Los Alamos

FIELD WORK PROPOSAL
FOR DOE PROGRAMS

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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8. DOE Program Manager Dr. Steve Eckstrand	Telephone Number 301-903-3752
9. Operations Office Work Proposal	Telephone Number
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Headquarters Organization OFES	12. Operations Office ALBUQUERQUE	13. Contractor Name Los Alamos National Laboratory
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17. Work Proposal Description (Approach; anticipated benefit; 200 words or less).

Los Alamos is a team member on the National Spherical Tokamak Experiment (NSTX) at the Princeton Plasma Physics Laboratory (PPPL), in Princeton, New Jersey. We have proposed a multi-year development of a new diagnostic to measure the direction of the internal magnetic field in NSTX, beginning in mid-FY04. This diagnostic will use the observation of the direction of the ablation cloud from micron-sized dust, moving at hypervelocities (~1-10 km/sec) across the plasma to infer the local B-field direction, at up to 100 points across the plasma per high-resolution image. A dust source with sufficient remote controls (on, off, rate) is the first development item for FY05. Then the source will be mated to a dust beam injector at LANL, with initial tests of carbon or plastic dusts in FY05-FY06, using up to 120 kV electrostatic acceleration. In FY06, tests on a cold magnetized linear plasma (RSX or FMP) at LANL will be conducted, verifying the system checkout before taking it to the more demanding NSTX environment.

18. Contractor Work Proposal Manager (Signature)	Date 3/1/2004	19. Operations Office Review Official (Signature)	Date

20. Detail Attachments (See attachments)

☐ a. Facility Requirements
☐ b. Publications
☐ c. Purpose
☐ d. Background
☐ e. Approach
☐ f. Technical Progress
☐ g. Future Accomplishments
☐ h. Relationships to Other Projects
☐ i. Environmental Assessment
☐ j. Explanation of Milestones
☒ k. Other (specify)

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OBLIGATIONS AND COSTS **Pg. 2**

Contractor Name	Work Proposal Number	Program Code	Revision Number	Date Prepared
Los Alamos National Laboratory	06SCPE873	E873		02/23/04

	PRIOR YEARS	FY-2004 (BY-2)	(BY-1) FY-2005 President's	(BY-1) FY-2005 Revised	(BY) FY-2006 Guidance	(BY) FY-2006 Request	
21. Staff (in staff years)	(optional)						
a. Scientific		0.60	0.58	0.58	0.59	0.59	
b. Other Direct		0.00	0.00	0.00	0.00	0.00	
c. Total Direct		0.60	0.58	0.58	0.59	0.59	
22. Operating Expense (in thousands)							
a. Total Obligations (BA)		276	275	275	289	289	
b. Total Costs (BO)		276	275	275	289	289	
23. Equipment (in thousands)							
a. Equipment Obligations (BA)		0	0	0	0	0	
b. Equipment Costs (BO)		0	0	0	0	0	

24. Five Year Plan (in thousands) constant BY $	(BY+1) FY-2007	(BY+2) FY-2008	(BY+3) FY-2009	(BY+4) FY-2010	TOTAL TO COMPLETE
a. Total Operating Obligations	0	0	0	0	
b. Total Operating Costs	0	0	0	0	
c. Total Equipment Obligations	0	0	0	0	
d. Total Equipment Costs	0	0	0	0	

25. Milestone Schedules (Tasks) (optional)	PROPOSED SCHEDULE	AUTHORIZED SCHEDULE
See attached.		

A full grant-style proposal, which changes the direction of our NSTX collaboration, was submitted to OFES in June 2003. As of this writing (3/1/2004) we have not received official word on proceeding (or not) with this proposal. The original text is provided in this FWP. The proposed milestones assumed a budget profile of approximately $340-360k per year, and will have to be de-rated depending on the actual funds received, which are assumed to be at continuation levels from the on-going NSTX experimental collaboration.

Reporting Requirements (Description)

See attached.

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Hypervelocity Dust Injection for NSTX Internal Magnetic Field Measurement

Principal Investigator: Z. Wang
Co- Principal Investigator: G. A. Wurden

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FIELD WORK PROPOSAL FOR DOE PROGRAMS

ABSTRACT

Making an internal magnetic field measurement is one of the most difficult and challenging diagnostics in high-temperature (>100 eV) fusion-relevant plasmas, such as NSTX. Simple magnetic probes (B-dot loops) burn-up, and/or perturb the plasma. Complicated neutral beam techniques (such as Motional Stark Effect) are expensive, and difficult to implement (especially at low magnetic field). We propose to measure the direction of the internal magnetic field in NSTX plasmas through injection and visualization of multiple hypervelocity (up to 10 km/s) dusts (radius 1-20 μm). Visualization and mapping of 2-D and 3-D internal magnetic field structure should be possible through optical imaging of plumes induced by the injected dusts, which can provide a source of neutral and ions particles far from the edge of the plasma. Our recent study [Wang and Wurden, Rev. Sci. Instrum. **74**, 1887, (2003)] indicates that the proposed dust injection would be simpler to use, have excellent time-resolution, be essentially non-invasive, more resilient, and cheaper to implement than existing internal magnetic field measurement techniques (internal magnetic probes, neutral beams, or macro-pellets). Existing (ancient) LANL hardware for micron dust acceleration would allow us to achieve 125 kV electrostatic acceleration of micron-sized dust to 1-10 km/s with modest further investment. Besides spherical tokamaks like NSTX, the proposed diagnostic would be also applicable to other magnetic confinement devices, in particular innovative confinement concepts, such as the RFP, spheromak, and FRC's (basically, in plasmas where the internal magnetic field is substantially modified by the plasma current). By the end of the three-year project, having prototyped this new diagnostic concept, we expect to obtain 2-D internal magnetic field pitch angle information, at multiple locations simultaneously inside the NSTX plasma.

NARRATIVE

I. Introduction

Background and significance

Internal magnetic field measurements are one of the most difficult diagnostics of high temperature laboratory plasmas. Solids cannot tolerate temperatures more than a few thousand ^{o}K before melting or structural damage takes place. Magnetic fields are the only known way to maintain a large temperature gradient between a cold material boundary and a hot plasma for a sufficiently long period of time. Due to complicated interaction between hot plasmas (including both ions and electrons) and the magnetic field, the internal magnetic field structure of a magnetic bottle (when plasma is present) usually changes from the vacuum magnetic field (when the plasma is absent). Knowledge of the internal magnetic field structure therefore is critical for generating hot plasmas and keeping them stable. Due to the hostile plasma conditions, however, existing high temperature plasma magnetic field measurements (such as neutral atomic beam-based spectroscopy, and macroscopic pellet injection) can only produce 1-D magnetic field information, and on many occasions, only point measurements are achieved. Interpretation of internal magnetic field structure based on these existing methods is prone to mistakes because of the fundamental property of magnetic fields, that the divergence $\nabla\cdot\mathbf{B} = 0$. In other words, two completely different magnetic field configurations can have the same local properties. Therefore, direct measurement of 2-D and even 3-D structure of internal magnetic fields inside hot plasmas is highly desirable and long sought after [Bohnet, 1995; Levington, 1999] in plasmas.

Based on our recent conceptual study [Wang and Wurden, *Review Sci. Instrum*. **74**, 1887, (2003)], we propose to develop a brand new hypervelocity dust injection technique (lithium and its compounds are among the most desirable candidate dusts) for *real time, two-dimensional* internal magnetic field visualization and mapping inside NSTX plasmas. To our knowledge, the proposed technology would be an entirely new type of plasma diagnostic. Our theoretical results suggest that the following design point and advantages for a lithium-based dust beam:

- **Micro-sec (μs) time resolution** determined by the short transit time of the lithium dusts and light detection (an existing DiCam Pro camera has sub-microsecond exposure time capability, we expect signal-to-noise ratios > 100 over plasma background light.);
- Using lithium-based (pure lithium, or lithium hydride for example) and other types of dusts, the characteristic line emission in **visible wavelength range** makes it straight-forward to image with visible light cameras.
- Dust size 1-30 μm makes the diagnostic **noninvasive** (*Each dust particle has* $10^{11} - 10^{15}$*atoms, which is much smaller than typical plasma inventory of* 10^{20});
- Injection of dust at a rate such that 100 or so are in the plasma at any one time, makes the diagnostic **two-dimensional** using a single fast imaging camera (we already own one of these). The diagnostic will become three-dimensional if we two fast imaging cameras at one time;
- **Electrostatic acceleration** of charged micron dust is a mature and reliable technology for micron dusts acceleration. $10^3 - 10^4$ m/sec has been achieved in the past for many kinds of dust [G. Stradling, G. Idzorek, et. al. 1990, or NASA micrometeorite studies from the 1960's].

Besides the benefit that such dust beams can be used effectively to measure internal magnetic field, other applications of the dust beam to the measurement of ion temperature profile (through the charge-exchange recombination process), plasma rotation [Fonck, 1984], electron density fluctuation [Durst, 1992], and impurity profiles [Isler, 1977; Synakowski, 1990] may also eventually be possible. These measurements will be minimally invasive to the magnetized plasma because of the low total particle, energy, and momentum content of the dust beam, relative to the plasma itself.

Neutral-based diagnostics have become key diagnostics for fusion plasmas. Neutral beam injection (NBI) and pellet injection (PI) are the best examples of "neutral" diagnostic for fusion-relevant high temperature plasmas. For neutral beam injection, mostly of hydrogen and its isotopes, electrostatically accelerated individual particles of a few hundred keV are neutralized in a gas chamber before traveling through the Telsa-magnitude magnetic field of an fusion device. Besides its use as an effective heating method, NBI is an important internal magnetic field measurement technique due to the motional stark effect. [Levinton, 1999] It is also well known that NBI causes plasma rotation and heating. Important components of a NBI include high voltage acceleration field, which is necessary due to the Child-Langmuir limit on NBI current, and gas neutralization, which allow accelerated beam ions to be neutralized for penetration into the core of a fusion plasma. The gas neutralization process reduces the beam intensity and puts extra requirement on vacuum interface with the fusion plasma. For pellet injection, mm-size macroscopic particle pellets are accelerated up to 8 km/sec by the state-of-the-art technology (but more typically 1-2 km/sec) [Mirola, 1995; Chang, 1980]. Penetration of such a pellet into the core of a plasma is one of the best known issues. Plasma electron heat flux can evaporate the pellet very quickly before it can reach the core of a plasma; it is estimated that at least a few times of the maximum speed presently achievable is necessary for effective penetration of a pellet in a fusion reactor [Parks, 1978]. In addition, each mm-size pellet brings with ~ 10^{20} particles, which is about the same order of magnitude as a typical fusion experiment particle inventory, therefore, plasma density can be strongly affected (which is a good thing if you want to do fueling). But at the same time, adverse phenomena, such as disruptions, are well known to occur for macroscopic pellet injection.

Our proposed dust injection technique has many attractive features that make it a potentially powerful diagnostic tool for fusion-relevant high-temperature plasmas. A comparison of the dust injection with neutral beams and pellet injection is shown in Fig.1. Each dust contains only up to a few times 10^{15} particles, which is much less than the total particle inventory in a fusion experiment, even if one inject hundreds of dusts into a plasma simultaneously. Disturbance to the plasma density will be highly localized for each dust. Yet each dust contain particles that can induce local neutral and ion densities much greater than 10^6 to 10^7 cm^{-3}, a typical number for neutral beam injection. Therefore dust induced photon flux could be enhanced by many orders of magnitude over a neutral beam injection. The unprecedented μs time resolution is guaranteed by the short exposure time of the imaging system and short life-time of each ionized plume from the dust within the plasma.

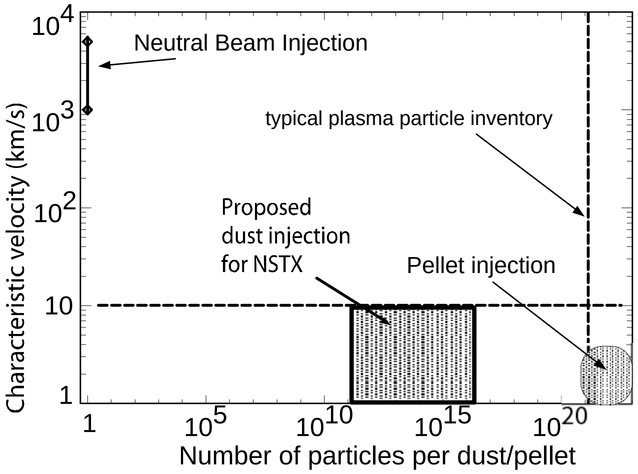

Figure 1: Comparison of the proposed dust injection with neutral beams and conventional pellets in number of particles and typical velocity.

Proposed dust injection diagnostic will be used to measure magnetic field pitch angle profile. Collecting sufficient light limits the time resolution (typically on the order of 1 ms) of conventional neutral beam based motional stark effect (MSE) diagnosis [Galambos, 1996]. Multiple shot-averaged signals were used in the past for better signal-to-noise in case of laser-induced fluorescence measurement [West, 1987]. For configurations such as NSTX (spherical tokamak), a spheromak or a field-reversed configuration when the magnetic field is much more complicated than that of tokamaks(which is predominantly toroidal), conventional MSE method is limited in its use, and also problematic due to the low absolute magnetic field strengths. In comparison to a neutral beam, each dust carries relatively large number of particles, so that localized photon signals over the conventional neutral beam case is greatly enhanced (proportional to the dust size). Sub-millisecond time-resolved measurement is possible with proposed dust injection, as opposed to neutral beams (MSE) that require longer exposure time to increase signal-to-noise (S/N) ratio, short exposure time (up to the life time of each dust, which is usually much less than 1 ms) may be best for S/N.

Hypervelocity dust penetration into the hot region of the plasma is not affected by magnetic field. The gyro-radius of a charged dust is larger by a factor of $\sqrt{N_c / N_q}$ than a comparable singly charged particle, where N_c is the number of particles per dust, and N_q is the number of charges per dust. The number $\sqrt{N_c / N_q}$ is at least 1000 for μm-size dusts. Therefore, a Tesla-magnitude magnetic field will not prevent such a dust from getting into the core of a plasma. A neutralization cell is not needed for proposed dust injection. These dusts can also be charged negatively to the electron emission limit corresponding to their size. [Draine, 1979] The negative charges will reduce the electron heating of the dust substantially; therefore enhance the lifetime of the dusts inside the plasma, and therefore deeper dust penetration into the plasma. Still, it is desirable to accelerate these dusts to as high a speed as possible. We will use the proven technology of electrostatic acceleration to minimize the risk of the technology. Electrostatic acceleration has been used successfully since 1960's for micron size dusts. Elimination of neutralization cell simplifies the vacuum interfacing of the dust injection technique. It is expected that a table-top size dust beam (limited by insulation stand-off requirements proportional to the high voltage used) can be put together to achieve the project goals described here.

In short, many **attractive features of the proposed dust injection** include:

- *2-D and potentially 3-D measurement of internal magnetic field; with the technology ultimately applicable to measurement of several crucial plasma parameters, internal magnetic field, ion temperature, impurity density, fluctuations;*
- *Microsecond time-resolution;*
- *Non-invasive, both in number of particles and in energy;*
- *Mature and proven technology for dust acceleration;*
- *Simple (no neutralization cell), compact in size;*

Work Proposed and Expected Results

The dust injection technique represents a new way to diagnose internal magnetic fields in a plasma (and therefore plasma current), the measurement of which is crucial to a fusion experiment like NSTX. The foci and goals of the proposed project are:

1. To resurrect an existing dust accelerator system and modify certain parts to accommodate lithium and other types of dust injection;
2. To accelerate dusts to hypervelocity in 1-10 km/s range using existing 125kV electrostatic method, with a delivery system consistent with the dust particle density as described;
3. To characterize and measure the dust beam properties, including dust charge, and final velocity;
4. To obtain optical images of the injected dusts into a test plasma at LANL, such as that of the P-24 Flowing Magnetized Plasmas facility, or Reconnection Scaling experiment;
5. To demonstrate internal 2-D magnetic field visualization and mapping by fielding the dust beam injection system in NSTX.

Previous works and related research efforts

There exists no technique today that can produce real time (with µs time resolution), 2-D magnetic field measurements in hostile, high temperature plasma conditions like NSTX. Various internal magnetic field diagnostics include the Zeeman effect of a neutral beam (such as with atomic lithium, as opposed to lithium dusts proposed here), use of intrinsic impurities or Li pellets, Motional Stark effect of hydrogen, deuteron or helium beams; Faraday rotation of far infrared lasers, Thomson scattering from cyclotron resonance, observation of luminous clouds of hydrogen pellet ablation, and orbital change of high-energy particles. These techniques are summarized for example by Nishino *et al*.[Nishino, 1991]. Recently, a concept based on monitoring the optical rotation of laser light reflected from a high-Verdet constant crystal, which was itself injected at 2 km/sec (called the Transient Internal Probe (TIP)) across a plasma, was also proposed by scientists at the University of Washington [Bohnet, 1995], and tested with modest success at the UW, (but later without success at SSPX at Livermore).

Figure 2: A TRACE satellite photo shows how Fe IX 17.1 nm emission illuminates solar coronal magnetic loops (courtesy Lockheed Martin Solar and Astrophysics Labs). In this case, the x-ray emission allows one to infer the local magnetic field direction. This concept is used to map and visualize internal magnetic field of laboratory plasmas by the proposed lithium or carbon dusts.

Dust interaction with the fusion plasmas, in particularly at the edge of fusion devices, is a well-known phenomena. [Winter, 1999] It is believed that so-called *UFO* phenomena are associated with dust motion in ASDEX. [Goodall, 1982] Narihara *et al.* reported enhanced laser scattering due to micron-size particles, and estimated their effect on the fusion plasma operations. [Narihara, 1997] However, there have been no detailed and systematic studies of the dust interaction with fusion plasmas. Using such dusts for fusion diagnostics was certainly not recognized in the past.

Development and understanding of a hypervelocity dust transport can also benefit the density, impurity control and boundary conditioning for a fusion reactor. As mentioned, micron dusts are known to exist in the fusion devices since the very beginning, their effects on the particle and energy confinement have drawn more and more attention. The proposed project may also provide useful data on micron dust transport within fusion plasmas. Further extension of this work may lead to better wall conditioning and particle control techniques.

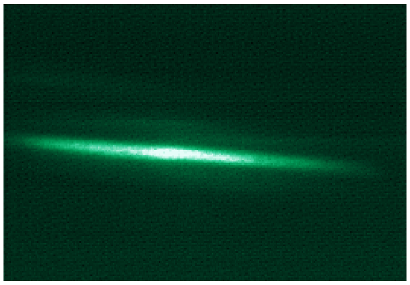

Figure 3: A gated image of the 460 nm Li+ plume from a large lithium pellet injected (away from the camera view) into the Alcator C-Mod plasma at MIT. The angle of the plume follows the local magnetic field line as the large pellet flies into the plasma.

Lithium dust can visualize and map magnetic field inside plasmas from the plume induced by the lithium atoms. Figure 2 shows the usefulness of 2D imaging to the determination of the local magnetic field structure above the

Sun by observing X-ray from solar arches. Complex structures are easily visualized that would be essentially impossible to determine using only single-point measurements. In a second example, Fig. 3 shows the time-resolved plume from a large lithium pellet injected into the Alcator C-Mod tokamak plasma, photographed from behind with our gated Xybion imaging camera. The angle of the plume with respect to the horizontal allows one to measure the local magnetic field angle in the tokamak, which is slightly different than the (large) vacuum toroidal magnetic field. However, a large pellet (~mm diameter) is a very perturbative diagnostic tool, and requires multiple fast images as the single fast pellet traverses the plasma.

Proposed dust diagnostics can also contribute to astrophysical research on the origin of the star and galaxies and laboratory plasma applications, such as plasma processing. Micron size dusts are believed to play central role in the stellar and planetary system formation. [Horedt, 1975] Micron grain contamination is a fundamental problem for plasma processing industry as micro-electronics go below μm feature sizes. Stability and charging of the micron dusts under hot plasma conditions are common issues for both the proposed project and these other research efforts.

II. Preliminary Studies

1. Dust velocity requirements for NSTX plasmas

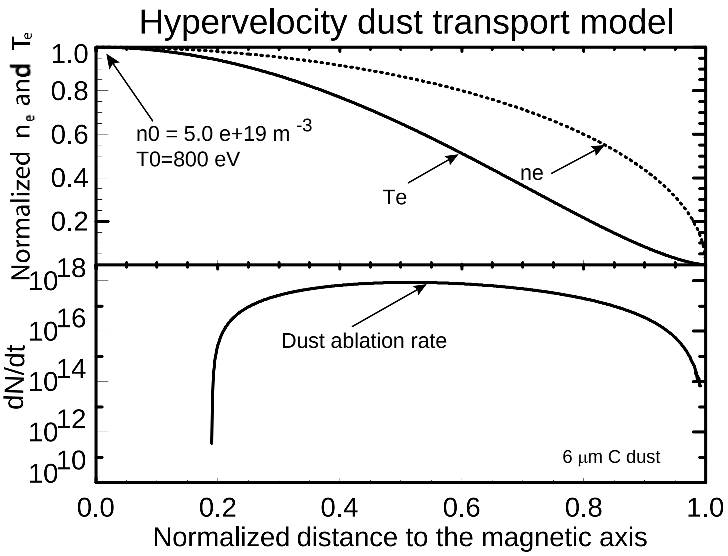

Figure 4: Carbon dust ablation rate (number of carbon atoms per second) for a 6 μm C dust injected at 2 km/sec. The peak NSTX plasma temperature is at 800 eV, peak density is at 5.0 × 10^{19} m^{-3}.

Many details relevant to the diagnostic is described in a recent paper [Wang and Wurden, *Review Sci. Instrum.* **74**, 1887, (2003)] In order to measure magnetic field deep inside the plasma (far away from the cold boundary, where one can use conventional probes), dusts need to be able to penetrate into the hot plasma before being evaporated and ionized. Therefore, the faster a dust moves, the deeper it can get into a plasma. We calculate dust penetration into the NSTX spherical tokamak (at Princeton Plasma Physics Laboratory) for both C and LiD dust (Li dust is believed to be difficult to produce to the best of our knowledge). For simplicity, a cooling cloud effect reduces the electron flux to about 30% of the value of a bare dust. New physics may exist with dust because of their small size, the details are given in our paper and will not be discussed here further. In both Fig. 4 and Fig. 5. The electron temperature distribution is assumed to be $T_e = T_{e0}\,[1-(r/a)^2]^{1.5}$, and $n_e = n_{e0}\,[1-(r/a)^2]^{0.5}$, with different peak values. The modeling confirms the penetration of different dusts inside the plasma for the injection velocities we are targeting at. We conclude that it is possible to achieve deep dust penetration into NSTX plasmas (100-1000 eV temperature, 10^{19} to 10^{20} m^{-3} peak density) with dust velocity in the range of 1-10 km/s and dust radius ranging from 1-20 μm.

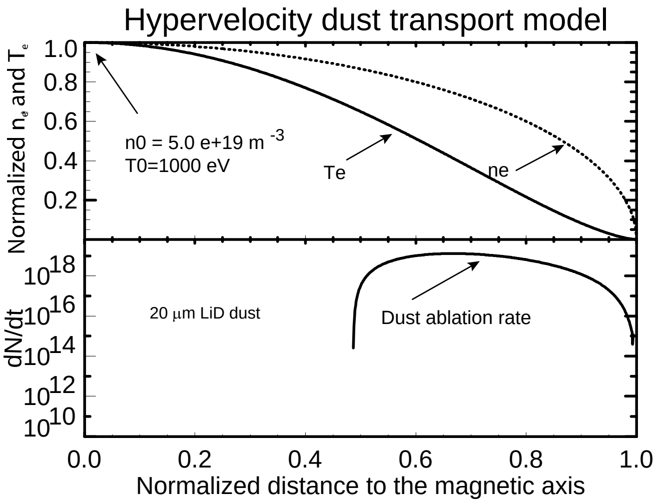

Figure 5: For a 20 μm LiD dust injected at 1.5 km/sec, dust particle ablation rate as a function of distance to the magnetic axis in NSTX. The peak plasma temperature is at 1 keV, peak density is at 5.0 × 10^{19} m^{-3}.

2. Photon emission and detection of injected hypervelocity dust

As described in a previous section, by fast imaging of the plume induced by the neutrals and ions of the dust particles, one can obtain the magnetic field line orientation inside the plasma. The photon signal per unit volume for each dust is much larger than a conventional neutral beam because the local dust plume density is close to the solid density (like a conventional pellet cloud). Another unique feature of the dust-induced plume is that it only lasts for a few times the ionization time of neutrals, ~ a few μs or less.

Longer exposure of a detector will not help signal-to-noise (S/N) since the total number of particle for each dust is fixed. The size of the dust plume is estimated to be a few mm to cm in size (perpendicular dimension), depending on the dust velocity. The aspect ratio of the plume along the magnetic field is about 5 to 10 times greater than the perpendicular direction. One gets the best S/N by exposing the imaging detector for as long as the dust cloud lasts. We own a DiCam Pro camera (1280x1024 resolution, 12-bit dynamic range) to obtain exposure times of 1 μs and two frames per plasma shot. This camera will be used in the later stage of the project on NSTX.

Several neutral and lines can be used for visualization of the magnetic field. These lines include Li I 670. 8 nm, C I 477.2 nm, Li II 460 nm, Li II 548.5 nm, and CIII 464.8 nm. Atomic lines can be used because the collisions between the plasma ions and neutrals will preferentially align the neutrals along the local magnetic field lines. We have estimated the total number of photons expected for lithium dusts. One example is shown in Fig. 6, where the dust characteristic and plasma condition are assumed to the same as described for Fig. 4. The number of photons available is about 10^{14} photons for Li I per dust/per μs of detection time, and the total collection efficiency is assumed to be 10^{-7} [Marmar:1996]. The noise level due to Bremsstralung is orders of magnitude less than this [Karzas:1961].

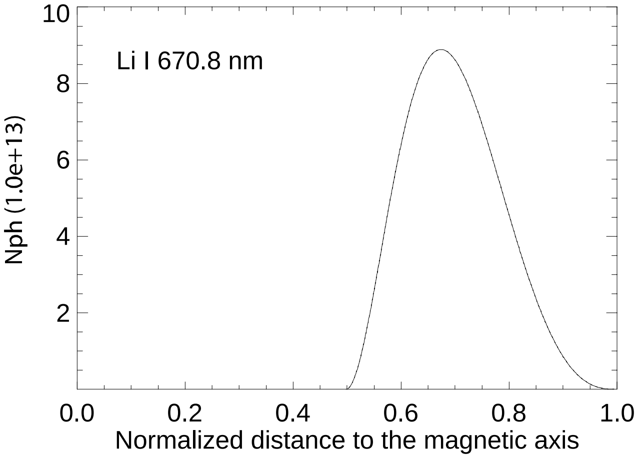

Figure 6: Li I 670. 8 nm photons emitted by a 20 μm LiD dust (1.5 km/s injection velocity) as a function of the distance to the magnetic axis of NSTX 1 keV, 5.0 x 10^{14} cm^{-3} plasma.

In an advanced version of dust type, carbon or lithium compounds may be doped by other impurities; If this is successful, the possible number of spectral lines for diagnostic application are huge. Ionic lines are preferred over the atomic lines (in particular for carbon) to reduce the contaminating signals from the edge. Zeeman splitting ($\Delta\lambda_z$) is proportional to magnetic field strength (B) and wavelength (λ_0) to the second power, $\Delta\lambda_z$ *(Å)* = $4.7 \times 10^{-13}\ g\ \lambda_0^2\ B$, where B is in gauss, g is the Lande g-factor and λ in *Å*. [Zirin:1987] For a lithium line of 5485 *Å*, Zeeman splitting is 2.1×10^{-5} B (*Å*), for 1 tesla field, the Zeeman splitting can be resolved by one-meter grating spectrometer with resolution greater than 0.2 *Å*. For a low field, say 2 kG or so, it would be difficult to use grating spectrometer. However, Fabry-Perot interferometer may be used instead for better resolution. [Wroblewski,1988]. Motional stark effect may also again be applicable for 2 kG low field because of the large number of photons associated with the proposed dust injection. [Levinton:1999].

3. Electrostatic acceleration of dusts to hypervelocity

Conventional acceleration schemes include electrostatic for neutral beam injection and pneumatic method for pellet injection. The pneumatic method won't be able to accelerate the proposed dusts to up to 10^4 m/sec, and also would be quite bulky, therefore, it is not the choice for acceleration. The electrostatic method can accelerate both single and multiple dusts and therefore offers great flexibility and freedom for diagnostic design and dust injection control. The final dust velocity depends on the charge state of the dust. As discussed in a previous section, both positively charged and negatively charged dust states are possible. Due to the high mobility of the electrons of the fusion plasmas, negatively charged state is the *natural* state for the dusts inside the plasma. The acceleration stage is outside the plasma and therefore both dust charge state can be controlled independently. Field emission sets the limit on the amount of charges that can be carried by a dust of radius R_d. The theoretical limit on the dust velocity is given by

$$U_{\max} = \sqrt{\frac{6\varepsilon_0 E_s V_0}{\rho R_d}},$$

in MKS units. In the above formulae, $\varepsilon_0 = 8.85 \times 10^{-12}$ Fm^{-1} is the permittivity of the vacuum. E_s is the maximum electric field due to the dust charging, E_s is usually in the range 10^9 to a few times 10^{10} V/m. Experimental data support this theoretical model. [Walsh, 1995] An interesting observation is that since the number of charges grows with radius as R_d^2, while the number of particles grows as R_d^3, therefore, we expect the electrostatic method would accelerate smaller dust to higher velocity because of the charge-to-mass ratio is inversely proportional to size R_d. We plotted expected dust velocity as a function of applied acceleration voltage, in particular, with the existing 125 kV system, velocity range of 1-10 km/s can be achieved depending on dust species, and size, shown in Fig. 7. This result is consistent with published experimental results.

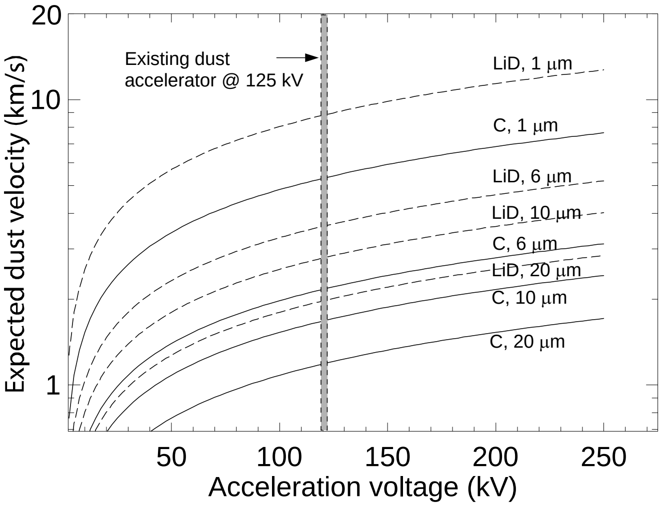

Figure 7: Electrostatic acceleration of a charged dust to hypervelocity is dependent on the dust size. Data shown are C and LiD dusts at an acceleration voltage of 200 kV.

III. Research Design and Methods

The proposed dust injection is based on a largely existing LANL hardware for dust acceleration used in the 1980s and 1990s (for micrometeorite impact studies); Existing hardware can substantially reduce the cost and the time needed to install the dust injection system in NSTX. The design of the diagnostic is shown in Fig. 8.

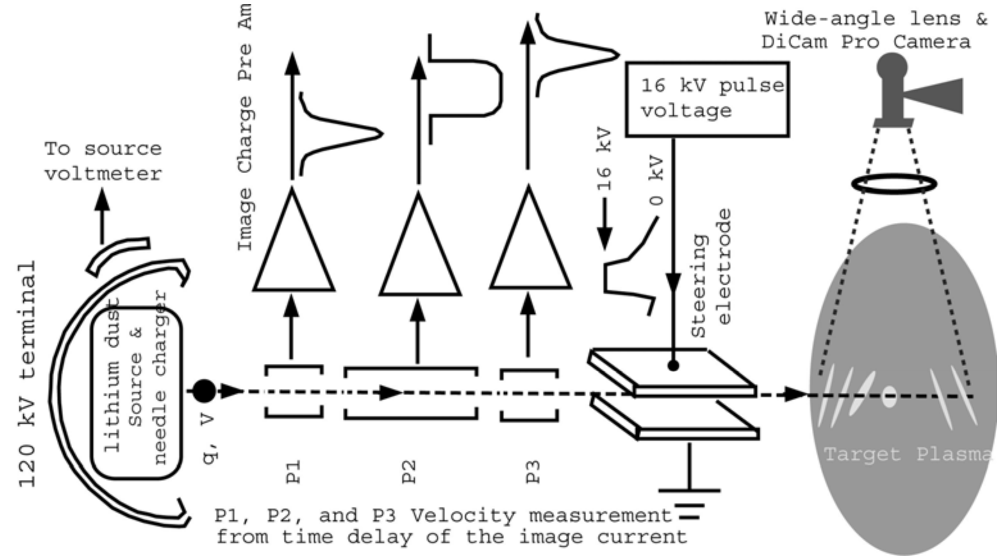

Figure 8: Schematic of the internal magnetic field measurement using proposed hypervelocity dust injection. Key components and typical dimension are shown. The acceleration channel can be oriented vertically to minimize the gravitational effect (collection optics are mounted to the side of NSTX vaccum tank).

Key components of the integrated system consists of:

1. **Dust source.** We need to modify the existing dust source to inject lithium and its compounds (it was formerly used for iron, graphite, and many other high-Z materials related to micro-meteor impact research), and demonstrate that we can do it horizontally.
2. **Electrostatic acceleration section.** The existing 120 kV accelerator system has completely functional components, (from the former LANL hypervelocity microparticle impact team) but an upgrade of the system to 200-300 kV would require fundamental change to the design (new supplies, more standoff, more careful corona shielding). But in any case, modification is required to meet new LANL high-voltage electrical safety requirements, which have changed substantially from 1980s when the system was built [G. Stradling, G. Idzorek, et. al. 1990]
3. **Dust characterization system.** This subsystem can measure the dust charge, dust velocity, and is still largely functional. We would add an aerogel catcher.
4. **Steering section.** We need to build steering electrodes for (electrostatic) dust steering, if sweeping of the beam is desired (depends on NSTX port access size).
5. **Imaging system.** A newly acquired DiCam Pro camera (1280x1024 pixels, with gated intensifier) has the resolution, sensitivity, and dynamic range required. Existing (LANL-installed) NSTX optical systems could provide initial (low-resolution) data.
6. **Vacuum system.** A separate (from the plasma) vacuum system may be required for the accelerator, to facilitate dust loading.

The **point design** of the diagnostic is: 20 micron (radius) lithium dust, 1.0 x10^{15} lithium atoms per dust particle, dust velocity = 1 km/s; peak photon emissivity = 1x 10^{21} s^{-1} cm^{-3} for 1.0 k eV, 10^{20} m^{-3} plasma (core parameter) with kG magnetic field.

To achieve the goal of measuring the direction of the internal magnetic field in NSTX, the research project will last three years. In FY04, the efforts will concentrate on resurrection of the dust source, identification and selection of appropriate dusts and initial set up of the electrostatic accelerator and remote control for the high voltage. This phase of work will take place in LANL, with 1 or 2 trips to Princeton to discuss the constraints on vacuum port and other NSTX specific design issues.

1. Dust Sources Development and Characterization

FY04 Objectives:

- Overall, to resurrect, design, and assemble the dust accelerator
- To develop reliable micron dust sources that are compatible with the chemical properties of lithium or its compounds; to select other possible kind of dust; (8 month)
- To develop methods that measure the dust size, number of particles per dust, and charging properties before acceleration; (5 month, overlap with other activities)
- To design and build high voltage remote control system; (2 Month, overlap with other activities)

FY04 Approach:

- ➢ Whenever we can, we will purchase dusts from industrial sources. Otherwise, we will explore methods (such as sputtering) to generate 1-30 μm size dusts of carbon, lithium or their chemical compounds in the laboratory when they can not purchased;
- ➢ To build necessary vacuum systems, data acquisition, and other infrastructures for the dust source and acceleration channel;

- To build dust source;
- To use electron beams and sharp needles to charge the dusts;
- To use microscope, filters, Faraday cup to characterize dust size, mass, and electric charges.

Micron carbon and its compounds are readily available for up to $500/g. Pure lithium micron-sized dust is not commerically available. However, other lithium compounds, such as Lithium Deutride (LiD), are more stable, and they can be purchased with modest price. To begin with, we could in any case, use any conveniently available dust material (carbon, plastic, glass).

Once the micron dusts are created and characterized, they can be dropped in a number of ways [Sheehan,1990; Walsh,1994] for acceleration. The characteristics of two dropper or disperser are list in the following table.

I. Comparison of two dust droppers for the proposed project

	Sheehan's disperser	Walsh's dropper
dust size (μm)	$0.5 \leq R_c \leq 200$	$3 \leq R_c \leq 150$
dust drop rate	$\leq 10^7$ cm^{-2} s^{-1}	≥ 1 s^{-1}
Size selection	Yes	Yes

2. Dust acceleration and characterization

Most of the work will be performed at LANL. The objectives for FY05 are

- Characterize dust acceleration using the electrostatic accelerator;
- Measurement of the final dust velocity and momentum (mass);
- Inject the dust to check cloud sizes in a local LANL plasma

FY05 Approach:

- To integrate the dust source with the electrostatic accelerator; (3 month)
- To control the acceleration high voltage remotely; (2 Month)
- To use time-of-flight (TOF) method to measure dust velocity using fast and ultra-low current amplifier; (3 Month)
- To use microbalance, aerogel detector, or Faraday cup to cross-calibrate the TOF measure the dust mass and momentum; (2 month)
- To steer hypervelocity dusts using bias kicker plates; (2 Month)
- To collaborate with Princeton team on vacuum port design and construction for the dust injector. (2 weeks)

Characterization of dust charging uses Faraday cup and sensitive pA-nA current amplifiers. A fast moving charged dust can induce image current in conducting walls, by using a few of the amplifier along the dust path, the rise time of the current will provide accurate information about the velocity of the dust while the magnitude of the current provides charge information about the dust; One can directly deposit dust on a conducting wall of the Faraday cup, which will be used as a cross calibration method. For 1-10 km/s dusts, secondary electron emission due to the dust collision with Faraday cup wall is not important.

Number of atoms and the dust mass can be derived through the dust charge measurement. The maximum number of charge state is reached through, say, e-beam charging. The maximal charge on a dust is related to the dust size as mentioned previously, $Q_{max} = 4\pi \times 10^9 \varepsilon_0 R_d^2$. Therefore, once Q_{max} is known, the dust radius R_d can be obtained. The dust mass and the number of atoms in each dust can be found using the density information for the dust, which is 1.8×10^{29} m^{-3} for carbon and 4.6×10^{28} m^{-3} for lithium deuteride. The distortion of the dust from an ideal sphere is unimportant using this charging method, because R_d appears to be the *effective* radius instead of actual radius.

3. Internal magnetic field measurement in NSTX

In the FY06, the last year covered by this research proposal, assuming success for the previous efforts, we will field the prototype dust injector at NSTX for internal magnetic field measurement. The objectives are

- To study dust penetration into the NSTX plasma as a function of its velocity and size;
- To study photon emission characteristics, measure photon flux along the dust trajectory; obtain the S/N ratio for the photon emission;
- To obtain 2-D internal magnetic field information using DiCAM Pro camera; data analysis and signal optimization;

FY06 Approach

- To ship and field the dust injector to a NSTX; (1-2 months)
- To write data analysis software and algorithm to retrieve data; (2 months)
- To use existing optics in the fusion device to detect photon emission along the trajectory of the dust propagation; in particular, to measure the size and shape of the micropellet clouds (6 months)
- To study dust penetration and magnetic field measurement; (6 months)

IV. Summary

Our objective is to develop innovative dust injector for internal magnetic field measurement in NSTX. In contrast to conventional pellet injection or neutral beam injection techniques that have been widely used in the past, micron-size dust cause negligible perturbation to plasma density, momentum and energy. The proposed diagnostic, which delivers high speed neutrals deep into the plasma, may also potentially allow ion temperature profile, plasma rotation and impurity profile measurements, in the absence of a diagnostic neutral beam.

Preliminary investigation using conventional pellet ablation model indicates appropriate dust penetration and sufficient photons for magnetic field (direction) measurements. New physical processes, such as electrostatic charging and shielding of electron heat flux, may be important for micron dusts because their sizes are less than the plasma Debye length. When these effects are included, theoretical results show the needed velocity for dust penetration might be reduced by up to 20 times, which potentially allows us measure NSTX internal magnetic field anywhere across the plasma volume. On the other hand, we rely on the elongation of the pellet cloud along the magnetic field line, and so our need to resolve the actual size of the cloud in the NSTX plasma will be an important experimental point (and perhaps limitation).

Electrostatic methods to accelerate dust up to 10^4 m/sec are well documented. Use of this technology reduces the risk of the proposed new diagnostic. Diagnostic design is based on largely existing LANL hardware, which substantially reduces costs. Dr. Wurden (in particular) has a long record with collaborations, diagnostics, and pellet injection into plasmas.

We plan the following deliverables:

1. To resurrect an existing dust accelerator system and modify certain parts to accommodate lithium and other types of dust injection;
2. To accelerate dusts to hypervelocity in 1-10 km/s range using existing electrostatic method, with a delivery system consistent with the dust particle density as described;
3. To characterize and measure the dust beam properties, including dust charge, and final velocity;
4. To obtain optical images of the injected dusts into a plasma, such as that of the P-24 Flowing Magnetized Plasmas facility, or Reconnection Scaling experiment, and also in NSTX; and
5. To demonstrate internal 2-D magnetic field visualization and mapping by the dust injection in NSTX.

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BUDGET AND BUDGET EXPLANATION

Our budget in the proposal, assumed the following profile, as indicated in the table below, which summarizes main elements of the request.

Category	FTE	FY2004 $k	FY2005 $k	FY2006 $k
Wang	0.35	42	44	45
Wurden	0.2	34	35	36
Technician	0.40	32	33	35
M&S		40	45	50
Total Direct cost		148	157	166
Organization overhead total		$177k	$185k	$195k
Total		$325k	$342k	$361k

Basically we are proposing a nominal ~1.0 FTE project coupled with no significant capital required. In year 3, a possible extensive off-site collaboration and travel for implement the proposed diagnostic to Princeton. By having two physicists involved, we can provide more continuity to the project, so that the entire burden doesn't rest on the shoulders of one person. The 0.40 man year of technician support is for CAD work, machining, high voltage integration, and some maintenance for the proper operation of the experiment.

The M&S funds in each year will be used for purchasing of chemical micron compounds, micron size filters, machining of vacuum components, power supply and micron source hardware. Computer hardware and software support also come from the M&S money.

However, in general FY05 President's budget guidance, and targets for FY06 have been indicated to be flat, by OFES Germantown. Therefore the above chart is subject to a slowed down rate of activity, if the budgets are truly held flat at the $275k level.

OTHER SUPPORT FOR THE INVESTIGATORS

It is anticipated that Dr. Wang will be supported ~ 0.6 FTE-time by other Los Alamos National Laboratory programs during the proposed period of this project. It is anticipated that Dr Wurden will be 0.2 FTE-time on this project and 0.5 FTE time by other MFE team projects (MTF project, UW collaboration), and 0.3 of his time as the LANL OFES Program Manager.

The other MFE team projects include Magnetized Target Fusion, Rotating Magnetic Field FRC research at U of Washington, (previously) NSTX gas puff imaging, Alcator C-mod IR imaging collaboration, all funded by DoE OFES. Within the lab, internal LDRD funding supports students on our projects, and also Dr. Wang's Flowing Magnetized Plasma (FMP) experiment.

BIOGRAPHICAL SKETCHES

ZHEHUI (Jeff) WANG

Zhehui (Jeff) Wang is the principal investigator of the plasma physics group (P-24) flowing magnetized plasmas (FMP) project, which is devoted to experimentally study the fundamental roles of magnetic field in astrophysics. He became a technical staff member of the P-24 group in 2001. He was a post-doc research associate with the same group between 1998 and 2001. He received his B. S. degree (major in Space Physics) from the University of Science and Technology of China in 1992. Then he was awarded the U. S. DoE fellowship for five years to support his graduate study at Princeton University. He obtained his Ph. D. in astrophysical science (plasma physics) from Princeton in 1998. He received the American Vacuum Society Graduate Research Award in 1998 for his Ph. D thesis work. He has had broad experience with developing plasma sources. One of his career highlights in plasma sources was the invention of a hollow cathode magnetron. Since he came to the Los Alamos National Laboratory (LANL), he has been studying plasma flow in coaxial channels as a part of Sustained Spheromak Physics experiment (SSPX) collaboration with LLNL. His collaboration with Dr. Cris W. Barnes led to new understanding of resistivity in MagnetoHydroDynamics (MHD) flow with Hall effect. Based on their findings, he and Dr. Barnes proposed a new configuration for effectively producing directed plasma flow in coaxial channels. A U.S. patent was awarded in Dec. 2002. Dr. Wang has broad interests in fundamental plasma physics research, such as plasma dynamos, plasma interaction with magnetic fields, plasma-based electric propulsion, innovative concepts for plasma confinement, and plasma technologies. One of his career goals is to develop plasma physics programs that synchronize physical understanding, experimental study under well-defined conditions, and exploration of new plasma applications.

Selected publications in peer-reviewed journals:

1. Z. Wang, V. I. Pariev, C. W. Barnes, and D. C. Barnes, "*Laminar plasma dynamos*," *Phys. Plasmas* **9**, 1491 (2002);
2. Z. Wang, "*Discrete rocket effect and its implication for micron grain acceleration*," *Appl. Phys. Lett.* ***80***, 1094 (2002);
3. Z. Wang and C. W. Barnes, "*On electrostatic acceleration of plasmas with the Hall effect using electrode shaping*," Phys. Plasmas **8**, 4218, (2001);
4. Z. Wang and C. W. Barnes, "*Exact solutions to magnetized plasma flow*," *Phys. Plasms* **8**, 957 (2001);
5. Z. Wang, G. A. Wurden, C. W. Barnes, C. J. Buchenauer, H. S. Mclean, D. N. Hill, E. B. Hooper, R. D. Wood, and S. Woodruff, "*Density and H_α diagnostics for the Sustained Spheromak Physics Experiment*," *Rev. Sci. Instrum.* **72**, 1059 (2001);
6. Z. Wang, S. A. Cohen, D. N. Ruzic and M. J. Goeckner, '*Nitrogen atom energy distributions in a hollow-cathode planar sputtering magnetron*,' Phys. Rev. E **61**, 1904 (2000);
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GLEN ANTHONY WURDEN

Glen A. Wurden, presently the Team Leader of the MFE Section in the P-24 Plasma Physics Group at Los Alamos, and acting OFES Program Manager at LANL, was born on Sept. 9, 1955 in Anchorage, Alaska. He attended public schools in western Washington, and went to the University of Washington with a National Merit Scholarship. There he earned three simultaneous B. S. degrees, in Physics, Mathematics, and Chemistry, summa cum laude (1977), graduating with the highest class honors as President's Medalist. He was awarded a National Science Foundation Graduate Fellowship, and chose Princeton University to specialize in Plasma Physics for his M.S. (1979) and Ph.D. (1982) Degrees. He is a member of Phi Beta Kappa, the APS, and a senior member of the IEEE.

He spent the summer of 1979 as a staff physicist working on x-ray and alpha particle imaging of inertial fusion targets on the Shiva laser at Lawrence Livermore Laboratory in California. Upon finishing his Ph.D. degree ("CO_2 Laser Scattering on Radio-Frequency Waves in the Advanced Concepts Torus") at Princeton, he obtained a position at Los Alamos National Laboratory in New Mexico as a J. R. Oppenheimer Postdoctoral Fellow in the CTR-8 plasma diagnostics group, and later a permanent staff position in the CTR-2 reversed field pinch experimental group. In August 1988 he moved to Germany for 16-months as a DOE Exchange scientist, working in the Max Planck Institute for Plasma Physics on the ASDEX tokamak, in Garching near Munich. After his return to Los Alamos at the end of 1989, he worked on the ZTH construction project (FIR interferometer, soft x-ray arrays, pellet injection) before taking a leave of absence to the U of Washington as an Acting Associate Professor of Nuclear Engineering in August 1990. He returned to the P-1 group (High Energy Density Physics, now P-24 Plasma Physics) at LANL in April 1992, and began working on diagnostic collaborations at TFTR (Princeton), JT-60U (Naka, Japan), Alcator C-Mod (MIT), and HBT-EP (Columbia University). He was a member of the LANL ATLAS Design Team, principally involved in diagnostic, target chamber, and magnetized target fusion (MTF) issues. His present collaborations include ones at NSTX, U of Washington, and MIT, as well as significant involvement in the new LANL FRX-L plasma injector experiment for MTF.

His research interests include a wide range of plasma diagnostic techniques[1], and their application to better understanding complex processes in hot fusion plasmas. He has particular research interests in far-infrared lasers, laser scattering, bolometry, fast pellet injection, fast X-ray and visible light imaging, neutron measurements, and concept improvement in fusion devices.

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DESCRIPTION OF FACILITIES and RESOURCES

For the research proposal we describe here, we will use a mostly existing dust accelerator system and a two-frame ms resolution DiCAM Pro camera to achieve the goals of internal magnetic field measurement. In addition, there are many capabilities at LANL, and resources which we bring to the project. Within the plasma physics group, the team has a full optics lab, an electronics shop, CAD capabilities, access to internal and external machine shops, and an extensive inventory of "data acquisition hardware". In addition, we have remote collaboration tools, such as ISDN video conferencing, computers on high-speed Internet lines, web servers (http://wsx.lanl.gov) to display archive digital data, etc.

With regards to specific high-value hardware, we have the following instruments and equipments which will be used in this proposal:

1. Existing dust accelerator. Value: > $100k;
2. DiCAM Pro Camera and imaging system in the third year on NSTX. Value: $45k
3. Complete vacuum system with pumps, gauges and vacuum vessel, Value: $50k
4. 120 kV HV supply
5. Original dust injector (which we will have to modify).