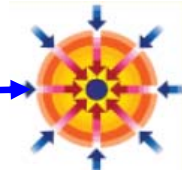
A VISION FOR HEAVY ION POLAR DIRECT DRIVE FUSION

...exploiting the intrinsic high efficiency of heavy ion beams for direct drive



Presented by B. Grant Logan
on behalf of the
U.S. Heavy Ion Fusion Science Virtual national Laboratory

Presented to: American Nuclear Society
Topical Meeting on the Technology of Fusion Energy
San Francisco, California
September 28 to October 2, 2008

*** This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Berkeley and Lawrence Livermore National Laboratories under Contract Numbers DE-AC02-05CH1123 and DE-AC52-07NA27344 , and by the Princeton Plasma Physics Laboratory under Contract Number DE-AC02-76CH03073.**

What we are seeking:

☞ ***Unlimited and affordable*** fusion energy to sustain 10 billion people living on a hotter planet→ all transportation fuel and all electricity for homes, commerce, food, and ocean desalination to grow the food.

☞ By ***unlimited*** we mean no fuel/material resource limits to produce the 30 TW_e needed for 10 B people "forever". By ***affordable*** we mean a target CoE < 3 cts/kW_{ehr} (for energy cost < 15% of 200T$/yr world GDP).

…and a pathway to get there→

- High gain inertial fusion with sufficient target ρr > 6-10 g/cm^2 to internally capture neutron energy into plasma energy for direct conversion → T-lean targets: DD fuel with a DT sparkplug. *[M. Tabak, Nucl. Fusion 36, 147 1996, and S. Atzeni, C. Ciampi, Nucl. Fusion 37, 1665, 1997. For MHD Direct Conversion →B.G. Logan, Fusion Engineering and Design 22, 151,1993]*
- Low drive energy for fuel compression & ignition (< 2 MJ for a DEMO, e.g., efficient direct drive with ramped ion beam range and/or shock ignition)
- Modular drivers (e.g., solenoid-focused induction linac modules).
- Thick-liquid-protected chambers to avoid frequent replacement of first walls (e.g., variants of HYLIFE, RPD with Flibe jets and/or vortices).

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/].*

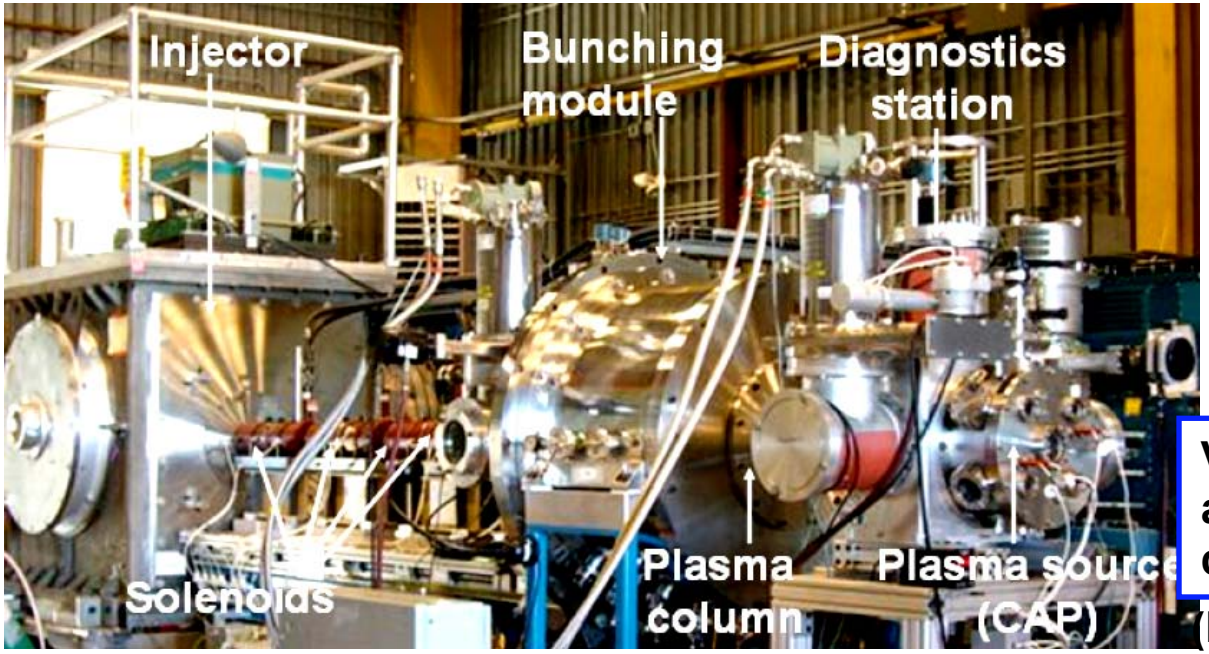
This presentation focuses on a heavy ion fusion test facility (HIFTF) and a follow-on power plant (HIFPP) using T-lean targets

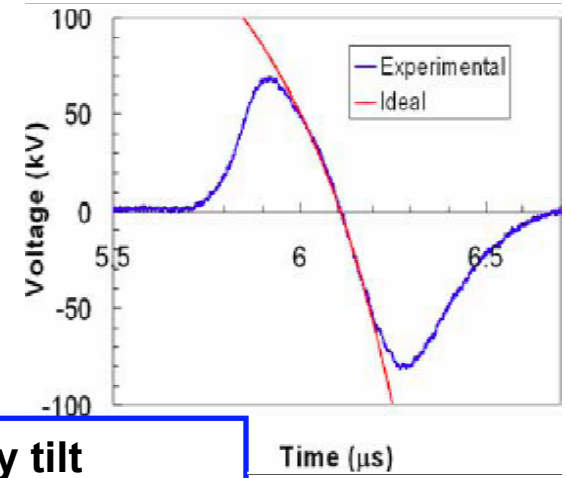
Ranges given in table reflect options under study

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

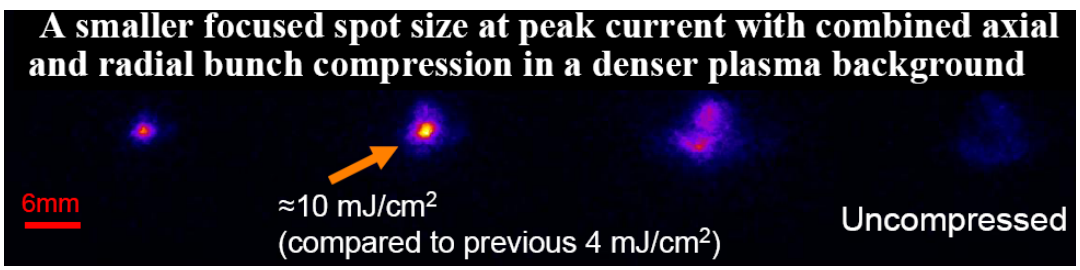
Breakthrough: Compression of intense velocity-chirped ion beams in plasma*. Now, radial and temporal compression→ > 1000 X n_{beam}

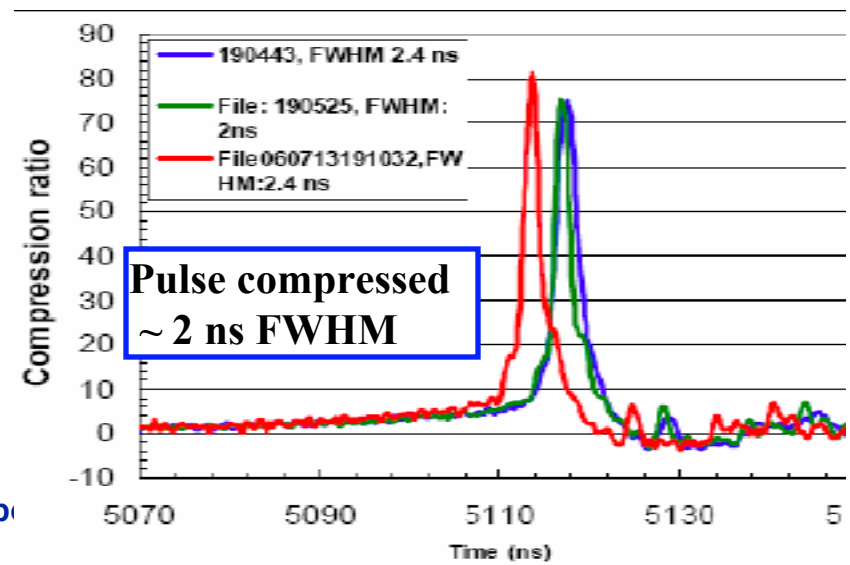




Velocity tilt accelerates tail, decelerates head

(Like chirped pulse compression)

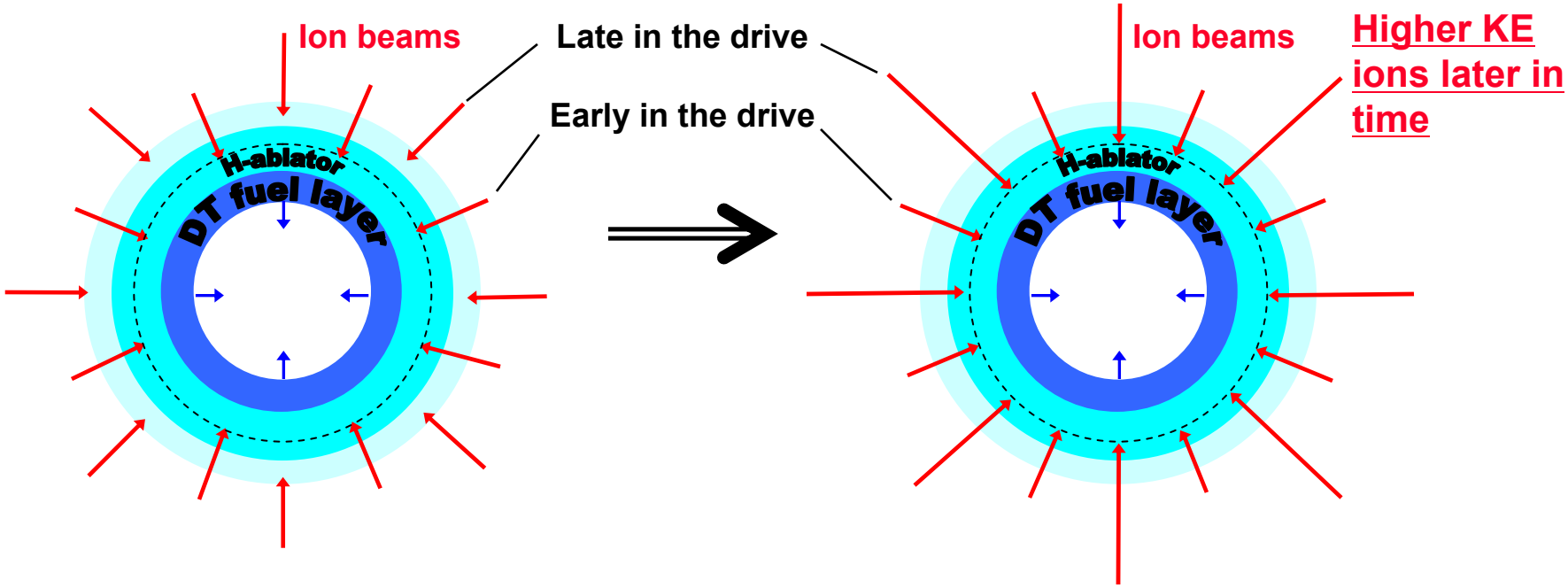




*cf Roy et al PRL 95(2005) 23481

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:*



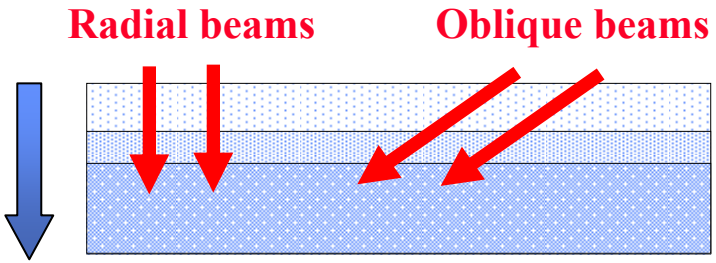
Constant* ion *range

→ decouples

Strongly-increasing >4X ion range

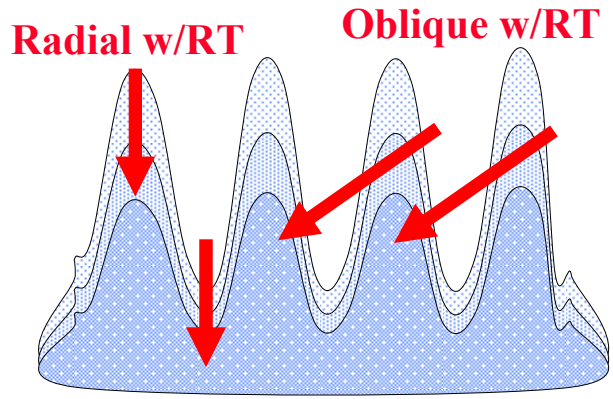
→ high hydro-coupling efficiency!

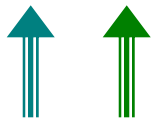
Oblique ion illumination with beam spot rotation (RF wobblers) can enhance ablative-stabilization and lengthen pressure gradient scale lengths behind the ablation front



Density gradient

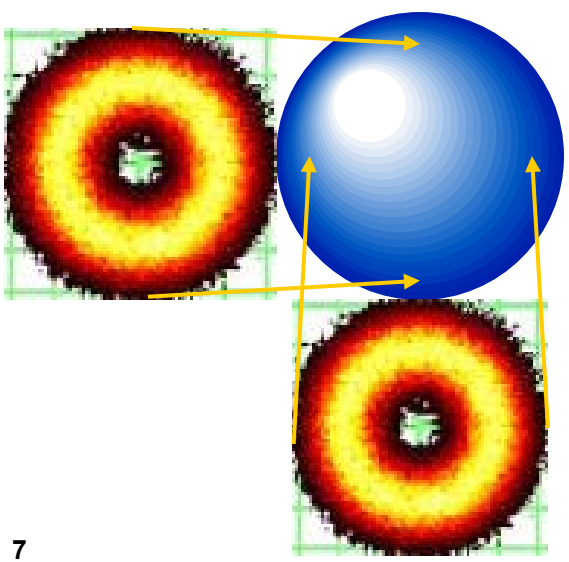
Un-perturbed ablator





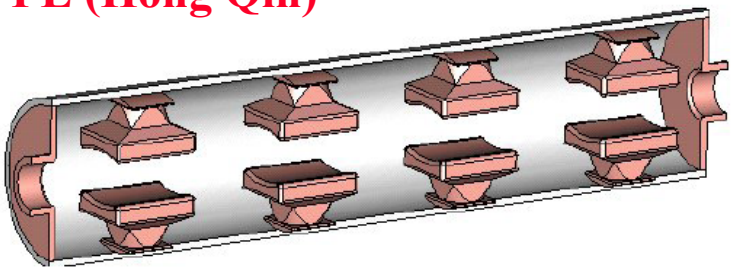
g-Acceleration, Gradient Te,

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

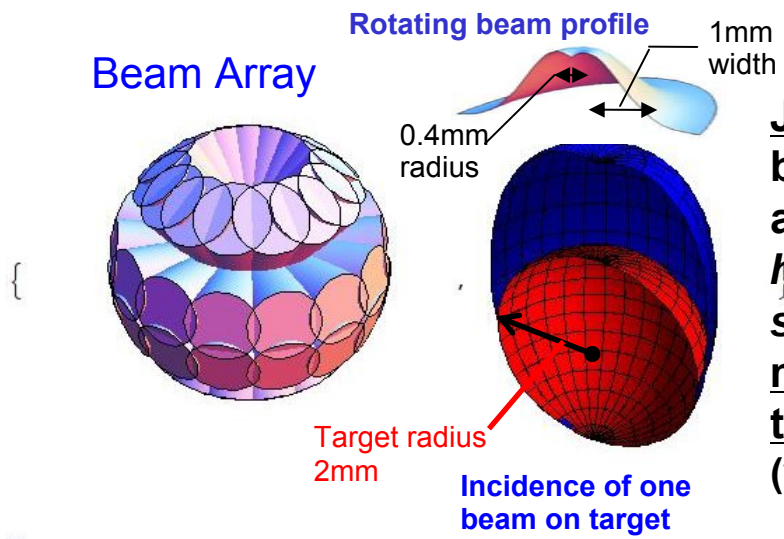


Projection of many overlapping hollow beams onto a spherical ablator leads to mostly-oblique ray-illumination in the foot pulse, and smoother.

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



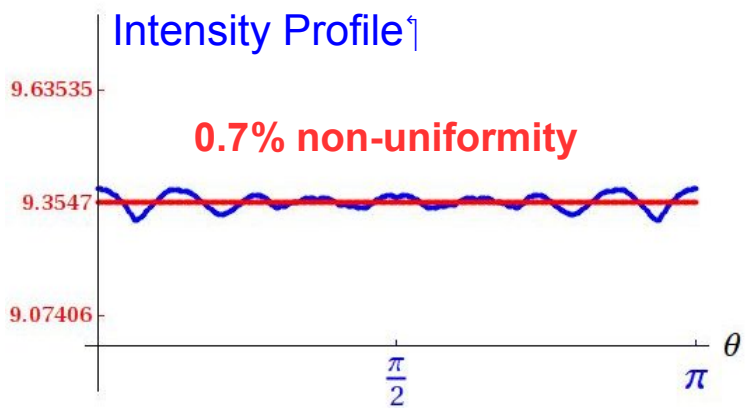
Jakob Runge, a German Fulbright summer student at LBNL, has developed a Mathematica model to explore the question: what minimum number of polar angles of annular ring arrays with beams *using hollow rotated beam spots* would be needed to achieve less than 1% non-uniformity of deposition?



16 each best for two-sided beamline layouts

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).

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.

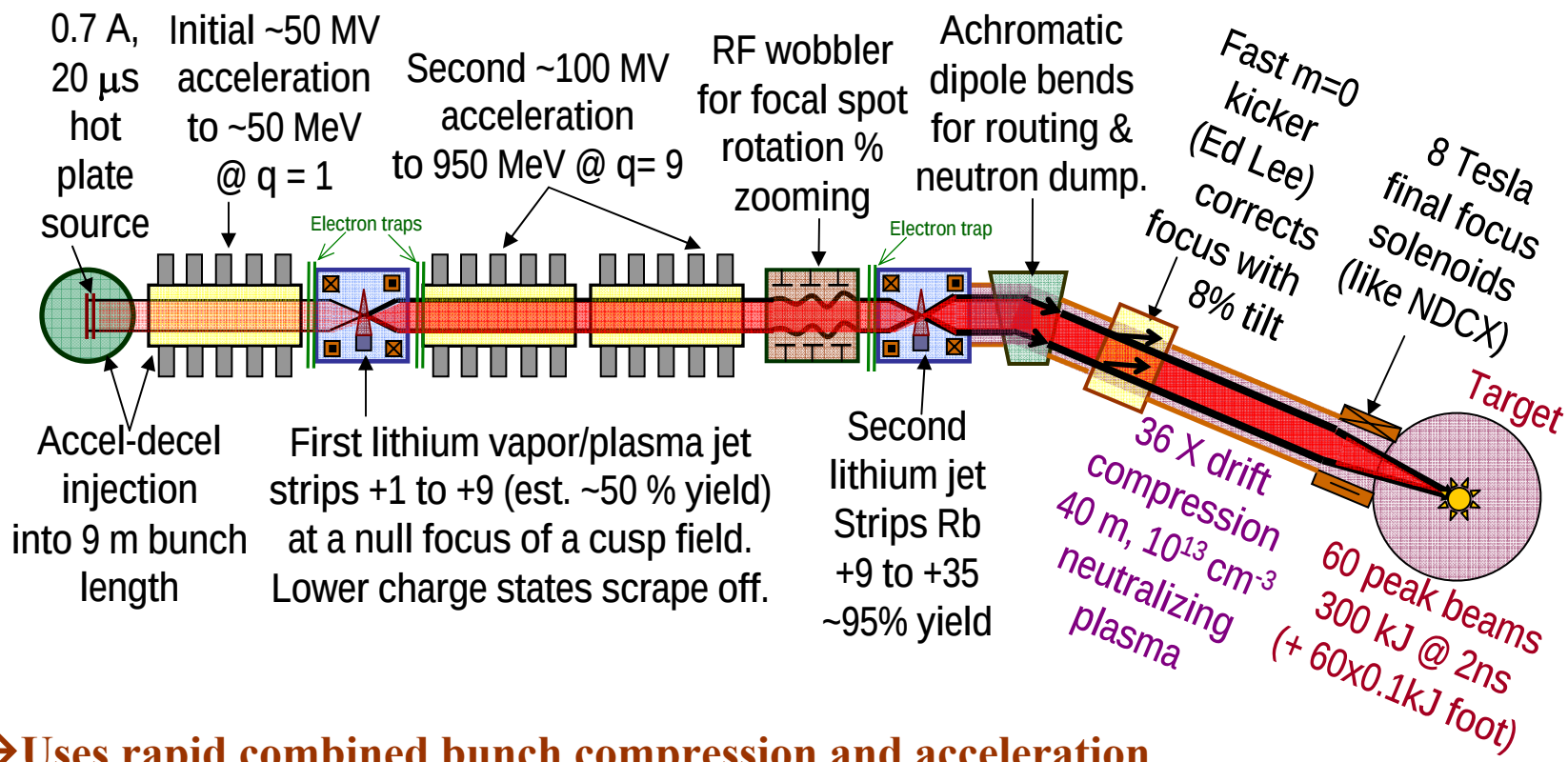
Option for a 5 kJ linac module for a 60-peak-beam HIFTF driver :

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.



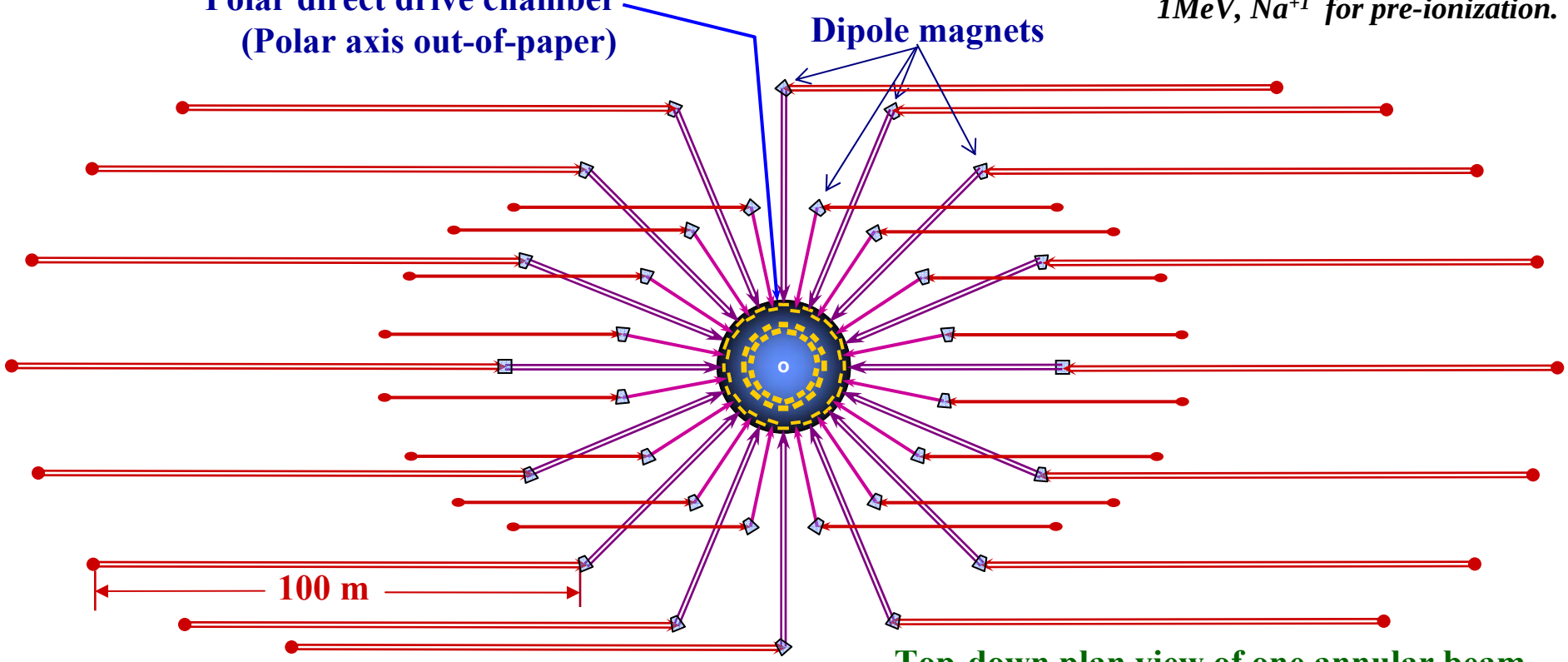
→**Uses rapid combined bunch compression and acceleration with downstream beam manipulations to be tested on NDCX-I&II**

→**Two of these drive test implosions in HIDDIX; 64 for peak drive for HIFTF.**

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.



64 Peak-drive accelerators

Peak-drive drift compression lines

64 Foot-drive accelerators

Foot-drive drift compression lines

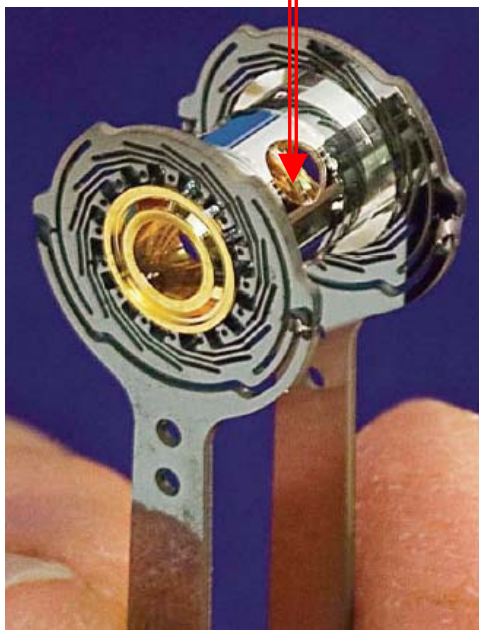
<u>Top-down plan view</u> of one annular beam array of 16 peak and 16 foot drive beams at one polar angle of 79 degrees. Beamlines for all 4 polar angels form beam array heights ~ widths ~ 80 m each side.

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:*

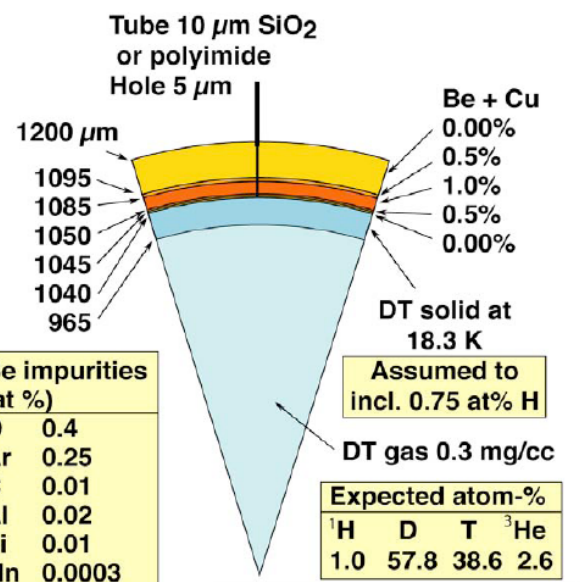
LASNEX giving the same coupling efficiency, could 200 kJ of ions absorbed (300 kJ incident with spill) with *same power vs time and the right range into H/DT ablators* get gain >*50?*

1 mm radius Be capsule



The National Ignition Campaign

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



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

Expected atom-%			
^{1}H	D	T	^{3}He
1.0	57.8	38.6	2.6

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

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

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

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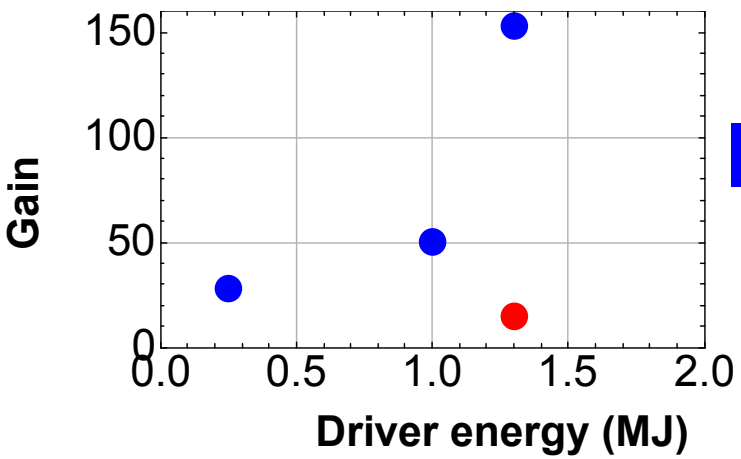
(Received 16 May 2008; accepted 4 June 2008; published online 9 July 2008)

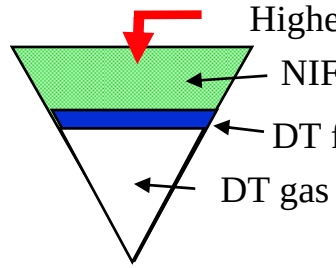
Issues with coupling efficiency, beam illumination symmetry, and Rayleigh-Taylor instability are discussed for spherical heavy-ion-beam-driven targets with and without hohlraums. Efficient coupling of heavy-ion beams to compress direct-drive inertial fusion targets without hohlraums is found to require 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. © *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 *<u>much less than 1 MJ?</u>*"

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



Next iteration for HIFTF target



Higher energy Rb^{+9} ions ramped 100-200 → 400-950MeV

NIF-scale capsule with graded DT→DD→H ablator
(More ablator mass→ lower aspect ratio)

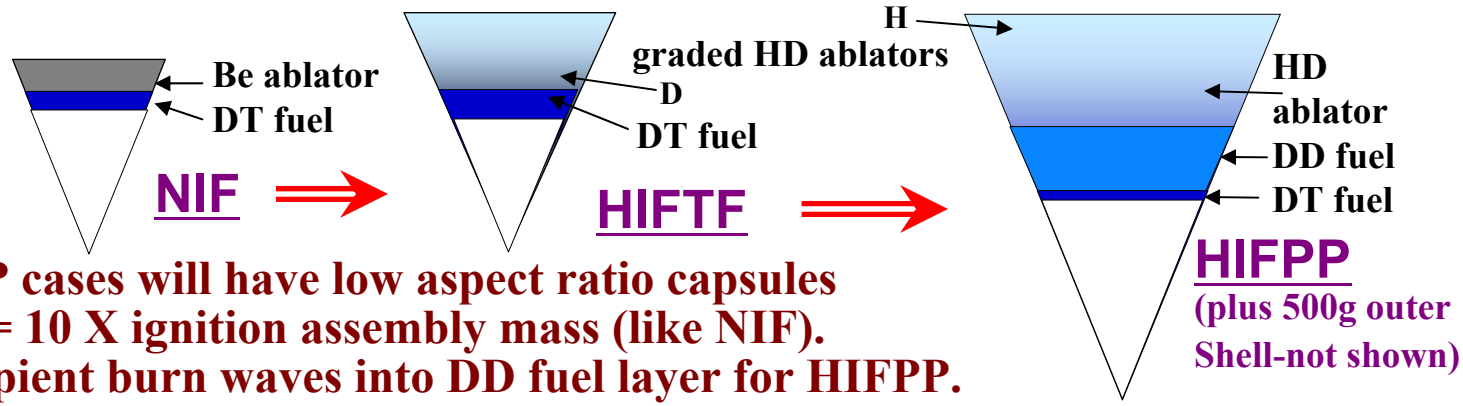
← expected gain > 50 for HIFTF @ lower 3.7e7 implosion velocity like NIF

1st HIFTF example

	NIF Ignition Baseline	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!)

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)

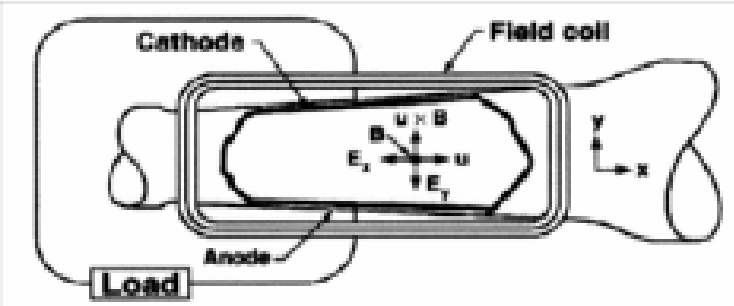
(Capsules not drawn to scale)→



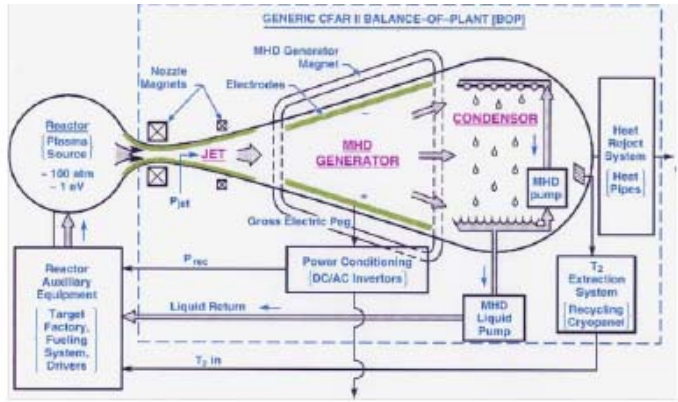
→HIFTF & HIFPP cases will have low aspect ratio capsules with ablator mass = 10 X ignition assembly mass (like NIF).
→HIFTF tests incipient burn waves into DD fuel layer for HIFPP.

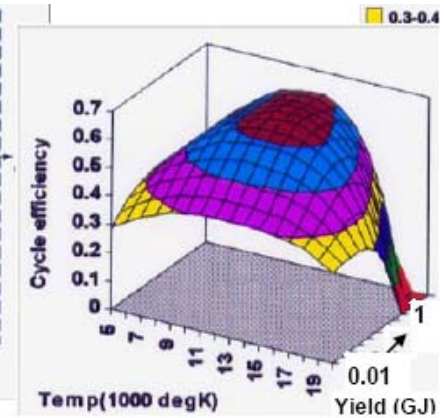
	NIF baseline	HIFTF (DT) (planned)	HIFPP (T-lean power plant)
Outer radius	1.2 mm	2 mm (TBD-Lasnex)	5 mm (M_o/M_f=10, Tabak dd core)
Energy into capsule	200 kJ (300eV x-rays)	250 kJ (heavy ions 2→10 mg/cm^2 ranges)	1.4 MJ (heavy ions 4→20 mg/cm^2 ranges)
Ignition masses (at stagnation)	0.24 mg DT core +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/cm^2	1.2 - 1.8 g/cm^2 (TBD)	8.1 g/cm^2 (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)

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 :

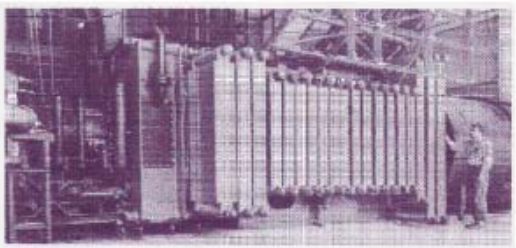
$$j \cdot E = -\frac{K(1-K)\,\sigma u^2 B^2}{1 + (\omega\tau^2)}$$

Magnet cost, Energy Density :

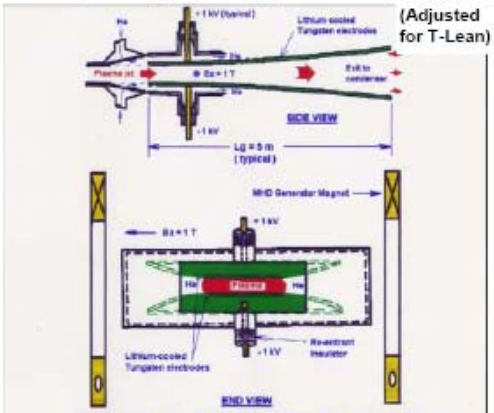
$$\text{Magnet Cost} / m^3 \sim B^2 / (2\mu_o)$$

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 / m^3 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



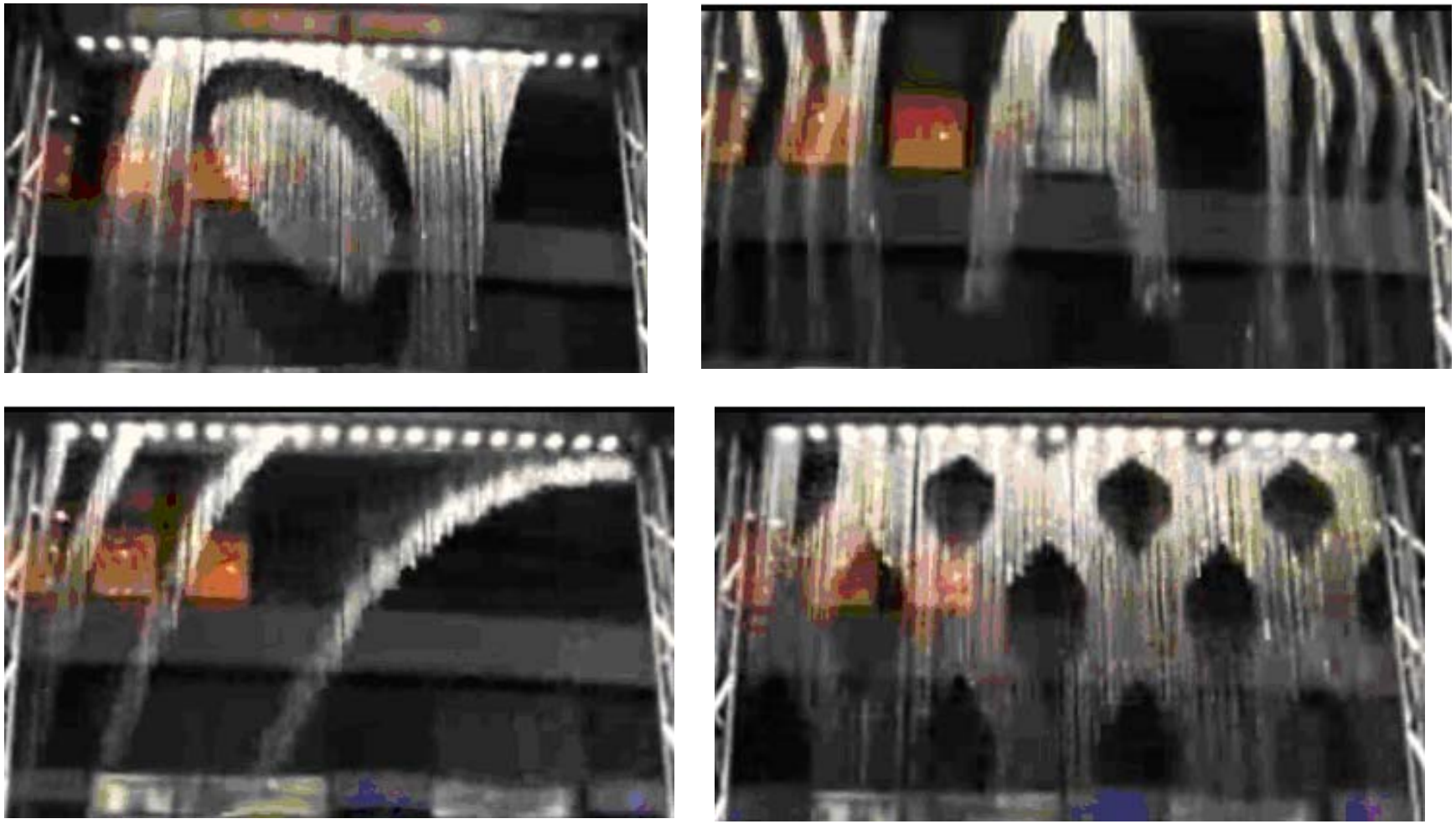
TYPICAL" CFARII MHD GENERATOR
Temp ~ 12000 deg K, Conductivity ~ 500 mho/m
Velocity ~ 10000 m/s, Efficiency ~ 80%(of kinetic)
Power (comparable size to MarkV) ~ 2000 MWe

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

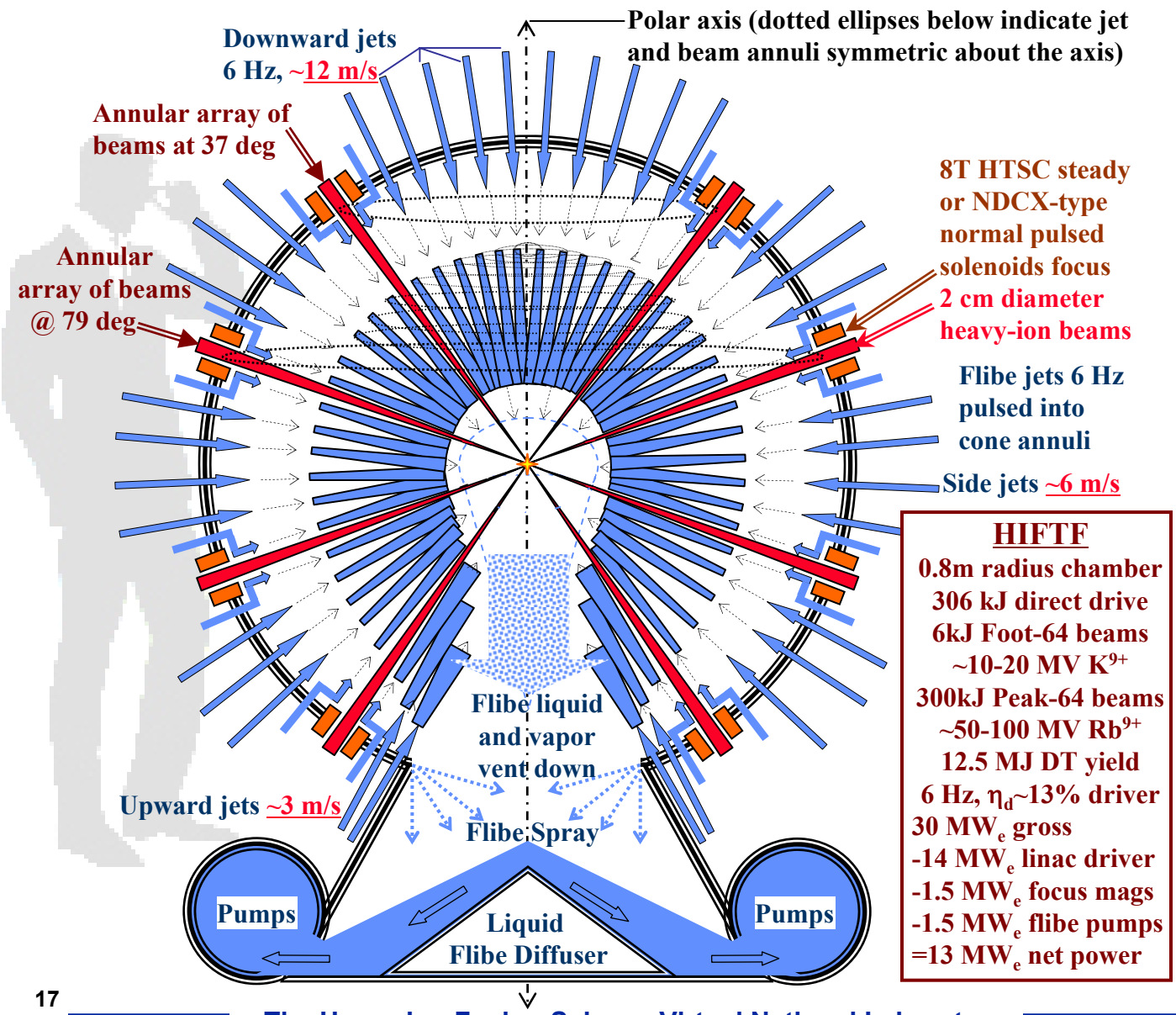
New pulsed-jet valve capability would enable thick liquid Flibe protection like HYLIFE to be adapted to *direct drive chambers*

[R. Moir, LLNL, 1999 HYLIFE note.

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



Concept for thick-liquid-protected chamber for polar direct drive

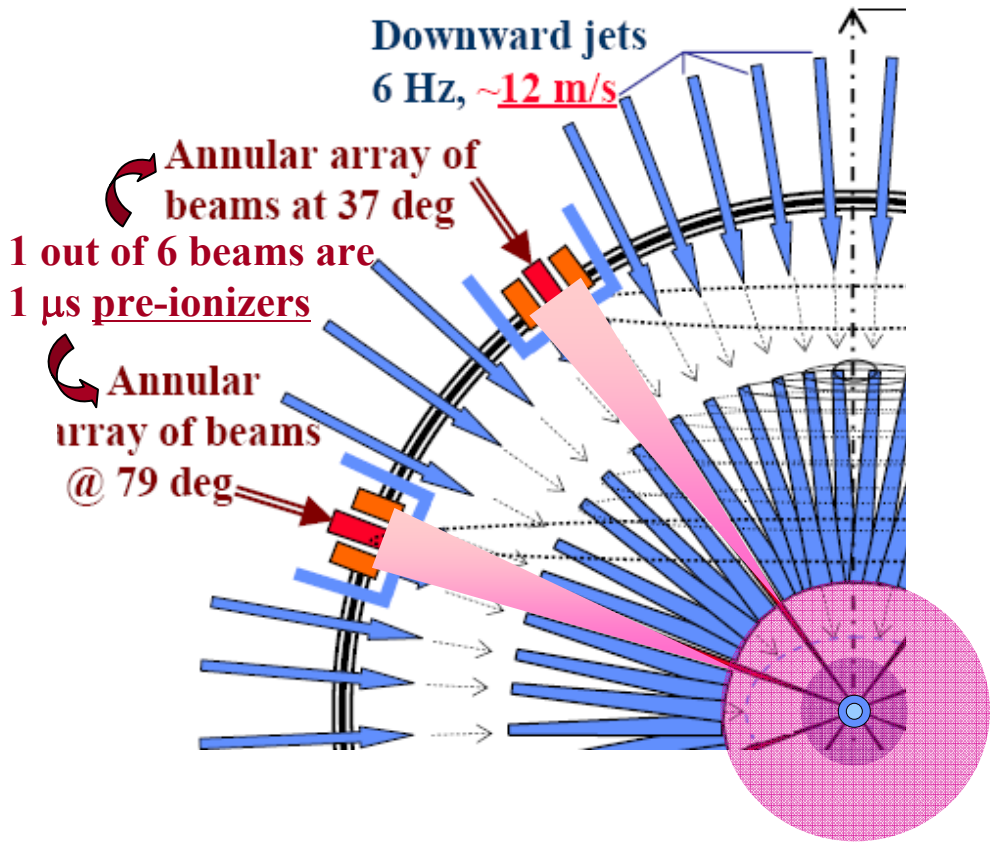


HIFTF

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.

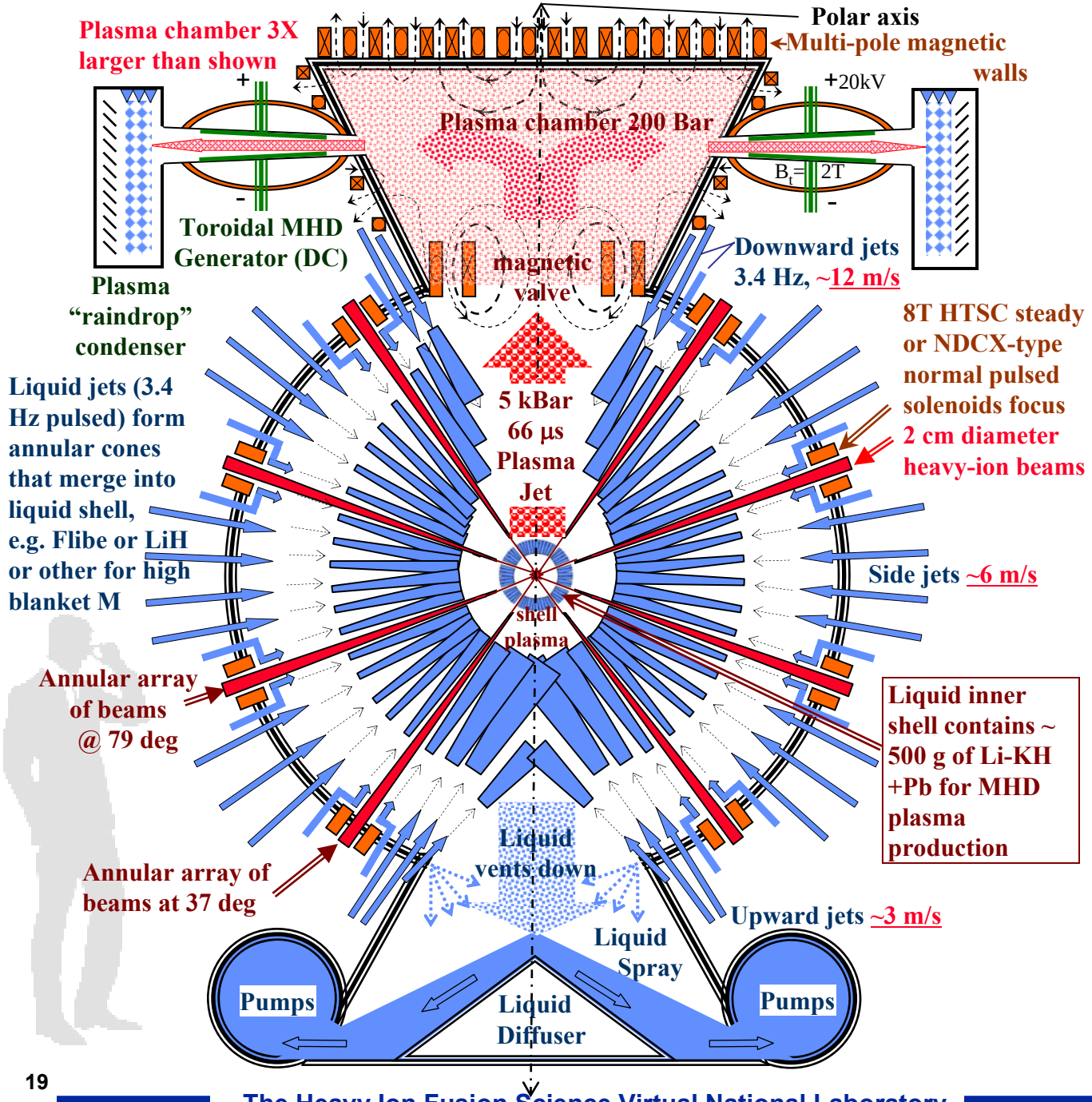
Driver ion beam space charge is neutralized by a cold Hydrogen gas puff pre-ionized by 24-low energy beams (1A, 1 MeV Na^{+1})



→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.

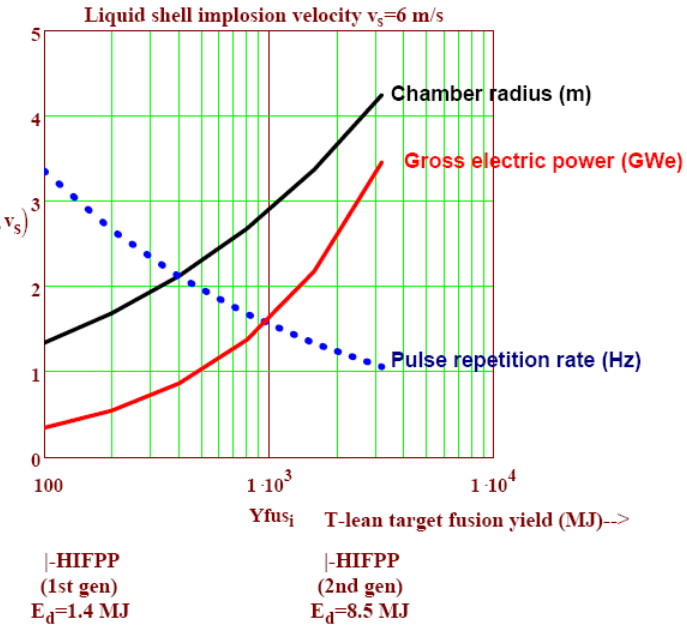


Advanced fuel HIF Power Plant (HIFPP) using direct drive compression of DD fuel with DT spark plug.

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

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

SUMMARY	POWER PLANT 1 MJ	DEMO 0.2 MJ	
T-lean fuel energy at ignition			
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 efficicency 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)	$\eta_{MHD} := 0.65$	$\eta_{MHD} := 0.4$	
	^| lowest CoE this case	$\eta_{MHDsteam} := 0.65$	
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	$CoE_A = 29.4$	$CoE_B = 125$	mills/kW_ehr
	-->may meet affordable CoE goal for 10 billion people	--> total capital < 1 B$ for DEMO for net power and tritium production	



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.

Conclusion: the potential attractiveness of advanced T-lean targets for direct conversion motivate further study. More theory, experiments and conceptual design needed for:

- **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 driver. The road to realize heavy ion direct drive fusion may be long, but the potential for very high coupling efficiency enabling direct plasma energy conversion justifies the effort.

Backup Slides

Acknowledgements:

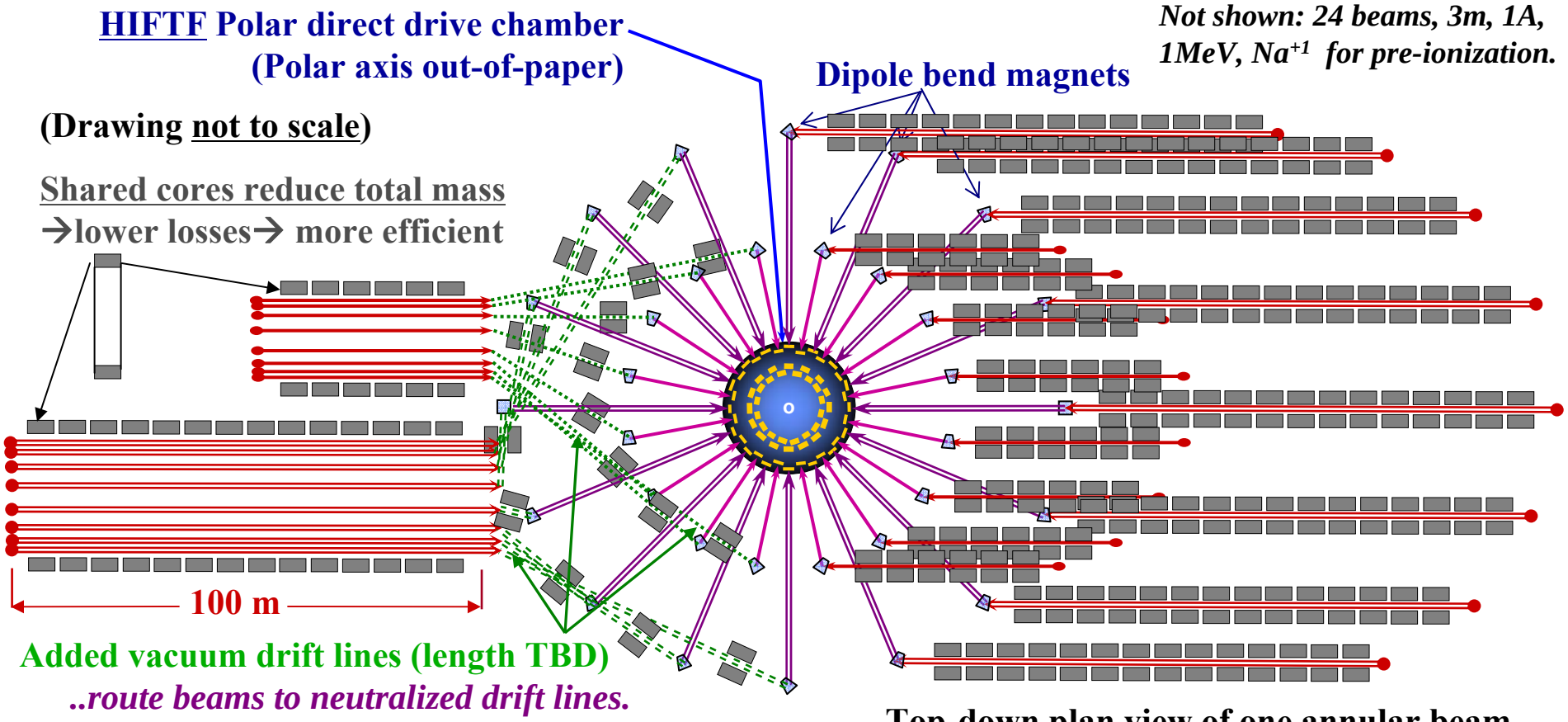
Thanks to all who have worked on heavy ion fusion, still on-going, but in particular:

- **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)

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



64 Peak-drive accelerators
Peak-drive drift compression lines
64 Foot-drive accelerators
Foot-drive drift compression 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).

Nov. 2006: Realizing heavy ion direct drive with the right range and angle might achieve high capsule coupling efficiency and RT stability like x-ray drive, we asked LLNL for new LASNEX calculations (initially 1-D).

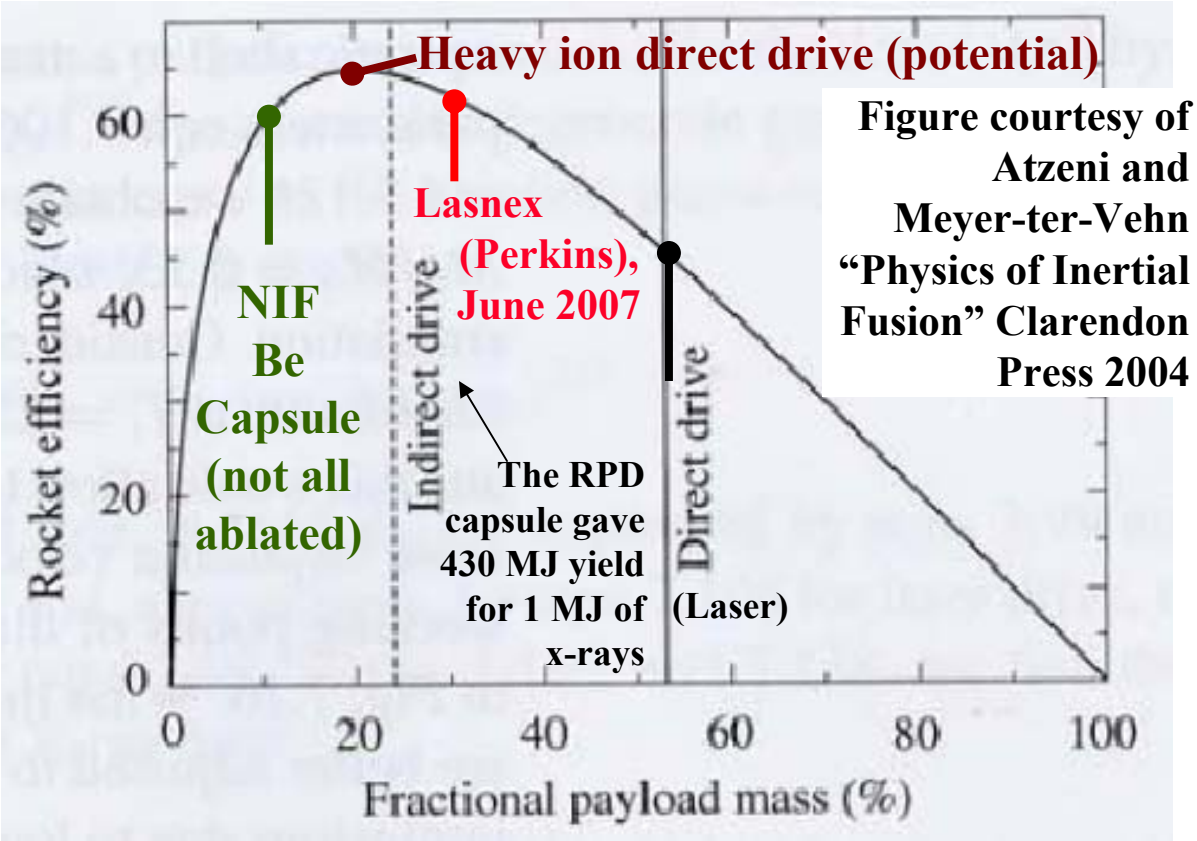


Figure courtesy of Atzeni and Meyer-ter-Vehn "Physics of Inertial Fusion" Clarendon Press 2004

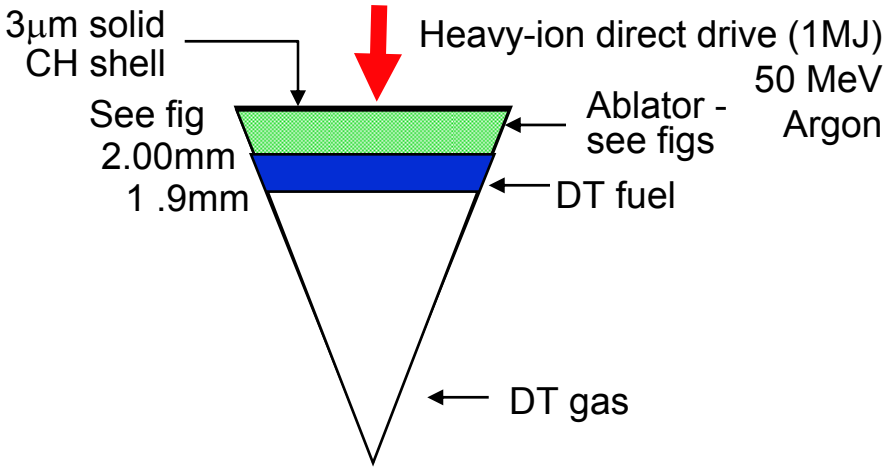
→Low-Z ablators (DT or H) for ion direct drive need small 13.6 eV ionization

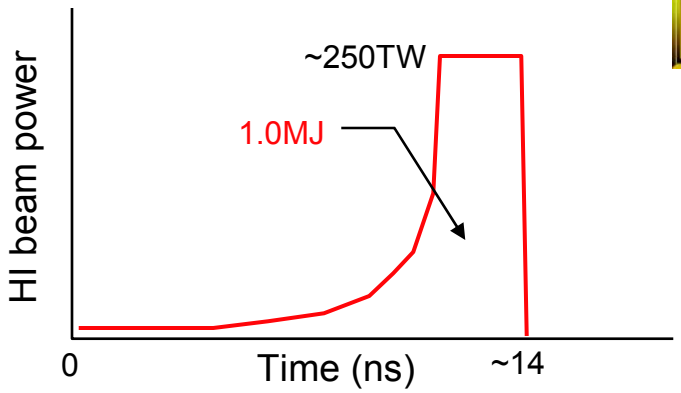
→X-rays couple well to Ablators, but Be, C ablators require significant ionization energy.

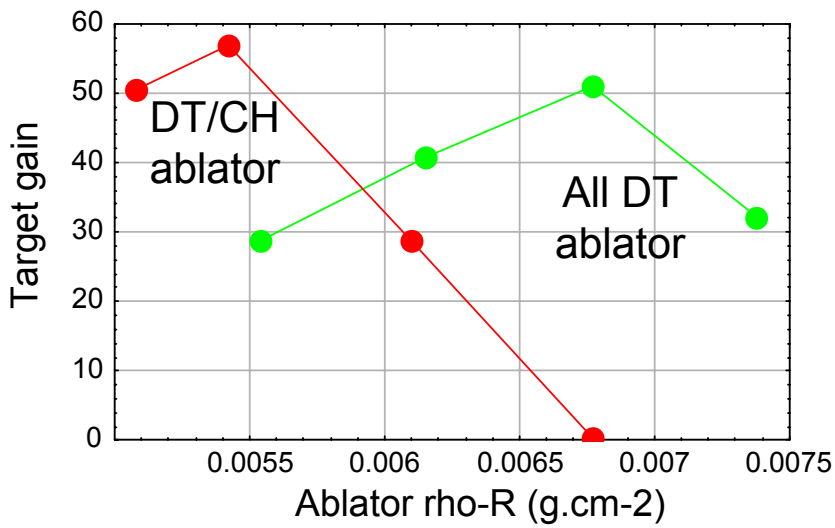
→Laser coupling is reduced with electron transport from low critical density to ablation front

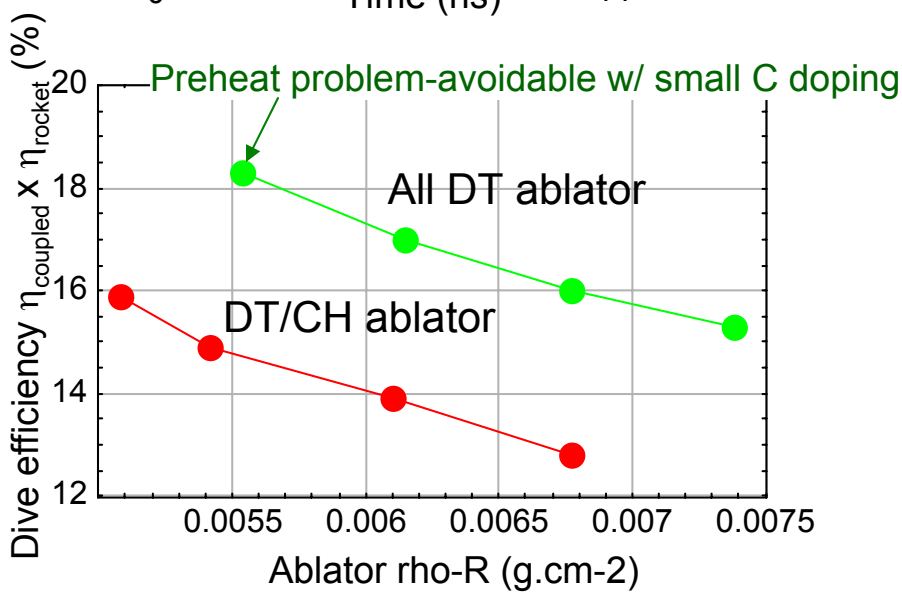
Heavy ion beams can suffer more parasitic energy loss on out-going ablation corona plasma than either x-ray or laser photons, *but with range-lengthening during the drive pulse, overall coupling efficiencies can still be higher*.

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



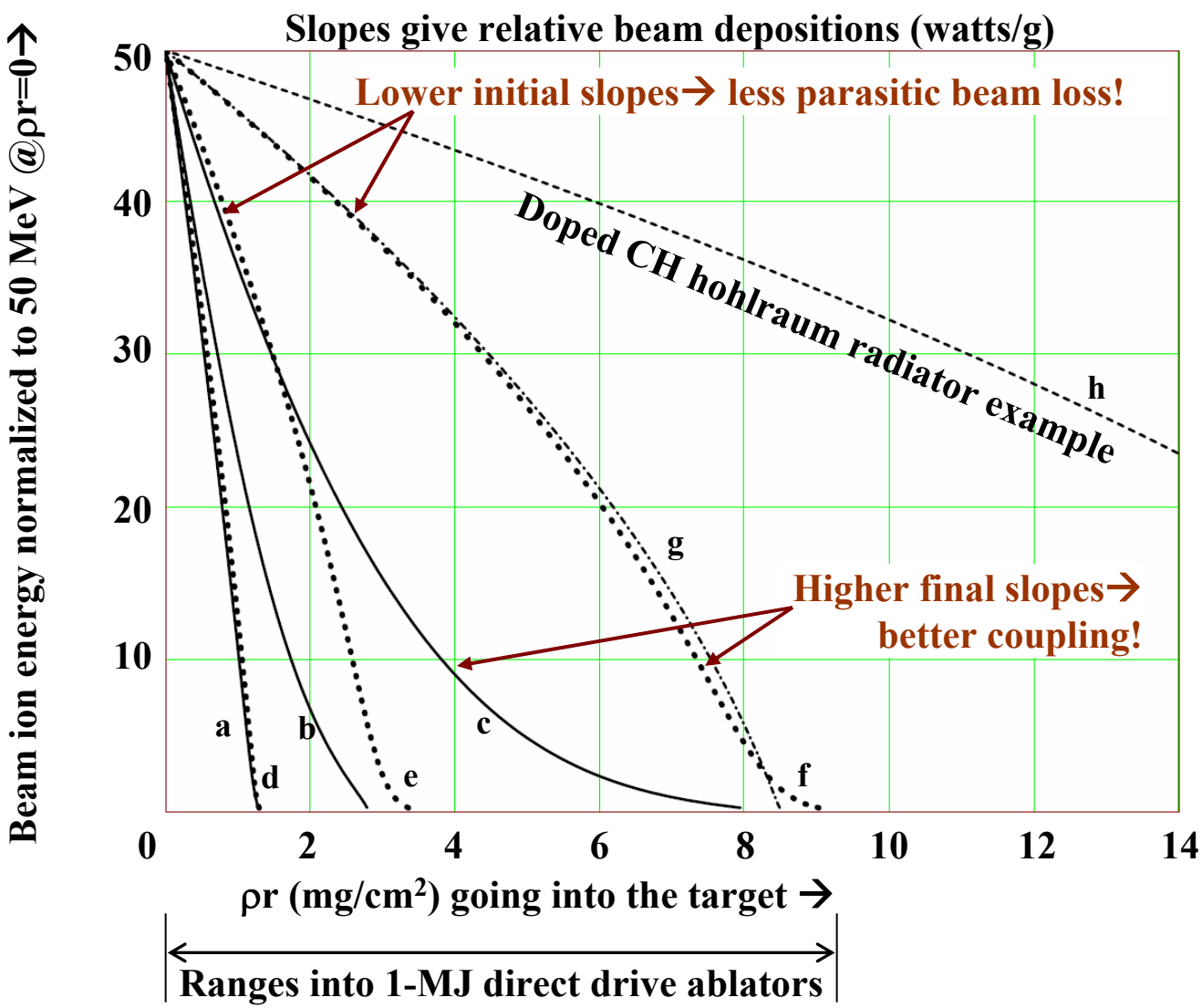






Analytic calculations estimate higher efficiencies (20-25%) substituting H for DT ablators, ramping up ion K.E. in time.

The high coupling efficiency (16%) in LASNEX derives from the ion range increasing strongly during the implosion. *Even higher coupling efficiency is predicted if we use ramped Argon ion beam energies100 MeV foot→500 MeV peak -next runs*

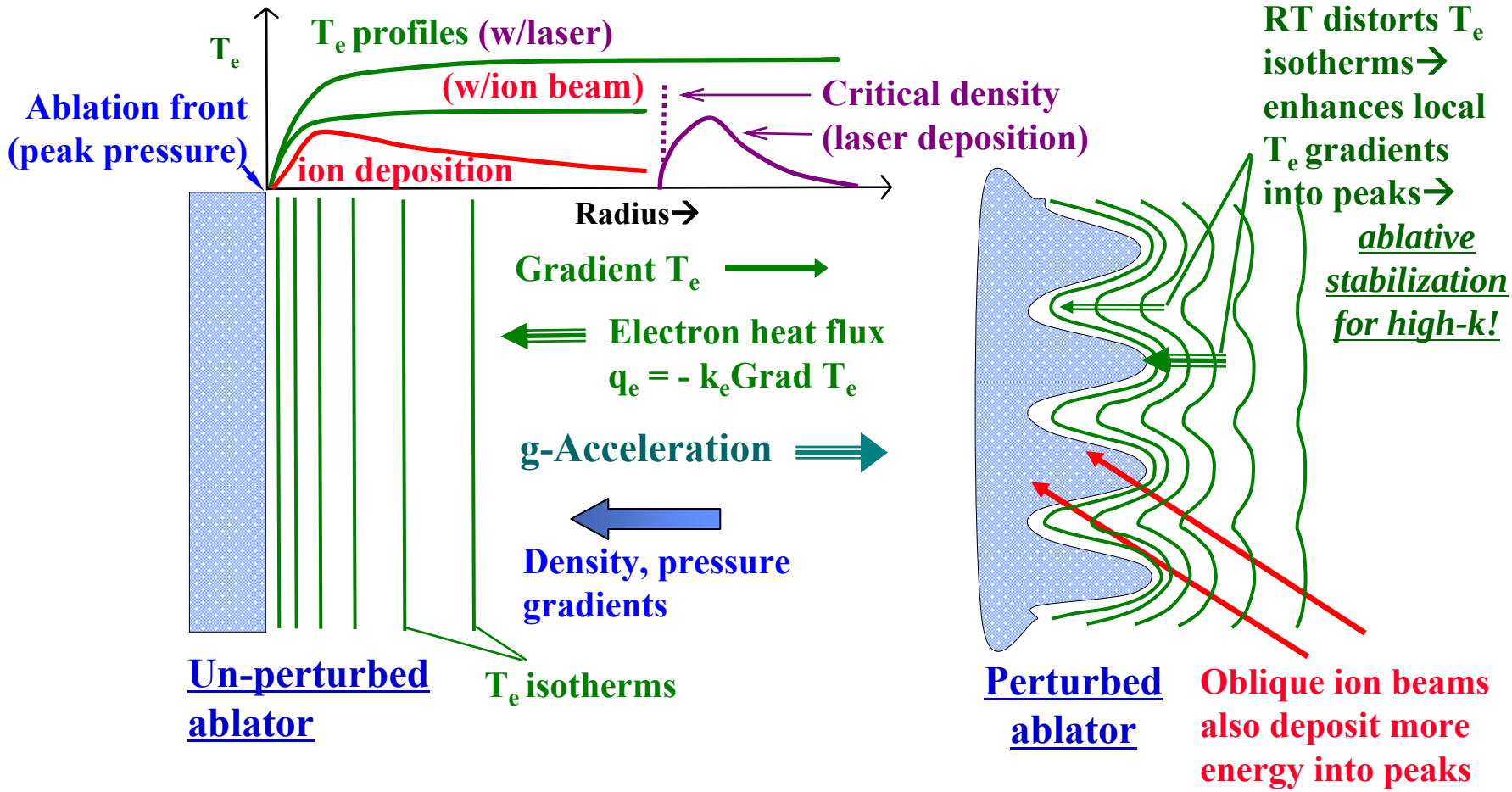


Legend-all Argon beams			
Line	Mat.	E_{beam}	T_e
a	CDT	50	20
b	CDT	50	400
c	CDT	50	1000
d	H	100	20
e	H	200	200
f	H	400	400
g	H	400	20
h	CH	400	200

(MeV) (eV)

All densities = 0.04 g/cm^3 except case h=0.94 g/cm^3

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)

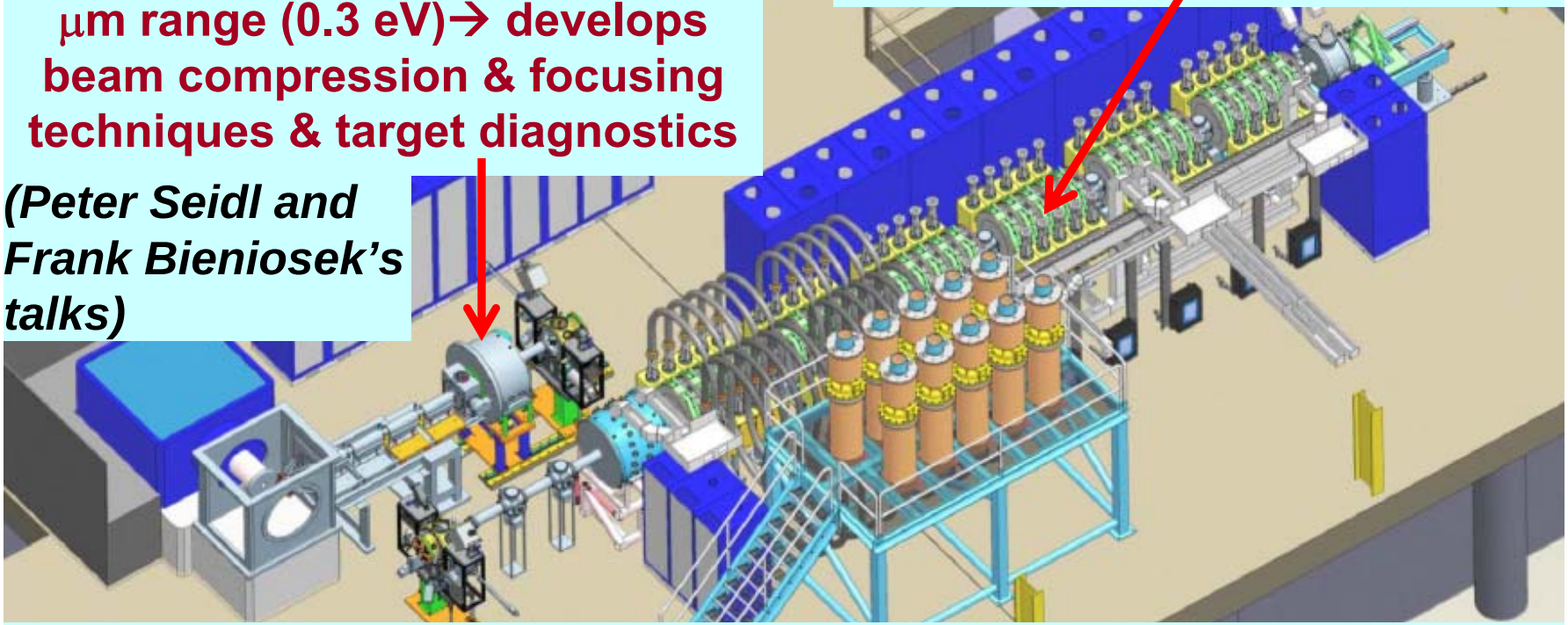
→ steeper pressure gradients behind ablation front (higher g driving RT for ions)

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

(Peter Seidl and Frank Bieniosek's talks)

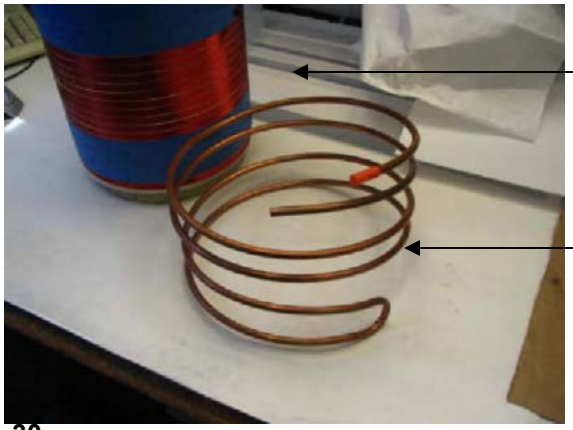
Planned NDCX-II beamline can use existing ATA equipment



NDCX-II would increase beam energy on target 100 times (0.1 to 0.3 J) @ 5 to 20 μm ranges → enable exploration of first ion-beam-driven planar, cylindrical and spherical hydro-experiments relevant to direct and indirect drive fusion

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

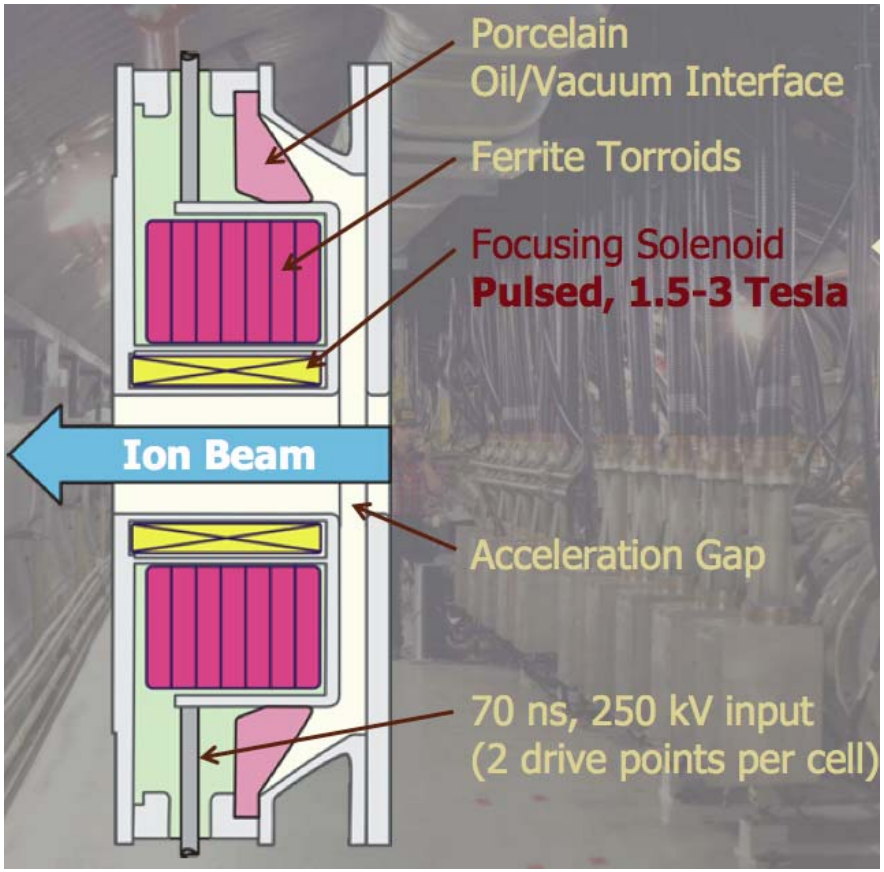
Test stand has begun to verify performance



solenoid

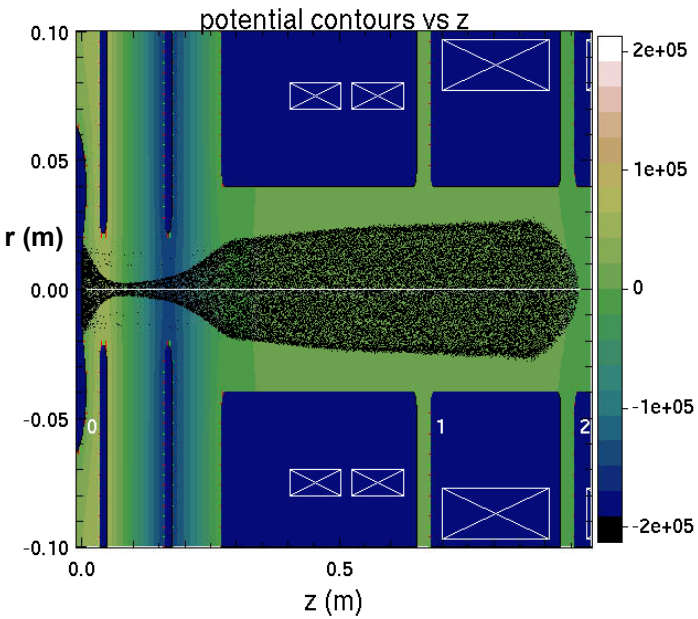
water cooling

Cells will be refurbished with stronger, pulsed solenoids

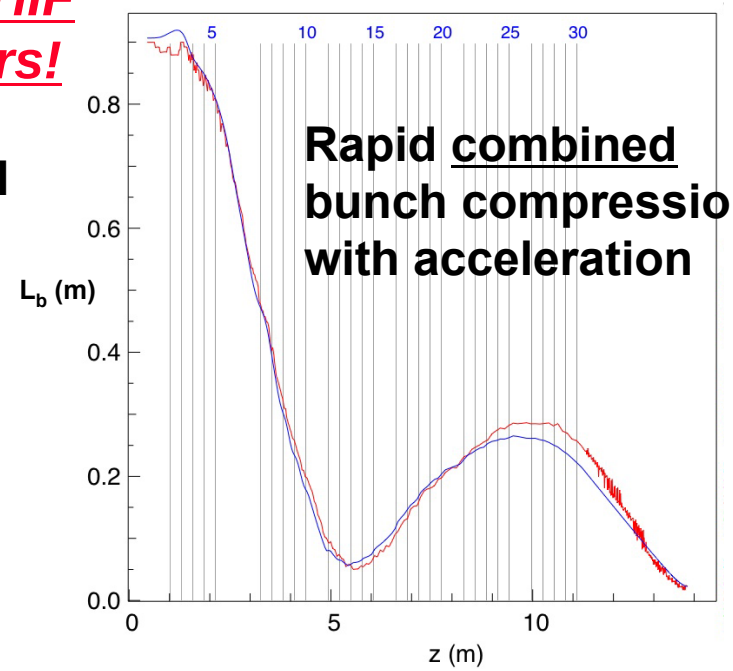


A first solenoid-focused induction accelerator for intense ion beams- NDCX-II will pioneer studies of accel-decel injection, combined rapid bunch compression with acceleration, and solenoid transport limits.

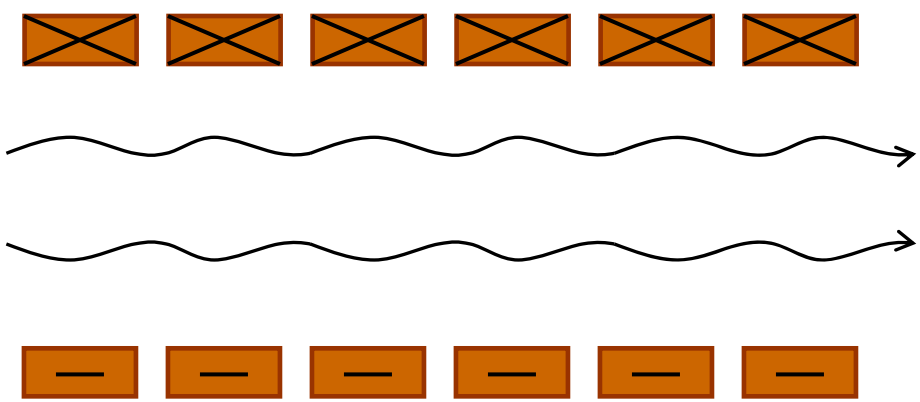
→Basis for HIF direct drivers!



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



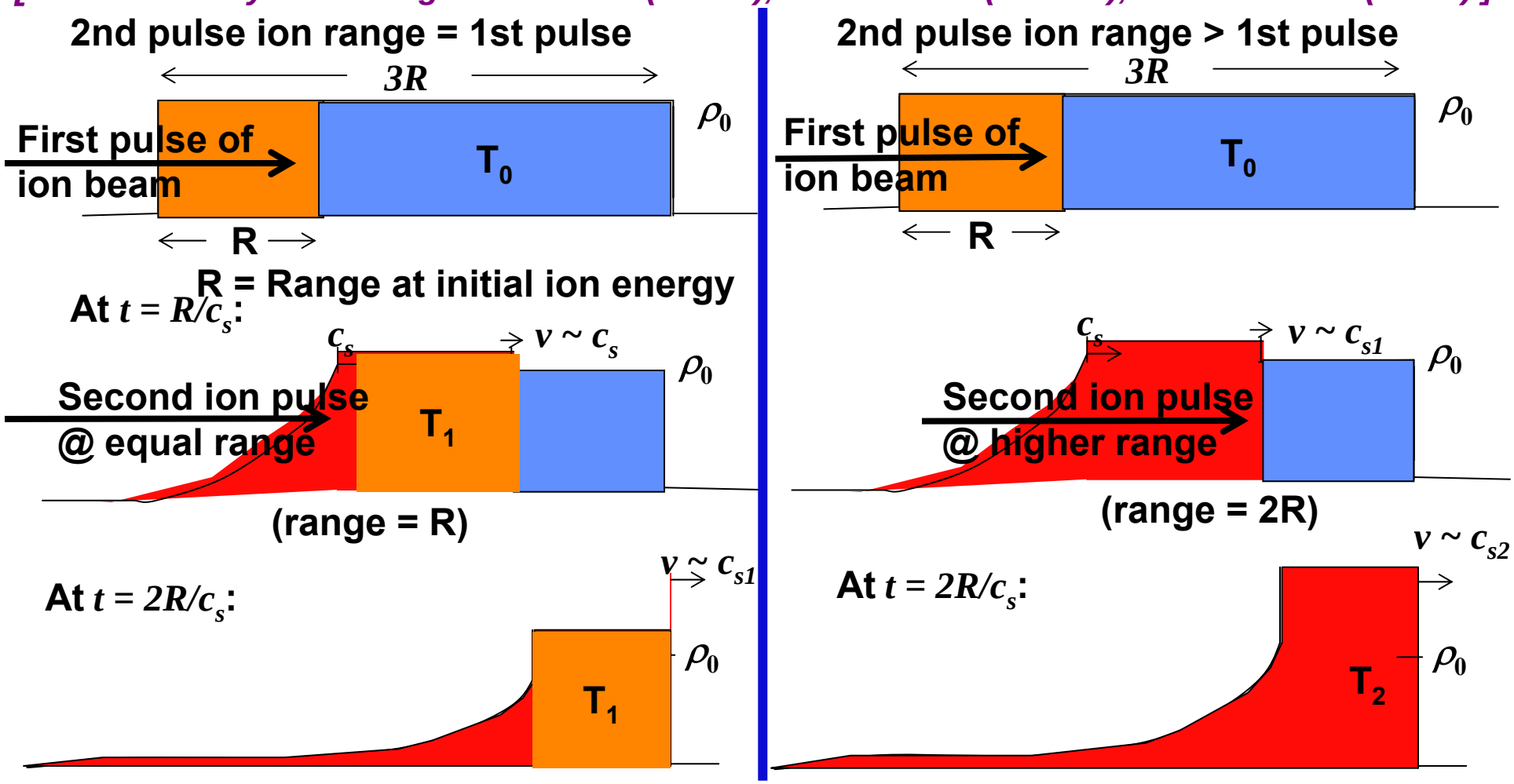
Rapid <u>combined</u> bunch compression with acceleration



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

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)]

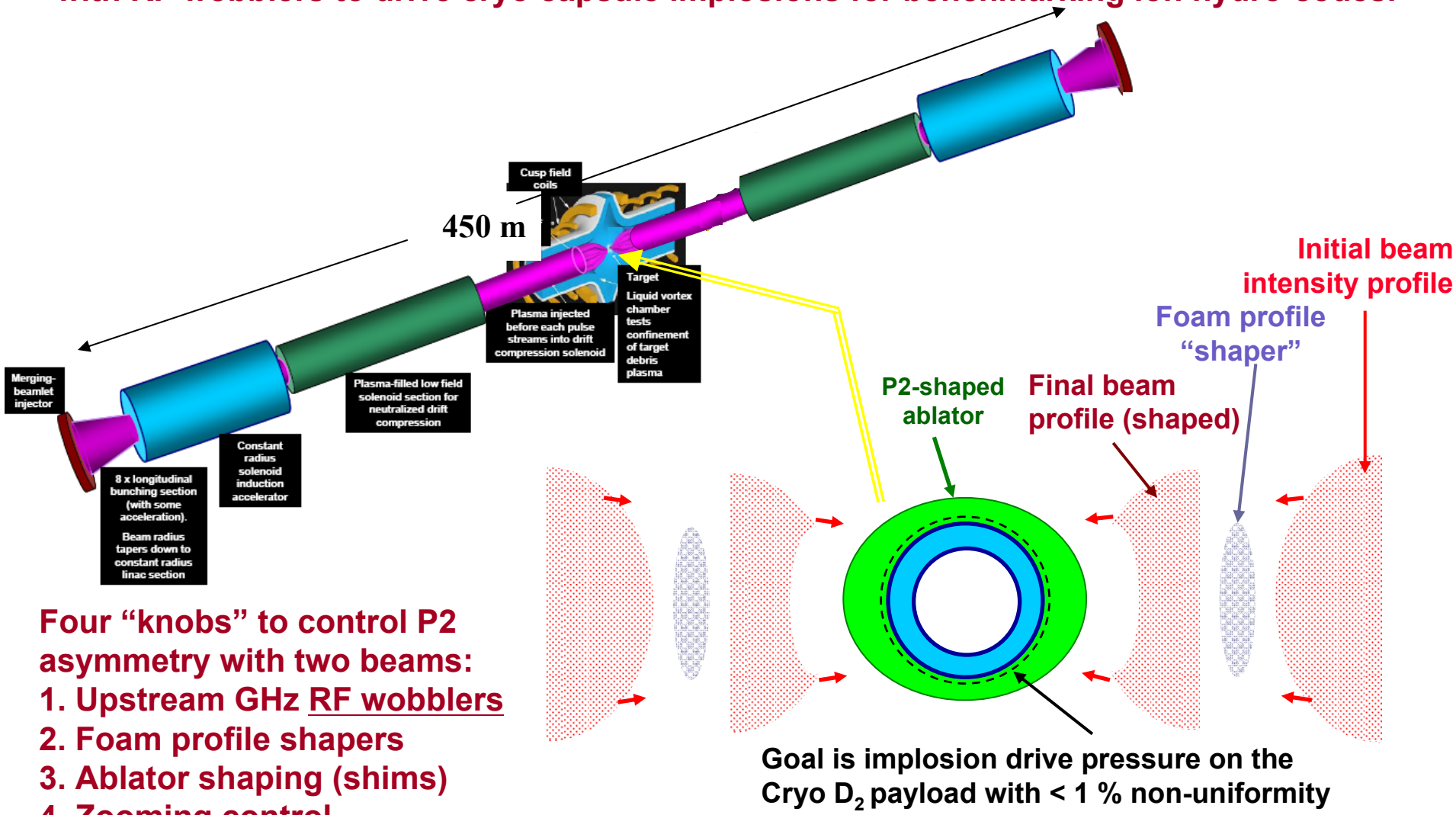


ρ vs z: At $t = 3R/c_s$: measure velocity of back of target.

T_0 T_1 $T_2 > T_1$

After NIF ignition we need new accelerator tool to explore polar direct drive hydro physics with heavy ion beams, in parallel with NIF operation.

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.



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

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

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

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

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, 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 $\omega_{pb}T_f <\sim 1$.

Example recent talks (May 14 & 21) -- ---can be downloaded from http://hifweb.lbl.gov/internal/NDCXII

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

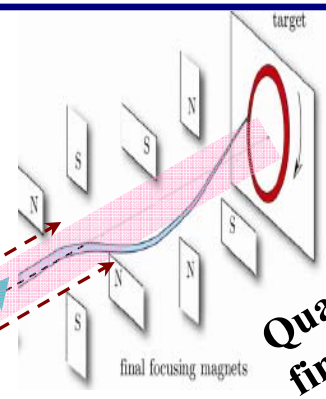
Does the relevant longitudinal scale length for Weibel growth reduce from 100 meters down to the helix pitch ~ 0.5 → 0.05 meters?

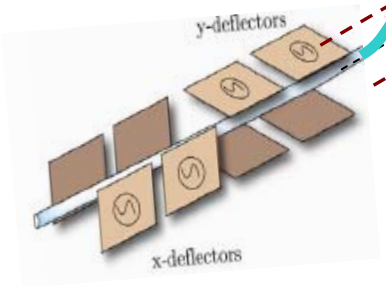
2.5 kg solenoid field constrains electron flow

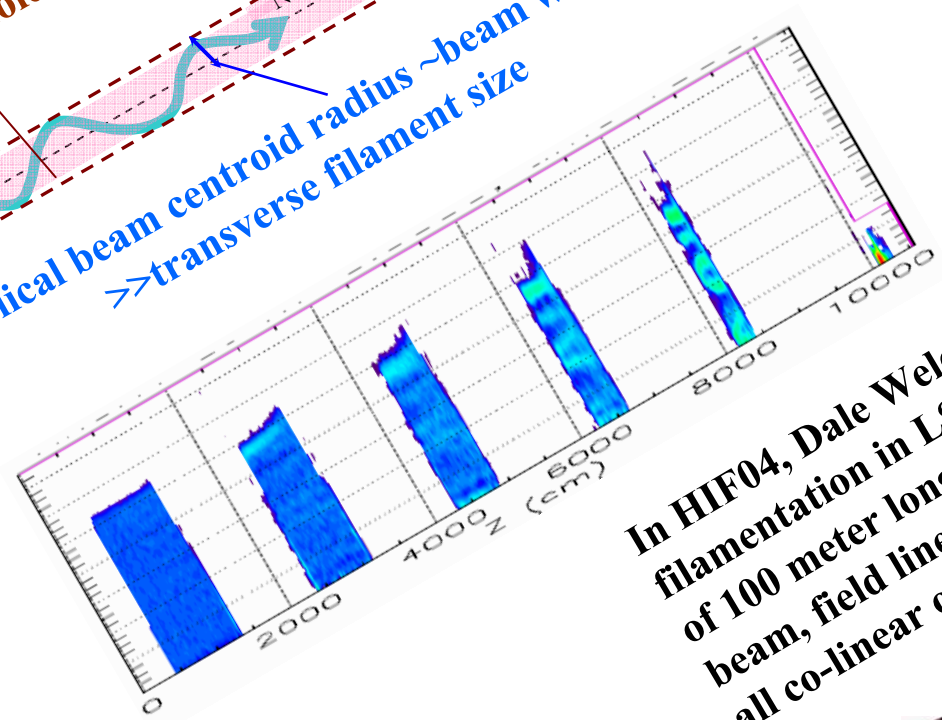
Neutralizing Plasma

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!

[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

$$-\frac{dE}{dx} = \underbrace{\left[\frac{4\pi e^4}{m_e c^2}\right]}_{5.1e-22\ keV\ cm^2} \underbrace{\left[\frac{N_0 \rho_T}{A_T}\right]}_{\frac{6e23\,g}{A\,cm^3}} \left[\frac{Z_{eff}^2}{\beta^2}\right] \left\{(Z_T - \bar{Z})\,\mathrm{Log}\,\Lambda_B + \bar{Z}\,G(\beta/\beta_e)\,\mathrm{Log}\,\Lambda_F\right\}$$

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

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

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

$\bar{I}$ = 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 $1/cm^3 = \bar{Z} N_0 \rho_T / A_T$

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

$\beta_{eff}^2 \equiv \beta^2 + \beta_e^2$, 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.

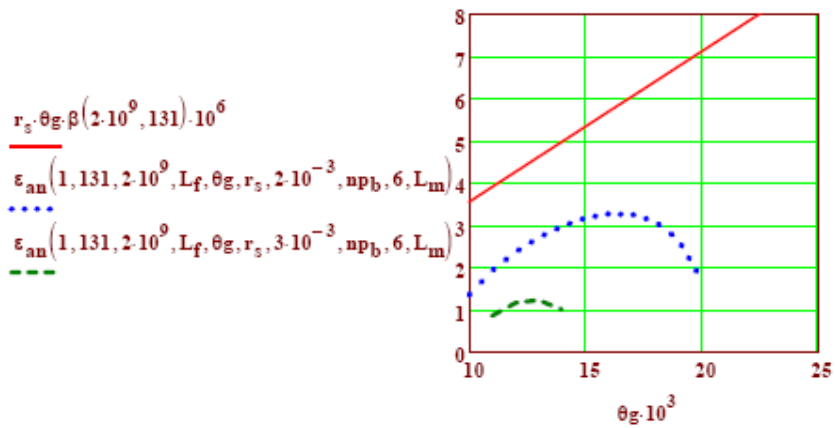
Figure 65 Comparing allowed accelerator emittance (normalized, in mm-mr) for the Snowmass 02 version of RPD (2 GeV Xe^{+1}) (A) versus allowed emittance for the stage three drive of the 1 MJ direct drive target (B).

Focus magnet length= L_m

$\theta g := 10\cdot10^{-3}, 11\cdot10^{-3} .. 25\cdot10^{-3}$

(A) RPD @ focal length $L_f := 6$ (m), $Ff := 6$ for quad focusing, and $r_s := 2.0\cdot10^{-3}$ (m) spot size

$np_b := 0.3$ (10^{11} cm^{-3} -->no plasma density between plasma plug and near-target), and magnet $L_m := 0.4$ (m)



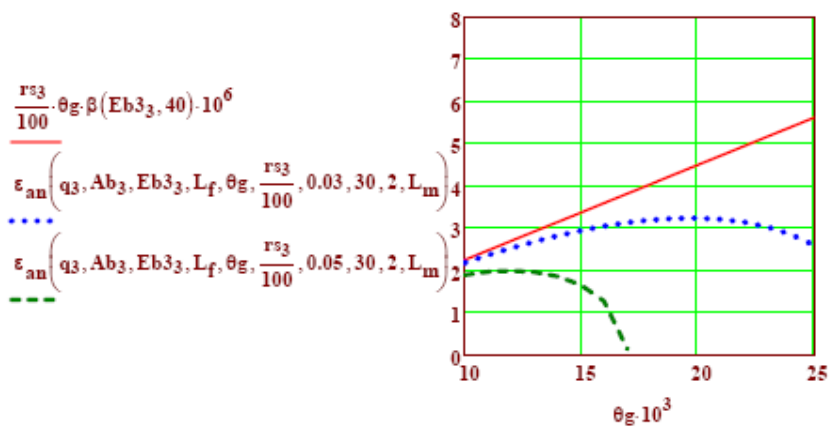
(A) Snowmass 2002 design
<--allowed emittance vs focusing angle (mr) if no plasma net perveance, no momentum spread, and no geometric aberrations.
<--allowed emittance with 0.2% momentum spread

<--allowed emittance with 0.3% momentum spread.

$L_m := 0.6$ (m)

(B) Stage 3 of 1 MJ target drive, Ar^{+16}, $\frac{Eb3_3}{10^6} = 348$ MeV, $L_f := 1$ m-focal length, $rs_3\cdot10 = 1.66$ (mm) spot size

$Ff := 2$ for solenoid-like cusp focusing, and $np_b := 30$ (10^{14} cm^{-3}) ave. plasma density in chamber.



(B) 1 MJ direct drive design stage 3 drive
<--allowed emittance vs focusing angle (mr) if no plasma net perveance, no momentum spread, and no geometric aberrations.
<--allowed emittance with 3% momentum spread
<--allowed emittance with 5% momentum (velocity) spread.

Starting guess for solver

$\theta_{fo} := 12\cdot10^{-3}$

We see from Figure 65B with 100X more plasma and 1 meter focal length, we can have a static focusing system for the modular 1 MJ driver that tolerates up to 5 % momentum /velocity range, which will allow us to dispense with time-dependent focusing for single short ion bunches. We can find the optimum focusing angle for the middle of each momentum range:

Given

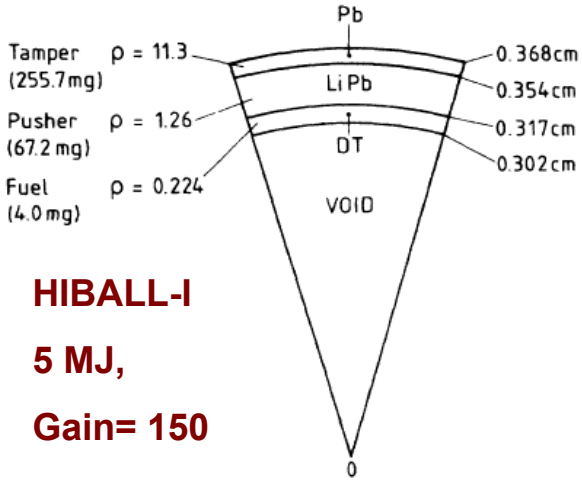
This model predicts emittance budgets for the RPD like was estimated at that time, assuming imperfect beam neutralization. More data from NDCX-I and II and theory is essential to confirm these models for focusing neutralized beams.

This model points to higher chamber plasma density required for the high-q ion beams for direct drive here.

Review: Debbie and Max did a good job of shrinking heavy ion indirect drive targets with close-coupled hohlraums, doubling the overall coupling efficiency from 2 % to 4%. But we explore heavy ion polar direct drive for the potential of *5 to10X higher coupling efficiencies.*

HIBALL (Long, Tahir)

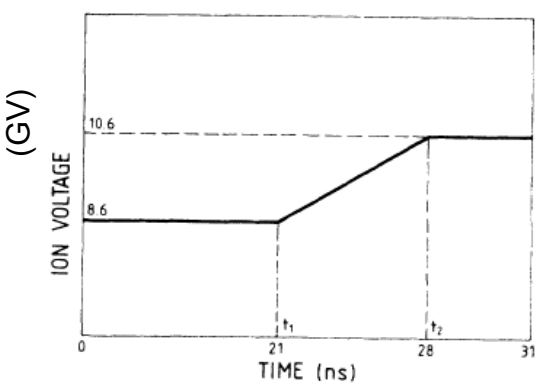
PR A Vol. 35, No. 6, March 1987



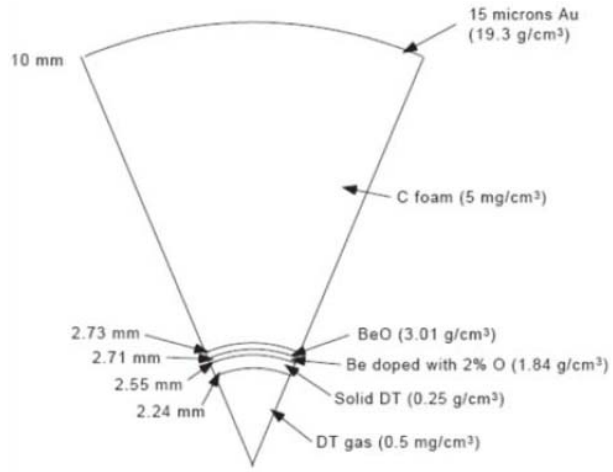
HIBALL-I

5 MJ,

Gain= 150



LIF Hohlraum (Allshouse, Callahan) Nuc. Fus. Vol. 39, No 7 1999



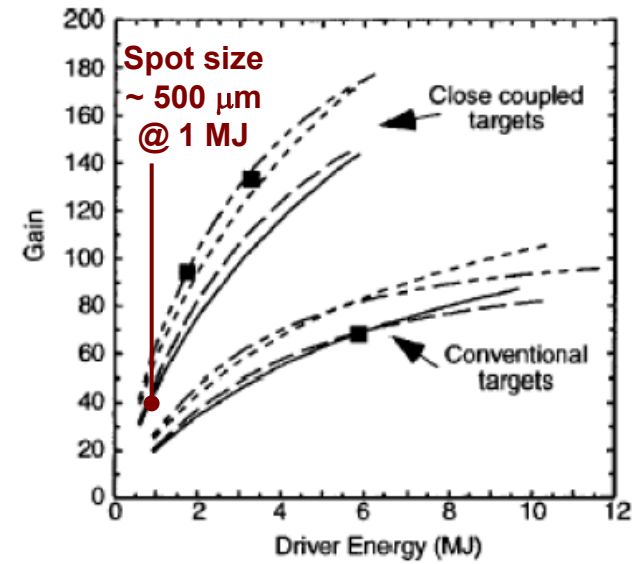
16 MJ Lithium ion drive

17→22 MeV,

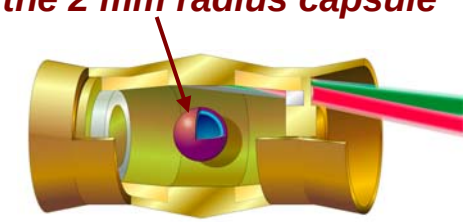
Gain= 37

Distributed Radiator (Callahan, Tabak)

Phys. Plasmas, Vol. 7, No. 5, May 2000



RPD: 3.3 GeV Bi foot, 4 GeV for peak. At gain=57, the 2 mm radius capsule absorbed 1 MJ out of 7 MJ total drive



We retain the hohlraum option for HIF, while we explore direct drive.

To fulfill our hopes to restore heavy-ion fusion research for IFE, we must be:

innovative and creative…

"Ah, but a man's reach
Should exceed his grasp,
Or what's a heaven for?"
- *Robert Browning*

..but also careful and wise…

"Mental things which have not passed through understanding are vain and give birth to no truth other than what is harmful. Those who wish to grow rich in a day shall live a long time in great poverty, as happens and will in all eternity happen to the alchemists, the would-be creators of gold and silver."
- *Leonardo Da Vinci*