15 %
- need >5 J energy in laser pulse (new technology)
  –> (Simulation: 200 TW –> 6J, 30 fs)



W. Lu et al., Phys. Plasmas, 7 (2009)

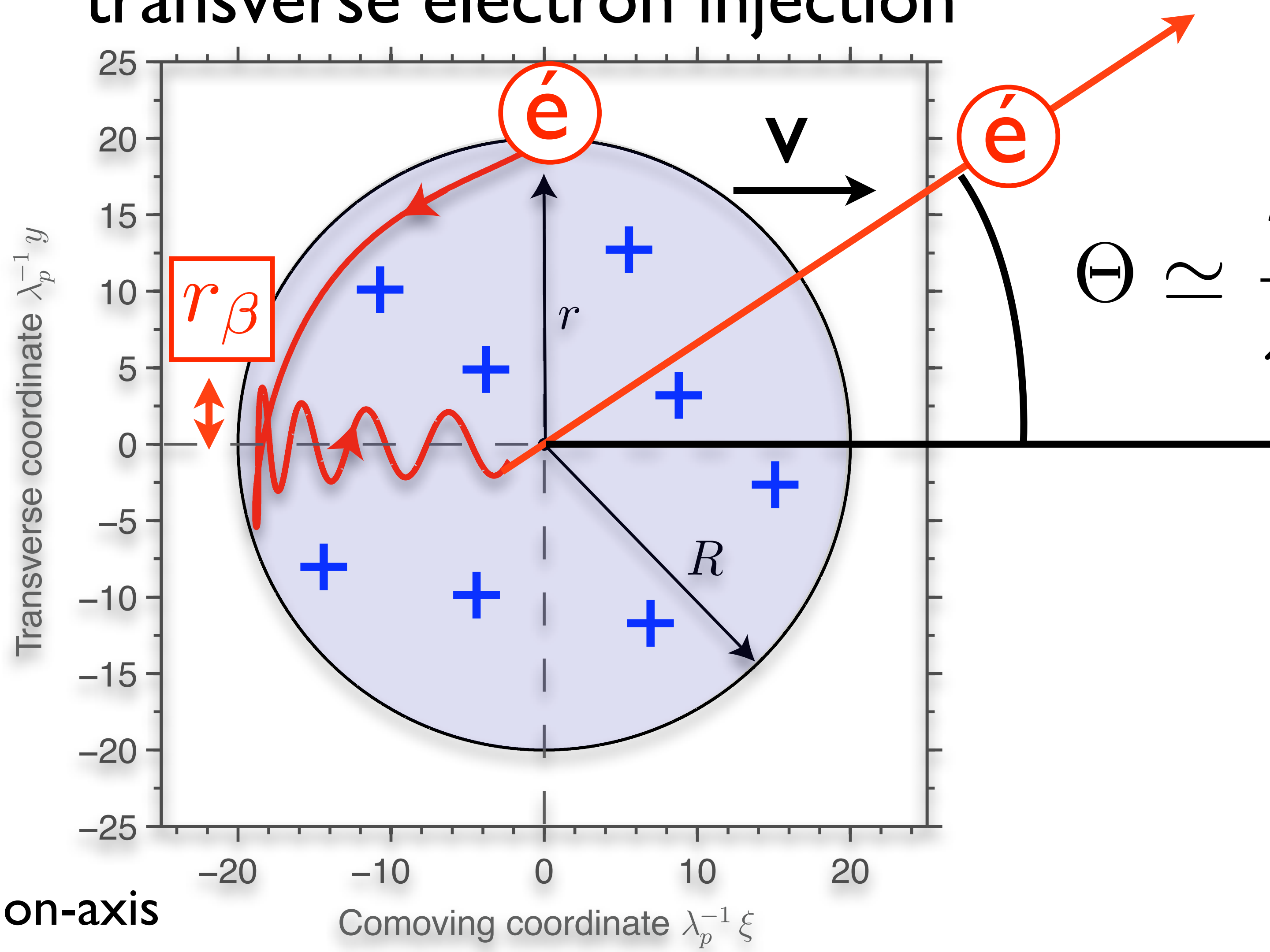
Most high-power laser system have pulses with less energy
–> have to rely on highly nonlinear laser-plasma interactions that increase laser intensity

Bubble Acceleration: The Details



W. Lu et al., Phys. Plasmas, 7 (2009)

transverse electron injection



$$\Theta \simeq \frac{r_\beta}{\lambda_\beta} \propto r_\beta \sqrt{\frac{n}{\gamma}}$$

electron gets injected on-axis
with largest transverse momentum

typical source size: (from PIC simulations) $r_\beta \approx 1\mu\text{m}$

-> divergence: $\Theta \approx 1\text{mrad}$

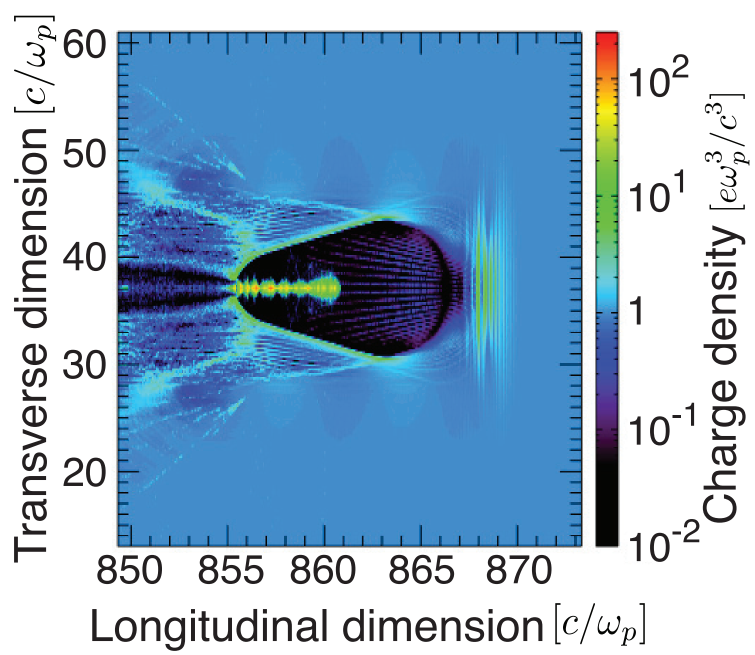
-> expected emittance: $\epsilon_n \approx 1\text{mm} \cdot \text{mrad}$

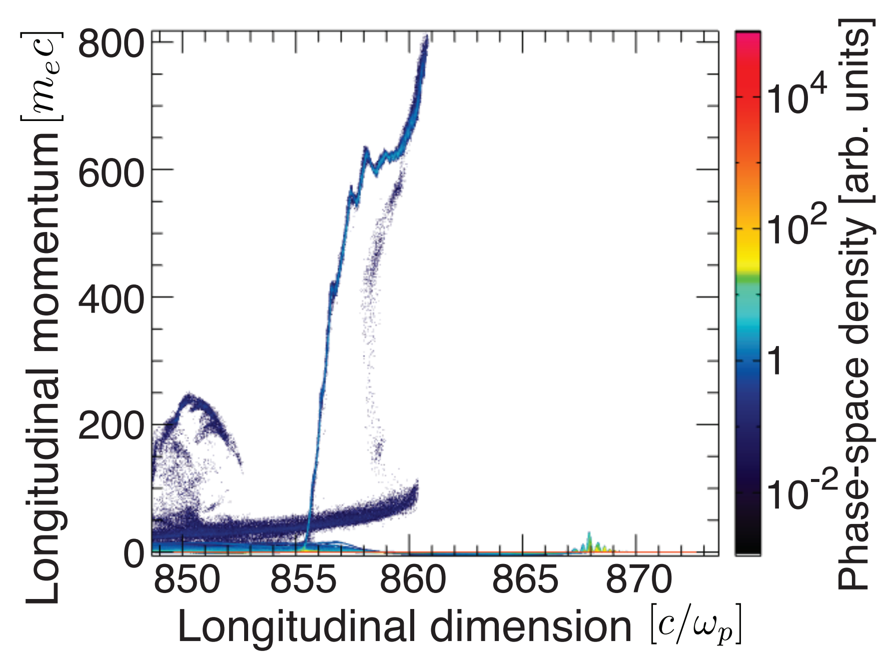
Bubble Acceleration: The Dirty Details

- transverse injection: large emittance

- self-injection in bubble regime
  -> no well-defined injection point (due to highly nonlinear modulations)
  -> termination of acceleration at different points in the acceleration phase
=> shot-to-shot variation in energy and energy spread

- sometimes even continuous injection (injection at all accelerating phases)
  -> large energy spread





Improvement of LWFA Beam Parameters as Drivers of Lightsources

- Electron energy — 200 MeV $\nearrow$ >1 GeV
- Charge — 10 pC $\nearrow$ >100 pC
- Energy spread — 5% $\searrow$ <1%
- Shot-to-shot stability (pointing, energy, ...)

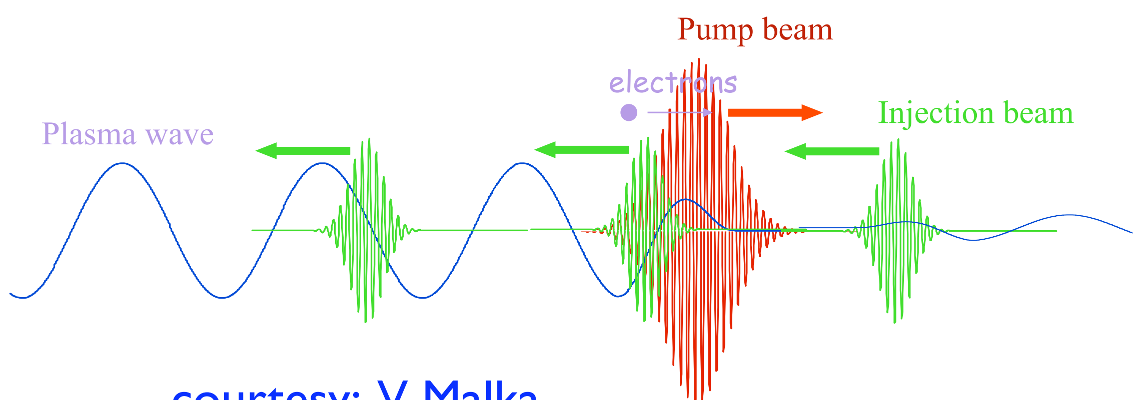
which parameters are left?

- bunch duration — τ <10 fs
- emittance — ε_n <1 mm mrad

New Schemes: Improve energy spread, emittance, stability

Decouple injector from accelerator (no self-injection)

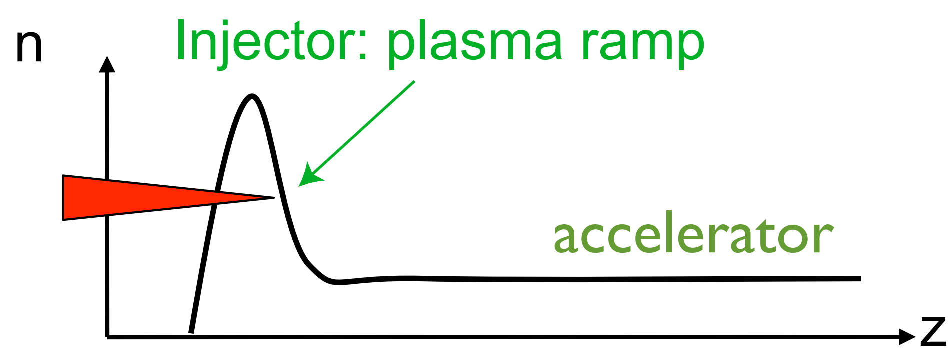
counter propagating laser pulses



courtesy: V. Malka

LOA: 1%-rms energy spread (10 pC)
C.Rechatin et al, PRL 102 (2009)

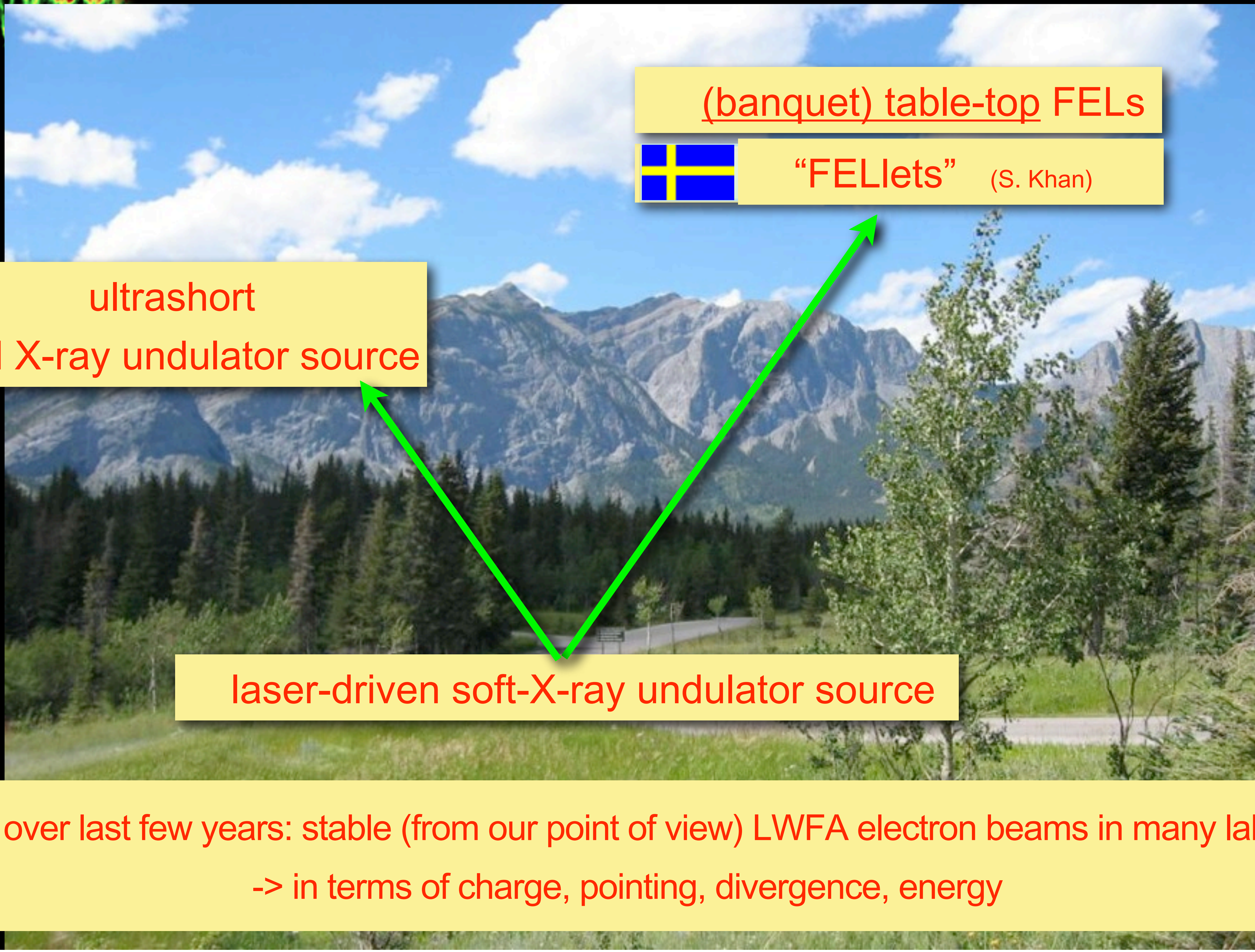
plasma density downramp



courtesy: W. Leemans

- control over injection: well defined injection (no continuous injection)
- no transverse injection
- promise to improve: energy spread, emittance, stability

Path to Laser-Driven Lightsources



(banquet) table-top FELs

“FELlets” (S. Khan)

ultrashort
hard X-ray undulator source

laser-driven soft-X-ray undulator source

over last few years: stable (from our point of view) LWFA electron beams in many labs

-> in terms of charge, pointing, divergence, energy