Working Group 3: High Energy Density Concepts and Exotic Accelerating Concepts

- **Talks presented**: 28
- **Joint sessions held**: one with WG1 (Computational Accelerator Physics), two with WG7 (EM Structure Based Accelerator Physics), one with WG7 & WG2 (High Gradient)
- **Major topics discussed**

1. Generation and properties of electron/muon/proton beams: David Cline (UCLA, muon cooling), Kai Tian (UMd) and Jing Zhou (MIT) (space-charged dominated beams)

Major Topics Discussed (cont)

2. **Novel numerical work for HEDP** (protons, relativistic electron beams for FI, Raman amplifiers): Oleg Polomarov (collective beam instabilities in plasmas, UT-Austin), Emmanuel D'Humieres (proton acceleration, UNR), Min Sup Hur (kinetic effects in Raman scattering)

3. Jointly with WG7: **Accelerators Based on Active Materials** (Banna, Schoessow, Tyukhtin)

4. Jointly with WG7: **Negative permittivity and permeability materials for structure-based accelerators** (Shvets, Shapiro, Antipov)

5. **Proton acceleration:** Roland Sauerbrey (microstructured targets), Igor Pogorelski (proton beams with a CO2 laser at BNL), Steve Reed (protons for medicine at UMich).

Major Topics Discussed (cont)

6. **Radiation sources:** Inverse Thompson scattering, including for positron production (Yoder, Pogorelsky, Gibson, Williams); terahertz radiation (Antonsen, Yugami), X-ray FEL theory (Charman)

7. **New approaches to laser-driven accelerators:** Autoresonant beatwave and relativistic bi-stability (Polomarov, UT-Austin and Lindberg, UC-Berkeley), electromagnetic cascade (Kalmykov, UT-Austin)

Tuesday AM
(Beams)

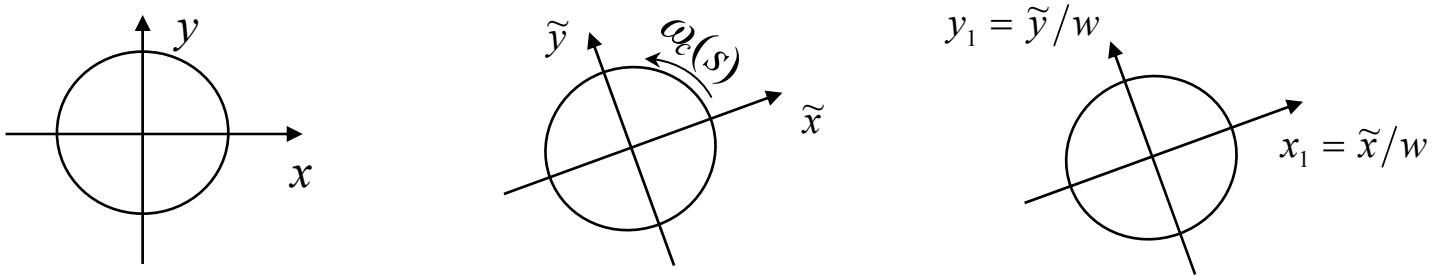
- “Experimental Observations of Beam Fluctuations in Space-Charge Dominated Beams “ Kai Tian (U. Maryland)
- “Overview of 6D Muon Cooling” D. Cline (UCLA)
- “Thermal rigid-rotor equilibrium of intense beam propagation through a periodic solenoidal focusing field” Jing Zhou, Ksenia Samokhvalova and Chiping Chen (MIT)

Thermal rigid-rotor equilibrium of intense beam propagation through a periodic solenoidal focusing field

Jing Zhou

- Thermal equilibrium theory developed for a periodically focused axisymmetric high-intensity beam with nonuniform thermal density.
- Analysis proceeds via a series of transformations:

Cartesian Coordinates (x, y, P_x, P_y) $\Rightarrow$ Larmor Frame $(\tilde{x}, \tilde{y}, P_{\tilde{x}}, P_{\tilde{y}})$ $\Rightarrow$ Courant-Snyder transformation $(x_1, y_1, P_{x1}, P_{y1})$

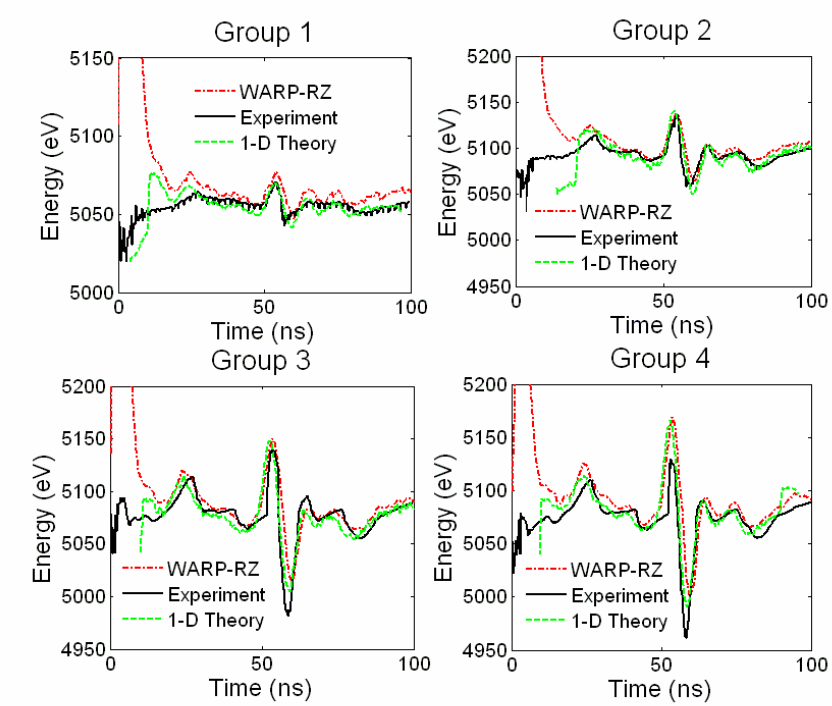


- Expressions for the beam envelope and statistical properties are derived.

Experimental Observations of Beam Fluctuations in Space-Charge Dominated Beams

Kai Tian

- Results of LSE experiment at UMER
- Generate and diagnose space charge waves
- "Using electron beams to simulate billion dollar machines". (Generalized perveance the same as e.g. a heavy ion fusion beam)



Comparisons of the mean energy from the experiment results, WARP and one dimensional cold fluid theory.

Joint Session with WG1 (Computational)

- Min Sup Hur, "Envelope-Kinetic Equation of a Plasma Wave"
- Oleg Polomarov, " Novel computational approach to Weibel instability and beam transport in overdense plasma"
- Emmanuel D'Humuiere, " PIC simulations of the interaction of high intensity lasers with ultra-thin targets"

Envelope-Kinetic Equation of a Plasma Wave

1. The electron trapping effects on Raman backscatter and laser amplification can be modeled by the Envelope-Kinetic equation of the plasma wave (Minsup Hur)

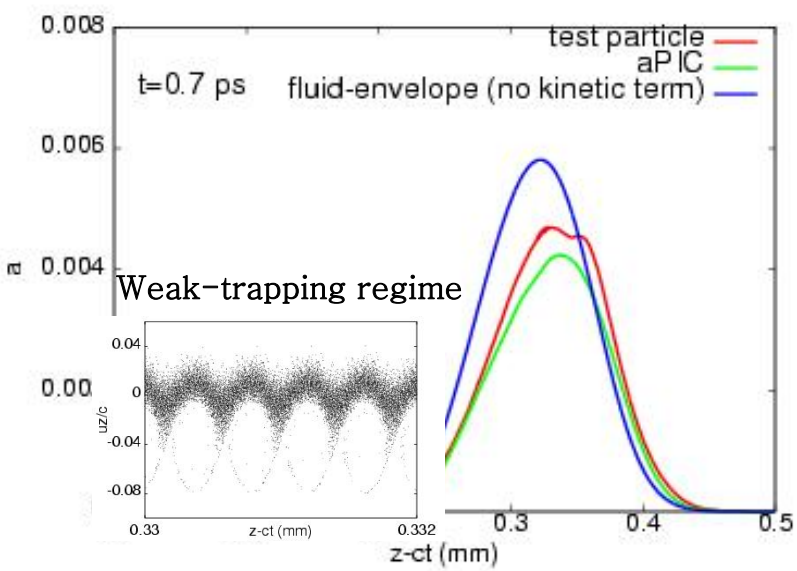
$$F_t + i\delta\omega F + \boxed{2\omega\left\langle \beta_j^2 e^{-i\phi_{\mathrm{PM}j}} \right\rangle} = -\frac{\omega}{2} a_s^* a_p$$

Kinetic term

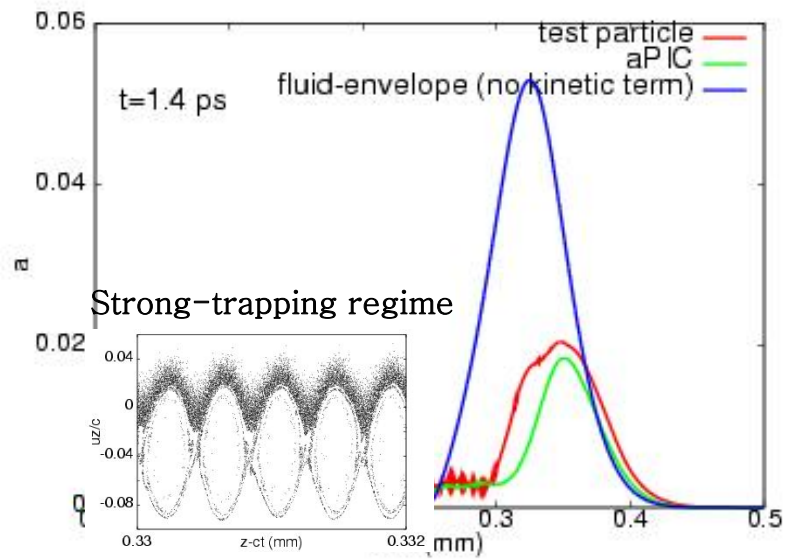
could be useful for treating colliding pulse injection!

2. Small number of test particles can be used to get the kinetic term. (test particle follows the equation of motion, but does not generate any field)

In the strong trapping regime, the test particle method gives a good agreement with the full kinetic result (aPIC), while the 3-wave model shows a large deviation.



Phase space near the peak

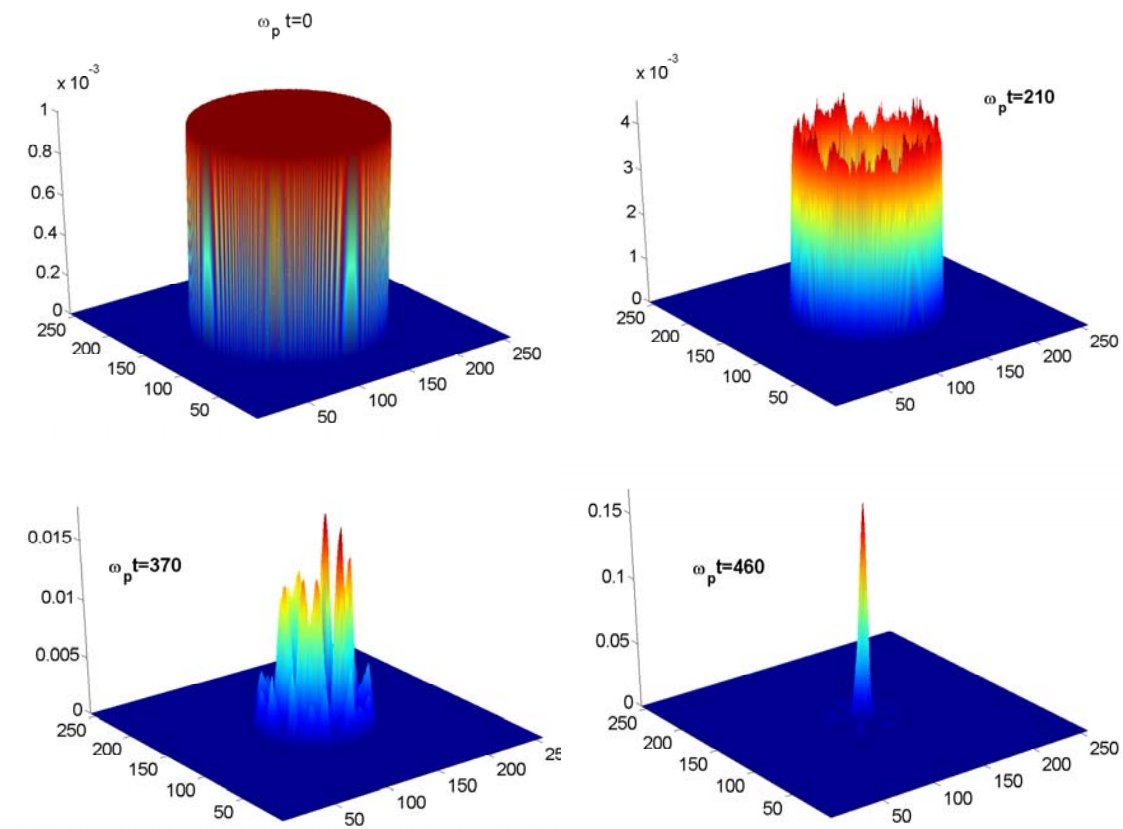


Phase space near the peak

Novel computational approach to Weibel instability and beam transport in overdense plasma

What's in the model:

1) Plasma electrons form a non-relativistic fluid
2) Beam electrons are relativistic particles
3) Quasi-neutrality of beam-plasma system
4) Conservation of generalized vorticity



Field Equations:

$$\nabla^2\psi - \frac{\omega_e^2}{c^2}\psi = -\frac{4\pi}{c}J_{bz}$$

$$\left(\nabla^2 - (\vec{\nabla}\ln n_e \cdot \vec{\nabla}) - \frac{\omega_e^2}{c^2}\right)B_z = \frac{4\pi n_e}{c}\vec{\nabla}\cdot\left(\frac{\vec{e}_z \times}{n_e}\right.$$

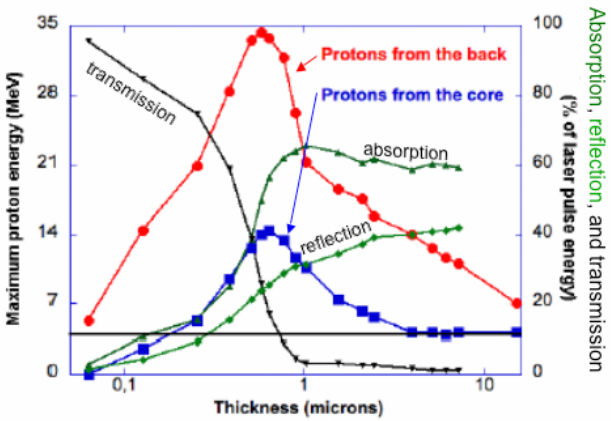
Beam Equations:

$$\frac{d\gamma_j \vec{v}_{j\perp}}{dt} = -\frac{ev_{jz}}{mc}\vec{\nabla}\psi + \frac{e^2}{2m^2c^2}\vec{\nabla}\psi^2 + \frac{eB_z}{mc}\vec{e}_z \times \vec{v}_{j\perp} + \frac{\partial \vec{v}_{e\perp}}{\partial t} + \vec{\nabla}\left(\frac{\vec{v}_{e\perp}^2}{2}\right)$$

$$\frac{d}{dt}\left(\gamma_j v_{jz} - \frac{e}{mc}\psi\right) = 0$$

Oleg Polomarov

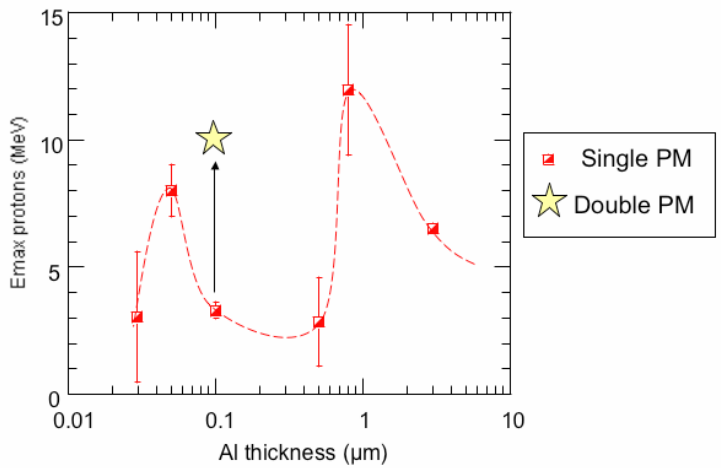
PIC simulations of the interaction of high intensity lasers with ultra-thin targets (Emmanuel D'Humiere)



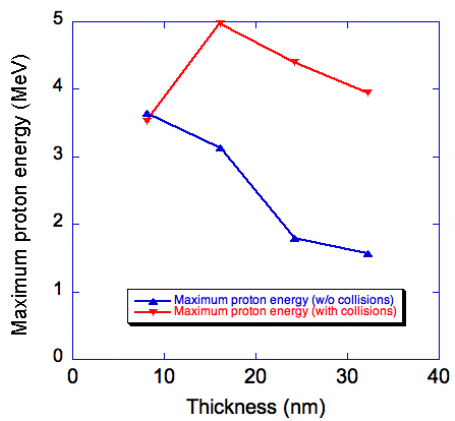
!! PIC simulations performed using a laser Pulse with **no** ASE

E. d'Humières et al., Phys. Plasmas **12**, 062704 (2005)

10^{20} W/cm^2, 36 fs, 10 n_c plasma.



Experimental results LULI: 20 J, 10^{18} W/cm^2, 350 fs (with one and two plasma mirrors)
Model prediction at 10^{18} W/cm^2 and 350 fs: 1 MeV.



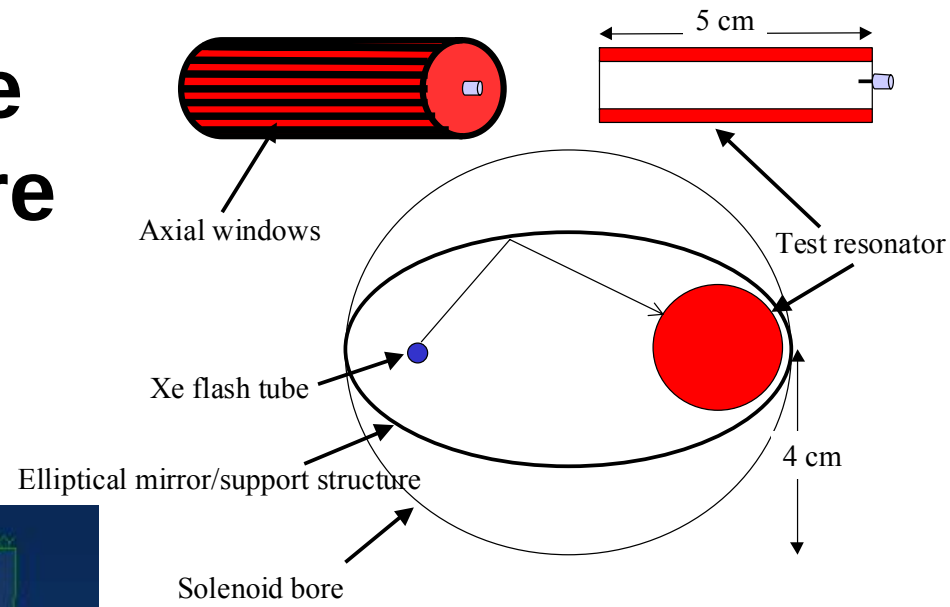
1D PIC simulations

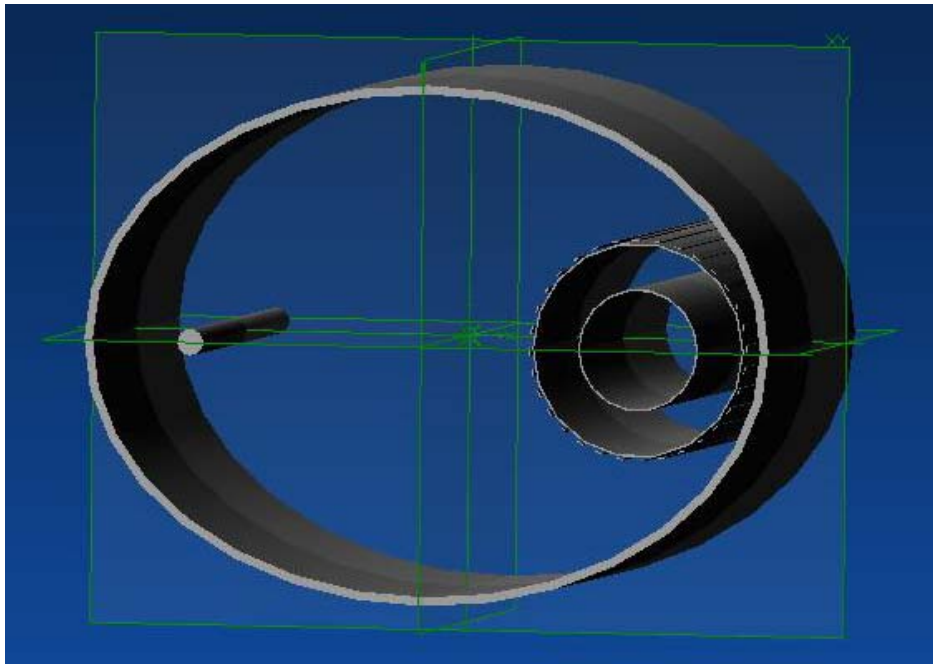
Volume electron heating and efficient proton acceleration can be achieved with ultra-thin targets. But a compromise between thickness and preplasma could be optimum.

Wednesday AM
(PASERs, Joint session with WG7)

- “Experimental Evidence for the PASER” Samer Banna and Levi Schächter (Technion)
- “Studies of Particle Acceleration by an Active Microwave Medium” P. Schoessow, A. Kanareykin, L. Schächter, A. Tyukhtin, E. Bagryanskaya, N. Yevlampieva
- “Wakefields Generated by Electron Beams Passing Through a Waveguide with an Active Medium” A. Tyukhtin (Saint-Petersburg State University)

Bench Test/Prototype Accelerating Structure





- Experiments planned at ANL/AWA
- Bench test of prototype accelerating structure
- Beam tests- gradients <66 MeV/m for 1 pC accelerated charge expected.

Wakefields Generated by Electron Beams Passing Through a Waveguide with an Active Medium

Andrey Tyukhtin, Saint-Petersburg State University

- Analytic studies of microwave PASER in “wakefield amplifier” configuration
- Investigate the effects of multiple modes of the structure occurring inside the gain bandwidth of the active material
- Consider weak and strong limits of resonant dispersion
- Advantages of amplification of the higher modes:

1. Amplification of the highest mode occurs in a structure with a thick active medium layer and hence more energy stored in the medium.
2. The dependence of the amplification on the geometry parameters for the higher modes is not very strong—possibility of amplifying several modes.
3. As a rule, the excitation of the highest amplified mode is rather effective.

Joint Session with WG7: MetaMaterials (and other negative permittivity/negative index materials) for particle accelerators

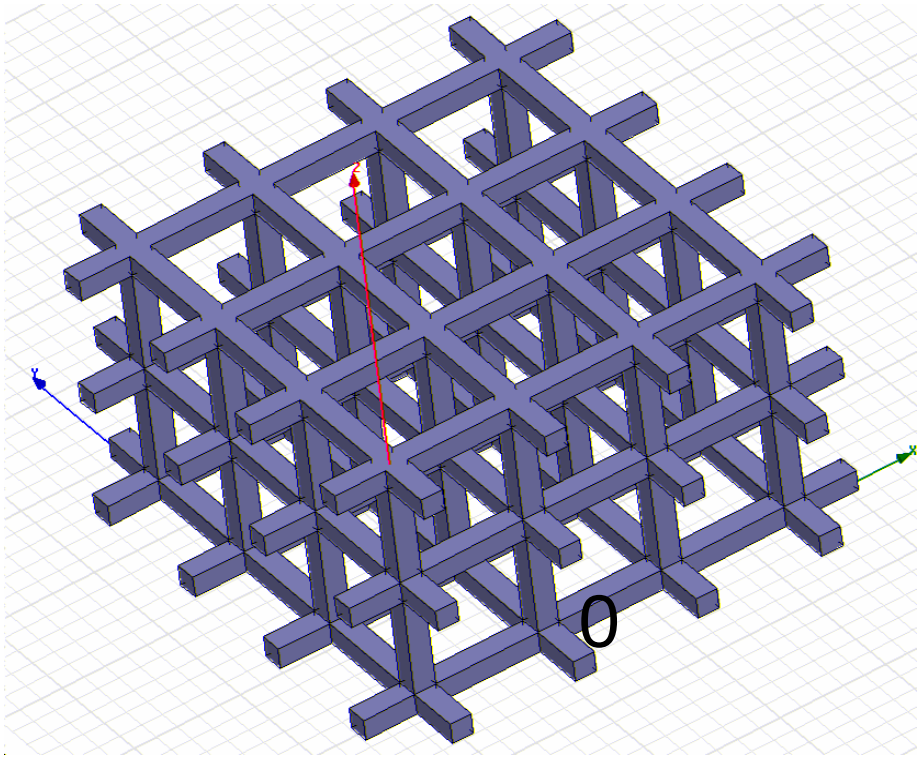
1. Gennady Shvets, "Side coupled surface wave accelerator based on SiC"
2. Sergey Antipov, "Left-Handed Structures for Accelerator Applications"
3. Michael Shapiro, "Negative Permittivity Accelerators"

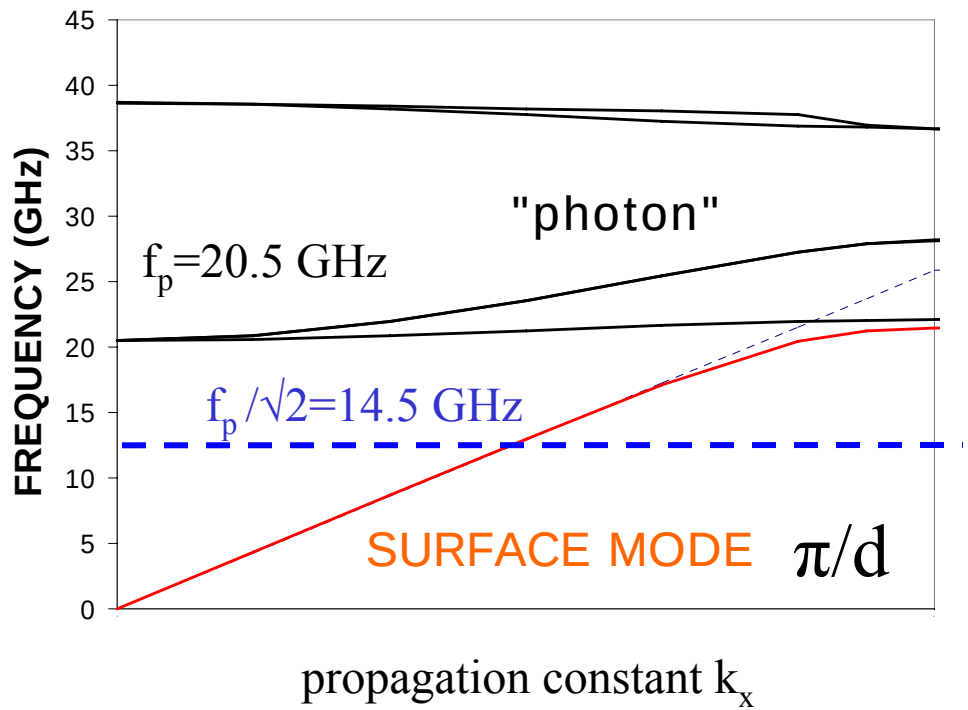
Negative Permittivity Accelerators

Shapiro, MIT: "artificial plasma" for particle acceleration

Can one develop a "hollow plasma channel accelerator" based on artificial plasma?

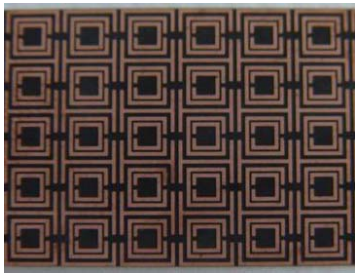
$$\varepsilon_p(\omega) = 1 - \omega_p^2 / \omega^2 \qquad \omega_p = \frac{c}{d}\left(\frac{2\pi}{\ln\frac{d}{w}}\right)^{1/2}$$

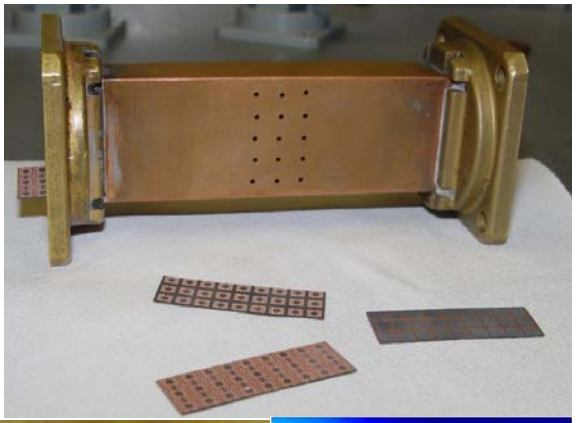


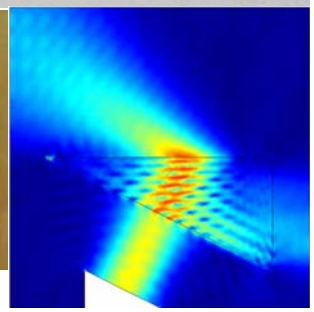


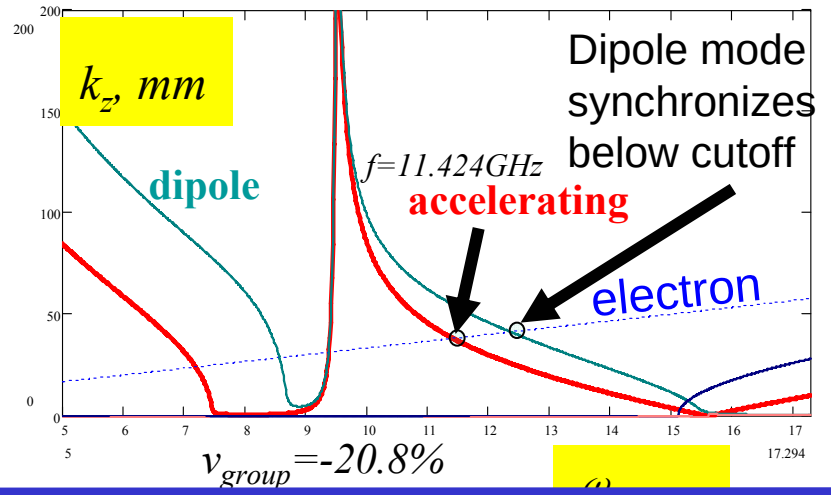
Left-Handed Structures for Accelerator Applications

- GHz range LH metamaterials were studied, designed and manufactured. Several unusual properties are demonstrated.
- Cold tests for X-Band waveguides loaded with metamaterials were performed.
- Metamaterial-loaded waveguide for accelerator purposes is studied.
  - Dispersion for TM modes derived
  - Suppression of the dipole modes is theoretically shown
  - LHM (11.424GHz) accelerator parameters are derived
  - Resonant losses → low Q=200
- Metamaterials change the dispersion relation for TM modes in the waveguides significantly and present an opportunity for a dipole-mode-free acceleration.

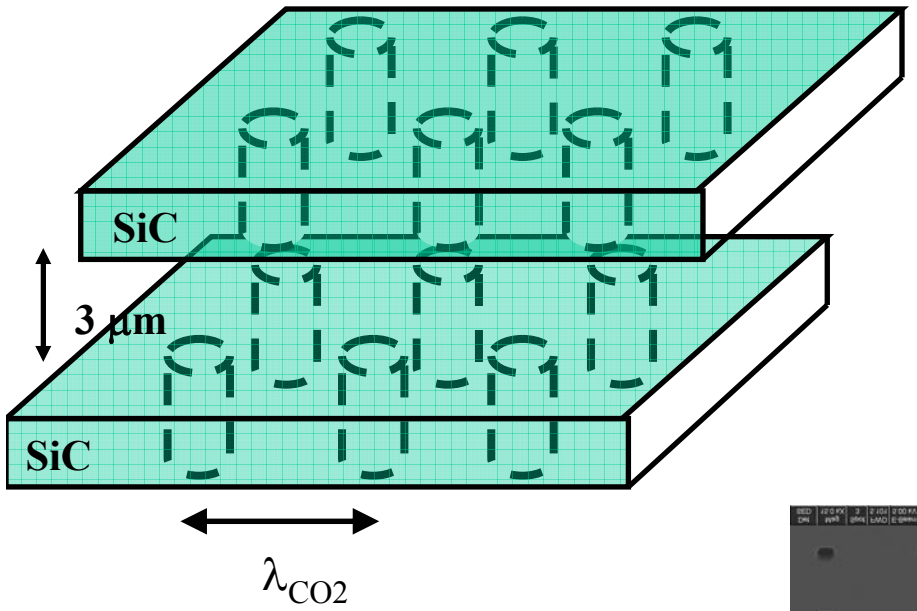


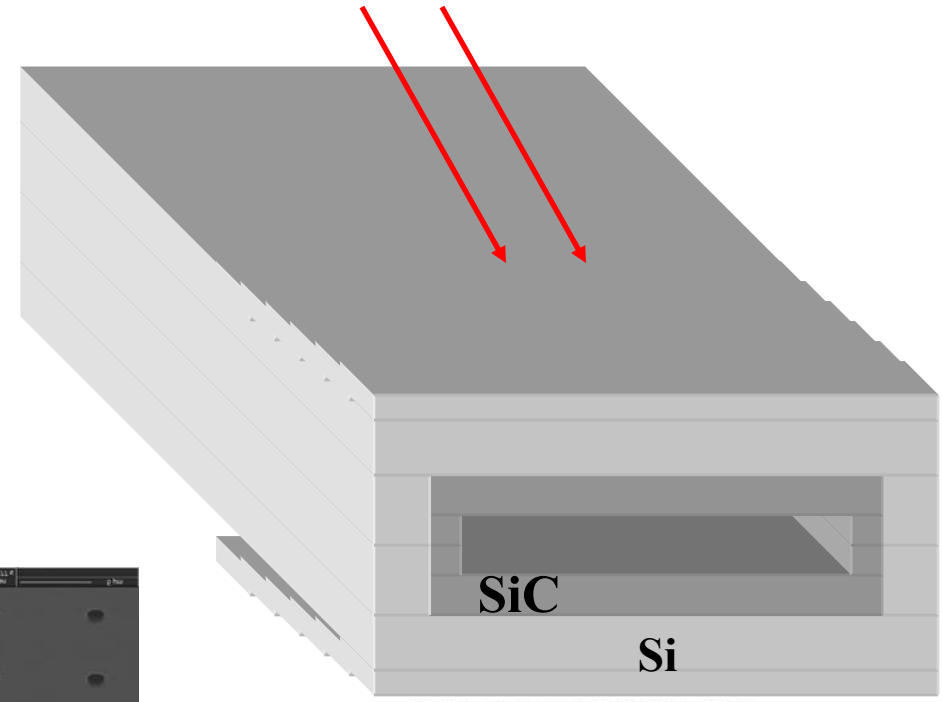


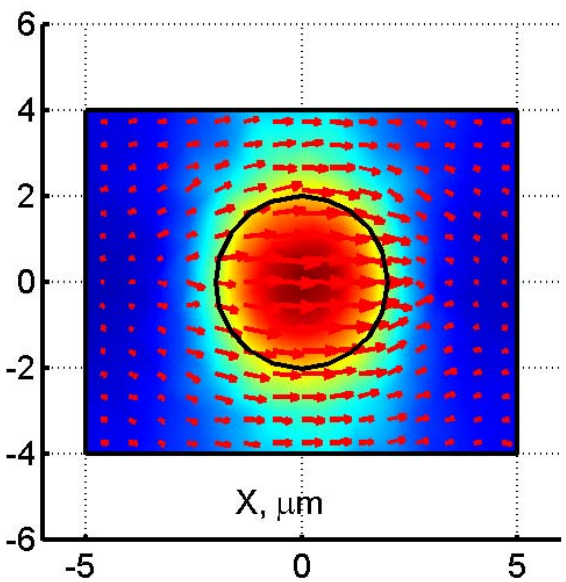


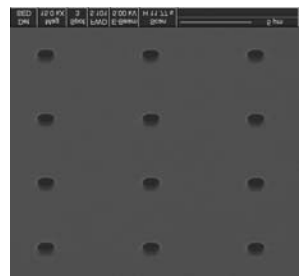


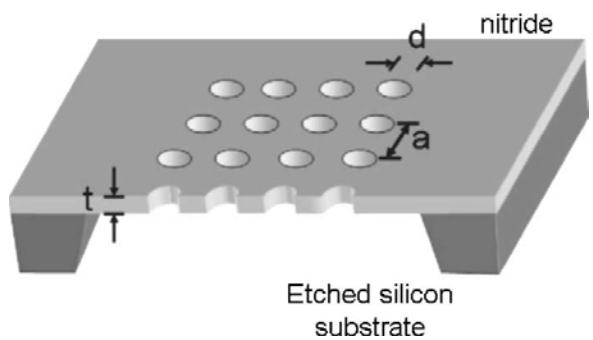
Side-coupled surface wave accelerator (Shvets)

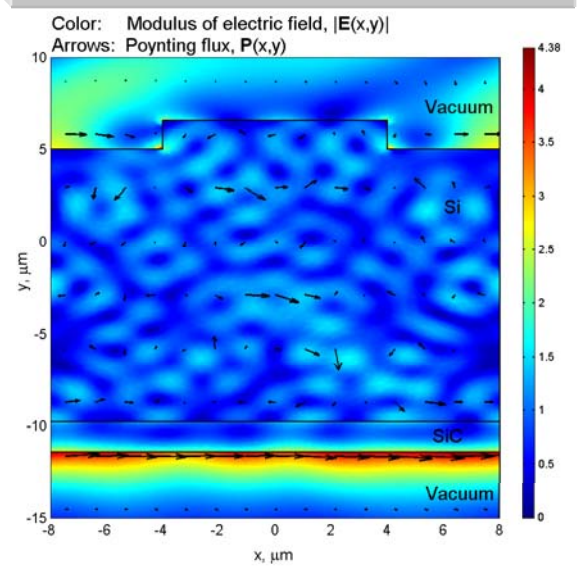






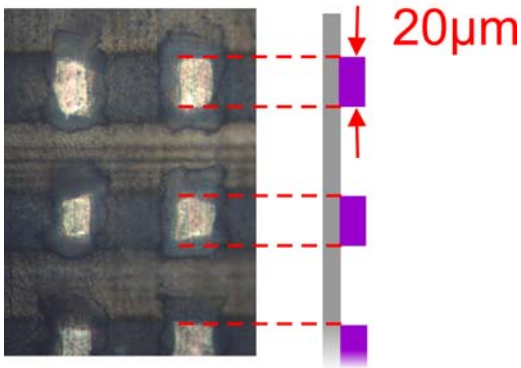


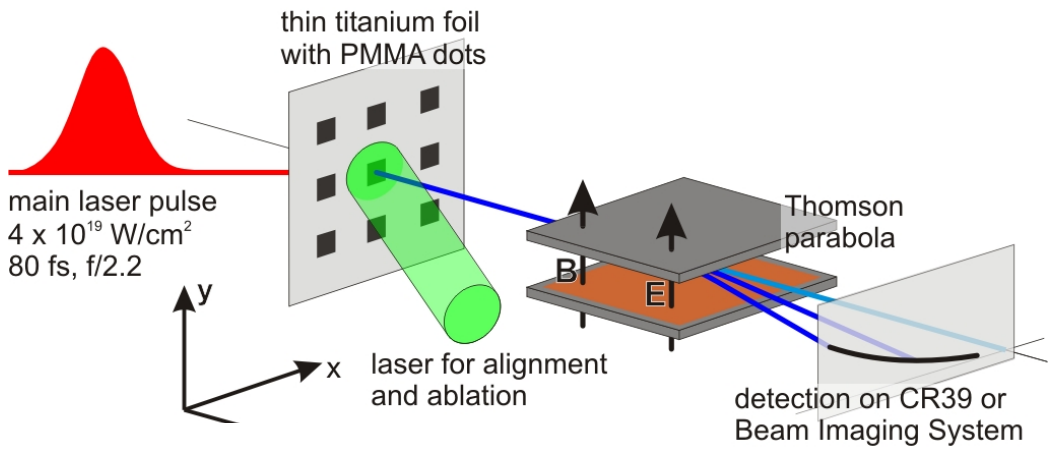


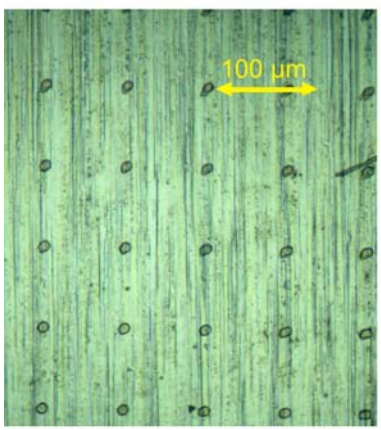


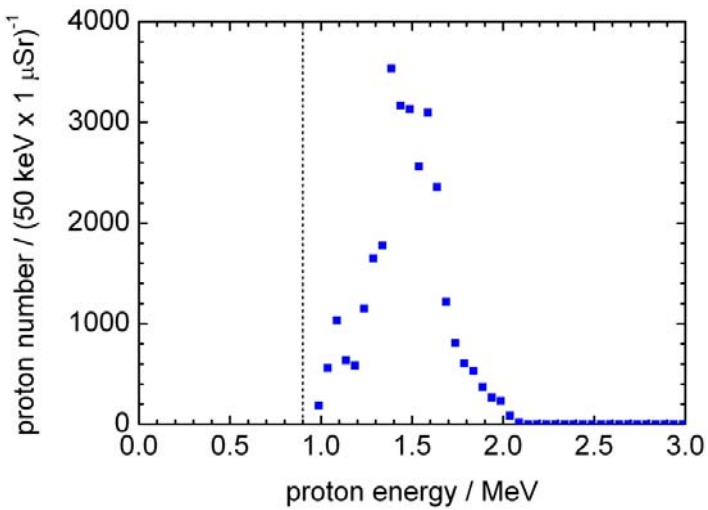
Acceleration of Protons from Microstructured Targets

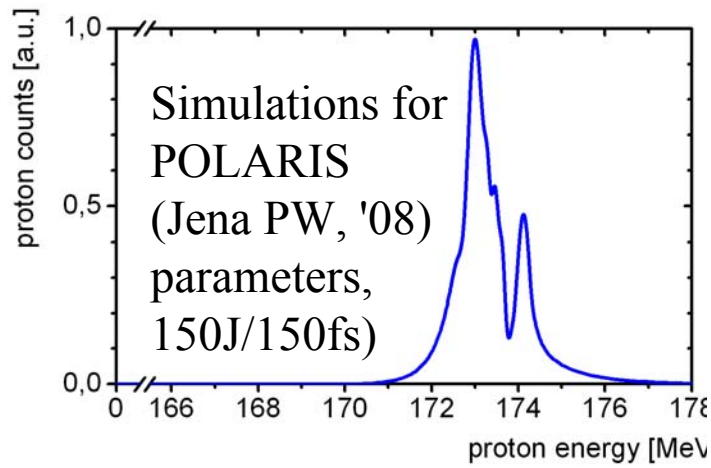
Roland Sauerbrey











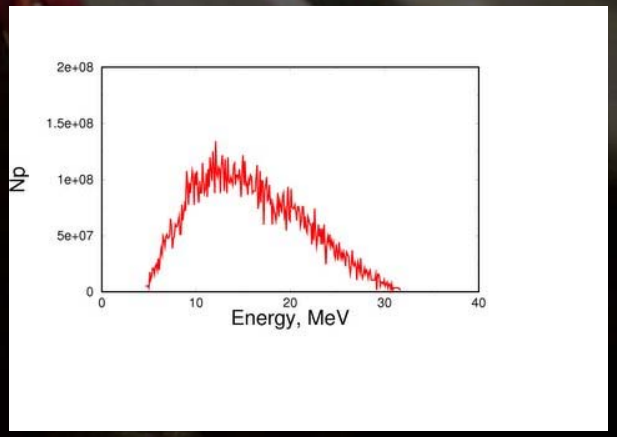
Discussed applications: proton shadowgraphy of hot and dense plasmas; low emittance, short pulse ion injectors; medical applications (isotope production and radiotherapy

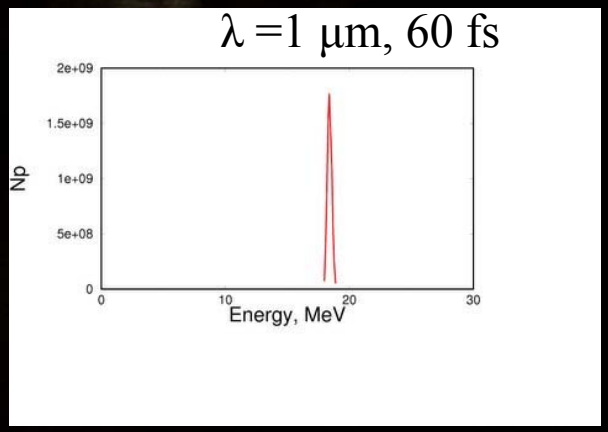
CO_2 laser advantage: proton acceleration in a structured target

- Ponderomotive electron energy $E_e \sim I^{1/2}\lambda$.
- Ion energy $E_i \sim E_e(\ln \tau_{/ln})^2$, thus, 1 TW, 5 ps 10 μm laser will be equivalent to 100 TW, 5 ps or 10 PW, 0.5 ps 1μm laser.
- At the same power and energy, CO_2 laser will provide the same ponderomotive action within $\sim\lambda^2$ (100 times) bigger area or $\sim \lambda^3$ (1000 times) bigger volume resulting in the 1000 times higher number of accelerated electrons.
- We expect that the number of accelerated ions will also **grow with** λ.

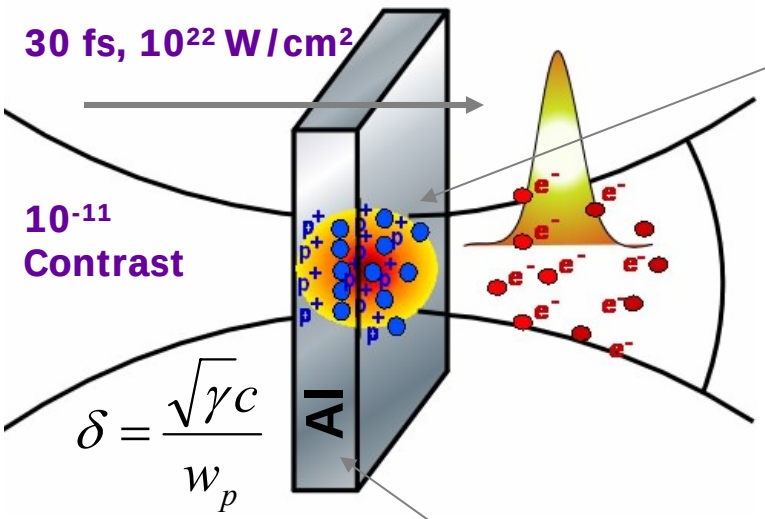
Shkolnikov and Pogorelsky, BNL

3D PIC by Alexander Pukhov
Compare 1 μm and 10 μm 20 TW lasers focused to 3λ





High Energy Proton Acceleration with ultra-clean ultra-intense laser beams (Steve Reed)



$$\delta = \frac{\sqrt{\gamma}c}{w_p}$$

Submicron target < 100 nm

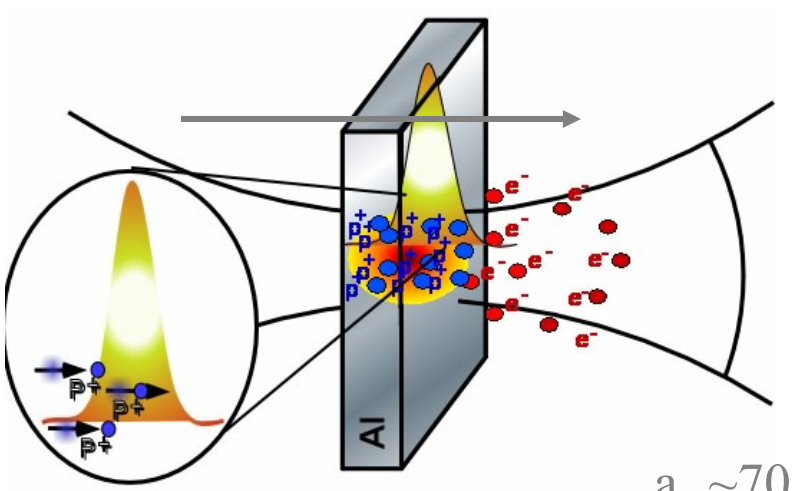
Coulomb Explosion Regine:

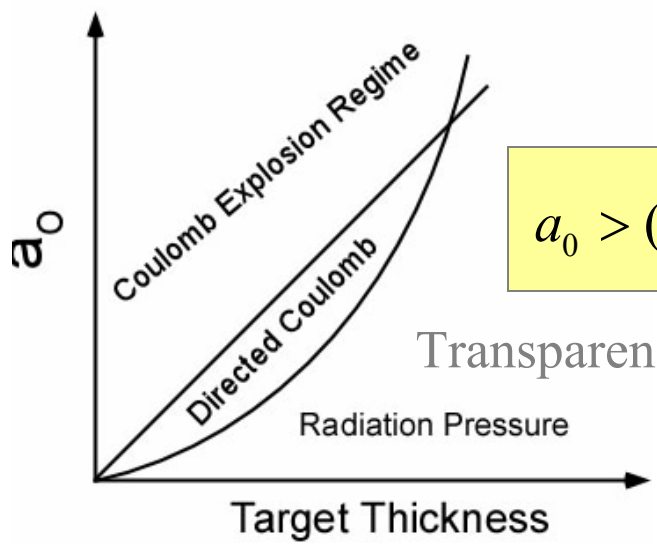
Expel all e$^-$ due to laser ponderomotive force

$$a > \pi^2 (N / N_{cr})(t / \lambda)$$

Maximum ion energy

$$E = 2\pi Z_a Z_i e^2 n_o l R_o$$





$$a_0 > (\omega_{pl} / c)^2 t^2$$

Transparency condition

a_0 ~70 for 10^{22} W/cm^2 Giving skin depth ~ 40nm

Discussions of Applications

- Low CW power → seek applications that do not require high average power:
  1. Radiation therapy
  2. Radiography, ultra-fast diagnostics of electric and magnetic fields
- HEP applications (i.e. injection into a linac/ring) not ruled out → due to low emittance no need to use H- for phase space density enhancement (Vladimir Shiltsev) although low average power still an issue…

Novel Radiation Sources

- **Inverse Compton Scattering, with applications to positron production for ILC**

  1. Rodney Yoder, "Inverse Compton Scattering Radiation Source via Self-Guiding in a Plasma"
  2. David Gibson, "High-brightness e-beams for the generation of high brightness X-rays (PLEIADES → T-REX)
  3. Igor Pogorelsky, "Demonstration of high photon yield and nonlinearity in relativistic Thompson scattering
  4. Oliver Williams, "Status of Nonlinear Inverse Compton Scattering Experiment at UCLA" (status report)
  5. Andrew Charman, "A Hilbert space formulation of and variational principle for spontaneous radiation

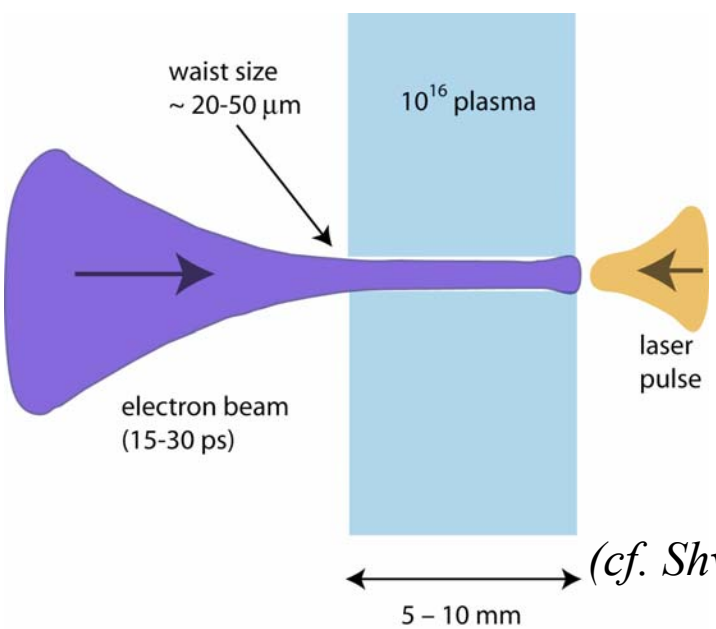
An Inverse-Compton-Scattering Source via Self-Guiding in a Plasma

- Photon production ~ $\sigma_T \frac{n_b n_\gamma}{Area} \sigma_{t,\gamma} \sigma_{z,b}$
- Want high photon density, but tight focus gives **strong diffraction**
- Beam limited by emittance

$$\beta = \sigma_r^2 / \varepsilon \leq 0.5 - 1 \text{ cm}$$

- Laser limited by diffraction

$$Z_R = \pi r_0^2 / \lambda_0 \leq 1 - 2 \text{ mm}$$



Parameter	X-ray source	γ-ray source
E-beam energy	37 MeV	1.6 GeV
E-beam spot (σ_r)	7.3 µm	2.3 µm
Normalized emittance (ε_n)	5 mm mrad	20 mm mrad
Beam length (σ_z)	3 mm	6 mm
Beam charge	100 nC	100 nC
Laser energy/pulse	0.5 J	1.5 J
Plasma density n_0	1 x 10^{16} cm^{-3}	1 x 10^{18} cm^{-3}
Scattered photon energy	33 keV	61 MeV
Photon number	~6 x 10^{10}	~8 x 10^{11}

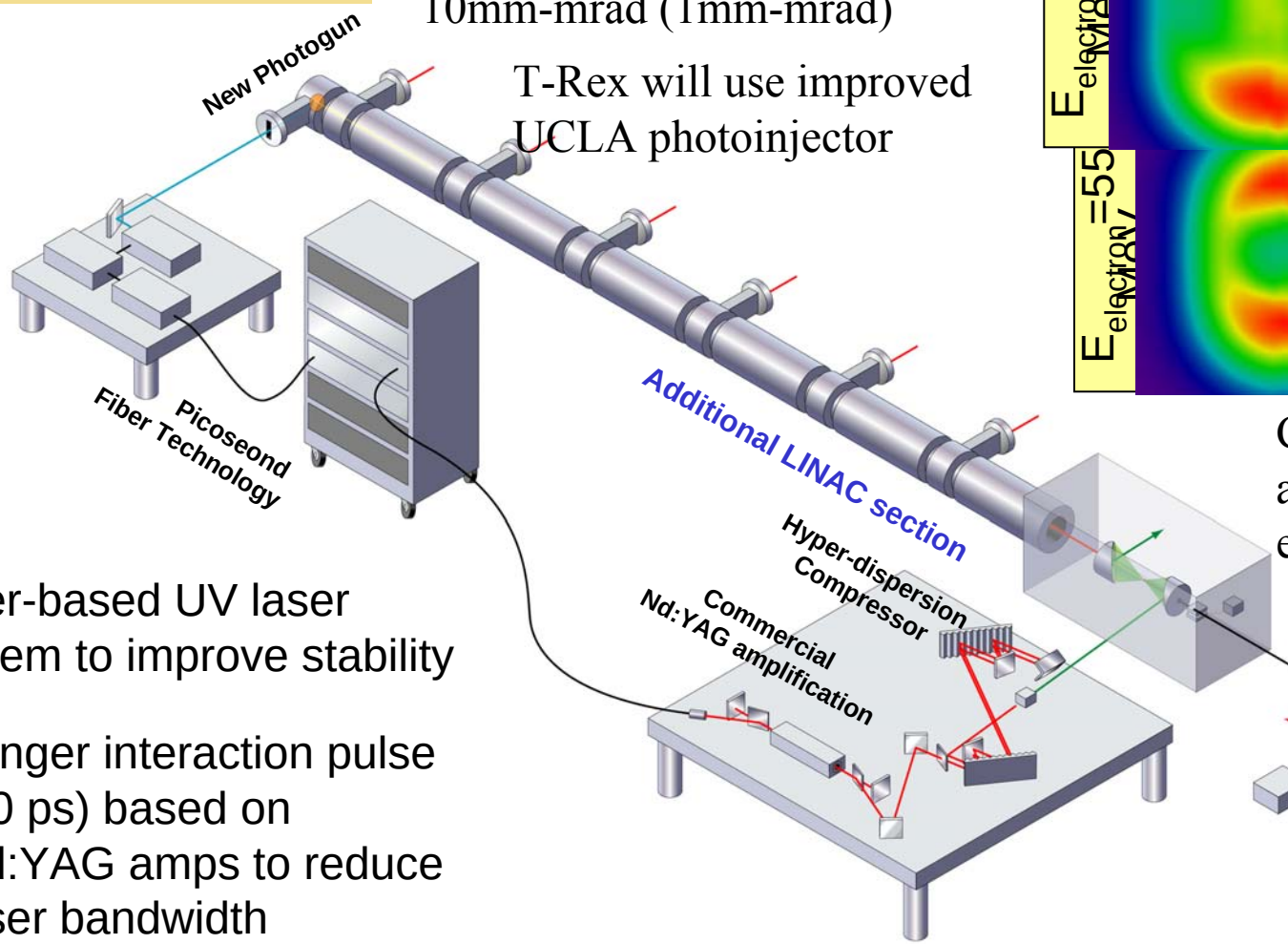
(cf. Shvets & Fisch, PRE 1997: co-propagating laser and e-beam)

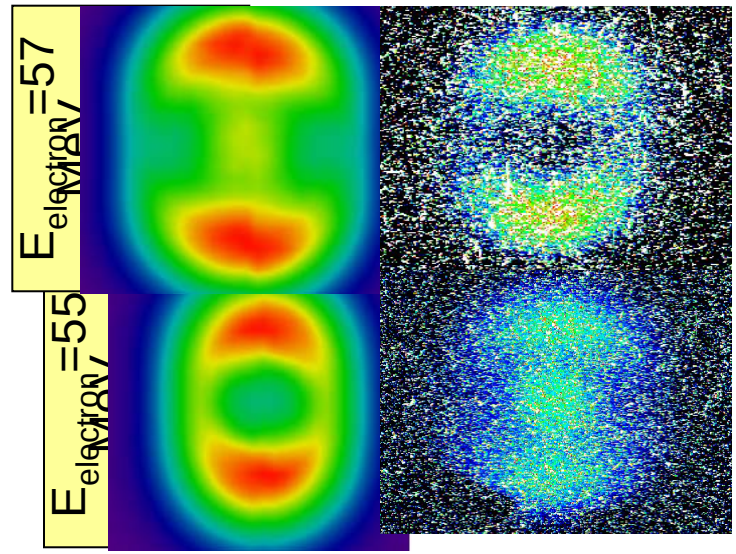
Thomson-Radiated Extreme X-rays = T-REX

135 MeV + 351 nm
= 1 MeV

Problems with PLEIADES photoinjector: 0.3nC (1nC), 10mm-mrad (1mm-mrad)

T-Rex will use improved UCLA photoinjector





Codes benchmarked against PLEIADES experiment

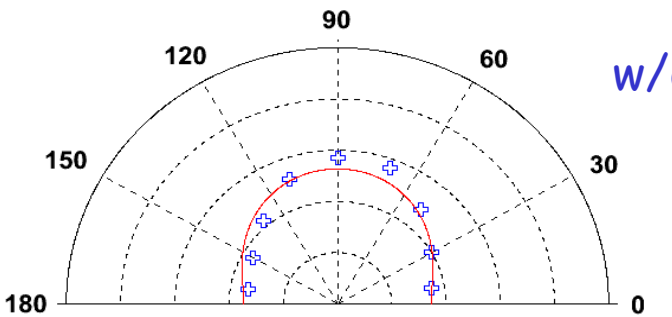
Fiber-based UV laser system to improve stability

Longer interaction pulse (10 ps) based on Nd:YAG amps to reduce laser bandwidth

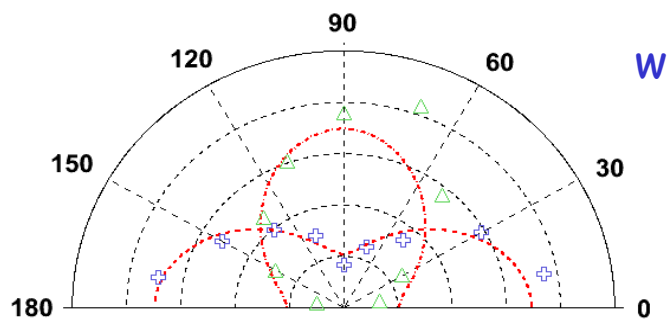
D. Gibson, LLNL

Demonstration of high photon yields and nonlinearity in relativistic Thomson scattering (Igor Pogorelsky)

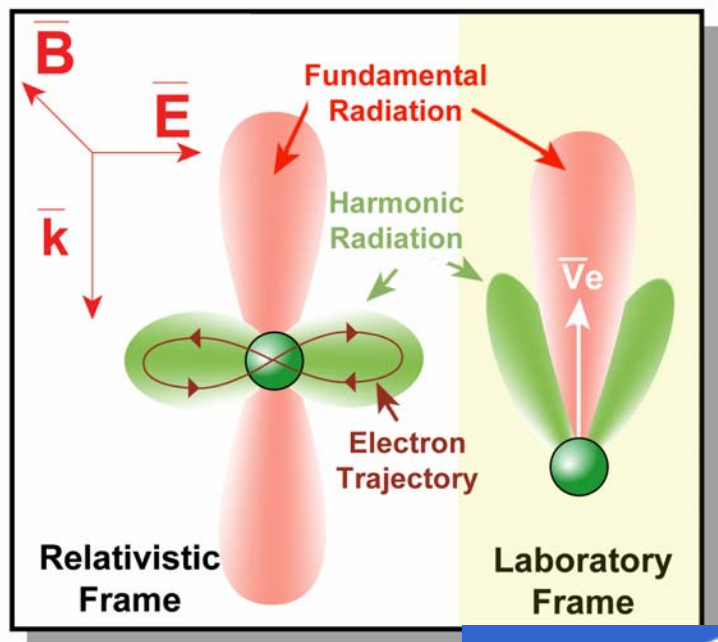
- CO_2-Laser/e-beam interaction conditions are optimized and a record-high x-ray yield has been achieved.
- Production of one x-ray photon per every electron demonstrated.
- Nonlinear scattering observed.
- A CO_2 laser system for ILC polarized γ-source based on intra-cavity Compton backscattering is within a reach.



w/o Ag filter



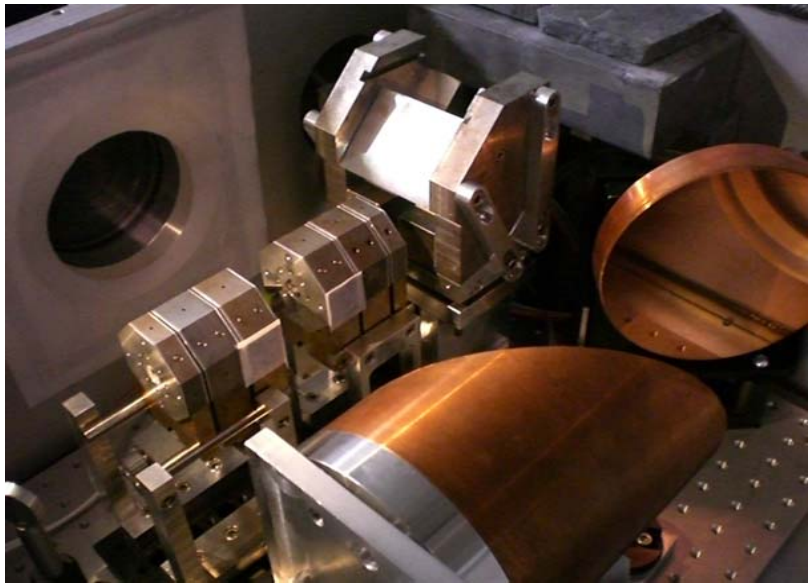
with Ag filter



BROOKHAVEN NATIONAL LABORATORY

Status of nonlinear ICS experiment at UCLA (Oliver Williams)

- Goal is to investigate the angular and frequency distribution of harmonics created in nonlinear interaction of electron beam with laser photons in presence of high laser vector potential, a_o=1
- Will also attempt to measure the expected red-shift of the fundamental with increased a_o
- Spatial and temporal alignment at the interaction point has been achieved
- EUV/Soft X-ray CCD camera to be used for imaging and possibly non-dispersive spectroscopy in single photon regime
- Method of verification of degree of polarization transferred from laser photons to scattered photons still being investigated; transmissive multilayer optics look promising
- Expect first light within next couple of months



Maximum Power Variational Principle for Spontaneous Wiggler Radiation

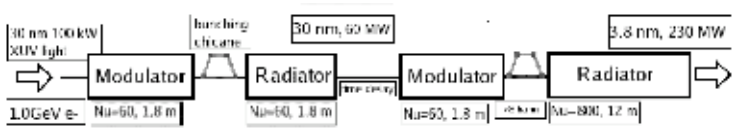
A.E. Charman, G. Penn, J.S. Wurtele

U.C. Berkeley Physics / LBNL Center for Beam Physics

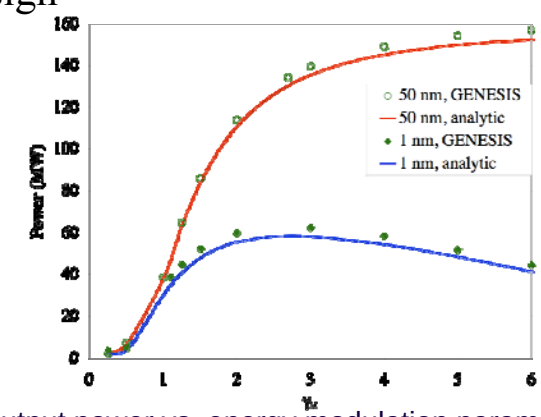
classical charges radiate spontaneously "as much as possible," consistent with energy conservation

- classical spontaneous radiation always maximizes power (spectral density), or equivalently maximizes the resemblance in shape between source current density and radiation pattern, subject to constraint that radiated power could have arisen from "virtual work" of sources on far-fields extrapolated back to interaction region
- provides an simple approximation technique directly applicable to any magnetic Bremsstrahlung radiation if recoil/back-action/gain/multiple scattering may be ignored, and possibly generalizable to Cerenkov, Smith-Purcell, or other radiation...
- radiation fields are analyzed in a Hilbert-space setting, either paraxial or full 3D
- radiation from given sources, satisfying an inhomogeneous wave equation, is approximated by source-free (homogeneous) solutions within a parameterized family of trial functions
- successfully applied to the efficient optimization of beam-line design for harmonic cascade FEL

comparison of variational principle (line) using adjustable Gaussian mode to full GENESIS macro-particle/Maxwell simulation



typical final stages of HHG FEL



output power vs. energy modulation parameter

Novel Radiation Sources

- **Terahertz radiation sources**

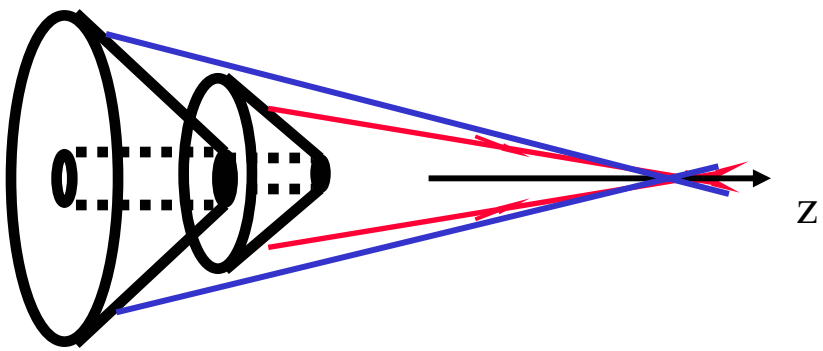
  1. Thomas Antonsen, "THz generation by ultra-short laser pulses propagating in nonuniform plasma channels"
  2. Noboru Yugami, " Generation EM waves by laser plasma interaction experiments in Utsunomiya University "

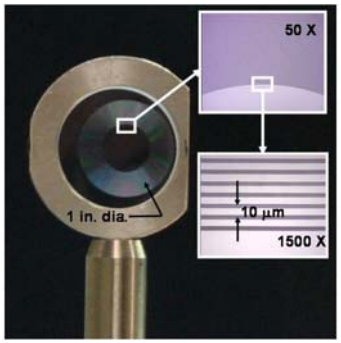
THz generation by ultra-short laser pulses propagating in nonuniform plasma channels

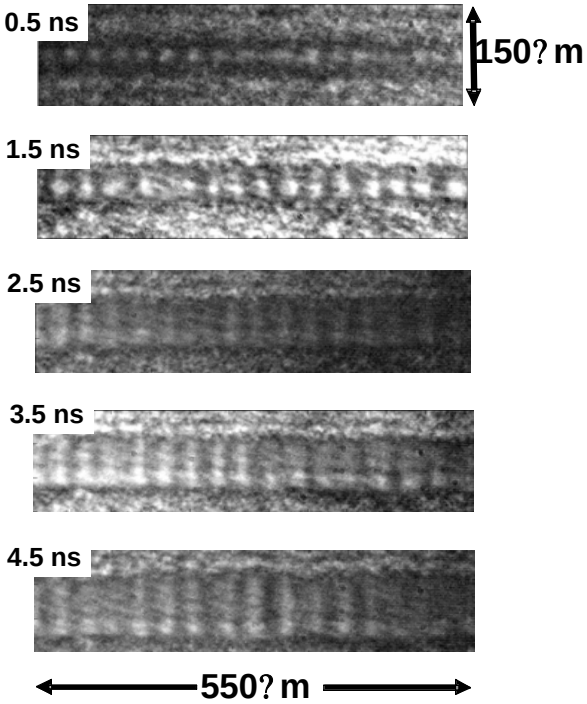
- **Ponderomotive driven currents couple to THz radiation in inhomogeneous plasma channels**

- **Such channels can be formed hydrodynamicaly using an axicon + ring grating → seeded**

- **Pump depletion rate due to radiation generation can exceed that of scattering and plasma wave generation**

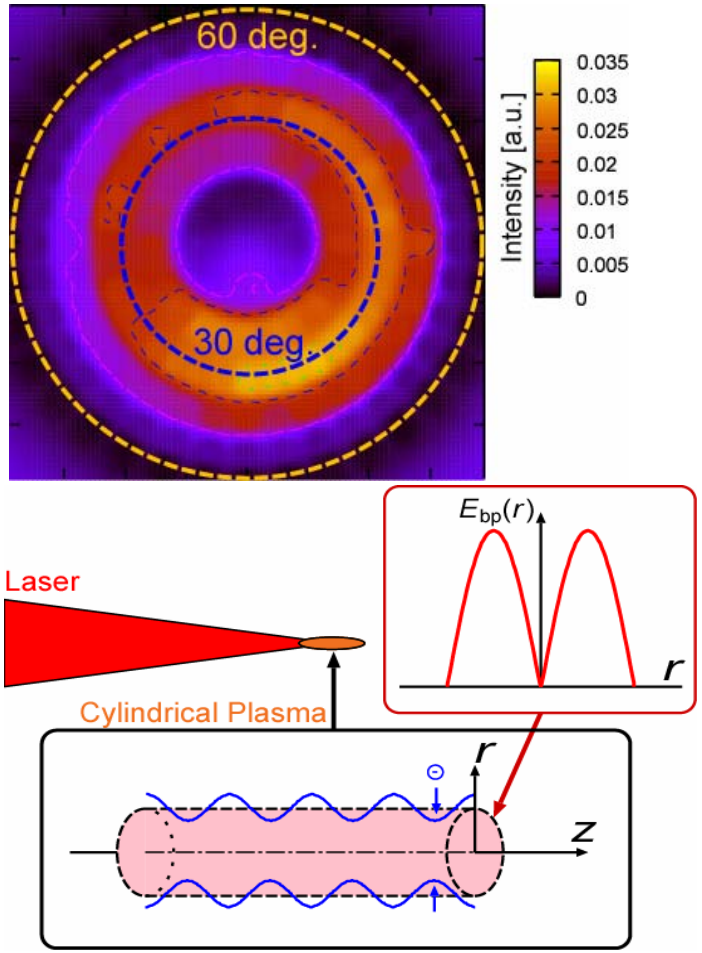


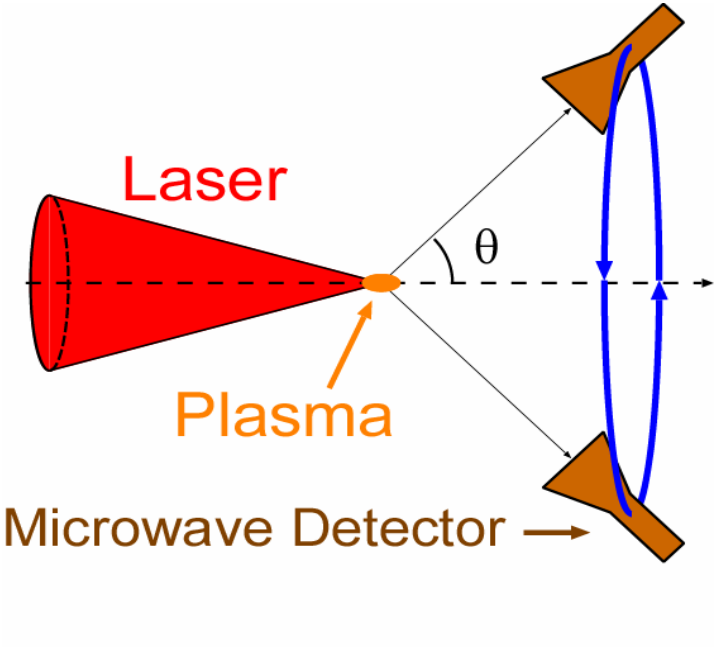




T. Antonsen et. al.

Recent Experiment
Low-laser-intensity (0.2 TW), Unmagnetized
Angular distribution of a 0.1-THz emission



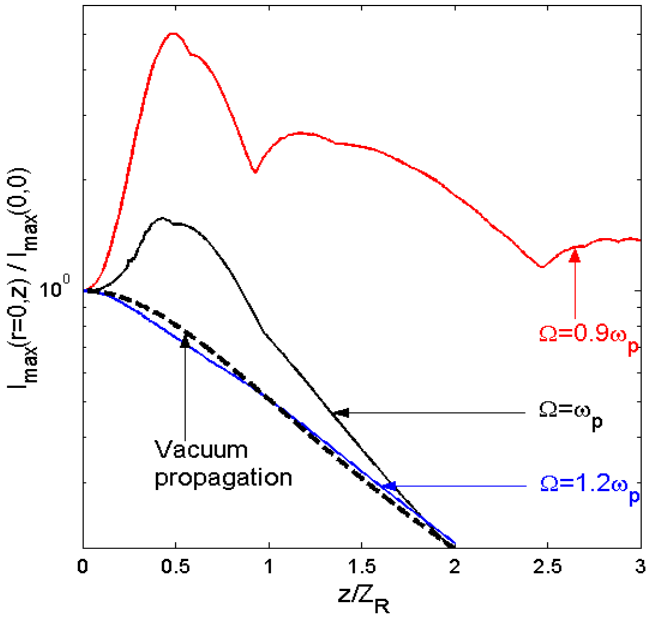


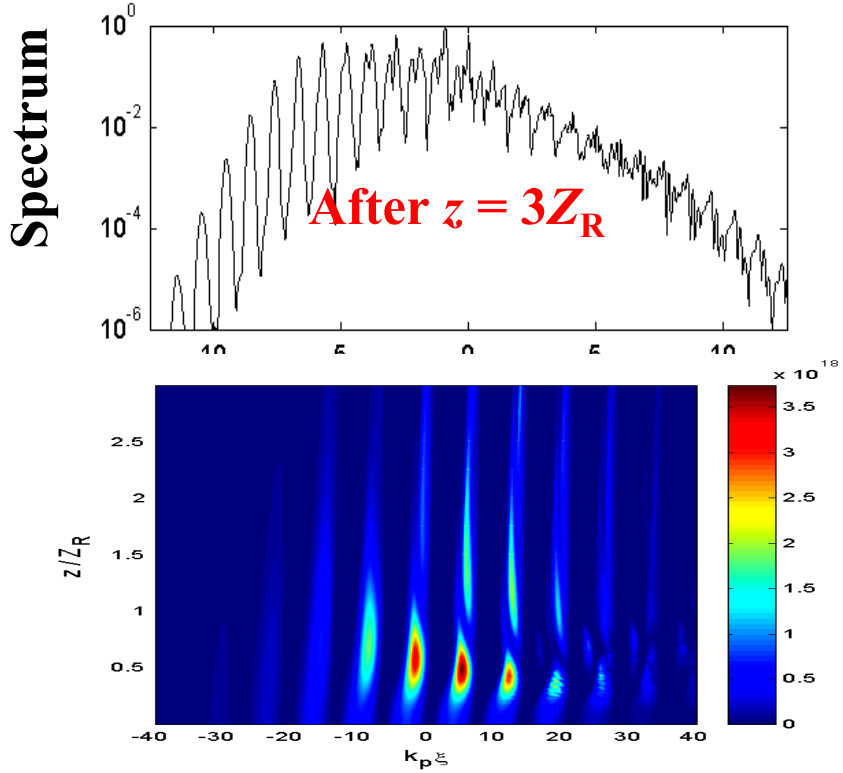
N. Yugami *et al*., (to be submitted).

New ideas in laser-plasma acceleration

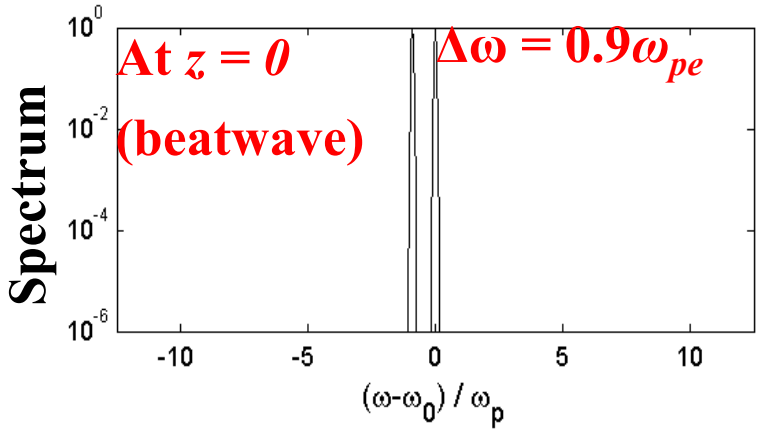
1. Serguei Kalmykov – “Electromagnetic cascade-induced guiding of intense laser beams and its application to compact electron accelerators”.
2. Ryan Lindberg – “Autoresonant beat-wave generation"
3. Oleg Polomarov – “Relativistic Dynamical Bi-Stability of plasma waves in a Plasma Wakefield Accelerator”.

EM Cascade Guiding/Compression: GeV Electrons In a PBWA



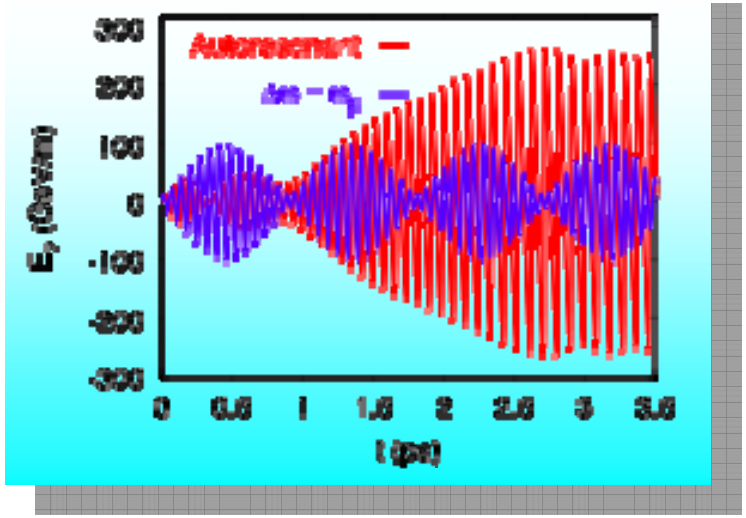


- ✓ EM cascading → trains of femtosecond laser pulses
- ✓ 3D dynamics: longitudinal compression compensates diffraction → cascade guiding over cm-long plasmas
- ✓ Electrons can be accelerated in the cascade guided plasma wave to a GeV (S. Kalmykov)

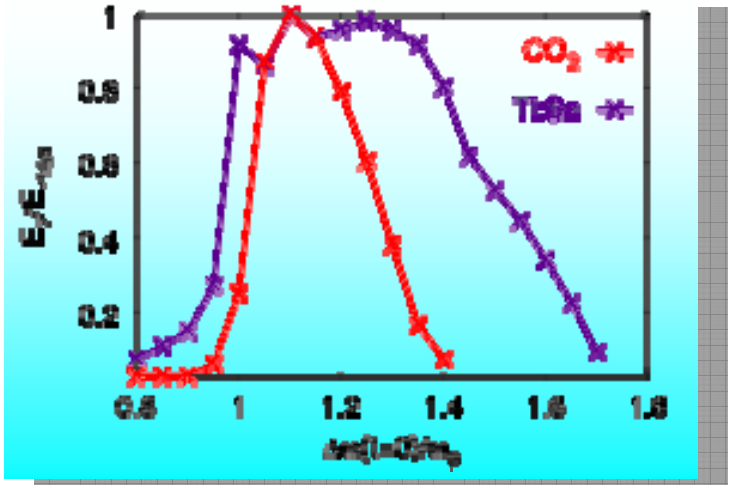


Autoresonant beatwave generation (Lindberg)

- Relativistic detuning limits in plasma beatwave accelerator (PBWA) can be overcome by slowly chirping lasers through resonance (autoresonance)
- Autoresonant excitation is robust to density mismatches and fluctuations
- Autoresonant phase-locking may provide absolute timing necessary for controlled electron injection
- Large amplitude accelerating gradients verified using fluid simulations
- Chirped, robust PBWA based on APTR appears feasible using current CPA or CO_2 laser technologies

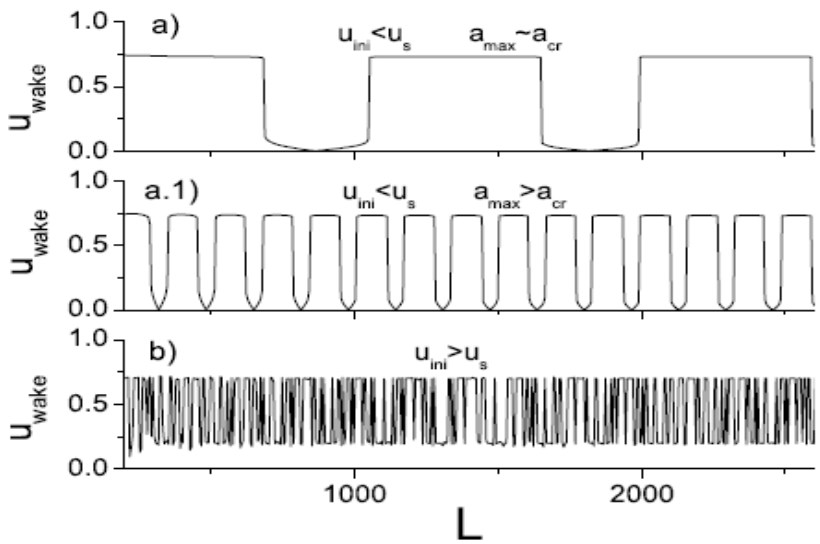


Large amplitude beatwave excitation

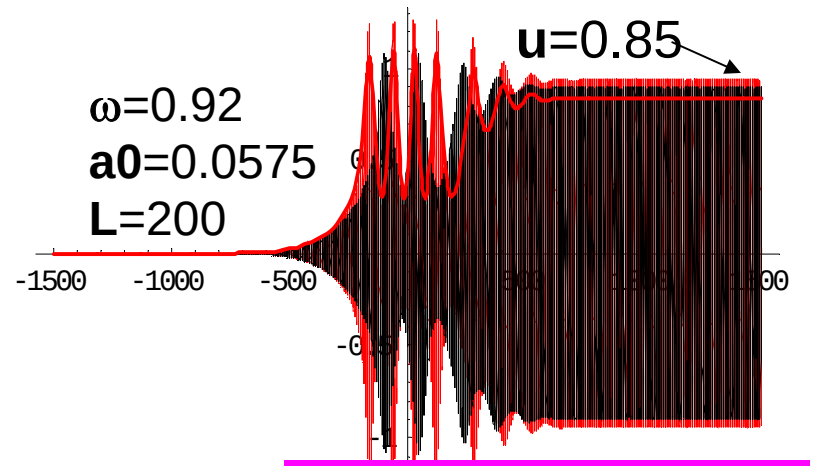


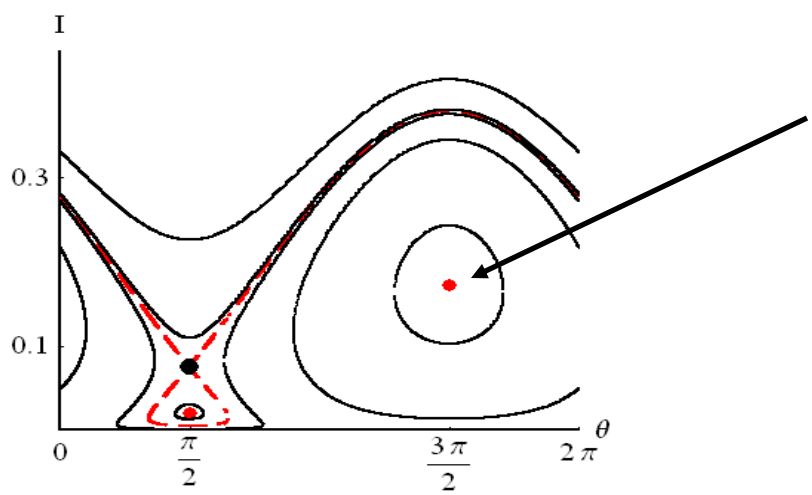
Robust generation of accelerating fields

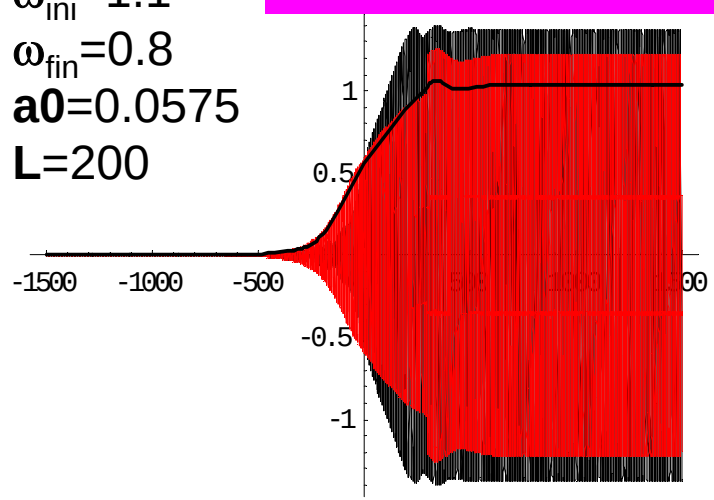
Relativistic Dynamical Bi-Stability of plasma waves in a Plasma Wakefield Accelerator (*O. Polomarov)*



Bi-stability





Auto-resonance

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ω_{fin}=0.8
a0=0.0575
L=200