Intense Diagnostic Neutral Beam for ITER

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Executive Summary

An intense pulsed diagnostic neutral beam (IDNB) is proposed to enable active spectroscopic diagnostics on ITER. The proposed intense neutral beam source will employ a magnetically insulated diode (MID) ion source, consisting of a plasma anode and a virtual cathode. Clean, intense (~25 A/cm^2) hydrogen or deuterium neutral beams will be generated with an energy up to 125 keV/amu. A short pulse (1 μs) operation provides a better S/N ratio because the short gating time minimizes the bremsstrahlung background, compared to conventional CW diagnostic neutral beam. Though the injector has a peak neutral beam power of 500 MW, the cost and the footprint of the system is much less than CW diagnostic neutral beam systems because its average power is only 100 kW. Measurements every ~ 30 ms can be obtained by a repetitive operation up to 33 Hz. Preliminary calculations indicate that this IDNB system can maintain a necessary S/N ratio of charge-exchange recombination spectroscopy (CHERS) signals even at the center of the burning plasma. This is encouraging since core CHERS will be critical to understand the physics of burning plasmas by providing ion temperature profile, impurity and helium ash measurements, and fast alpha distribution.

According to the report of the FESAC panel on "A Burning Plasma Program Strategy to Advance Fusion Energy", it is the second highest priority for US " to develop enabling technology that supports the burning plasma research and positions the US to more effectively pursue burning plasma research" in overall objectives for US participation in the Burning Plasma Program. Furthermore, the panel recognizes that the highest priority for US contributions to the ITER project should go to such areas as "baseline diagnostics, plasma control, remote research tools, etc." Thus, we believe that our proposal of IDNB clearly address the issues raised by FESAC panel on a burning plasma program and US participation to the program.

The proposed work consists of the following: 1) complete nearly finished Continuous High Average-power Microsecond Pulser (CHAMP) facility at LANL, 2) characterize and optimize the MID system performance regarding beam extraction, gas puffing, pulse length, repetition rate, and electrode lifetime, 3) achieve a beam divergence of 1 degree or less by modifying the electrode system and using additional beam optics, 4) test beam neutralization, 5) evaluate gas handling requirements and implement pumping system for repetition rate of ~ 33 Hz. Particular emphasis will be given to beam divergence, maximum repetition rate, and system reliability. The proposed system will be the first IDNB source with a MID ion source used for magnetic fusion devices. We are requesting $1.5 M/yr for 4 years to undertake this project. Upon completion of this project, an IDNB source will be available for implementation on a major magnetic fusion facility to demonstrate its benefits and reliability.

Will be presented at U.S. ITER Forum at University of Maryland on May 8th, 2003

1. Background

A diagnostic neutral beam (DNB) plays a critical role in magnetic fusion research by providing a tool to enable measurements of many important plasma parameters all the way into the hot core of a tokamak. Charge–exchange recombination spectroscopy (CHERS) using a neutral beam is currently the primary diagnostic of ion temperature profiles, plasma rotation, and impurity density profiles [1,2]. In the case of burning plasmas, CHERS is also a primary candidate to study the problems of alpha particle dynamics and helium ash in the core. The same beam is also used to measure the magnetic field pitch angle via motional Stark effect (MSE), thus providing a current profile measurement [3]. Even at present, existing DNB's face experimental challenges due to the insufficient penetration of the neutral beam into the core region, resulting in low signal to noise (S/N) ratios in large and/or dense plasmas [4,5]. For the next generation burning magnetic fusion devices such as ITER, these challenges are much more difficult to overcome. This is because the signal decreases with the plasma density and plasma minor radius, while the noise increase from background plasma emission, particularly from the ubiquitous bremsstrahlung emission. Initial evaluations indicate that it is likely to lose CHERS capability in the core region ($r/a < 0.25$) of ITER, if the conventional CW DNB is used [6]. Indeed, the present ITER plan doesn't even bother to aim the proposed CW DNB to the core [7].

Instead, we propose a short pulse, repetitive, intense diagnostic neutral beam, based on the concept proposed by Rej et al [8], for CHERS and MSE measurements in burning plasma experiments. A short pulse beam provides a better S/N ratio for a given average power because the short gating times of the detectors minimizes the bremsstrahlung background, and reduces the dynamic range required in the detection system. In such pulsed system, the time between measurements is limited by the repetition rate of the beams. For example, an IDNB source using 1 μs long pulses at a repetition rate of 30 Hz can have S/N ratio improvement of 1000 using only ~3% of the average beam power compared to a CW DNB source. Since the cost and engineering complexity scales with the average beam power, the pulsed intense beam approach represents a pragmatic and economical path to the next generation IDNB.

An important advantage of a pulsed IDNB system is that it can provide the beam emission intensity greater than visible background bremsstrahlung even at the center of the plasma in an ITER-class plasma [9]. Figure 1 utilizes the plasma density and temperature profile for a fully ignited case from the ITER database, a flat electron temperature profile at 20 keV and a flat electron density profile around $1\text{x}10^{14}$ cm^{-3}. Note that this calculation, done in 1997, is based on the earlier design parameters of ITER. The calculation assumes the following; fixed beam energy = 125 keV/AMU, beam current of 40 A for CW DNB and 40 kA for IDNB with a 1 μs pulse duration, beam area of 20 cm x 20 cm at the focus, and off-midplane injection. It is noted that the beam emission intensity is based on He II 4-3 emission at 486 nm.

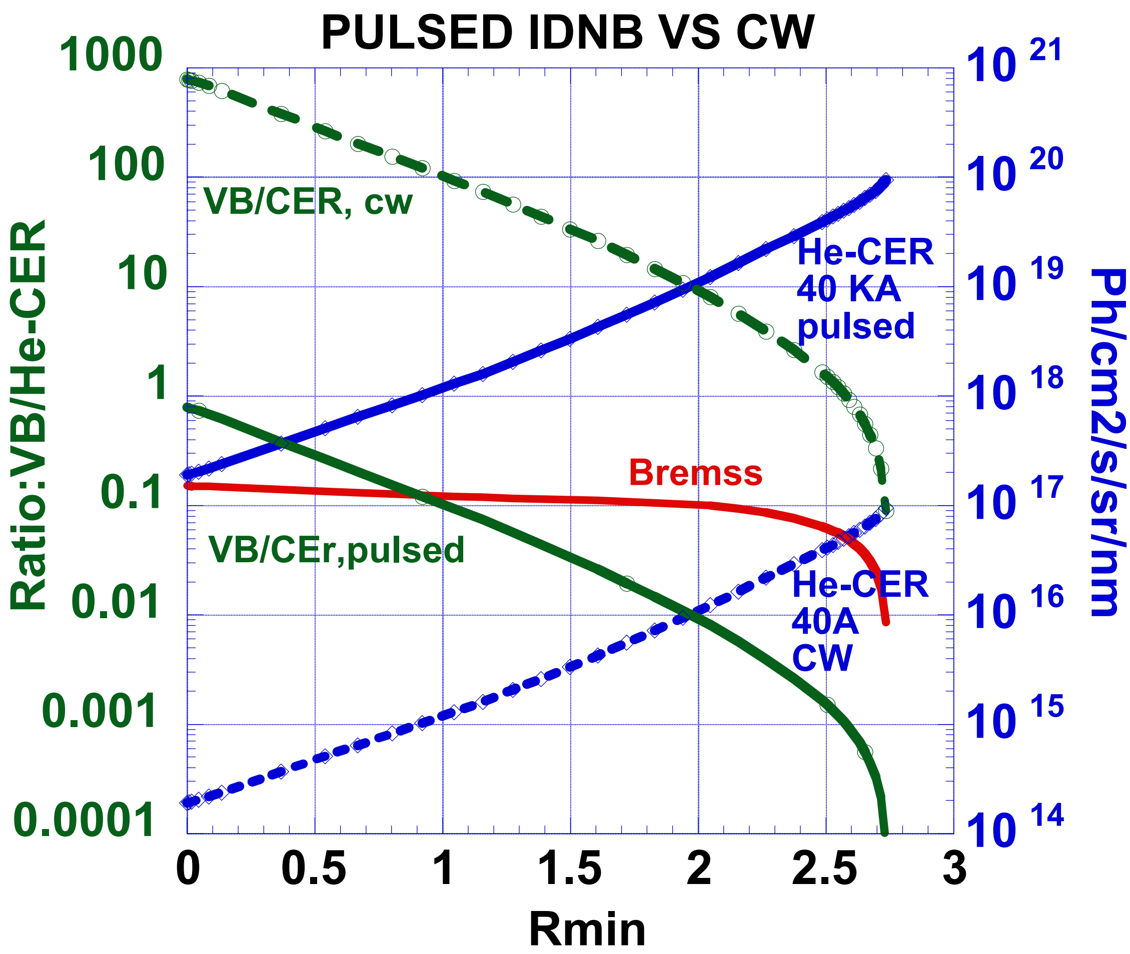

Figure 1 Comparison of S/N ratio of CHERS measurements between pulsed IDNB and CW DNB in ITER for a 125kV/amu deuterium beam. Courtesy of Thomas et al [9].

2. Research Plan

An IDNB source based on MID must address the following five key areas before being deployed at magnetic fusion devices such as ITER: 1) beam intensity and energy, 2) pulse duration and repetition rate, 3) beam divergence, 4) beam neutralization, and 5) component lifetime and reliability. The following research plan is proposed to address these issues.

1. Completion of CHAMP facility: 6 Months (10/2004-3/2005)

Originally designed as an intense ion beam source for material processing applications, the nearly completed Continuous High Average-power Microsecond Pulser (CHAMP) facility provides an ideal starting point for the proposed IDNB development [10,11]. Most of hardware for CHAMP is already in place (*see appendix on existing facilities*). This will expedite the R & D efforts to characterize and optimize the magnetically insulated diode (MID) system performance. With an exception of beam focusing, the CHAMP design parameters are very similar to the proposed IDNB system. In Table 1, we compare the design parameters of the CHAMP and the proposed IDNB system with the existing DNB system in DIII-D [12]. It is noted that the design parameters of CHAMP are chosen within the beam parameters that have been achieved in various ion sources (though not simultaneously) [13-15]. Therefore, successful operation of CHAMP achieving its design parameters represents important step in this proposal. Several key issues such as beam extraction, gas puffing, pulse length, repetition rate, and electrode lifetime, will be investigated from the early phase, providing ample time to address these issues.

Parameter	Proposed IDNB	Demonstrated*	CHAMP Design	D III-D NB
Beam Energy	100-125 kV/amu	80-300 kV	200-250 kV	30 -93 kV
Spot size (HWHM)	5 cm	10 cm	5 cm	8 cm (X), 15 cm (Y)
Neutral beam current density	25 A/cm^2	> 100 A/cm^2 (ion beam)	> 100 A/cm^2 (ion beam)	~ 200 mA/cm^2
Divergence	~ 1 ˚	~0.8 ˚	Large (spot focus)	0.6 ˚ (X), 1.2 ˚ (Y)
Pulse duration	1 μs	1.5 μs	1-2 μs	2 s
Repetition rate	33 Hz (30 ms resolution)	0.03 - 90 Hz	1- 30 Hz	CW (gating time by signal intensity)

Note: *Demonstrated beam parameters are selected from different magnetically insulated ion beam sources, but not yet obtained in a single device simultaneously (Ion current density from Ref. 13, Beam divergence from Ref. 14, and Repetition rate from Ref. 15).

Table 1. Comparison of operating parameters among the proposed IDNB, demonstrated operation of previous MID sources, CHAMP design, and D III-D NB system.

2. Operation of CHAMP and Characterization of MID: 18 Months (4/2005 – 9/2006)

As shown in Figure 2, CHAMP employs a magnetically insulated diode (MID) to provide an intense ion beam [10,11]. The intense ion beam is produced by the following sequence in CHAMP. First, a slow current pulse with a 500 μs rise time is applied to the insulating coils. This produces magnetic fields of about 1.5 kG, parallel to the fast induction coil surface and the cathode surface. This is followed by a fast rising pulse (rise time ~ 100 μs) to a puff valve allowing the gas flow radially through the nozzle over the surface of the induction coils. The puff gas is then inductively ionized by applying a fast current pulse to the four parallel, two-turn induction coils. The fast pulse of 1 μs, 30 kV produces a time varying current of several thousand amperes in the induction coil, resulting in a large azimuthal electric field (~ 200 V/cm). The azimuthal electric fields breakdown the puff gas and induces azimuthal current in the plasma. The resulting j_θ x B_r force pushes the plasma toward the A-K gap entrance, thus separating the charged particles from neutral gas. Due to the quasi-static radial magnetic field produced by the insulating coils, the plasma will be stagnated outside the anode housing aperture. Finally, a positive accelerating voltage will be applied to the anode assembly, propelling the ions with up to 250 kV of energy toward the grounded cathode. Electrons, however, will be trapped in the A-K gap along the insulating magnetic field lines due to their smaller gyro-radius. This allows ion beam extraction beyond the Child-Langmuir space charge limit.

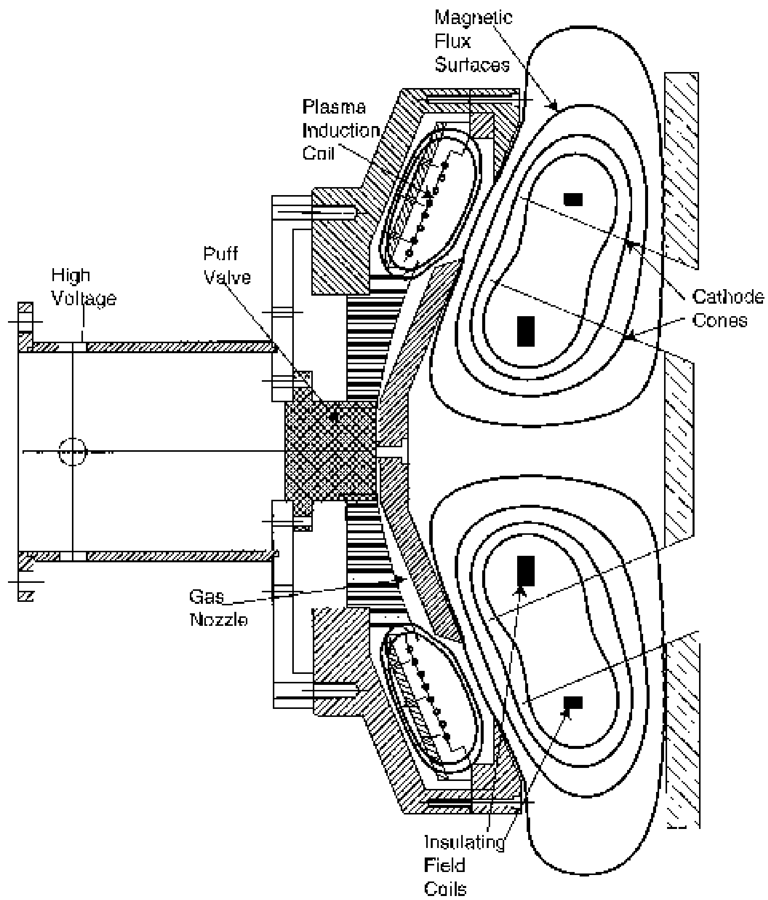

Figure 2 Schematic of CHAMP ion source.

Operation of CHAMP will allow us to test the following three key operational issues of MID: a) efficient ionization by fast induction coils and ion extraction from anode plasmas, b) optimal operation of slow insulating coils and ion beam acceleration in the A-K gap, and 3) heat flux to the electrode structures and electrode lifetime. Efficient ionization is important for minimizing charge exchange collisions in the A-K gap and increasing the repetition rate of the ion source. Subsequent extraction of ions into the A-K gap is important for providing intense ion beams. In addition, the anode plasma dynamics during the ion extraction will also impact the resulting beam profile. Slow insulating coils provide quasi-static magnetic fields that confine the electrons in the A-K gap while accelerating ions. The required magnetic field to confine the electrons in a gap of spacing d with an applied voltage of V_0 is called the critical field. In cgs unit, it is given by

$$\int (Bdx)^* = (2eV_0 / r_e)^{1/2} (1 + eV_0 / 2m_e c^2)^{1/2}$$

where r_e is the classical electron radius [16]. The expression includes a relativistic correction. In 1D MID, the critical magnetic field, B* is ~ 1.3 kG for a 1.5 cm gap with an applied voltage of 250 kV. Early studies of the ion dynamics in the A-K gap of 1-D MID have shown that the maximum enhancement of ion current in the A-K gap over the Child-Langmuir (CL) limit occurs when the insulating magnetic field strength is equal to the critical field [17-19]. However, if the insulating field is comparable to the critical field, the electron loss also increases in the A-K gap, causing excessive heat load to the electrode structures. This will be a critical issue for the proposed IDNB source operation. An ion current enhancement of about 75 is needed to draw a deuterium ion beam of ~ 150 A/cm^2 for a gap spacing of 1.5 cm at 250 kV, considering the neutralization efficiency, *e.g.* ~ 15% neutralization at 125 keV/amu. Some loss of electrons in the A-K gap is inevitable and the subsequent heat load to the electrode structures can limit the repetition rate of the ion source and result in eventual electrode failure due to erosion.

Various diagnostics such as electrostatic and magnetic probes, microwave interferometer, and time-resolved spectroscopy will be used to monitor the anode plasma dynamics and beam acceleration in the A-K gap. Infrared imaging of the electrode component will measure the heat flux to the electrode structures. This will be followed by evaluation of component lifetime and reliability. Though earlier works on the MID using MAP typically lasted about 1,000 shots before a repair [13,115], recent progress in commercializing the intense ion beam source for surface treatment has resulted in much longer component lifetime. For example, Quantum Manufacturing Technologies (QMT), Inc. (now out of business) had commercialized an intense ion beam source (150 ns pulse of 400 kV ion beam) with a lifetime in excess of several tens of thousand pulses [20,21]. The result is promising for MID to achieve a reasonable lifetime of ~ 10,000 pulses, which will be necessary for IDNB source.

3. Modeling Efforts: 36 months (10/2004 – 9/2007)

In conjunction with experimental efforts, three key areas of IDNB development will be studied using numerical modeling in collaboration with Plasma Theory Group (T-15) in LANL and Mission Research Corporation (MRC) in Albuquerque. Those are: plasma formation and dynamics in magnetically-confined anode plasma (MAP), beam extraction of MID, and beam focusing optics.

For MAP simulation, we will work with MRC to simulate the gas breakdown, anode plasma dynamics and ion extraction into the A-K gap. MRC has previously carried out calculations similar to those required for this project for a MAP diode designed at Sandia National Laboratories. In addition, MRC was actively involved for many years in the intense, high-voltage ion beam program for inertial-confinement fusion at Sandia National Laboratory, which used a solid LiF (lithium fluoride) anode and a magnetically insulated AK gap to generate a lithium ion beam [22]. MRC will use the 3-D, parallelized, particle-in-cell code LSP [23]. LSP was recently ported to the Q machine, a massively parallel computer at LANL under an Institutional Computing Technical Committee (ICTC) computer account awarded to model an electron induction accelerator for radiography. MRC will apply for an ICTC account to carry out the calculations for this proposal.

With the output from MAP simulation, we will work with Plasma Theory Group (T-15) in LANL to simulate the beam acceleration in the A-K gap using CELESTE implicit particle-in-cell code [24]. As a fully kinetic PIC code, CELESTE can handle both ion and electron trajectories in a self-consistent manner. In addition, CELESTE can handle multiple time scales, e.g. electron cyclotron frequency, ion transit frequency and pulse duration using an implicit formulation. This is critical to investigate the ion flux enhancement over CL limit, beam profile and electron heat flux to the electrodes. A thorough investigation on beam instability in the A-K gap will be conducted. Finally, CELESTE implements the immersed boundary method to handle complex geometries [25]. This will be useful to use CELESTE as a tool to design system modification.

The outputs from CELESTE code will have initial beam profile out of A-K gap, both in configuration and velocity space distribution. By implementing electric quadrupole optics as boundary conditions, beam focusing will be simulated using either LSP or CELSETE code with electric quadrupole beam optics

4. Electrode modification and construction of new MID system: 12 months (1/2006 – 12/2006)

CHAMP was designed to produce a ballistically focused ion beam to maximize the beam intensity at the focal point (30 cm from the A-K gap). The plan is to perform initial experiments in CHAMP and then to design electrode modification based on the experimental results and numerical simulations of MID operations. As mentioned earlier, both CELESTE and LSP code can handle flexible geometry to provide guidelines for the system modification. The following issues will be considered and incorporated into a new MID system:

- Long focal length: to produce parallel beam with 1˚ divergence in conjunction with downstream beam optics
- Minimization of annular region: to produce a flat radial profile. New insulating slow coils will be design that can handle the heat load.
- Gas puff system: to produce gas distribution for efficient ionization and minimal residual gas loading.
- Cooling system: to mitigate the heat load to various electrode structures and erosion problems.

5. Beam divergence: 15 months (1/2007 – 3/2008)

The critical challenge in this proposal is to address the beam divergence of the IDNB. The distance ranges from a few meters (in current devices) to over ten meters (in ITER). At one degree of beam divergence, the resulting beam spread will amount to 5 cm over a 3 m path length and to 17 cm over a 10 m path length, reducing the spatial resolution of the measurements. It is out goal to achieve a beam divergence of less than 1 degree for this project, while investigating and understanding fundamental and technical limitations. This will be sufficient for an early deployment to existing devices. Furthermore, it may be possible to obtain a spatial resolution of 10 cm even with 1˚ beam divergence by improving signal processing for a high S/N ratio from IDNB.

A downstream section containing electric quadrupole lenses will be installed between the cathode output and the neutralizer cell to improve the beam divergence [26]. A goal is to obtain a beam divergence of 1 degree using the modified electrode system and the external beam optics outside the A-K gap. It is noted that the previous work using MID have achieved a beam divergence of 0.8 degree [14]. Resulting beam properties, such as longitudinal and transverse beam energy distribution, beam current, focusing and divergence, will be characterized using arrays of Faraday cups and calorimeters, and time integrated X-ray emission from the aluminum target. These measurements will be compared with the modeling results and optimization of the MID system will be conducted.

One interesting possibility is to shape the beam in a thin sheet of 20 cm wide and 1 - 2 cm high. It is then possible to illuminate the poloidal cross section of the plasma using the vertical port and to measure the beam induced emission from the side port using 2D array detector. This will allow a direct 2D imaging of various plasma parameters such as ion temperature and alpha particle density with a unprecedented spatial resolution (~ 1 mm resolution, compared to 2-3 cm resolution). It's an example of experimental flexibility for an IDNB which has beam intensity to spare and can be controlled independently from the neutral heating beam.

6. Beam neutralization: 6 months (4/2008 – 9/2008)

The last part of the project is to neutralize the intense ion beam. Previous work on neutralization of an intense ion beam showed that neutralization efficiency up to equilibrium fraction could be obtained at an equivalent neutral flow of 4.6 times the CL limit for the ion diode [27]. We will construct a neutralization chamber (~200 liter volume) and test the neutralization efficiency as a function of gas puff volume. An array of neutral detectors using secondary electron emission will be constructed to monitor the final neutral beam characteristics, such as beam intensity and spatial profile, as well as beam divergence. In addition, the pumping requirement will be studied to determine the maximum pulse repetition rate, in conjunction with the potential deployment in existing tokamaks.

3. Deliverables

At the completion of the project, we expect to deliver an intense neutral beam system that can be deployed to existing fusion devices as an IDNB source. The neutral beam source will have the following parameters: neutral beam current ~ 2 kA, beam diameter 10 cm, beam energy up to 125 keV/amu, beam divergence ~ 1 degree, rep-rate ~33 Hz, and 1 μs pulse duration. It is noted that the specific neutralization/pumping systems need to fit the requirement of existing fusion devices and will not be a part of this deliverable. Instead, we will collaborate with the hosting institution regarding design parameters for efficient neutralization and adequate pumping.

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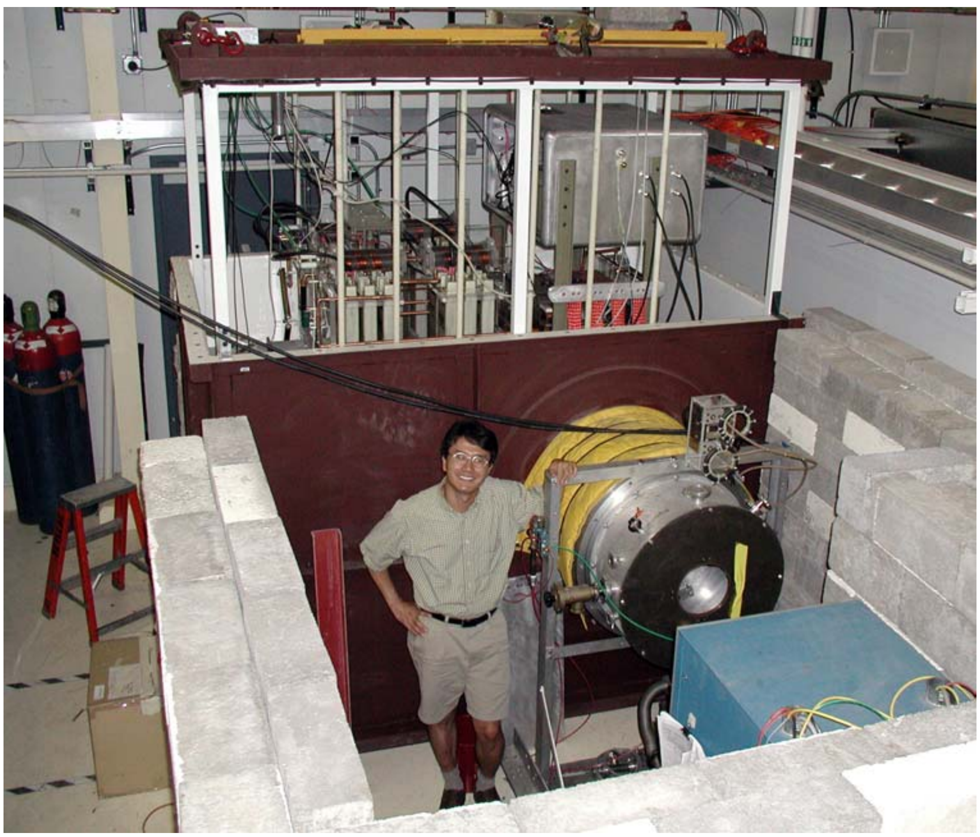
Appendix: Description of Facilities and Resources

Due to the previous LANL internal funding ($850,000 of LDRD unburdened funding of equipment and labor), most of hardware have been purchased and installed in the CHAMP facility, *see picture below*. The following list shows the existing hardware (with the actual cost before overhead).

- Diode Assembly: Fast coil assembly ($20k), Fast coil driver ($10k), Puff valve ($5k), Puff valve driver ($10k), Hot deck ($10k), Instrumentation ($10k), and Power supply ($10k)
- Slow Coil System: Slow coils ($10k), Slow coil driver ($20k), Cooling system ($5k), and Power supply ($10k).
- Vacuum System: Pumps ($50k), Vacuum hardware ($20k), and Instrumentation ($10k).
- Accelerator: Step up transformer ($15k), Capacitors: ($20k), Thyratron controllers ($30k), Hardware ($15k), Oil Tank ($10k), and Power supplies ($40k).



An additional power supply (1A@ 150 kV) is available for charging the accelerator capacitor bank up to ~ 40 Hz. A large oil diffusion pump (10,000 liter/s) to remove the residual gas in the diode assembly is currently at our disposal to support the project. In addition, a number of diagnostic tools (Fast imaging camera, visible spectrometer with CCD, Data acquisition system, etc) are available to support this proposal. A control system similar to the charging/safing setup on the new FRX-L facility at LANL will be implemented. This existing hardware will expedite the R & D schedule greatly at a much reduced cost, important for decision making on US participation with ITER R&D.