Technion - Israel Institute of Technology
Department of Electrical Engineering

Brookhaven National Laboratory
Accelerator Test Facility

PASER

Particle Acceleration by Stimulated Emission of Radiation

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Outline

- Overview and motivation
- PASER – essence of the concept
  - Wake-field amplification
  - Acceleration of a train of bunches
- PASER – beam-wave interaction
- Experimental setup
- Experiment parameters
- Summary

Overview – Acceleration Concepts

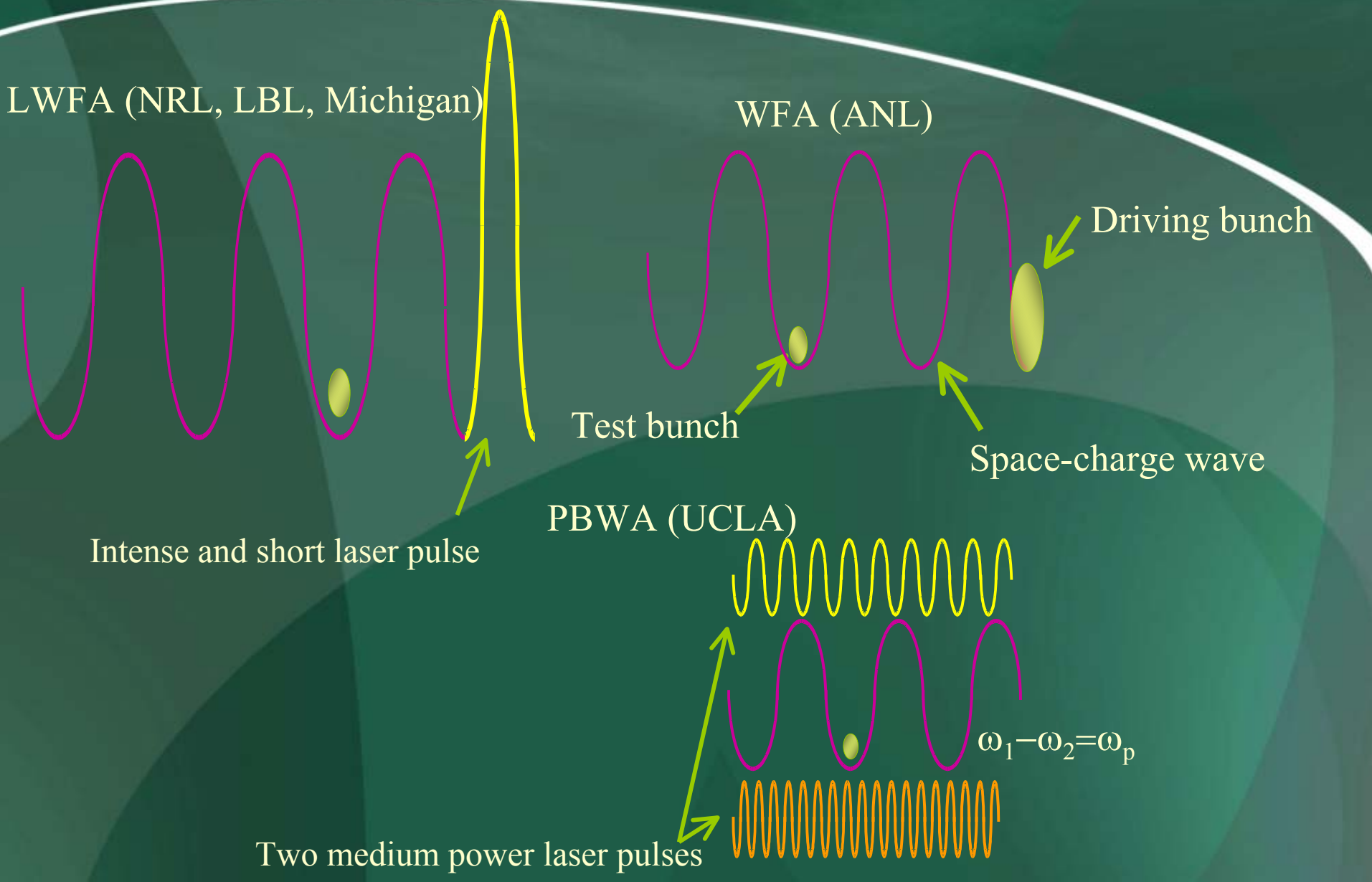
Inverse radiation processes

- Slow-wave
  - Cerenkov
  - Smith-Purcell
- Fast-wave
  - FEL
  - Cyclotron
- Transition radiation
- Laser

Wake-field processes

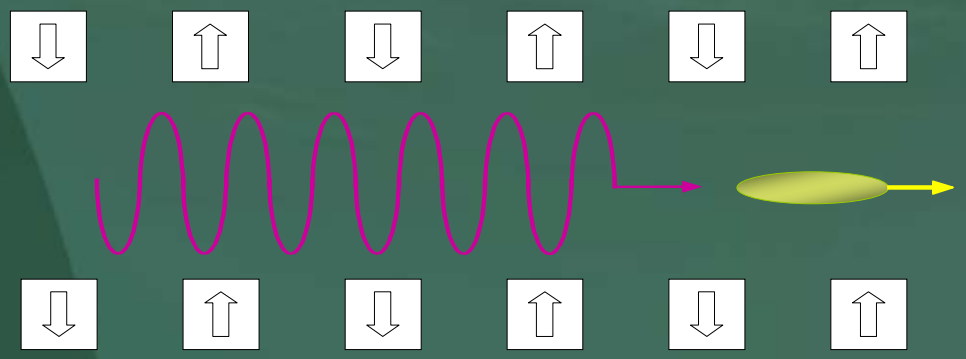
- Laser wake-field
- Plasma wake-field
- Dielectric wake-field
- Plasma beat wave

Overview – Acceleration Schemes



Overview – Acceleration Schemes

Inverse FEL (BNL)



Inverse Smith-Purcell

Inverse Cerenkov

(BNL)

Overview –Energy Source for Acc. Process

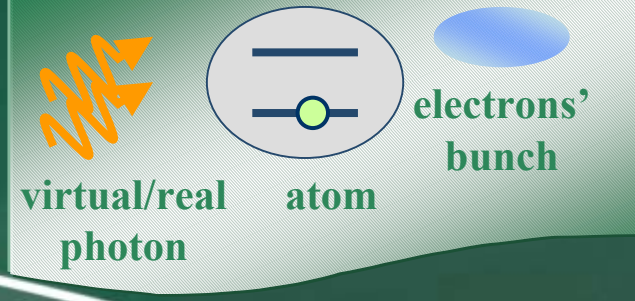
Macroscopic structures

- Cavity (Circular acc.)
- Coupled cavities (linear acc.)
- Electron bunch (wake-field acc.)
- Laser pulse (laser-plasma schemes)

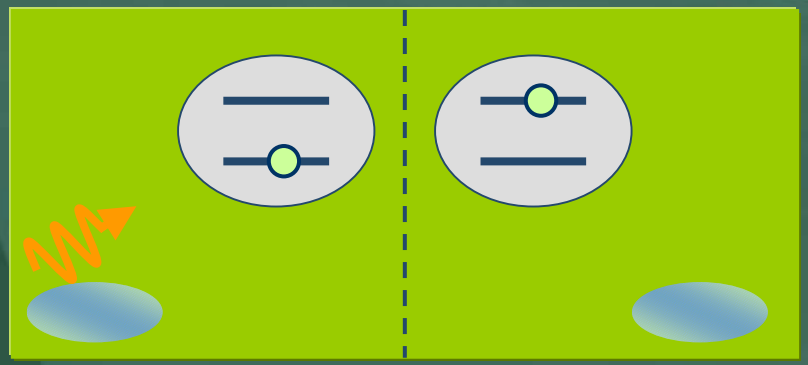
Microscopic structures

- Atom/Molecule (Ar^+, CO_2)
- Dopant in solid-state (Nd:YAG, Ti:Sapphire)

Motivation:
Frank-Hertz, LASER, PASER



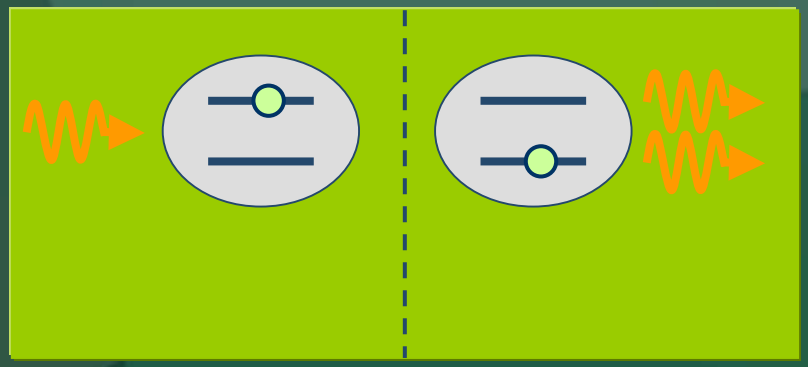
Frank-Hertz



Deceleration

LASER

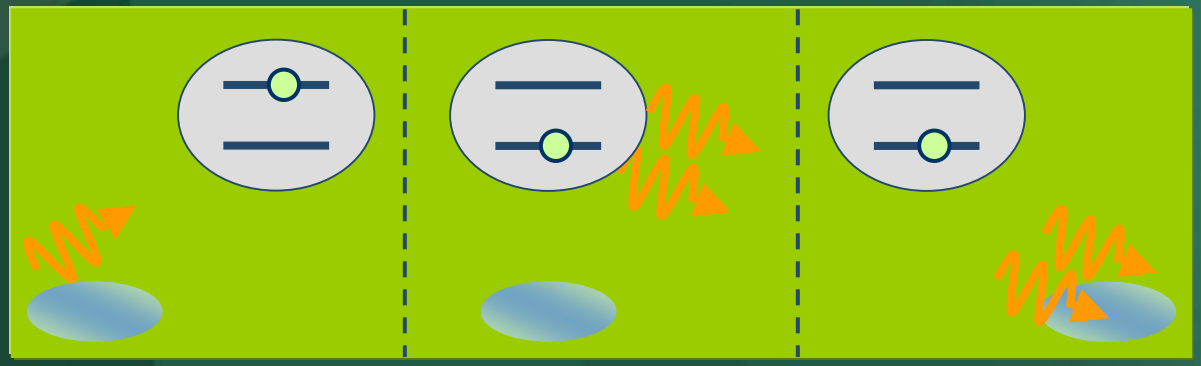
Light Amplification by Stimulated Emission of Radiation



L. Schächter, PLA,205, p. 335 (1995)

PASER

Particle Acceleration by Stimulated Emission of Radiation



Acceleration

Motivation: Wake-field in a medium

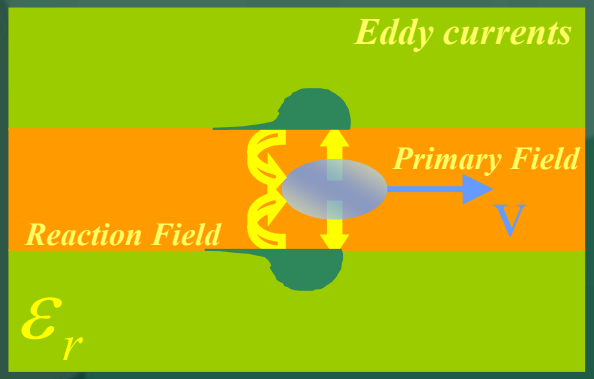
$$\varepsilon_r = \varepsilon_{\mathrm{Re}} + j\varepsilon_{\mathrm{Im}}$$

Passive Dielectric

$$v > c/\sqrt{\varepsilon_{\mathrm{Re}}} \quad ; \quad \varepsilon_{\mathrm{Im}} = 0$$

Decelerating Force

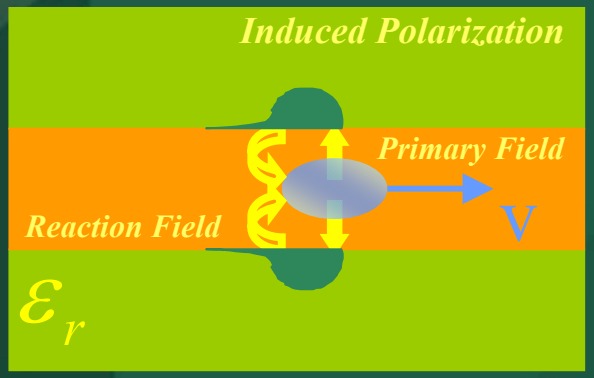
Resistive Material



$$\varepsilon_{\mathrm{Re}} = 1 \quad ; \quad \varepsilon_{\mathrm{Im}} < 0$$

Decelerating Force

Active Medium



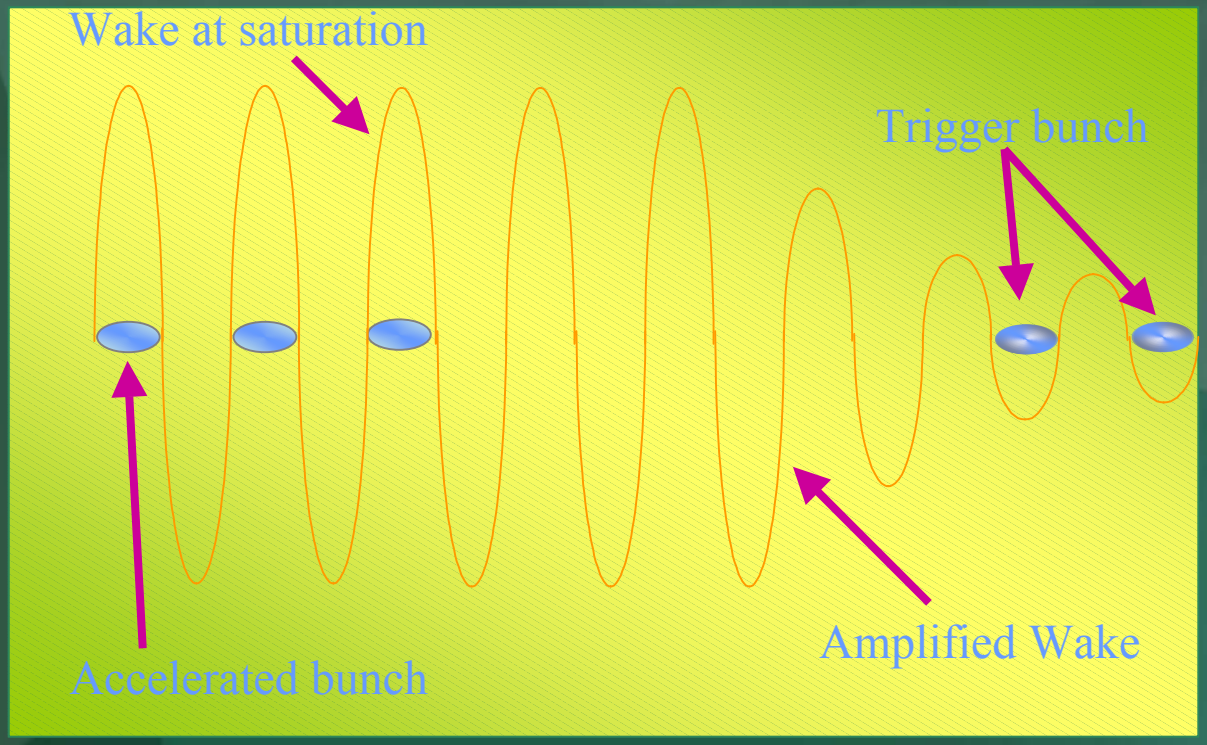
$$\varepsilon_{\mathrm{Re}} \gg \varepsilon_{\mathrm{Im}} \quad ; \quad \varepsilon_{\mathrm{Im}} > 0$$

Accelerating Force

PASER – Possible Implementation

1

Wake-Field Amplification



- Competition with Cerenkov radiation.
- Wake amplification reduces the population inversion.
- Saturation of bunch-wave interaction.

L. Schächter,
PRL, 83, 1, p. 92 (1999)

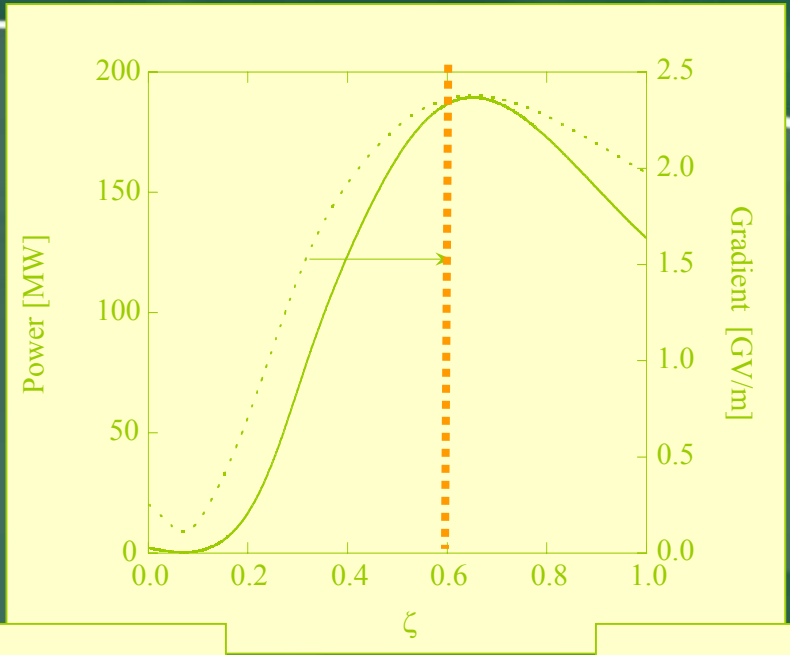
PASER – Beam-wave interaction

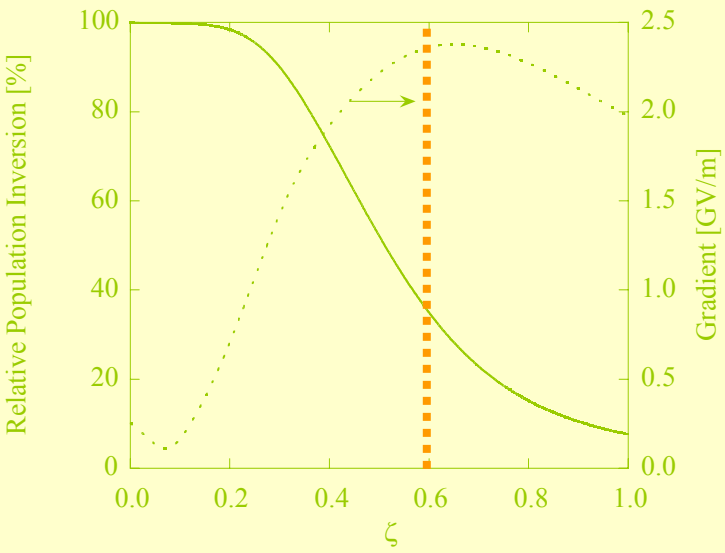
$$\left.\begin{aligned}
\frac{d}{d\xi}\ a &= \alpha\ \left\langle e^{-j\chi_i}\right\rangle + \left(\frac{1}{2}\sigma\ \ N_{ph} d\right)\ a \\
\frac{d}{d\xi}\ \gamma_i &= -\frac{1}{2}\left[a\ \ e^{j\chi_i}\ +\ c.c.\right] \\
\frac{d}{d\xi}\ \chi_i &= \Omega\left(\frac{1}{\beta_i} - \frac{1}{\beta_{ph}}\right) \\
\frac{d}{d\xi} N_{ph} &= -\left(\frac{|a|^2}{2\alpha}\right)\left(\sigma\ \ d\ \ N_e\ \ \frac{mc^2}{\hbar\omega}\right)\ N_{ph}
\end{aligned}\right\} \Rightarrow \frac{d}{d\xi}\left[\underbrace{\left\langle\gamma_i\right\rangle - 1}_{Kinetic\ \ Energy} + \underbrace{\frac{|a|^2}{2\alpha}}_{EM\ \ Energy} + \underbrace{\frac{N_{ph}\hbar\omega}{N_e\ \ mc^2}}_{Energy\ \ in\ \ Medium}\right] = 0$$

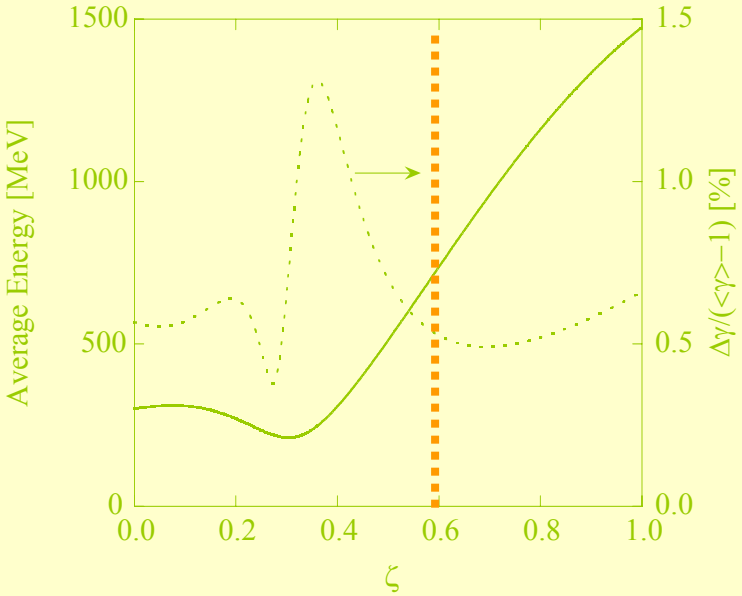
L. Schächter,
PRL, 87, 1, p. 134802-1 (2001)

PASER – Beam-wave interaction

L. Schächter,
PRL, 87, 1, p. 134802-1 (2001)





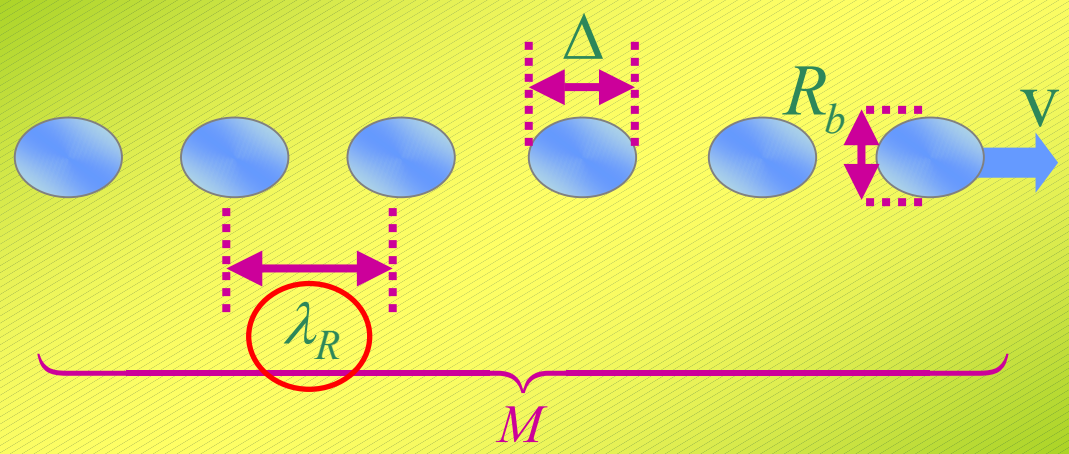


PASER – Essence of the Concept

2

Train of Micro-Bunches

$$\varepsilon = 1 + \frac{\omega_p^2}{\omega_R^2 + 2j\alpha\omega - \omega^2}$$



Number of micro-bunches in one macro bunch

- The train consists of M micro-bunches, each one of length Δ and radius and charge (q)
- Maximum energy transfer is obtained on resonance i.e. the resonance frequency of the medium is given by $\omega_R = 2\pi c / \lambda_R$

PASER – Efficiency (relative change in the kinetic energy)

Interaction length

Transverse form factor

Longitudinal form factor

$$\eta \equiv \frac{W}{N_{el} mc^2 (\gamma - 1)}$$

$$\approx \frac{8N_{el}}{\gamma - 1} \frac{w_n d \left(\pi r_e^2\right)}{\hbar \omega_R} S\left(2\pi \frac{R_b}{\lambda_R \gamma}\right) \mathrm{sinc}^2\left(\pi \frac{\Delta}{\lambda_R}\right)$$

$$\eta \approx 9\%$$

Number of electrons in macro-bunch

Energy density at resonance

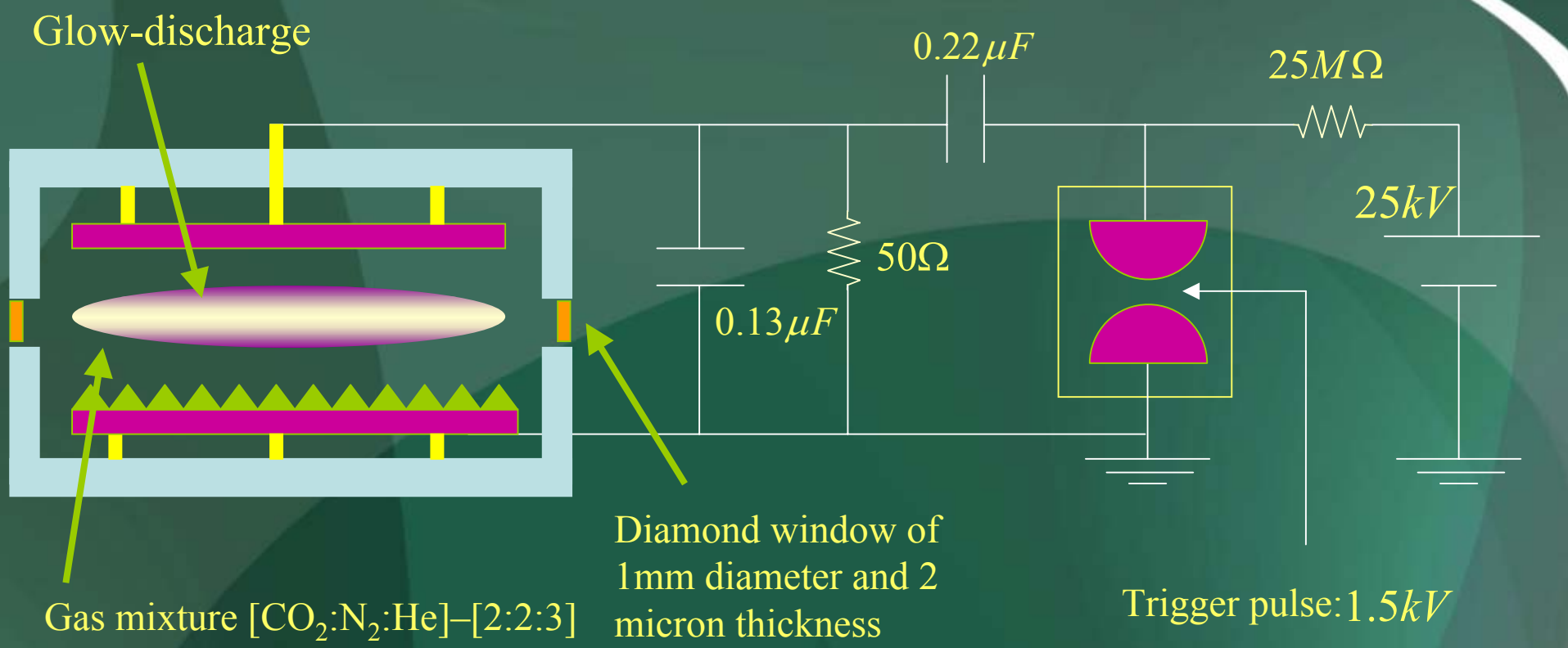
$mc^2(\gamma - 1) = 70 MeV$ $\quad$ $d \sim 0.5 m$

$w_{ph} = 10^2 J/m^3$ $\quad$ $\lambda_R = 10.6 \mu m$

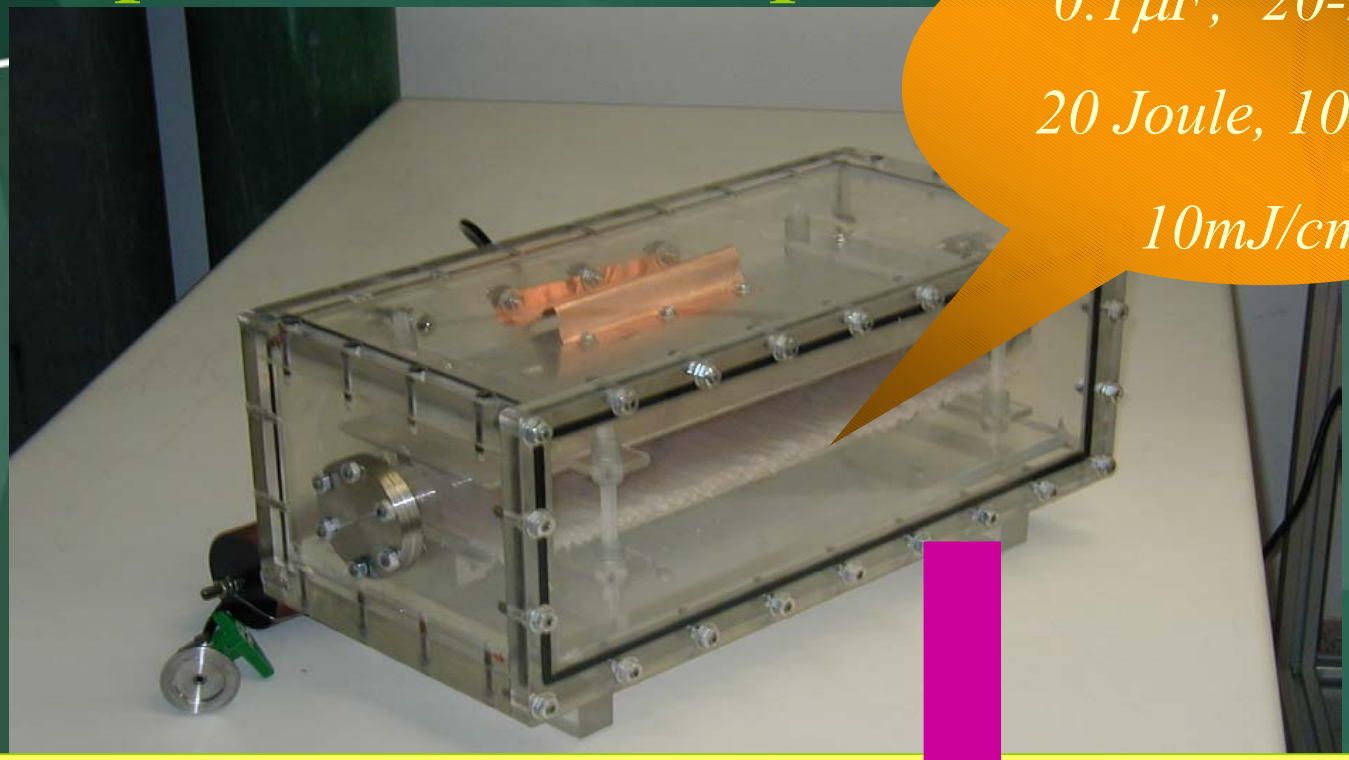
$N_{el} = 5 \times 10^9$ $\quad$ $\Delta \sim 0.5 \lambda_R$

$$S(u) \equiv \frac{4}{u^2} I_1(u) K_1(u) + \frac{2}{u}\left[I_1(u) K_0(u) - I_0(u) K_1(u)\right]$$

Experimental setup



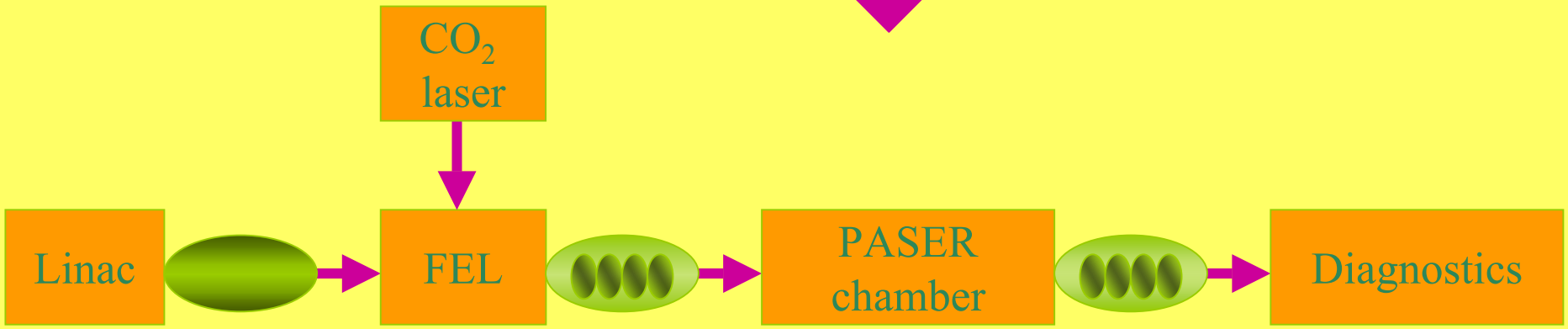
Experimental setup



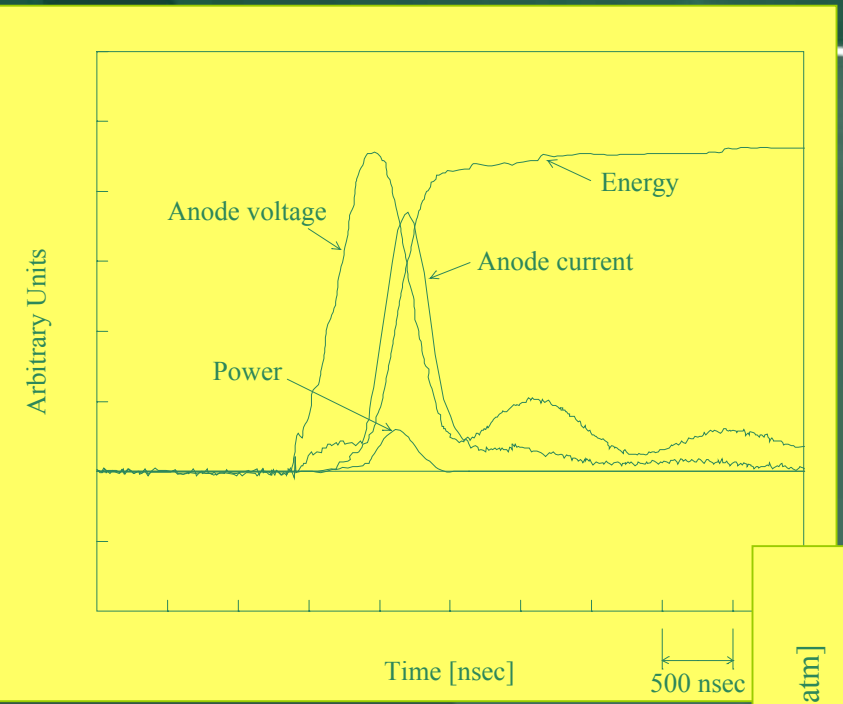
0.1μF; 20-25kV,

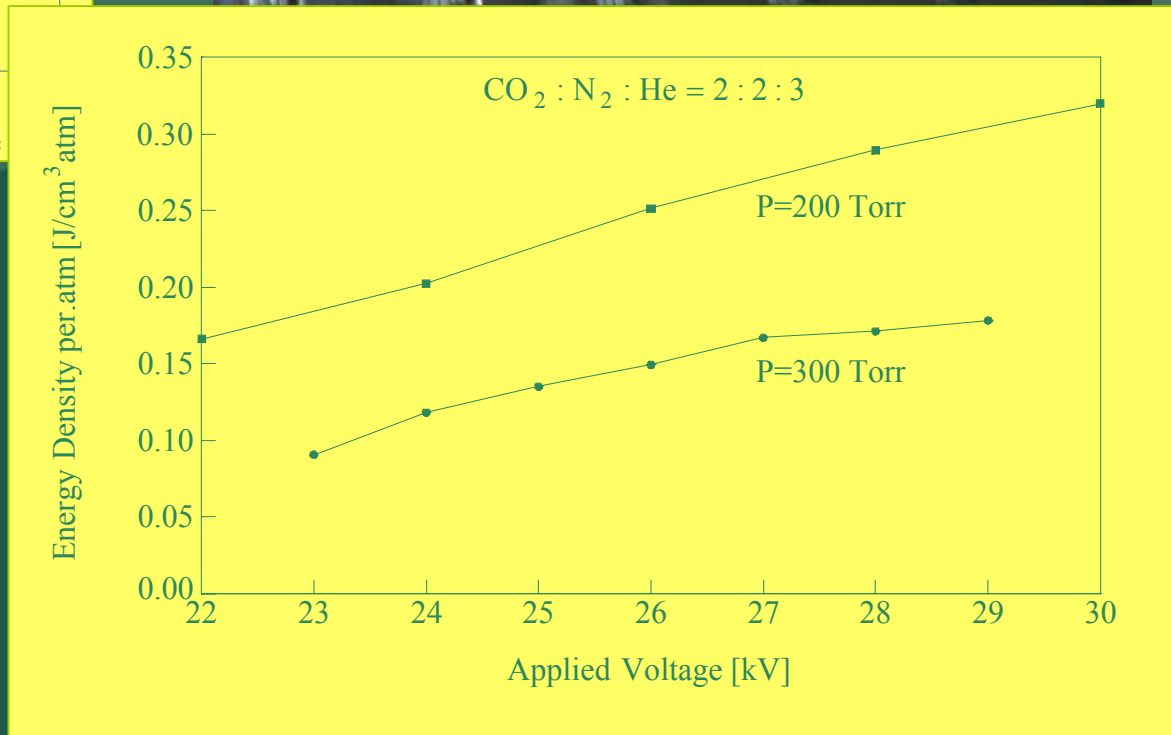
20 Joule, 100nsec

10mJ/cm^3



PASER Chamber Characteristics





Experiment parameters

PASER's chamber parameters

- pressure 0.2-0.3 [atm]
- Interaction length 40 [cm]
- window's thickness 2 [μm]
- window's diameter 1[mm]
- population inversion density 10^3 [J/m^3]

E-beam parameters

- Energy 70 [MeV]
- charge in a macro-bunch 0.5 [nc]
- emittance 2 [mm-mrad]
- pulse duration 5 [ps]
- diameter 100 [μm]
- energy spread after bunching 1%

Laser pulse parameters (CO_2)

- wavelength 10.6[μm]
- power 30 [GW]
- focal width 200 [μm]
- pulse duration 200 [ps]
- rep. rate 33-50 [kHz]

Experiment's main steps

- ***Step* I: *CO_2 laser off and PASER chamber off .***
  Effect of passive PASER chamber on uniform macro-bunch.
- ***Step* II: *CO_2 laser on and PASER chamber off .***
  Effect of passive PASER chamber on bunched macro-bunch.
- ***Step* III: *CO_2 laser off and PASER chamber on.***
  Effect of active PASER chamber on uniform macro-bunch.
- ***Step* IV: *CO_2 laser on and PASER chamber on.***
  Effect of active PASER chamber on bunched macro-bunch.

Schedule

- October 2002: Experiment approved by Steering Committee
- August 2004: Israeli NSF approved funding for the experiment – due October 2006.
- April 2005: Dr. Samer Banna (Post Doc) came to ATF
- August 2005: Experiment scheduled.
- February 2006: Second run

Summary

- Wake generated by a bunch in a medium may be amplified by the active medium. Electrons of the bunch or of a trailing bunch may be accelerated by the amplified wake. High accelerating gradient may be produced by the wake when the active medium reaches saturation.
- Energy exchange may be obtained when a train of micro-bunches that is modulated at frequency of the resonance frequency of the medium it traverses.