Overview of Fusion Program at LBNL *

B. Grant Logan

Presented to the Fusion Power Associates

30-Year Anniversary Meeting and Symposium

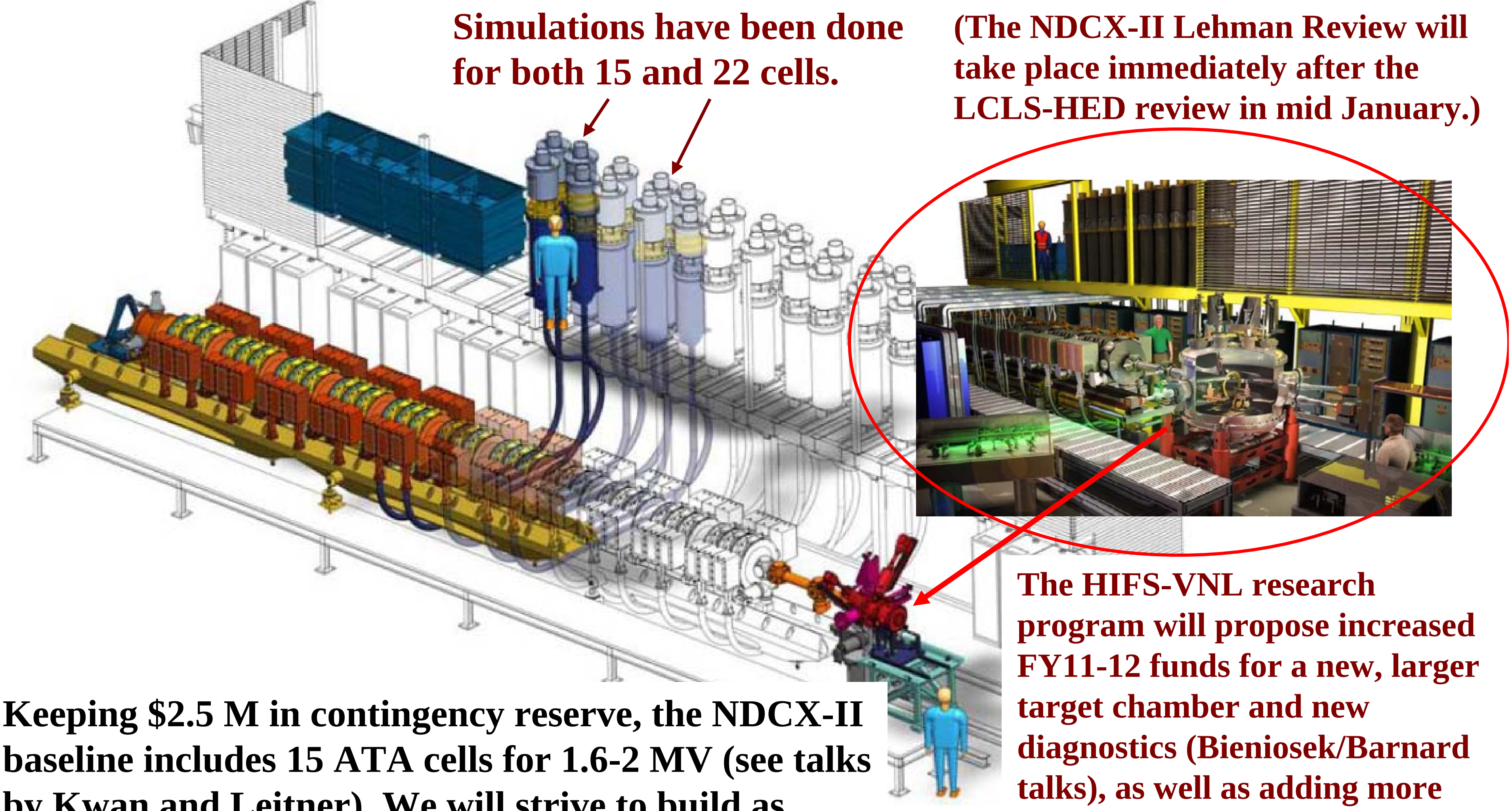
On behalf of the
U.S. Heavy Ion Fusion Science Virtual National Laboratory
(LBNL, LLNL, and PPPL)

Capitol Hill Club, Washington DC

December 203, 2009

*** This work was supported by the Director, Office of Science, Office of Fusion Energy Sciences of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231 by the Lawrence Berkeley National Laboratory, under Contract No. DE-AC52-07NA27344 by the Lawrence Livermore National Laboratory, and under Contract Number DE-AC02-76CH03073 by the Princeton Plasma Physics Laboratory.**

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.



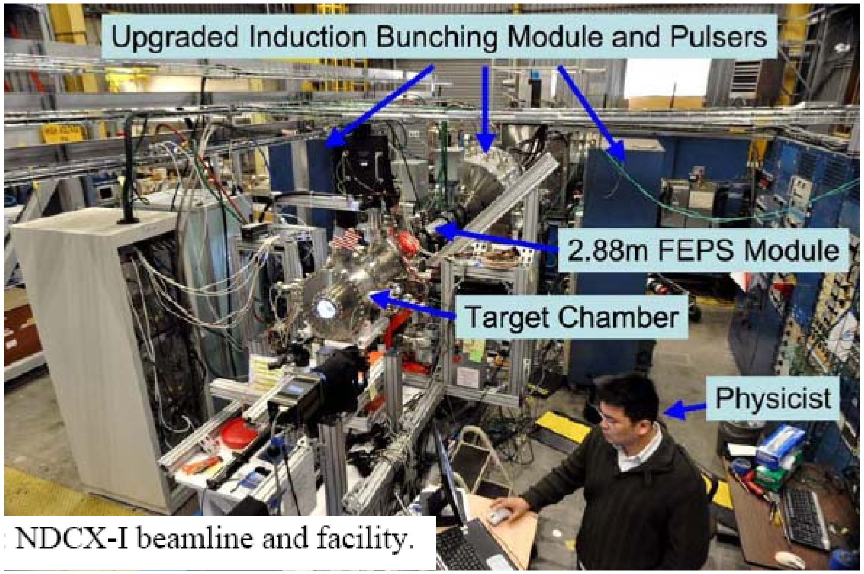
Simulations have been done for both 15 and 22 cells.

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

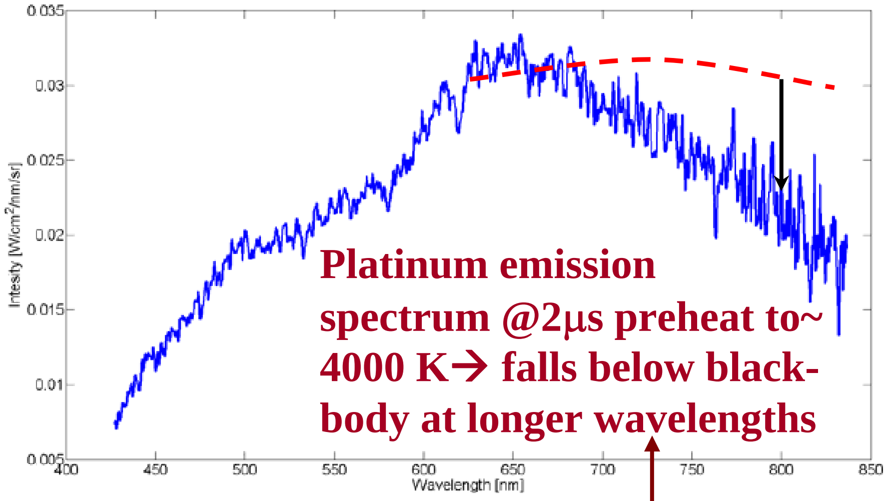
The HIFS-VNL research program will propose increased FY11-12 funds for a new, larger target chamber and new diagnostics (Bieniosek/Barnard talks), as well as adding more acceleration cells to extend accessible WDM states.

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.

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.



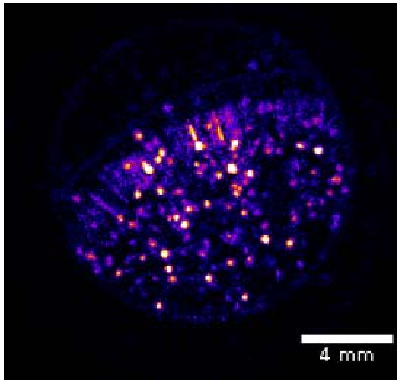
NDCX-I beamline and facility.



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

lse.

←A movable target foil holder (with small scintillator below it) greatly shortens time to alignment and increases target shot rate.



←Shower of hot debris (droplets) 500 ms after the beam pulse.

(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

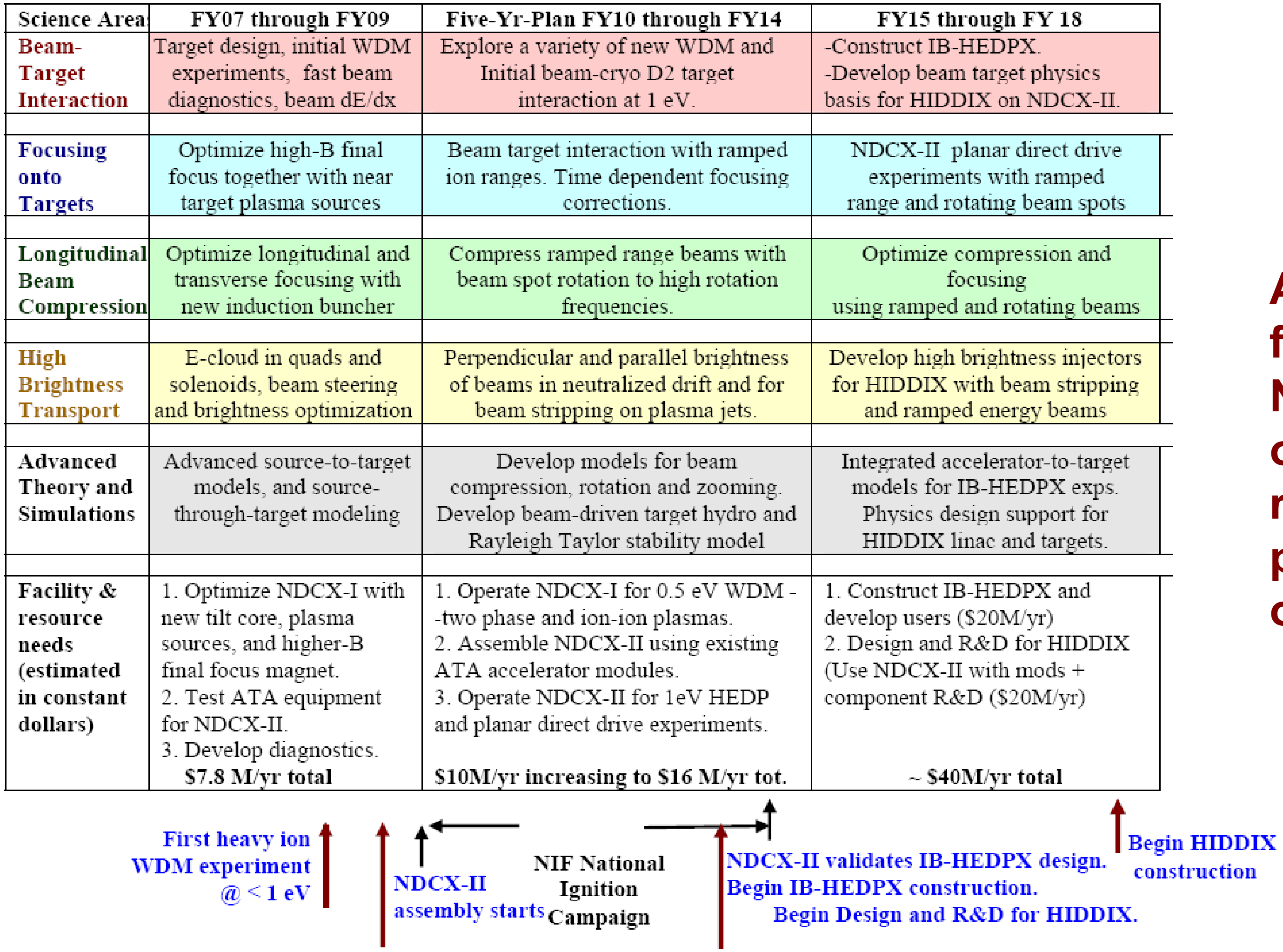
HEDLP solicitation proposal awarded to use the versatile STS-100 equipment at PPPL to perform VNL heavy-ion-beam research

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

Science Area	FY07 through FY09	Five-Yr-Plan FY10 through FY14	FY15 through FY 18
Beam-Target Interaction	Target design, initial WDM experiments, fast beam diagnostics, beam dE/dx	Explore a variety of new WDM and Initial beam-cryo D2 target interaction at 1 eV.	-Construct IB-HEDPX. -Develop beam target physics basis for HIDDIX on NDCX-II.
Focusing onto Targets	Optimize high-B final focus together with near target plasma sources	Beam target interaction with ramped ion ranges. Time dependent focusing corrections.	NDCX-II planar direct drive experiments with ramped range and rotating beam spots
Longitudinal Beam Compression	Optimize longitudinal and transverse focusing with new induction buncher	Compress ramped range beams with beam spot rotation to high rotation frequencies.	Optimize compression and focusing using ramped and rotating beams
High Brightness Transport	E-cloud in quads and solenoids, beam steering and brightness optimization	Perpendicular and parallel brightness of beams in neutralized drift and for beam stripping on plasma jets.	Develop high brightness injectors for HIDDIX with beam stripping and ramped energy beams
Advanced Theory and Simulations	Advanced source-to-target models, and source-through-target modeling	Develop models for beam compression, rotation and zooming. Develop beam-driven target hydro and Rayleigh Taylor stability model	Integrated accelerator-to-target models for IB-HEDPX exps. Physics design support for HIDDIX linac and targets.
Facility & resource needs (estimated in constant dollars)	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**	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 1eV HEDP and planar direct drive experiments. **$10M/yr increasing to $16 M/yr tot.**	1. Construct IB-HEDPX and develop users ($20M/yr) 2. Design and R&D for HIDDIX (Use NDCX-II with mods + component R&D ($20M/yr) **~ $40M/yr total**

First heavy ion WDM experiment @ < 1 eV

NDCX-II assembly starts

NIF National Ignition Campaign

NDCX-II validates IB-HEDPX design.
Begin IB-HEDPX construction.
Begin Design and R&D for HIDDIX.

Begin HIDDIX construction

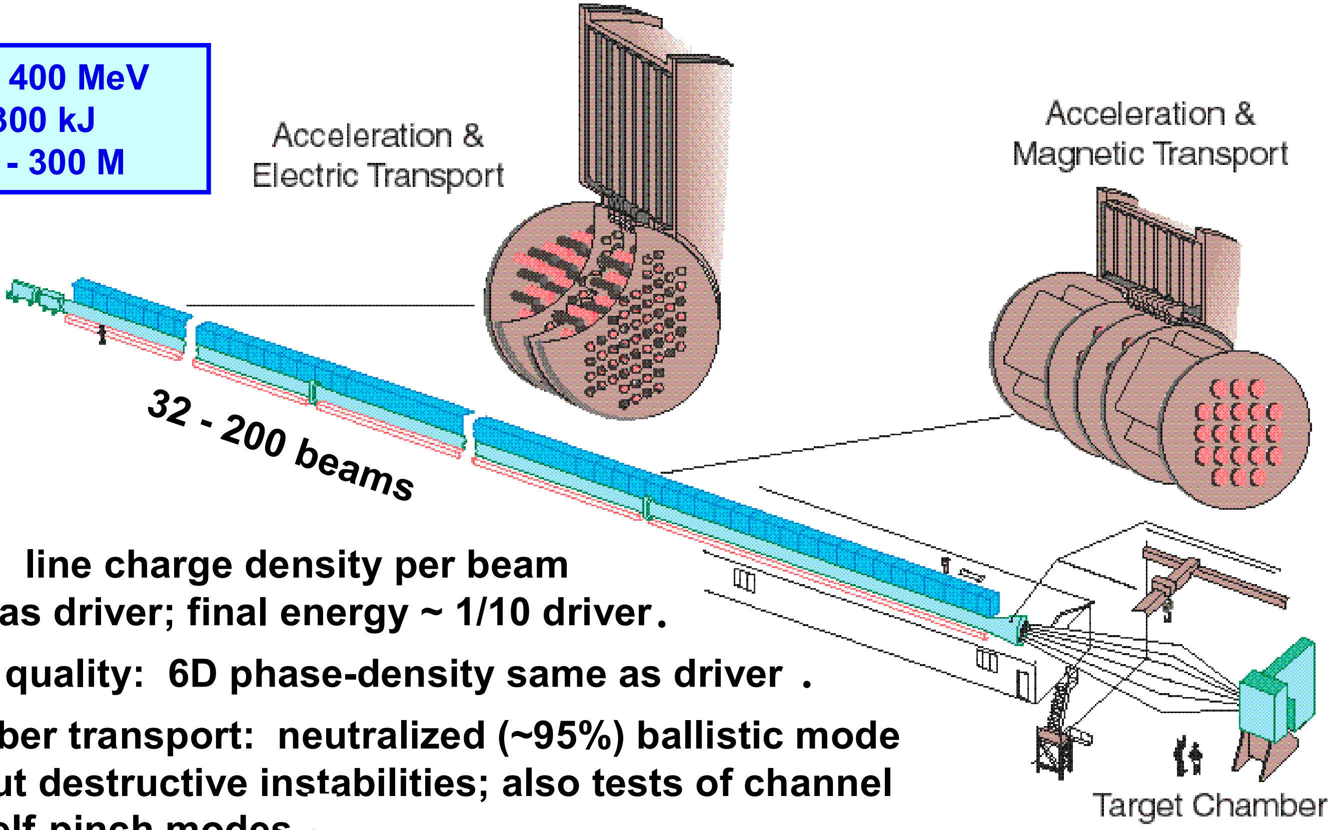
ARRA funding for NDCX-II put our research plan back on track!

* **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 .

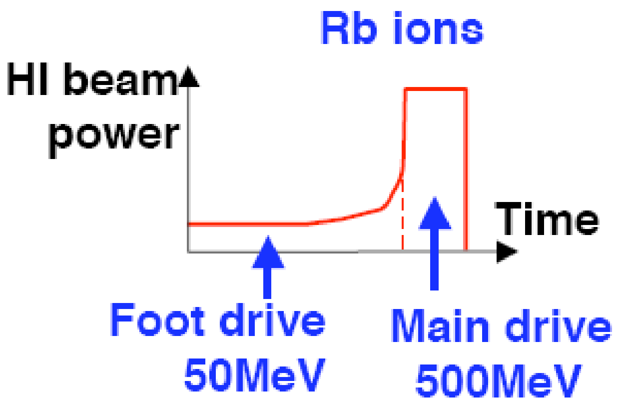
Chamber technology: test driver/chamber interface .

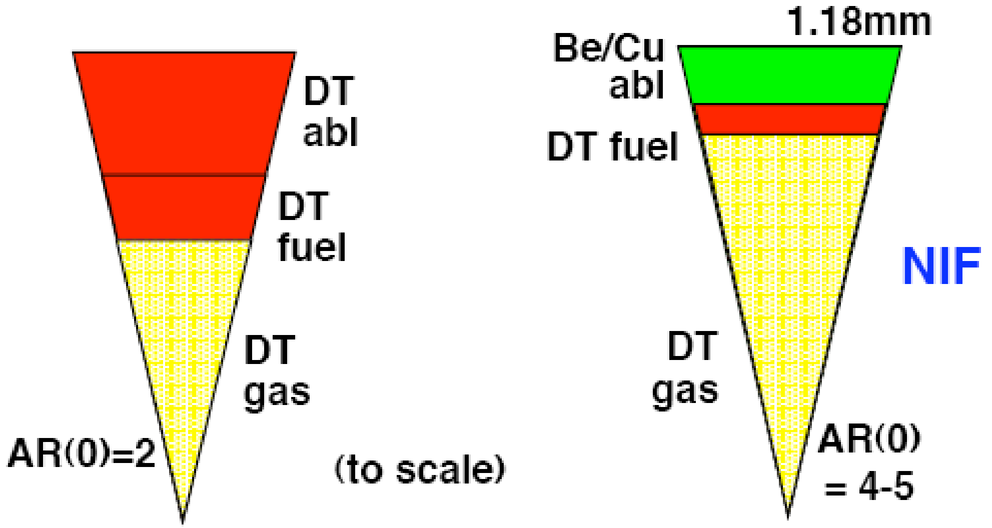
Target temperature: 50 - 100 eV.

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

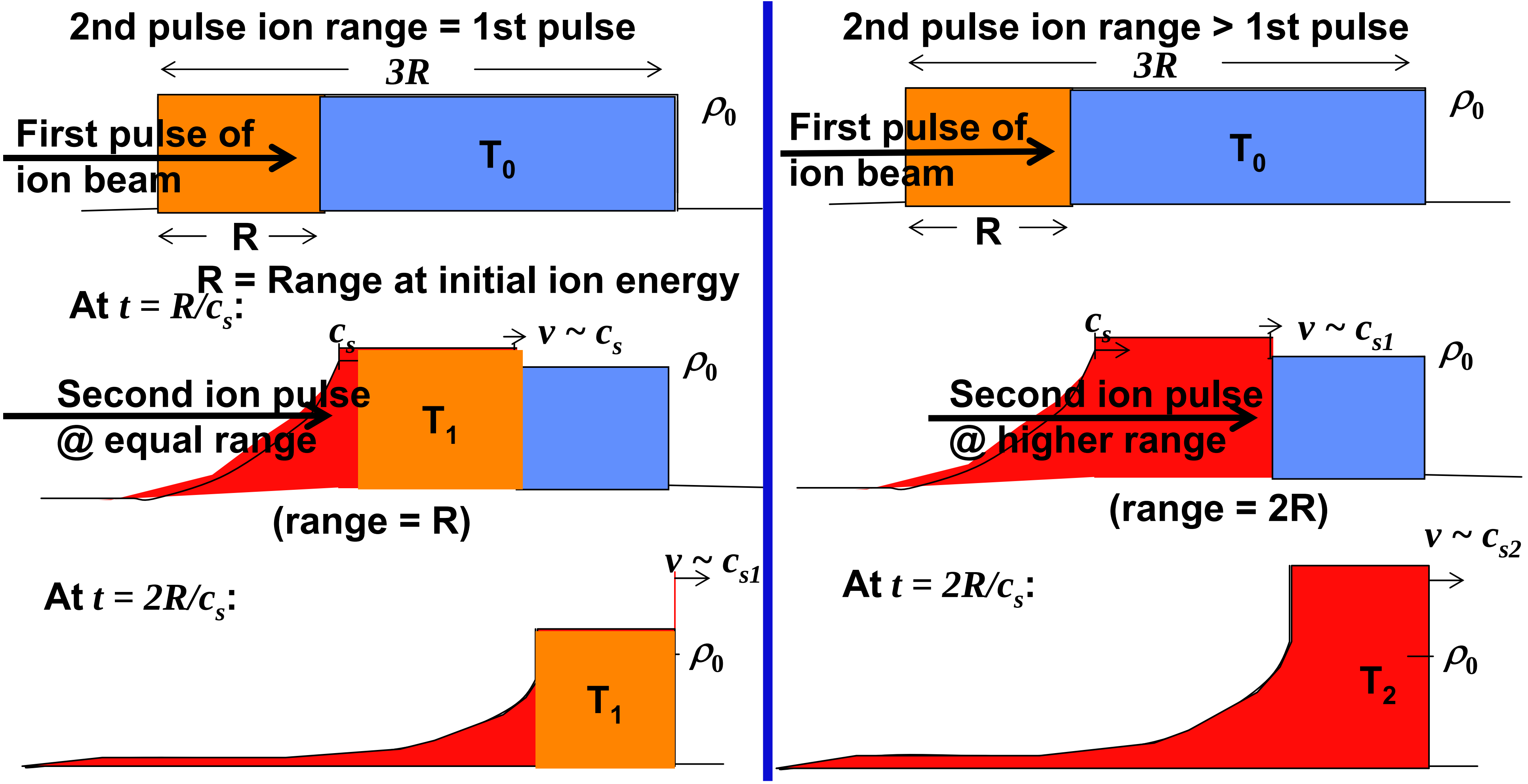




	HI Direct Drive	NIF Indirect Baseline
Driver energy (MJ)	0.44	1.3
Peak drive power (TW)	205	350-425
Yield (MJ) / Gain	20.8 / 47	20.0 / 15
$\eta_{abs} * \eta_{hydro}$	0.09	0.02
In-flight aspect ratio	25	33

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

R = Range at initial ion energy

At $t = R/c_s$:

(range = R)

At $t = 2R/c_s$:

2nd pulse ion range > 1st pulse

(range = 2R)

At $t = 2R/c_s$:

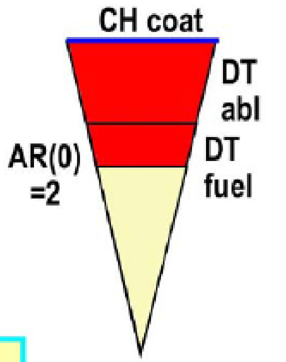
ρ vs z: At $t = 3R/c_s$: measure velocity of back of target.

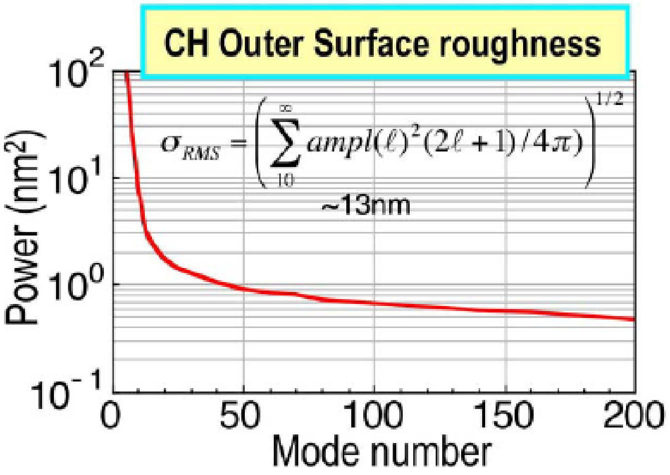
🟦 T_0 🟧 T_1 🟥 $T_2 > T_1$

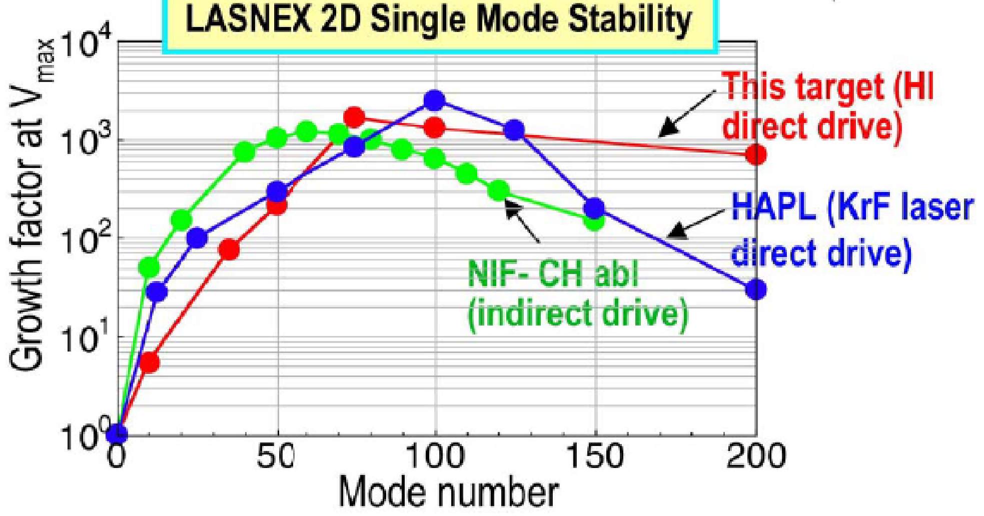
Since the last PAC’s advice regarding direct drive target stability, more stable heavy ion direct drive targets have been evaluated for 2-D Rayleigh Taylor growth factors (see John Perkins’s talk)

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)







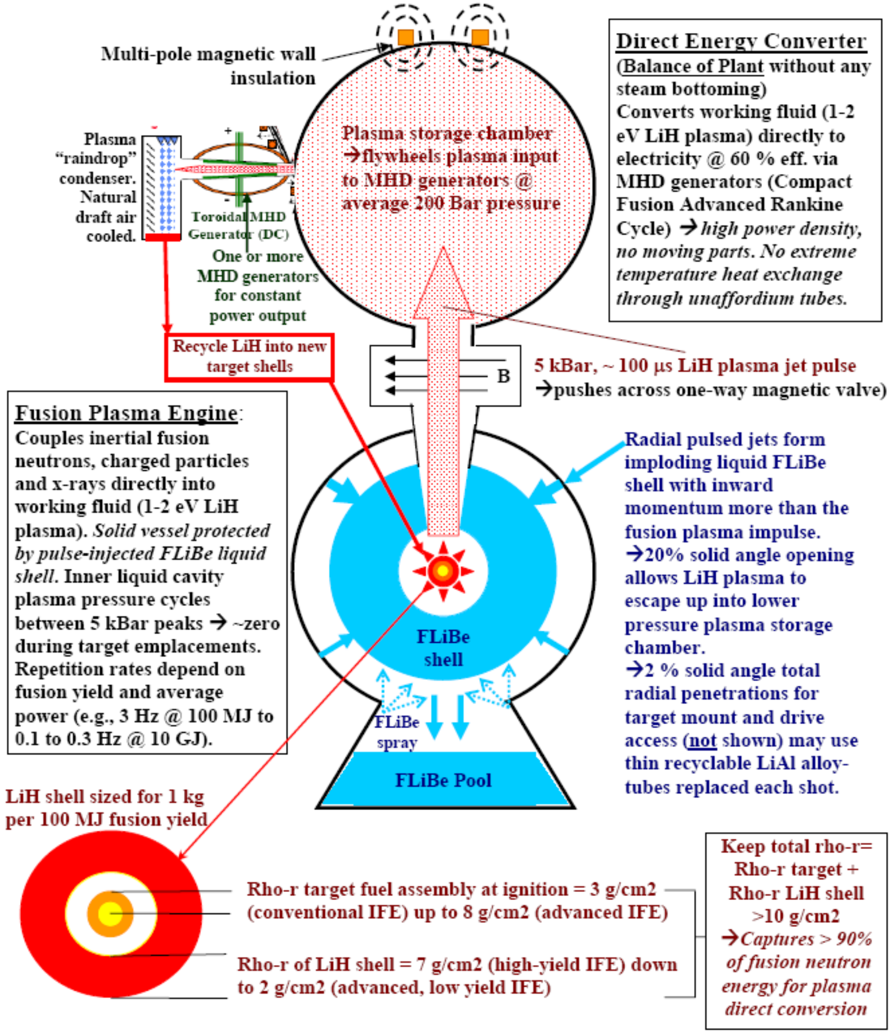
⇒ Even with linear (unsaturated) growth, perturbations are unlikely to penetrate shell at late time

High energy density plasma *(energy conversion?!)*

"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?



Multi-pole magnetic wall insulation

Plasma "raindrop" condenser. Natural draft air cooled.

Toroidal MHD Generator (DC)

One or more MHD generators for constant power output

Plasma storage chamber →flywheels plasma input to MHD generators @ average 200 Bar pressure

<u>Direct Energy Converter</u>
(<u>Balance of Plant</u> without any steam bottoming)
Converts working fluid (1-2 eV LiH plasma) directly to electricity @ 60 % eff. via MHD generators (Compact Fusion Advanced Rankine Cycle) →*high power density, no moving parts. No extreme temperature heat exchange through unaffordium tubes.*

Recycle LiH into new target shells

5 kBar, ~ 100 μs LiH plasma jet pulse
→pushes across one-way magnetic valve)

<u>Fusion Plasma Engine</u>:
Couples inertial fusion neutrons, charged particles and x-rays directly into working fluid (1-2 eV LiH plasma). *Solid vessel protected by pulse-injected FLiBe liquid shell*. Inner liquid cavity plasma pressure cycles between 5 kBar peaks → ~zero during target emplacements. Repetition rates depend on fusion yield and average power (e.g., 3 Hz @ 100 MJ to 0.1 to 0.3 Hz @ 10 GJ).

Radial pulsed jets form imploding liquid FLiBe shell with inward momentum more than the fusion plasma impulse.
→20% solid angle opening allows LiH plasma to escape up into lower pressure plasma storage chamber.
→2 % solid angle total radial penetrations for target mount and drive access (<u>not</u> shown) may use thin recyclable LiAl alloy-tubes replaced each shot.

LiH shell sized for 1 kg per 100 MJ fusion yield

Rho-r target fuel assembly at ignition = 3 g/cm2 (conventional IFE) up to 8 g/cm2 (advanced IFE)

Rho-r of LiH shell = 7 g/cm2 (high-yield IFE) down to 2 g/cm2 (advanced, low yield IFE)

Keep total rho-r= Rho-r target + Rho-r LiH shell >10 g/cm2
→*Captures > 90% of fusion neutron energy for plasma direct conversion*

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.

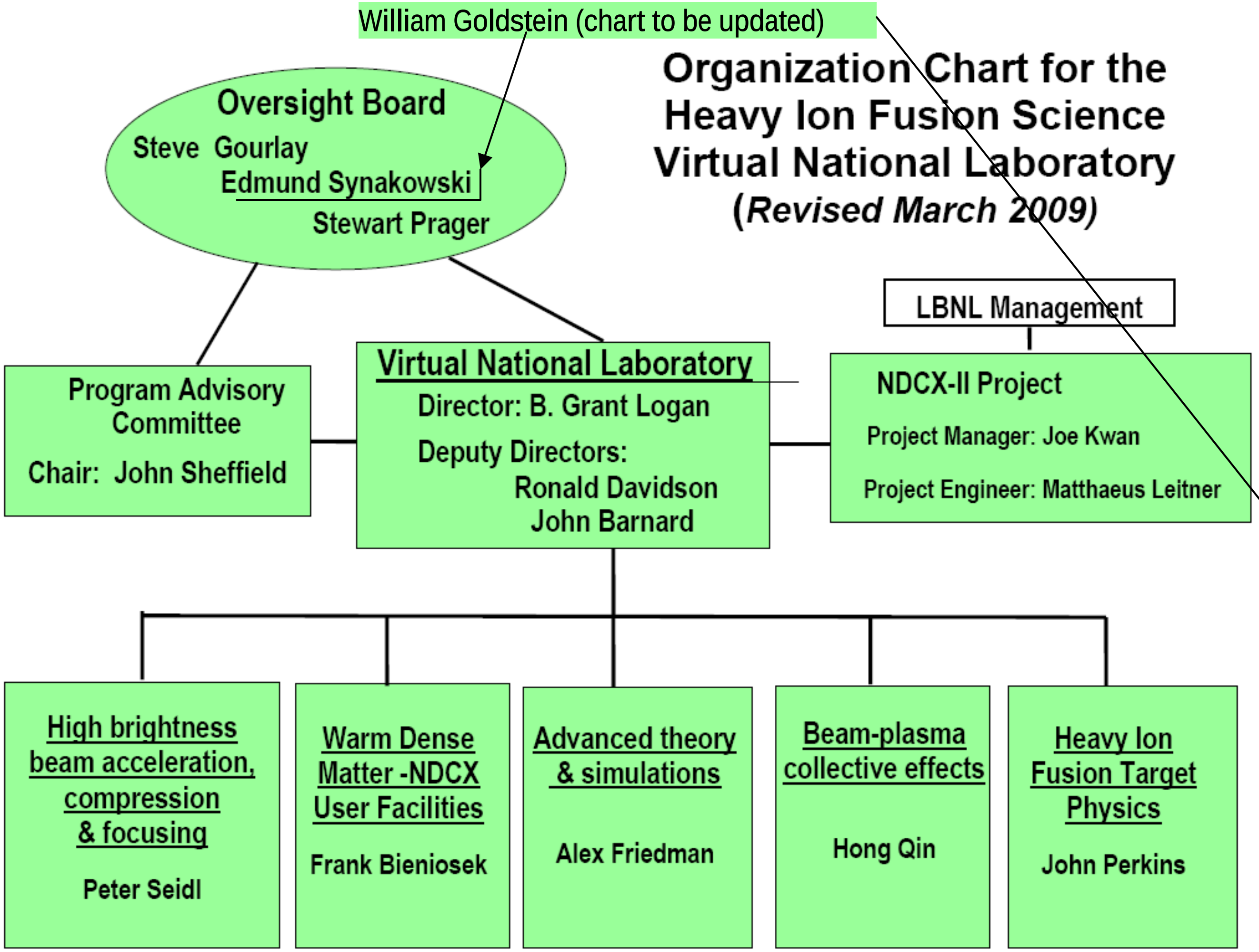
Backup slides

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).



William Goldstein (chart to be updated)

Organization Chart for the Heavy Ion Fusion Science Virtual National Laboratory (*Revised March 2009*)

Oversight Board
Steve Gourlay
Edmund Synakowski
Stewart Prager

Program Advisory Committee
Chair: John Sheffield

Virtual National Laboratory
Director: B. Grant Logan
Deputy Directors:
Ronald Davidson
John Barnard

LBNL Management

NDCX-II Project
Project Manager: Joe Kwan
Project Engineer: Matthaeus Leitner

High brightness beam acceleration, compression & focusing
Peter Seidl

Warm Dense Matter -NDCX User Facilities
Frank Bieniosek

Advanced theory & simulations
Alex Friedman

Beam-plasma collective effects
Hong Qin

Heavy Ion Fusion Target Physics
John Perkins

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.

Date 3/11/09
Stephen Gourlay

Date 3/17/09
Edmund Synakowski

Date 3/10/09
Stewart Prager

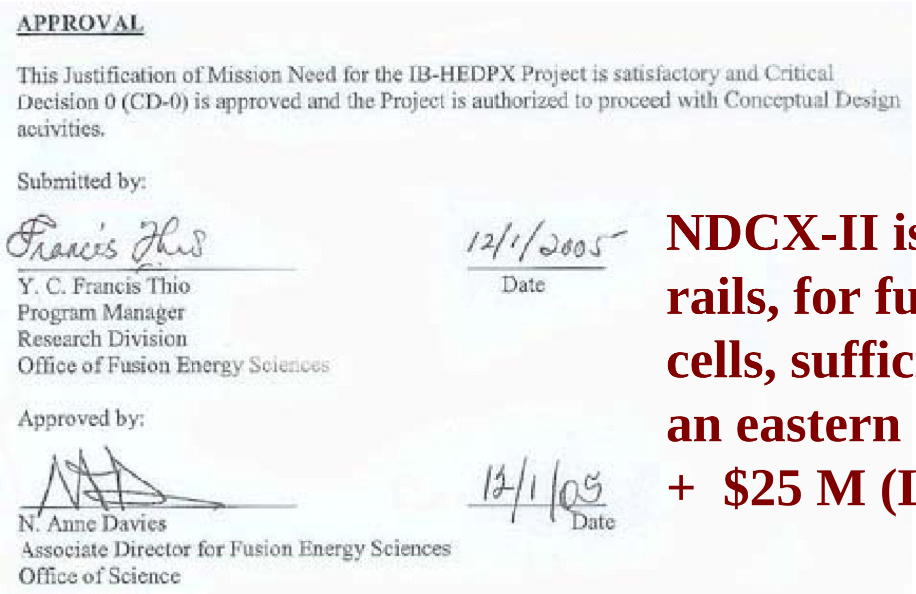
(New VNL laboratory director endorsements will be needed October 2010 for the next 5-year renewal of the VNL covering FY12-FY16)

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-1 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.

$50M IB-HEDPX would provide a full capability (p>1 Mbar) for HEDP users as an upgrade from NDCX-II. Note this CD-0 (Dec05) calls for NDCX-II as a prerequisite. →NDCX-II commissioning will satisfy this pre-requisite in FY12.



APPROVAL

This Justification of Mission Need for the IB-HEDPX Project is satisfactory and Critical Decision 0 (CD-0) is approved and the Project is authorized to proceed with Conceptual Design activities.

Submitted by:

Francis Thio
Y. C. Francis Thio
Program Manager
Research Division
Office of Fusion Energy Sciences

12/1/2005
Date

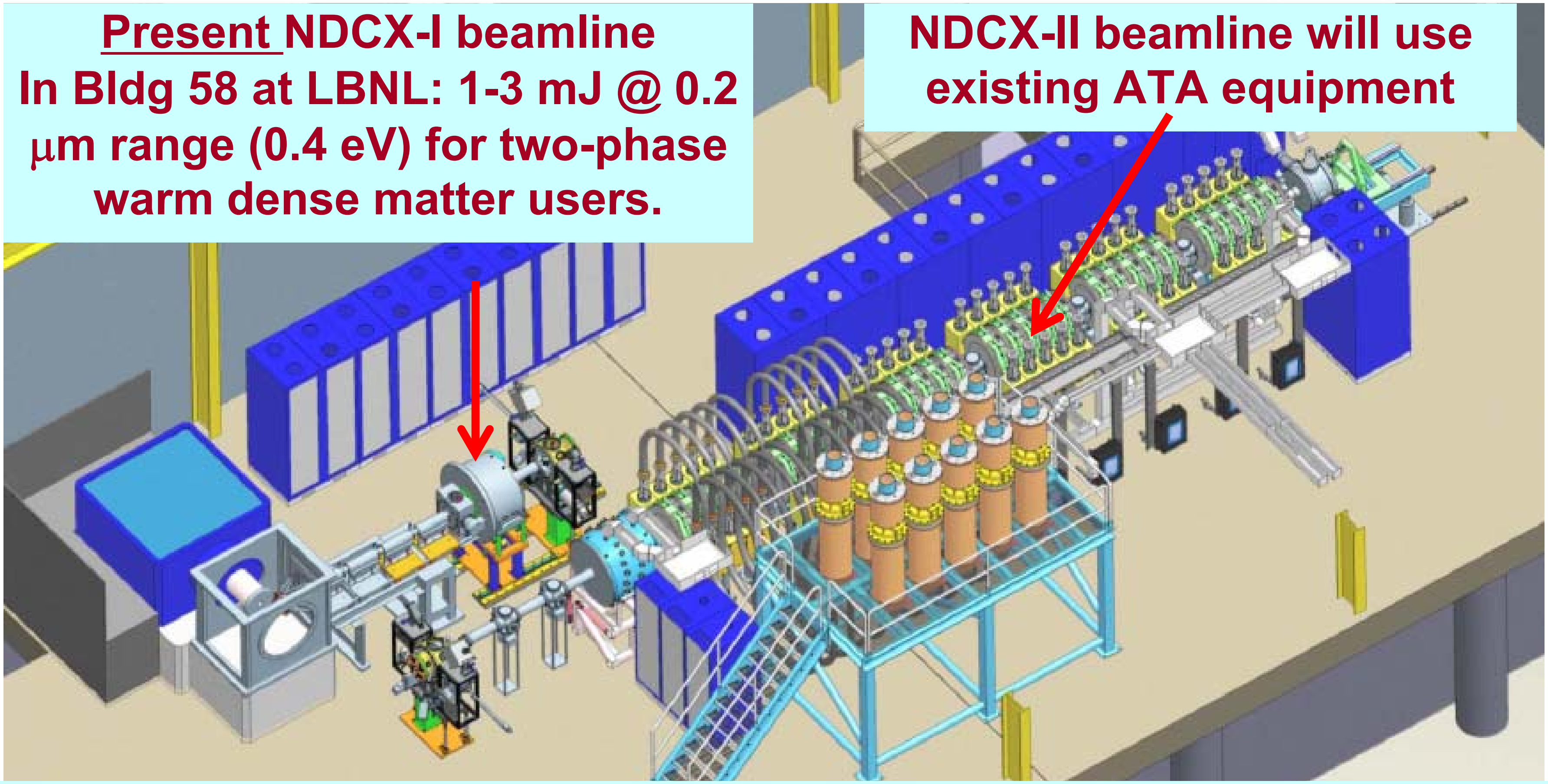
Approved by:

N. Anne Davies
Associate Director for Fusion Energy Sciences
Office of Science

12/1/05
Date

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.

NDCX-II beamline will use existing ATA equipment

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

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)

($K)	FY05	FY06	FY07	FY08	FY09 (Full-use) Increments	FY10 (Full use) Increments
LBNL	6000	5,360	4,700	4,700	1,300 operating + 1,700 equip*	1,300 operating + 2,500 equip*
LLNL	2,650	2,475	2,035	2,120	1,180 operating	1,180 operating
PPPL	1,603	1,142	980	990	588	588
Totals VNL (total FTEs)	10,253 (43 FTEs)	8,977 (37 FTEs)	7,715 (33 FTEs)	7,810 (32 FTEs)	3068 operating +1,700 equip for NDCX-II (43 FTEs)	3068 operating +2,500 equip for NDCX-II (44 FTEs)
				Totals (K$)→	11,028 operating +1,700 equip	11,028 operating +2,500 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.

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

NIF ignition needed before these steps

Proposed funding by year for long range HIFS-VNL research plan

FY10	FY11	FY12	FY13	FY14	FY15	FY16	FY17	FY18	FY19
13	15	16	17	17	30	30	30	30	30

NDCX-I operation

NDCX-II operation

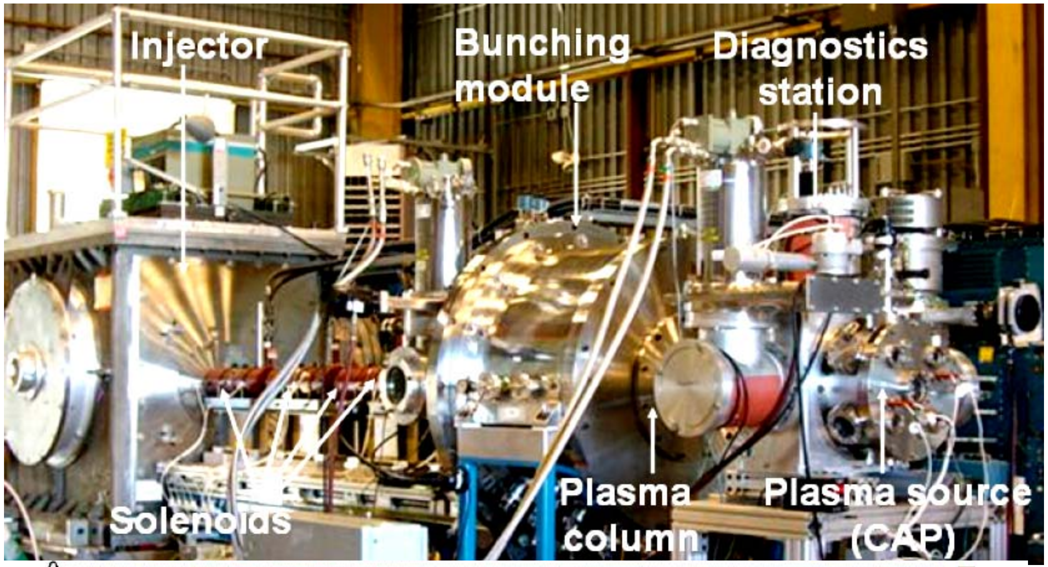
IB-HEDPX construction

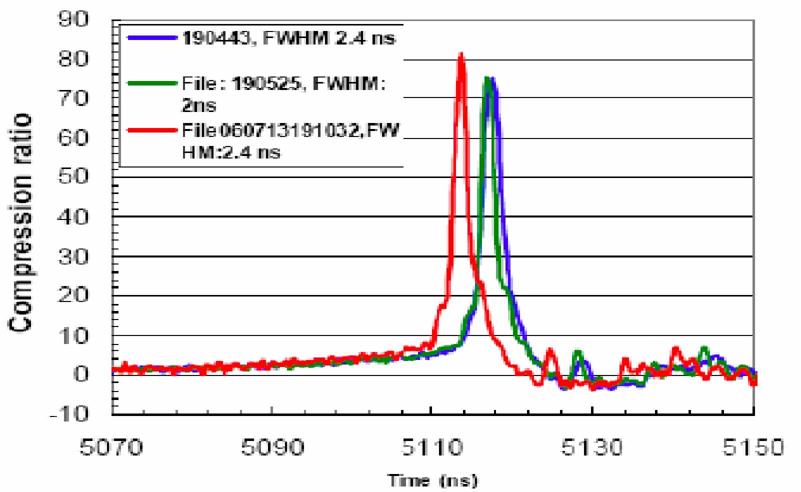
Advantages of Heavy Ion Fusion, plus NIF ignition, should renew interest in Heavy Ion Fusion

- 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]*

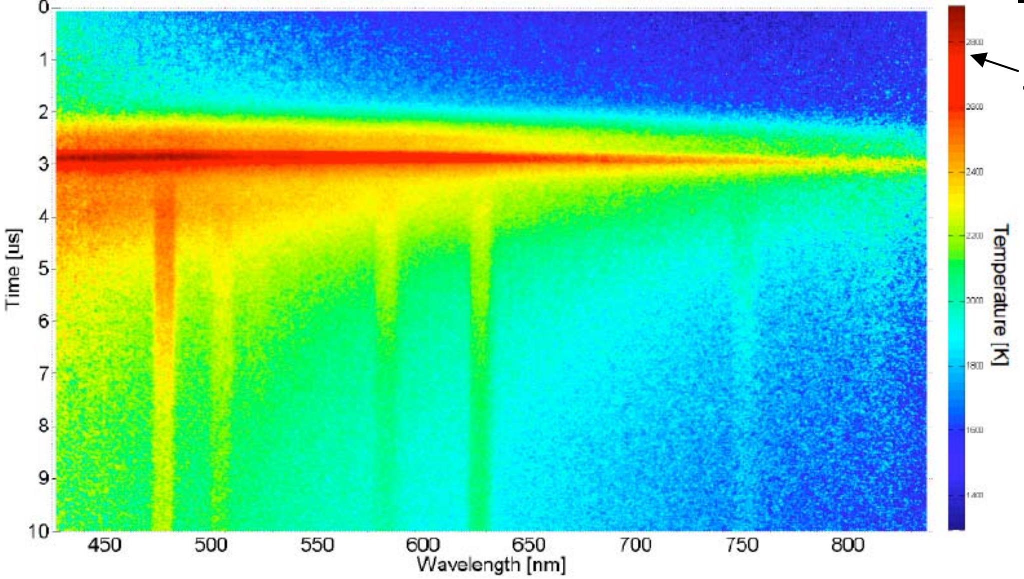
Copies of these reviews available upon request
1979 Foster Committee
1983 Jason Report (JSR82-302)
1986 National Academies of Sciences Report
1990 Fusion Policy Advisory Committee report (Stever Panel)
1993 Fusion Energy Advisory Committee (Davidson Panel)
1996 FESAC report (Sheffield Panel)

Breakthrough: Compression of intense velocity-chirped ion beams in plasma*. Now, radial and temporal compression→ > 2000 X n_{beam}





Velocity ramp accelerates tail, decelerates head, compressing beam ~ 2 ns FWHM



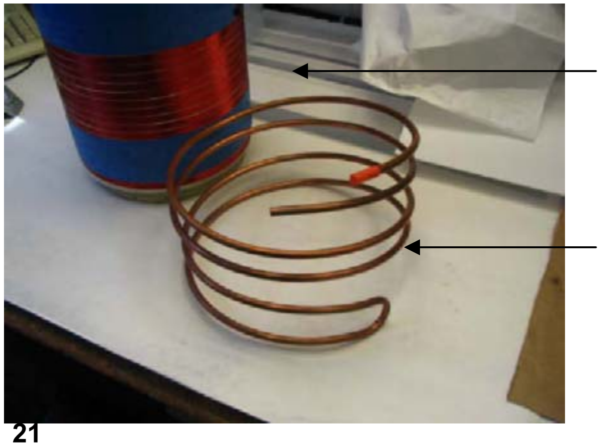
2800 K (*will be higher after emissivity correction*)

← time of arrival of 2 ns compressed pulse onto 100 nm gold foil target after 3 μs of uncompressed beam preheating. Streak camera spectra showing emission lines from gold vapor indicating temperatures above 3100 K.

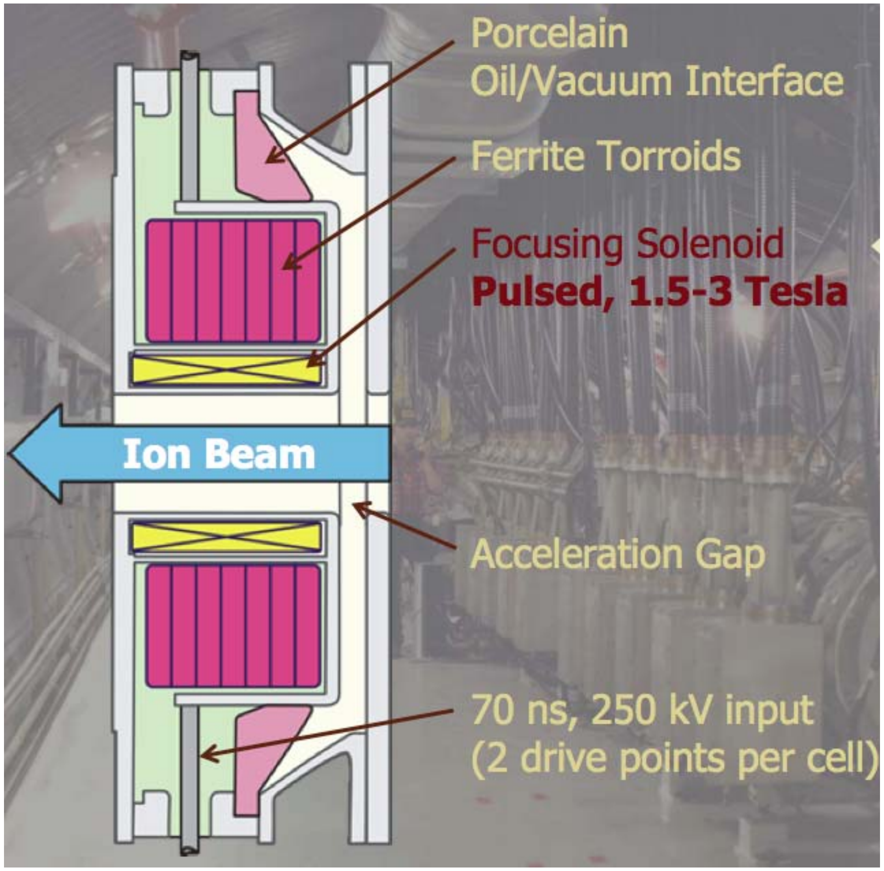
*cf Roy, et. Al. PRL 95(2005) 23481

Induction cells for NDCX-II are available from LLNL's decommissioned ATA facility

Test stand has begun to verify performance

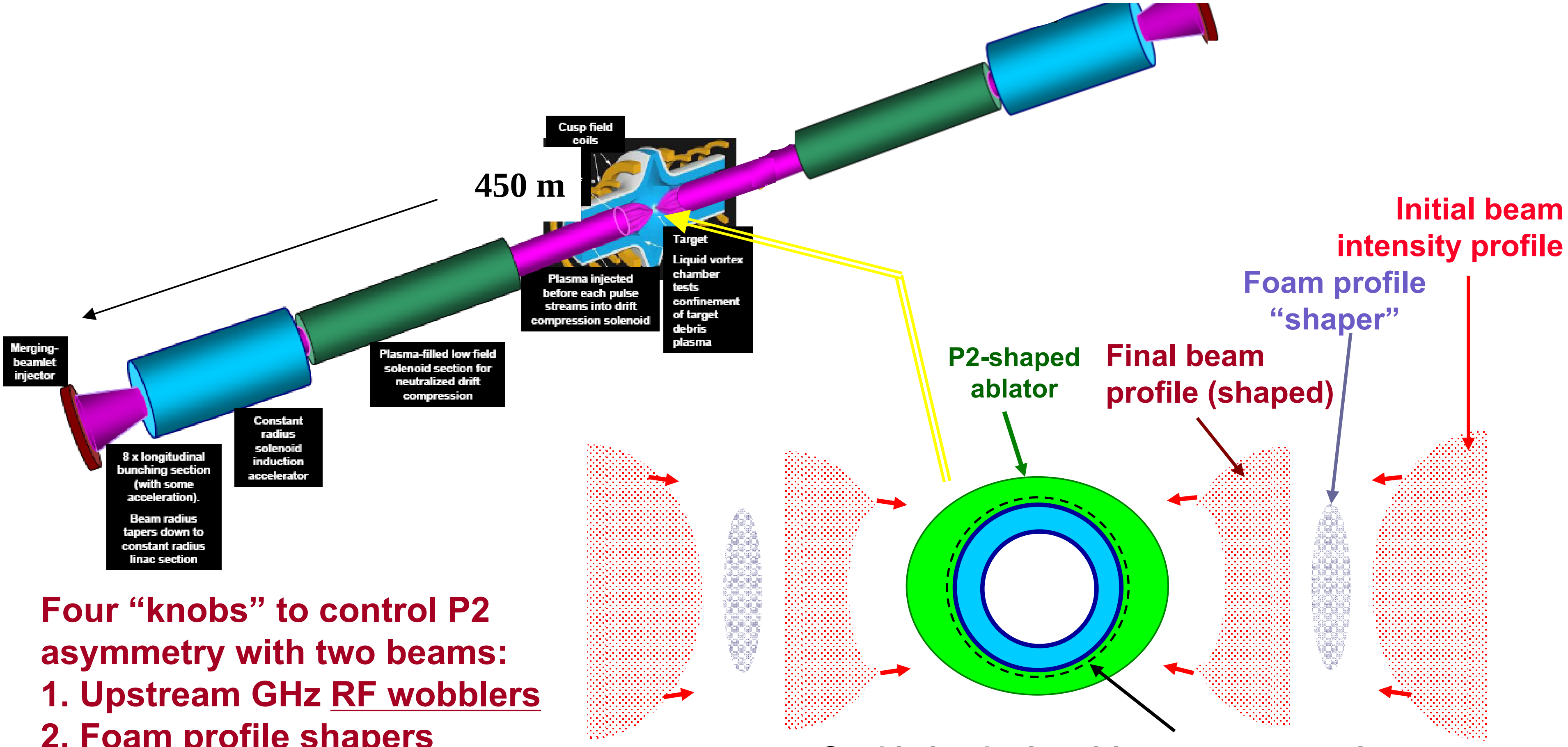


Cells will be refurbished with stronger, pulsed solenoids



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.



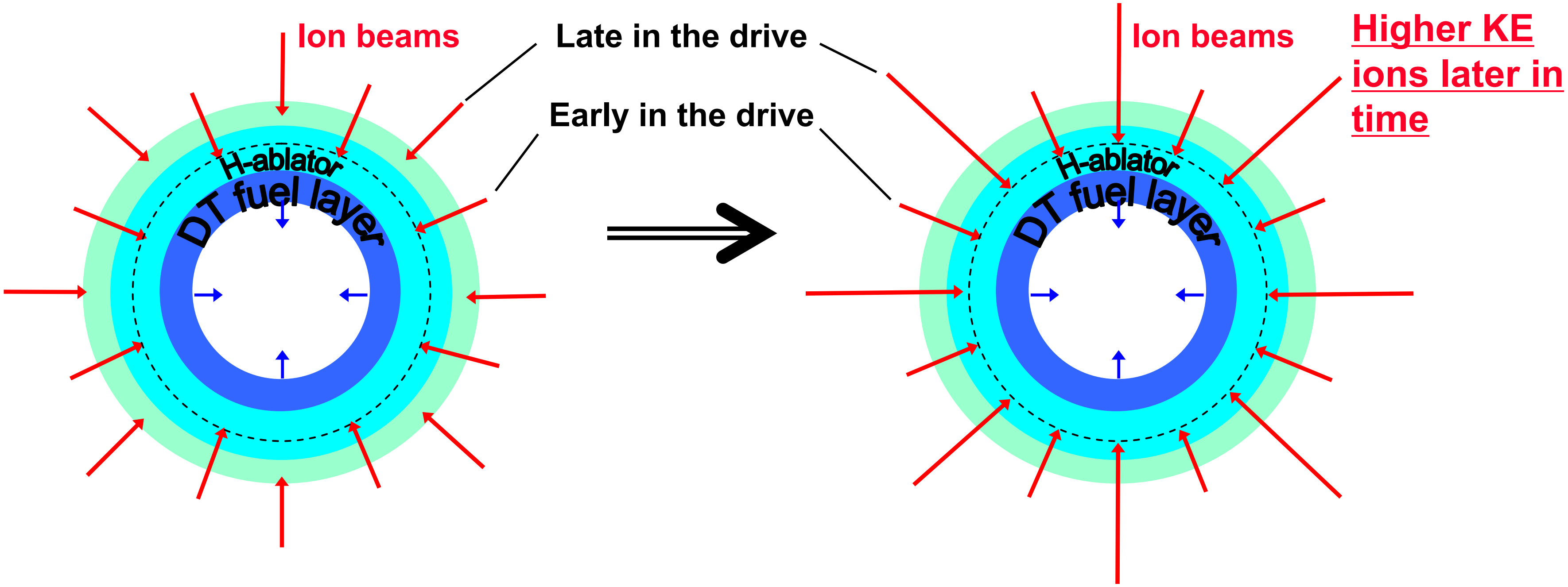
Four "knobs" to control P2 asymmetry with two beams:

1. Upstream GHz RF wobblers
2. Foam profile shapers
3. Ablator shaping (shims)
4. Zooming control

Goal is implosion drive pressure on the Cryo D_2 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:*



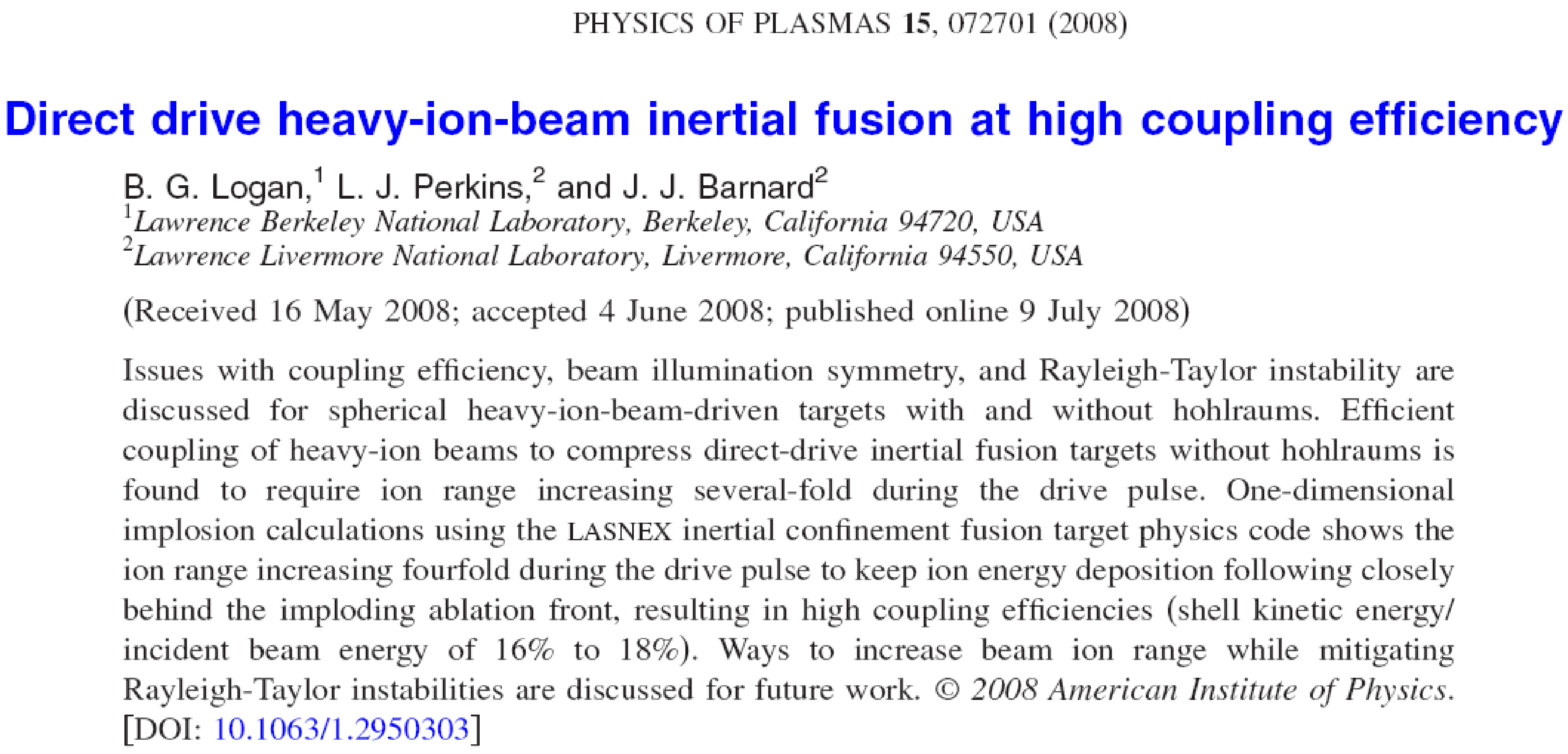
Higher KE ions later in time

***Constant** ion range*

→ decouples

***Strongly-increasing >4X** ion range*

→ high hydro-coupling efficiency!



PHYSICS OF PLASMAS **15**, 072701 (2008)

Direct drive heavy-ion-beam inertial fusion at high coupling efficiency

B. G. Logan,[1] L. J. Perkins,[2] and J. J. Barnard[2]
[1] *Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2] *Lawrence Livermore National Laboratory, Livermore, California 94550, USA*

(Received 16 May 2008; accepted 4 June 2008; published online 9 July 2008)

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?*”

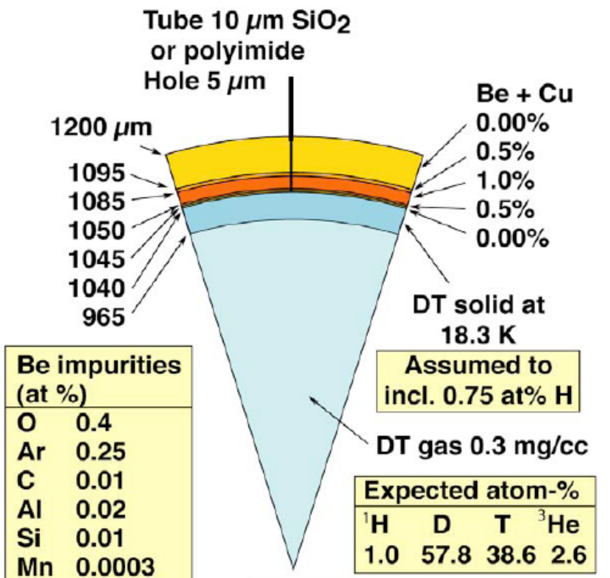
NIF ignition, *if successful*, will validate *15% hydro-coupling efficiency* in ablative capsule drive (capsule gain 100 with 200 kJ x-ray absorbed).

→*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?

1 mm radius Be capsule

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



Be impurities (at %)	
O	0.4
Ar	0.25
C	0.01
Al	0.02
Si	0.01
Mn	0.0003
Fe	0.01
Ni	0.002

Assumed to incl. 0.75 at% H

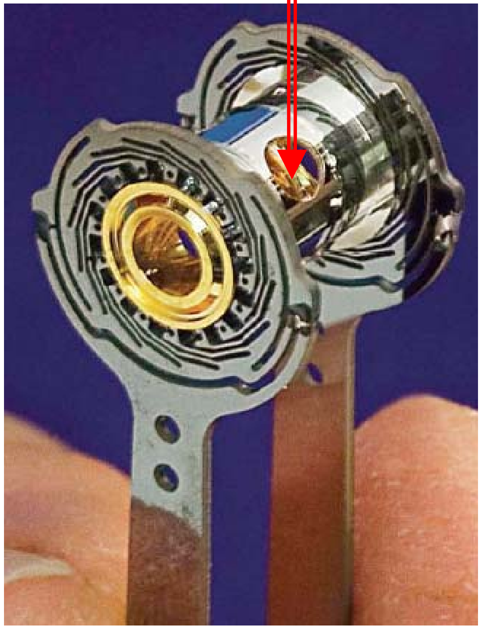
Expected atom-%

^{1}H	D	T	^{3}He
1.0	57.8	38.6	2.6

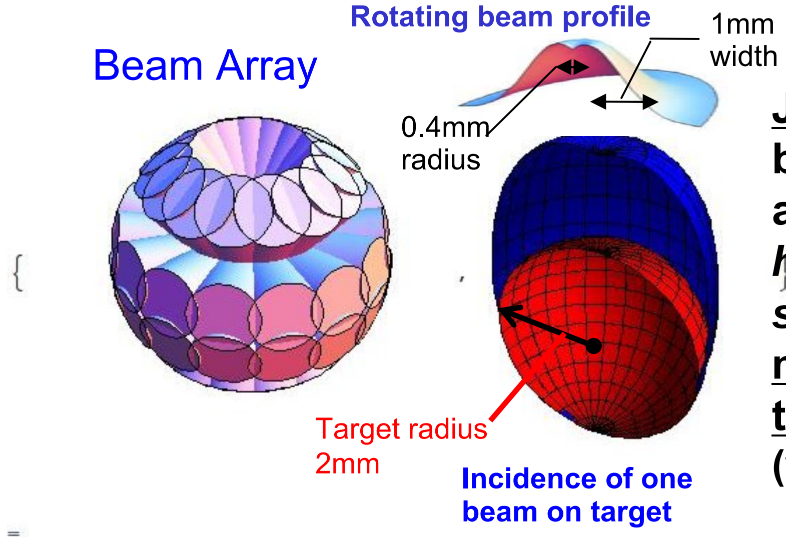
Inner 0.75 μm of Be contains two layers of 12-at% Be(B)

Details in boxes are point-design specifics, not requirements

Parameter	Be(285) "current best calc"
Absorbed energy (kJ)	203
Laser energy (kJ) (includes ~8% backscatter)	1300
Coupling efficiency	0.156
Yield (MJ)	19.9
Fuel velocity (10^7 cm/sec)	3.68
Peak rhoR (g/cm^2)	1.85
Adiabat (P/P$_{FD}$ at 1000g/cc)	1.46
Fuel mass (mg)	0.238
Ablator mass (mg)	4.54
Ablator mass remaining (mg)	0.212
Fuel kinetic energy (kJ)	16.1



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?



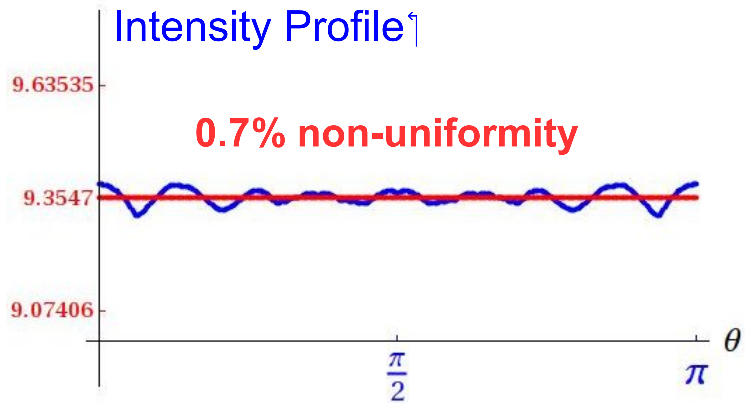
Just four annular rings of beams (15 each, 60 total) at ±37.3° and ±79.3°, *with hollow, rotated beam spot projections* give a maximum deviation from the mean of 0.7% **(with 21% spilled intensity).**

16 each best for two-sided beamline layouts

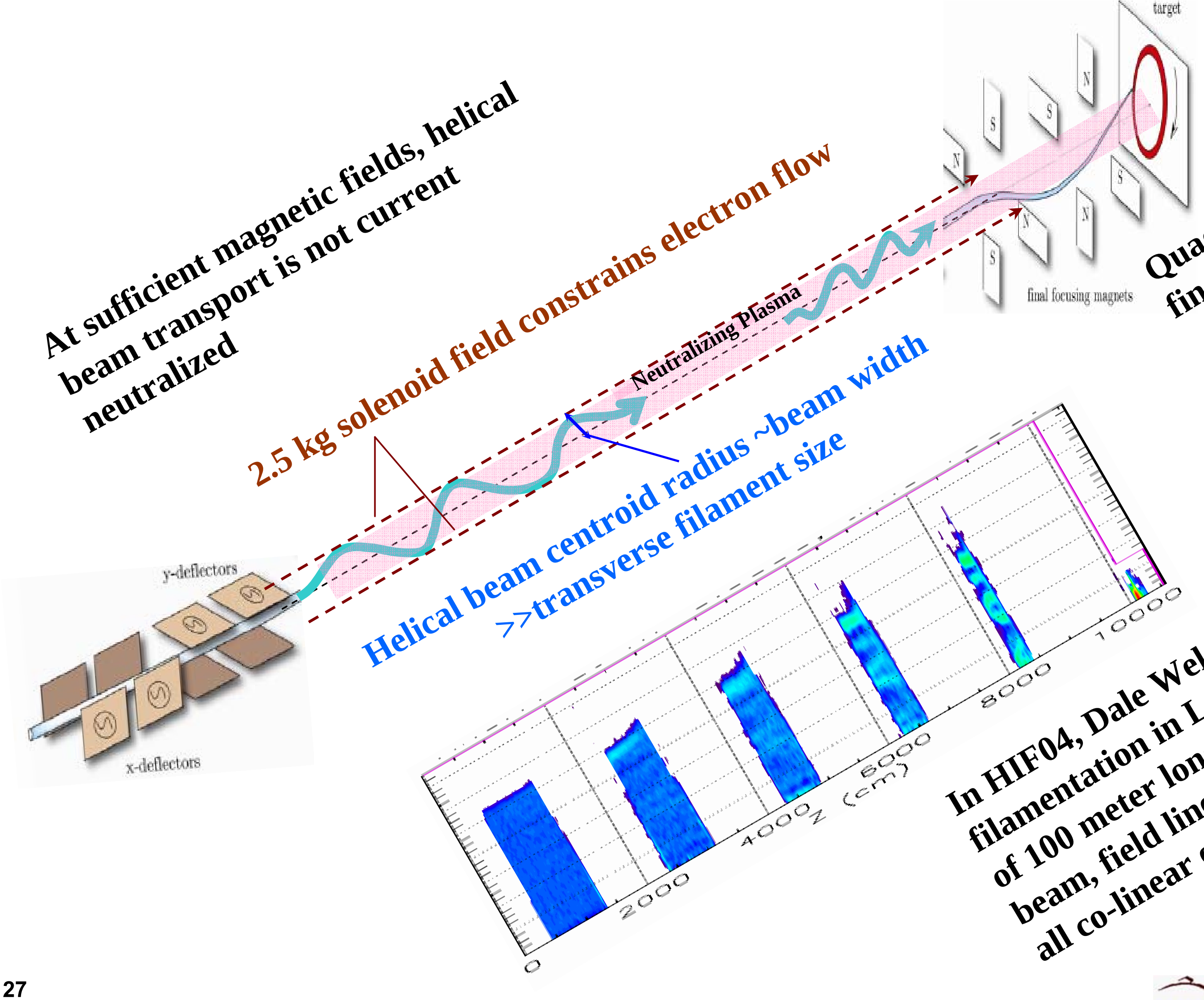
4 polar angles only, *not 4π* !

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



At sufficient magnetic fields, helical beam transport is not current neutralized

2.5 kg solenoid field constrains electron flow

Helical beam centroid radius ~beam width >>transverse filament size

Quads or Solenoid final focus magnets

In HIF04, Dale Welch found filamentation in LSP simulation of 100 meter long NDC: beam, field lines, and electron flows all co-linear over 100 meters!