Virtual Emerging Concepts Center (VECC)

a proposal submitted in response to Program Announcement LAB01-10, "Scientific Discovery through Advanced Computing: Advanced Computational Research in Fusion Science"

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Budget Request:

FY 2001	$600K
FY 2002	$750K
FY 2003	$800K

No use of Human Subjects in this project. No use of Verterbrate Animals in this project.

Abstract: OFES resources invested in emerging fusion concepts will be maximally leveraged by the development of modern computational methods and their application to key issues. A range of possible concepts may be addressed in time. However, the present small incremental activity proposed here will achieve critical mass by proceeding in a sequential, topical approach. Initially (first 2 years) the focus will be exclusively on key issues related to the use of a Field-Reversed Configuration (FRC) as a target for Magnetized Target Fusion (MTF).

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Narrative

I. Background and Significance

I.A: The VECC

This proposal describes an initiative to form a virtual center for the computational/ theoretical study of the physics of "Emerging Concepts (EC)" for controlled fusion. [Snowmass EC] Emerging concepts are defined as those fusion approaches which incorporate physics or other technical features which are "orthogonal"[Comments EC] to the mainline approaches. Mainline fusion approaches are: 1) Magnetic confinement in toroidal systems with dominant toroidal magnetic field (B_T); and 2) Conventional hot-spot Inertial Confinement Fusion (ICF). Although many of the computational techniques proposed here apply directly to analysis and simulation of mainline fusion concepts, these applications are not our present focus.

Emerging Concepts include the catalog (Table 1) assembled by the community at the time of the Snowmass 1999 Fusion Workshop,[Snowmass EC] but this list is intended to be neither inclusive nor exclusive. Rather, the listed concepts are a working tabulation of those new, old, and improved fusion approaches which offer simultaneously unique physics opportunities and potential breakout technical approaches to fusion science.

During the past ½ decade, the US fusion program has undergone a major realignment to place increased emphasis on EC's as well as other Innovative Confinement Concepts (ICC), such as the Spherical Torus and the Compact Stellarator. While this redirection has done much to accelerate the pace of innovations within the program, theoretical and, especially, computational support of numerous smaller experimental programs has not kept pace. Limited resources and competing mainline and other priorities have restricted the theoretical support applied to much of the US fusion portfolio to inappropriately small levels. This has limited the effectiveness and pace of these programs, and accordingly, the return on the program's investment there.

We propose to establish a virtual center (Virtual Emerging Concepts Center or VECC) with the following structure:

> Organization & Administration: The Los Alamos National Laboratory (LANL) will serve as the organizing force and provide administrative support for VECC activities. Dr. Daniel C. Barnes of LANL will act as interim coordinator of VECC activities. A loose-knit coalition of appropriate researchers will be formed and their activities coordinated under this initiative.
>
> Charter: To serve as a center of excellence for a thematic, sequential approach to the development and application of computational tools to address the crucial physics issues of EC's.

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CONCEPT	DESCRIPTION	NEW FEATURE(S)
Reversed Field Pinch (RFP)	**Low B_T, self-organized, moderate β, relative of tokamak**	**Five-fold increase in energy confinement by profile control**
Spheromak	**Compact torus; no B_T**	**Operating modes to minimize turbulence, modern wall conditioning.**
Field Reversed Configuration (FRC)	**Zero B_T everywhere; very high β; strong kinetic stabilization**	**Stability at R/ρ_i=4, evidence of self-organization, rotating magnetic field current drive.**
Ion Ring	**Large ion orbit version of FRC**	**Potential stabilizing element for FRC.**
Magnetized Target Fusion (MTF)	**Combines magnetic insulation with inertial compression by relatively massive, slow liner**	**Dramatic advance in liner technology. Variety of suitable plasma targets with sufficient confinement.**
Dipole	**Levitated internal ring, poloidal B only**	**Simple magnetic field geometry. Theoretically shown to support high β with MHD and drift wave stability.**
Centrifugal	**Mirror B geometry with large rotation driven by applied E**	**Theoretical simulation of stability with flow shear indicates strong potential well formation.**
Mirror/Gas Dynamic Trap	**B mirror with electrostatic plugging in collisionless or collisional regime**	**Novosibirsk GDT indicates β =30%, classical behavior of sloshing ions and classical electrons at T_e=150 eV.**
Electrostatic	**Ions confined and spherically focussed by large E**	**Pulsating electrostatic trap (POPS) eliminates ion collisional isotropization.**
Flow Pinch	**Z-pinch stabilized by strong axial flow**	**Sheared flow stabilization.**
Fast Ignitor	**High density inertial pre compression followed by petawatt ignition pulse**	**Petawatt laser technology.**
Other	**See notes and discussion**	

Table 1: Partial List of Emerging Concepts and their dominant technical features (From Ref. Snowmass EC). Reference numbers have been removed.

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Organizational Approach: A thematic, sequential approach will be adopted. During a 2-3 year period, research will be focused on one or two critical physics/technical areas identified with a single EC. As the concept and/or issues change in the future, the membership will change to engage the most capable and expert fusion and computational scientists. Similarly, the coordination role will rotate as appropriate on a roughly 5 year schedule.

I.B: FRC/MTF as VECC initial project

This proposal is for initial computational work at VECC. While there are many computationally challenging problems which could be selected as a focus, we have chosen two problems related to the same configuration which are at an appropriate stage of computational development to both be poised to utilize future advances in the HPC environment and simultaneously have already required and utilized HPC to advance physics knowledge. Initially, VECC will focus on two key physics issues associated with the Field-Reversed Configuration (FRC), and its potential application as a target for Magnetized Target Fusion (MTF). These issues represent crucial physics questions for the FRC and its application to MTF, and require very large-scale computational tools to advance theoretical understanding. Thus, this proposal assembles a blue-ribbon staff of researchers to address two of the topical areas solicited by LAB 01-10:

Macroscopic equilibrium and stability
Boundary layer effects in plasmas

I.C: FRC Physics

The FRC[Tuszewski rev.] (Fig.1) is one of the oldest alternative approaches to toroidal confinement. In this geometry, first studied over forty years ago, a very-elongated toroidal z-pinch is formed in a theta pinch by initially reversing the bias field, compared to the main implosion field. Subsequent reconnection of the bias and main fields induces a large toroidal current, which provides all of confinement and heating to the configuration. While such a geometry should be strongly unstable, based on MHD theory, gross stability for up to 100 Alfven (growth) times is observed. This stability is somewhat understood as the product of a combination of large-orbit ion effects, sheared rotation, Hall and other nonideal electron effects, and possibly plasma outflow.

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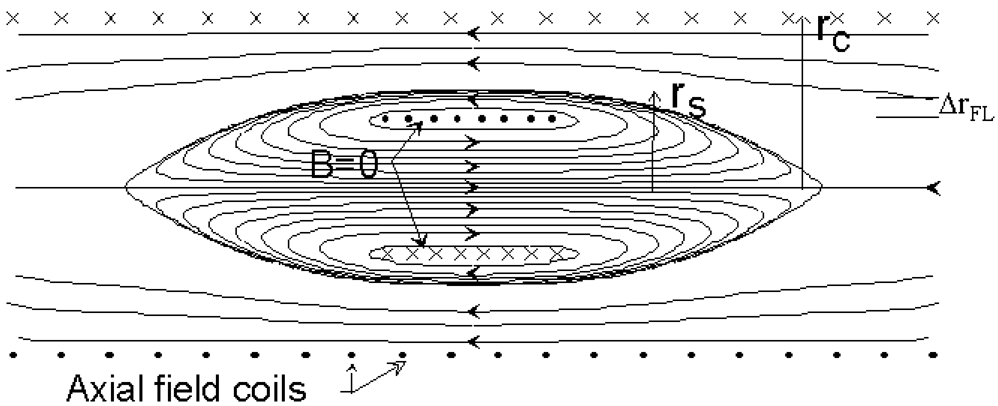

Figure 1: Field-Reversed Configuration showing poloidal magnetic flux contours and principal geometric parameters.

The present experimental data base and theoretical understanding has suggested that FRC's might be useful as fusion systems in two independent applications. First, additional investigation and development of large s (say up to 20) (s is separatrix radius divided by mean ion gyroradius) may lead to an interesting steady-state fusion configuration. Second, already demonstrated parameters make the FRC interesting as a target for subsequent MTF compression.

MTF is a community-wide proposal[MTF web] to use existing, proven imploding-liner technology to compress and heat a preformed FRC target plasma. Currently, the MTF experimental program is tasked to design, operate, and diagnose a FRC formation experiment. The goal of this experiment is production of an deuterium FRC target of density 10^{23} m^{-3}, temperature of 300 eV, and lifetime of > 10 μs. While these parameters represent a modest extension of demonstrated FRC parameters,[MTF web] achieving the goal requires a careful experimental and theoretical program. This current experimental program is at the level of $2M/yr for three years.

In addition to the MTF focused FRC experimental work, a large, ongoing experimental program is focused on the investigation of long-time-scale FRC stability and confinement. A relatively recent and very important innovation is the addition of rotating magnetic fields (RMF) as a current drive and stabilization technique. RMF breaks the axisymmetry of the FRC and produces a three-dimensional, time-dependent "equilibrium" state.

Extensive studies of FRC stability, using both fluid (MHD)[MHD '70's ref.] and kinetic hybrid (Vlasov-fluid[VF '70's ref.] or VF) models were carried out in the past. These studies produced results consistent with those obtained recently.[VF recent ref.] To summarize a large body of work, it has been found that the internal tilt mode is destructively unstable (according to theory/computation) in a static, ideal MHD FRC. Addition of toroidal flow (rotation) either rigid or sheared has little effect on this mode, slightly reducing growth rates and contributing little nonlinear stabilization. When finite ion orbit effects are included, say by using the VF model, the tilt growth rate may be substantially reduced when *s* is small enough. No theoretical or numerical calculation to date has definitively shown *positive* stability, in which all large-scale modes have a real frequency or are damped.

FRC experiments show quite a different stability picture. For *s* (< 2 – 3) sufficiently small, there are no observed large scale modes, on time scales of 10 – 100 Alfven times (tilt growth times). Further, detailed diagnostics, such as Mirnov probes show significant MHD activity, including n = 1 (n is toroidal mode number) with tilt parity during formation. In virtually all small *s* cases, this mode activity dies away rapidly, rather than showing slow growth. Additional evidence of robust FRC stability at small *s* is provided by translation and trapping experiments, in which the FRC may slam into a mirror at three times the Alfven (thermal) velocity, certainly inducing large n = 1 perturbations from field errors, misalignments, *etc.* Under such conditions, a slowly growing tilt mode would certainly be excited to a significant amplitude and would have an observable effect.

Experiments with *s* moderately larger (~ 3 – >5) show additional unexplained phenomena. Depending on formation technique, collisionallity, *etc.* a spectrum of modes may be seen to grow systematically or (apparently) randomly, with an unclear effect on the configuration. Degraded performance is often observed, with the signature being anomalously rapid decay of the flux, or sudden loss of flux, with recovery at a reduced *s* value. While a tilt signature was inferred from Mirnov signals under one condition,[PRL ref.] there remain unexplained phenomena even for this case. When the entire data base of moderate *s* FRC operation is considered, it is much more difficult to say that the tilt has been identified or a (empirical) stability condition positively inferred.

There are at present at least two interpretations of the experimental data. One empirical stability scaling argues that the stability condition is that *s* (or S_* , the ion skin depth parameter, defined as the ratio of separatrix radius to ion collisionless skin depth) divided by elongation E be sufficiently small. An alternative interpretation is that there is some upper limit on *s* independent of elongation (for E > about 3.5), and that performance degrades gradually rather than suddenly above this limit.

Thus, two important unexplained theoretical questions concerning FRC stability are:

- What additional physics not yet considered might explain positive stability?
- What is the stability scaling for E > 3.5?

Both of these questions are important for the MTF target plasma, since stability for > 20 MHD growth times are required and a moderately elongated target plasma will become a quite elongated plasma during compression. Additionally, an understanding of FRC stability limits and their scaling is crucial for continued progress toward s values relevant for steady-state FRC fusion applications.

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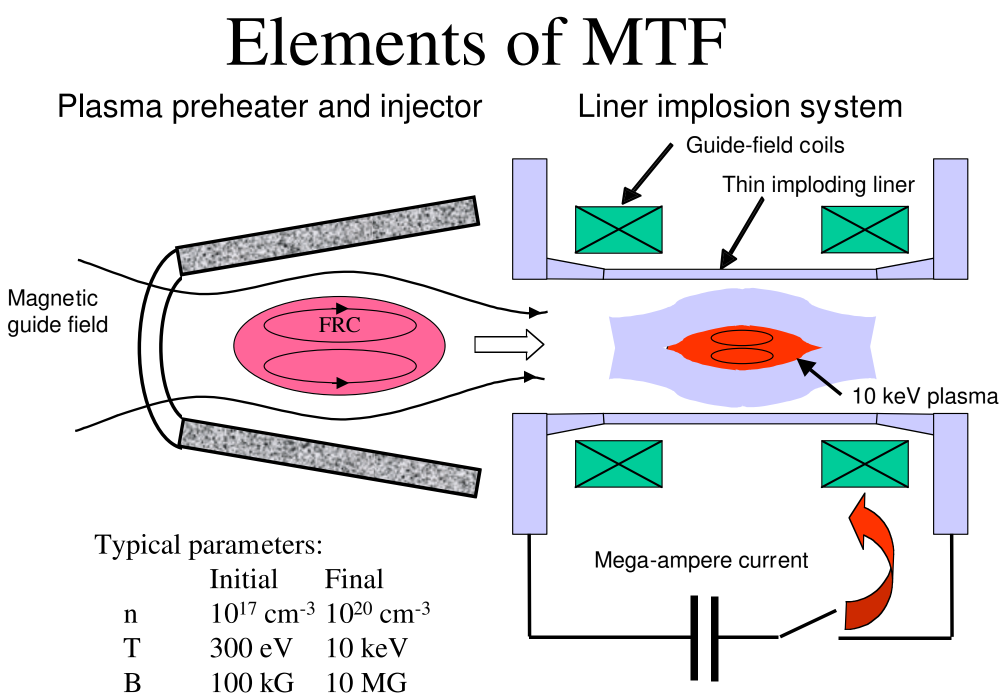
I.D: MTF Physics

The MTF approach operates in a density regime intermediate between the two traditional extremes of magnetic confinement (MFE) at relatively low static pressures and inertial confinement fusion (IFE), which requires the creation of extreme pressure pulses. In MTF, a warm magnetized plasma is compressed adiabatically to thermonuclear temperatures and inertially confined by a dense, converging metal wall. The short-term goal of MTF research is to provide a proof of principle demonstration in which an FRC is compressed with a cylindrical liner (Fig. 2).



While near-term MTF experiments may operate in the "conventional" MFE regime of $\beta < 1$ magnetically confined plasmas, eventual utilization of fast liner inertia requires[High-gain ref.] higher plasma pressures than those that can be confined solely by magnetic fields compatible with flux retention by a converging conductor. Thus, unlike magnetic confinement concepts, MTF proposes to take advantage of wall support in order to achieve very high beta. This means that the wall directly supports the plasma pressure by contact with the cooler edge of the hot fusion plasma.

The MTF wall is thus subjected to the heat loss both conducted through a dense edge plasma and that radiated from the core and edge plasma. The first wall suffers destructive damage as in IFE, and target designs incorporate this feature. The crucial requirement is that the evolution of wall material into the plasma be sufficiently mitigated to limit deleterious effects on the fusion plasma. In advanced designs it is anticipated that the "first" wall material would provide additional fusion fuel and thereby lead to higher gain targets.

Consider the MTF sequence of wall interaction events and their consequences. It is useful to enumerate all possible such events and consequences, even though the relative importance of each depends on the details of target plasma formation and subsequent compression.

Initially, the creation of the magnetized plasma target (possibly an FRC) requires that high currents flow in the plasma and possibly (depending on the method of target plasma formation) into the liner wall as well. These currents create a magnetic field which diffuses into the liner, ohmically heating it. Some amount of impurities generated at the wall may penetrate into the plasma.

Next, the rate of compression is very slow compared to the plasma sound speed. A wall speed on the order of only 1 cm/us or less is anticipated. The compression time scale means that the warm plasma adiabatically readjusts to the decreasing volume. On the profile relaxation time scale, the target plasma may experience a relaxation toward the wall that will momentarily carry both plasma and field to the wall until total pressure balance is achieved. Thus, some expansion cooling occurs in the core of the target plasma may occur, while the edge becomes more dense and emissive. Initially the plasma is not thermonuclear (only about 100-200 eV) and still a relatively pure hydrogenic plasma, the radiation from the plasma core and edge is meager, and the heating of the wall by thermal conduction and Ohmic dissipation in the skin layer will dominate.

During the compression there is little back pressure at first, but pressure continually builds. The plasma temperature and density grow as thermal conduction is reduced by increasing magnetic field and decreasing collisionality, until the radiation from the dense plasma regions near the wall may dominate heat transfer to the walls. The wall is subjected to increased heating and pressure.

As the plasma pressure becomes comparable to the dynamic pressure of the liner, the interface between the liner and the plasma will begin to decelerate. This may lead to hydrodynamic (e.g., RT) instability, which distorts the plasma/wall interface, increasing the area of wall contact, which may enhance cooling to the wall. In addition, the self-compression of the liner material increases the wall heating and absorbs energy that would otherwise go into heating the plasma. Clearly it is important to have a detailed EOS for the wall material.

Because compression is subsonic, convection-driven flows may develop in a multi-dimensional description of the MTF system. Such flows may ultimately carry more heat to the wall than is carried by conduction or radiation. Also, they may carry any evaporated material from the wall into the plasma, and increase the plasma emissivity.

Likewise, KH instability can lead to material being entrained in the flow and mixed with the bulk plasma.

Plasma emissivity is strongly dependent on the amount and composition of material evolved into it. This is a highly coupled problem, where the plasma temperature and density determines the ionic species in the plasma and the radiation from the ionic species determines the cooling of the plasma, and therefore trajectory in phase space for the plasma compression.

As fusion temperatures are approached energetic charged particles are created along with neutrons. This adds to the wall heating. It may also increase the wall pressure above the plasma pressure momentarily, especially if the plasma is insufficiently dense. The hydrodynamic response of the wall would only partially make up (through additional compression) for a lower self-heating rate due to the fusion energy lost to the wall.

The development of a comprehensive model of these complex, coupled plasma/material phenomena is described in the remainder of this proposal.

I.E: Scientific impact of VECC work on FRC/MTF

The VECC initial work on MTF/FRC problems will greatly impact this component of EC research by providing a more clear understanding of FRC macrostability, by identifying expected MTF wall-contact phenomena, and by providing a quantitative extension of our capability to model and interpret past and future experimental EC results. VECC will both extend OFES theory/computational research in support of EC's and serve as a demonstration of the cost-effective application of modern computational techniques to plasma fusion research.

In addition to the scientific impact within the OFES community, the range of physics opportunities associated with MTF/FRC in particular and with EC's in general provides a large overlap with many areas of plasma and high energy density physics. The proposed computational advances have obvious relevance to: all compact torus geometries including both FRCs and spheromaks; kinetic plasma macroscopic modes; and plasma-wall contact situations of importance ranging from thermal plasma applications to ICF regime applications. For example, magnetized targets are being considered in an ICF context in Germany. Furthermore, the extension of tools for the kinetic modeling of large-scale phenomena is an important challenge for plasma science, and will have applications to space and beam physics, as well as to energetic particle effects in mainline fusion concepts.

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II. Preliminary Studies

II.A: FRC Stability

II.A.1: Computational Physics Background

Once MHD stability studies carried out in the late '70's[MHD '70's refs.] demonstrated unambiguously that an FRC would be violently unstable to the internal tilt (and many other modes) in the MHD limit, work became focused on how strong kinetic effects might modify this unrealistic (in light of experimental observations) picture. As computational capabilities have advanced during the ensuing 2+ decades, ever more ambitious kinetic calculations have been carried out by several groups.[VF recent refs.]

Standard (explicit), full electromagnetic PIC codes suffer from prohibitively small time steps required to resolve light propagation through the spatial grid spacing even in cases when the plasma wave frequencies of interests are well below that of the purely electromagnetic mode. In addition, the performance of these codes is typically degraded by the necessity to accurately describe high-frequency, Langmuir (electron) plasma oscillations. These difficulties can be best resolved by directly solving the full set of closely coupled Maxwell and particle equations [Hewett:87], [Tanaka:93], or by ignoring the transverse component of the displacement current in the Ampere law and solving the reduced (Darwin) set of equations [Hewett:94]. Both approaches require implicit numerical techniques and have so far suffered from the lack of fast, parallel (scalable) elliptic solvers. Fortunately, explicit calculations can be enabled for quasineutral plasma motions by neglecting displacement current altogether in the Maxwell equations and treating the background electrons as a massless fluid. It is this approximation that is currently implemented in the FLAME code developed at Cornell and GA by Omelchenko [Omelchenko:97], and the M3D-B code developed by Belova [Belova] and collaborators.

In each of these codes, ions are advanced in time according to the collisionless Vlasov equation

$$\frac{\partial F}{\partial t} + \mathbf{v} \bullet \frac{\partial F}{\partial \mathbf{v}} + \frac{q}{M}(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \bullet \frac{\partial F}{\partial \mathbf{x}} = 0 \quad , \tag{1}$$

where F is the unknown ion distribution function evolving in the time t over the phase space $(\mathbf{x},\mathbf{v})$, with $\mathbf{x}$ the ion position vector and $\mathbf{v}$ the ion velocity vector, where q is the ion charge and M the ion mass, and where $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic fields. Equation (1) is solved in the Klimontovich representation using the Particle-in-cell (PIC) method. Thus,

$$F \approx \sum_p S(\mathbf{x} - \mathbf{x}_p)\delta(\mathbf{v} - \mathbf{v}_p) \quad , \tag{2}$$

where $S \sim \delta$ is a suitable local interpolation function from particles to mesh and where δ is the Dirac delta function. The phase-space coordinates $(\mathbf{x}_p,\mathbf{v}_p)$ associated with particle p

are advanced along individual ion orbits, which are the characteristics of (1). In addition to the full PIC ion treatment outlined in (2), the δf method[Belova] (described subsequently) has also been applied advantageously, especially in cases of slow linear growth.

Electrons are treated as a massless fluid according to

$$0 = -en(\mathbf{E} + \mathbf{u}_e \times \mathbf{B}) - \nabla P_e - \nabla \bullet \vec{\Pi}_e \quad , \tag{3}$$

where e is the elemental charge, $n = n_e = n_i$ the number density of both electrons and ions, $\mathbf{u}_e$ is the electron fluid velocity, P_e the electron scalar pressure and $\vec{\Pi}_e$ the traceless part of the electron stress tensor.

The electron equation is implicitly coupled with the appropriate (pre)Maxwell equations

$$\begin{aligned} \frac{\partial \mathbf{B}}{\partial t} &= -\nabla \times \mathbf{E} \quad , \\ \mathbf{J} &= \frac{1}{\mu_0} \nabla \times \mathbf{B} \quad , \end{aligned} \tag{4}$$

where $\mathbf{J}$ is the total current density, μ_0 is the permeability of free space, and where the displacement current has been neglected for the low-frequency modes of interest. The second member of (4) is used to obtain the electron current with the ion current given by time advancing the ions as described in (1) and (2). Thus, (3) becomes

$$\mathbf{E} = \frac{1}{en}\left[\left(\frac{1}{\mu_0}\nabla \times \mathbf{B} - \mathbf{J}_i\right) \times \mathbf{B} - \nabla P_e - \nabla \bullet \vec{\Pi}_e\right] \quad , \tag{5}$$

The $\mathbf{E}$ given by (5) is used to time-advance $\mathbf{B}$ in the first member of (4). The coupling of $\mathbf{E}$ to $\mathbf{B}$, and also P_e and $\vec{\Pi}_e$ introduces electron time scale constraints on this solution. To date, most calculations have been done with cold electrons, for which model the only such coupling is through the Hall effects included in the dependence of $\mathbf{B}$ on $\mathbf{E}$. These simple electron physics make the field solve practical with elementary techniques. For example, both substepping and simple iteration have been used successfully here. Inclusion of more realistic electron models greatly complicates the field-solve problem, and forms a large part of the research proposed in the following Sec.

II.A.2: Existing Codes

<u>FLAME</u>

FLAME is a C++ based, object-oriented code which is massively parallel using a domain decomposition paradigm. M3D-B is a modern fortran code which has run in a multitasking environment on a few processor machine.

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FLAME was designed to meet the most essential requirements of high performance computing (HPC). The code is built on top of an object-oriented, C++ class library created to abstract generic elements of particle and finite difference solvers as well as their concurrent (message passing or shared memory) implementations on high-performance, massively parallel RISC systems. This easy-to-use library provides a transparent, flexible and extendable framework for developing next-generation parallel PIC codes. The key HPC features of this package are:

- Arbitrary (rectangular) computational domain decomposition and subdomain processor assignment order.
- Run-time domain repartitioning and processor load balancing.
- Pre-computed grid communication patterns based on given finite-difference stencils.
- Independent sets of particle and field (grid) decomposition domains. Unified algorithm for interprocessor communication of particles and grids.
- State-of-the-art visualization package (Data Explorer, IDL).
- Availability in C++ (template classes, g++/xlC) and Fortran 90 (object-based modules, pgf90).
- Abstract (MPI) message-passing interface layer enabling straighforward parallel code development and testing on serial computers.

Originally, FLAME was designed to simulate low-frequency physics of 3-D ion beam/ring propagation, stability, focusing and compression in magnetized plasmas {Omelchenko:97}. It has since been successfully applied to study the stability of other magnetic confinement configurations {Omelchenko:00}.

In the MTF context FLAME contains the following physics modules:

- Generation and stability of FRCs/ion rings (2-D/3-D)
- FRC translation and coalescence (2-D)
- Static and liner magnetic compression of FRCs/ion rings (2-D/3-D)

<u>M3D-B</u>

In the M3D-B FRC global stability code[Belova00,Belova01] two different physical models have been implemented: a 3D nonlinear one-fluid MHD model, and a 3D nonlinear hybrid scheme with δf particle ions and fluid electrons. The linearized form of the equations has been included in the code as an option.

In the MHD version of the code, the nonlinear resistive one-fluid MHD equations are advanced using a second-order, explicit, time-stepping scheme with fourth-order accurate spatial derivatives. A cylindrical grid is employed and finite difference approximations are used in all three directions. The conservative form of the equations and the time-centered trapezoidal leap-frog scheme used for the time evolution ensure very good energy conservation, with the change in the total energy being less than 0.1% of the perturbation energy.

Hyperresistivity in the induction equation and artificial viscosity in the momentum equation are added for numerical stability in the nonlinear runs. A two-dimensional self-consistent equilibrium is found by solving the Grad-Shafranov equation for the field and plasma pressure including equilibrium flows, and this is used as an initial condition for 3D stability calculations. The vacuum region is modeled as a highly resistive, low density plasma.

The hybrid scheme assumes quasi-neutrality, fluid electrons and particle ions.
The particle ion motion is described by the Lorenz force equations with the standard leapfrog scheme used for the time advance. The fluid equations are advanced on a finite-difference mesh in a cylindrical coordinate system, while the particle pushing and current and density accumulation are done on a 3D Cartesian grid. Quadratic spline interpolation is used for mapping between the cylindrical and the Cartesian meshes, while linear spline interpolation is used in the particle loops (gather/scatter operations). Since the computational time required to advance the particles greatly exceeds the time needed to advance the field equations, subcycling is used to update the fields with small enough time step to avoid numerical instability at small *s*. The particle coordinates and weight factors are advanced with a larger time step, which is limited by the ion cyclotron motion and is typically set to $\Delta t = 0.1/\omega_{ci}$, where ω_{ci} is the ion cyclotron frequency.

The δf method \cite[Parker93] is utilized to reduce numerical noise in the simulations. In the δf scheme the equilibrium distribution function is assumed to be known analytically, so the zero-order ion density and current can be calculated. The perturbed part of the distribution function is calculated along a set of characteristics by assigning a weight $w \sim \delta F$ to each simulation particle. The particle weights are then used to calculate the perturbed ion density δn and current $\delta \mathbf{i}$. Since the particle weight is no longer a constant of the motion (as in the conventional PIC method), the evolution equation for the weight has to be added to the equations of motion:

$$\frac{dw}{dt} = -\frac{(1-w)}{F_o}\frac{d\,F_o}{dt} \quad , \tag{6}$$

where $w = \delta F/F$, F is the ion distribution function, and F_0 the equilibrium ion distribution function. In the simulations δF can be approximated by the weighted Klimontovich distribution in analogy to (2)

$$\begin{aligned}\delta F &= \sum_m w_m \delta(\mathbf{x}-\mathbf{x}_m)\delta(\mathbf{v}-\mathbf{v}_m)\\ &\approx \sum_m w_m S(\mathbf{x}-\mathbf{x}_m)\delta(\mathbf{v}-\mathbf{v}_m) \quad ,\end{aligned}$$

where S is the (linear) shape function as earlier, and the perturbed ion density and current density are calculated as follows

$$\begin{aligned} \delta n_i &= \sum_m w_m S(\mathbf{x} - \mathbf{x}_m) \quad , \\ \delta \mathbf{J}_i &= \sum_m w_m \mathbf{v}_m S(\mathbf{x} - \mathbf{x}_m) \quad . \end{aligned} \tag{7}$$

The equilibrium ion distribution function F_0 is a function of the constants of motion, which in the case of an azimuthally symmetric equilibrium, are the particle energy, $\mathcal{E} = m_i v^2/2 + e\,\Phi$, and the azimuthal angular momentum, pj = $m_i\, r\, v_\varphi - e\ \psi$, where $\psi = -\, r\, A_\varphi$ is the poloidal magnetic flux function, and Φ is the equilibrium electrostatic potential. Two classes of kinetic equilibria were studied. The first class has zero electron current and no electric field. All current is carried by the ions and an exponential rigid-rotor distribution function is used. The second class of equilibrium distribution functions is $F_0 = F(\mathcal{E})$, with $J_i = 0$ and all current is carried by the electrons. Since in both cases the ion pressure is a scalar, Grad-Shafranov equation has been solved to find an equilibrium solution.

II.B. Wall Contact

II.B.1: Computational Physics Issues

It is readily apparent from the previous qualitative discussion on wall support and wall interaction in section I (Background and Significance) above that there are a multitude of closely coupled processes that are important in a magnetized fusion target. Detailed modeling requires inclusion of a diverse set of physical processes with adequate numerical algorithms for accurate accounting for all these processes. Some of the processes may be important in only one or another phase of the target plasma compression, but a successful target design requires inclusion of all the possibly important processes. There is no unknown physics in the processes, but many of the complex interactions between the various processes have only been glimpsed in simple survey codes. Detailed design requires a comprehensive computer code with adequate dimensionality [Lindemuth].

Such a code puts a significant demand on current computing capacity, which cannot be met with simple linear programming and cumbersome algorithms. A massively parallel code and clever management of efficient algorithms will be required. There is no single existing code that is ideal for MTF design, but there are reasonable starting points for developing a comprehensive computer code with adequate dimensionality for MTF.

We anticipate that the code development will begin by assembling a skeleton that will be successively fleshed out to form the final comprehensive code that is desired. The intent is to create a code that is useful from the beginning, but increases in utility and reliability as the project proceeds. The first important step will be to decide on which framework is most versatile (e.g., SPH, AMR, adaptive mesh, ALE, Euler, or Lagrange hydro) how to

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include the requisite dimensionality without imposing a computational burden for the simpler sets of problems. Likewise we will adopt a magnetic field treatment that insures the most comprehensive applicability of the code. (e.g., the vector potential formulation used by Frese[Frese]).

One demanding aspect to the plasma/wall interaction (i.e., wall contact) is the need for tracking accurately the material conditions as it evolves from the solid wall into the plasma. The proper treatment of the liner may require implementation of material strength, but initially treating the solid part of the wall as a liquid (no strength) may suffice. Nevertheless, it is important to anticipate later inclusion of strength. Likewise, initially the fusion physics may neglect the energetic fusion product transport, but eventually it will become important.

In the interest of having a (practical result = useful code) at an early stage, we plan to segment the modular development into distinct separate sub-projects that focus on the various stages of the MTF target compression. For example, initially the liner acts as a solid with little plasma/wall interaction aside from the hydrodynamic coupling and field compression. Later the plasma/wall interaction becomes important. Later still the detailed atomic physics in the plasma may become important. Finally, the fusion physics should dominate.

II.B.2: Existing Codes

It is important to use the experience gained from applying legacy and existing codes to the problems that are relevant to the plasma/wall interaction problem. There are both main frame and PC based codes currently in use for various design problems that have aspects of interest to MTF design. Most of these were written in Fortran and typically use a serial programming style. For example, Lindemuth's MHRDR code[Lindemuth] treats only a single material and uses ideal boundary conditions at the wall [Lindemuth] . For the multi-material MHD codes that currently exist, there are no detailed interface models that properly treat the evolution of material from the wall into the plasma. Without a detailed interface model, proper treatment of the evolution of material from the wall into the plasma requires extremely fine zoning in the wall for both Lagrange and Euler codes. This causes a severe restriction in the time step and renders the code impractical for application to some MTF design problems. We know of no MHD codes that include detailed atomic physics, something that could be important for MTF. A starting point for including detailed atomic physics is available in the form of an astrophysics code used to model gaseous nebulae [RCK].

Simulations can also be carried out with Trac-II, a 2-D axisymmetric (r-z) magnetohydrodynamic (MHD) code. The code solves for all components of the magnetic field (Bz,Br,Bϕ) and fluid velocity vectors (vz,vr,vϕ). Thermal and electrical conduction are included in Trac-II. The EOS is modeled using QEOS, an analytic EOS model that is valid over a large range of energies and densities. Electrical resistivity is calculated using a four-phase (solid-liquid-gas-plasma) model based on the Mott-Jones model in the liquid-solid state, the Saha gas model in the vapor state (to calculate

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electron-ion and electron-neutral contributions), and the Lee-More model in the plasma state.

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III. Research Design and Methods:

III.A: FRC Stability

III.A.1: Physics Issues

We propose to develop a single modular, quasineutral, hybrid kinetic simulation code which incorporates all the essential features of the previous codes in a HCP environment. We further propose to extend the physics models and required numerical solution techniques to include additional physics beyond those previously tractable. In particular, more complete electron physics will be treated.

The current explicit computational schemes ignore many electron effects. Consider, for example, effects associated with the rapid toroidal precession of electrons due to curvature and ∇B drifts of the electrons. As pointed out by Ryutov,[Ryutov, Sherwood] such electrons may have a response very different from the MHD **E** x **B** motion. For example, there is one class of electrons which completely decouple from low frequency MHD modes, and which may provide an "anchor" because of charge uncovering effects. A simple analysis shows that these effects will enter exactly near known theoretical or empirical FRC stability boundaries.

Consider an elliptically shaped FRC poloidal cross section, and a thermal electron. Even with large ion orbits, electrons are reasonably strongly magnetized and most will have guiding center motion. The toroidal precession frequency of electrons due only to the curvature drift is estimated for some median field line, say one lying half way between the magnetic field null at the O-point and the separatrix. The resulting average precession frequency is

$$\overline{\Omega}_{\kappa} \approx \frac{2\pi\, T_e}{e\, B_o R_o^2} \quad , \tag{8}$$

where T_e is the electron temperature, B_o the external magnetic field, and R_o the major radius of the FRC.

Now consider when the average precession of (8) is comparable to the MHD growth rate for the $n = 1$ tilt (comparable to the growth rate for all macro MHD modes). Since $\gamma_{MHD} \sim v_A / E\, R_o$, where v_A is the Alfven velocity, and E the separatrix elongation, there results

$$\frac{S_*}{E} < 2\pi \frac{T_e}{T_o} \quad , \tag{9}$$

for MHD growth rate less than average curvature drift precession frequency. In (7), T_o is the total temperature (electron + ion). Condition (9) is numerically very close to that proposed by Tuszewski.[Tusz PPPL?] Thus, the previous treatement of electrons as a fluid (especially a cold fluid) seems a suspect assumption for FRC stability calculations, and it seems likely that electron motional effects will strongly affect the previous predictions.

Other electron effects which may also dramatically affect FRC stability include:

1) rapid parallel electron motion and associated averaging along magnetic field
2) distinct response of electrons trapped near field line ends.

To include these effects while retaining quasineutrality, we propose to develop a quasineutral, hybrid-PIC package, Q-PHYSICS (Particle HYbrid Simulation-Implicitly Coupled Scheme), that will implicitly couple electron and ion dynamics to the electric field calculation via PIC or fluid equations of motion to insure robust numerical stability for large timesteps. The combination of the electron (and ion) equations of motion and Faraday law will result in a closely coupled set of algebraic grid-point equations in the form of an implicit nonlinear or matrix equation.

It is proposed to develop and implement several new electron models for Q-PHYSICS. These will be derived from the electron drift-kinetic (DK) equation in the limit of rapid parallel motion and, optionally, rapid toroidal precession. The full integral equations which determine the bounce (and, or course, gyro) averaged response to **E** may be simplified under various assumptions on electron motion. These simplified responses will be used to obtain closure relations for the electron fluid equation (3), or alternatively used directly to compute the electron response. In either case, the result is schematically $\mathbf{J}_e = \mathcal{L}(\mathbf{E})$, where $\mathcal{L}$ represents a differential or integral operator, depending on the details of the model.

In contrast to (5), which apparently gives **E** directly in terms of explicitly known quantities, the more complex electron physics models require the solution of the implicit, coupled Maxwell-Newton-Hydro equation

$$\mathcal{L}\left(\mathbf{E}^{n+1}\right) = -f\, c^2 \Delta t^2 \nabla \times \nabla \times \mathbf{E}^{n+1} + \text{explicit terms} \quad , \tag{10}$$

where f is a time centering parameter, and where superscripts have been used to indicate time levels.

Fast and accurate solution of (10) in two and three dimensions is vital to the ultimate success of the Q-PHYSICS model. Previous attempts to achieve this goal involved predominantly traditional iterative sparse matrix solvers (e.g. the bi-conjugate gradient or Gauss-Seidel methods). Being applied to a nonlinear system, these methods converge very slowly. We propose to apply modern Newton-Krylov (NK) methods to the solution of (10). To accelerate convergence on long wavelength errors we propose to use the multigrid method as a preconditioner, with a traditional iterative solver (relaxation) applied on each subset of the original grid. Unlike fast direct matrix solvers, this technique is perfectly scalable with the number of processors and, therefore, is ideally suited for implementation on the massively parallel, teraflop systems of the future. In this effort, we will benefit directly by related expertise at LANL and LLNL, much of which is described in another SciDAC proposal entitled “Center for Implicit, Nonlinear, Extended MHD Scalable Calculations". We expect that Q-PHYSICS will provide a challenging testing ground for these new implicit, Newton-Krylov multigrid algorithms aimed at solving the closely coupled Maxwell-Newton-Hydro equations.

Development of an accurate and numerically useful electron model represents a great challenge, and constitutes the principal intellectual content of this proposal. This problem, in a different context (that of turbulent electrostatic or electromagnetic transport in a sheared magnetic field) is receiving the attention of many computational fusion physicists. We are proposing to develop this capability in a simpler physical situation. In contrast to transport applications, the FRC stability application:

- Has little or no magnetic shear in the background B
- Assumes strict quasineutrality
- Is focused on higher-frequency modes (Alfven contrasted to drift)
- Has uniformly small $k_{\|}$

In spite of these simplifications, we propose to maximize the rate of progress by simultaneously evaluating several alternative electron models for Q-PHYSICS. The main approach will be to analytically obtain a completely consistent response from the DK equation, as outlined above, and to combine this with the implicit solution of (10) using scalable NK iterative methods. In parallel, we will also extend recent work on gyroviscous fluid closures developed by Belova, and evaluate the recently developed split-weight δf schemes for our application. Additionally, numerical schemes to directly carry out the bounce-averaging will be pursued as an alternative to analytic integral equation methods.

Electron physics
- Apply recently derived gyroviscous closure
- Apply split-weight electron scheme
- Develop bounce-average formulation a la gyrokinetic gyroaveraging

\delta f applied to ions or electrons

Improved vacuum region treatment
- implicit displacement (this is Yuri's concept, for example)
- 2 region treatment with plasma boundary tracking
- improved cold background fluid vacuum treatment

Alternative particle approaches will also be investigated. In these models, the electron drift-kinetic equation will be solved by PIC methods directly to obtain $\mathbf{J}_e$. Various bounce averaging strategies include orbit averaging, or multipoint sampling of the parallel motion. Eqn. (10) will be used to advance $\mathbf{E}$. If desired, a Newton-Krylov outer iteration on the electron particle advance may then be carried out to obtain a converged full particle solution.

In addition to improving electron physics, Q-PHYSICS will incorporate an improved treatment of the low-density "vacuum" region outside the FRC separatrix. Two distinct approaches are to divide the problem into two regions, with detection of the plasma boundary and a separate elliptic solution in the vacuum region, or to treat the vacuum as a low-density, cold plasma region. One limit of the latter approach is to include the displacement current in (10). In any case, implicit differencing of the vacuum waves is required to obtain a practical algorithm, and the NK formulation accomplishes this differencing in a natural manner.

In addition to this focus on additional physics in a HCP modular code, VECC work will concentrate on uniform problem set up and visualization packages. This work will facilitate the comparison of results obtained by different members of the collaboration, and make available problem set ups for the previously obtained results as a validation and benchmark comparison.

One need for the desired study of large elongation is the computation of FRC equilibria at very large *E*. Barnes[Barnes PoP] has recently found a universal pressure profile which is useful for this purpose in the MHD limit. Solutions obtained by this method will be added to a catalog of other previous MHD equilibria with various separatrix shape, separatrix radius, and elongation. Additionally, the problem set up modules will facilitate the specification of plasma parameters outside the MHD model, such as ion and electron temperatures, and rotation.

Additional boundary conditions may also be developed for the Q-PHYSICS calculations. For example, the addition of even or odd axial parity RMF fields or of non uniform axial motion of the confining wall may be desirable extensions.

B. Wall-Contact

Both the wall and plasma physics need enhancements over existing codes. It is important to have a multi-material capability, which employs an EOS with phase changes. Good conductivity and opacity databases are a necessity. Strength may be important for some MTF embodiments, and impurity transport must be included to accurately model the late stages of the target plasma compression. Both material diffusion and convection (possibly using marker particles [4]) should be treated.

As the plasma heats up and wall impurities enter the plasma, atomic physics will become important, especially for analyzing diagnostics from the experiments. The implementation of the atomic physics should use detailed balance, but statistical equilibrium probably suffices (as opposed to using rate equation for all the ionic energy levels). There will be a need adequate atomic physics data base. Radiation transport must treat both the continuum and the lines. Some lines may be optically thick, which may require implementing diffusion-like physics (e.g., complete redistribution) across line profile.

A separate problem setup capability allows independent development of the physics package and a user friendly problem generation code. Parameter incompatibility warnings are an invaluable aid for complex problem setup. The interactive setup code should allow an easy changes to the input for making parameter studies, and it should

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generate a problem input file to be read by the physics code. User selection of run-time physics options will avoid wasted computational work for those problems where it is known that only a few physics processes are important. The problem generation code should also provide a graphics file that is compatible with the post processor used to display the physics package results. Link and restart capabilities are extremely useful.

In the physics code implicit MHD is very important, because the sound velocity and Alfven speed in the plasma are typically high relative to the wall speed, leading to needlessly restrictive time steps in an explicit algorithm. Some of the atomic physics processes are best described by sparse matricies, so an efficient sparse matrix algorithm will be required.

We intend to use a modular approach to code development. Segmenting the modular development into distinct separate sub-projects that focus on the various stages of the MTF target compression should produce a useful code at an early date. A wisely chosen code framework will allow continued fleshing out of the code. Parallelized and/or vectorized modules will be developed to handle numerically intensive algorithms. However, for many algorithms linear programming should suffice.

C. Work Breakdown by Task and Milestones

The work-breakdown structure for the research program outlined previously is shown by the tasks of Table 2.

$$\text{VECC} = \sum_{\textit{FRC Computing}} \left\{ GA,\ LANL,\ LLNL,\ PPPL \right\}$$

1. FRC Stability
1.1 Electron physics
1.1.1 Drift-Kinetic moment solution
1.1.1.1 Closure approximations for (3)
1.1.1.2 Direct $\mathbf{J}_e$ approximations
1.1.2 Drift-Kinetic particle solution
1.1.2.1 DK particle mover
1.1.2.2 Orbit (bounce) averaging
1.1.2.3 Moment-based field advance
1.1.2.4 Implicit particle advance
1.1.3 Implicit field solution
1.1.3.1 Difference formulation
1.1.3.2 Multigrid preconditioner
1.1.4 Vacuum region algorithm
1.1.4.1 Two-region formulation
1.1.4.2 Implicit wave formulation
1.2 Computational physics results
1.2.1 Electron effects with cold ions
1.2.2 Stability study at large E
1.2.3 Converging wall stability

2. Wall contact
2.1 Wall confinement physics
2.1.1 Wall behavior
2.1.1.1 EOS and opacity
2.1.1.2 Magnetic diffusion
2.1.1.3 Ablation model
2.1.1.4 Rayleigh-Taylor instability of the plasma-liner interface
2.1.2 Incorporation of anlomalous transport model into two-fluid equations
2.1.3 Plasma transport in 2D geometry
2.1.4 Macroscopic 3D plasma instabilities in systems with wall confinement
2.1.5 Impurity transport (convection and diffusion)
2.1.6 Atomic physics and transport to wall
2.1.6.1 Atomic parameter database
2.1.6.2 Statistical equilibrium model
2.1.6.3 Cooling rates
2.1.6.4 Continuum and line transport
2.1.7 Fusion physics
2.1.7.1 Alpha particle confinement
2.1.7.2 Burning plasma instabilities
2.2 Test problems for validation and verification
2.2.1 Cooling of a1-D magnetized plasma to a static cold wall
2.2.2 Compression by a constant velocity wall
2.2.3 2-D instability and plasma convection
2.3 Computational Studies
2.3.1 Effect of wall material on compression of clean plasma
2.3.2 Wall material impurity transport into plasma
2.3.3 Effect of impurity concentration on plasma compression
2.3.4 Requirements for reaching fusion conditions

3. Computer science issues
3.1 Parallel libraries
3.2 Problem set up extensions
3.3 Post processing extensions
3.4 Definition/development of physics modules
3.5 Definition/development of numerical algorithm modules

Table 2: Research tasks for VECC study of FRC/MTF physics issues

$$\text{VECC} = \sum_{\textit{FRC Computing}} \left\{ GA,\ LANL,\ LLNL,\ PPPL \right\}$$

The proposed VECC work will be accomplished during the remainder of FY01 (assuming a start date of 5/1/1) and FY02 and 03. A table of milestones is:

Test uniform set up on M3D-B and FLAME	8/31/1
Obtain analytic DK bounce-averaged electron closure	9/1/1
Particle electron model numerical formulation	10/30/1
Evaluate electron models with cold ion fluid	12/31/1
Converging wall stability calculation	12/31/1
Implicit Q-PHYSICS with cold electrons	3/31/2
Improved vacuum treatment incorporated	5/31/2
Electron model incorporated	8/31/2
Elongation stability study completed	12/31/2

MILESTONES FOR WALL-CONTACT??

$$\text{VECC} = \sum_{\textit{FRC Computing}} \left\{ GA,\ LANL,\ LLNL,\ PPPL \right\}$$

IV: Consortium Arrangements:

Personnel

VECC combines and augments efforts at Los Alamos, Princeton, General Atomics, and Livermore. Specific staff are: (LANL) D. Barnes, R. Faehl, R. Kirkpatrick, I. Lindemuth; (PPPL) E. Belova, S. Jardin; (GA) Y. Omelchenko, P. Parks, M. Schaffer; (LLNL) J. Hammer, D. Ryutov. Fractional incremental support will be provided for these staff under this proposal.

Budget: The anticipated budget is $600K/yr.

Organization and Management

Los Alamos will serve as the lead institution and provide coordination and administrative support for the VECC activities. Dan Barnes will be the Principal Investigator.

$$\text{VECC} = \sum_{\text{FRC Computing}} \{ GA, LANL, LLNL, PPPL \}$$

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$$\text{VECC} = \sum_{\text{FRC Computing}} \left\{ GA,\ LANL,\ LLNL,\ PPPL \right\}$$

Budget

Detailed DOE budget sheets for each participating institution are attached as the following pages. It is assumed that HPC computing resources will be provided through DOE for the work proposed here.

The total budgets by FY are:

FY01
FY02
FY03

3.9 Biographical Sketches

Daniel C. Barnes

Education:

Purdue University	Ph.D. Applied Mathematics	(1975)
	M.S. Applied Mathematics	(1969)
	B. S. Physics	(1965)

Experience:

Dr. Barnes is an internationally recognized expert in the fields of plasma physics and computational physics. He has over 23 years experience in the solution of complex, nonlinear problems involving both fluid and kinetic descriptions of plasmas and other physical systems. He has authored or co-authored over seventy refereed papers in this field, and has given numerous invited papers on this and related subjects. His present research interests include kinetic and fluid simulations of magnetically-confined plasmas, compact fusion systems based on electrostatic confinement of charge neutral and nonneutral plasmas, and electromagnetic solvers for Vertical Cavity Surface-Emitting Lasers (VCSEL's).

Dr. Barnes is distinguished by his proven ability to both conceive new methods by which important technical problems may be attacked, as well as his ability to carry out detailed modeling and designs to realize these new concepts. He holds four patents, and is the inventor of numerous other technical methods and devices. He also has a demonstrated ability to interact well with and supervise fellow researchers and plan, organize, and carry out new projects.

Dr. Barnes received his B.S. degree as a National Merit Scholar in 1965 and then joined the Applied Research Division of the U.S. Naval Avionics Facility as a Staff Physicist. There he performed six-degree-of-freedom airframe simulation, and was involved in electro-optical guidance system research and development. He was granted two patents for the latter work. During this time he began graduate studies in Applied Mathematics at Purdue University, where he became an NSF Fellow. His research involved equilibrium and stability problems for toroidal magnetohydrodynamic systems. He received his Ph.D. in 1975.

In October 1974 Dr. Barnes joined the magnetic fusion theory group at Los Alamos National Laboratory, where he worked on problems relevant to the Scyllac and Compact Torus experiments. His research was instrumental in explaining observed phenomena in both devices. In 1978 he served as a Visiting Scientist at the Courant Institute of Mathematical Sciences of New York University. He was promoted to Associate Group Leader for Magnetic Fusion Theory in 1979.

Dr. Barnes joined the staff of the Institute for Fusion Studies (IFS) at the University of Texas in 1980. There he continued his research in computer simulation of magnetically confined plasmas. He participated in the U.S./Japan exchange on plasma theory, including living and working at the Institute of Plasma Physics, Nagoya, Japan. He also chaired the IFS computer committee.

In 1984, Dr. Barnes joined Science Applications International Corporation (SAIC) where he initiated and managed the Austin, Texas SAIC office. He investigated several problems related to FRC formation and stability. He also numerically studied magnetic structures in the solar atmosphere. He developed a computer based model for the plasma armature in complex rail gun geometries, and applied this model to the Eglin AFB AFATL MARC-I and MARC-IV devices, explaining most features of the experimental observations. He conceived the HARM (**H**old **A**nd **R**elease **M**agnetically) concept for rail gun initiation which was investigated experimentally by AFATL. Dr. Barnes developed the concept of Magnetically

Insulated Impact Fusion. He is also co-inventor of the Illuminated Aerial Marker, and holds two patents related to this development.

In September 1989, Dr. Barnes returned to Los Alamos National Laboratory where he lead the Plasma Theory, Computation, and System Studies Group of the Controlled Thermonuclear Division until 1991. He subsequently became Group Leader for Plasma Theory at Los Alamos and Chief Scientist of NambeTech, a small research and development oriented New Mexico Corporation. He is currently Technical Staff Member of the Plasma Applications Group. Dr. Barnes is a Fellow of the American Physical Society and has served as Chair of the Division of Plasma Physics.

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Elena V. Belova is an Associate Research Physicist at the Princeton University Plasma Physics Laboratory. Her research interests include: kinetic effects on the MHD stability, interaction of energetic particles with MHD waves, global stability of the Field-Reversed Configurations, numerical simulations, developing fluid/kinetic(gyro-kinetic) hybrid models of plasmas. She has authored or co-authored more than 14 publications in plasma physics. She received a M.S. in physics from Moscow Institute of Physics and Technology (Russia), and worked as a junior research scientist at the Space Research Institute in Moscow, Russia till 1992. She received a Ph. D. in plasma physics from Dartmouth College, Hanover NH in 1997. Following a three year post doctoral position with Princeton Plasma Physics Laboratory, she joined PPPL staff in 2000. She is currently active in the area of MHD and hybrid simulations of the stability of the Field-Reversed Configurations, including the effect of sheared rotation, shaping, conducting shells (MHD) and kinetic effects on the tilting instability, and a development of the FLR-corrected fluid and drift-kinetic models.

James H. Hammer:

PRESENT POSITION:

Physicist

X-Division, Defense and Nuclear Technologies Directorate

GENERAL:

Born in Phoenix, Arizona, 1951. Received B.S. (Physics) from Arizona State University, 1973; received Ph.D. (Physics), at University of California, Berkeley, 1978. Fellow of the American Physical Society.

Began employment at Lawrence Livermore National Laboratory (LLNL), 1979, Magnetic Fusion Energy, Theoretical Computations Group. Work included examination of theoretical issues related to compact torus (CT) experiments. Developed a model of helicity injection that provided the first quantitative explanation of flux amplification, originally observed by H. Alfven in plasma-gun-produced spheromak experiments. Conducted many studies (both numerical and analytical) of magnetohydrodynamic equilibrium and stability of various magnetic fusion devices.

Taught graduate plasma physics course at U.C. Davis, Department of Applied Science LLNL campus, 1980.

Served as program leader for the LLNL compact torus acceleration experiment 1991-1994. Made significant contributions to the invention and development of the CT accelerator, CT fueling and current drive for tokamaks, and the CT pulsed x-ray source. The CT accelerator has emerged as a leading candidate for deep penetration fueling of magnetic fusion devices.

Made significant contributions to the invention and development of the fast ignitor Inertial Confinement Fusion (ICF) concept, a method for greatly enhancing gain through ignition of compressed fuel with a short pulse laser.

Made fundamental contributions to the modeling of magneto-Rayleigh-Taylor instabilities in imploding z-pinches and invented a method for reducing instability with tailored density profiles.

Invented and developed, together with Max Tabak, a target design using z-pinch driven-hohlraums to achieve high yield, indirect drive ICF. The design is currently undergoing experimental proof-of-principle tests on the Z accelerator at Sandia National Laboratories in Albuquerque, N.M. (SNL), and has been chosen as the primary ICF approach at SNL.

Contributed to many alternative approaches to fusion and been a vocal advocate for a renewed investigation of alternate concepts.

Modeled laser-driven hohlraums for the Nova, Omega and NIF lasers including the effects of laser-induced magnetic fields.

Holds a patent for a method of tapping electrical energy from the solar wind for space power and propulsion.

Employed since 1993 in the ICF Applications Group, X-Division at LLNL, as project leader for the study of the use of pulse power machines for ICF and high energy density physics.

$$\text{VECC} = \sum_{\textit{FRC Computing}} \left\{ \textit{GA, LANL, LLNL, PPPL} \right\}$$

REVIEW AND INVITED TALKS:

"Compact Torus Theory and Experiment", Review talk at the American Physical Society Division of Plasma Physics Annual Meeting, *Bull. Am. Phys. Soc.*, **26**, 971 (1981).

"Experimental Demonstration of Compact Torus Compression and Acceleration", Invited talk at the American Physical Society Division of Plasma Physics Annual Meeting, *Bull. Am. Phys. Soc.*, **35**, 1941 (1990).

"Two-dimensional Radiation-Magnetohydrodynamic Simulations of SATURN Imploding Z-Pinches", Invited talk at the American Physical Society Division of Plasma Physics Annual Meeting, *Bull. Am. Phys. Soc.*, **40**, 1863 (1995).

"High Gain ICF Target Design for a Z-pinch Driven Hohlraum", Invited talk at the American Physical Society Division of Plasma Physics Annual Meeting, *Bull. Am. Phys. Soc.*, **43**, 1919 (1998).

"High Yield ICF with a Z-pinch Driven Hohlraum", Invited talk at the 1st International Conference on Inertial Fusion Sciences and Applications, Bordeaux, France, September 1999.

SELECTED PUBLICATIONS AND REPORTS :

J. H. Hammer and W.B. Kunkel, "Equilibrium Theory of Toroidal Magnetic Cusp Confinement with Internal Circulation," *Phys. Fluids,* **19**, 438 (1976).

E. Hameiri and J. H. Hammer, "Unstable Continuous Spectrum in Magnetohydrodynamics," *Phys. Fluids,* **22**, 1700 (1979).

J. H. Hammer, "MHD Tilting Modes for Arbitrary Pressure and Configuration," *Nuclear Fus.,***21**, 488 (1981).

E. Hameiri and J.H. Hammer, "Turbulent Relaxation of Compressible Plasmas," *Phys. Fluids,* **25**, 1855 (1982).

J. H. Hammer and H. L. Berk, "A Steady State Beam Driven Field-Reversed Mirror," *Nuclear Fus.* **22**, 89 (1982).

C.W. Hartman and J.H. Hammer, "New Type of Collective Accelerator," *Phys. Rev. Lett.* **48**, 929 (1982).

W. C. Turner, G. D. Goldenbaum, E. H. A. Granneman, J. H. Hammer, C. W. Hartman, D. S. Prono, and J. Taska, "Investigations of the Magnetic Structure and the Decay of a Plasma-Gun-Generated Compact Torus," *Phys. Fluids* **26,** 7 (1983).

J.H. Hammer, “Reconnection in Spheromak Formation and Sustainment”, in *Magnetic Reconnection in Space and Laboratory Plasmas,* (E.W. Hones Jr., Ed.) Geophysical Monograph 30, American Geophysical Union, Washington D.C., 1984, p. 319.

J. H. Hammer and H. L. Berk, "Finite Orbit Analysis for Long Wavelength Modes in a Plasma with a Hot Component, *Phys. Fluids* **28,** 8 (1985).

D. J. Meeker, J. H. Hammer, and C. W. Hartman, "A High Efficiency ICF Driver Employing Magnetically Confined Plasma Rings, "*Fusion Technology* **8**, 1, pt. 2B, (1986).

J. H. Hammer, C. W. Hartman, J. L. Eddleman, and H. S. McLean, "Experimental Demonstration of Acceleration and Focusing of Magnetically Confined Plasma Rings," *Phys. Rev. Lett.* **61,** 2843 (1988).

L.J. Perkins, S.K. Ho, and J.H. Hammer, "Deep Penetration Fueling of Reactor-Grade Tokamak Plasmas with Accelerated Compact Toroids," *Nuclear Fus.* **28**, 1365 (1988).

A. W. Molvik, J. L. Eddleman, J. H. Hammer, C. W. Hartman, and H. S. McLean, "Quasistatic Compression of a Compact Torus, *Phys. Rev. Lett.* **66,** 165 (1991).

J. H. Hammer, J. L. Eddleman, C. W. Hartman, H. S. McLean, and A. W. Molvik, "Experimental Demonstration of Compact Torus Compression and Acceleration", *Phys. Fluids B.* **3**, 2236 (1991).

M. Tabak, J.H. Hammer, M.E. Glinsky, W.L. Kruer, S.C. Wilks, J. Woodworth, E.M. Campbell, and M.D. Perry, "Ignition and High Gain with Ultrapowerful Lasers,"*Phys. Plasmas* **1**, 5 (1994).

S. Maxon, J.H. Hammer, J.L. Eddleman, M. Tabak, G.B. Zimmerman, W.E. Alley, K.G. Estabrook, J.A. Harte, T.J. Nash, T.W.L. Sanford, and J.S. DeGroot, "Magnetohydrodynamic Solution for a Z-Pinch Showing the Production of a Hot Spot", *Phys. Plasmas* **3**, 1737 (1996).

J.H. Hammer, J. L. Eddleman, P.T. Springer, M. Tabak, A. Toor, K.L. Wong, G.B. Zimmerman, C. Deeney, R. Humphreys, T.J. Nash, T.W.L. Sanford, R.B. Spielman, and J.S. De Groot, "Two-dimensional Radiation-Magnetohydrodynamic Simulations of SATURN Imploding Z-Pinches", *Phys. Plasmas* **3**, 2063 (1996).

R.P. Drake, J.H. Hammer, C.W. Hartman, L.J. Perkins and D.D. Ryutov, "Submegajoule Liner Implosion of a Closed Field Line Configuration", *Fusion Technology* **30**, 310 (1996).

$$\text{VECC} = \sum_{\textit{FRC Computing}} \{ GA,\ LANL,\ LLNL,\ PPPL \}$$

J.H. Hammer, M. Tabak, S. Wilks, J. Lindl, P.W. Rambo, A. Toor, G.B. Zimmerman and J.L. Porter, "High Yield Inertial Fusion Design for a Z-Pinch Accelerator",*Proc. of the 17th IAEA Fusion Energy Conference, Yokohama, Japan*, *paper F1-CN-69/IFP/18* , October 19-24, 1998.

S.H. Glenzer, W.E. Alley, K.G. Estabrook, J.S. De Groot, M.G. Haines, J.H. Hammer, J.P. Jadaud, B.J. MacGowan, J.D. Moody, W. Rozmus, L.J. Suter, T.L. Weiland, and E.A. Williams, "Thomson Scattering from Laser Plasmas", *Phys. Plasmas*, **6**, 2117 (1999).

J.H. Hammer, M. Tabak, S.C. Wilks, J.D. Lindl, D.S. Bailey, P.W. Rambo, A. Toor, G.B. Zimmerman, J.L. Porter, Jr., "High Yield ICF Target Design for a Z-pinch Driven Hohlraum", *Phys. Plasmas*, **6**, 2129 (1999).

J.H. Hammer and D.D. Ryutov, "Linear Stability of an Accelerated Wire Array", *Phys. Plasmas*, **6**, 3302 (1999).

$$\text{VECC} = \sum_{\textit{FRC Computing}} \left\{ GA,\ LANL,\ LLNL,\ PPPL \right\}$$

Stephen C. Jardin is a Principal Research Physicist at the Princeton University Plasma Physics Laboratory. He is presently Co-Head of the Computational Plasma Physics Group at PPPL, Head of the Next Step Options Physics, and Theory Department MHD Coordinator. He has been Lecturer with Rank of Professor in the Princeton University Astrophysics Department since 1986. He holds a BS in Engineering Physics from the University of California, a MS (Physics) and MS (Nuclear Engineering) from MIT, and a PhD in Astrophysics from Princeton University (1976). He was the primary developer of several widely used MHD equilibrium, stability, and transport codes including the Tokamak Simulation Code (TSC). He holds 4 US Patents, has had over 150 refereed publications in plasma physics, and has supervised 6 Princeton University PhD students. He is a member of Phi Beta Kappa and a Fellow of the American Physical Society. He has held key positions in several fusion device design teams including those for S-1, PBX-M, CIT, BPX, TPX, ARIES, and ITER. He is presently a member of the NERSC Executive Committee Users Group, the ESNET Steering Committee, and is Chair of the NERSC Program Advisory Committee and of the National Transport Code Collaboration (NTCC) Program Advisory Committee.

$$\text{VECC} = \sum_{\textit{FRC Computing}} \left\{ GA,\ LANL,\ LLNL,\ PPPL \right\}$$

RONALD CRECELIUS KIRKPATRICK has been a staff member at **Los Alamos National Laboratory** since **1973**.

He has degrees in **Electrical Engineering** (BS, 1959) and **Physics** (MS, 1963) from **Texas A&M University** and in **Astronomy** (PhD, 1969) from the **University of Texas** at Austin.

His background includes work in the electrical power industry, flight instrumentation, high temperature experiments, shock wave physics, numerical computation of partition functions, radiative recombination coeficients and transition probabilities, modeling of planetary nebulae, A/D interface design, teaching Physics and Astronomy, investigating the physics of fusion ignition, development of special purpose research codes for the design of fusion experiments, studies of laser interaction with matter, and calculation of charged particle energy deposition in magnetized plasmas.

He worked at Gulf States Utilities Company, NASA Ames Research Center, Southwest Research Institute, the University of Texas, Applied Research Laboratory (UT), NASA Goddard Space Flight Center, and Texas A&M University prior to going to Los Alamos National Laboratory.

He is a member of the **American Astronomical Society** and the **International Astronomical Union**, and has published a few dozen scientific and technical papers.

Irvin R. (Irv) Lindemuth

Dr. Lindemuth is currently Project Leader for Pulsed Power Science, Technology, and International Collaboration in the High Energy Density Hydrodynamics Program at the Los Alamos National Laboratory, where his primary responsibility is to provide technical leadership for a scientific collaboration between Los Alamos and Los Alamos' Russian counterpart, the All-Russian Scientific Research Institute of Experimental Physics (VNIIEF) at Sarov (Arzamas-16). Prior to joining Los Alamos in 1978, he was a technical staff member in A-Division at the Lawrence Livermore National Laboratory where he was involved in fusion research. Dr. Lindemuth received his B.S. degree in Electrical Engineering from Lehigh University in 1965 and his M.S. and Ph.D. degrees in Engineering--Applied Science from the University of California, Davis/Livermore in 1967 and 1971, respectively. His thesis research was conducted under the advisorship of Dr. John Killeen, founder of the National Magnetic Fusion Energy Computer Center. His areas of expertise include thermonuclear fusion and advanced numerical methods for the computer simulation of fusion plasmas and related pulsed power technology. He has published numerous papers in refereed journals and proceedings of major international conferences. He has been involved in a wide range of fusion and high energy density physics programs spanning essentially all of the ten orders of magnitude in density and time space from magnetic fusion energy plasmas to inertial confinement fusion plasmas. An internationally recognized pioneer in the application of implicit, non-split computational methods to magnetohydrodynamics, he has achieved widespread recognition for his large-scale numerical simulations of a variety of fusion and other high-density plasma systems. In addition to his accomplishments in modeling high temperature plasmas, he has formulated a variety of novel pulsed power computer codes that have led to important advances in laboratory programs. His codes have stimulated the development of several types of fast opening switches. He is a US pioneer on magnetized target fusion (MTF) and performed the first comprehensive survey of the parameter space in which MTF was likely to work. Even before the collapse of the Soviet Union, he recognized that the Soviets had developed advanced technology in the areas of ultrahigh magnetic fields and ultrahigh energy electrical pulse generation that significantly exceeded US capabilities and that were motivated by the Soviet MTF program known as MAGO. Dr. Lindemuth played an essential role in establishing the collaboration with VNIIEF, a collaboration that provides US access to Russian advances in MTF and pulsed power technology. In 1992, he was the recipient of a Los Alamos Distinguished Performance Award for his work in the formative stages of the LANL/VNIIEF collaboration.

Yuri A. Omelchenko

Senior Scientist

EDUCATION

M.S. *(magna cum laude*, Space Physics and Computer Science),
Moscow Institute of Physics and Technology, 1987
Ph.D. (Plasma Physics), Moscow Institute of Physics and Technology, 1991

POSITIONS

1991-1993 — Postdoctoral Research Fellow, Plasma Physics Department,
The Space Research Institute of Russian Academy of Sciences
1993-1998 Visiting Scientist/Research Associate III,
Laboratory of Plasma Studies, Cornell University
1998-present Sr. Scientist (Scientist III), General Atomics

EXPERIENCE

Dr. Yuri A. Omelchenko is a Senior Scientist in the Theory and Computational Science Division, General Atomics. At GA, his theoretical and computational research has focused on rotational shear generation in tokamaks from ICRH and 3-D stability of FRCs and ion rings. He has developed a 3-D, parallel, object-oriented, hybrid, Particle-in-Cell code, FLAME for studying quasineutral ion and electron beam physics and stability of high-beta magnetic confinement configurations. He recently discovered the crucial role of self-generated toroidal field in stabilizing the FRC tilt mode. Before joining GA, Dr. Omelchenko worked with Prof. Ravi Sudan at the LPS, Cornell University, leading the design and implementation of advanced computational tools in support of the Cornell FIREX program. He made a fundamental contribution to the overall experimental design by predicting the conditions for ion ring trapping and reversal. From this work he has developed, optimized and parallelized a number of simulation codes that have since been in use at the LPS and GA. At the Moscow Institute of Physics and Technology, he worked with Prof. Vitali Shapiro (now at UCSD) on turbulent electron/ion beam-plasma interactions in space plasmas. Dr. Omelchenko has over 30 publications in refereed journals and conference proceedings.

PUBLICATIONS

[1] Nonlinear Stability of Field-Reversed Configurations with Self-Generated Toroidal Field, w/M. Schaffer and P. Parks, submitted to *Phys. Plasmas* (2001).

[2] Kinetic Simulations of the Formation and Stability of the Field-Reversed Configuration, *Phys. Plasmas* **7**, 1443 (2000).

[3] A 3-D Darwin-EM Hybrid, PIC Code for Ion Ring Studies, w/R.N. Sudan, *J. Comp. Phys.* **133**, 146 (1997).

PAUL B. PARKS

Principal Scientist

EDUCATION

B.S. (*magna cum laude*, with high distinction in Physics), University of Illinois, 1973
M.S. (Nuclear/Electrical Engineering), University of Illinois, 1975
Ph.D. (Nuclear/Electrical Engineering), University of Illinois, 1977

POSITIONS

1977-1985 — Senior Scientist, General Atomics
1985-1993 — Staff Scientist, General Atomics
1993-2001 — Principal Scientist, General Atomics

EXPERIENCE

Dr. Parks is a highly versatile plasma physicist who has extensive experience in a number of diverse theoretical and applied areas connected with fusion and non-fusion research. He is internationally recognized for his pioneering work on pellet ablation in tokamak plasmas. Dr. Parks has worked on a variety of radio-frequency (rf) concepts including fast wave antenna/plasma coupling, Faraday shields, resonant cavity launchers, and rf ponderomotive stabilization of MHD instabilities. He has published a book on pellet ablation in plasmas, and holds (with others) a U. S. Patent for a novel rf cavity launcher, which was built and successfully operated on the DIII–D tokamak.

With Dr. R.K. Fisher, he started a DOE-funded program in collaboration with Princeton Plasma Physics Laboratory and Ioffe Institute using high-speed low-Z refractory pellets as a plasma diagnostic tool for measuring the distribution function of confined alpha particles. From 1988 to 1995 he was in charge of the modeling effort for the project, which recently led to the first measurements of fusion born fast alpha particles inside the Princeton TFTR tokamak.

He has done original work in the area of tokamak current drive, impurity control, plasma-surface interactions, advanced propulsion concepts, and MHD generators. Since 1996 his more recent contributions have been in the areas of disruption mitigation. He helped devise an elegant theoretical model for the penetration of a liquid jet into a tokamak plasma, and developed an analytical theory of avalanche runaway electron generation in tokamak plasmas which agrees well with Fokker-Planck and Monte Carlo numerical simulations. Dr. Parks has also contributed to alternate confinement concepts, such as Magnetized Target Fusion and Field Reversed Configurations. He is actively involved with researchers at the National Institute for Fusion Science in Japan on a 2D numerical simulation of pellet ablation. Dr. Parks is lead theorist on an OFES funded Fast Ignition concept evaluation program.

$$\text{VECC} = \sum_{\textit{FRC Computing}} \left\{ \textit{GA, LANL, LLNL, PPPL} \right\}$$

Dr. Parks recently gave an invited talk at the 41st annual APS meeting (1999) on a theory of fuel mass transport during pellet injection in toroidal confinement devices, which exploits the magnetic curvature drift current. He has authored and co-authored over 65 papers in the refereed Physical Journals, and has DOE Q and DOE Secret clearances.

SELECTED First Authored Publications

1. "Model of Neutron production rates from Femtosecond Laser-Cluster Interaction", GA-A23574, Jan 2001 submitted to *Phys Rev. A* (with T.E. Cowan, R.B. Stephens, and E. M. Campbell).
2. "Radial Displacement of Pellet Ablation Material in Tokamaks Due to the Grad-B Effect," *Physics of Plasmas 7 1968 (2000)*; Invited Talk presented at the 41st American Physical Society Division of Plasma Physics Meeting, Seattle, WA, Nov.15-19 1999, (with W.D.Sessions and L.R. Baylor).
3. "Avalanche Runaway Growth Rate from a Momentum-Space Orbit Analysis," *Physics of Plasmas* 6 2523 (1999) (with M.N. Rosenbluth and S.V Putvinski).
4. "Self-Similar Adiabatic Compression of Highly-Elongated Field-Reversed Configurations," *Nuclear Fusion* 39 747 (1999)
5. "High-Velocity Liquid Jet Injection into Tokamak Plasmas for Disruption Mitigation," *FusionTechnology* 35 267 (1999) (Special Edition on Innovative concepts) (with M.N. Rosenbluth, S.V. Putvinski, and T.E. Evans).
6. "Equilibrium Pellet and Liquid Jet Shape Under High Ablation Pressures," *Physics of Plasmas* 5 1380 (1998) (with M.N. Rosenbluth)
7. "Theory of Pellet Cloud Oscillation Striations," *Plasma Physics and Controlled Fusion* 38 1 (1996).
8. "Effect of Stochastic Ripple Diffusion on the Detection of Fusion Product Ions by Charge- Exchange Pellet Diagnostics," *Nuclear Fusion* 35 1297 (1995) (with R.K. Fisher, J.M. McChesney).
9. "Layering of Inertial Confinement Fusion Targets in Microgravity Environments," *Journal of Applied Physics* 77 1048 (1995) (with R.L. Fagaly).
10. "Effect of Magnetic Field on the Distribution of Ions Striking a Planar Target," *Physics of Plasmas* 1 3883 (1994) (with S.I. Lippmann).
11. "Model of Ablation Flow Near Light-Atom Pellet with Surface Boundary Conditions," *Nuclear Fusion* 34 417 (1994) (with G.A. Gerdin, et al).
12. "Electric Field and Current Distribution Near the Ablation Cloud of a Pellet Injected Into a Tokamak," *Nuclear Fusion* 32 2137 (1992).
13. "Pfirsch-Schluter Effect on Divertor Biasing." *Nucl. Fusion* 31 373 (1991).
14. "Pellet Ablation Flow Near the Stagnation Plane at Low Magnetic Reynolds Number," *Nucl. Fusion* 31 1431 (1991).
15. "Current/Melt Wave Model for Transitioning Solid Armature," *Journal of Applied Physics*, 67 3511 (1990).
16. "An Analytic Solution for the Efficiency and Gain of a CARM Oscillator," *IEEE Transactions on Plasma Science*, 18 223 (1990).

Dmitri Ryutov

Graduated Summa Cum Laude from Moscow Institute of Physics and Technology at 1962. PhD from Kurchatov Atomic Energy Institute (Moscow) at 1966. In 1966-1968 worked as a junior scientist at Kurchatov Institute. In 1968-1997 held consecutively positions of senior scientist, division leader, deputy director, chief scientist at the Institute of Nuclear Physics (Novosibirsk). Since 1994 is with Lawrence Livermore National Laboratory (in 1994-1997 – on leave from the Novosibirsk Institute). At present, is a senior scientist with MFE program. In 1973-1994 held a Chair of plasma physics at the Novosibisk State University. Supervised ~20 PhD students. Scientific interests include fusion research, E-beams, high-energy-density physics, astrophysics, and advanced dynamics. Academician, Russian National Academy of Sciences. APS Fellow.

10 relevant publications.

1. D.D. Ryutov. "Controlled thermonuclear fusion in a dense quasistationary plasma", Sov.Physics-Uspekhi, v.18, p.466 (1975)
2. G.E.Vekshtein, D.D. Ryutov, and P.Z. Chebotaev "Diffusion of heavy impurities in a dense, wall-confined plasma". Sov.J.Plasma Phys., v.1, p.220 (1975)
3. G.E.Vekshtein, D.D. Ryutov, M.D. Spektor, and P.Z. Chebotaev. "Nonmagnetic containment of a dense plasma." J. Appl. Mech. & Tech. Phys., v. 15, p. 731 (1976)
4. R. P. Drake, J. Hammer, C. Hartman, J. Perkins, and D.D. Ryutov. "Submegajoule liner implosion of a closed field line configuration." Fusion Technology, v. 30. 310 (1996)
5. D.D. Ryutov. "Which version of the drift-wave instability theory should be applied to MTF devices?" In: MTF R&D Roadmap White Paper, LA-UR-99-3627, July 1999.
6. D.D. Ryutov, M.S. Derzon and M.K. Matzen "The physics of fast Z pinches." Rev. Mod. Phys., v. 72, #1, 167 (2000)
7. D.D. Ryutov. "Stabilization of FRC by charge-uncovering effect." Invited talk at Intern. Sherwood Theory Conf., March 27-29, UCLA (UCRL-MI-137226)
8. D.D. Ryutov. "Radical restructuring of the fusion effort." Comments on Modern Phys., v.2, p. 139 (2000)
9. D.D. Ryutov, R.E. Siemon. "Magnetized Plasma Configurations for Fast Liner Implosions: a Variety of Possibilities." To appear in Comments on Plasma Phys. and Contr. Fus., February 2001
10. D.D. Ryutov. "Alpha particles play a relatively minor role in MTF systems," submitted to Fusion Technology (UCRL-JC-142550)