Free Electron Laser (FEL) and Inverse Free Electron Laser (IFEL)

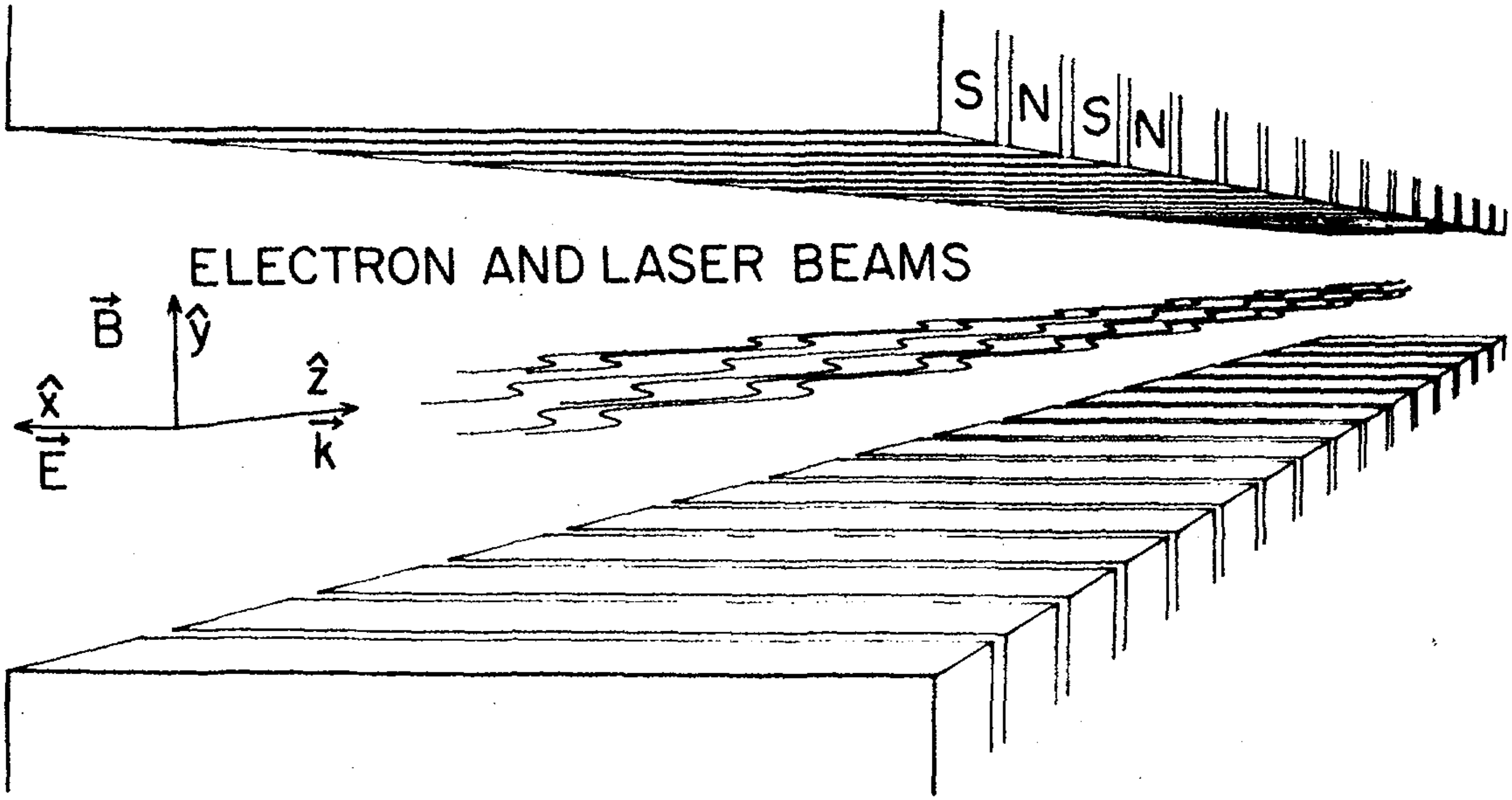


FIG. 1. Schematic view of IFEL accelerator.

The longitudinal component describes the change in the energy of the electron and can be written as

$$mc^2 \frac{d\gamma}{dt} = e\vec{v}_T \bullet \vec{E}_l - \frac{dP_{rad}}{dt}$$

Energy exchange between the electron and laser beam

Electron to laser : FEL

Laser to electron: IFEL

Assume rate of change of radiative loss is zero: $\frac{dP_{rad}}{dt} = 0$

$$mc^2 \frac{d\gamma}{dt} = e\vec{v}_T \bullet \vec{E}_l$$

$$\frac{d\gamma}{dz} = \frac{1}{c}\frac{d\gamma}{dt}$$

Assume a helical wiggler and a circularly polarized laser or planar wiggler with linearly polarized laser. One can calculate the transverse velocity v_T of the electron in the magnetic field and the scalar product of v_T and E_l

Courtesy:

E. D. Courant, C. Pellegrini and W. Zakowicz, Phys Rev A 32 (1985) 2813

R. B. Palmer J. Appl. Phys. 43, (1972) 3014

$$\frac{d\gamma}{dz} = E_0 \alpha e^{\left\{2\pi i z\left[\frac{1}{\Lambda}+\frac{1}{\lambda}\left(1-\frac{1}{\beta\cos\alpha}\right)\right]+i\phi\right\}}$$

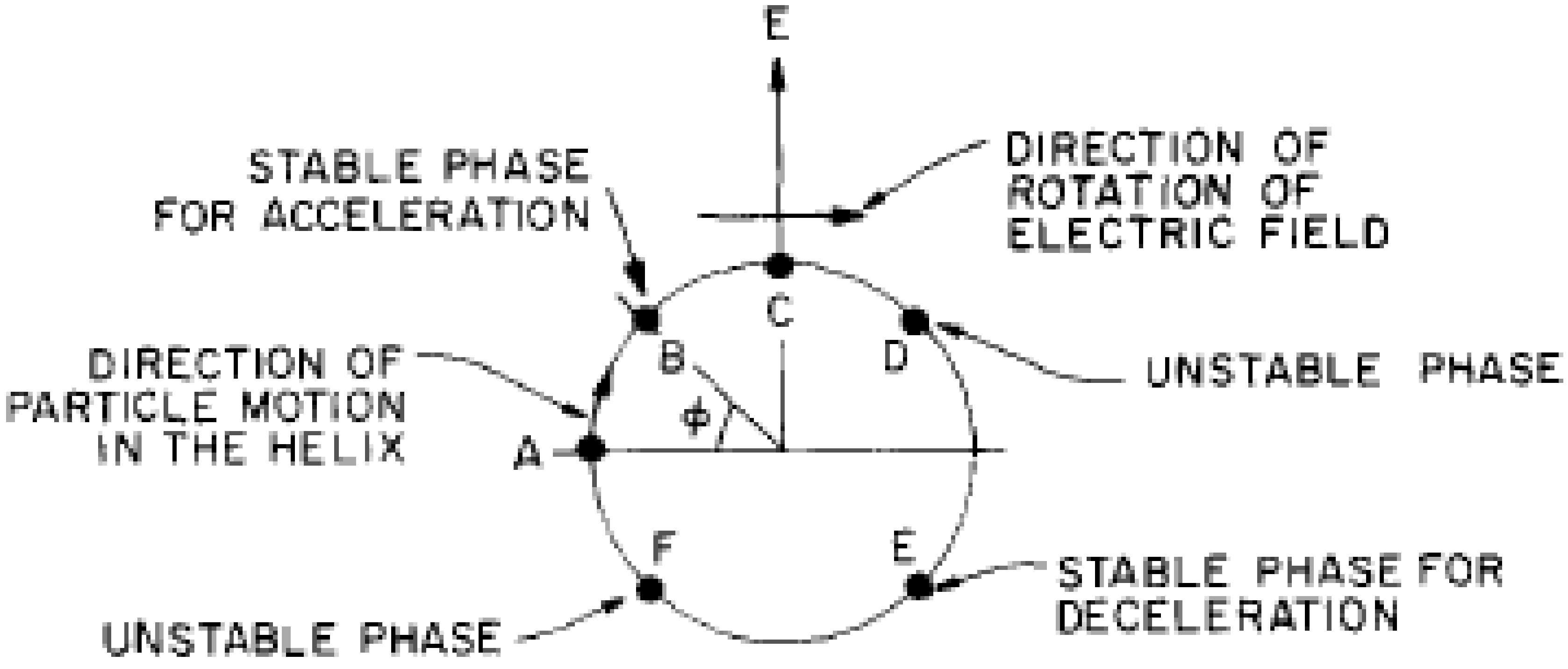
where E$_0$ is the amplitude of the laser field, ά is the angle between the particle and the z axis, Λ is the wiggler period, λ is the wavelength of the laser and Φ is the relative phase of the particle in the helix to the electric field of the laser.

If the wiggler is designed such that

$$\frac{1}{\Lambda} = -\frac{1}{\lambda}\left(1-\frac{1}{\beta\cos\alpha}\right)$$

then,

$$\frac{d\gamma}{dz} = \alpha E_0 \cos\phi$$



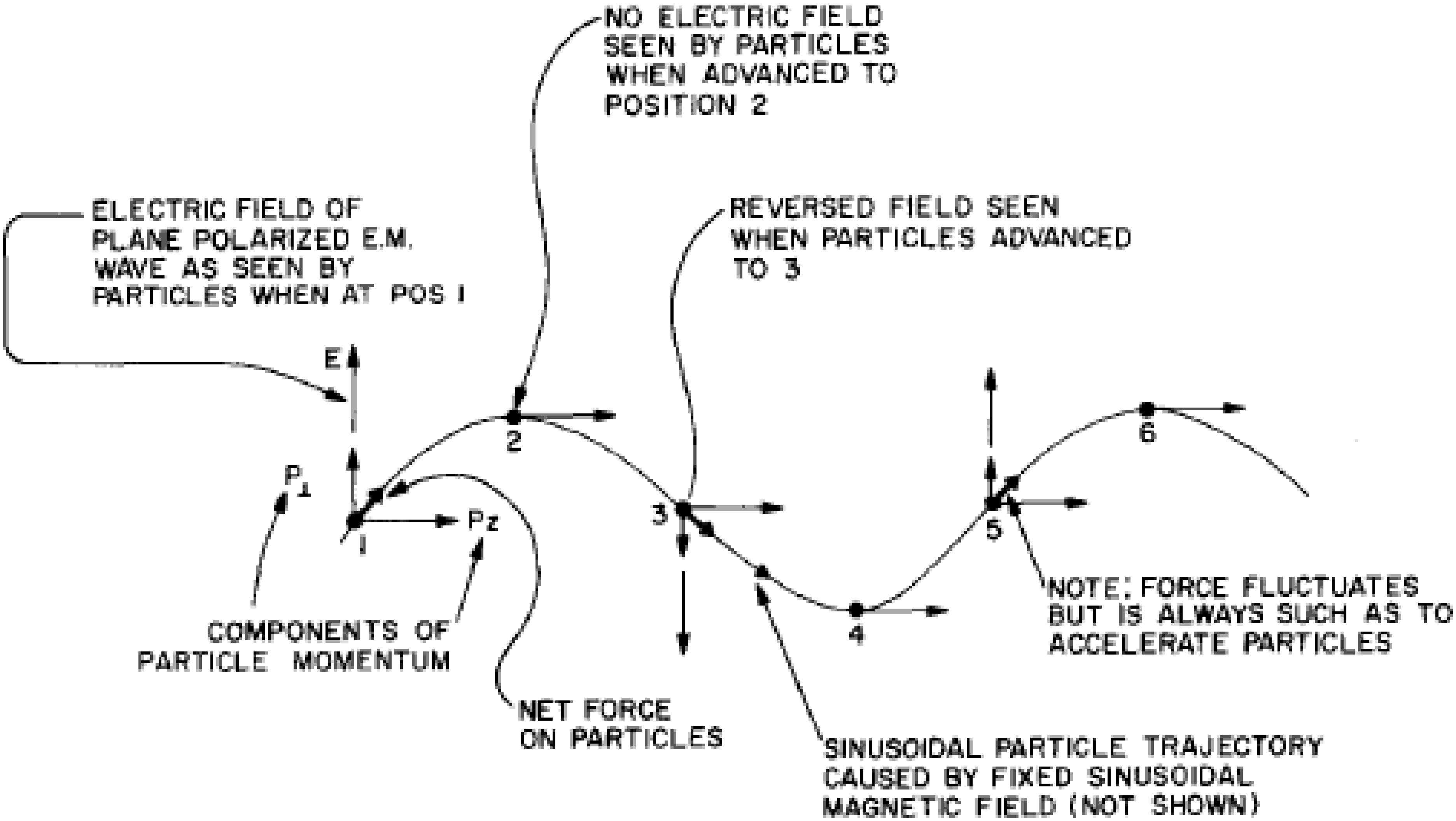
Particles at

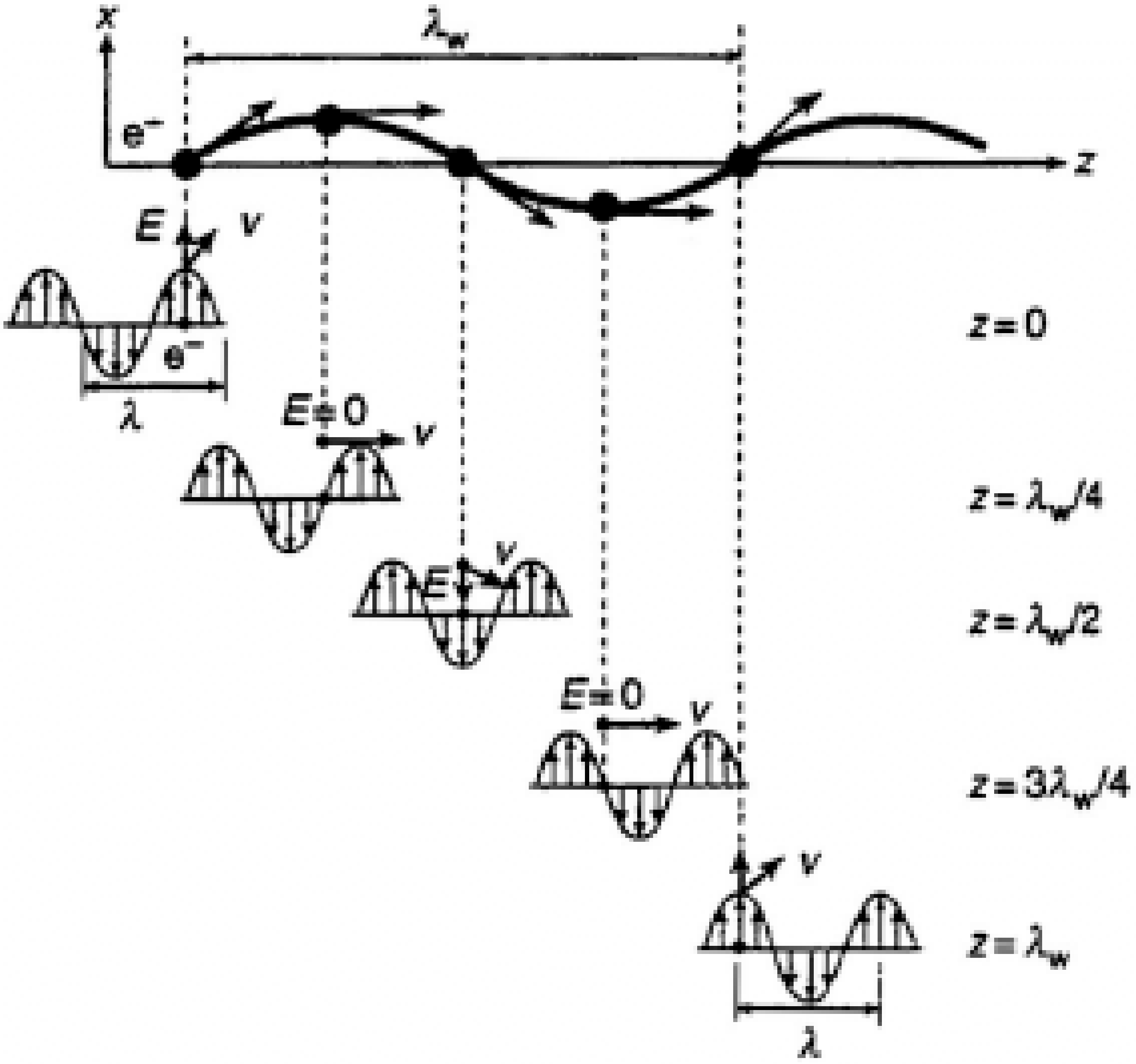
A: Max acceleration, but unstable

B: Medium acceleration, stable-slow ones speed up, fast ones slow down-IFEL condition-bunching, coherence

C: No acceleration

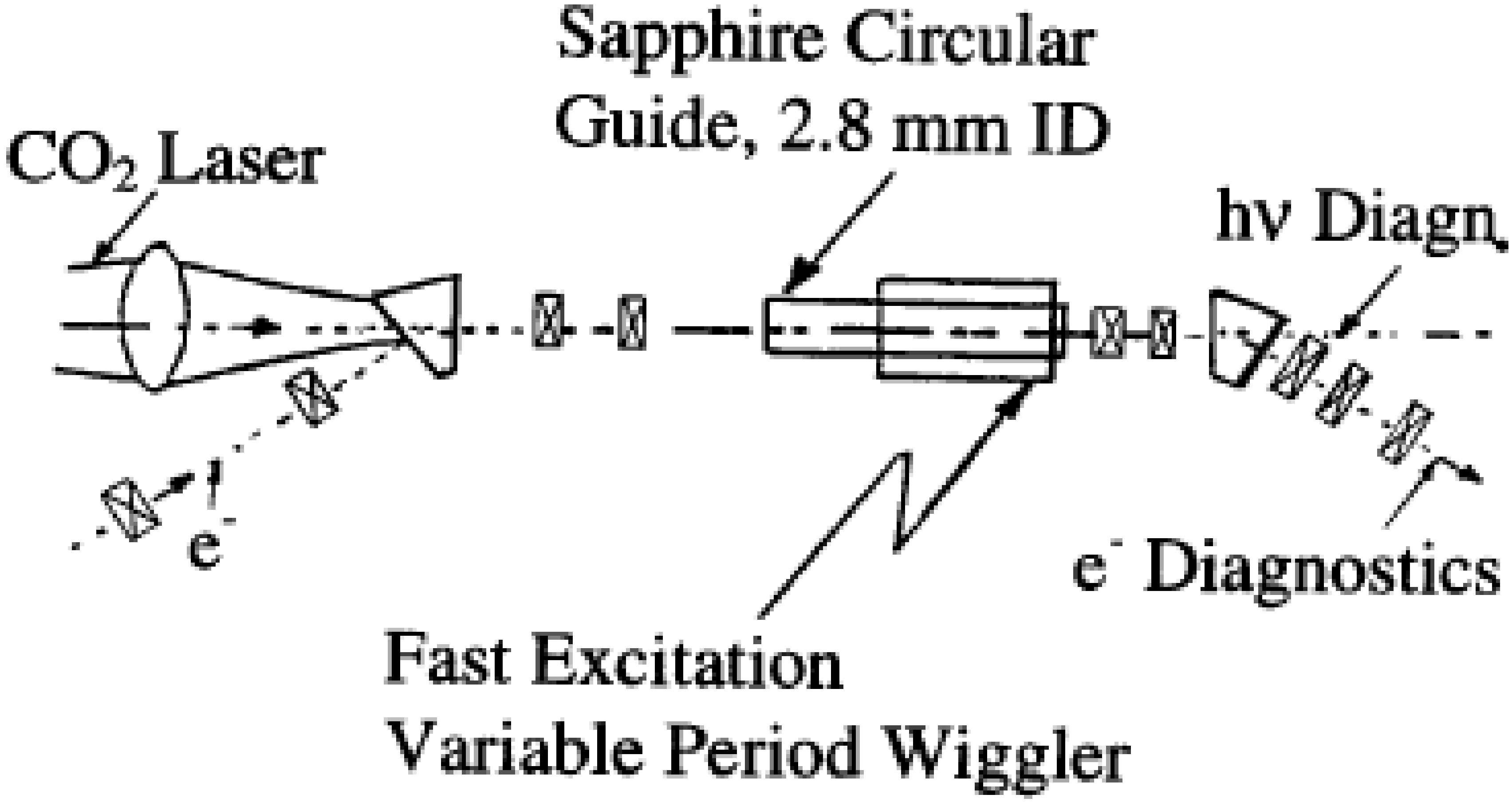
E: Medium deceleration, FEL condition


NO ELECTRIC FIELD SEEN BY PARTICLES WHEN ADVANCED TO POSITION 2
ELECTRIC FIELD OF PLANE POLARIZED E.M. WAVE AS SEEN BY PARTICLES WHEN AT POS I
REVERSED FIELD SEEN WHEN PARTICLES ADVANCED TO 3
E
P⊥
Pz
1
2
3
4
5
6
COMPONENTS OF PARTICLE MOMENTUM
NET FORCE ON PARTICLES
NOTE: FORCE FLUCTUATES BUT IS ALWAYS SUCH AS TO ACCELERATE PARTICLES
SINUSOIDAL PARTICLE TRAJECTORY CAUSED BY FIXED SINUSOIDAL MAGNETIC FIELD (NOT SHOWN)



Snap shot of electron trajectory and electric field of laser for FEL as they progress along one period of the wiggler

Courtesy: http://reu.physics.ucla.edu/common/papers/2007/affolter_matthew.pdf



Courtesy: A. van Steenbergen et al. Phys Rev. Lett. 77 (1996), 2690

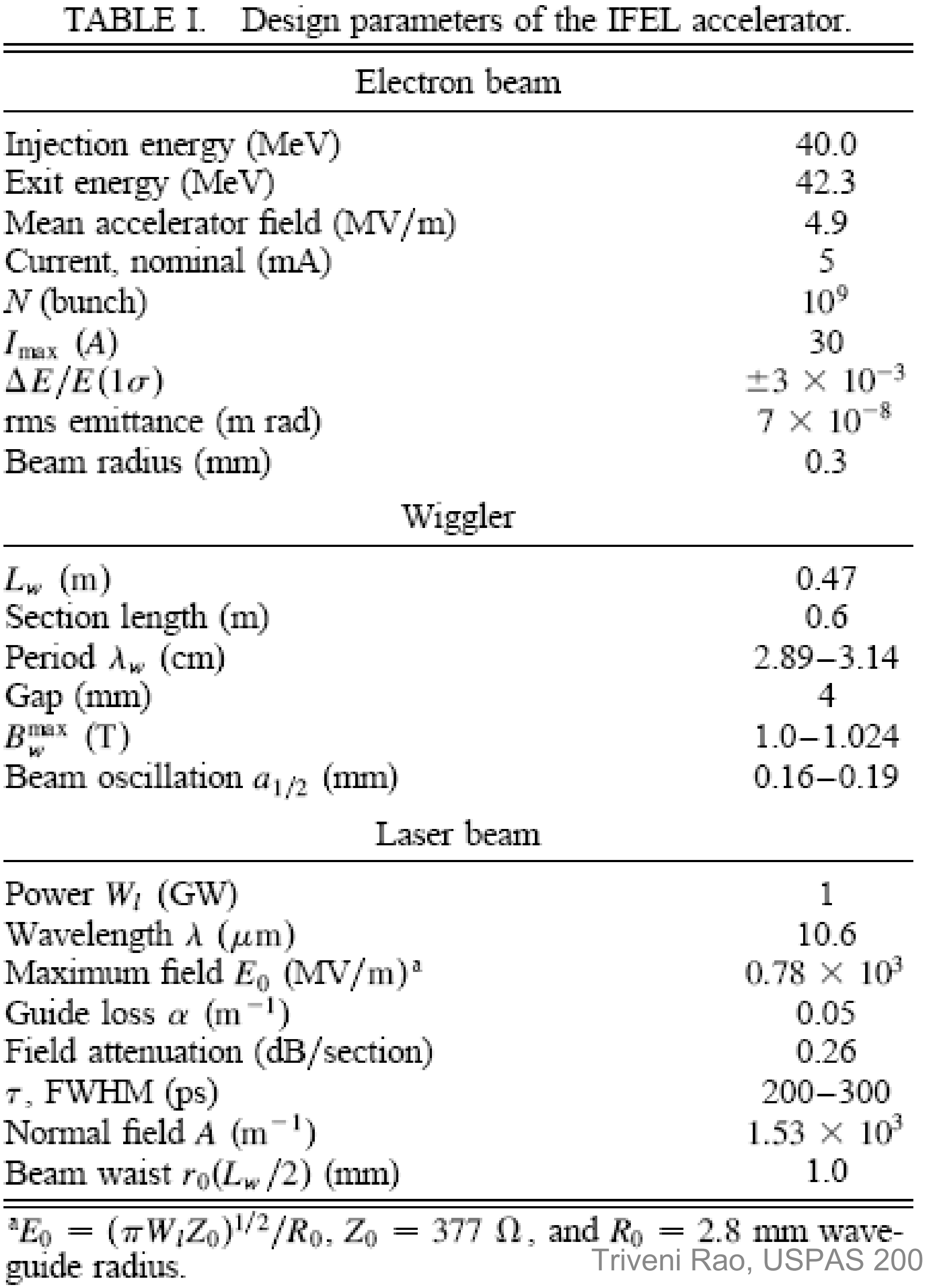


TABLE I. Design parameters of the IFEL accelerator.

Electron beam	
Injection energy (MeV)	40.0
Exit energy (MeV)	42.3
Mean accelerator field (MV/m)	4.9
Current, nominal (mA)	5
N (bunch)	10^9
$I_{\max}$ (A)	30
$\Delta E/E(1\sigma)$	$\pm 3 \times 10^{-3}$
rms emittance (m rad)	7×10^{-8}
Beam radius (mm)	0.3
Wiggler	
L_w (m)	0.47
Section length (m)	0.6
Period λ_w (cm)	2.89–3.14
Gap (mm)	4
$B_w^{\max}$ (T)	1.0–1.024
Beam oscillation $a_{1/2}$ (mm)	0.16–0.19
Laser beam	
Power W_l (GW)	1
Wavelength λ (μm)	10.6
Maximum field E_0 (MV/m)[a]	0.78×10^3
Guide loss α (m^{-1})	0.05
Field attenuation (dB/section)	0.26
τ, FWHM (ps)	200–300
Normal field A (m^{-1})	1.53×10^3
Beam waist $r_0(L_w/2)$ (mm)	1.0

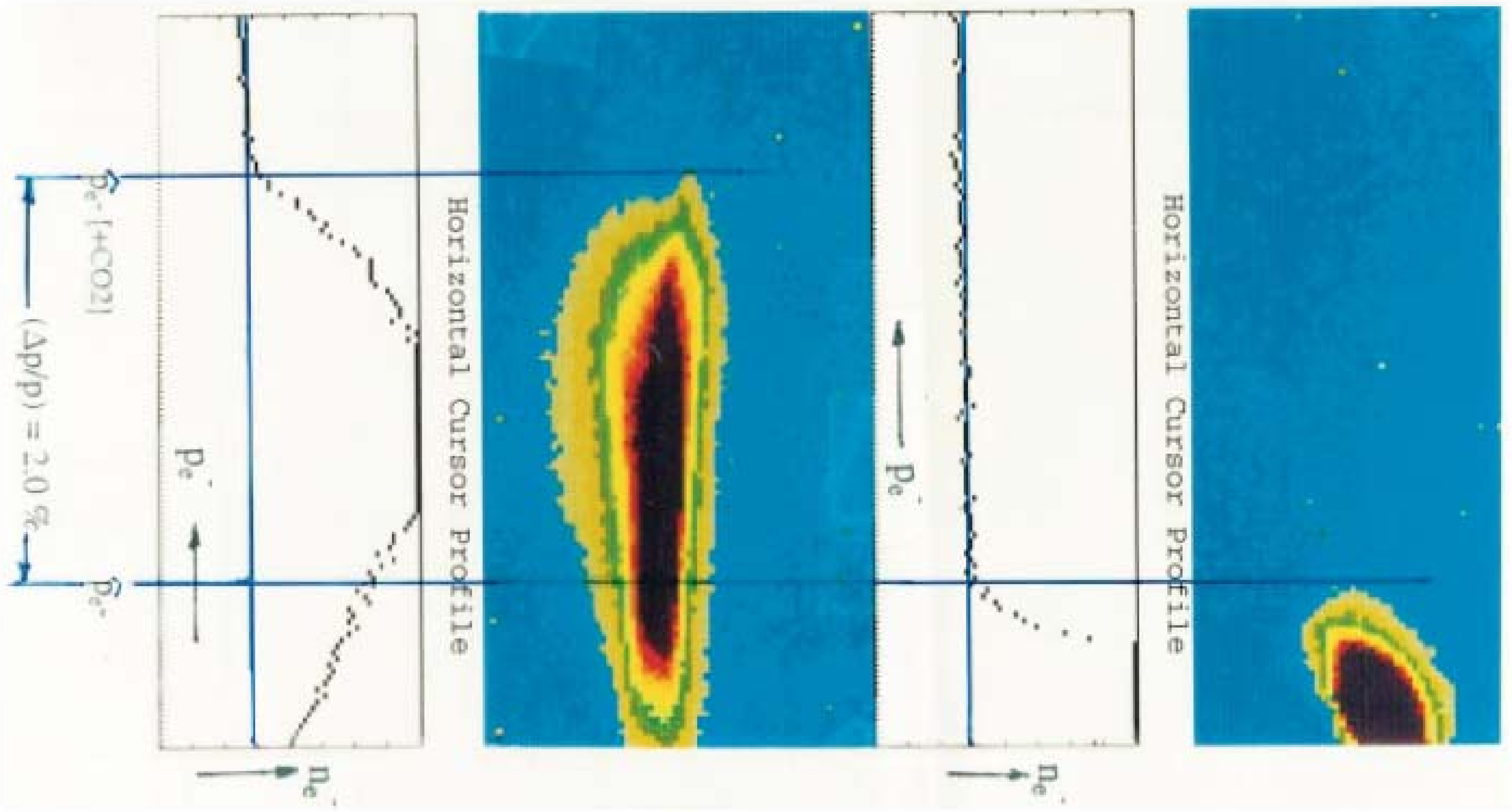
[a] $E_0 = (\pi W_l Z_0)^{1/2}/R_0$, $Z_0 = 377\ \Omega$, and $R_0 = 2.8$ mm waveguide radius.

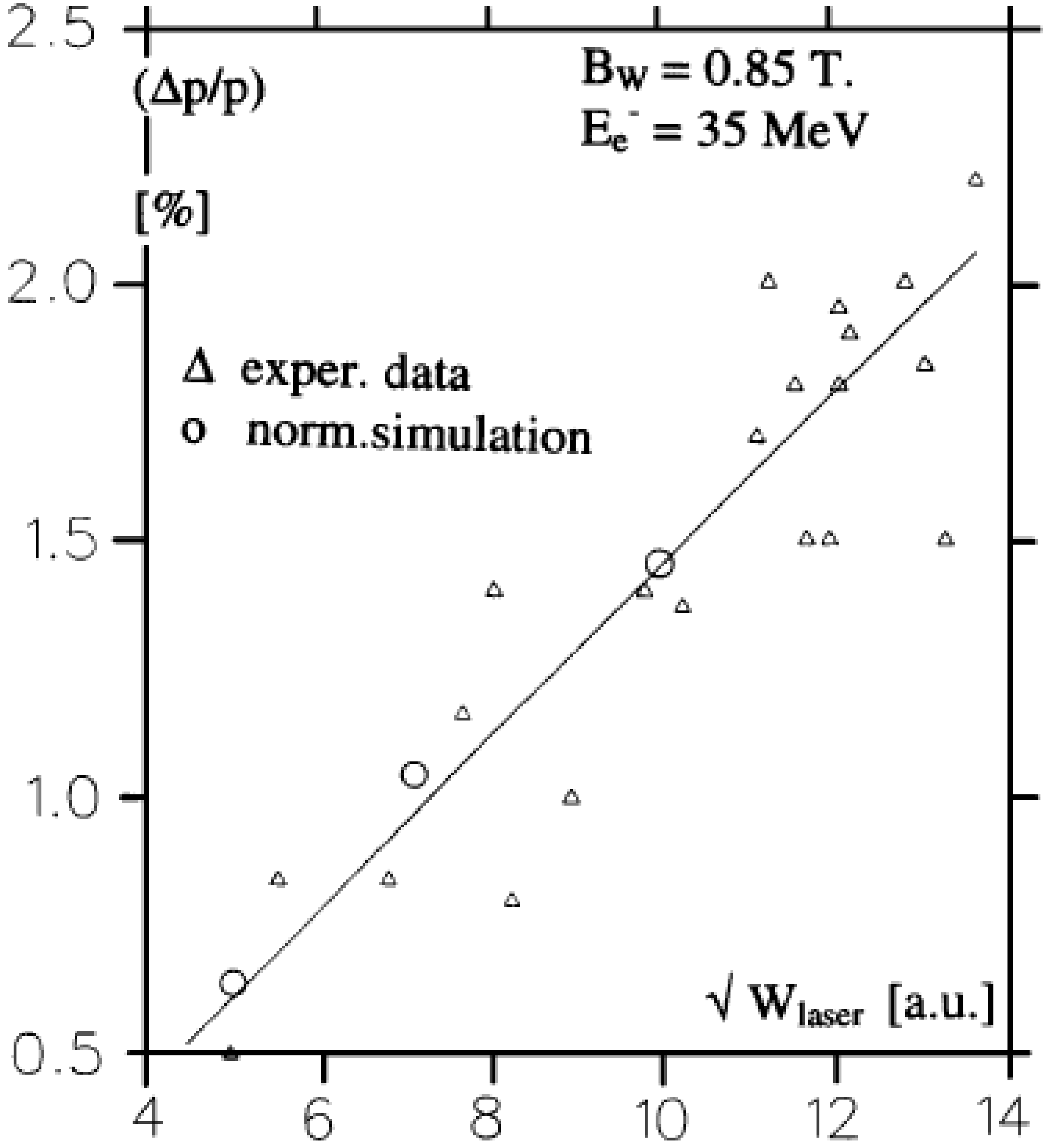
CO_2 laser

EH_{11} mode stabilized with in Rayleigh length from entrance

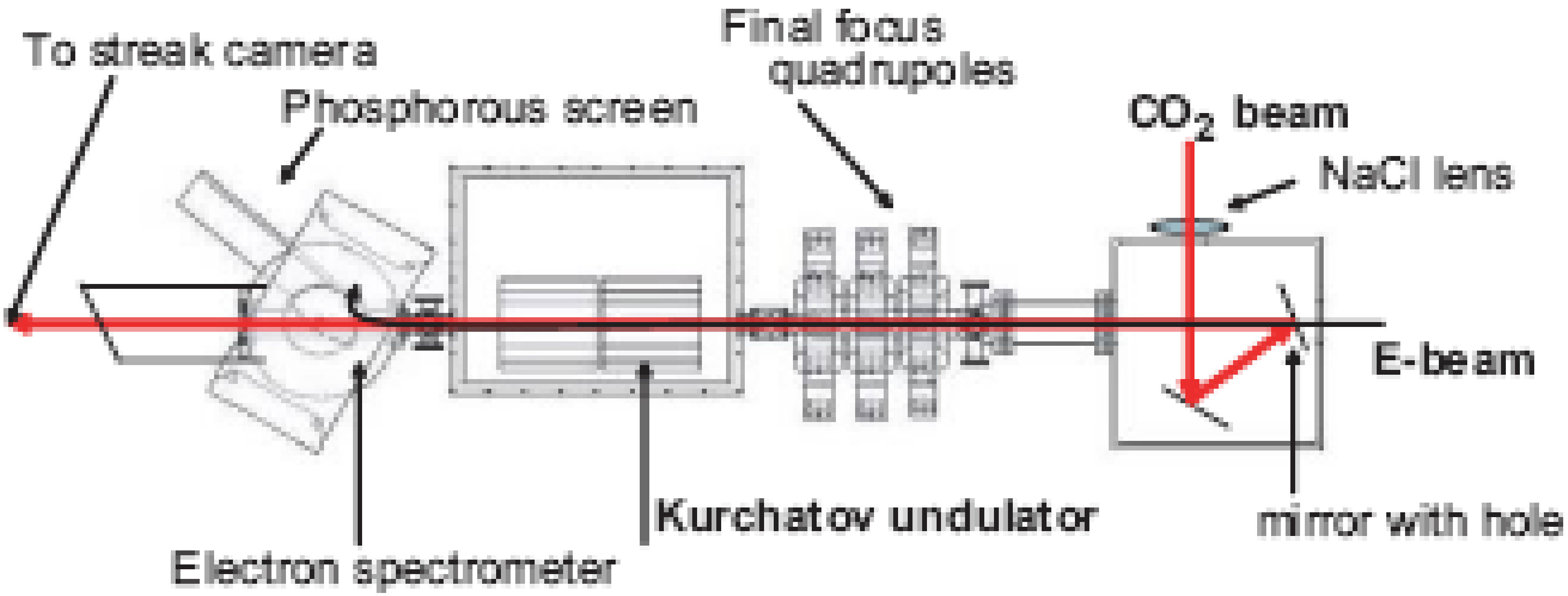
2.8 mm ID, 0.6 m long sapphire circular waveguide

Evidence of Acceleration

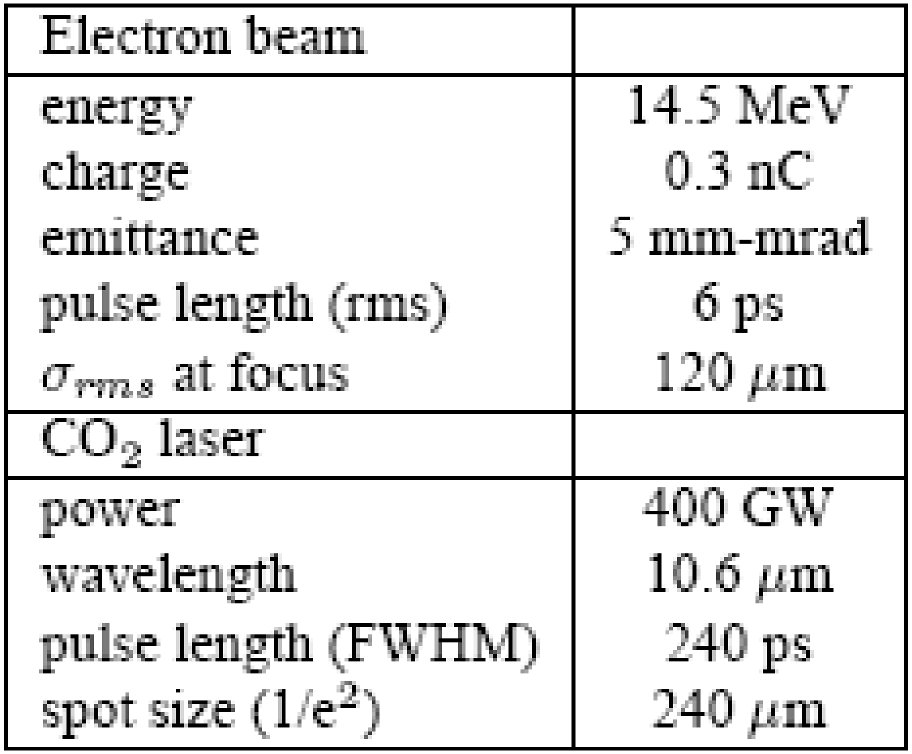




Acceleration Linear in electric field of laser

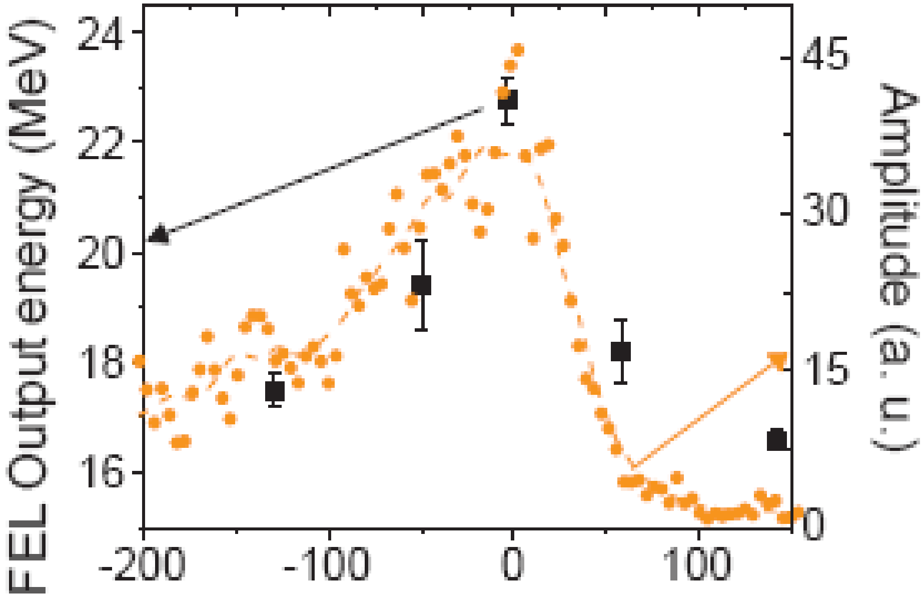


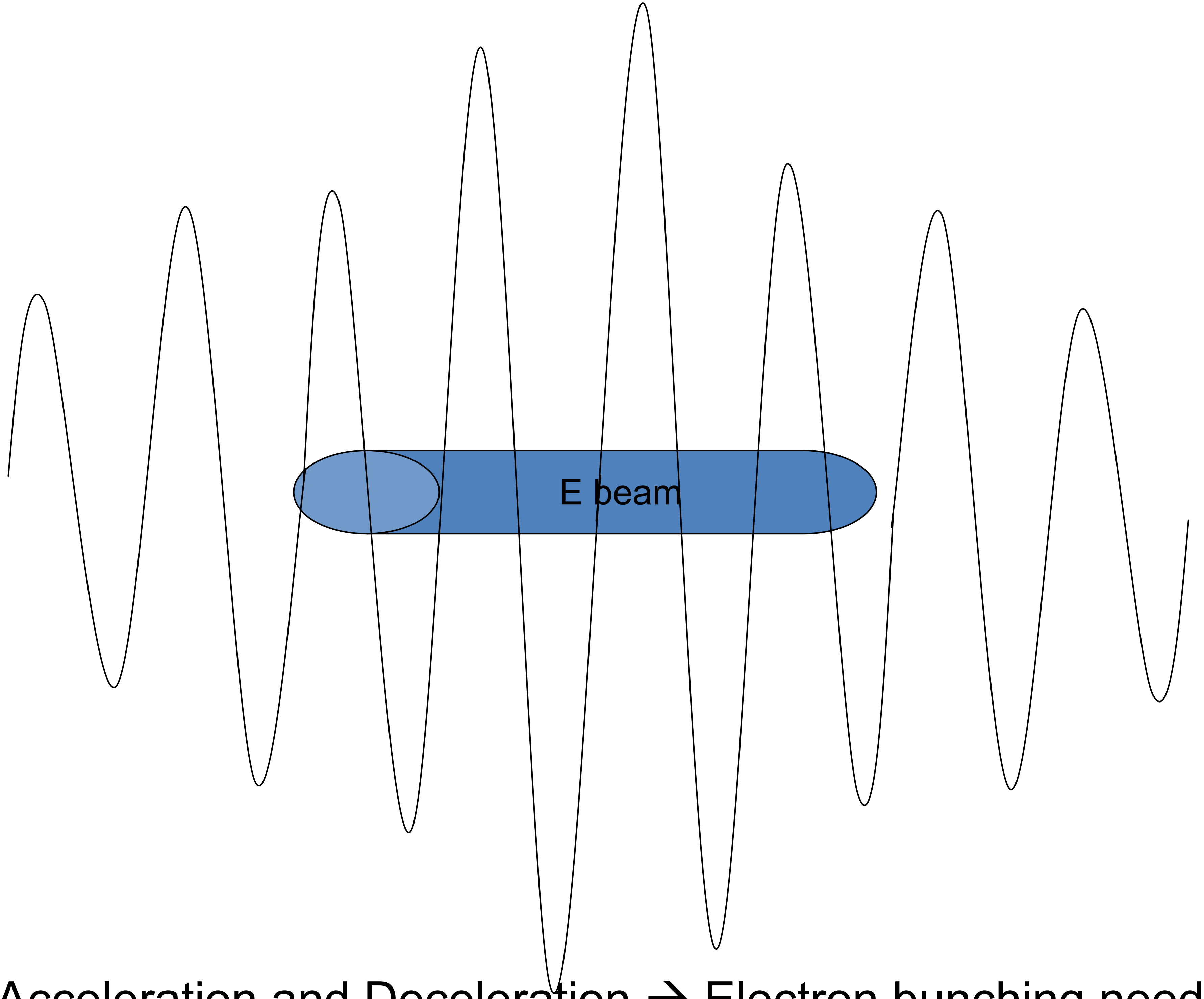
Courtesy: P. Musumeci et al., Proc. Of 2005 PAC P. 500



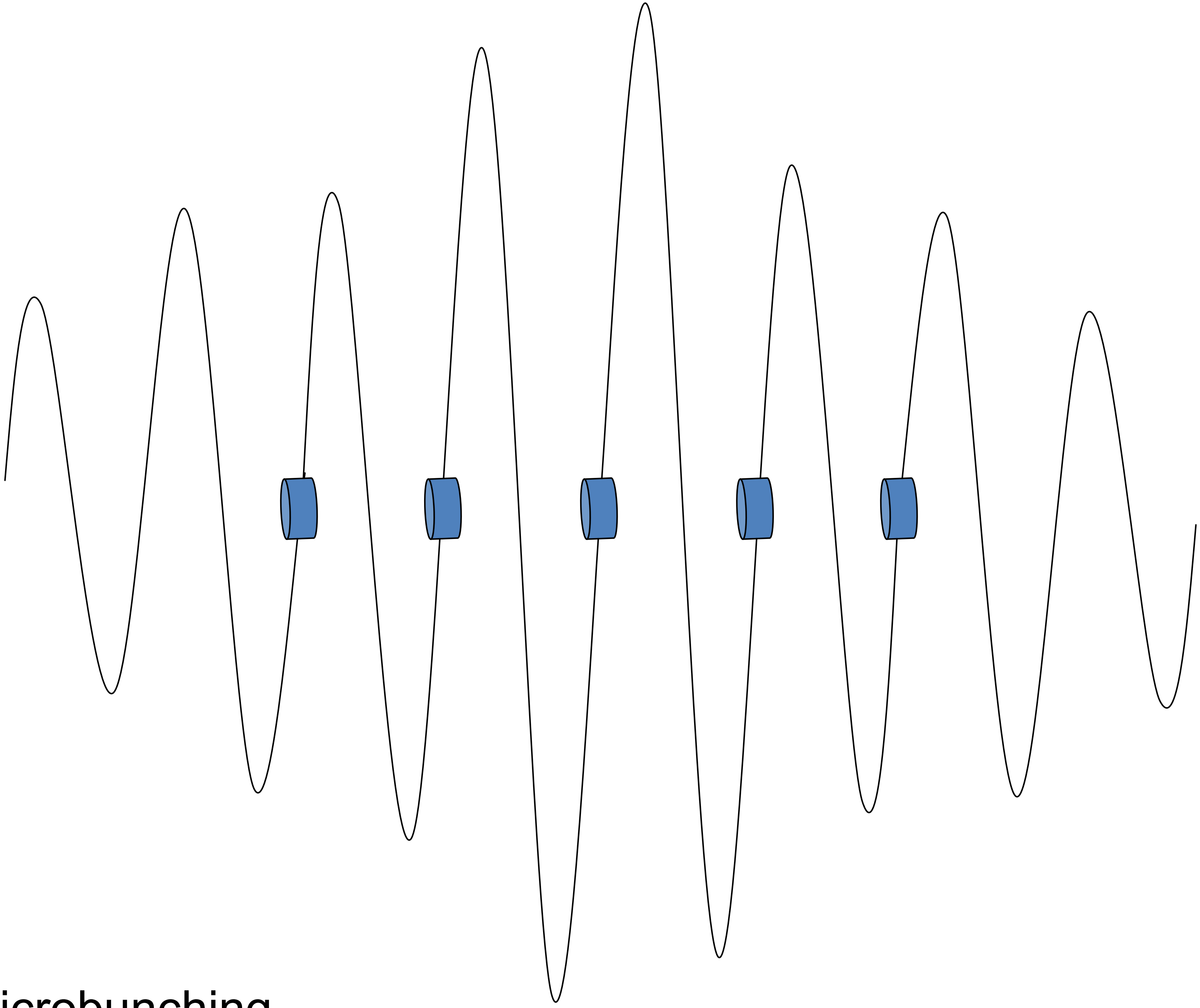
Electron beam	
energy	14.5 MeV
charge	0.3 nC
emittance	5 mm-mrad
pulse length (rms)	6 ps
σ_{rms} at focus	120 μm
CO_2 laser	
power	400 GW
wavelength	10.6 μm
pulse length (FWHM)	240 ps
spot size ($1/e^2$)	240 μm

- ➢20 MeV (150%) energy gain
- ➢>70Mv/m gradient
- ➢>5% of particles trapped for acceleration



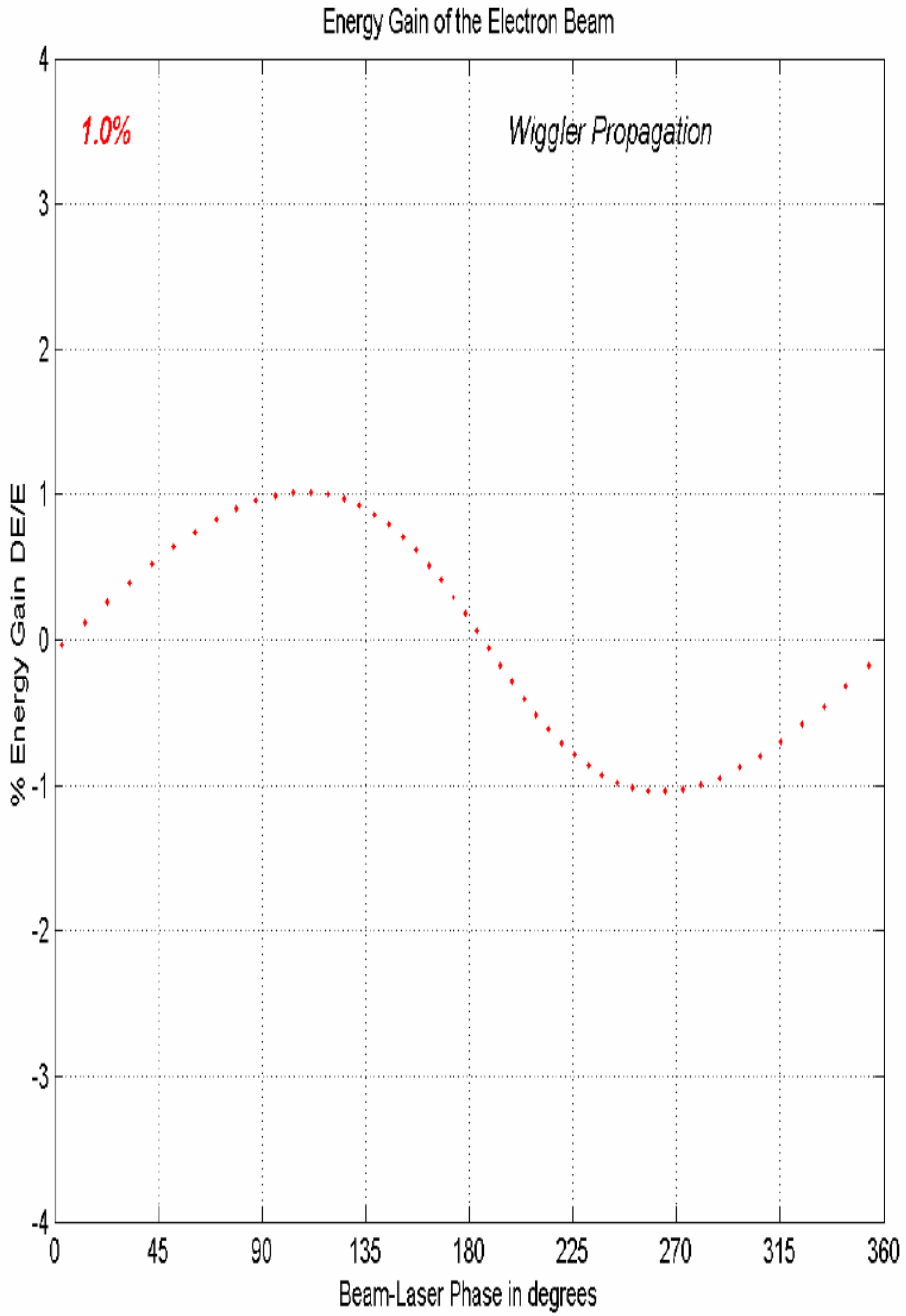


Acceleration and Deceleration → Electron bunching needed



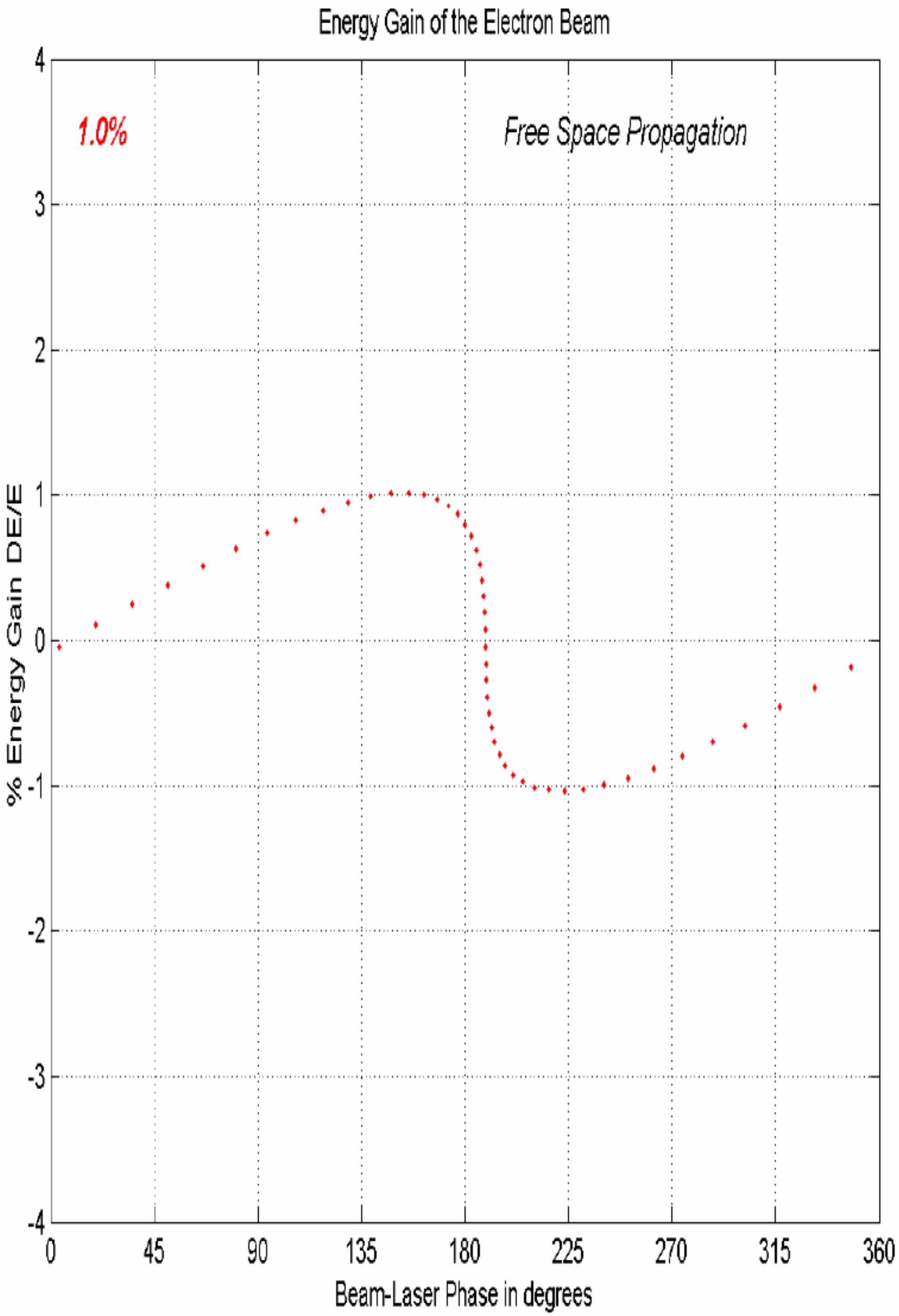
Microbunching

Energy modulation in wiggler



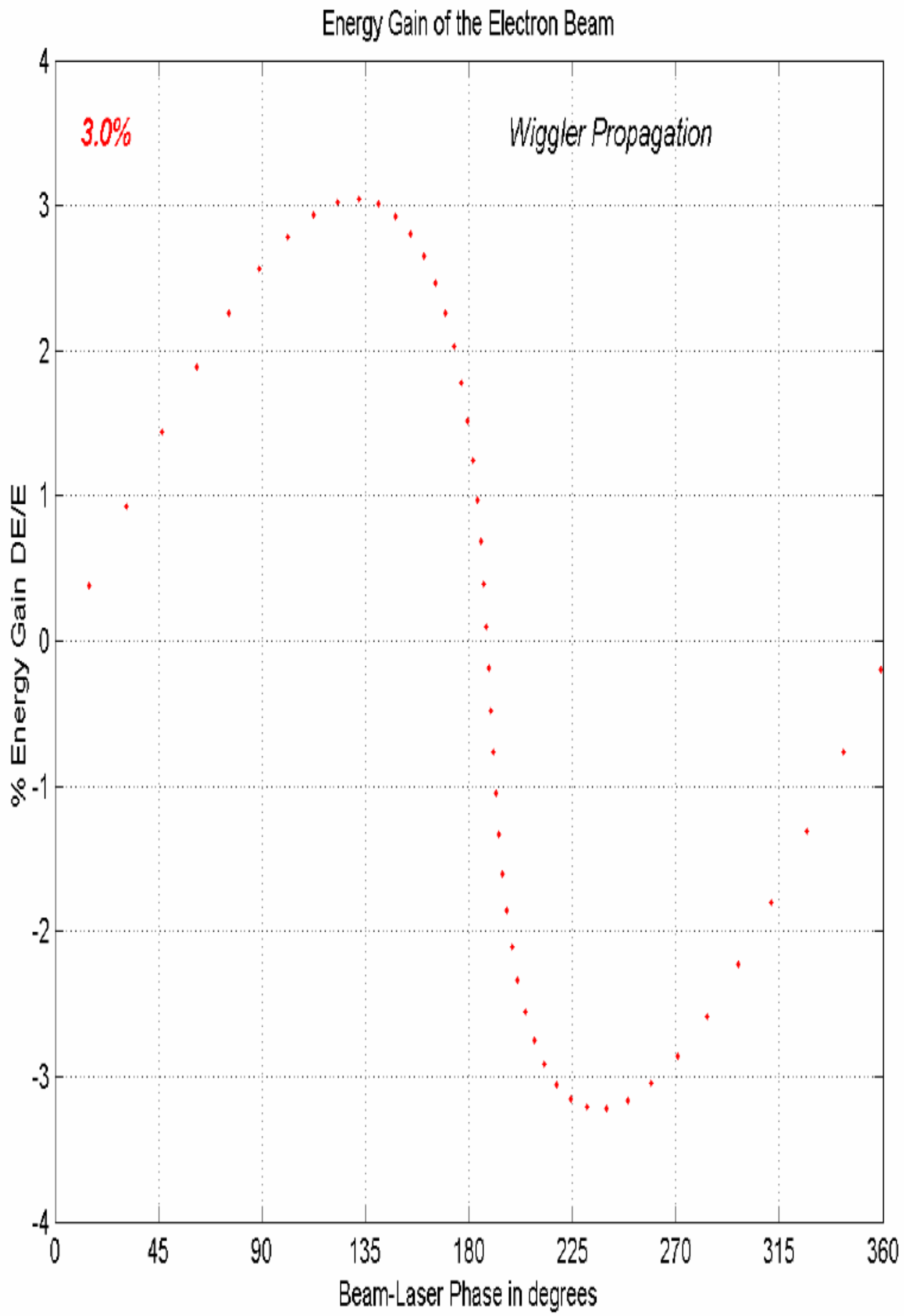
http://www-scf.usc.edu/~kallos/Files/AAC04%20Presentation%20-%20IFEL%20Buncher%20-%20Themos%20Kallos.pdf

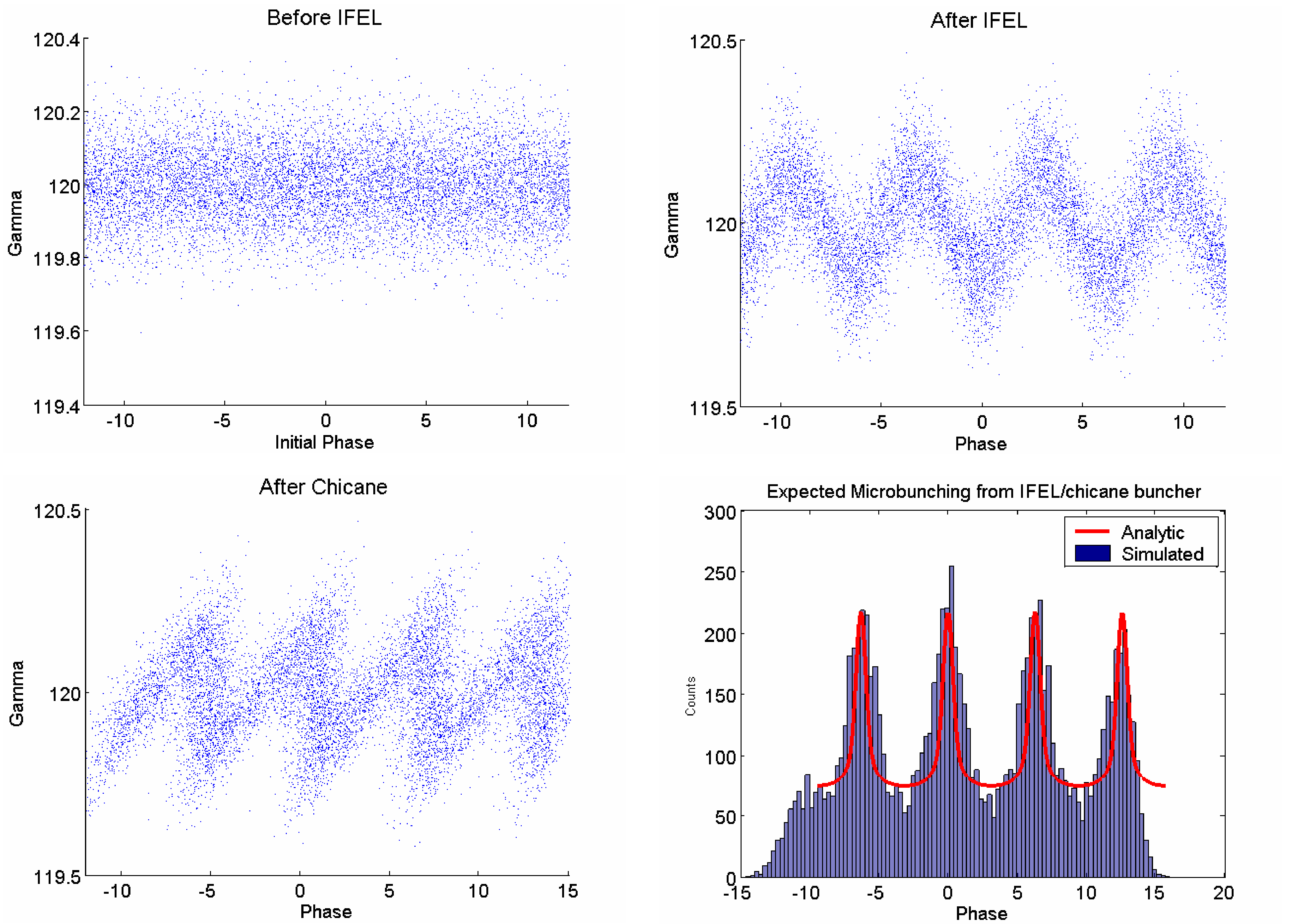
Charge distribution after transit- left hand side faster e catch up with right hand side slower e



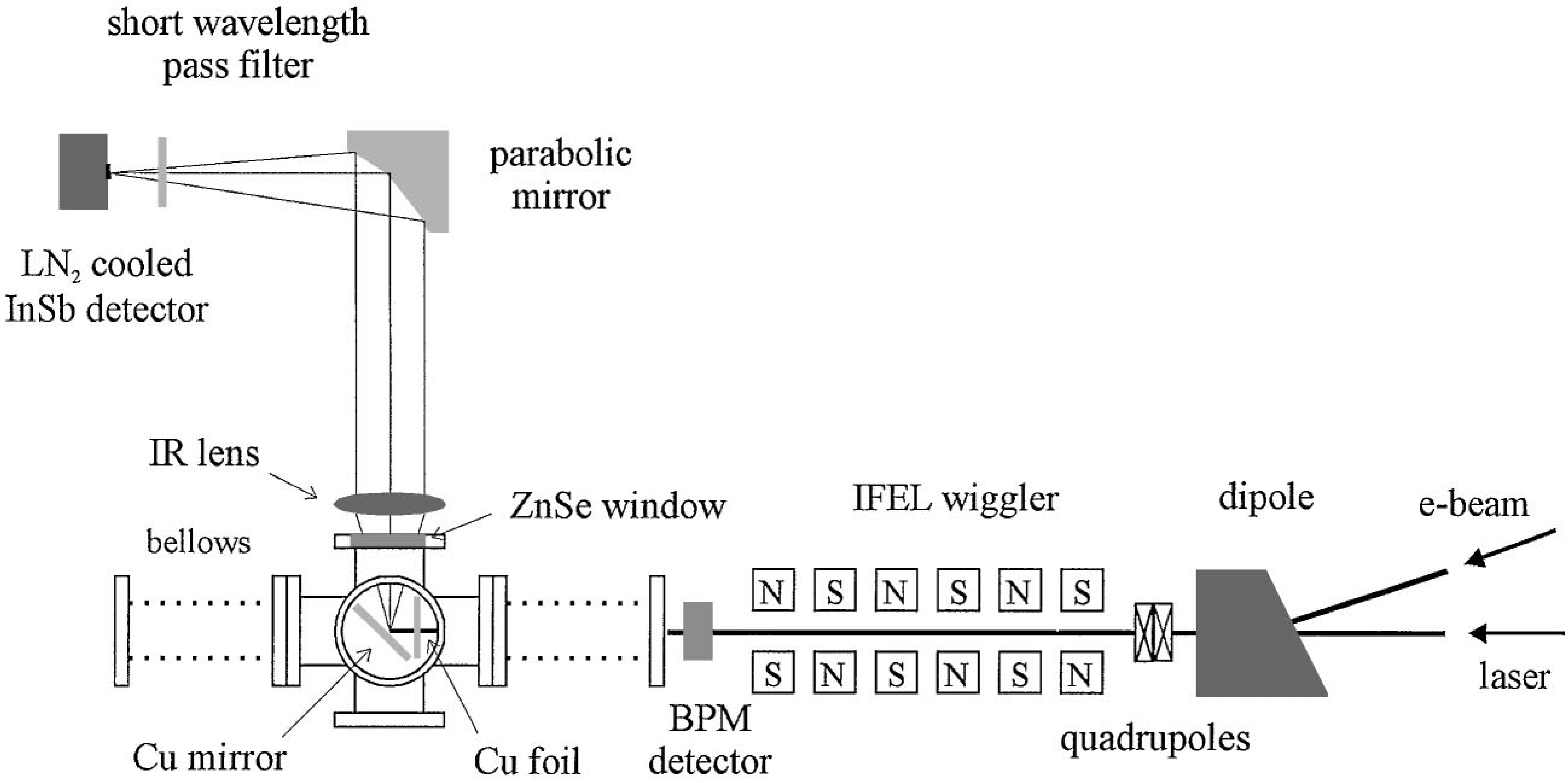
Further transport

Optimal positioning of next stage

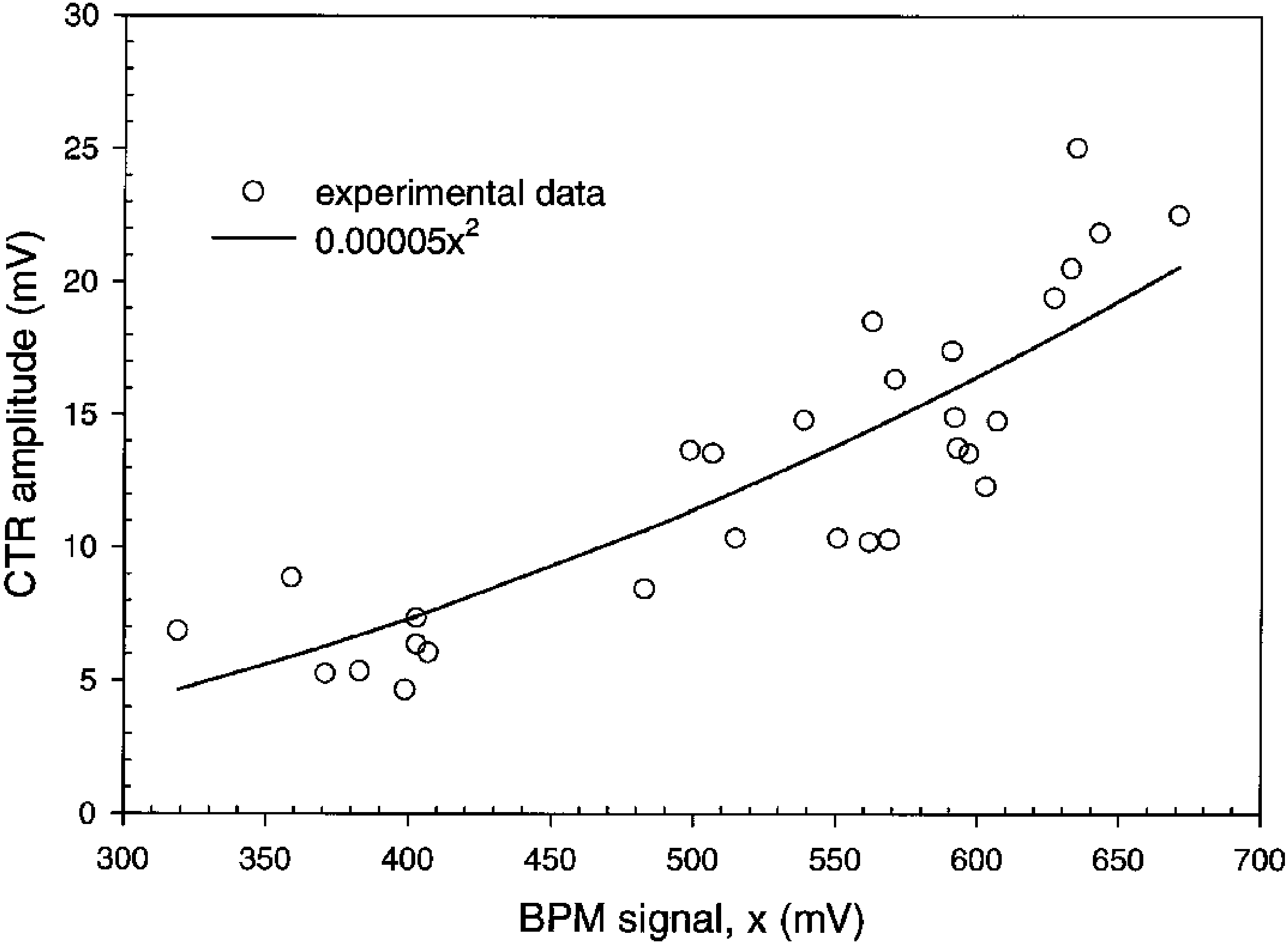




http://scitation.aip.org/getpdf/servlet/GetPDFServlet?filetype=pdf&id=APCPCS000737000001000342000001&idtype=cvips&prog=normal: C. Sears et al. Proc PAC 07 WEXKI02 p. 1894



Courtesy: Y. Liu et al Phys Rev. Lett. 80, (1998) 4418

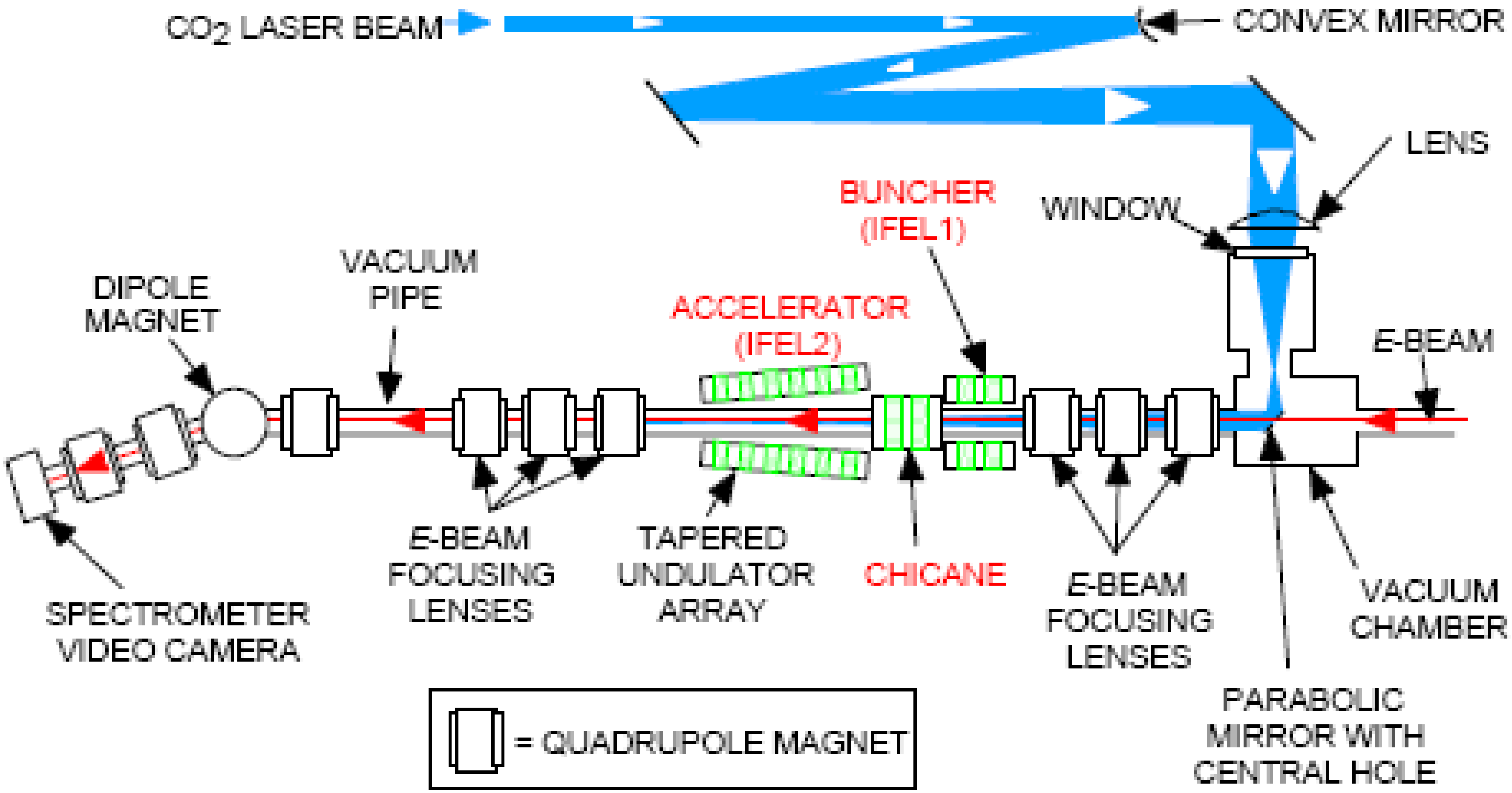


Coherent transition radiation signal

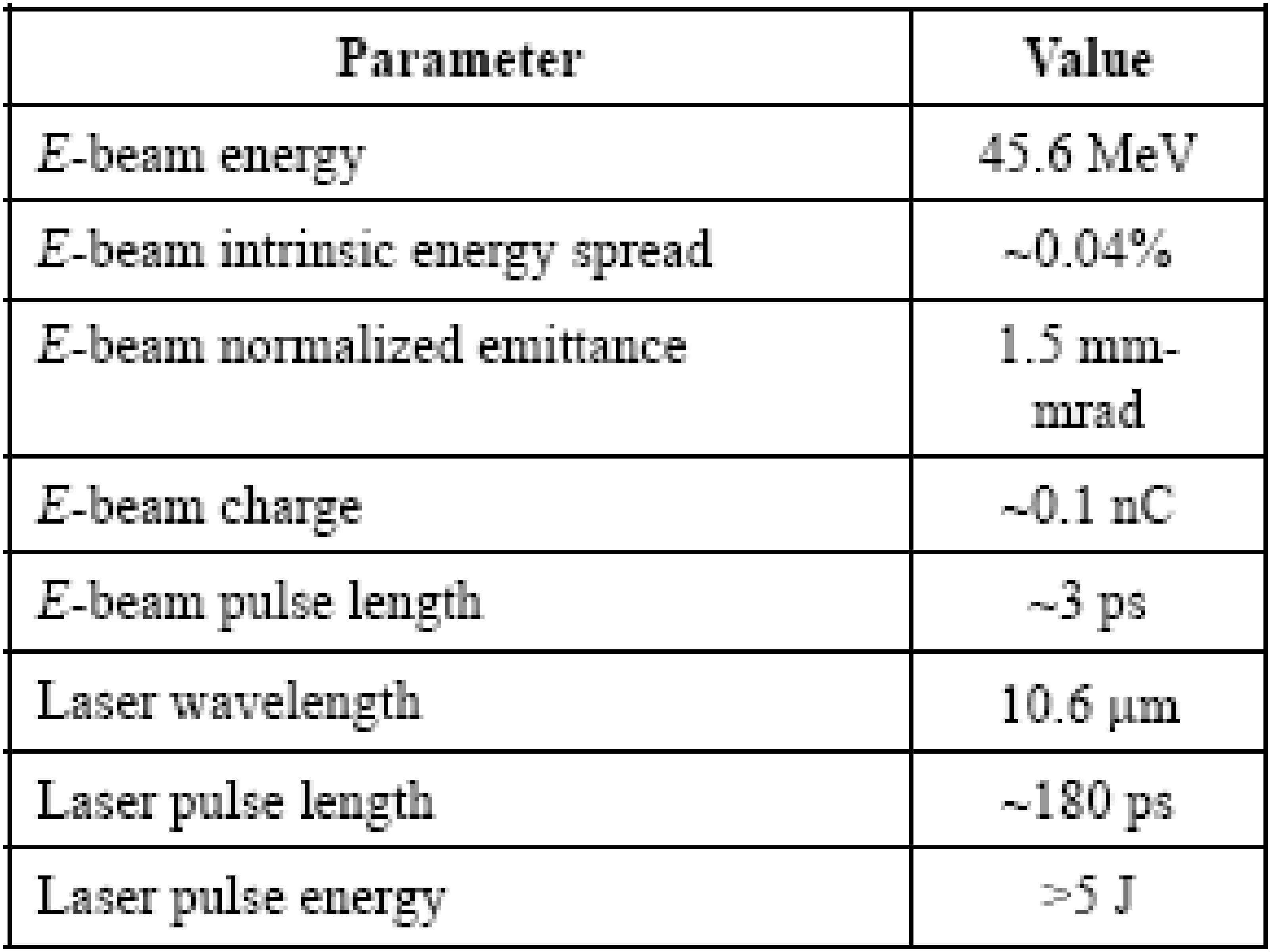
Applications of Micro-bunching

- Seeder for staged acceleration
  - Staged IFEL, ICA, LW
- Seeder for FEL
  - Normal FEL at fundamental wavelength
  - High harmonic generation
- Source of short bunch length electrons
  - Attosecond e beam generation
- Source of coherent radiation
  - CTR, THZ (300 μm)

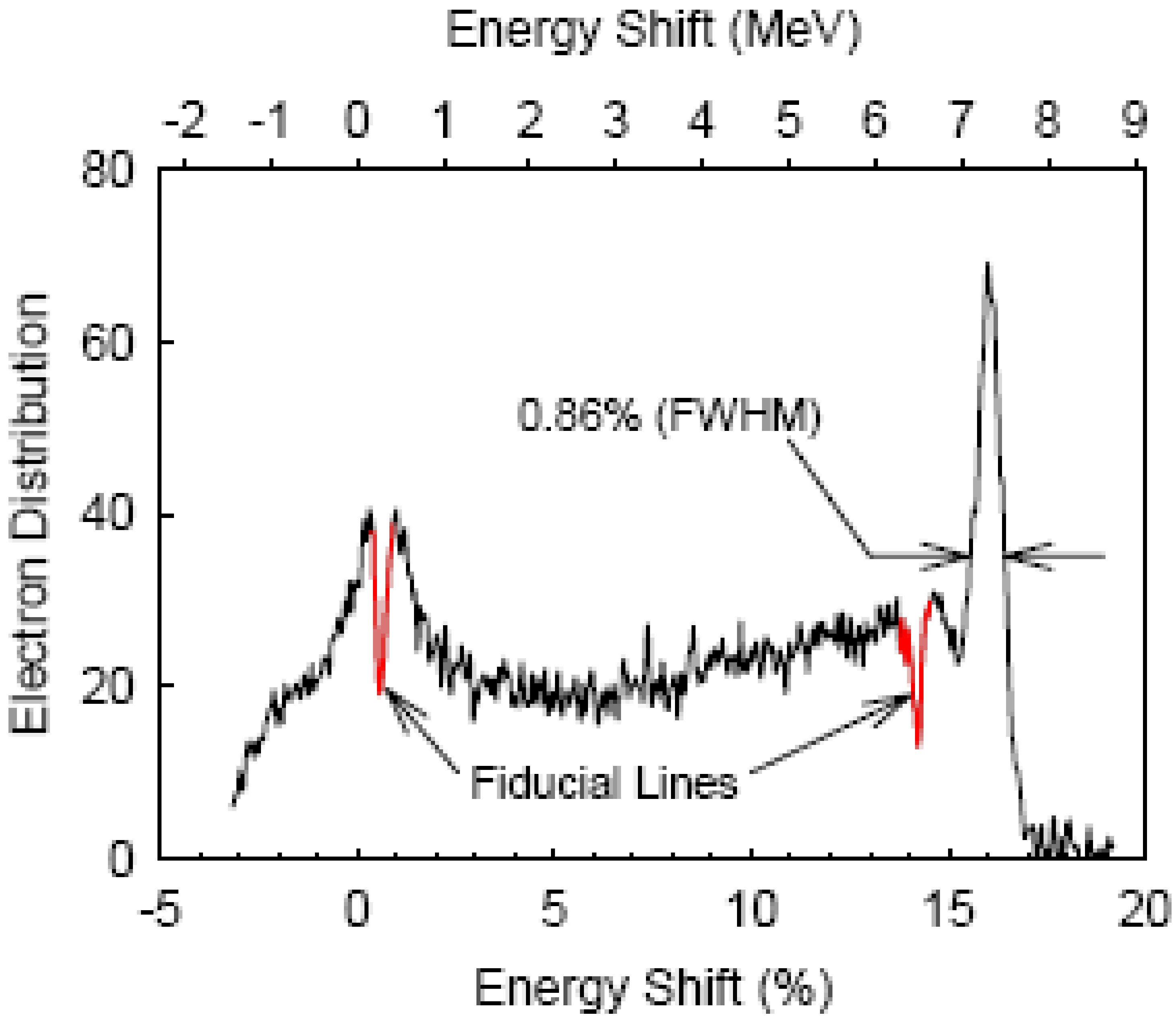
Seeder for staged acceleration



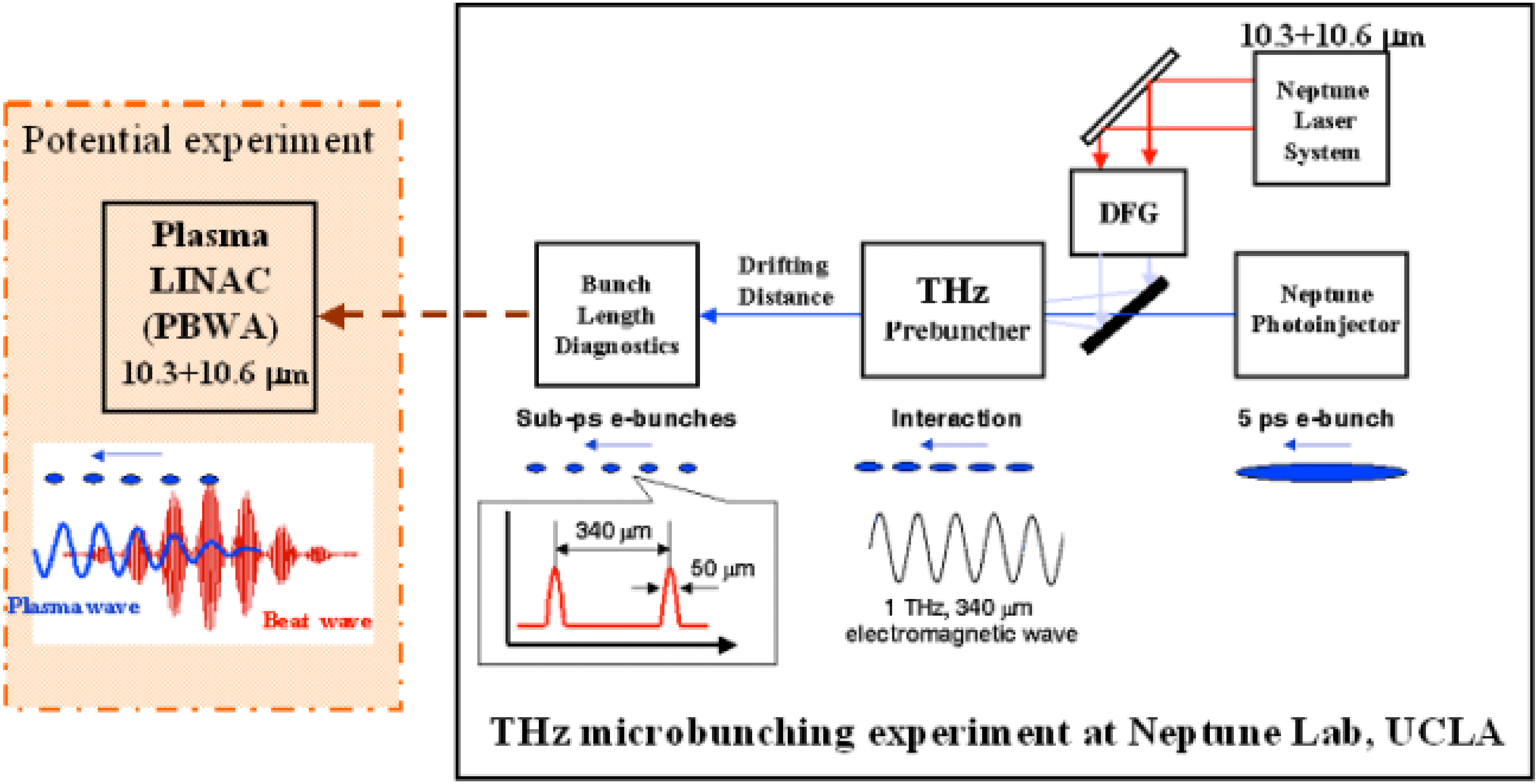
Courtesy: W. Kimura et al. Proc. Of 2003 PAC, 1909



Parameter	Value
E-beam energy	45.6 MeV
E-beam intrinsic energy spread	~0.04%
E-beam normalized emittance	1.5 mm-mrad
E-beam charge	~0.1 nC
E-beam pulse length	~3 ps
Laser wavelength	10.6 μm
Laser pulse length	~180 ps
Laser pulse energy	>5 J


Energy Shift (MeV)
-2
-1
0
1
2
3
4
5
6
7
8
9
80
60
40
20
0
Electron Distribution
0.86% (FWHM)
Fiducial Lines
-5
0
5
10
15
20
Energy Shift (%)

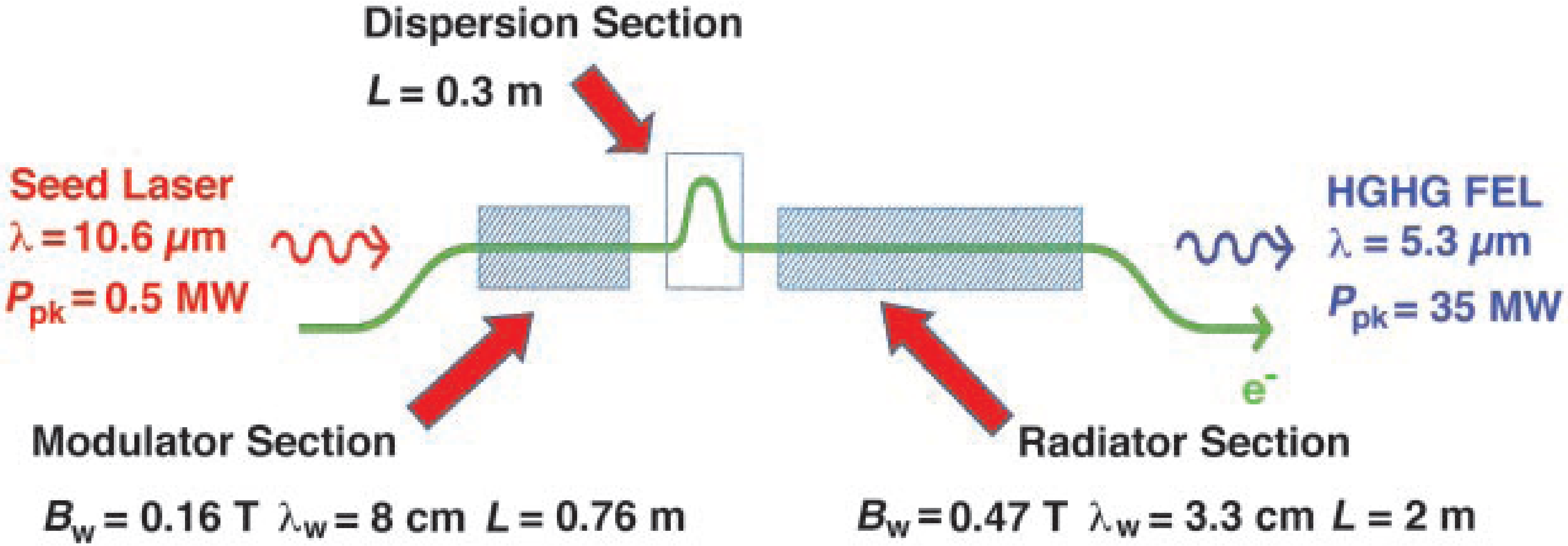
FEL SEEDER



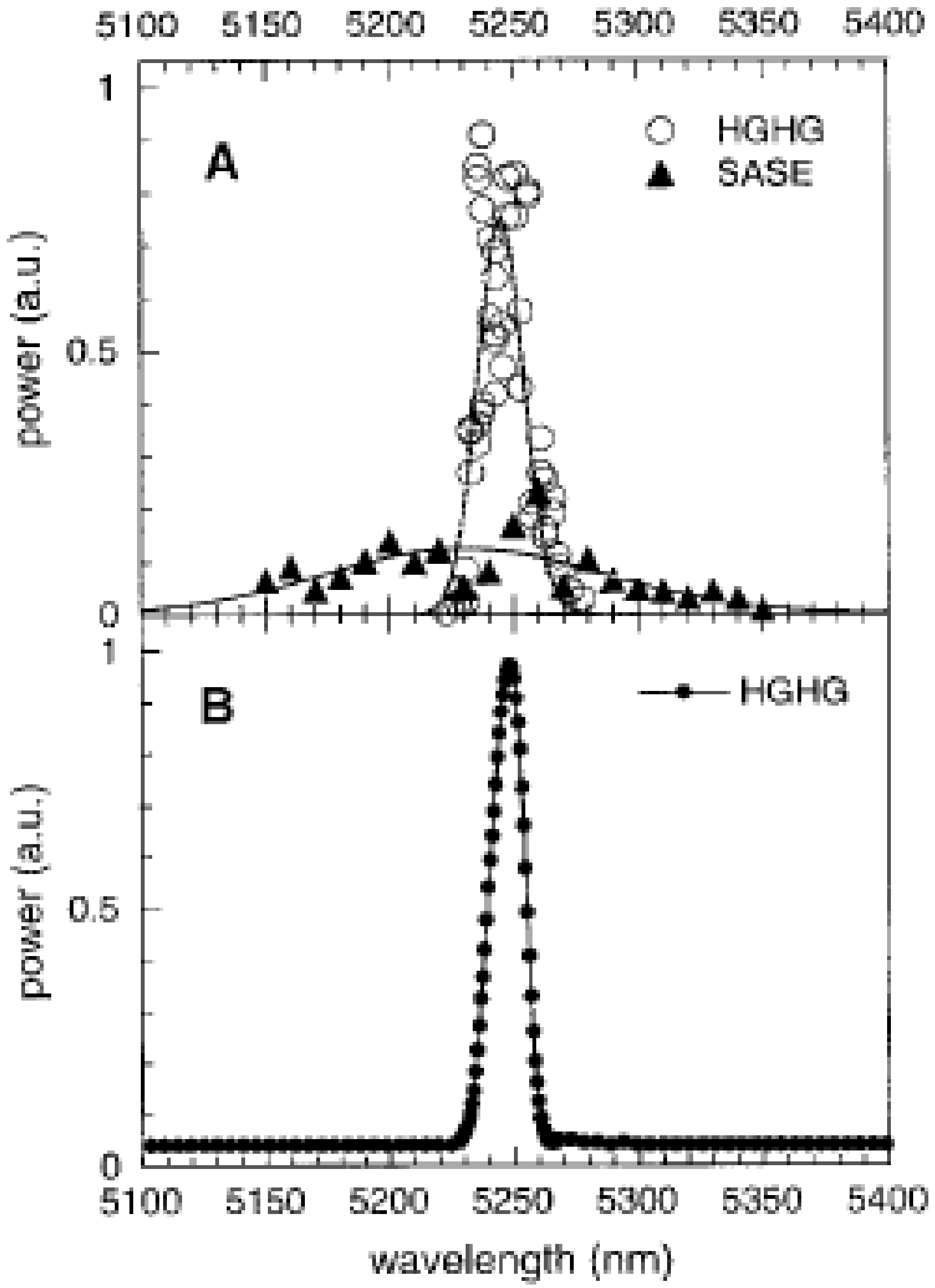
Micro bunches 340 μm apart → seed for THZ FEL

Courtesy: C. Sung et al. Proc. Of 2005 PAC, P. 2812

High Gain Harmonic Generator



Courtesy: L. H. YU et al. Science 289, (2000) 932



A: Comparison of HGHG and SASE

Spectral width of HGHG 15 nm,<< SASE (90 nm)

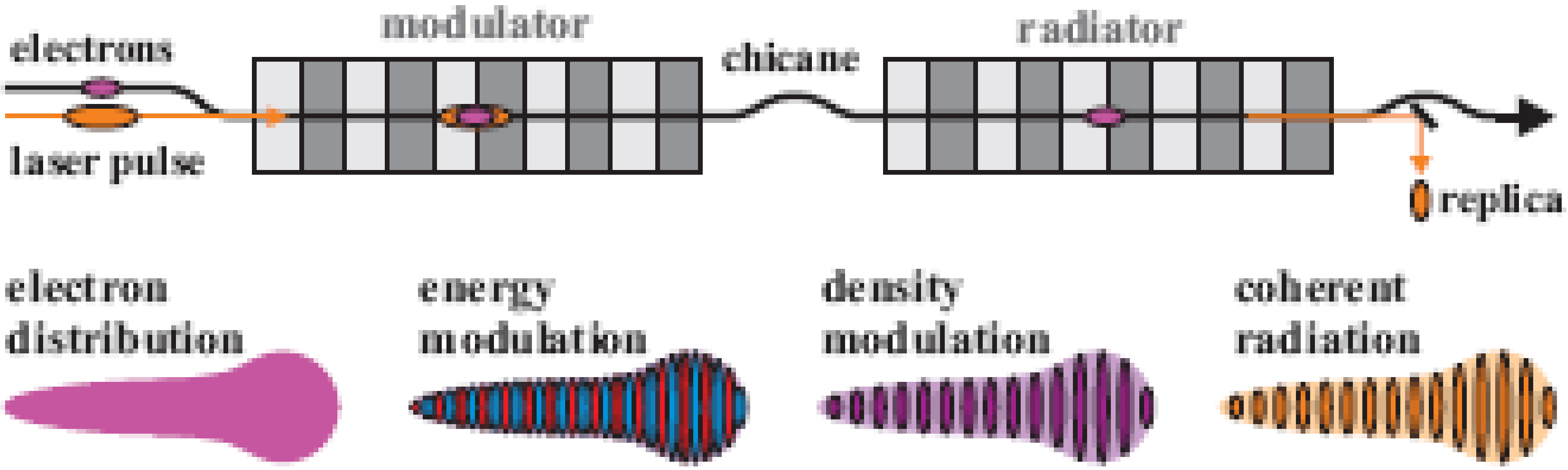
Amplitude of HGHG is $>10^6$ of SASE

B: Spectral distribution of HGHG signal

Technique used to generate VUV, X ray FEL beams: BESSY, SDL @ BNL, LBL, UCB

Source of radiation and use of radiation for electron diagnostics

Slice emittance, longitudinal distribution of short (100 fs) electron bunch can not be measured by standard techniques→ generate optical replica of the electron beam



Use standard optical technique to measure beam parameters

Courtesy: E. Saldin et al. Proc. Of PAC 07, P. 965

Attosecond electron beam generation

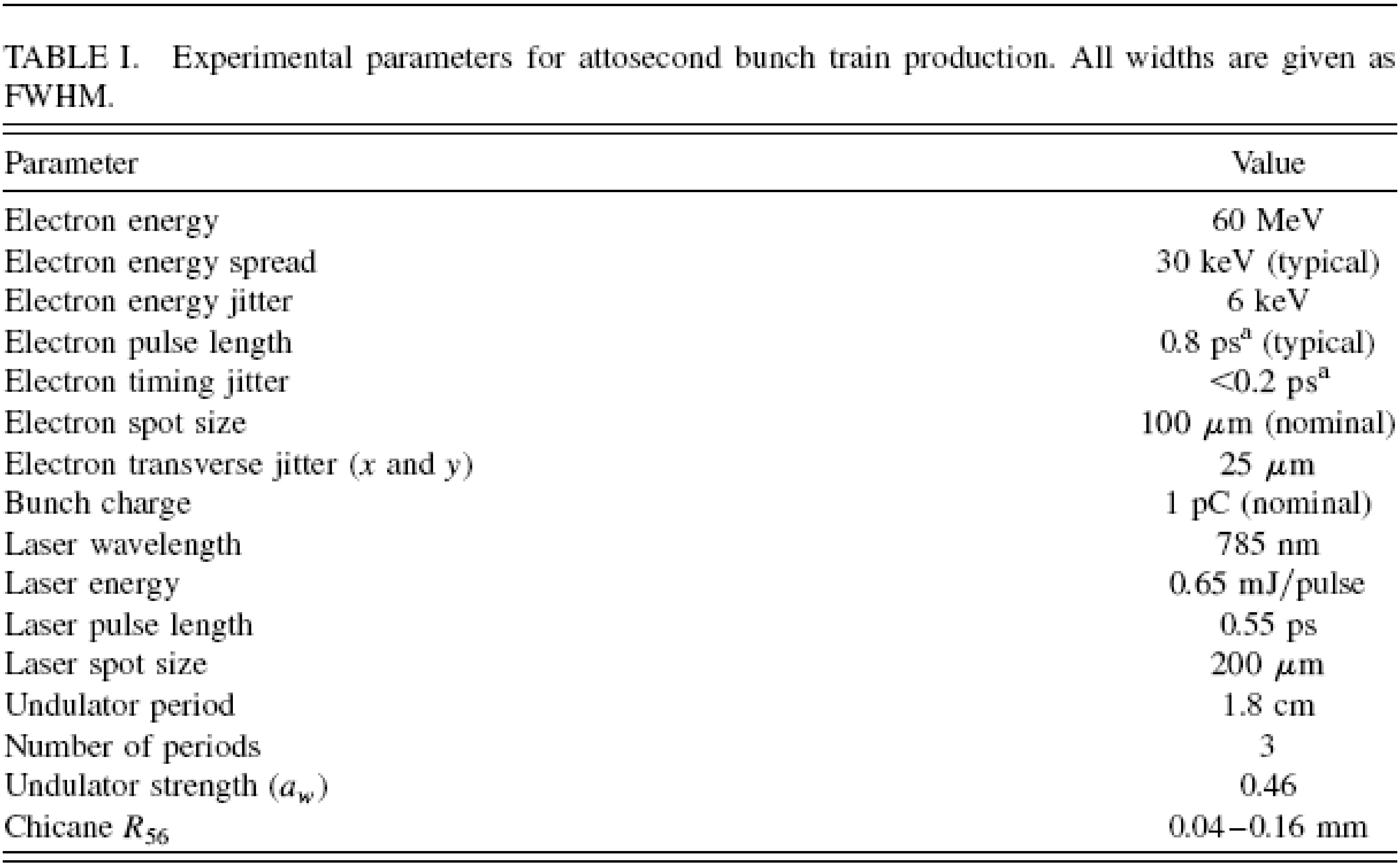
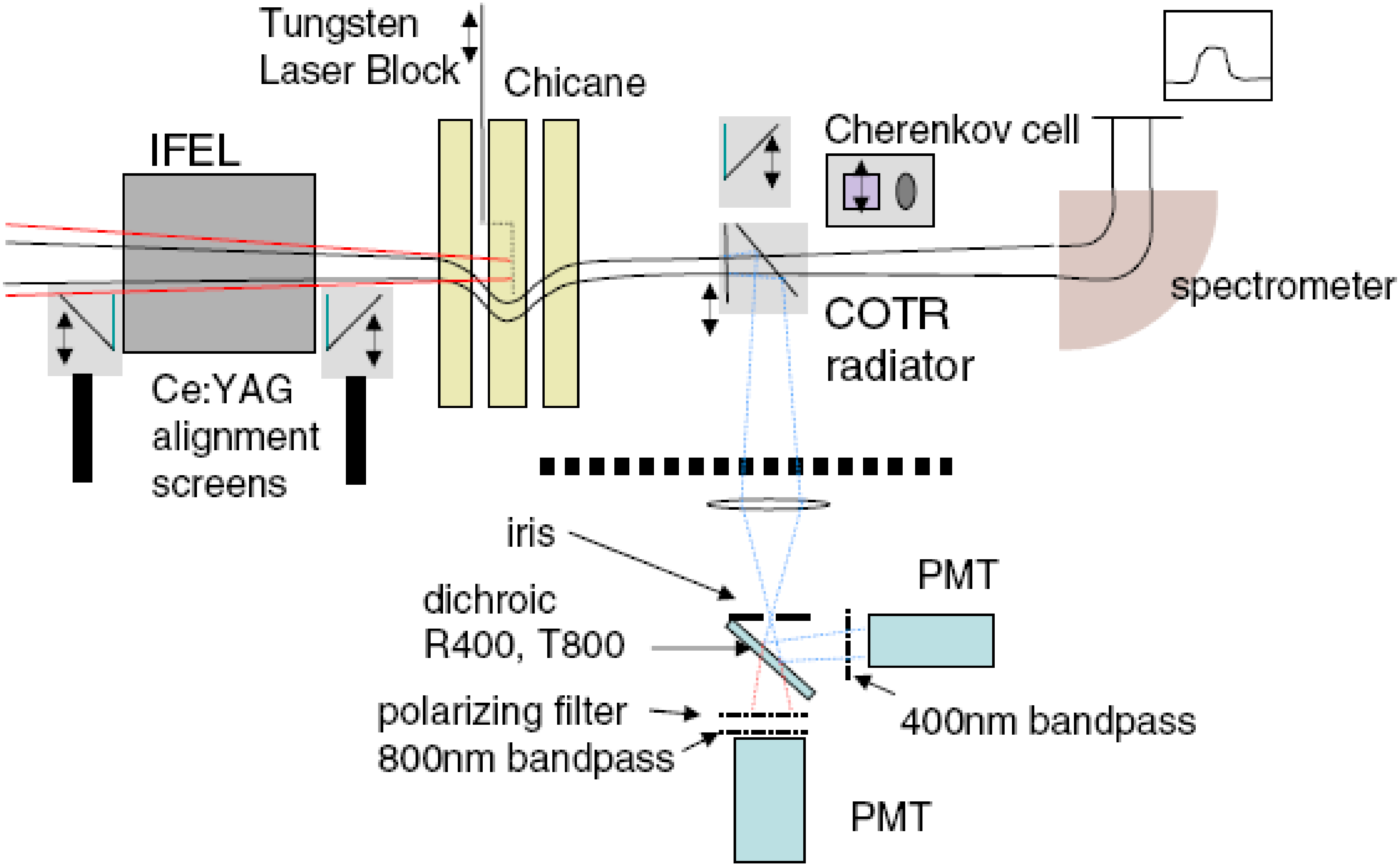
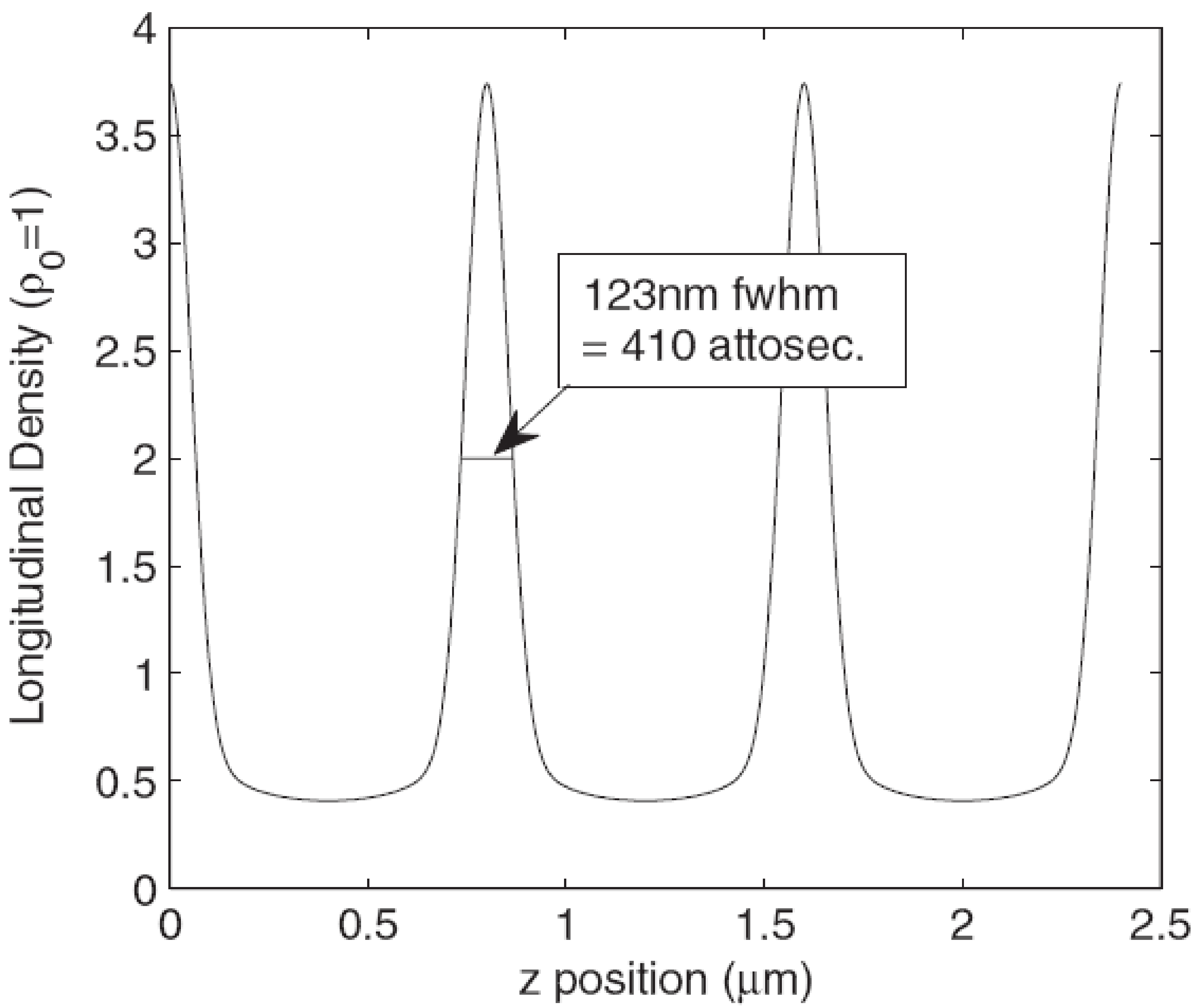


TABLE I. Experimental parameters for attosecond bunch train production. All widths are given as FWHM.

Parameter	Value
Electron energy	60 MeV
Electron energy spread	30 keV (typical)
Electron energy jitter	6 keV
Electron pulse length	0.8 ps[a] (typical)
Electron timing jitter	<0.2 ps[a]
Electron spot size	100 μm (nominal)
Electron transverse jitter (x and y)	25 μm
Bunch charge	1 pC (nominal)
Laser wavelength	785 nm
Laser energy	0.65 mJ/pulse
Laser pulse length	0.55 ps
Laser spot size	200 μm
Undulator period	1.8 cm
Number of periods	3
Undulator strength (a_w)	0.46
Chicane R_{56}	0.04–0.16 mm



Courtesy: C. Sears et al. Phys. Rev. Spl. Topics AB, 11, (2008), 061301



Opens up possibility of accelerating with high intensity Ti:Sa laser