Conceptual Design of High Coherence Femtosecond Electron Diffractometer at FREIA

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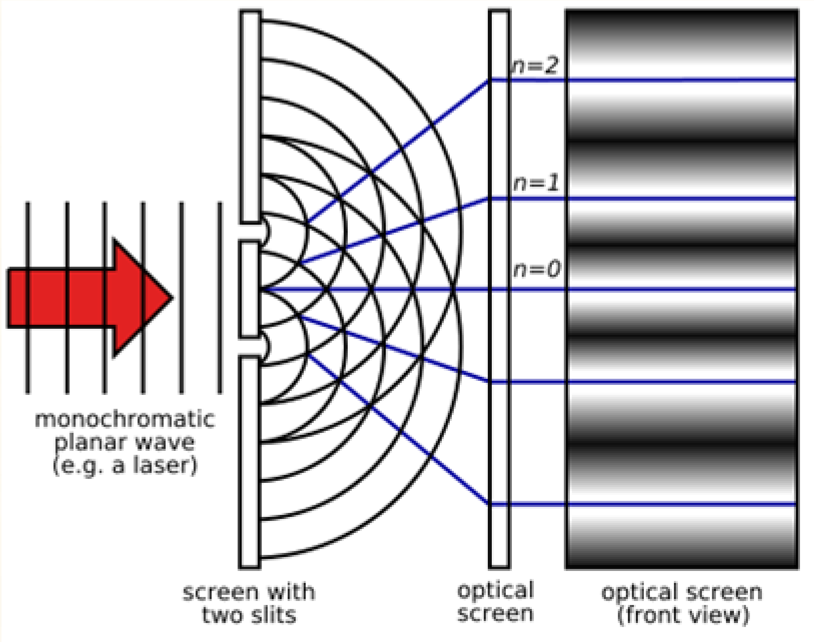
Magnus Jobbs, Vitaliy Goryashko

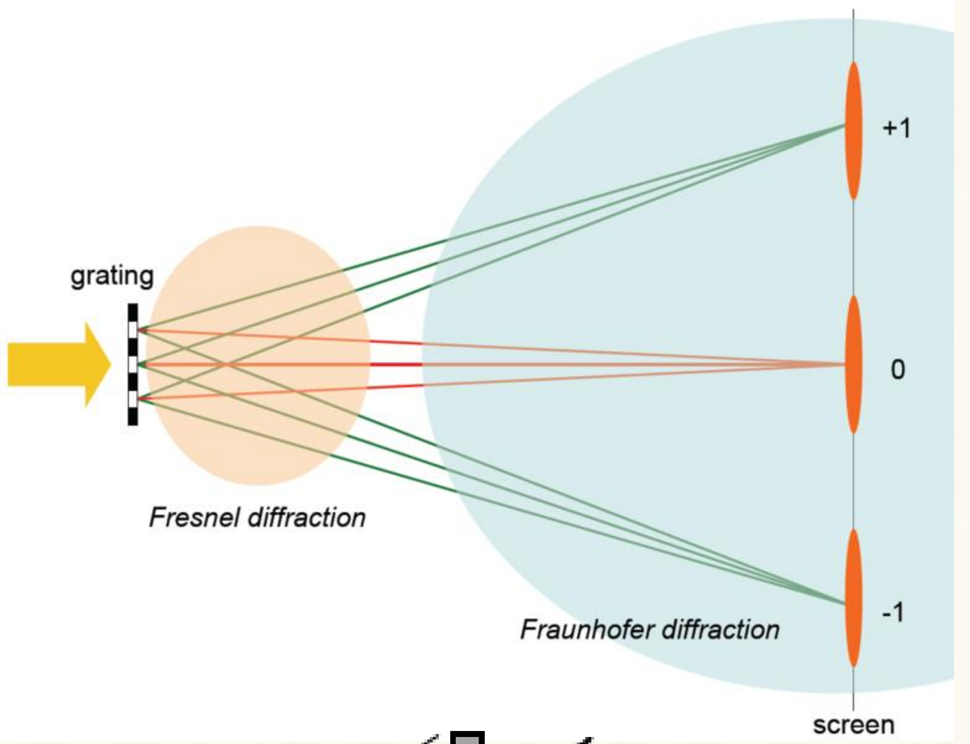
2018, Uppsala

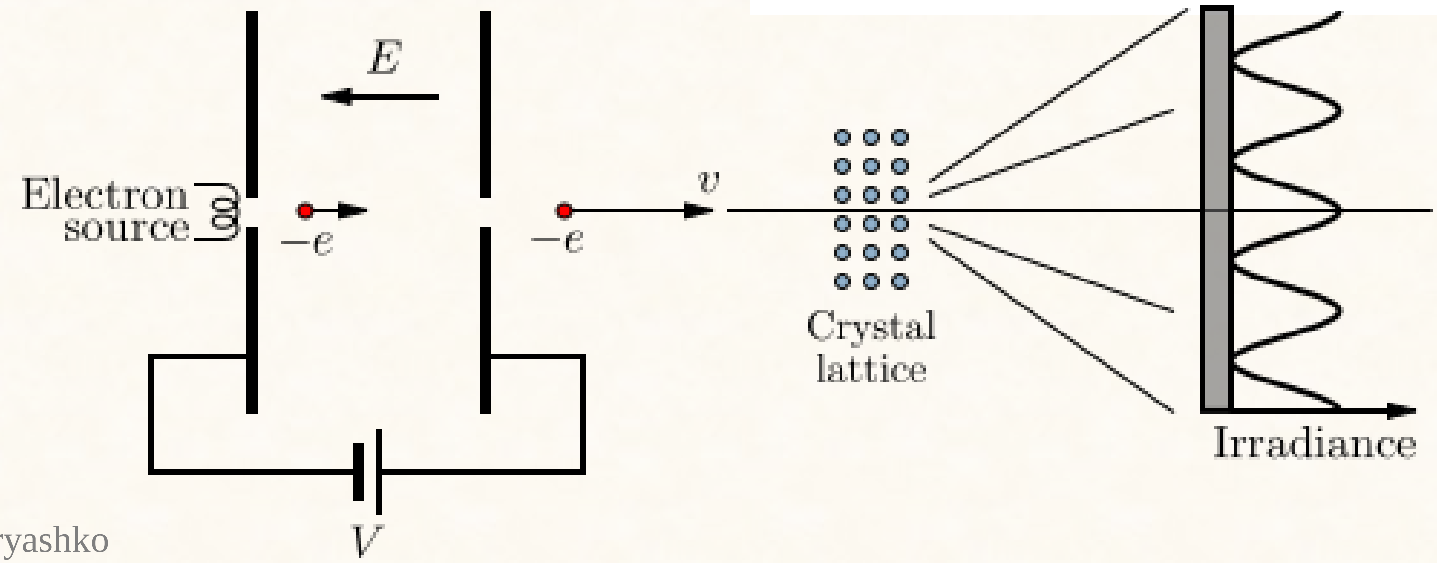
Outline

- Electron diffraction
- Transverse coherence and beam quality
- Requirements on the beam
- UEDs around the world
- Proposed set-up
- Some preliminary results
- Photo-injector
- Photo-injector + booster

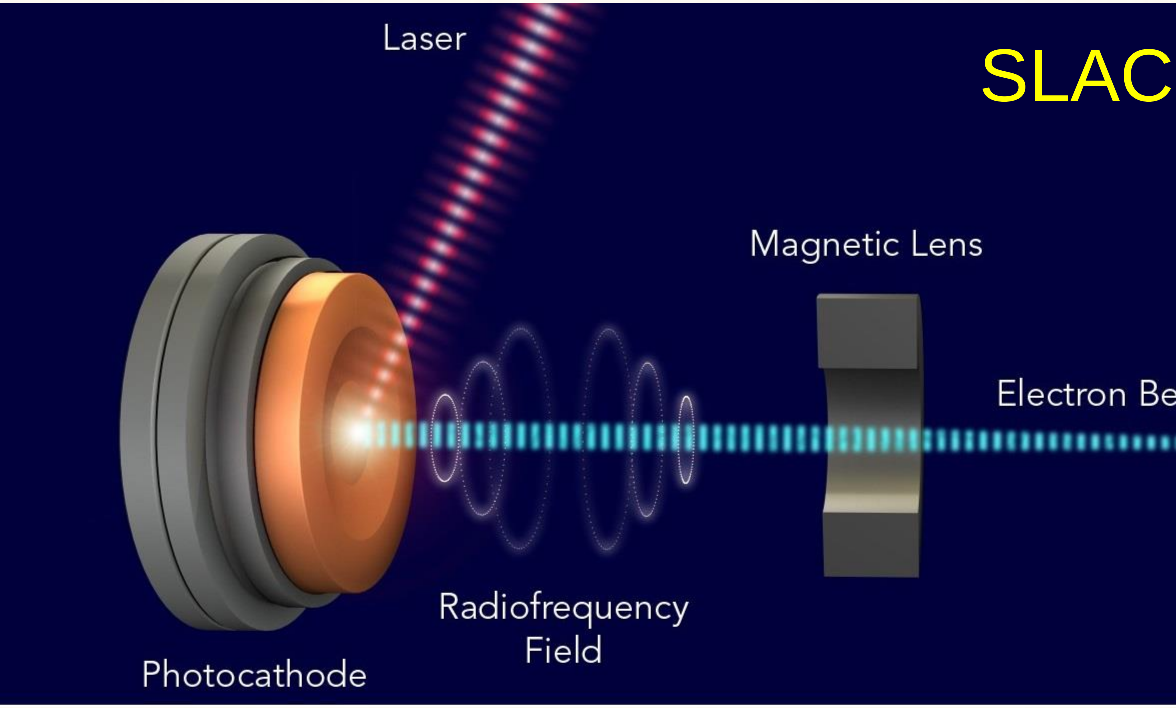
Principles of diffraction studies

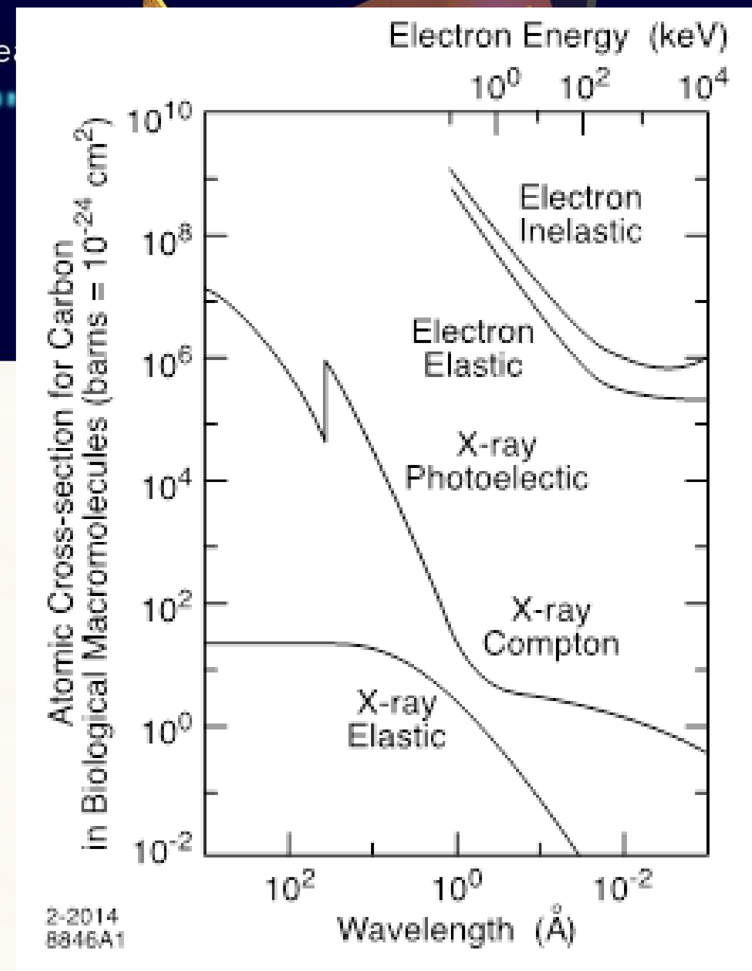




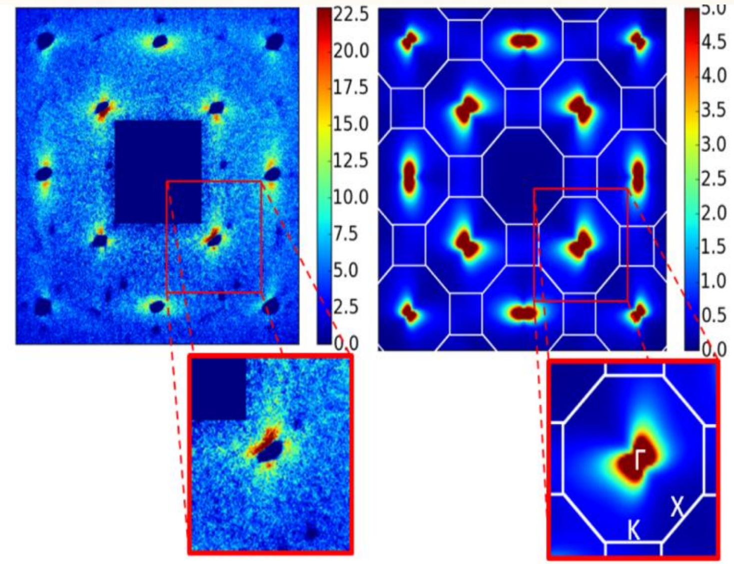


Modern electron diffractometer





diffraction from transient phonons in 20 nm thin single-crystalline Au films



T. Chase. APL. **108**, 041909 (2016)

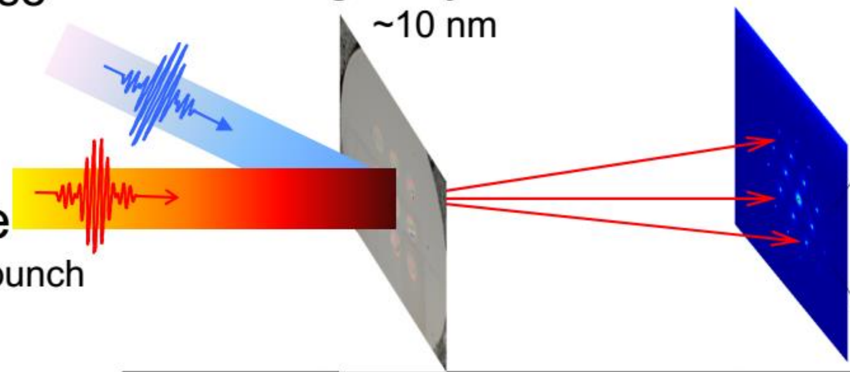
Vitaliy Goryashko

Ultrafast dynamics: Laser induced melting in Au

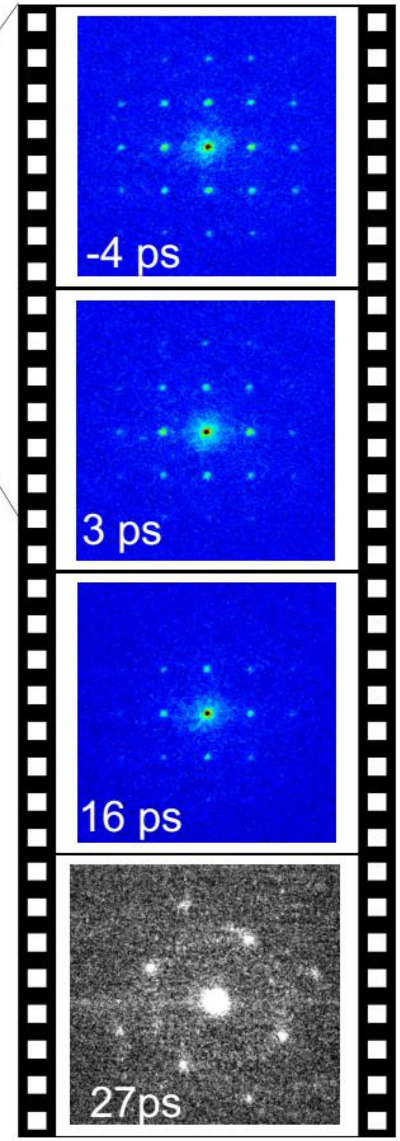
Pump laser pulse
385nm,90fs

Single crystal Au
~10 nm

Electron pulse
3 MeV, 90fs, $10^5 e^-$/bunch



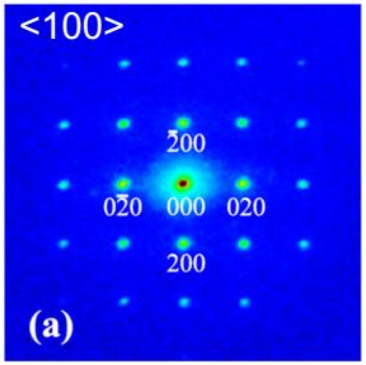
Movie of laser melting on Au

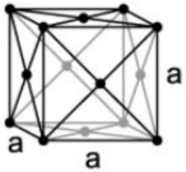


solid

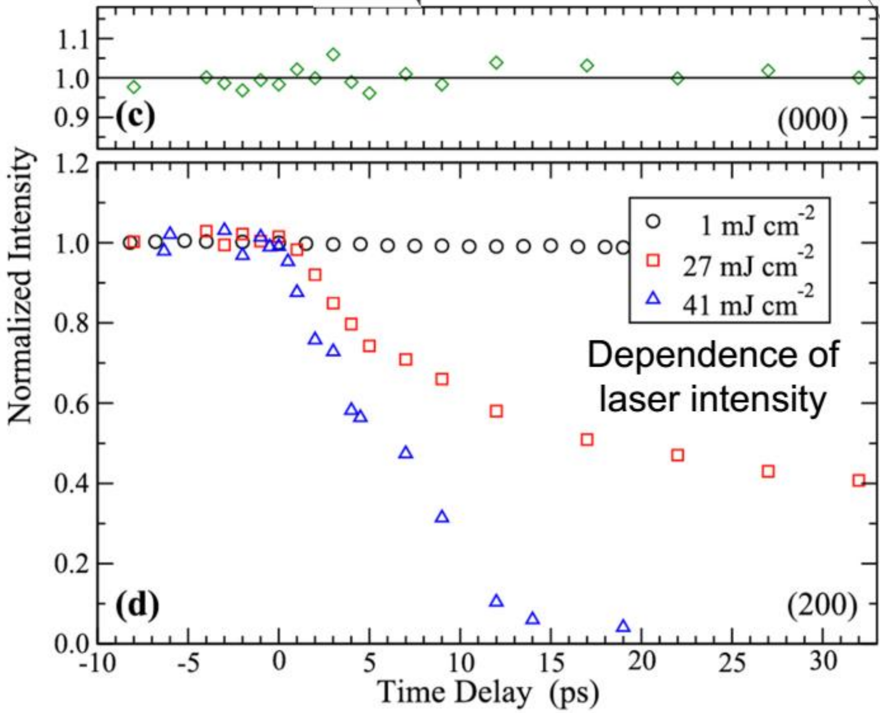
liquid

ED image of single-crystal Au





a=4.07864Å

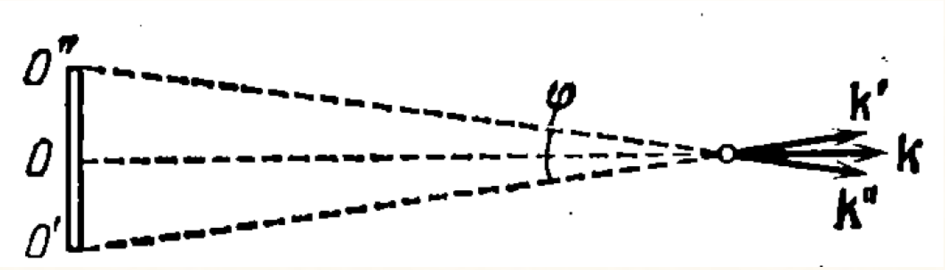


Appl. Phys. Lett. 103, 253107(2013); Phys. Rev. B 88, 184101(2013)

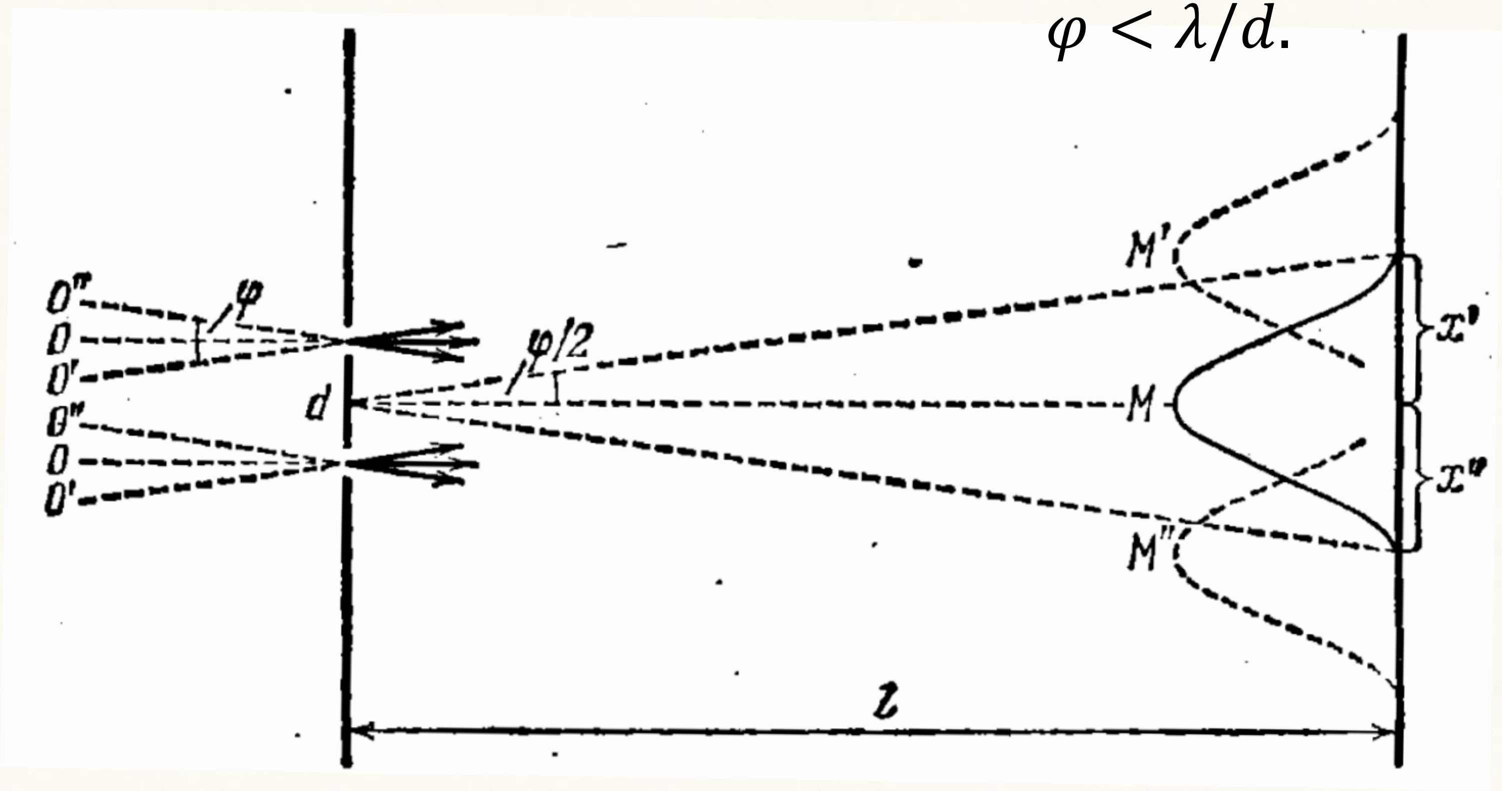
Adopted from Jinfeng Yang's talk at IPAC17

Transverse coherence and beam quality

Interference of waves from an extended source

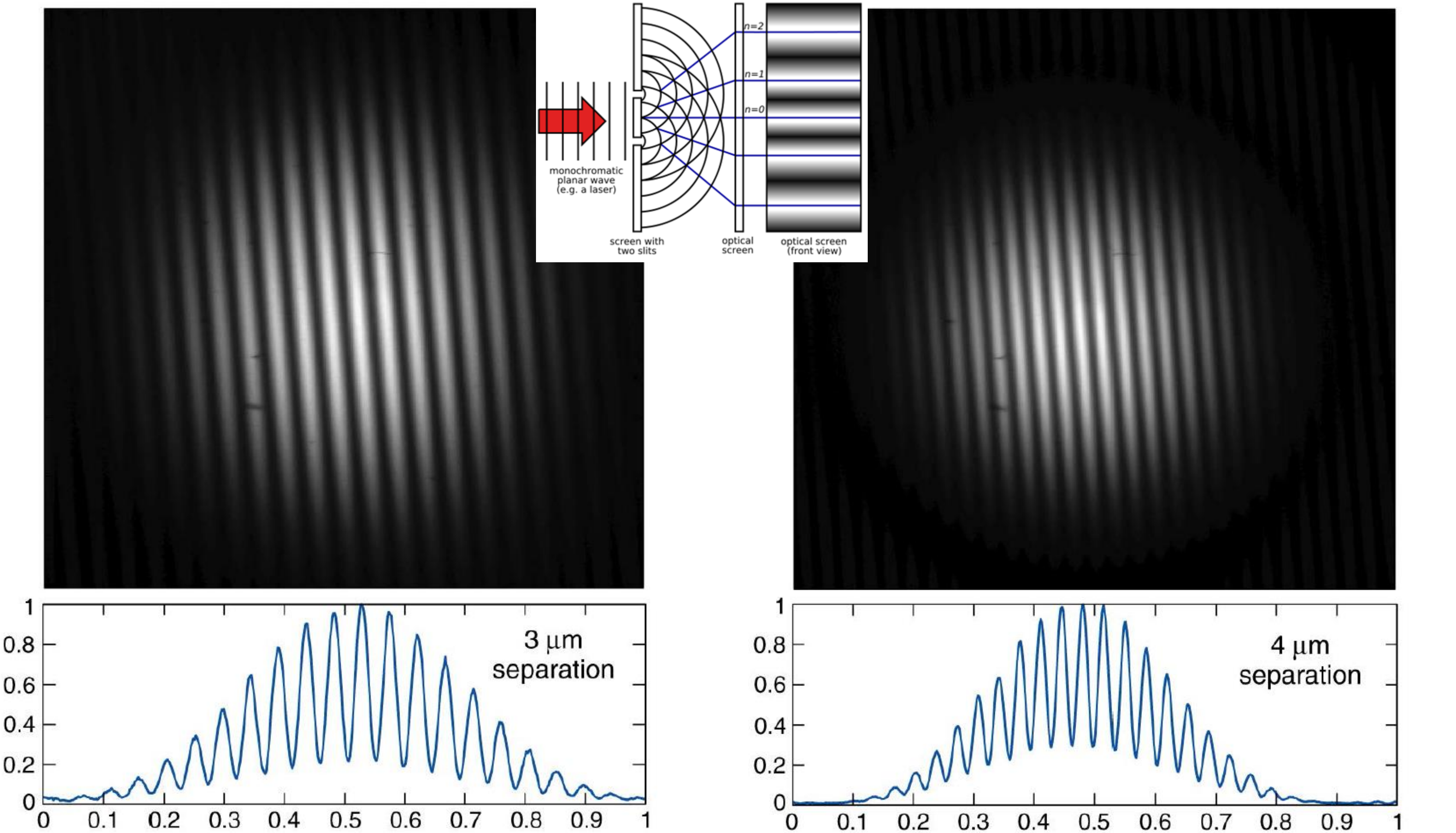


- the fringe shift is $\delta x = L\varphi/2$
- the distance between fringes $\Delta x = L\lambda/d$
- we request that $\delta x < \Delta x$, then $\varphi < \lambda/d$.



The transverse coherence distance is $\rho_c \sim \frac{\lambda}{\varphi}$.

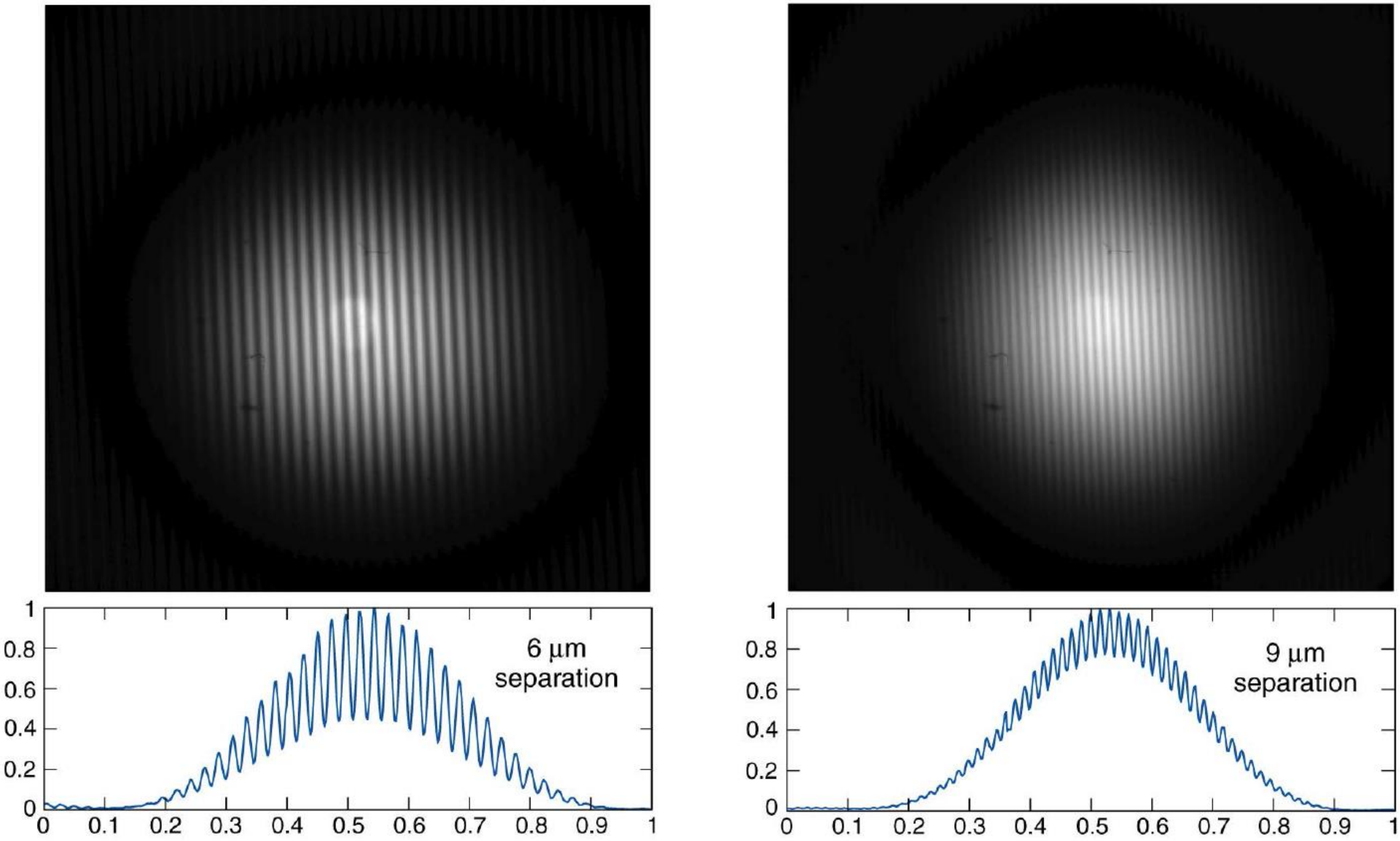
Example of spatial coherence of undulator radiation



Courtesy of Chang Chang, UC Berkeley and LBNL.

λ = 13.4 nm, 450 nm diameter pinholes, 1024 x 1024 EUV/CCD at 26 cm ALS, 1.9 GeV, λ_u = 8 cm, N = 55

Cont'd



Courtesy of Chang Chang, UC Berkeley and LBNL.

λ = 13.4 nm, 450 nm diameter pinholes, 1024 x 1024 EUV/CCD at 26 cm ALS, 1.9 GeV, λ_u = 8 cm, N = 55

Transverse coherence and beam quality

transverse coherence length

$$L_c \equiv \frac{\lambda_D}{2\pi\sigma_\theta}.$$

emittance at waist

$$\varepsilon_n = (1/mc)\sigma_b\sigma_p.$$

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

coherence at sample

$$L_c \equiv \frac{\hbar}{mc}\frac{\sigma_b}{\varepsilon_n}.$$

coherence at sample

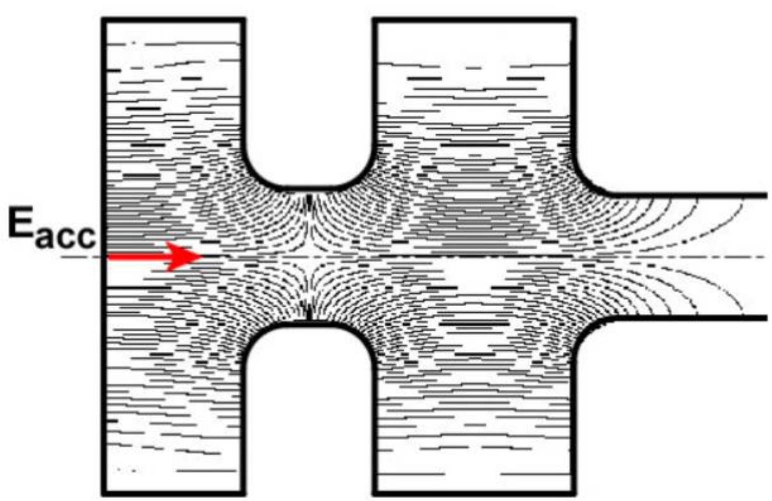
$$L_c \equiv \frac{\hbar}{\sqrt{mkT}}\frac{\sigma_{sample}}{\sigma_{source}},$$

Limitation on resolution

$$\sigma_{sample} \gg L_c\sqrt{\frac{Q}{E_{acc}}\frac{mkT}{2\pi\epsilon_0}}.$$

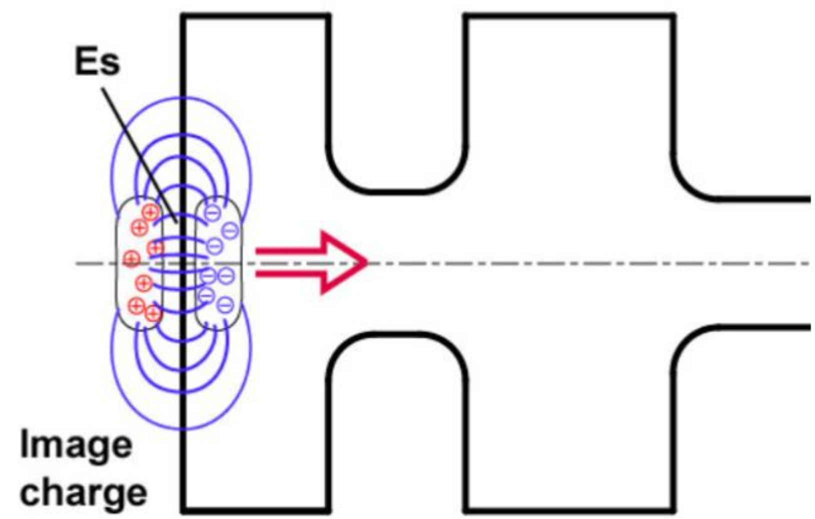
$$E_{acc} \gg E_{Coloumb}$$

Acceleration rf field



+

Space charge field



Requirements on the beam (tentative)

Some physics requirements:

- observation of processes on 100 fs scale -- **stability**
- imaging beyond crystalline samples -- **coherence**
- single-short imagining down to a single molecule – **high e-flux**

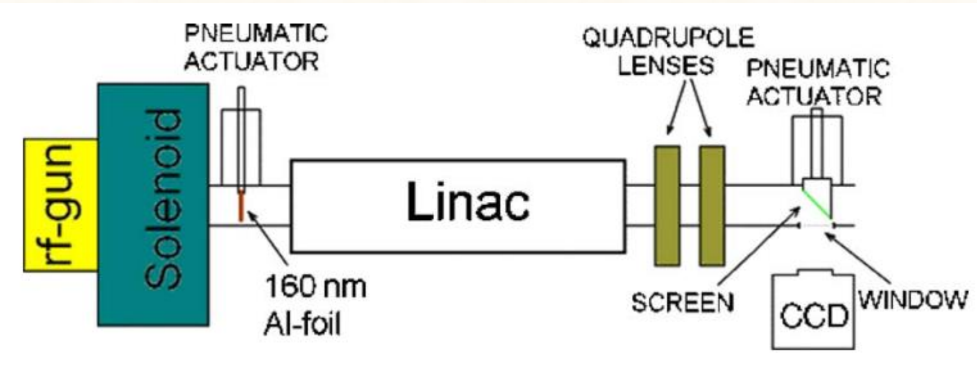
Beam at the sample:

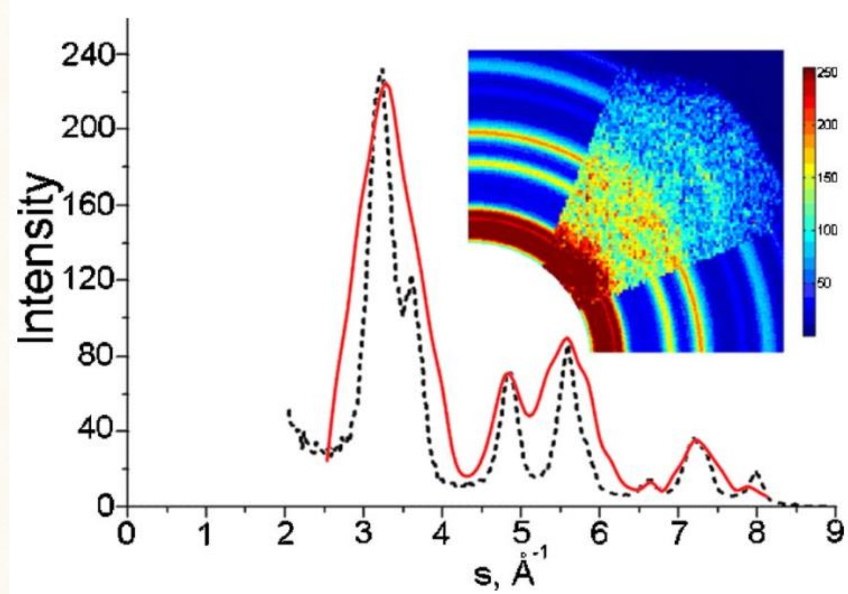
- Beam energy 2-3 MeV
- Beam charge 0.1-10 pC
- RMS spot size 1-100 um
- HWFM duration 100-0.1 ps
- Coherence length 1-10 nm
- Energy spread < 1%

UEDs around the world

Ultrafast time-resolved electron diffraction with megavolt electron beams

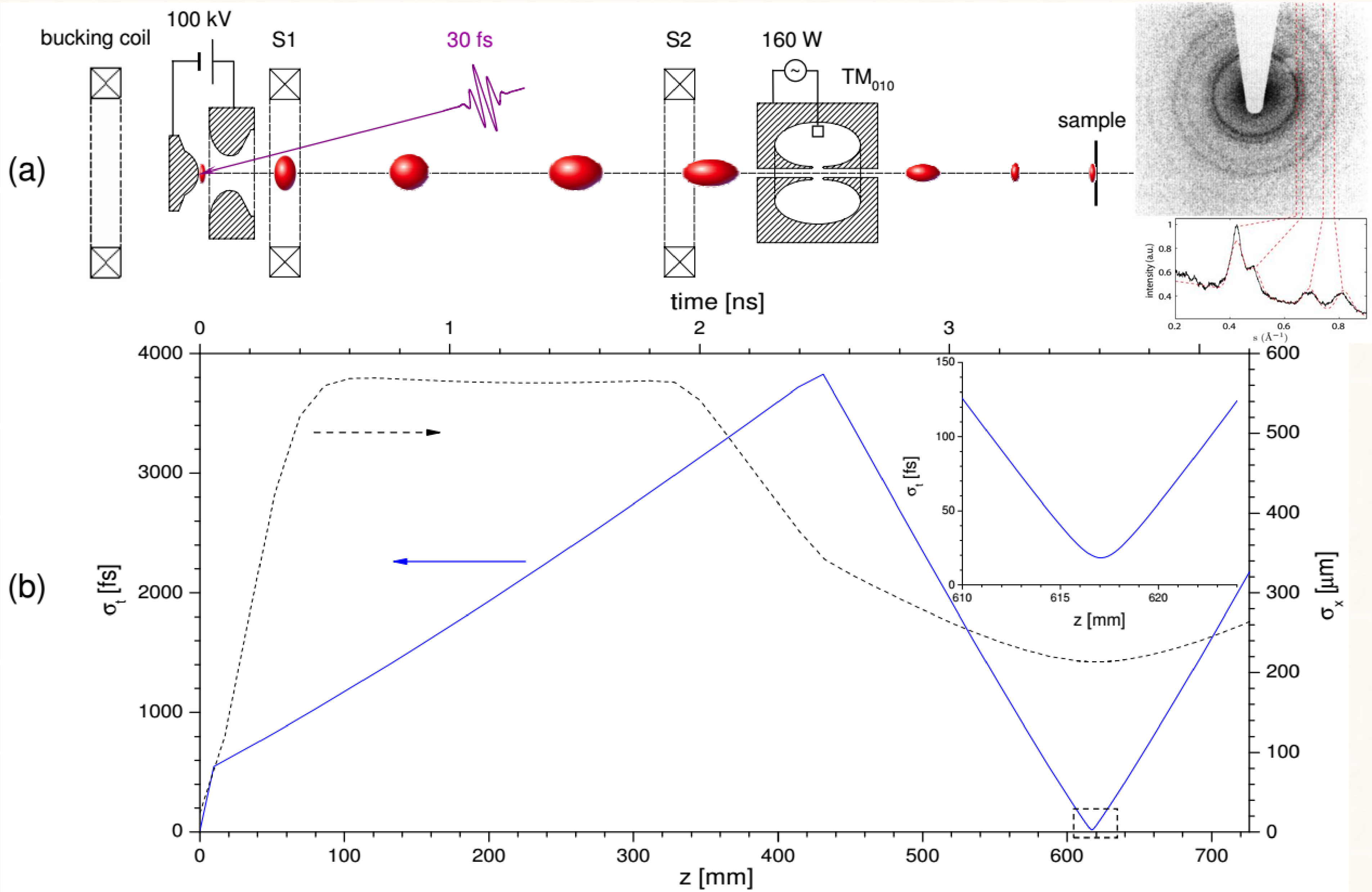
J. B. Hastings[a)]
SLAC, Stanford University, Menlo Park, California 94025



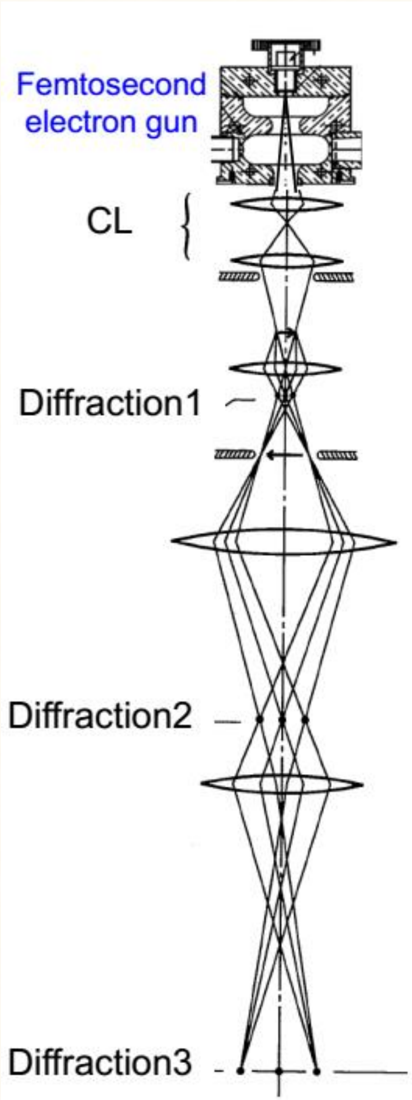


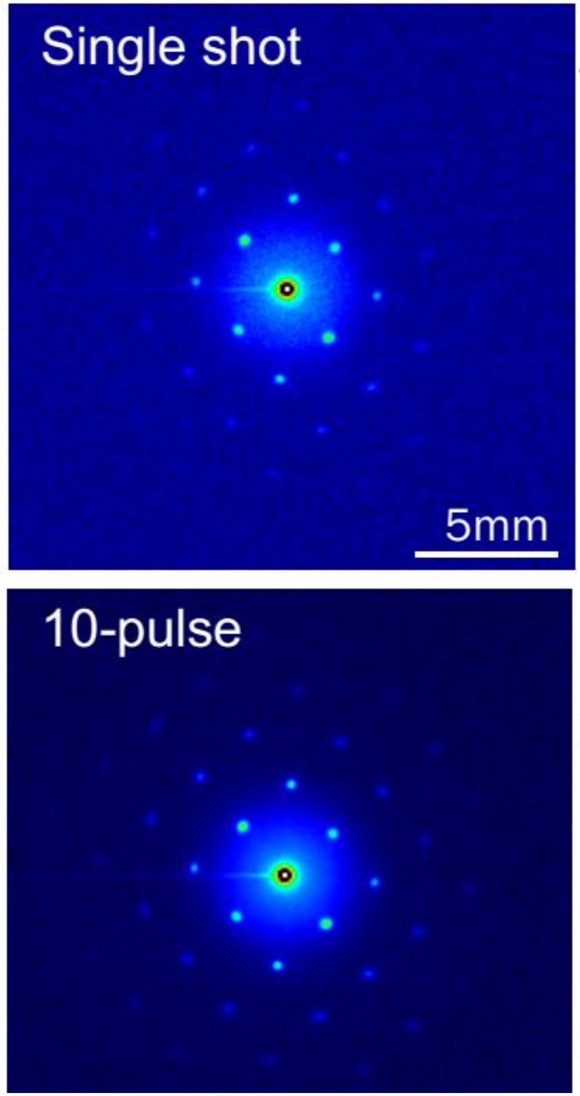
Parameter	Value	Units
Charge	2.9	pC
Energy	5.4	MeV
rms energy spread	6	keV
rms pulse length	560	fs
Longitudinal emittance	2.5	keV ps
Normalized emittance	0.85	μm
Geometric emittance	0.075	μm
Minimum rms divergence	45	μrad
Solenoid field	1.7	kG
Gun gradient	104	MV/m
Laser gun phase	40	degrees

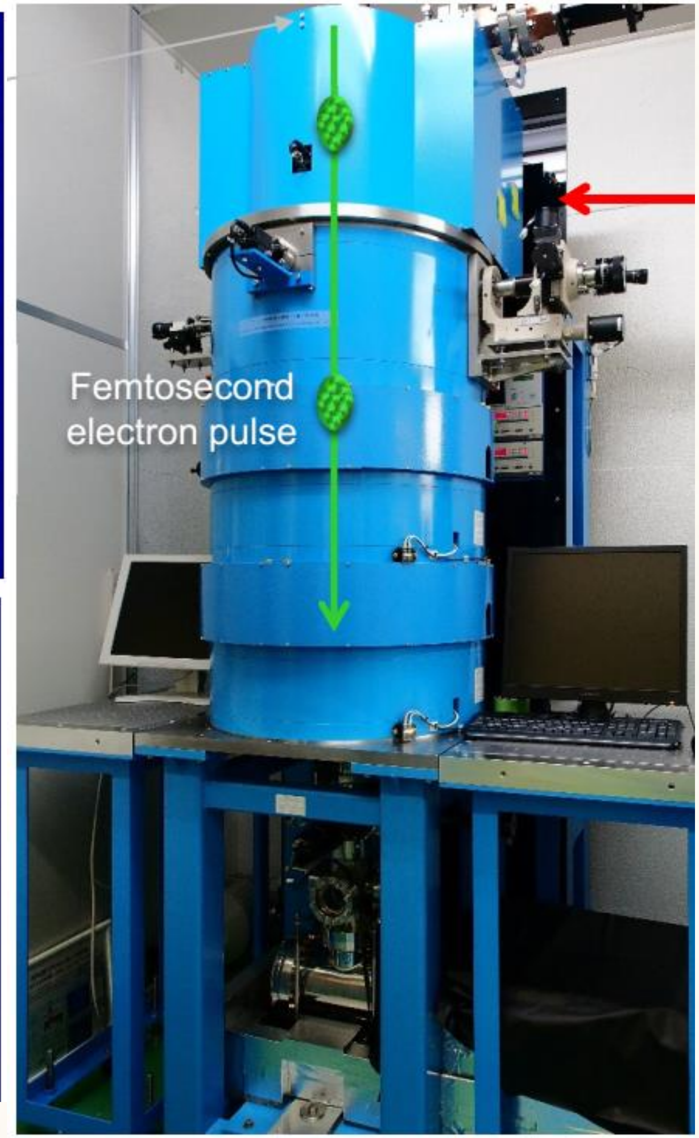
Eindhoven UED (2007): 100 kV, sub-100 fs, 200 fC



Osaka UED (2010): 3 MeV, 150 fs, 1000 fC



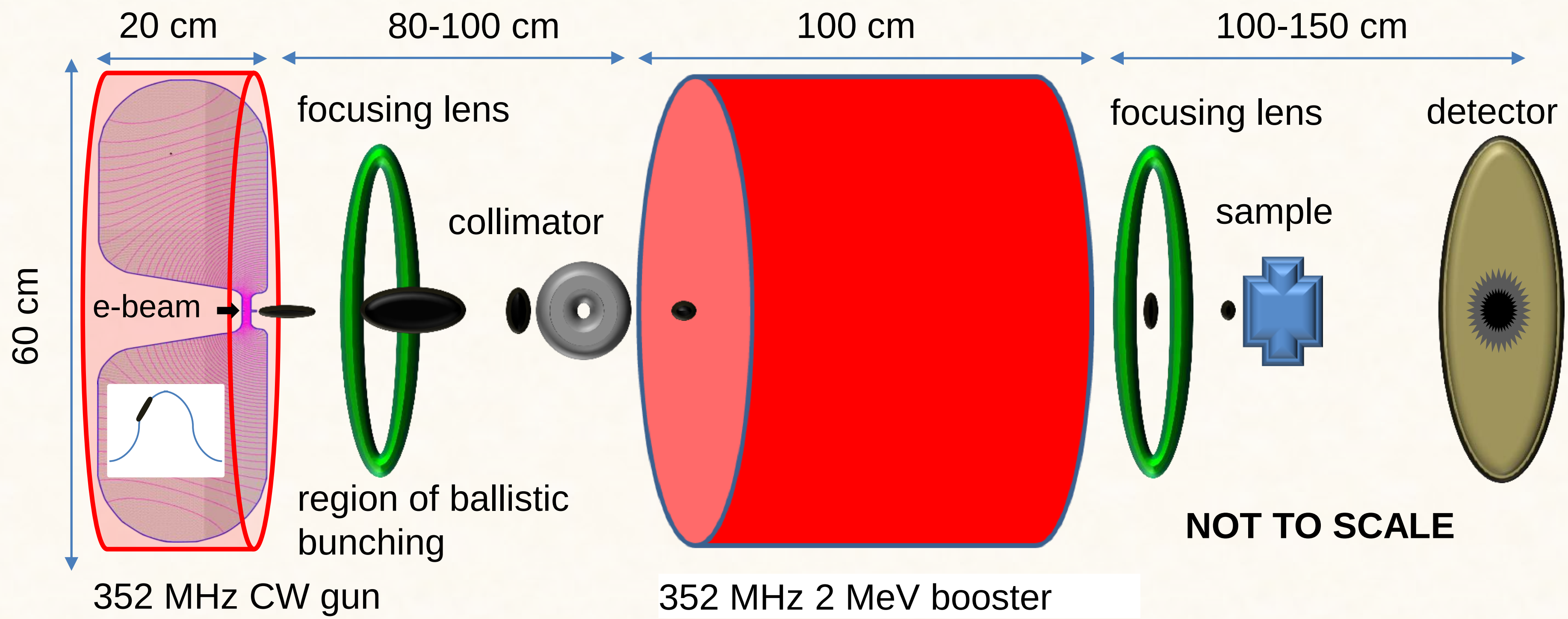




Size: 3m(H) x 0.7m(D)

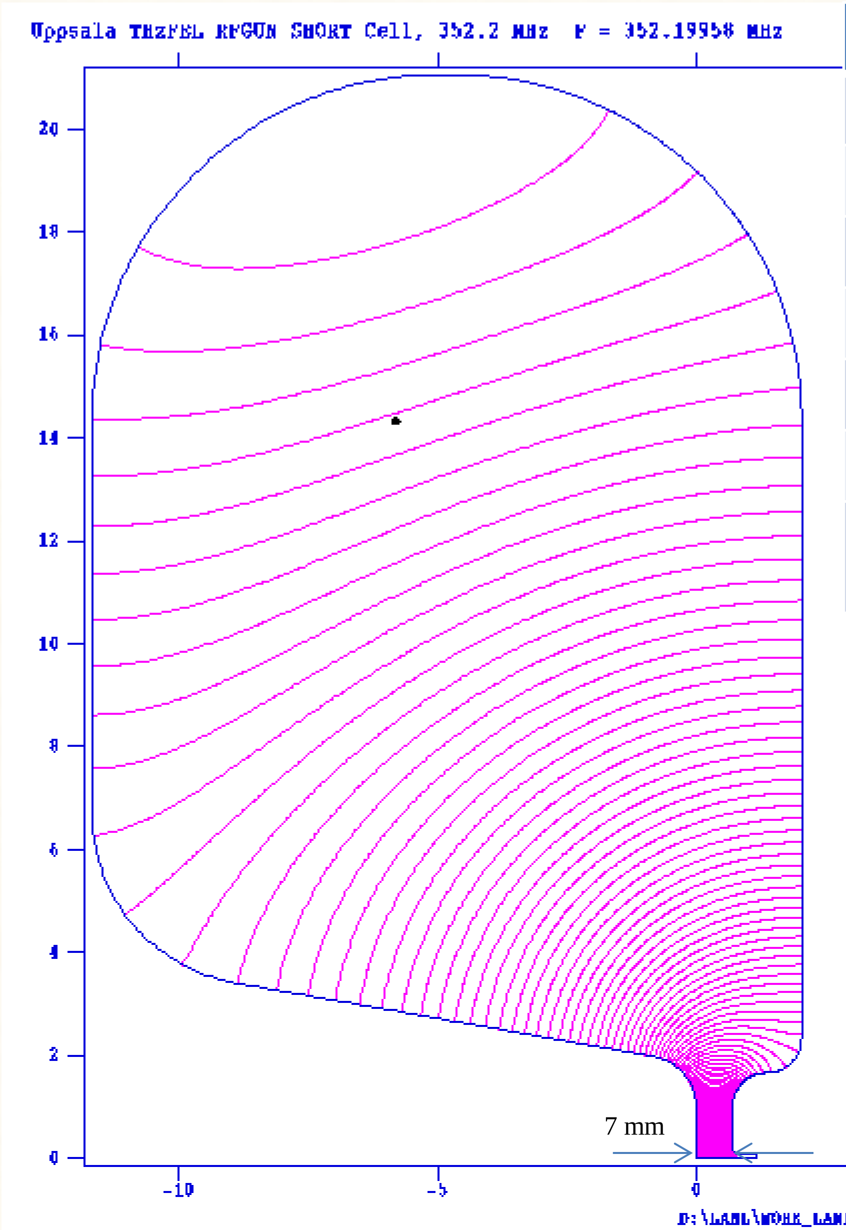
proposed FREIA-UED

FREIA UED



Beam at the sample:
Beam energy 2 MeV
Beam charge 20-200 fC
RMS spot size 10-300 um
HWFM duration 100-0.05 ps
Beam emittance 10-20 nm
Energy spread 0.05%
Coherence length 1-5 nm

Photo Gun 352.2 MHz Cavity

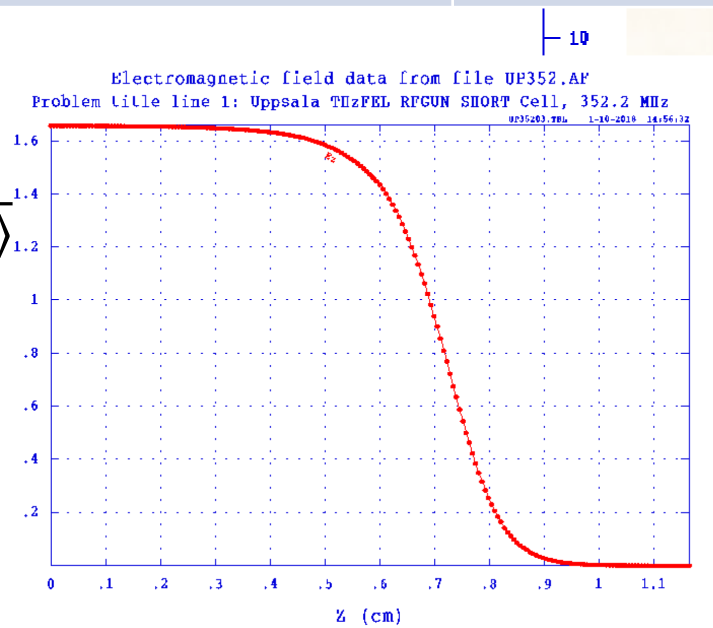


r (cm)

z (cm)

PARAMETERS	VALUE
Quality, Q_0	28310.7
Shunt Impedance, Z_{sh}	547 MΩ/m
Average Gradient, $\langle E_z \rangle$	24.1 MV/m
Electric field at Cathode	40 MV/m
Rf Phase of Crest, ψ	18 °
Power Dissipation, P_{diss}	12.4 kW
Energy Gain, V_{acc}	119.7 keV

$$\frac{E_z}{\langle E_z \rangle}$$



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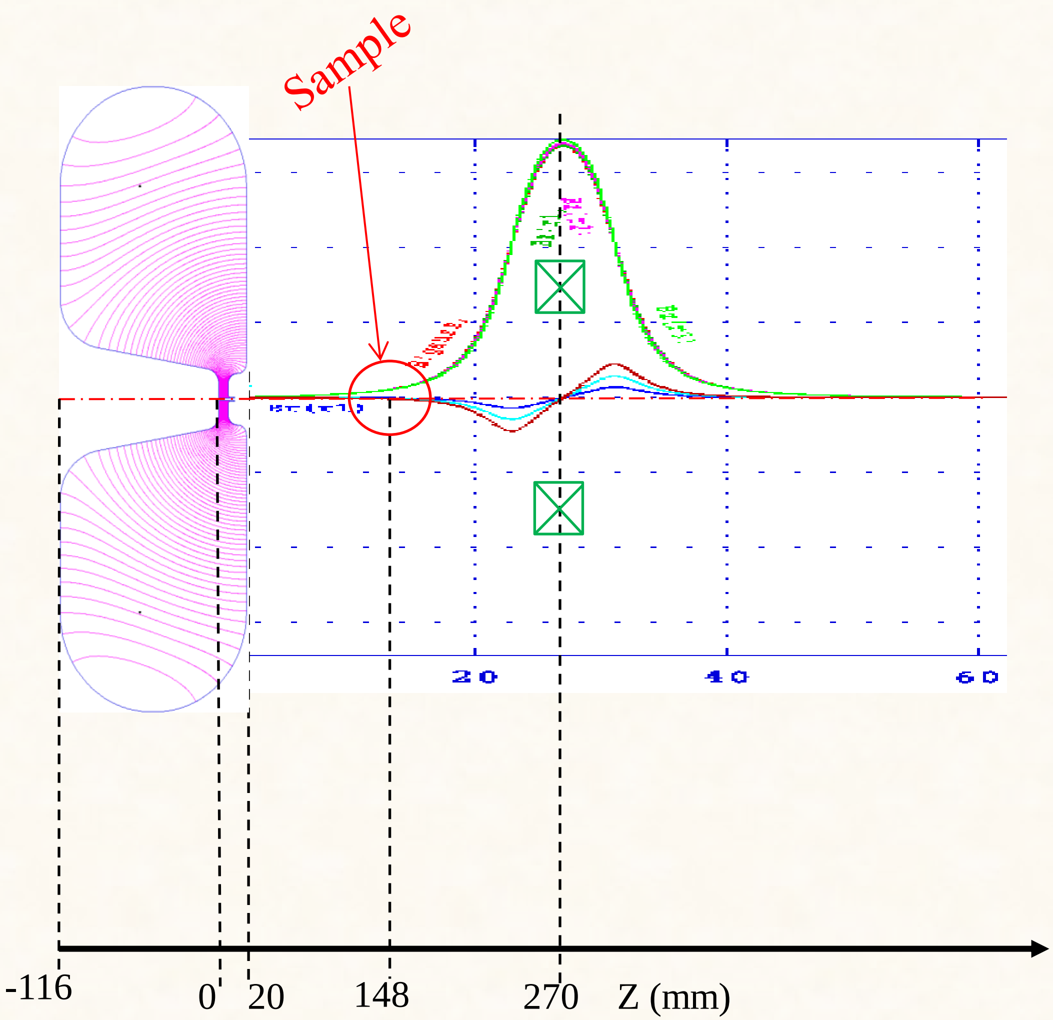
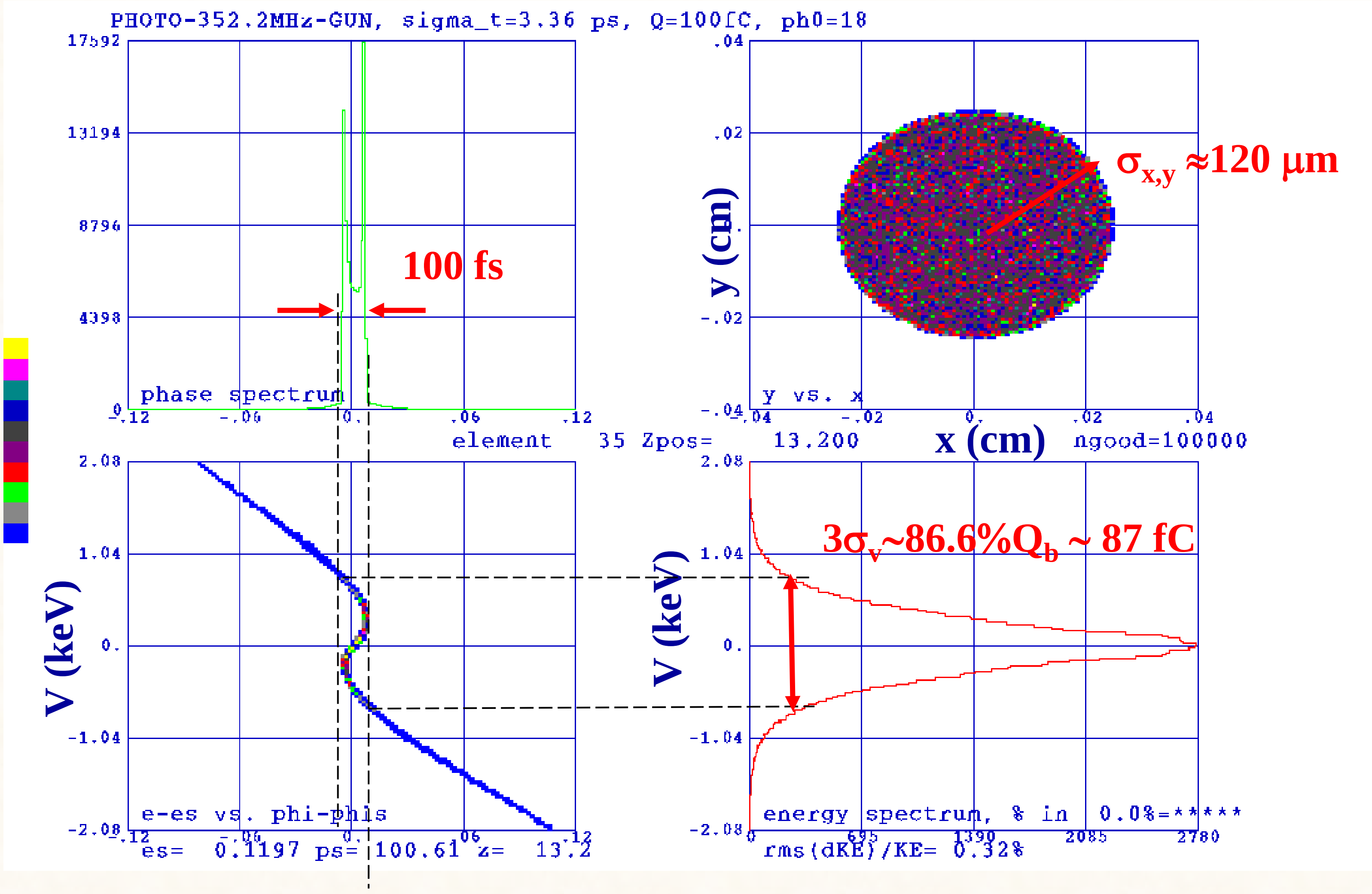
Single-Cavity Low Energy Scheme



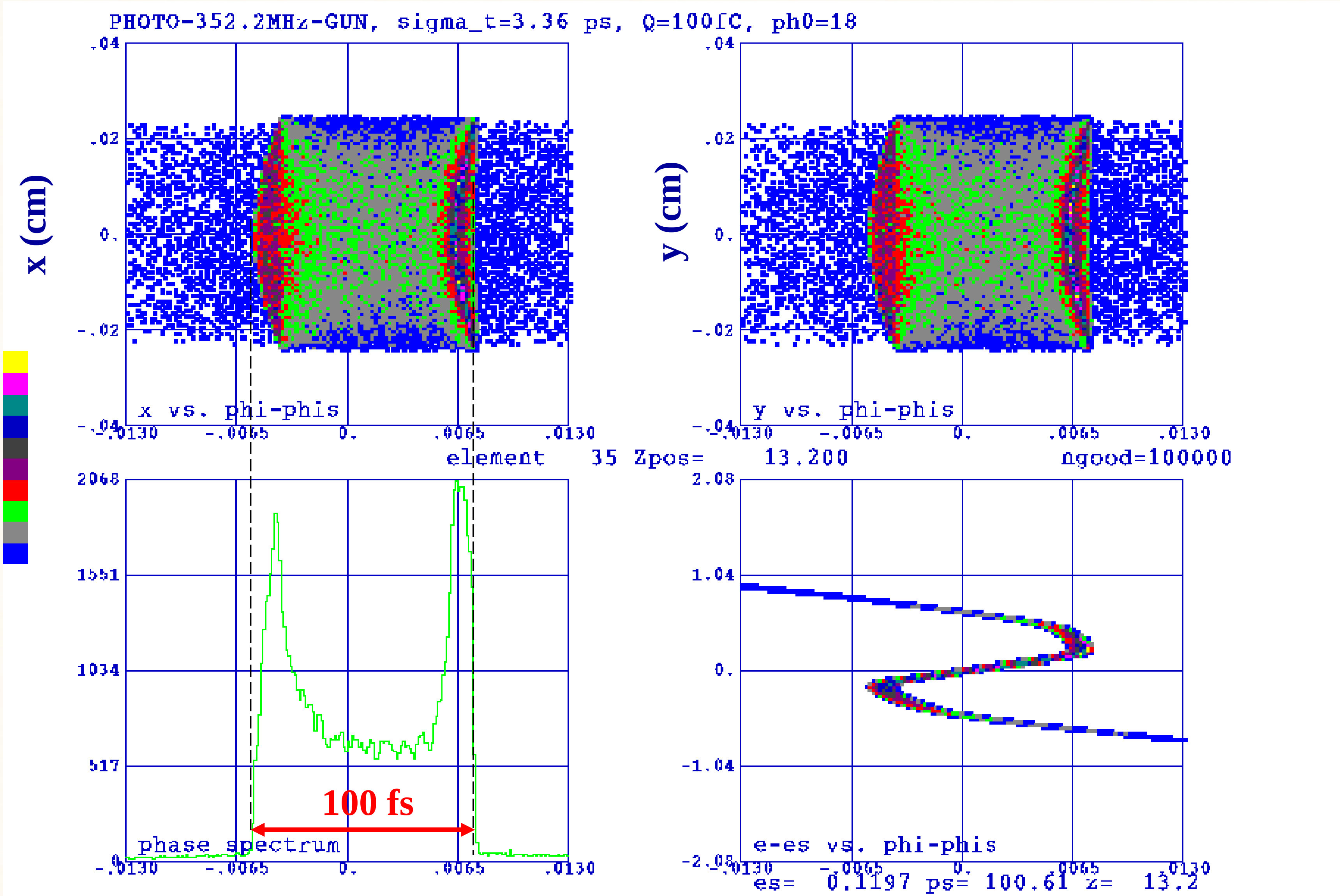
INITIAL BEAM FOR PARMELA	VALUE
Charge	100 fC
Energy	0.27 eV
RMS Radius	15 µm
RMS Duration	3.36 ps
Norm. emittance	0 nm rad

The profile and magnitude of the magnetic focusing field are not optimal.

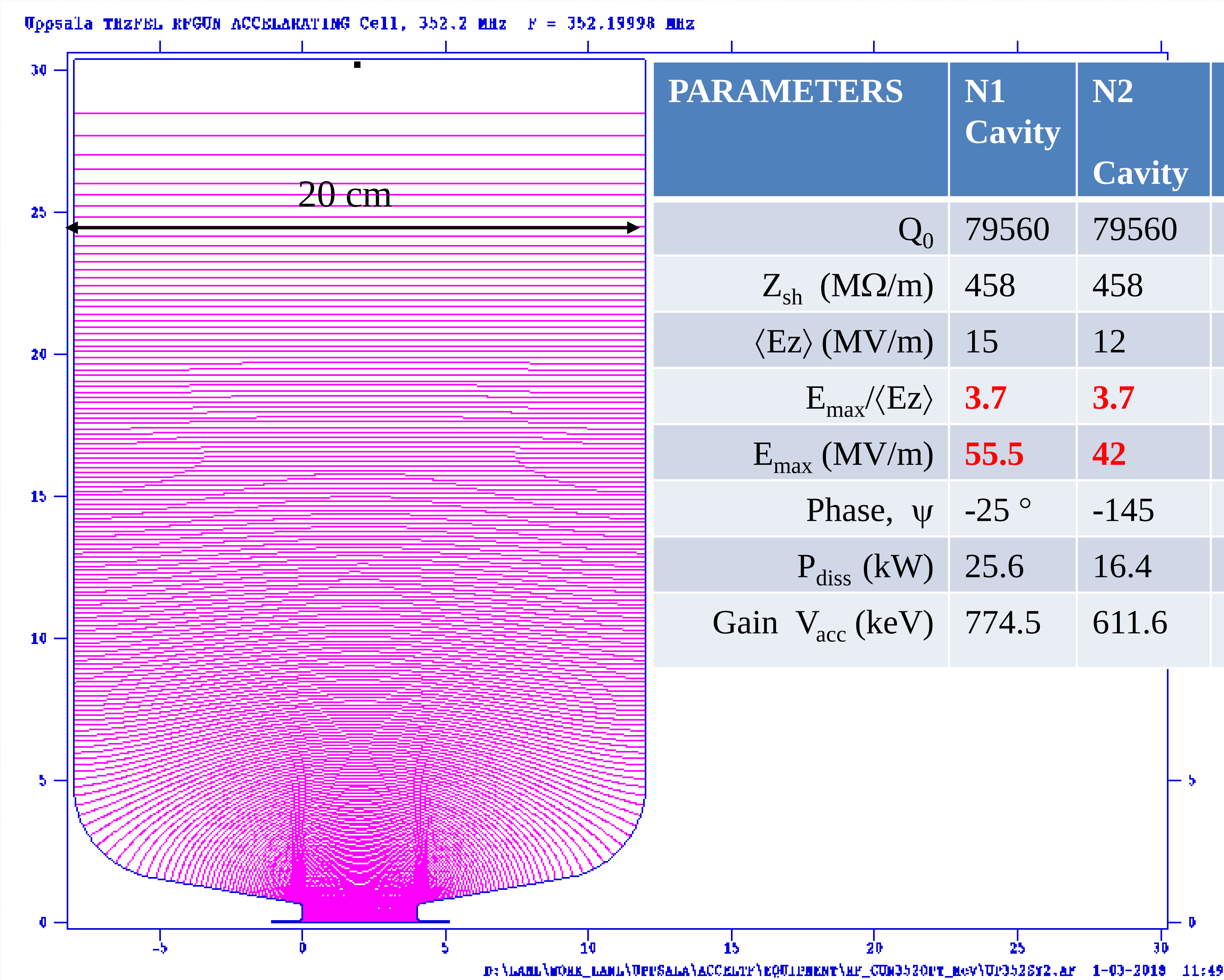
100 fs 87 fC Bunch at Sample (z=132 mm)



100 fs 87 fC Bunch at Sample (z=132 mm): cont'd

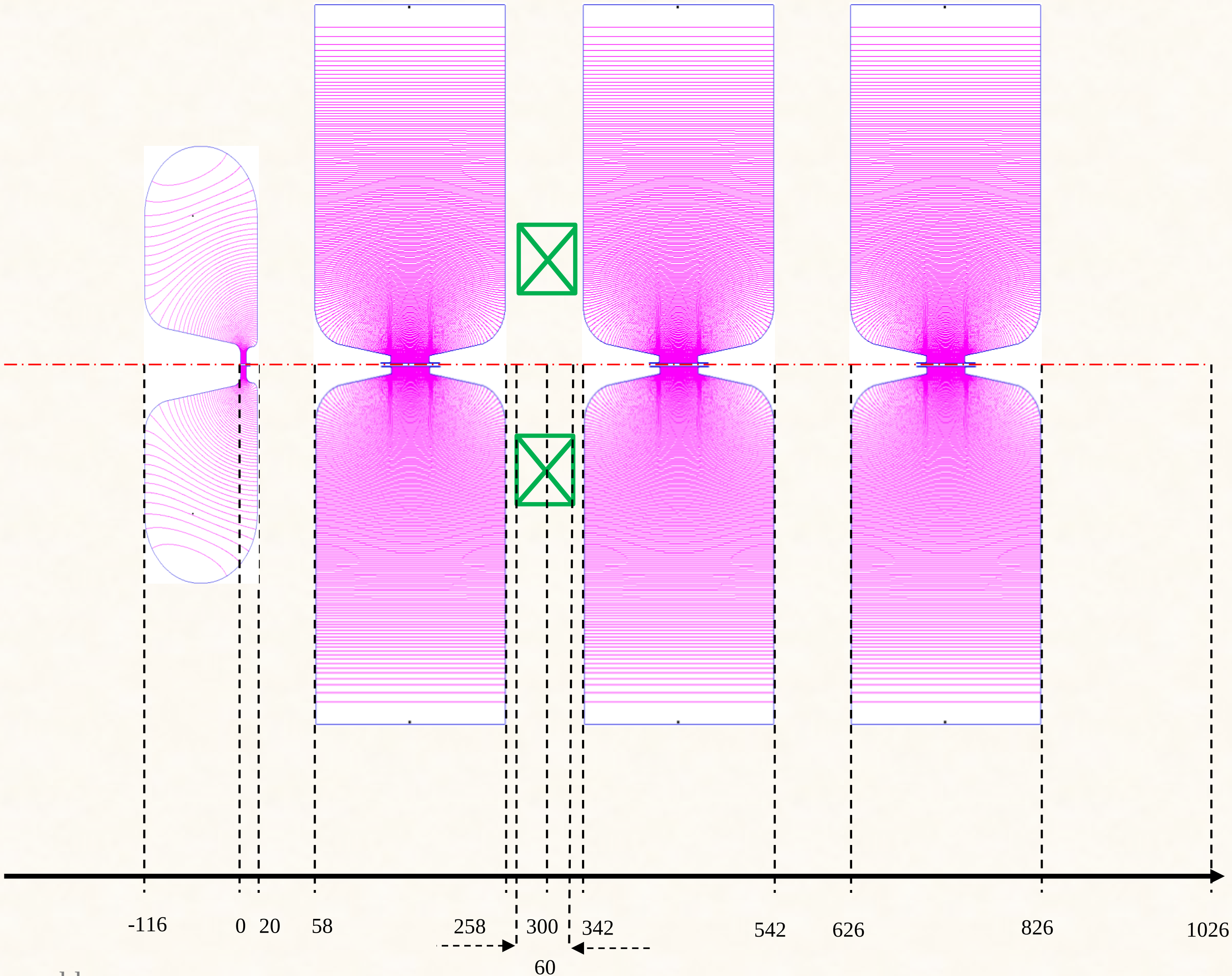


Booster Cavity



PARAMETERS	N1 Cavity	N2 Cavity	N3 Cavity
Q_0	79560	79560	79560
Z_{sh} (MΩ/m)	458	458	458
⟨Ez⟩ (MV/m)	15	12	12
E_{max}/⟨Ez⟩	**3.7**	**3.7**	**3.7**
E_{max} (MV/m)	**55.5**	**42**	**42**
Phase, ψ	-25 °	-145	-265
P_{diss} (kW)	25.6	16.4	16.4
Gain V_{acc} (keV)	774.5	611.6	602.4

Multi-cavity high-energy scheme



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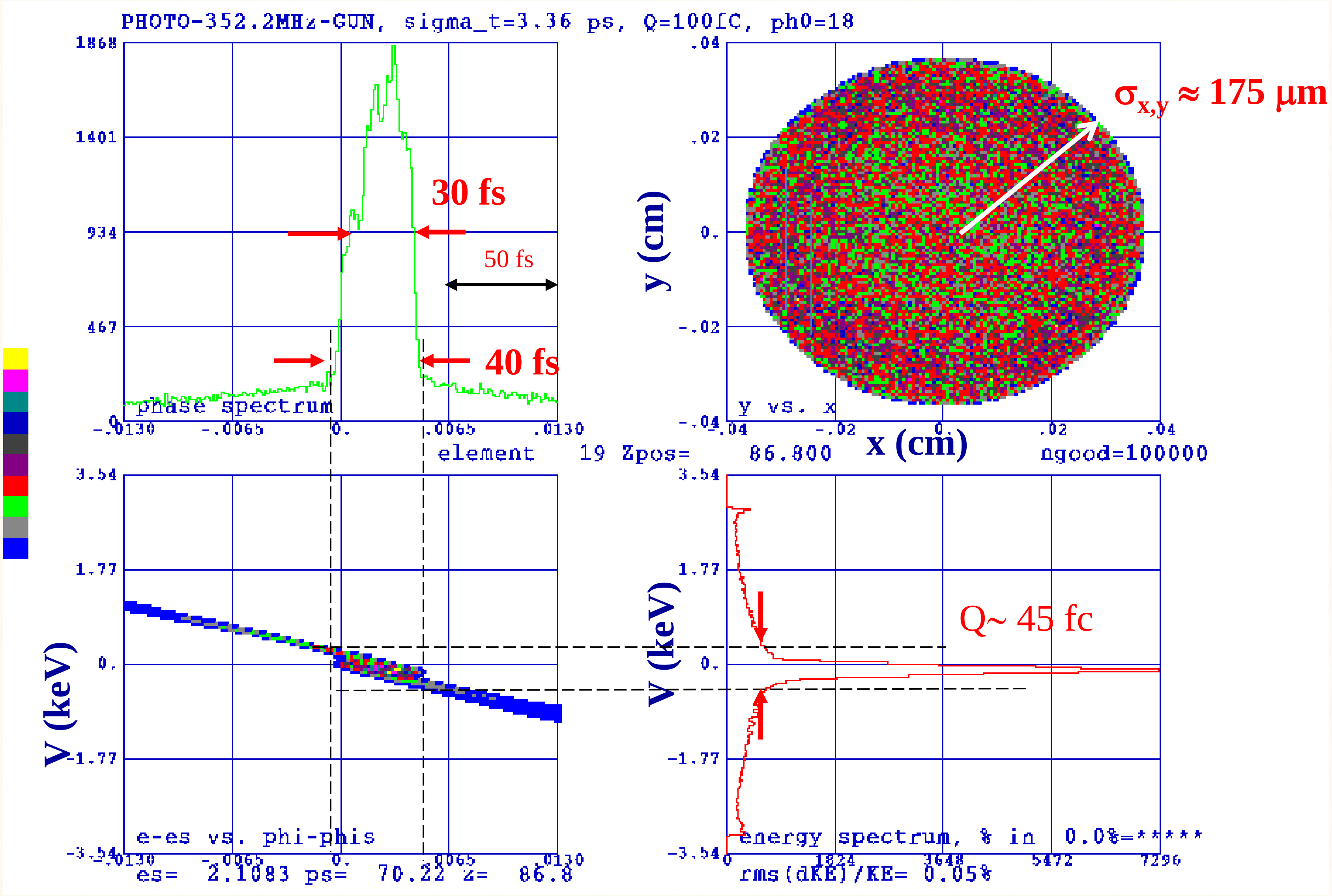
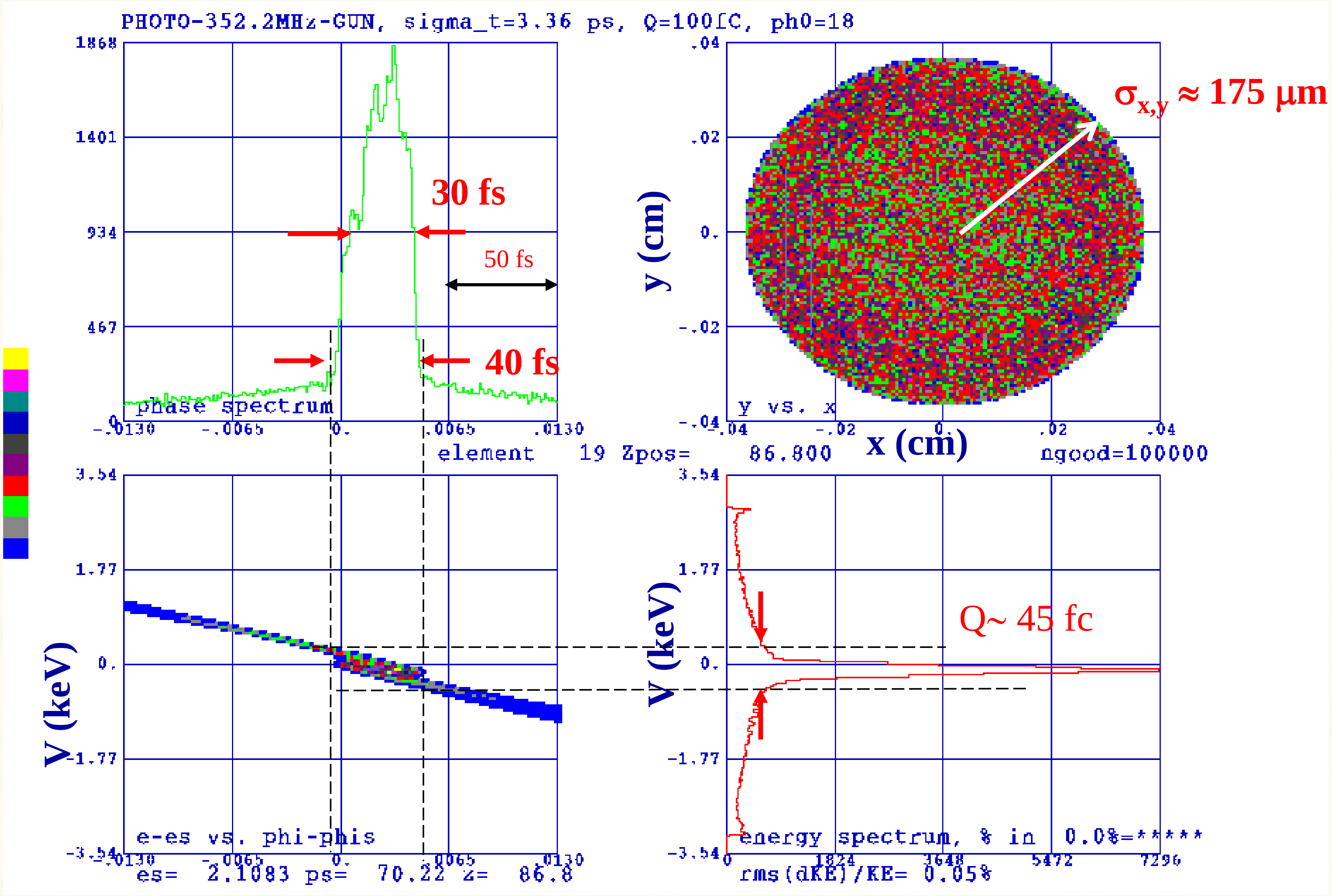
2.1 MeV bunch at sample (z=868 mm)



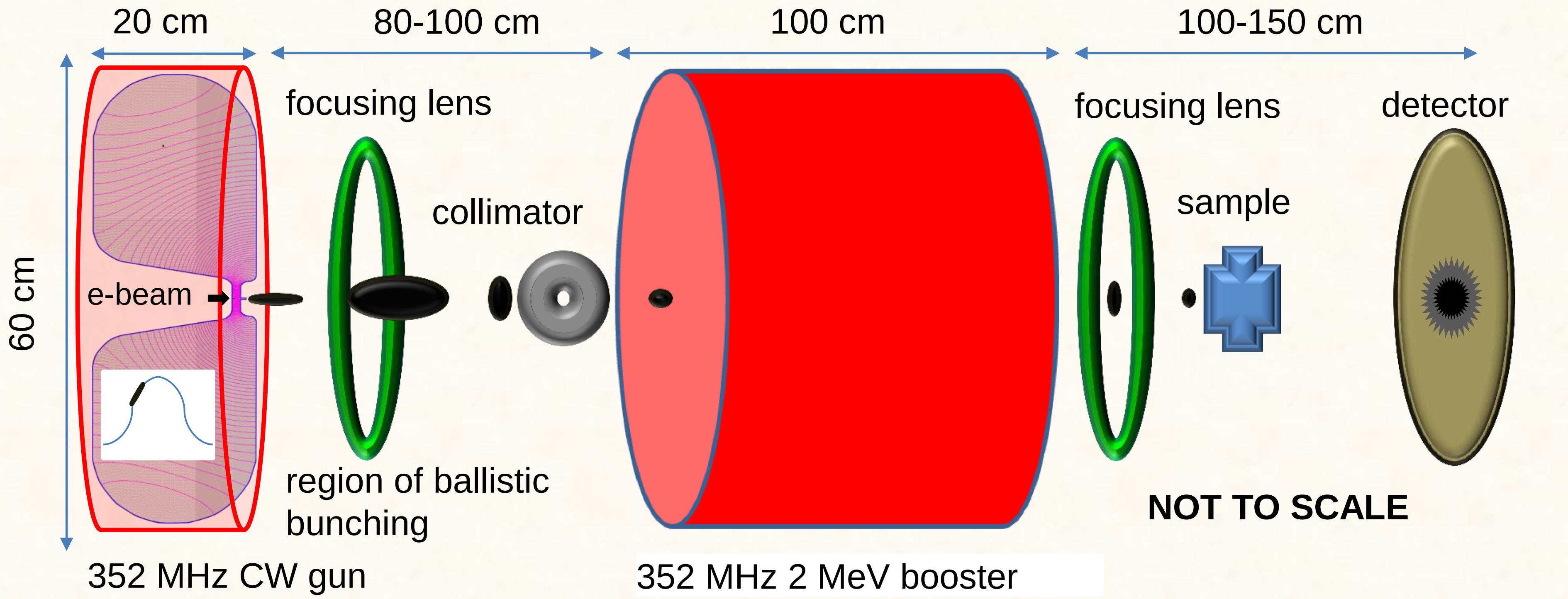
2.1 MeV bunch at sample (z=868 mm)



Summary

INITIAL BEAM	VALUE
Charge	100 fC
RMS Duration	3.36 ps
Energy	0.27 eV
RMS Radius	15 µm
Norm. emittance	12 nm rad
Coherent Length	0.48 nm

FINAL BEAM	VALUE
Distance to Sample	868 mm
FWHM	40 fs
Charge	45 fC
Energy	2.108 MeV
RMS Radius	175 µm
Average Current	1.125 A
Emittance Growth	9 nm rad
Norm. emittance	15.0 nm rad
Energy spread	<0.05%
Coherent Length	4.5 nm



20 cm
80-100 cm
100 cm
100-150 cm
60 cm
focusing lens
focusing lens
detector
collimator
sample
e-beam
region of ballistic bunching
NOT TO SCALE
352 MHz CW gun
352 MHz 2 MeV booster