A new vision for Heavy Ion Fusion*

Presented by B. Grant Logan

on behalf of the

U.S. Heavy Ion Fusion Science Virtual National Laboratory

(LBNL, LLNL, and PPPL)

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LBNL and LLNL

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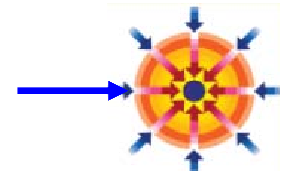
Advances in U.S. Heavy Ion Fusion Science support a sequence of heavy-ion-beam-driven facilities for HEDP <u>and</u>

...exploiting the intrinsic high efficiency of velocity ramped-heavy ion beams <u>for direct drive</u>



Anders, A.[1], Barnard, J. J.[2], Bieniosek, F.M.[1], Briggs, R.J.[1], Cohen, R.H.[2], Davidson, R.C., [3] Dorf, M.[3],Efthimion, P.C. [3], Faltens, A.[1], Friedman, A.[2], Greenway, W.G.[1], Gilson, E.P.[3], Grisham, L.[3], Grote, D.P.[2], Haber, I.[5], Henestroza, E.[1], Jung, J-Y.[1], Kaganovich, I.[3], Kisek, R.[5], Kwan, J.W.[1], Lee, E. P.[1], Leitner M.[1], Lidia, S.M.[1], Logan, B.G.[1], Lund S.M.[2], Moir, R.W.[2],Molvik, A.W.[1], More, R.M.[1], Ni, P.A.[1], Perkins, L. J.[2],Qin, H.[3], Rose, D.V.[4], Roy, P.K.[1], Startsev, E.A.[3], Seidl, P.A.[1], Sharp, W.M.[2], Vay, J-L.[1], Waldron, W.L.[1], Welch, D.R.[4], Yu, S. S.[1]

1. Lawrence Berkeley National Laboratory
2. Lawrence Livermore National Laboratory
3. Princeton Plasma Physics Laboratory
4. Voss Scientific, Inc.
5. University of Maryland

Scientific objectives and key features of a sequence of heavy-ion-beam driven facilities for high energy density physics and fusion

Ranges given in table reflect options under study

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}, or Na^{+3}	3.5 - 5	3.5 - 15	0.1 - 0.28	1-2 (or 5 w hydro)	7 - 4 (in solid Al)	0.25 to 1
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

Table 4.1, page 43 of an HIF White Paper available upon request

Recent innovations, together with NIF ignition, support a new vision for heavy ion fusion:

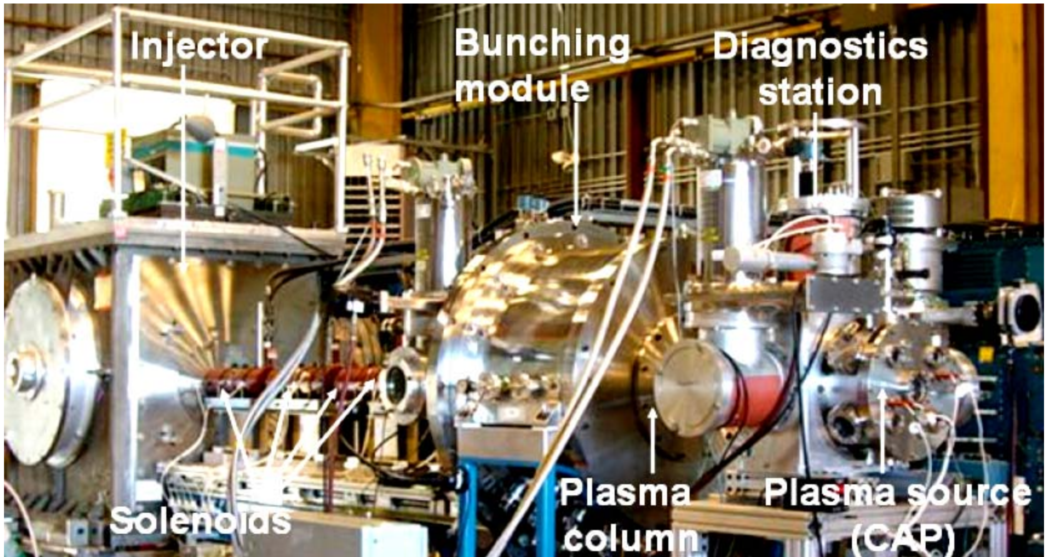
- **Heavy ion beam intensity increases > 1000X with velocity increasing in time with space charge neutralized by background plasma.** *[Neutralized Drift Compression Experiment (NDCX): P. K. Roy, et. al. Phys. Rev. Lett. 95, 234801 (2005), and J.E. Coleman et al., in Proc. of the 2007 Particle Accelerator Conf., Albuquerque, NM, 2007(IEEE catalog# 07CH37866, USA, 2007). Time-dependent chromatic focusing correction experiment planned in NDCX next year].*

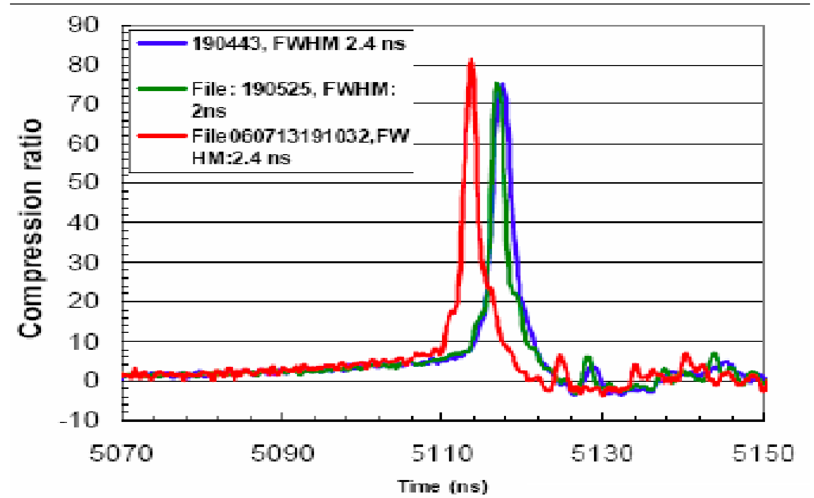
- **High coupling efficiency of heavy ion beam direct drive in ablative rocket regime *(also uses beam velocity increasing in time).*** *[B. G. Logan, L. J. Perkins, and J. J. Barnard, Phys. Plasmas 15, 072701 (2008)].*

- **Beam spot rotation on target with helical RF-beam perturbations upstream** *[B. Sharkov (Russia), S. Kawata (Japan), H. Qin (USA)]*→ **enables direct drive with only 4 polar angles @< 1% non-uniformity for direct drive** *[J. Runge, Germany].*

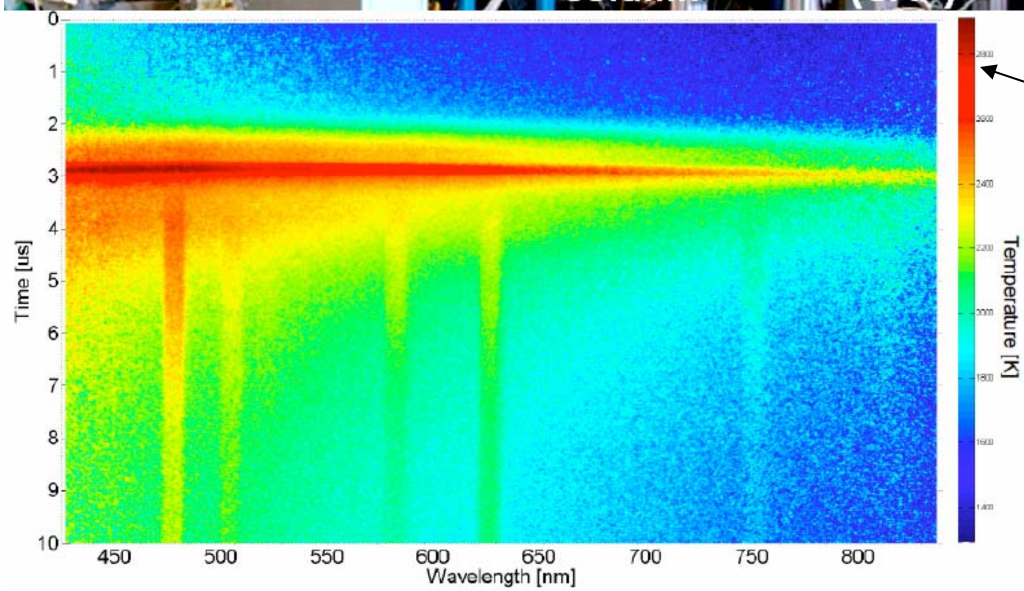
- **New agile on/off valve technology for liquid jets adapted to provide thick liquid protection for direct drive chambers.** *[R. Moir, LLNL, 1999 HYLIFE note and recent advances-see http://videos.komando.com/2008/08/19/water-painting/].*

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

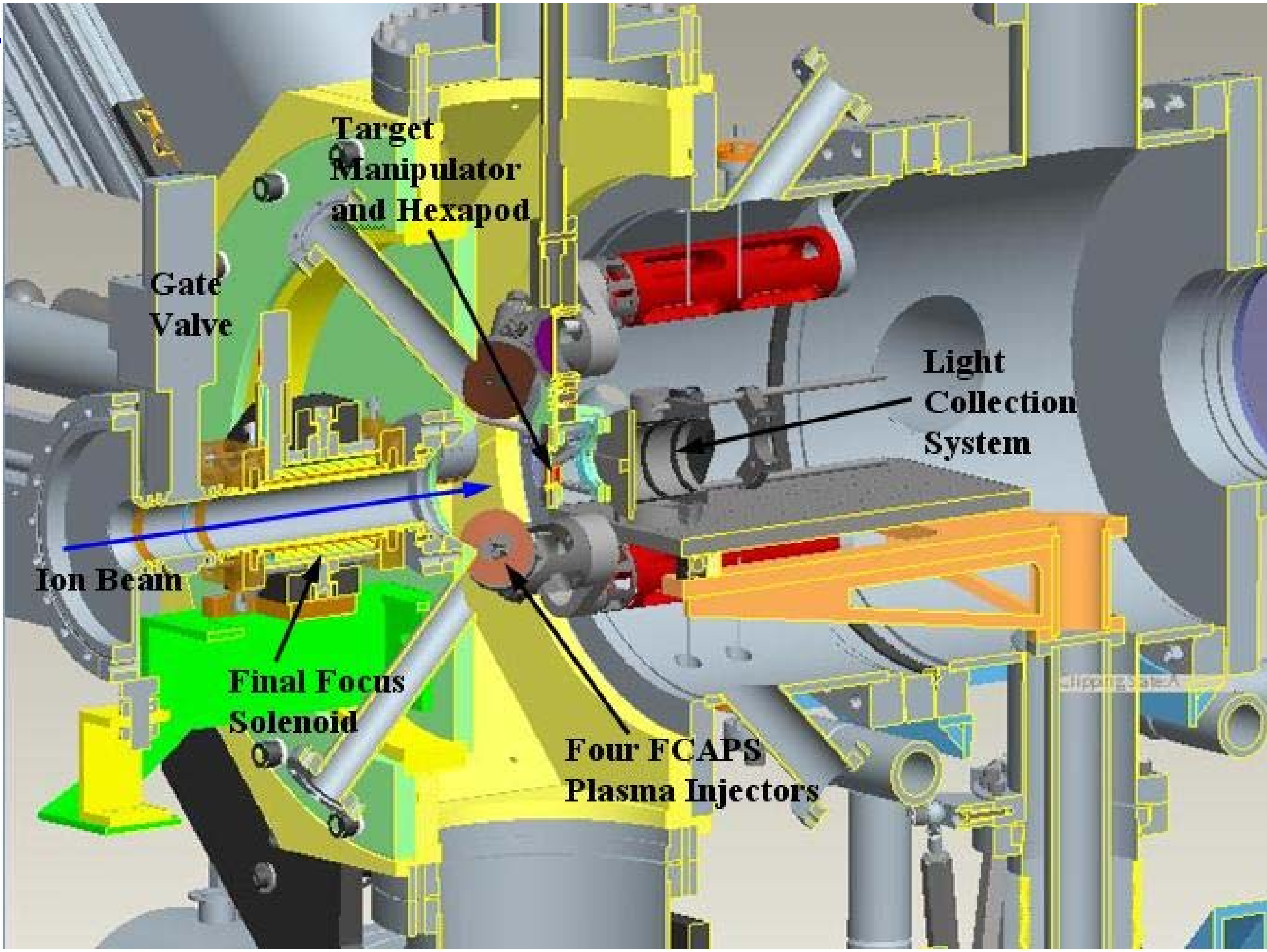


2800 K (*will be higher after emissivity correction*)

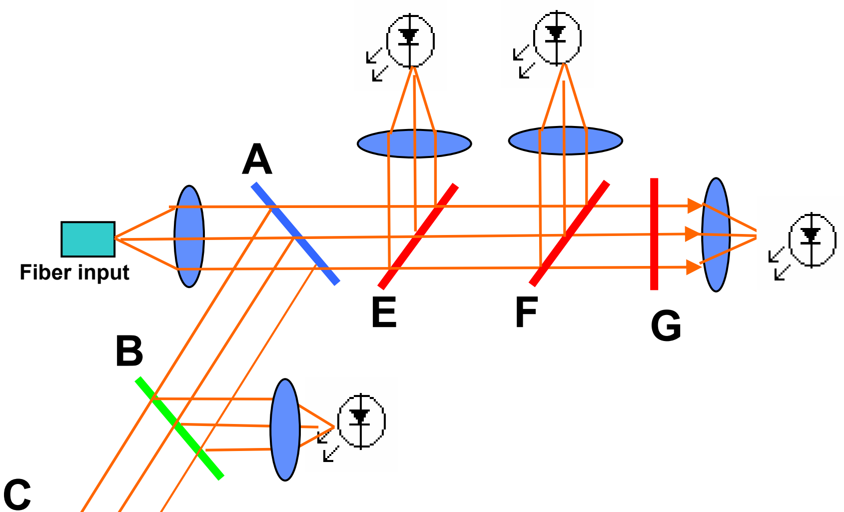
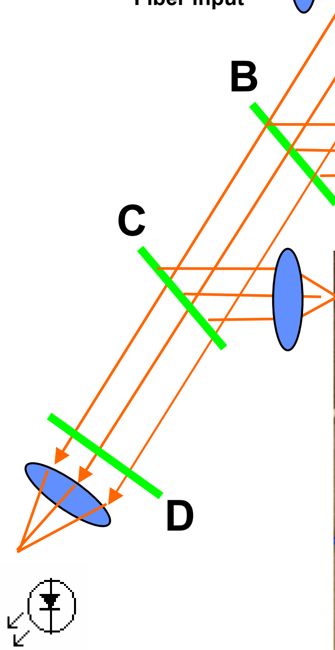
← time of arrival of 2 ns compressed pulse onto 100 nm gold foil target after 3 μs of uncompressed beam preheating. Streak camera spectra showing emission lines from gold vapor indicating temperatures above 3100 K.

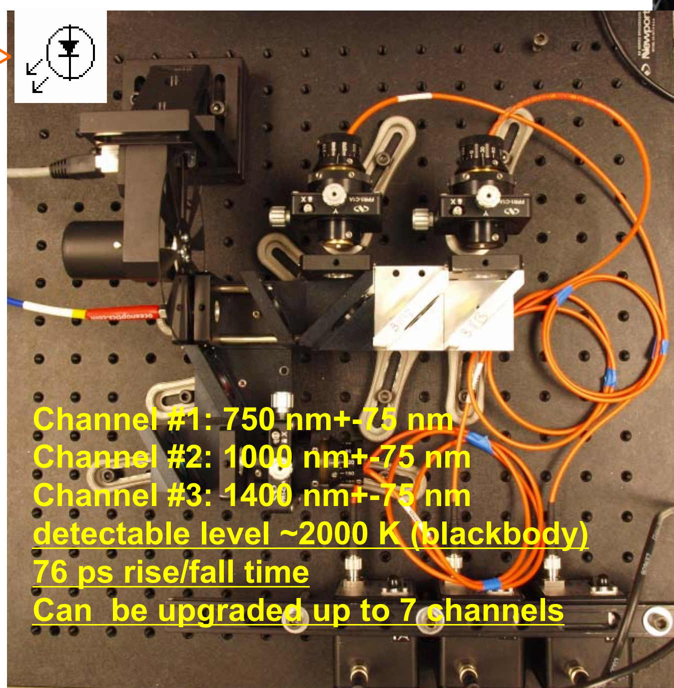
*cf Roy, et. Al. PRL 95(2005) 23481

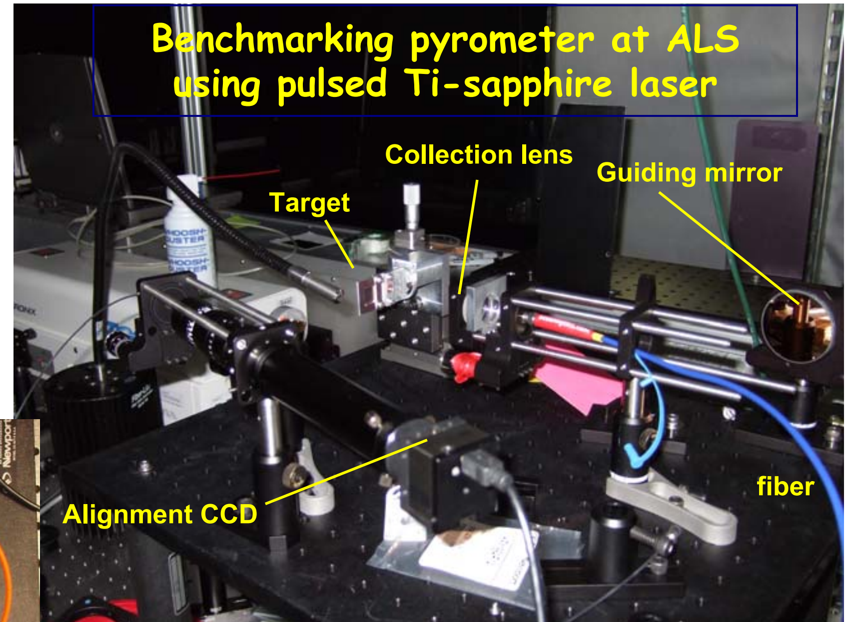
NDCX-I WARM DENSE MATTER TARGET CHAMBER

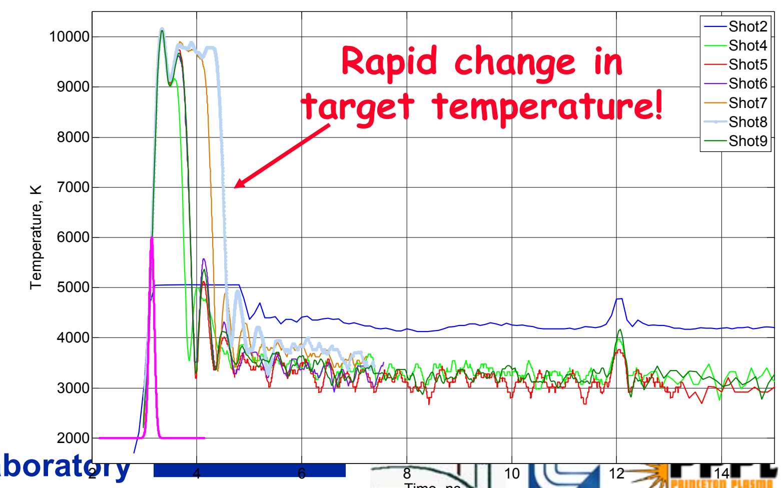


Ultra-fast optical pyrometer for experiments at NDCX



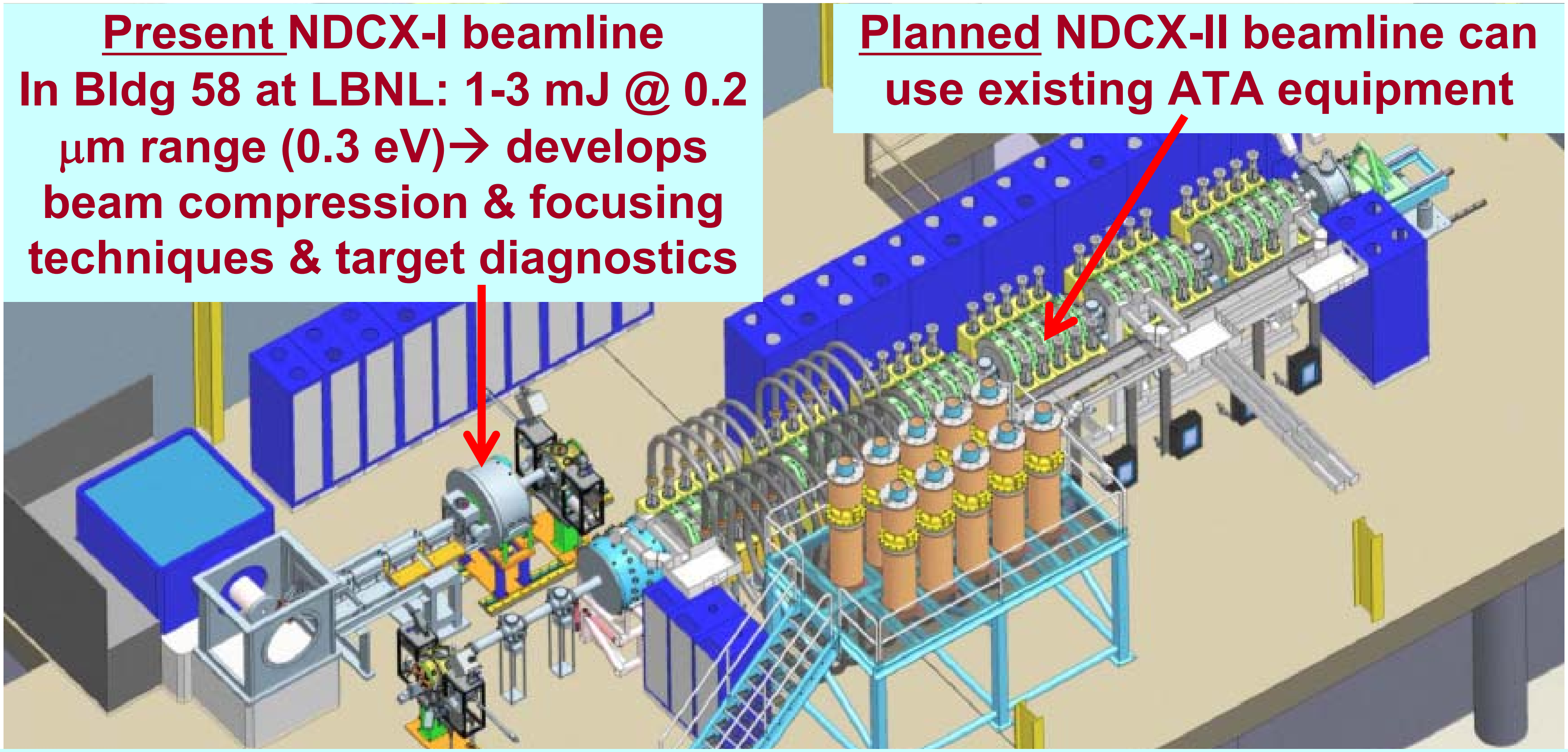




We plan to assemble NDCX-II with largely existing equipment, enabling higher energy WDM and planar direct drive hydro coupling experiments

Present NDCX-I beamline In Bldg 58 at LBNL: 1-3 mJ @ 0.2 μm range (0.3 eV)→ develops beam compression & focusing techniques & target diagnostics

Planned NDCX-II beamline can use existing ATA equipment

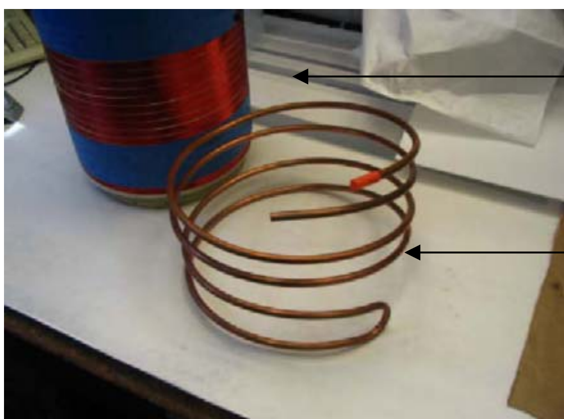


NDCX-II would increase beam energy on target 100 times→ enables HEDP-WDM and direct drive hydro-coupling experiments.

→Integrated Beam High Energy Density Physics Experiment: there are enough ATA accelerator modules to build a longer, 25 MV IB-HEDPX

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

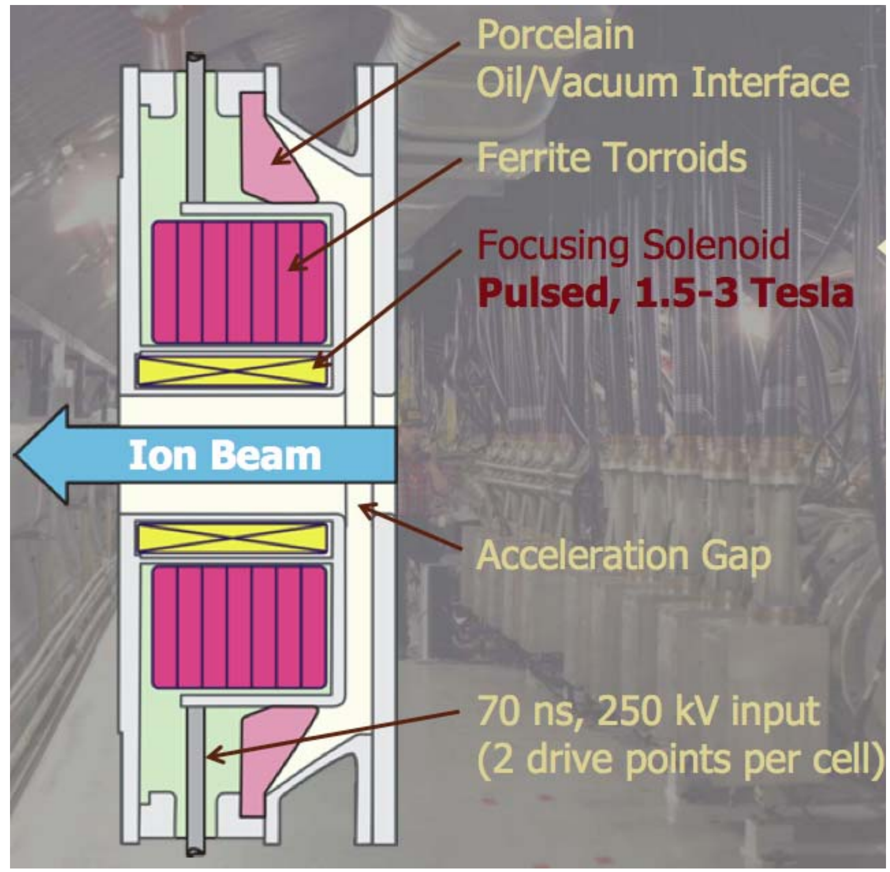
Test stand has begun to verify performance



solenoid

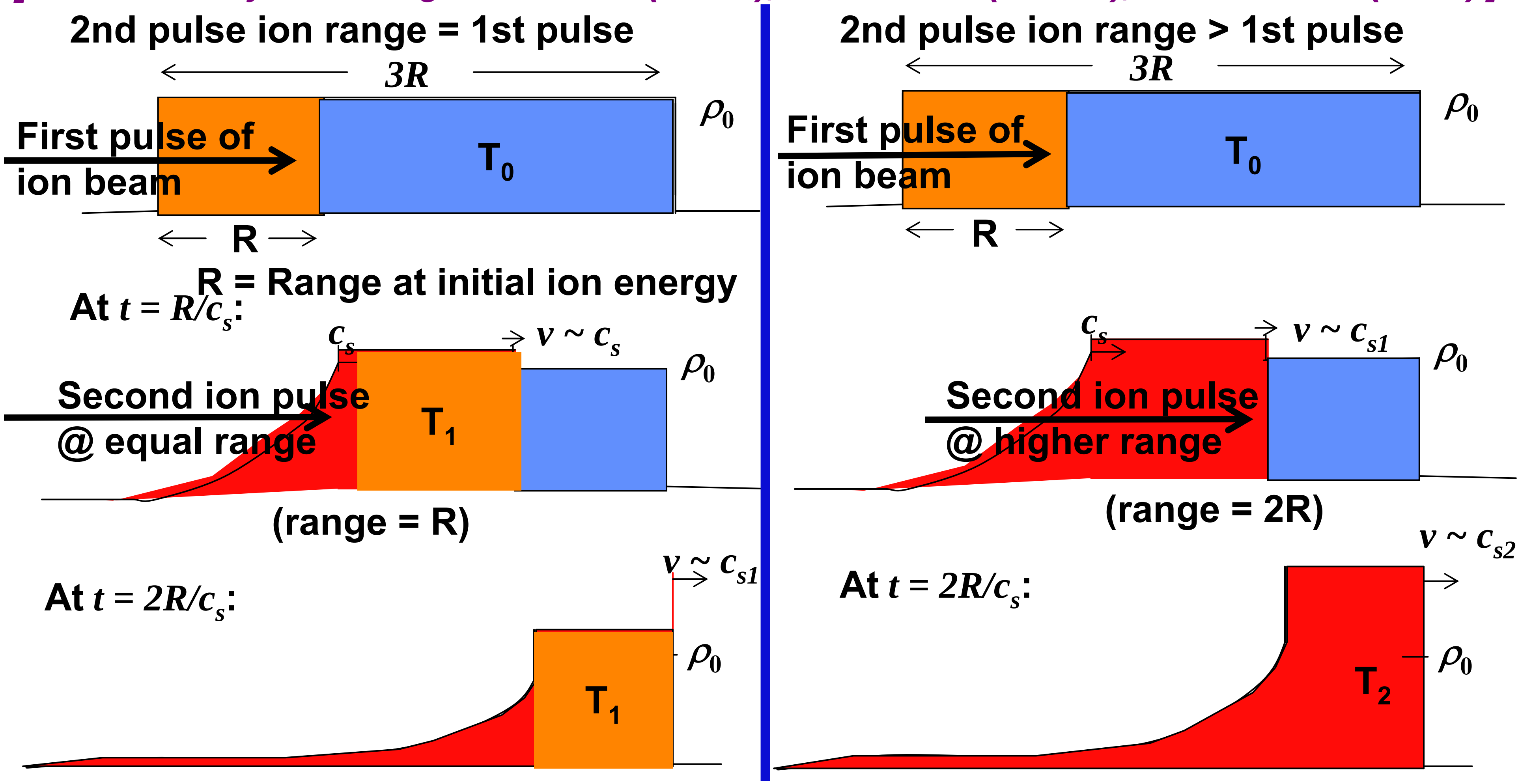
water cooling

Cells will be refurbished with stronger, pulsed solenoids



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)]

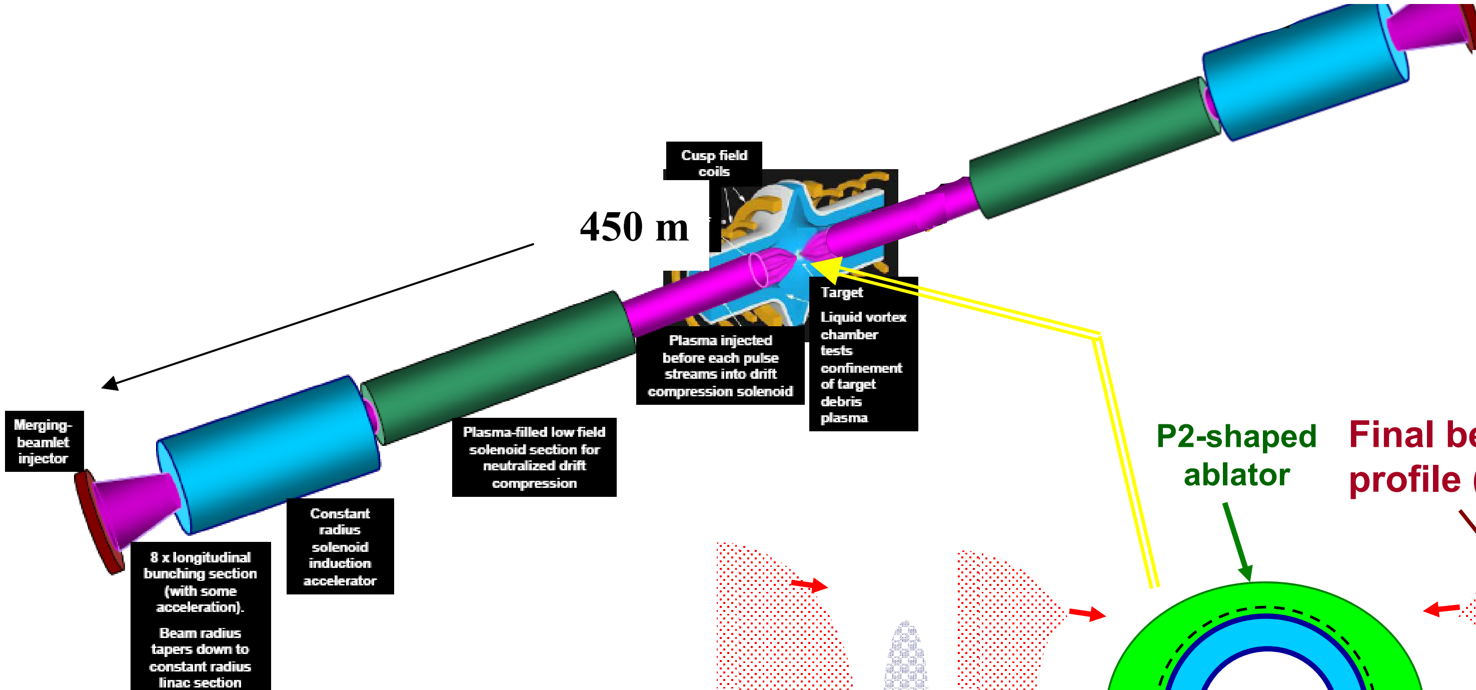


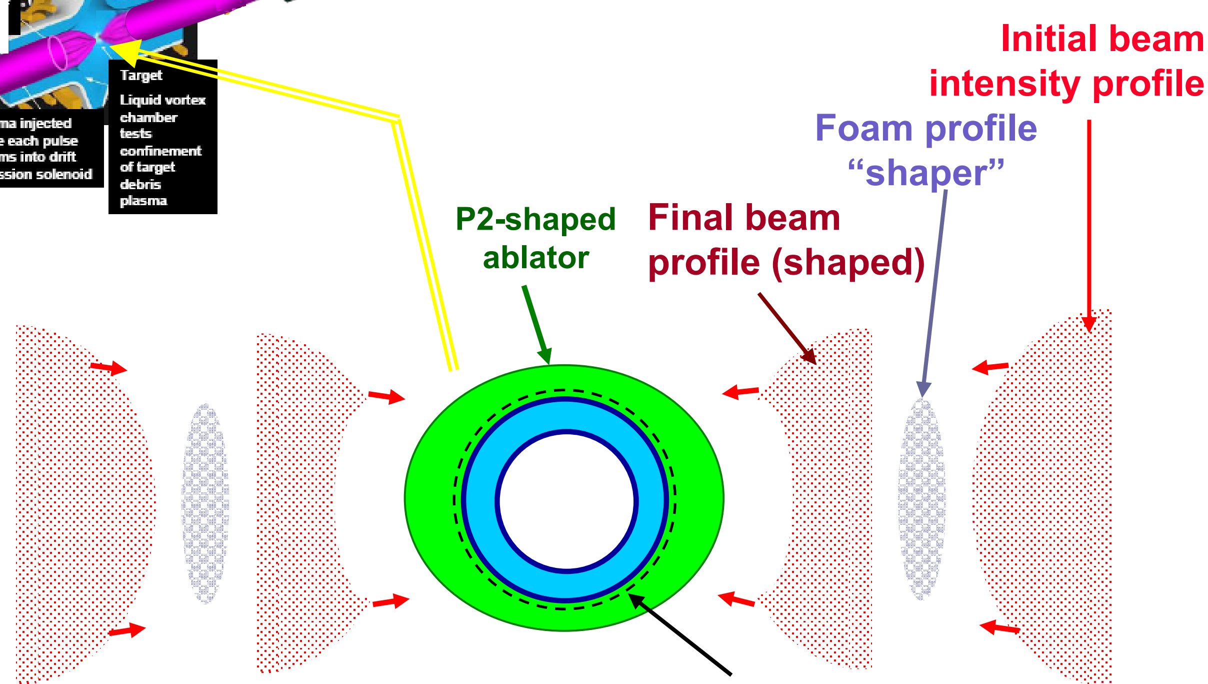
ρ vs z: At $t = 3R/c_s$: measure velocity of back of target.

T_0 T_1 $T_2 > T_1$

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.





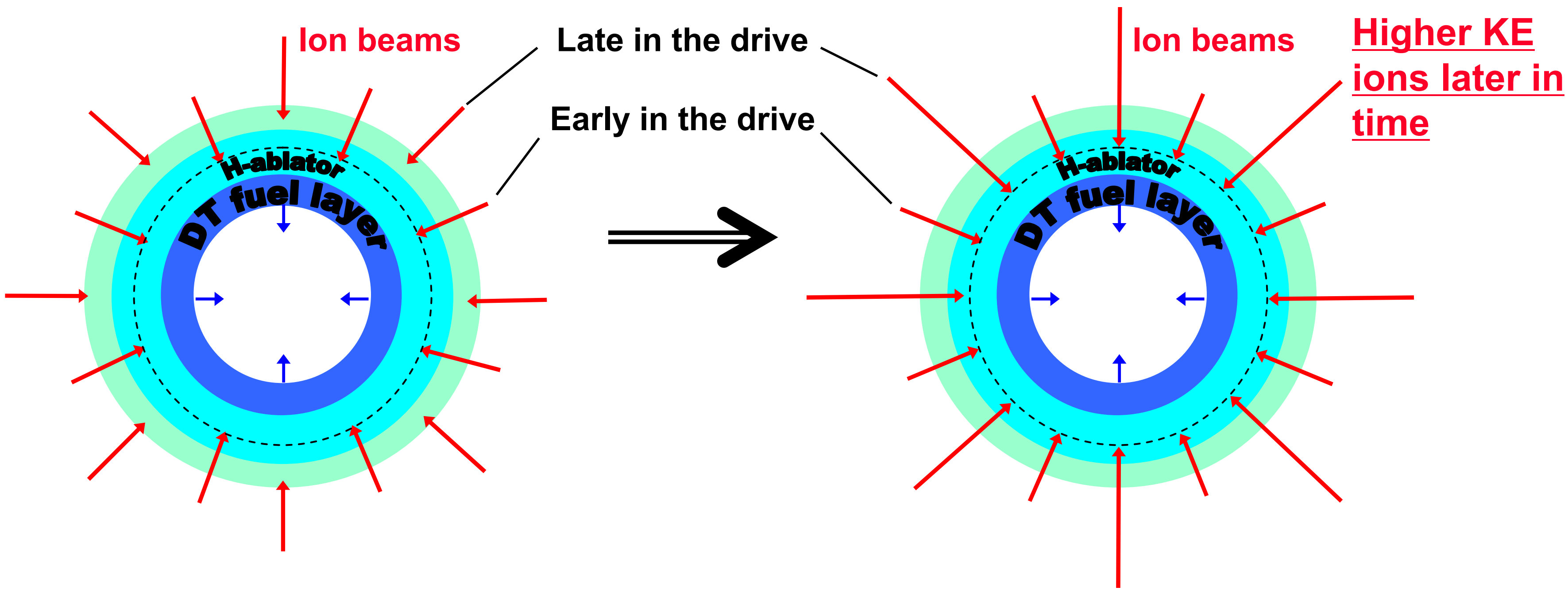
Four "knobs" to control P2 asymmetry with two beams:

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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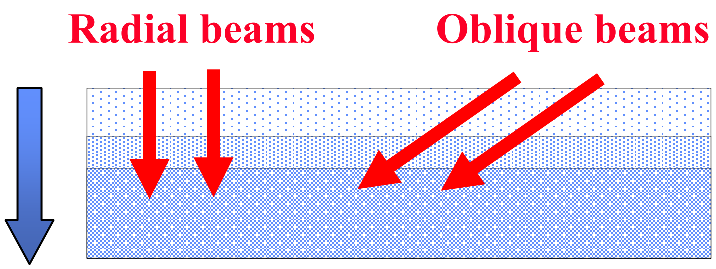
Issues with coupling efficiency, beam illumination symmetry, and Rayleigh-Taylor instability are discussed for spherical heavy-ion-beam-driven targets with and without hohlraums. Efficient coupling of heavy-ion beams to compress direct-drive inertial fusion targets without hohlraums is found to require 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]

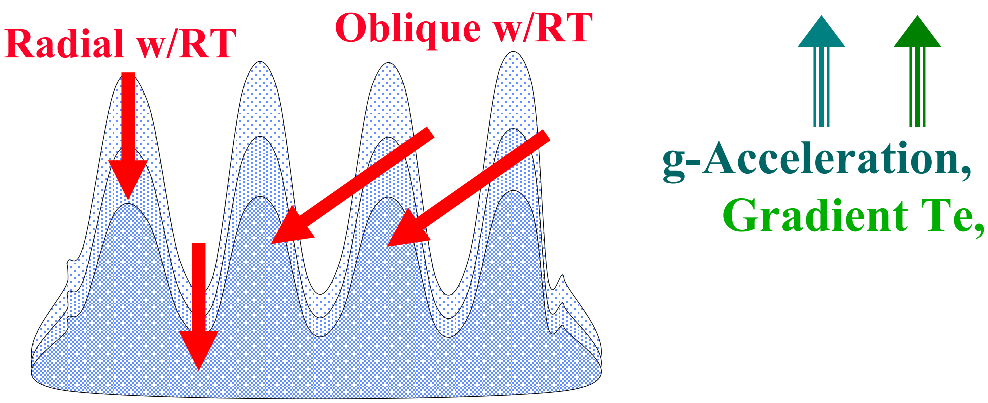
John Nuckolls (April 2008) : "This is a real advance! Now, how are you going to exploit it? Can you apply this high coupling efficiency to reduce drive energy to *much less than 1 MJ?*"

We collaborate with our Japanese colleagues to explore *oblique ion illumination with beam spot rotation (RF wobblers) to enhance ablative- and dynamic stabilization and lengthen pressure gradient scale lengths behind the ablation front*

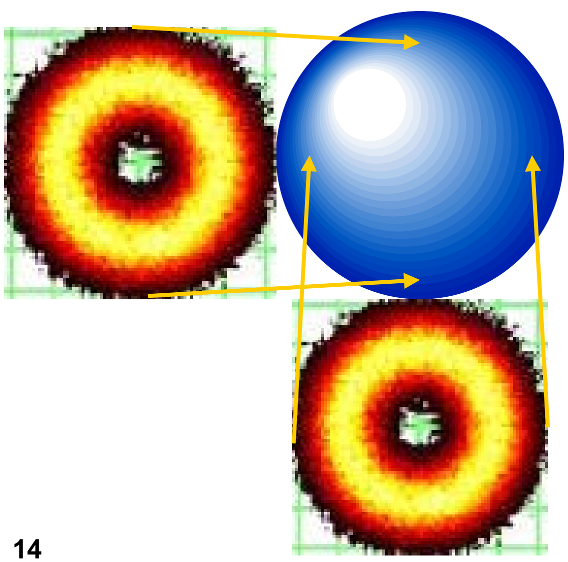


Density gradient

Un-perturbed ablator

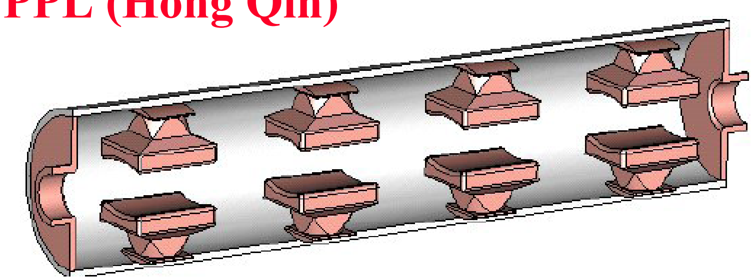


Perturbed ablator. Oblique ion rays may ablate high density spikes faster when ion range > λ_{RT} → improved ablative stabilization.

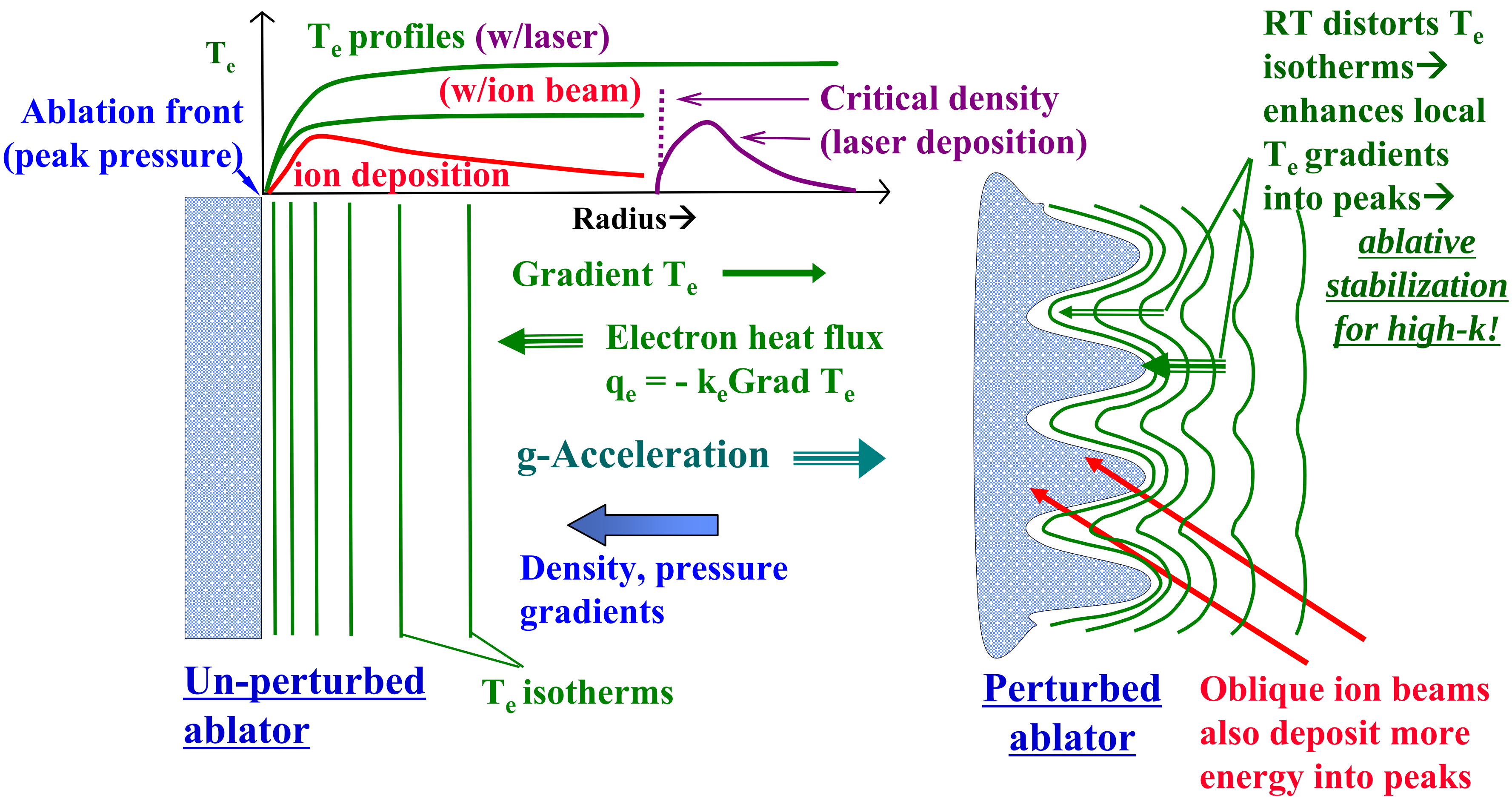


Projection of many overlapping hollow beams onto a spherical ablator leads to mostly-oblique ray-illumination in the foot pulse, and smoother.

RF wobblers useful for beam smoothing, focus zooming & RT control (GSI, ITEP, PPPL (Hong Qin)



Ablative stabilization of high-k RT modes depends on local electron temperature gradients from peak beam deposition to ablation front

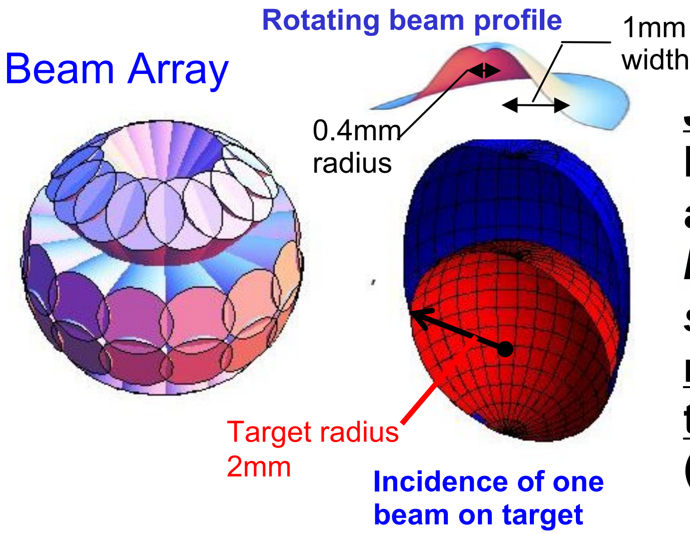


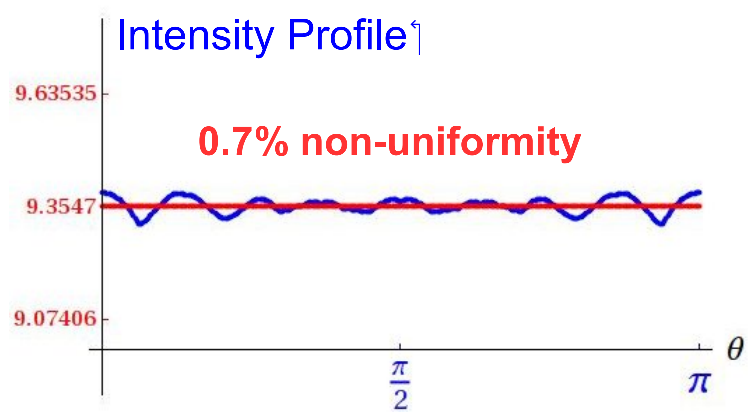
Ion versus laser beams-for the same PdV work at the ablation front:

→ ion beam energy deposited closer to ablation front (higher coupling efficiency)

→ steeper pressure gradients behind ablation front (higher g driving RT for ions)

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

4 polar angles only, *<u>not 4π</u>!*

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.

Our Japanese collaborators explore 3-D versions of this rotating-beam drive geometry.

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

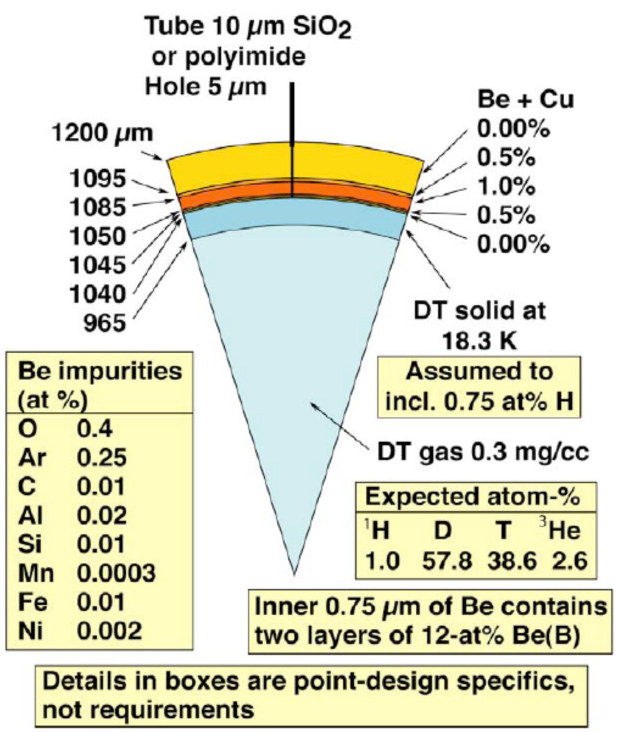
→*Idea for an HIFTF test facility:*

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?

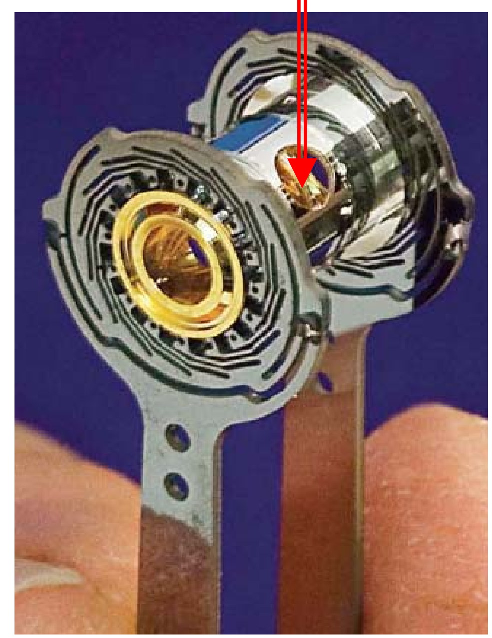
1 mm radius Be capsule

The National Ignition Campaign

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

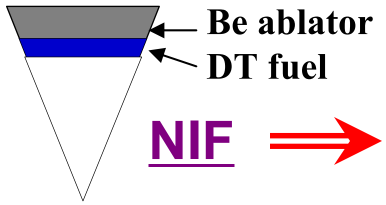


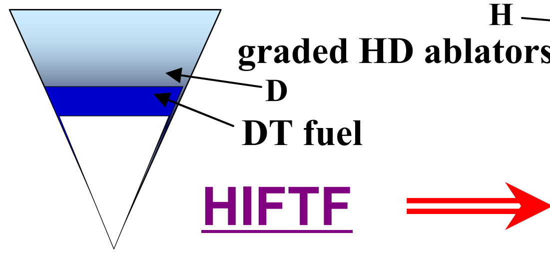
Parameter	Be(285) "current best calc"
Absorbed energy (kJ)	203
Laser energy (kJ) (includes ~8% backscatter)	1300
Coupling efficiency	0.156
Yield (MJ)	19.9
Fuel velocity (10^7 cm/sec)	3.68
Peak rhoR (g/cm^2)	1.85
Adiabat (P/P_{FD} at 1000g/cc)	1.46
Fuel mass (mg)	0.238
Ablator mass (mg)	4.54
Ablator mass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

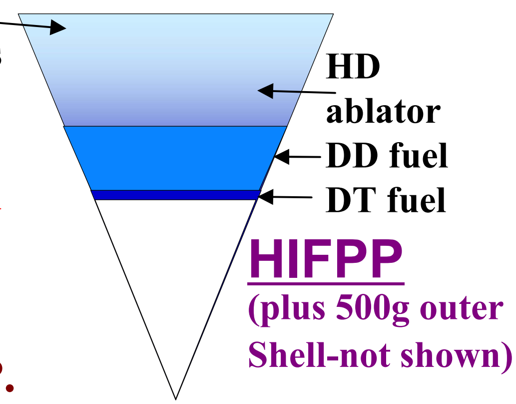


NIF-scale capsules prototype central ignition for the smallest DT heavy-ion fusion test facility (HIFTF) and for follow-on T-lean power plant (HIFPP)

(Capsules not drawn to scale)→





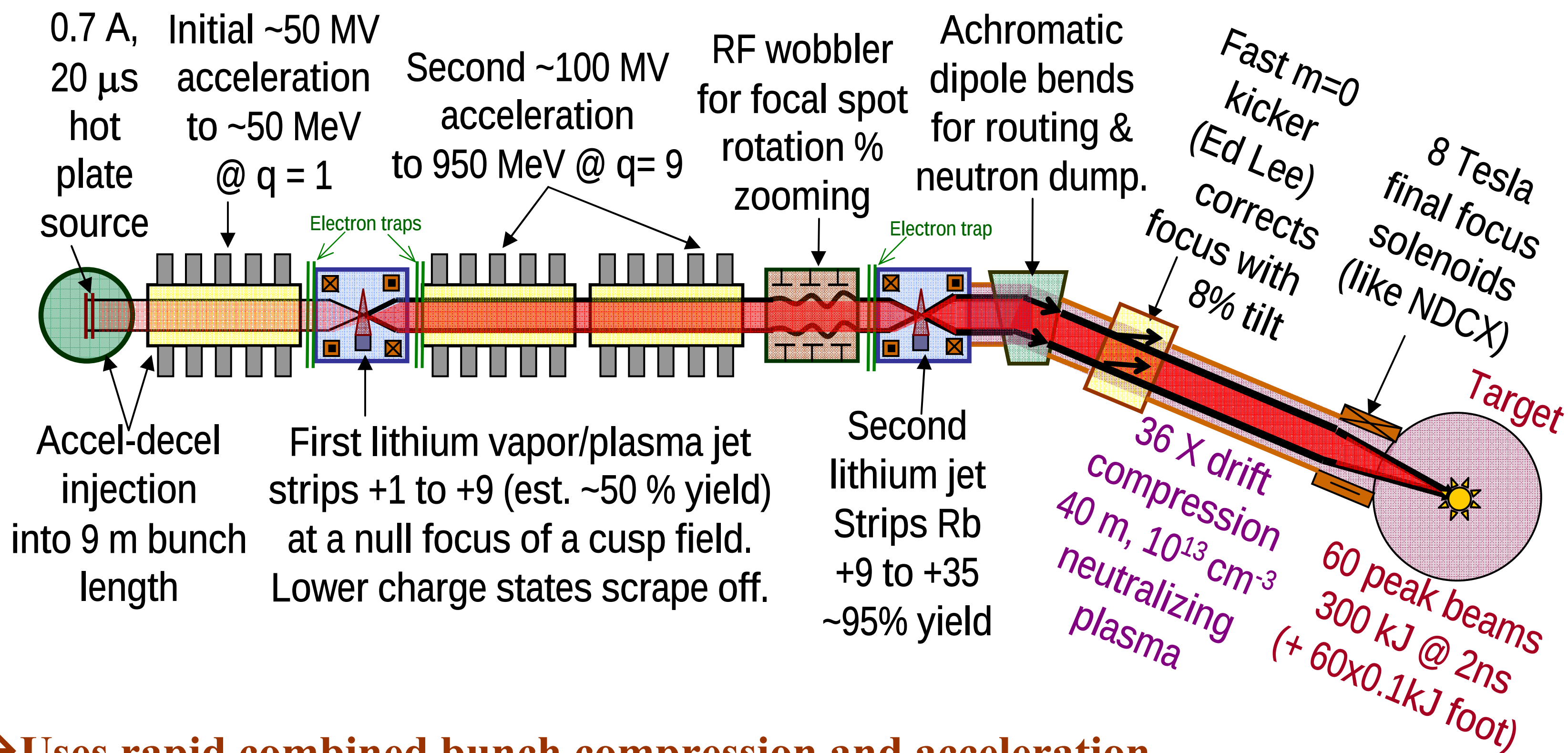


→HIFTF & HIFPP cases will have low aspect ratio capsules with ablator mass = 10 X ignition assembly mass (like NIF).
→HIFTF tests incipient burn waves into DD fuel layer for HIFPP.

	NIF baseline	HIFTF (DT) (planned)	HIFPP (T-lean power plant)
Outer radius	1.2 mm	2 mm (TBD-Lasnex)	5 mm (M_o/M_f=10, Tabak dd core)
Energy into capsule	200 kJ (300eV x-rays)	250 kJ (heavy ions 2→10 mg/cm² ranges)	1.4 MJ (heavy ions 4→20 mg/cm² ranges)
Ignition masses (at stagnation)	0.24 mg DT core +0.21 mg Be outer	0.24 mg DT core +0.21 mg D outer	0.24 mg DT core ← equal +6.5 mg D outer
Imp. Velocity; Coupling efficiency	3.7 e7 cm/s 15%	~3.9 e7 cm/s 17% (1-D Lasnex)	3.3 e7 cm/s (Tabak dd model) 25% (analytic model)
Fuel assem. energy	30 kJ (16 in DT)	30 kJ (16 in DT, 14 in D)	350 kJ (in D+DT spark)
Rho-r	1.85 g/cm²	1.2 - 1.8 g/cm² (TBD)	8.1 g/cm² (not inc. outer shell)
Fusion yield	20 MJ (DT)	>12 MJ (DT-26% plasma) (TBD-Lasnex)	100 MJ (DD-DT→92% plasma w/ K-LiH-Pb converter shell)

Option for a 5 kJ linac module for a 60-peak-beam HIFTF driver :

Induction acceleration efficiency 13% (@ 640 A/beam),
Modest linac length and cost (100-m linac @ q = 9, 1.5 MV/m).
Manageable beam perveance K~10^{-3}, injector source I_s<1 A @ q=1.
1 GeV Rubidium^{+9} beam linac module with two stages of beam stripping.

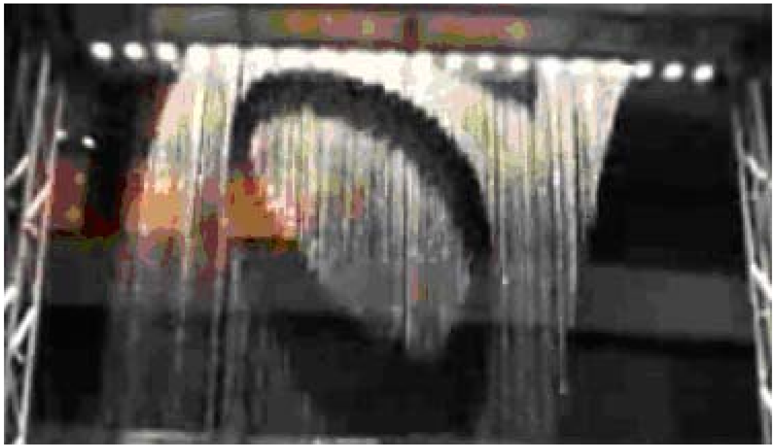


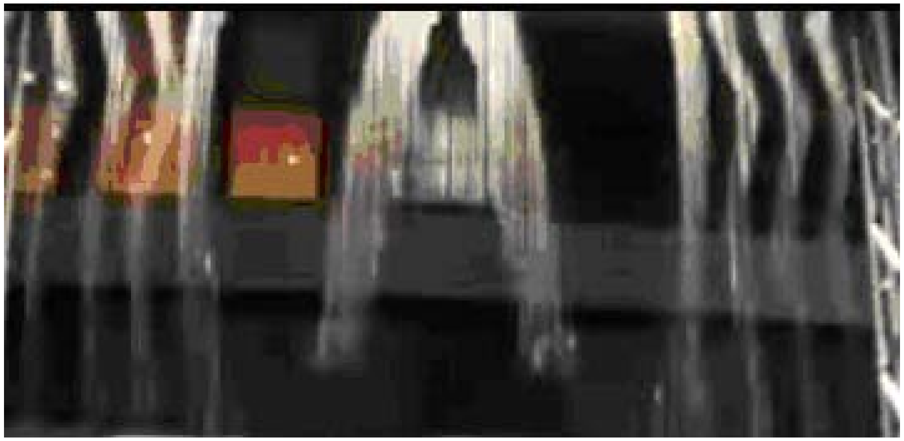
→Uses rapid combined bunch compression and acceleration with downstream beam manipulations to be tested on NDCX-I&II
→Two of these drive test implosions in HIDDIX; 64 for peak drive for HIFTF.

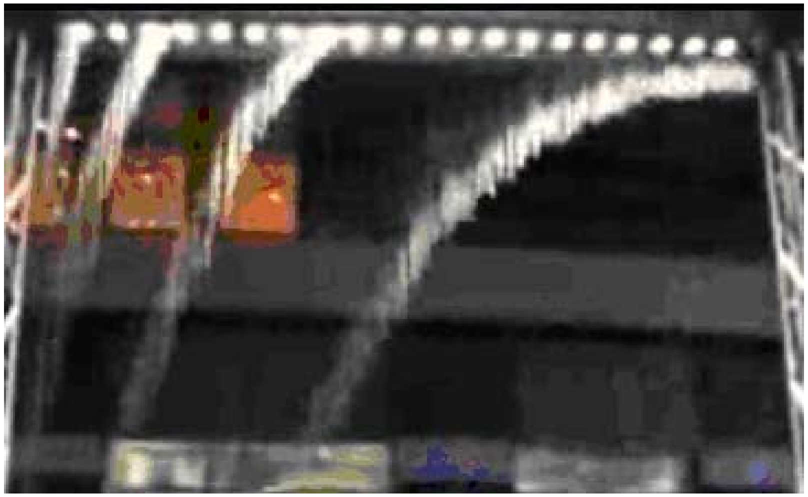
New pulsed-jet valve capability would enable thick liquid Flibe protection like HYLIFE to be adapted to *direct drive chambers*

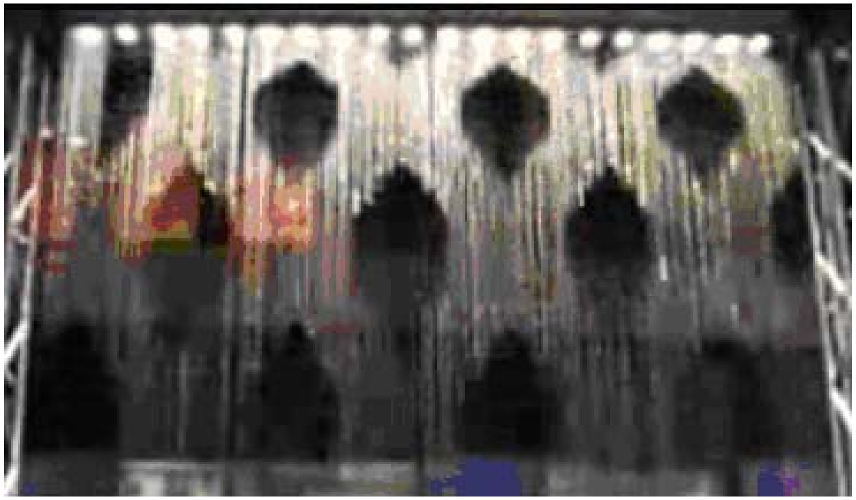
[R. Moir, LLNL, 1999 HYLIFE note.

***Water fountain pictures from** http://videos.komando.com/2008/08/19/water-painting/].*

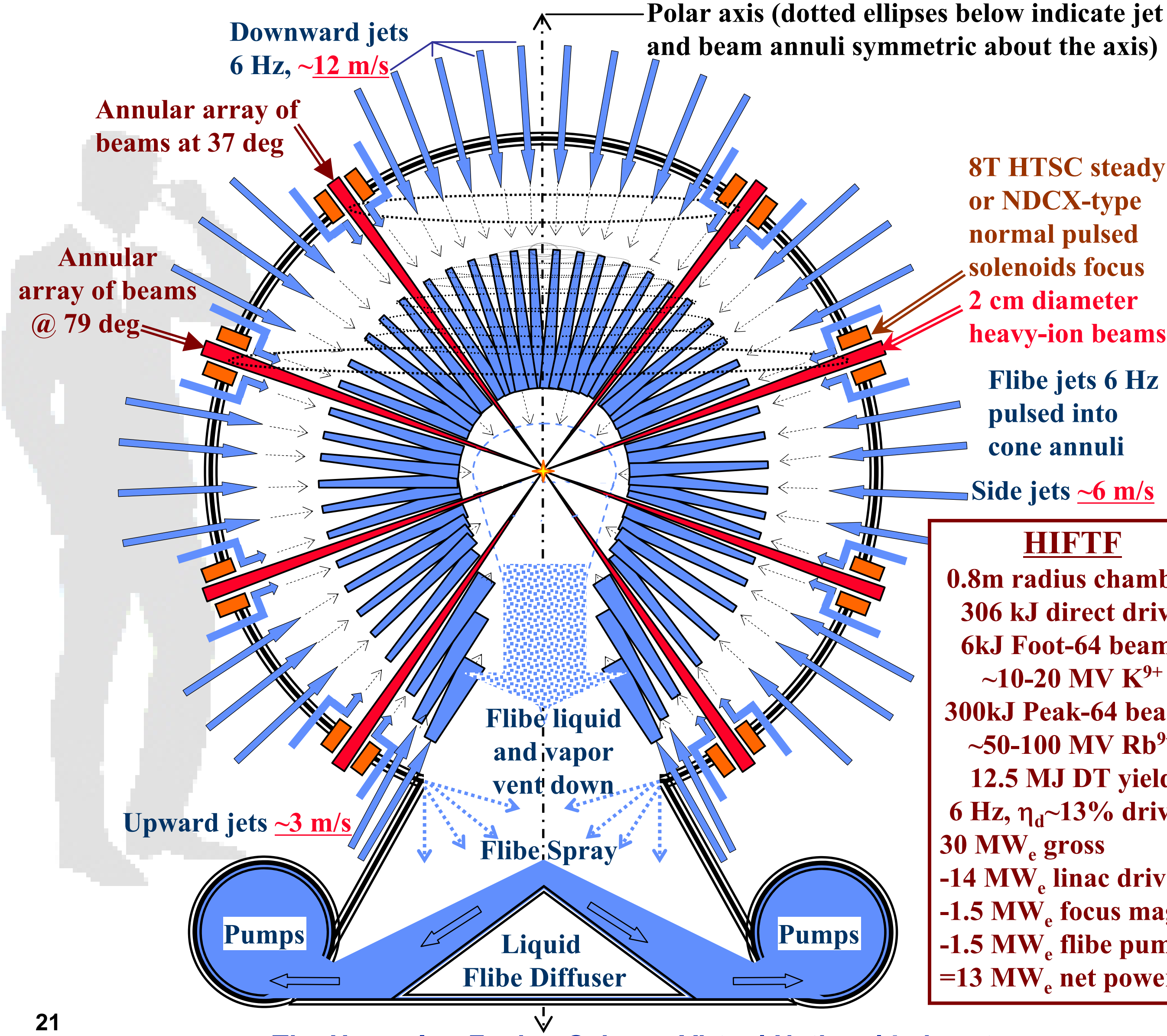






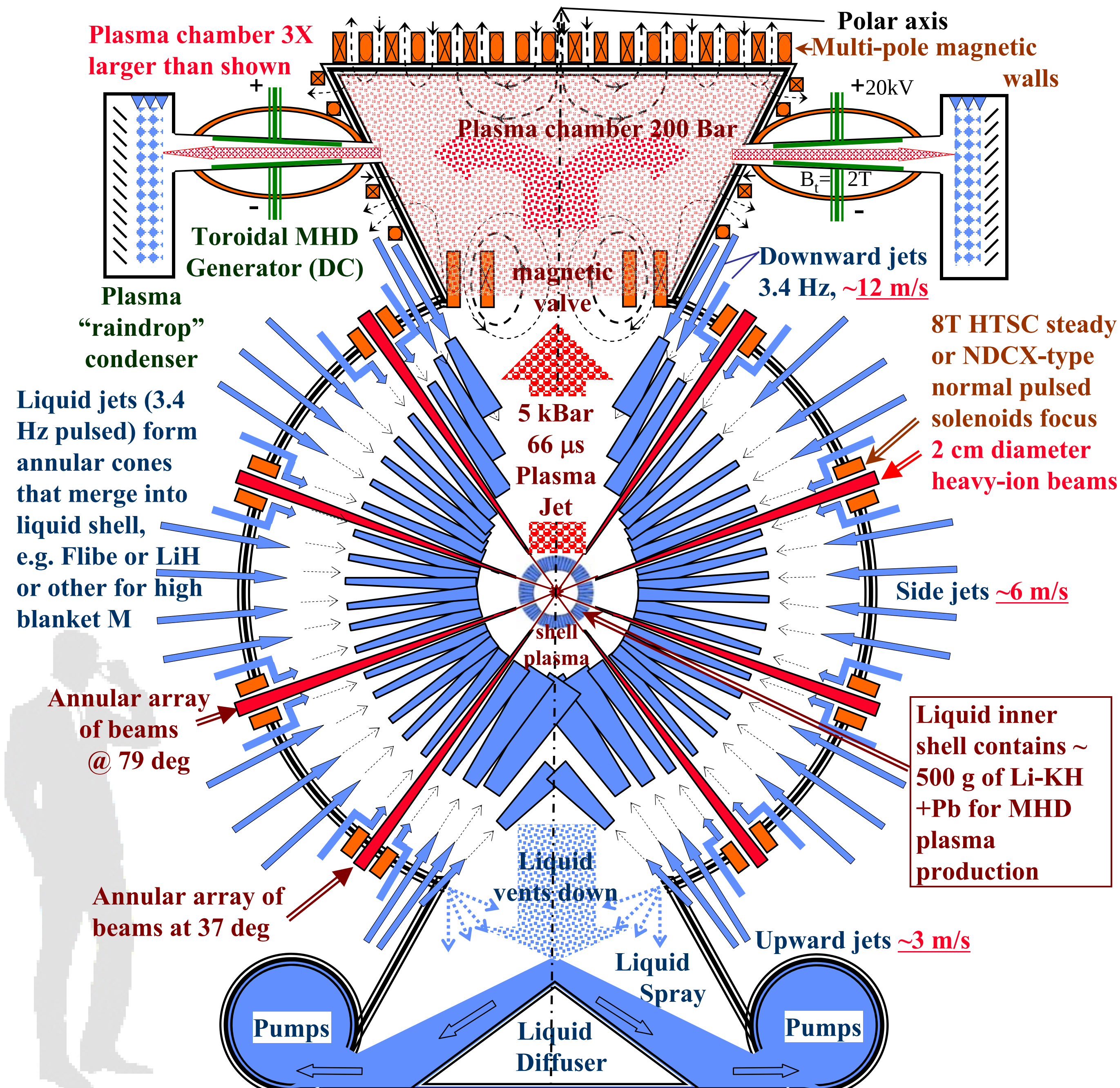


Concept for a small heavy-ion fusion test facility (HIFTF): *polar direct drive*



HIFTF
0.8m radius chamber
306 kJ direct drive
6kJ Foot-64 beams
~10-20 MV K^{9+}
300kJ Peak-64 beams
~50-100 MV Rb^{9+}
12.5 MJ DT yield
6 Hz, η_d~13% driver
30 MW_e gross
-14 MW_e linac driver
-1.5 MW_e focus mags
-1.5 MW_e flibe pumps
=13 MW_e net power

- **Pulsed jets (Moir: 1999 HYLIFE notes) merge radially halfway into chamber, forming a 30-cm thick *liquid imploding shell* with annular beam access around the axis at shot time, @ 4 angles.**
- **Liquid shell mass and momentum sufficient that pocket pressurization due to non-neutron fusion yield slows but does not reverse the liquid radial velocities of all but the slowest upward jets.**
- **Jet velocities decrease with polar angle for net momentum of the liquid and post-shot vapor to vent downwards to clear the chamber.**



Advanced fuel HIF Power Plant (HIFPP) using direct drive compression of DD fuel with DT spark plug.

1.4 m radius chamber

1.6 MJ direct drive:

Foot-64 beams

~20-40 MV K^{9+}

Peak-128 beams

~100-200 MV Rb^{9+}

100 MJ DD/DT yield

1.5 Blanket energy M

3.4 Hz, η_d~13% driver

η_{conv}= 0.7 [0.5 MHD + 0.4 thermal bottom]

357 MW_e gross

-42 MW_e linac driver

-8 MW_e all magnets

-7 MW_e liquid pumps

= 300 MW_e net power

Conclusion: a sequence of cost effective heavy ion beam experiments and facilities can provide the basis for an attractive new vision for heavy ion fusion energy. More work is needed on:

- **Beam brightness, neutralization, collective effects, stripping.**
- **More implosion calculations in the ramped ion energy, $v_b > v_{eth}$ regime.**
- **Development of RF wobblers and time-dependent focus control for hollow-beam spots.**
- **2-D and 3-D symmetry and Rayleigh Taylor stability studies.**
- **Pulsed liquid jet control for direct-drive chamber protection.**
- **MHD conversion efficiency experiments using surrogate arc-jet plasma sources.**

→We have workable designs for indirect drive HIF @ 7 MJ and hybrid-drive HIF @ 4 MJ. The journey to heavy ion fusion @ < 1 MJ drive may be long, but the potential for higher coupling efficiency to reduce driver cost makes it worthwhile.

Post-script regarding fusion-fission hybrids for energy

- **Tomorrow Ryan Abbott will brief you on a recent LLNL initiative- Laser Inertial Fusion-fission Energy (LIFE), a NIF-scale laser driving NIF-like hohlraum targets @ 10 Hz, producing 400 MW of fusion neutrons used to *completely burn-up depleted uranium or spent nuclear fuel for energy (fusion n+U→Pu→200 MeV/fission).***

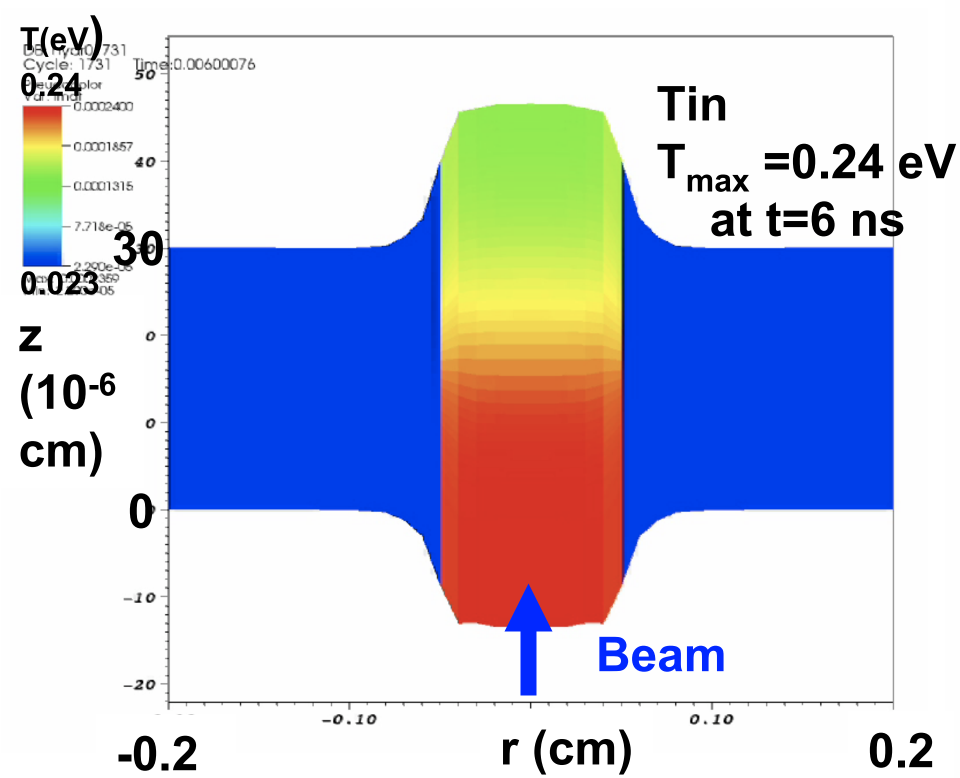
- **The goal of extracting 30 X more energy per ton of uranium ore than nuclear reactors, without enrichment or reprocessing, is based on success of NIF, requires stronger neutron flux and total fluence than previous hybrid proposals, and *motivates a large, nearer-term, R&D program to address many technical issues*.**

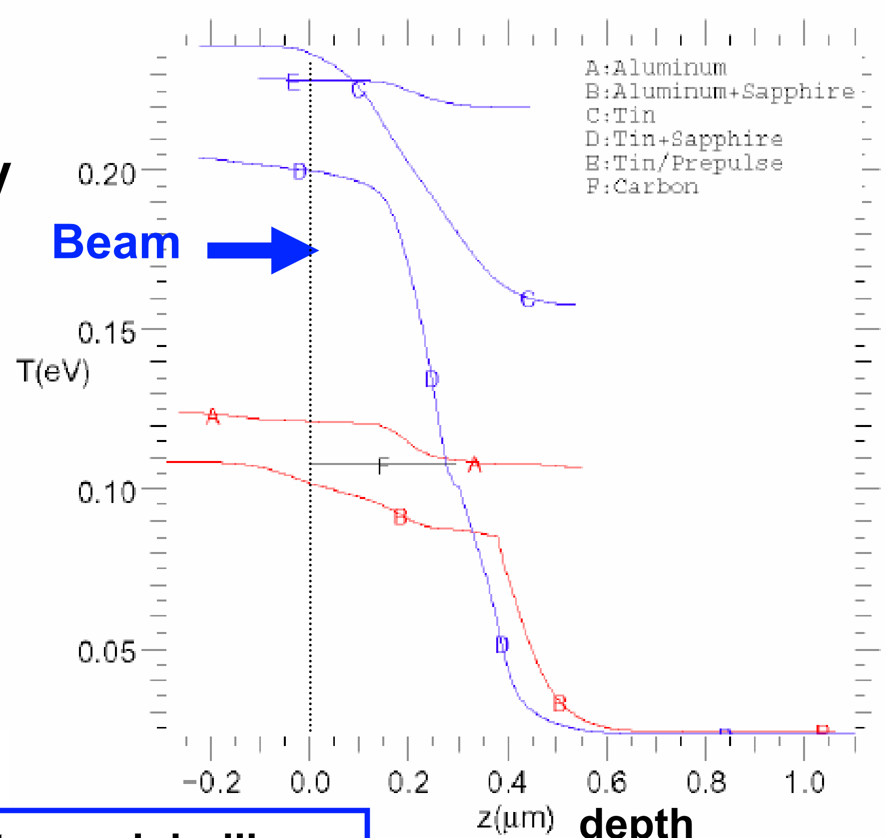
- **The LIFE initiative will also motivate studies of other inertial fusion drivers and magnetic fusion drivers to meet the same goal. Advanced IFE concepts such as HIF direct drive may provide the same minimum fusion gains ~ 20 for smaller hybrids with 250 kJ drive energy, < 0.3 GW fission/unit vs 3 GW for LIFE-scale units.**

Backup slides

HYDRA simulations of NDCX-I planar targets predict temperatures of a few tenths of an eV.

Simulation assumptions: Ion energy: 350 keV Energy fluence: 0.1 J/cm^2 Spot radius: 0.5 mm Pulse duration: 2ns FWHM Total energy deposited: 0.8 mJ Peak current: 1 A (40 times compression) Total charge: 2.3 nC

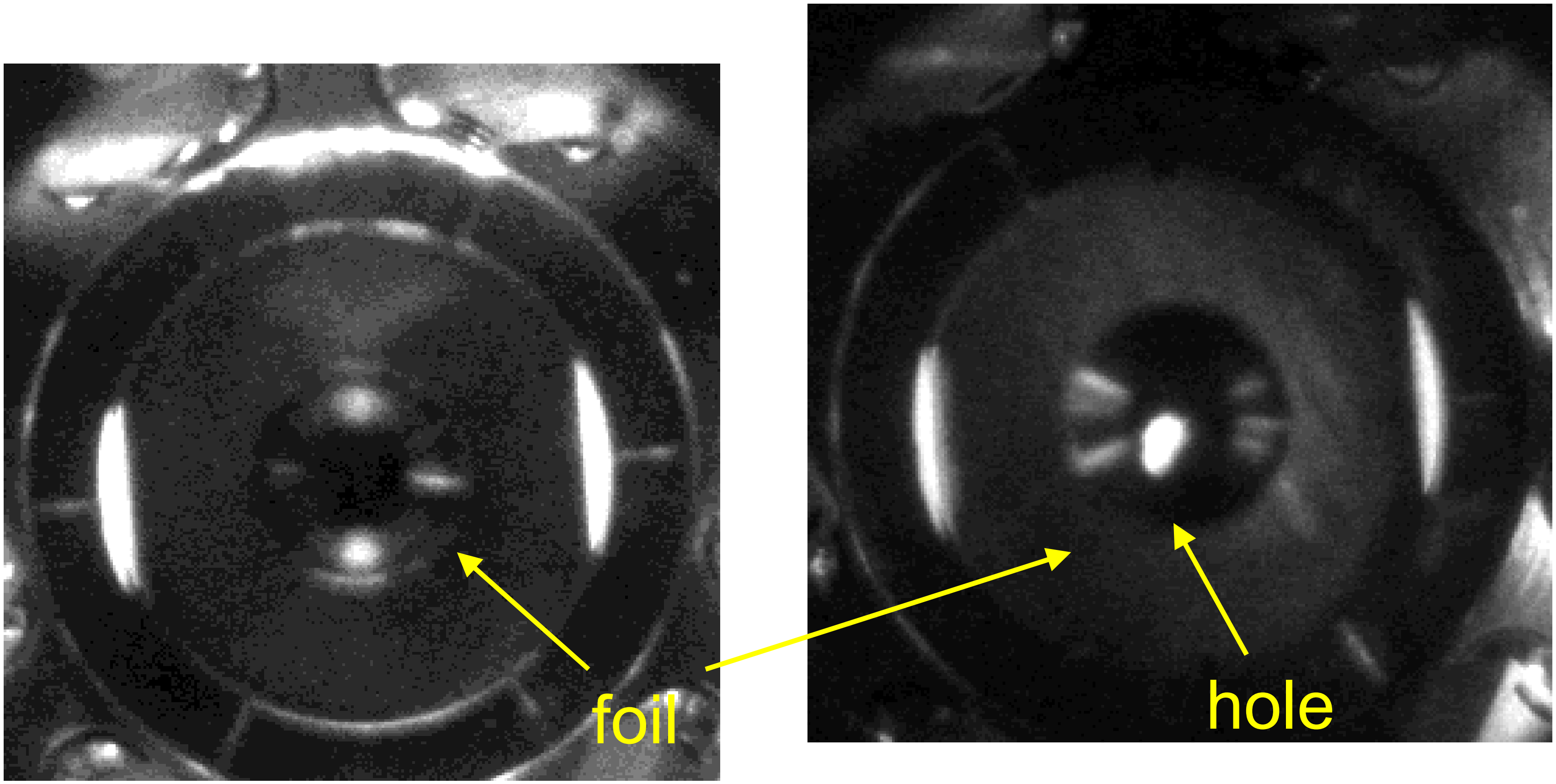




Energy required to reach boiling point (J/cm^2): 0.12 (Au); 0.25 (Al)

HYDRA simulations by Enrique Henestroza

First attempt to make a hole in gold foil target using NDCX-I beam was successful (August 2008)

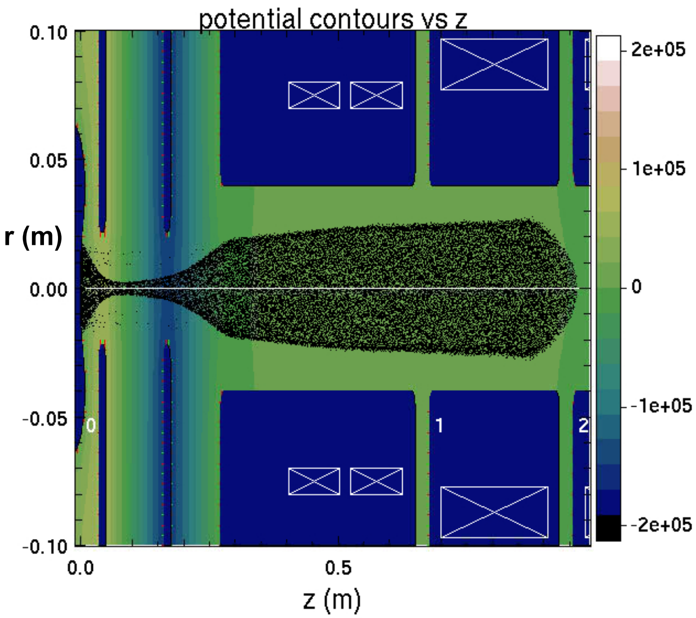


before

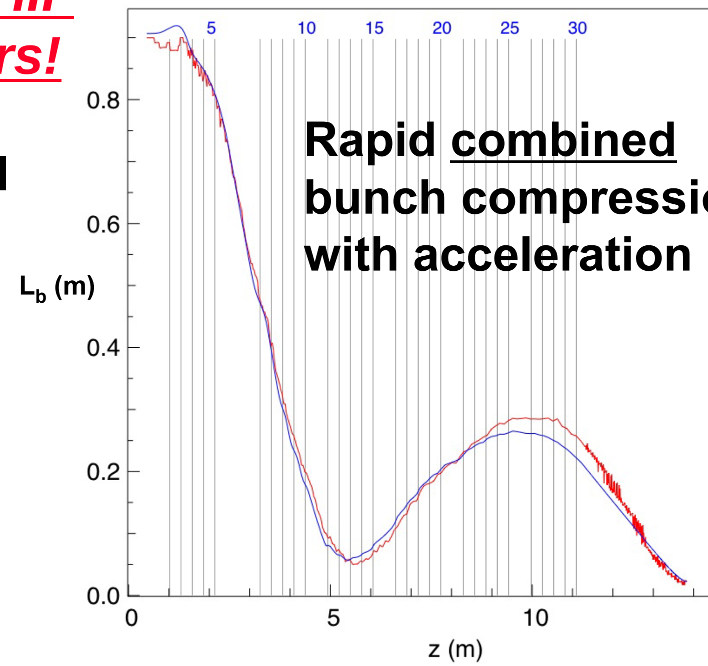
after

A first solenoid-focused induction accelerator for intense ion beams-
NDCX-II will pioneer studies of accel-decel injection, combined rapid bunch compression with acceleration, and solenoid transport limits.

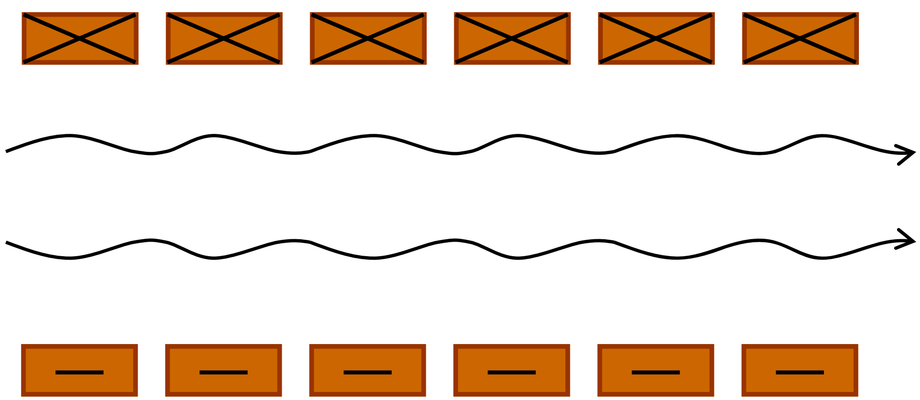
→Basis for HIF direct drivers!



←Accel-decel injection into a <u>high line-charge density</u>

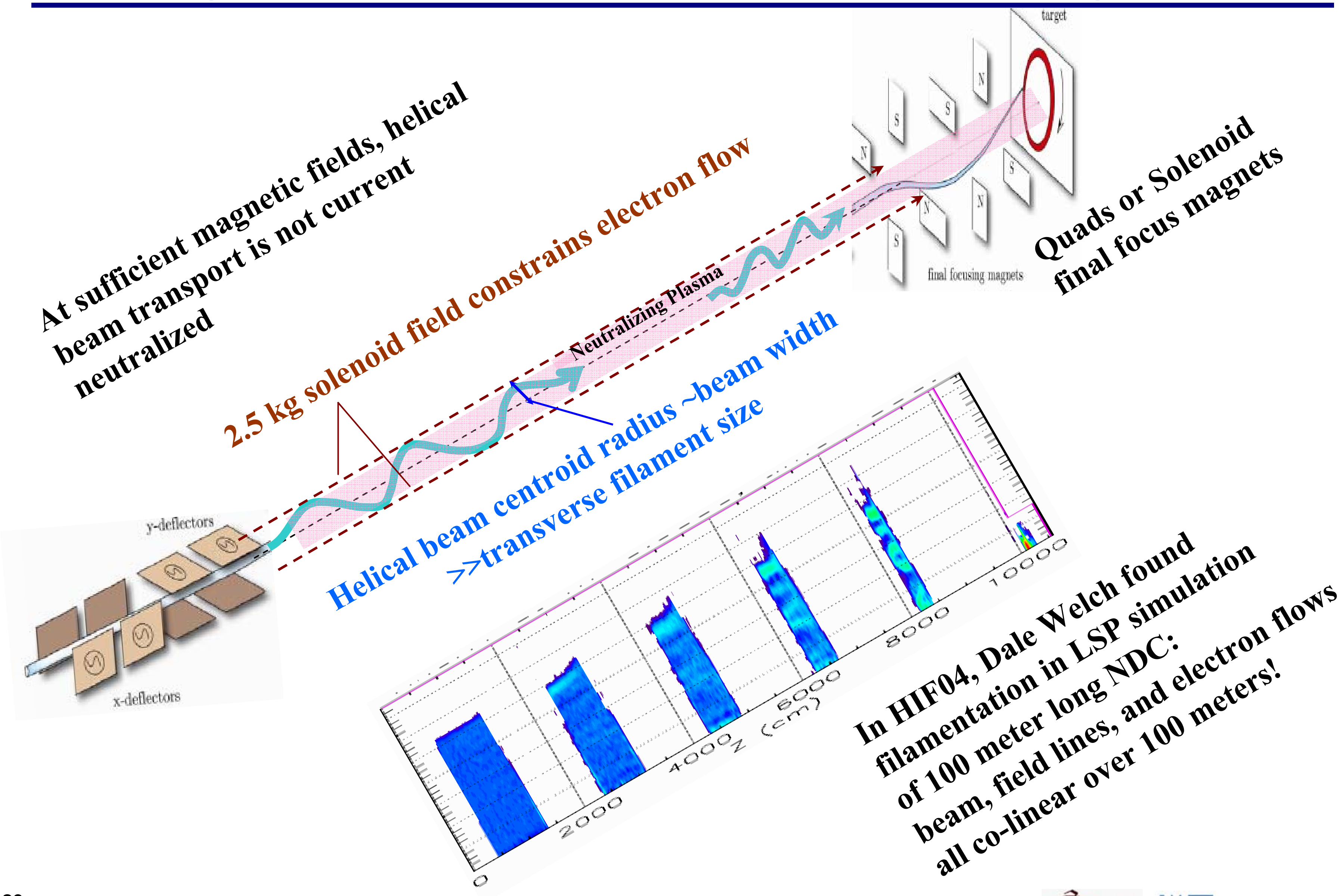


Rapid <u>combined</u> bunch compression with acceleration



NDCX-II <u>solenoid transport</u> will explore velocity spread, halo, and e-cloud limits.

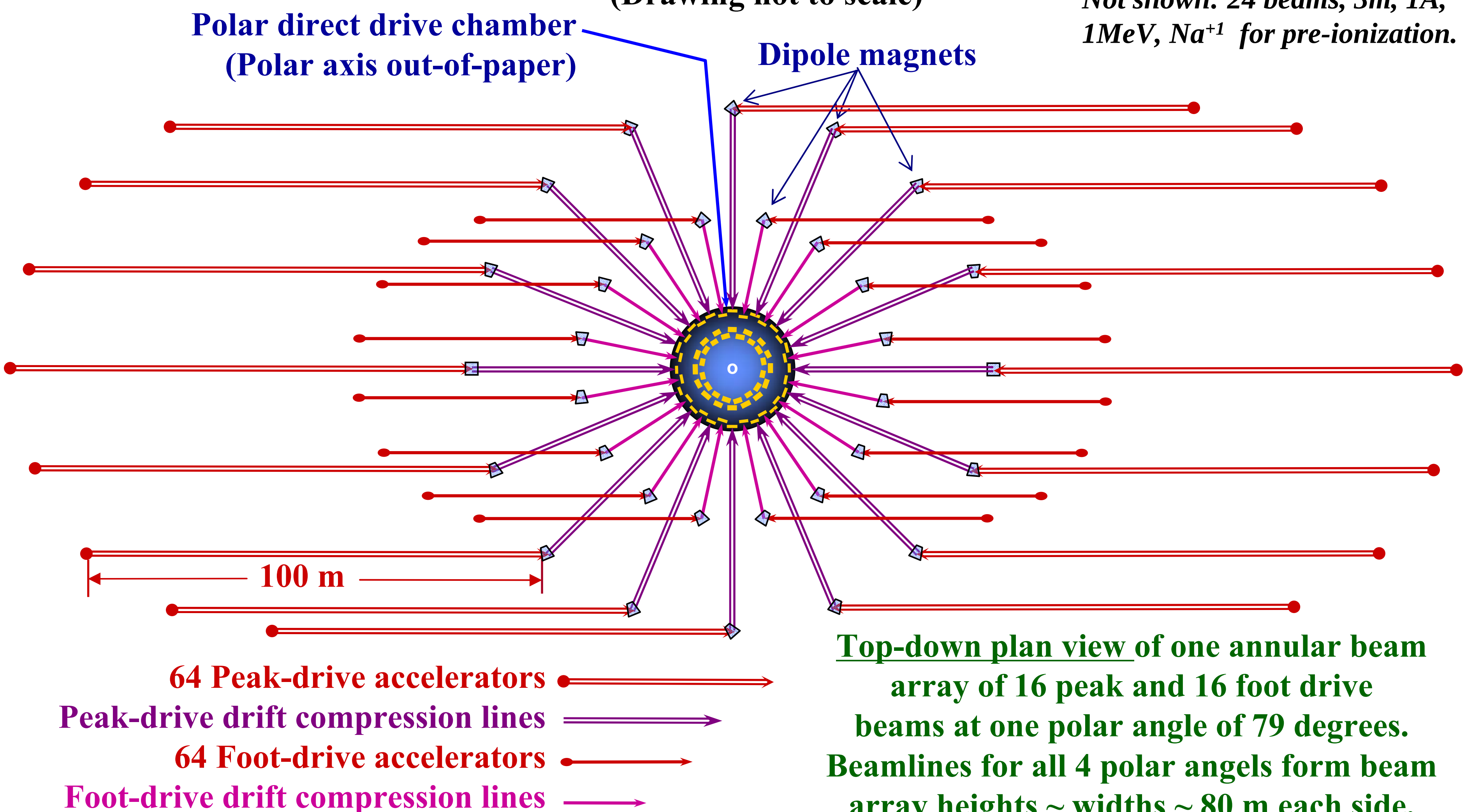
Beam filamentation (Weibel) instability should be investigated with *rotating helical beams* during NDC



To compact beamline service and maintenance, dipole magnets bend 128 driver beams total from two beamline arrays into plasma-neutralized drift compression lines directed to final focus into the direct drive chamber:

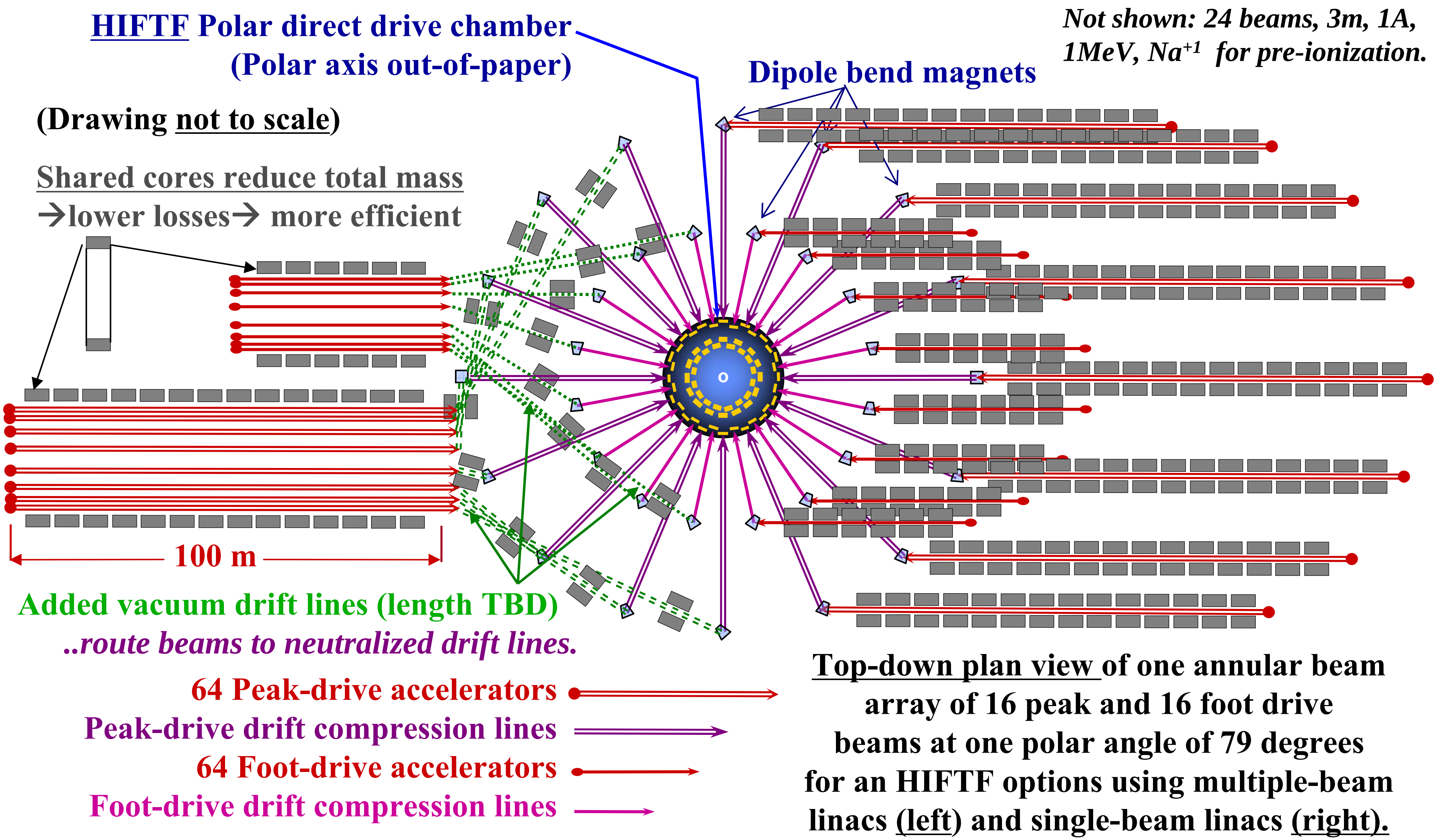
(Drawing not to scale)

Not shown: 24 beams, 3m, 1A, 1MeV, Na^{+1} for pre-ionization.



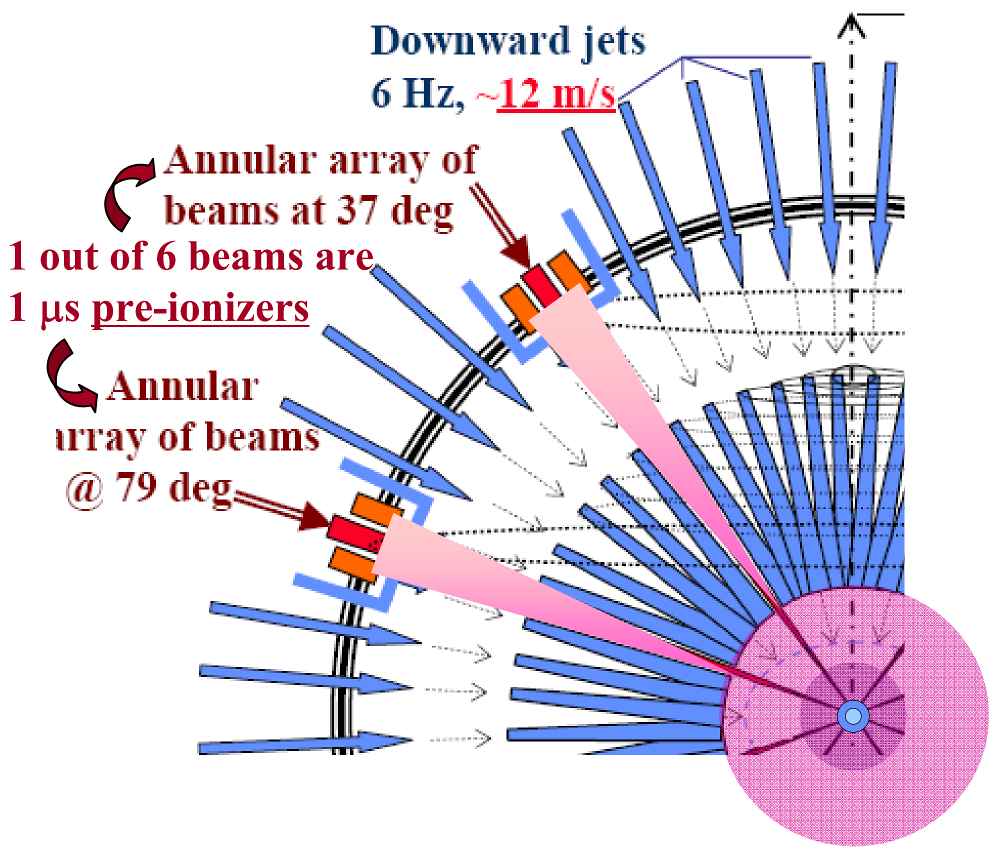
<u>Top-down plan view</u> of one annular beam array of 16 peak and 16 foot drive beams at one polar angle of 79 degrees. Beamlines for all 4 polar angels form beam array heights ~ widths ~ 80 m each side.

Future studies should consider options to use multiple-beam induction linacs (more efficient with shared cores, but with added vacuum drift lines)



Top-down plan view of one annular beam array of 16 peak and 16 foot drive beams at one polar angle of 79 degrees for an HIFTF options using multiple-beam linacs (left) and single-beam linacs (right).

Driver ion beam space charge is neutralized by a cold Hydrogen gas puff pre-ionized by 24-low energy beams (1A, 1 MeV Na^{+1})

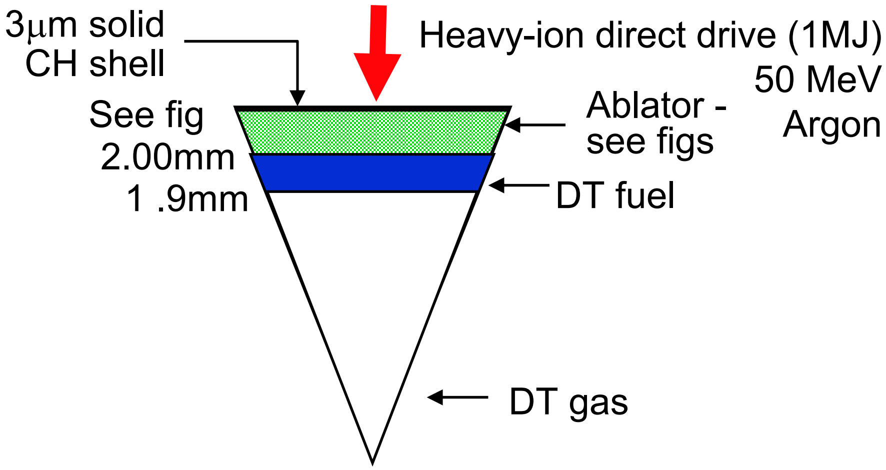


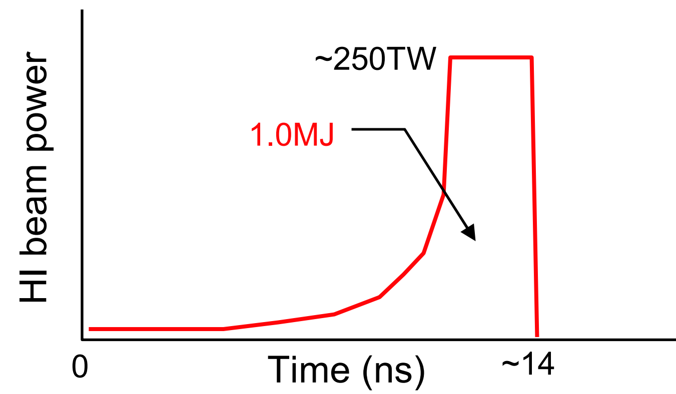
→This pre-ionization approach can be tested on HCX at LBNL

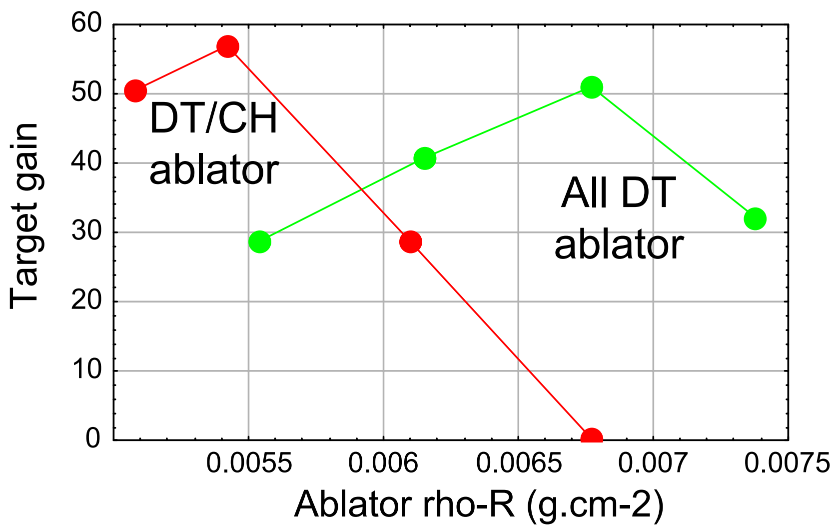
Pre-ionization steps to neutralize foot and peak driver beam space charge

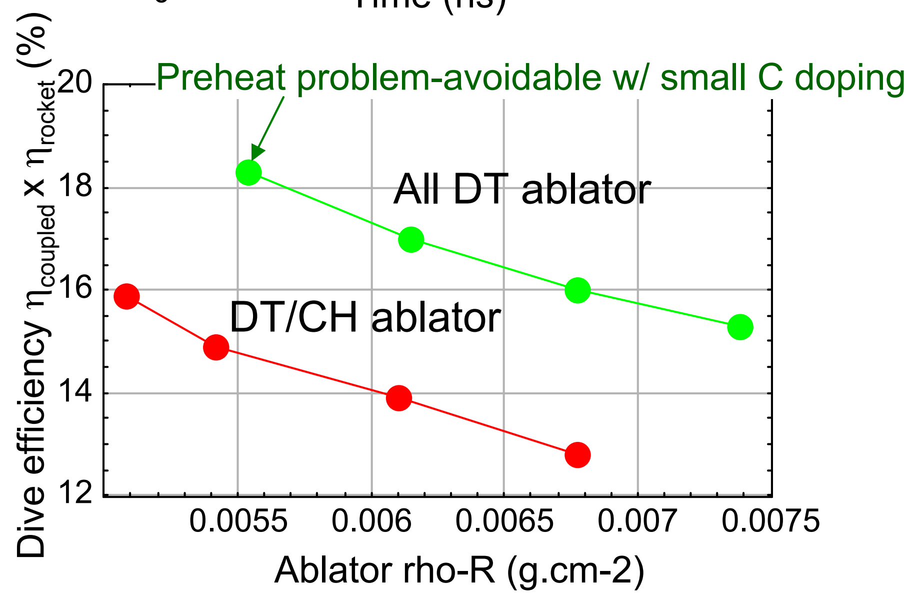
1. **Cryo-capsule target injected @ 50-100 m/sec (may need some reflective coating or frost layer to avoid pre-heat in 600 deg C, 10^{13} cm^{-3} Flibe vapor)**
2. **A few ms before arrival of cryo-capsule target at chamber center, a pre-injected 1 mg H_2 pellet is vaporized by a low energy laser into 100 deg K gas cloud.**
3. **H_2 gas cloud expands to chamber wall, presenting H and e^- densities= 10X the peak driver beam charge densities occurring at peak drive (6e16 cm^{-3} at center to 6e14 cm^{-3} at final focus radii**
4. **24 pre-ionizer beams fire 1 μs to ionize (<<1 %) H_2 gas to electron densities > 2-3 X the foot beam charge densities.**
5. **Foot beams further ionize the remaining H_2 neutrals to 10X the subsequent peak driver beam densities.**

Heavy-ion direct drive LASNEX runs (June 2007) by John Perkins (LLNL) found high target gains ≥ 50 at 1MJ with low range ions @ <u>high</u> coupling efficiency (16%) (published Phys. of Plasmas 15, 072701 2008)









Analytic calculations estimate higher efficiencies (20-25%) substituting H for DT ablators, ramping up ion K.E. in time.

[1]LLNL presentation, "Implementing Ion Beams in Kull and Hydra," T. Kaiser, G. Kerbel, M. Prasad

A MathCAD model and LASNEX use the same ion ray dE/dx formulary as in the HYDRA ion package documentation

$$-\frac{dE}{dx} = \underbrace{\left[\frac{4\pi e^4}{m_e c^2}\right]}_{5.1e-23\ keV\ cm^2} \underbrace{\left[\frac{N_0 \rho_T}{A_T}\right]}_{\frac{6e23\,\rho}{A\,cm^3}} \left[\frac{Z_{eff}^2}{\beta^2}\right] \left\{(Z_T - \overline{Z}) \operatorname{Log} \Lambda_B + \overline{Z}\, G(\beta / \beta_e) \operatorname{Log} \Lambda_F\right\}$$

ρ_T = target density in g/cm^3, A_T = target atomic weight

Z_T = target atomic number, $\overline{Z}$ = target ionization state

$\Lambda_B = \frac{2 m_e c^2 \beta^2}{\overline{I}}$, $\Lambda_F = \frac{m_e c^2 \beta^2}{\hbar \omega_p}$, $G(x) = erf(x) - x\, erf'(x) \approx 1$ for $x >> 1$

$\overline{I}$ = average ionization potential $\approx .01 Z_T\ keV$ (Bloch's rule)

ω_p = plasma frequency $= \sqrt{4\pi e^2 n_e / m_e} = 56416\sqrt{n_e}\,/\sec$

$\hbar\omega_p = (3.7e-14)\sqrt{n_e}\ keV$, n_e = electron density in $1/cm^3 = \overline{Z} N_0 \rho_T / A_T$

Ion Beam : $\beta = v/c$, $\gamma = \frac{1}{\sqrt{1-\beta^2}} = 1 + \frac{E}{Mc^2}$

E = Kinetic Energy of Ion Beam in keV,

Mc^2 = Ion Beam Rest Energy $= A_{IonBeam}\,(9.3e5)\ keV$

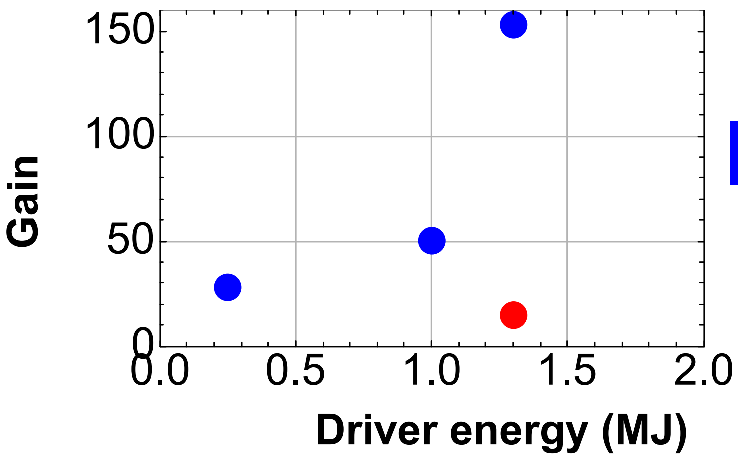
$m_e c^2$ = Electron Rest Energy $= 511\ keV$

Betz Empirical $Z_{eff} = Z_{IonBeam}\left[1 - \exp(-137\,\beta_{eff} / Z_{IonBeam}^{.69})\right]$

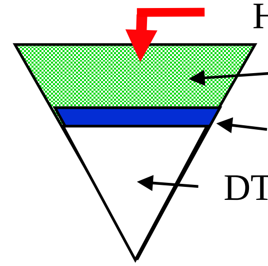
$\beta_{eff}^2 = \beta^2 + \beta_e^2$, with $\gamma_e = \frac{1}{\sqrt{1-\beta_e^2}} = 1 + \frac{kT_e}{m_e c^2}$

This Chandrasekhar function G (x=ion/electron speed) explains why the range increased 4X during the drive to enable high coupling efficiency in Perkins' LASNEX run.

LASNEX 1-D design for 250 kJ HIFTF heavy ion direct drive *in progress* (John Perkins, 8-08)



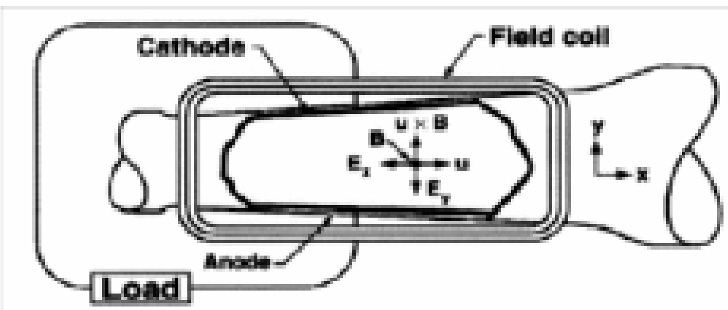
Next iteration for HIFTF target



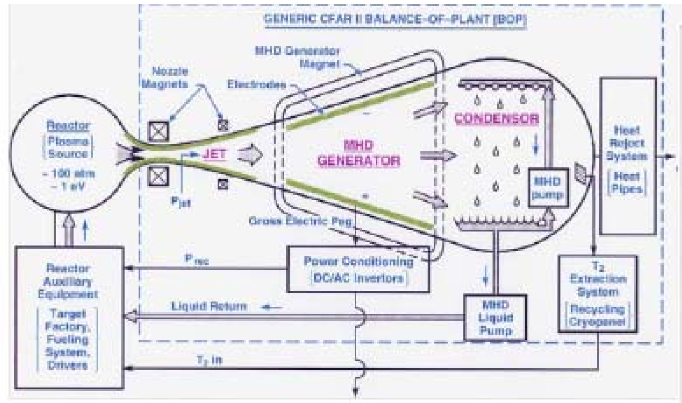
← expected gain > 50 for HIFTF @ lower 3.7e7 implosion velocity like NIF

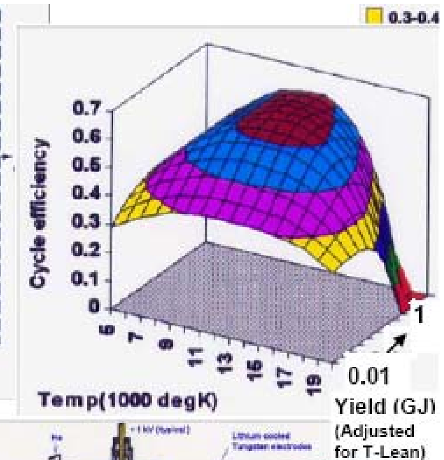
	NIF Ignition Baseline	1st HIFTF example HI Direct Drive NIF-like	HI Direct Drive MJ-Class	HI Direct Drive Shock Ignited
Drive type	Laser indirect drive → x-rays at 285eV	HI direct drive 50MeV Ar (foot) 100MeV (main)	HI direct drive 50MeV Ar	HI direct drive + HI shock ignition
Drive energy (MJ)	1.3	0.25	1.0	1.0 (assembly) +0.3 (shock)
Yield (MJ)	20	7.0	50	199
Gain	15	28	50	153
rhoR (g/cm2)	1.8	1.04	1.24	2.25
Peak velocity (cm/s)	3.7e7	5.2e7 (too high!)	4.44e7 (too high)	2.2e7
Drive efficiency	0.023	0.17	0.15	0.086 (but low velocity!)

High ρr + target shells capture >90% of fusion yield as 3 eV plasma →30X more energy per kg than chemical combustion with 15 x higher plasma temperatures →100X more power density (~ σu^2) than "old" MHD, →30X more kWe per ton power density than conventional steam-turbine generators → 10X lower balance of plant costs!



Schematic diagram of a dc magnetohydrodynamic generator. (Rosa)





Momentum :

$$\rho u \frac{du}{dx} + \nabla p = j \times B - \rho u^2 \frac{df}{dx}$$

Energy :

$$\rho u \frac{d}{dx}\left[\frac{u^2}{2} + h\right] = j \cdot E - qr$$

Continuity :

$$\rho u A = \text{constant}$$

Load Factor :

$$K = \frac{E}{uB}$$

Electric Power Density :

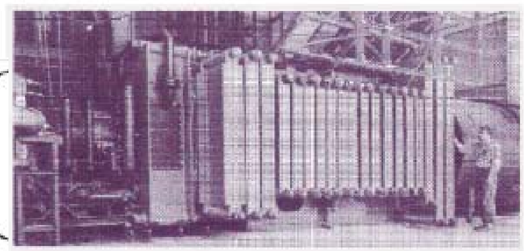
$$j \cdot E = -\frac{K(1-K)\,\sigma\, u^2 B^2}{1 + (\omega\tau^2)}$$

Magnet cost, Energy Density :

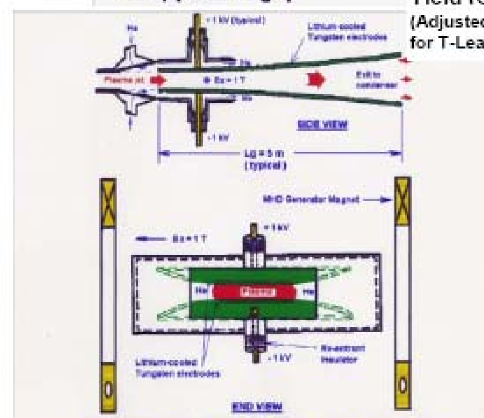
$$\text{Magnet Cost} / m^3 \sim B^2 / (2\mu_o)$$

where ρ = mass density, u = velocity, x = distance along channel, p = pressure, j = current density, B = magnetic field, E = electric field, σ = electrical conductivity, $\omega\tau$ = Hall parameter, h = specific enthalpy, f = friction due to mass inflow from wall transpiration cooling, qr = heat loss / m³ due to radiation losses, A = channel area.

→ MHD Magnet Cost / kWe ~ $B^2 / j \cdot E$ → Figure-of-merit \$ / kWe ~ $(\sigma u^2)^{-1}$



THE AVCO MARK V "ROCKET GENERATOR"
(from Rosa, MHD Energy Conversion, 1968)
Temp ~ 3000 deg K
Conductivity ~ 100 mhos/m
Velocity ~ 1000 m/s
Efficiency ~ 10% (of chemical)
Power (above unit) ~ 20 MWe

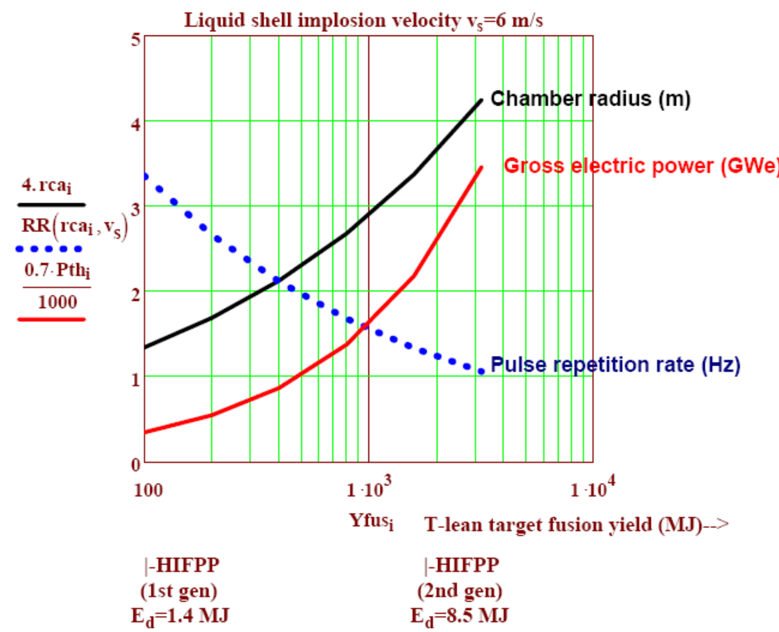


TYPICAL" CFARII MHD GENERATOR
Temp ~ 12000 deg K, Conductivity ~ 500 mho/m
Velocity ~ 10000 m/s, Efficiency ~ 80%(of kinetic)
Power (comparable size to MarkV) ~ 2000 MWe

[B.G. Logan, Fusion Engineering and Design 22, 151,1993]

Summary of cost model for reference CFAR power plant and DEMO updated for T-lean targets.

SUMMARY	POWER PLANT	DEMO	
T-lean fuel energy at ignition	1 MJ	0.2 MJ	
Energy delivered to ablation front	$E_{da}(1.5,1) = 2.55$	$E_{da}(1.5,0.2) = 0.49$	MJ
Capsule implosion efficiency	$\eta_c(1.5,1) = 0.39$	$\eta_c(1.5,0.2) = 0.41$	
Overall coupling efficiency beam-to-fuel corrected for parasitic loss on ablation plasma	$\eta_{dfA} = 0.25$	$\eta_{dfB} = 0.23$	
H_2 ablation front temperature	$T_{ex}(1.5,1) = 26.3$	$T_{ex}(1.5,0.2) = 36$	eV
Fusion yield	$Y_f(1.5,1) = 494$	$Y_f(1.5,0.2) = 43$	MJ
Driver energy	$1 \cdot \eta_{dfA}^{-1} = 4.06$	$0.2 \cdot \eta_{dfB}^{-1} = 0.85$	
Driver efficiency	$\eta_{dA} := 0.4$	$\eta_{dB} := 0.2$	
Driver electric input energy/pulse	$1 \cdot \eta_{dA}^{-1} \cdot \eta_{dfA}^{-1} = 10.1$	$0.2 \cdot \eta_{dB}^{-1} \cdot \eta_{dfB}^{-1} = 4.3$	
Target gain	$Y_f(1.5,1) \cdot \eta_{dfA} \cdot 1^{-1} = 122$	$Y_f(1.5,0.2) \cdot \eta_{dfB} \cdot 0.2^{-1} = 51$	
Fusion energy conversion eff. (lowest CoE for Demo requires 35% steam bottoming cycle to get 0.65 conversion overall)	$\eta_{MHD} := 0.65$ ^| lowest CoE this case	$\eta_{MHD} := 0.4$ $\eta_{MHDsteam} := 0.65$	
Gross electric output (per pulse)	$W_e(0.65,1.5,1) = 278$	$W_e(0.65,1.5,0.2) = 20.5$	
Net electric output per pulse, inc 5 % aux	$W_{netA} = 254$	$W_{netB} = 15.2$	
Pulse repetition rate	$RR_A := 6$ ←higher jet velocities	$RR_B := 8$	
Net electric power	$P_{netA} = 1522$	$P_{netB} = 122$	
Driver direct cost	$C_{driver}(\eta_{dfA},1) = 528$	$C_{driver}(\eta_{dfB},0.2) = 111$	
Vessel direct cost	$C_{vessel}(1.5,1) = 59$	$C_{vessel}(1.5,0.2) = 8.5$	M$
Balance-of-Plant direct cost	$C_{mhdBoP}(1522) = 104$	$C_{mhdBoP}(122) + C_{steamBoP}(122) = 64$	M$
Other direct costs	$C_{other}(1522) = 103$	$C_{other}(122) = 38$	M$
Cost of Electricity, inc. targets and O&M	$CoE_A = 29.4$ -->may meet affordable CoE goal for 10 billion people	$CoE_B = 125$ --> total capital < 1 B$ for DEMO for net power and tritium production	mills/kW$_e$hr



If rep rate cannot be maintained at 6 Hz with faster jets in larger chambers, then this inset figure shows higher power levels are still achievable.

Recent theory progress in the VNL supports our understanding of NDCX experiments and gives us the tools we need in neutralized beam compression and focusing for HEDP and heavy ion fusion.

Physics of Ion Beam Pulse Neutralization in Solenoidal Magnetic Field

I.D. Kaganovich, M. Dorf, E. A. Startsev, R. C. Davidson, A. B. Sefkow

Princeton Plasma Physics Laboratory, USA

Ion beam propagation through a background plasma along a solenoidal magnetic field:

Waves Excitation and the Electrostatic Plasma Lens Effect

Dynamics of electromagnetic two-stream interaction processes during longitudinal and transverse compression of an intense ion beam pulse propagating through background plasma.*

Edward Startsev and Ronald C. Davidson

Conclusions

- Neutralized drift compression can reach 300x300 = 10^5 combined longitudinal and transverse compression,
  - 1000 compression was achieved,
  - further progress requires better alignment of radial and longitudinal focal planes and optimization.

- *$\alpha=\omega_{ce}/2\beta\omega_{pe}$ determines the properties of the plasma response to the charge bunch moving along the magnetic field*

M. Dorf, I. Kaganovich, E. Startsev, R. Davidson

- *α<1: response is paramagnetic; electric field is defocusing*
  α>1: response is diamagnetic; electric field is focusing
  α=1: large amplitude waves (Helicon branch) are excited

Conclusions, part I

- It is found that the longitudinal beam compression strongly modifies the space-time development of the electrostatic two-stream instability.
- In particular, the dynamic compression leads to a significant reduction in the growth rate of the two-stream instability compared to the case without an initial velocity tilt by a factor

$$G_{max}/G_{max}^{notilt} \sim (\omega_{pb}/\omega_{pe})^{1/3} \ll 1$$

- The number of e-foldings is proportional to the number of beam-plasma periods $1/\omega_{pb}$ during the compression time T_f.
- The two-stream instability is complectly mitigated by the effects of dynamical beam compression when $\omega_{pb}T_f <\sim 1$.

Acknowledgements:

Thanks to all who have worked on heavy ion fusion, still on-going, but in particular:

- To all those in the VNL who have made neutralized drift compression, a key enabling technique for HEDP and HIF, today a reality (in no particular order): Larry Grisham, Dale Welch, Adam Sefkow, Prabir Roy, Enrique Henestroza, Ron Davidson, Peter Seidl, Josh Coleman, Eric Gilson, Phil Efthimion, Matthaeus Leitner, Will Waldron, John Barnard, Alex Friedman, Bill Sharp, Hong Qin, Igor Kaganovich, Ed Startsev, and many others.
- To Dick Briggs and Ed Lee, who advocated and defined the modular solenoid approach to HIF more than 10 years ago, in 1997, and to Wayne Meier, for systems analysis of the approach.
- To Simon Yu, who organized modular solenoid driver studies in 2002-2003, and implemented elements of the approach in NDCX-I and in initial plans for NDCX-II.
- To Ralph Moir, who gave us an idea on how to apply liquid jets to protect direct drive chambers.
- To George Caporaso, who supported our efforts through the VNL PAC, and gave us the 40 ATA modules that will allow us to build NDCX-II for first direct drive experiments at a low cost.
- To Matthaeus and Daniela Leitner, who made us aware of possibilities for high-q ion sources using high-powered gyrotrons, and the related Russian work.
- To Roger Bangerter, who urged another, closer look at 6-D phase space constraints in our work.
- Last but not least: To our US target experts who have given us a great gift of research opportunity and guidance in re-considering heavy ion direct drive:

John Perkins, John Nuckolls, Max Tabak, Dave Bailey, Craig Sangster, and to our international colleagues who have encouraged us to pursue heavy ion direct drive: Masakatsu Murakami, Dieter Hoffmann, Naeem Tahir, Claude Deutsch, Juergen Meyer-Ter-Vehn, Boris Sharkov, Shigeo Kawata, and Roberto Piriz.

(Our apologies to any we may have forgotten to include here)