Heavy-Ion-Driven High Energy Density Laboratory Plasmas / Inertial Fusion Energy (Neutralized Drift Compression eXperiment-II) *

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LBNL, LLNL, PPPL

Presented at
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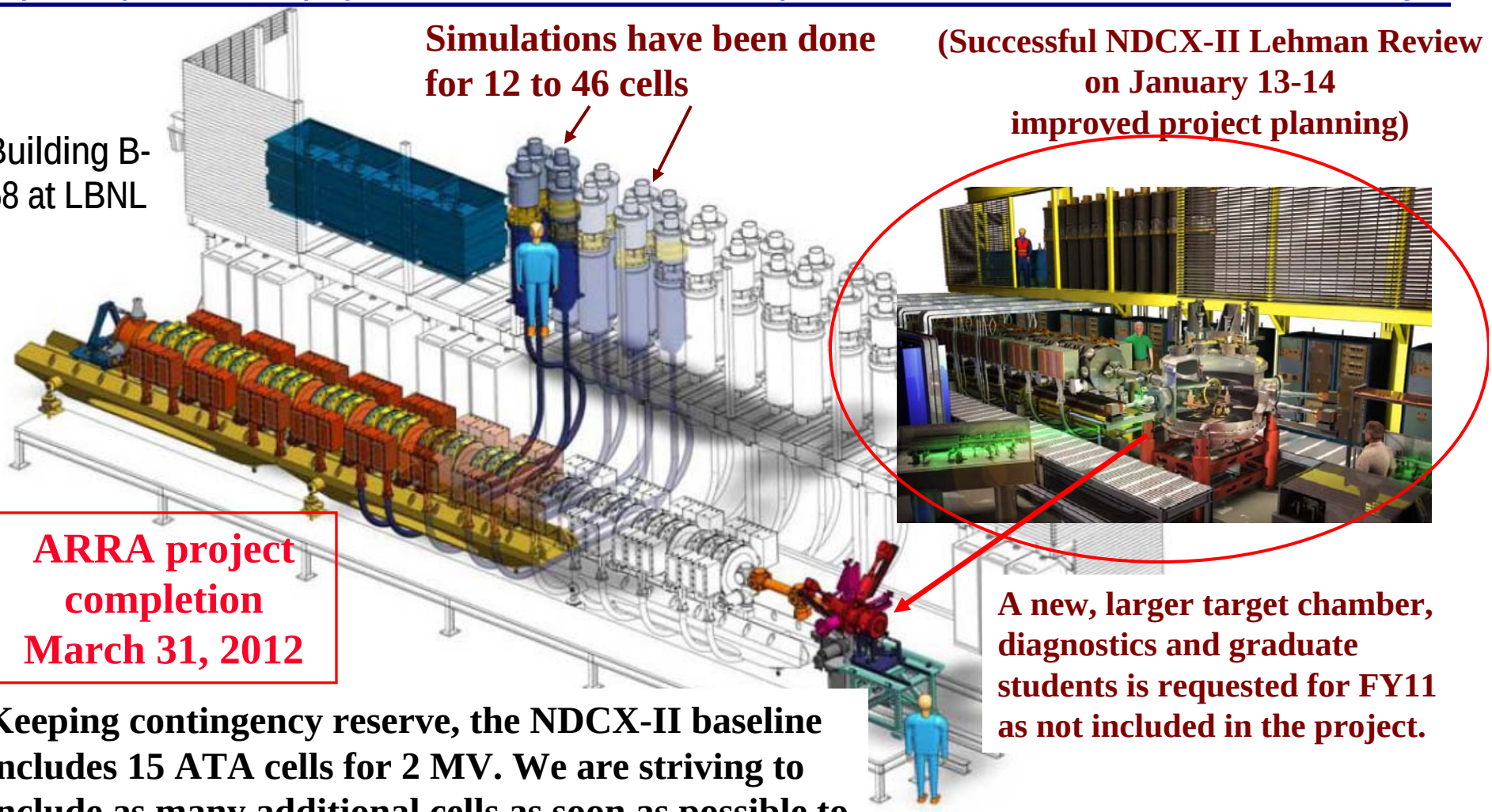
**** HIFS-VNL: A collaboration between Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, and Princeton Plasma Physics Laboratory, USA.**

DOE approved NDCX-II for $11M of stimulus funding as a major facility for both HEDLP and heavy ion fusion. Higher energy and sub-nanosecond pulses on targets will improve capability for WDM physics and enable shock experiments related to advanced HIF targets.



Keeping contingency reserve, the NDCX-II baseline includes 15 ATA cells for 2 MV. We are striving to include as many additional cells as soon as possible to maximize capability ***(we possess 50 cells for 10 MV for quick future expansion to IB-HEDPX).***

Department of Energy
Washington, DC 20585

June 30, 2009

MEMORANDUM FOR: DISTRIBUTION
(See Attached List)

FROM: for EDMUND SYNAKOWSKI
ASSOCIATE DIRECTOR
FOR FUSION ENERGY SCIENCES
OFFICE OF SCIENCE

The NDCX-II Work Authorization Statement recognizes the HIFS-VNL research priorities for both HEDLP and HIF

Specific Recovery Act Statement of Work:

$8,800,000 is provided under **AT5015031** for increased U.S. leadership in the competitive arena of High Energy Density Laboratory Plasmas (HEDLP) research, an advanced area of science that is important to the nation's economic, energy and nuclear security. The funding will also provide for an upgrade to the existing Neutralized Drift Compression Experiment (NDCX-I) at Lawrence Berkeley National Laboratory (LBNL) to increase the energy on target by a factor of 100, which will allow both the Heavy Ion Fusion (HIF) and Warm Dense Matter (WDM) research communities to explore scientific conditions that have not been available in any other device. An additional **$2,200,000** is anticipated in a subsequent AFP following the risk assessment process, bringing the total to **$11,000,000**.

7. **Future Budget Needs:**
These new experimental facilities will require continued funding for research and facility operations will be needed.

(dollars in thousands)						
Impact Description	FY2010	FY2011	FY2012	FY2013	FY2014	FY2015
NDCX-II	$0	$1,000	$7,000	$8,000	$8,000	$8,000

End Notes: + $1 million per year for users starting in FY11 (1st set of 3-year grants); + $4 million per year for operations, + $1 million per year for users (2nd set of 3-year grants), and + $1 million per year for user tech support in FY12, and +$1 million for users in FY13 (3rd set of 3-year grants).

Selected findings of the Dec.16 HIFS-VNL PAC report:
(John Sheffield-Chair, Dieter Hoffmann, George Caporaso, Scott Parker, Larry Grisham, Mike Campbell, Bill Barletta)

• "The budget of the current program does not permit operation of NDCX-II as a user facility. An annual increment of 8M$ over the present level for NDCX-II commissioning, operations and user support (as described in the NDCX-II Work Authorization Statement) would be appropriate to yield a vigorous successful program."

•"Effective use of all the facilities under the purview of HIFS-VNL should be exploited to capitalize on success of ignition experiments on NIF motivating an expansion of work on IFE. The primary instrument for conducting VNL research should be NDCX-II, defined in conjunction with potential users."

•"To maximize the scientific impact of NDCX-II, a new, larger target chamber with an expansive set of diagnostics will be essential. The chamber needs to be designed with substantial input from the external user group."

•"The PPPL 100 kV Test Stand should be used to address relevant questions for NDCX-II such as laser flash heating of a Li source to improve lifetime, and developing neutralization techniques. The 100 kV Test Stand is important for performing intense studies on large volume plasma generation."

•"The program plan presented has a healthy balance of beam physics and WDM physics. It is critical that the HIF program continue focused research on beam quality, including smaller spot size, beam momentum tilt improvements, chromatic aberrations, etc., to provide a knowledge base for future HIF driver design and construction."

Proposed HIFS-VNL research for FY11 and FY12 will address-

HEDLP scientific issues that are essential to the achievement of high gains and improved inertial fusion energy concepts should be given a high priority within the Joint HEDLP Program. *All of these high-priority issues are either not addressed or are only partially addressed by the NNSA-ICF program. Out of fourteen, six high-priority scientific issues are identified that can be addressed by the Joint Program with existing facilities (Excerpted from FESAC HEDLP Panel Report):*

2. Transport and energy coupling of intense particle beams in high energy density plasmas.

Science question: How are intense charged-particle beams transported in and how does their energy couple to HED plasmas.

Since the January 2009 FESAC report, recent work on high gain HIF targets using shock ignition is also relevant to FESAC priority # 5 :Implosion hydrodynamics for high gains:

5. Implosion hydrodynamics for high gains. *Science question:* How can HED plasmas be assembled to the densities and pressures required for maximizing the fusion-energy output?

6. Integrated target physics for inertial fusion energy. ***Science question:*** **What are the optimal target designs to achieve high gains with good stability and efficient driver coupling?**

The HIFS-VNL field work proposals for FY11 and 12 are consistent with the NDCX-II Work Authorization Statement for "Full Use" operations and research using NDCX-II

→Consistent with the five year first quarter of the 20-year HIFS-VNL program plan developed for 2006 - 2025.

→Purpose of 5-yr plan is to achieve three major objectives:

1. Explore Warm Dense Matter (WDM) physics with unique intense heavy ion beam techniques, extended to sub-nanosecond pulses in NDCX-II, and provide a user facility for the US HEDLP program and collaborators from GSI, ITEP, Japan, and China, who can significantly benefit from access to an operating heavy ion WDM target facility.
2. Provide the basis for extending and expanding the heavy-ion-driven HEDP program beyond WDM physics studies towards heavy ion inertial fusion target physics (e.g. sub-ns shocks) to be carried out when ignition is achieved in NIF.
3. Provide the scientific basis for IB-HEDPX, an advanced and higher-energy heavy ion WDM user facility for the US HEDLP program in the 2015-2025 time frame.

In addition to NDCX-I and 100 kV test stand used to develop techniques and diagnostics needed for NDCX-II, we propose incremental program funding above present levels to support three critical NDCX-II milestones necessary for NDCX-II target experiments beginning in 2012.

FY11

June 2011 "Complete conceptual engineering design of a new target chamber and physics specifications for associated diagnostics on NDXC-II"

(This allows the new target chamber to be constructed during NDCX-II commissioning while using the existing NDCX-I target chamber in FY12).

September 2011 "Develop execution plan for NDCX-II operation including commissioning, scheduling for first target experiments, and associated technical support"

(We will solicit user input during an international HEDLP user workshop for NDCX-II: - see workshop web site http://hifweb.lbl.gov/public/BeamHEDP2010/Home.html)

FY12

September 2012 "Report characterizing initial NDCX-II beams to support NDCX-II research"

(Commissioning will be completed in several-month blocks through FY13, with initial target experiments scheduled in between)

HIFS-VNL tri-lab program budgets* by year to date. Incremental budget requests** for FY11 and FY12 to prepare for full use operation of NDCX-II (WAS)

($K)	FY05	FY08	FY09	FY10	FY11 (Full-use) Increments**	FY12 (Full use) Increments**
LBNL	6000	4,700	4,700	4,625	800 operating +200 equip.***	2,400 operating +1,000 equip.***
LLNL	2,650	2,120	2,120	2,120	730 operating	1,480 operating
PPPL	1,603	990	990	990	560 operating	1,210 operating
Totals VNL (tot. FTE)	10,253 (43 FTEs)	7,810 (32 FTEs)	7,810 (27 FTEs)	7,725 (25 FTEs)	2,090 operating +200 equip.*** (34 FTEs*)	5,090 operating +2,500 equip.*** (43 FTEs*)
				Totals (K$)→	9,815 operating +200 equip.***	12,815 operating +1,000 equip.***

*Does not include NDCX-II ARRA Project funds/FTEs nor OFES HEDLP user grant funding

**Increments relative to FY10 VNL base program levels

*** Mostly procurements for new NDCX-II target chamber and HEDLP diagnostics

Impacts on HIFS-VNL research vs FY12 budget level

- **OFES has not yet informed the HIFS-VNL of any allocation of the 6.4 M increase in FY11 funds for HEDLP to support NDCX-II.**
- **The HIFS-VNL requests 2090 K operating + 200K equipment incremental over FY10 for design and procurement of a new target chamber and diagnostics, development of new compression and focusing towards sub-ns pulses, new work on shock ignition target physics, and for more graduate students.**
- **Without this increase in FY11, NDCX-II will not be ready to support operations and users as identified in the NDCX-II WAS timeline (no adequate target chamber, facility, or diagnostics for users).**
- **Assuming the requested budget for FY11, the impact of FY12 budgets = requested level FY11 -10% will put most new diagnostics and extensions of NDCX-II on hold (e.g., more acceleration cells), and require a layoff of 2-3 FTE's at LBNL now on the NDCX-II project who will be needed to support full NDCX-II operations.**
- **FY12 = FY11+2% will barely support NDCX-II users but not adequately support VNL research as identified in the NDCX-II WAS, and would be inadequate to support work on high gain target physics related to heavy ion fusion.**
- **FY12= FY11+20% as requested will support full NDCX-II operation as identified in the WAS and will support more VNL research, including high gain target physics related to heavy ion fusion.**

NDCX-II commissioning starts April 1, 2012. HEDLP experiments start early FY2013.

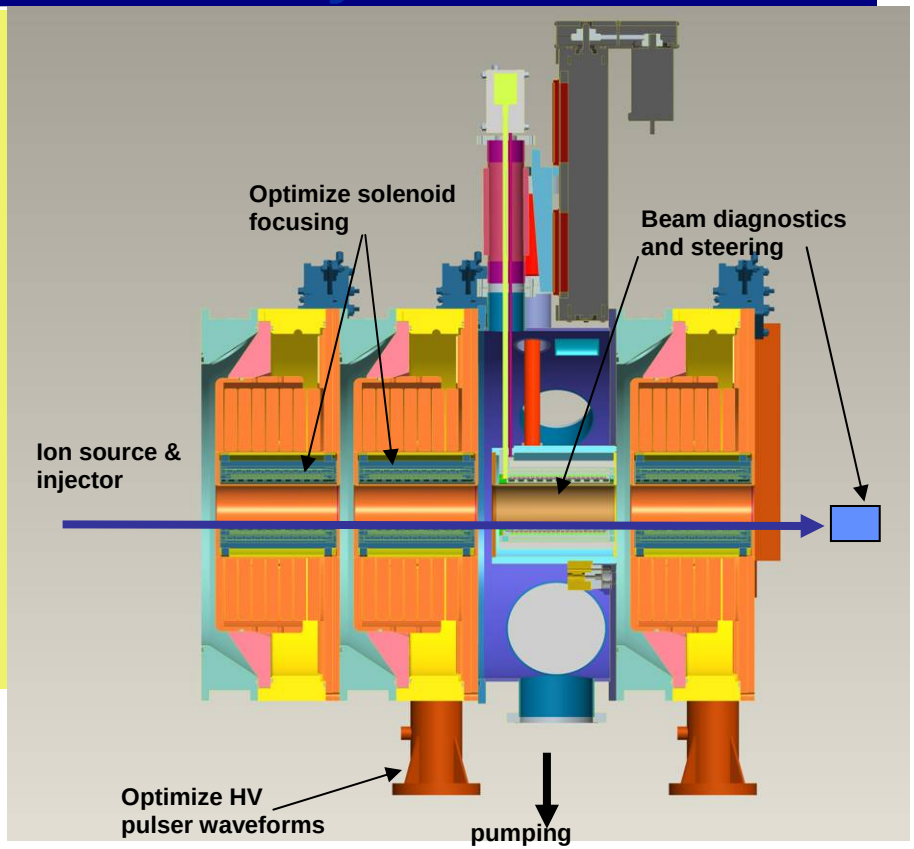
NDCX-II commissioning will start mid-FY12:

- Optimize solenoid focusing according to beam current.
- Optimize HV pulse waveforms for bunch compression.
- Beam halo control (secondary electrons) and steering corrections to improve quality of the beam bunch entering a target chamber.
- Optimize final focusing and beam neutralization to produce a beam spot on the target foil.
- Beam diagnostics to measure voltage, current, pulse length, position, and intensity profile.

Milestone in Sep 2012 -- Characterization of initial NDCX-II beams to support NDCX-II research

HEDLP experiments will start in early FY13:

- Makes use of the initial NDCX-II beams that are already much more powerful than that in NDCX-I
- Further optimization to increase beam current and voltage to maximize beam power on target
- Further adjustment in final focusing and beam neutralization to minimize beam spot size
- Check out HEDLP target diagnostics



VNL base program funding must ramp up to take over facility operation by end of FY12.

- NDCX-II project budget ($11 M) covers minimal beam diagnostics; no commissioning.
  - Requires transfer of final focus solenoid, target chamber, & target diagnostics, shutting down NDCX-I and its ongoing support for NDCX-II.

- With requested funds, users can greatly improve experimental utilization and effectiveness

- Increased DOE support in FY11-15 (in WAS)
  - Commissioning & operation
    - Facility-more cells.
    - Enhanced focusing and diagnostics
    - Targets & target chamber
    - Computation & theory support
  - Technician support for all target-area users
  - OFES grants for HEDLP users.

- Program funds must ramp up before FY12
  - Operate NDCX-I/II
  - Hire new staff (including post-docs/students)

FY	$M Comm. & ops.	$M Tech supt.	$M User supt.	Total
11	0	0	1	1
12	4	1	2	7
13	4	1	3	8
14	4	1	3	8
15	4	1	3	8

(Budget numbers from NDCX-II WAS)

The HIFS-VNL has hosted 4 previous workshops on heavy ion driven HEDP/WDM, which has generated a growing roster of very interested collaborators:

- GSI/TU Darmstadt WDM experimental groups
- Siegfried Glenzer, NIF/laser diagnostics
- Dave Eder, LLNL, NIF target holder
- Andrew Forsman, GA, laser diagnostics
- Phil Heimann, LBNL, pyrometer diagnostic of laser-heated target at ALS
- Alice Koniges, WDM modeling (ALE-AMR) to include surface tension effects
- Dick Lee, LLNL, WDM isochoric heating
- Richard More, WDM theory
- Andrew Ng, UBC, WDM shock experiments on NDCX-II
- Roberto Piriz, U Castilla-La Mancha, Spain, WDM shock modeling
- Tim Renk, Sandia, ion beam effects on materials
- Edward Ruden, AFWL, GHz/THz for target conductivity measurements
- Toru Sasaki, Nagaoka U., x-ray backlighting
- Naeem Tahir, GSI, WDM shock modeling
- Sergei Ushakov, UC Davis, high temp materials for rocket and jet engines
- Seth Veitzer, Tech-X, cone focusing
- Jonathon Wurtele, UC Berkeley, WDM simulations and theory
- Hitoki Yoneda, UEC Tokyo, optical properties of WDM
- Simon Yu, Chinese U. of Hong Kong, bubble collapse, ion coupling to shocks
- Students: Alex Zylstra (porous targets), Julian Armijo (droplet evolution), Siu-Fai Ng (bubble collapse, ion coupling to shocks), Michael Hay (ion direct drive targets)

The Heavy Ion Fusion Science Virtual National Laboratory invites interested potential NDCX-II users to a workshop on ion-beam-driven HEDP experiments, target chamber, diagnostics and modeling.

- Ion-beam driven HEDP workshop for user input for NDCX-I/II user facility, target chamber and diagnostics to take place in Pleasanton, CA, June 22-24, 2010 . For information and registration: http://hifweb.lbl.gov/public/BeamHEDP2010/Home.html

- NDCX-II (1.5-3 MeV Li^+ sub-ns beam pulse, 1-3 eV target temperature) to be available for first target experiments after beam commissioning, ~ late 2012.

- New target chamber with enhanced capability for diagnostics to be designed for installation on NDCX-II; *e.g.* high-power lasers, cryo-targets, x-ray diagnostics.

- Experiments planned to be in collaboration with other institutions and groups, e.g. GSI, LCLS, NIF, Japan, China, and others.

Selected PPPL VNL Milestones for FY11 and FY12 (see PPPL Field Work Proposal for a complete set)

FY11

- Complete initial physics study of stabilization techniques for the Rayleigh-Taylor instability in ion beam-target interactions using innovative beam delivery methods, such as wobbler rotation and/or oblique incidence (August, 2011).

- Begin experimental studies of the efficacy of magnetic insulation for electrostatic accelerators on the Princeton 100kV test-stand (August, 2011).

FY12

- Complete initial development and optimization of molecular dynamics code for studying the equation-of-state and phase transitions in warm dense matter regime (December, 2011).

- Complete initial testing, characterization and optimization of high-density-producing plasma source on NDCX-II (July, 2012).

Additional milestones for PPPL VNL with incremental funding level

- Identify numerically the class of self-consistent periodic kinetic 'equilibria' for intense beam propagation in alternating-gradient focusing systems, and extend the nonlinear perturbative particle simulation method to intense beam propagation in periodic focusing systems with self-consistent, periodic kinetic equilibria; compare with the results of Hamiltonian averaging techniques for periodic focusing systems (August, 2011).

- Develop atomic physics suite for high energy density physics experimental applications, including the calculation of charge-exchange, stripping and ionization cross-sections and equilibrium charge for intense beam propagation in gas, plasma and solid-state media (August, 2011).

- Complete assembly of advanced plasma source test stand at PPPL and begin tests of advanced plasma source configurations that can provide high density plasmas in NDCX-II (August, 2011).

- If adequate funding has been provided to re-commission the 100 kV test stand at PPPL, begin experiments to better characterize the ion temperatures of positive and negative ions extracted from ion-ion halogen plasmas as compared to positive ions extracted from conventional electron-ion plasmas, and compare electron currents extracted from electron-ion plasmas to those from ion-ion plasmas (December, 2011).

- Assuming that the ion-ion plasma experiments have been initiated, continue experiments on the 100 kV test stand at PPPL to develop an understanding of the ion-ion plasma state and its possible applications. Explore whether or not the magnetic filter field used in earlier experiments is necessary for the existence of a sustained-duration ion-ion plasma state, and how it affects beam extraction characteristics (August, 2012).

Heavy Ion Beam Research

PPPL Funding Request for FY2011 and FY2012 in VNL Task Areas

	FY 2011-2012	FY 2011	FY 2012
Task Area	**Guidance***	**Increment**	**Increment**
1	**$600K**	**$250K**	**$500K**
2 + 3	**$390K**	**$310K**	**$710K**
Total	**$990K**	**$560K****	**$1,210K****

1. Theory and modeling.
2. Plasma source development/neutralized transport experiments.
3. Warm dense matter/atomic physics.

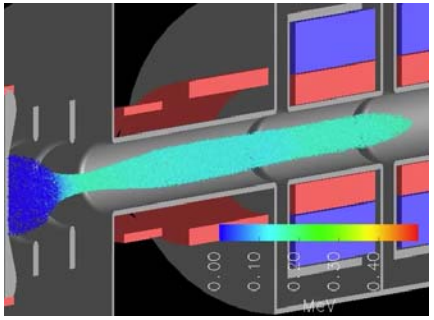
* Taken to be the same as FY2009 funding total.

** Incremental requests are relative to the guidance funding levels for FY11 and FY 12.

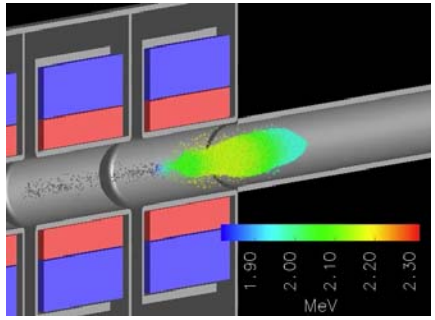
Discovery: rapid initial bunch compression enables NDCX-II

- A new, fast 1-D (longitudinal) code ASP was developed – it enabled efficient exploration of the very large parameter space
- Rapid initial bunch compression allows re-use of 70-ns pulsed power sources from the ATA accelerator
- Detailed 3-D simulations using the Warp code confirmed the physics design & set engineering requirements

During injection



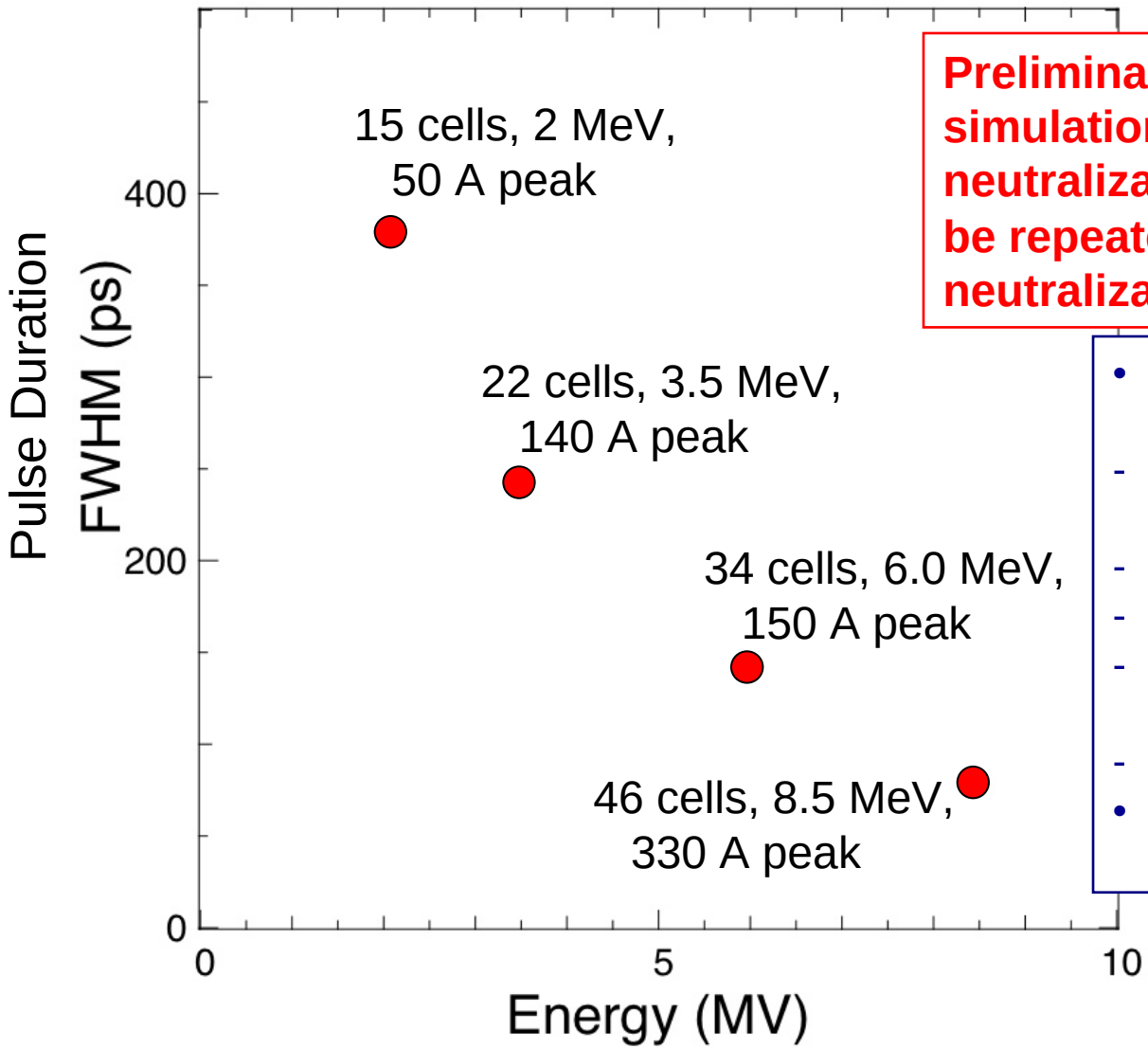
Entering final compression



Ref: A. Friedman, et al., *Phys Plasmas*, in press (2010)

	NDCX-I	NDCX-II (baseline)
Ion species	K^+ (A=39)	Li^+ (A=7)
Ion energy	300-400 keV	(1.5 MeV) → > 4 MeV
Focal radius	1.5 - 3 mm	(0.5 mm)
Pulse duration	2 - 4 ns	~(1 ns) → < 200ps ?
Peak current	~ 2 A	~ (10 A) → > 100 A?

Simulations show compressed pulse duration in NDCX-II varies approximately inversely with kinetic energy, assuming ideal neutralization.

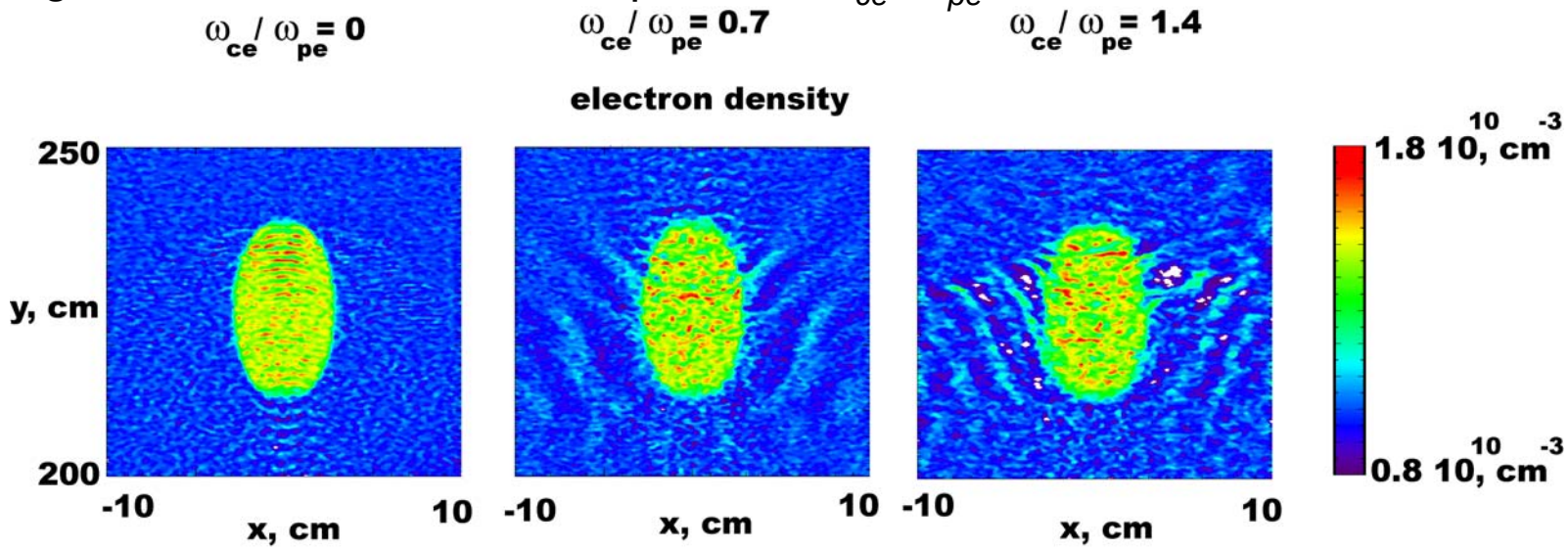


Preliminary results of Warp PIC simulations assuming ideal neutralization. These will be repeated with full plasma neutralization physics models.

- Separate studies have examined effects of:
  - timing jitter and voltage ripple in accelerating waveforms
  - injector voltage ripple
  - misalignments
  - 1 mA/cm^2 source (2 mA/cm^2 assumed here)
  - source temperature
- Modest degradation due to these effects is observed

Analytical studies show that the solenoidal magnetic field influences the degree of neutralization

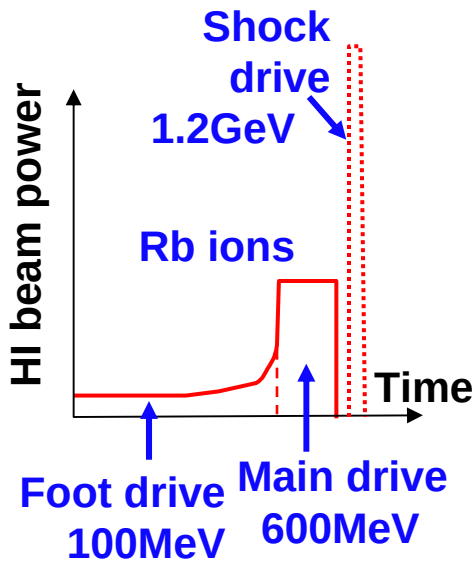
Plots of electron charge density contours in (x,y) space, calculated in 2D slab geometry using the LSP code with parameters: Plasma: $n_p=10^{11}cm^{-3}$; Beam: $V_b=0.2c$, 48.0A, r_b=2.85cm and pulse duration τ_b=4.75 ns. A solenoidal magnetic field of 1014 G corresponds to $\omega_{ce}=\omega_{pe}$.

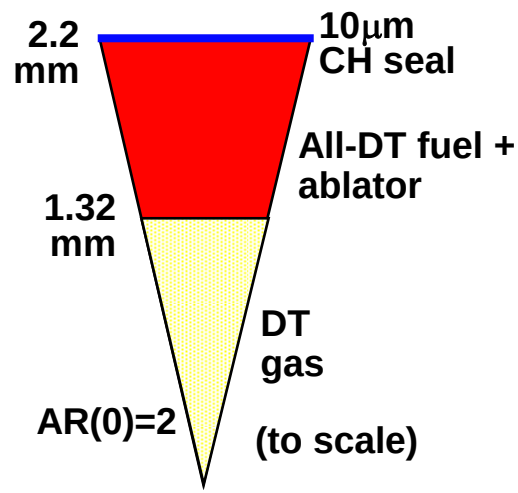


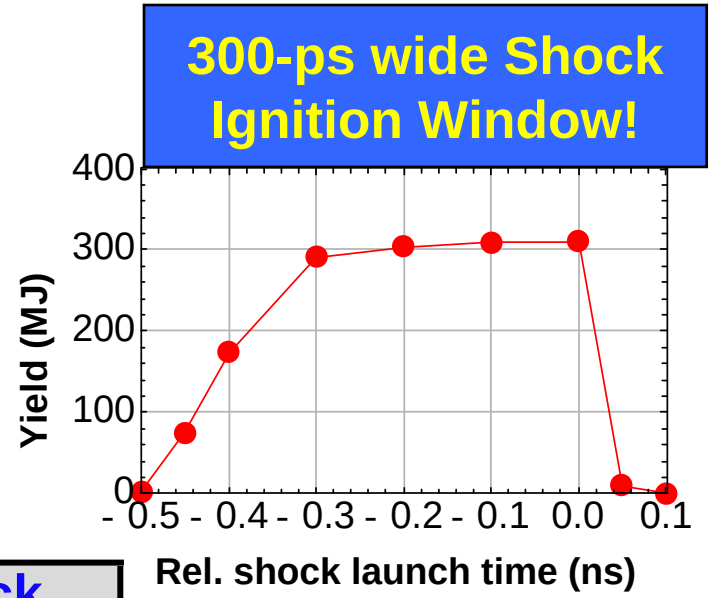
- In the presence of a solenoidal magnetic field, whistler waves are excited, which propagate at an angle with the beam velocity and can perturb the plasma ahead of the beam pulse.

I. D. Kaganovich et al., Phys. Rev. Lett. 99, 235002 (2007); E. A. Startsev et al., Phys. Plasmas15, 062107 (2008); I. D. Kaganovich et al., Phys. Plasmas 17, in press (2010).

High density fuel assembly with shock ignition: Initial LASNEX 1D runs *(John Perkins, January 28, 2010)*







	Hotspot Ignition	Shock Ignition	x 0.4 for Nuckolls gain 1000
Driver energy (MJ)	2.60	1.49 + 0.8 (sh)	0.6 + 0.32 (sh)
Peak drive power (TW)	500	200 + 1250 (sh)	80 + 500 (sh)
Yield (MJ) / Gain	317 / 122	310 / 136	124 MJ yield
Convergence ratio	28.4* (17.0**)	30.9* (18.5**)	
In-flight aspect ratio	14.0	8.7	

*** Conventional definition CR = $r_{shell\text{-}out}(0)/r_{HS}(t_{ign})$ ** Using CR = $r_{shell\text{-}in}(0)/r_{HS}(t_{ign})$**

Opportunities for R&D Using the PPPL 100 kV Test Stand

HEDLP solicitation proposal funding awarded to PPPL to use the versatile STS-100 equipment to perform VNL heavy-ion-beam research

Research Topics:

- **Advanced plasma source development for NDCX-I and NDCX–II.**
- **Investigate plasma injection into multi-Tesla solenoidal magnetic field.**
- **Study negative and positive ion beams extracted from ion-ion plasmas.**
- **Perform advanced studies of short-pulse, high current density, ion extraction from aluminosilicate ion sources.**
- **Magnetic insulation.**

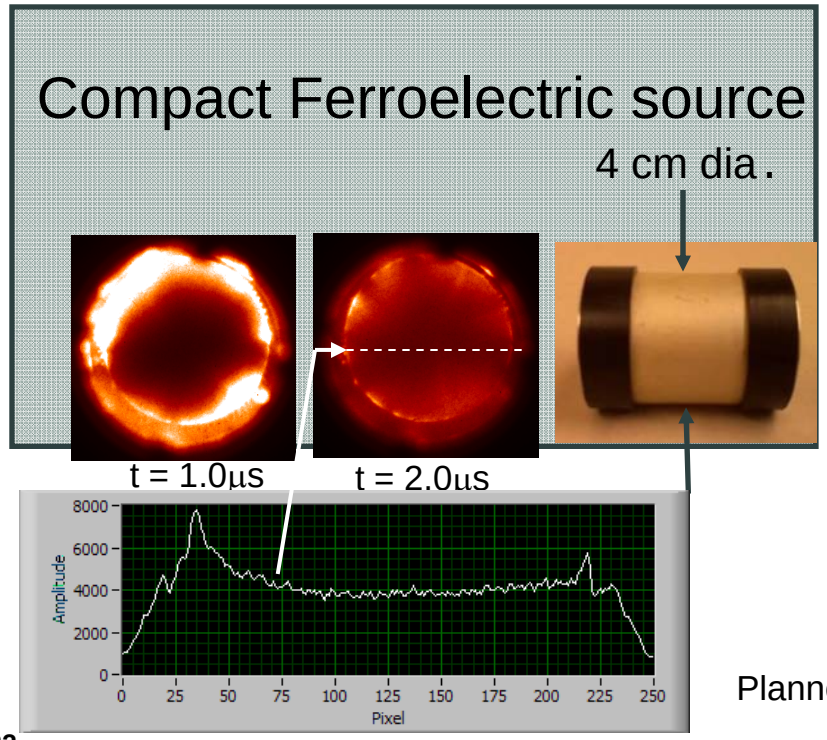
The STS-100 previously at LLNL.

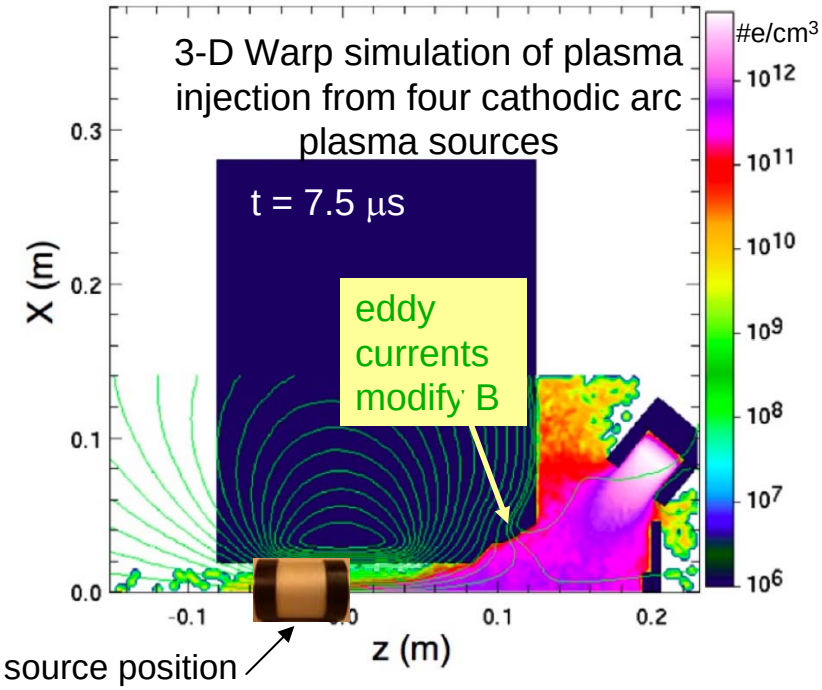
Compact Plasma Sources are Being Developed to Fill the Final Focusing Multi-Tesla Solenoid with Plasma

- A 1.50”-diameter ferroelectric plasma source is being developed in order to fill the bore of the multi-Tesla final focusing solenoid.

- Plasma produced near the wall is expected to follow the magnetic field lines and deliver plasma to the mid-plane of the magnet at large radius.

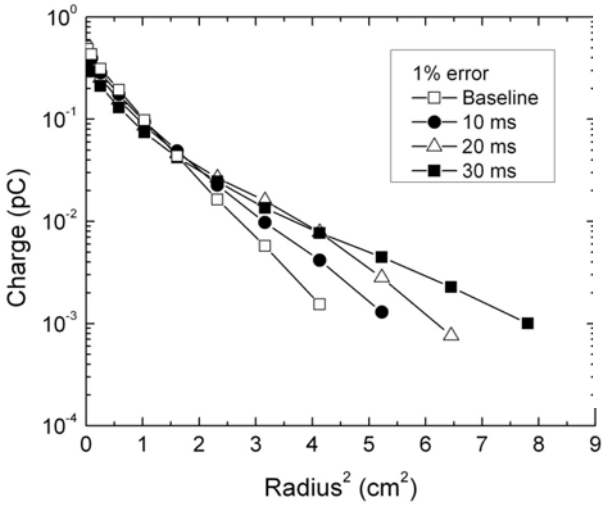
- Plasma source tests without magnetic fields show that the plasma uniformly fills the volume of the plasma source.

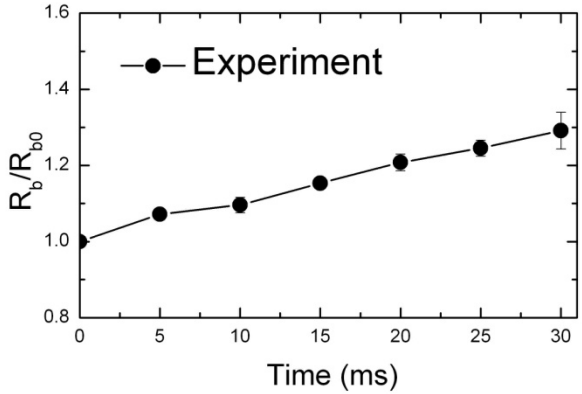


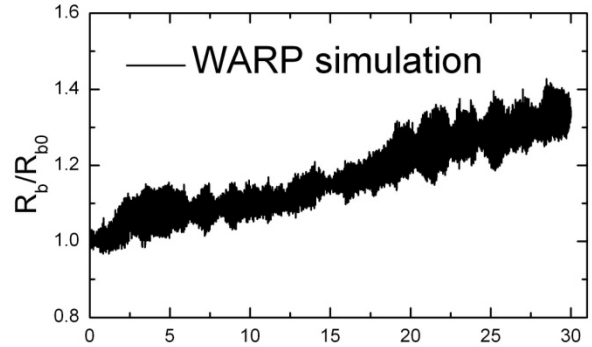


Improved Capability to Study High-Intensity Beams Will Enable PTSX to Better Study Emittance Growth Over Large Equivalent Propagation Distances Relevant to HIF Drivers

Experiments on PTSX using moderate density beams demonstrate noise-induced profile broadening, and therefore emittance growth, over 1800 lattice periods. WARP simulations corroborate this.







Changing from sinusoidal waveforms to FODO waveforms increases the normalized intensity, enabling PTSX to perform experiments studying the combined effects of lattice noise and space-charge on long-distance beam propagation.

FODO

R_b = 1.0 cm

kT = 0.08 eV

s = 0.45

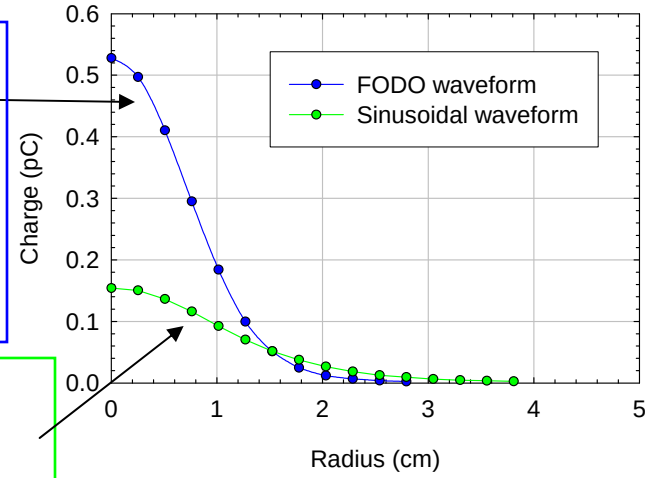
45% less emittance

Sinusoidal

R_b = 1.5 cm

kT = 0.17 eV

s = 0.16



$$s \equiv \frac{\omega_p^2}{2\omega_q^2} < 1$$

s is the normalized intensity.

Here, ω_p is the plasma frequency and ω_q is the average transverse focusing frequency.

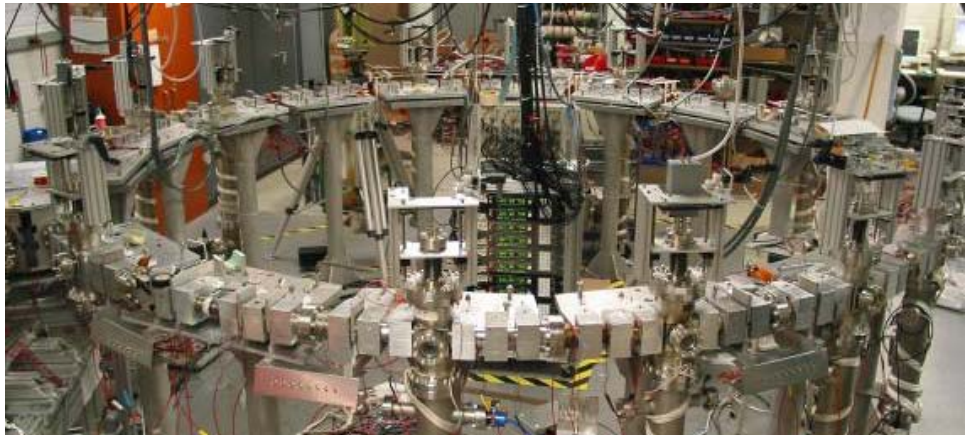
University of Maryland Electron Ring (UMER):
Scaled experiments using low-energy, high-current electron beams

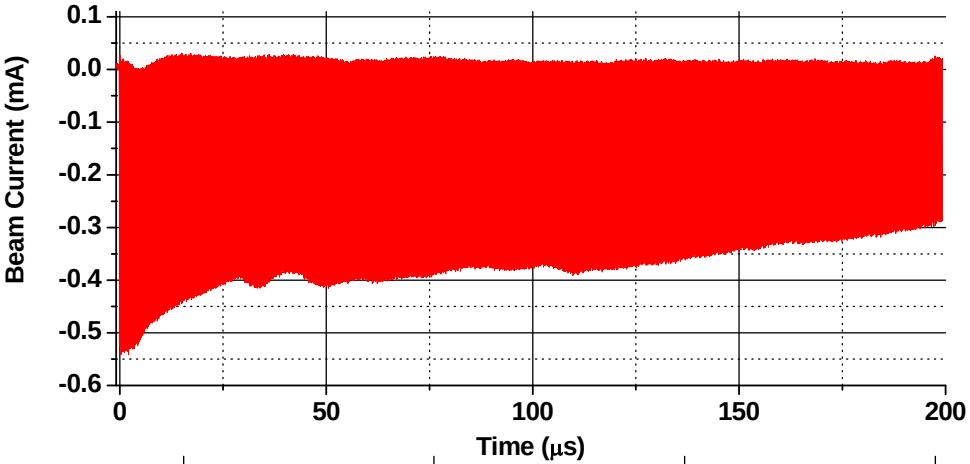
Goal: To demonstrate transport over long distance for intense beams of relevance to drivers for HIF and HEDP.

Status: Recently exceeded 1000 turns with longitudinal induction focusing

Ongoing Work:

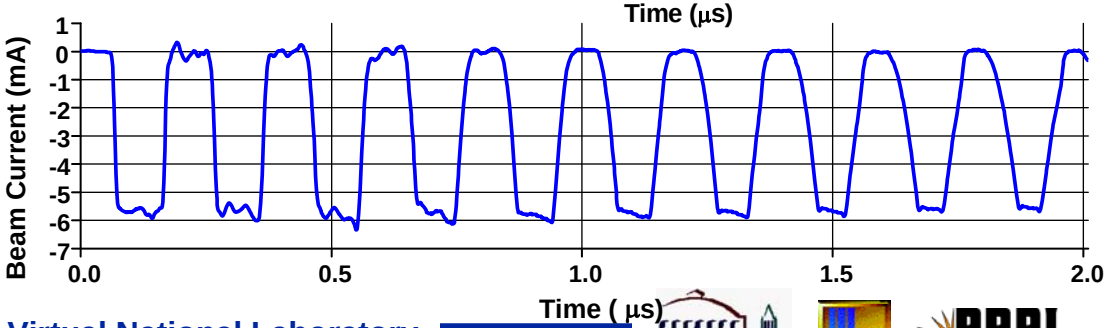
- Extending focusing to higher-current beams
- Designing acceleration stage
- Halo, emittance growth, and other topics





0.6 mA beam,
$k/k_o = 0.851$
>1000 Turns
with longitudinal focusing;

6 mA beam,
$k/k_o = 0.629$
10 - 100 Turns with ***no*** longitudinal focusing



The HIFS VNL continues to have a very strong publication record

In 2009 and 2010 (to date):
> 11 Invited talks at major meetings
48 Peer-reviewed papers (including submitted, accepted, and published)
43 Published conference papers, publications, and reports
19 Abstracts (contributed papers)

This list includes:
27 papers at Particle Accelerator Conference, Vancouver, BC 2009
15 presentations at APS DPP, Atlanta, GA, 2009
4 presentations at Inertial Fusion Science and Applications, SF, CA 2009
18 Nuclear Instruments and Methods in Physics Research
8 Physics of Plasmas
3 Physical Review Letters
5 Physical Review Special Topics Accelerators and Beams
2 Review of Scientific Instruments
1 High Energy Density Physics; 1 Laser and Particle Beams

Conclusions

- Significant scientific advances and discoveries in recent years have enabled:
  - Compression & focusing of ultra-short ion pulses in plasmas.
  - Unique approaches to High Energy Density Laboratory Plasmas and heavy ion fusion target physics.

- The proposed research has high scientific significance to both HEDLP in the near term, and to heavy ion fusion in the longer term*

- Proposed experiments highly leverage existing equipment very effectively and are modest in cost.

The requested full-use budget cases for FY11 and FY12 funding allows us to fully utilize the NDCX-II facility for research important to both HEDLP and heavy ion fusion beginning in FY12.

*http://www.acceleratorsamerica.org/symposium/agenda.html