The US Program in Heavy Ion Fusion Science and Warm Dense Matter*

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Presented to

12th US-Japan Workshop on Heavy Ion Fusion and High Energy Density Physics,

on behalf of the

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

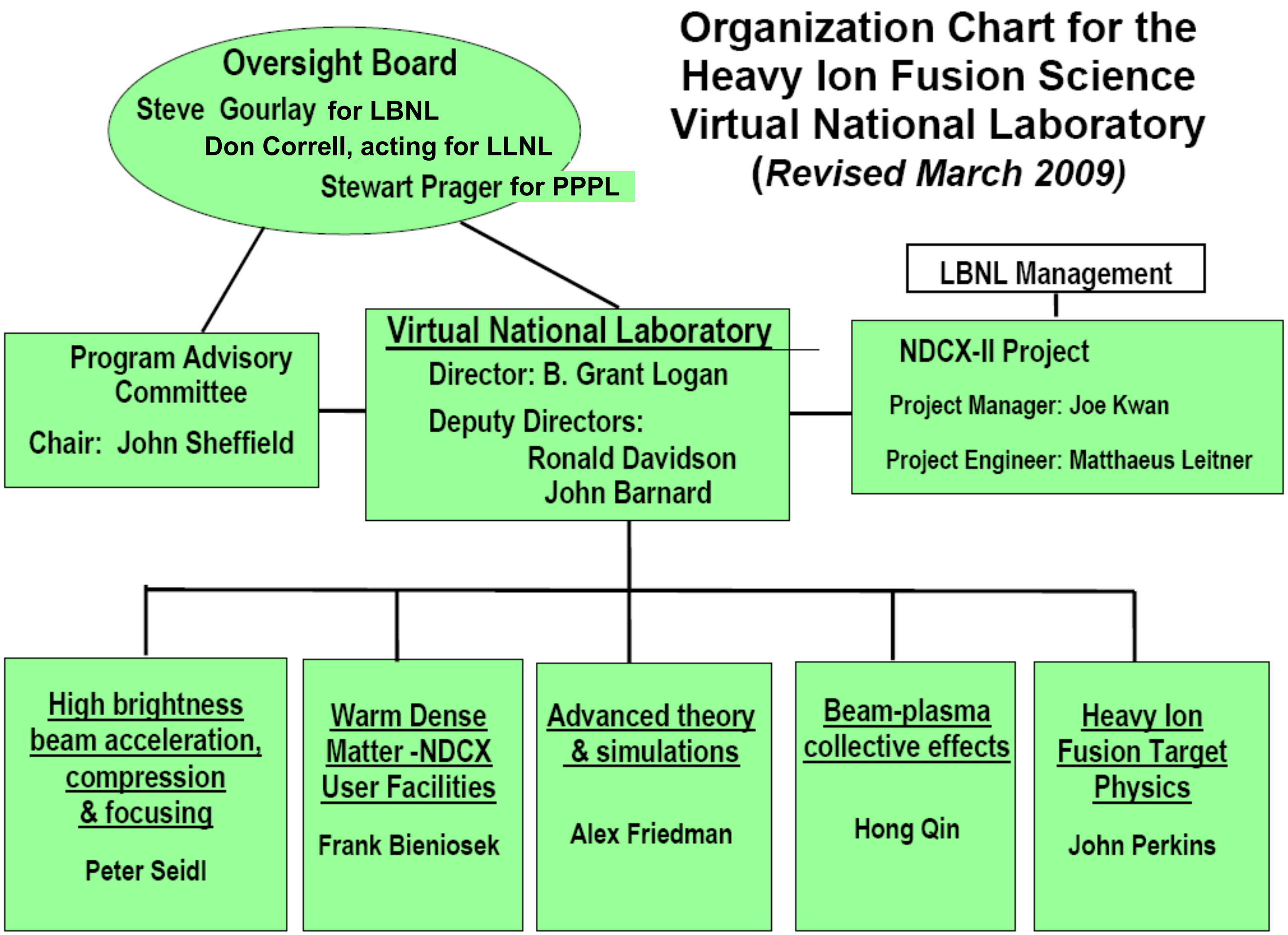
Intercontinental Hotel, San Francisco

September 7-8, 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.**

A recent picture showing some of the HIFS-VNL staff (PPPL staff not present) in the Building 58 experimental area at LBNL.

The research scope of the HIFS-VNL (LBNL,LLNL,PPPL) is now broadened for heavy-ion-beam-driven fusion and HEDP



The revised VNL research scope, including use of NDCX-I and II, addresses research opportunities identified in the Jan 2009 FESAC HEDLP report (see Ron Davidson's talk).

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

Igor Kaganovich will discuss intense beam neutralization physics underpinning many of these areas on Tuesday

The US program of heavy ion fusion (HIF) and high energy density physics (HEDP) is anticipated to grow, *with more effort towards HIF.*

Since the last US-Japan Workshop, several events motivate growth in applications of intense heavy ion beams to fusion and HEDP:

1. **In January, the US Fusion Energy Science Advisory Committee recommended a broader scope of R&D beyond basic HEDP science, *including target and beam physics supporting HIF*. (See Ron Davidson's talk today, and John Perkins's talk tomorrow)**
2. **DOE approved construction funding to start NDCX-II this July. (See Joe Kwan's talk tomorrow regarding the NDCX-II project). *NDCX-II will be used for both IFE and HEDP physics, when it starts operation in FY12, as the FESAC report recommends.***
3. **The US National Ignition Campaign began this March 2009 when NIF construction was completed. DOE expects more support for Inertial Fusion Energy research after NIF ignition is achieved.**

→ The US and Japan can continue dual-benefit R&D towards HIF and HEDP, while we can work together planning to add/ renew R&D in some neglected areas needed for HIF drivers, targets and chambers.

NDCX I is laying the groundwork for NDCX II.

(Frank Bieniosek and Pavel Ni)

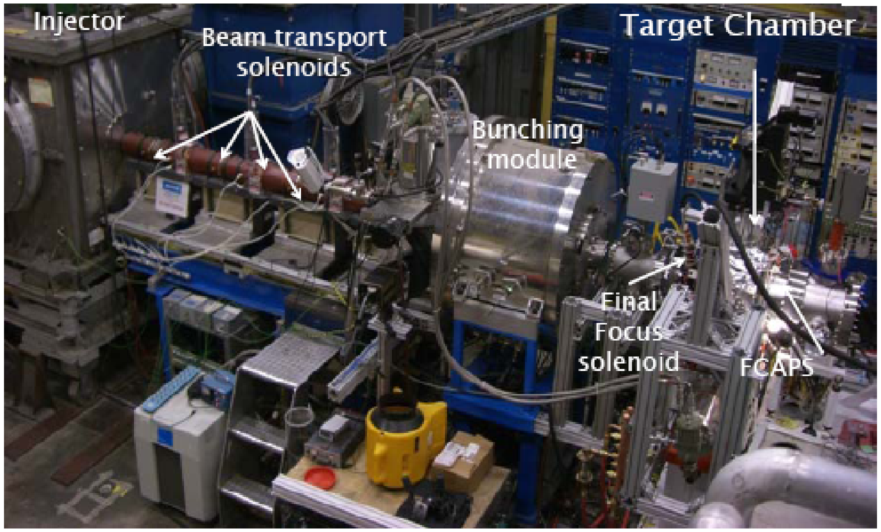
NDCX I

0.35 MeV,

0.003 μC

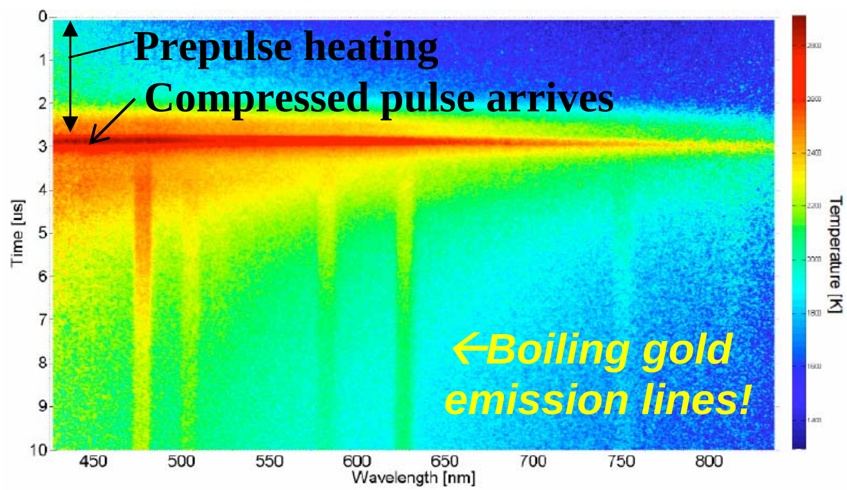
2 ns

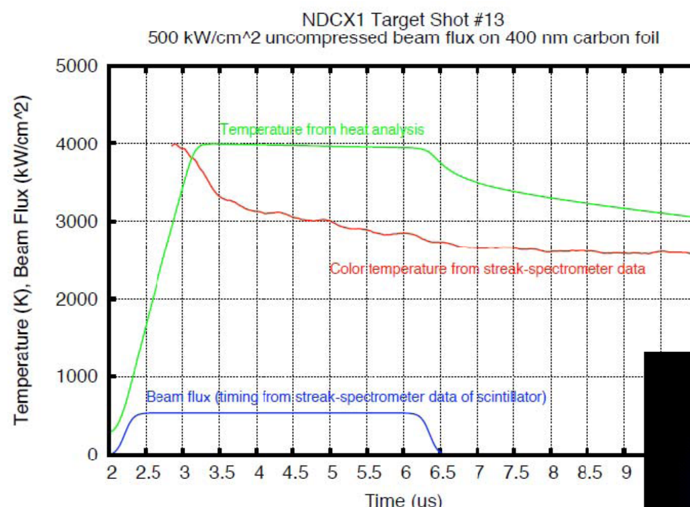
Now

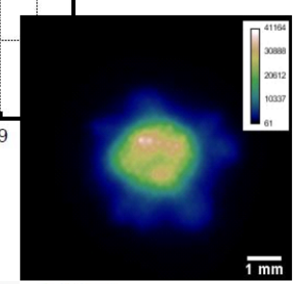


- Explore liquid/vapor boundaries at T ~ 0.4 eV
- Evaporation rates/ bubble and droplet formation
- Test beam compression physics
- Develop diagnostics

NDCX-I targets are getting hotter!



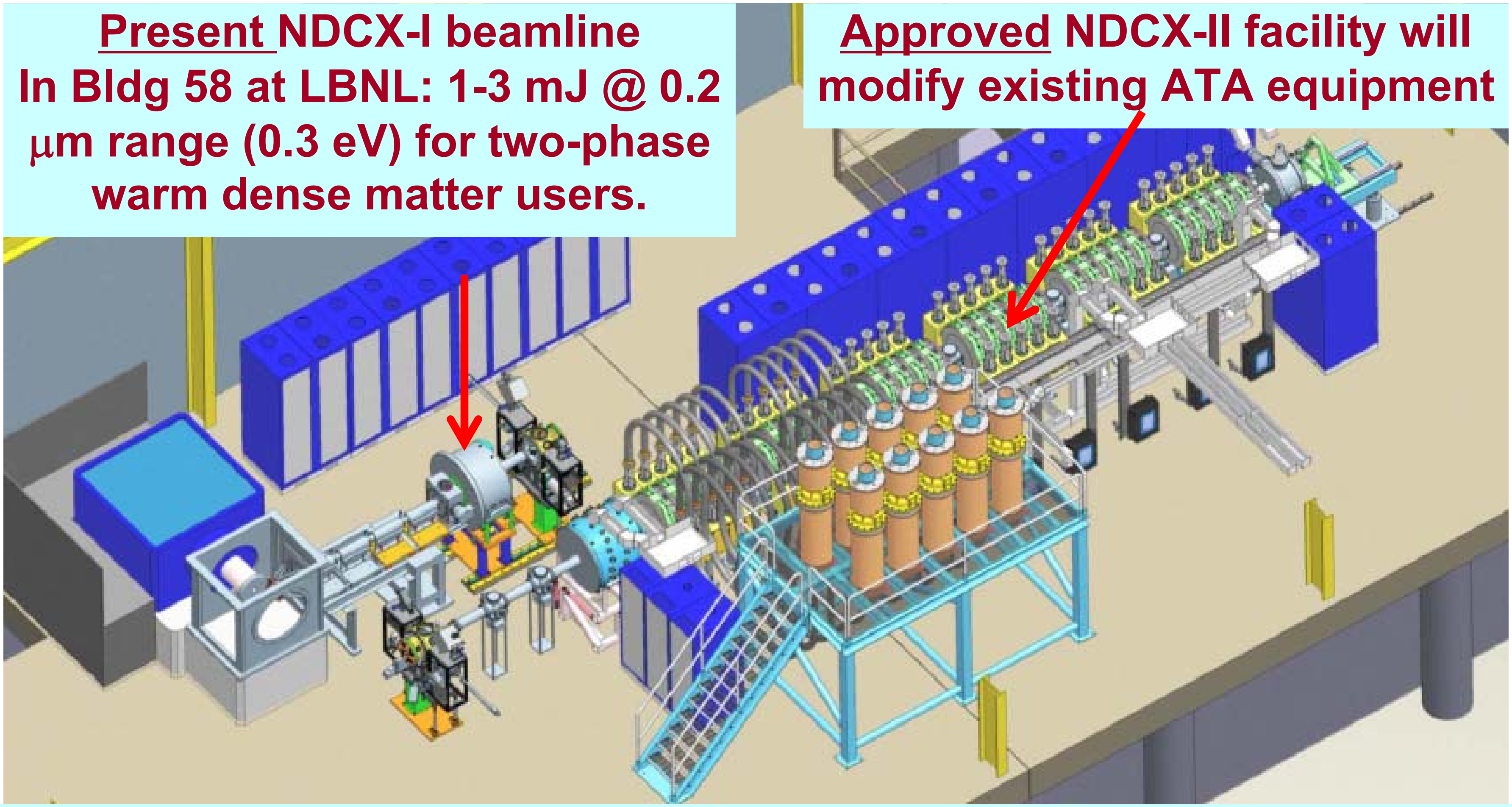




Construction of NDCX-II will enable higher energy WDM and planar direct drive hydro coupling experiments to begin in 2012 (Joe Kwan)

Present NDCX-I beamline In Bldg 58 at LBNL: 1-3 mJ @ 0.2 μm range (0.3 eV) for two-phase warm dense matter users.

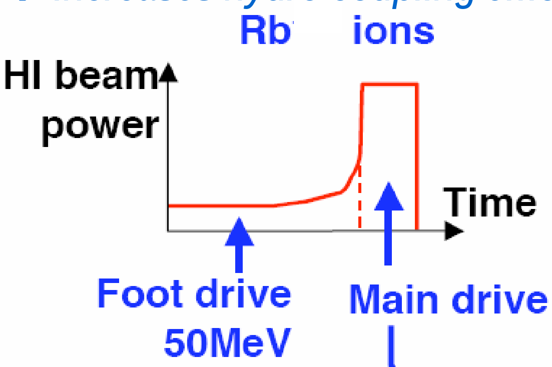
Approved NDCX-II facility will modify existing ATA equipment

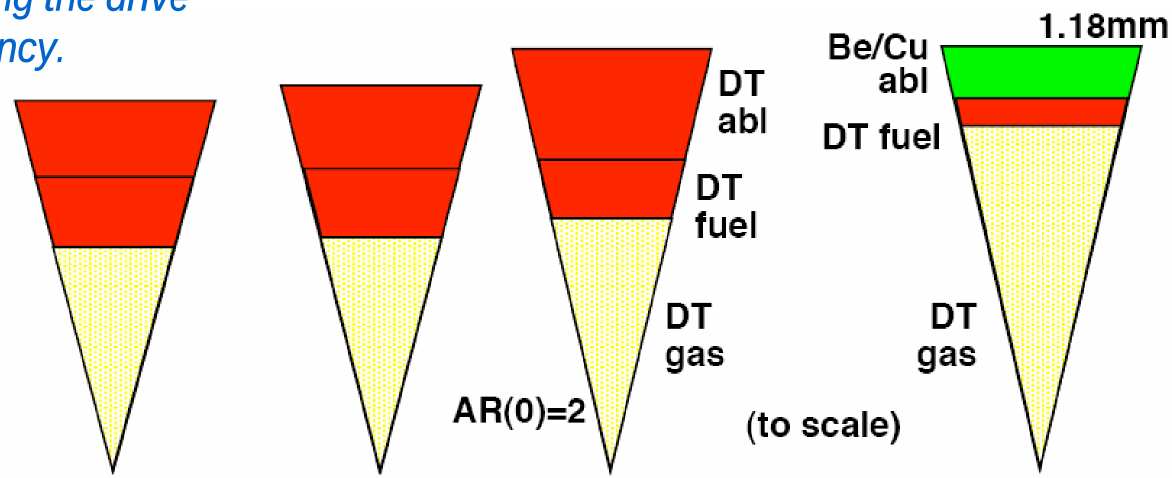


NDCX-II will increase beam power on target 100 times NDCX-I
→ enables WDM > 1 eV and direct drive hydro-coupling experiments.

NIF ignition could validate key requirements for adequate gain HIF achievable in NIF-similar-scale fuel capsules *using direct drive @ 300-500 kJ driver energy. John Perkins, February 2009)*

Ion energy and range increase during the drive
→ increases hydro coupling efficiency.

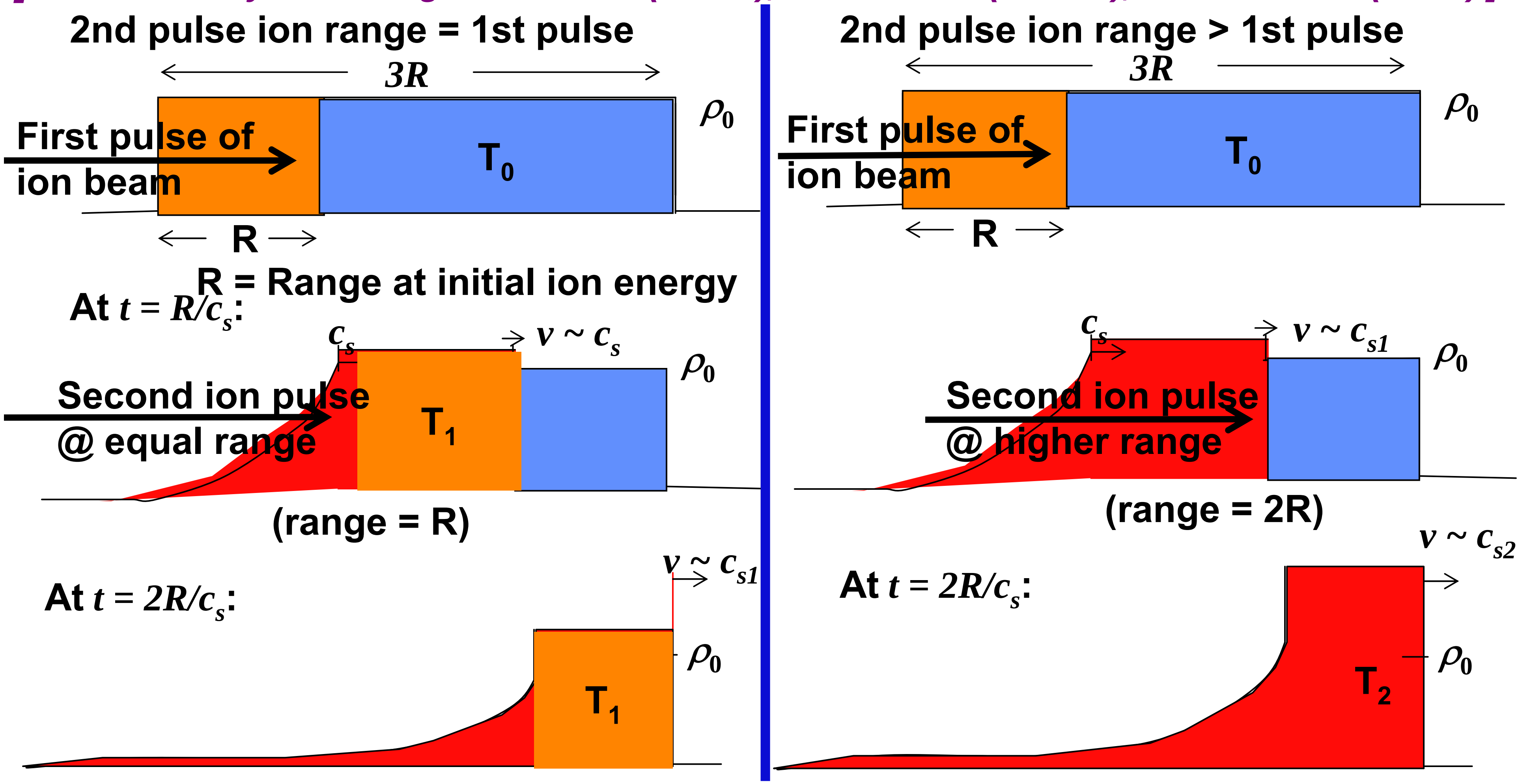




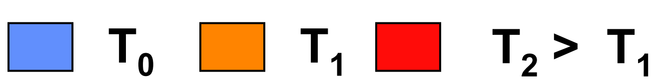
	50MeV	200MeV	500MeV	NIF
$m_{ablator}/m_{fuel}$	1.8	2.1	3.0	18
Driver energy (MJ)	0.32	0.36	0.44	1.3
Peak drive power (TW)	175	195	205	320
Yield (MJ) / Gain	24.7 / 77	21.6 / 60	20.8 / 47	20.0 / 15
$\eta_{absorbed}$ / η	0.97 / 0.10	0.91 / 0.10	0.88 / .09	0.16 / 0.02
In-flight aspect ratio	25	27	25	32
Convergence ratio	35	30	31	34
In-flight adiabat α	1.9	2.4	3.2	1.4

NDCX II can explore improvement in hydro-coupling efficiency with increasing ion range, either ramped or double pulse.

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



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



Several plenary talks at this IFSA 2009 show that major plans for laser-based Inertial Fusion Energy R&D are underway worldwide

- Key 1.01 Kunioki Mima (Included R&D plans for "LIFT" -a fast ignition based fusion DEMO test facility proposed by ILE, Osaka).
- Key 1.03 John Nuckolls (Proposed initiation of R&D for IFE on a "faster track")
- Plenary 2.0.1 Ed Moses "Overview and IFE vision (LIFE)"
- Oral 3.3.1 Carlo Alberto Cecchetti "HIPER-towards a high repetition rate target area"
- Oral 3.3.4 John Caird "Diode Pumped Solid State Laser (DPSSL) Design for Laser Inertial Fusion Energy (LIFE)"
- Oral 4.1.3 Christopher Edwards: "HIPER-the European Path to Inertial Fusion Energy".

NIF ignition should renew interest not only in laser IFE, but also in Heavy Ion Fusion, for reasons that still apply today

- 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)

Its time to re-examine options, issues and R&D facilities for heavy ion fusion R&D (example Tables are incomplete-need to be filled-in)

Example HIF driver options, some associated key issues & R&D facilities

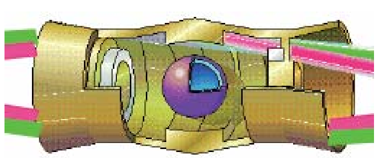
HIF Driver Options	Multi-beam LIA-magnetic quadrupole	Multi-beam LIA magnetic solenoids	Multi-beam LIA- electric quadrupoles	Modular set single-beam LIA-solenoids	Induction Synchrotron , RF linacs
Key Issues	SC magnet cost and multi-beam E-cloud issue	SC magnet cost & multi-solenoid field asymmetries	Limited λ_b & longitudinal compression under accel.	Efficiency>0.2 requires high λ_b>100 μC/m >2 kA/beam!	Viable only for 100 GeV targets? # of beams > 1?
R&D Facilities -up to non-ignition scale implosions	**Modified HCX** + 10 kJ IRE scale linac for direct drive exp. or MJ-scale for indirect drive	**Modified HCX** + 10 kJ IRE scale linac for direct drive exp. or MJ scale for indirect drive	**Modified** HCX + 10 kJ IRE scale linac for direct drive or MJ scale for indirect drive	**NDCX-II** experiments using higher q/A ions + 10 kJ IRE scale linac for direct drive	**KEK-AIA?** 10 kJ scale accelerator tests, then MJ scale for implosion test

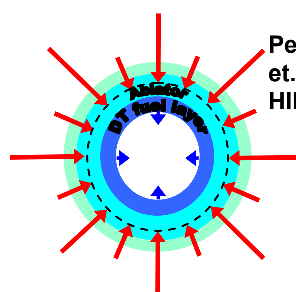
→Peter Seidl will be organizing HIF "Renew" workshops (soon-dates TBD)

Example HIF target options, associated issues, R&D facilities

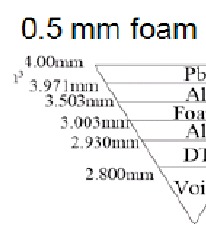
HIF Target Options	Indirect-Drive Hohlraum, cylindrical, two sided illumination	Direct-drive, ablative, multi-polar angle ring illumination	Direct/Indirect "Cannonballs" (Spherical hohlraums)	Direct-drive Cylindrical (ITEP-TWAC)- Fast Ignition
Key Issues	Low ~<2% coupling efficiency→7 to 8 MJ (RPD)	High contrast pulse shape, beam balance, # beams need	Case losses, minimum Tr for radiation coupling test	Cost of 100 GeV, 10 MJ beams, beam spot rotation
R&D facilities (*non*-ignition scale)	1 GeV, > 1 MJ, >60 beams,~ 0.5 mm spots for hohlraum implosion test	HIDDIX (IRE~ 100 MeV, 10 kJ scale, 60+ ? beams for cryo implosion test	~> 1 GeV, > 1 MJ, spot size < 1 mm, > 60? beams for implosion test	TWAC, KEK-AIA? Beam requirements for implosion test?

(Callahan, et.al. HIF-04)



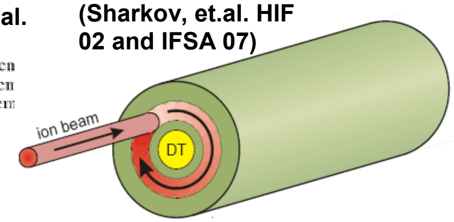


Perkins, et. al. HIF08



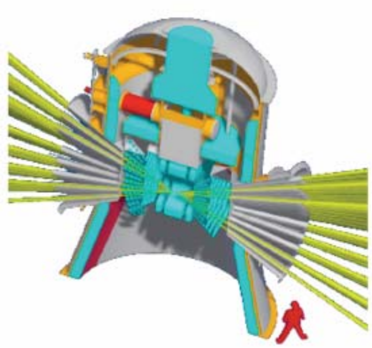
(Kawata, et.al. IFSA 07)

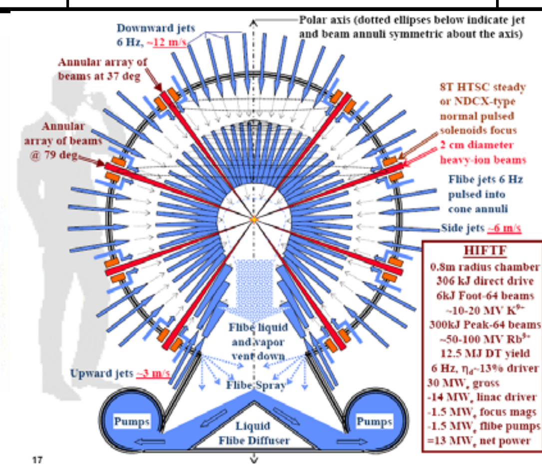
(Sharkov, et.al. HIF 02 and IFSA 07)

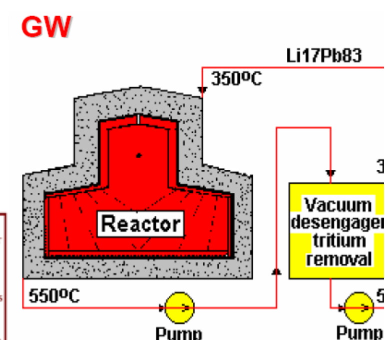


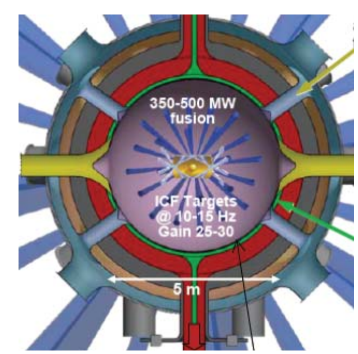
Example HIF chamber options, associated issues, and R&D facilities

HIF Chamber Options	**Thick liquid chambers- oscillating jets** (HYLIFE)	**Pulsed radial liquid jets, polar geometry** (TOFE 08)	**Thin liquid metal surface-protected chambers** (ITEP)	**Solid wall, gas protected Dry wall** (LIFE)
Key Issues	Pumping power, oscillating nozzles, pulse rates < 6 Hz	Pumping power, precision jet control for polar beam ring access	Recovery rate for re-wetting walls. Neutron damage to structures.	Cryo targets in 6000K hot gas, solid wall metal dust blowout
R&D facilities (*non*-ignition scale)	1 M $ scale exp. followed by 10 M$ scale hydro-equiv water simulator tests	1 M $ scale exp. followed by 10 M$ scale hydro-equiv water simulator tests	1 M $ scale exp. followed by 10 M$ scale hydro-equiv Hg or NaK metal film recovery test	Collaborative experiments in planned LLNL Mini-Chamber facility for LIFE









Summary

- NDCX-I has established credibility 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 funding allows the Heavy Ion Fusion Science Virtual National Laboratory to pursue research opportunities identified in the FESAC-HEDLP report and to pursue our roadmap towards heavy ion fusion.
- Commencement of the NIF Ignition Campaign, together with NDCX-II funding and advances in high beam coupling efficiency for heavy ion direct drive, motivate preparations and planning for a significant growth in the HIF program, restarting accelerator driver chamber and target research, once NIF achieves ignition.

Backup slides

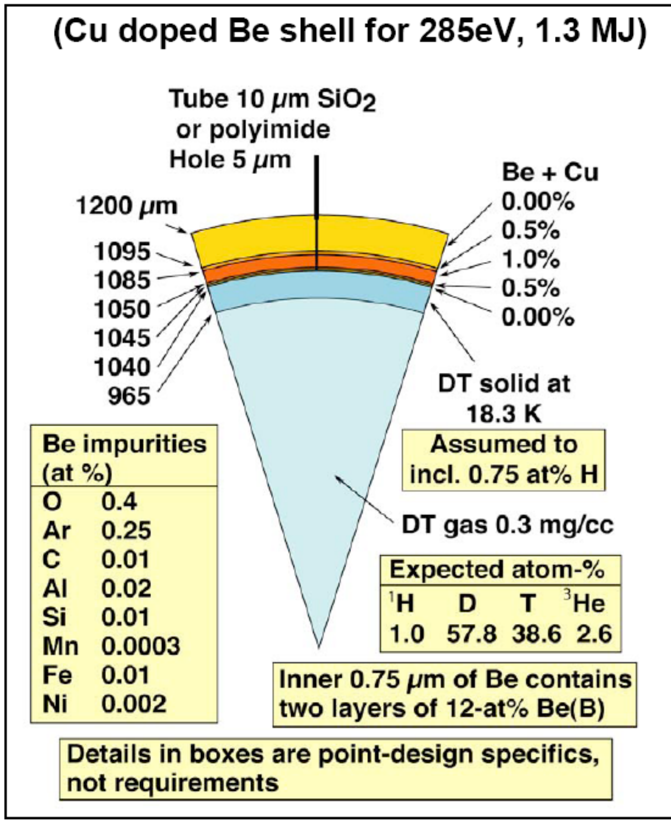
NIF ignition, *if successful*, will validate *15% hydro-coupling efficiency* in ablative capsule drive (capsule gain 100 with 200 kJ x-ray absorbed).

→*Idea for an HIFTF test facility:*

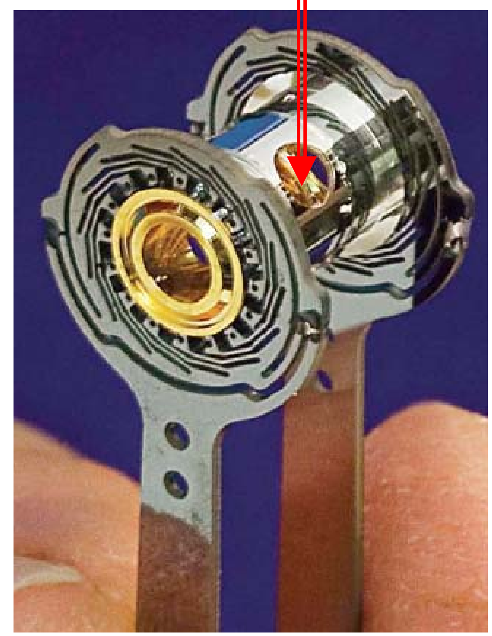
LASNEX giving the same coupling efficiency, could 200 kJ of ions absorbed (300 kJ incident with spill) with *same power vs time and the right range into H/DT ablators* get gain >50?

1 mm radius Be capsule

The National Ignition Campaign



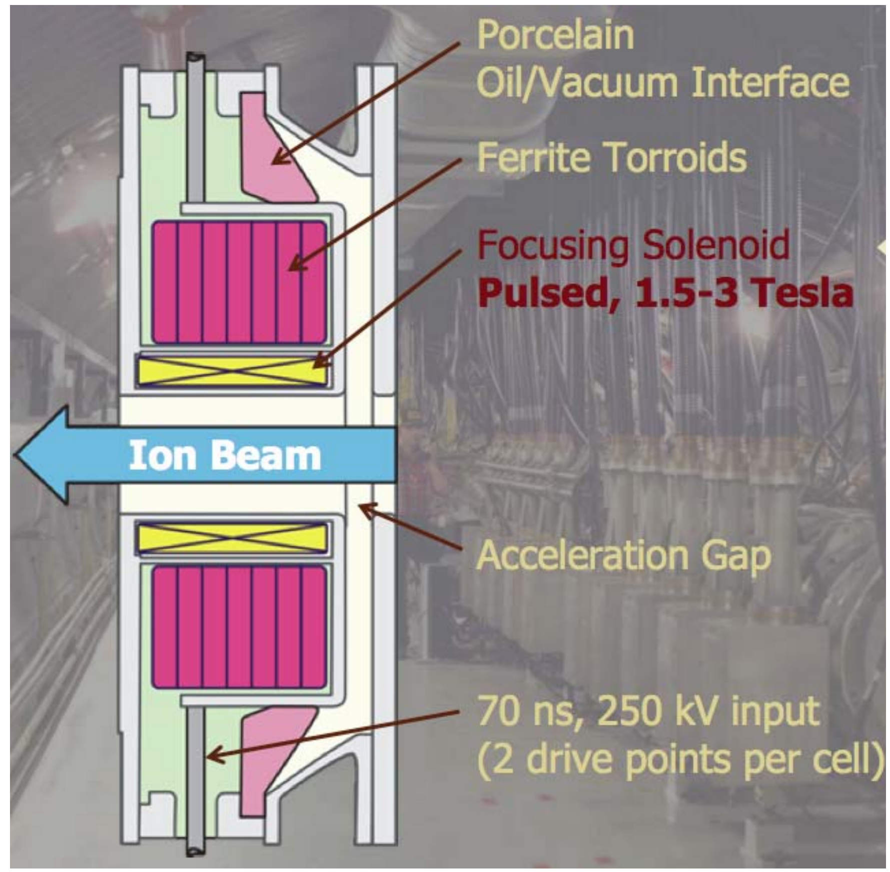
Parameter	Be(285) "current best calc"
Absorbed energy (kJ)	203
Laser energy (kJ) (includes ~8% backscatter)	1300
Coupling efficiency	0.156
Yield (MJ)	19.9
Fuel velocity (10^7 cm/sec)	3.68
Peak rhoR (g/cm^2)	1.85
Adiabat (P/P_{FD} at 1000g/cc)	1.46
Fuel mass (mg)	0.238
Ablator mass (mg)	4.54
Ablator mass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

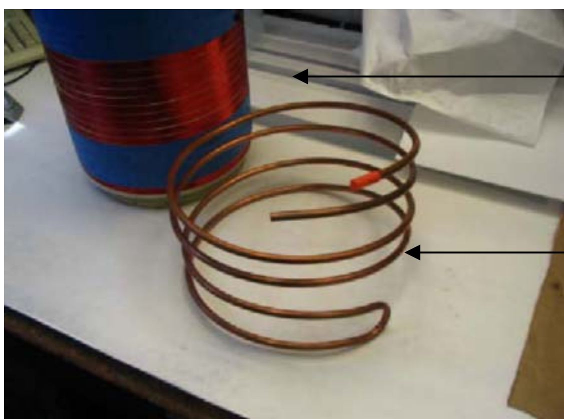


Induction cells for NDCX-II are available from LLNL's decommissioned ATA facility

Test stand has begun to verify performance

Cells will be refurbished with stronger, pulsed solenoids



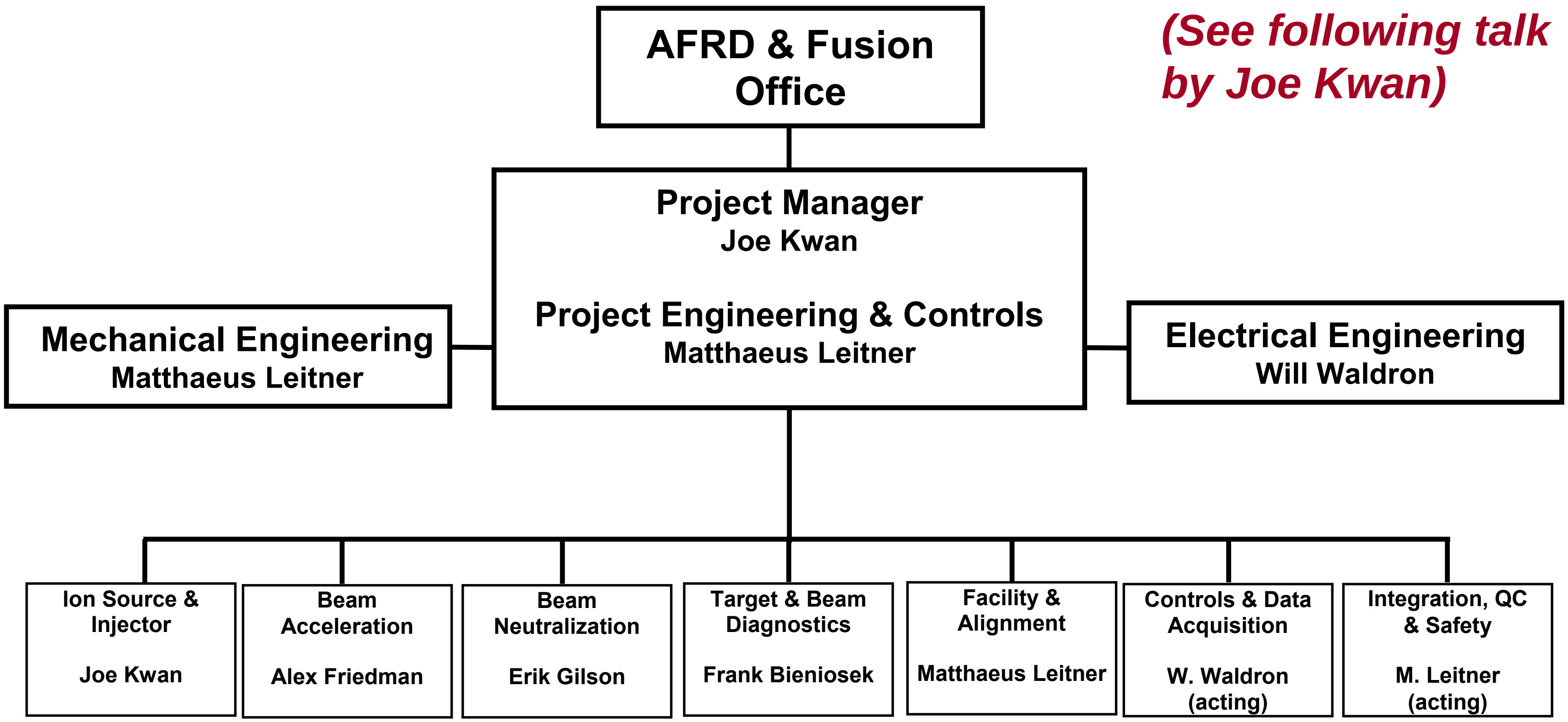


solenoid

water cooling

The HIFS-VNL program Advisory Committee endorsed the NDCX-II *approach* utilizing existing ATA accelerator components. We initiated tests for refurbishment of ATA components last year. *There will be a Lehman review of cost, schedule and risk management plan in October.*

(See following talk by Joe Kwan)



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

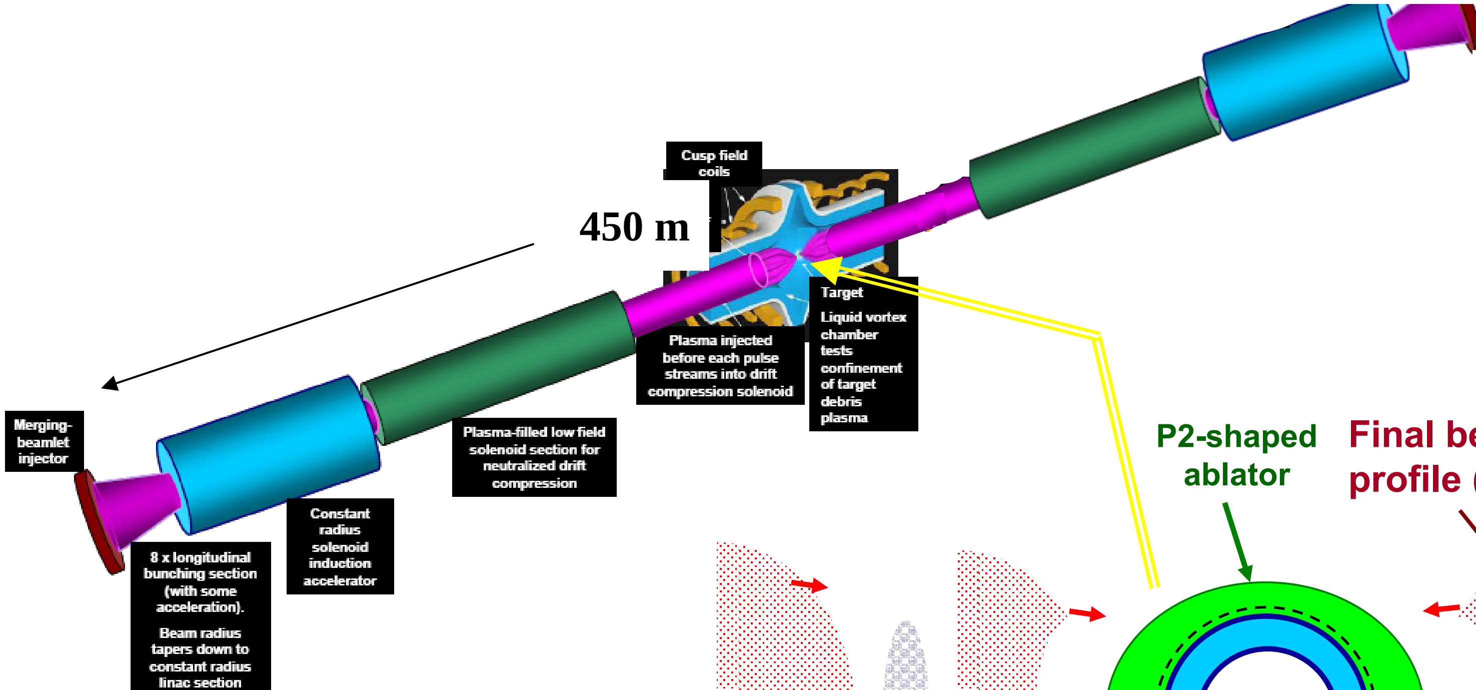
NIF ignition needed before these steps

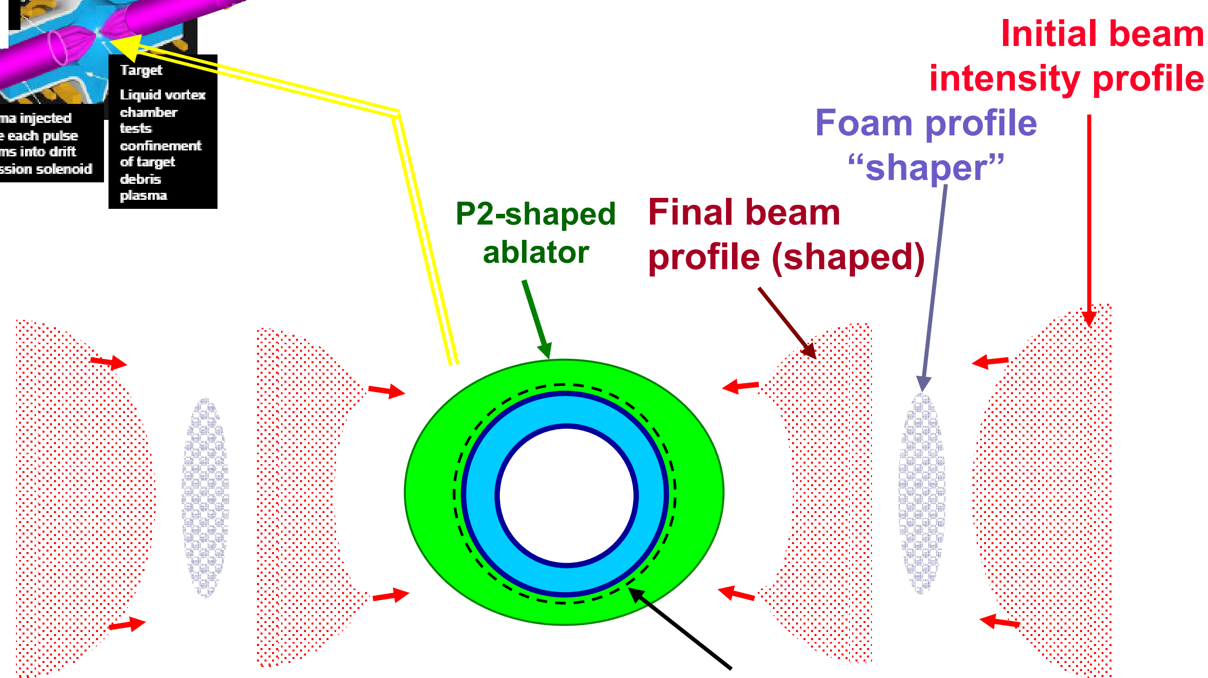
Proposed funding by year for long range HIFS-VNL research plan

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**

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.





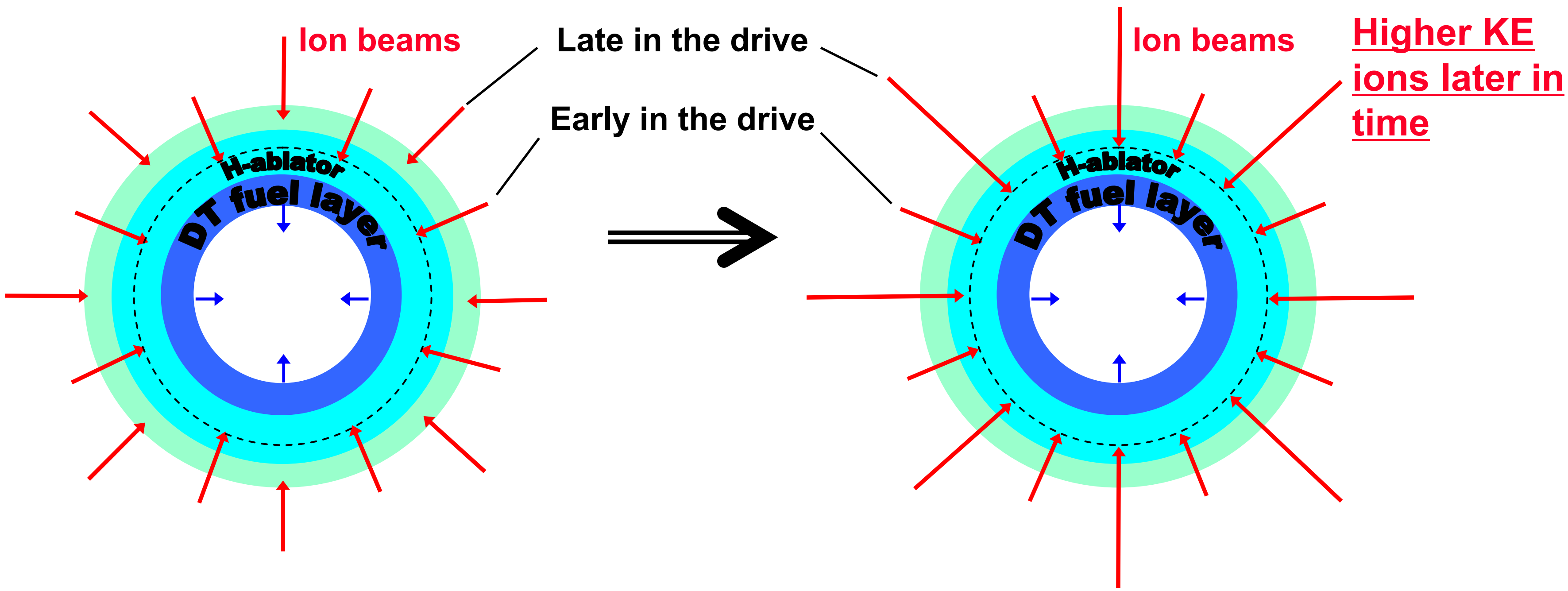
Four "knobs" to control P2 asymmetry with two beams:

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:*



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

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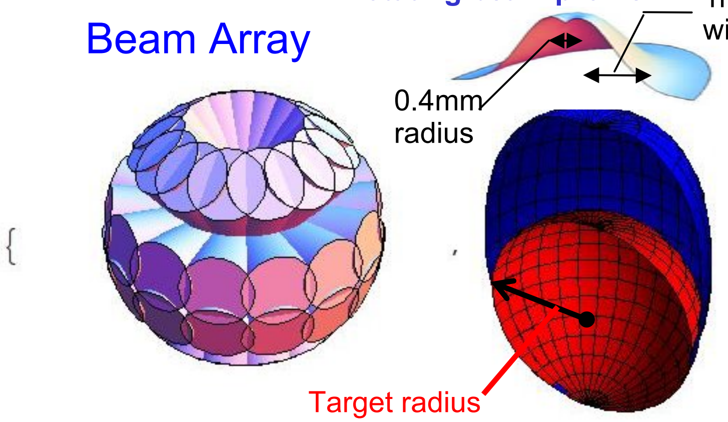
(Received 16 May 2008; accepted 4 June 2008; published online 9 July 2008)

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.
[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?*"

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?

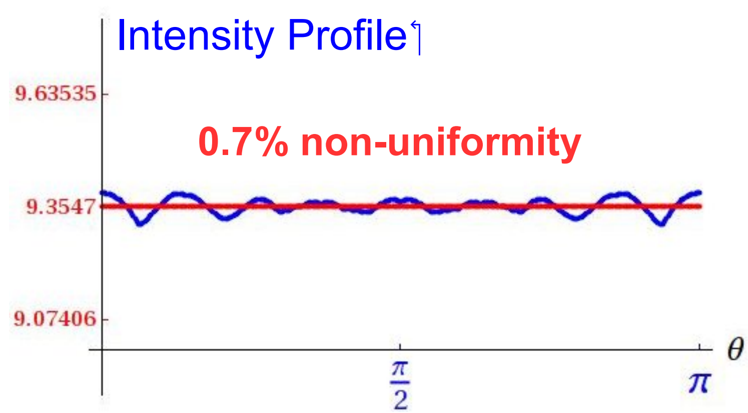


16 each best for two-sided beamline layouts

<u>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%</u> (with 21% spilled intensity).

4 polar angles only, *<u>not 4π!</u>*

(To be published in Physics of Plasmas)



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.

Beam filamentation (Weibel) instability should be investigated with *rotating helical beams* during NDC