1: OVERVIEW OF U.S. HEAVY ION FUSION SCIENCE PROGRAM
2: EXPLORING HEAVY ION POLAR DIRECT DRIVE FUSION

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Presented by B. Grant Logan on behalf of the
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First authors and titles of US HIF08 talks/papers

B. G. Logan “1: OVERVIEW OF THE U.S. HEAVY ION FUSION SCIENCE PROGRAM. 2: CONCEPT FOR HEAVY ION DIRECT DRIVE FUSION”

P. A. Seidl “PROGRESS IN BEAM FOCUSING AND COMPRESSION FOR WARM DENSE MATTER EXPERIMENTS”

R. C. Davidson “SURVEY OF COLLECTIVE EFFECTS AND BEAM PLASMA INSTABILITIES IN INTENSE HEAVY ION BEAMS”

P. K. Roy “SPACE-CHARGE NEUTRALIZING PLASMA FOR BEAM DRIFT COMPRESSION EXPERIMENTS”

E. P. Gilson "METER-LONG PLASMA SOURCE FOR HEAVY ION BEAM CHARGE-NEUTRALIZATION"

I. D. Kaganovich "RECENT THEORETICAL ADVANCES IN THE SELF-CONSISTENT CHARGE AND CURRENT NEUTRALIZATION OF INTENSE ION BEAM PULSES PROPAGATING ALONG A SOLENOIDAL MAGNETIC FIELD THROUGH A BACKGROUND PLASMA"

F. M. Bieniosek “HIGH ENERGY DENSITY PHYSICS EXPERIMENTS WITH INTENSE HEAVY ION BEAMS”

E. Henestroza “HYDRODYNAMIC SIMULATIONS OF THE NDCX-I TARGET EXPERIMENTS”

J. J. Barnard “ION BEAM HEATED TARGET SIMULATIONS AND ANALYSIS FOR WARM DENSE MATTER PHYSICS AND INERTIAL FUSION ENERGY”

First authors and titles of US HIF08 talks/papers (Cont.)

A. Friedman “TOWARD A PHYSICS DESIGN FOR NDCX-II, A PLATFORM FOR STUDYING ION BEAM-HEATED MATTER”

W. Sharp “DEVELOPING ACCELERATION SCHEDULES FOR NDCX-II”

L. Grisham "PERSPECTIVES ON THE ROLE OF NEGATIVE IONS AND ION-ION PLASMAS IN HEAVY ION FUSION SCIENCE, MAGNETIC FUSION ENERGY AND RELATED FIELDS”

S. Lund "BEAM STABILITY AND CONTROL IN SOLENOIDAL TRANSPORT CHANNELS"

I. D. Kaganovich "CALCULATION OF CHARGE-CHANGING CROSS SECTIONS OF IONS OR ATOMS COLLIDING WITH FAST IONS USING THE CLASSICAL TRAJECTORY METHOD"

E. A. Startsev "DYNAMICS OF ELECTROMAGNETIC TWO-STREAM INTERACTION PROCESSES DURING LONGITUDINAL AND TRANSVERSE COMPRESSION OF AN INTENSE ION BEAM PULSE PROPAGATING THROUGH BACKGROUND PLASMA"

H. Qin "ADVANCED NUMERICAL SIMULATIONS OF TEMPERATURE ANISOTROPY INSTABILITIES AND COLLECTIVE INTERACTION PROCESSES FOR HIGH-INTENSITY BUNCHED ION BEAMS"

E. P. Gilson "RECENT ADVANCES IN THE PHYSICS OF COLLECTIVE EXCITATIONS AND TRANSVERSE COMPRESSION DYNAMICS IN THE PAUL TRAP SIMULATOR EXPERIMENT"

Overview of the US heavy ion program

- At HIF06, program leaders (US, Germany, Russia, and Japan) promised to renew focus towards heavy ion fusion for this meeting.
- The US contributes 17 talks/papers to HIF08, describing significant progress since HIF06 on fundamental intense heavy-ion beam and target physics, including compression and focusing of intense heavy ion beams in neutralizing background plasma, associated atomic physics, beam-plasma interactions, including collective effects and instabilities, warm dense matter physics, and target hydrodynamic simulations.
- All of this US progress contributes to both basic high energy density physics as well as to heavy ion fusion generally.
- Since HIF06, there has been a breakthrough finding of a high coupling efficiency regime for heavy ion ablative direct drive specifically.
- There is not enough time in this presentation to summarize all the excellent US progress that is going to be well-covered in separate talks, and also describe heavy ion direct drive fusion and how the base program progress enables this approach to fusion energy.
- With apologies to the HIF08 organizing committee who invited this US overview, the rest of this talk will be devoted to the second topic:

Exploring heavy ion direct drive fusion, …*because heavy ion beams could do this best!*

At IFSA 2007, B$-class IFE initiatives were presented by JA, EU, and US--each based on laser fast ignition, assuming NIF ignition. *We <u>need</u> an HIF option with <~MJ driver energy like fast ignition!* Basic motivations for HIF still apply today! (See next)

The NIF Ignition Campaign begins next year!

Laser and pulsed-power drivers have advanced significantly, but the reasons Heavy Ion Fusion has advantages identified in many past DOE reviews *still apply today*:

(a) High energy particle accelerators of MJ-beam energy scale have separately exhibited intrinsic efficiencies, pulse-rates, average power levels, and durability required for IFE.

(b) Thick-liquid protected target chambers with 30 year plant lifetimes, compatible with indirect-drive or polar direct-drive target illumination geometries to be tested in the National Ignition Facility.

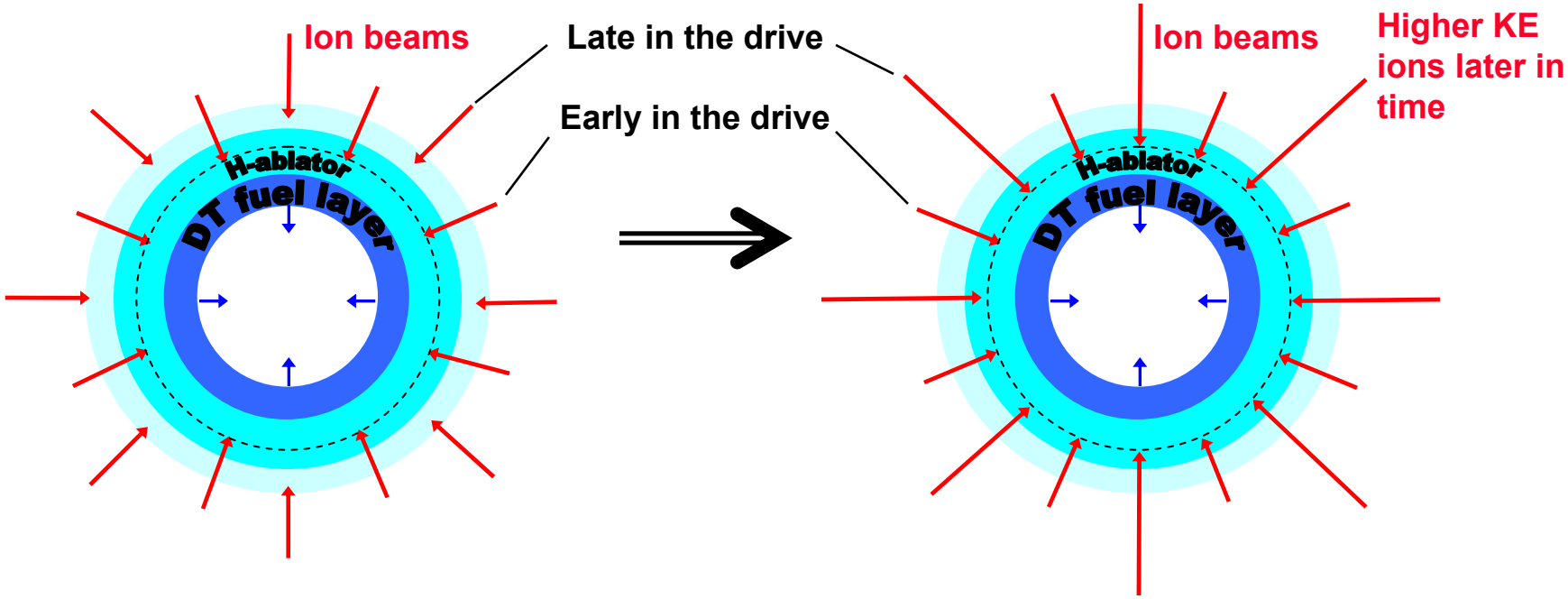
(c) Focusing magnets for ion beams avoid direct line-of-sight damage from target debris, neutron and gamma radiation.

(d) Several heavy ion power plant studies have shown attractive economics (competitive CoE with nuclear plants) and environmental characteristics (no high level waste; only class-C low level waste).

Following our success in velocity-chirp compression of intense ion beams to few-nanosecond pulses in plasmas,

we have another powerful fusion idea:

(John Barnard's talk)



Constant* ion *range

→ decouples

Strongly-increasing >4X ion range

→ high hydro-coupling efficiency!

We seek a research path to lower-drive energy heavy ion fusion that can:

(a) exploit the intrinsically much higher coupling efficiency of direct drive to greatly reduce driver energy requirements as well as accelerator beam energy to do target experiments;
(John Barnard's talk)

(b) utilize advances in intense beam compression developed in the Neutralized Drift Compression Experiment (NDCX-I)
(Peter Seidl and Frank Bieniosek's talks)

(c) incorporate rapid combined bunch compression and induction acceleration to be validated in NDCX-II using ATA modules.
(Alex Friedman's talk/Bill Sharp's poster)

The heavy ion program retains the option of indirect drive targets, while we pursue new research opportunities for direct drive. Much higher accelerator energy/cost would be required for ion indirect drive experiments, so despite the risks, pursuit of direct drive is an opportunity for an more affordable HIF research path.

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).

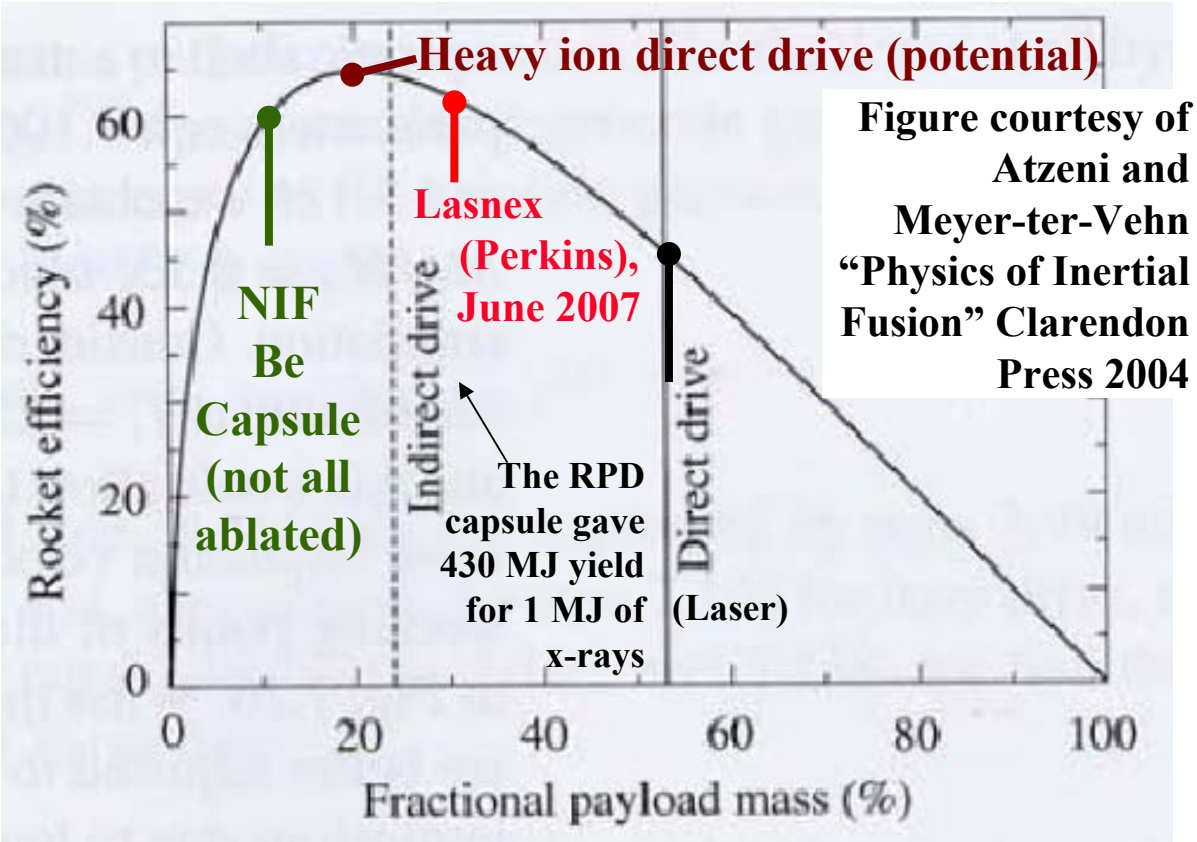


Figure courtesy of Atzeni and Meyer-ter-Vehn "Physics of Inertial Fusion" Clarendon Press 2004

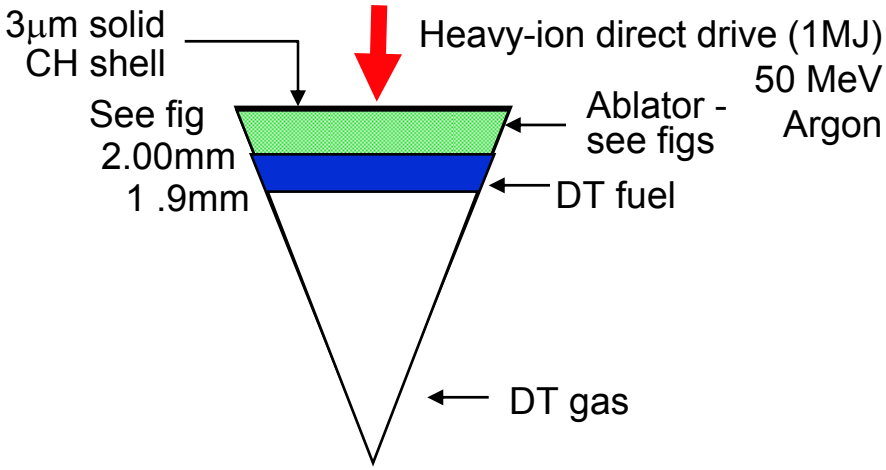
→Low-Z ablators (DT or H) for ion direct drive need small 13.6 eV ionization

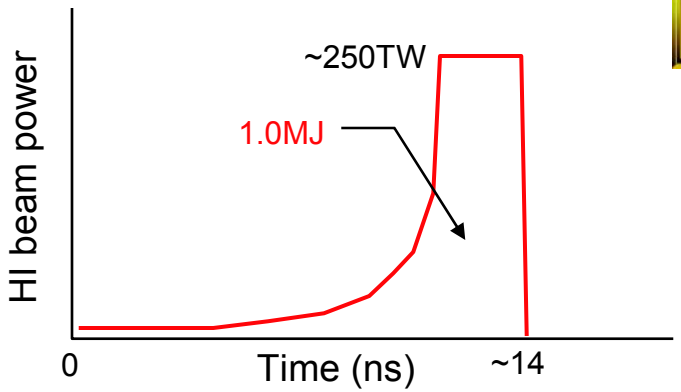
→X-rays couple well to Ablators, but Be, C ablators require significant ionization energy.

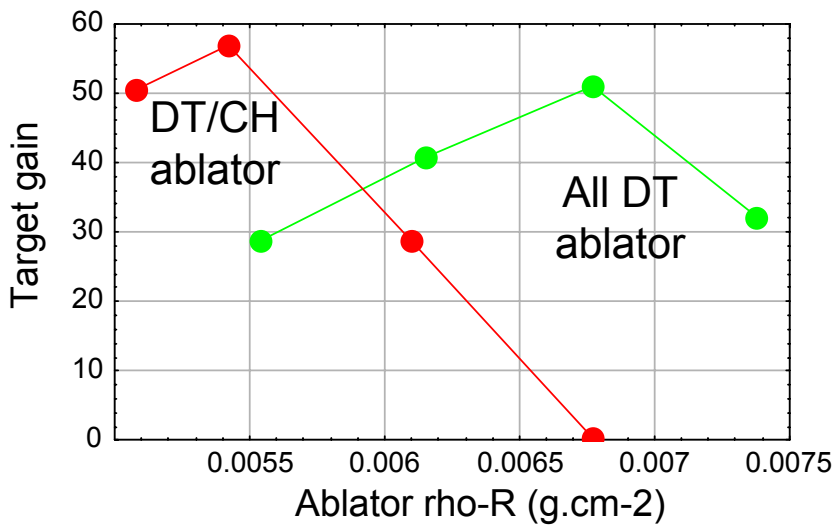
→Laser coupling is reduced with electron transport from low critical density to ablation front

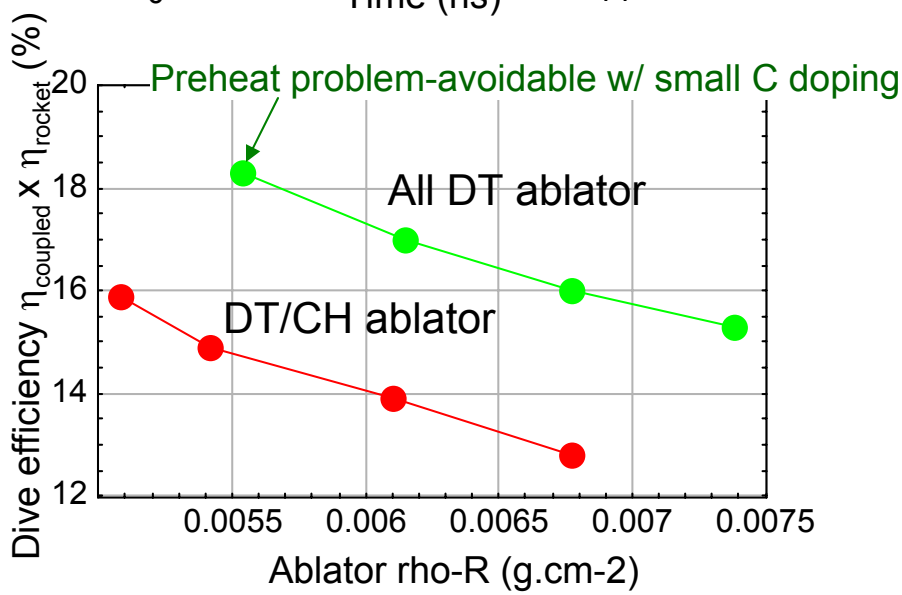
Heavy ion beams can suffer more parasitic energy loss on out-going ablation corona plasma than either x-ray or laser photons, *but with range-lengthening during the drive pulse, overall coupling efficiencies could still be higher*.

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)



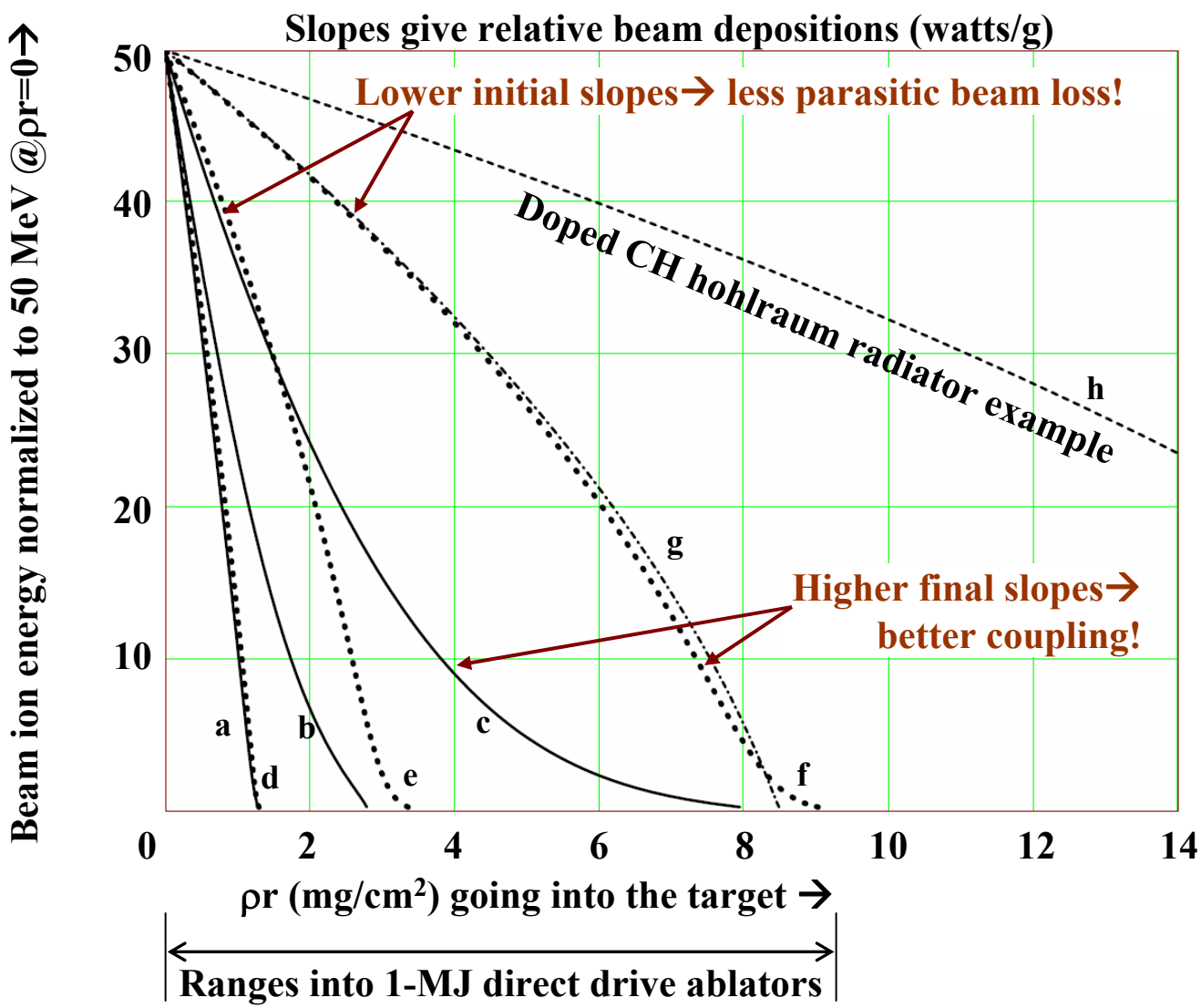






Analytic calculations estimate higher efficiencies (20-25%) substituting H for DT ablators, ramping up ion K.E. in time.

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

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. © *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>*"

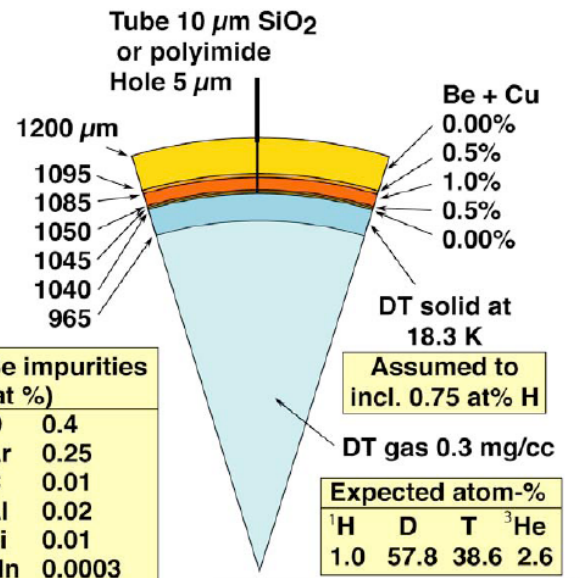
NIF ignition, *if successful*, will validate *15% hydro-coupling efficiency* in ablative capsule drive (capsule gain 100 with 200 kJ x-ray absorbed).

At equal 15 % 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* reach gain 70?

1 mm radius Be capsule

The National Ignition Campaign

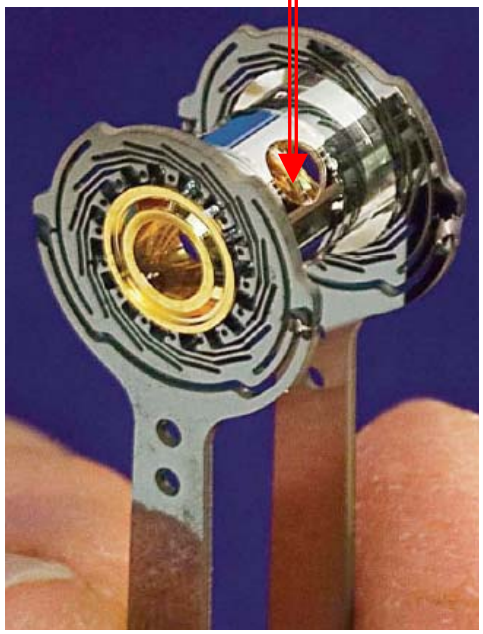
(Cu doped Be shell for 285eV, 1.3 MJ)



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

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



There are several new research areas that must be addressed to exploit the potential of high coupling efficiency for heavy ion direct drive:

1. **4X-range increases by *ramping up ion kinetic energy* to ion energies sufficient for beam perveances < 10^{-3} in the linacs.**

2. **Practical linac designs that can accelerate, compress and focus the required *large (>100% $\Delta v/v$) velocity ramps and ion ranges.***

3. **Uniform beam energy deposition into spherical ablators *in polar-drive geometry with reasonable numbers of beams.***

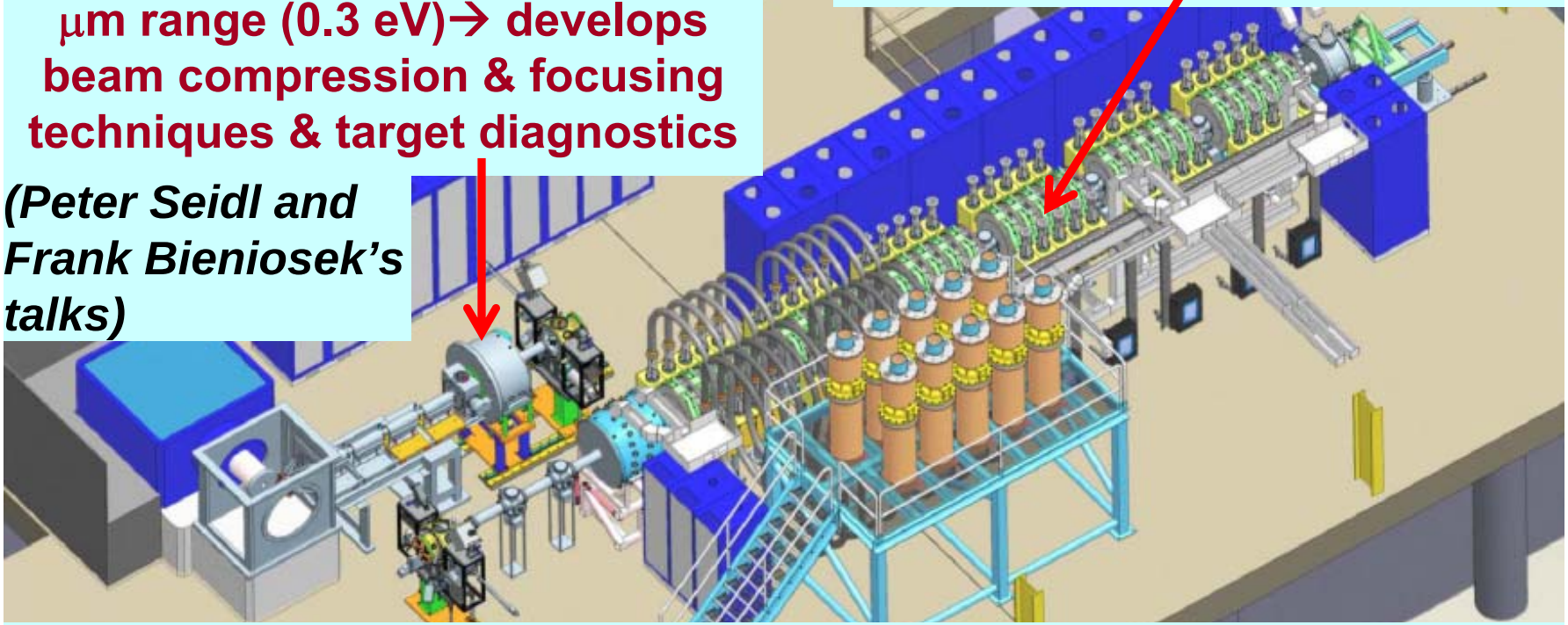
4. **2-D and 3-D implosion calculations for Rayleigh-Taylor growth factors, *and 10kJ-scale implosion experiments to validate codes*.**

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

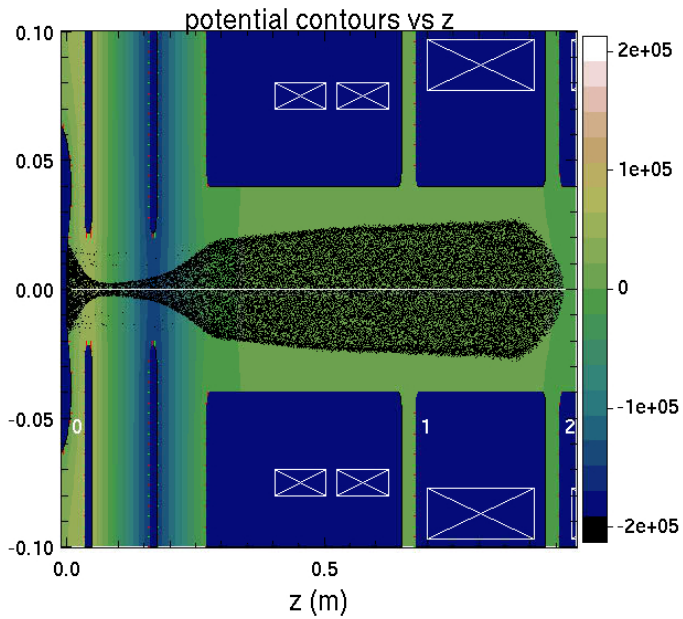
(Peter Seidl and Frank Bieniosek's talks)

Planned NDCX-II beamline can use existing ATA equipment

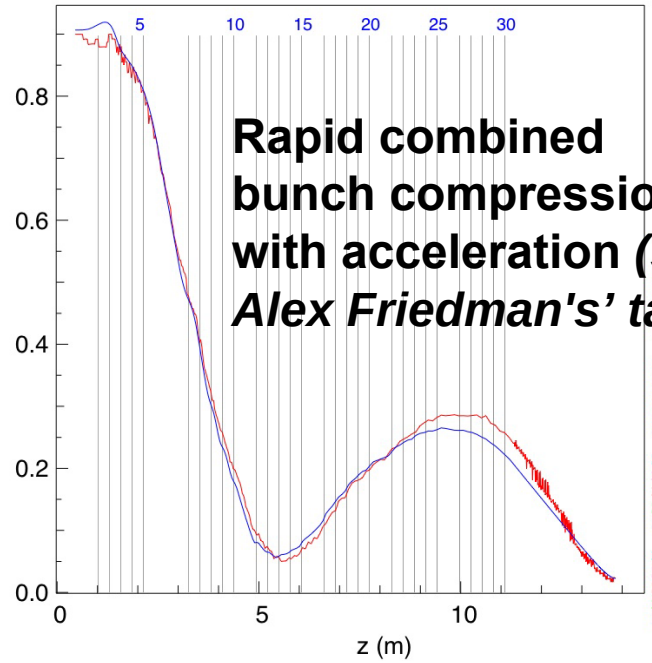


NDCX-II would increase beam energy on target 100 times (0.1 to 0.3 J) @ 5 to 20 μm ranges → enable exploration of first ion-beam-driven planar, cylindrical and spherical hydro-experiments relevant to direct and indirect drive fusion *(John Barnard's talk)*

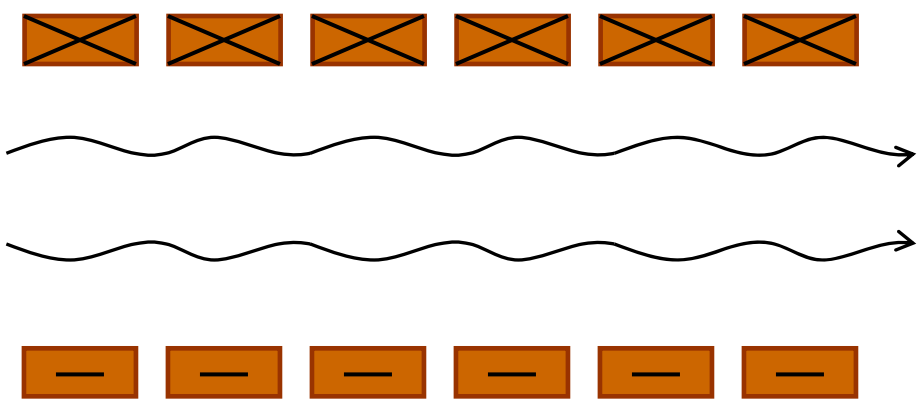
A first solenoid-focused induction accelerator for intense ion beams- NDCX-II will pioneer studies of accel-decel injection, combined rapid bunch compression with acceleration, and solenoid transport limits.



←Accel-decel injection into a high line-charge density (see Bill Sharp's poster)



Rapid combined bunch compression with acceleration *(see Alex Friedman's' talk)*

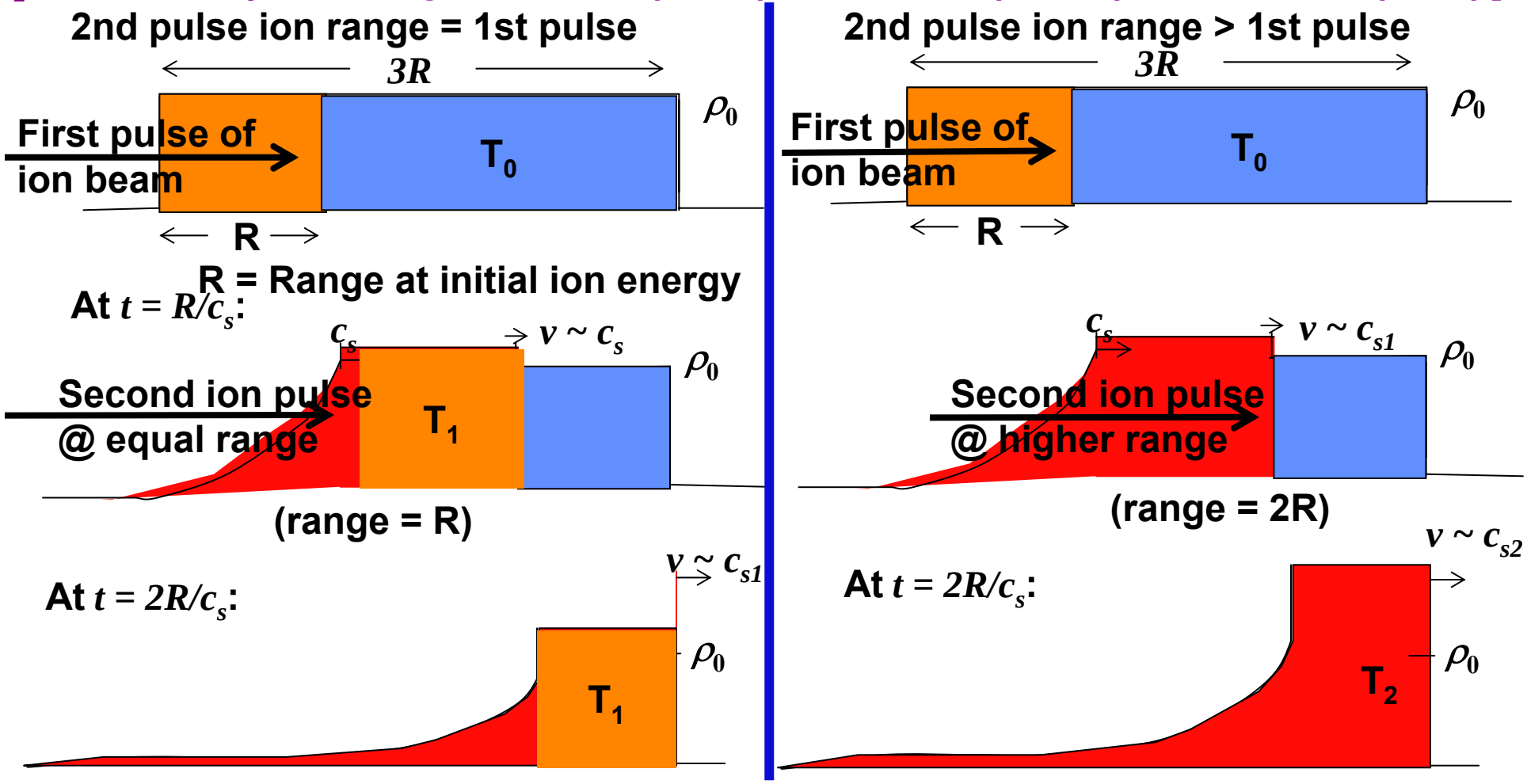


Solenoid transport limits and halos

(see Steve Lund's Talk)

A "double-pulse" experiment* on NDCX II will demonstrate the improvement in coupling efficiency with increasing ion range

[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 $T_2 > T_1$

*or, single pulse with ramped ion velocity

Ion beam requirements

driving Perkins' 1.2 mg DT fuel capsule to 160 kJ K.E.

←Comparing: CH:DT ablators @ M_o/M_f=2.3 (from LASNEX run w/ 50 MeV Argon ions)

Common beam requirements for ref CH:DT ablator case 1 (on the target)

	Pulse time (from τ=0 start) τp_τ =	Target radius $\frac{rs_\tau}{0.1}$ =	Power $\frac{Pbeam_\tau}{10^{12}}$ =	Intensity $\frac{Sb_\tau}{10^{15}}$ =	~ req. ion range $\frac{\rho rab_\tau}{10^{-3}}$ =
@ half-foot	2.5	2.1	1.5	0.003	1.2
@ half-pedestal	7.7	1.9	50	0.106	1.9
@ half-main	10.3	1.7	254	0.734	4.7
@ drive end	12.3	1	254	1.869	9.8
(on the target)	ns	mm	TW	10^{15} W/cm^2	mg/cm^2

Common beam requirements for hydrogen ablator 3: more mass for M_o/M_f=5.

	Pulse time (longer) (from τ=0 start) $1.9\cdot\tau p_\tau$ =	~fuel radius $\frac{rs_\tau}{0.1}$ =	Power (lower) $\frac{Pbeam_\tau}{1.9\cdot 10^{12}}$ =	Intensity $\frac{Sb_\tau}{1.9\cdot 10^{15}}$ =	~ req. ion range $\frac{1.72\cdot\rho ra}{10^{-3}}$
@ half-foot	4.7	2.1	1	0.001	2.1
@ half-pedestal	14.6	1.9	26	0.056	3.3
@ half-main	19.5	1.7	134	0.386	8.1
@ drive end	23.3	1	134	0.984	16.8
	ns	mm	TW	10^{15} W/cm^2	mg/cm^2

←with H ablators (M_o/M_f=5) (from analytic model)

Final beam perveances still too high → neutralization needed!

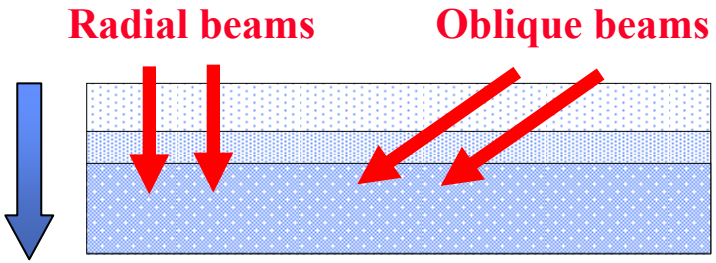
⇓

Linac beam requirements for different q=1 ions corresponding to H ablator case. 50 beams, 20 X drift compression (6.4X for stage 1)

All 40 ns linac beam durations drift compress to H target stage $\delta\tau$'s

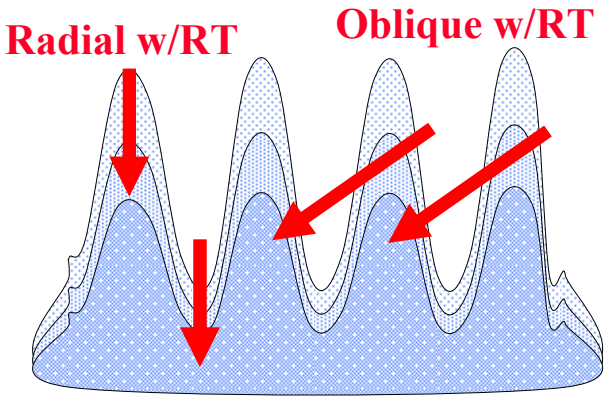
Argon $\frac{Eb3A_\tau}{10^6}$ =	$\frac{Ib3A_\tau}{10^3}$ =	Perveance (at target) $\frac{Kb3A_\tau}{10^{-3}}$ =	Ion/e speed $\beta 3A_{\beta e_\tau}$ =	Krypton $\frac{Eb3K_\tau}{10^6}$ =	$\frac{Ib3K_\tau}{10^3}$ =	Perveance (at target) $\frac{Kb3K_\tau}{10^{-3}}$ =	Xenon $\frac{Eb3X_\tau}{10^6}$ =	$\frac{Ib3X_\tau}{10^3}$ =	Perveance $\frac{Kb3X_\tau}{10^{-3}}$ =	Ion/e speed $\beta 3X_{\beta e_\tau}$ =
119	0.1	0.424	27.03	253	0.1	0.093	370	0.04	0.04	26.35
189	2.8	4.449	7.12	431	1.2	0.818	663	0.79	0.35	7.37
348	7.7	4.898	6.17	861	3.1	0.734	1397	1.91	0.27	6.82
572	4.7	1.402	6.6	1498	1.8	0.183	2534	1.05	0.06	7.64
MeV	kA	x10^{-3}		MeV	kA	x10^{-3}	MeV	kA	x10^{-3}	

Until recently, radially-directed ion beams were feared to enhance RT growth. *We now think oblique ion illumination with beam spot rotation can enhance ablative-stabilization and lengthen pressure gradient scale lengths behind the ablation front*



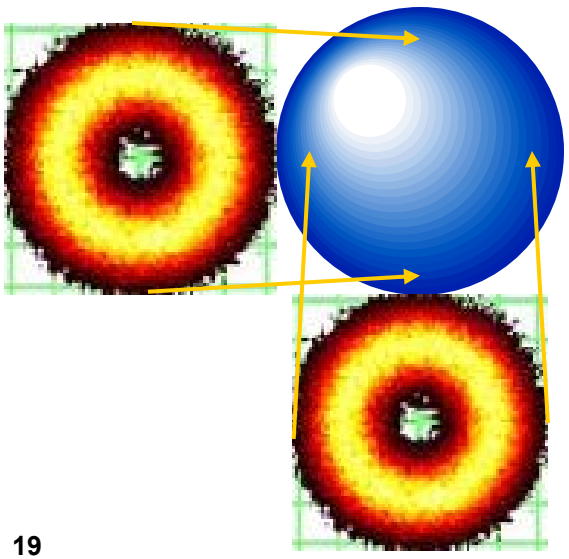
Density gradient

Un-perturbed ablator



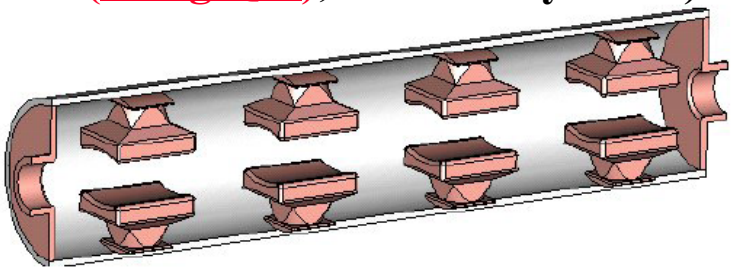
Perturbed ablator. Oblique ion rays may ablate high density spikes faster when ion range > λ_{RT} → improved ablative stabilization.

g-Acceleration, Gradient Te, (or, gradient x-ray flux in hohlraums)



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), Utsunomiya U…)



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

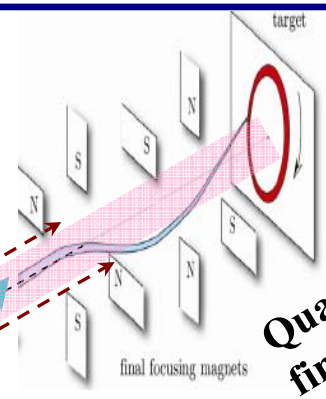
Does the relevant longitudinal scale length for Weibel growth reduce from 100 meters down to the helix pitch ~ 0.5 → 0.05 meters?

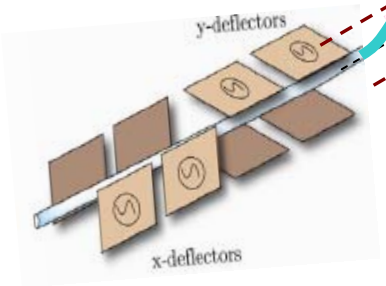
2.5 kg solenoid field constrains electron flow

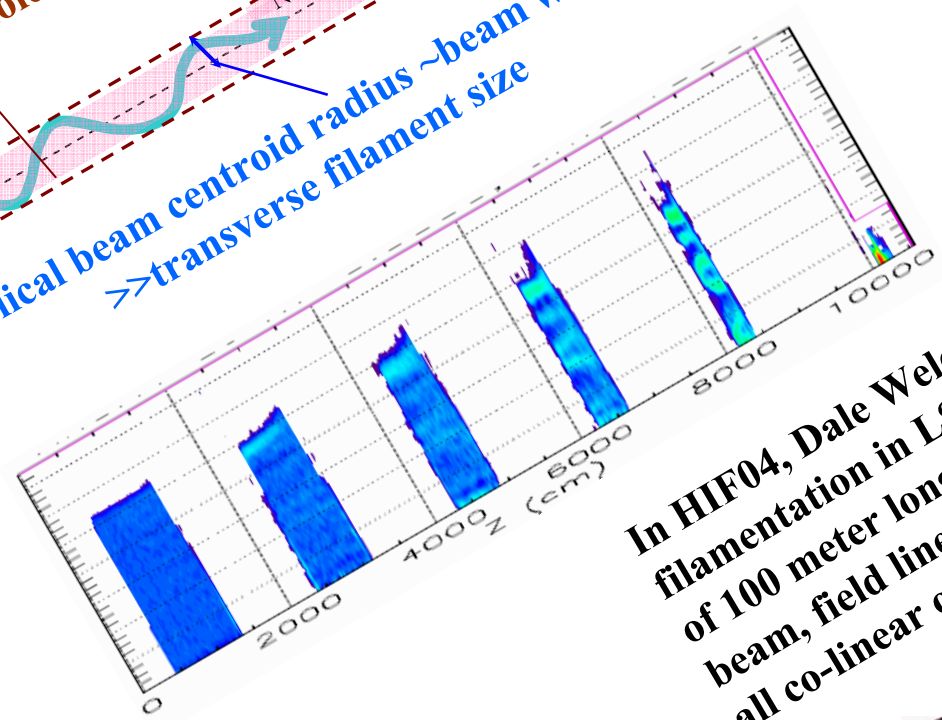
Neutralizing Plasma

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

Quads or Solenoid final focus magnets



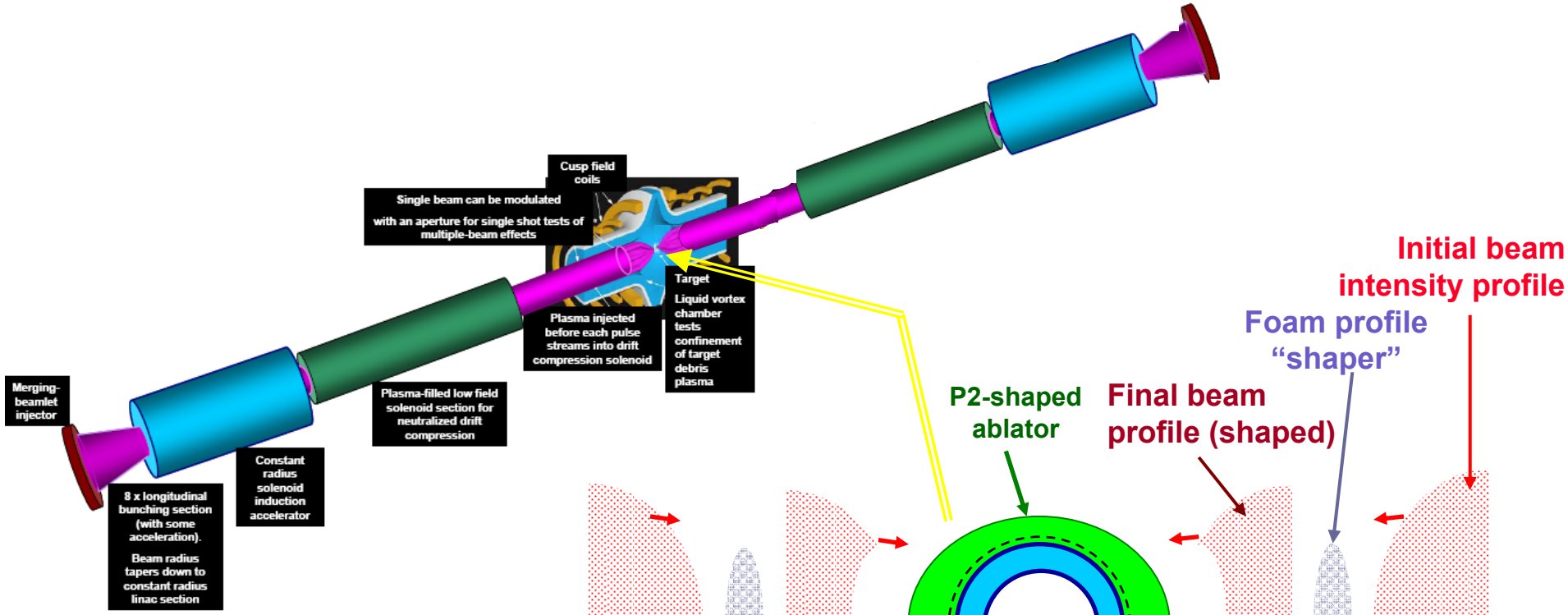




In HIF04, Dale Welch found filamentation in LSP simulation of 100 meter long NDC: beam, field lines, and electron flows all co-linear over 100 meters!

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.

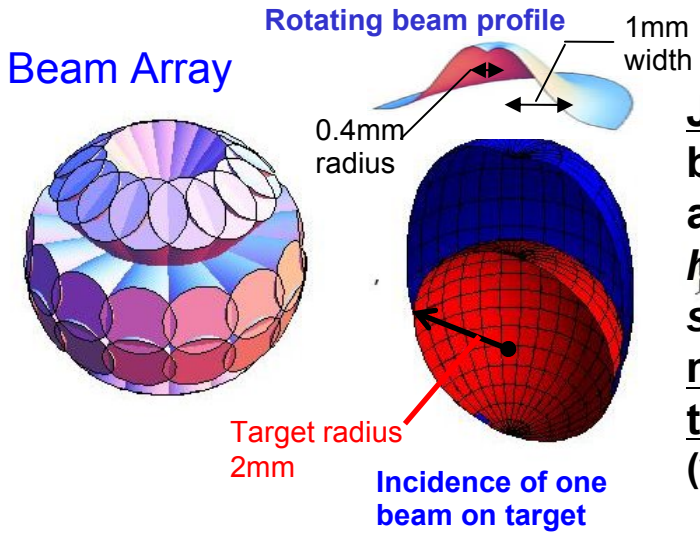


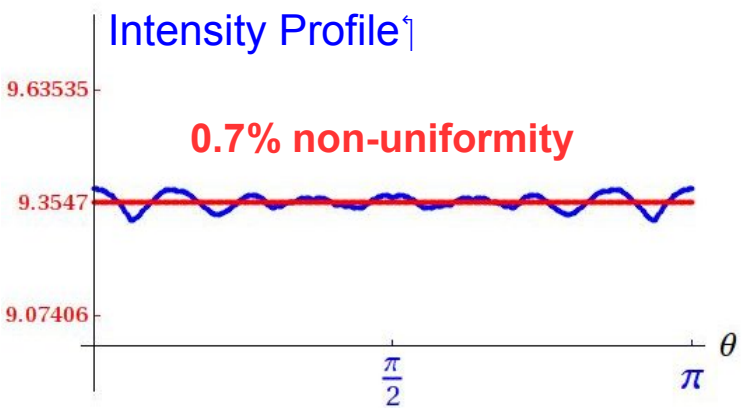
Four "knobs" to control P2 asymmetry with two beams:

1. Upstream GHz 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

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?





<u>Just four</u> annular rings of 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).

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

S. Kawata and his HIF collaborators have agreed to collaborate with us in exploring symmetry and stability for HIF direct drive in the high efficiency ablative rocket regime. We very much appreciate their interest!

Fusion power plant studies:

Attempting end-to-end self-consistent solutions-

-has always been difficult for any honest fusion effort…
-requires many iterations for partial self-consistency…
-uncovers more issues unforeseen at the start…
-and ends up guiding needed future work!

This tradition will undoubtedly apply to heavy ion polar direct drive fusion, but dare we try now, at such an early stage, to see how all we have considered so far might look put together for a
Heavy Ion Fusion Test Facility (HIFTF)?

Yes- because it's the fastest way to discover the most critical physics problems that need to be solved, even conceptually at first. Hopefully, in 20 more years, we might attain the knowledge base sufficient to start construction of an HIFTF, which will then uncover even more unforeseen problems, hopefully, engineering ones that can ultimately be solved to realize practical fusion energy!

20 X drift compression (6.4X for stage 1)

50 beams each stage (200 total)

Case 1 target: CH:DT ablator, Mo/Mf=2.3, Ar+1

	Pulse time $\frac{\delta\tau a_\tau}{10^{-9}}$ =	Incident ion KE $\frac{EboA_\tau}{10^{6}}$	Bunch length $Lb1Aa_\tau$	Beam current = $IbAa_\tau$ =	Perveance $\frac{KaA_\tau}{10^{-3}}$ =	Bunch charge $\frac{QA_\tau}{10^{-6}}$ =	Line-Charge density $\frac{\lambda A_\tau}{10^{-6}}$ =	Self Ez field $\frac{EzA_\tau}{10^{6}}$ =
@ half-foot	40	41	0.56	113	1.8	5	11	0.7
@ half-pedestal	40	42	0.57	1179	17.7	47	117	7.4
@ half-main	40	42	0.57	6016	91	241	599	37.9
@ drive end	40	98	0.86	2604	11.2	104	171	7.1
	(ns)	(MeV)	(m)	(A)	(x 10^{-3})	(μC)	(μC/m)	(MV/m)

Case 3 target: H ablator, Mo/Mf=5, Ar+1

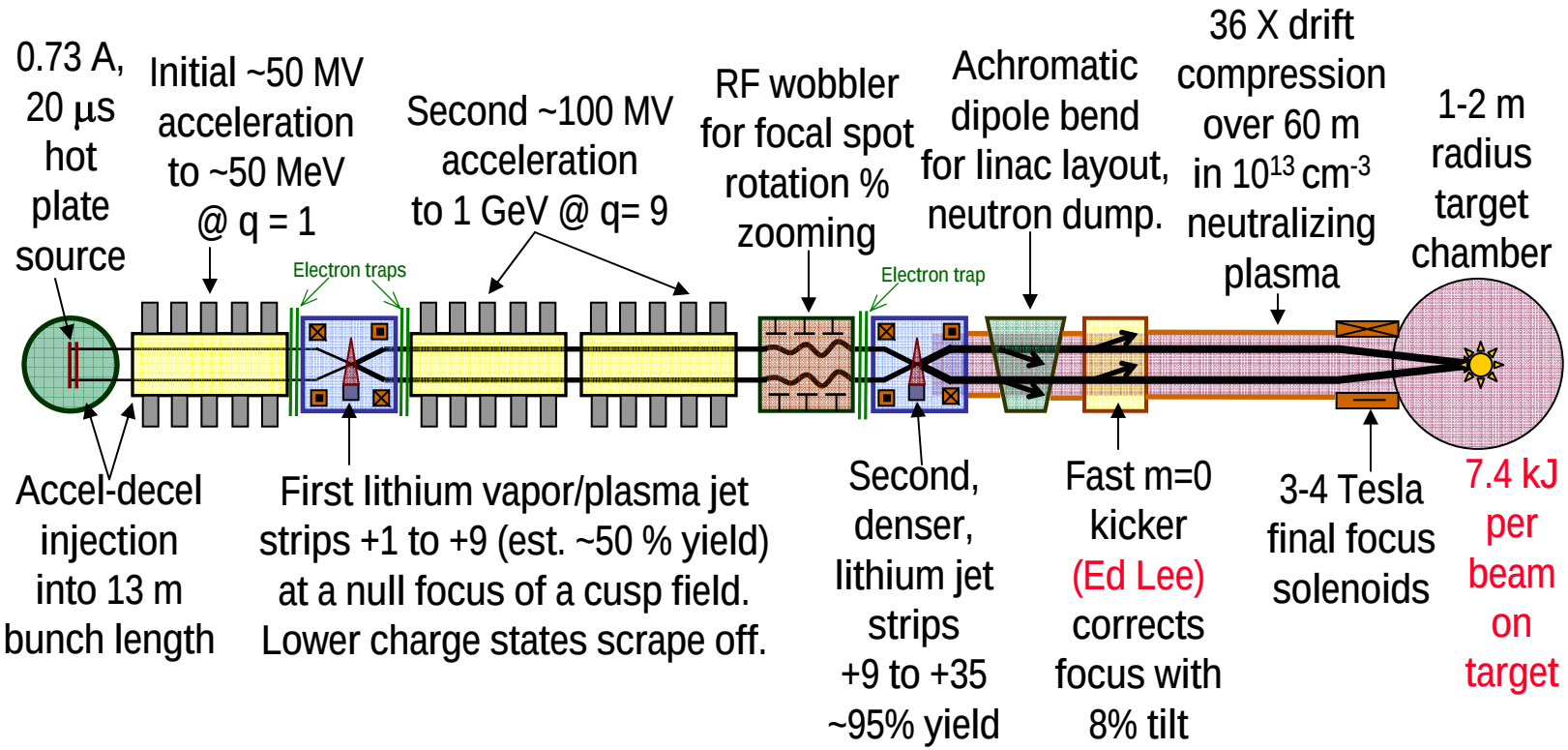
	Pulse time $\frac{\delta\tau 3a_\tau}{10^{-9}}$ =	Incident ion KE $\frac{Eb3A_\tau}{10^{6}}$	Bunch length $Lb3Aa_\tau$	Beam current = $Ib3Aa_\tau$ =	Perveance $\frac{K3aA_\tau}{10^{-3}}$ =	Bunch charge $\frac{Q3A_\tau}{10^{-6}}$ =	Line-Charge density $\frac{\lambda 3A_\tau}{10^{-6}}$ =	Self Ez field $\frac{Ez3A_\tau}{10^{6}}$ =
@ half-foot	76	119	1.8	21	0.07	2	1	0.02
@ half-pedestal	76	189	2.3	139	0.22	11	7	0.1
@ half-main	76	348	3.1	385	0.24	29	13	0.16
@ drive end	76	572	3.9	234	0.07	18	6	0.06
	(ns)	(MeV)	(m)	(A)	(x 10^{-3})	(μC)	(μC/m)	(MV/m)

H ablators are *required* to raise the beam energy enough for perveances in the linac (~< 10^{-3} needed for longitudinal bunch control).

However, average beam currents are marginal for induction linac efficiency with single beam linacs (η_d ~8% , $\eta_d G$ ~ 4 @ gain 50).

Three ways to improve: (1) raise target gain to 100 (most desirable); (2) raise the beam current by 2-3 X (possible with K<10^{-3} constraint), (3) use multiple beams per induction core (gives up modular development).

A possible option for a one-beam linac driver module:
induction acceleration efficiency 13% (@ 640 A/beam),
modest linac length and cost (150 m linac @ q = 9, 1 MV/m),
manageable beam perveance K~10^{-3}, injector source I_s<1Amp @ q=1,
and avoids uncontrolled stripping in neutralizing plasma drift & focus:
1 GeV Rubidium^{+9} beam linac module with two stages of beam stripping.

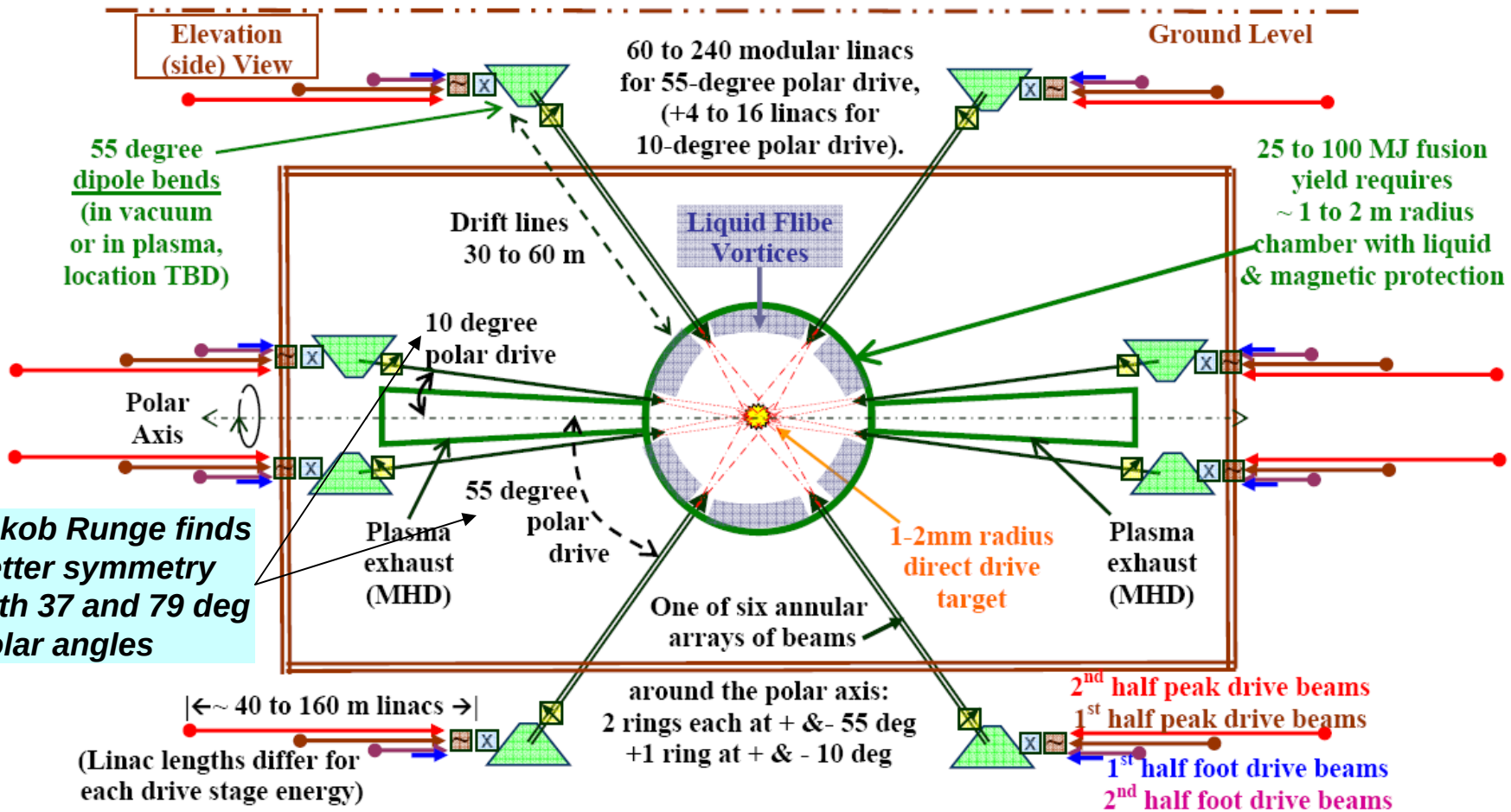


- Uses rapid combined bunch compression and acceleration with downstream beam manipulations <u>that can be tested on NDCX-II</u>
- Two of these would drive <u>test implosions in HIDDIX</u>; ~50 would provide <u>stage 3 drive for HIFTF</u>.

Concept guiding heavy-ion polar-direct-drive fusion study (preliminary)

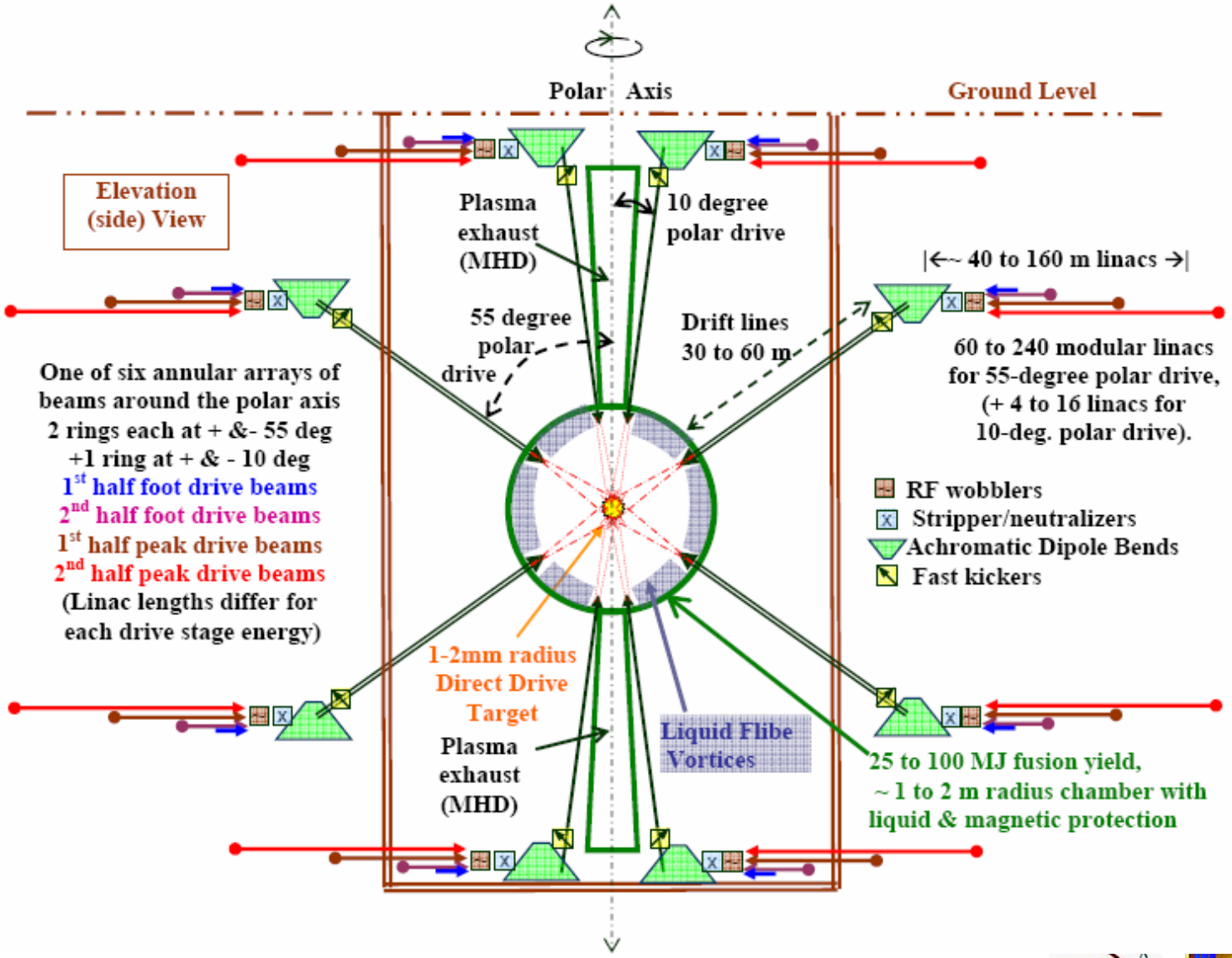
- Ion range increases during direct drive to maximize coupling efficiency-see publication.
- 300 kJ - 1.2 MJ total, corresponding gains 70 – 120 (will depend on target optimization).
- Pulse shaping, range and power ramping enabled with four different ion species and energies.
- Helical RF modulation projected into hollow, rotating beam spots for target smoothing/zooming.
- Total of 64 to 256 modular solenoid induction linacs, up to 150 MV, 7 kJ each.
- Neutralized beam compression and focusing after acceleration based on NDCX-I methods.
- Combined bunch compression, acceleration and RF modulation to be tested on NDCX-II.
- Polar direct drive with rotated beam spots to be tested on HIDDIX using two driver linacs.

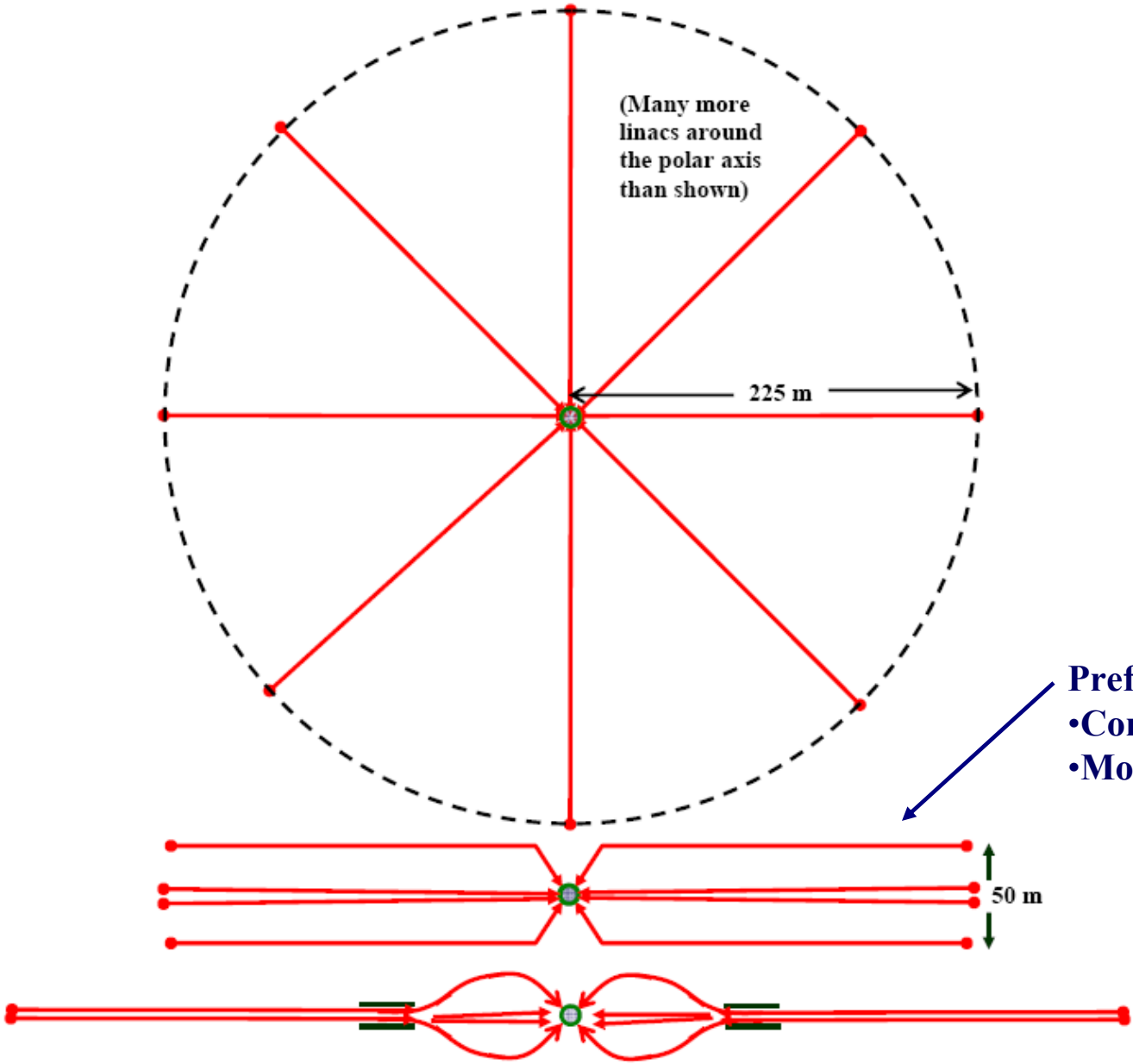
Horizontal Polar Axis Option



Jakob Runge finds better symmetry with 37 and 79 deg polar angles

Concept guiding heavy ion polar direct drive fusion study (preliminary) Vertical polar-axis option.





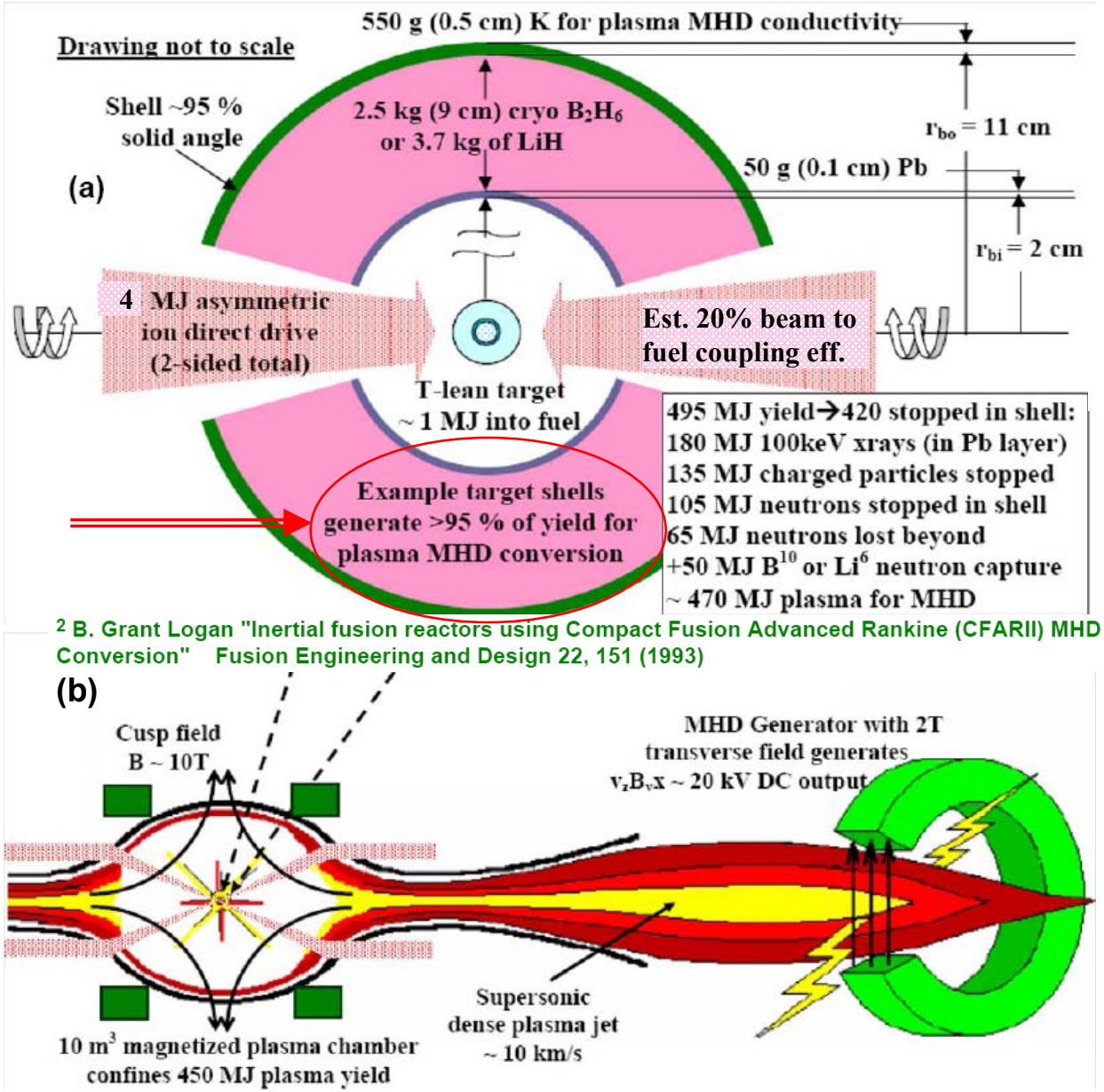
Top Down Plan Views
-options for heavy ion polar direct drive→ linac layouts for vertical vs horizontal polar axis

← **Vertical polar axis** option with beamline bends to keep linacs horizontal.
(**without bends**, circle radius is 20 % less)

Preferred option:
- Compact driver layout
- Modular development

← **Horizontal polar axis** option for separated horizontal linacs.

← Option for multiple - beam linacs each side



[2] B. Grant Logan "Inertial fusion reactors using Compact Fusion Advanced Rankine (CFARII) MHD Conversion" Fusion Engineering and Design 22, 151 (1993)

Figure 4: (a) Example target shell for efficient conversion of T-lean target output into 1 to 2 eV dense plasma for direct MHD conversion. All shell materials condense and recycle (Rankine cycle).
(b) Schematic of the CFAR MHD scheme (adapting the old 1992 CFAR Logo!)--no detailed design yet.

The 1 MJ HIFTF is a logical step towards <u>an ultimate goal</u>: High efficiency direct drive of high ρr, neutron absorbing targets for direct conversion!

Note key facts about the marriage of T-lean targets (Max Tabak 1996) to CFAR MHD conversion:
(1) Most T-lean target yield can be captured for direct plasma MHD conversion, even down to 1MJ–scale DEMO drivers.
(2) Plasma conductivity is 10^4 times greater at 25,000 K than at 2500 K→ the extractable MHD conversion power density ~σu^2, where u~10km/s is the plasma jet velocity, is >30 times the power density of steam turbine generators[2].
→As a consequence, the CFAR Balance of Plant *cost* can be much lower, < $ 80 M/ GWe!

Conclusion: more theory, experiments and conceptual design needed:

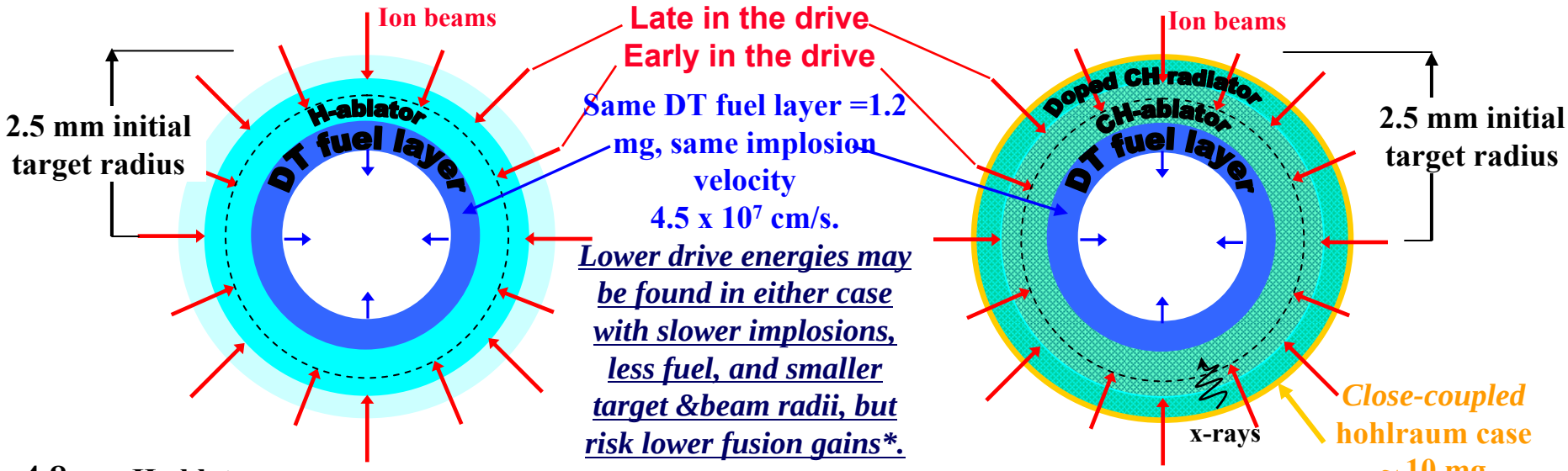
- **Limits on neutralized beam compression, including beam-plasma instabilities, to reach > 20,000 combined beam density compression ratios. (see Igor Kaganovich's talk)**
- **More implosion calculations in the ramped ion energy, $v_b > v_{eth}$ regime.**
- **Development of RF wobblers for hollow-beam spot control.**
- **2-D and 3-D symmetry and Rayleigh Taylor stability studies.**
- **Stripping, bending and focusing of high q ions in background plasma.**
- **Time-dependent corrections for focusing with velocity tilt.**
- **Beam brightness limits on current and line-charge density for focusing.**
- **…and many other issues…**

❖*The road to realize heavy ion direct drive fusion will be long and uncertain, but the potential for lower drive energy and high gain makes the journey worthwhile.*
❖*Direct drive offers affordable target physics opportunities we can learn along the journey that will be as exciting as the destination.*
❖*NIF ignition is coming → there is much more to do → collaborators are welcome!*

Backup Slides

Spherical ion beam illumination can be considered for either ablative direct drive or close-coupled spherical hohlraums (aka "Cannonballs"), *but for equal fuel mass, implosion velocity, and ion range, hohlraums require more energy*.

***Both** cases have symmetry & Rayleigh-Taylor stability concerns, to be discussed shortly….*



4.8 mg H ablator mass

Ablative Direct Drive Example

→1 MJ drive @ gain 50 (1-D Lasnex)

At ion speeds > v_{eth} (e.g., 400 MeV Ar in low-Z, H_2 ablators), ion beam energy deposition *would migrate radially away from the imploding ablation front (de-coupling) unless ion energy ramps up* during the drive sufficient to keep ion ranges chasing the ablation front.

32 mg (CH ablator + radiator mass)

Spherical-Illumination Indirect Drive Example

→2.6 MJ drive @ gain 19, (model est. includes losses in case) for same yield & ion range w/ higher Z ablators/radiators (e.g., 400 MeV Ar in doped CH). *Deposition of fixed 400 MeV beams migrates out radially; late radiation drive compensates decoupling*;

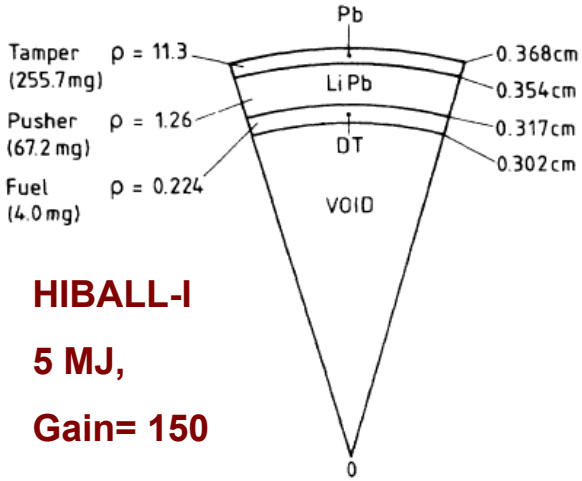
→x-rays chase the imploding ablation front.

NIF has 0.24 mg fuel mass @ 3.7 x 10^7 cm/s for capsule gain=100

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)

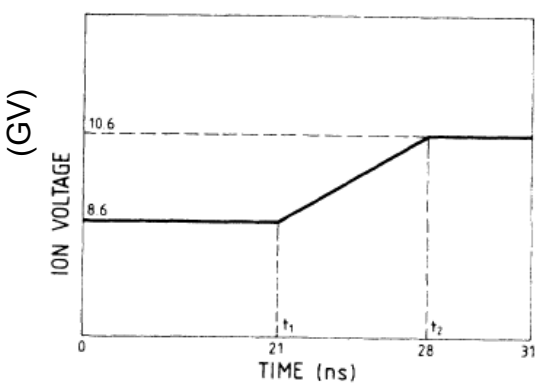
PR A Vol. 35, No. 6, March 1987



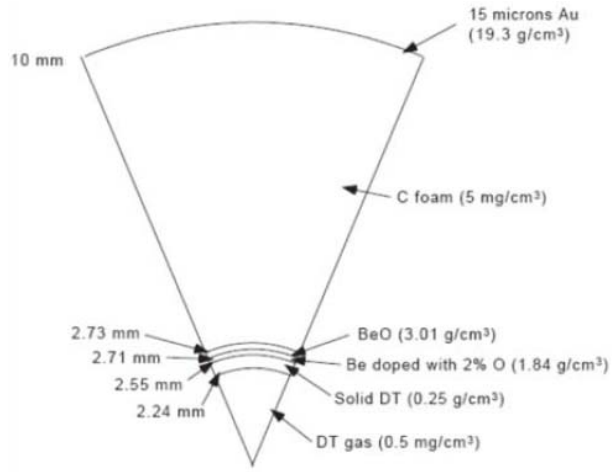
HIBALL-I

5 MJ,

Gain= 150



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



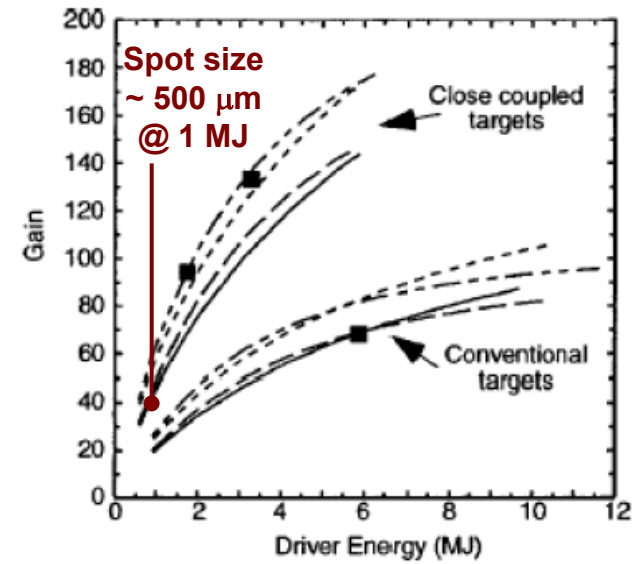
16 MJ Lithium ion drive

17→22 MeV,

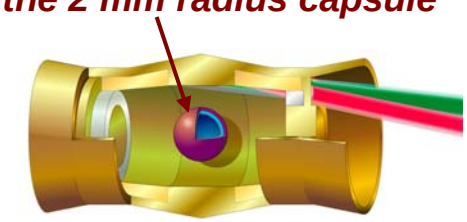
Gain= 37

Distributed Radiator (Callahan, Tabak)

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



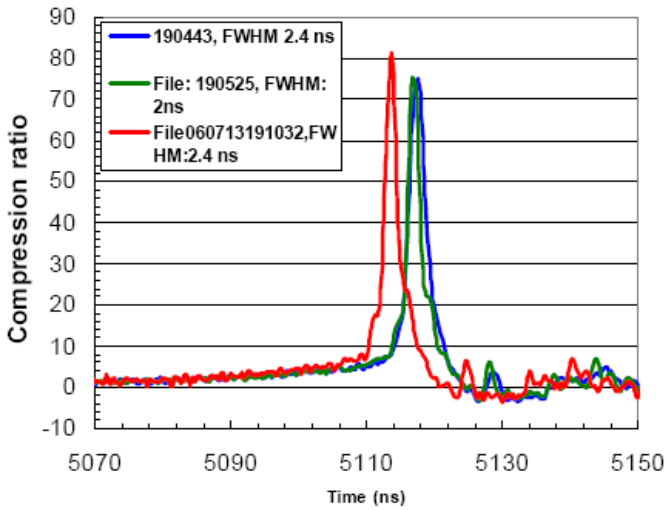
RPD: 3.3 GeV Bi foot, 4 GeV for peak. At gain=57, the 2 mm radius capsule absorbed 1 MJ out of 7 MJ total drive

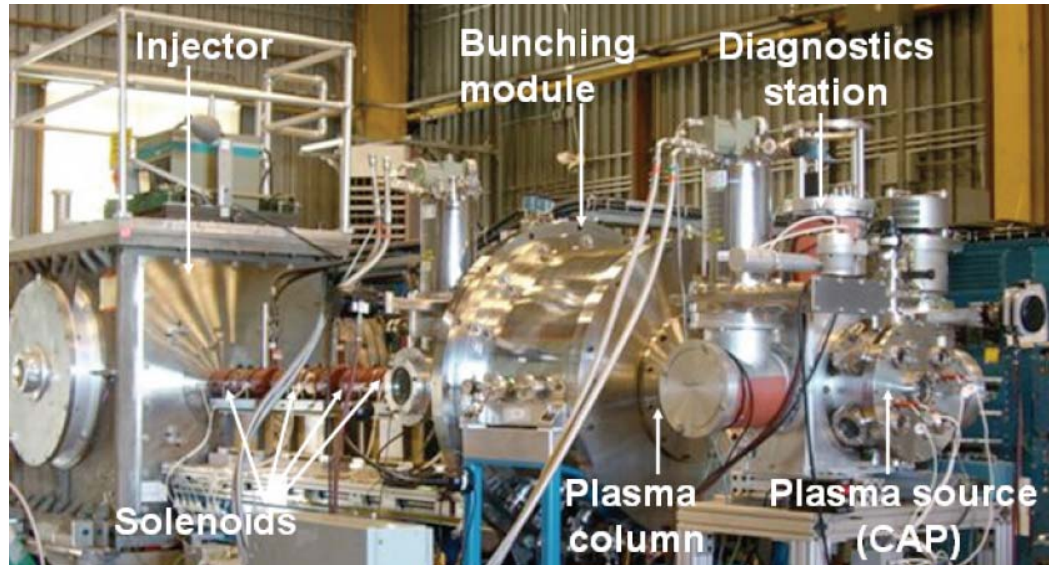


We retain the hohlraum option for HIF, while we explore direct drive.

Beam compression [15x radial (2004), 80x longitudinal (05), 1000x combined (07)] in the neutralized drift compression experiment (NDCX-I) continues progress towards combined values >20,000 needed for HEDP and heavy ion fusion

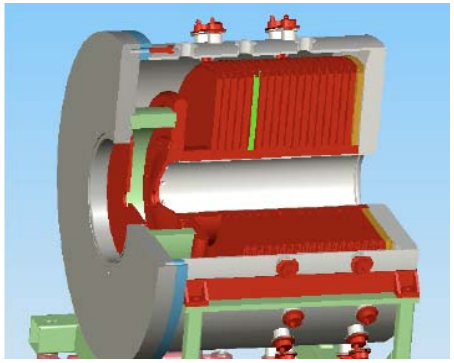
Shorter pulses (2.4 ns) obtained w/ new PPPL Ferro-electric plasma source



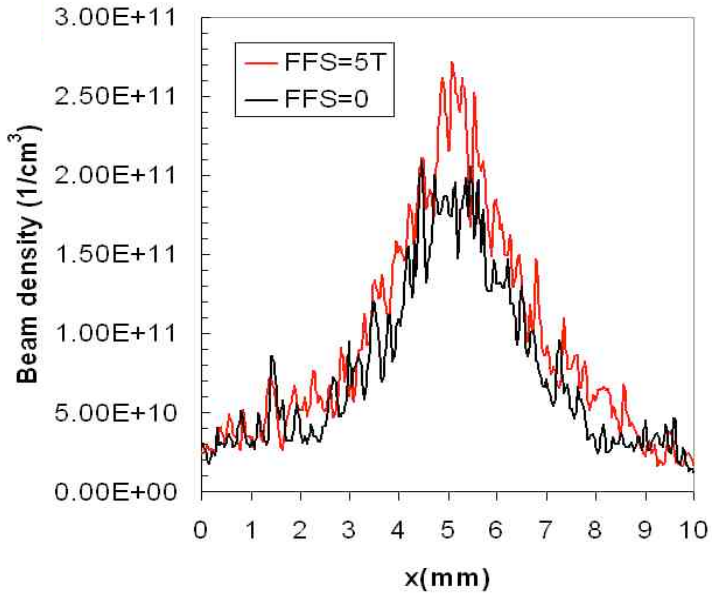


(PPPL FEPS)

Simulations (Adam Sefkow) predict higher compression with new induction buncher (08)

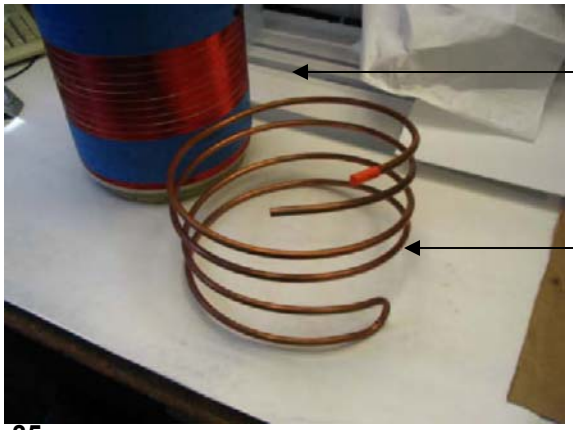


First combined radial and longitudinal compression: ***to be repeated with more plasma for better beam neutralization***

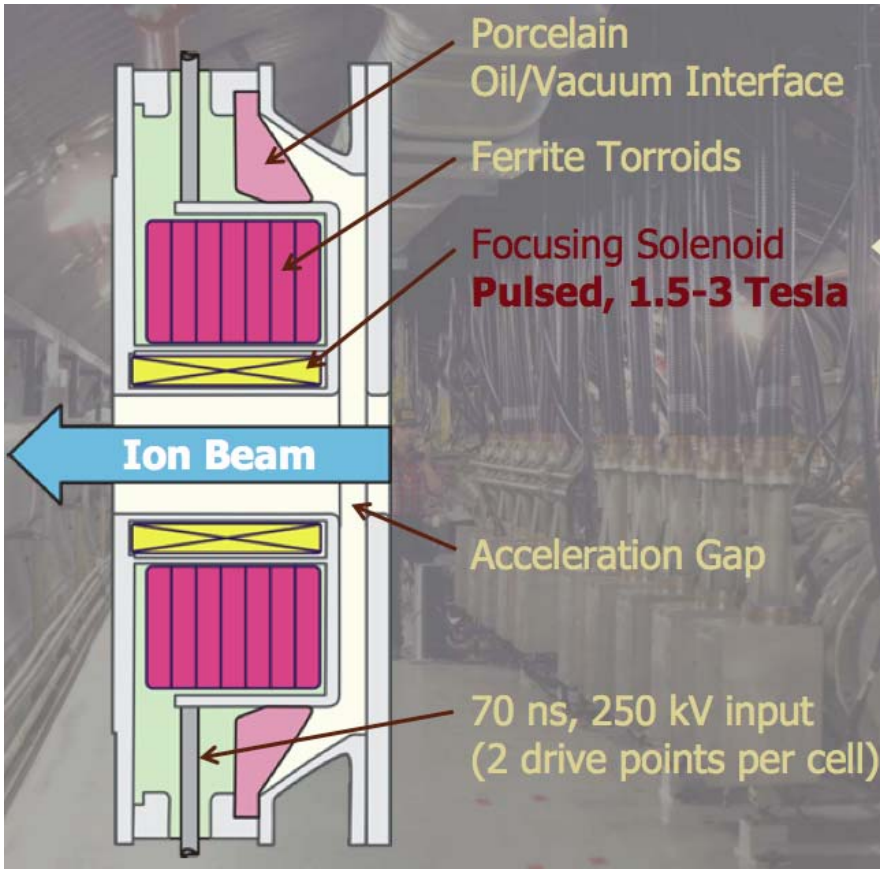


Induction cells for NDCX-II are available from LLNL's decommissioned ATA facility

Test stand has begun to verify performance



Cells will be refurbished with stronger, pulsed solenoids



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

[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

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

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

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

$\Lambda_B = \frac{2 m_e c^2 \beta^2}{\bar{I}}$, $\Lambda_F = \frac{m_e c^2 \beta^2}{\hbar \omega_p}$, $G(x) = erf(x) - x\,erf'(x) \approx 1$ 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 $= A_{IonBeam}\ (9.3e5)\ keV$

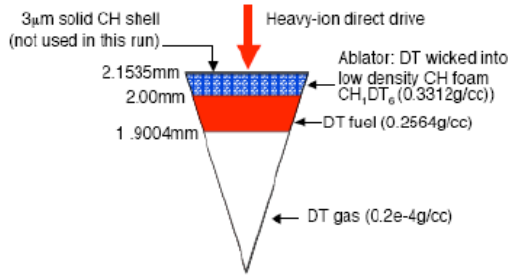
$m_e c^2$ = Electron Rest Energy $= 511\ keV$

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

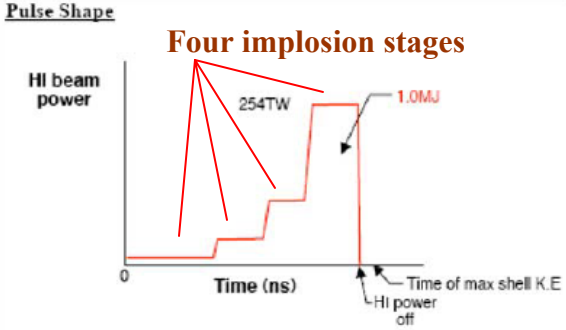
$\beta_{eff}^2 \equiv \beta^2 + \beta_e^2$, with $\gamma_e = \frac{1}{\sqrt{1-\beta_e^2}} = 1 + \frac{kT_e}{m_e c^2}$

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.

Capsule Parameters



Pulse Shape



Main Results

Heavy-ion drive	50MeV Ar (z = +8 accel, +16 drift/focus)
Drive energy	1.0MJ
Yield	50.4MJ
Gain	50.4
Peak velocity	4.45e7cm/s
Energy in ingoing shell at peak KE	133kJ(kinetic energy) + 26.0kJ (thermal compression energy)
Peak rho-R at stagnation	1.24 g.cm-3

Time(ns)	Power (TW)
0	0
0.251	1.5
4.65	1.5
5.151	12.50
6.65	12.50
7.151	50.0
8.25	50.0
8.751	253.61
11.75	253.6
12.251	0

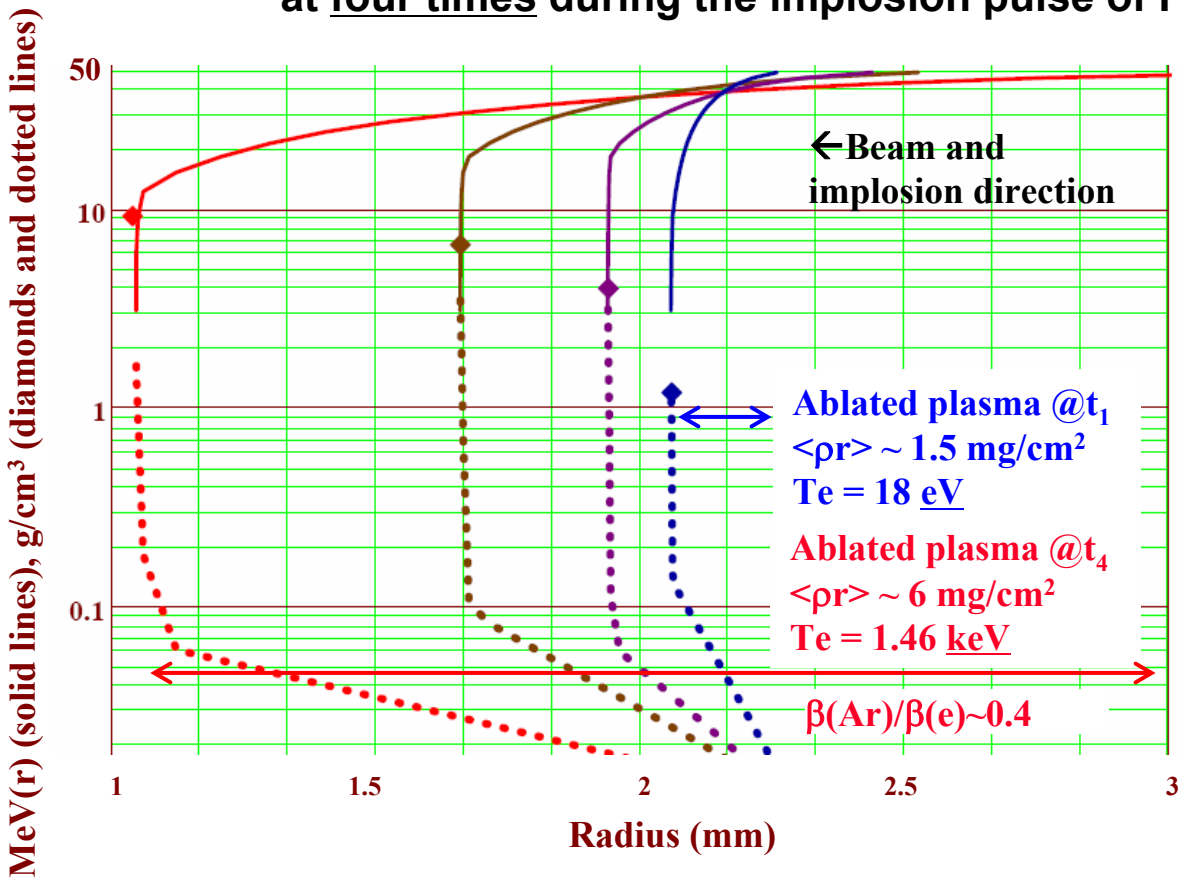
			At radius of peak drive pressure					At 50% deposition radius			
Time	Mass fraction ablated	Rho-R to vel reverse (g/cm2)	Radius (cm)	Peak press (Pa)	Temp (kev)	Max density (g/cc)	Ingoing KE (J)	Radius (cm)	Temp (kev)	Density (g/cc)	Outward velocity (10^8cm/s)
Halfway thru foot 2.45ns	0.174	0.00650	0.206	2.20e11	8.80e-4	2.39 (shocked value travel. thru 0.331g/cc backgro und)	206.	0.214	1.84e-2	0.110	0.0126
Halfway thru 3rd pedestal 7.7ns	0.253	0.00638	0.194	1.26e12	3.19e-3	4.02 (ditto)	1.51e3	0.216	0.419	0.0198	0.0448
Halfway thru main pulse 10.25ns	0.497	0.00583	0.166	5.07e12 (=50 Mbar)	6.74e-3	6.68	2.418e4	0.192	1.024	0.0379	0.122
End of HI drive 12.25ns	0.621	0.0105	0.104	8.91e12 (=89 Mbar)	7.86e-3 (much higher at radii outside and inside this	9.31	118e5 (peak KE comes later – see below)	0.163	1.46	0.0276	0.101

We developed a MathCAD model to explain Perkins' LASNEX run output for 50 MeV Ar, and to derive beam requirements for future runs with hydrogen ablators and higher, ramped-energy ion beams.

We derived four different sets of beam energies/ranges to drive each of the four implosion stages shown here, designed to deliver the same total beam energy of 1 MJ, and the same implosion velocity for the same fuel mass to get the same gain with the same 50 MJ of fusion yield, but with higher ion kinetic energies up to 500 MeV (more practical for linac design)

With $v_{beam} < v_{eth}$ @ 50 MeV incident, the ablation plasma Te increases with beam power enough that the ion range rises by 4X matching the rising ablation plasma column density →enough to allow the beam range to chase the ablation front closely→ good coupling efficiency!

Snapshots of the modeled ion energy $E_{ion}(r)$ (solid lines, in MeV) and plasma densities (dotted lines, in g/cm^3) versus radius (in mm) at four times during the implosion pulse of Perkins' 50 MeV Ar run:



← incident energy =50 MeV *(constant in time)*

t_1= 2.45 ns, halfway in foot

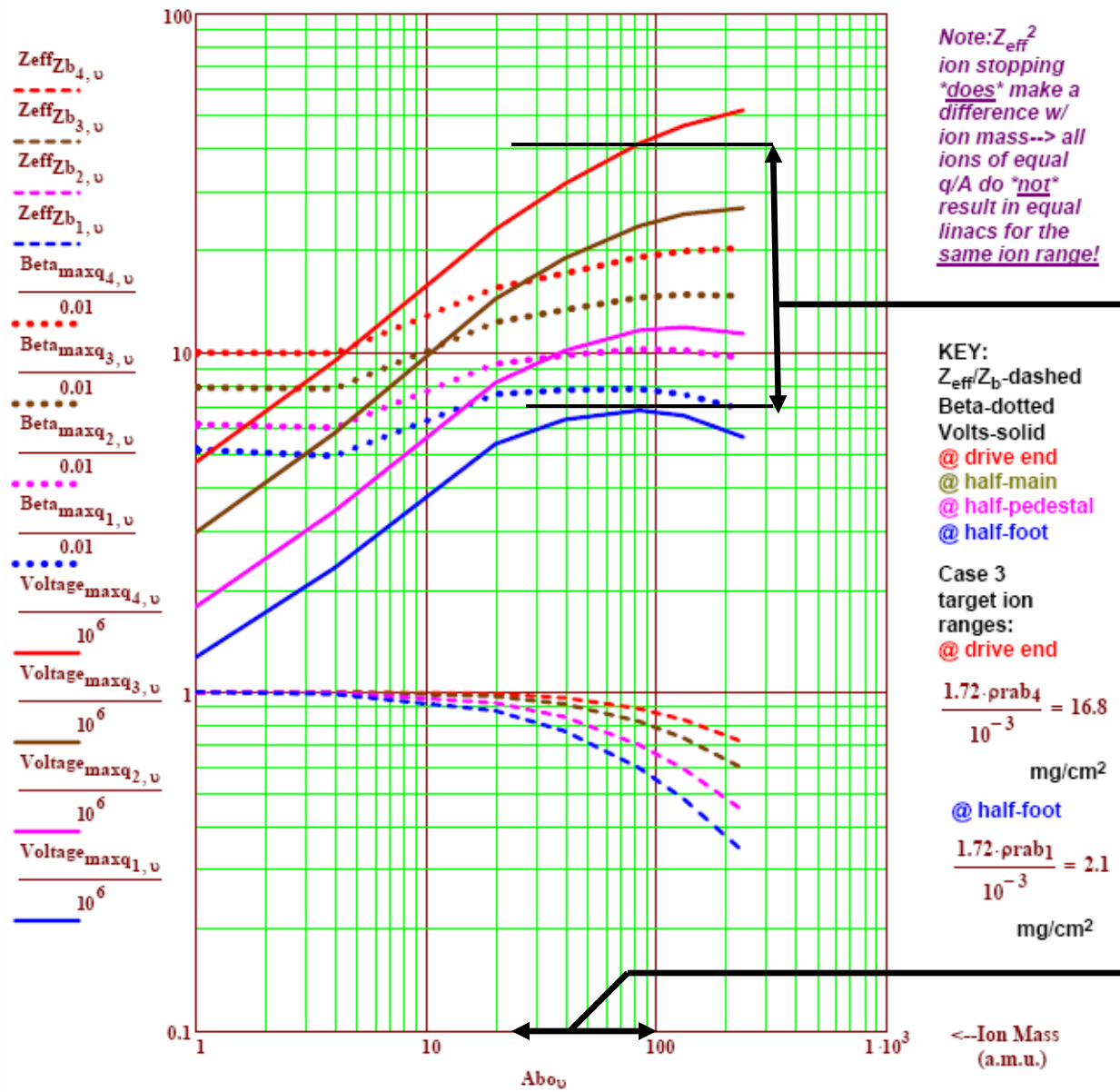
t_2= 7.7 ns, halfway in pedestal

t_3=10.25 ns, halfway in peak

t_4= 12.25 ns, end of drive

Diamond-shaped points give the dense DT shell density (g/cm^3) and radius (mm) at each time. Note the shell radius is about half of the initial radius by the end of the drive pulse.

Using highly-stripped, medium mass ions A~ 20-80, the 1 MJ direct drive target ranges require *moderate linac voltages 8 to 40 MV.*



→Short linacs

8 to 40 MV!

Note: (1) that Zeff /Zb begins to fall below 1 at A > 40 for the set of ranges needed for 1 MJ direct drive. (2) At these moderate ion A and K.E., ion beam drift compression and focusing *requires plasma neutralization.*

A ~ 20 to 80

Beam spot rotations around the polar axis might give sufficient symmetry with a reasonable number (< 50 beams each side)

Worth pursuing, needs 2-D target implosion calculations, easier for θ_b=45 deg …

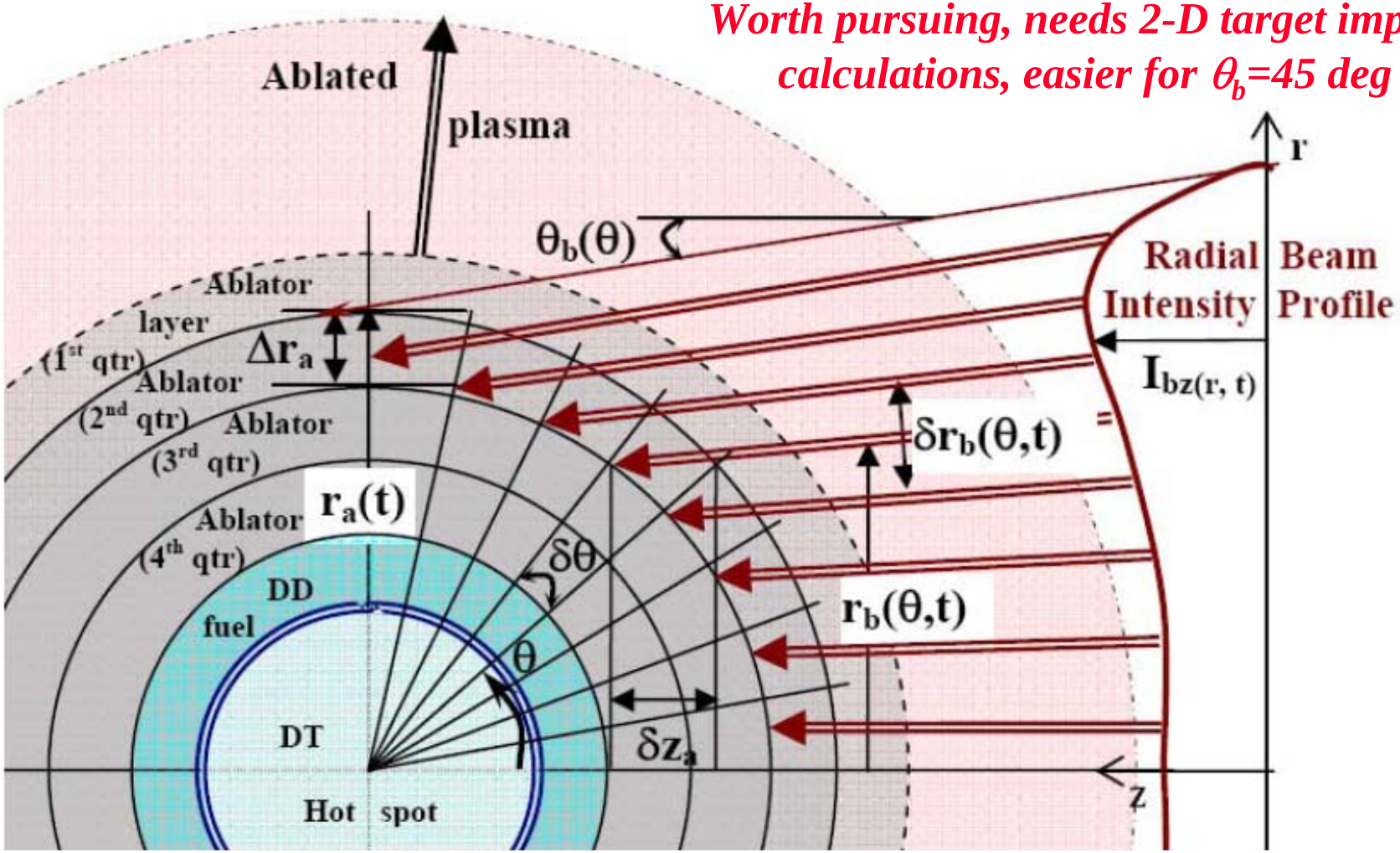


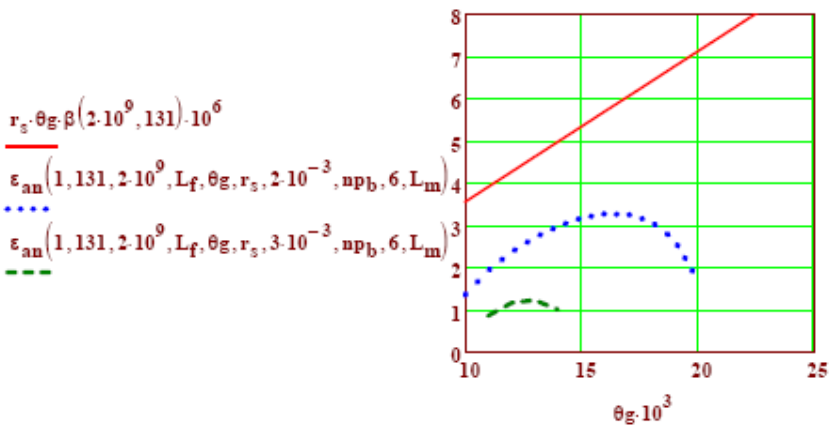
Figure 65 Comparing allowed accelerator emittance (normalized, in mm-mr) for the Snowmass 02 version of RPD (2 GeV Xe^{+1}) (A) versus allowed emittance for the stage three drive of the 1 MJ direct drive target (B).

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)



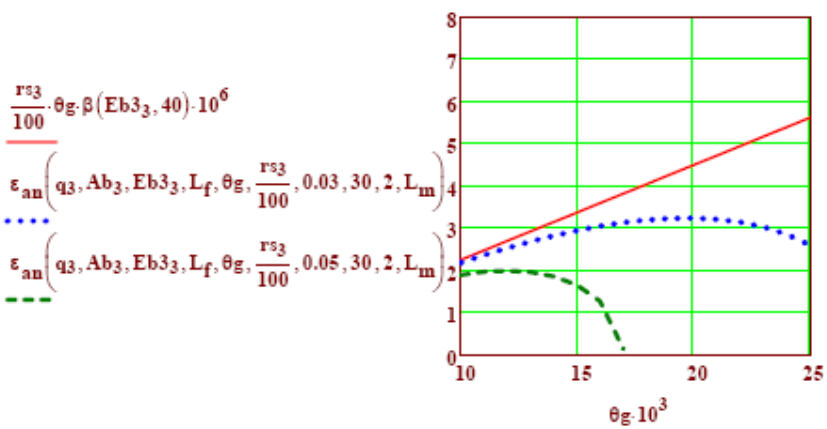
(A) Snowmass 2002 design
<--allowed emittance vs focusing angle (mr) if no plasma net perveance, no momentum spread, and no geometric aberrations.
<--allowed emittance with 0.2% momentum spread

<--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.

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*

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

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