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14. ABSTRACT The subject of our project supported by the AFOSR is the dynamics of intense charged beams focused by magnetic fields. There are several applications for this kind system, ranging from microwaves to controlled nuclear fusion. Our group is currently formed by Prof. F.B. Rizzato, Prof. R. Pakter, and Prof. Y. Levin, alongside with close collaborators Prof. Antônio Endler and Prof. Roger Nunes. Several graduate students are also involved with our research projects. We were mostly interested in the study of relaxation processes and halo formation of nonuniform relativistic high-intensity beams propagating in vacuum tubes. Some of our research effort also contemplates microwave coherence in nonlinear media and wake field electron acceleration.					
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• Objectives

Our main program involves the study of nonlinear properties of intense beams of charged particles transported under the action of magnetic focusing fields. This kind of system finds a very wide range of applications, such as particle acceleration, RF generation, communication technologies, and controlled nuclear fusion.

Considerable amount of attention has been dedicated to the analysis of emittance growth in beams initially far from equilibrium. Emittance growth is related to particles ejected from the beam core and is a limiting factor for beam performance. Recent papers by our and other groups show that beam inhomogeneities are frequently behind particle ejection, acting either as the central mechanism driving ejection, as in wave breaking of coasting beams, or as a mechanism simply assisting emittance growth, as when core particles scattered off small inhomogeneities are further driven away by strong envelopes oscillations. In any case, particles acquire very large velocities and may cause beam losses. Recent works by the group show how judiciously chosen initial mismatches of the beam envelope can largely help to postpone wave breaking and emittance growth in the case of inhomogeneous profiles.

Other recent lines of investigation involve the study of asymptotic distribution functions for initially mismatched beams, nonlinear interactions of lasers and beams of particles in wakefield acceleration and free-electron lasers, and the detailed account of strong relativistic effects across the transport axis. In this latter case, in particular, the nonlinear dependence of mass on transverse relativistic velocities acts as a source of inhomogeneity, also driving the beam toward highly nonlinear wave breaking states, even when the initial beam is radially uniform.

• Research Effort

The group works with theoretical tools and self-consistent methods of numerical simulations. Particle dynamics is studied with help of paraxial equations solved simultaneously with the relevant Poisson and vector potential equations. In inhomogeneous and relativistic systems, fluid models with Lagrange coordinates are also employed to describe particle dynamics prior to the wave breaking phenomenon discussed earlier. The machinery of Lagrangian average methods is then set to work to estimate the size of resonances covered by test particles. With that knowledge emittance can be

estimated, which has been verified to be in very good agreement with full numerical simulations discussed in recent works listed later.

Our initial studies with free-electron lasers make use of similar techniques. We have recently seen that the phenomenon of wave breaking can also be present in the ponderomotive bucket wells of the system, provided space-charge effects are not neglected. Space-charge is currently recognized as an important factor in this type of system and related effects, like wave breaking, can be crucial in governing relaxation and gain saturation.

We have also investigated with a little more care the problem of relaxation in mismatched homogeneous beams. Both in theoretical and computational approaches, violent relaxation was seen in the transport of matched and mismatched beams.

In a recent new field of interest the group has dedicated some time to investigate the problem of the self-consistent dynamics of laser pulses and wakefield potentials, so relevant for proposed models of high-gain particle acceleration. Theoretical studies, again based on average Lagrangians and also on wave simulation via finite differences, have both shown several interesting regimes of interaction. One relevant finding is that the pulse width can be trapped in stable states. This is of interest either for signal propagation if the trapping region sits away from the resonant width for plasma wave generation, or for particle acceleration if the width coincides with the plasma resonance.

All these results have been published in refereed journals and presented in major conferences in the area.

• **Group Members and Group Activities During the Period**

The group is currently formed by Profs.: Felipe Barbedo Rizzato, Renato Pakter, Antônio Endler and Roger Pizzato Nunes. The first two researchers, along with Prof. Yan Levin of the Statistical Mechanics group, are supported by the AFOSR grant. All the researchers, except Roger Nunes, are faculty at the Instituto of Physics of the University. Prof. Roger Pizzato Nunes, a former graduate student of the group, recently joined the Electrical Engineering Department of our University. We have 2 PhD students, 4 students working on their Master dissertations and one posdoc who has recently joined the group. Former PhD students recently moved to Europe for posdoc positions: Dr. Wilson Simeoni at CEA, France, and Dr. Everton Granemann Souza at CERN.

• Most Recent Publications and Conferences

(i) We now proceed to list recent publications of the group more directly related to the AFOSR project:

1. NUNES, R.P.; RIZZATO, F.B., Nonlinear dynamics of relativistic charged particle beams. *Applied Physics Letters* **98**, 551501 (2011).
2. BONATTO, A.; PAKTER, R.; RIZZATO, F.B., Self-consistent dynamics of electromagnetic pulses and wakefields in laser-plasma interactions. *Laser and Particle Beams*, accepted (2011).
3. SOUZA, E.G., ENDLER, A.; PAKTER, R., RIZZATO, F.B.; NUNES, R.P., The controlling role of envelope mismatches in intense inhomogeneous charged beams. *Applied Physics Letters* **96**, 141503, (2010).
4. SOUZA, M.; STEFFENS, F.M.; PAKTER, R.; RIZZATO, F.B., Standard map in magnetized relativistic systems: Fixed points and regular acceleration. *Physical Review. E* **82**, 026402, (2010).
5. TELES, T.N.; PAKTER, R.; LEVIN, Y., Emittance growth and halo formation in the relaxation of mismatched beams. *Physical Review Special Topics. Accelerators and Beams*, **13**, 114202, (2010).

1. (ii) As mentioned earlier, we presented our results at the:

- 2011 IPAC, San Sebastián, Spain;
- 2011 PAC, New York, USA;
- 2010 IPAC, Kyoto, Japan;
- 2010 High-Intensity and High-Brightness Hadron Beams, Lucern, Switzerland ;
- 2010 ICPP, Santiago, Chile;
- 2010 Soft Matter Conference ISMC2010, Granada, Spain;
- 2010 StatPhys24, Cairns, Australia;
- 2010 The International Congress of Pacific Basin Societies, Honolulu, Hawaii .

(iii) Additional papers dealing with relaxation in charged systems:

- LEVIN, Y.; PAKTER, R., Phys. Rev. Lett. **107**, 088901 (2011).
- PAKTER, R.; LEVIN, Y., Phys. Rev. Lett. **106**, 200603 (2011).
- TELES, T.N.; LEVIN, Y.; PAKTER, R., Mon. Not. R. Astron. Soc, doi:10.1111/j.1745-3933.2011.01112.x (2011)
- TELES, T.N.; LEVIN, Y.; PAKTER, R.; RIZZATO, F.B., J. Stat. Mech. P05007 (2010).

(iv) US Collaborations:

We maintain active collaboration with Dr. Chiping Chen from the MIT Plasma Science and Fusion Center and Prof. Mark Hess from Indiana University.

• **Description of the Current Group Projects Sponsored by AFOSR Grant**

The controlling role of envelope mismatches in inhomogeneous beams.

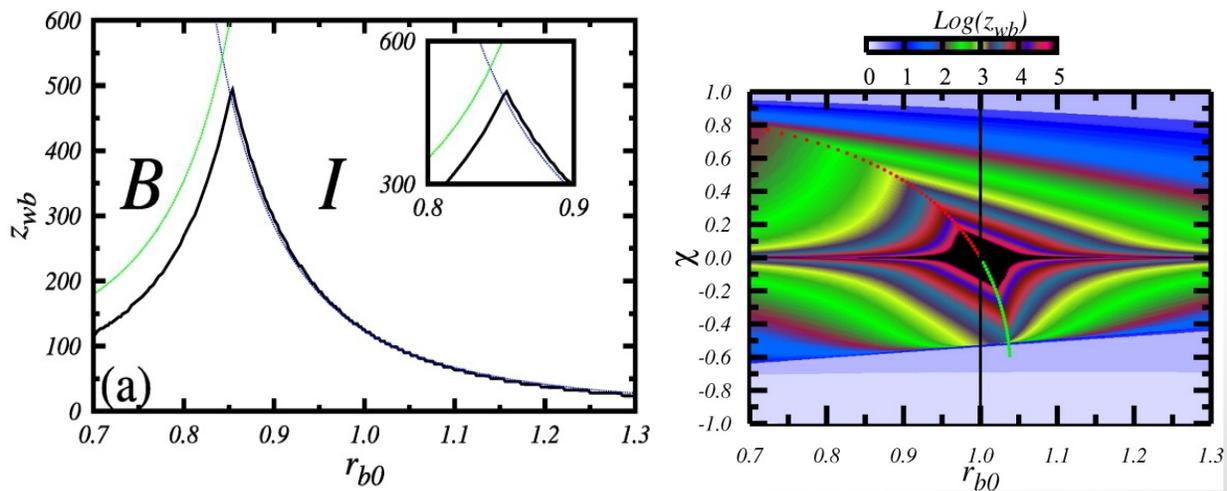
A fundamental issue in the dynamics of magnetically focused beams designed to meet requirements in vacuum electronics, concerns relaxation when the beam profile is not homogeneous. On general grounds of energy conservation one concludes that relaxation takes place as the coherent fluctuations of beam inhomogeneities are converted into particle kinetic energy and field energy. Recent works actually show that in the case of cold beams relaxation proceeds in two basic steps. Wave breaking initially pushes particles off the beam, and then ejected particles form a relaxing hot halo as they absorb energy from macroscopic oscillations of the remaining beam core. Wave breaking is therefore a key feature in the process.

Attention has been mostly drawn to the effects the degree of inhomogeneity has on wave breaking. Two instances were then identified. Originally, a threshold was obtained in terms of gradients in the amplitude of waves propagating across the beam. As particles largely displaced from their equilibrium positions are released, they overtake each other in less than one plasma wave cycle creating density singularities and wave breaking; for small displacements, breaking is absent. A more thorough

analysis however shows that not only amplitude gradients, but also formerly neglected gradients of the spatially varying frequency of the density waves is a key factor determining wave breaking. The physical process is different from the previous, as one shows that no threshold exists in this latter case. Particles slowly move out of phase due to small differences in their oscillatory frequencies, until a time when one eventually catch up with another creating again infinite densities and breaking.

In addition to the inhomogeneity effect, one should also note that since wave breaking is essentially dictated by compressions and rarefactions of beam densities, it may be quite possible that expansions or contractions of the beam transversal size have a noticeable effect on the process. In particular we show that, contrarily to the homogeneous beam case where envelope mismatch is an undesirable feature, for inhomogeneous beams it may largely delay wave breaking, extending beam lifetime.

Our results are well summarized with help of the following figures. In the first we depict the wave breaking time (z_{wb}) as a function of the envelope mismatched radius. In the second we offer a full view of breaking time, coded in colors, in a parameter space where the horizontal coordinate is the beam radius and where the vertical coordinate is the degree of inhomogeneity. Both figures make clear that for any given inhomogeneous initial condition, a judiciously chosen envelope mismatch can extend beam lifetime.



Nonlinear dynamics of fully relativistic beams.

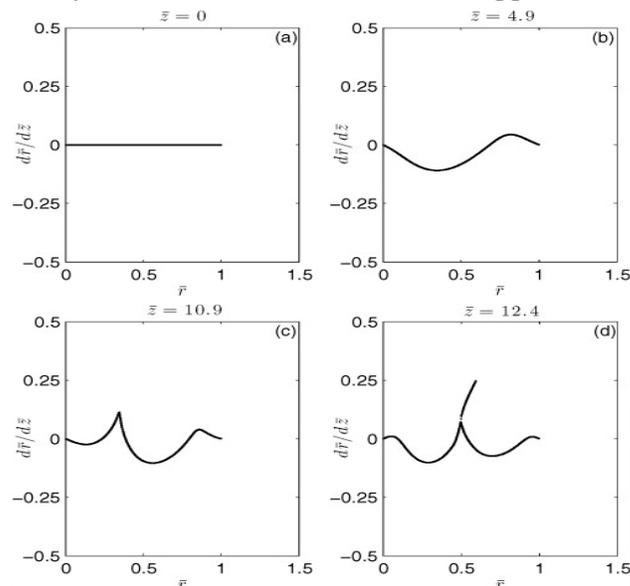
Non neutral beams usually evolve to equilibrium as they eject a representative amount of its

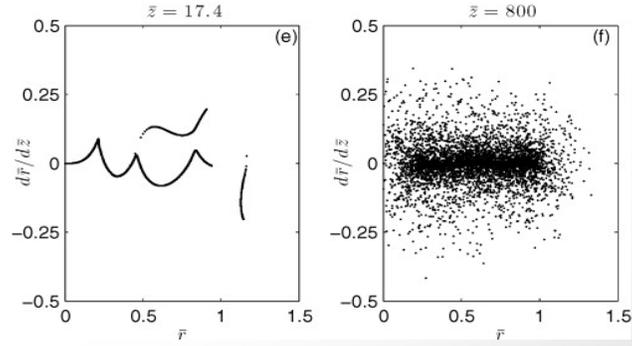
constituents in the focusing channel. The ejected particles form a rarified population around a denser region in the beam phase-space. While the first population is recognized as the beam halo, the second one is denoted as the beam core. Halos have many undesired implications on the accelerator structure, reducing beam lifetime and increasing maintenance costs. Also, there are many applications in which beam halo has to be, if not suppressed, at least minimized.

The way beam particles self-consistently interact and generate a halo depends on the beam initial distribution. For initially cold, quasihomogeneous, and mismatched beams, it has been found that, while the initial spurious inhomogeneity is the forerunner mechanism that allows particles to be progressively excited, in fact the envelope mismatch is the mechanism effectively responsible for halo formation. On the other hand, for initially cold nonhomogeneous but envelope matched beams, it has been found that the forerunner mechanism by which particles are ejected from the core is through phase-space wave-breaking. Once out of the beam core, the ejected particles are permanently excited by a process called charge redistribution. If in this last situation the mismatch is also present, then envelope oscillation acts as another source of energy to excite beam particles. The only difference is that now the coupling is resonant.

In the cases mentioned above, no account has been given about relativistic effects in the beam transverse dynamics. In fact, a paraxial approximation has been considered, which implies that, although the beam could be relativistic in the longitudinal direction, its transversal dynamics was purely classic and nonrelativistic. However, notwithstanding the many situations in which this is an adequate approximation, in many others one can assure that this is not or have to be reformulated to include the desired relativistic effects. The mass correction introduced by the relativistic effects can be more or less impacting on the dynamics of beam particles and must be understood. For this purpose, an analytical description for the relativistic dynamics of beam particles is developed.

The following figure shows what happens when relativity is taken into account to describe a beam which would be perfectly matched in the nonrelativistic approximation.





One observes that the initial homogeneous condition does not stay still. As relativity is considered, the beam, which would rest in equilibrium in the nonrelativistic approximation, evolves towards wave breaking nonlinear states and subsequent relaxation with halo generation.

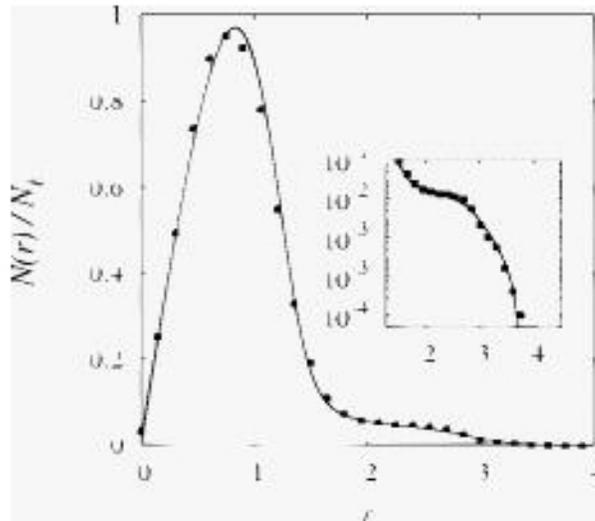
Relaxation for beams with arbitrary initial distributions.

The understanding of physics involved in the transport of high-intensity charged-particle beams is of fundamental importance in the development of a new generation of accelerators and electromagnetic wave generators to be used in applications such as heavy ion fusion, high-energy physics, communication, materials processing, and cancer therapy. A very detrimental effect that may seriously influence the efficiency of such devices is a halo formation and emittance growth of the beam. These not only cause degradation of the beam quality but may also be responsible for the activation of accelerator channel wall and pulse shortening in microwave devices. Emittance growth is generally associated with the relaxation of initially nonstationary beam toward a more stable stationary configuration. The emittance growth can be calculated if the final stationary distribution is known. However, the determination of this distribution is not an easy task because particles in an intense beam interact through long-range forces, which prevent the system from relaxing to the true thermodynamic equilibrium. Instead these systems get trapped in metastable states, the lifetime of which diverges with the number of particles. To understand the properties of these states, one cannot use the standard statistical mechanics, and new nonequilibrium theories must be developed.

In this line of research, we present a theoretical framework that allows us to accurately calculate the density and the velocity distributions of particles in the final stationary state achieved by a space-charge dominated beam focused by a uniform external magnetic field. Our approach is based on the theory of violent relaxation in gravitational systems, modified so as to explicitly account for the effects

of single particle resonances responsible for the halo formation. The difference regarding previous work of the group is that the theory is now applicable to arbitrary initial conditions. In this letter we will show how the theory can be used to accurately calculate the density and the velocity distributions as well as to account for the emittance growth of a charged-particle beam launched with a thermal (Maxwell) velocity distribution. The predictions of the theory have been successfully tested against the molecular dynamics simulations.

We now offer a simple view of the respective results.



The above figure shows the relaxed particle density of an initially thermal beam with scaled perveance $K^* = 1$ and mismatch of 75% ($\mu = 1.75$). The points are the results of the simulations, and the solid line is the prediction of the theory. Inset shows the exponential decay of the halo close to one particle resonance energy.

Nonlinear laser-plasma interactions (plasma based accelerators and free-electron lasers)

(a) Wakefield acceleration: Propagation of intense electromagnetic pulses in plasmas is a subject of current interest in a variety of areas that make use of the available modern laser technologies, among which we include particle and photon acceleration, nonlinear optics, laser fusion and other nonlinear processes.

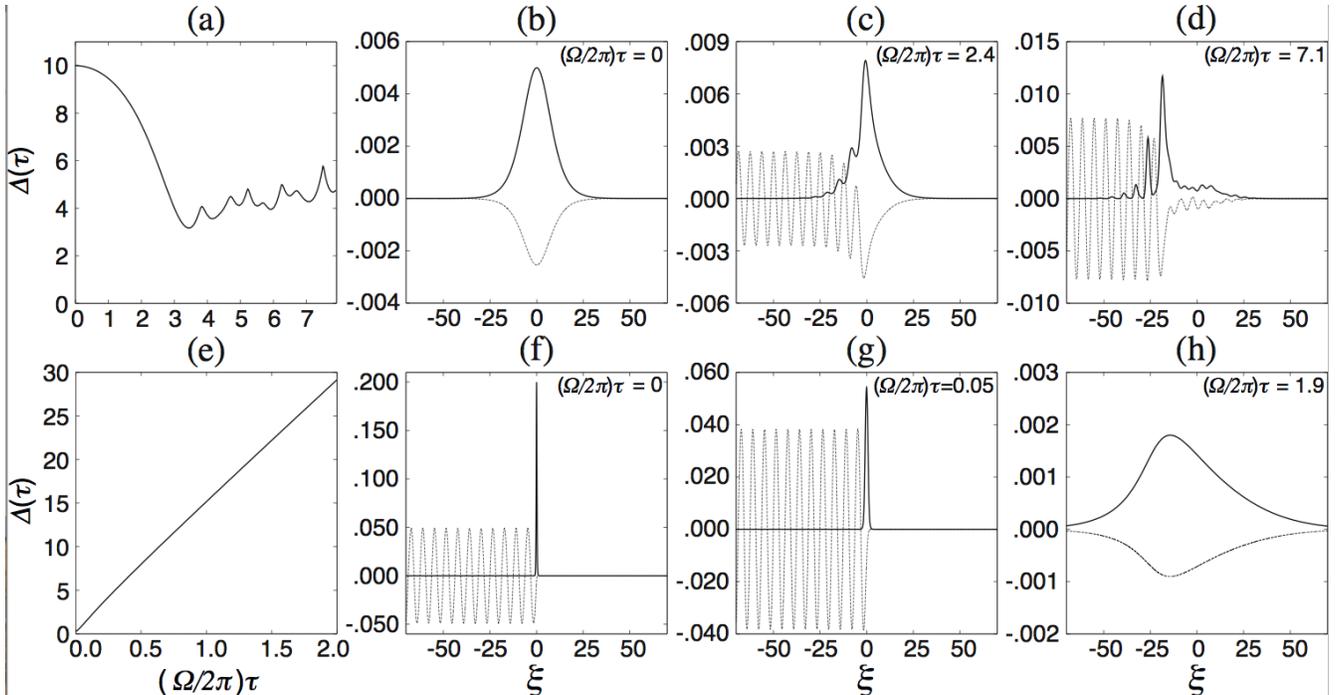
Intense electromagnetic pulses displace plasma electrons and create a resulting ambipolar space-charge field with the associated density fluctuations. The ambipolar field here is known as the wakefield and can be used as an accelerating structure if stable and coherent enough that witnesses

particles can absorb energy in a resonant fashion. Since the pulse couples with the wakefield, generation of the latter can affect the behavior of the former. Therefore it is of interest to examine the coupled dynamics involving both fields.

This sort of investigation has been done in the literature. However, since focus has been mostly directed to fast pulses propagating nearly at the speed of light c , underdense plasma approximations are frequently used where the plasma frequency ω_p is taken as small quantity. In this case phase and group velocity are approximated by the speed of light, and pulse distortions are either sometimes neglected, or treated under stationary wave assumptions.

A series of results of laser-plasma interactions are thus very specific to the underdense approximations, and our intention is therefore to examine how the system behaves when the approximation is relaxed. In particular, underdense approximations turn out to be too restrictive if one desires to follow the time dependent dynamics of laser pulses along the direction of modulation. In more specific terms, we shall investigate to what extent can an electromagnetic pulse retain its initial shape following its interaction with the wakefield, a relevant issue not only to accelerators but also to all sort of transmission of information using electromagnetic solitons.

For a given pulse power, the dynamics is largely dictated by the pulse width. One of the findings here is that while wider pulses with widths sufficiently larger than the plasma wave length c/ω_p may keep their shapes even in the presence of space-charge fields, narrow pulses with widths comparable to the plasma wavelength always tend to spread as time evolves. All depends ultimately on the pulse power and on relative roles played by relativistic and ponderomotive nonlinearities.



The above panel shows initial findings: pulses are highly distorted if they come from large initial widths towards the resonant width $\Delta \sim c/\omega_p$, and only moderately distorted if coming from initially narrow widths. This helps to decide which kind of laser pulses should be used. In panels b,c,d,f,g and h, the dotted line represents the wakefield and the solid line, the laser field. τ is time, ζ is coordinate, and Ω is the oscillatory frequency of the laser field.

(b) Free-electron lasers: Free-electron lasers can be described along similar lines as in the previous topic on wakefields. Electrons respond to the combined action of electromagnetic modes (wiggler and laser) and energy exchange between electrons and the modes can amplify the latter. The purpose of the investigation is to examine the effects of electronic space-charge on the system. Space-charge has been considered in the past. In the present project we intend to show how space-charge in the device cause wavebreaking and subsequent growth saturation.

• Numerical Techniques

In all cases what has to be done is the integration of several thousands of particles interacting via Coulomb fields. Two ways are devised to perform the integration: (i) Green functions techniques and (ii) mean field techniques such as particles-in-cell and Gaussian models for spherical symmetric distributions.

In the former case (i) we first obtain the field generated by each particle, including boundary effects like those provided by conducting walls. Electric fields are then calculated and the acceleration of each particle is obtained. To emulate the effects of an infinite number of particles, a soft core potential is used to remove singular effects arising from the close encounter of groups of particles. This model is quite effective but time consuming since it does not deal with mean fields which would be more convenient for a assembly of many particles.

Mean field models of case (ii) take into account the statistical properties of this large number of particles. Particle-in-cell is effective when emittance is not too small, which poses a small restriction on its use. Gauss's law involves direct integration of Poisson's equation for spherical symmetric distributions and assumes each single particle under the mean field produced by all others. It is very effective, but, as mentioned, can be used only under the restriction of azimuthally symmetric

distributions.

As for the time advance of the equations governing the particle orbits, Runge-Kutta algorithms with automatically varying time steps prove to be quite satisfactory.

Wave dynamics are treated likewise: space discretization is used and each node is then time integrated with time-advance algorithms. In computational terms the scale is similar to the one associated with the beam systems.

Our codes are fully available.

• **Conclusions and Acknowledgements**

During this second (of three) year of support by the AFOSR/SOARD grant FA9550-09-1-0283, we maintained our productivity in the area of waves and beams. Papers were published and presented at major conferences, and a number of students obtained their PhD degrees. All in all, we considered the group performance as positive, and express our gratitude to the Scientific Office and the South America division for their continued efficiency, help, interest, and extreme friendliness.