Inverse Cherenkov Accelerator in Magnetized Plasma (ICAMP)

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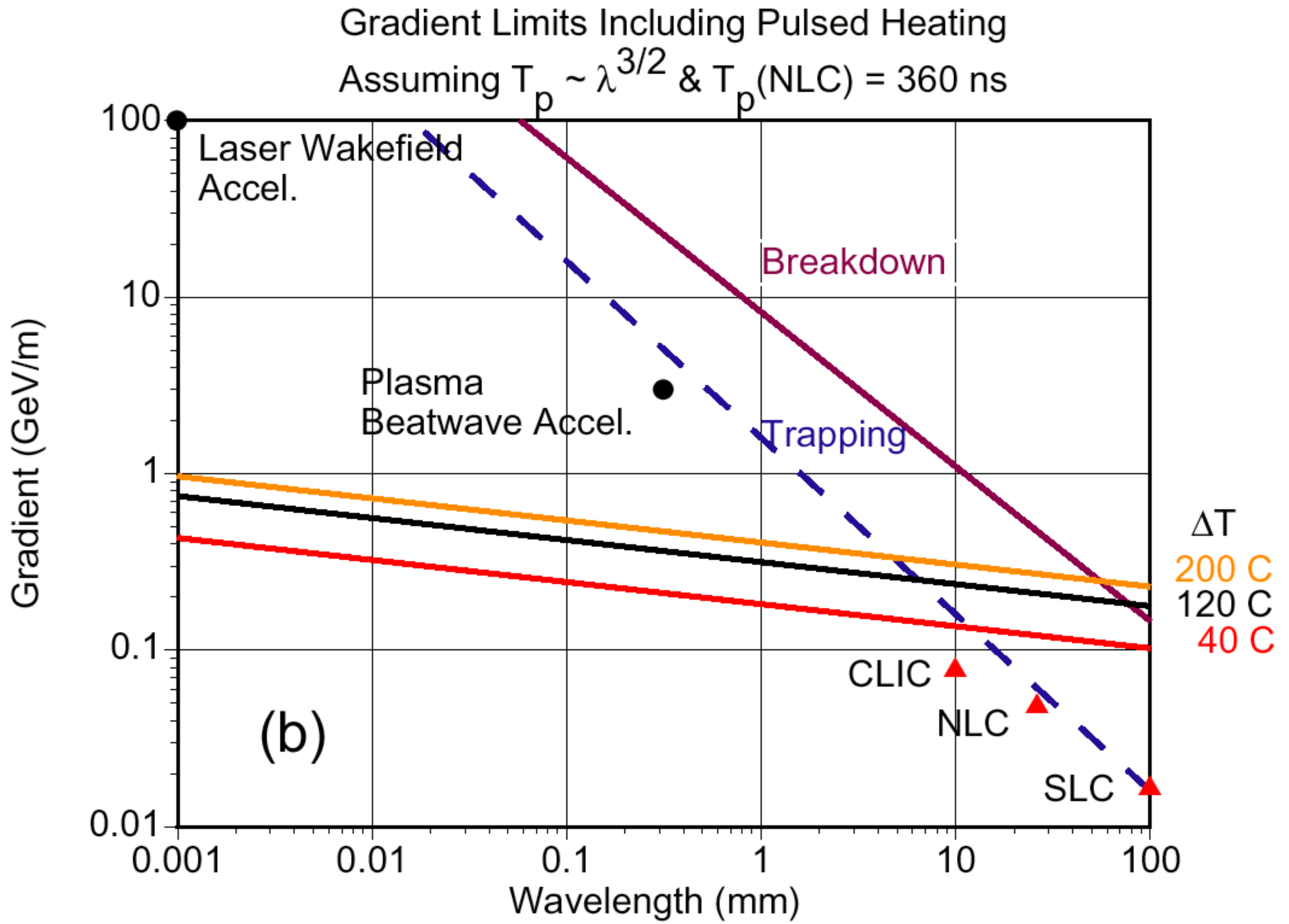
FNPL Advisory Committee Meeting, Fermilab, 10/14/2002

Develop structures which

- do not melt
- can be made very small
- very cheap (replaced every shot)
- supports high accelerating fields



Pulse heating is thought to be the most serious limit to scaled solid-state structures

(Courtesy D. Whittum)

Roadmap of the talk

• **<u>Objective</u>:**
develop a new advanced accelerator which is plasma-based and powered by high-frequency microwaves

Build upon advances in high-frequency radiation sources and the development of long homogeneous low-density (10^{12} - 10^{16} cm^{-3}) plasmas

Plasmas have been driven by lasers and beams, but never by microwaves

• **<u>How are we going to do this</u>?**

By introducing a new type of a plasma accelerator: Inverse Cherenkov Accelerator in Magnetized Plasma (ICAMP)

We like plasmas for acceleration because…

•They support high accelerating fields

→ not really, the trapping limit $eE = mc\omega$ is the same for any accelerator

•Accelerating field frequency is determined by plasma density, not the feature size

→ dense plasma translates into high frequency

$$\omega \propto \omega_p \equiv \sqrt{\frac{4\pi e^2}{m}} \qquad \text{v.s.} \qquad \omega \propto \frac{c}{d}$$

•It is easy to make very small plasmas using lasers

•Plasmas can be single-pulse heated to 10 keV, and recycled at high rate → ultimate disposable structure

Plasma accelerators of electrons

What does a conventional accelerator do?
(1) Compress RF energy from klystrons, etc.
(2) Make EM fields longitudinal and luminous

ICAMP accomplishes these goals:

- **100% efficient conversion of RF waves into longitudinal plasma waves → accelerate electrons → scalable to high freq.**

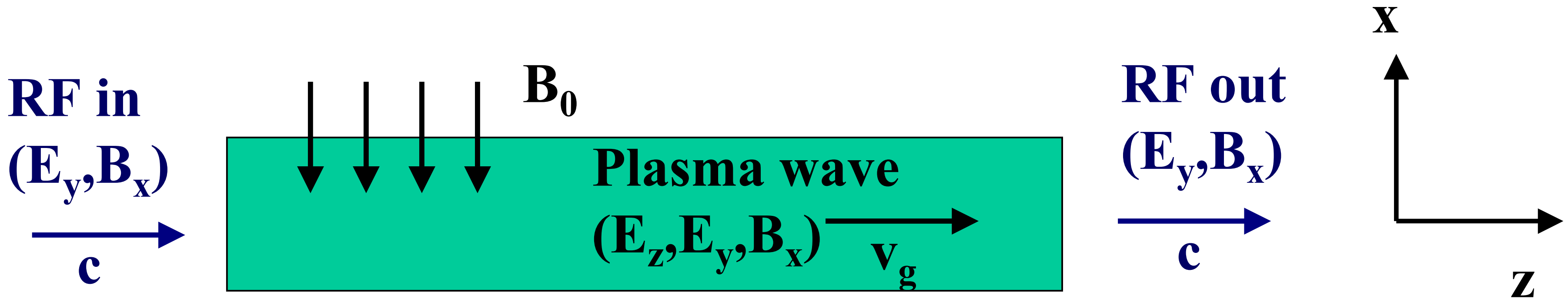
Example: $n=10^{14}$ cm^{-3} → f = 100 GHz, B = 1 T
E_z=300 MeV/m. Compare: 20 MeV/m at SLAC

$$\text{Resonant condition}: \mathrm{v}_{\mathrm{ph}} = \frac{\omega_p}{k} = \mathrm{c}$$

- **Slow group velocity results in energy density compression**

Expensive delay line distribution system for NLC achieves 75MW → 600MW conversion. Issues: high-power RF components

Inverse Cherenkov Accelerator



$\omega = kc$ for $\omega = \omega_p$

•**Original idea** (Yoshii, Katsouleas et.al., 1998): use electron bunch or laser pulse to produce plasma wave and convert it into THz radiation

•**Accelerator-relevant idea** (Shvets, 2002): inject RF and convert it into plasma wave.

•**Ultimate parameters**:
$f = 300$ GHz, $n = 10^{15}$ cm^{-3}, $B_0 = 1$T, $W = 1$ GeV/m

Wave Excitation in Magnetized Plasma: Theory

- **Dispersion Relation of Extraordinary Mode (E-field perpendicular to B-field) in Plasma**

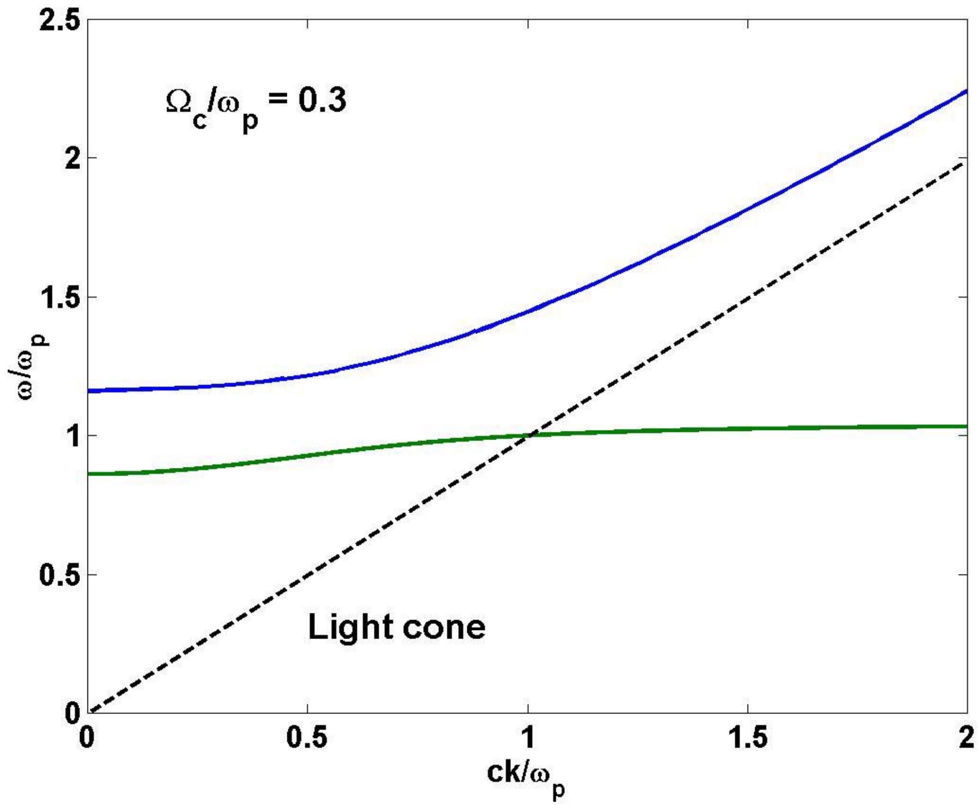
$$\frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_p^2}{\omega^2}\frac{\omega^2 - \omega_p^2}{\omega^2 - \omega_H^2}$$

where ω_p → plasma frequency, $\omega_H^2 = \omega_p^2 + \Omega_c^2$ → upper hybrid

$\Omega_c = \frac{eB}{mc}$ → cyclotron frequency. **Note**: $\omega = kc$ for $\omega = \omega_p$

- **Engineering formulas:** $\Omega_c = 30$ GHz/Tesla and $\omega_p = 10^4(n_p)^{1/2}$

Cherenkov Wave Propagation



Resonance at $\omega = 1.04\ \omega_p$ → make sure plasma density is just right (with 8 percent accuracy)

Properties of the Cherenkov Wake

- **Longitudinal E-field exceeds transverse fields → high shunt impedance → good for acceleration**

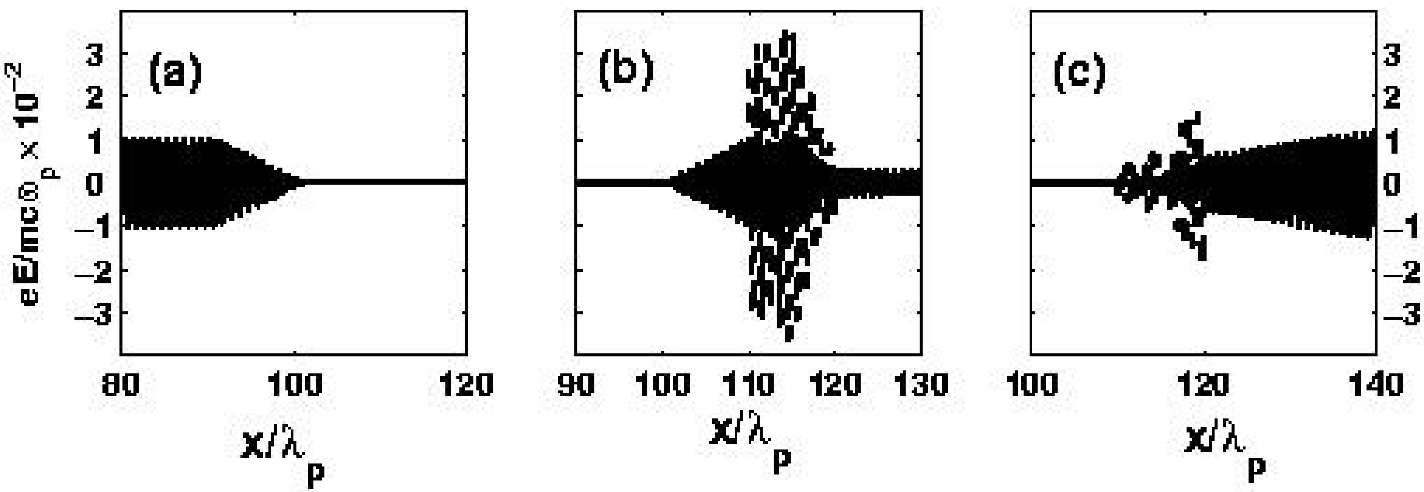
$$\frac{E_{II}}{E_{\perp}} = \frac{\omega_p}{\Omega_c}$$

For $n_p = 10^{14}$ cm^{-3}, $\omega = 100$ GHz and B = 1 T
$E_x/E_y = 3$ → wake has low group velocity

- **Group velocity scales as $(\Omega_c/\omega_p)^2$ → large energy compression in the plasma $v_g/c = 1/10$**

- **Because transverse E and B are equal, there is perfect impedance matching with vacuum → no reflection off vacuum-plasma interface**

1-D PIC Simulation of ICAMP



T=0 — EM pulse enters…

T=100 λ/c — Compresses…

T=200 λ/c — Exits

Parameters:
$\omega = \omega_p$, $\omega_c/\omega_p = 0.3$,
$L_{pl} = 10\ \lambda$

Numbers: B = 1 Tesla,
$n_p = 10^{14}$ cm^{-3}, f = 100 GHz

A = 0.1 cm^2, P = 3MW

E = 36 MV/m

Conclusions

- **Inverse Cherenkov Accelerator in Magnetized Plasma (ICAMP) shows the path to microwave-driven plasma acceleration**
- **Appealing features include:**
  RF power compression
  Relativistic electron acceleration
  Extension to high frequencies
  Perfect impedance matching
- **Initial experiments at FNPL: use 11 GHz klystrons and the previously developed plasma source**
- **Work to do: fully understand entrance into plasma**
- **Limitations: synchrotron losses for E > 100 GeV**