The laser electron accelerator project

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Goal

Experimental demonstration of acceleration
from crossed laser beams in vacuum

Talk Outline

Introduction

- motivation
- physics for crossed laser beam acceleration

Description of the LEAP project

- The SCA-FEL facility at HEPL
- The laser system
- The accelerator cell
- Diagnostics
- Chosen parameters

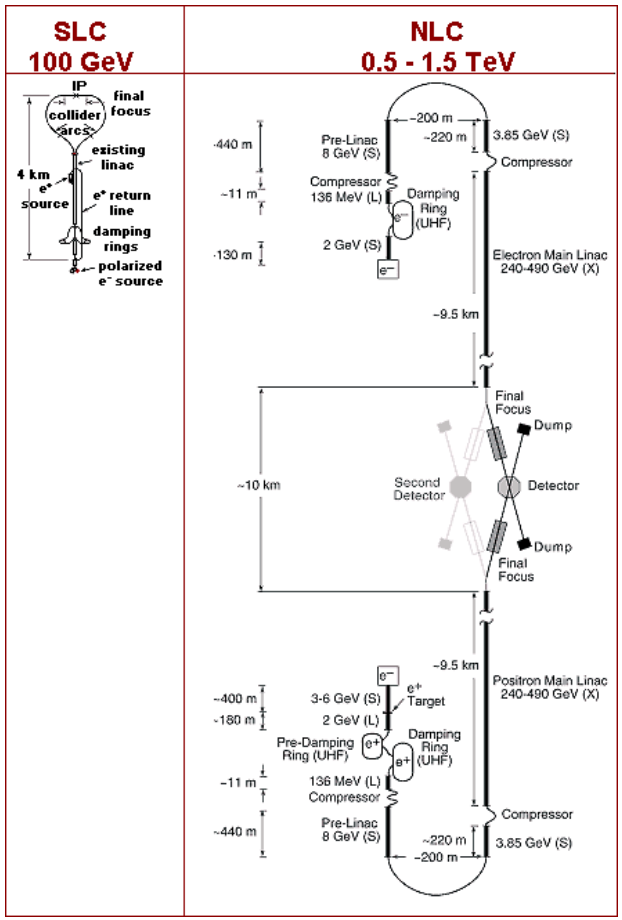
Present status of LEAP

- results
- obstacles

Future experiments

- Optical bunching
- Multi cell experiments
- Laser phase locking

Motivation



For the next generation of experiments with e^+e^- collisions TeV energies necessary

- SLAC provides ~ 50 GeV beam

Need for high gradient accelerators

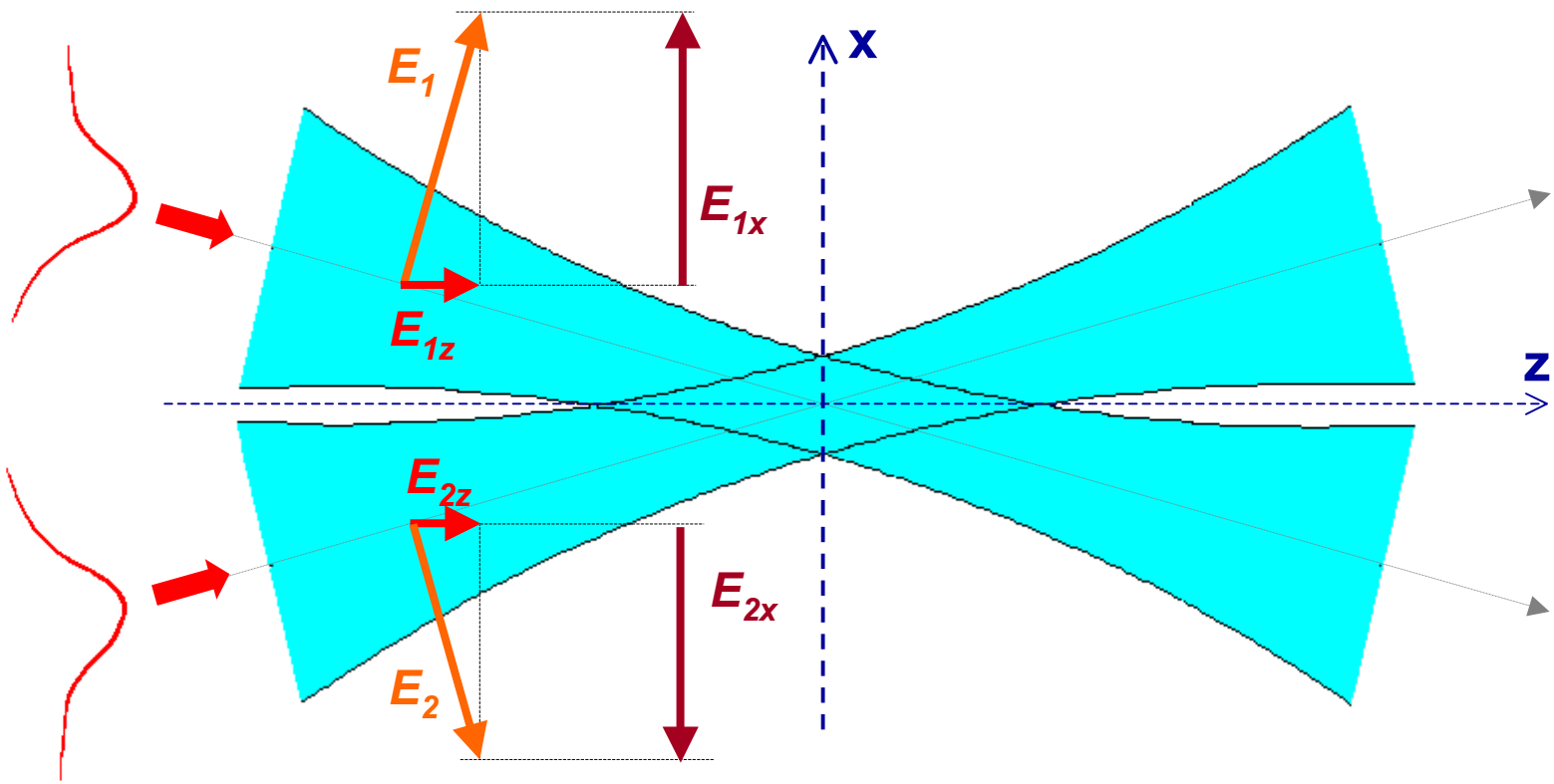
- 1 GeV/m gradient desirable

LEAP acceleration

- no lateral deflection
- vacuum
- damage threshold limits gradient

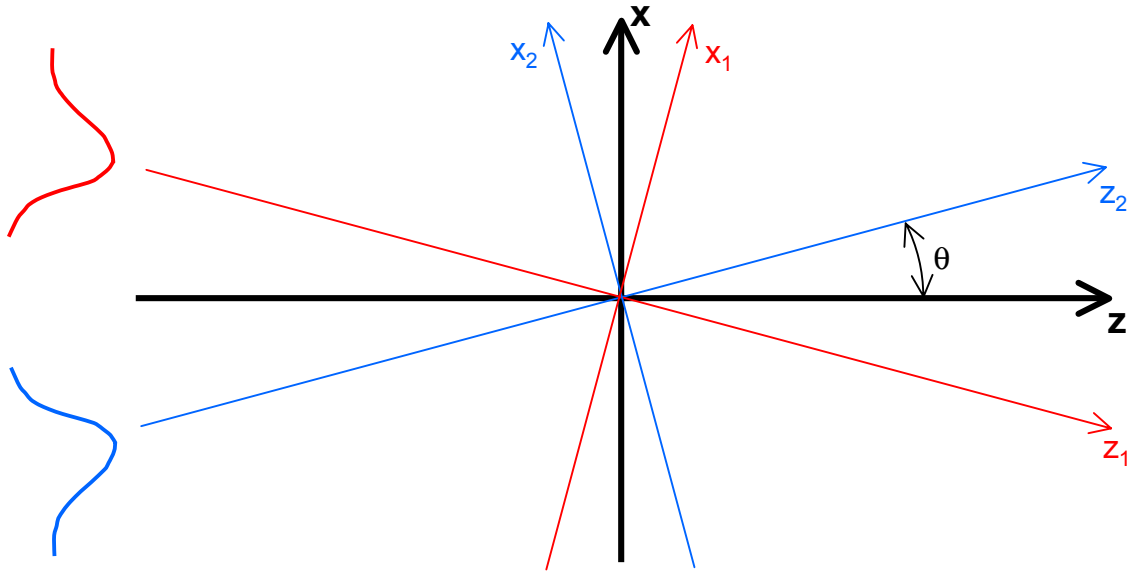
Crossed laser beam geometry

The laser beams are polarized in the XZ plane, and are out of phase by π



$E_{1x} + E_{2x} = 0$ → no transverse deflection

$|E_{1z} + E_{2z}| > 0$ → nonzero electric field in the direction of propagation



$$E_{x1} = \frac{E_0\omega_0}{\omega_1}\cdot\exp\left(-\frac{r_1^2}{\omega_1^2}\right)\cdot\cos\psi_1$$

$$E_{x2} = \frac{E_0\omega_0}{\omega_2}\cdot\exp\left(-\frac{r_2^2}{\omega_2^2}\right)\cdot\cos\psi_2$$

$$E_{z1} = \frac{2E_0x_1}{k\cdot\omega_1^2}\cdot\exp\left(-\frac{r_1^2}{\omega_1^2}\right)\cdot\left(\sin\psi_1 - \frac{z_1}{Z_R}\cos\psi_1\right)$$

$$E_{z2} = \frac{2E_0x_2}{k\cdot\omega_2^2}\cdot\exp\left(-\frac{r2^2}{\omega_2^2}\right)\cdot\left(\sin\psi_2 - \frac{z_2}{Z_R}\cos\psi_2\right)$$

$$\psi_1 = kz_1 - \omega\cdot t + z_1r_1^2/\left(Z_R\omega_1^2\right) - \tan^{-1}\left(z_1/Z_R\right)$$

$$E_z = -\left(E_{x1}-E_{x2}\right)\cos\theta + \left(E_{z1}+E_{z2}\right)\sin\theta$$

$$E_x = +\left(E_{x1}+E_{x2}\right)\cos\theta + \left(E_{z1}-E_{z2}\right)\sin\theta$$

P.Sprangle, E. Esarey, J. Krall, A. Ting, Opt. Comm. 124, 69 (1996)

$$E_z = \underbrace{-\frac{2E_0 \sin\theta}{(1+\hat{z}^2\cos^2\theta)^{3/2}} \exp\left[-\frac{\left(\hat{z}/\theta_d\right)^2 \sin^2\theta}{1+\hat{z}^2\cos^2\theta}\right]}_{Magnitude} \times \underbrace{\cos\psi_t}_{Phase}$$

$$\psi_t = \underbrace{k\cdot z\cdot\cos\theta - \omega\cdot t}_{Plane\ Wave\ Phase} + \underbrace{\frac{\hat{z}^3\cos^3\theta\cdot\tan^2\theta}{\theta_d{}^2\left(1+\hat{z}^2\cos^2\theta\right)}}_{Math} \underbrace{-2\cdot\tan^{-1}\left(\hat{z}\cos\theta\right)}_{Gouy\ Phase} + \phi_0$$

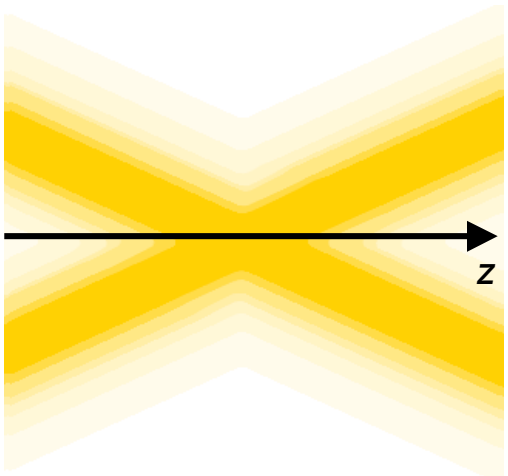
Observations:

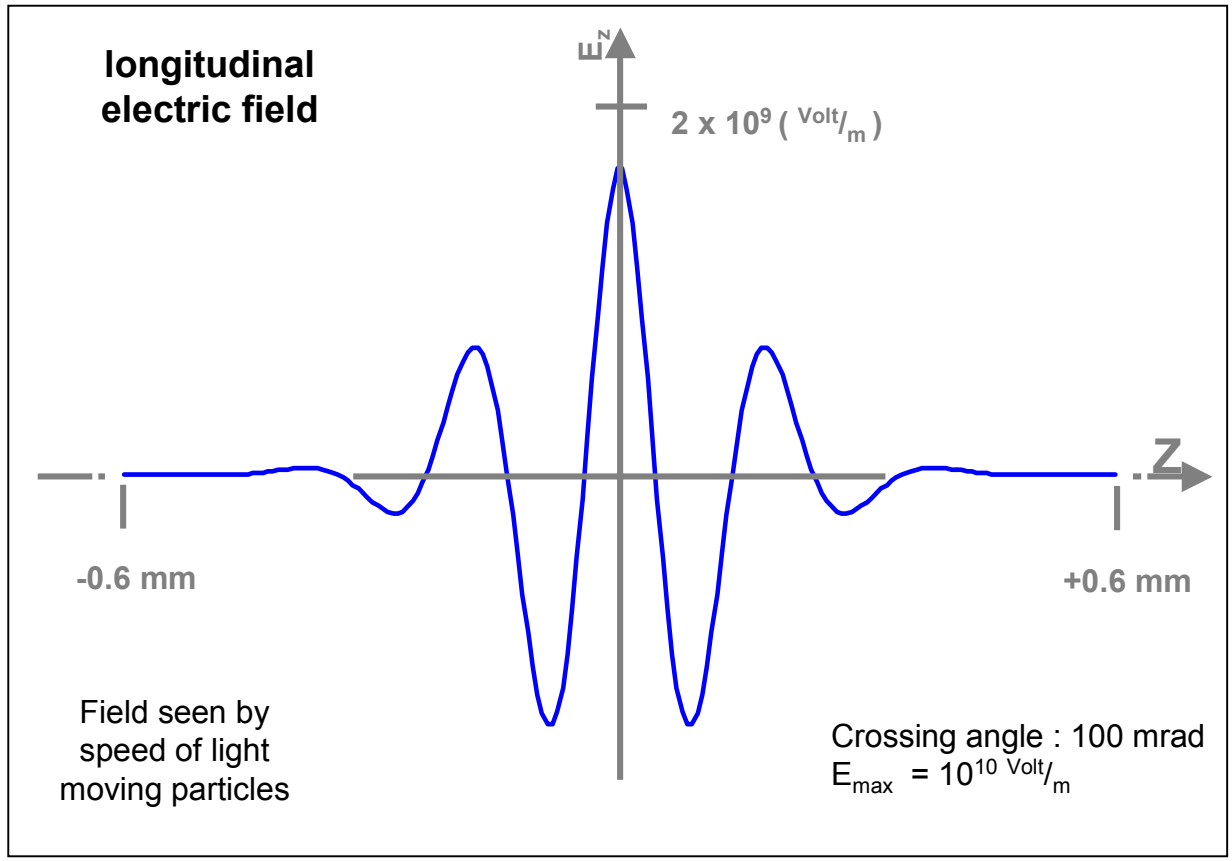
1) zero transverse field
no deflection

2) nonzero longitudinal field

3) the phase velocity of the field travels faster than *c*

Particle traversing
a pair of crossed
laser beams





In the example above the electron-laser **slippage distance** is of the order of 0.1 mm

It depends on
- wavelength
- spot size of the laser

} divergence angle θ_d

- crossing angle of the laser beams → θ
- energy of the e-beam → γ

$$z_s = \lambda \cdot \frac{\gamma^2}{1+\left(\theta^2 + 2\theta_d{}^2\right)\cdot\gamma^2}$$

The accelerator cell

nonzero energy gain

↓

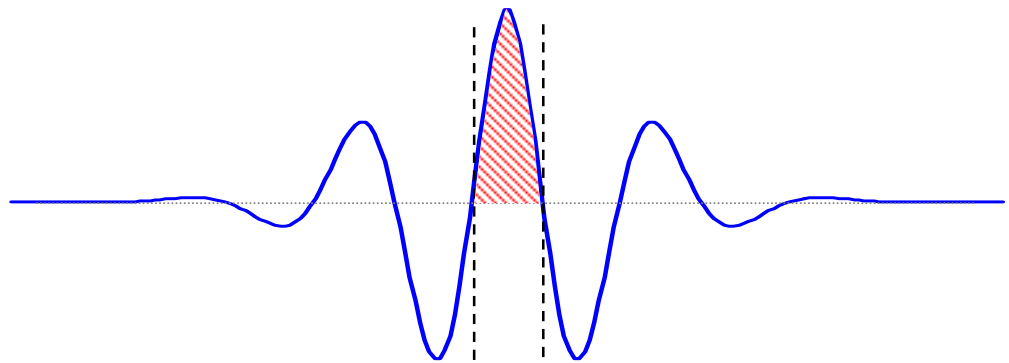
laser-electron interaction over a finite distance

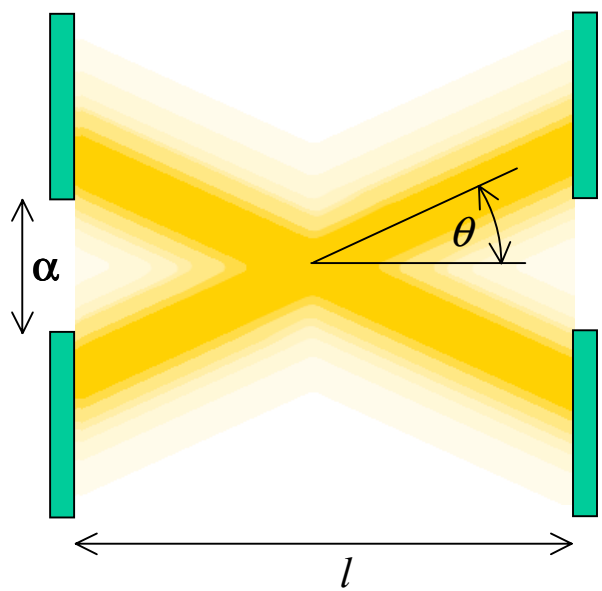
↓

provide a structure with reflective walls to confine the laser interaction

↓

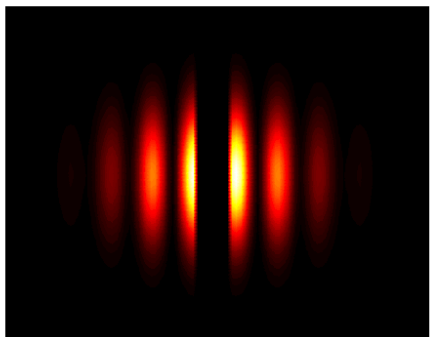
need apertures for e-beam to travel in vacuum



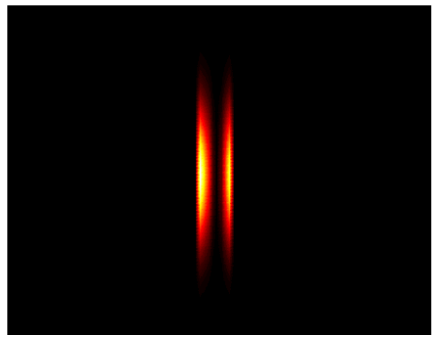


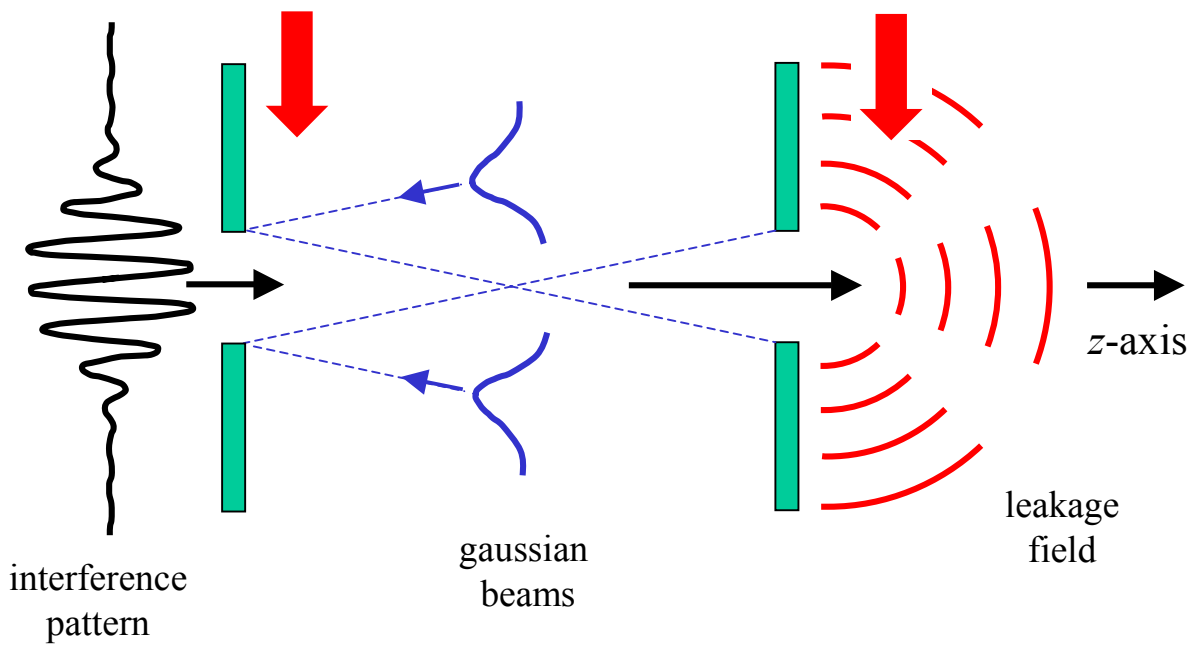
Degradation effects of the field from slits

truncated input field



leakage field behind slit





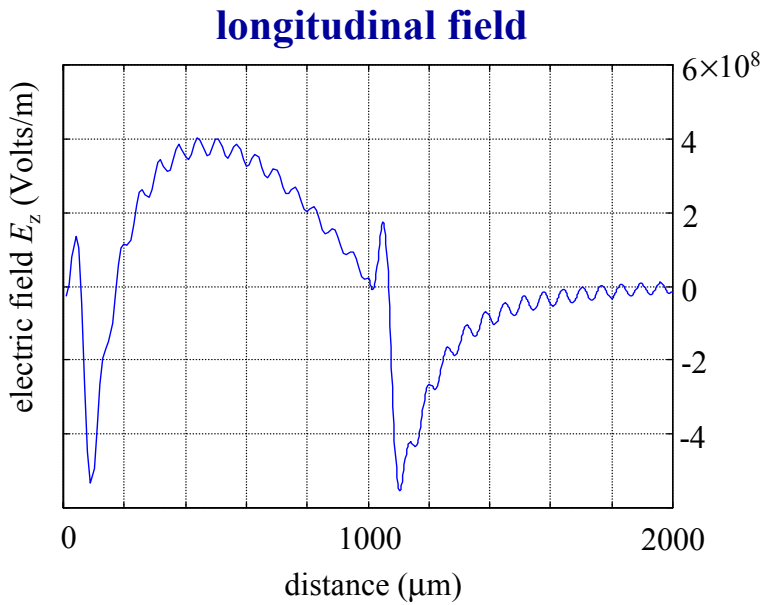
slit =16 μm, ωo = 50 μm, θ = 20 mrad

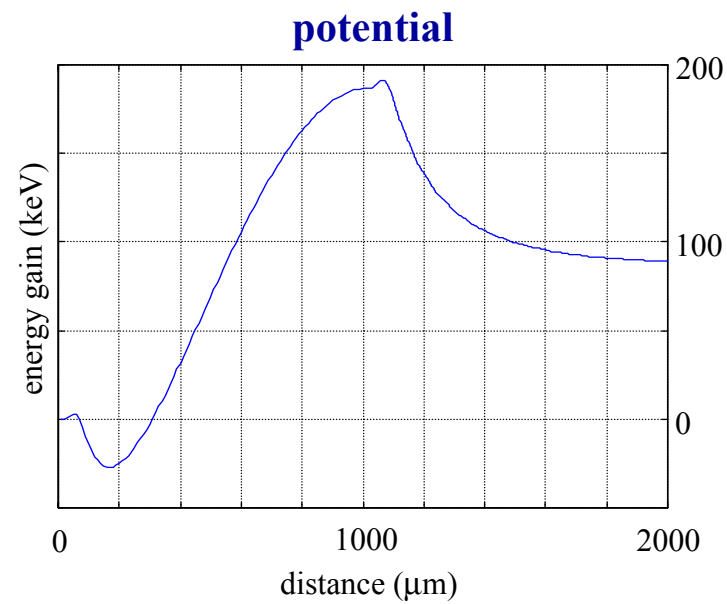
Consequences

1) loss of laser field in the accelerator cell region

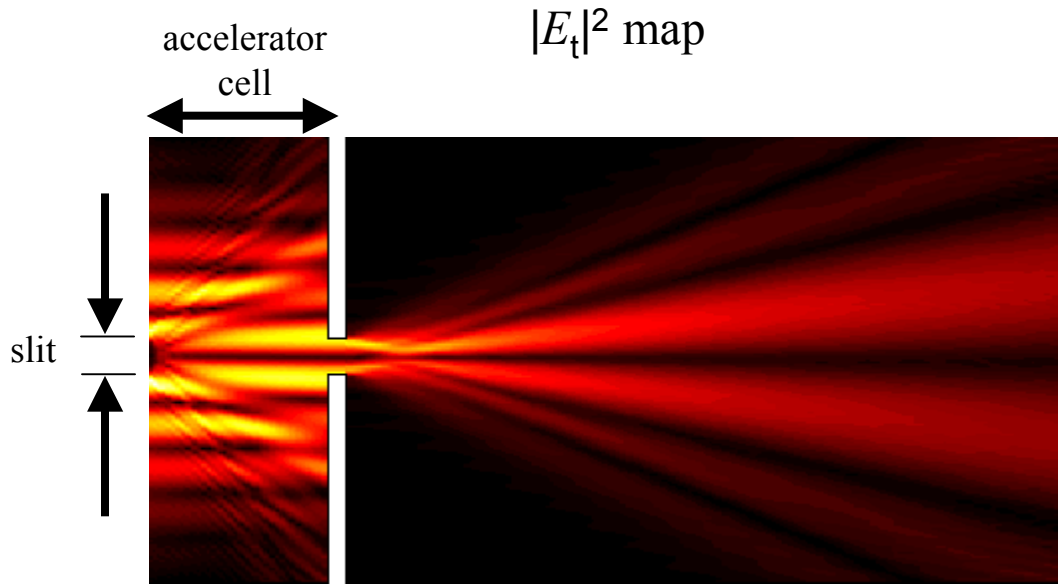
2) leakage field behind the accelerator cell

Example: slit =16 μm, ωo = 50 μm, θ = 20 mrad





$|E_t|^2$ map

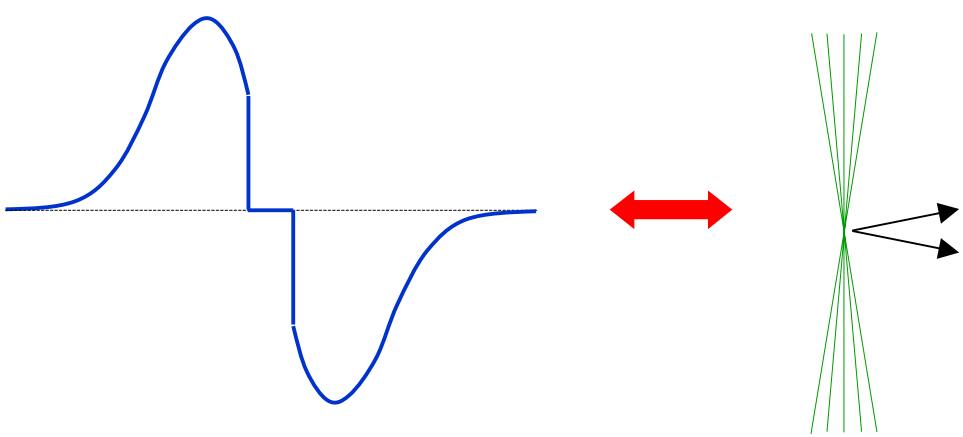


analytical expressions for crossed gaussian beams
not adequate for a real accelerator cell possessing a slit

plane-wave vector decomposition method† for
the estimate effective laser field

truncated laser field

set of plane waves



1) find the plane wave spectrum at the input plane

$$a(\alpha,\beta) \approx \frac{1}{\lambda^2} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E_x(x,y)\cdot e^{-i(kx\alpha+ky\beta)}dxdy$$

2) propagate the spectrum to the desired location

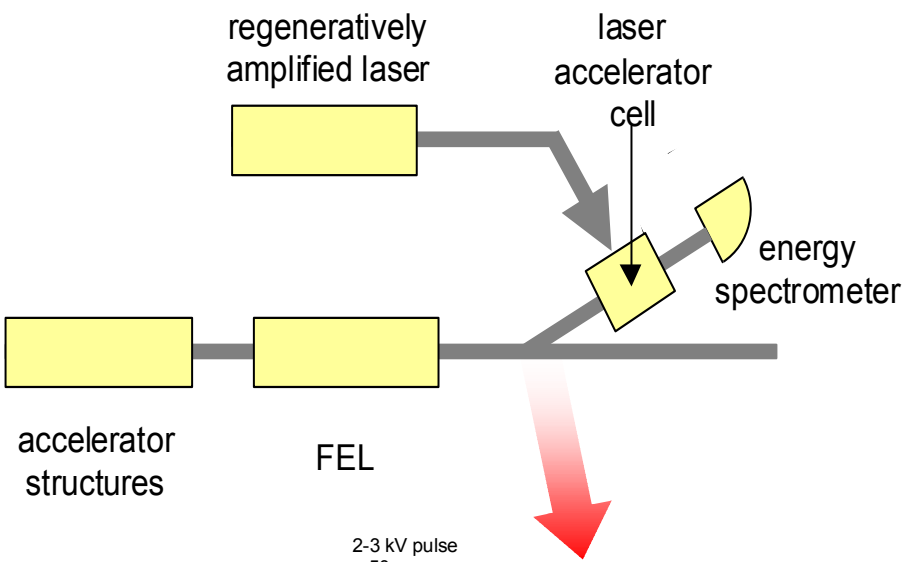
$$a_{1x}(\vec{r}) = a_{0x}(0)\cdot e^{ik(x\sin\alpha+y\sin\beta)}\cdot e^{ikz\sqrt{1-\sin^2\alpha-\sin^2\beta}}$$

3) find the longitudinal field

$$E_{oy}(x,y) = \int_{-\pi/2}^{\pi/2}\int_{-\pi/2}^{\pi/2} a_x(\alpha,\beta)\cdot\sin\alpha\cdot e^{i(kx\sin\alpha+ky\sin\beta)}$$

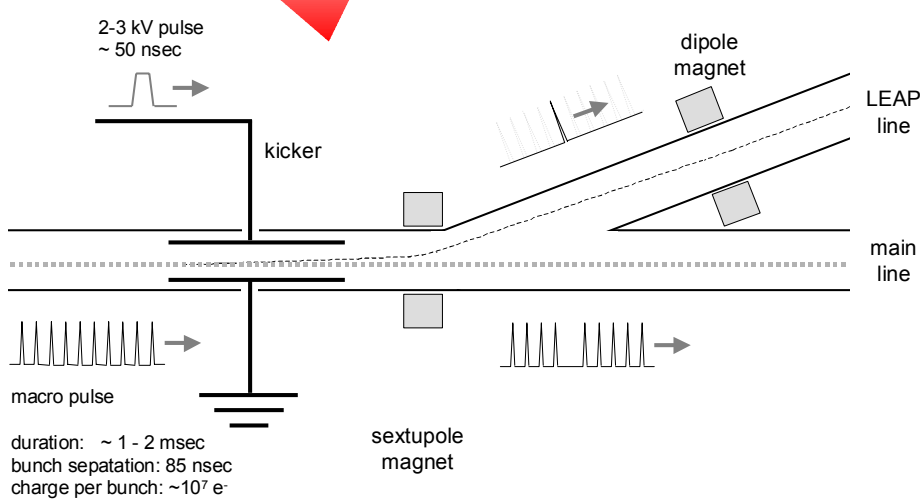
† J. Appl. Phys **50** (10) 1979, p 6120

The SCA-FEL facility



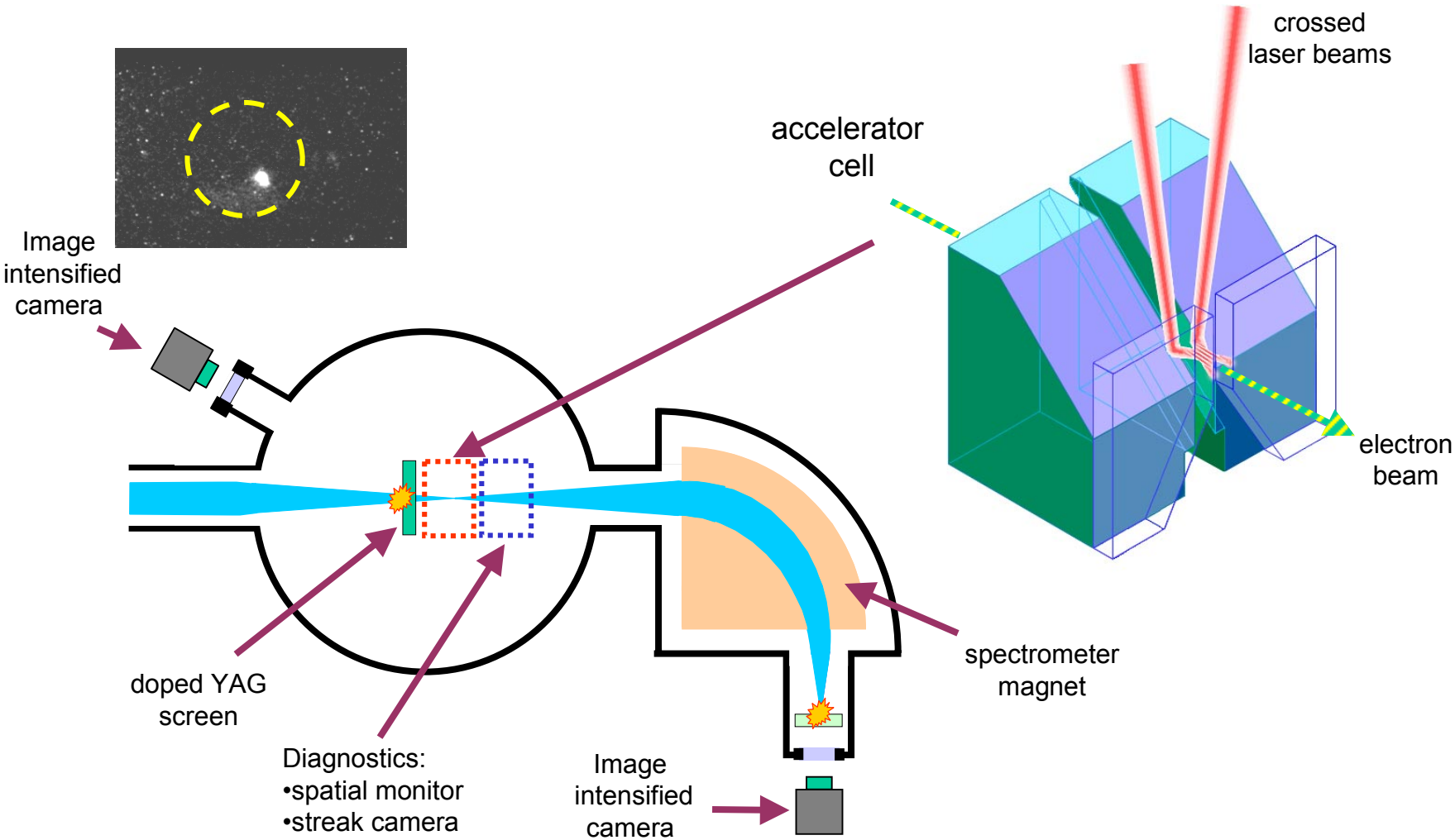
Electron and laser beam parameters

Ti:Sa amplified laser	Wavelength	800 nm
	Pulse duration	0.1 - 30 psec
	Repetition rate	10 Hz
	Energy per pulse	1.0 mJ
	FWHM spot size	130 μm
SCA electron beam	Energy	32 MeV
	Repetition rate	10 Hz
	Macropulse period	0.1 sec
	Micropulse period	85 nsec
	Bunch length	2 psec
	FWHM energy spread	16 keV
	Electrons per bunch	10^7
	Invariant emittance	8π mm-mrad

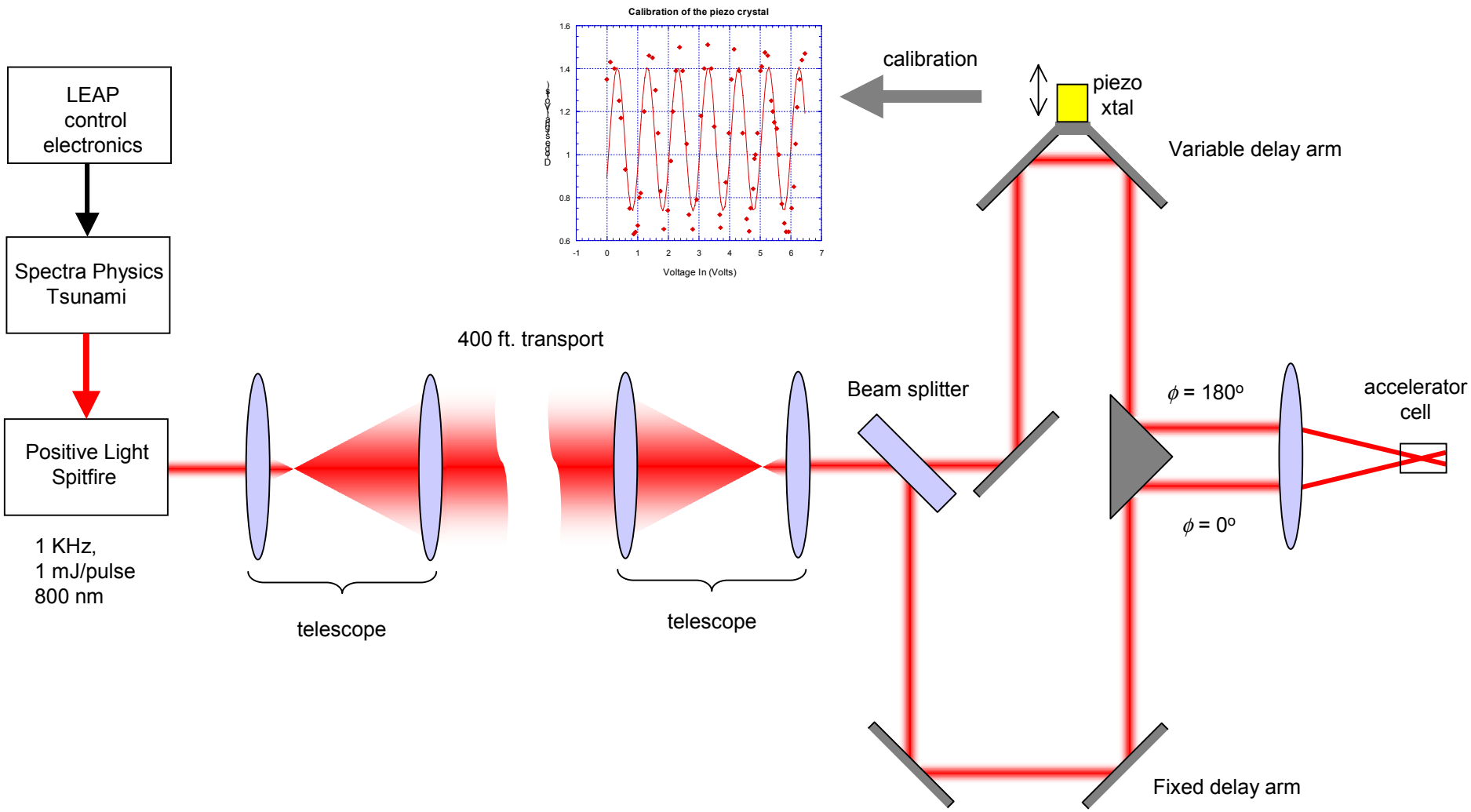


The LEAP experiment

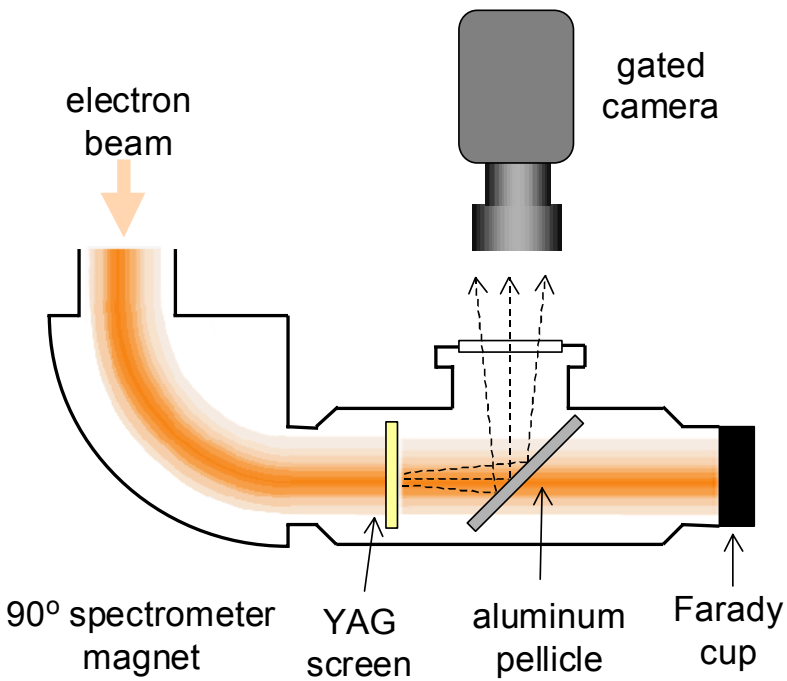
Proof of principle experiment with one accelerator cell

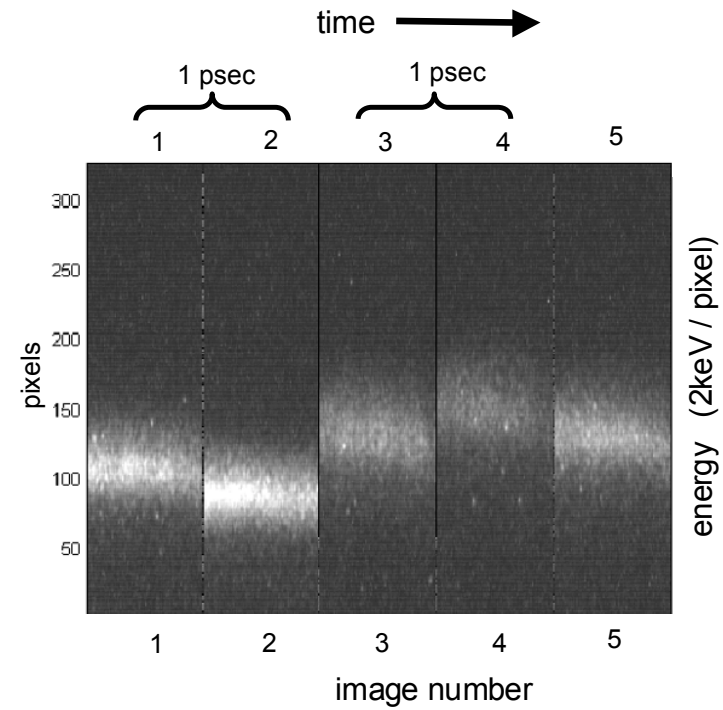


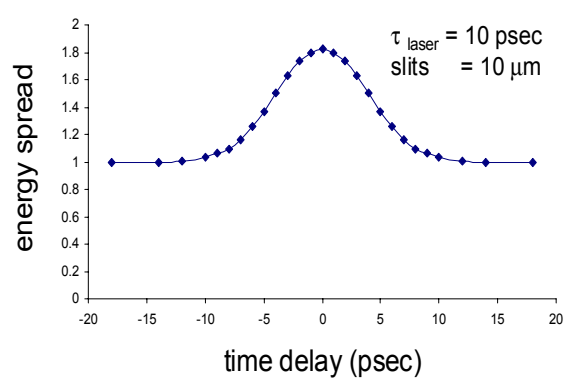
The optical transport

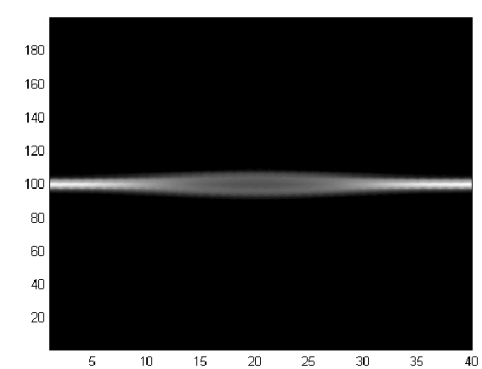


The data collection

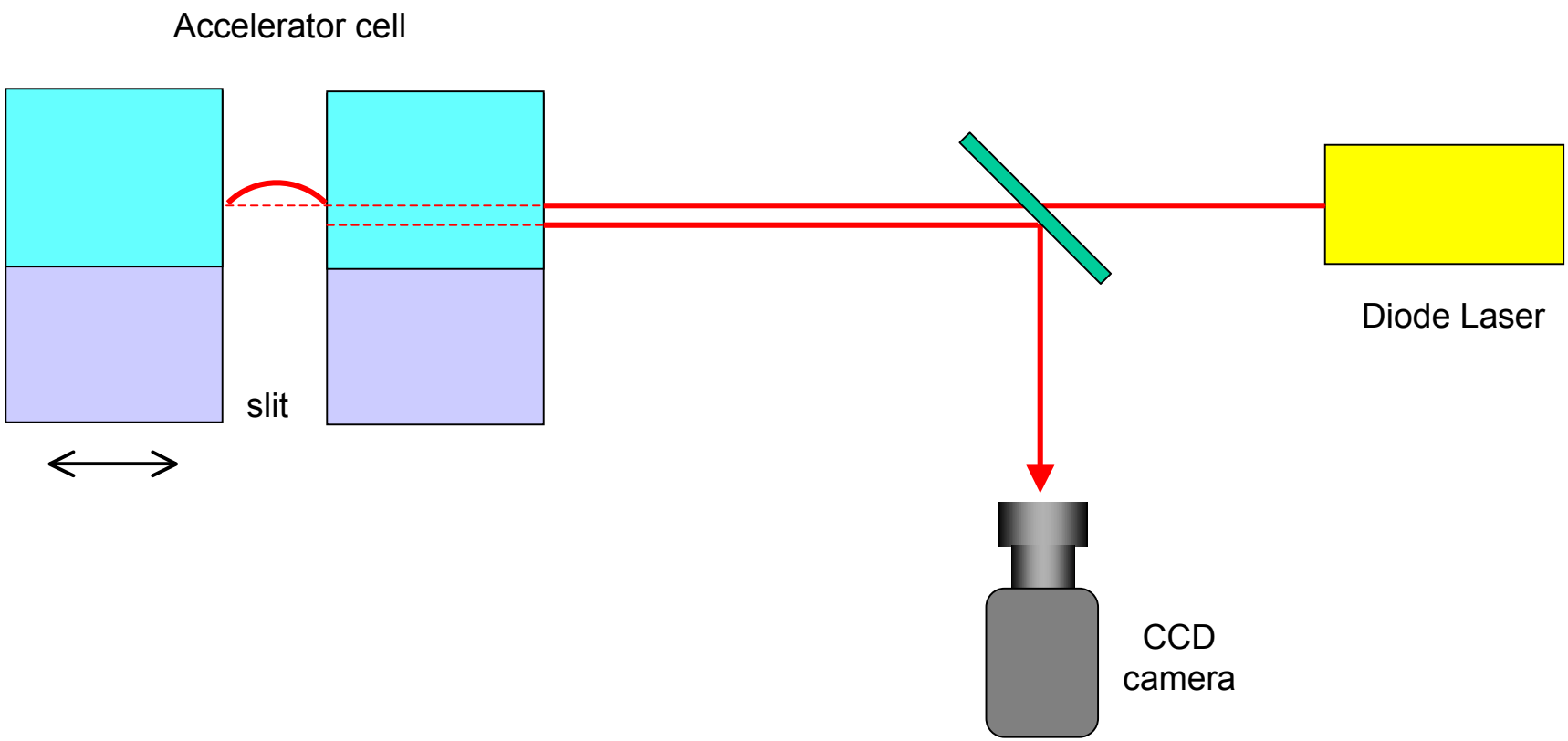




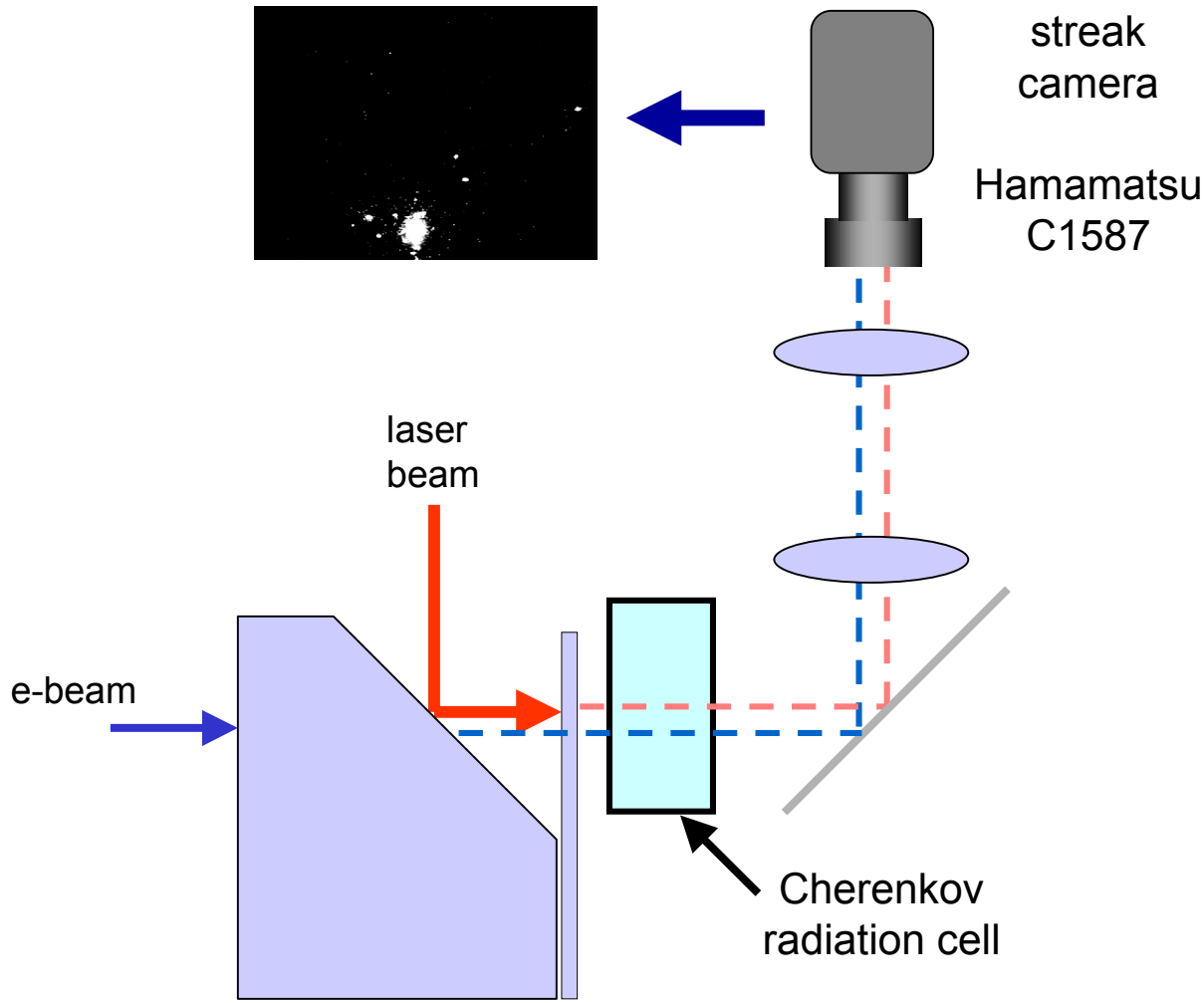




The slit width monitor

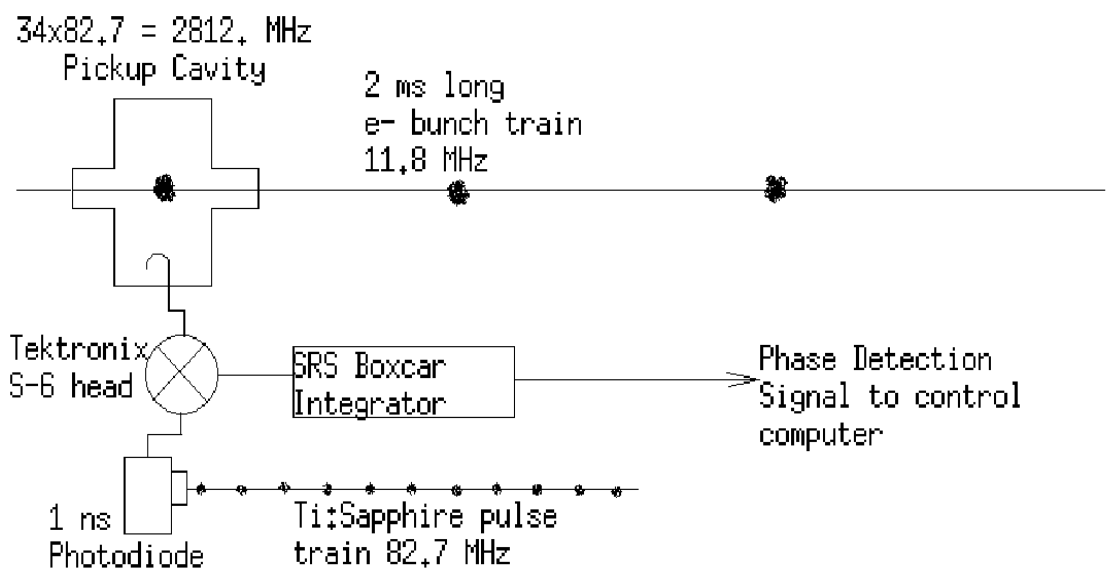


The timing monitor

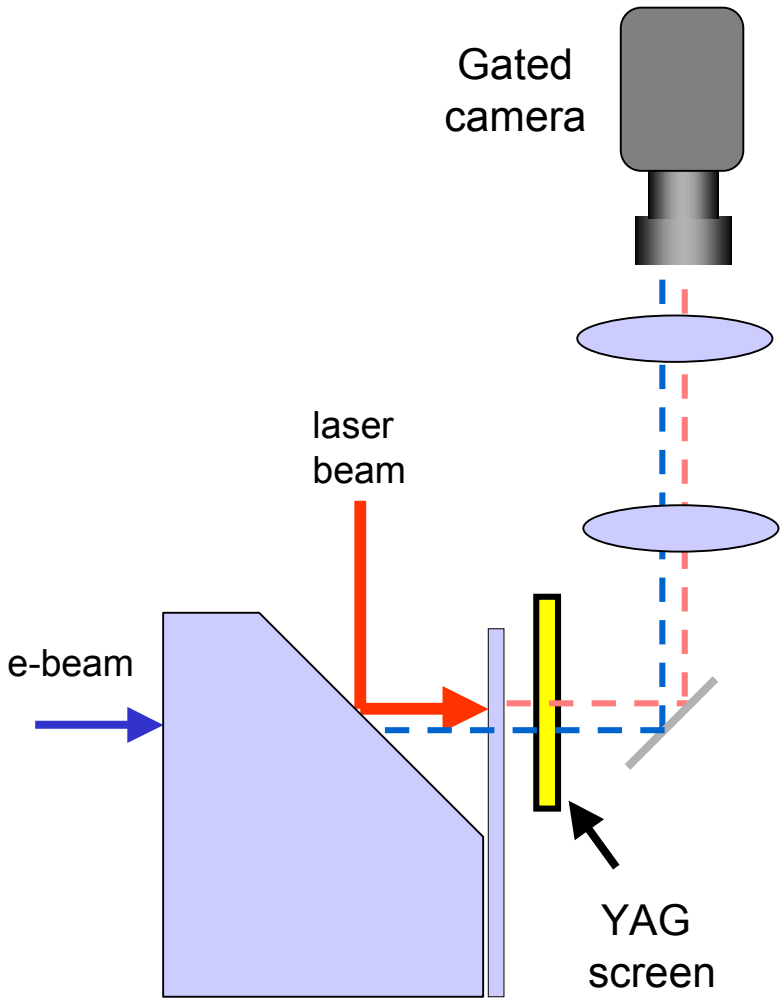


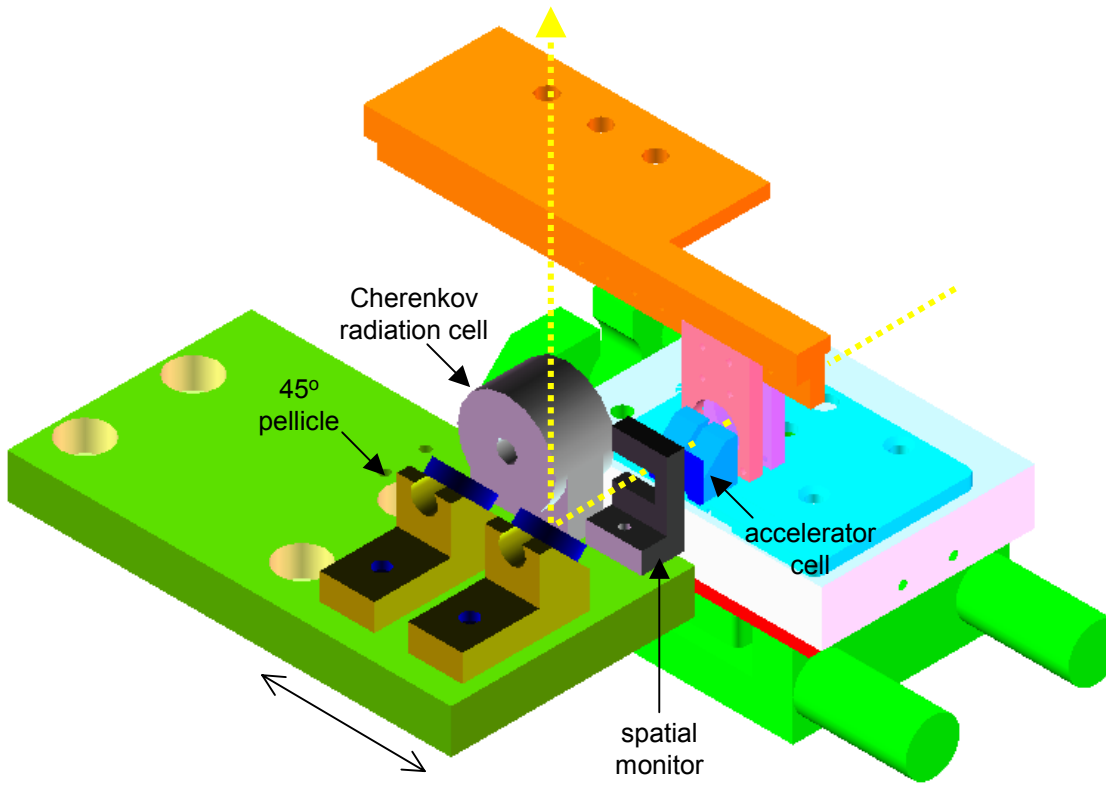
The timing monitor (cont'd)

Phase detection between the electron beam and photodiode signal or reference 1 GHz R.F. signal

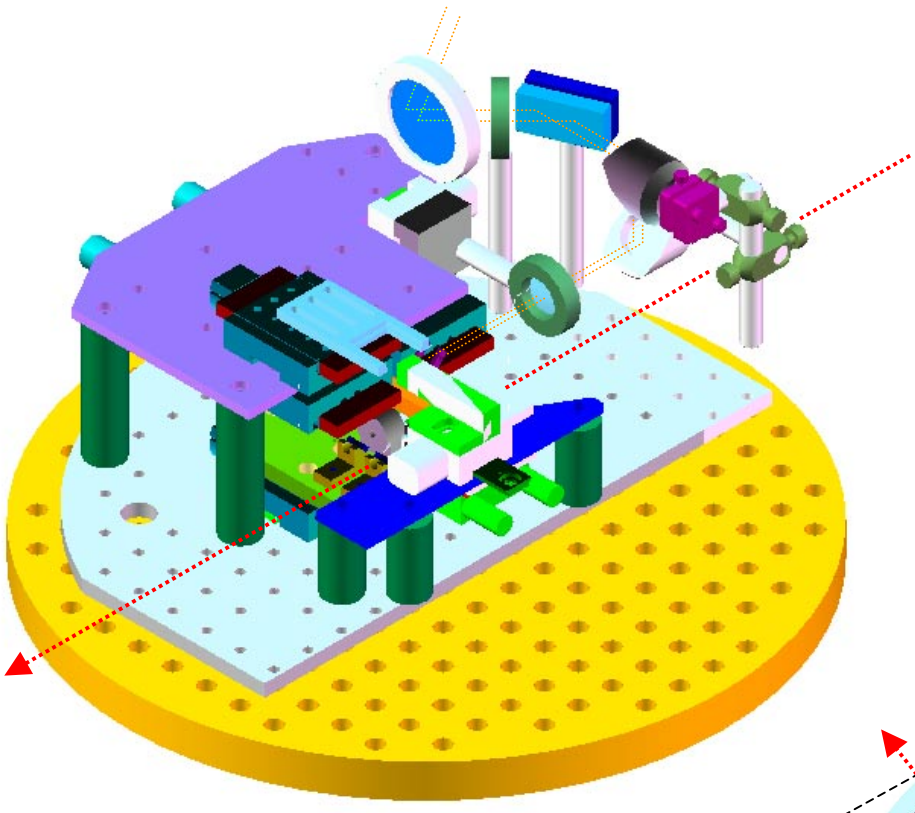


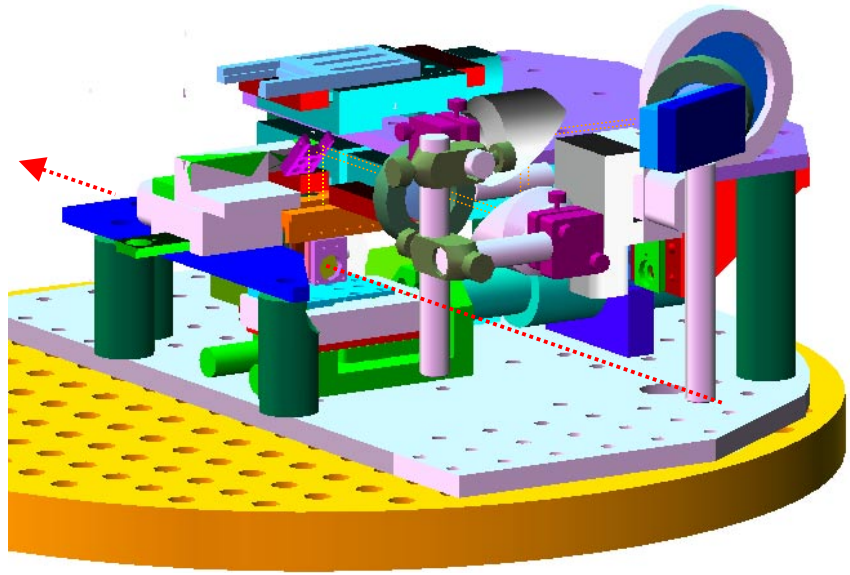
The spatial monitor

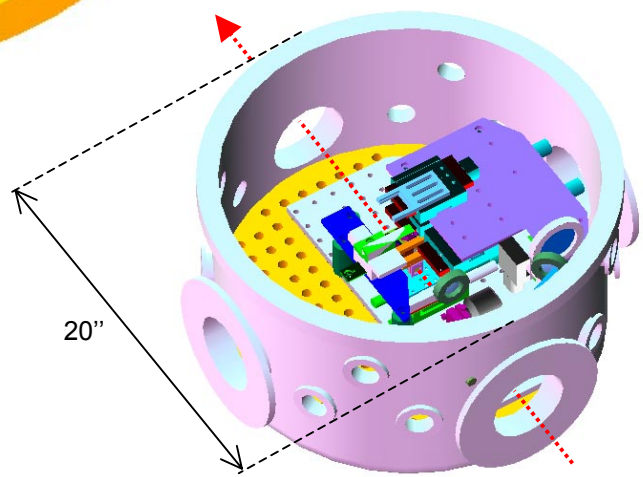




The interaction chamber





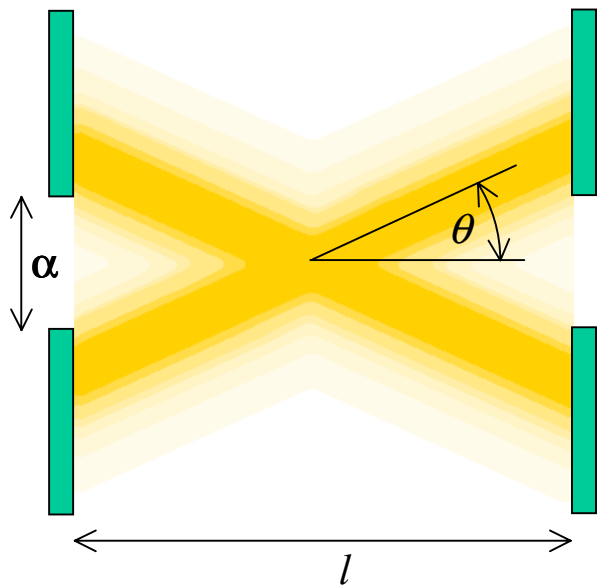


Choice of parameters

Maximize laser acceleration effect

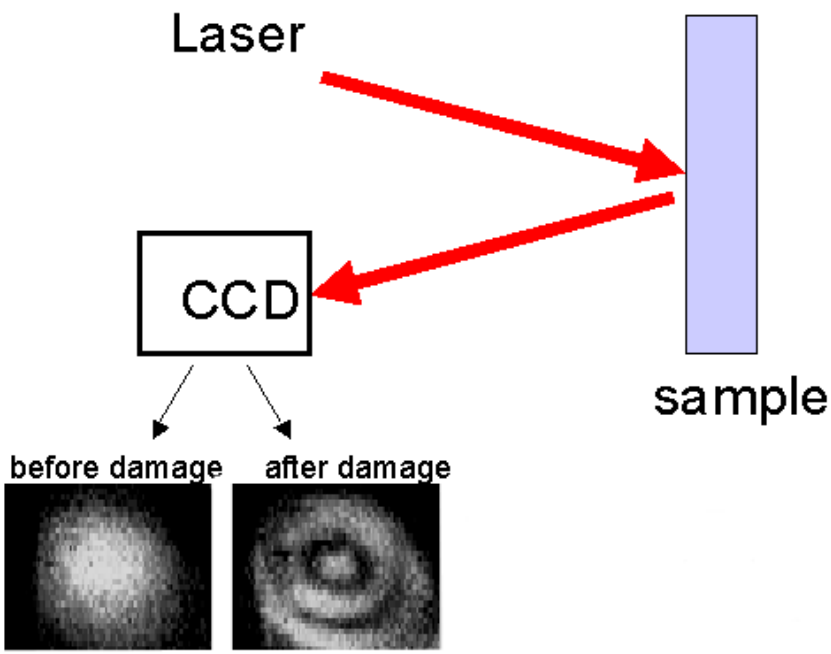
optimize

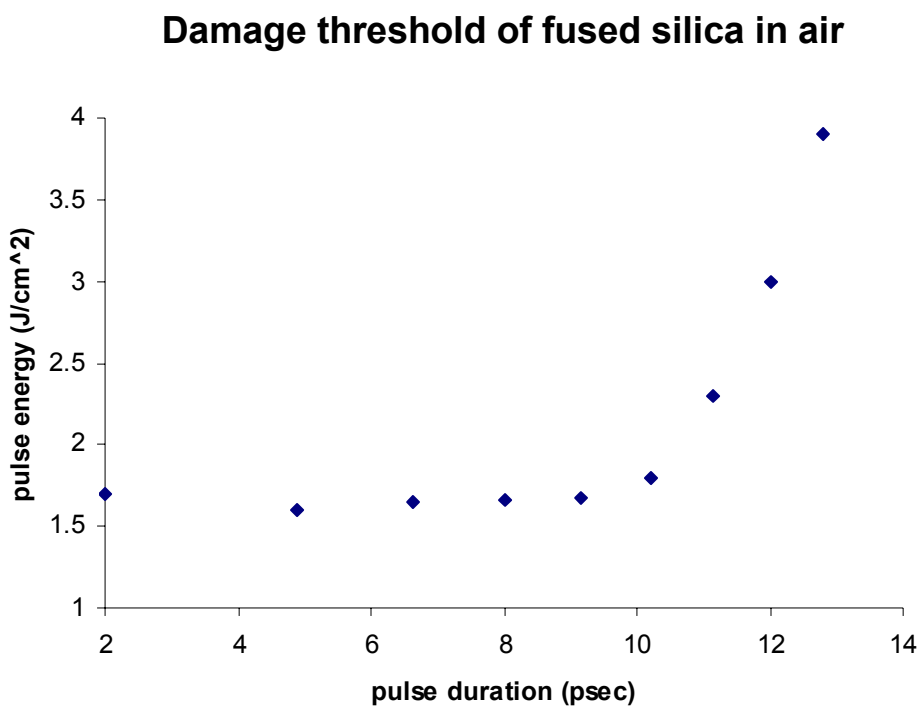
- laser power and pulse duration
  power ~ 0.5 J/cm^2
  T_{laser} ~ 5-10 psec
- laser beam crossing angle
  23 mrad
- accelerator cell length
  800 μm
- slit width
  < 10 μm



Damage threshold of dielectric materials

For pulses below 10 psec laser damage threshold is constant

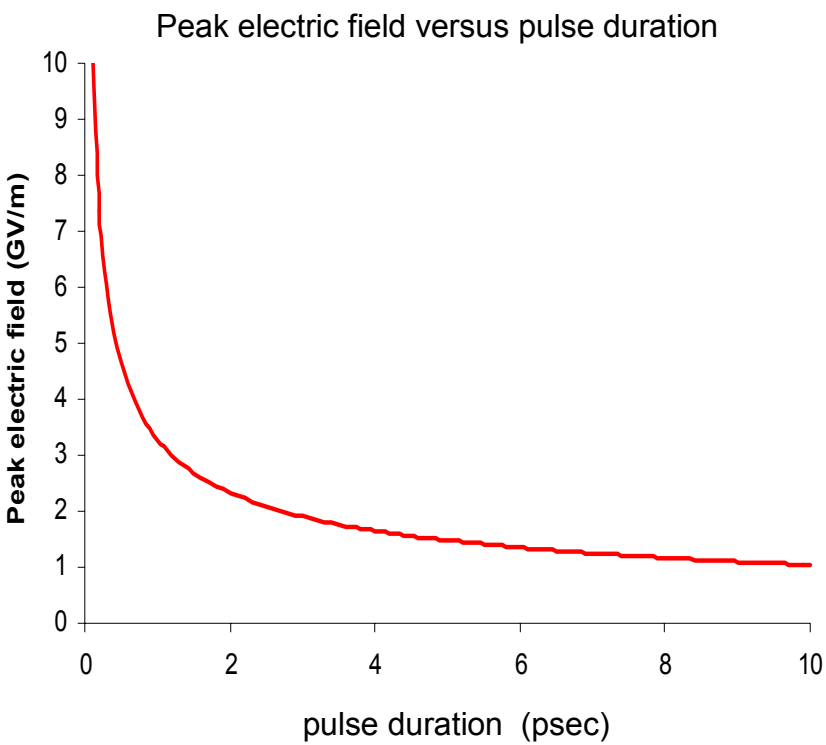


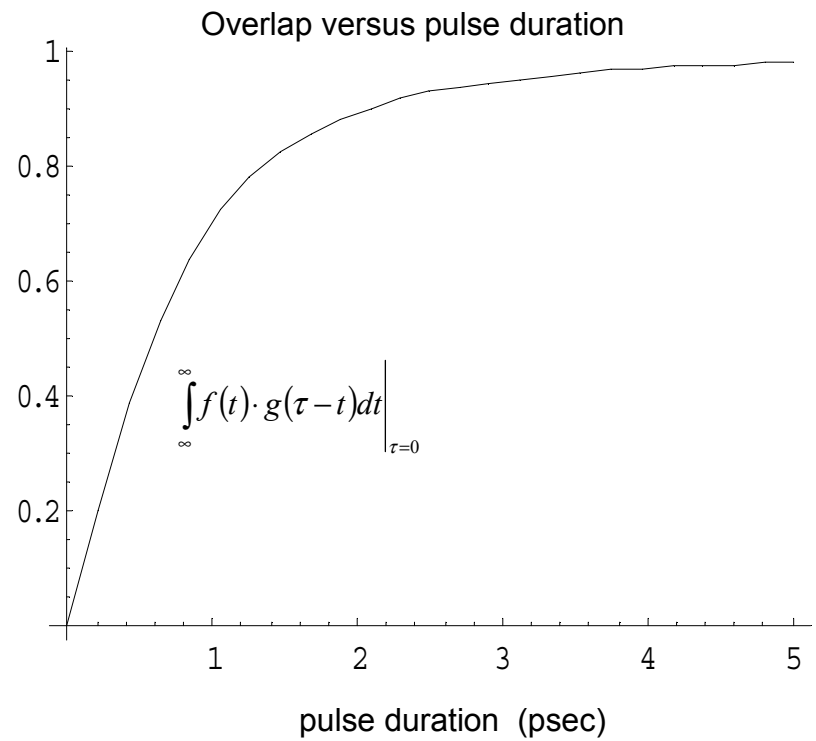


$$U_{\text{damage}} \approx 2\text{J/cm}^2$$

J. Appl. Phys **85**,6803 (1999)

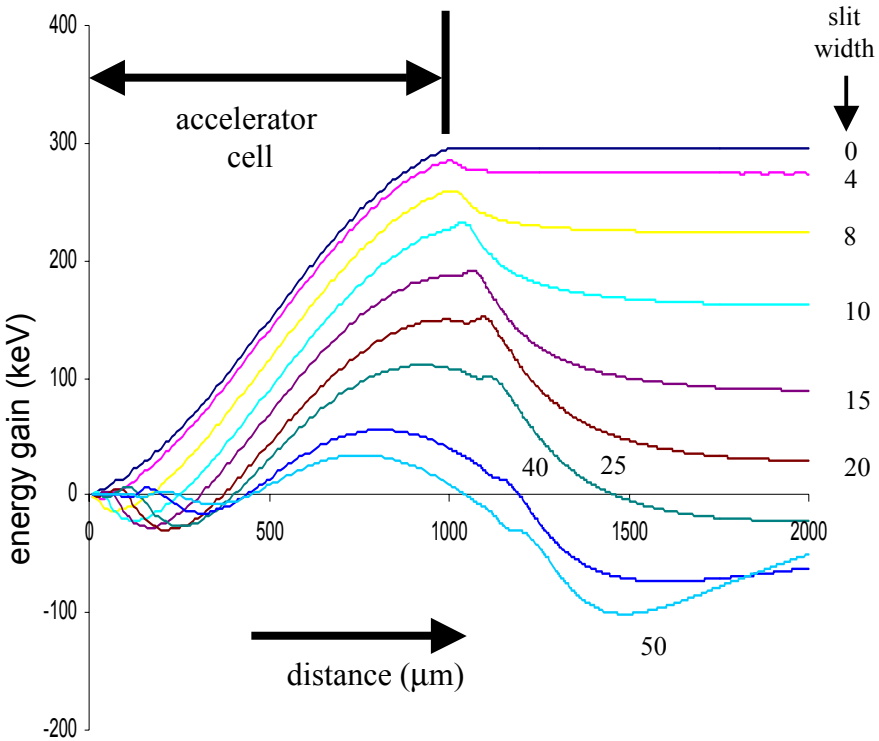
laser peak field and pulse duration



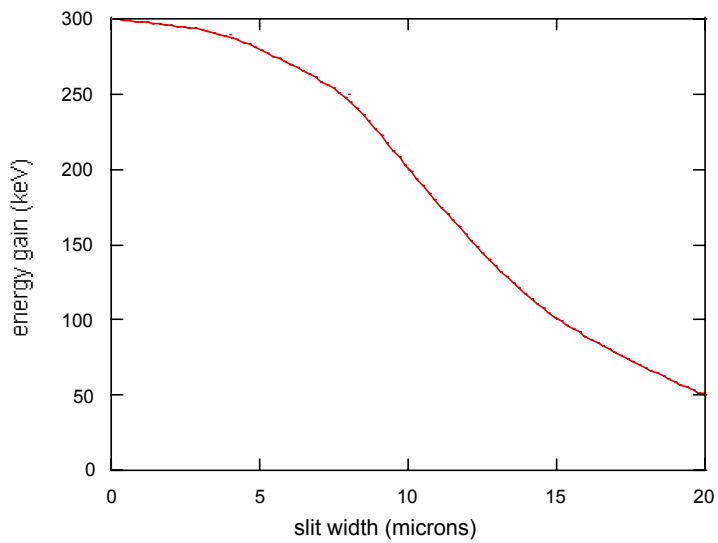


Slit width

Energy gain curves

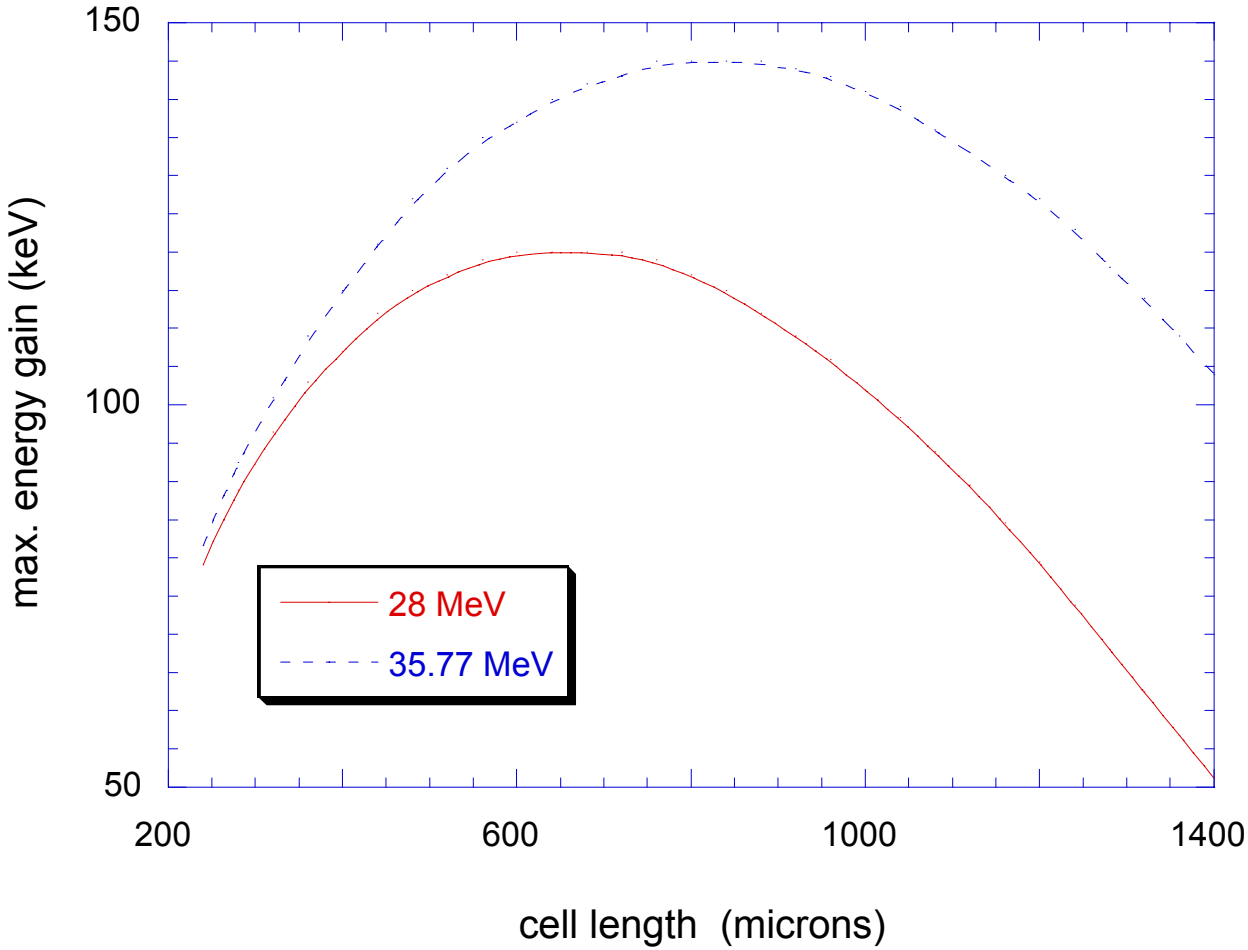


Energy gain versus slit width



With a 10 μm slit ~ 30% of the energy gain is lost

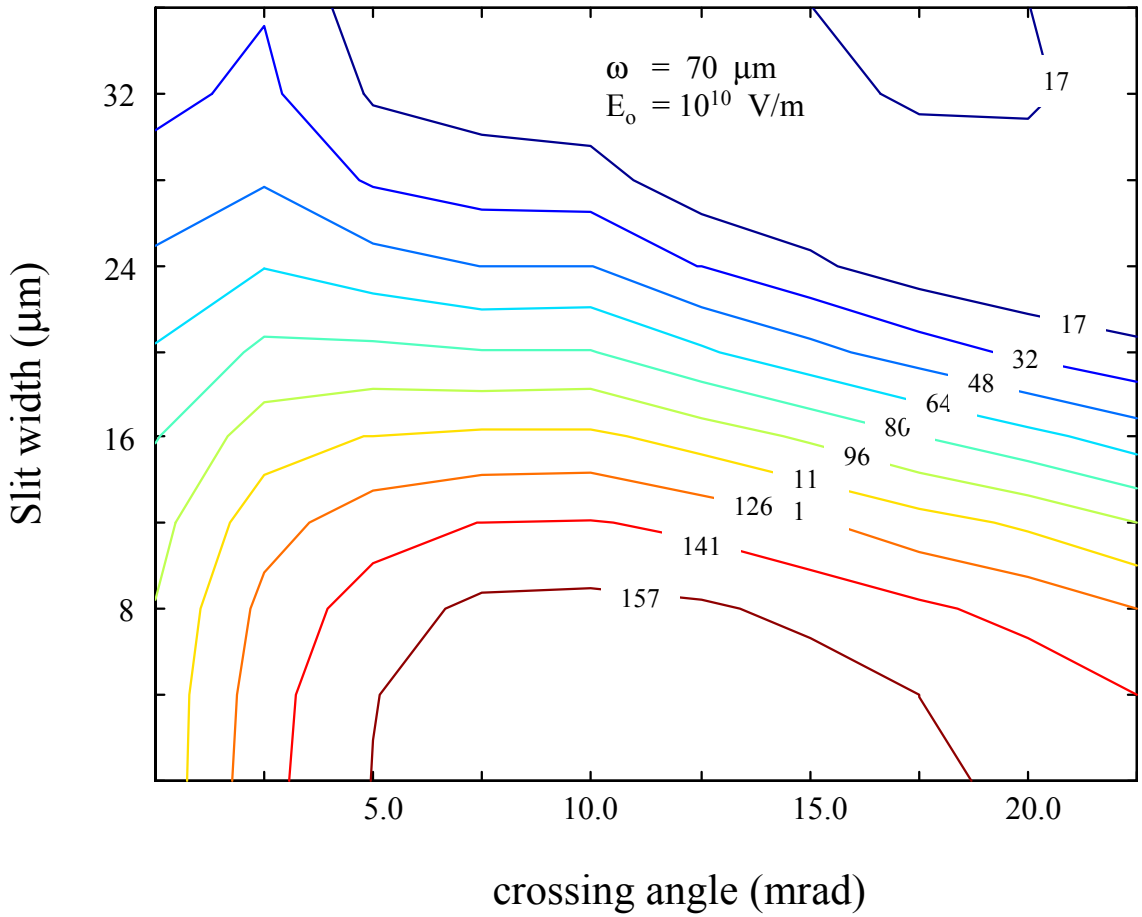
Cell length



The optimum cell length is ~ 800 μm

Laser beam crossing angle

Contour map of angle, slit-width combinations



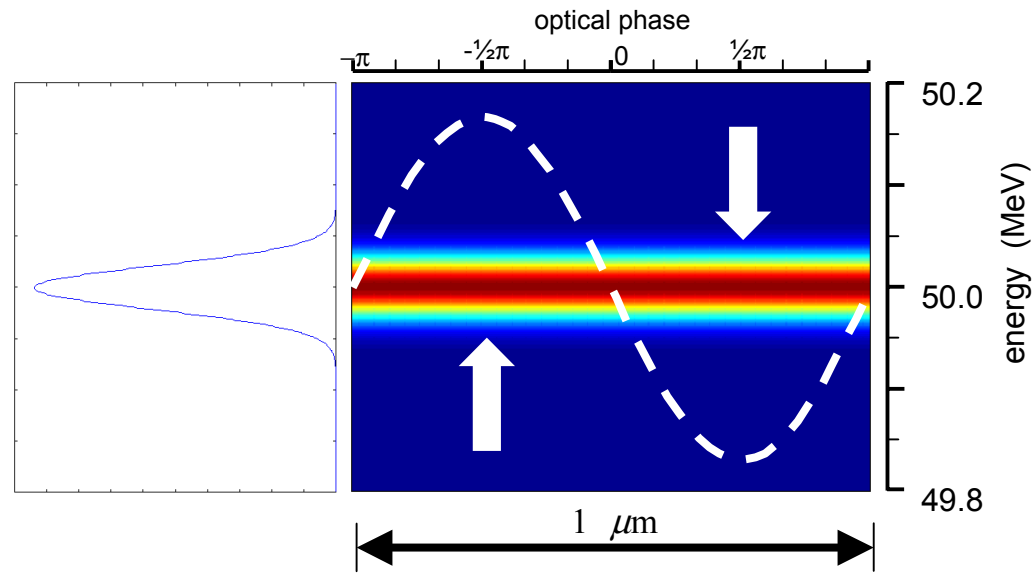
The optimum laser crossing angle is ~ 23 mrad

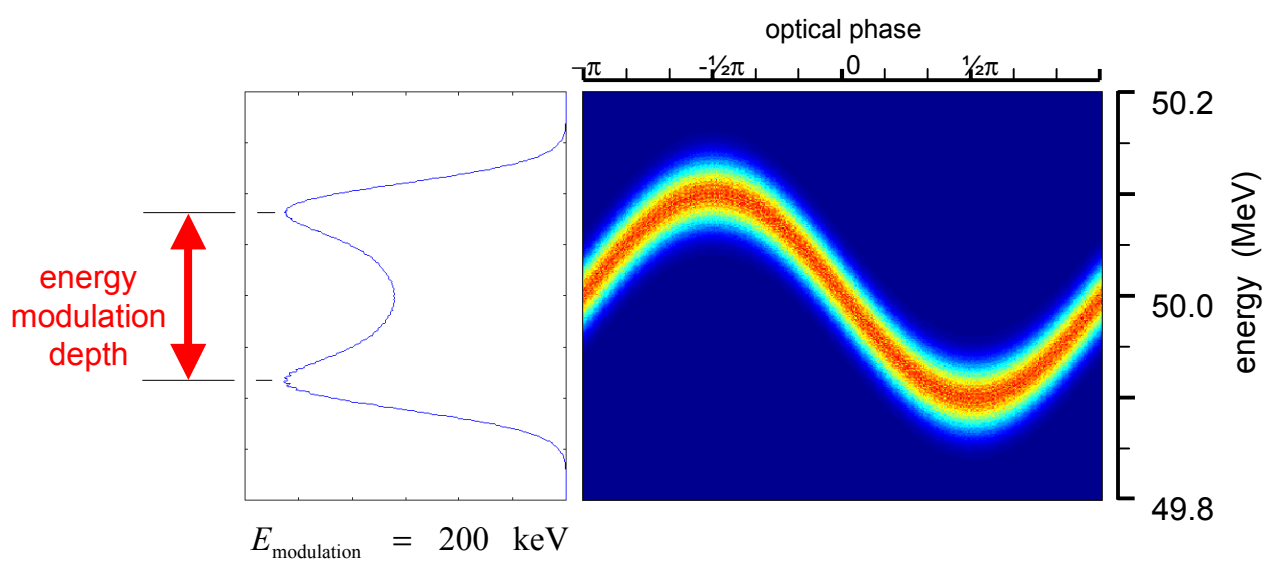
Expected spectrometer images

The electron beam is not optically bunched

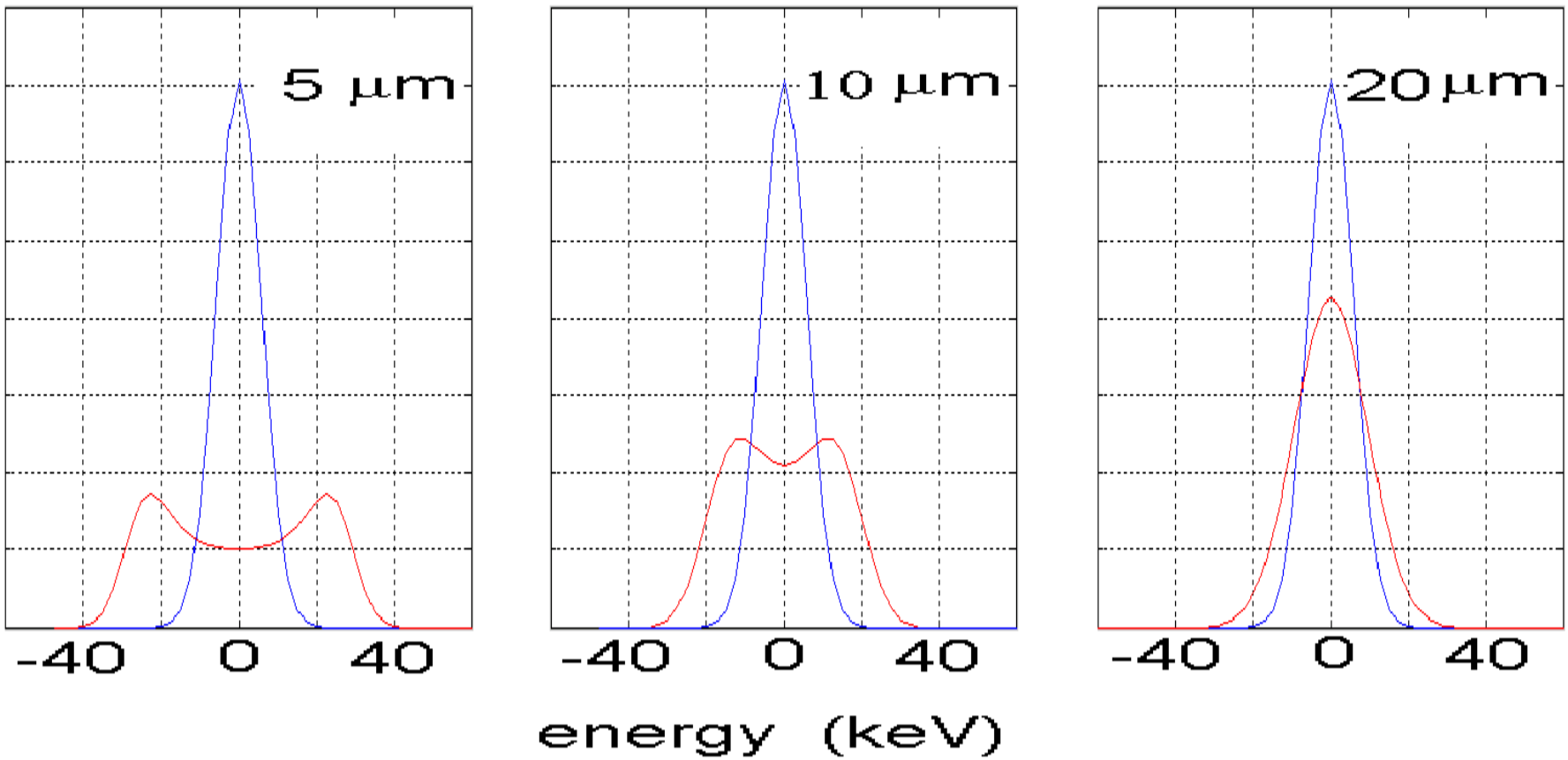
$\lambda_{\text{laser}} \sim 1\mu\text{m}$ $\quad l_{\text{bunch}} \sim 1\text{mm}$

The electron beam samples all optical phases of the laser field. Both acceleration and deceleration are expected



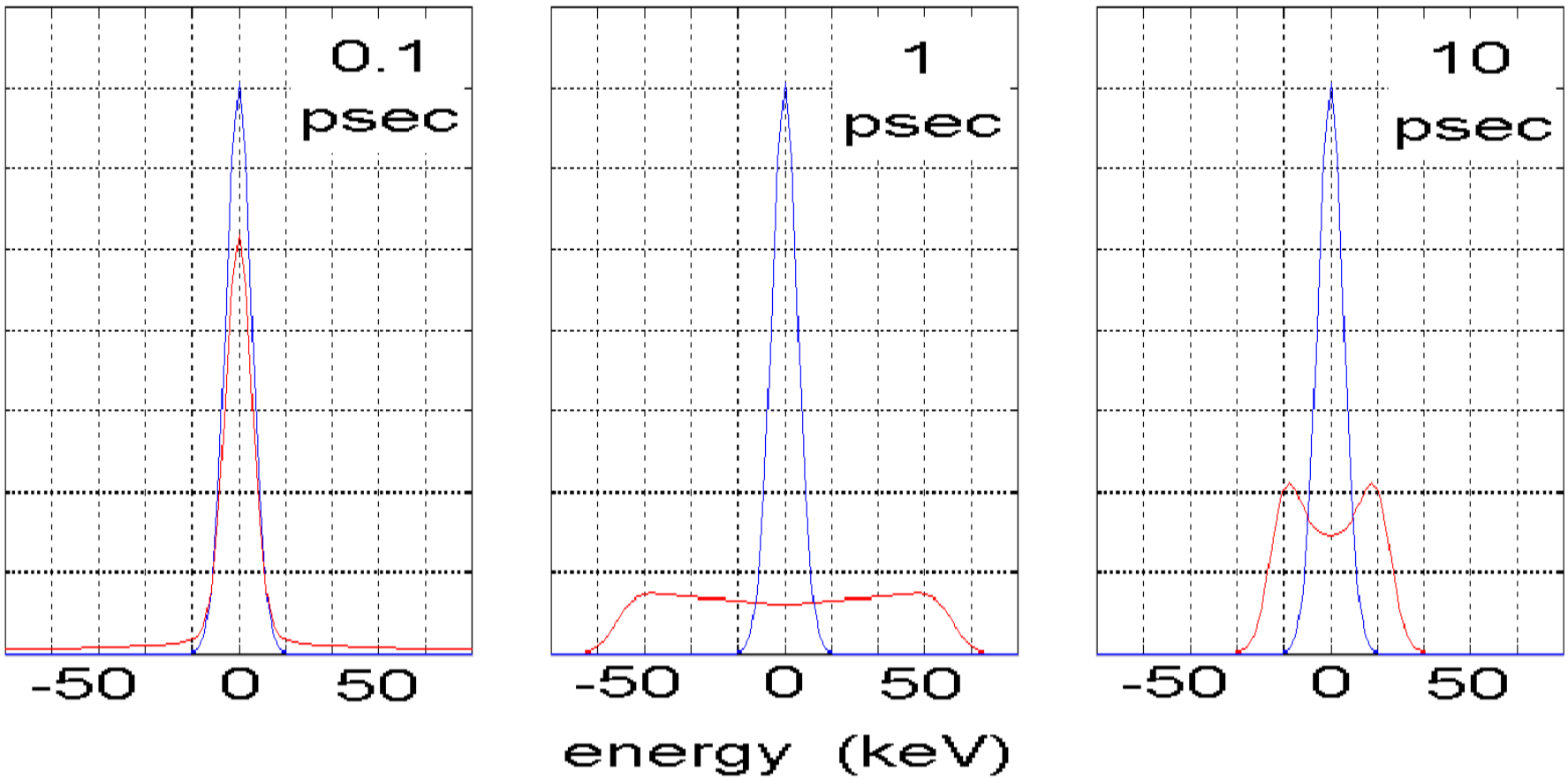


Effect from the slit width



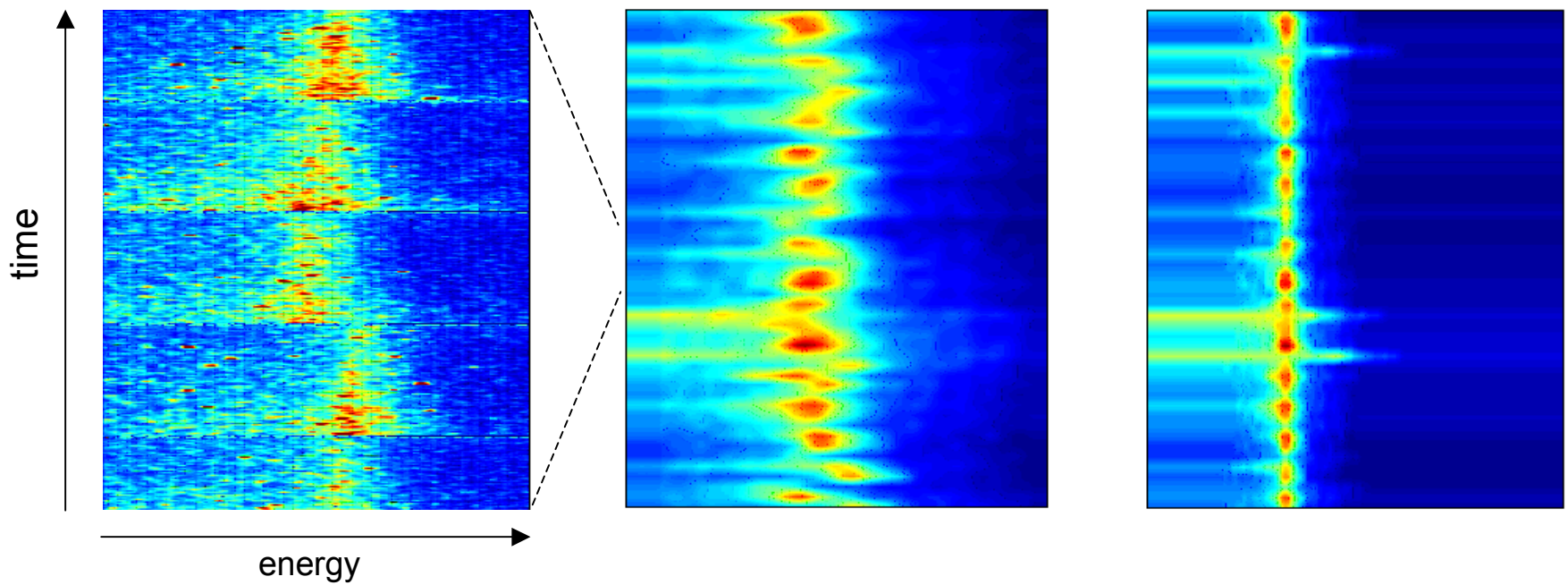
5 psec laser pulse
1 psec electron beam

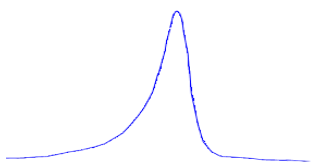
Effect of the laser pulse duration



5 μm slits
1 psec electron beam

Observed spectrometer images

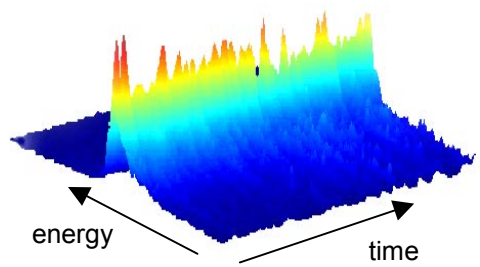




Generation of energy profile sequence

Centering and rejection of peaks

average profile per time step

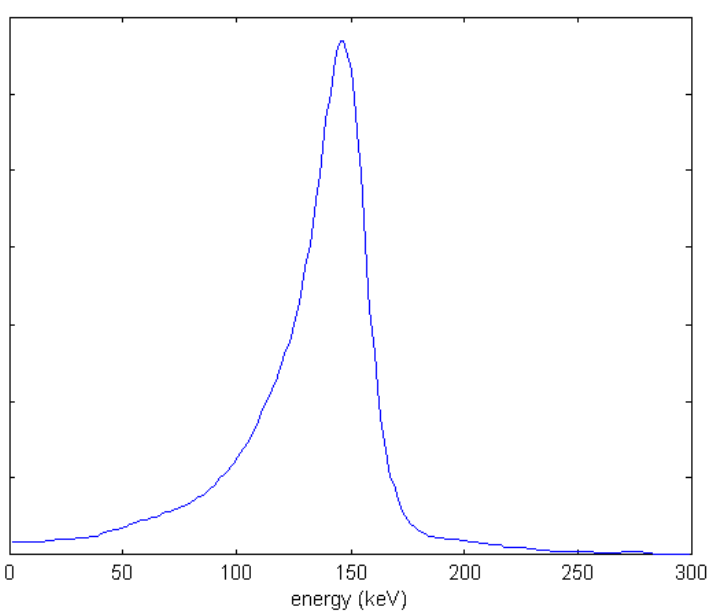


Observed spectrometer images

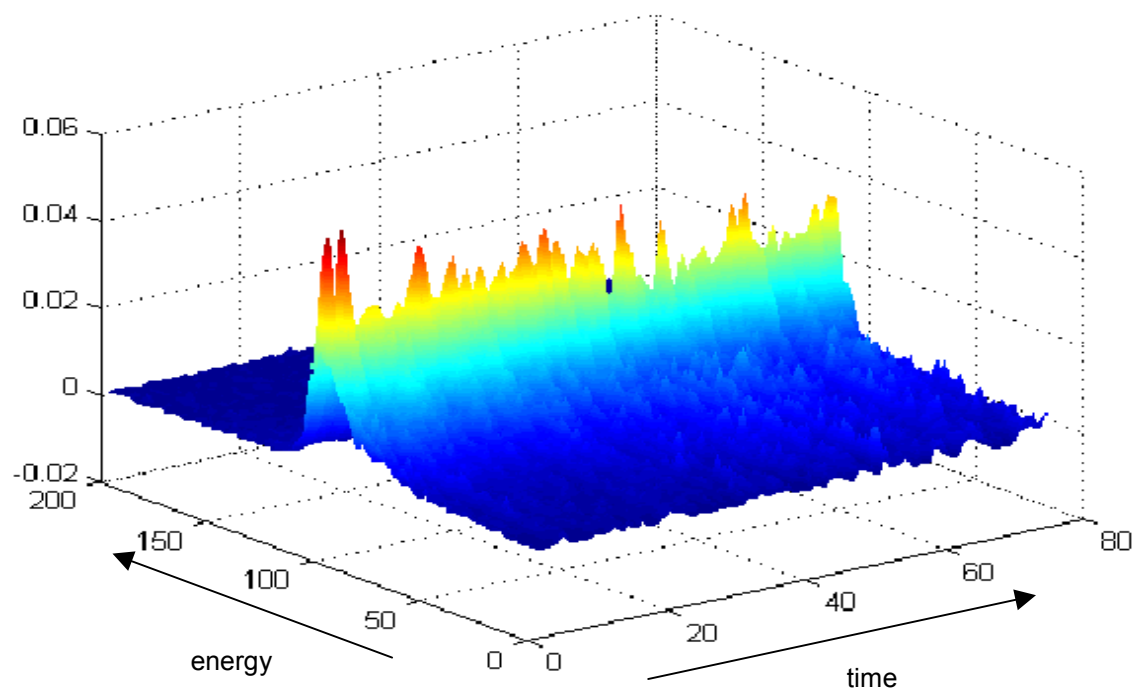
run 0261.dat

λ	800	nm
laser Spot size	250	μm FWHM
pulse energy	0.5	mJ/pulse
laser pulse duration	1.0	psec FWHM
laser crossing angle	23	mrad
slit width	5.0	μm
accelerator cell length	800	μm
electron beam γ	63	
e-beam pulse duration	5	psec

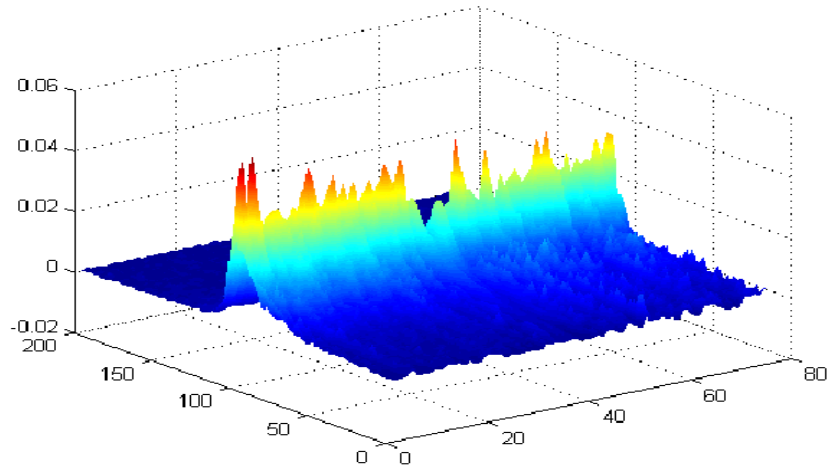
Single energy profile



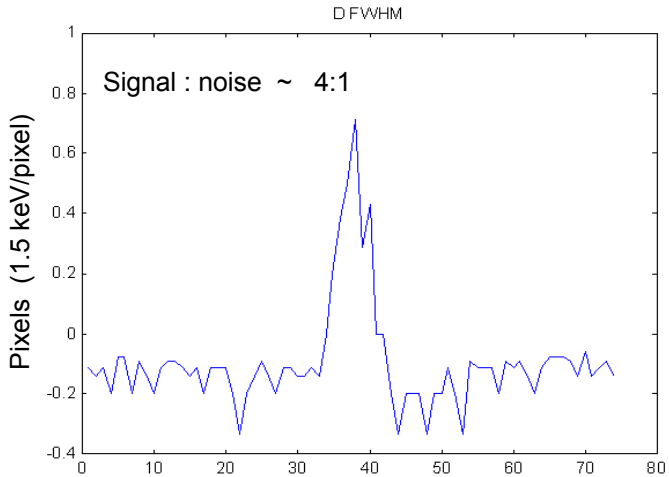
energy profile sequence



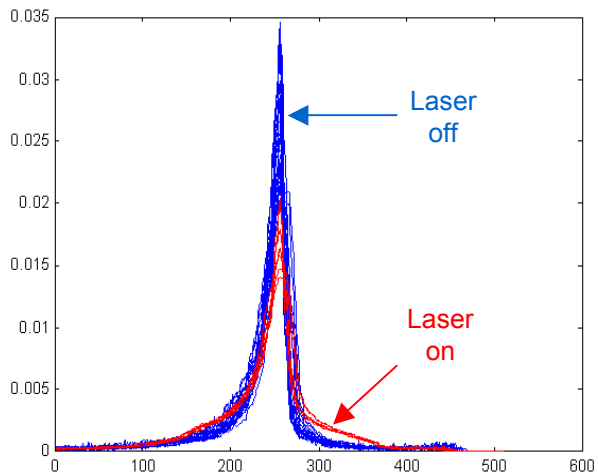
Expected laser effect on the energy spectrum



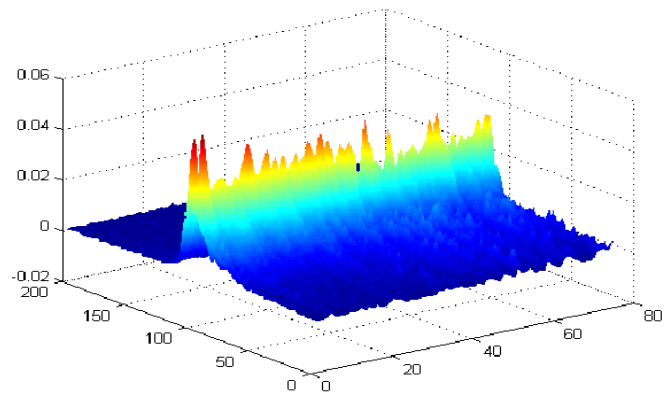
energy profile sequence



Deviation of the full width-half max from the average full width half max. of the energy profile



Position jitter
and
poor overlap



Present situation

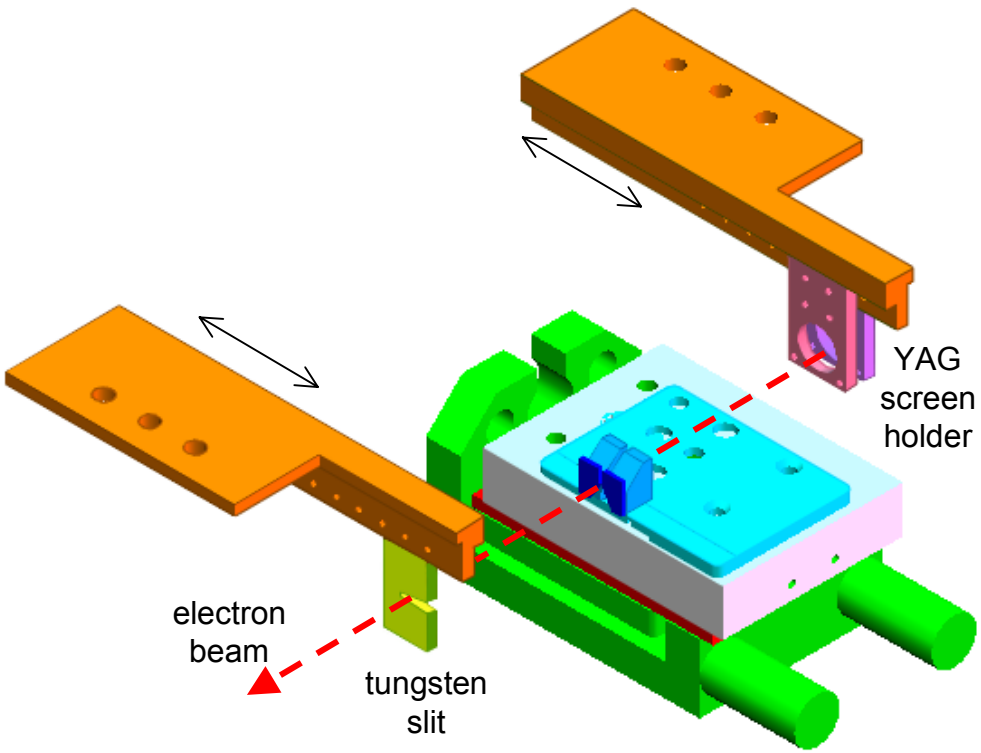
Achievements

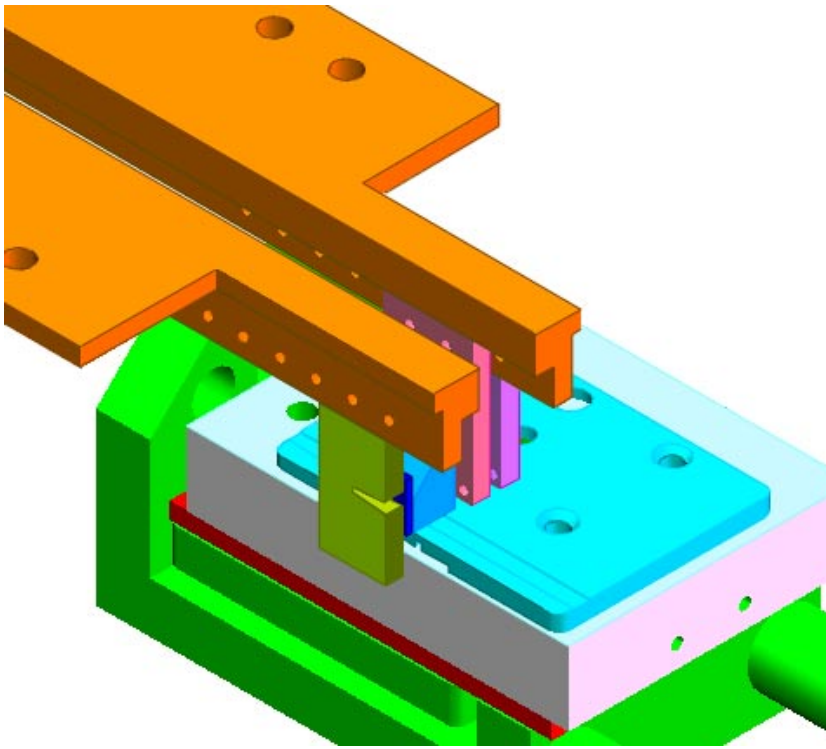
1) Detection and characterization of single e-beam bunches
2) Spatial Overlap
3) Timing overlap
4) Transmission through a 5 μm slit

Problems / challenges

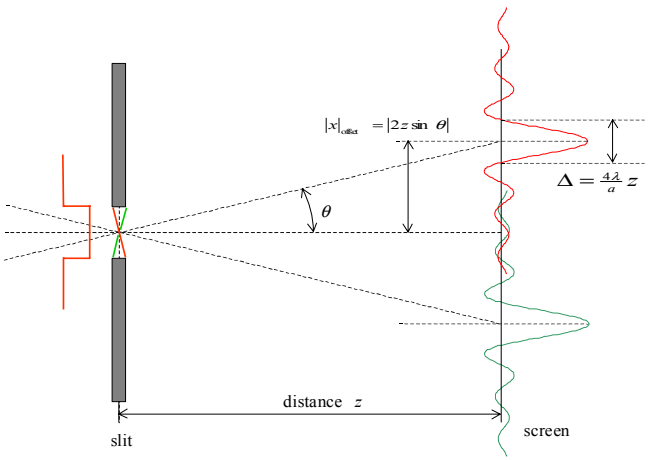
1) Lack of knowledge of electric field inside the accelerator cell
2) Beam position jitter

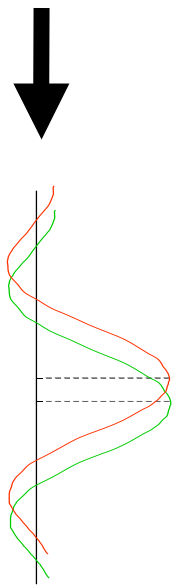
Position filter for the electron beam

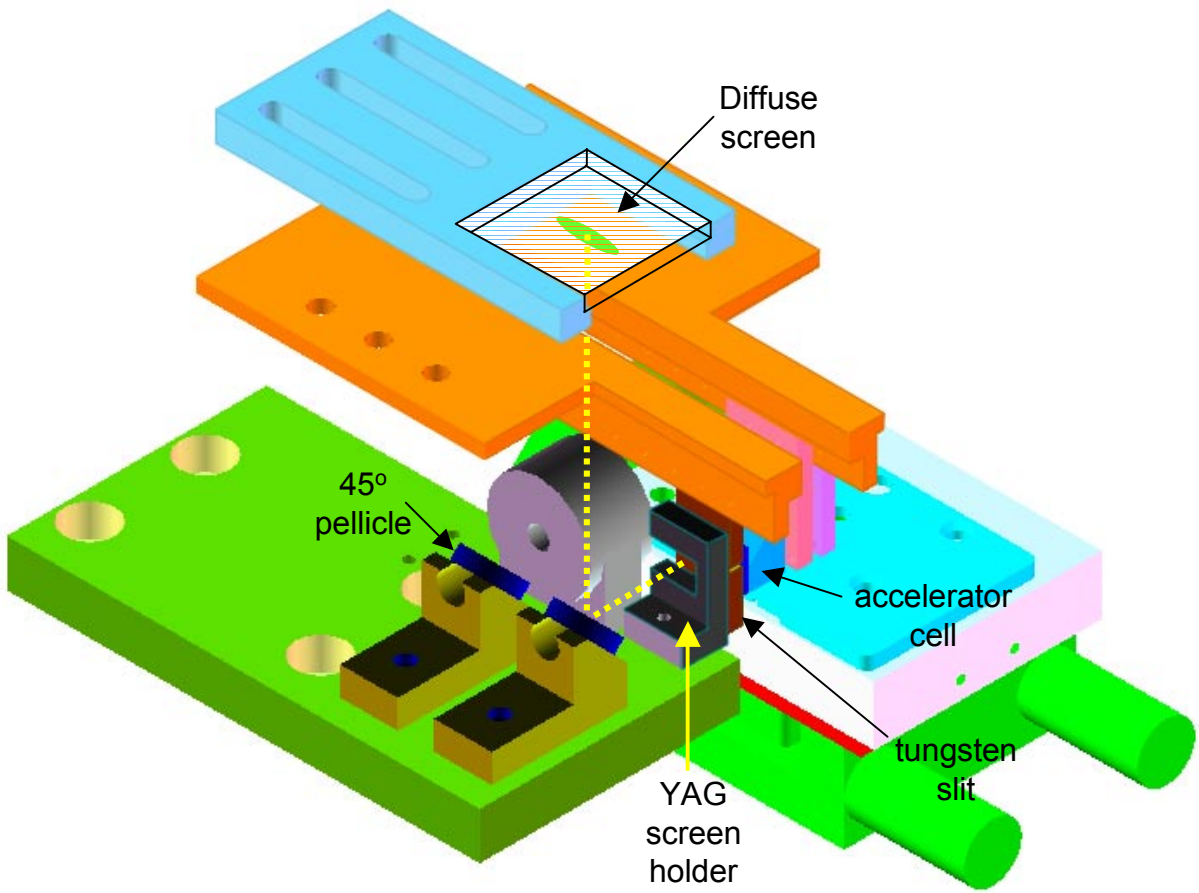




Laser electric field monitor



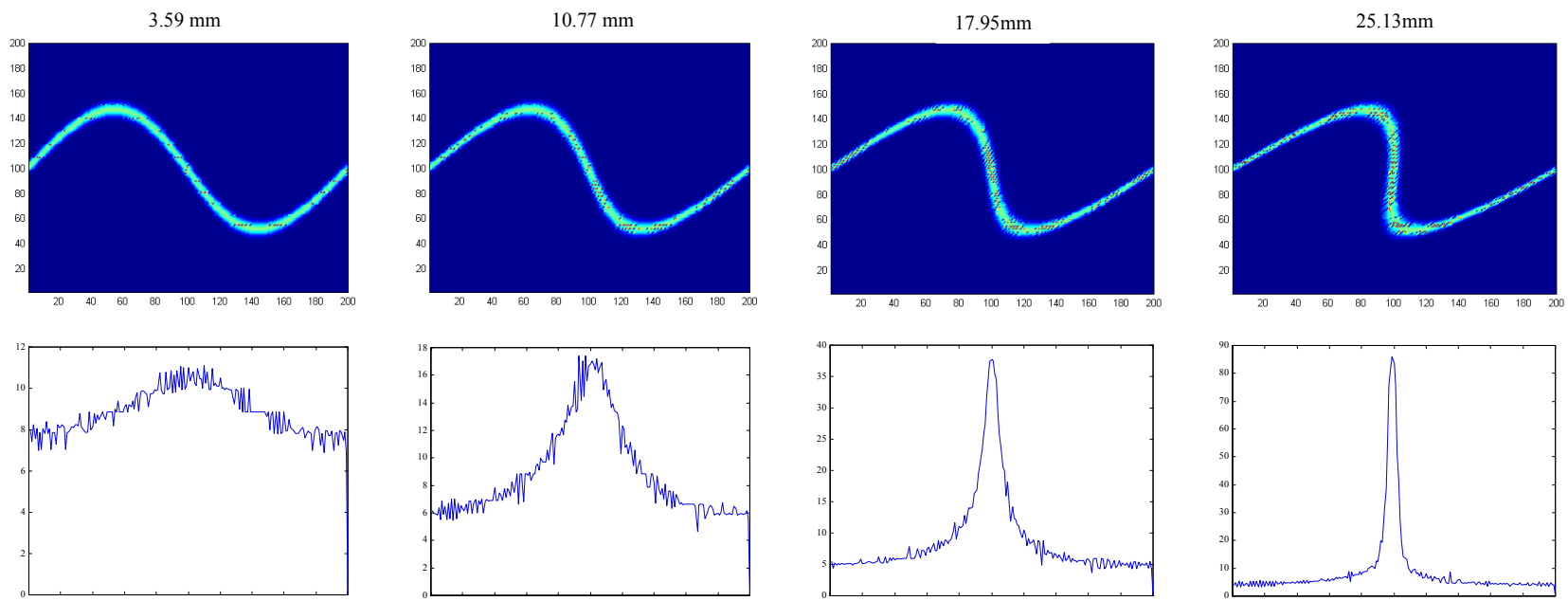




Future Experiments

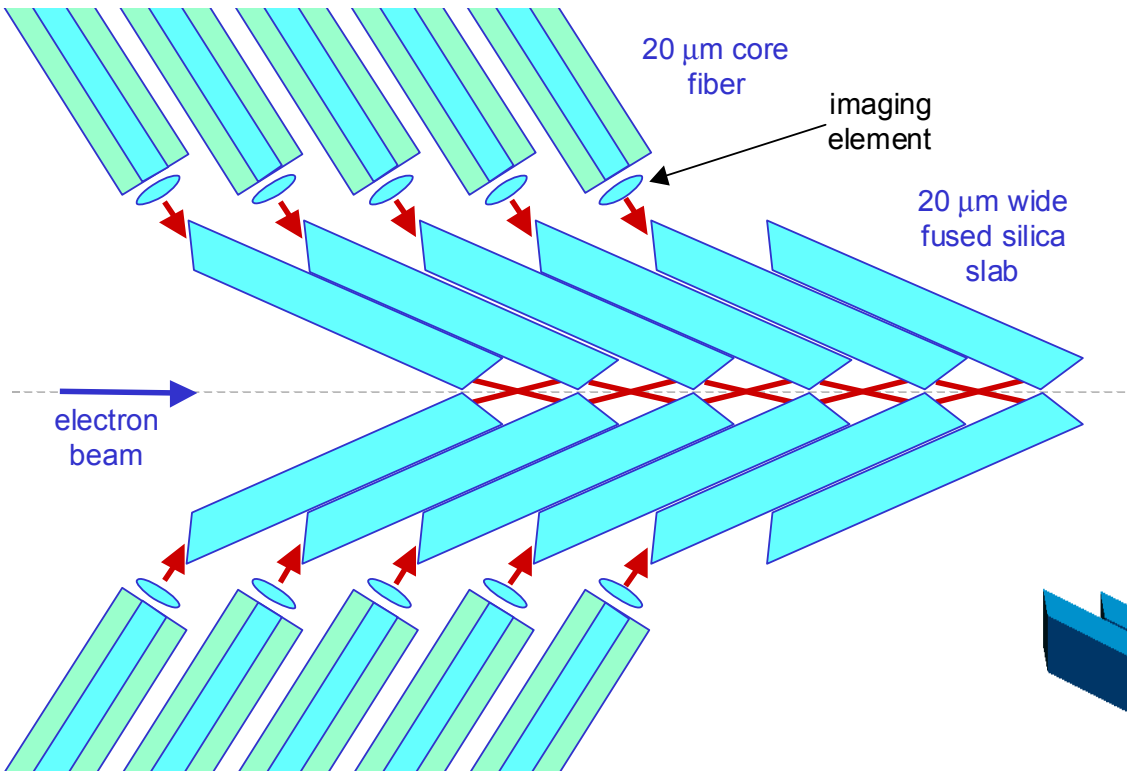
I. Optical bunching

Simulation for 10 successive accelerator cells



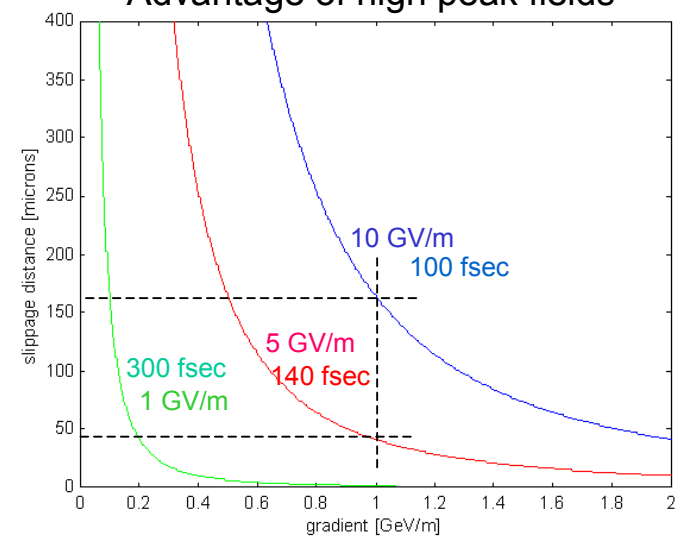
Future Experiments

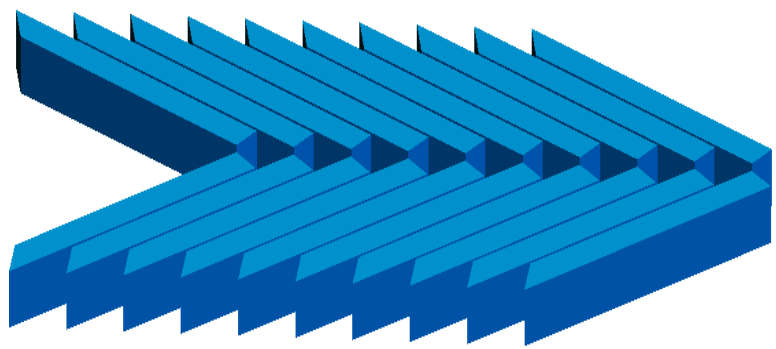
II. Multi-accelerator cell experiments



Proposed multi-cell accelerator structure

Advantage of high peak fields





Future Experiments

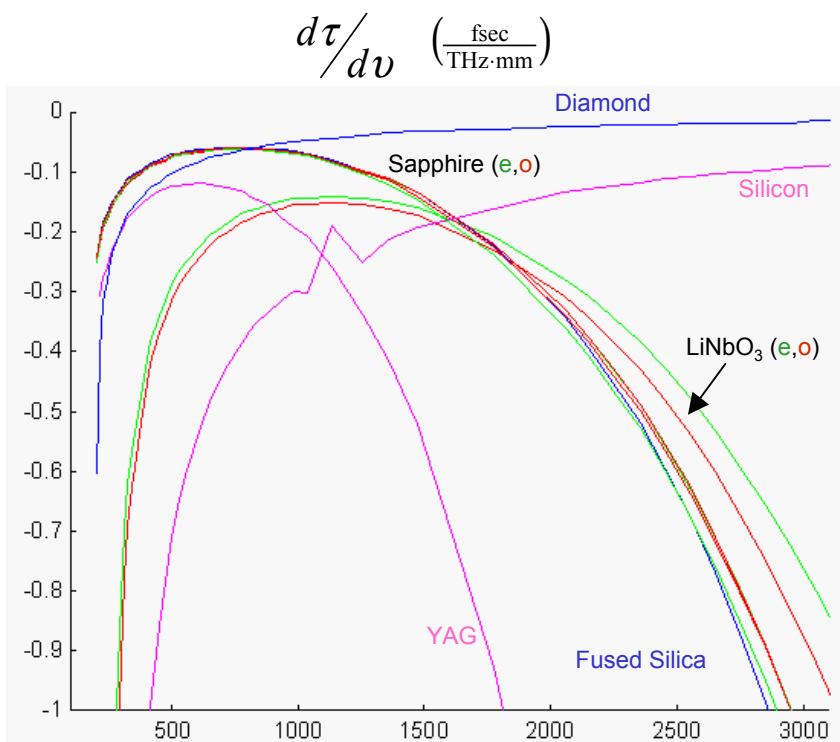
III. Research on material properties

Desired Material features

- low dispersion
- low nonlinear optical coefficients
- high chemical stability in vacuum
- high damage threshold (" □1□ □J □/□c□m□ psec laser pulses)
- high thermal conductivity and heat capacity
- low thermal expansion coefficient
- easy to machine
- availability

material	density g cm^{-3}	thermal expansion 10^{-6} K^{-1}	dn/dT 10^{-6} K^{-1}	thermal conductivity W K^{-1} m^{-1}	heat capacity J K^{-1} g^{-1}
Fused Silica	2.202	0.51	11	138	0.7458
Sapphire ne Sapphire no	3.987	6.77	-	58	0.777
quartz ne quartz no	2.648	10.49	-	-	0.7458
Silicon	2.329	2.618	135	191	0.7139
YAG	4.55	7.5	9.1	12	0.625
Diamond	3.515	1.25	9.6	<2800	0.5169

Dispersion curves



Summary

Features of X-laser acceleration

- Linear acceleration, Gradient $\propto$ Longitudinal electric field
- Vacuum
- Gradient limited by damage threshold $P_{laser} \approx 1 \ J/cm^2$

Relevant parameters

- Accelerator cell length $L_{cell} \approx 800 \ \mu m$
- Laser crossing angle $\theta_{laser} \approx 23 \ mrad$
- Slit width $\alpha_{slit} \leq 10 \ \mu m$
- Laser optical phase $\phi_{laser} = 180^o$

Experiment

- The accelerator cell
- The optical transport system
- The energy spectrometer
- Laser and e-beam Diagnostics

Present status

- Spatial overlap
- Temporal overlap
- Single electron bunches
- Transmission through a <10 μm slit
- Control of laser-electron interaction length

} solved

- Beam position jitter
- Lack of knowledge of optical phase

} upcoming run

Future research

- Optical bunching
- Multiple accelerator cell structure development
- Research on materials