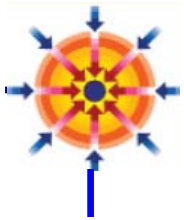
Heavy Ion Driven Direct Drive Inertial Fusion --new VNL research opportunities--



Heavy ion beams may do this best!

B. Grant Logan, HIFS-VNL

Abstract:

Efficient coupling of heavy ion beams to direct drive targets without hohlraums is discussed, as well as proposed approaches to mitigate symmetry, RT instability issues, and new VNL research opportunities.

Prologue

We continue pursuing HEDP research that began in 2003- (First WDM experiments on NDCX-I this fall). Its time to look again at heavy ion fusion (this talk). Commencement of the NIF ignition campaign motivates reconsideration of heavy ion fusion that builds upon our advances in compressing/focusing neutralized ion beams.

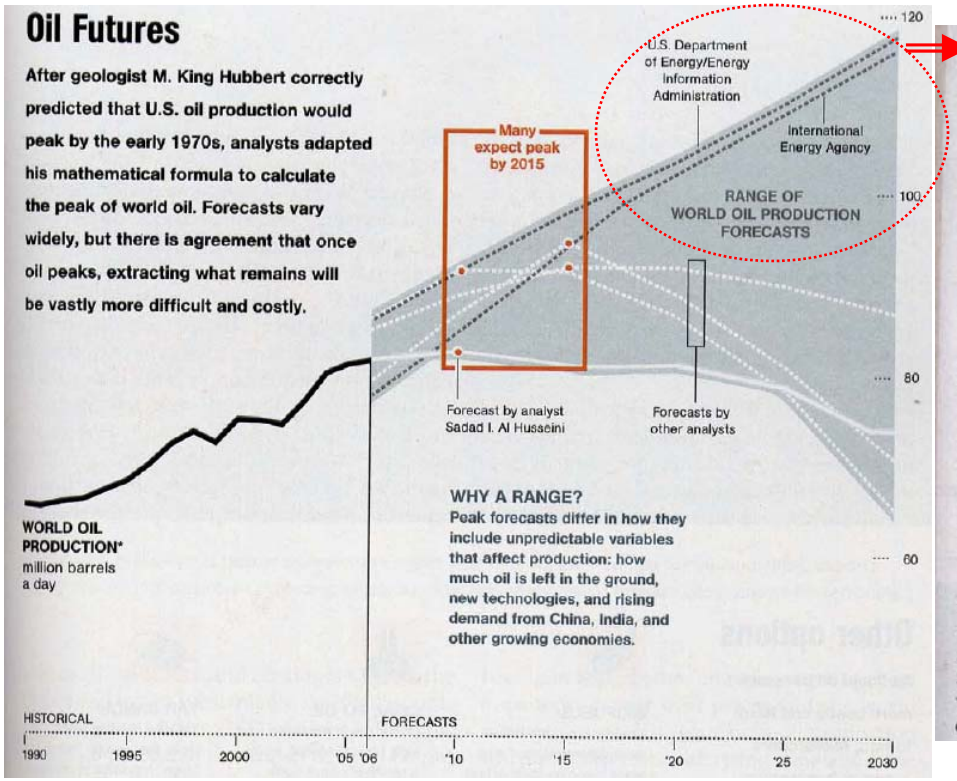
Presented to the PPPL Colloquium

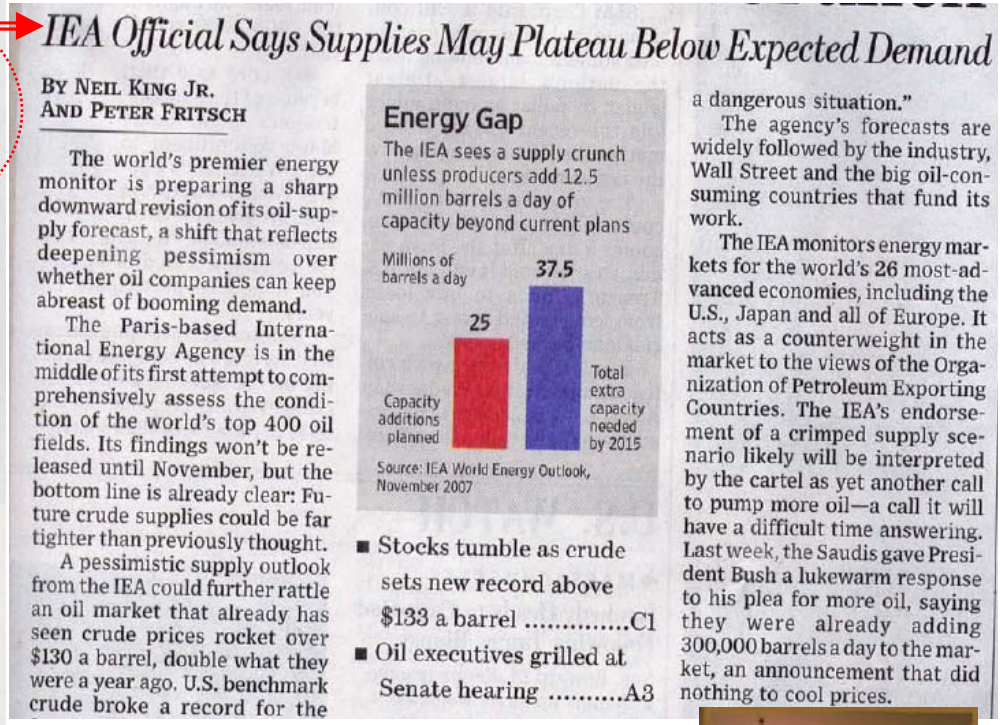
May 28, 2008

*** 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.**

Why discuss HIF now? →New opportunities (this talk) and fusion funding (coming):
The EIA (DOE) and the International Energy Agency (IEA) are finally revising their forecasts for future world oil production *to face reality*.

Wall Street Journal, front page, May 22, 2008





IEA Official Says Supplies May Plateau Below Expected Demand

BY NEIL KING JR. AND PETER FRITSCH

The world's premier energy monitor is preparing a sharp downward revision of its oil-supply forecast, a shift that reflects deepening pessimism over whether oil companies can keep abreast of booming demand.

The Paris-based International Energy Agency is in the middle of its first attempt to comprehensively assess the condition of the world's top 400 oil fields. Its findings won't be released until November, but the bottom line is already clear: Future crude supplies could be far tighter than previously thought.

A pessimistic supply outlook from the IEA could further rattle an oil market that already has seen crude prices rocket over $130 a barrel, double what they were a year ago. U.S. benchmark crude broke a record for the

Energy Gap

The IEA sees a supply crunch unless producers add 12.5 million barrels a day of capacity beyond current plans

Millions of barrels a day

Capacity additions planned: 25

Total extra capacity needed by 2015: 37.5

Source: IEA World Energy Outlook, November 2007

■ Stocks tumble as crude sets new record above $133 a barrel C1

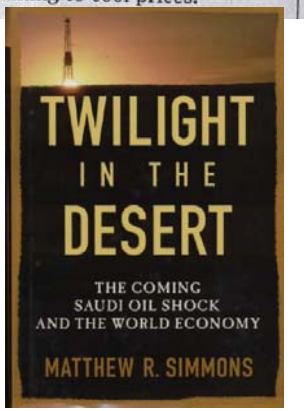
■ Oil executives grilled at Senate hearing A3

a dangerous situation."

The agency's forecasts are widely followed by the industry, Wall Street and the big oil-consuming countries that fund its work.

The IEA monitors energy markets for the world's 26 most-advanced economies, including the U.S., Japan and all of Europe. It acts as a counterweight in the market to the views of the Organization of Petroleum Exporting Countries. The IEA's endorsement of a crimped supply scenario likely will be interpreted by the cartel as yet another call to pump more oil—a call it will have a difficult time answering. Last week, the Saudis gave President Bush a lukewarm response to his plea for more oil, saying they were already adding 300,000 barrels a day to the market, an announcement that did nothing to cool prices.

→<u>Public pressure</u> may soon force US Federal energy R&D spending (all types) to increase to 1980 levels of % of GDP. Under this scenario, US fusion research could increase <u>6 fold</u>.



At IFSA 2007, B$-class IFE initiatives were presented by JA, EU, and US-all based on laser fast ignition, and assuming NIF ignition. *We need an HIF option* →note original motivations for HIF still apply today! (See next)

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.

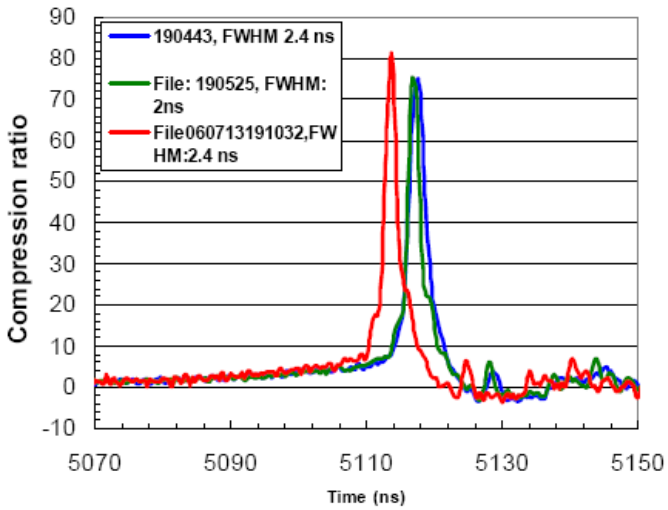
(b) Thick-liquid protected target chambers with 30 year plant lifetimes, compatible with indirect-drive or polar direct-drive target illumination geometries to be tested in the National Ignition Facility.

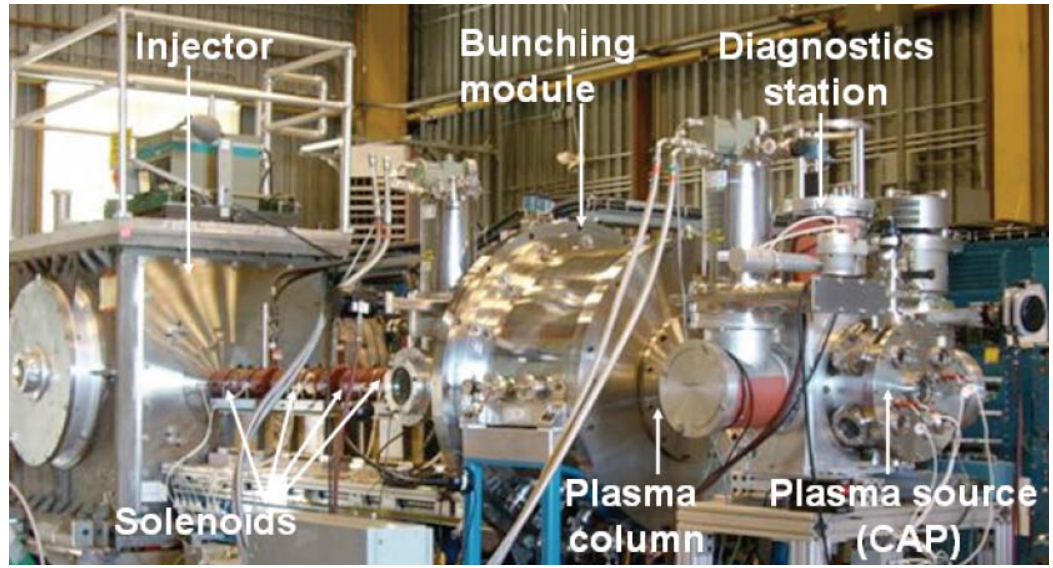
(c) Focusing magnets for ion beams avoid direct line-of-sight damage from target debris, neutron and gamma radiation.

(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).

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

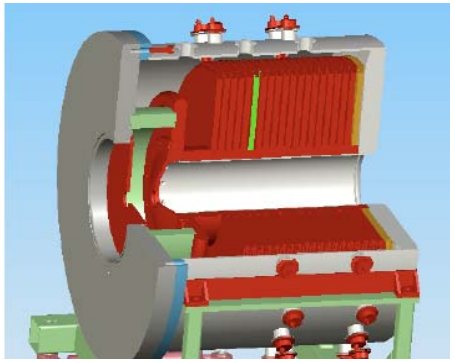
Shorter pulses (2.4 ns) obtained w/ new PPPL Ferro-electric plasma source



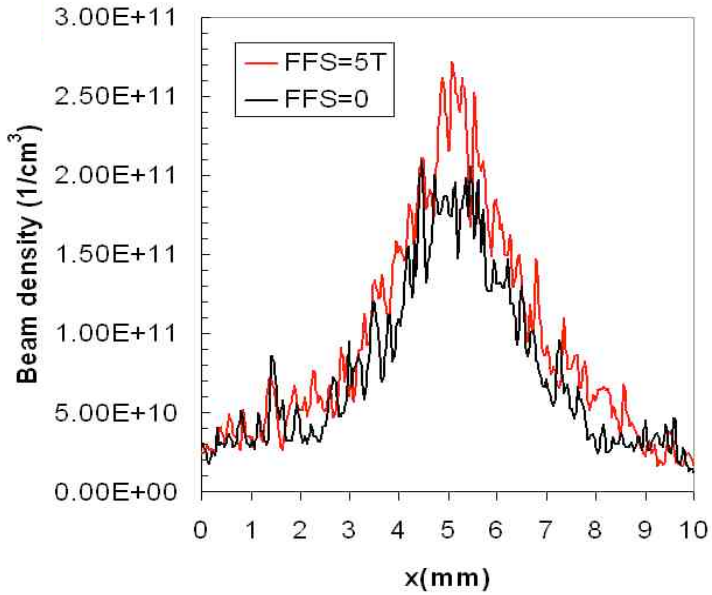


(PPPL FEPS)

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***



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

Regarding HIF: What's new (additional research opportunities):

1. **Large (4 to 6 X) ion range ramp up during ion direct drive, either by $v_b < v_{eth}$, or by ion energy ramping (preferred)→** ***Avoids de-coupling from the ablation front without x-ray drive in hohlraums*.***

2. **Use of hydrogen ablators to increase stopping power and raise ion energies (to 240 MeV Ne, or 400 MeV Ar). →** ***Allows beam perveances << 1 in vacuum regions of the accelerator.***

3. **Use of highly stripped, helium-like, medium mass ions for larger numbers (>>100) of smaller, NDCX-II-size linacs. →*****Maintains linac efficiency for ηG >10 keeping induction gradients > 2 xE_z ($d\lambda_b/dz$).***

4. **Applying RF wobbler-beam rotation for oblique ion illumination, (rather than purely radial). →*****May reduce RT growth rates, primarily during the most crucial early foot-period of the drive.***

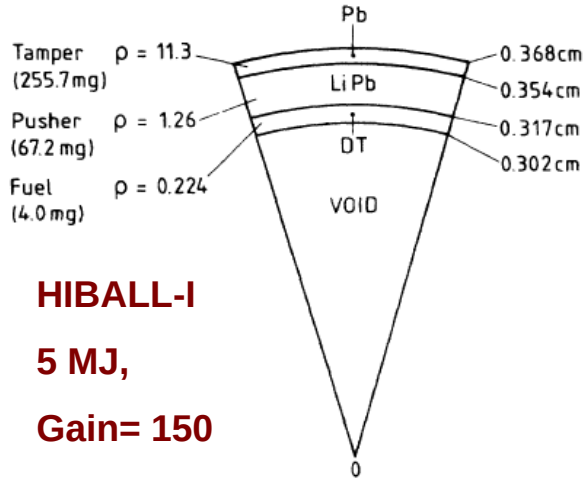
5. **A chamber-final focus geometry accommodating many beams with different ion species to drive each of four stages of the implosion with near common ion rigidities (B-rho). →*****Reduces ion $\delta v/v$ ramp range per stage, and reduces chromatic focusing aberrations.***

** Submitted this month for publication*

<u>Review:</u> Debbie and Max did a good job of shrinking heavy ion hohlraums with close-coupled hohlraums, doubling the overall coupling efficiency from 2 % to 4%. *We are re-examining heavy ion direct drive seeking 5 to10X higher coupling efficiencies.*

HIBALL (Long, Tahir)

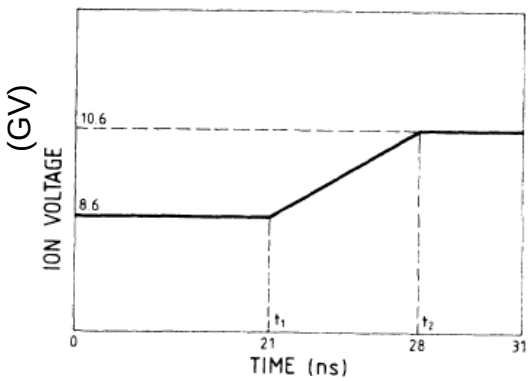
PR A Vol. 35, No. 6, March 1987



HIBALL-I

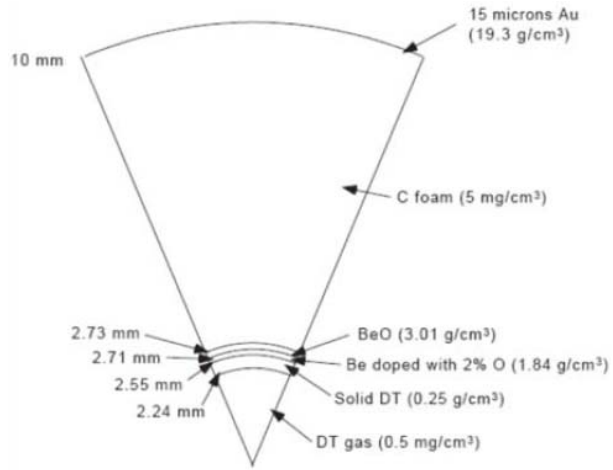
5 MJ,

Gain= 150



LIF Hohlraum (Allshouse, Callahan)

Nuc. Fus. Vol. 39, No 7 1999



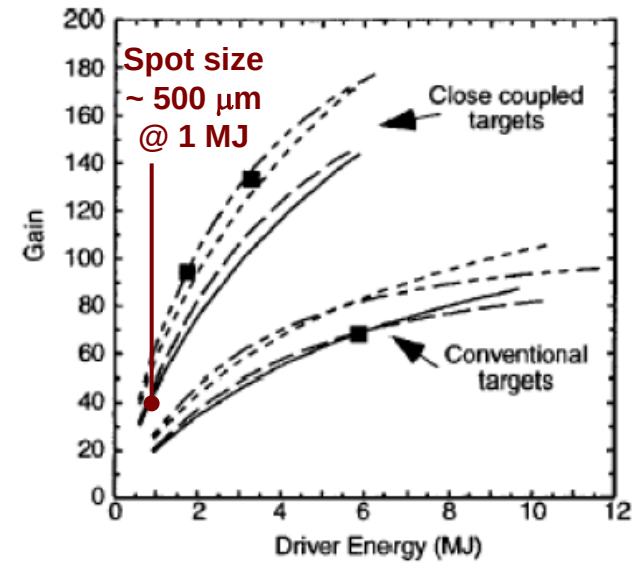
16 MJ Lithium ion drive

17→22 MeV,

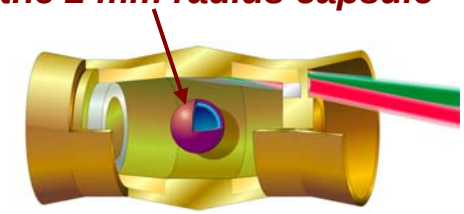
Gain= 37

Distributed Radiator (Callahan, Tabak)

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

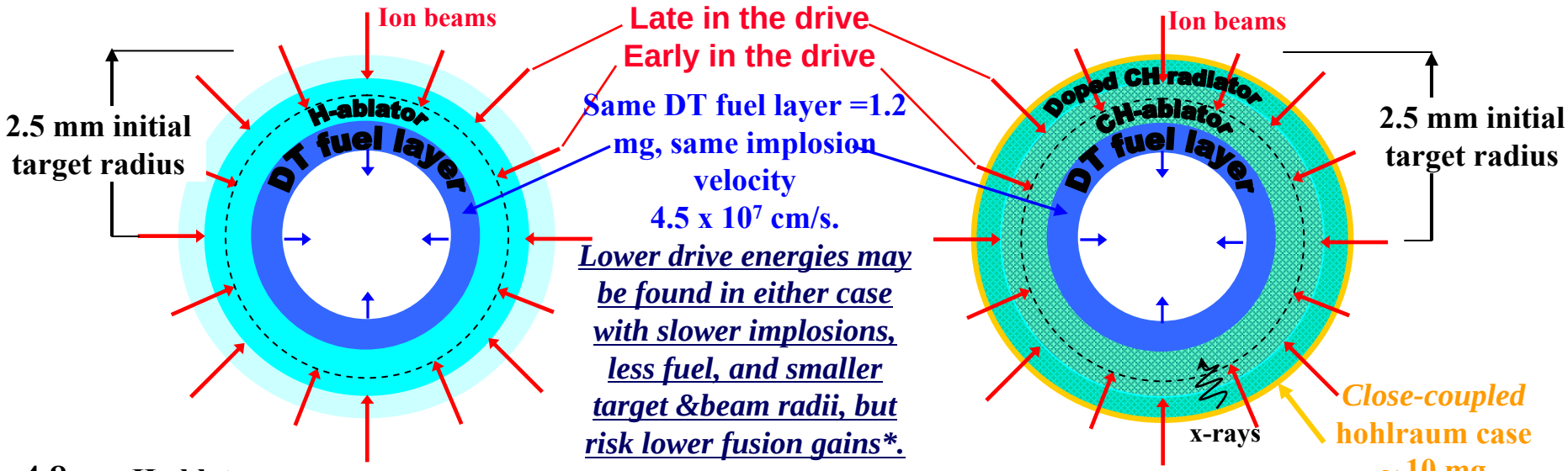


RPD: 3.3 GeV Bi foot, 4 GeV for peak. At gain=57, the 2 mm radius capsule absorbed 1 MJ out of 7 MJ total drive



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

32 mg (CH ablator + radiator 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.

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

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).

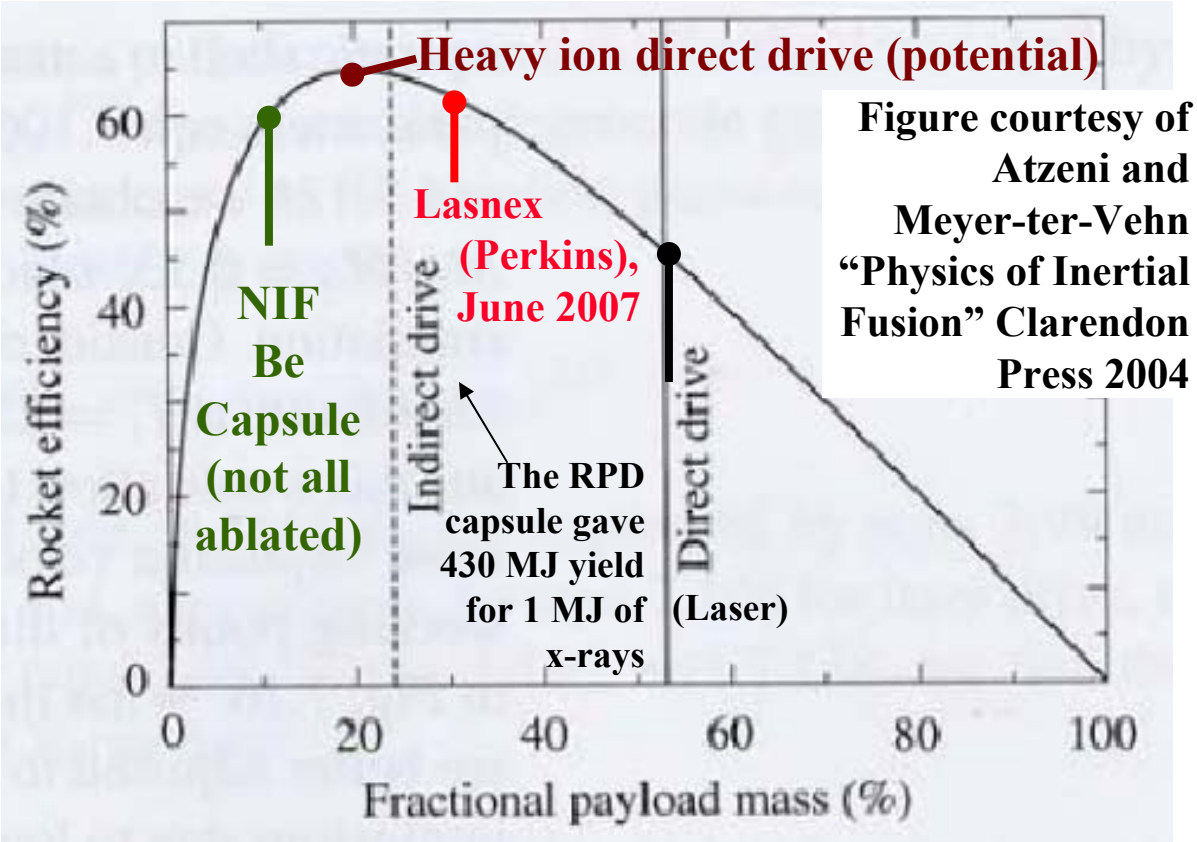


Figure courtesy of Atzeni and Meyer-ter-Vehn "Physics of Inertial Fusion" Clarendon Press 2004

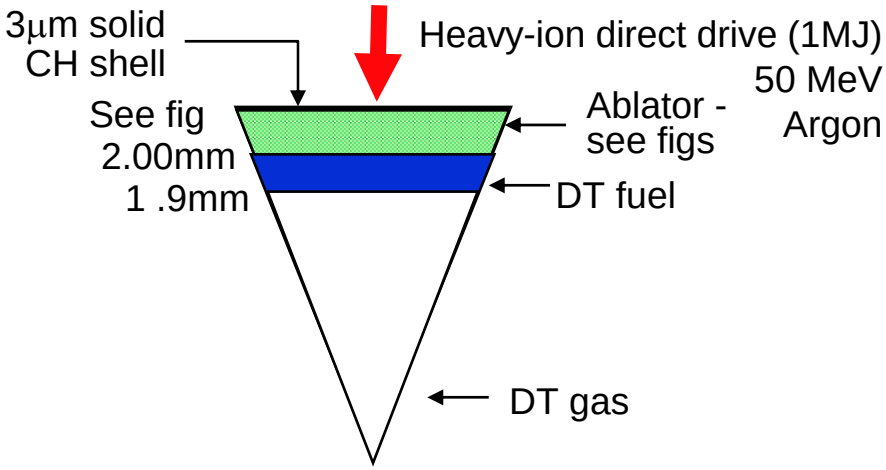
→Low-Z ablators (DT or H) for ion direct drive need small 13.6 eV ionization

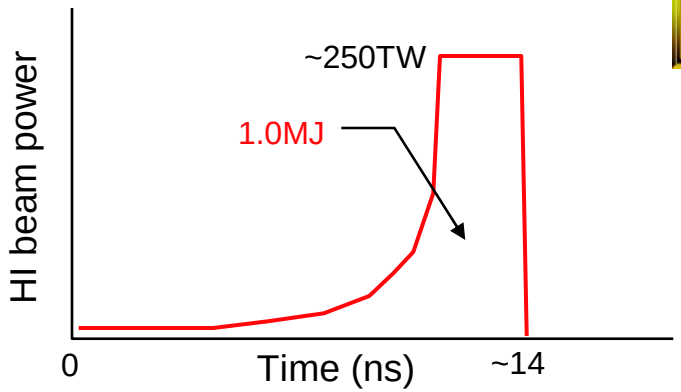
→X-rays couple well to ablators, but not enough to compensate for x-ray conversion & hohlraum losses. Be, C ablators require significant ionization energy.

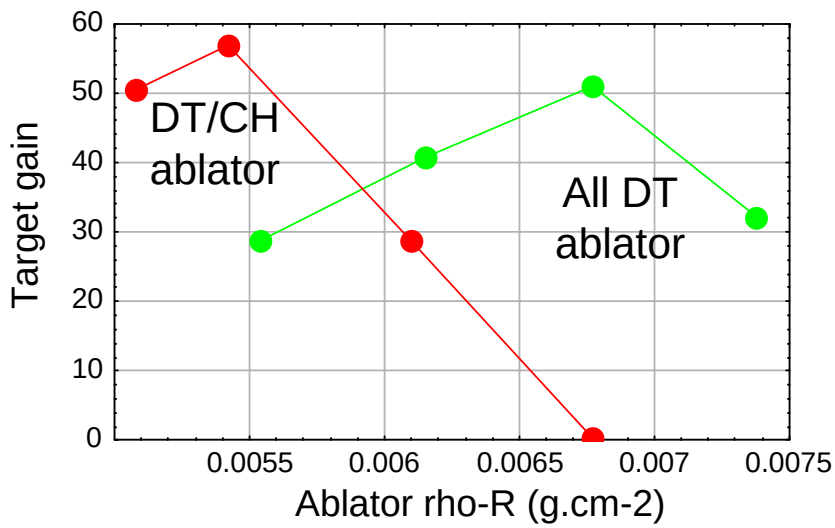
→Laser coupling is reduced with electron transport from low critical density to ablation front

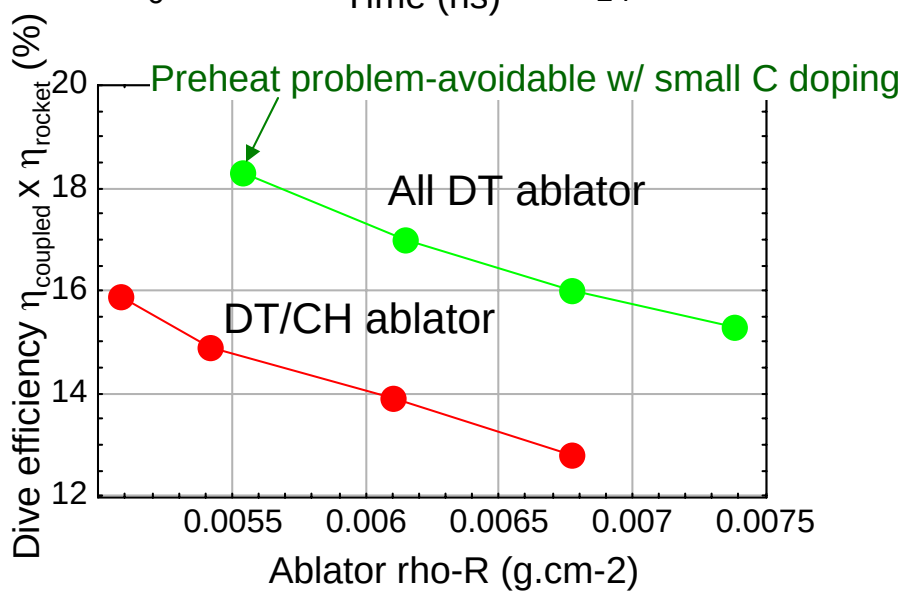
Heavy ion beams can suffer more parasitic energy loss on out-going ablation corona plasma than either x-ray or laser photons, *but with range-lengthening during the drive pulse, overall coupling efficiencies can still be higher*.

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%) .(Submitted for publication)









Higher efficiencies (20-30%) may be possible using H ablators and by ramping the ion kinetic energy

[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

$\Lambda_B = \frac{2m_e c^2 \beta^2}{\bar{I}}$, $\Lambda_F = \frac{m_e c^2 \beta^2}{\hbar\omega_p}$, $G(x) = erf(x) - x\,erf'(x) \approx 1$ 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 $= 511\ keV$

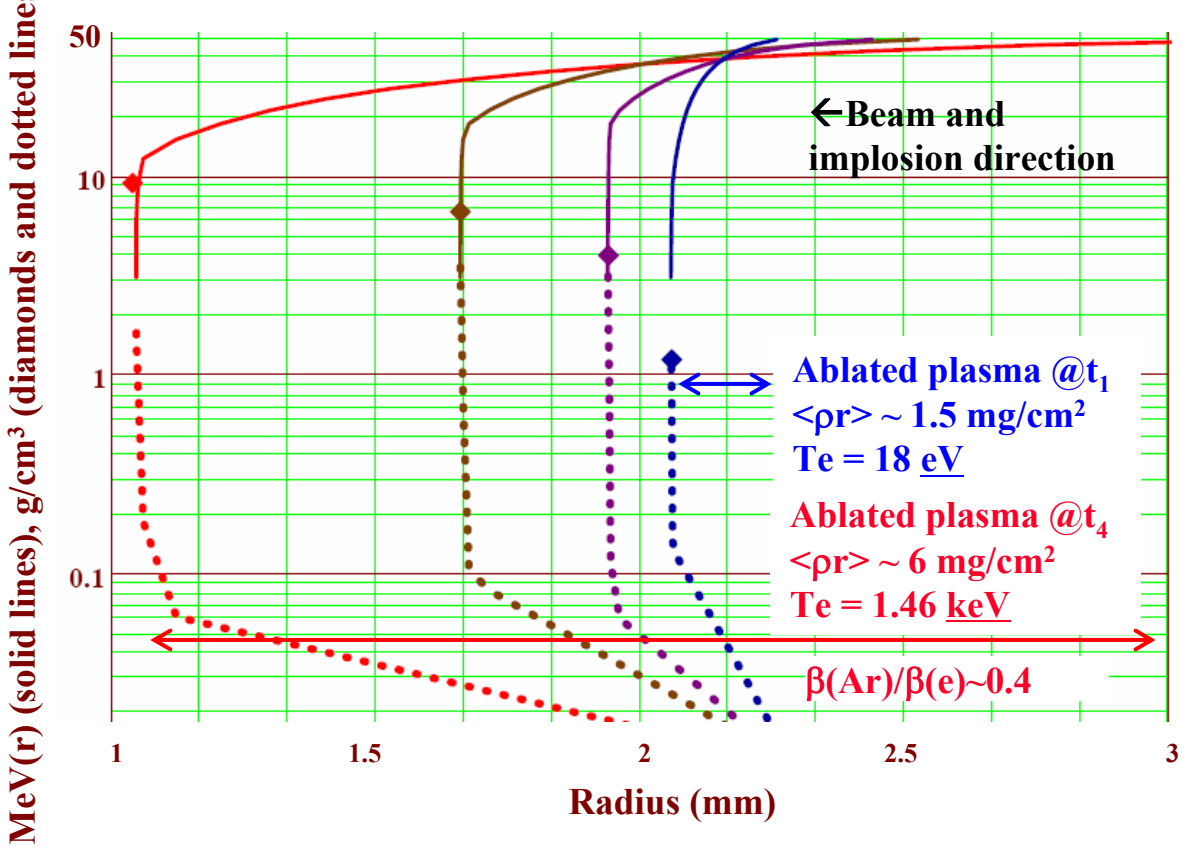
Betz Empirical $Z_{eff} \equiv Z_{IonBeam}\left[1 - \exp(-137\,\beta_{eff} / Z_{IonBeam}^{.69})\right]$

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

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!

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

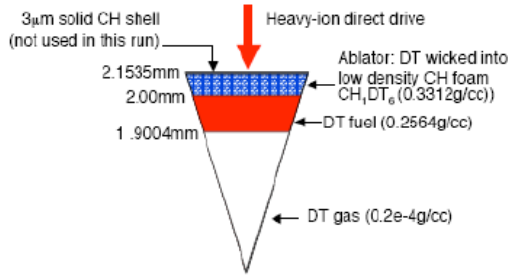
t_2= 7.7 ns, halfway in pedestal

t_3=10.25 ns, halfway in peak

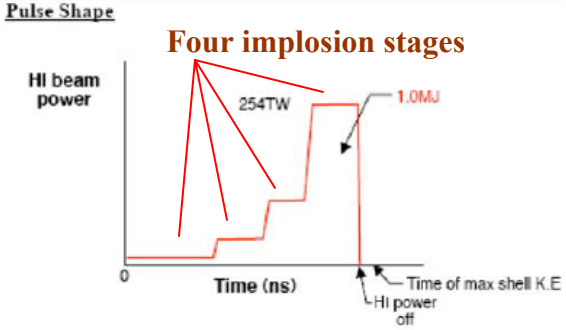
t_4= 12.25 ns, end of drive

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.

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

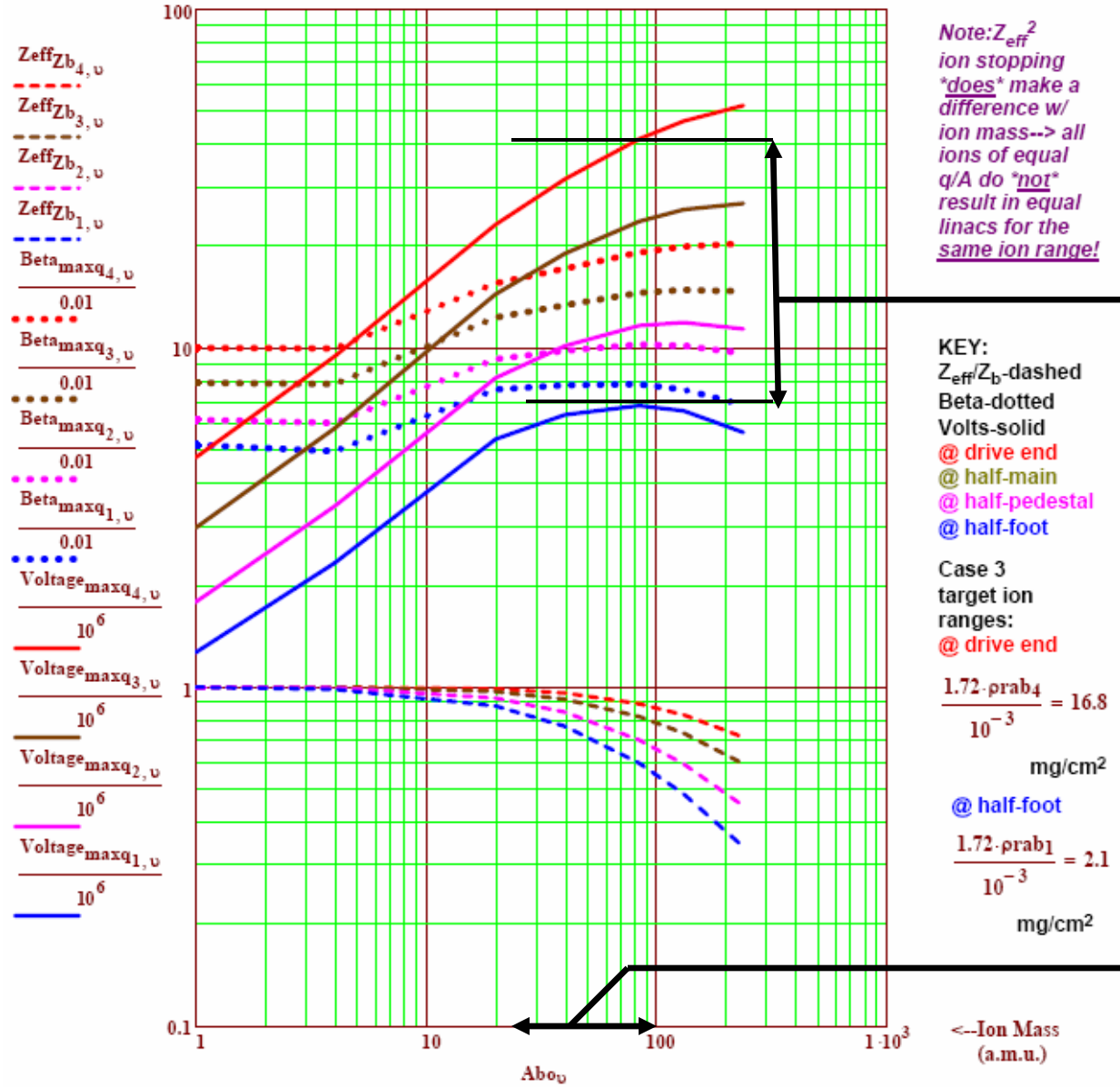
Time(ns)	Power (TW)
0	0
0.251	1.5
4.65	1.5
5.151	12.50
6.65	12.50
7.151	50.0
8.25	50.0
8.751	253.61
11.75	253.6
12.251	0

			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)

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



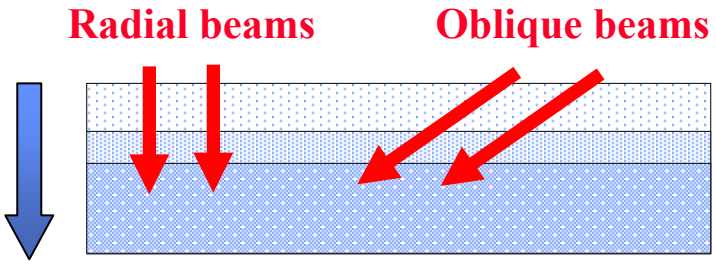
→Short linacs

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.*

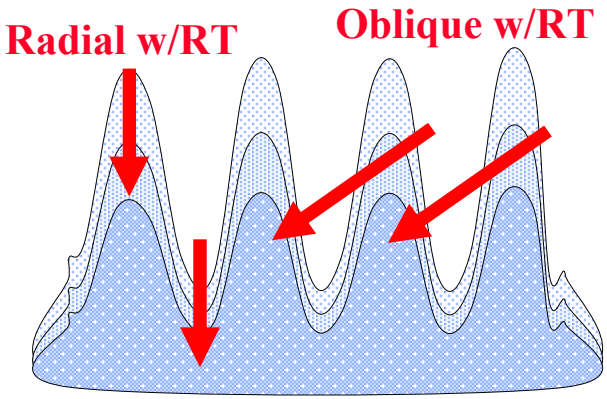
A ~ 20 to 80

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



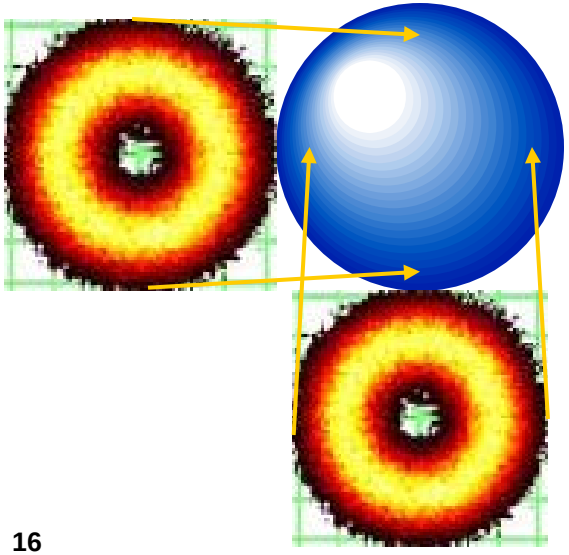
Density gradient

Un-perturbed ablator



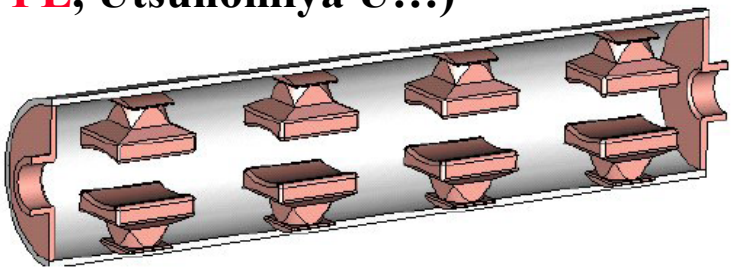
Perturbed ablator. Oblique ion rays may ablate high density spikes faster when ion range > λ_{RT} → improved ablative stabilization.

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.

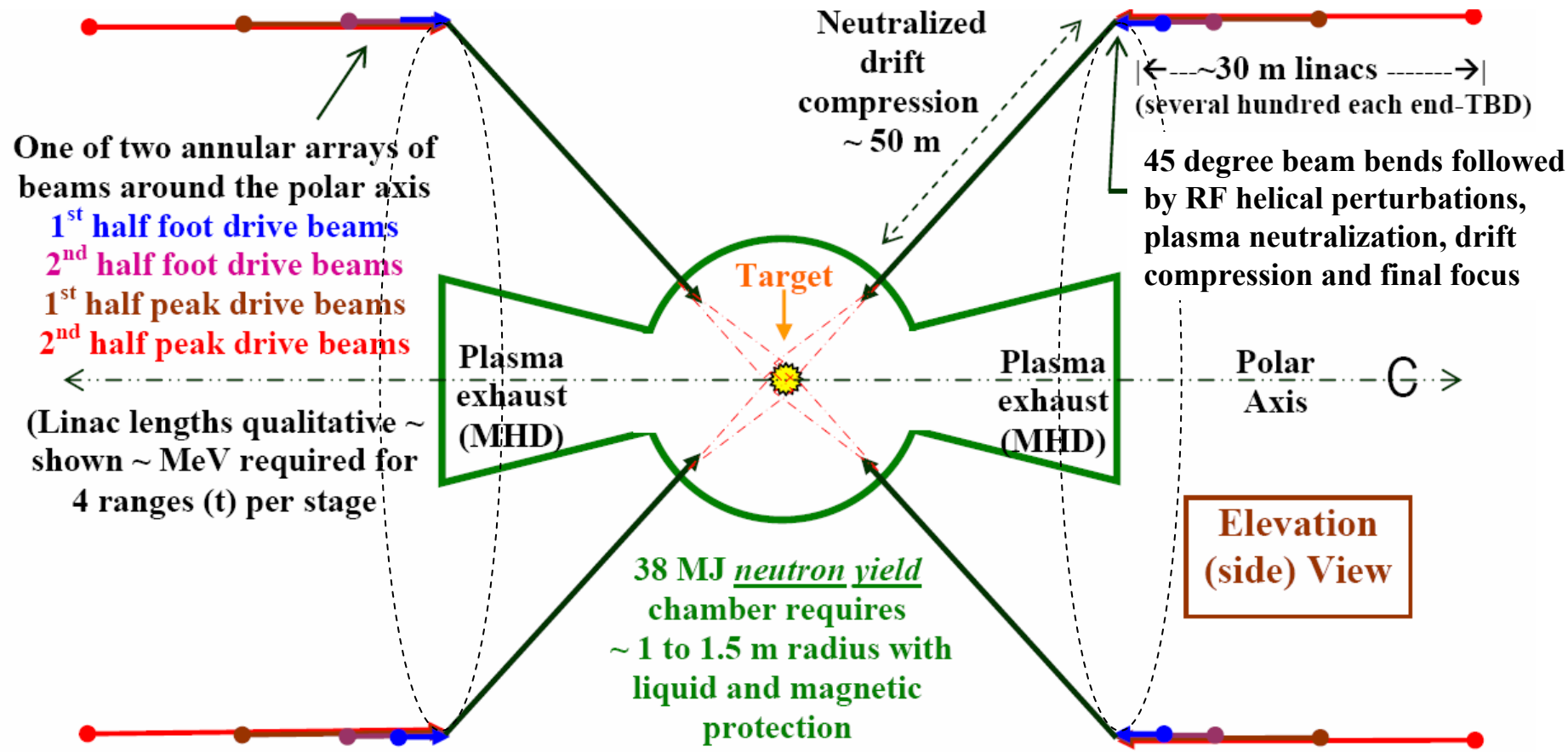
RF wobblers useful for beam smoothing, focus zooming & RT control (GSI, ITEP, PPPL, Utsunomiya U…)



Concept for Heavy Ion Fusion Direct Drive:

- Four stages of drive power, 1 MJ total, 250 TW peak
- DT target gain = 50, driver efficiency x gain =15
- Ramped ion energies at moderate range (~ 100 to 500 MeV Argon)
- Beam spot rotation using RF wobblers for uniformity, R-T mitigation
- Plasma-neutralized drift compression, focus, and chamber as in NDCX

North American porcupine
Erethizon dorsatum

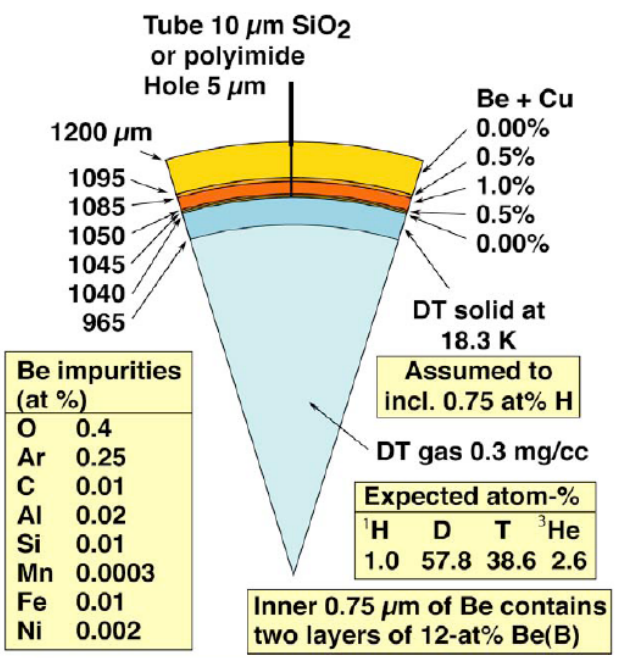


NIF ignition tests planned to start next year could point to the possibility of gain 100 with *200 kJ ion beam energy!*

At <u>equal</u> 15 % coupling efficiency, 200 kJ of ions with the *right range into DT ablators* could achieve the same ignition and fusion yield as the NIF Be capsule with 200 kJ soft x-ray drive.

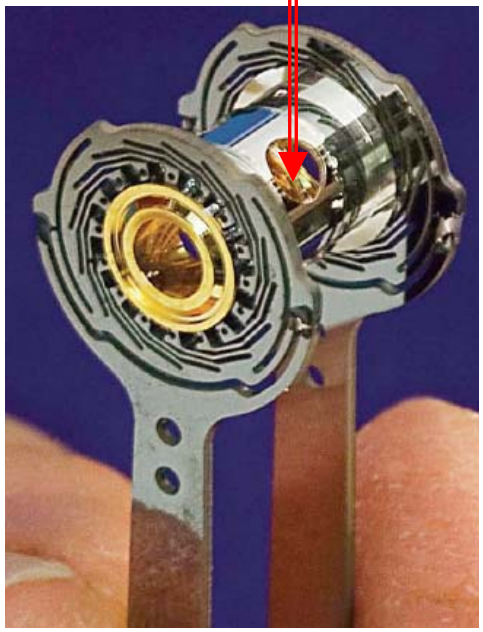
The National Ignition Campaign

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



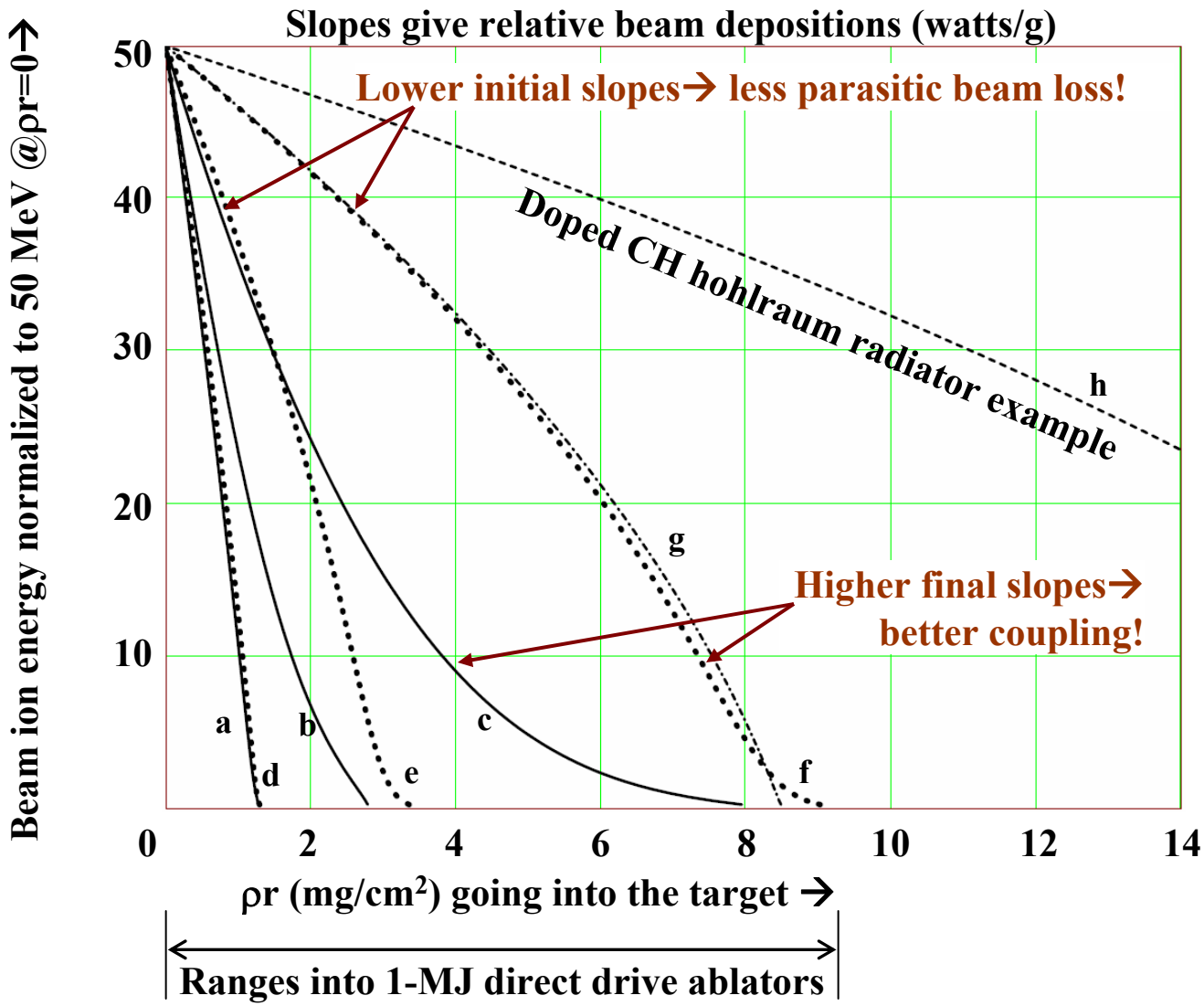
Details in boxes are point-design specifics, not requirements

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



New research opportunities for the Heavy Ion Fusion Science Virtual National Laboratory (LBNL, LLNL, PPPL) + potential new collaborators

The high coupling efficiency (16%) in LASNEX derives from increasing ion range during the implosion. Even higher coupling efficiency is predicted *if we use ramped Argon ion beam energies100 MeV foot→400 MeV peak -next runs*



Legend-all Argon beams

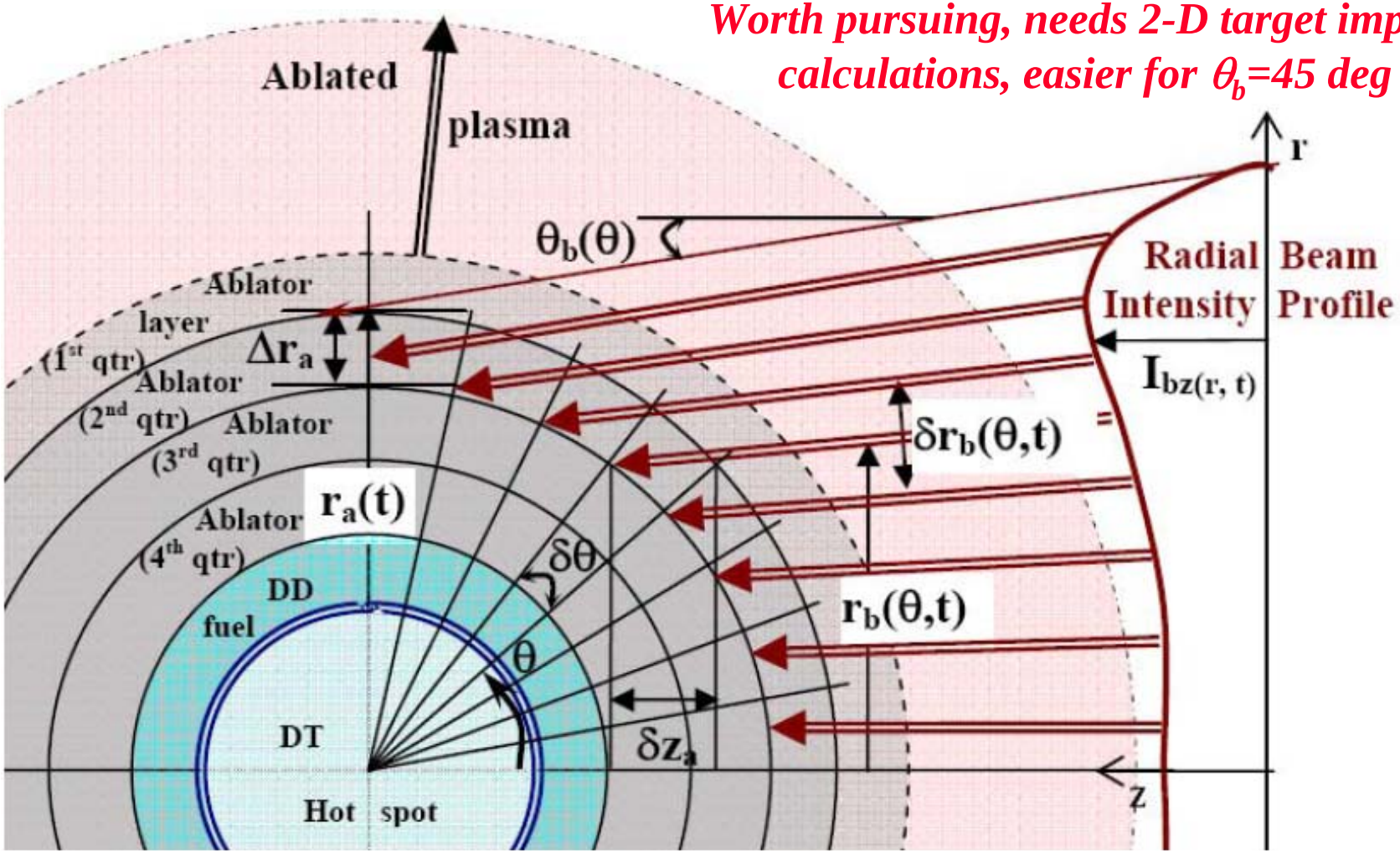
Line	Mat.	E_{beam}	T_e
a	CDT	50	20
b	CDT	50	400
c	CDT	50	1000
d	H	100	20
e	H	200	200
f	H	400	400
g	H	400	20
h	CH	400	200

(MeV) (eV)

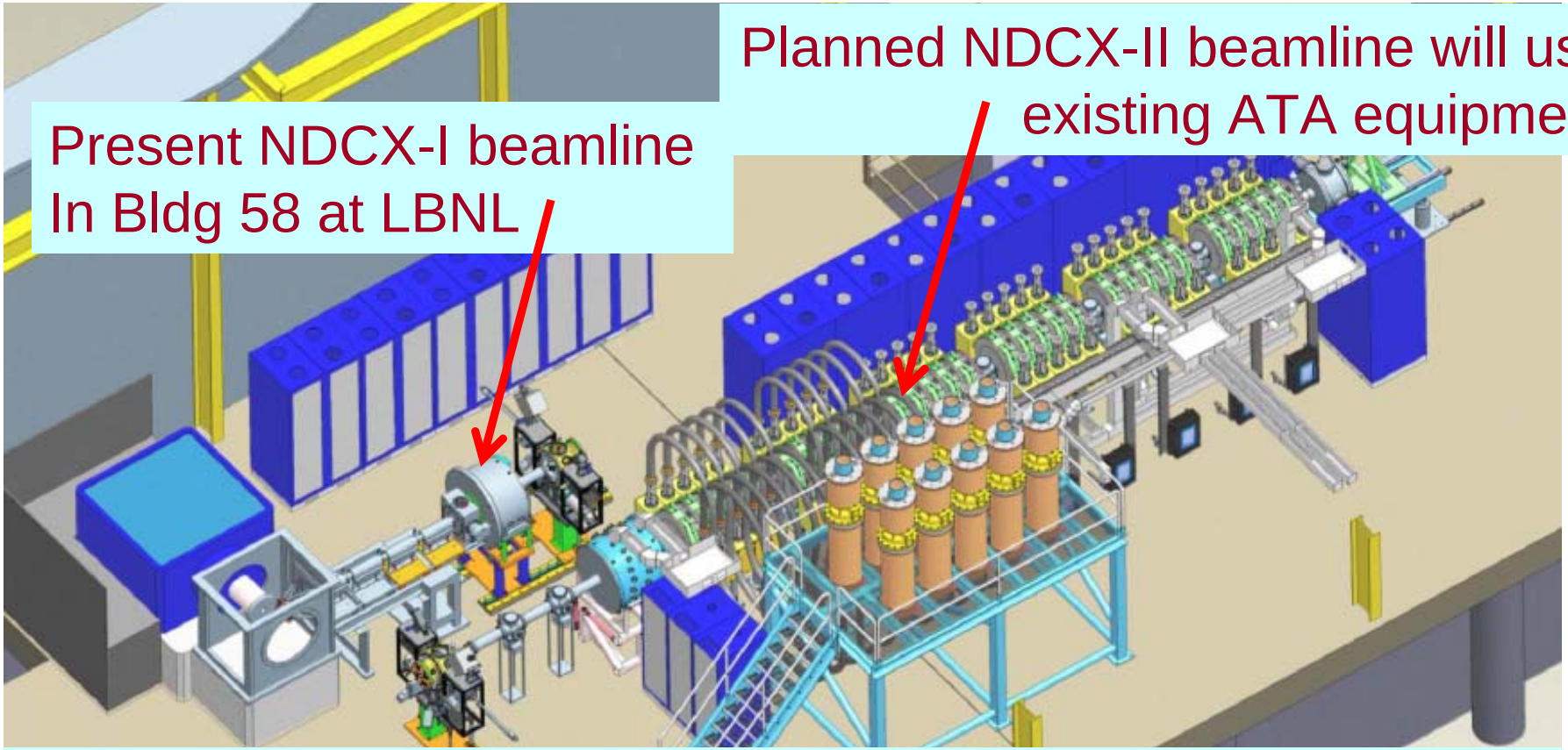
All densities = 0.04 g/cm^3 except case h=0.94 g/cm^3

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 …

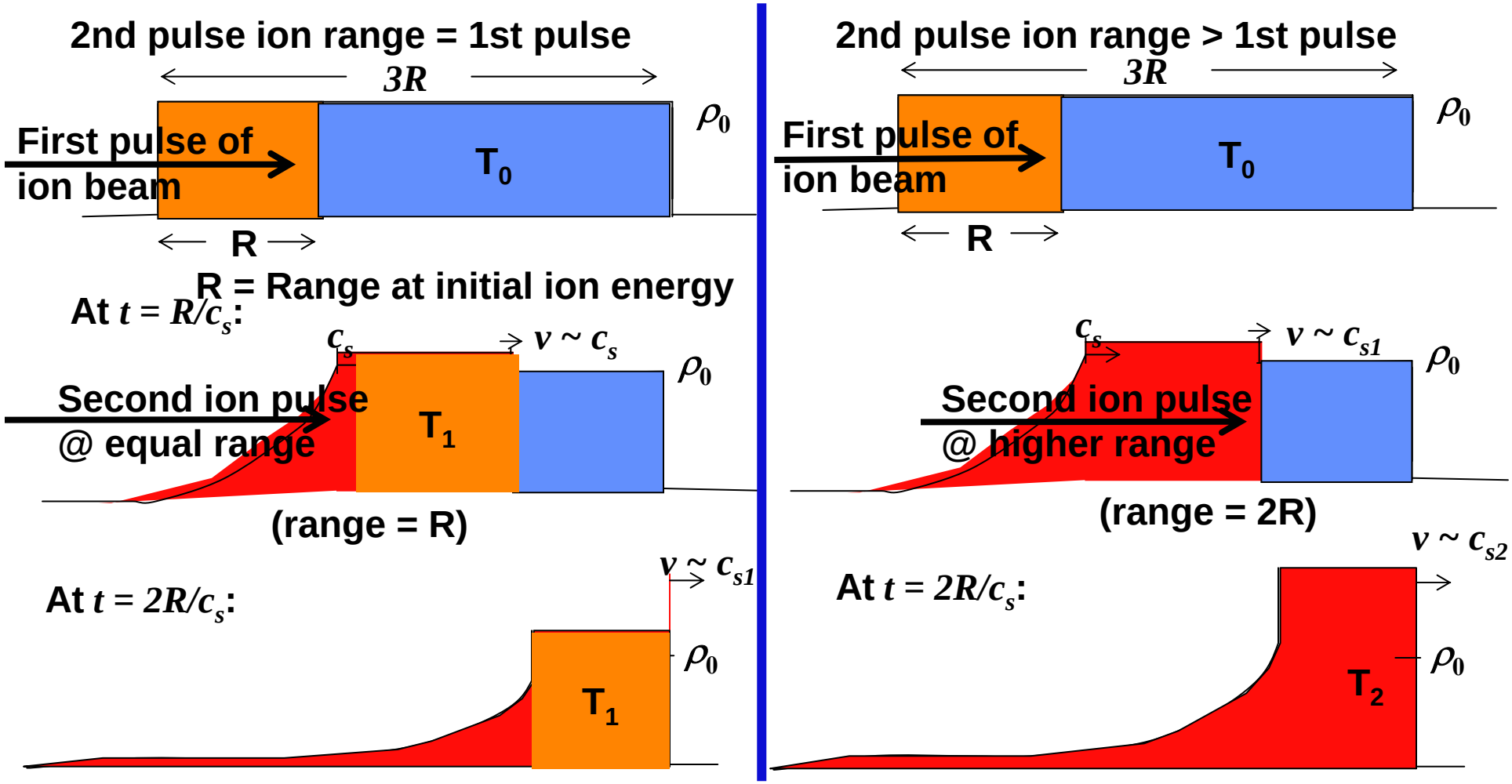


For $5M hardware, we could complete NDCX-II assembly (first operation for initial scaled direct drive experiments) by FY2011, using existing ATA equipment now at LBNL.



The current NDCX-I beamline will continue to optimize beam compression techniques and planar target diagnostics for NDXC-II while NDCX-II is assembled in 09, 10 and 11

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



ρ vs z:

At $t = 3R/c_s$: measure velocity of back of target;

T_0 T_1 $T_2 > T_1$

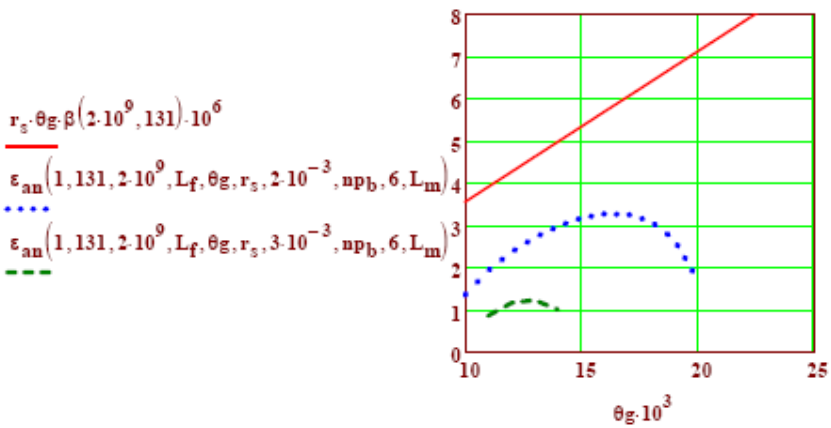
Figure 65 Comparing allowed accelerator emittance (normalized, in mm-mr) for the Snowmass 02 version of RPD (2 GeV Xe^{+1}) (A) versus allowed emittance for the stage three drive of the 1 MJ direct drive target (B).

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)



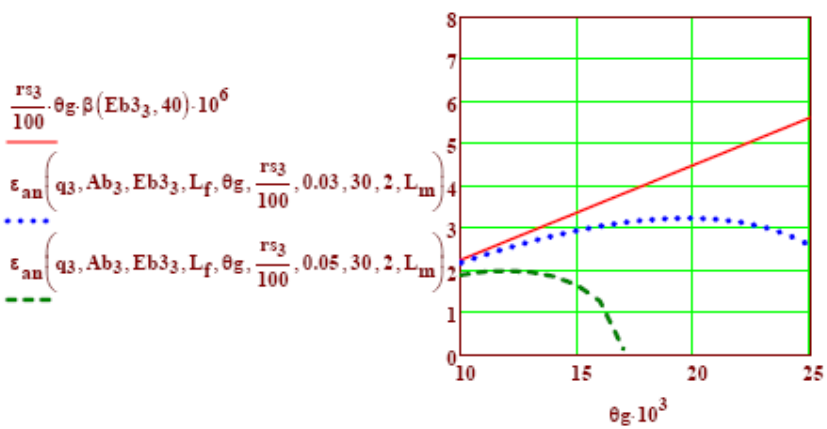
(A) Snowmass 2002 design
<--allowed emittance vs focusing angle (mr) if no plasma net perveance, no momentum spread, and no geometric aberrations.
<--allowed emittance with 0.2% momentum spread

<--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.

Pulsed ECR source for high currents of high charge-state ions for HIF

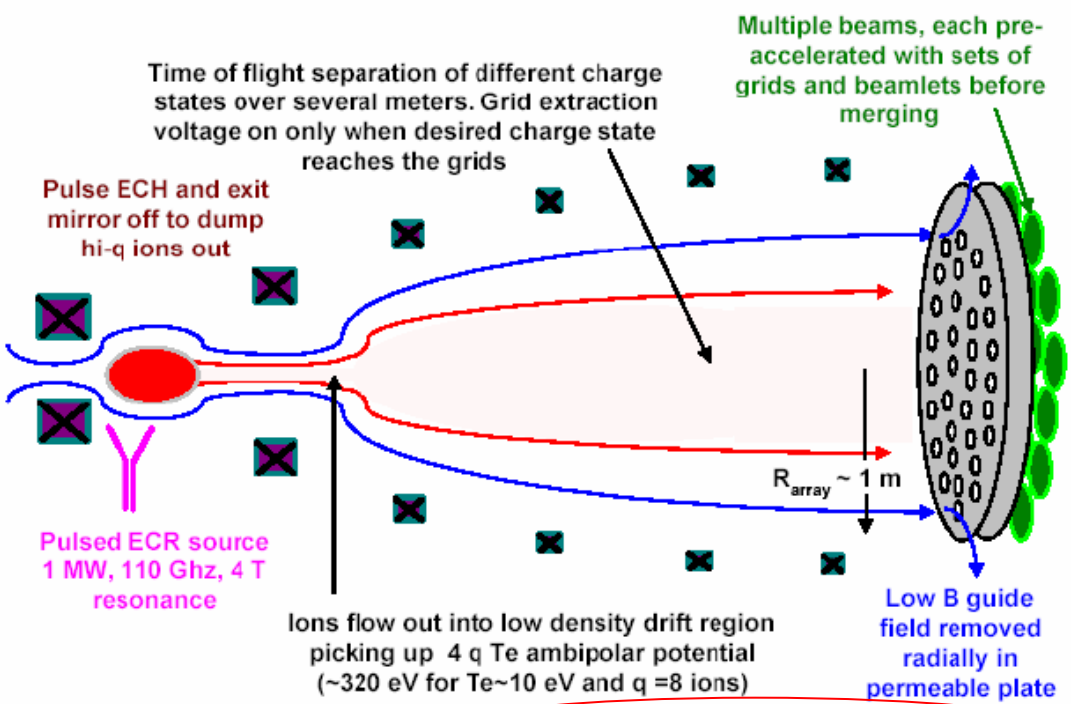


Figure 59. Conceptual hi-q ion ECR source from April 2002 notes with Daniella and Mattaheus Leitner and Joe Kwan, is similar to some Russian sources (see below).
Below excerps from proposal by Skalyga, Golubev (IAP-RAS) send to LBNL in 2002:

"Quasi-Gasdynamic ECR source of plasma with multicharged ions (MCI).
Recent experimental and theoretical investigations carried out in IAP RAS allowed us to develop a new kind of pulsed ECR sources of MCI – quasi-gasdynamic ECR ion sources. On the base of these investigations we propose an ion source pumped by 100 GHz, 500 kW gyrotron with 1 ms pulse duration. Such a quasi-gasdynamic ECR source is able to generate pulsed plasma flows with maximum of the ion charge state distribution and ion current density as shown in Table 1. Typical transvers dimension of plasma flow is 1 cm."

Gas dynamic ECR plasma source	Plasma ion separator	Ion extractor

Carbon	+4	14 A/cm^2
Nitrogen	+5	14 A/cm^2
Oxygen	+6	14 A/cm^2
Argon	+8	11 A/cm^2
Xenon	+14	7 A/cm^2

For details on ion source /injector model see pgs 129 to 132 in the MathCAD doc.

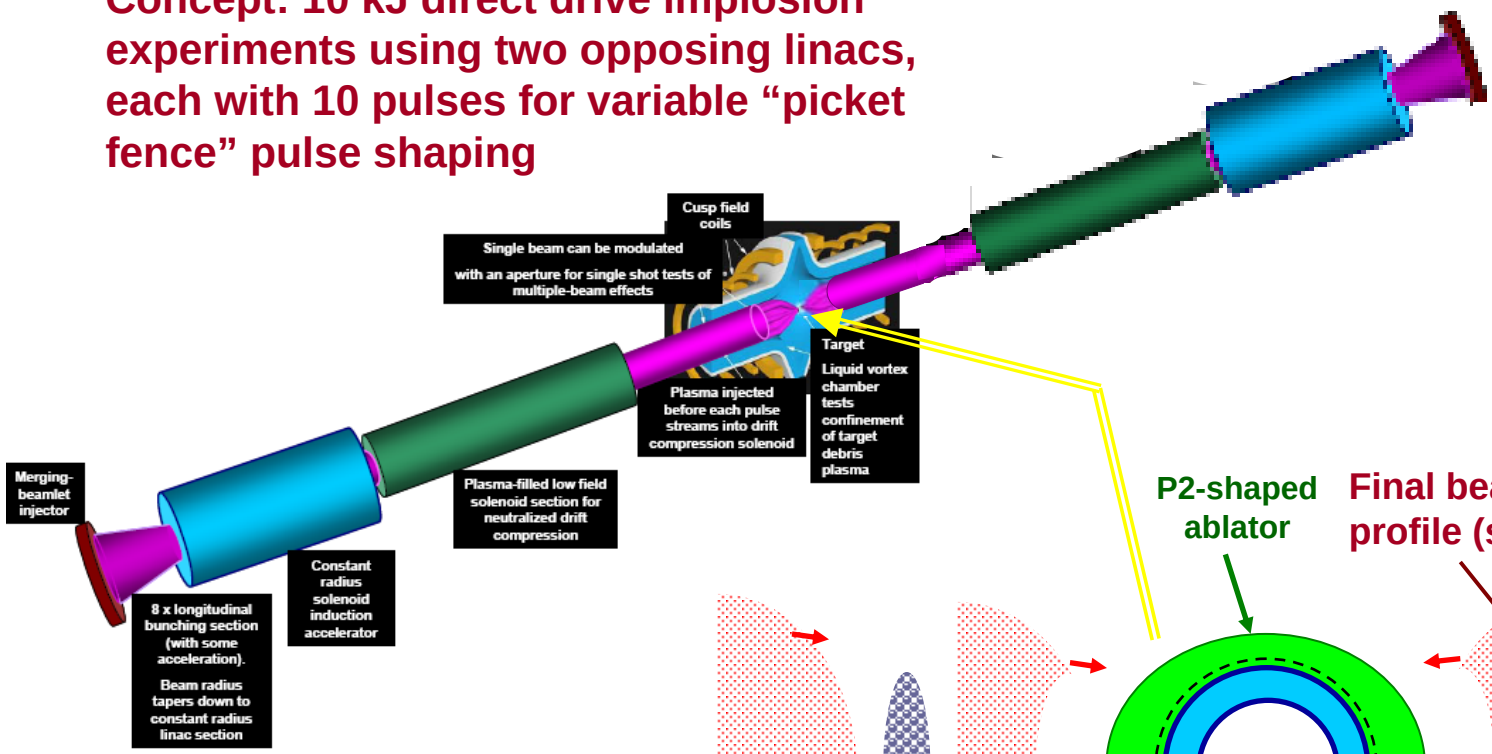
High-q ion injector concept: Marriage of four elements:

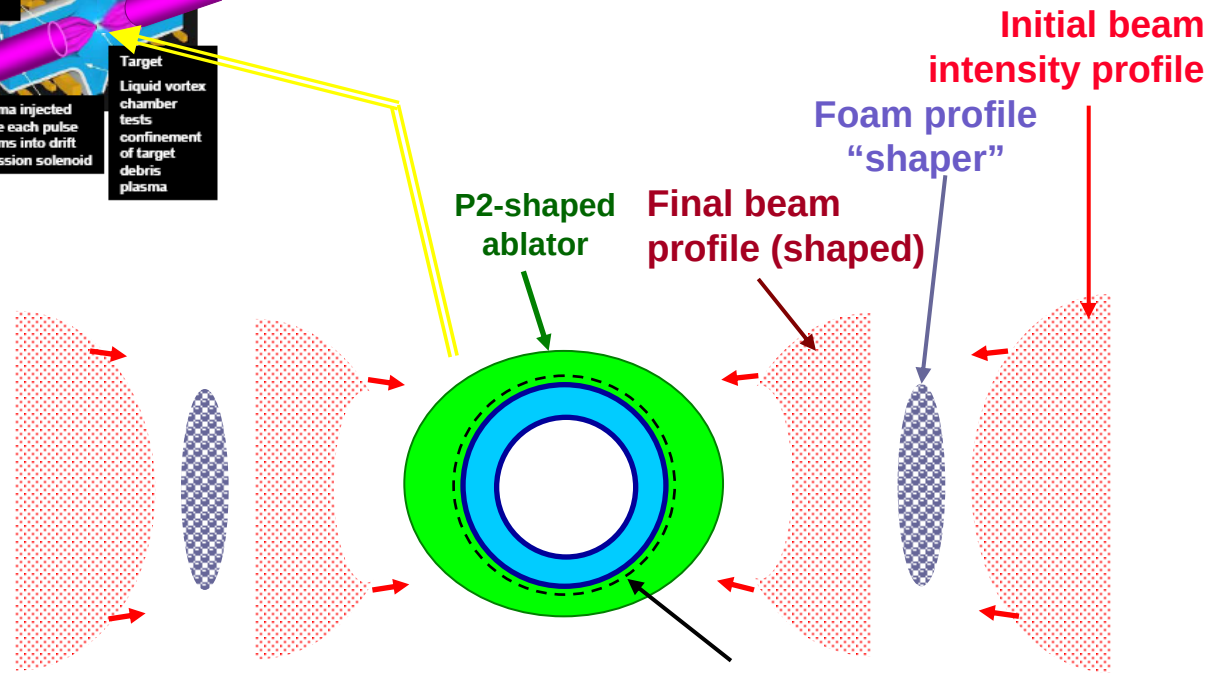
(1) pulsed 10 μs, 1 MW (10 J) gyrotron ECR source of 10^{14} helium-like noble gas ions (Russian style),
(2) time-of-flight separator,
(3)charge separation by mico-grid extractor (an old Kwan LDRD idea) into another Kwan extractor scheme
(4) STS-500-like Einzel lens array to pre-accelerate macro-beamlets of Ne^{+8} to q x 500 kV ion energies before merging into multi-ampere beams.

Note radial expansion of ions cools transverse ion temperature, and taking a slice of the longitudinal distribution extracts a lower $T_{s//}$ effective temperature.

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

Concept: 10 kJ direct drive implosion experiments using two opposing linacs, each with 10 pulses for variable "picket fence" pulse shaping

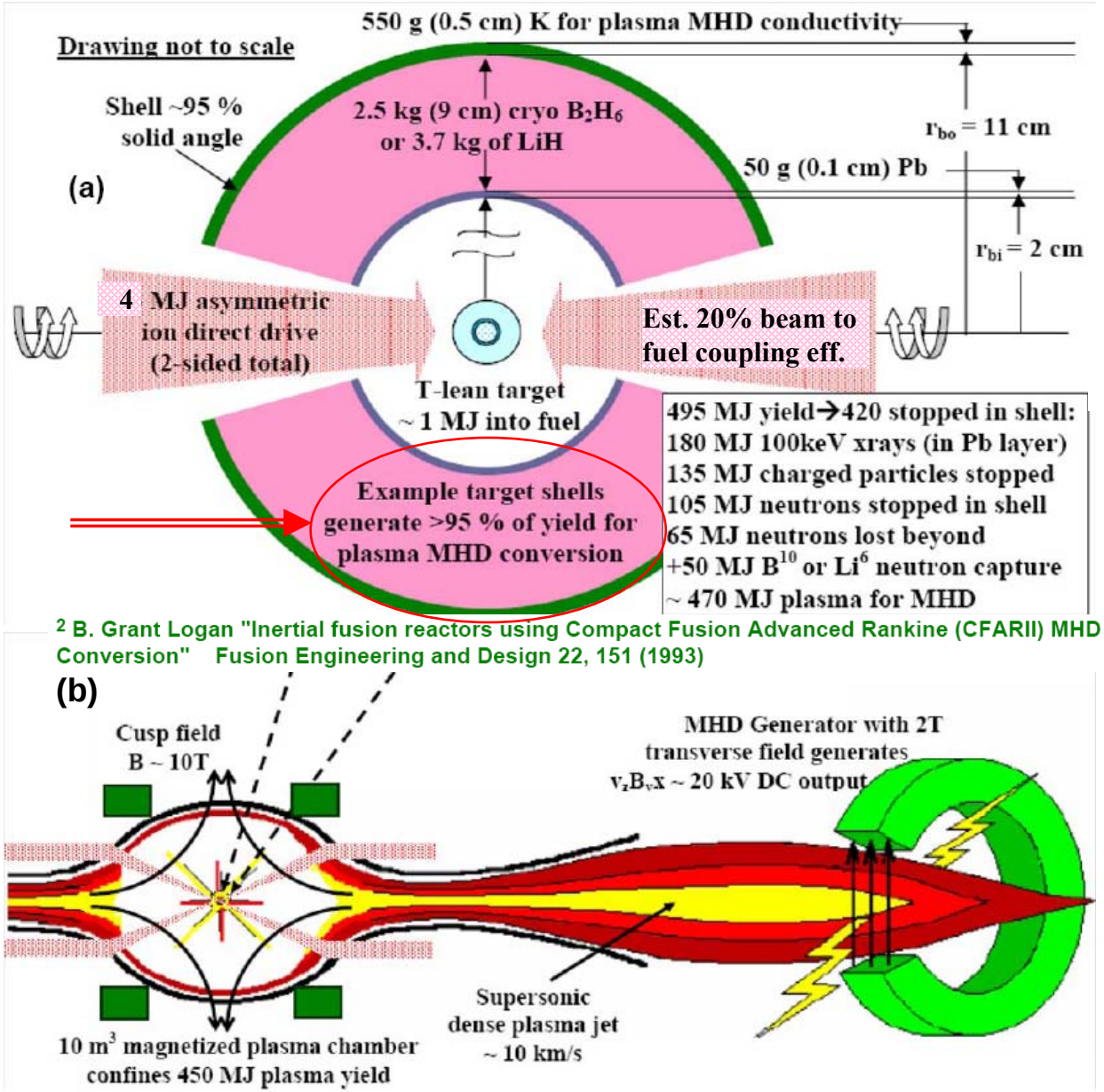




Four "knobs" to control P2 asymmetry with two beams:

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



[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 DT DEMO is a logical step towards an ultimate goal: 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: much further work is needed in many areas…

- More theory and experiments on neutralized beam compression, including beam-plasma instabilities, to understand requirements/constraints for > 20,000 combined compression ratios.
- More implosion calculations in the ramped ion energy, $v_b > v_{eth}$ regime.
- Focusing of high q ions for the direct drive chamber concept, including methods for plasma pre-fill.
- T-breeding, neutron transport and damage lifetime calculations for direct drive HIF chambers.
- Direct drive target fabrication and injection with H2 ablators: target protection during injection into plasma pre-filled chambers: protective coatings and/or sabots may be needed.
- Determining plasma needed for stable compression of high-q ions in the NDC lines, and beam wobbling for direct drive smoothing and RT.
- Scattering loss and MHD stability calculations for high power pulsed ECR ion sources in the Russian gas-dynamic regime-also for NDCX-II.
- WARP simulations of the micro+ macro beamlet extractor approach for high-q ions.
- Longitudinal bunch control during acceleration of high-q ions.

Much more to do → collaborators welcome!

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*

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.**
- **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 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, Wayne Meier, 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)