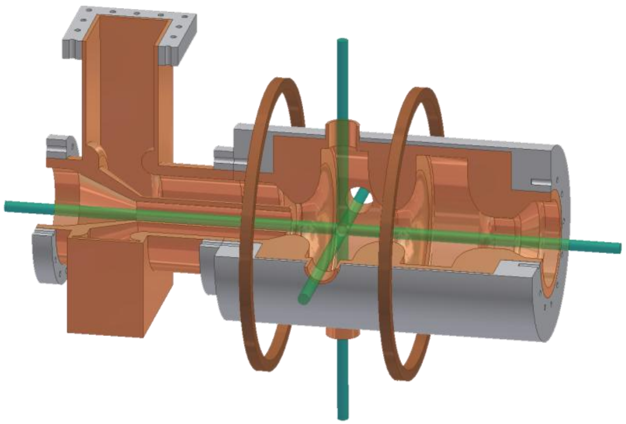
A laser-cooled electron source for single-shot femtosecond X-ray and electron diffraction



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Eddie Rietman
Ad Kemper
Harry van Doorn

Netherlands Technology Foundation

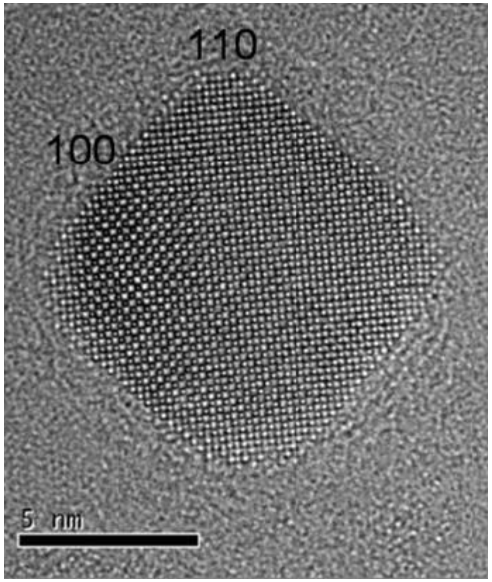
NL Foundation for Fundamental Research on Matter

FEI Company

Structural dynamics...

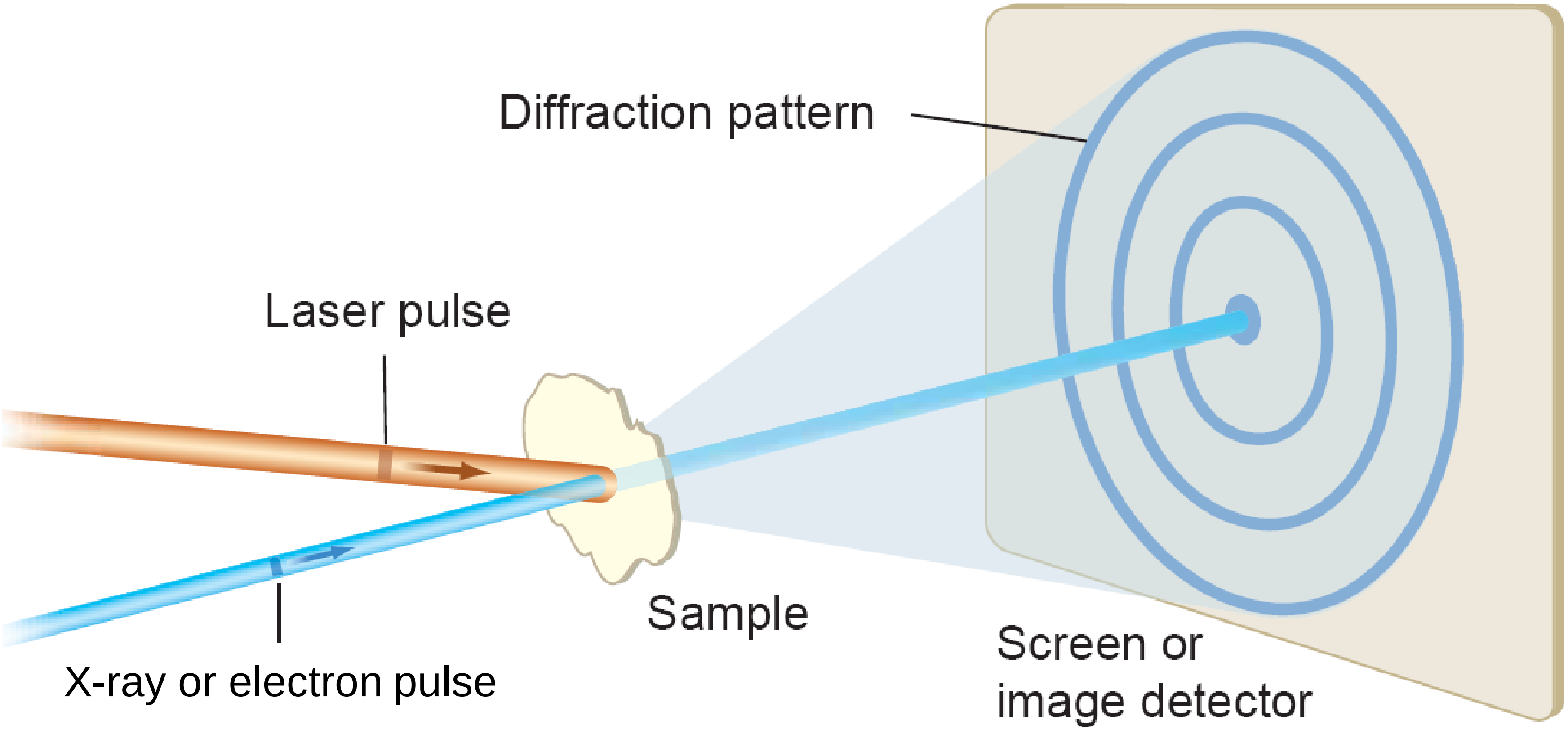
resolve atomic **length** *and* **time** scales:

1 Å @ 100 fs

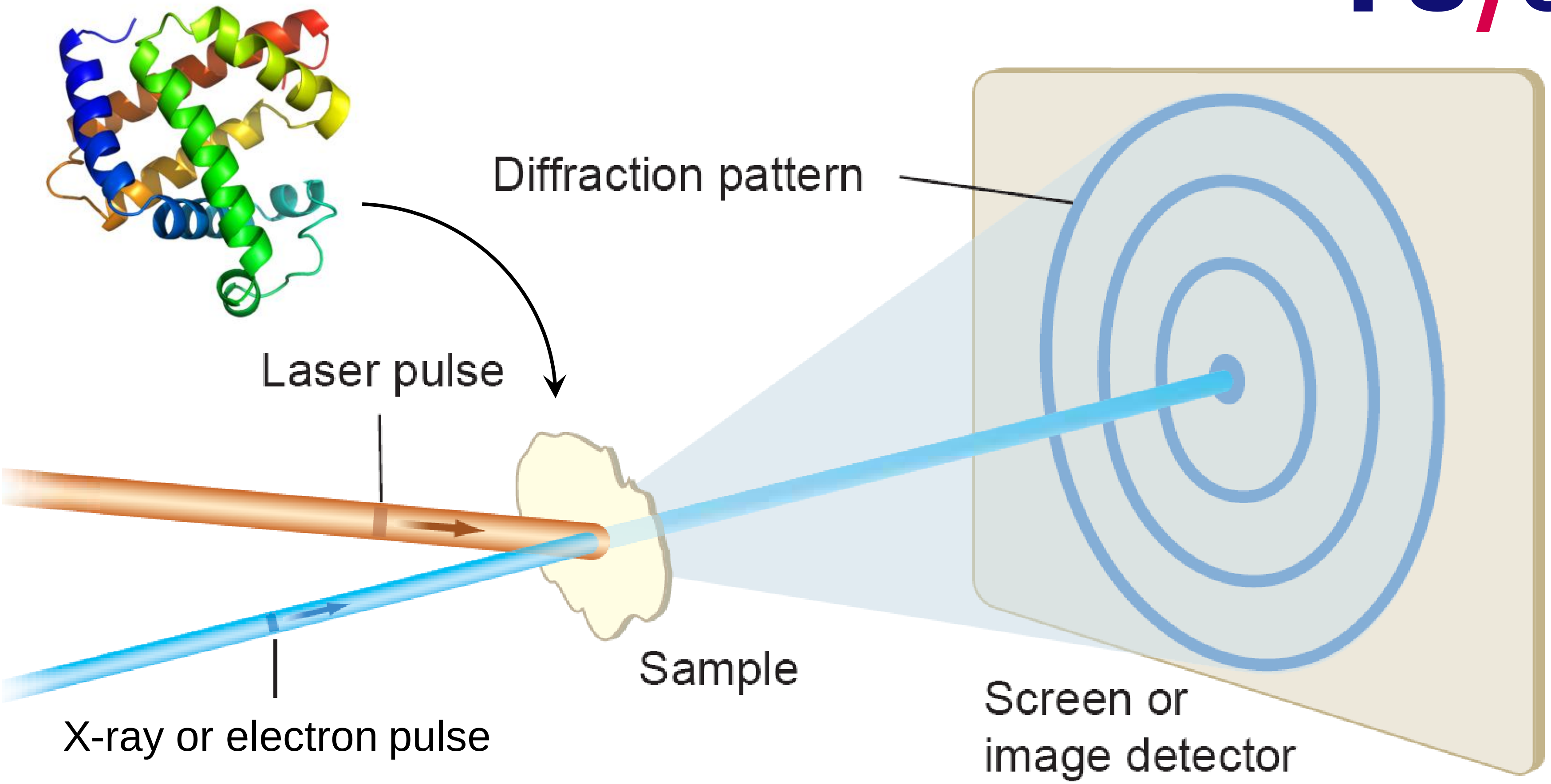


CeO_2 catalyst nanoparticle

Myoglobin

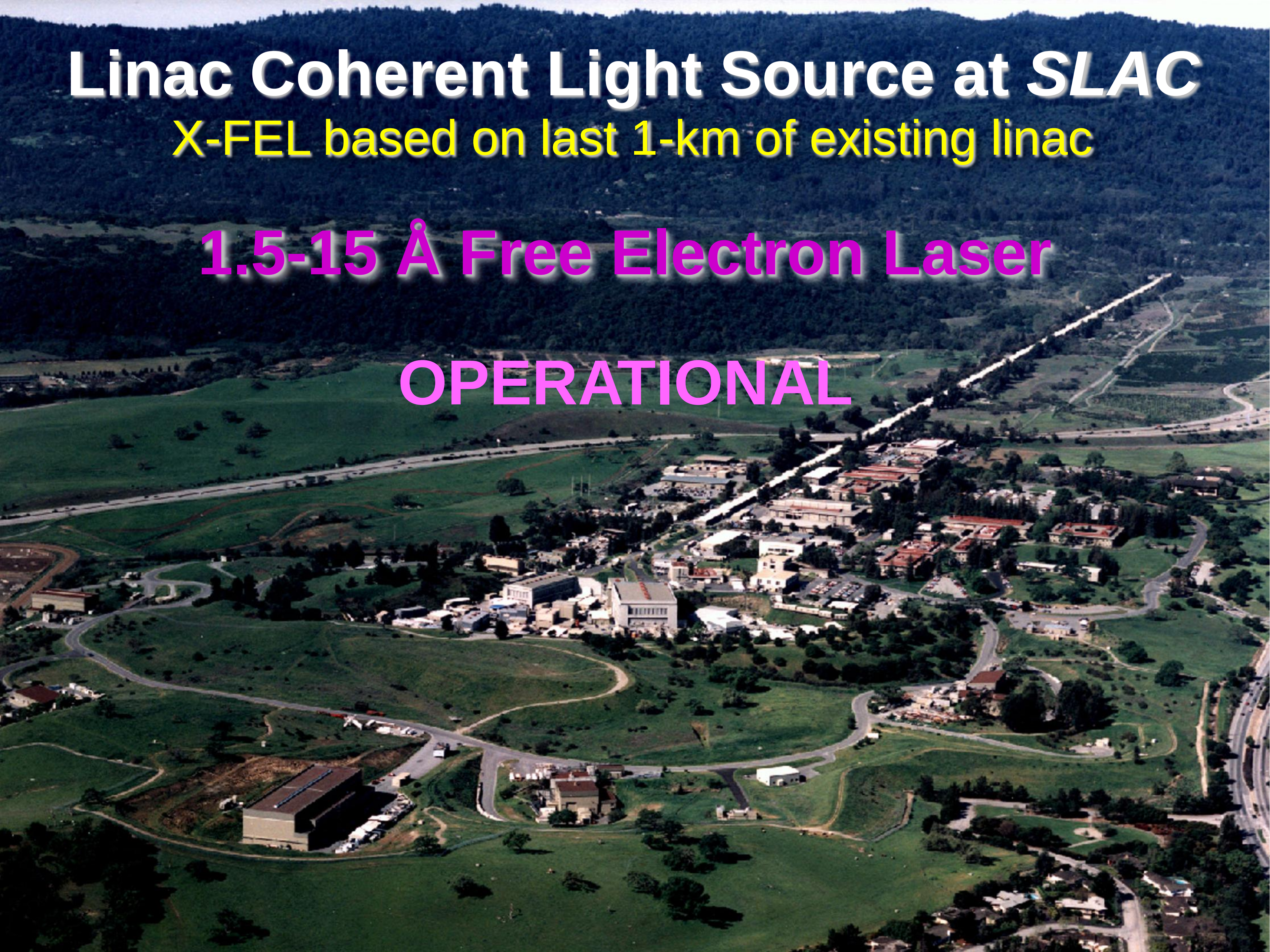


ultrafast diffraction

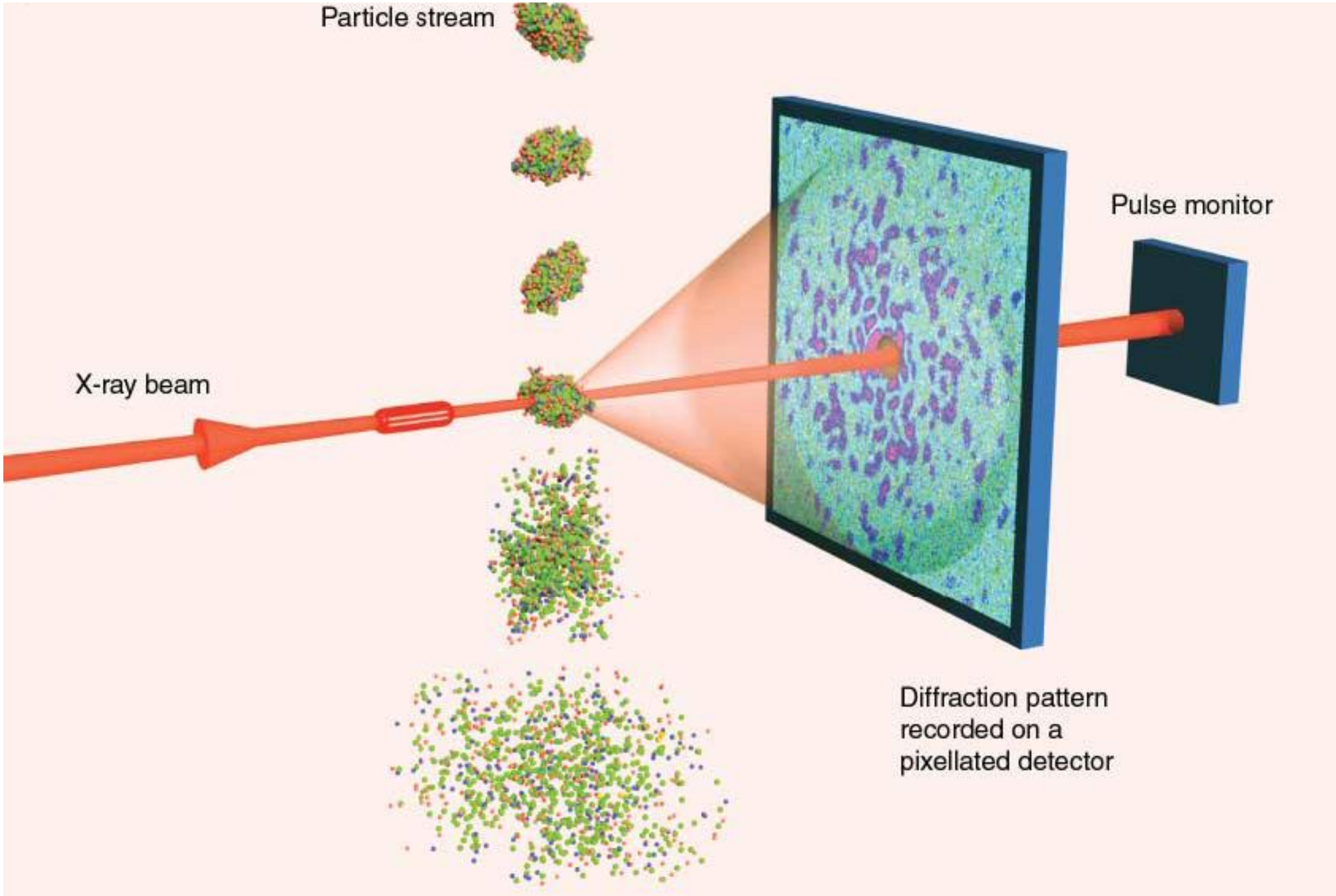


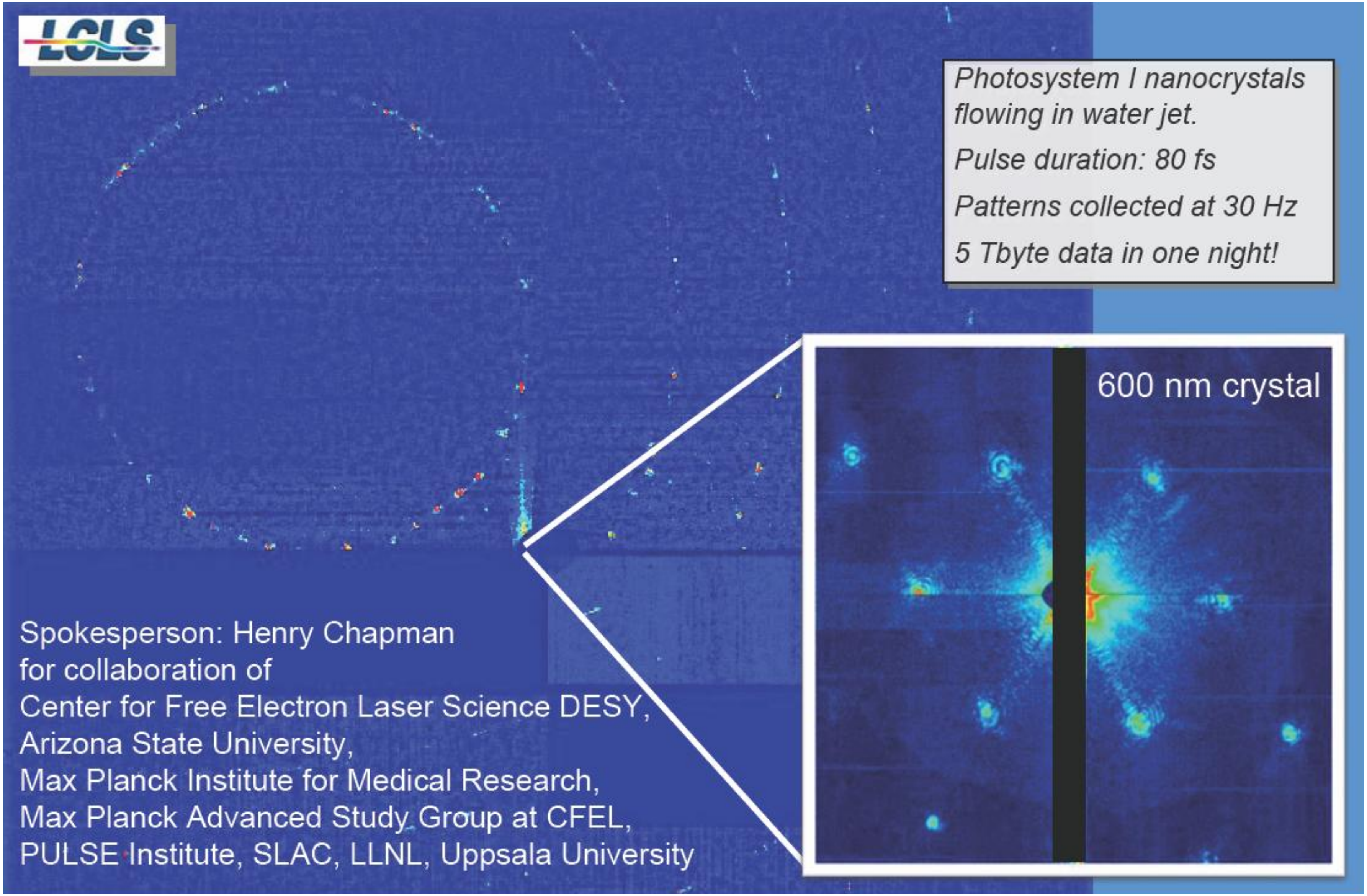
ultrafast diffraction

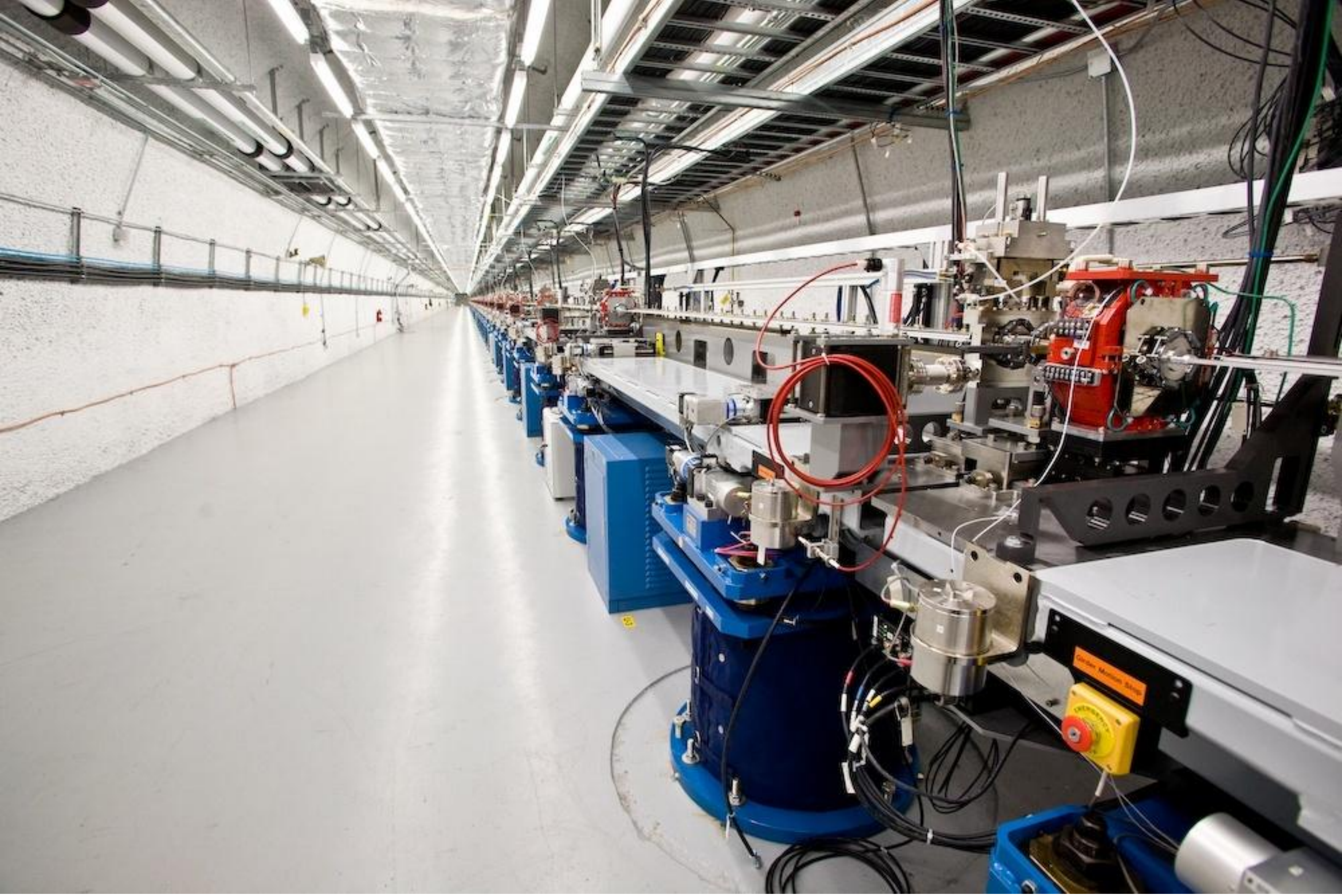
radiation damage, repeatability → *single-shot!*


Linac Coherent Light Source at *SLAC*
X-FEL based on last 1-km of existing linac
1.5-15 Å Free Electron Laser
OPERATIONAL

Coherent Diffractive Imaging of Biomolecules




LCLS
Photosystem I nanocrystals flowing in water jet.
Pulse duration: 80 fs
Patterns collected at 30 Hz
5 Tbyte data in one night!
600 nm crystal
Spokesperson: Henry Chapman
for collaboration of
Center for Free Electron Laser Science DESY,
Arizona State University,
Max Planck Institute for Medical Research,
Max Planck Advanced Study Group at CFEL,
PULSE Institute, SLAC, LLNL, Uppsala University



LCLS…

X-ray light sources: modern day cathedrals…

…how about small chapels?

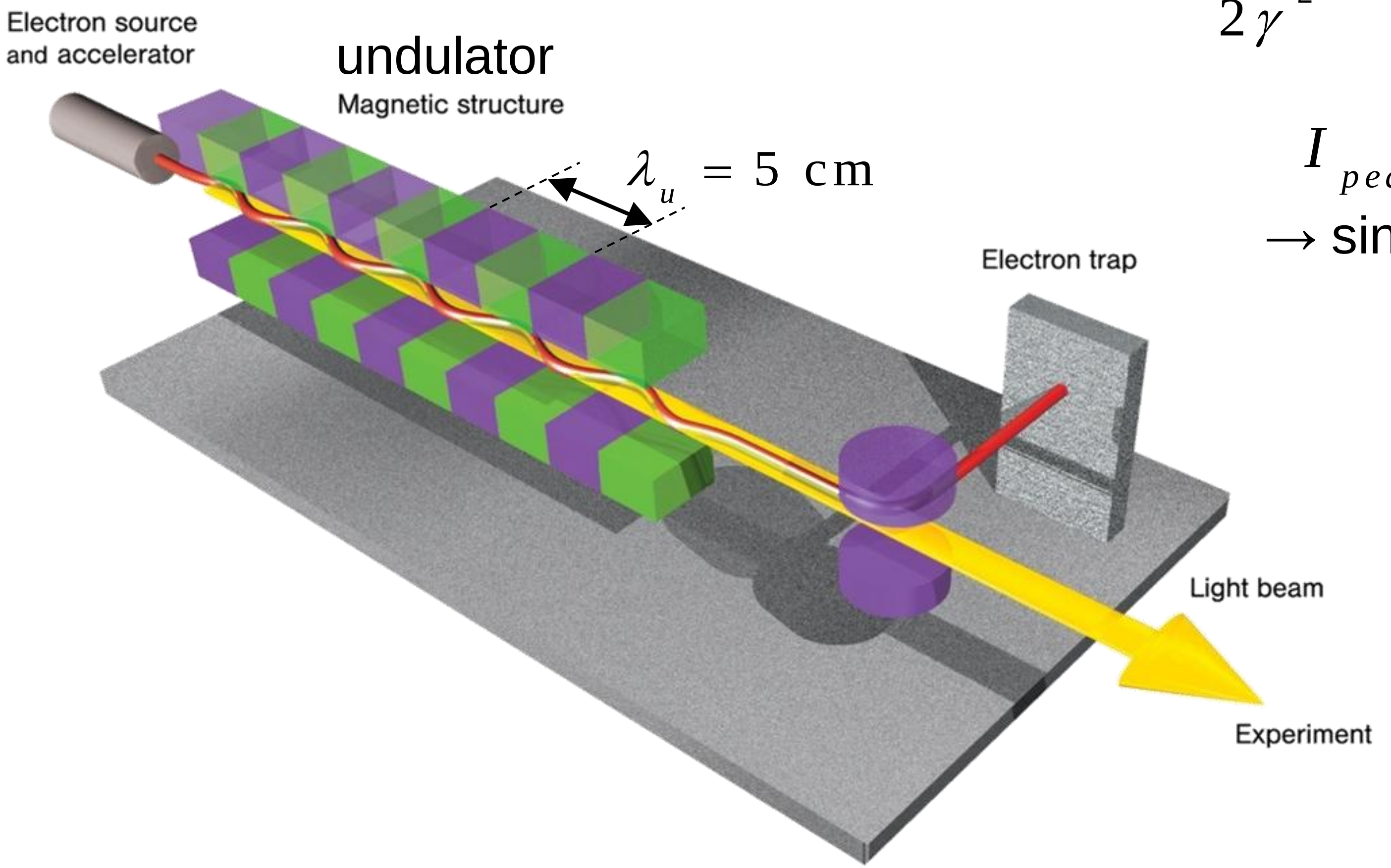
Single-pass X-ray FEL

$$\lambda_{rad} \approx \frac{\lambda_u}{2\gamma^2} \approx 10^{-10}\ \mathrm{m}$$

$I_{peak} \sim \mathrm{kA}$

→ single-pass gain

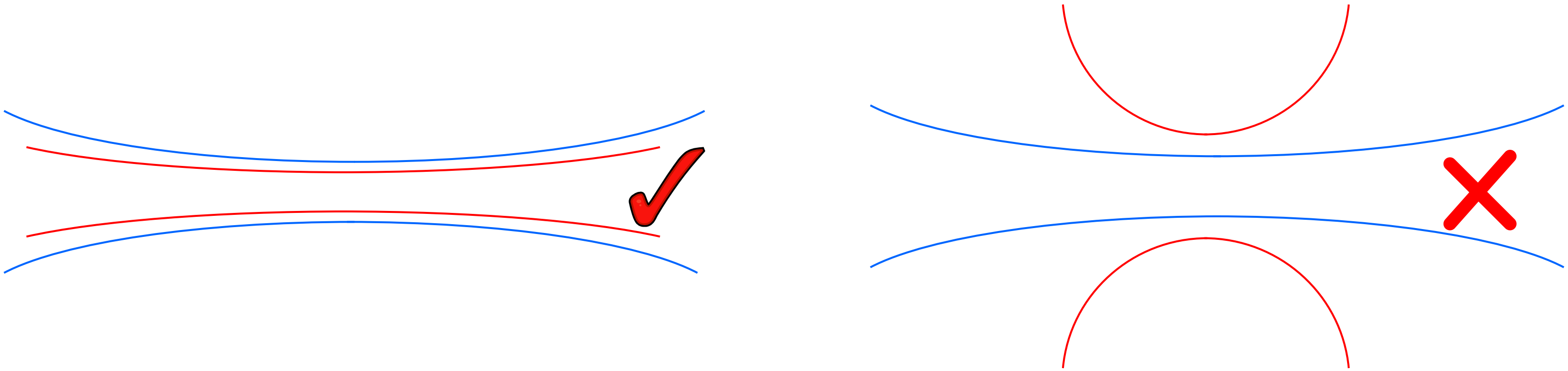
10 GeV



Why ultracold?

Electron beam emittance: $$\varepsilon_n = \frac{\sigma_x \cdot \sigma_{p_x}}{m c} \approx \gamma \cdot \sigma_x \cdot \sigma_\theta$$

Single-pass gain → $$\frac{\varepsilon_n}{\gamma} \approx \sigma_x \cdot \sigma_\theta \sim \frac{\lambda_{rad}}{4\pi}$$



Overlap between electron and X-ray beam…

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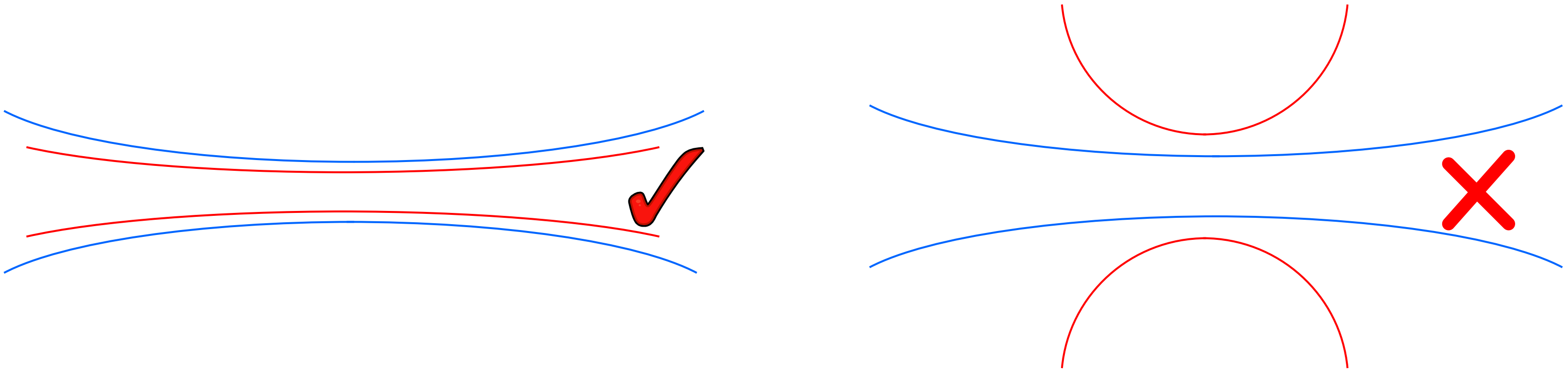

…lower normalized emittance → less acceleration.

Why ultracold?

Electron beam emittance: $$\varepsilon_n = \frac{\sigma_x \cdot \sigma_{p_x}}{mc} \approx \gamma \cdot \sigma_x \cdot \sigma_\theta$$

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$$\varepsilon_n = \sigma_{source} \sqrt{\frac{kT_e}{mc^2}}$$

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cannot be reduced very much (bunch charge)

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500× lower!!

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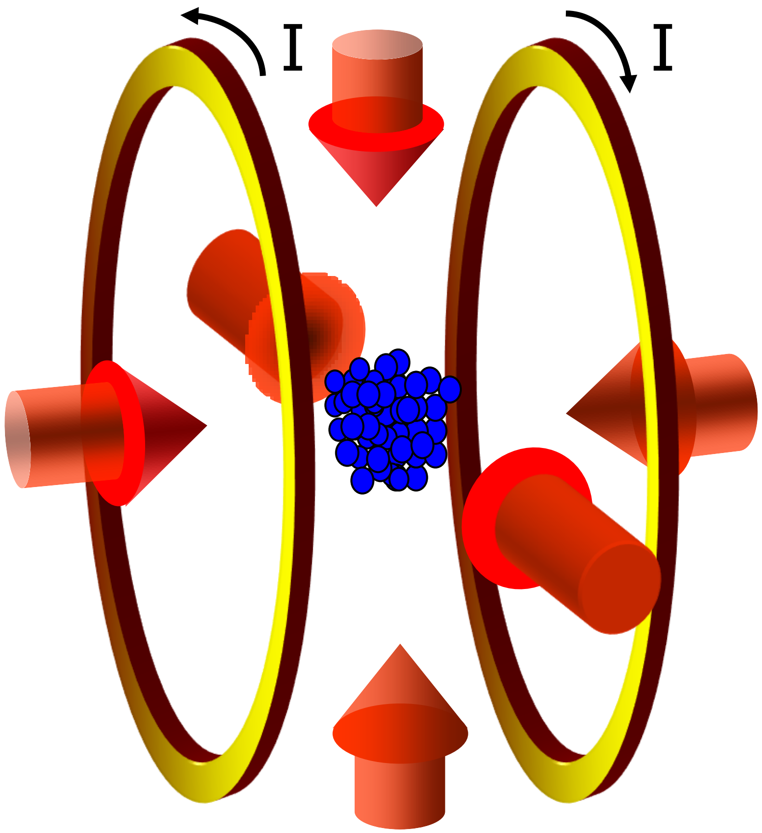
$$\varepsilon_n = \sigma_{source} \sqrt{\frac{kT_e}{mc^2}}$$

500× lower!!

Cold source → compact X-FEL!

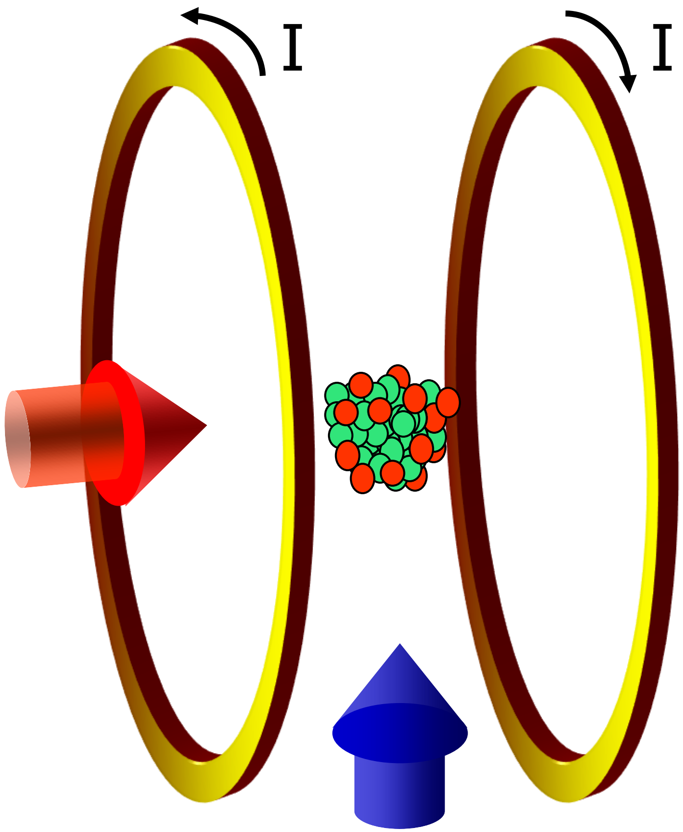
Laser-cooled charged particle source

Magneto-Optical Trap (MOT)



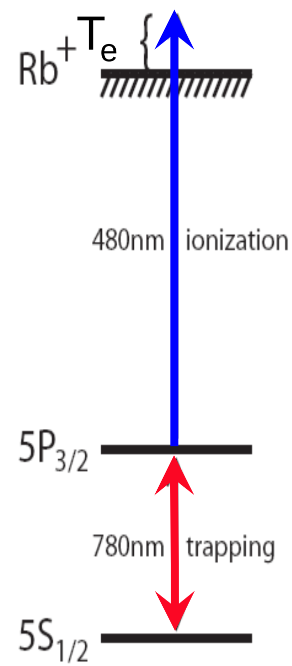
$N \leq 10^{10}$ Rb atoms,
$R = 1$ mm, $n \leq 10^{18}$ m^{-3}
$T < 0.001$ K

Ultracold Plasma



Killian et al., PRL **83**, 4776 (1999)

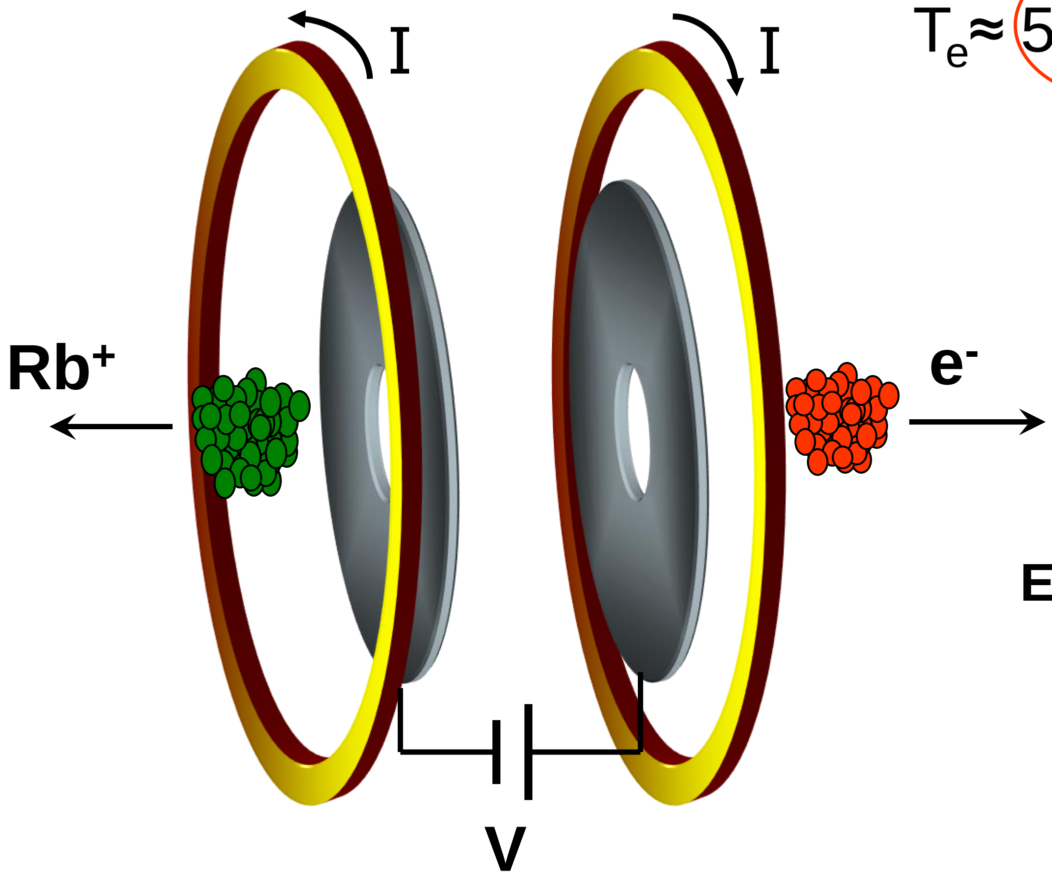
Electron temperature



$$kT_e \approx \frac{\hbar}{\tau}$$

$$\tau = 1\ \mathrm{ps} \rightarrow T_e \approx 10\ \mathrm{K}$$

Ultracold beams!



$T_e \approx$ 5000 K (0.5 eV) → **10 K**

conventional photo & field emission sources

Emittance $\varepsilon_n \sim \sqrt{T_e}$

~20× lower than conventional sources

Claessens et al., PRL **95**, 164801 (2005)

Moreover...

- *Each shot a new source – no cathode problems;*
- *Up to 10 nA average current: 10 pC @ 1kHz;*
- *Ionization volume fully controlled by laser beam overlap;*
- *ultracold **ion** bunches → model system for space charge dynamics.*

Outline

Ultracold electron beams

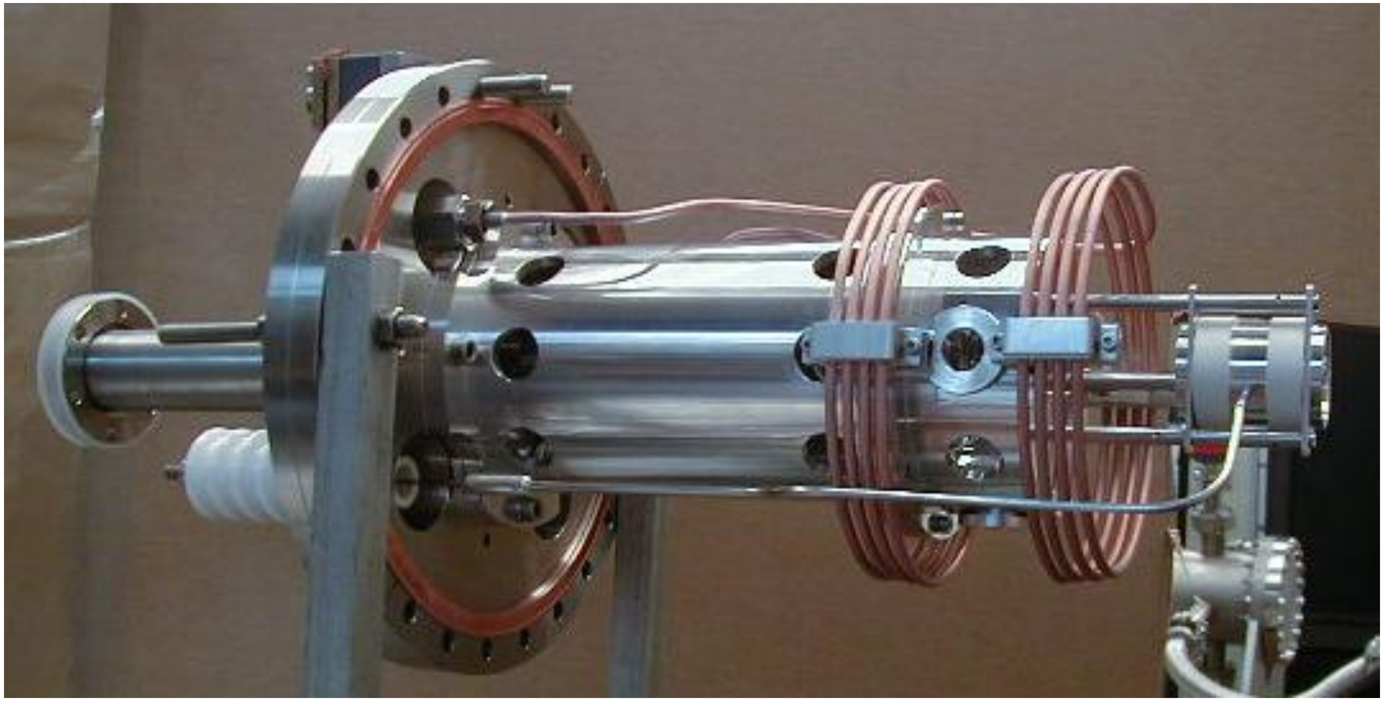
- *photo-ionization experiments*
- *implications for compact X-FEL*

Single-shot, femtosecond electron diffraction

- *RF bunch compression*
- *ultracold electron source*

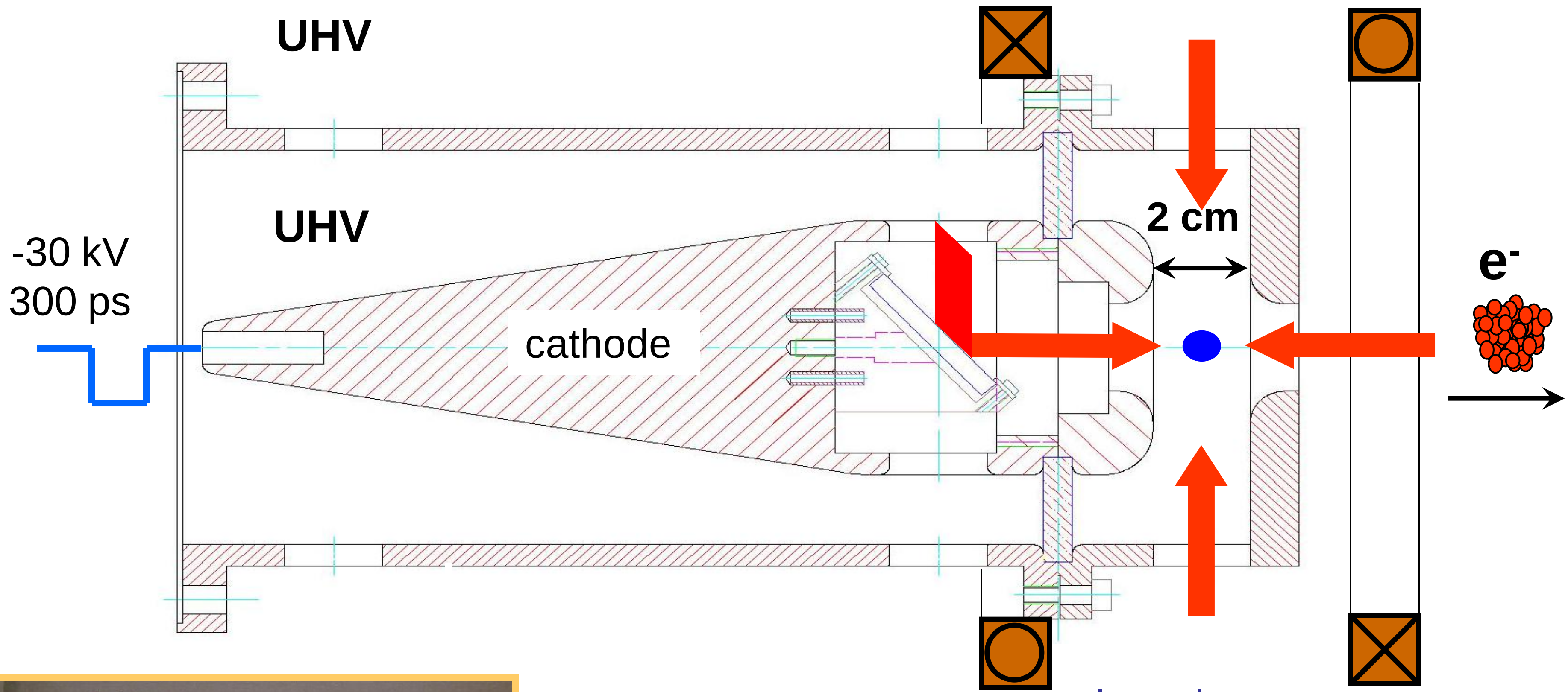
Ultracold beam experiments

Ultracold beam experiments



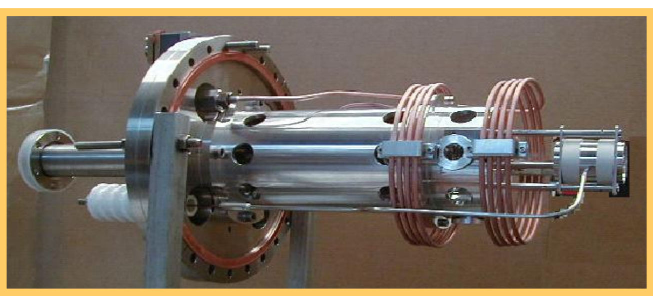
Claessens et al., PRL **95,** 164801 (2005);
Claessens et al., Phys. Plasmas **14**, 093101 2007;
Taban et al., PRSTAB **11**, 050102 (2008);
Reijnders et al., PRL **102**, 034802 (2009);
Taban et al., EPL**91**, 46004 (2010);
Reijnders et al., PRL **105**, 034802, (2010).

Ultracold beam experiments



laser beams

(trapping, ionization)



Ultracold beam experiments

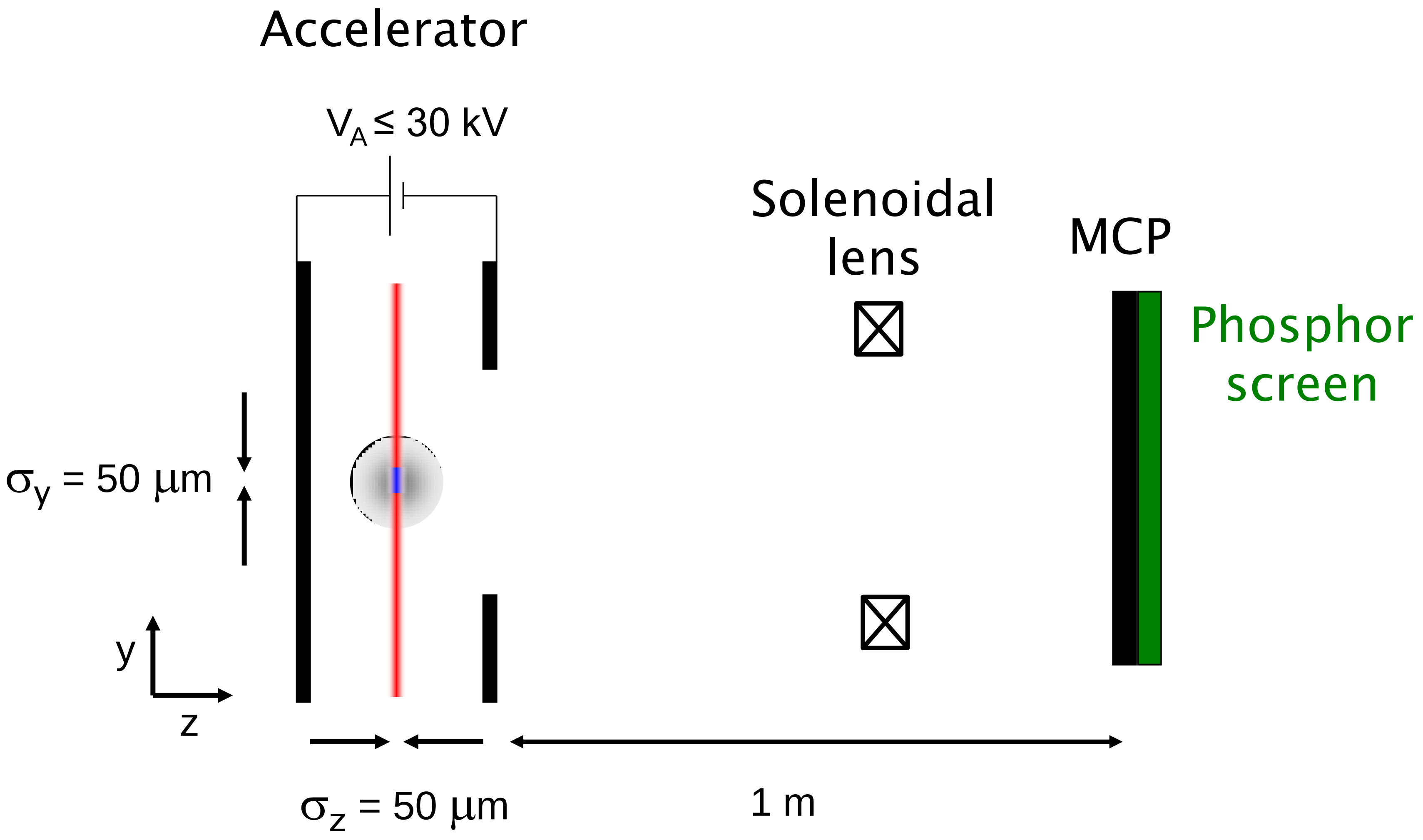
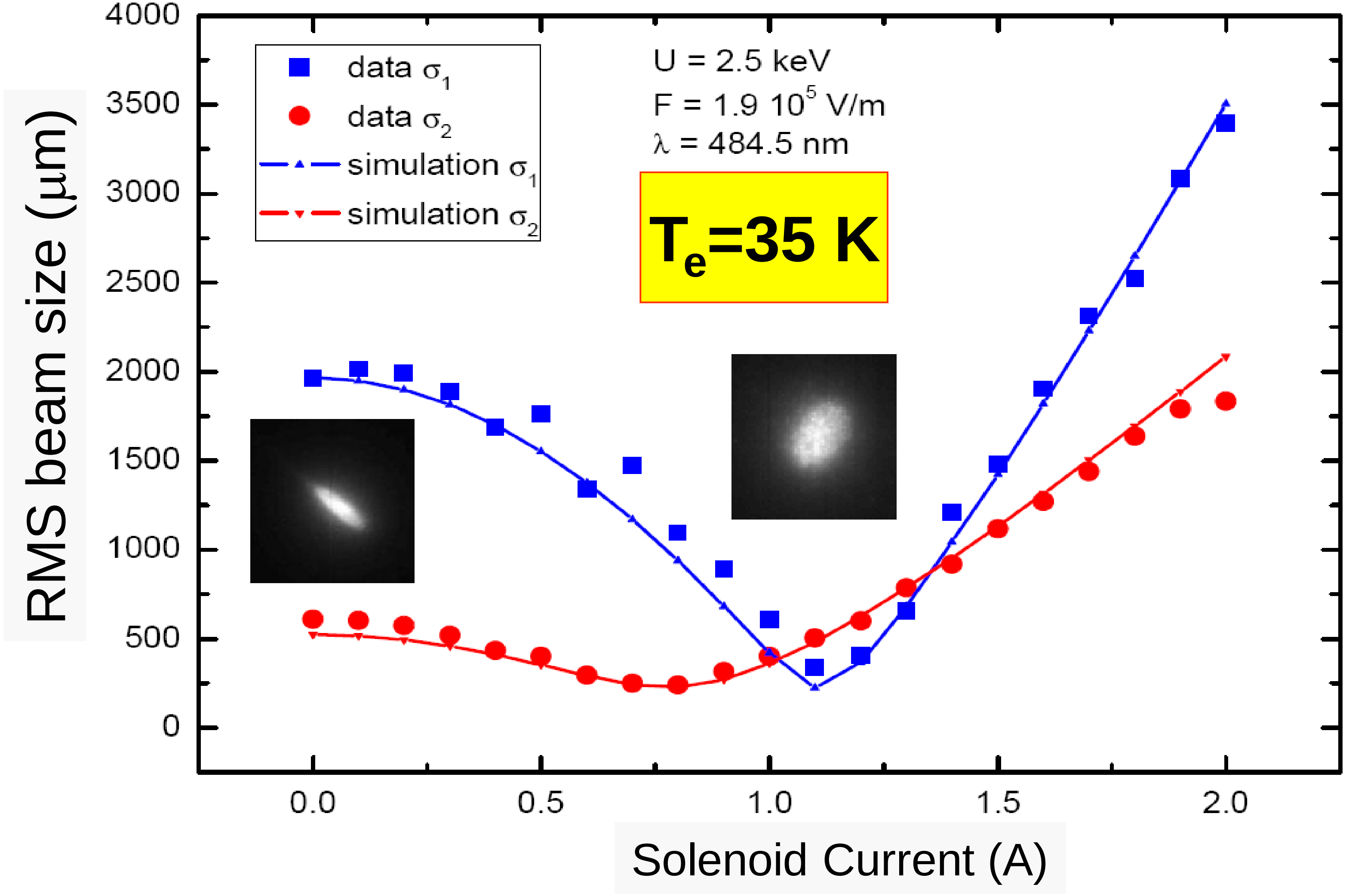
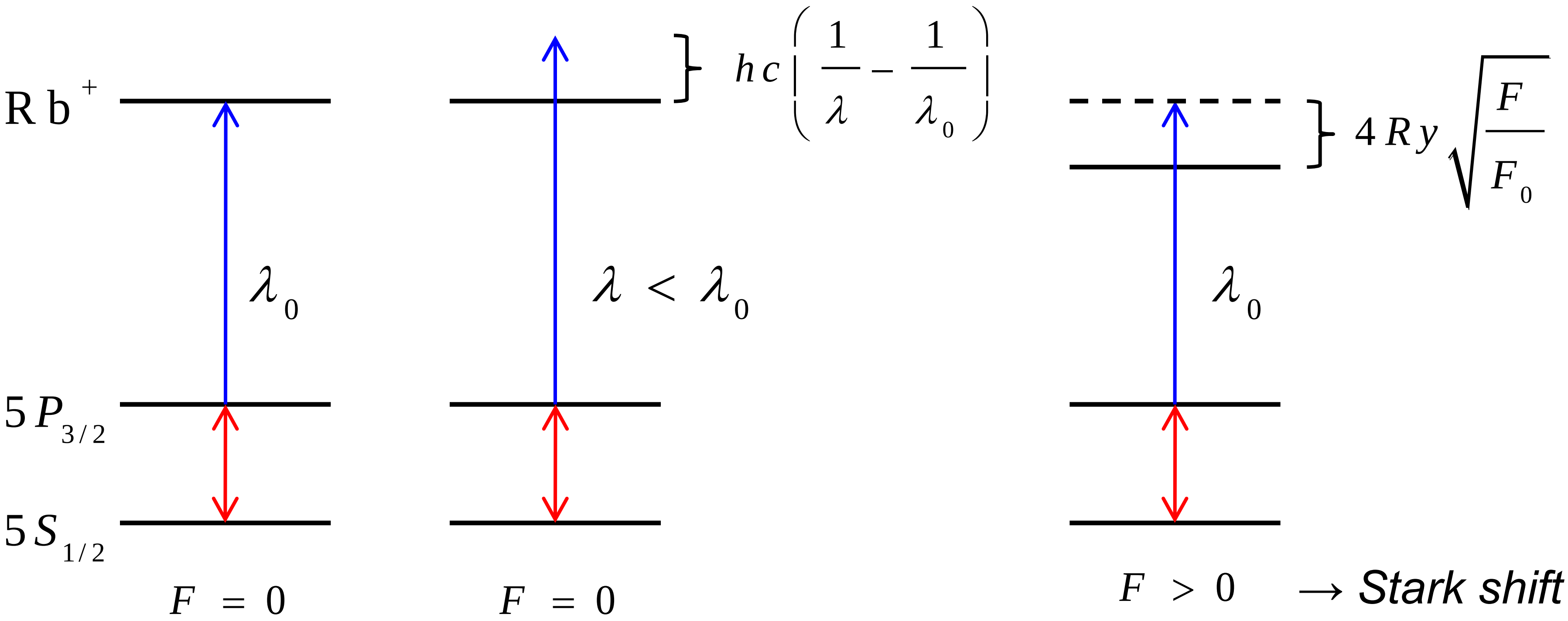


Photo-ionization experiment:
beam waist scans @ fixed energy

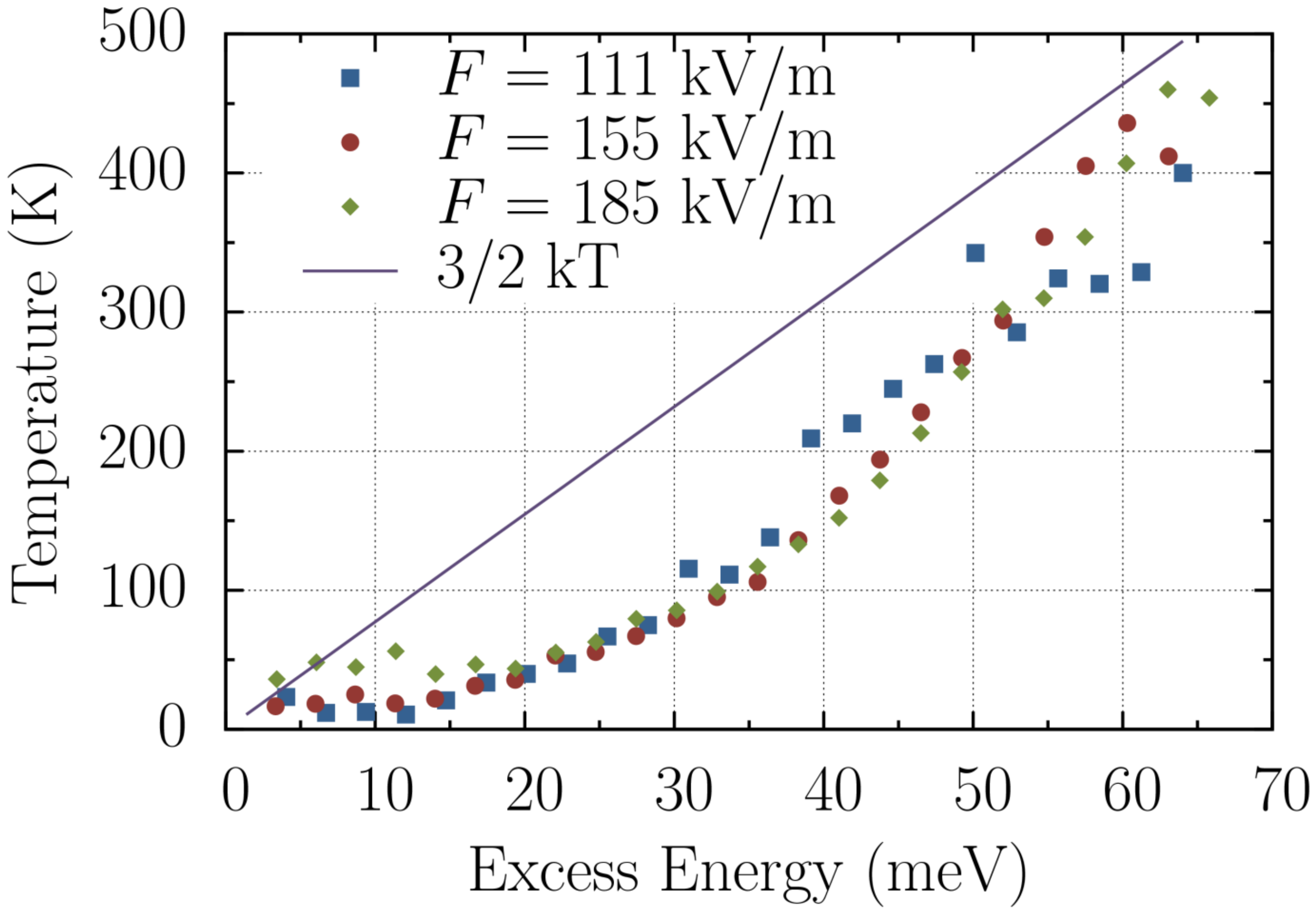


Excess energy

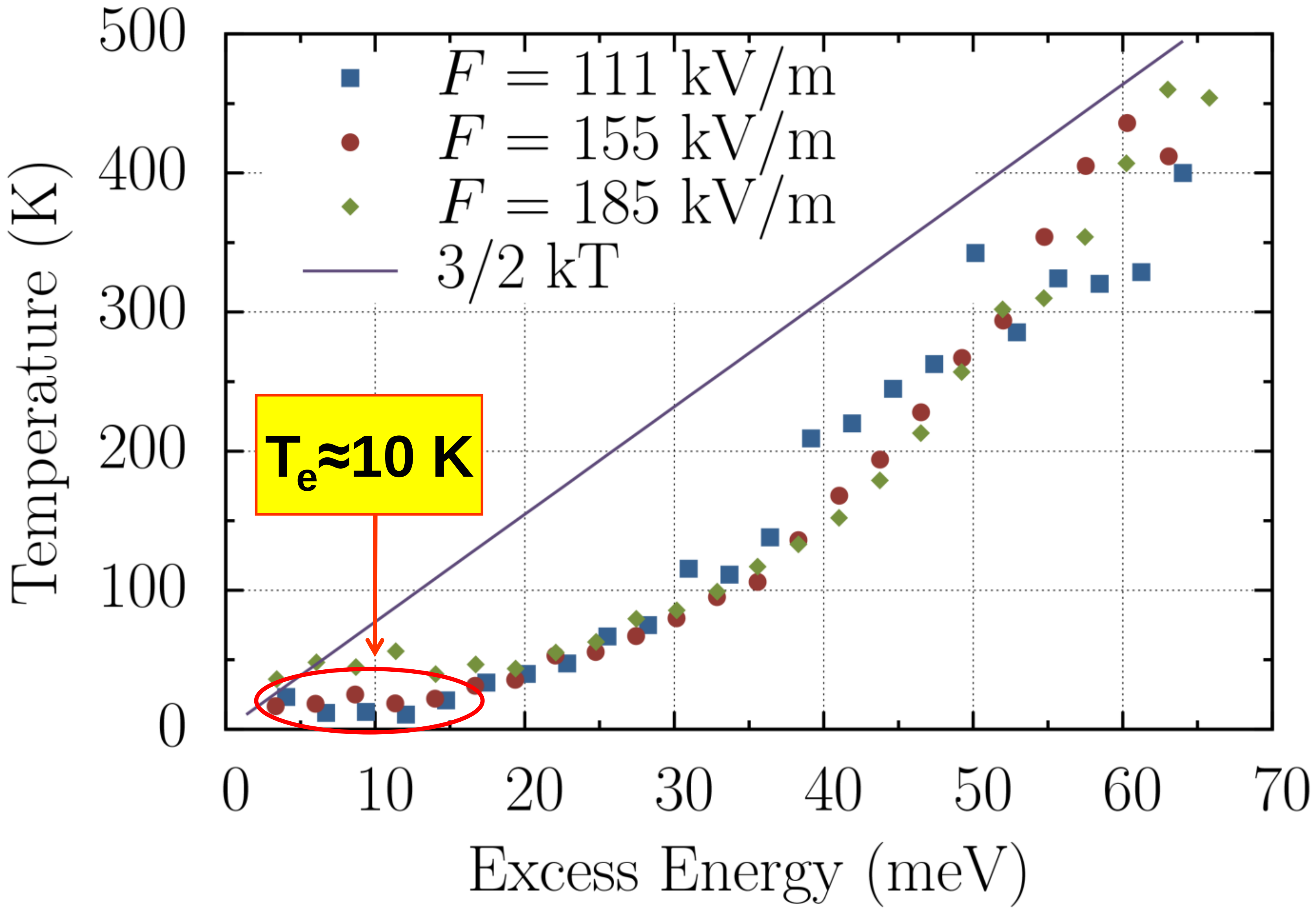
$$E_{exc} = hc\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right) + 4Ry\sqrt{\frac{F}{F_0}}$$



Electric field strength *F*



$F = 111$ kV/m
$F = 155$ kV/m
$F = 185$ kV/m
3/2 kT
Temperature (K)
Excess Energy (meV)
0
100
200
300
400
500
0
10
20
30
40
50
60
70



Temperature (K)
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3/2 kT
Te≈10 K
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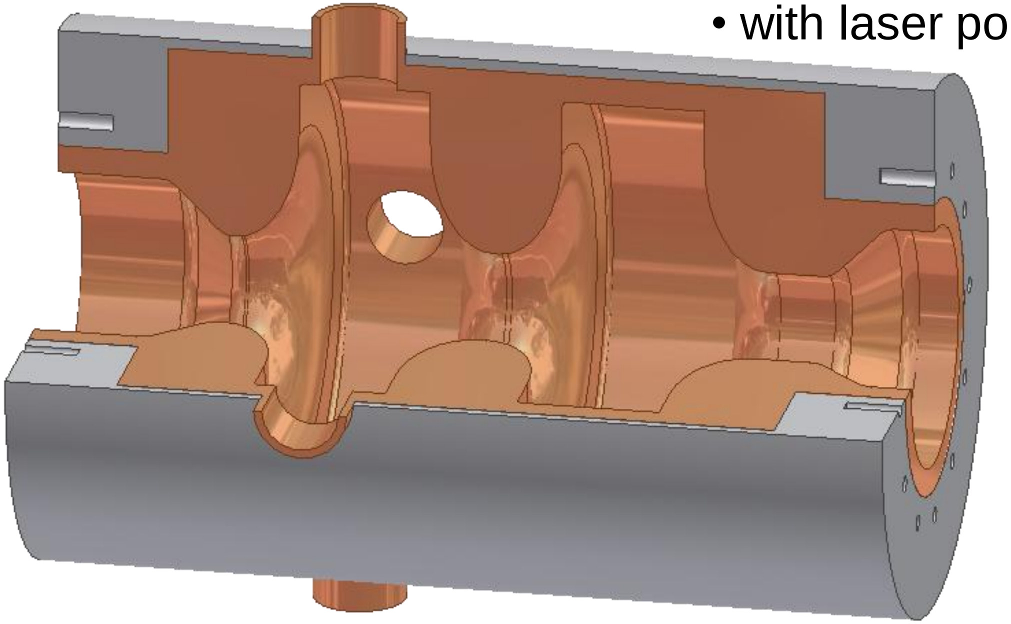
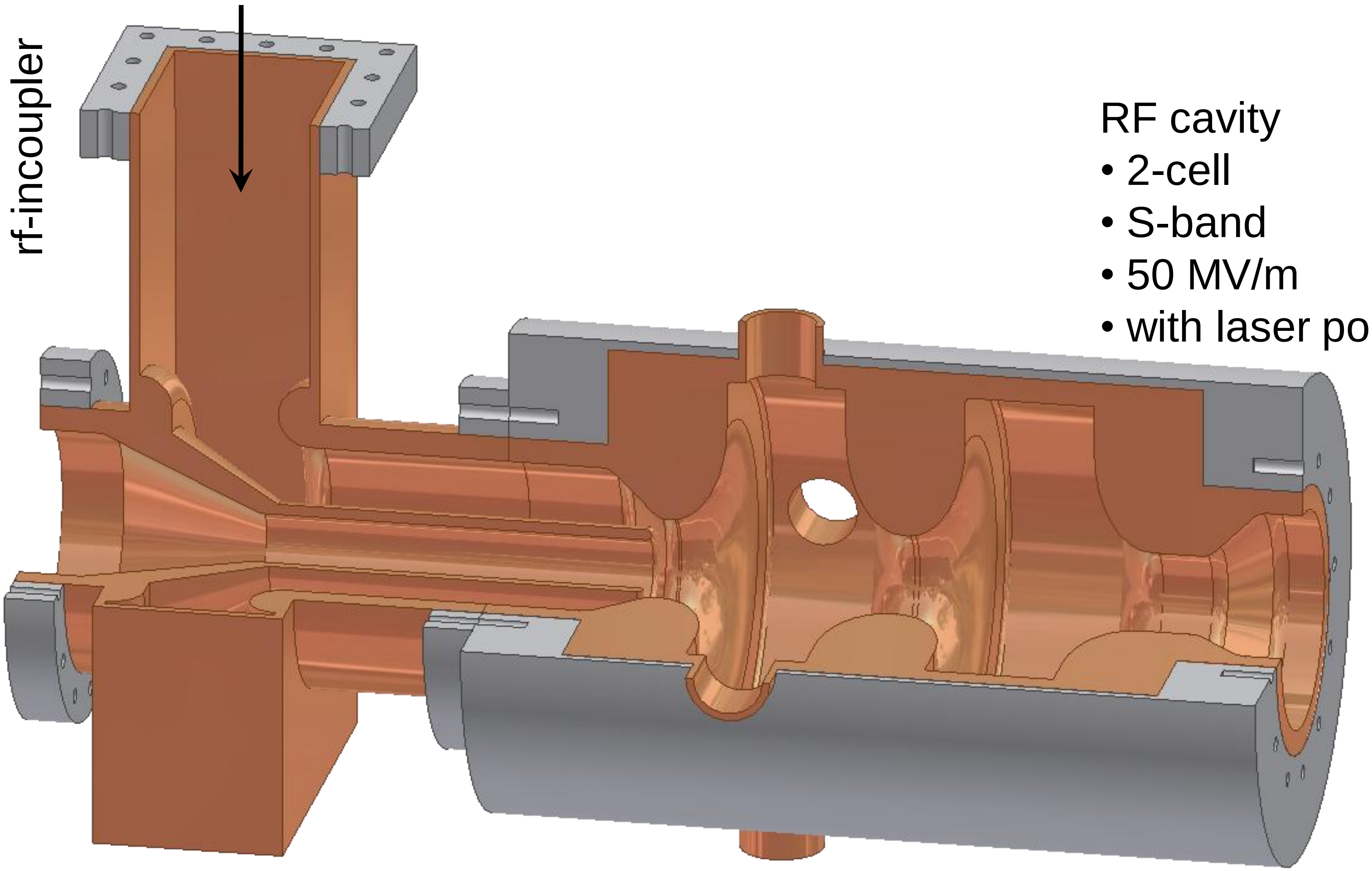
Implications for X-FEL: GPT simulations



RF cavity
- 2-cell
- S-band
- 50 MV/m
- with laser ports

Implications for X-FEL: GPT simulations



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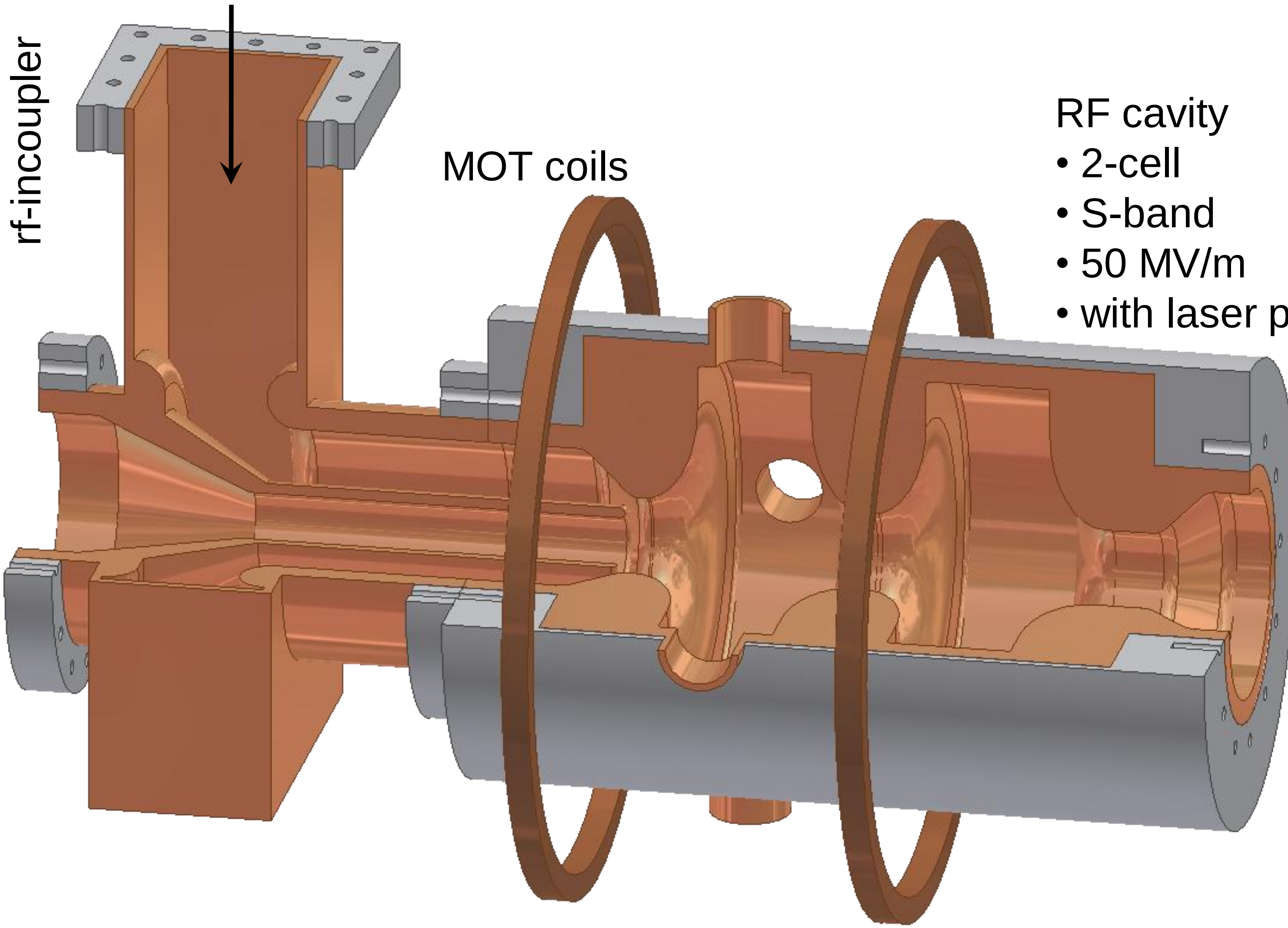
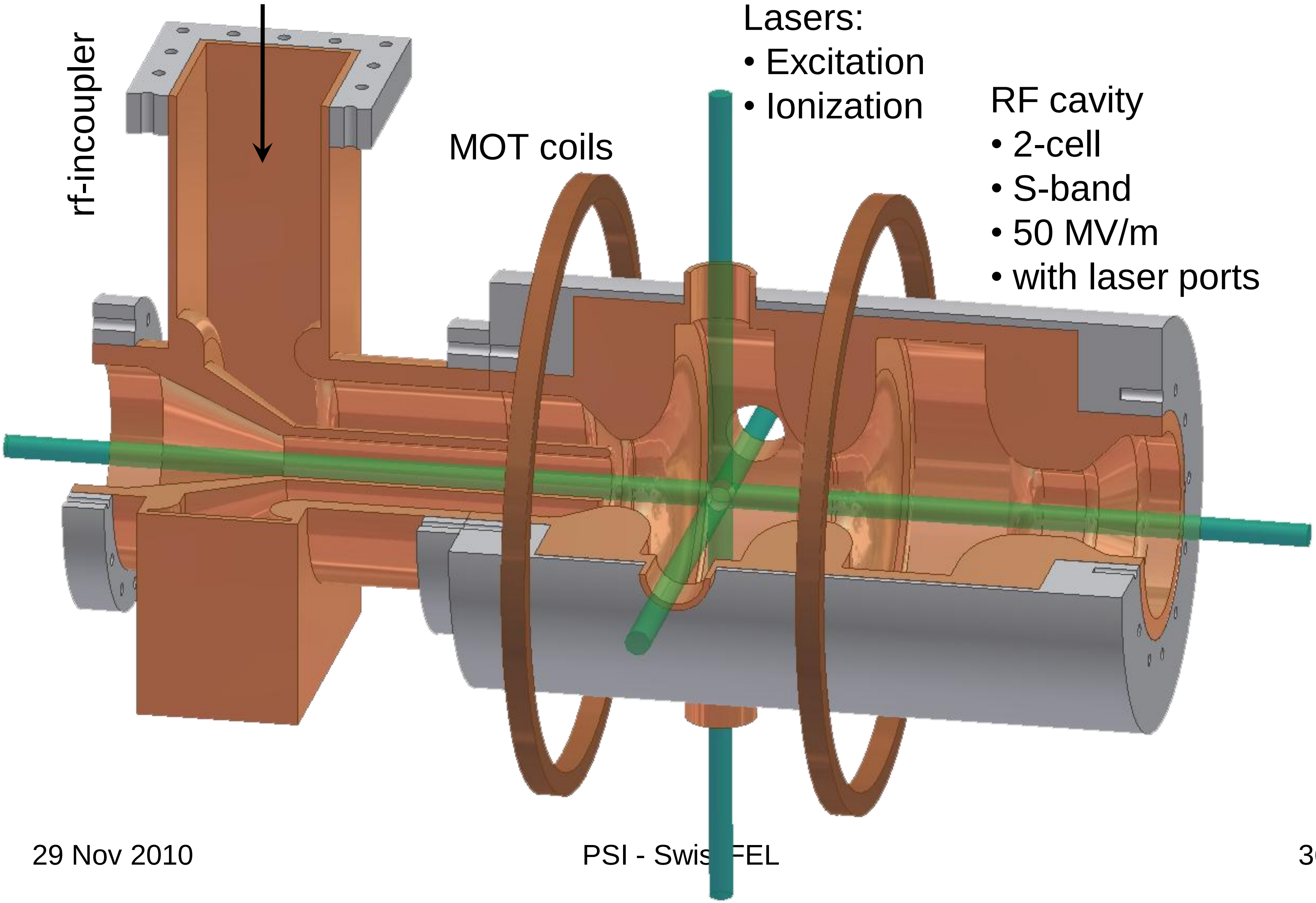
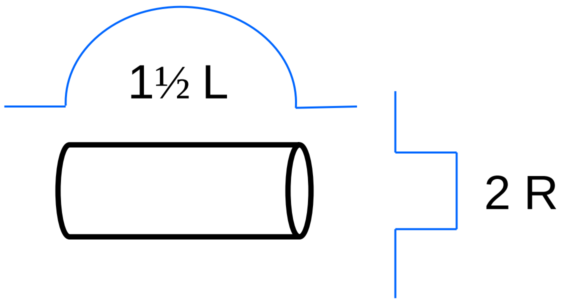


Implications for X-FEL: GPT simulations



Implications for X-FEL: GPT simulations

Initial conditions	
Charge	**1-100 pC**
MOT Density	$10^{18}/m^3$
Ionizaton volume	Uniform in r
	Parabolic in z
Aspect ratio (R/L)	1:10
Ionization time	1 ps
Initial temperature	10 K
Cavity parameters	
Maximum field	50 MV/m
Field-balance	1:1

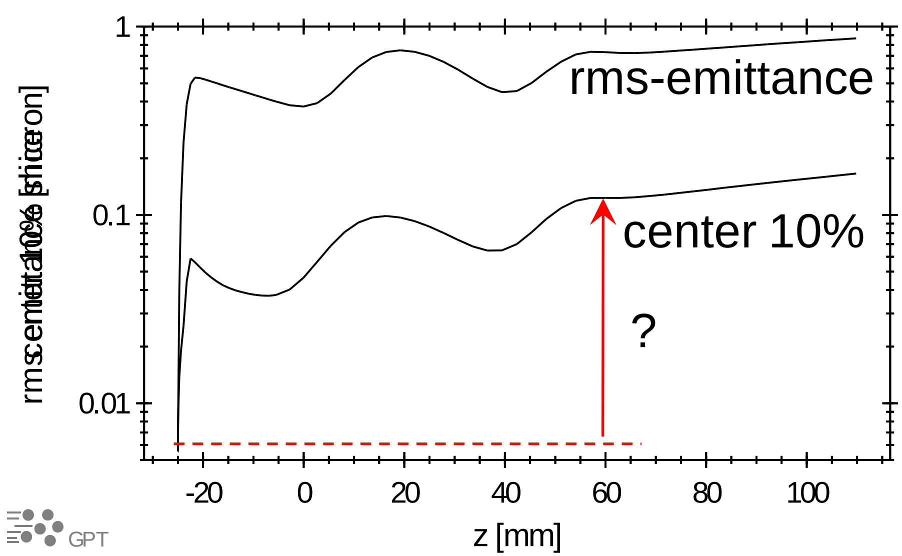


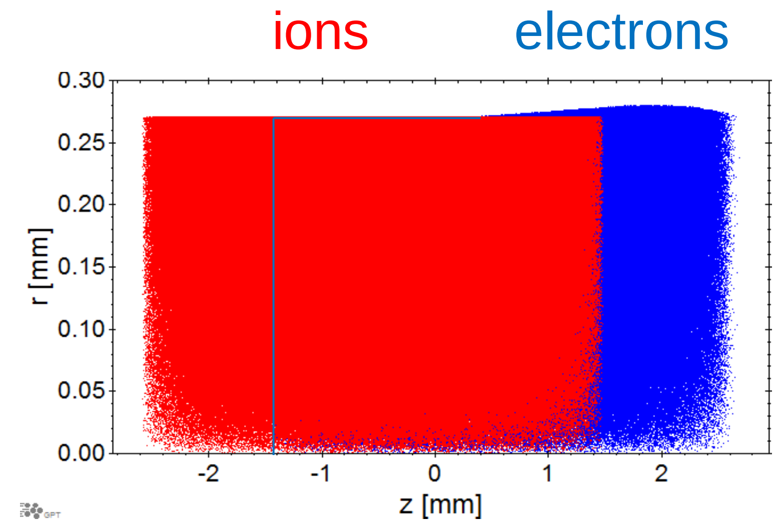
$$Q = 100 \text{ pC} \Rightarrow R = 270 \ \mu\text{m}$$

$$Q = 1 \text{ pC} \Rightarrow R = 58 \ \mu\text{m}$$

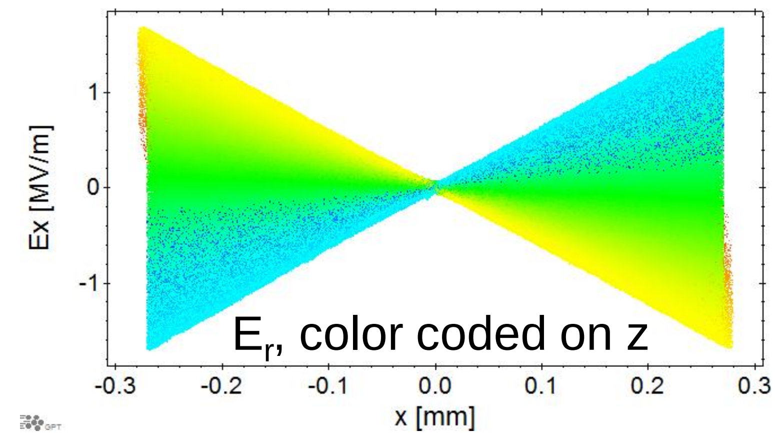
Implications for X-FEL: GPT simulations

Acceleration of 100 pC to 2 MeV





Emittance compensation schemes?



Basic FEL equations:

$$\frac{\varepsilon_n}{\gamma} = \frac{\lambda_{rad}}{4\pi} \qquad \lambda_{rad} = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

$$L_g = \frac{1}{\sqrt{3}}\sqrt[3]{\frac{2mc\,\gamma^3\sigma^2\lambda_u}{\mu e K^2 I}} = \frac{4\pi\sigma^2}{\lambda_{rad}}$$

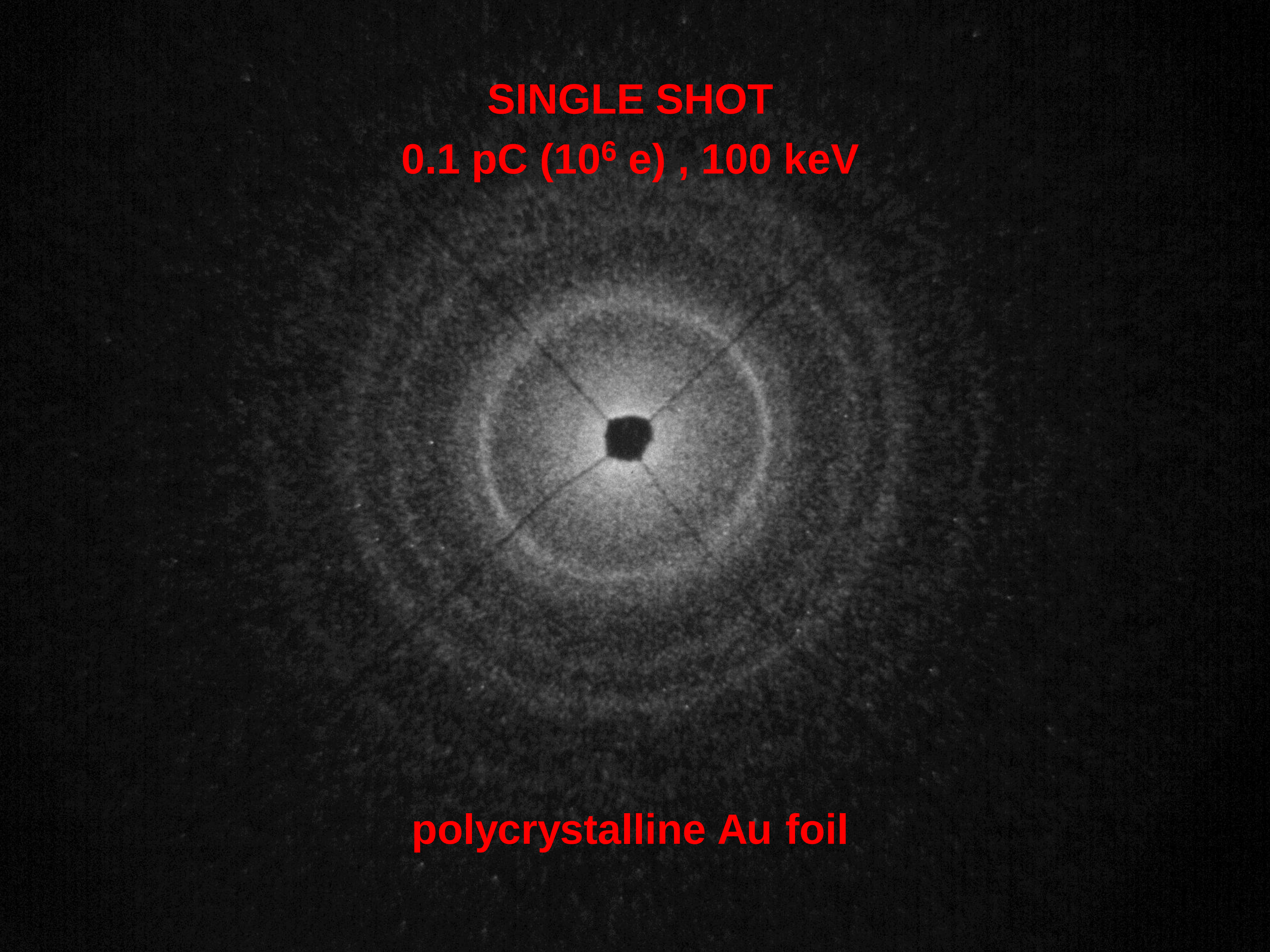
$$\rho_{FEL} = \frac{1}{4\pi\sqrt{3}}\frac{\lambda_u}{L_g} \qquad P = \gamma\frac{mc^2}{e} I\,\rho_{FEL}$$

$$\sigma_W = \frac{\rho_{FEL}}{2}\gamma\frac{mc^2}{e} \qquad I_{\max} = \frac{Q}{\varepsilon_z / \sigma_W}$$

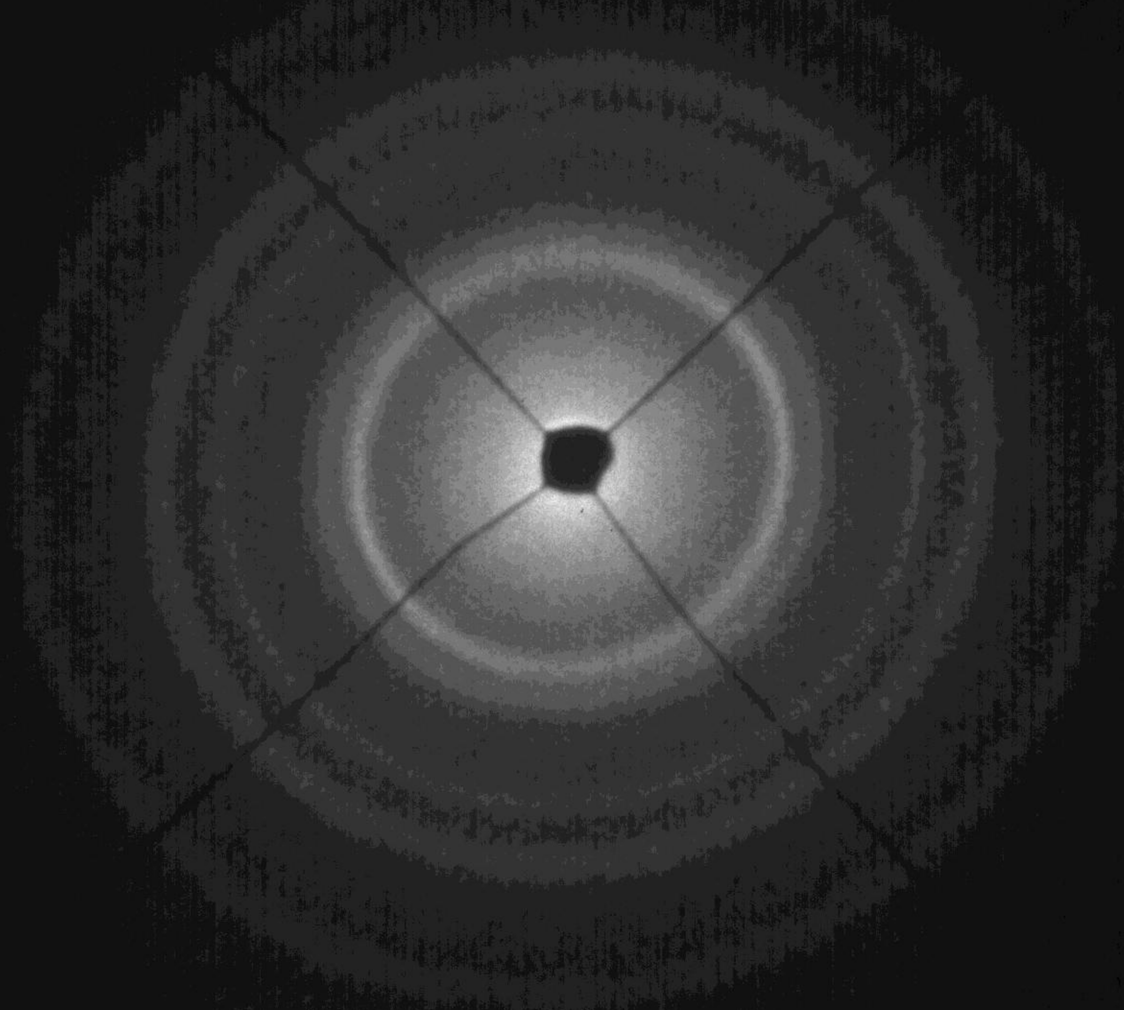
Two scenarios: high and low charge

Charge	100	1	pC
Maximum field	50	20	MV/m
Slice emittance	0.1	0.02	micron
Assumed peak current	1	0.1	kA
Wavelength	0.5	0.1	nm
Energy	1.3	1.3	GeV
ρ_{FEL}	0.005	0.0016	
λ_U	4	0.8	mm
Gain Length	37	23	mm
Power (1D)	6	0.2	GW
Repetition rate (10^{11}/s)	0.1	10	kHz

Single-shot femtosecond electron diffraction


SINGLE SHOT
0.1 pC (10^6 e) , 100 keV
polycrystalline Au foil

average of 20 single shot pictures



polycrystalline Au foil

SINGLE SHOT

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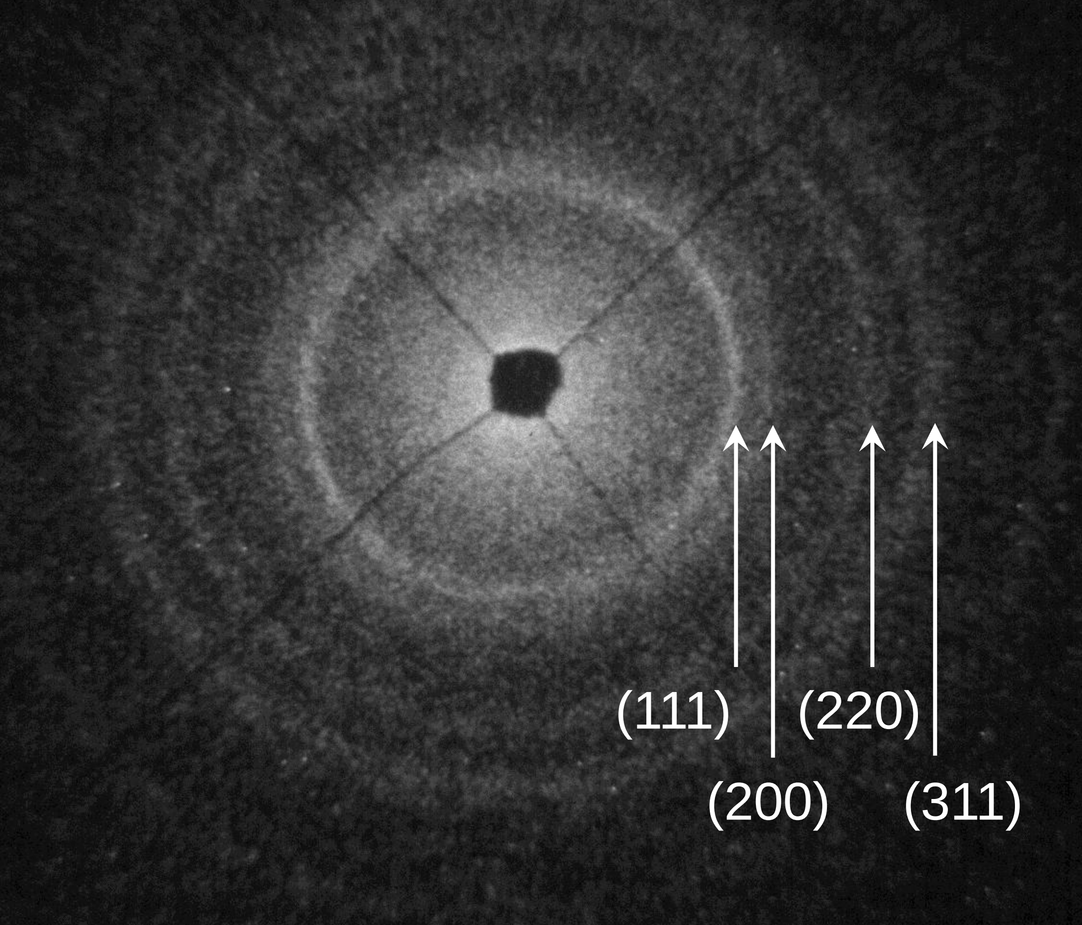
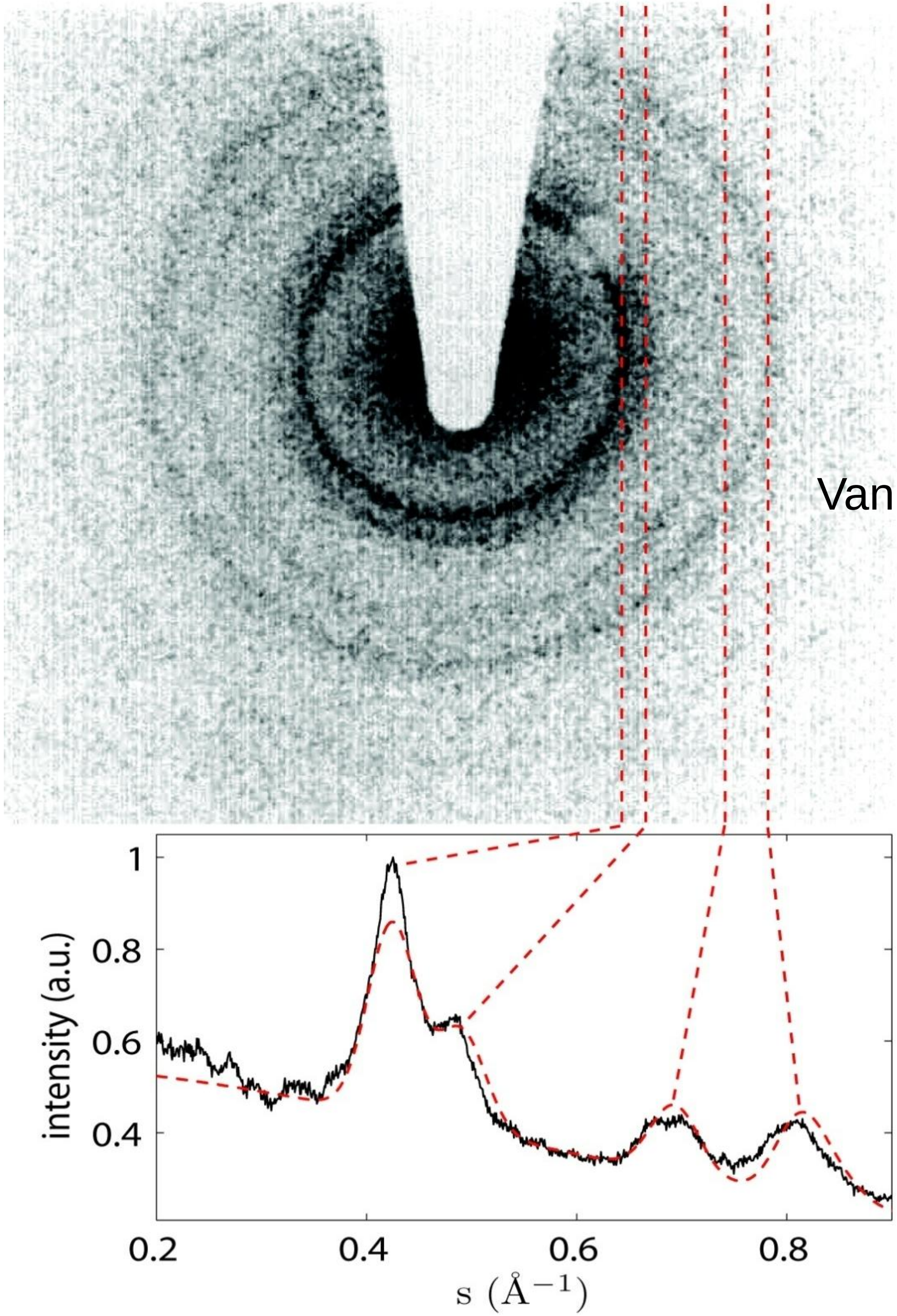


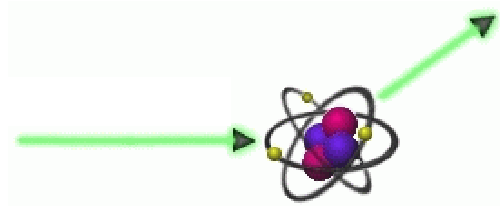
polycrystalline Au foil

9 nm Au foil
U = 95 keV
Q = 0.2 pC



Van Oudheusden et al., PRL (2010)

Why use electrons?



X-rays:
Thomson scattering

$$\sigma_T = 6.6 \times 10^{-29}\ \mathrm{m}^2$$

high density, bulk

Electrons:
Rutherford scattering

$$\sigma_R > 10^{-24}\ \mathrm{m}^2$$

gas phase, surfaces

Complementary information!

Electrons vs X-rays

Property	***Electrons*** (100 keV)	***Hard X-rays*** (10 keV)
Wavelength / Å	0.04	1.2
Mechanism radiation damage	Secondary electron emission	Photoelectric effect
Ratio (inelastic/elastic) scattering	3	10
Energy deposited per elastic event	1	>1000
Elastic mean free path	1	10^5-10^6

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1000× less radiation damage per count!

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Wavelength / Å	0.04	1.2
Mechanism radiation damage	Secondary electron emission	Photoelectric effect
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Energy deposited per elastic event	1	>1000
Elastic mean free path	1	10^5-10^6

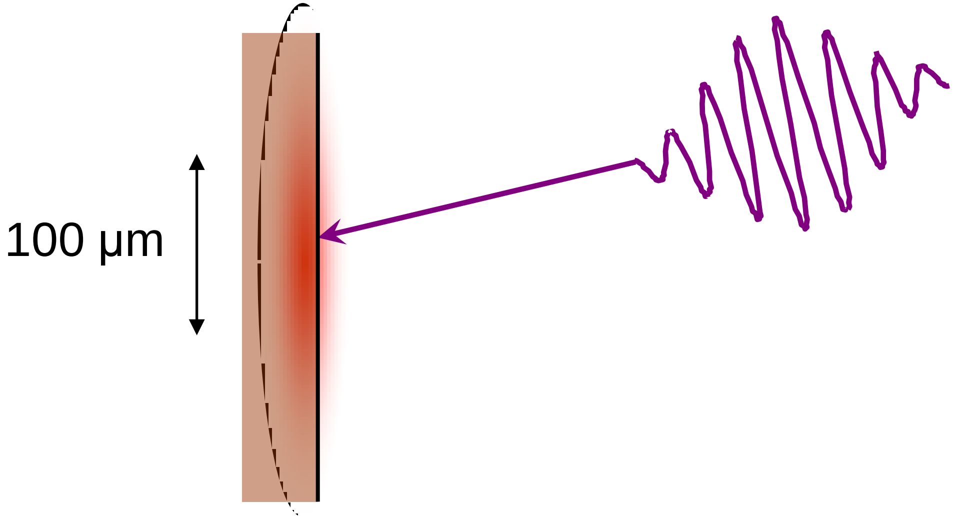
10^6 electrons sufficient for single-shot diffraction!

Electrons – why not?

Electrons – why not?

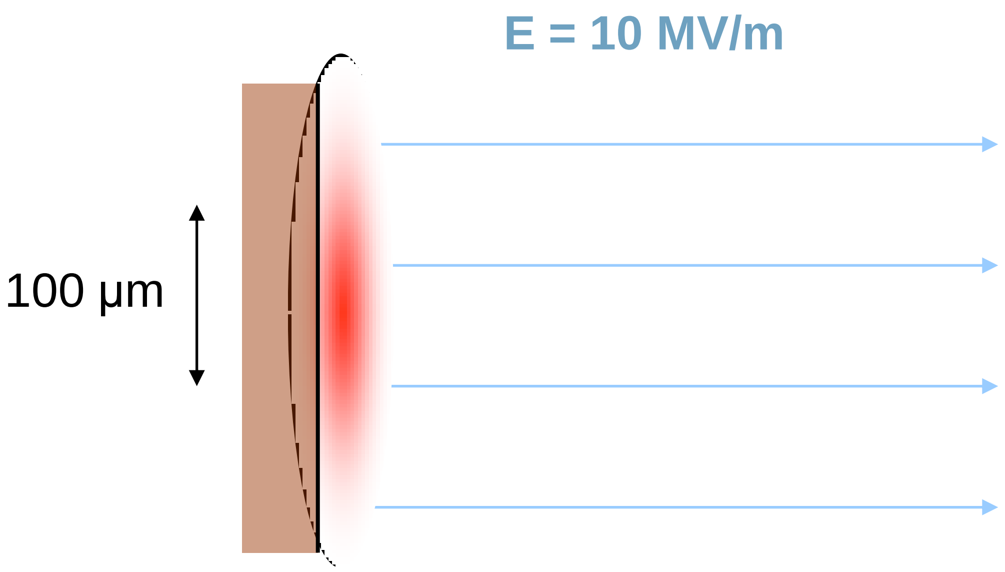
Source brightness & Coulomb forces

femtosecond laser photoemission...



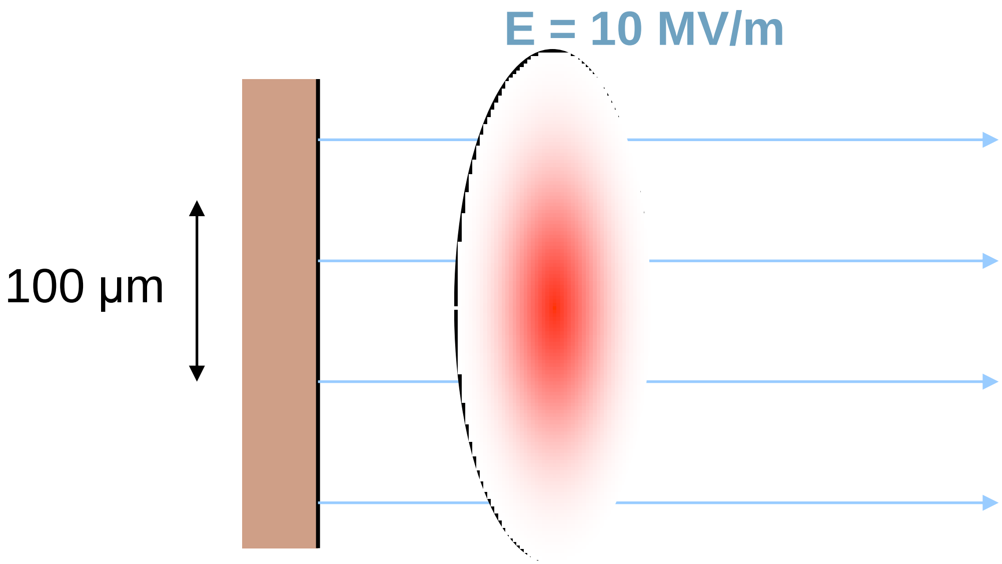
10^6 electrons from 100 μm spot

...electron bunch acceleration...

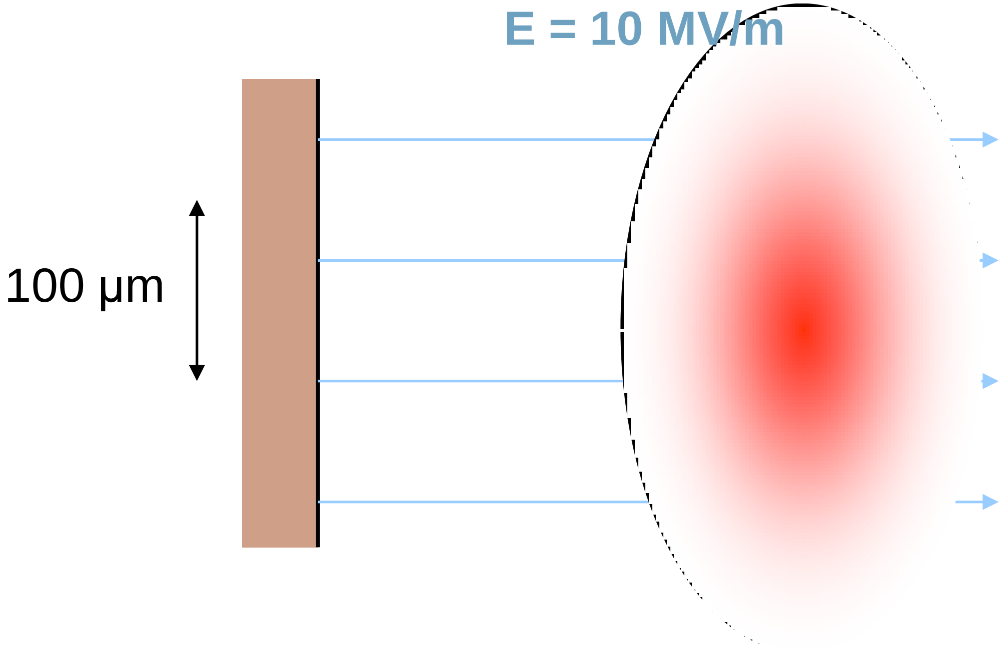


10^6 electrons from 100 μm spot & 10 MV/m ✓

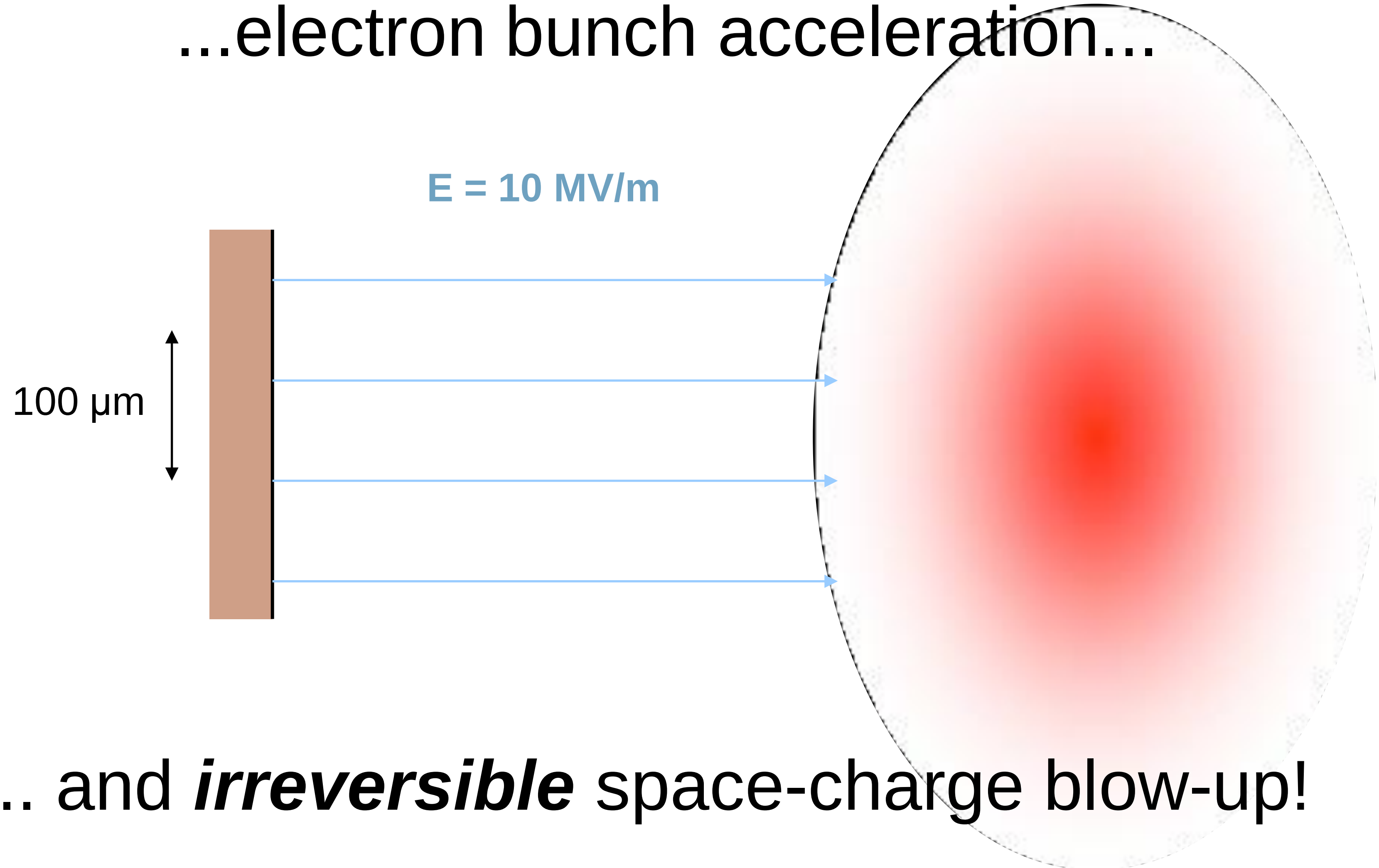
...electron bunch acceleration...



...electron bunch acceleration...

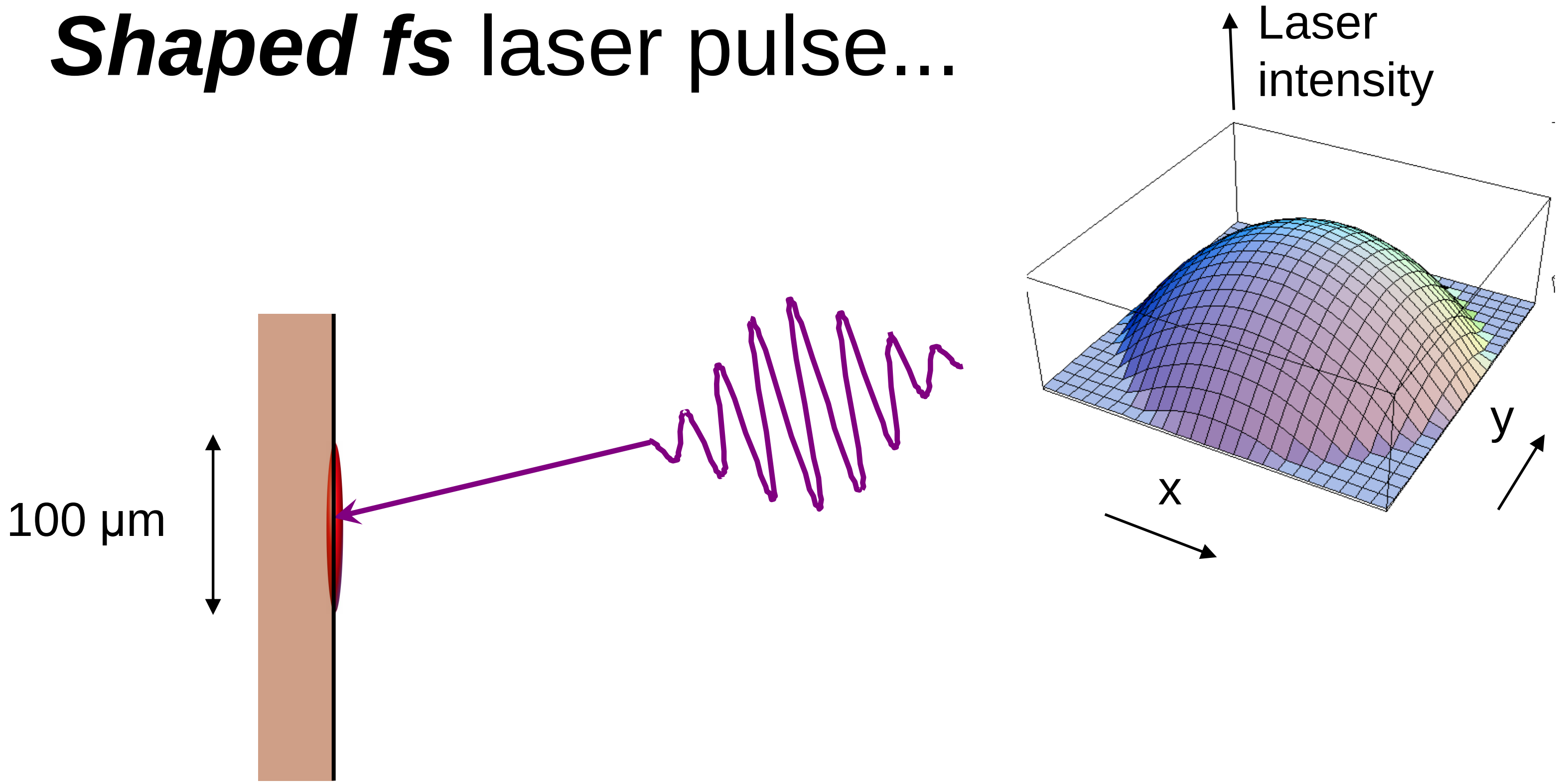


...electron bunch acceleration...



... and ***irreversible*** space-charge blow-up!

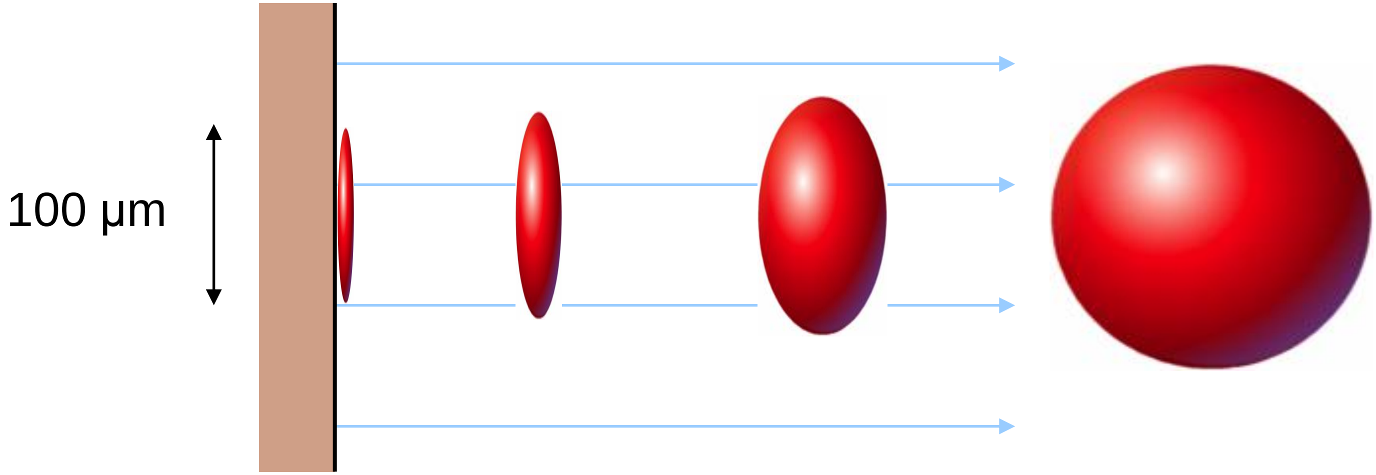
Shaped fs laser pulse...



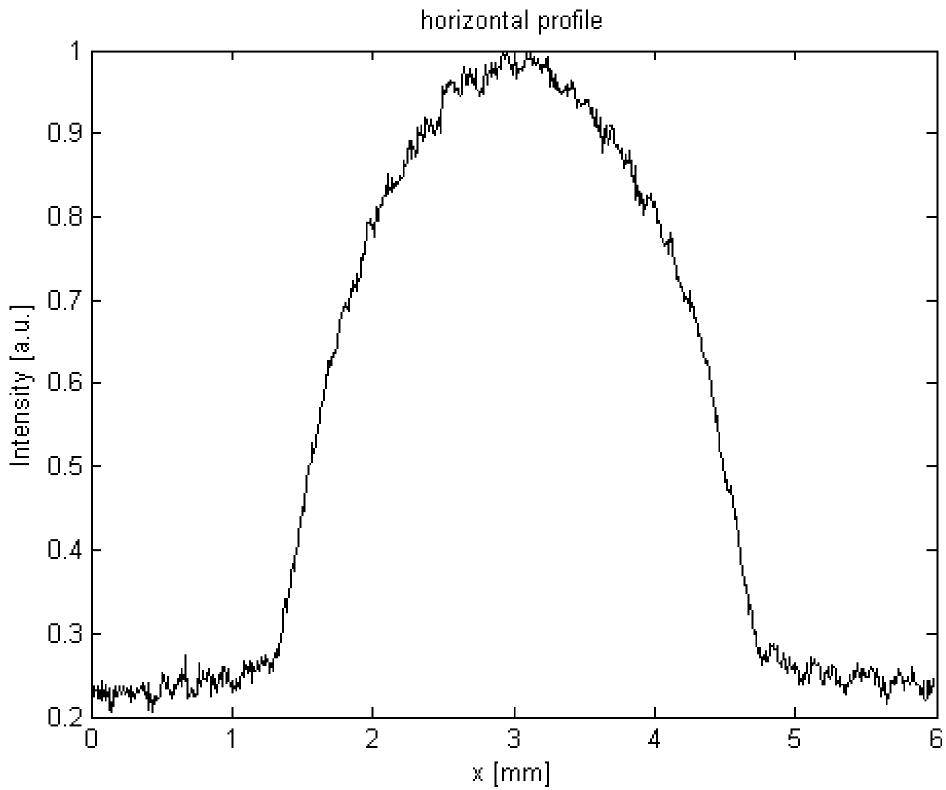
Luiten et al., PRL **93**, 094802 (2004)

...evolution into ***uniform ellipsoid***.

→ ***linear & reversible*** Coulomb expansion



Luiten et al., PRL **93**, 094802 (2004)



Phosphor screen image integrated over y-direction

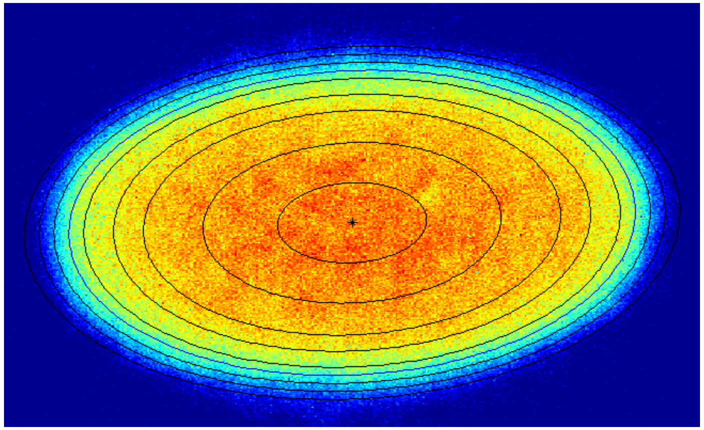
Thijs van Oudheusden, TU/e:

hard-edged, uniform ellipsoids

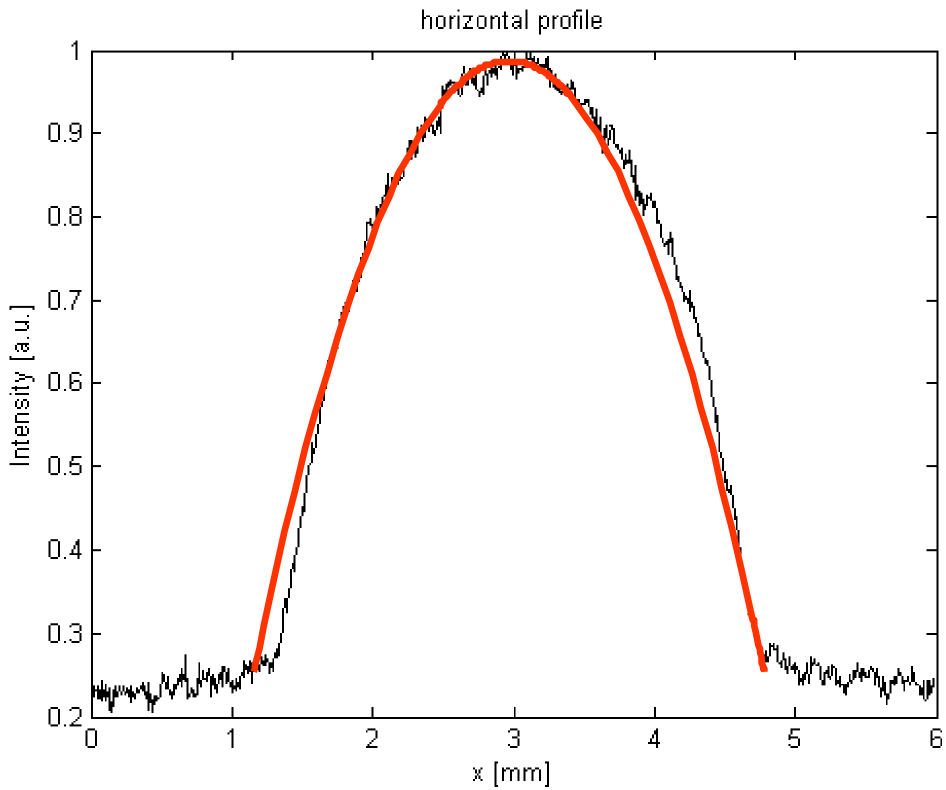
U = 95 keV, Q = 0.2 pC

phosphor screen image

y →



x →



Phosphor screen image integrated over y-direction

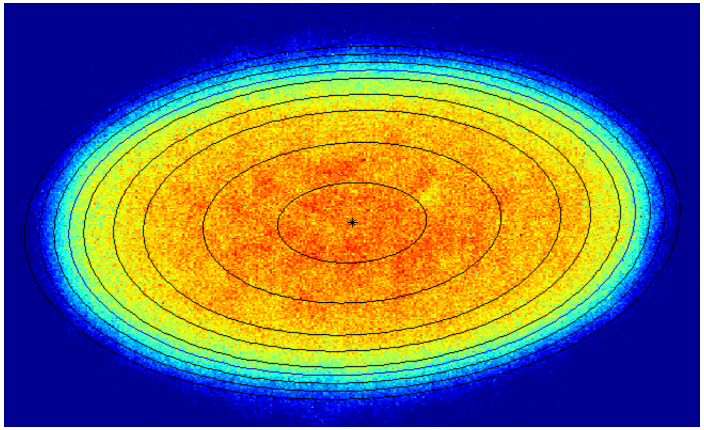
Parabola

Thijs van Oudheusden, TU/e:

hard-edged, uniform ellipsoids

U = 95 keV, Q = 0.2 pC

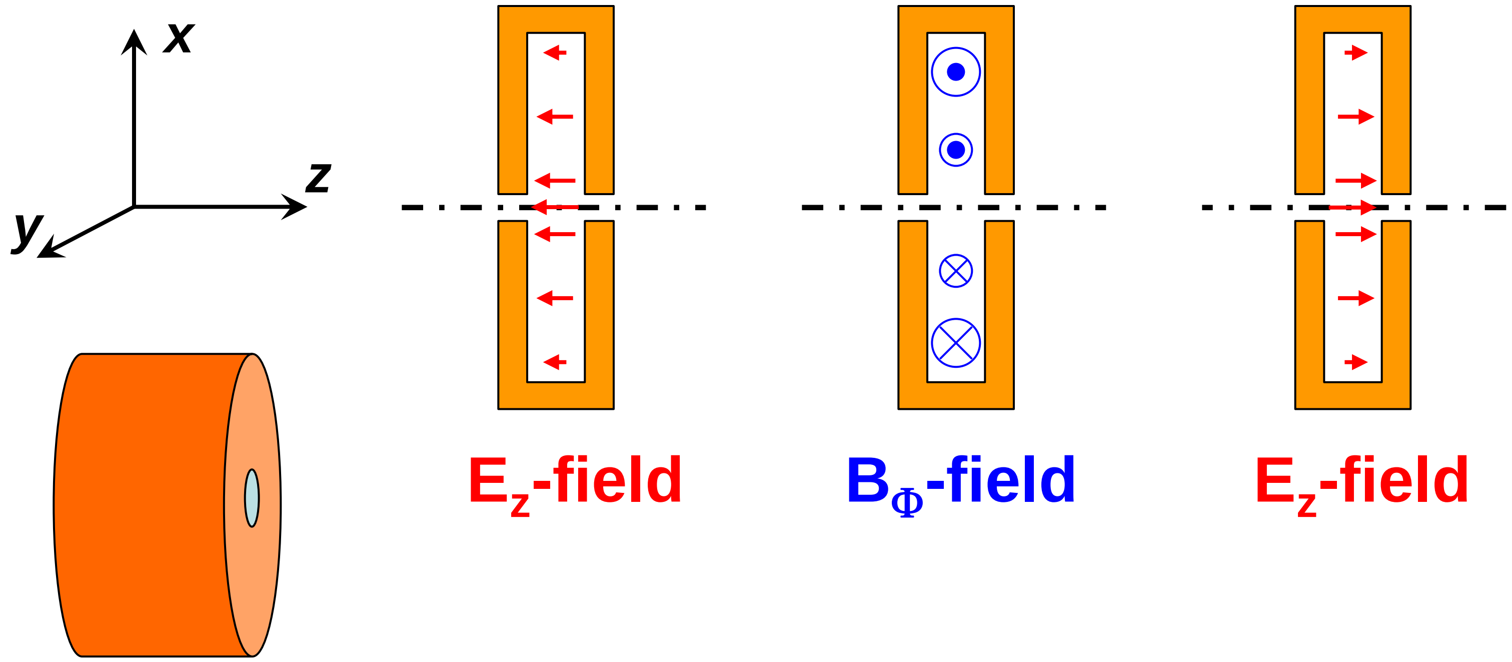
phosphor screen image



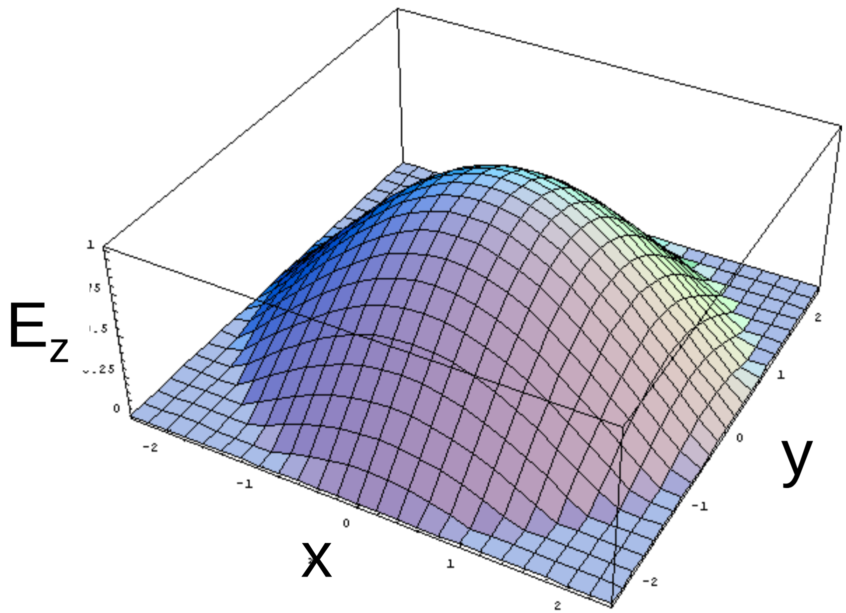
y →

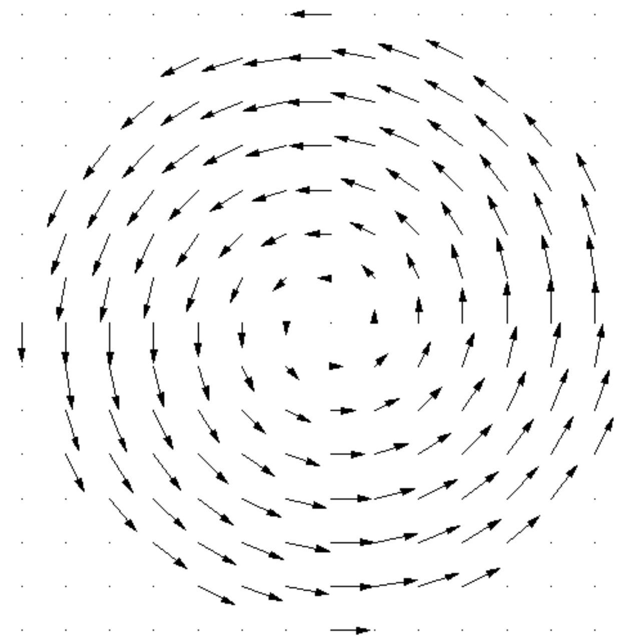
x →

Bunch compression with 3 GHz RF cavity in TM_{010} mode



Bunch compression with 3 GHz RF cavity in TM_{010} mode

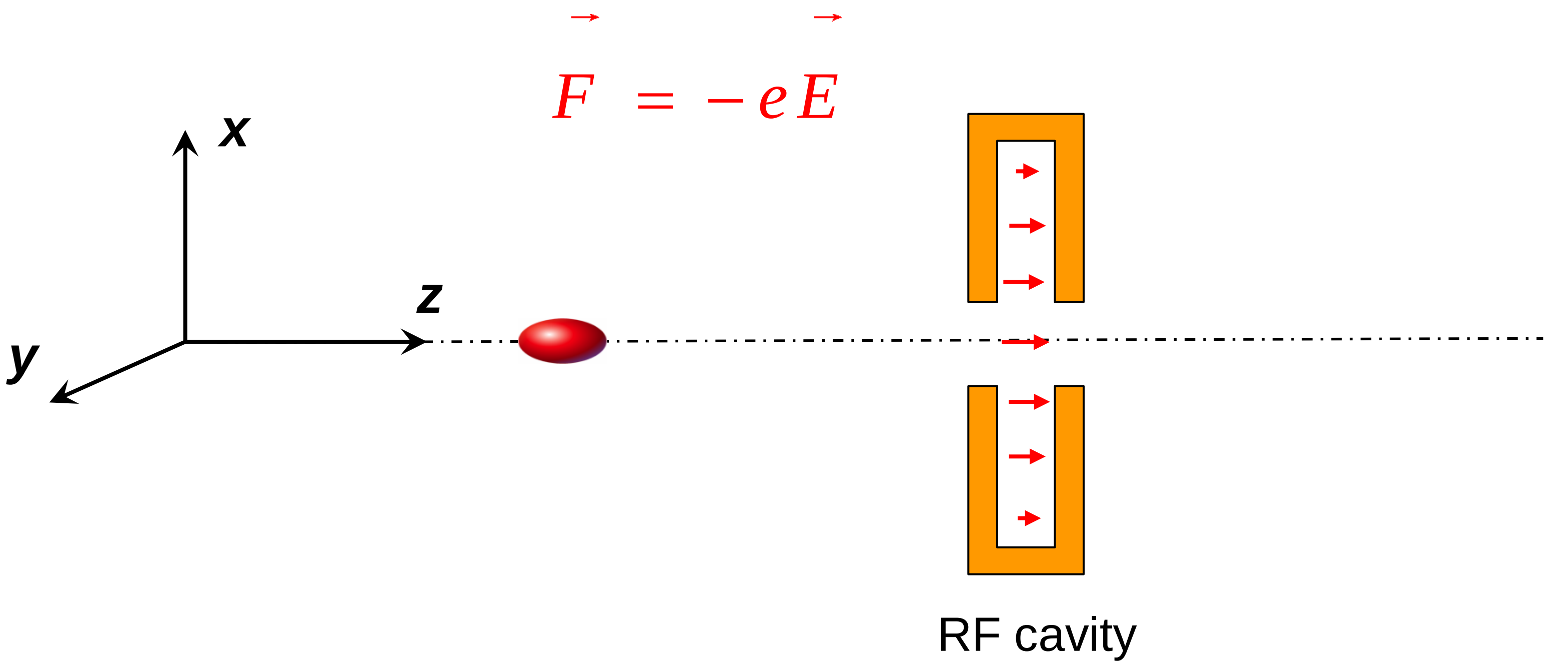




TM_{010} : E_z-field

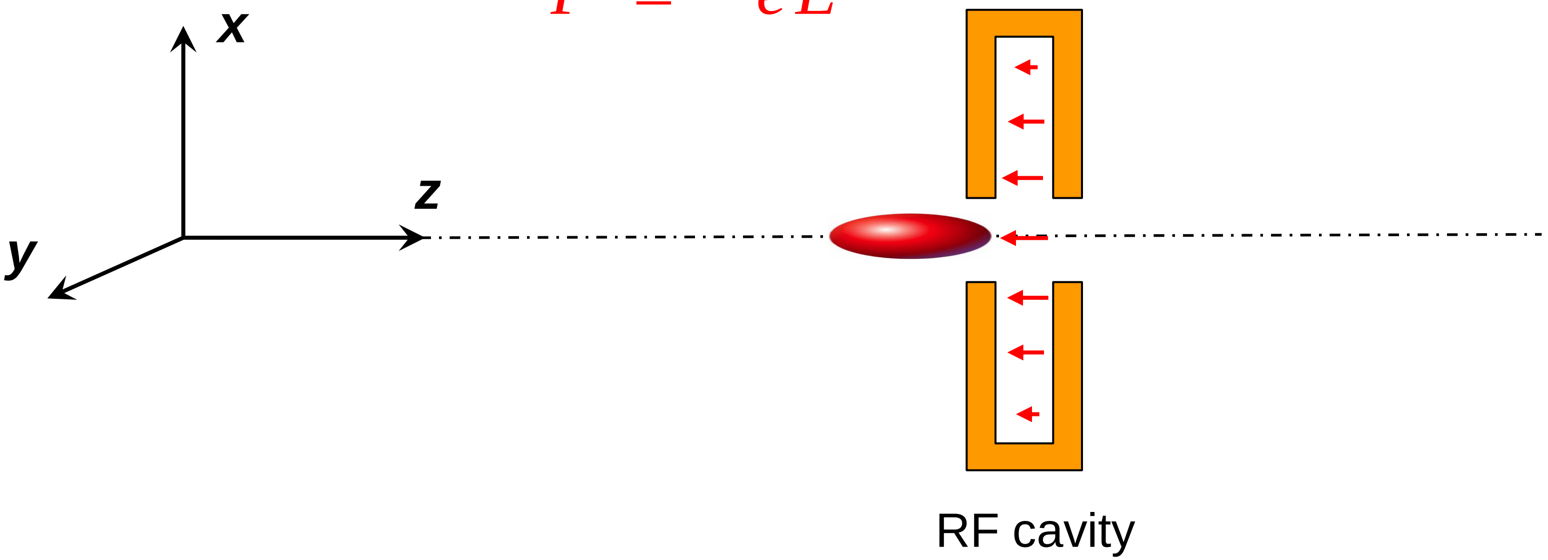
TM_{010} : B_Φ-field

Bunch compression with 3 GHz RF cavity in TM_{010} mode



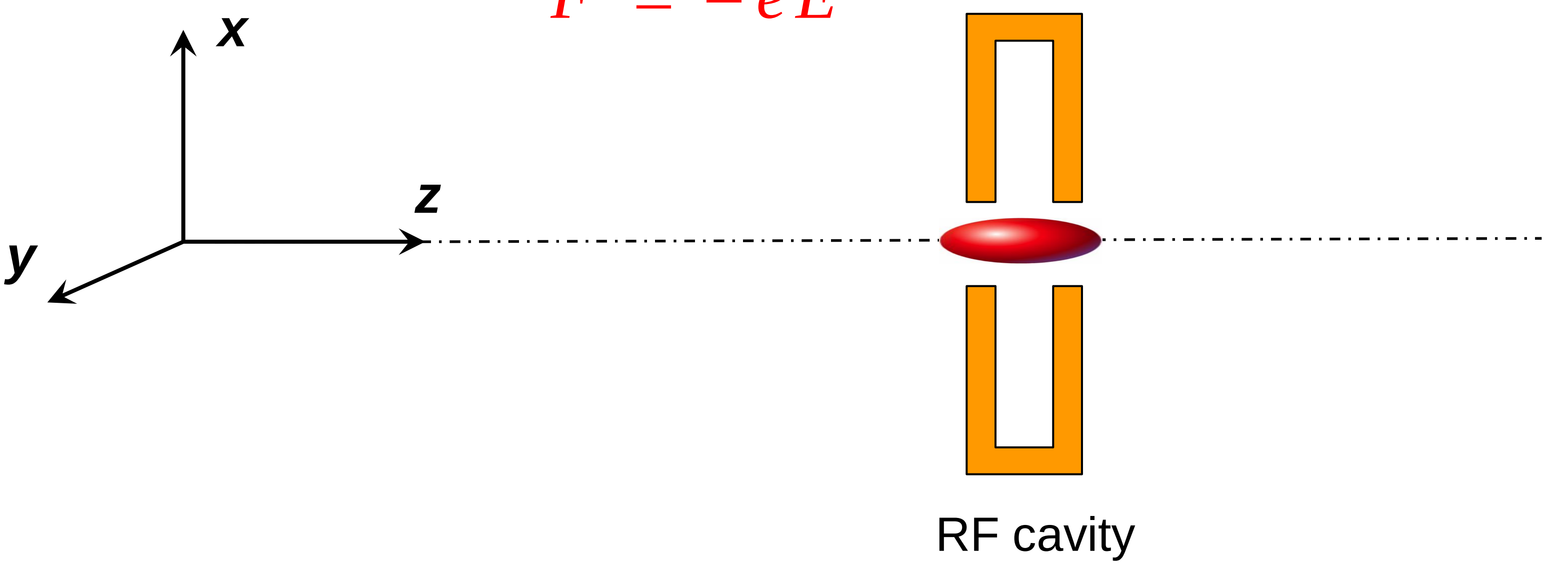
Bunch compression with 3 GHz RF cavity in TM_{010} mode

$$\vec{F} = -e\vec{E}$$



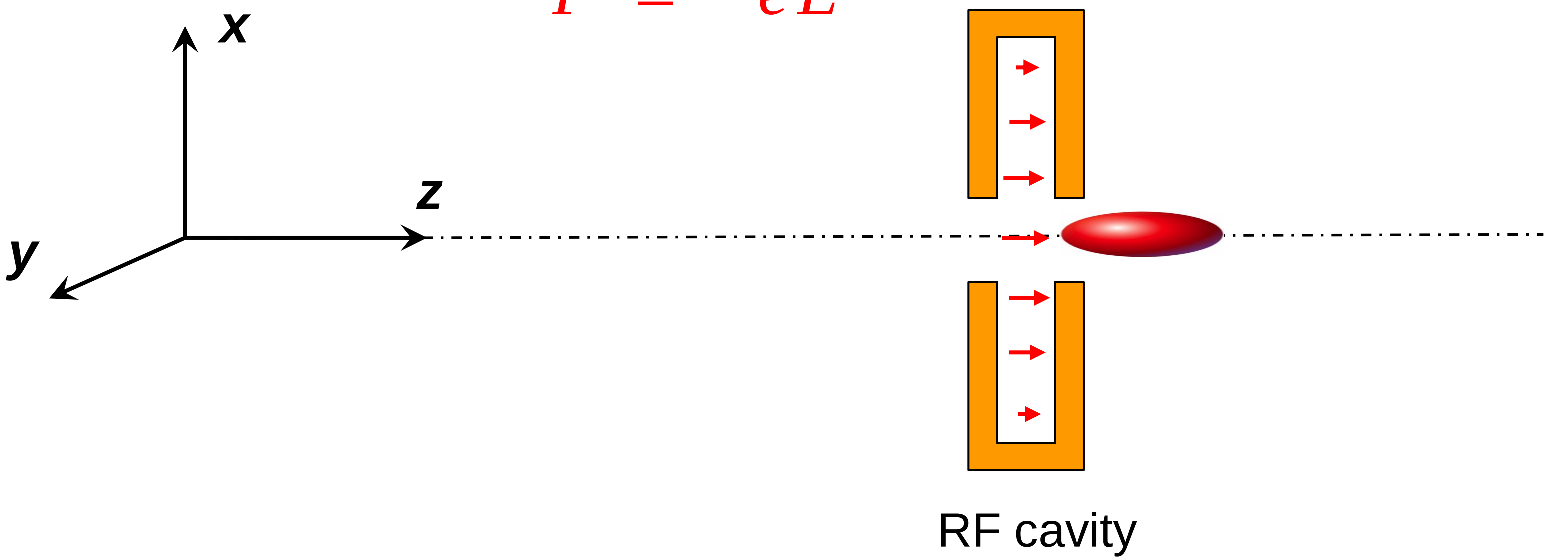
Bunch compression with 3 GHz RF cavity in TM_{010} mode

$$\vec{F} = -e\vec{E}$$

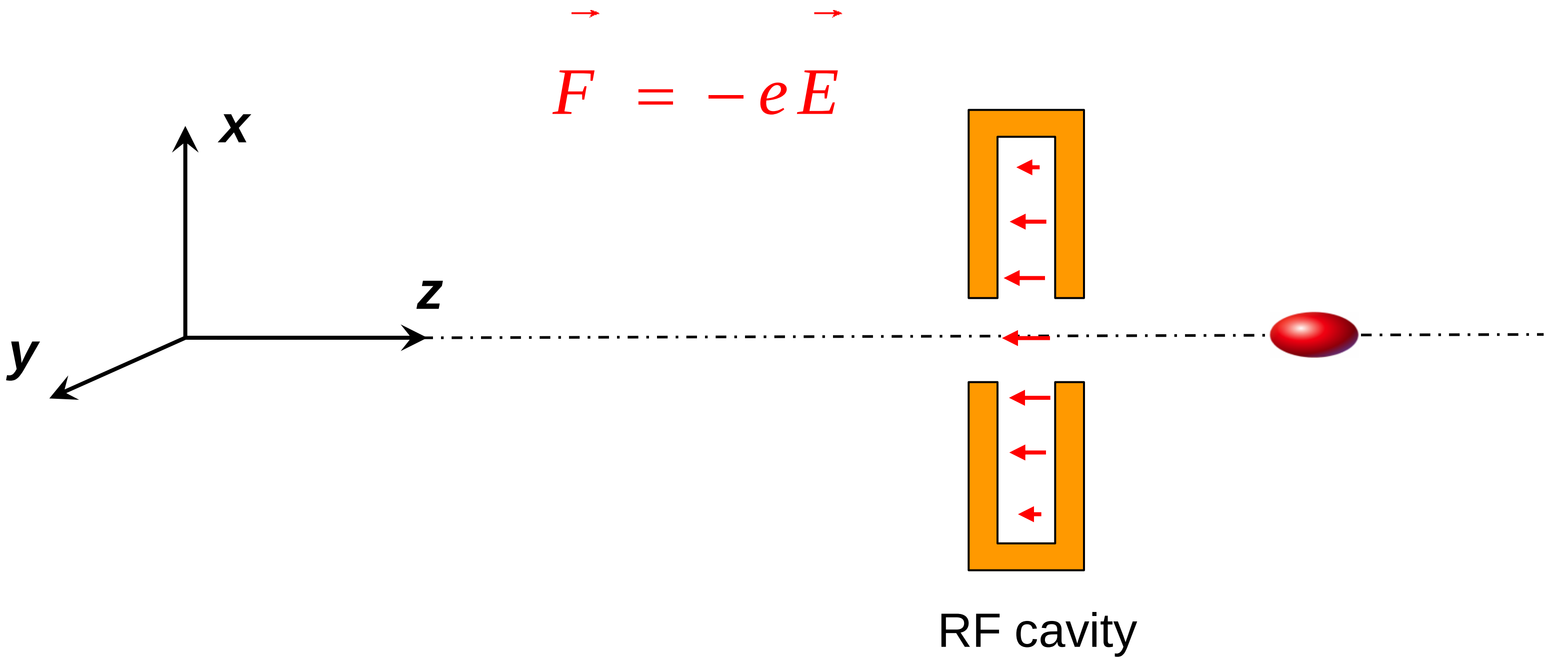


Bunch compression with 3 GHz RF cavity in TM_{010} mode

$$\vec{F} = -e\vec{E}$$

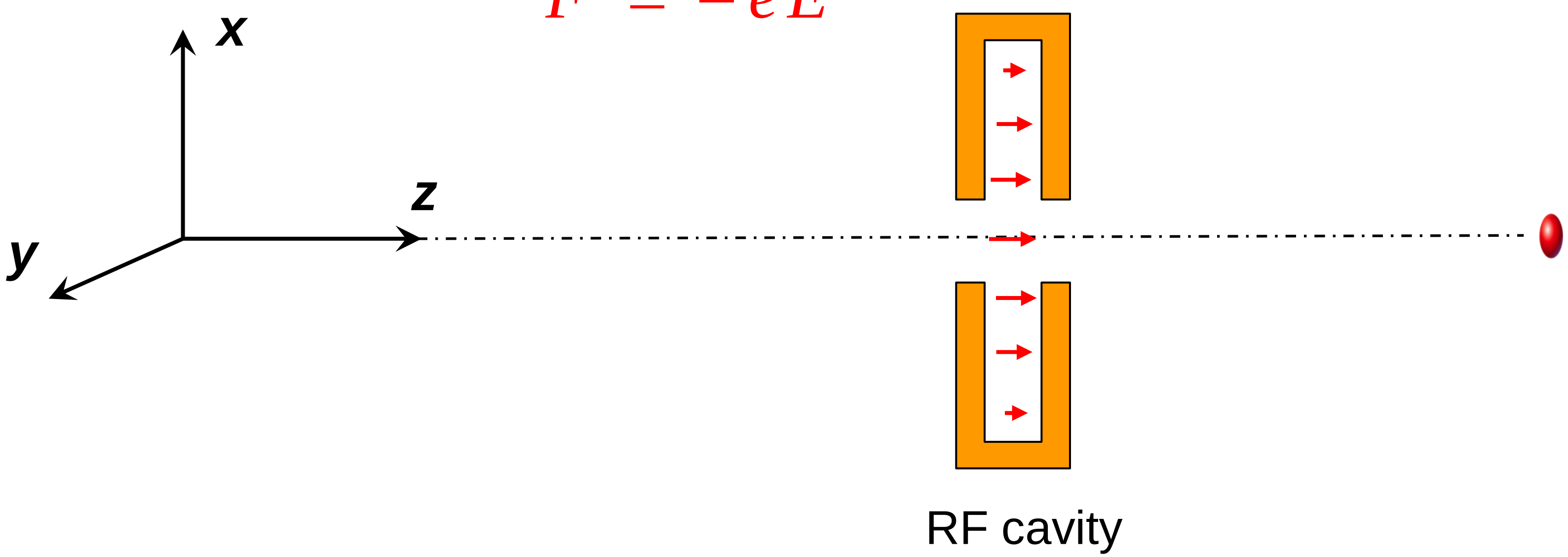


Bunch compression with 3 GHz RF cavity in TM_{010} mode

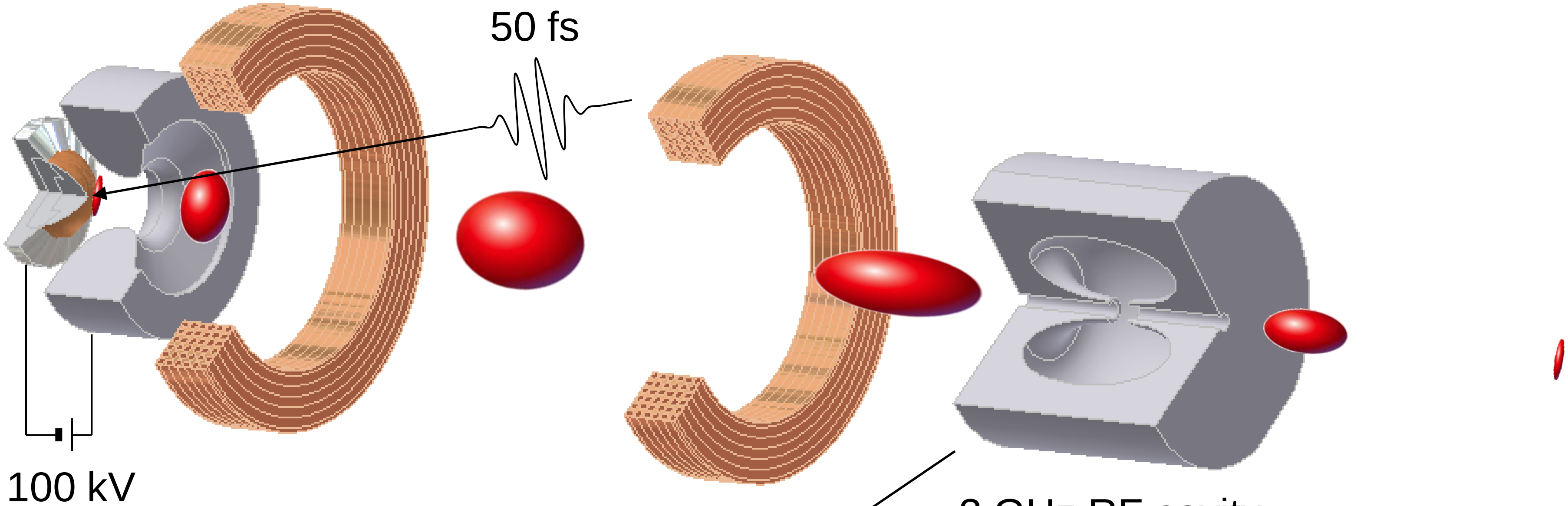


Bunch compression with 3 GHz RF cavity in TM_{010} mode

$$\vec{F} = -e\vec{E}$$

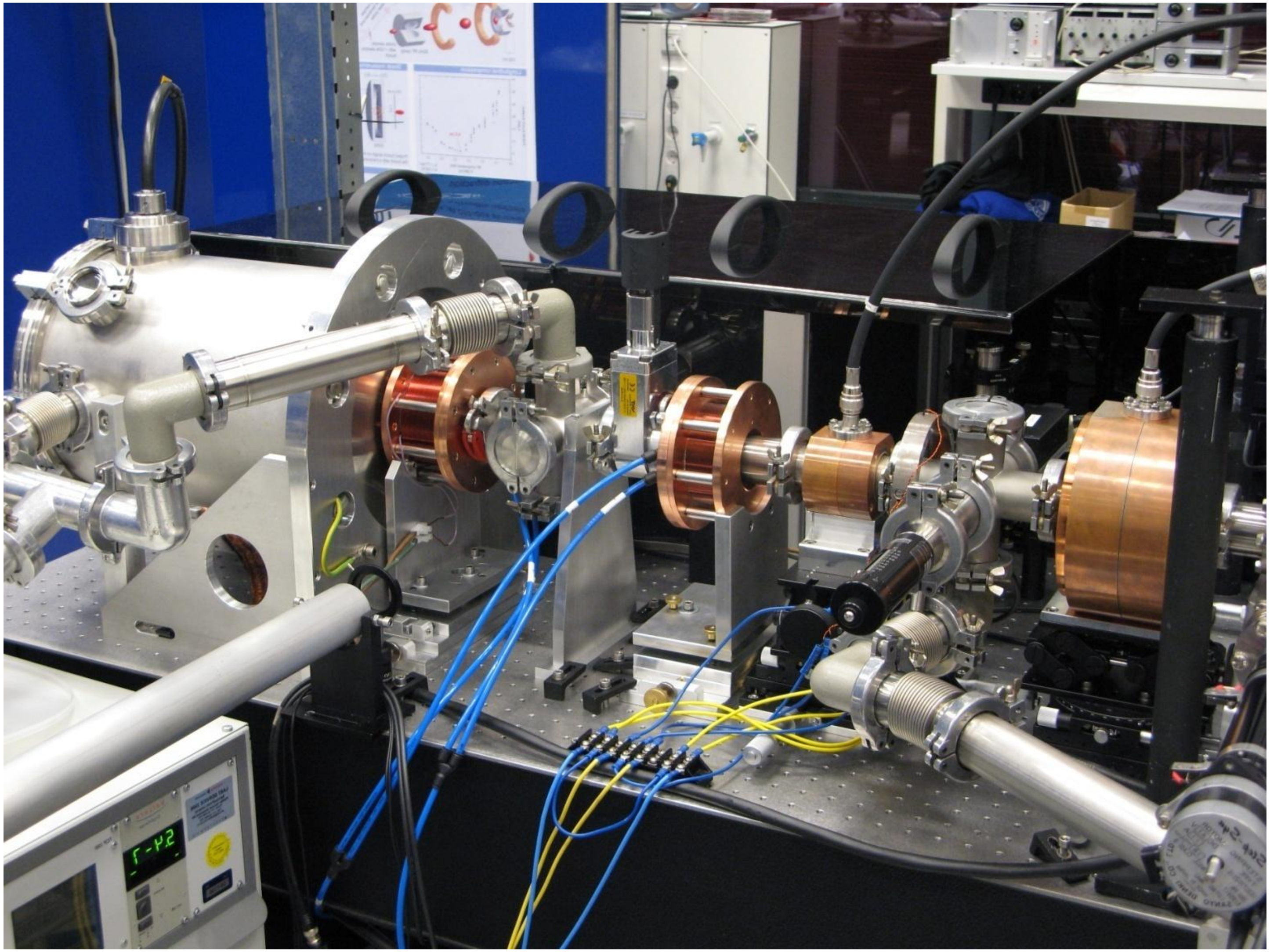


The setup



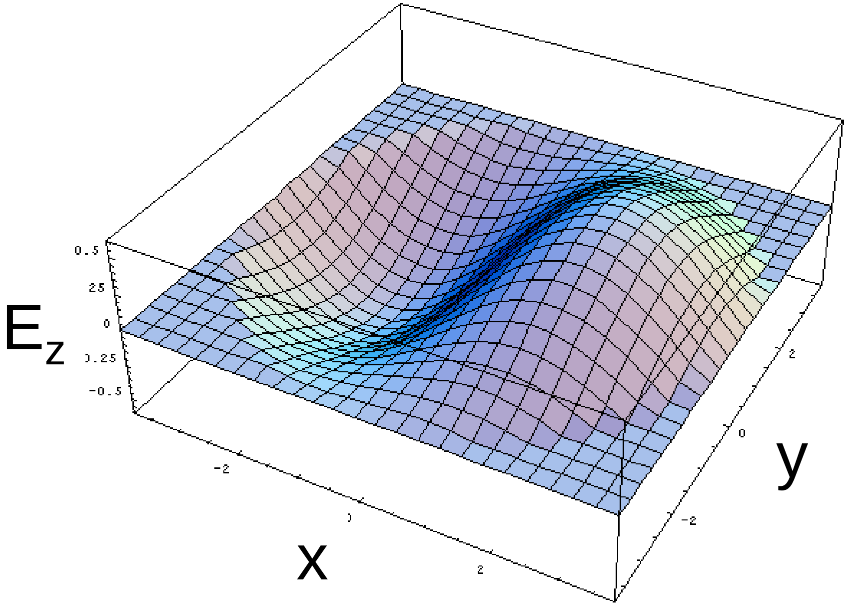
Van Oudheusden et al., JAP **102**, 093501 (2007)

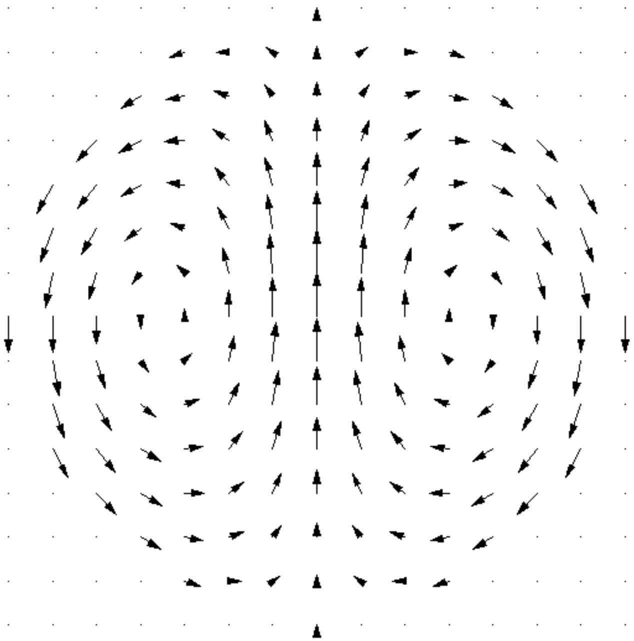
The setup



Bunch length measurement with RF streak cavity

RF cavity TM_{110} mode

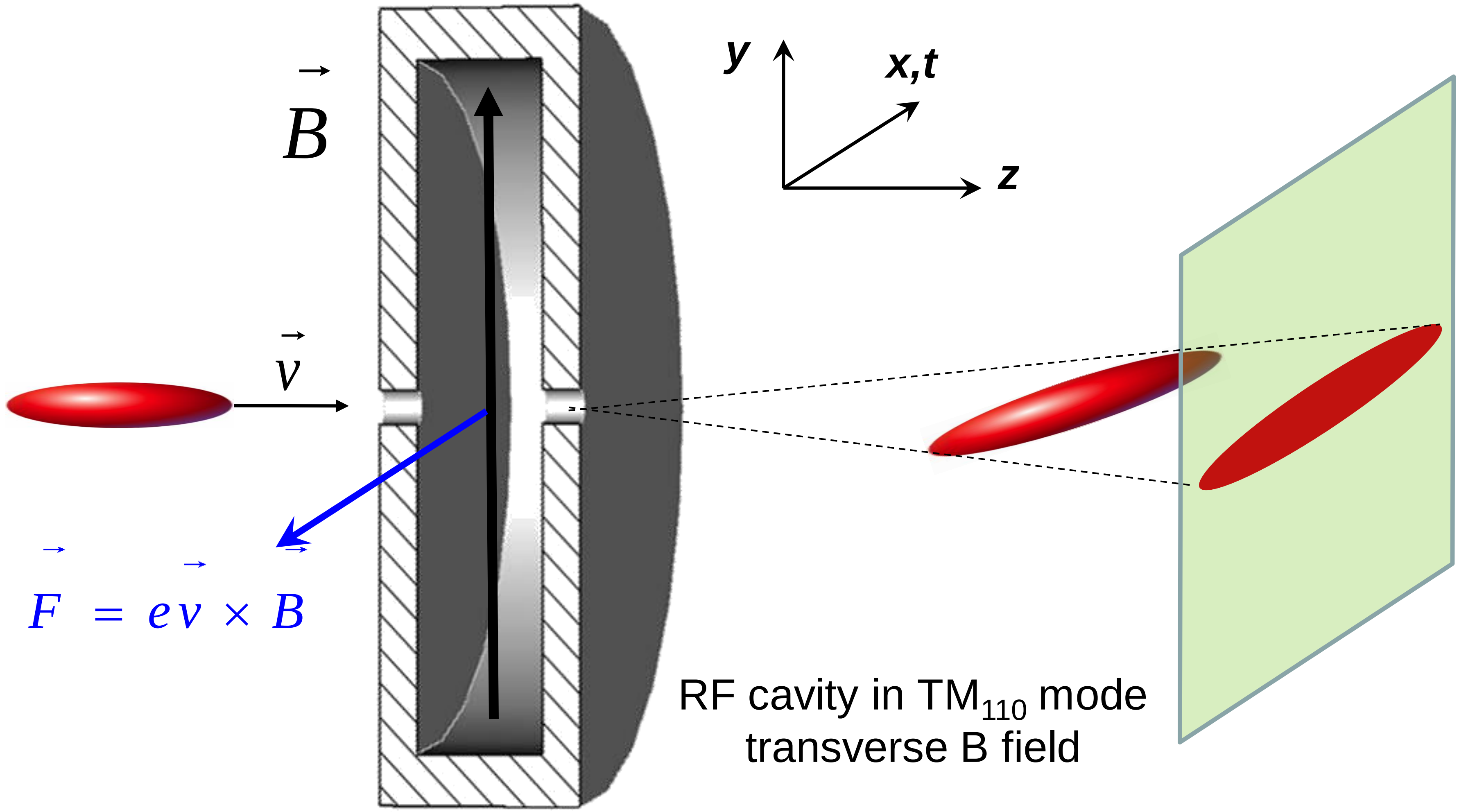




TM_{110} : E_z-field

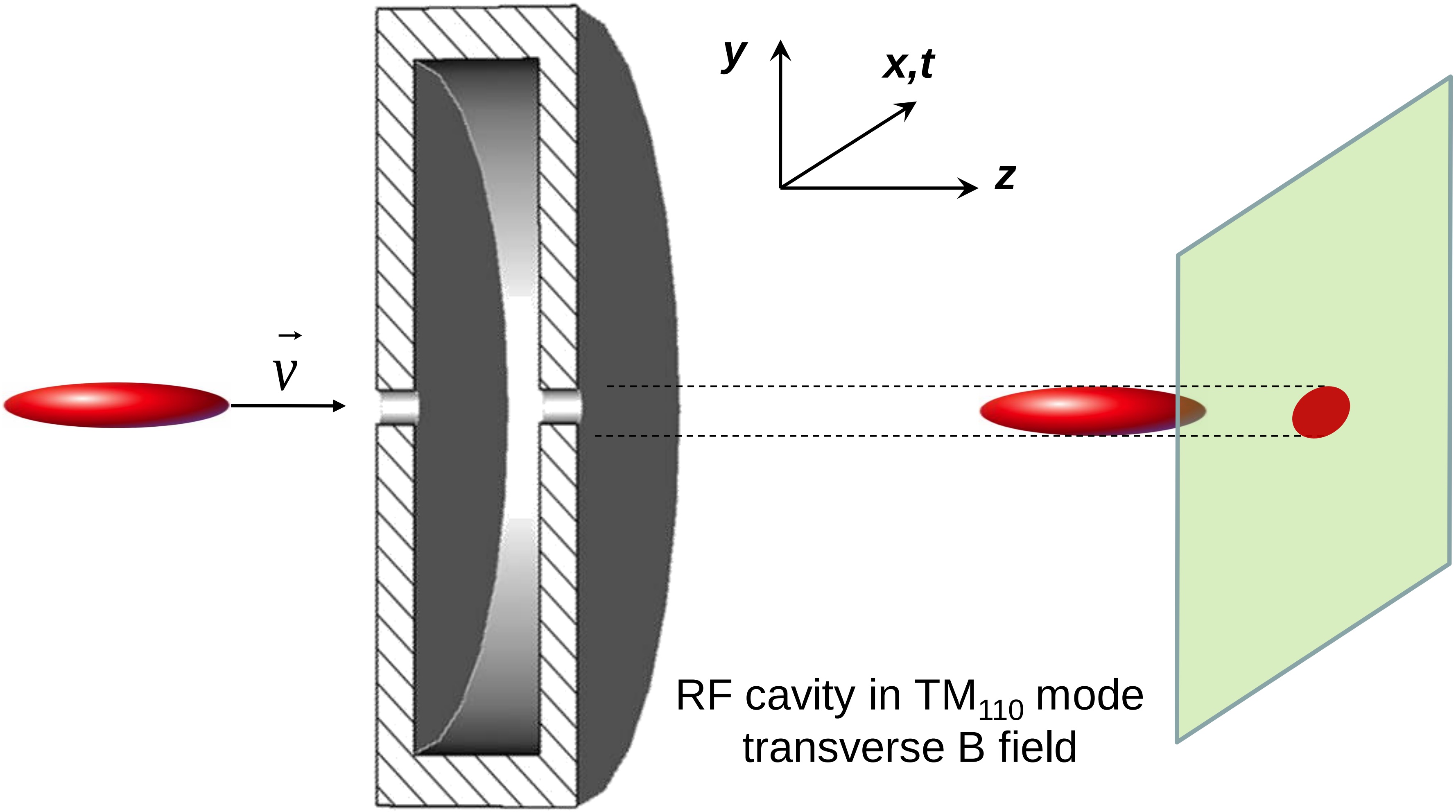
TM_{110} : B_x,B_y-field

Bunch length measurement with RF streak cavity



Limitation temporal resolution:

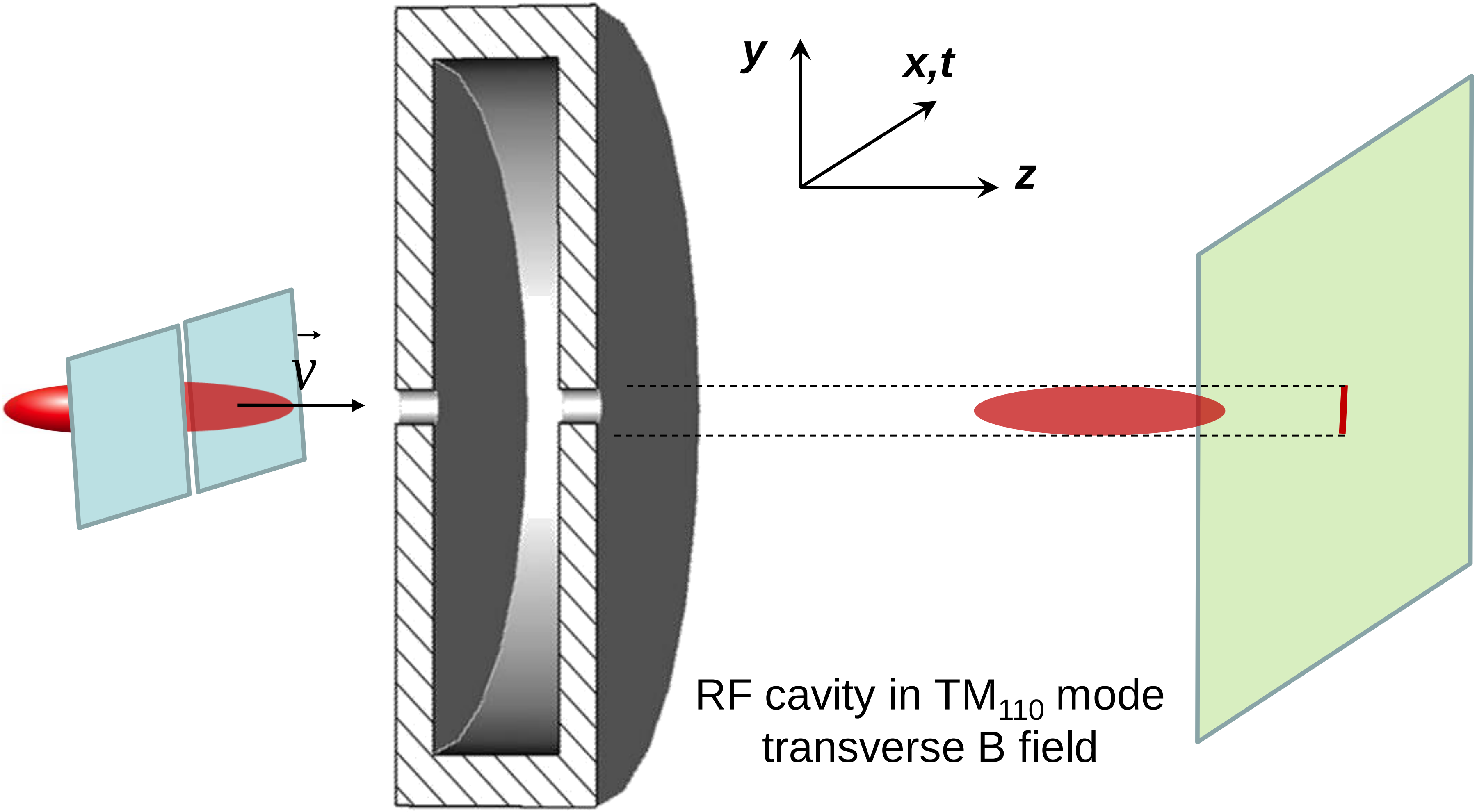
Cavity off



RF cavity in TM_{110} mode
transverse B field

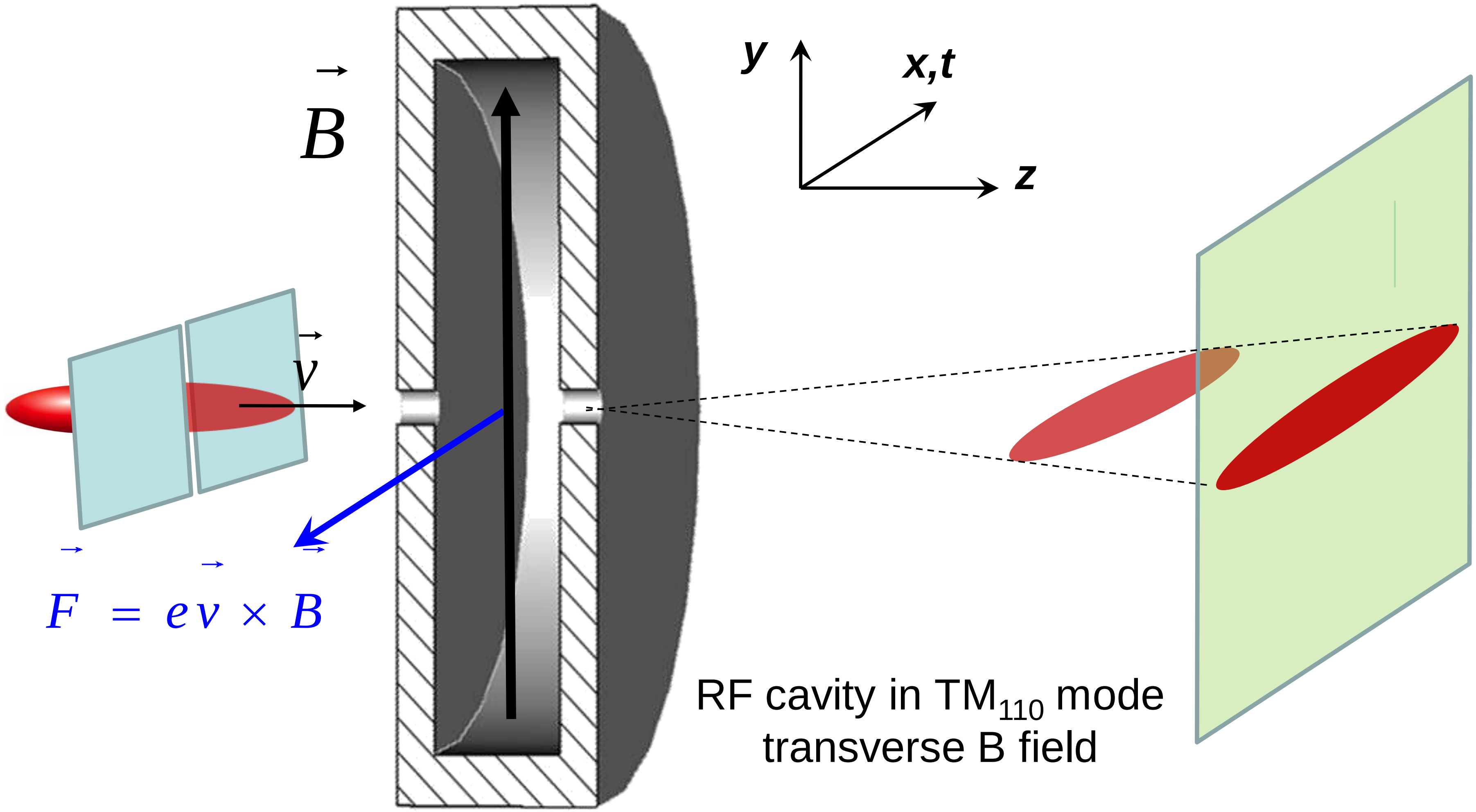
10 µm slit to improve temporal resolution

Cavity off

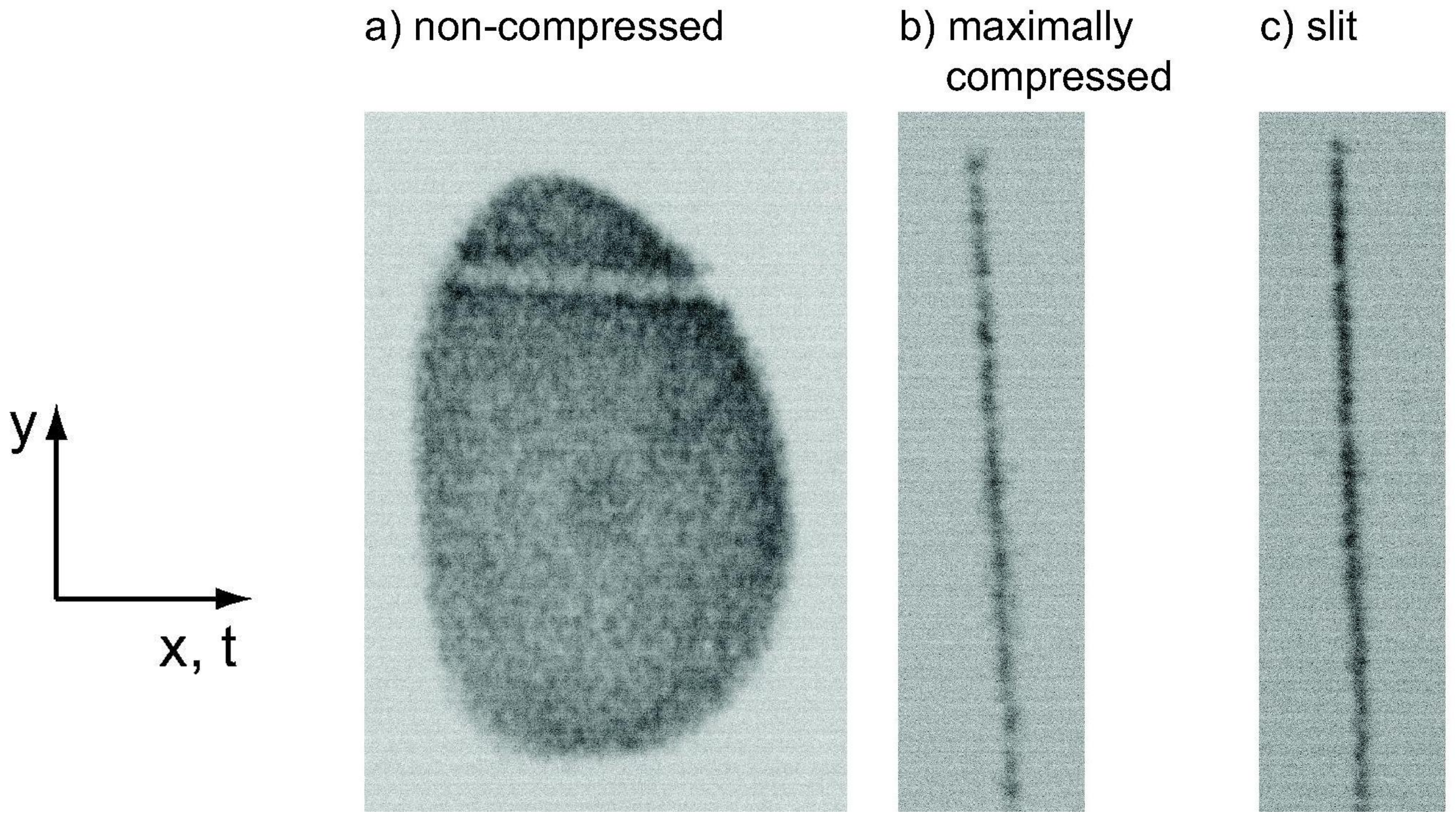


10 μm slit to improve temporal resolution

Cavity on

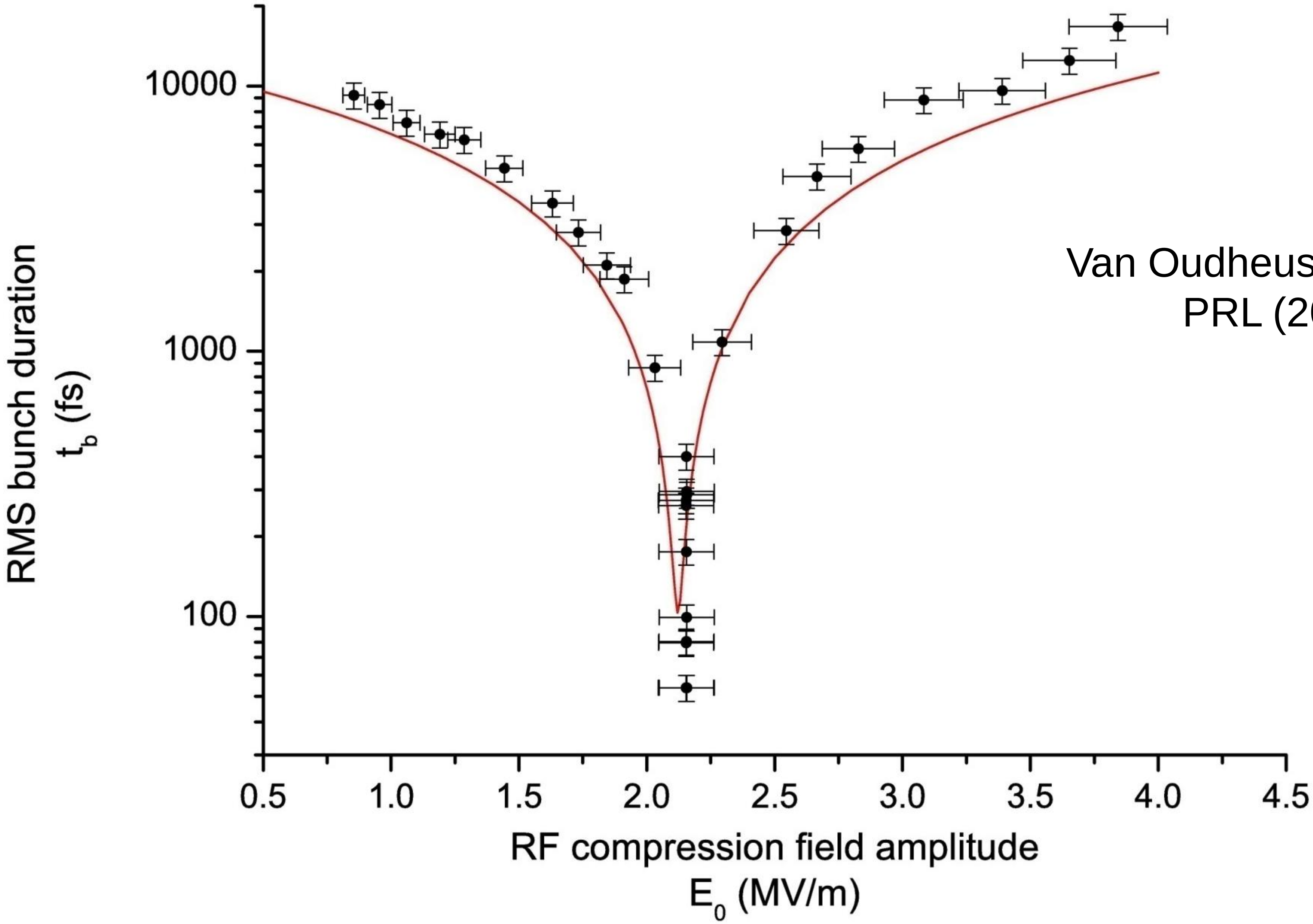


Streak image on screen



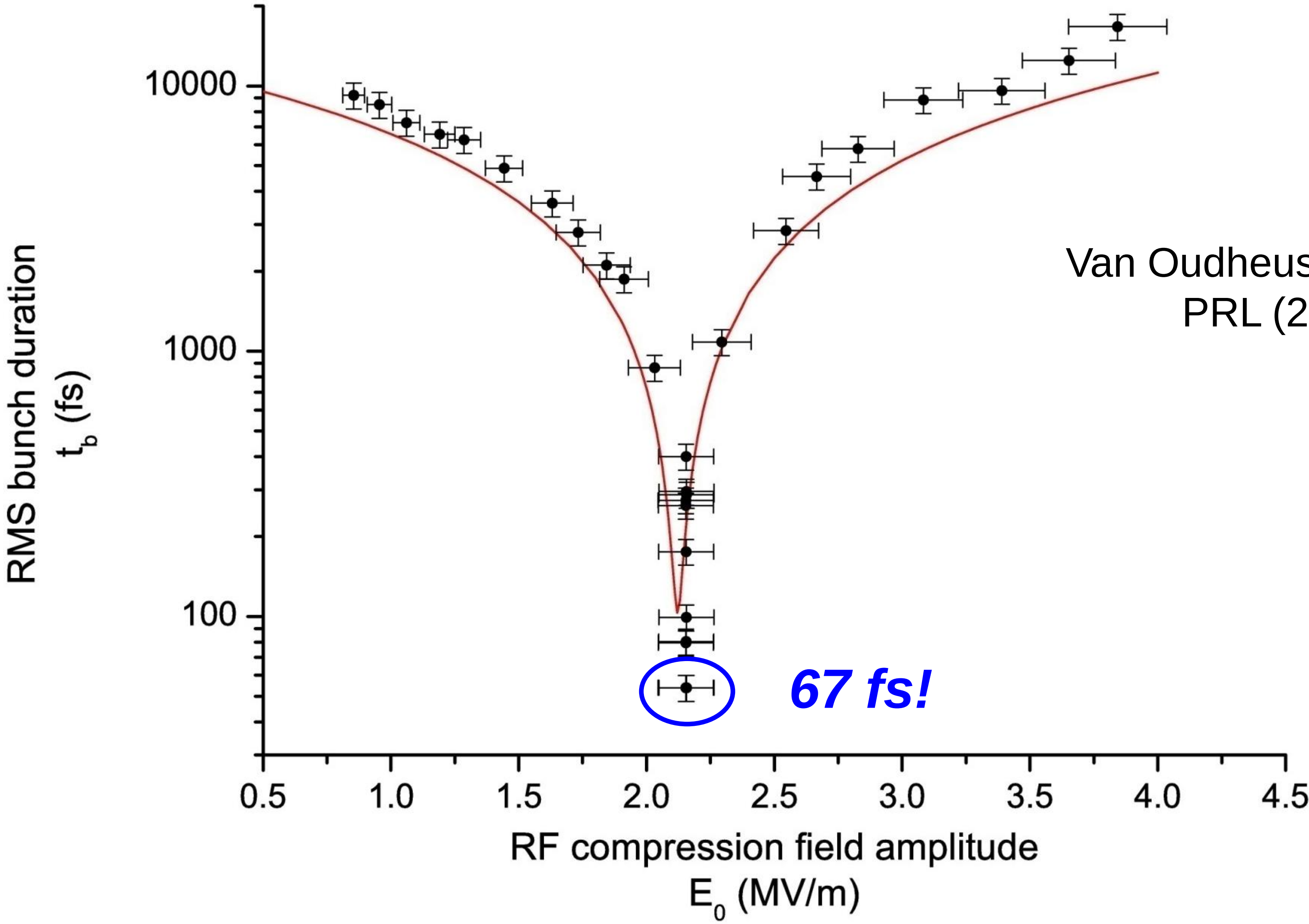
Streak cavity on ***cavity off***

RF bunch compression

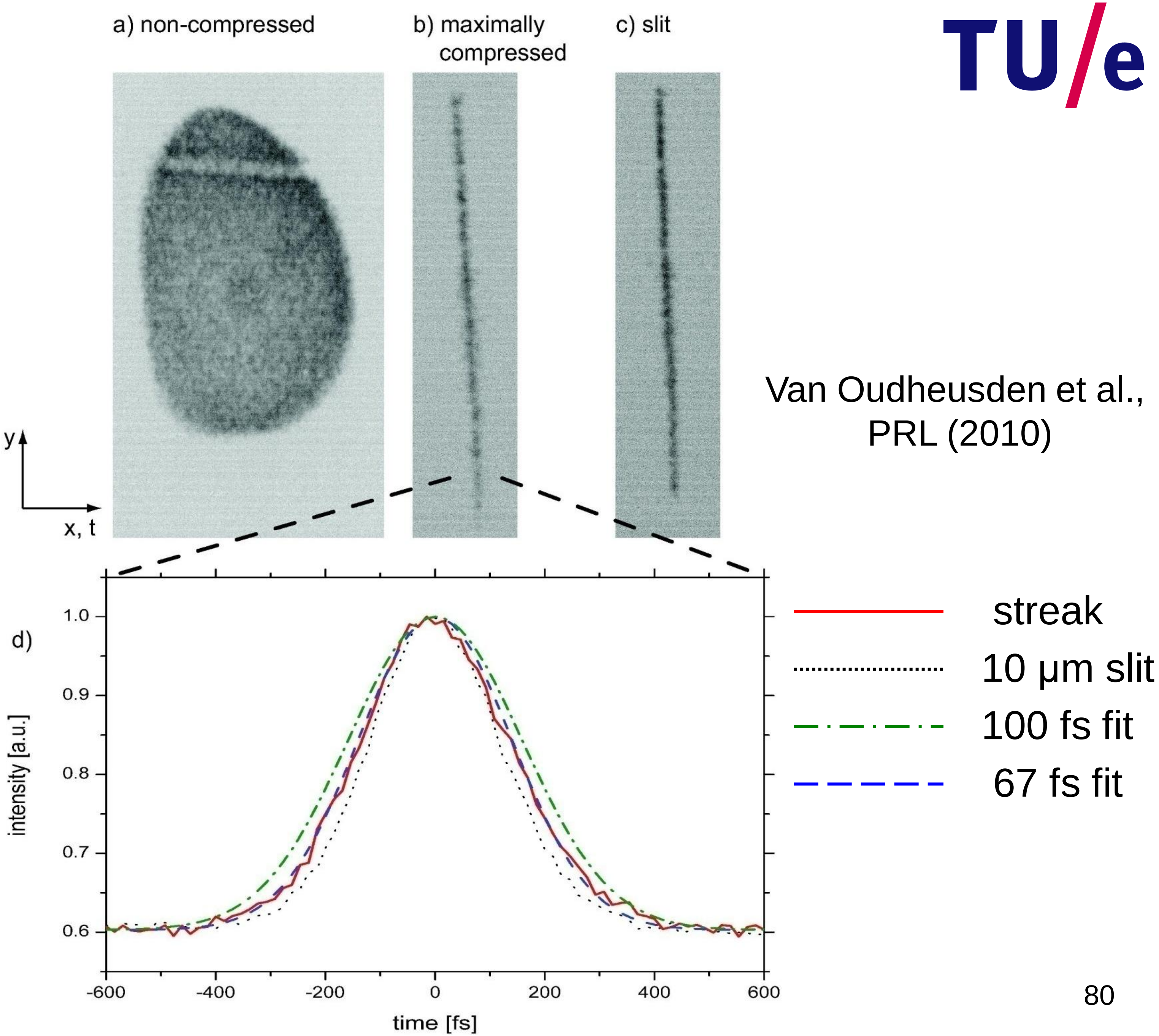


Van Oudheusden et al.,
PRL (2010)

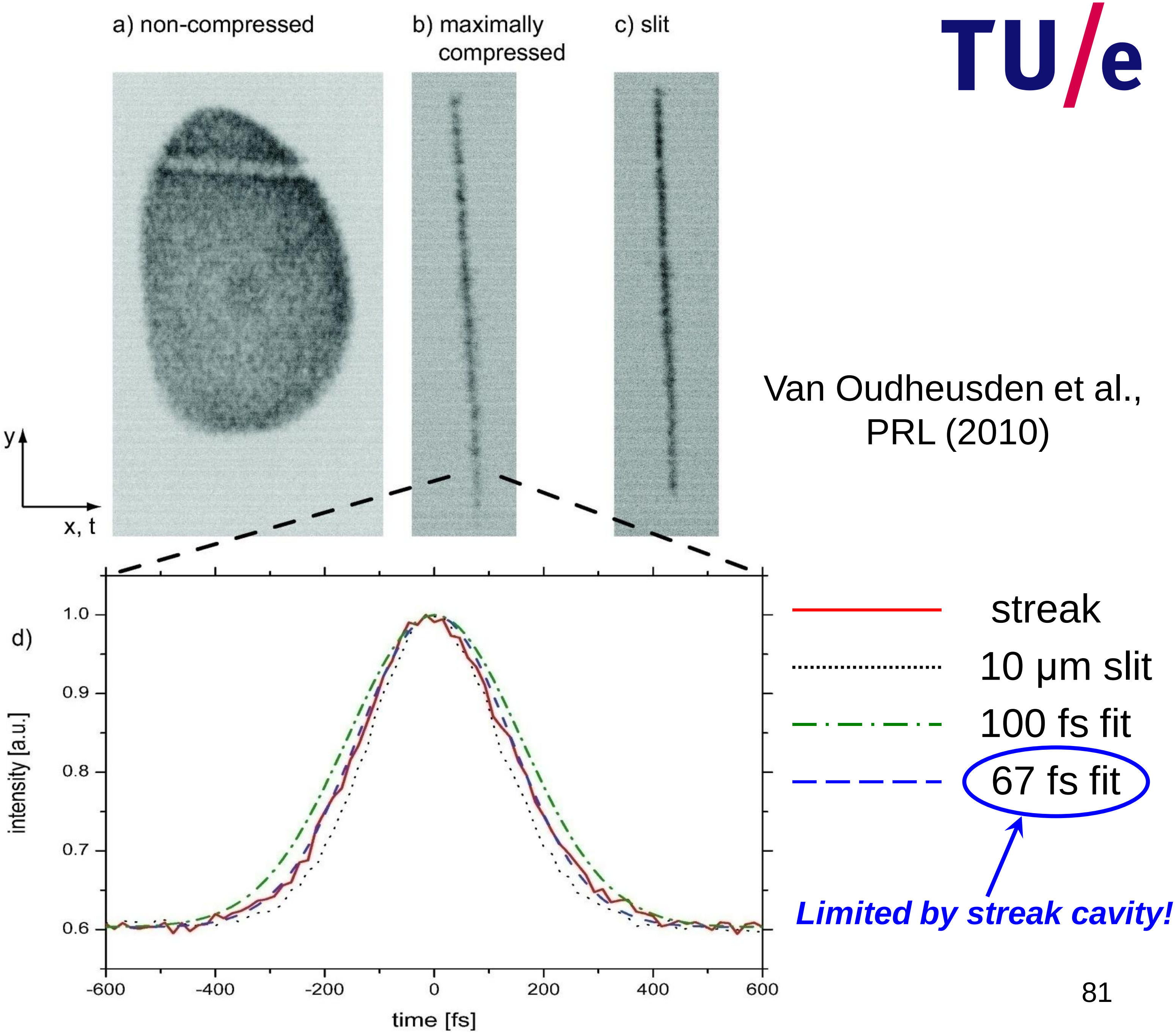
RF bunch compression



Van Oudheusden et al., PRL (2010)

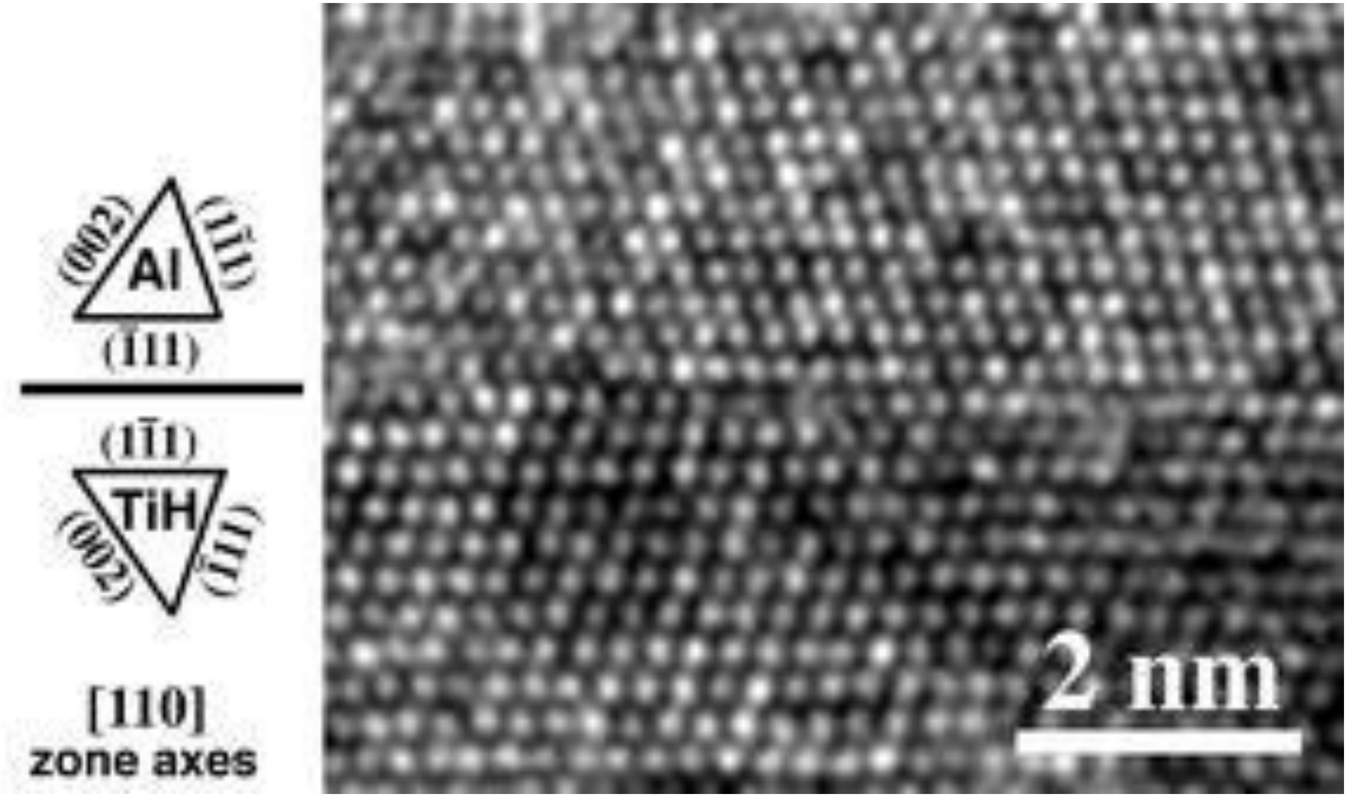


Van Oudheusden et al., PRL (2010)



Van Oudheusden et al., PRL (2010)

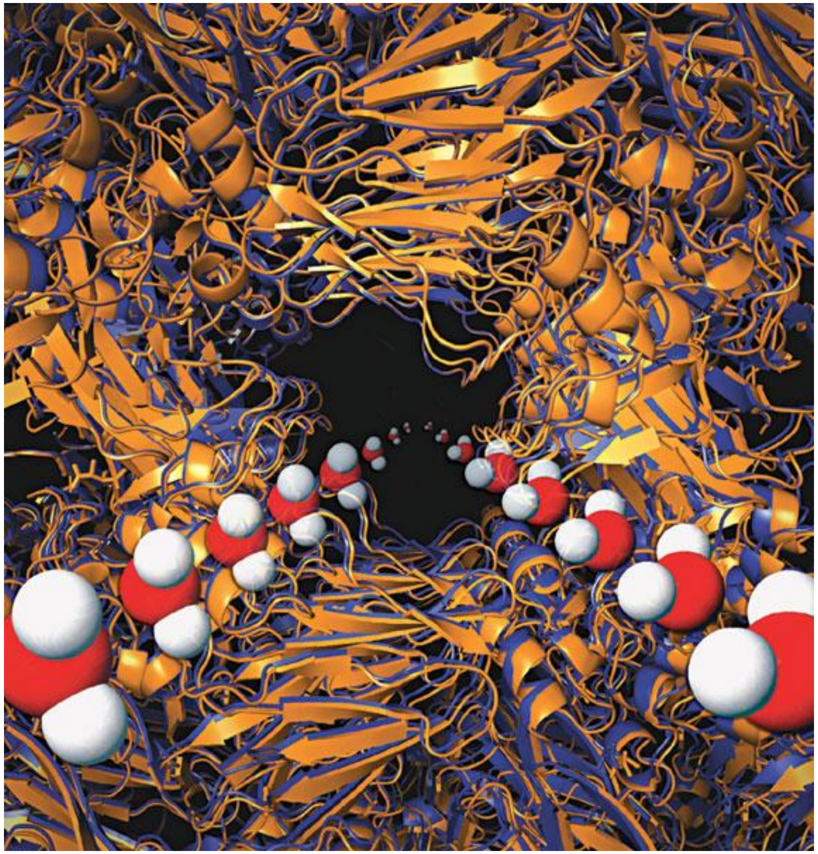
Crystals of atoms or small molecules:



coherence length ≤ 1nm sufficient

→ ***conventional photocathode source OK!***

Crystals of biomolecules…



a = 5-10 nm

coherence length ≥ 10 nm required

→ ***ultracold electron source!***

Summary

- *Ultracold laser-cooled electron source:* $T_e \approx 10$ *K;*
- *Ultracold source interesting for compact X-FEL;*
- *Single-shot, sub-ps electron diffraction demonstrated;*
- *RF compression of 100 keV, 0.1 pC bunches: 10 ps →100 fs;*
- *Ultracold source & RF bunch compression → single-shot, femtosecond electron diffraction of biomolecules.*