# 1st Experimental Evidence for PASER: Particle Acceleration by Stimulated Emission of Radiation

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PAC07 - Albuquerque, June 27th 2007

# Acknowledgements

- **Acknowledgements**
  - Ilan Ben-Zvi (BNL)
  - Accelerator Test Facility Staff (BNL)
  - Wayne D. Kimura (STI Optronics)
  - Feng Zhou (SLAC)
- **Supported by**
  - The Israel Science Foundation (ISF)
  - The United States Department of Energy (DoE)

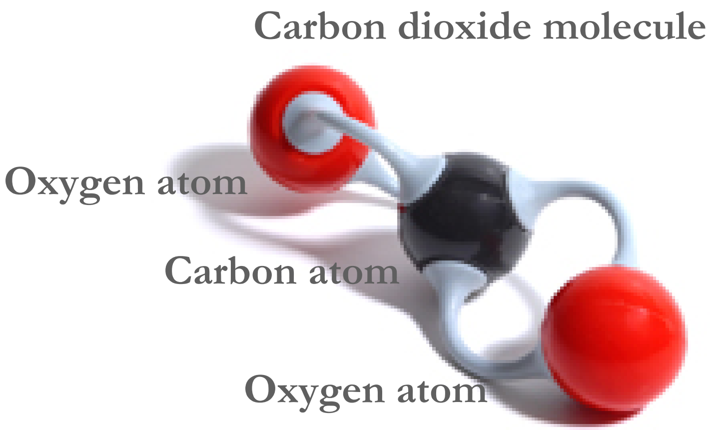
# Outline

- **Motivation**
- **Essence of PASER**
  - Macroscopic perspective
  - Microscopic perspective
  - Theoretical model
- **Proof-of-principle experiment**
  - Experimental setup
  - Experimental evidence
- **Future directions**
  - Boosting the gradient
  - PASER staging
- **Concluding remarks**

# Motivation – Energy Sources

## Macroscopic Structures

- Cavity (Circular Acc.)
- Coupled cavities (linear Acc.)
- Electron bunch (Wake-field Acc.)
- Laser pulse (Laser-plasma schemes)



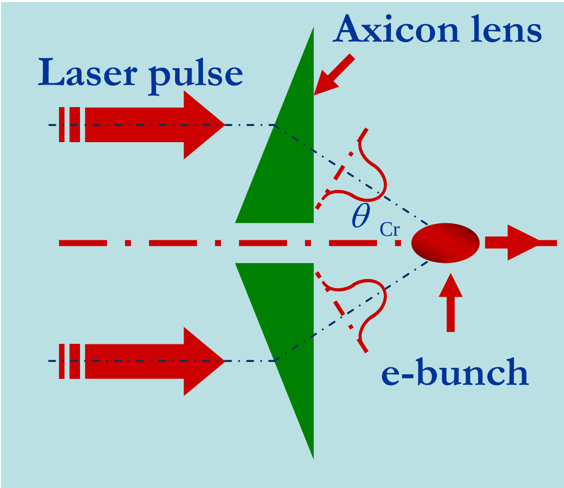


## Microscopic Structures

- Atom/molecule ($Ar^+$, $CO_2$)
- Solid-State (Nd:YaG)

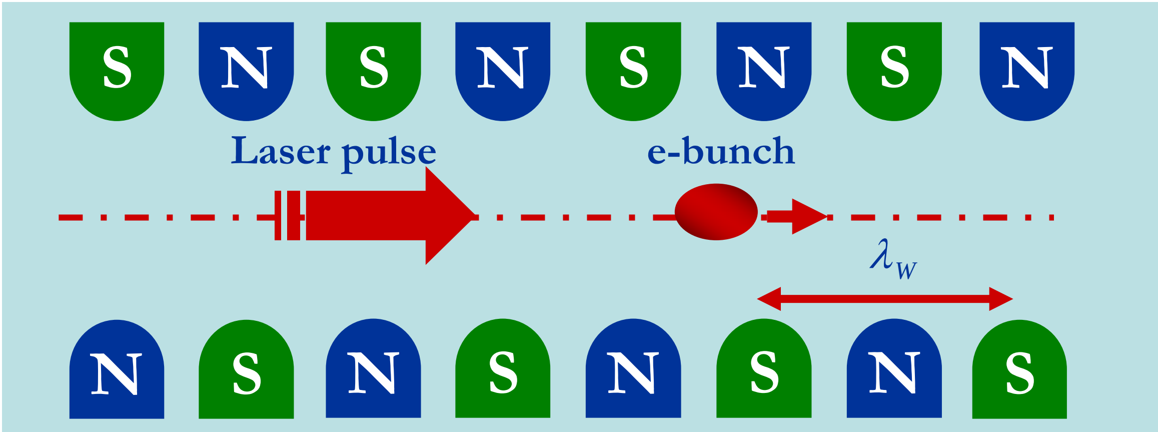
# Motivation – Inverse Radiation Processes

## ICA




**PASER = Inverse-laser acceleration scheme**

## IFEL



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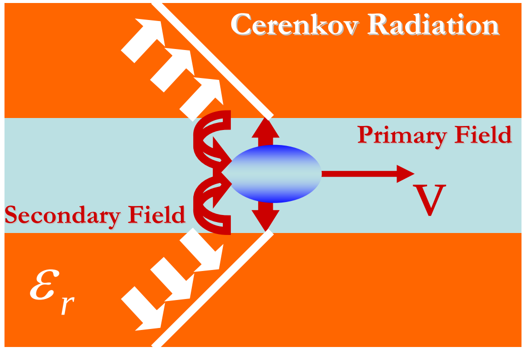
# Essence of PASER – Macro

## 1 Passive Dielectric

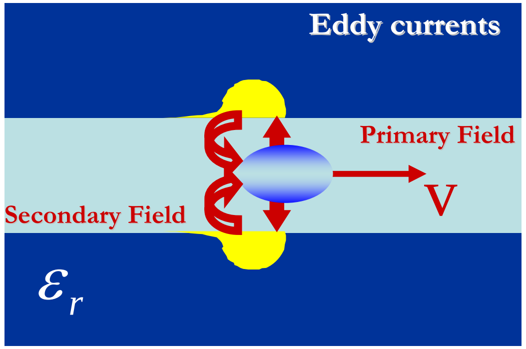



$$\mathrm{Re}(\varepsilon_r) < \left(\frac{c}{\mathrm{v}}\right)^2$$

$$\mathrm{Im}(\varepsilon_r) = 0$$

**Decelerating Force**

## 2 Resistive Material

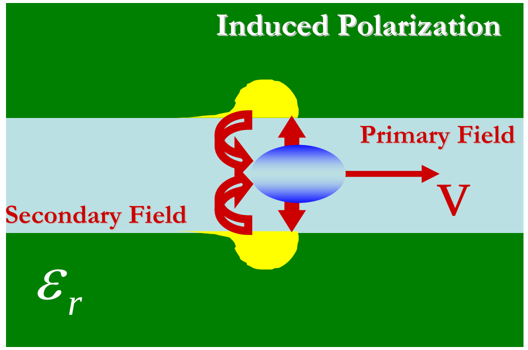



$$\mathrm{Re}(\varepsilon_r) = 1$$

$$\mathrm{Im}(\varepsilon_r) = -\frac{\sigma}{\varepsilon_0 \omega} < 0$$

**Decelerating Force**

## 3 Active Medium




$$\mathrm{Re}(\varepsilon_r) >> \mathrm{Im}(\varepsilon_r)$$

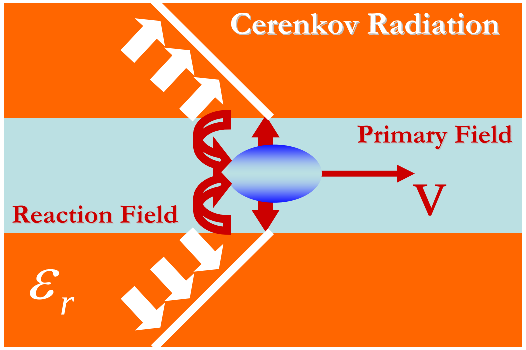
$$\mathrm{Im}(\varepsilon_r) > 0$$

**Accelerating Force**

Schächter, PRE 53, p. 6427, 1996

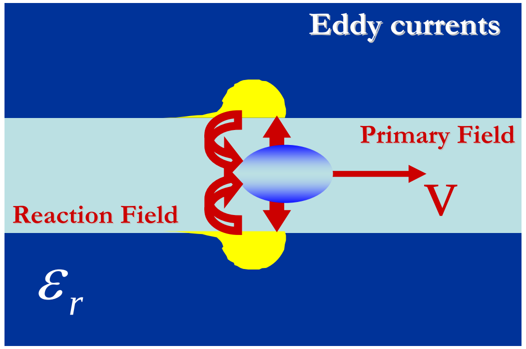
# Essence of PASER – Macro

## 1 Passive Dielectric



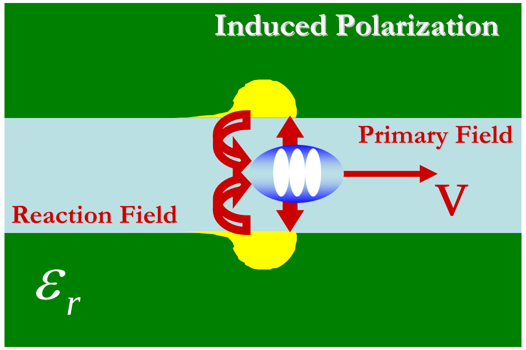

Broadband Field
Broadband Material

## 2 Resistive Material




Broadband Field
Broadband Material

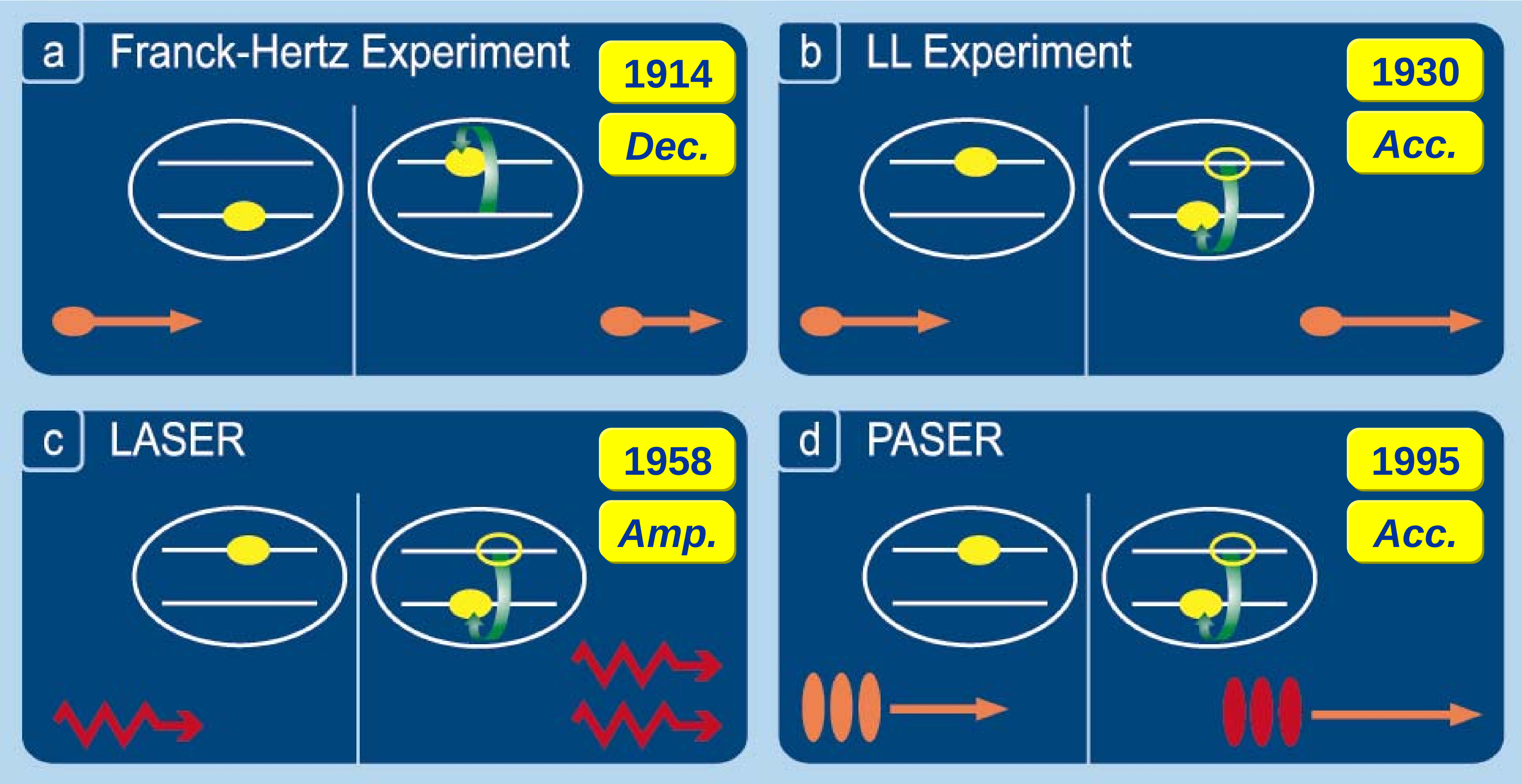
## 3 Active Medium




Narrowband Field
Narrowband Material

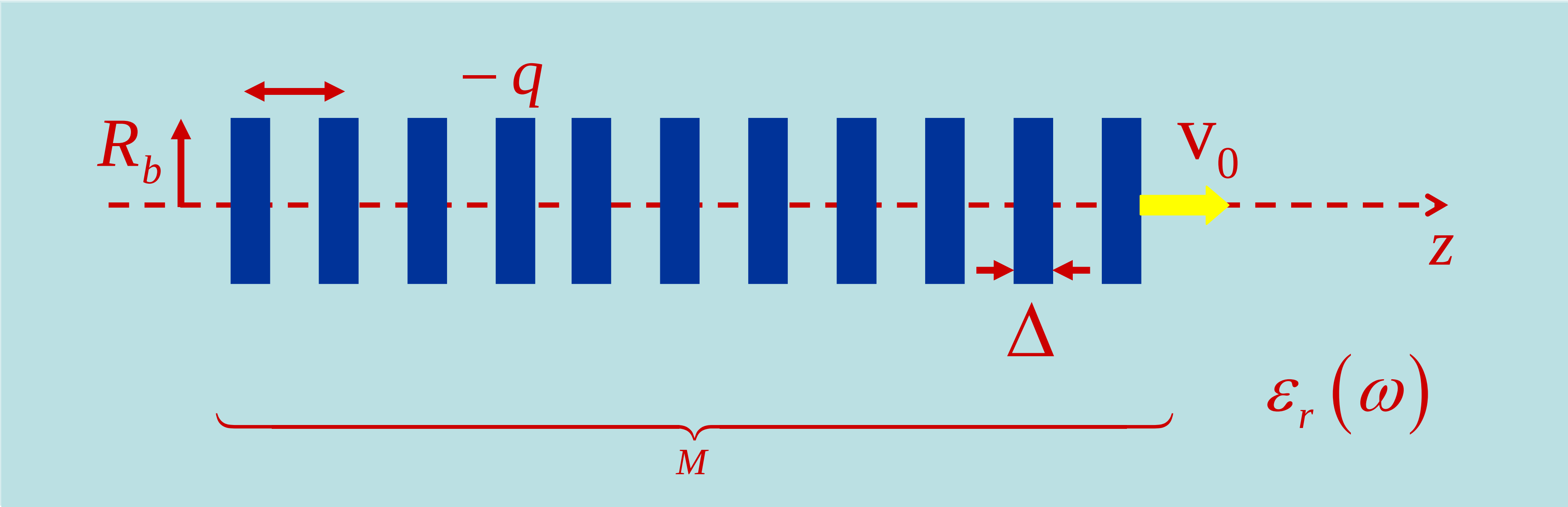
Train of bunches !!!

# Essence of PASER – Micro




Schächter, Phys. Lett. A 205, p. 355, 1995
Banna, Berezovsky and Schächter, PRL 97, 134801, 2006

# Essence of PASER – Theoretical Model



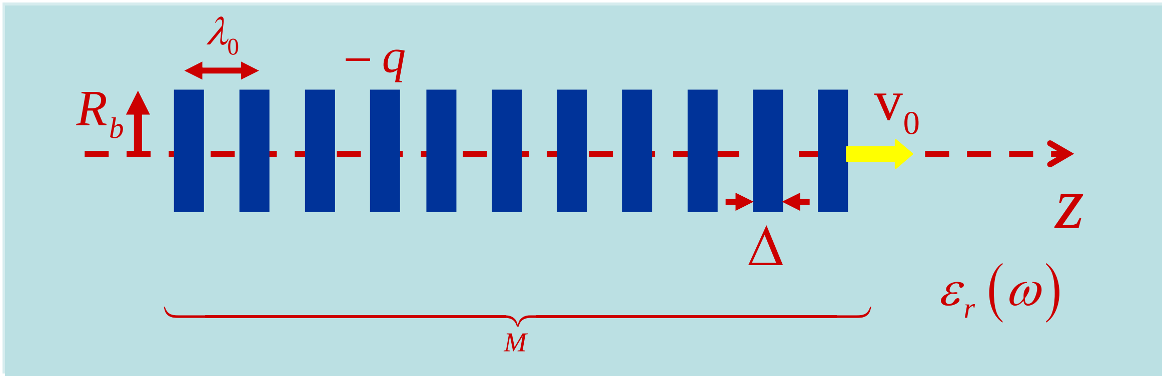

## Assumptions

- Linear medium
- Medium has a single resonance
- No Cerenkov radiation
- Constant longitudinal velocity
- No transverse motion
- Uniform micro-bunches

Banna, Berezovsky and Schächter, PRE 74, 046501, 2006

# Essence of PASER – Theoretical Model

## Relative Change in Kinetic Energy




# of electrons in macro-bunch

Energy density stored at resonance

$$\frac{\Delta E_k}{E_k} \simeq \frac{4N_{\mathrm{el}}}{\gamma-1}\left[d\left(\pi r_e^2\right)\frac{\mathrm{w}_{\mathrm{act}}}{\hbar\omega_0}\right]\mathrm{sinc}^2\left(\pi\frac{\Delta}{\lambda_0}\right)\mathrm{sinc}^2\left(\frac{\pi M}{2\gamma^2}\right)F_\perp\left(2\pi\frac{R_b}{\lambda_0}\right)$$

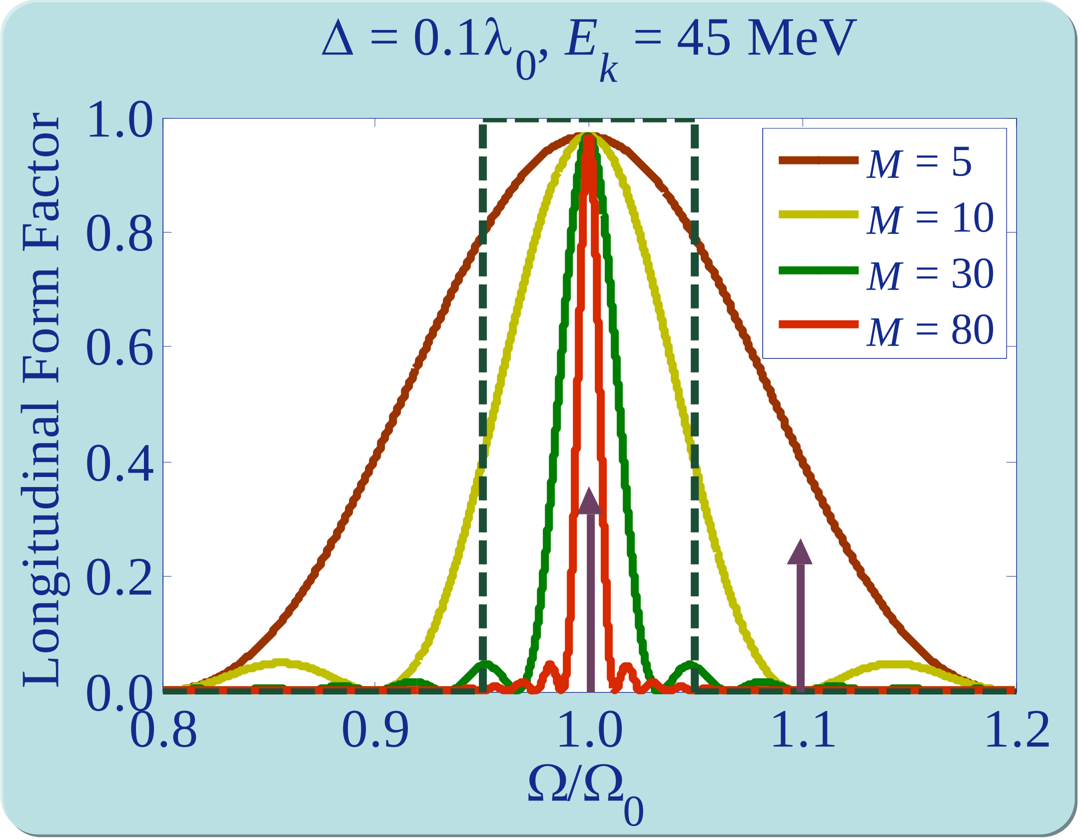
$$r_e \equiv \frac{e^2}{4\pi\varepsilon_0 mc^2}$$

$$F_\perp(u) \equiv \frac{2}{(u)^2}\left(1\text{-}2\mathrm{I}_1(u)\mathrm{K}_1(u)\right)$$

Banna, Berezovsky and Schächter, PRE 74, 046501, 2006

# Essence of PASER – Theoretical Model

## Frequency Selection




$$F_{\parallel}\left(\Omega,\beta,M,\bar{\Delta}\right) \equiv \mathrm{sinc}^2\left(\frac{\Omega}{2\beta}\bar{\Delta}\right)\frac{\mathrm{sinc}^2\left(\frac{\Omega}{2\beta}M\right)}{\mathrm{sinc}^2\left(\frac{\Omega}{2\beta}\right)}$$

$$\frac{1}{T_2} = 5\times10^8\ \mathrm{sec}^{-1}$$

$CO_2$ relaxation time

$M > 30$

$$@CO_2:\ \lambda_0 = 10.2\ \mu\mathrm{m};\ \lambda_1 = 9.2\ \mu\mathrm{m}$$

Banna, Berezovsky and Schächter, PRE 74, 046501, 2006

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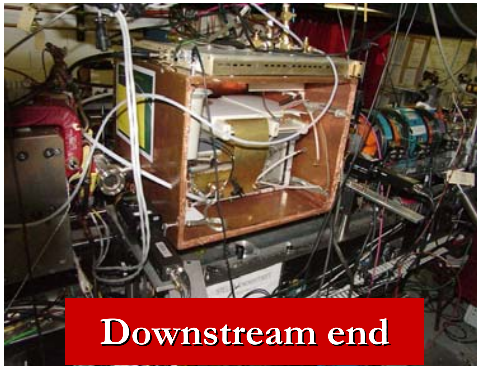
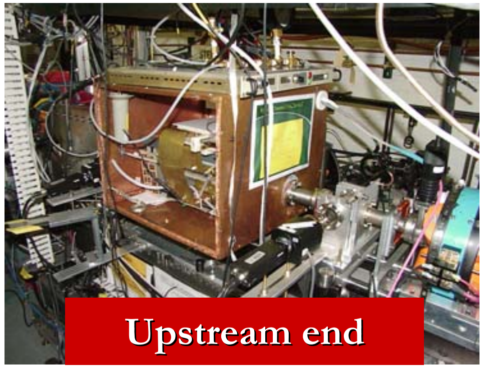
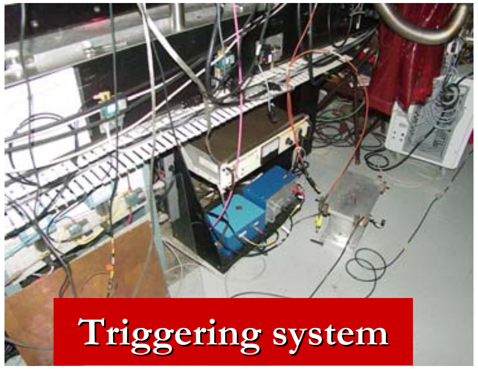
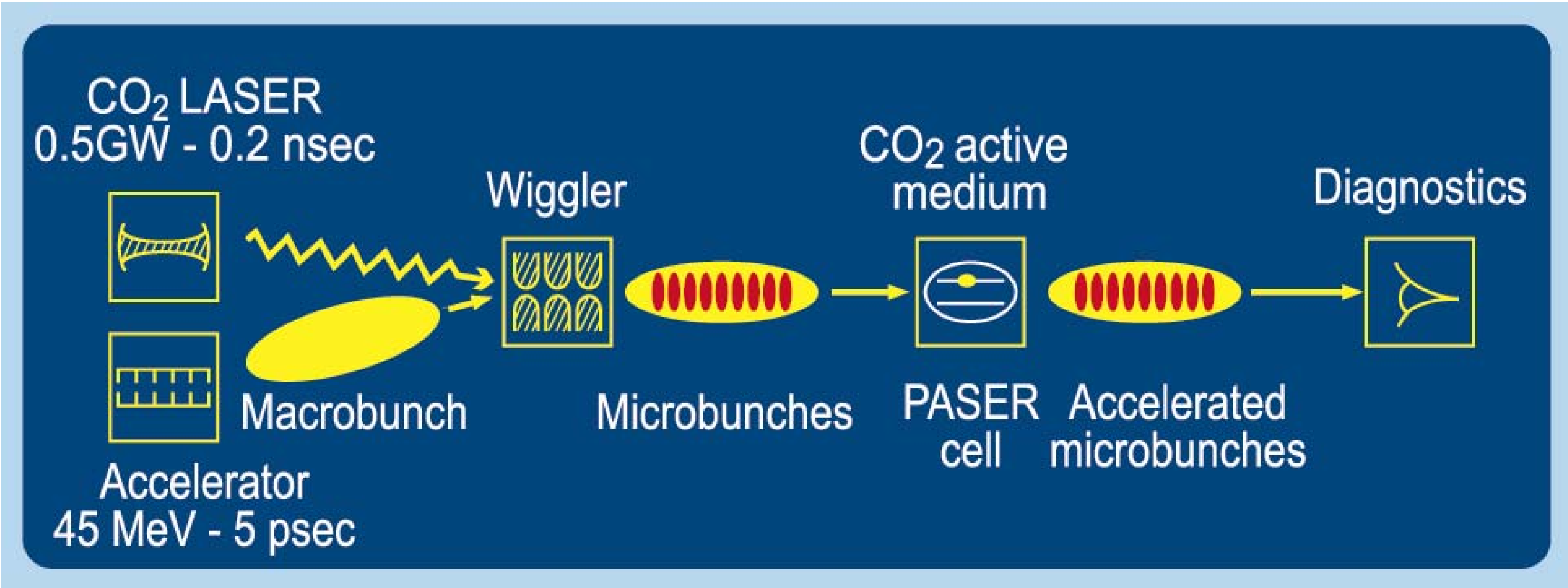
# Experimental Setup



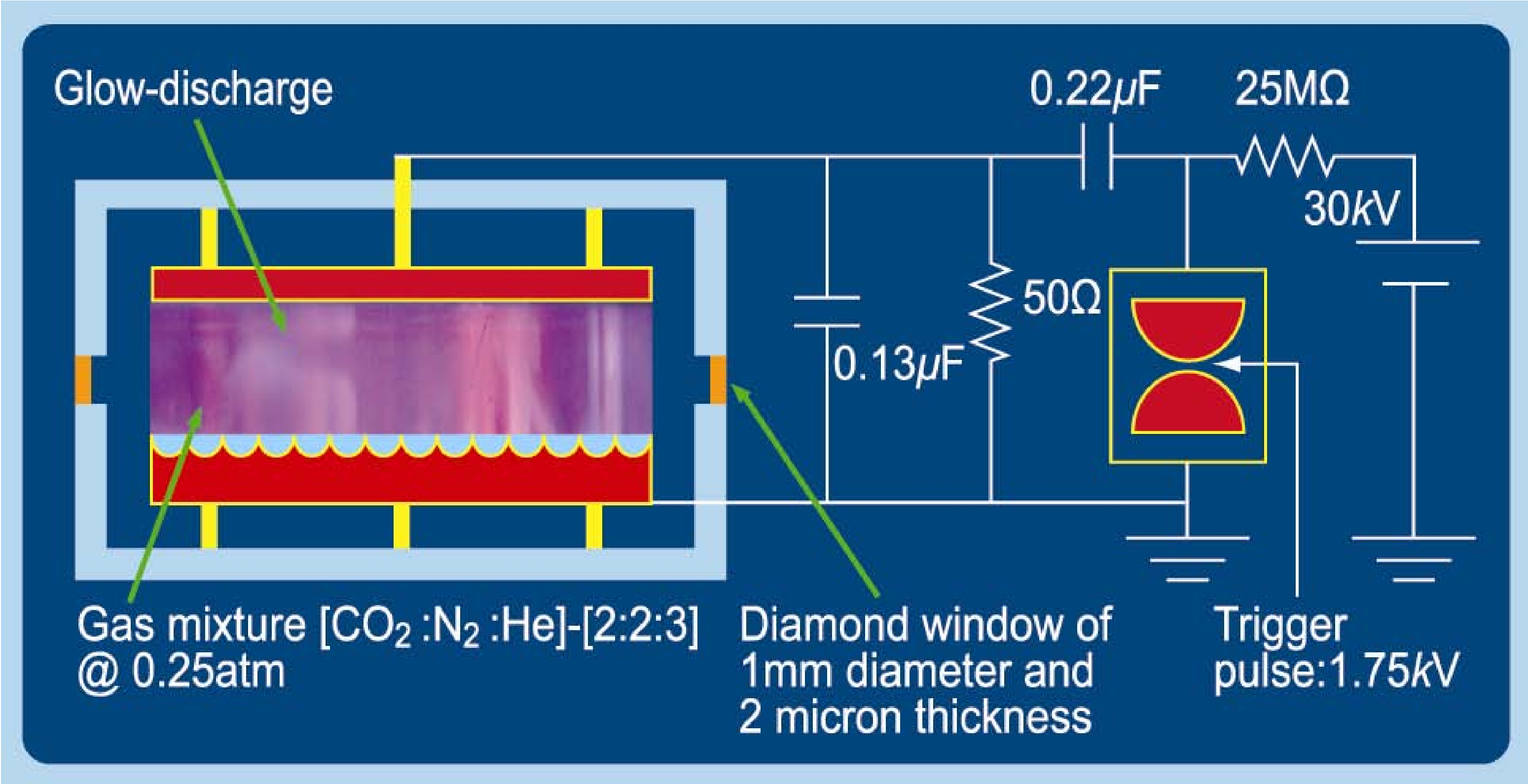



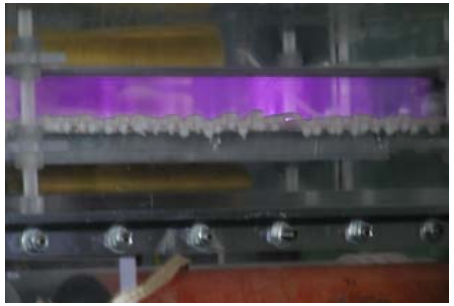



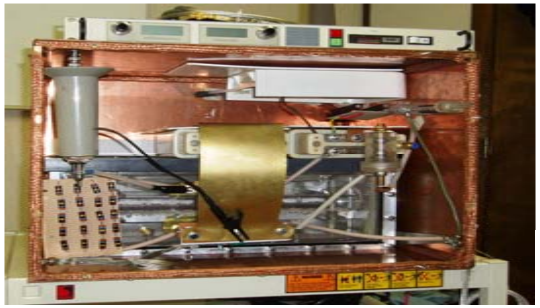




Banna, Berezovsky and Schächter, PRL 97, 134801, 2006
Banna, Berezovsky and Schächter, PRE 74, 046501, 2006

# PASER System





# Experiment Parameters

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## e-beam Parameters

| | |
|---|---|
| Energy | 45 MeV |
| Intrinsic energy spread | 0.03% |
| Normalized emittance | 1.5 mm-mrad |
| Charge – macro-bunch | 100 pC |
| Pulse duration | 5 psec |
| Focus size (rms) | 100 microns |

## Laser Pulse Parameters

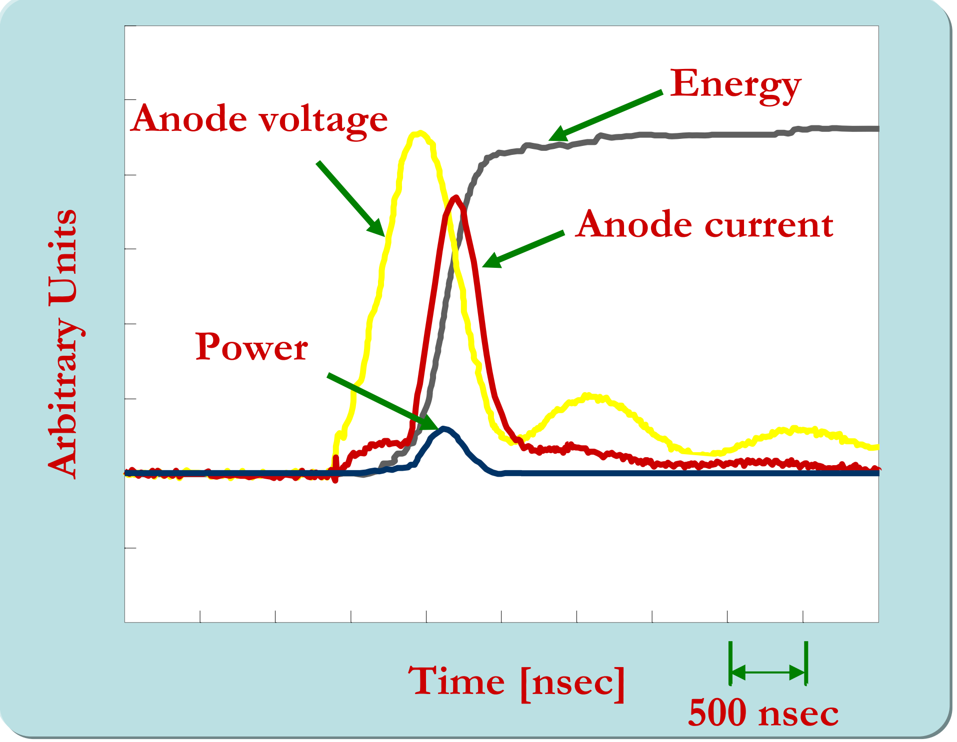
| | |
|---|---|
| Wavelength | 10.2 microns |
| Duration (FWHM) | 200 psec |
| Peak power | 0.5-1 GW |

## PASER Cell Parameters

| | |
|---|---|
| Gas mixture pressure | 0.25 atm |
| Gap between electrodes | 2.5 cm |
| Electrodes size | 40 cm x 12 cm |
| Window thickness | 2 microns |
| Window diameter | 1 mm |
| Discharge voltage | 25-30 kV |
| Cell transmission | 50%-60% |

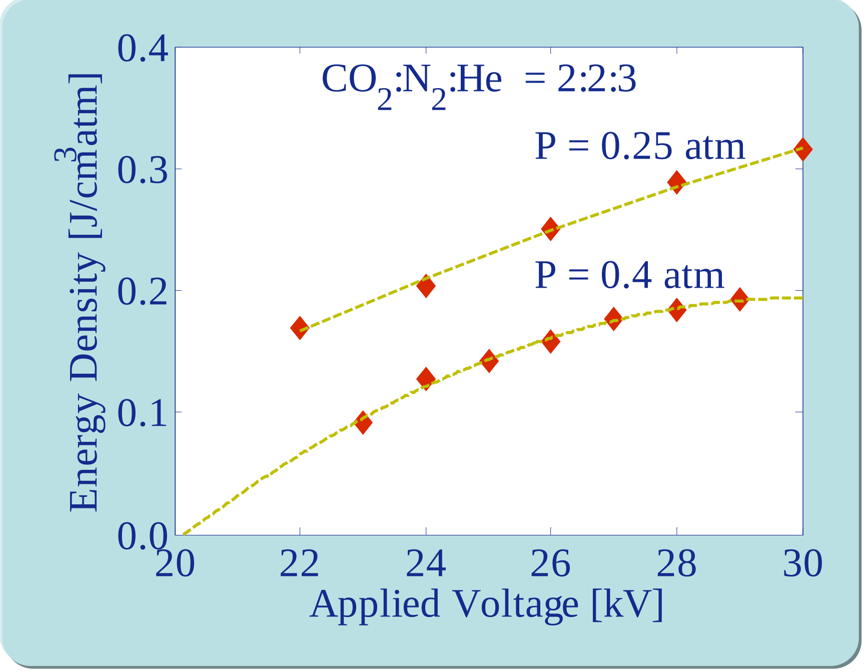
Banna, Berezovsky and Schächter, PRL 97, 134801, 2006
Banna, Berezovsky and Schächter, PRE 74, 046501, 2006

# PASER System Characteristics



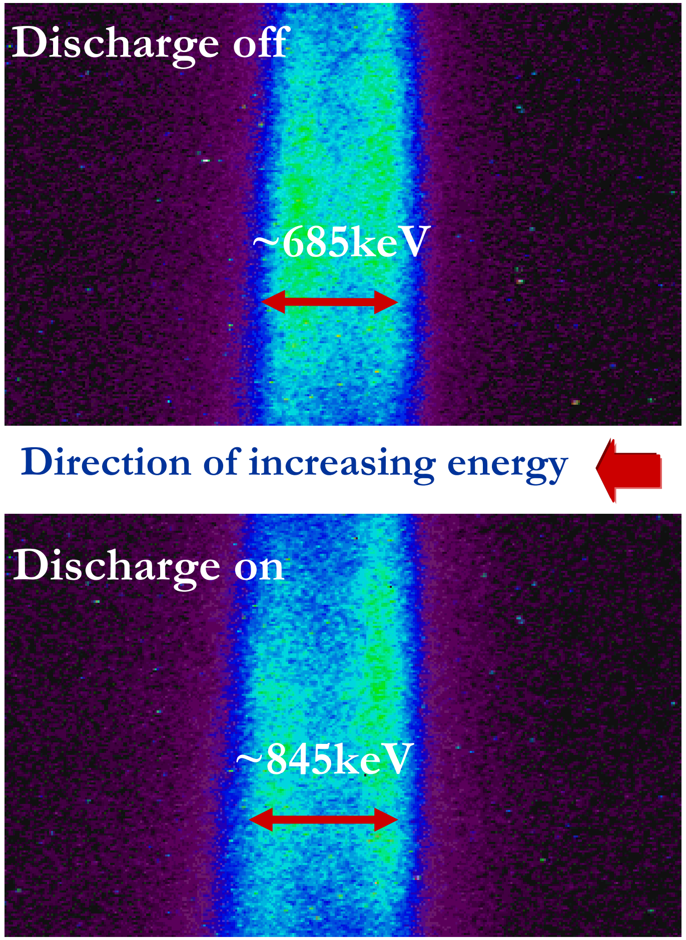

**Discharge Electrical Characteristics**

**Energy Stored in the Excited Gas**

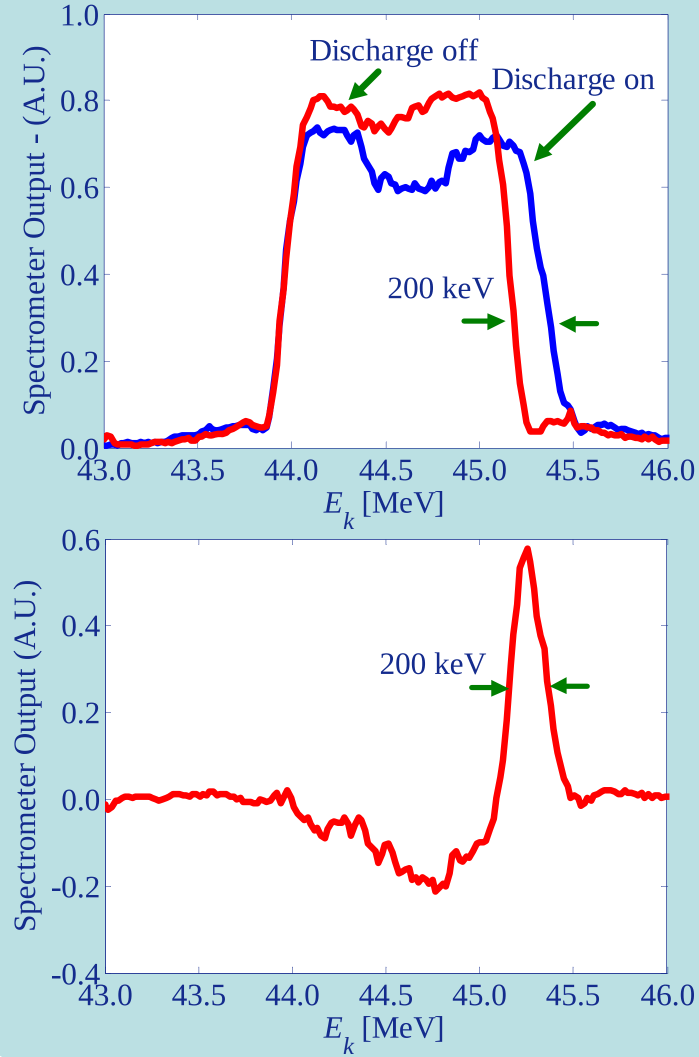


# Experimental Evidence

~1.5% peak-to-peak energy modulation




2,000,000 collisions



# Novel Acceleration Scheme Unveiled

PRL **97,** 134801 (2006) PHYSICAL REVIEW LETTERS week ending 29 SEPTEMBER 2006

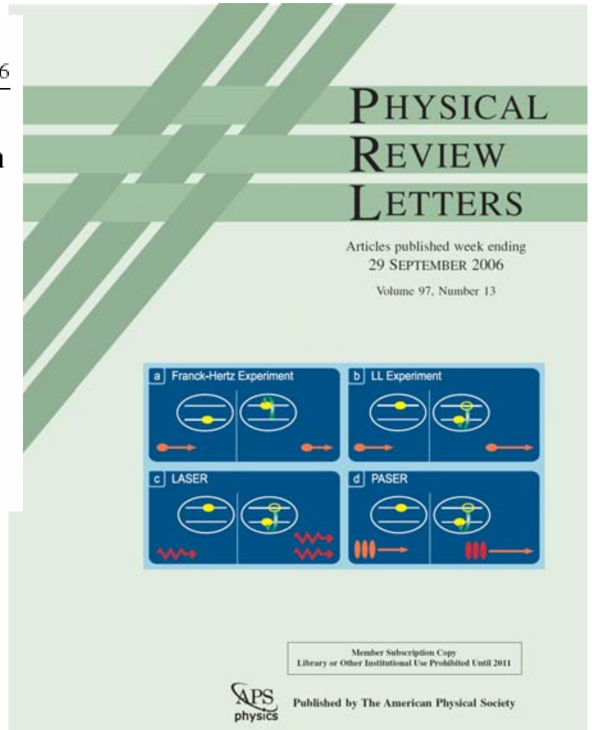
**Experimental Observation of Direct Particle Acceleration by Stimulated Emission of Radiation**

Samer Banna,* Valery Berezovsky, and Levi Schächter

*Department of Electrical Engineering, Technion-Israel Institute of Technology, Haifa 32000, Israel*

(Received 4 June 2006; published 28 September 2006)

We report the first experimental evidence for direct particle acceleration by stimulated emission of radiation. In the framework of this proof-of-principle experiment, a 45 MeV electron macrobunch was modulated by a high-power $CO_2$ laser and then injected into an excited $CO_2$ gas mixture. The emerging microbunches experienced a 0.15% relative change in the kinetic energy, in a less than 40 cm long interaction region. According to our experimental results, a fraction of these electrons have gained more than 200 keV each, implying that such an electron has undergone an order of magnitude of $2 \times 10^6$ collisions of the second kind.




APS NEWS February • 2007 1

## Physics News in 2006

A Supplement to *APS News* Edited by Phil Schewe, Ben Stein and Ernie Tretkoff

**Particle Acceleration by Stimulated Emission of Radiation–PASER for Short**

Particle Acceleration by Stimulated Emission of Radiation (PASER for short), a sort of particle analog of the laser process, has been demonstrated, for the first time, by a team of physicists from the Technion-Israel Institute of Technology using the accelerator facilities at the Brookhaven National Lab.

NEWS NATURE|Vol 443|21 September 2006

**That's no laser, it's a particle accelerator**

CERN COURIER NEWS

BROOKHAVEN

Researchers unveil the PASER: a novel acceleration scheme

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  - **Boosting the gradient**
  - **PASER staging**
- **Concluding remarks**

# Advanced PASER – Collaborators

STI OPTRONICS

- Stephen C. Gottschalk
- Wayne D. Kimura
- Sam A. McCormack

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Israel Institute of Technology

- Samer Banna
- Valery Berezovsky
- Levi Schächter

- David Cline
- Xiaoping Ding
- Lei Shao


BROOKHAVEN
NATIONAL LABORATORY

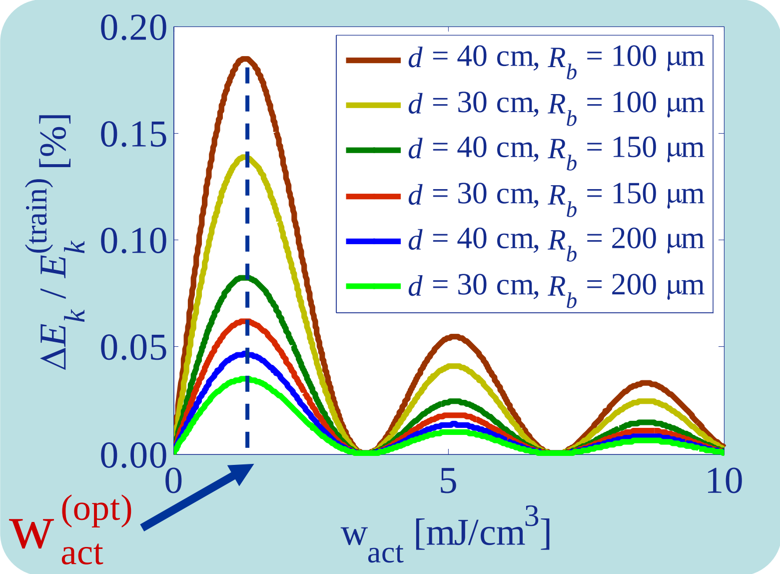
- Marcus Babzien
- Karl Kusche
- Jangho Park
- Igor Pavlision
- Igor Pogorelsky
- Daniil Stolyarov
- Vitaly Yakimenko

UWPS

- Loren C. Steinhauer

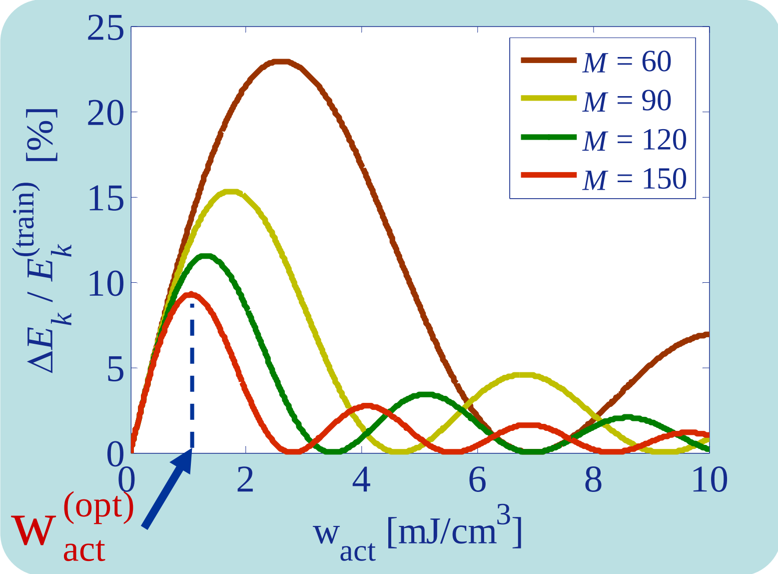
# Boosting the Gradient

## Optimizing the Energy Density




- Apply beam focusing in the cell
- Improve excitation efficiency
- Increase the gas pressure

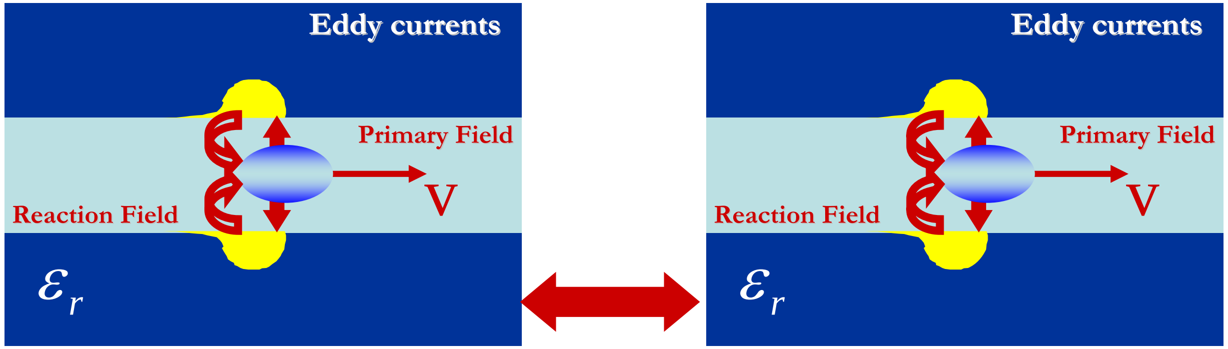
## Optimizing # of Micro-bunches




- Increase the amount of charge
- Improve bunching efficiency

# Staging of PASER Cells

## Resistive Medium

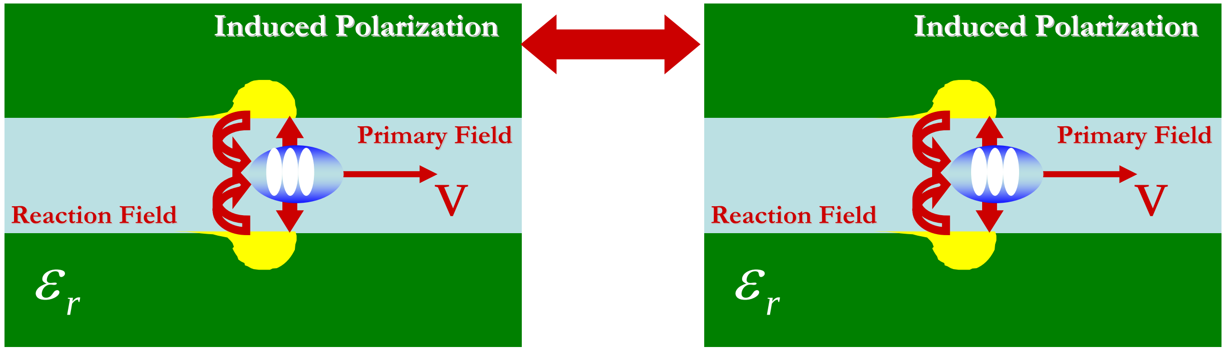



The wake-field phase corresponds to a decelerating force

## Active Medium

Drift region

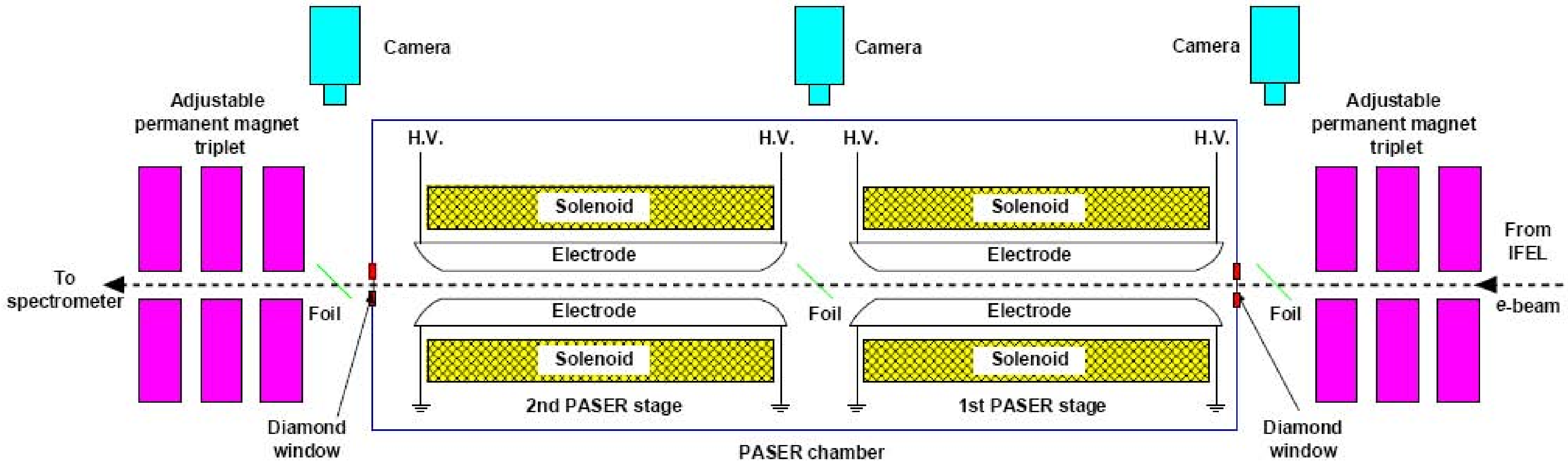
The phase of the wake is determined regardless the length of the drift region




The wake-field phase corresponds to an accelerating force

# Staging of PASER Cells

- No external intervention for phase matching is required in PASER
- The phase of the accelerating field is established internally
- Staging PASER cells is natural



# Solid-State PASER

**Solid-State (Nd:YAG) PASER**

$\lambda_0 = 1.06\mu m$

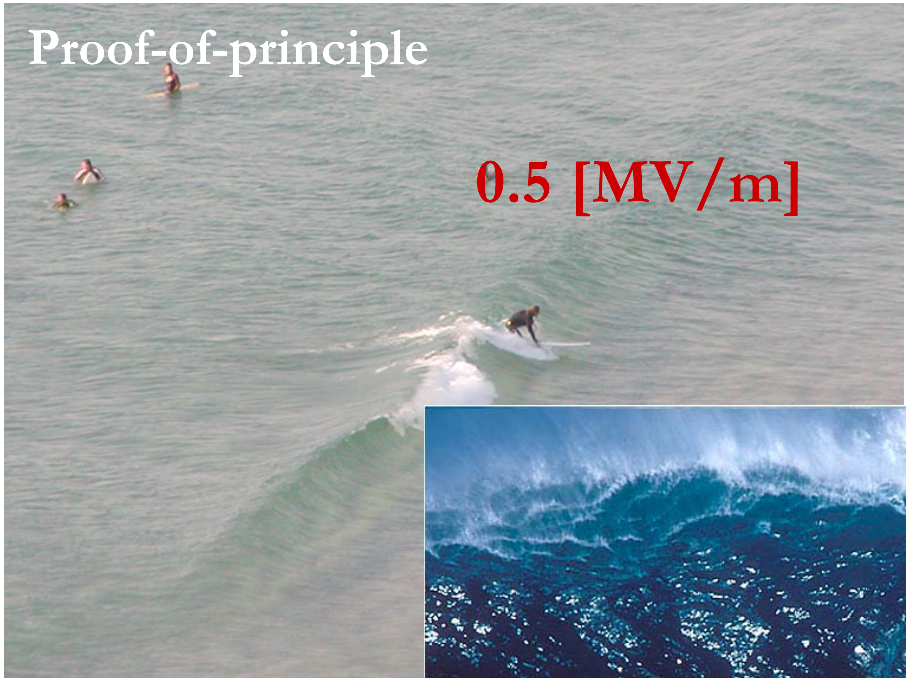
**Advantages:**

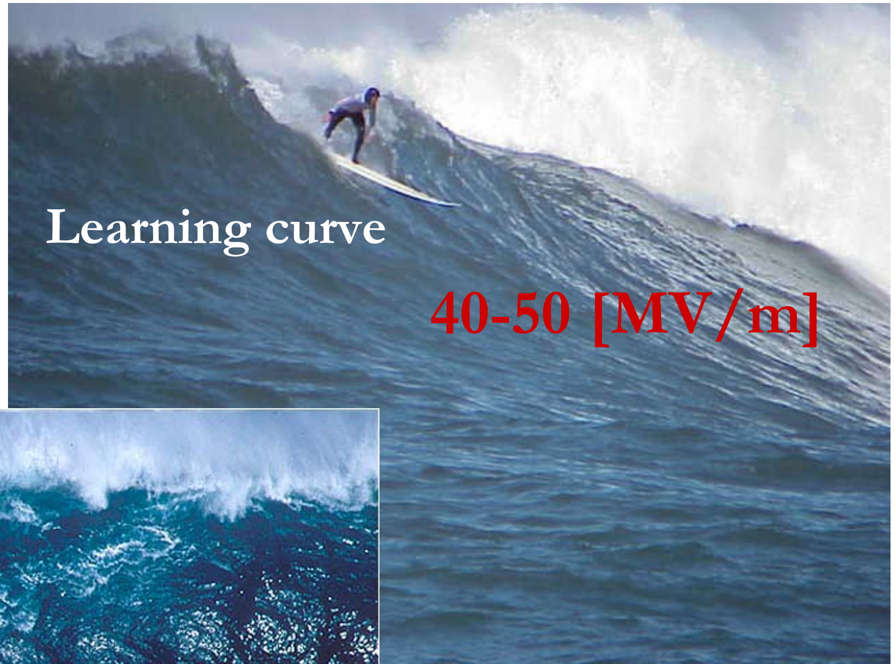
- 10 times more energetic photons
- Higher density of population inversion
- Electrons travel through vacuum tunnel
  - Eliminate windows and gas scattering (emittance)

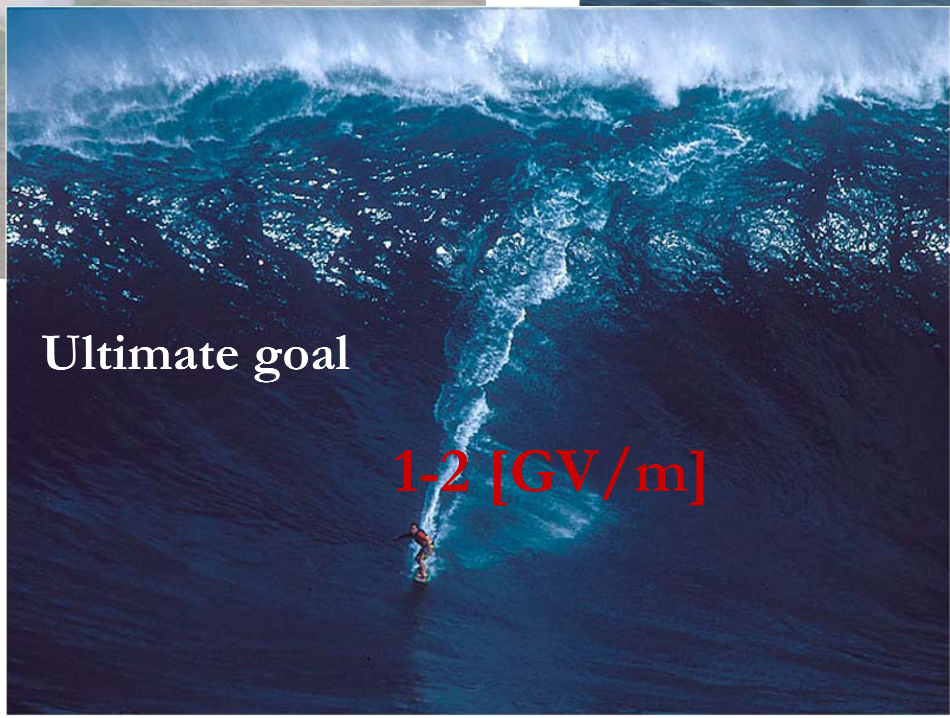
**Challenges:**

- Micro-bunches at 1 micron wavelength
- Efficient interaction requires GeV electrons

# Road Map


Proof-of-principle
0.5 [MV/m]


Learning curve
40-50 [MV/m]


Ultimate goal
1-2 [GV/m]

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# Concluding Remarks

- **PASER is a novel technique for accelerating relativistic particles**
  - Requires only a train of electron micro-bunches with a spacing corresponding to the transition wavelength of the active medium.
  - No need for phase matching between the accelerated electrons and the active medium. Therefore, staging of PASER cells is natural.
- **Proof-of-principle demonstration was achieved at BNL-ATF**
  - Energy gain of 200 keV in the kinetic energy of a mono-energetic ~45 MeV macro-bunch was observed, corresponding to ~2,000,000 collisions of the second kind.
  - Experimental results are in very good agreement with an analytic model for the interaction of a train of micro-bunches with an active medium.
- **Near future proposed program aims to**
  - Boost the gradient up to 100MV/m based on gaseous medium.
  - Demonstrate staging of PASER cells.