Advanced Acceleration Concepts

Levi Schächter

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Acknowledgement

- *R.H. Siemann (SLAC)*
- *W. D. Kimura (STI)*
- *I. Ben-Zvi (BNL)*
- *D. Sutter (DoE)*

Outline

- ***Some brief guidelines***
- ***Novel Acceleration Schemes: Concepts & Results***
- ***Concluding Remarks***

Guidelines

What will be presented next as Advanced Acceleration Concepts:

1. ***Focuses on gradients*** ≥ 1 [GV/m]
2. ***As reference:*** ***SLC*** ~ 20 [MV/m]

   NLC ~ 50 [MV/m]
3. ***Discuss*** e^- ***&*** e^+
4. ***Optical regime***

Inverse Radiation Processes

- ***Inverse Cerenkov (slow wave)***
- ***Inverse FEL… (fast-wave)***
- ***Inverse Transition Radiation (LEAP)***
- ***Inverse Laser (Amplified Wake)***

Space-Charge Wakes

- ***Laser Wake-Field***
- ***Plasma Wake-Field***
- ***Plasma Beat-Wave***
- ***Resonant Absorption***

Inverse Radiation Processes

Inverse Cerenkov: *An Optical Acceleration Structure ?!*

- At optical wavelengths (1μm) dielectrics have higher E_{th} .

  $E_{max} \sim 2\,\mathrm{GV/m}\ @ \le 0.5\mathrm{psec}$

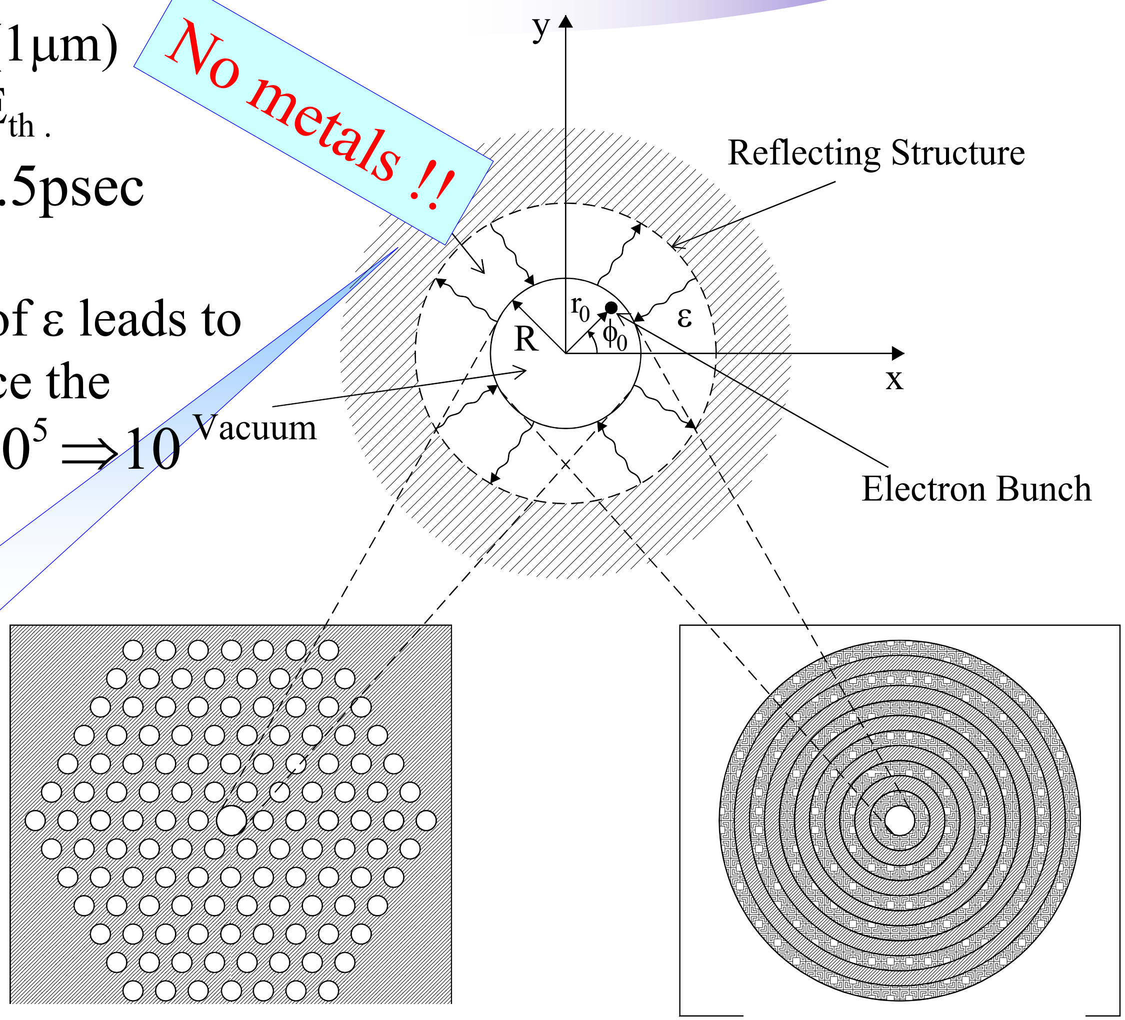
- Frequency dependence of ε leads to reduced wake effect since the

  $\#\ \text{of modes drops}:\ 10^5 \Rightarrow 10$

- Technion & SLAC

No metals !!

- Field Confinement
- Highest Symmetry
- Reduce Max. Field



Photonic Band Gap

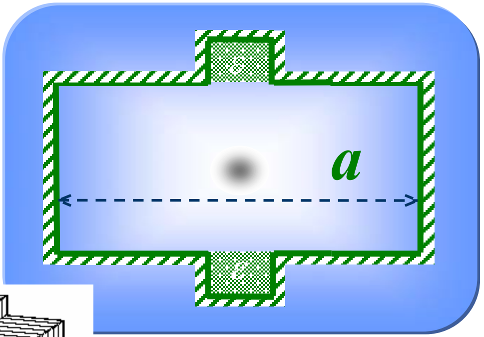
Optical Fibers

Inverse Radiation Processes

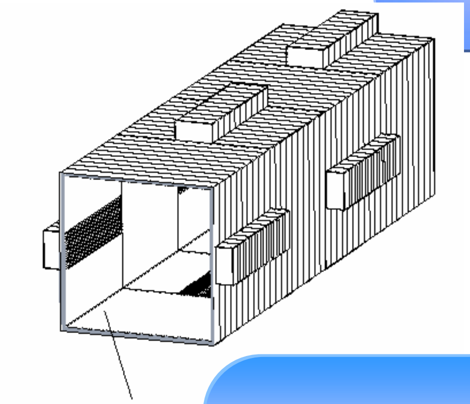
Figures of Merit -- Emittance & Planar Structures

- In an *azimuthally symmetric* structure, the ratio of the transverse force to the longitudinal force is virtually negligible since

$$\left|\frac{F_\perp}{F_z}\right| \approx \frac{1}{4\gamma^2}\left(\frac{\omega}{c}R_b\right)$$



- In a *non-symmetric* structure of a typica transverse dimension a,



$$\left|\frac{F_\perp}{F_z}\right| \approx \left(\frac{\omega}{c}a\right)^{-1}$$

$$\frac{\varepsilon^{(\mathrm{out})}-\varepsilon^{(\mathrm{in})}}{\varepsilon^{(\mathrm{in})}} \simeq \frac{4.14}{1+\left(\frac{N_{st}}{15}\right)^2}$$

Schächter; AAC'2002 Proceedings

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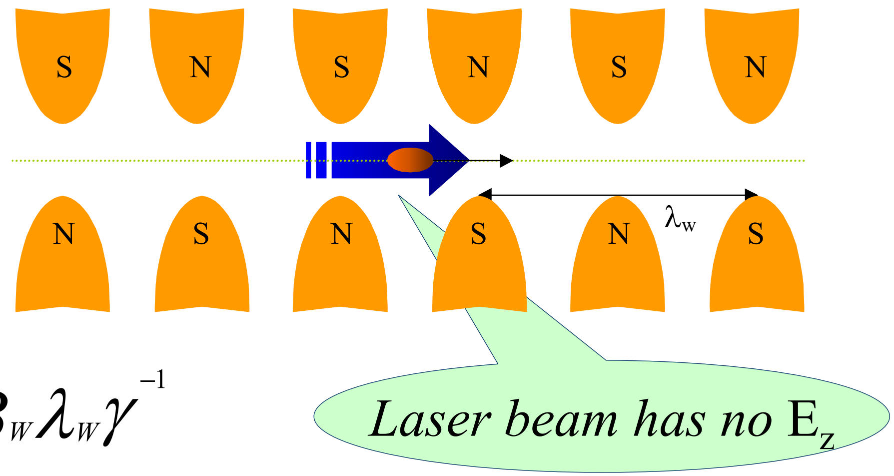
Inverse Radiation Processes

Inverse Free Electron Laser *(R. Palmer 1972)*



- Electrons oscillate in a transverse magnetic field.
- Ponderomotive force may accelerate electrons.
- Acceleration: $E_{ACC} \propto E_L B_W \lambda_W \gamma^{-1}$
- Deceleration: $E_{DEC} \propto B_W^2 \gamma^2$
- Threshold: $E_{ACC} > E_{DEC} \Rightarrow I > I_{th} \propto B_W^2 \lambda_W^{-2} \gamma^6$
- Example:

B_w=1T, λ_w=2cm @ 1 TeV => $I_{th}=10^{25}$ W/cm^2 !!

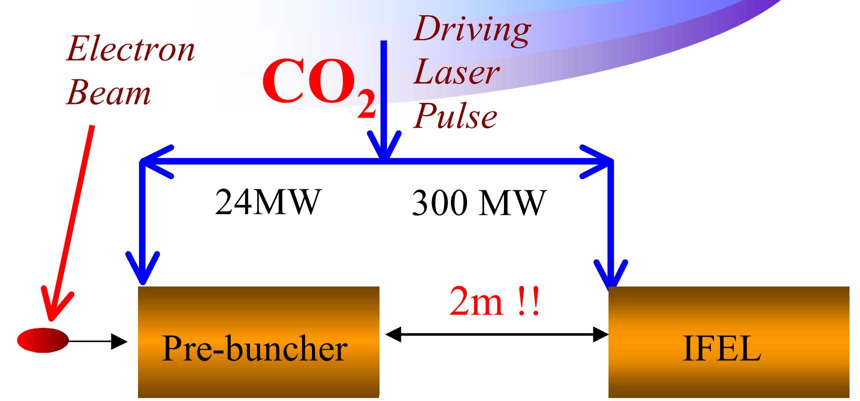
B_w=1T, λ_w=2cm @ 1 GeV => $I_{th}=10^{7}$ W/cm^2 .

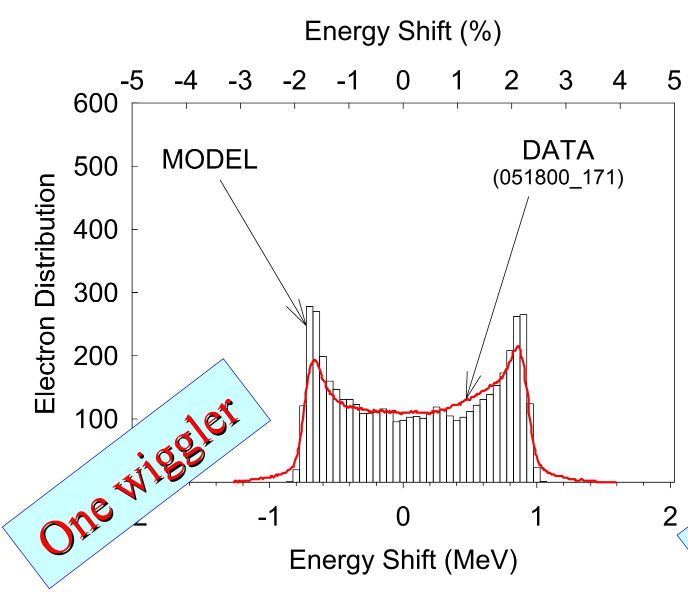
Inverse Radiation Processes

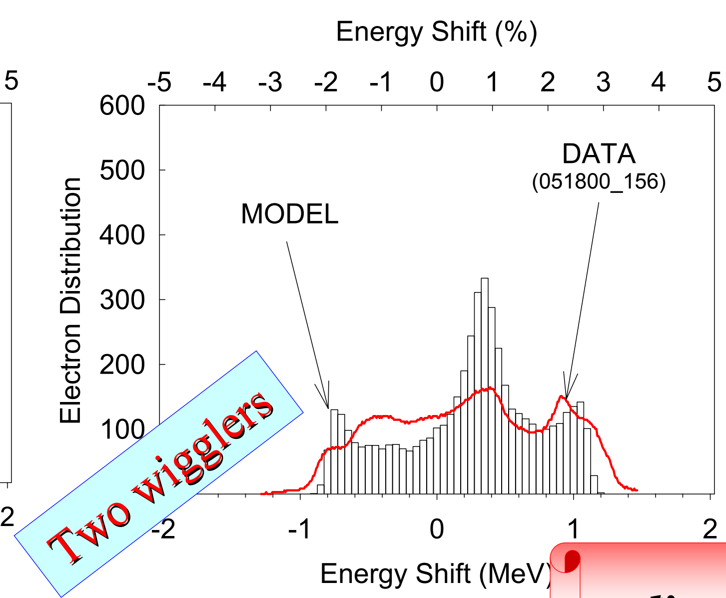
Inverse Free Electron Laser

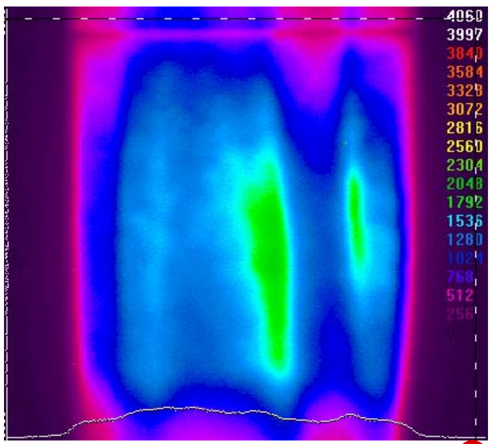
Kimura, PRL, 86, 4041 (2001)

- STELLA Experiment: BNL-ATF, STI & UCLA
- Goal: Staging optical modules









alignment & phase-control @ 10.6μm

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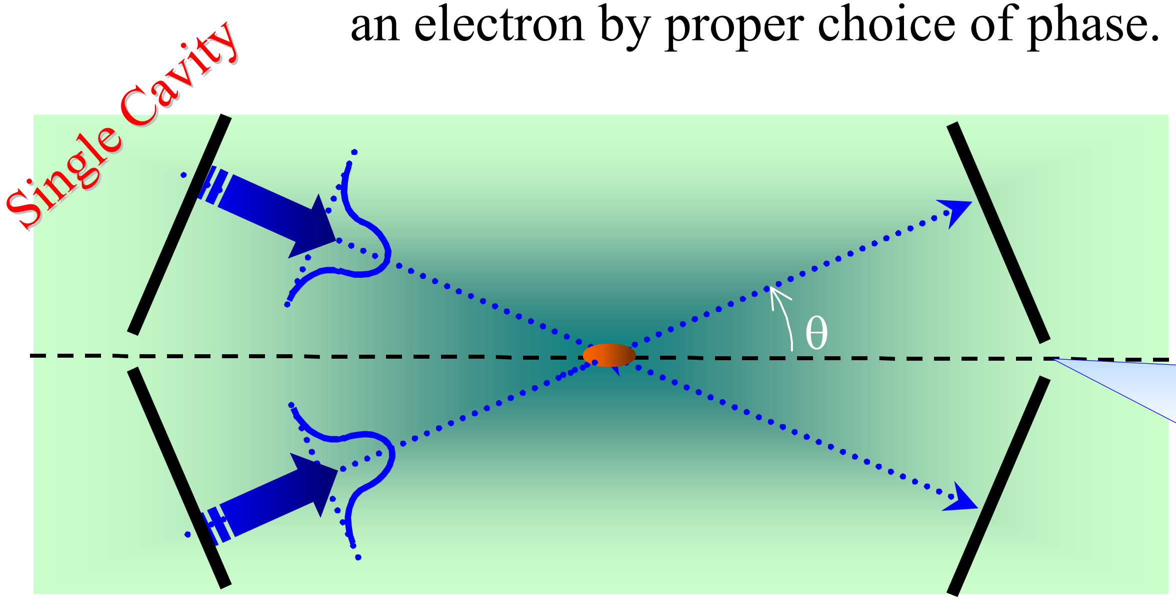
Inverse Radiation Processes

Inverse Transition Radiation

LEAP: **L**aser driven **E**lectron **A**ccelerator **P**rogram (Stanford U.)

Huang & Byer APL 68, 753 (1996)

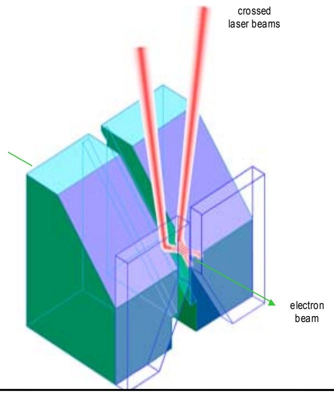
- Electron traversing a discontinuity generates radiation.
- Illuminating a geometric discontinuity may cause acceleration of an electron by proper choice of phase.



Lawson-Woodward: Interaction in finite-length region

Direct Laser Acceleration

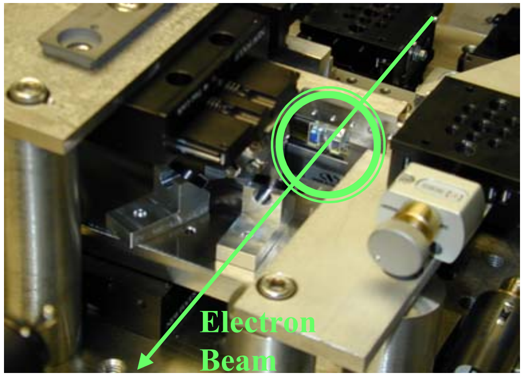
Lasers promise extraordinary accelerating fields, provided efficient coupling structures can be developed

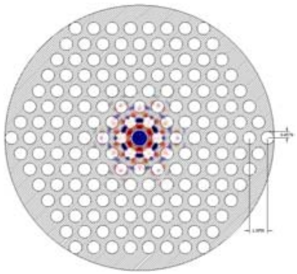


The E163 Experiment (Stanford/SLAC/Tsing Hua)

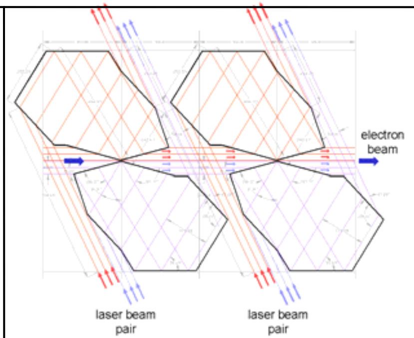
Objective: To demonstrate laser driven electron acceleration in a dielectric structure in vacuum.

The acceleration cell: Two Gaussian beams of 800 nm laser light cross at 1.4^o to form the acceleration field. Electrons are injected between the prisms into the crossed laser field.

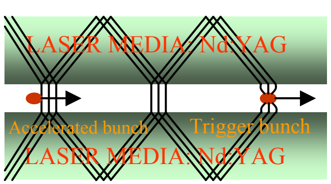




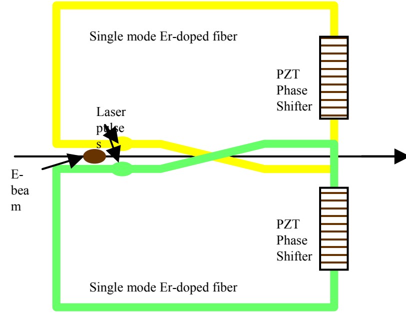
Photonic Band Gap Fiber Accelerator (SLAC/Technion): Higher-order mode-free accelerator structure with good coupling impedance that can be fabricated by standard fiber bundle assembly methods.



Lithographic Accelerator Structures (SLAC/Stanford): Lithographic, planar structures designed to use one laser pulse to accelerate many parallel electron bunches



Cerenkov Amplification Accelerator (Technion/SLAC): Cerenkov wake of triggering bunch is amplified in laser media, accelerating trailing bunch.



Ring Resonated Laser Accelerator (SLAC/Stanford): Laser accelerator embedded in ring resonator to use one laser pulse to accelerate many successive electron bunches

Levi Schächter, CERN, *October 2002*

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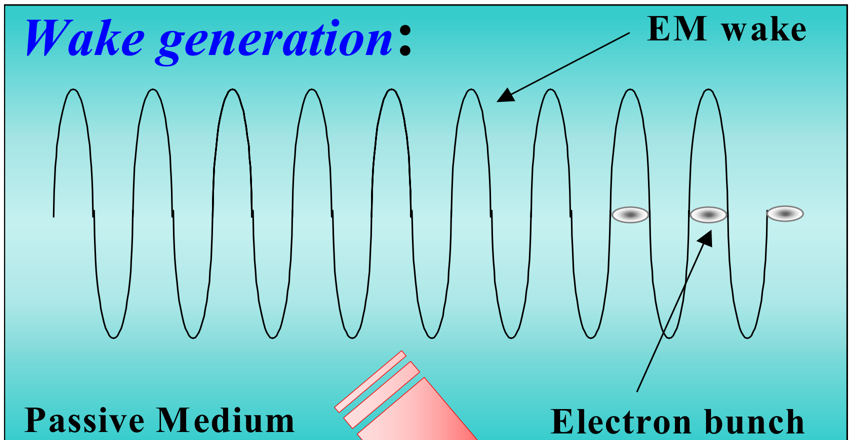
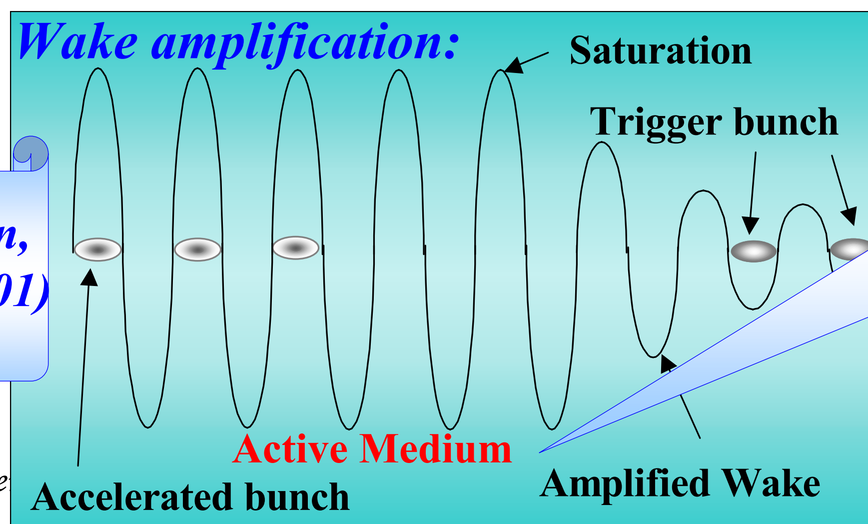
Inverse Radiation Processes

Inverse Laser: Wake Amplification Accelerator





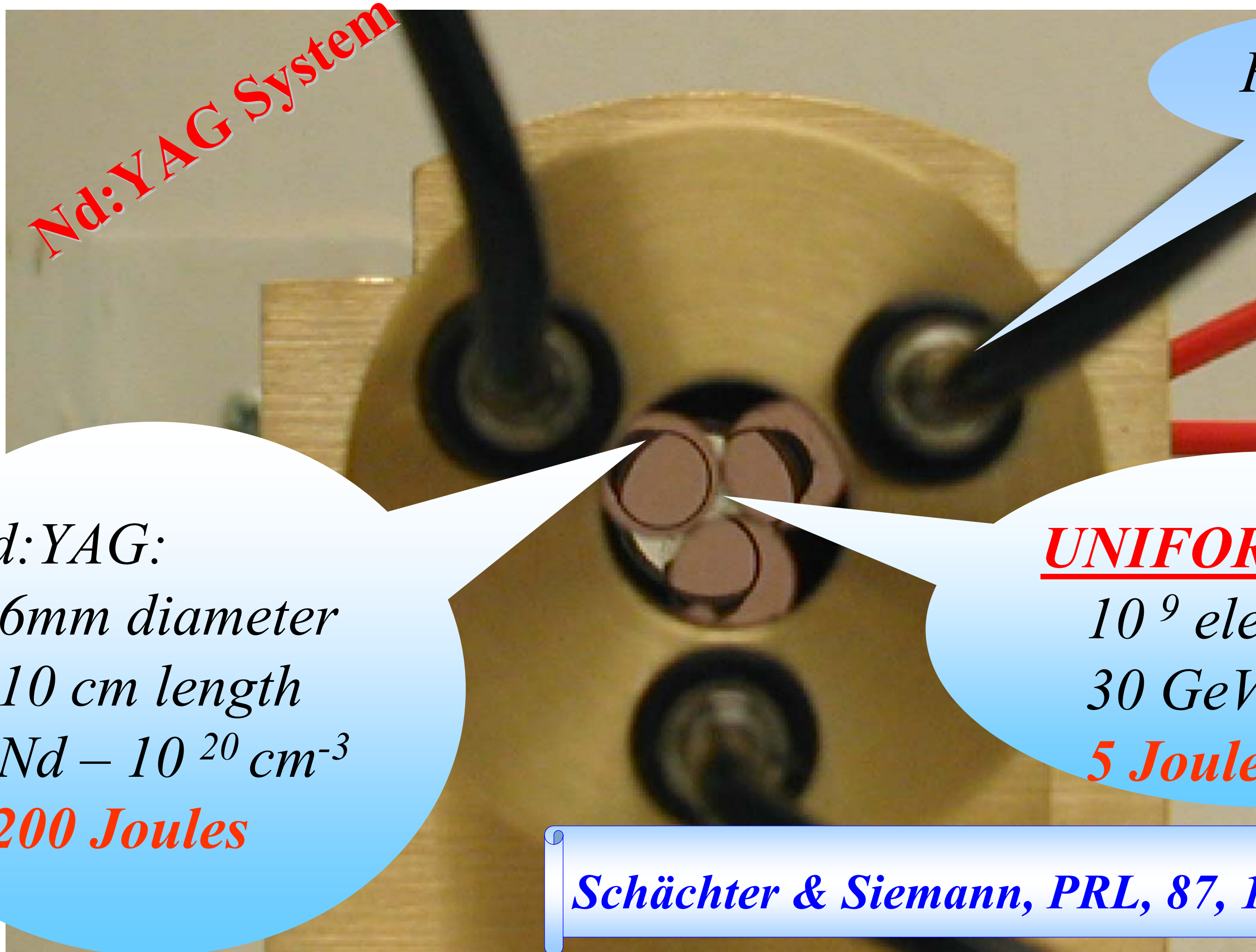
Schächter & Siemann, PRL, 87, 134802 (2001)

Energy stored in Active Medium

Inverse Radiation Processes

Inverse Laser: Wake Amplification Accelerator

Conceptual experiment proposed to ORION @ SLAC



Nd:YAG System

Flash-Lamp

Nd:YAG:
- *6mm diameter*
- *10 cm length*
- *Nd – 10^{20} cm^{-3}*
- ***200 Joules***

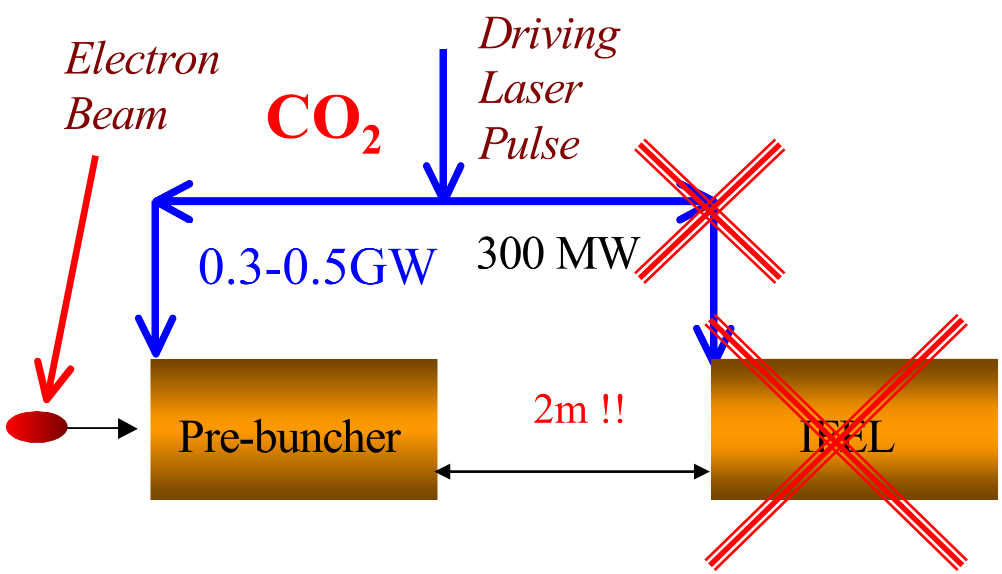
UNIFORM *Beam:*
10^{9} electrons
30 GeV
5 Joules

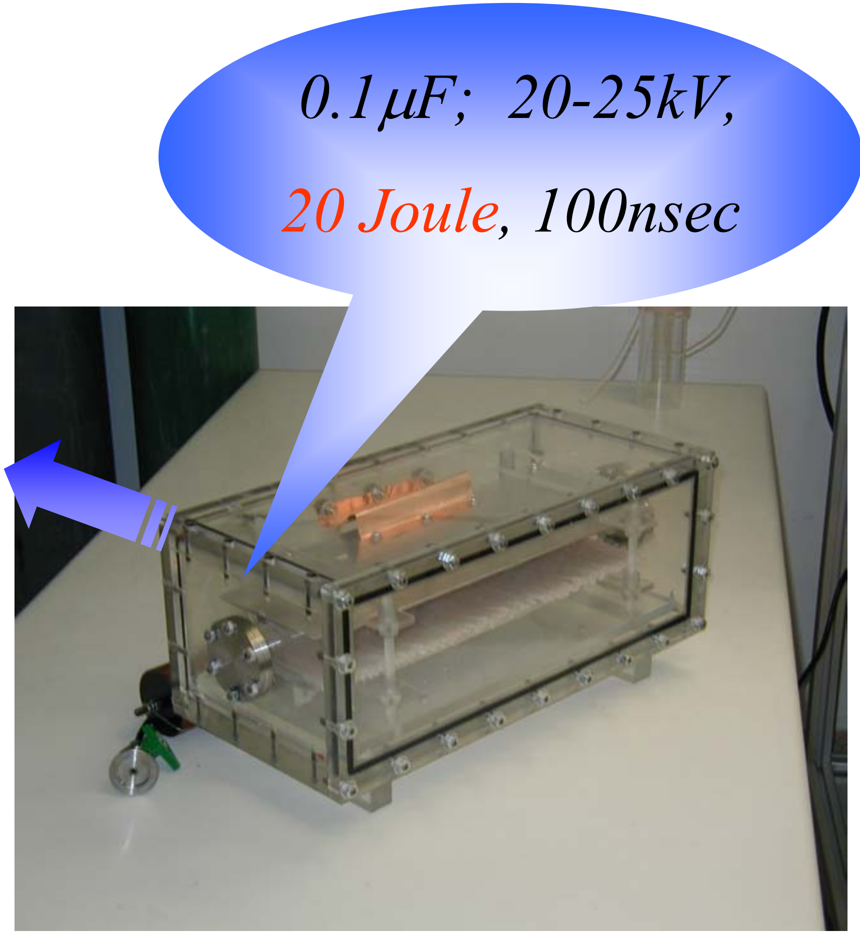
Schächter & Siemann, PRL, 87, 134802 (2001)

Inverse Radiation Processes

Inverse Laser: Wake Amplification Accelerator

Conceptual experiment proposed to ATF@BNL:





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Space-Charge Wakes

*Tajima & Dawson, PRL, **43**, 267(1979)*

Suggested first to use *SPACE-CHARGE WAVES* for the acceleration of electrons. Many variants have been considered:

Plasma Beat Wave Accelerator

*Joshi, Nature, **311**, 525 (1984) -- UCLA*

Self-Modulated Laser Wake-Field Accelerator

*Sprangle, PRL, **72**, 2887 (1994) -- NRL*

Laser Wake-Field Accelerator

*Tajima & Dawson, PRL, **43**, 267(1979) -- UCLA*

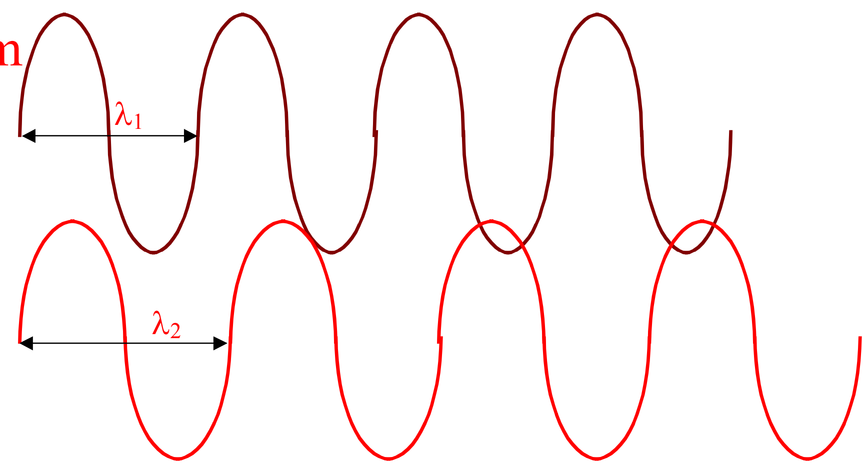
Space-Charge Wakes

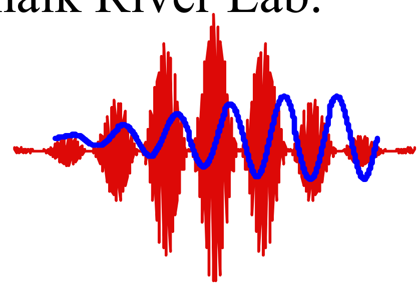
Plasma Beat Wave Accelerator

Joshi, Nature, 311, 525 (1984) -- UCLA

- Two laser pulses of different wavelength are beating in a plasma whose frequency corresponds to the difference between the two.
- The resulting resonant space-charge wave may accelerate electrons.
- Experiment:
  - 2MeV injected electrons (10 psec)
  - 2GV/m effective gradient along 1cm
- Other experiments:
  - Japan, Univ. of Osaka
  - UK, Imperial College
  - France, Ecole Politechnique
  - Canada, Chalk River Lab.

$$\omega_1 - \omega_2 \simeq \omega_{plasma}$$





Space-Charge Wakes

Self-Modulated Laser Wake-Field Acceleration

Sprangle, PRL, 72, 2887 (1994) -- NRL

- Intense laser pulse excites **F**orward **R**aman **I**nstability that in turn "decays" into Stokes and Anti-Stokes modes that beat with pump wave to generate an intense electric field (SC).
- 1993 LLNL-UCLA

  Coverdale, PRL, 74, 4659(1995)

- 1994 Rutherford Appleton Laboratory

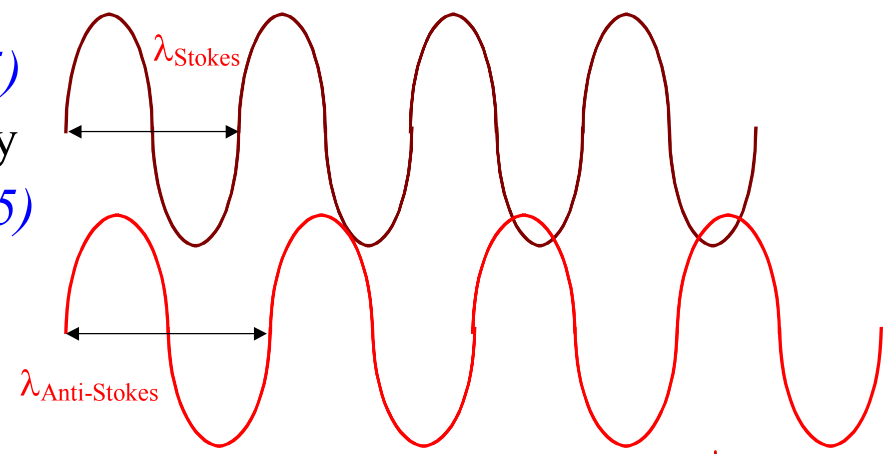
  Modena, Nature, 377,606 (1995)

  30TW, 800fs, 5-15x10^{18} cm^{-3}.

  Outcome 94MeV

  Deduced gradient:

  150 GV/m !!

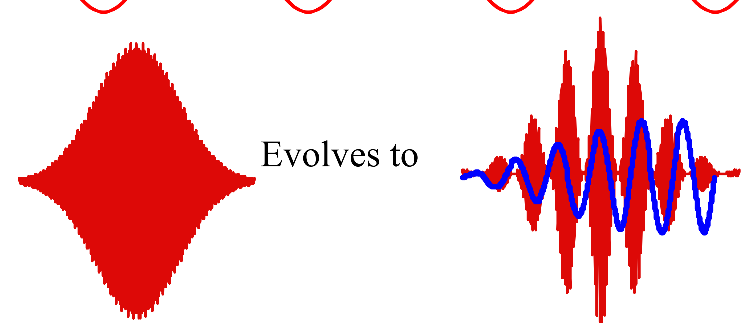


- Others

  NRL

  U. Michigan

  Ecole Politechnique (*200 GV/m !!*)



Space-Charge Wakes

Laser Wake Field Acceleration

*Tajima & Dawson, PRL, **43**, 267(1979)*

- Intense and short laser pulse generates a plasma wake that may accelerate electrons.
- 1996 Ecole Politechnique

  Amiranoff PRL, 81, 995 (1998)

  3MeV input

  4.6 MeV output

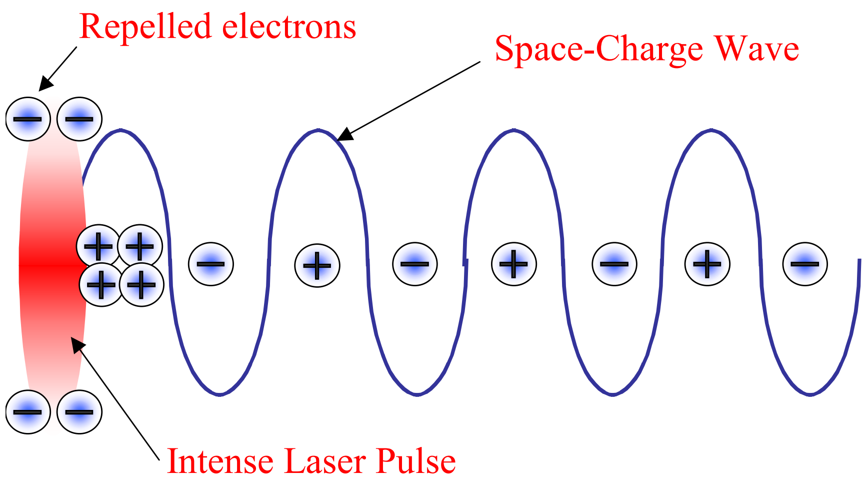
  Deduced gradient:

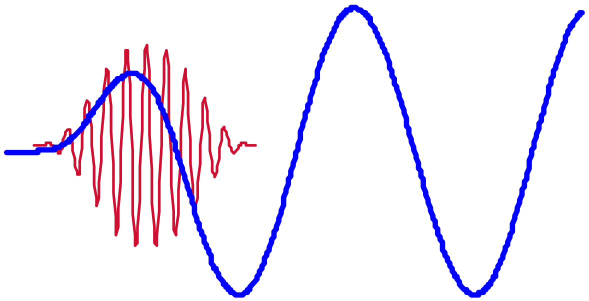
  1.5 GV/m !!
- Others

  U. Michigan

  LBL

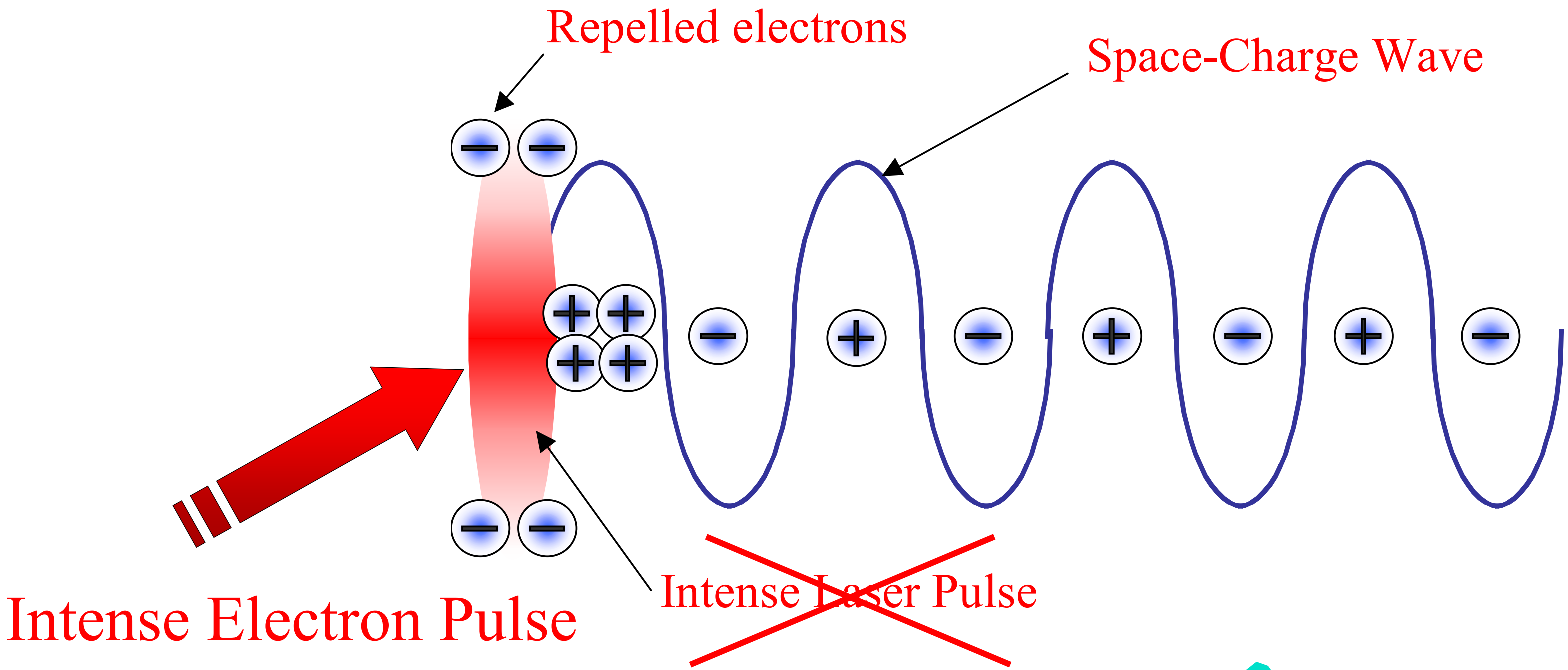
  Japan: JERI, KEK

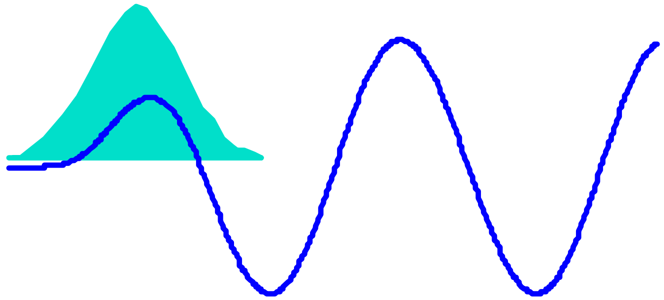




Space-Charge Wakes

Plasma Wake Field Acceleration



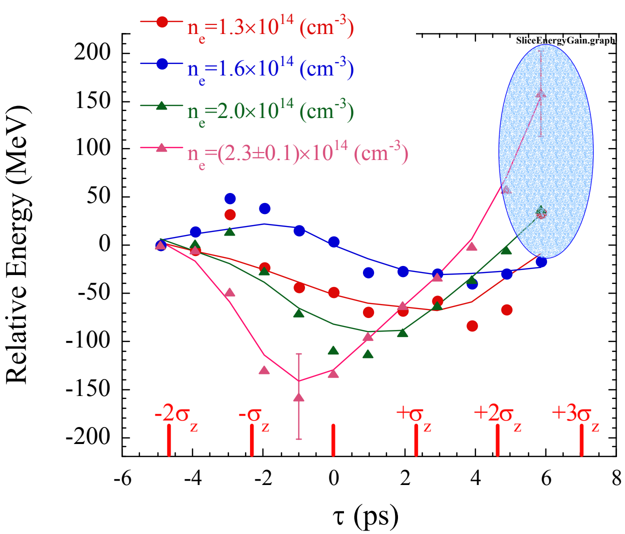


Beam-Plasma Experiments at ORION

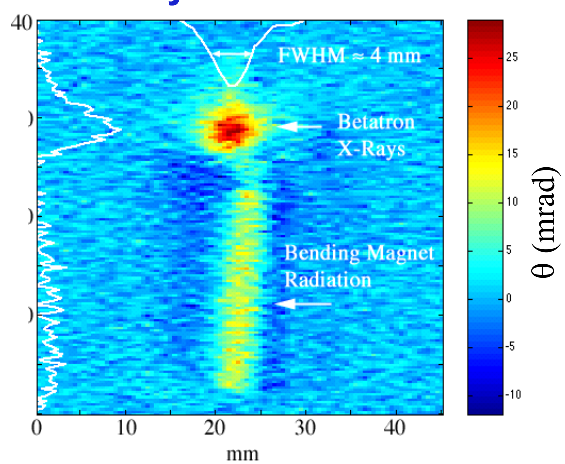
Wide range of phenomena observed to date in E-157 and E162:

- ✓ Focusing of e^- & e^+ beams; stable propagation through an extended plasma
- ✓ Electron beam deflection analogous to refraction @ boundary
- ✓ X-ray generation due to betatron motion in the blown-out plasma ion column
- ✓ Energy loss in the core and energy gain in the tail (>100 MeV/m) over 1.4m

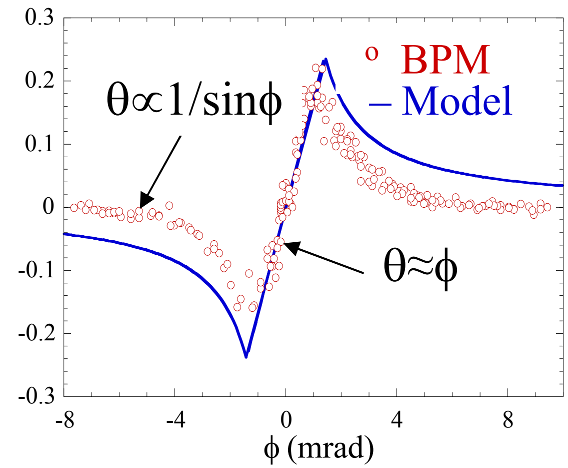
Back e^- accelerated

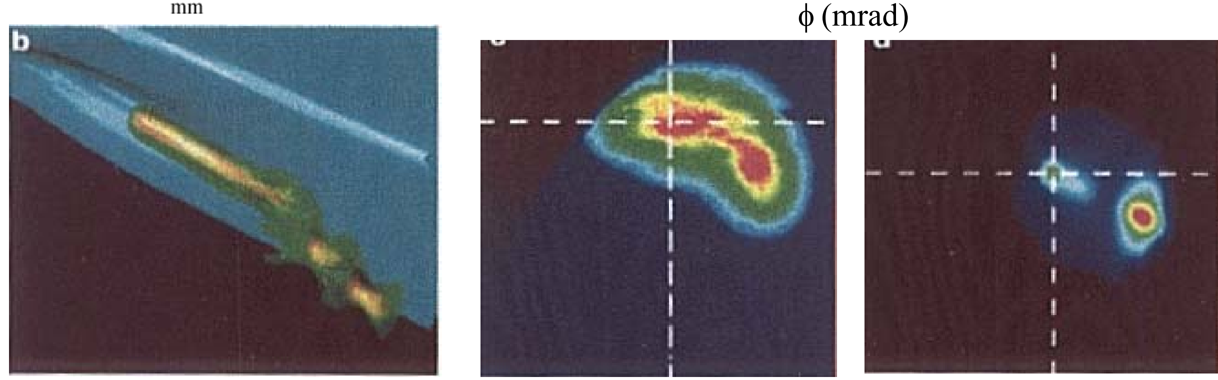


X-ray Generation



Beam Refraction





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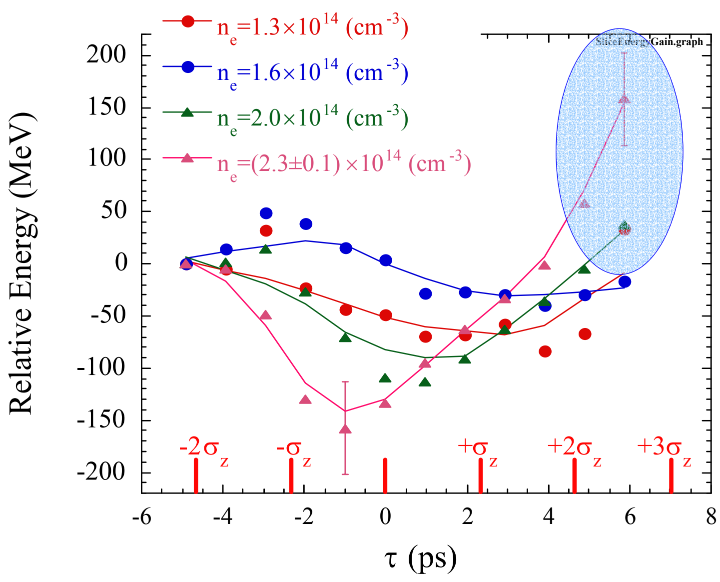
Beam-Plasma Experiments at ORION

Still much to do in E164 (FFTB) and at the future ORION:

- Demonstrate **$1/\sigma_z^2$ scaling law** and > GeV/m gradient ⇨ **E-164** (Spring 2003)
- Plasma source development: higher densities and hollow channels for positron
- Robustness against hose instability …

Back e^- accelerated

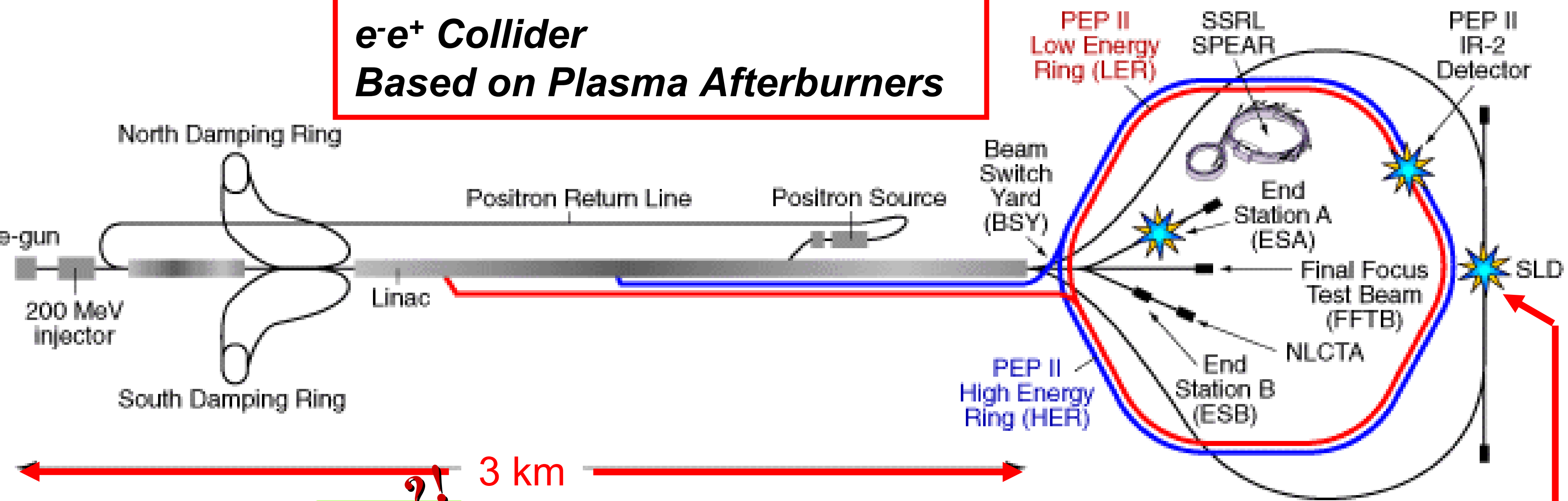


Plasmas Have Extraordinary Potential

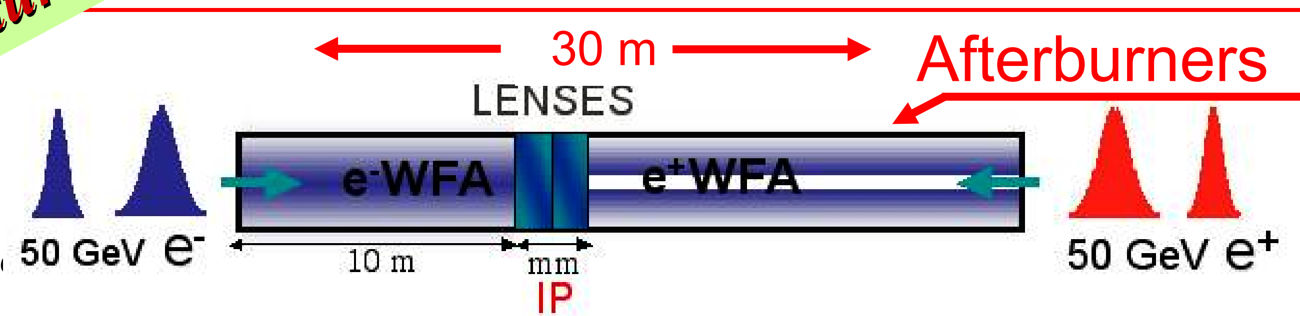
Stanford Linear Accelerator Center | UCLA | USC

Investigating the physics and technologies that could allow us to apply the enormous fields generated in beam-plasma interactions to high energy physics via ideas such as:

A 100 GeV-on-100 GeV e^-e^+ Collider Based on Plasma Afterburners



Not remote future ?!



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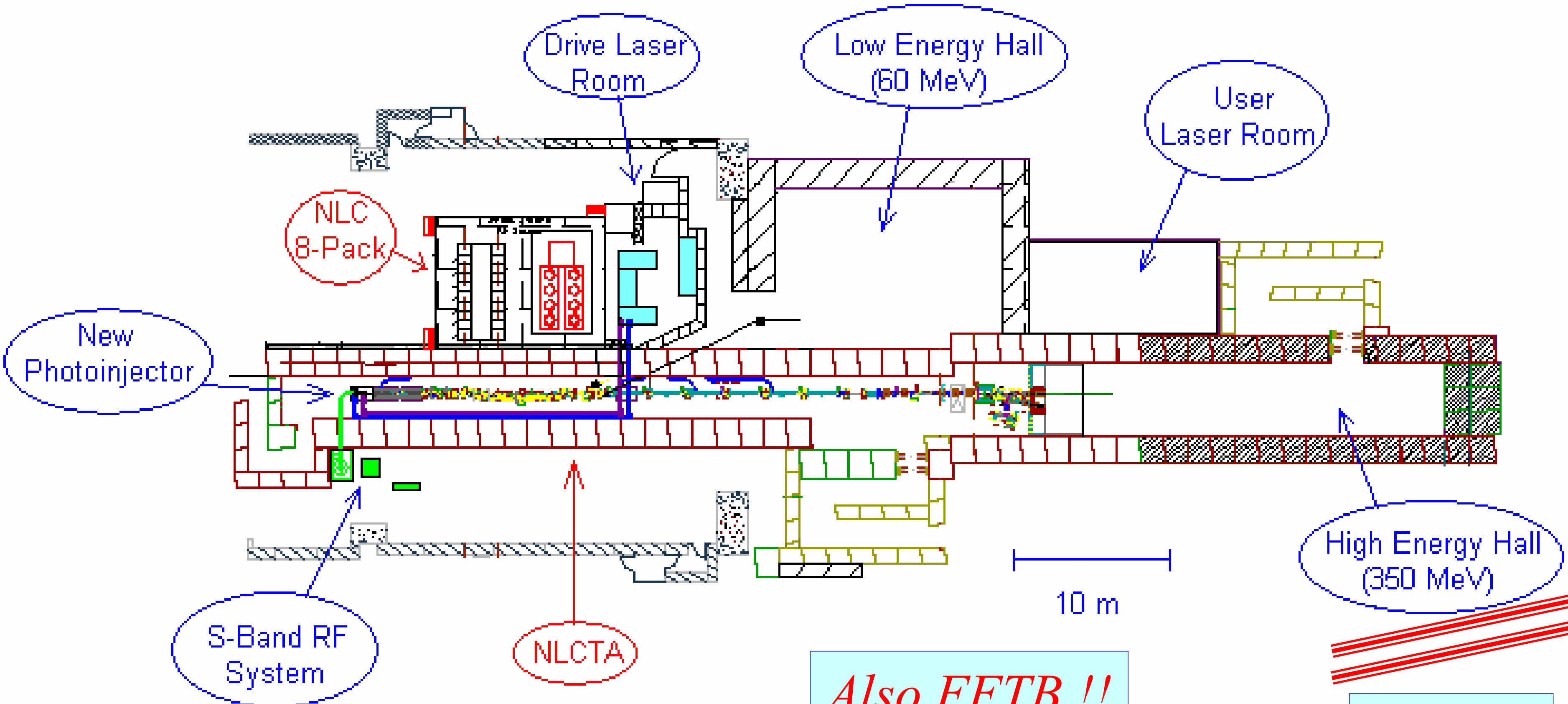
ORION Facility at NLCTA



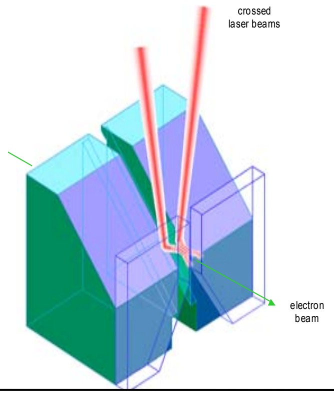
Also FFTB !!
30GeV

1GeV ?

http://www-project.slac.stanford.edu/orion/

Direct Laser Acceleration

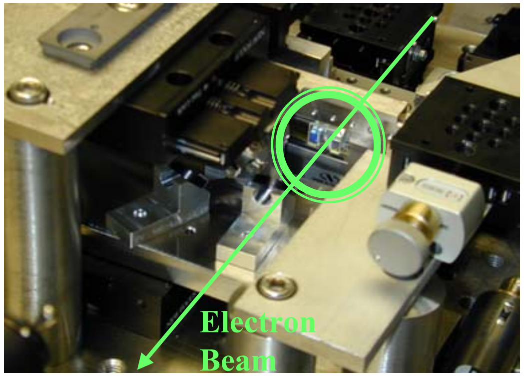
Lasers promise extraordinary accelerating fields, provided efficient coupling structures can be developed

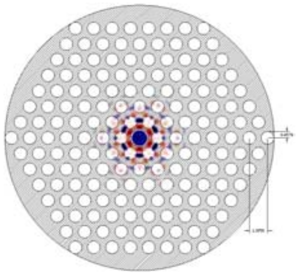


The E163 Experiment (Stanford/SLAC/Tsing Hua)

Objective: To demonstrate laser driven electron acceleration in a dielectric structure in vacuum.

The acceleration cell: Two Gaussian beams of 800 nm laser light cross at 1.4° to form the acceleration field. Electrons are injected between the prisms into the crossed laser field.





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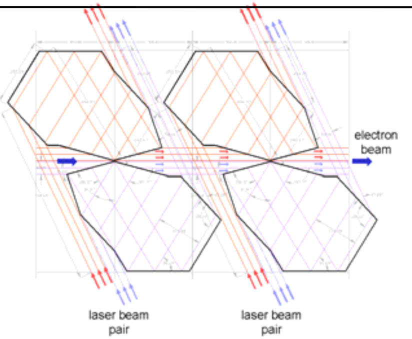
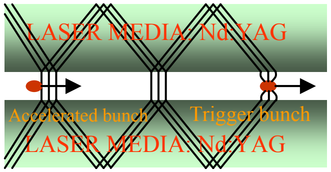


Lithographic Accelerator Structures (SLAC/Stanford):

Lithographic, planar structures designed to use one laser pulse to accelerate many parallel electron bunches



Cerenkov Amplification Accelerator (Technion/SLAC):

Cerenkov wake of triggering bunch is amplified in laser media, accelerating trailing bunch.

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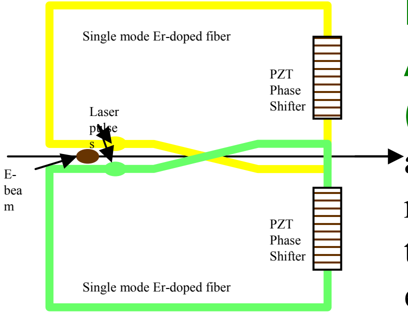

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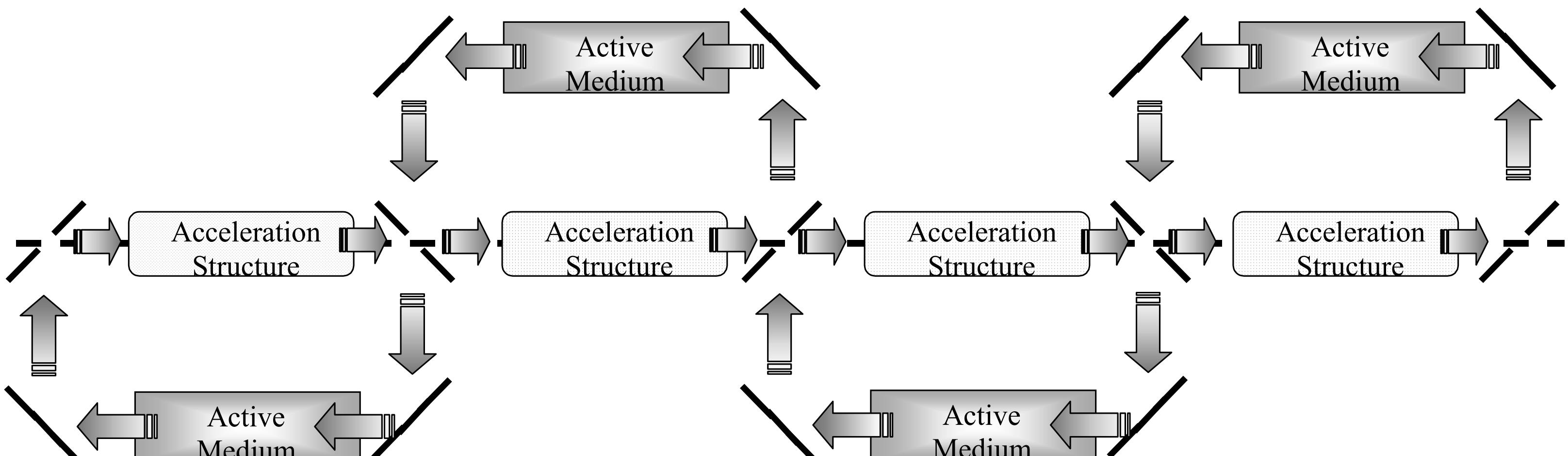
Concluding Remarks

- Plasma based schemes have promising perspectives with regard to a single module acceleration gradient (>100GV/m) however, emittance and phase control over many modules remain open questions. Other open questions: dark-current, instabilities, asymmetries, high rep. rate operation…. Great perspective as "afterburners" in existing accelerator; injectors… all plasma optical accelerator. Not remote future !!
- Inverse radiation schemes promise a "moderate" gradient (1GV/m) but preliminary results of staging optical modules seem very promising. Open questions: manufacturing constraints (asymmetry thus emittance), geometric and material tolerances, non-linear (Kerr) effect in dielectrics, ……
- Wake amplification in an active medium may prove to be of practical implementation since most of the *infra-structure* has been already developed by the communication and semi-conductors industry for low peak power but high average power: high-efficiency diode-lasers, materials for optical fibers and auxiliary equipment.

Concluding Remarks

- Recycling (M. Tigner). All laser based schemes rely on the fact that a relatively small fraction of the *energy stored in the laser cavity* is extracted and used in the *acceleration structure*. Conceptually, it seems possible to take advantage of the high intensity electromagnetic field that develops in the cavity and *incorporate the acceleration structure in the laser cavity*.
- According to estimates, the rep-rate of each macro-bunch is 1GHz and each macro-bunch is modulated at the resonant frequency of the medium (e.g. 1.06μm).
- The amount of energy transferred to the electrons or lost in the circuit is *compensated by the active medium* that amplifies the *narrow band wake* generated by the macro-bunch.



Concluding Remarks

- In the US, all this activity and much more, is part of the DoE's

  Advanced Technology R&D Program

  conducted by Dr. Dave Sutter.

- A list of US Institutions (from west to east):

SLAC/Stanford U	***ANL***	***Maryland***
UCLA	***Michigan***	***NRL***
LBL/ UC Berkley	***MIT***	***…..***
UCSD	***BNL***	
USC	***Yale/Columbia***	


Thank you !!