Overview of Fusion Program at LBNL *

B. Grant Logan

Presented to the Fusion Power Associates
30-Year Anniversary Meeting and Symposium

On behalf of the
U.S. Heavy Ion Fusion Science Virtual National Laboratory
(LBNL, LLNL, and PPPL)

Capitol Hill Club, Washington DC
December 203, 2009

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Progress - DOE approved NDCX-II for $11M of ARRA funding in March, an NDCX-II Project Team was formed in April, and construction started in July after $11M of equipment money arrived.

Keeping $2.5 M in contingency reserve, the NDCX-II baseline includes 15 ATA cells for 1.6-2 MV (see talks by Kwan and Leitner). We will strive to build as many additional cells as soon as we can to maximize capability (up to 33 cells for 5 MV) for experiments.

(The NDCX-II Lehman Review will take place immediately after the LCLS-HED review in mid January.)

Simulations have been done for both 15 and 22 cells. (The HIFS-VNL research program will propose increased FY11-12 funds for a new, larger target chamber and new diagnostics (Bieniosek/Barnard talks), as well as adding more acceleration cells to extend accessible WDM states.)
Long microsecond beam prepulses preheat NDCX-I targets to boiling prior to compressed pulse heating→ evidence of droplet formation→ scientific interest for target fragmentation codes. NDCX-II with all-compressed (1 ns) beam pulses will study homogeneous WDM-EOS.

Platinum emission spectrum @2μs preheat to~ 4000 K→ falls below black-body at longer wavelengths

(We are working on theoretical models for droplet formation and emissivity of droplets to explain the above-see 4thQTR report)
Opportunities for R&D Using the PPPL 100 kV Test Stand

HEDLP solicitation proposal awarded to use the versatile STS-100 equipment at PPPL 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.
VNL research plans for the next 10 years (from earlier 20 year plan)

Ten-year science plan for ion-beam-driven HEDLP and heavy ion fusion

<table>
<thead>
<tr>
<th>Science Area</th>
<th>FY07 through FY09</th>
<th>Five Yr-Plan FY10 through FY14</th>
<th>FY15 through FY 18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam-Target Interaction</td>
<td>Target design, initial WDM experiments, fast beam diagnostics, beam dE/dx</td>
<td>Explore a variety of new WDM and Initial beam-cryo D2 target interaction at 1 eV.</td>
<td>- Construct IB-HEDPX. - Develop beam target physics basis for HIDDIX on NDCX-II.</td>
</tr>
<tr>
<td>Focusing onto Targets</td>
<td>Optimize high-B final focus together with near target plasma sources</td>
<td>Beam target interaction with ramped ion ranges. Time dependent focusing corrections.</td>
<td>NDCX-II planar direct drive experiments with ramped range and rotating beam spots</td>
</tr>
<tr>
<td>Longitudinal Beam Compression</td>
<td>Optimize longitudinal and transverse focusing with new induction buncher</td>
<td>Compress ramped range beams with beam spot rotation to high rotation frequencies.</td>
<td>Optimize compression and focusing using ramped and rotating beams</td>
</tr>
<tr>
<td>High Brightness Transport</td>
<td>E-cloud in quadrupoles and solenoids, beam steering and brightness optimization</td>
<td>Perpendicular and parallel brightness of beams in neutralized drift and for beam stripping on plasma jets.</td>
<td>Develop high brightness injectors for HIDDIX with beam stripping and ramped energy beams</td>
</tr>
<tr>
<td>Facility resource needs</td>
<td>1. Optimize NDCX-I with new tilt core, plasma sources, and higher-B final focus magnet. 2. Test ATA equipment for NDCX-II. 3. Develop diagnostics. $7.8 M/yr total</td>
<td>1. Operate NDCX-I for 0.5 eV WDM - -two phase and ion-ion plasmas. 2. Assemble NDCX-II using existing ATA accelerator modules. 3. Operate NDCX-II for 1 eV HEDP and planar direct drive experiments. $10M/yr increasing to $16 M/yr tot.</td>
<td>1. Construct IB-HEDPX and develop users ($20M/yr) 2. Design and R&amp;D for HIDDIX (Use NDCX-II with mods + component R&amp;D ($20M/yr)</td>
</tr>
</tbody>
</table>

ARRA funding for NDCX-II put our research plan back on track!

* Excerpted from Figure 4.2 of White Paper on Heavy-Ion-Beam-Driven High Energy Density Physics and Inertial Fusion (September, 2008); IB-HEDPX = Integrated Beam-High Energy Density Physics Experiment; HIDDIX=Heavy Ion Direct Drive Implosion Experiment; NDCX=Neutralized Drift Compression Experiment.
We are re-evaluating all accelerator driver and target options for HIF, to exploit past R&D and near-term facility capabilities (Peter Seidl’s talk)

The figure below depicts an earlier concept presented at Snowmass 2002 for a development accelerator called the Integrated Research Experiment. HIF credibility would be enhanced if such a facility could do Gekko-XII or Omega-scale (10 kJ-scale) target implosion experiments.

~ 200 - 400 MeV
~ 30 - 300 kJ
~ $150 - 300 M

Scale: line charge density per beam same as driver; final energy ~ 1/10 driver.
Beam quality: 6D phase-density same as driver.
Chamber transport: neutralized (~95%) ballistic mode without destructive instabilities; also tests of channel and self-pinch modes.
Chamber technology: test driver/chamber interface.
Target temperature: 50 - 100 eV.
The National Ignition Campaign on the completed NIF is progressing well. NIF ignition will motivate heavy ion fusion, both indirect and direct drive.  
*(from John Perkins, February 2009)*

**LASNEX 1-D with 3-D ion beam ray-trace**

**HI beam power**

- Foot drive 50MeV
- Main drive 500MeV

**Rb ions**

**Time**

**HI Direct Drive**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver energy (MJ)</td>
<td>0.44</td>
</tr>
<tr>
<td>Peak drive power (TW)</td>
<td>205</td>
</tr>
<tr>
<td>Yield (MJ) / Gain</td>
<td>20.8 / 47</td>
</tr>
<tr>
<td>( \eta_{\text{abs}} \times \eta_{\text{hydro}} )</td>
<td>0.09</td>
</tr>
<tr>
<td>In-flight aspect ratio</td>
<td>25</td>
</tr>
</tbody>
</table>

**NIF Indirect Baseline**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>350-425</td>
</tr>
<tr>
<td></td>
<td>20.0 / 15</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>33</td>
</tr>
</tbody>
</table>
An experimental implementation is to be planned for NDCX-II hydro-coupling experiments with ramped energy beams.

[Simulations by Siu Fai Ng & Simon Yu (CUHK), Seth Veitzer (Tech-X), John Barnard (LLNL)]

2nd pulse ion range = 1st pulse

First pulse of ion beam → $T_0$

$R = \text{Range at initial ion energy}$

At $t = \frac{R}{c_s}$:

$\rho_0$

Second ion pulse @ equal range $\rightarrow c_s \rightarrow v \sim c_s$

(range = $R$)

At $t = 2\frac{R}{c_s}$:

$\rho_0$

$T_1$

$v \sim c_{s1}$

2nd pulse ion range > 1st pulse

First pulse of ion beam → $T_0$

$R = \text{Range at initial ion energy}$

At $t = \frac{R}{c_s}$:

$\rho_0$

Second ion pulse @ higher range $\rightarrow c_s \rightarrow v \sim c_{s1}$

(range = $2R$)

At $t = 2\frac{R}{c_s}$:

$\rho_0$

$T_1$

$v \sim c_{s2}$

$\rho \text{ vs } z$: At $t = 3\frac{R}{c_s}$: measure velocity of back of target.

$T_0$ $T_1$ $T_2 > T_1$
Since the last PAC’s advice regarding direct drive target stability, more stable heavy ion direct drive targets have been evaluated for 2-D Rayleigh Taylor growth factors (see John Perkins’s talk).

Implosion stability should be good because of:
- (a) ablation stabilization (but less at higher mode numbers)
- (b) no ablator/fuel mix
- (c) low Atwood numbers,
- (d) low inflight aspect ratios (big fat shells)

⇒ Even with linear (unsaturated) growth, perturbations are unlikely to penetrate shell at late time.
“Subsidies or taxes should not be counted on to sustain non-carbon alternatives in the long term, if those alternatives cannot become competitive with coal” – Guess who

An IFE driver, target factory, chamber and primary coolant loop must total less than 3 cts/kW_e hr (< ~1 B$) to replace a coal boiler and CO_2 scrubber, if the IFE Balance-of-Plant also costs $1B.

What if the working fluid for an IFE engine (laser, heavy ion, or pulsed power) could capture 100 MJ of target yield/kg, including most neutron energy, for direct MHD conversion to electricity @ 60% efficiency and for less than 0.5 cts/kW_e hr cost?

Interested? Email John Perkins or myself, re 2-pg white paper. Join us in a new IFE skunkworks.
Summary

• NDCX-I has established a scientific basis that intense heavy ion beams can be compressed and focused to the short pulses needed for HEDLP and for heavy ion fusion targets.

• NDCX-II stimulus funding allows the Heavy Ion Fusion Science Virtual National Laboratory to pursue research opportunities identified in the FESAC-HEDLP report and our roadmap towards heavy ion fusion, as well as provide the basis for IB-HEDPX.

• Commencement of the NIF Ignition Campaign, together with NDCX-II funding, motivate preparations for a significant growth in the program, and restarting accelerator driver research, once NIF achieves ignition.
Backup slides
High energy density plasma energy conversion research leads to
deeply compelling HED plasma science questions
(not only Balance of Plant engineering work)

(1) How can high gain IFE target yields mix with surrounding
matter to form 2 eV, 1 Mb, warm dense matter?
(2) How irreversible (dissipative) is the penetration of a dense HED
plasma jet across a magnetic field?
(3) How rapidly will embedded magnetic fields damp HED plasma
turbulence?
(4) Are parallel or transverse magnetic fields most effective in
laminarizing plasma flows in the boundary layers?
(5) How does optically thick radiation heat transport internal to
dense MHD plasmas transition to surface black body flux to walls
in laminar boundary layers, and what determines the transition
depth where optical depths ~ 1?
(6) What Mach number would maximize j dot E in an MHD channel?

Fusion energy into working fluids @ > 10 X specific energy
density of chemical combustion research unique to IFE
The VNL org chart was revised in March to recognize the new NDCX-II project and broaden research towards FESAC HEDLP opportunities in warm dense matter, intense beam-plasma collective interactions, and heavy ion fusion target physics (see Davidson’s talk).

We welcome Bill Goldstein as the new LLNL VNL Board member, replacing Ed Synakowski. We thank Don Correll who has served as acting board member since Ed left for OFES.

(New VNL laboratory director endorsements will be needed October 2010 for the next 5-year renewal of the VNL covering FY12-FY16)
Justification of Mission Need CD-0 for the Integrated Beam High Energy Density Physics Experiment (IB-HEDPX)

The overall IB-HEDPX program addresses a critical issue for high energy density physics in the near term, and inertial fusion energy in the long term, namely, the integration of the generation, injection, acceleration, transport, compression, and focusing of an ion beam of sufficient intensity for creating high energy density matter and fusion ignition conditions. The heavy ion beams required are very intense yet virtually collisionless, so that the beam distribution retains a long memory of effects from each region the beam passes through. Thus, the beam distribution that heats the target depends on the evolution of the beam distribution in all of the upstream regions. An integrated beam experiment IB-HEDPX is therefore essential for testing integrated beam models, and for accurate prediction of the beam energy deposition in target physics experiments. A secondary, but equally important, objective of the program is to create a critically needed user facility for experimental research in warm dense matter. Such a facility is lacking at present.

NDCX-II, requiring approximately $5 M hardware as an upgrade of the present NDCX-I facility in Year 1 and 2, is necessary R&D to assess the performance requirements of injection, acceleration and focusing of short pulses needed for the IB-HEDPX

NDCX-II is constructed as a modular system on rails, for future expandability. We have 50 ATA cells, sufficient for an upgrade to 8-10 MV, with an eastern extension of the B58 high bay: ~$25 M + $25 M (LCLS-HED-scale) user area ~ $50M.
NDCX-II will enable higher energy WDM research as well as HIF-relevant hydro-coupling physics

Present NDCX-I beamline
In Bldg 58 at LBNL: 1-3 mJ @ 0.2 μm range (0.4 eV) for two-phase warm dense matter users.

For a modest program supplement, we propose to continue operating NDCX-I to optimize beam focusing, target diagnostics, and cultivating WDM users, until NDCX-II commissioning is completed ~ end of FY12

NDCX-II beamline will use existing ATA equipment
Near-term HIFS-VNL budget needs for both NDCX-I and NDCX-II HEDLP

*(Table from last OFES Budget Planning Mtg. March 2008 - presented to TV George June 2009)*

<table>
<thead>
<tr>
<th>($)</th>
<th>FY05</th>
<th>FY06</th>
<th>FY07</th>
<th>FY08</th>
<th>FY09 (Full-use) Increments</th>
<th>FY10 (Full use) Increments</th>
</tr>
</thead>
<tbody>
<tr>
<td>LBNL</td>
<td>6000</td>
<td>5,360</td>
<td>4,700</td>
<td>4,700</td>
<td>1,300 operating + 1,700 equip*</td>
<td>1,300 operating + 2,500 equip*</td>
</tr>
<tr>
<td>LLNL</td>
<td>2,650</td>
<td>2,475</td>
<td>2,035</td>
<td>2,120</td>
<td>1,180 operating</td>
<td>1,180 operating</td>
</tr>
<tr>
<td>PPPL</td>
<td>1,603</td>
<td>1,142</td>
<td>980</td>
<td>990</td>
<td>588</td>
<td>588</td>
</tr>
<tr>
<td>Totals VNL (total FTEs)</td>
<td>10,253 (43 FTEs)</td>
<td>8,977 (37 FTEs)</td>
<td>7,715 (33 FTEs)</td>
<td>7,810 (32 FTEs)</td>
<td>3068 operating +1,700 equip for NDCX-II (43 FTEs)</td>
<td>3068 operating +2,500 equip for NDCX-II (44 FTEs)</td>
</tr>
</tbody>
</table>

Totals (K$) $11,028 operating +1,700 equip

ARRA now provides NDCX-II $11M=5M hardware+6M labor.
NDCX-I facility still needs $1 M/yr more to support HEDLP users.
We could restore accelerator science using HCX for another $1 M/yr.
The proposed OFES heavy ion fusion science/warm dense matter research program would support the first three steps in the roadmap developed for the FESAC HEDLP panel last summer.

Table 4.1, from page 43 of the HIF White Paper prepared for the FESAC HEDLP panel.

<table>
<thead>
<tr>
<th>HEDP/Inertial Fusion Energy Science Objective (Facility)</th>
<th>Ion</th>
<th>Linac voltage - MV</th>
<th>Ion energy - MeV</th>
<th>Beam energy - J</th>
<th>Target pulse - ns</th>
<th>Range -microns (in .)</th>
<th>Energy density (10^{11} \text{J/m}^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam compression physics, diagnostics. Sub-eV WDM. (NDCX-I) (1 beam)</td>
<td>K+</td>
<td>0.35</td>
<td>0.35</td>
<td>0.001-0.003</td>
<td>2-3</td>
<td>0.3/1.5 (in solid/20% Al)</td>
<td>0.04 to 0.06</td>
</tr>
<tr>
<td>Beam acceleration and target physics basis for IB-HEDPX. (NDCX-II) (1 beam)</td>
<td>Li(^+1)</td>
<td>3.5 - 5</td>
<td>3.5 - 5</td>
<td>0.1 - 0.14</td>
<td>1-2</td>
<td>7 - 20 (in solid/20%Al)</td>
<td>0.25 to 0.4</td>
</tr>
<tr>
<td>User facility for heavy-ion driven HEDP. (IB-HEDPX) (1 beam)</td>
<td>Na(^+1) or K(^+3)</td>
<td>25</td>
<td>25 – 75</td>
<td>3 – 5.4</td>
<td>0.7</td>
<td>11 – 8 (in solid Al)</td>
<td>2.2 To 5.8</td>
</tr>
<tr>
<td>Heavy-ion direct drive implosion physics. (HIDDIX) (2 beams)</td>
<td>Rb(^+9)</td>
<td>156</td>
<td>1000</td>
<td>2x7.5 (kJ)</td>
<td>2 - 4</td>
<td>1000 (in solid Z=1)</td>
<td>18</td>
</tr>
<tr>
<td>Heavy ion fusion test facility - high gain target physics. (HIFTF) (40-200 beams)</td>
<td>Rb(^+9)</td>
<td>156</td>
<td>1000</td>
<td>300 to 1500 (kJ)</td>
<td>12 -24</td>
<td>1000 (in solid Z=1)</td>
<td>90</td>
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Proposed funding by year for long range HIFS-VNL research plan

<table>
<thead>
<tr>
<th>FY10</th>
<th>FY11</th>
<th>FY12</th>
<th>FY13</th>
<th>FY14</th>
<th>FY15</th>
<th>FY16</th>
<th>FY17</th>
<th>FY18</th>
<th>FY19</th>
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<tbody>
<tr>
<td>13</td>
<td>15</td>
<td>16</td>
<td>17</td>
<td>17</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

NDCX-I operation  
NDCX-II operation  
IB-HEDPX construction

11/30/2009

The Heavy Ion Fusion Science Virtual National Laboratory
Advantages of Heavy Ion Fusion, plus NIF ignition, should renew interest in Heavy Ion Fusion

• MJ-beam accelerators have separately exhibited intrinsic efficiencies, pulse-rates, average power levels, and durability required for IFE.
• Thick-liquid protected target chambers are designed to have 30 year plant lifetimes.
• Focusing magnets for ion beams avoid direct line-of-sight damage from target debris, n and γ radiation.
• Heavy ion power plant studies have shown attractive economics and environmental characteristics (only class-C low level waste). [Yu et al., Fusion Sci. Tech. 44, 2 (2003) 329]

Copies of these reviews available upon request
1979 Foster Committee
1983 Jason Report (JSR82-302)
1986 National Academies of Sciences Report
1990 Fusion Policy Advisory Committee report (Stever Panel)
1993 Fusion Energy Advisory Committee (Davidson Panel)
1996 FESAC report (Sheffield Panel)
Breakthrough: Compression of intense velocity-chirped ion beams in plasma*. Now, radial and temporal compression $\rightarrow >2000 \times n_{beam}$

Velocity ramp accelerates tail, decelerates head, compressing beam $\sim 2$ ns FWHM

$2800$ K (will be higher after emissivity correction)

$\leftarrow$ time of arrival of $2$ ns compressed pulse onto $100$ nm gold foil target after $3 \mu$s of uncompressed beam preheating.

Streak camera spectra showing emission lines from gold vapor indicating temperatures above $3100$ K.

*cf Roy, et. Al. PRL 95(2005) 23481
Induction cells for NDCX-II are available from LLNL’s decommissioned ATA facility

Test stand has begun to verify performance

Cells will be refurbished with stronger, pulsed solenoids

- Porcelain Oil/Vacuum Interface
- Ferrite Torroids
- Focusing Solenoid Pulsed, 1.5-3 Tesla
- Acceleration Gap
- 70 ns, 250 kV input (2 drive points per cell)

solenoid

water cooling
Heavy-Ion Direct-Drive Implosion Experiment (HIDDIX): use two 5 kJ-scale linacs with RF wobblers to drive cryo capsule implosions for benchmarking ion hydro-codes for heavy ion direct drive fusion. → Provides a new accelerator tool to explore polar direct drive hydro physics with heavy ion beams, in parallel with NIF operation.

Four “knobs” to control P2 asymmetry with two beams:
1. Upstream GHz RF wobblers
2. Foam profile shapers
3. Ablator shaping (shims)
4. Zooming control

Goal is implosion drive pressure on the Cryo D₂ payload with < 1 % non-uniformity
Following our success in velocity-chirp compression of intense ion beams to few-nanosecond pulses in plasmas, we have another powerful fusion idea which also uses ion velocities increasing in time:

**Constant ion range**
- → decouples

**Strongly-increasing >4X ion range**
- → high hydro-coupling efficiency!
Direct drive heavy-ion-beam inertial fusion at high coupling efficiency

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Issues with coupling efficiency, beam illumination symmetry, and Rayleigh-Taylor instability are discussed for spherical heavy-ion-beam-driven targets with and without hohlraums. Efficient coupling of heavy-ion beams to compress direct-drive inertial fusion targets without hohlraums is found to require ion range increasing several-fold during the drive pulse. One-dimensional implosion calculations using the LASNEX inertial confinement fusion target physics code shows the ion range increasing fourfold during the drive pulse to keep ion energy deposition following closely behind the imploding ablation front, resulting in high coupling efficiencies (shell kinetic energy/incident beam energy of 16% to 18%). Ways to increase beam ion range while mitigating Rayleigh-Taylor instabilities are discussed for future work. © 2008 American Institute of Physics. [DOI: 10.1063/1.2950303]

John Nuckolls (April 2008) : “This is a real advance! Now, how are you going to exploit it? Can you apply this high coupling efficiency to reduce drive energy to much less than 1 MJ?”
NIF ignition, *if successful*, will validate 15% *hydro-coupling efficiency* in ablative capsule drive (capsule gain 100 with 200 kJ x-ray absorbed).

→ Idea for an HIFTF test facility:

LASNEX giving the same coupling efficiency, could 200 kJ of ions absorbed (300 kJ incident with spill) with *same power vs time* and the *right range* into H/DT ablators get gain >50?

(Cu doped Be shell for 285eV, 1.3 MJ)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Be(285) &quot;current best calc&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorbed energy (kJ)</td>
<td>203</td>
</tr>
<tr>
<td>Laser energy (kJ) (includes ~8% backscatter)</td>
<td>1300</td>
</tr>
<tr>
<td>Coupling efficiency</td>
<td>0.156</td>
</tr>
<tr>
<td>Yield (MJ)</td>
<td>19.9</td>
</tr>
<tr>
<td>Fuel velocity (10⁷ cm/sec)</td>
<td>3.68</td>
</tr>
<tr>
<td>Peak rhoR (g/cm²)</td>
<td>1.85</td>
</tr>
<tr>
<td>Adiabat (P/P_FD at 1000g/cc)</td>
<td>1.46</td>
</tr>
<tr>
<td>Fuel mass (mg)</td>
<td>0.238</td>
</tr>
<tr>
<td>Ablator mass (mg)</td>
<td>4.54</td>
</tr>
<tr>
<td>Ablator mass remaining (mg)</td>
<td>0.212</td>
</tr>
<tr>
<td>Fuel kinetic energy (kJ)</td>
<td>16.1</td>
</tr>
</tbody>
</table>
Jakob Runge, a German Fulbright summer student at LBNL, has developed a Mathematica model to explore the question: what minimum number of polar angles of annular ring arrays with beams using hollow rotated beam spots would be needed to achieve less than 1% non-uniformity of deposition?

Just four annular rings of beams (15 each; 60 total) at $\pm37.3^\circ$ and $\pm79.3^\circ$, with hollow, rotated beam spot projections give a maximum deviation from the mean of 0.7% (with 21% spilled intensity).

40 beams total give less than 1.4% and 32 beams total still give about 2%. With smaller ring radii the spill can be reduced, but unwanted radial incidence increases (RT instabilities). Smaller widths are desirable.

(To be published in Physics of Plasmas)
Beam filamentation (Weibel) instability should be investigated with rotating helical beams during NDC. The filamentation in LSP simulation of 100 meter long NDC: beam, field lines, and electron flows all co-linear over 100 meters!

In HIF04, Dale Welch found filamentation in LSP simulation beam width ~transverse filament size, field lines co-linear over entire 100 meter length. At sufficient magnetic fields, helical beam transport is not current neutralized. Neutralizing plasma trains electron flow and constrained beam width. Helical beam centroid radius ~ beam width. Neutralizing 2.5 kg solenoid field and transient filamentation beam is not neutralized.