Heavy Ion Fusion: Options and Strategy

Preview: Slides gleaned from several HIFS-VNL seminars and discussions since the last VNL PAC regarding heavy ion fusion R&D strategy for the upcoming NAS study.

A detailed HIF R&D roadmap is still being formulated. Presentations for the two NAS panels can be decided after the panel agendas become available.

A new IFE program should include heavy ion fusion R&D because of long-recognized HIF advantages:

(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.** ***Advantage of being able to build upon a credible high energy particle accelerator experience base.***

(b) **Thick-liquid protected target chambers with 30 year plant lifetimes, compatible with indirect-drive target illumination geometry to be tested in the National Ignition Facility.** ***Minimizes risk from a long fusion materials development program outcome.***

(c) **Focusing magnets for ion beams avoid direct line-of-sight damage from target debris, neutron and gamma radiation.** ***Detailed studies show shielded final focus magnets can last for many full power plant years of operation.***

(d) **Because heavy ions can penetrate metal cases surrounding cryogenic-DT fuel, can drive targets efficiently, and injected HIF targets can be protected against hot IFE chamber gas.** ***Facilitates target injection.***

(e) **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).** ***Molten salt (HYLIFE-II type) chambers cost < \$10 M / GW_{th} → multi-unit plants sharing one driver, direct conversion of neutron energy at high yields → < 3 cts /kW_ehr***

The National Ignition Facility will soon reach unprecedented fuel compressions and neutron yields. Hot spot ignition and propagating fusion burn @ convergence ratios > 30 and fuel densities > 1000 g/cm^3 :

Truly a grand challenge!

→ *We will learn much very soon!*

Heavy ion fusion can use a variety of driver, focusing, chamber, and target options:

Accelerator
- Induction Linac
- RF Linac
- RF Linac + Storage Ring/ Synchrotron
- Induction Recirculator
- Dielectric Wall Accelerator

→

Focusing
- Ballistic, Neutralized
- Ballistic, Vacuum
- Self Pinch, 2-stage

→

Chamber
- Thick-Liquid-Protected Wall
- Thin-Liquid-Protected Wall
- Solid Dry Wall + Gas Fill
- Granular-Solid Flow Wall

→

Target
- Indirect Drive, Central Hot Spot Ignition
- Indirect Drive, Fast ignition
- Direct Drive, Central Hot Spot Ignition
- Polar Direct Drive + Shock Ignition
- Hydro Drive +Fast or Shock Ignition

HIF R&D effort has been mostly on the blue- type options in this chart.
Induction or RF drivers with > 100 beams might apply to any target option.

A balanced IFE research program includes

Target physics & design

Direct and indirect drive targets for power plant and for an intermediate target and accelerator physics facility

Symmetry requirements, beam pointing

Stability

Accelerator physics & driver design:

Multi-beam ion sources, injection, matching

Focusing elements: magnetic, electric quads, solenoids

Halo formation and control

Acceleration

Neutralized & un-neutralized drift compression

Achromatic focusing systems

Time dependent chromatic correction

Final focusing, reactor interface, design

Reactor and driver interface

Tritium breeding

Radiation shielding

Liquid protection

Enabling technology

Pulsed power

Insulators (eg: glassy ceramics, embedded rings)

Superconducting materials (Nb3Sn)

Quadrupole, solenoid design

Focusing arrays

Reactor materials and components

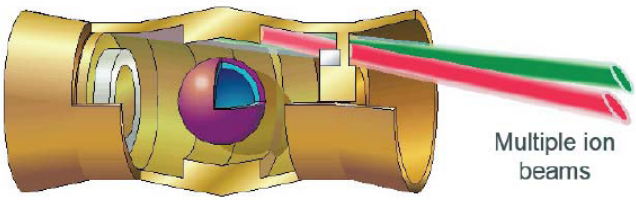
R&D for driver, chamber, and target fabrication are governed by target design requirements.

For prudent risk management, HIF should not be limited solely to central hot spot ignition.

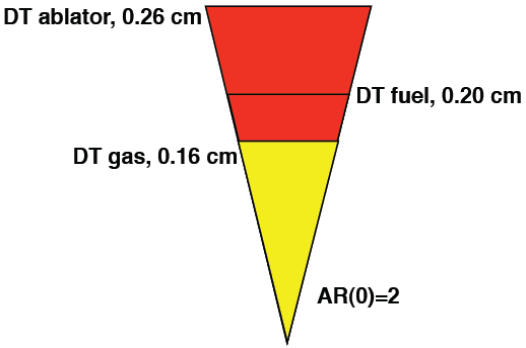
There are several classes of HIF targets to consider with different risks and R&D paths.

There are three options for heavy-ion fusion targets:

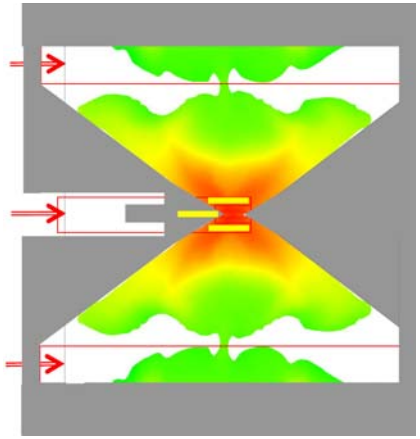
1. **<u>Indirect drive (2-sided hohlraum)</u>** ***2-D Lasnex design (2002):*** **7 MJ, 3→ 4 GeV Bi^{+1} , gain 68.**
   Two-sided illumination.



2. **<u>Heavy-ion direct drive</u>** ***1-D Hydra design (2010):***
   3.6 MJ, 0.22 → 2.2 GeV, Hg^{+1} ion beams, gain 150.
   Future 2-D design planned for polar drive illumination, with shock ignition assist.



3. **<u>X-target hydro-drive</u>** ***2-D Hydra design (2010):***
   3 MJ compression+3 MJ ignition, all 60 GeV U beams, gain 50. One-sided illumination (paper in progress)



→All three options are intended to use multiple-beam linac drivers with thick-liquid-protected chambers to mitigate material neutron damage risks.

All prudent HIF development plans have called for a series of R&D steps with increasing beam energy and cost, each step addressing key requirements and risk issues for the next higher cost step:

1. A step of ~10 MV, 50 M$ scale addressing integrated beam injection, acceleration, drift compression and focusing to a target plane (ILSE, IBX, IB-HEDPX)---lets call this step IBX for short.
2. A step of ~0.2 to 1 GeV, 500-700 M$-scale addressing driver-scale beam brightness, compression and focusing with multiple beams capable of heating targets to ~100 eV. [HTE, IDF, IRE, Heavy Ion Driven Implosion eXperiment (HIDIX)]
3. A step of 3 to 20 GeV, ~3 B$-scale, capable of demonstrating >~ 100 MW of average fusion power for sustained periods (days to weeks) [EPR, ETF, Heavy-ion fusion test facility (HIFTF)]

Risk management: The National Ignition Campaign (NIC) experience makes clear that achieving ignition will require mastering precision beam symmetry, balance, pointing and pulse shaping with laser techniques that will not all carry over to heavy ion driven targets→ Given high cost of Step 3, acceptable risk requires Step 2 to address *ion-specific implosion symmetry and pulse-shaping* needed for Step 3→ In turn, Step 1 must address the key beam manipulations that Step 2 will require.

Because of target risk, heavy-ion-driven 10 kJ scale implosion and single shot MJ ignition experiments should precede any full ETF phase

Modified 2002 Snowmass logic for HIF: NIF + IRE/HIDIX + ignition tests qualify full HI-ETF

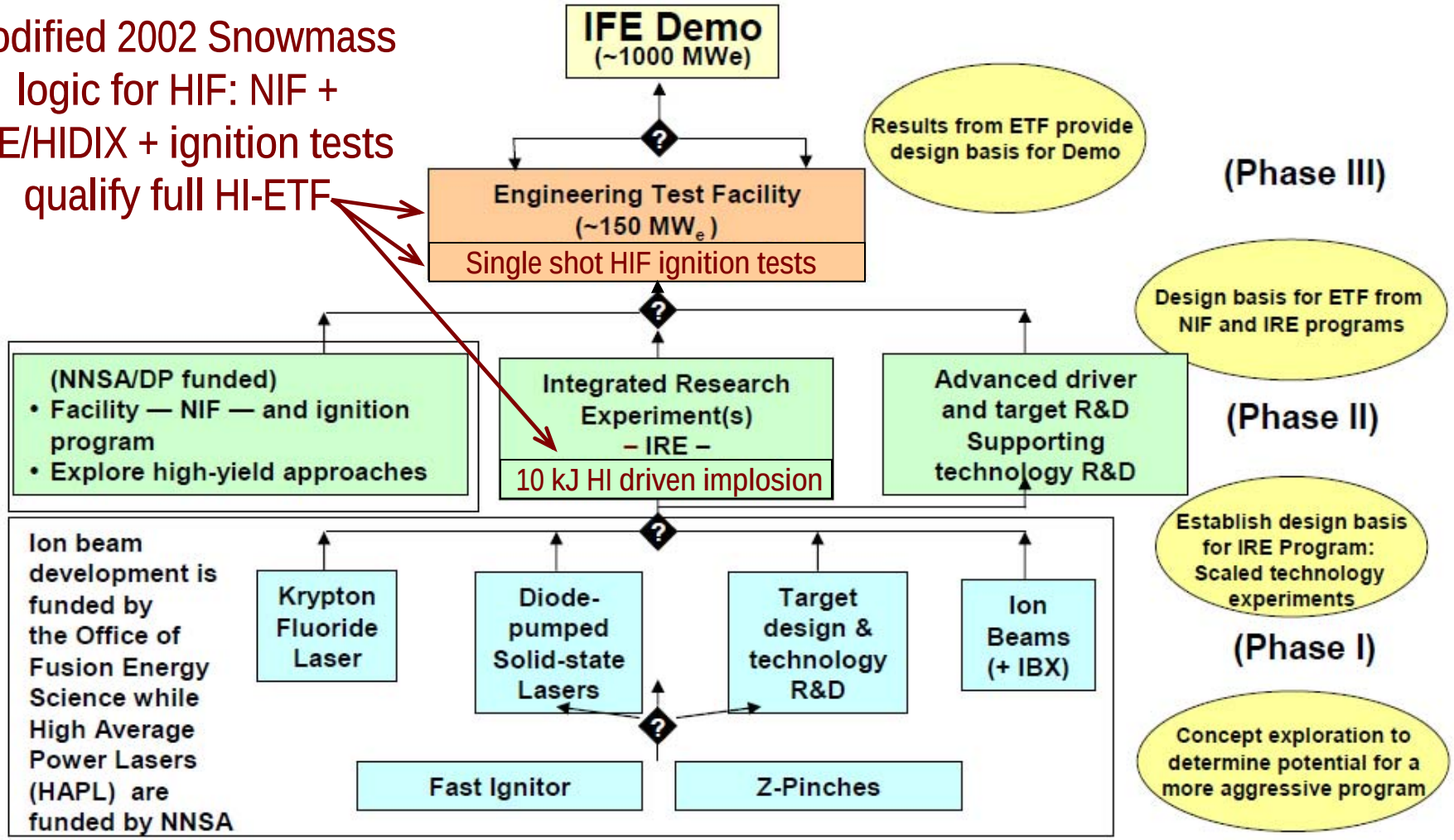


Figure 3. The Inertial Fusion Energy Roadmap **(2002 Snowmass Executive Summary for IFE)**

Regarding realistic budget/schedule for HIF-IFE…

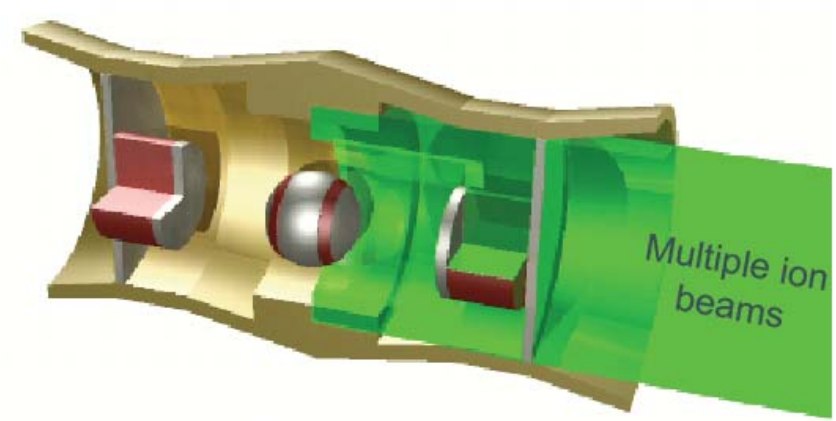
→ **An IRE-scale accelerator (300 m long, multiple beams (20 to 40), 10-30 kJ total beam energy, ~500 M$ in 2015 $) will *not* fit within the first five year phase of the envisioned national HIF program.**

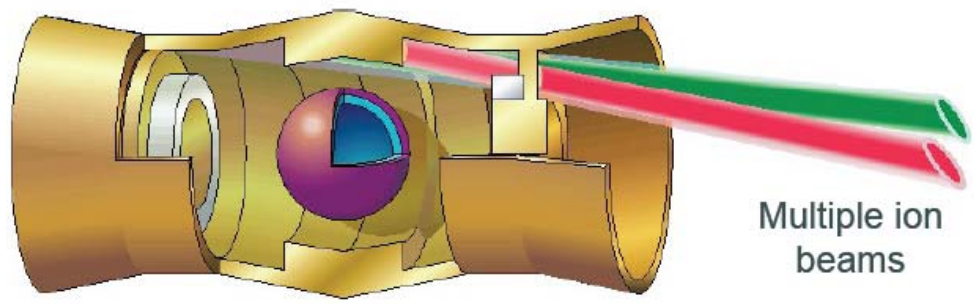
→ **IB-HEDPX, because its lower cost ~ 50 M $, and the fact that it can be built quickly in <3 years by adding all 50 ATA modules to an eastward rail and building annex extending east of NDCX-II, could fit *and operate* within the Five Year Phase I.**

→ **Any IRE-scale step following a successful IB-HEDPX must do more than just prototype driver efficiency, durability, and cost/J: to provide credibility to a HFTF-ETF, it must support heavy-ion driven implosion experiments of 10 kJ scale: Heavy-Ion-Driven Implosion Experiment (HIDIX). The IRE/HIDIX needs gas/e-cloud control data to be obtained from HCX-II operated at 5 Hz.**

HIF option: indirect drive two-sided hohlraum

A: HIF target option heavy ion driven hohlraums (e.g., Robust Point Design -M. Tabak and D. Callahan, LLNL)





"Hybrid" target

Beam spot 3.8 mm x 5.4 mm

6.7 MJ beam energy

Gain = 58

E_{beam} = 3 – 4.5 GeV, Pb^+

"Distributed Radiator" target

Beam spot 1.8 mm x 4.1 mm

5.9 MJ beam energy

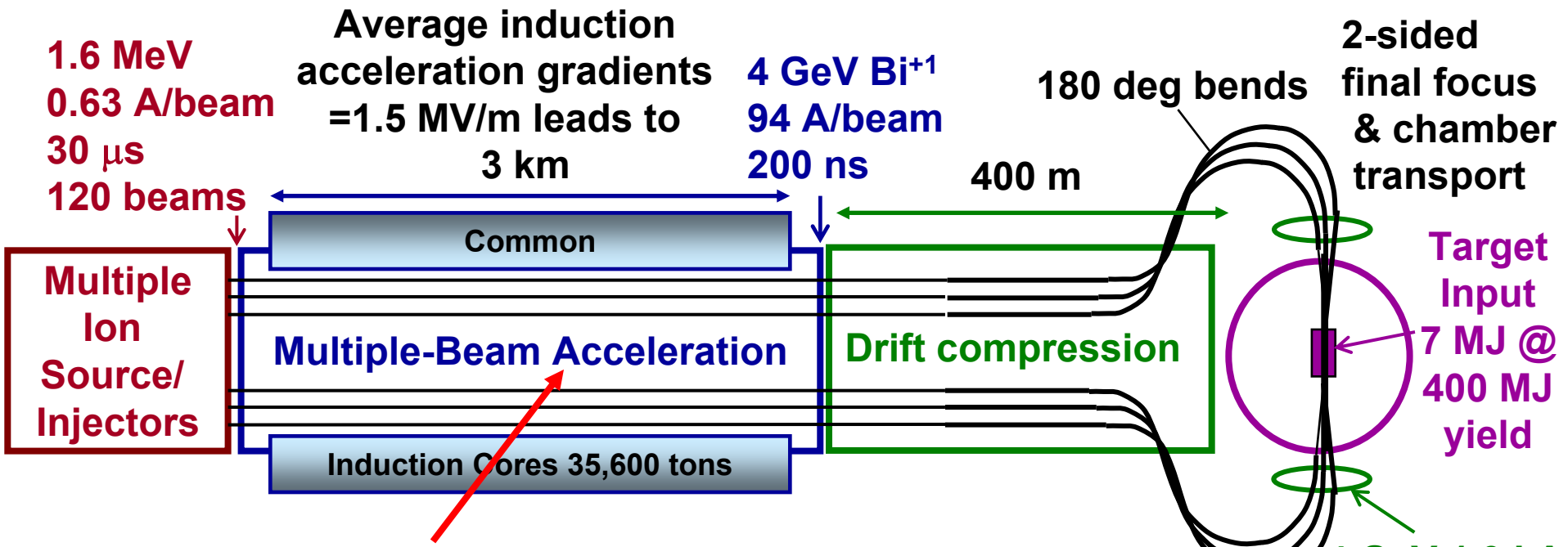
Gain = 68,

E_{beam} = 3.3 - 4 GeV, Pb^+

D. Callahan et al., Laser and Particle Beams, **20** (2002)

The last heavy-ion-fusion point design, based on a 2-D distributed radiator hohlraum target design (RPD), was published in 2003.

(Caveat: the RPD did not address 5 Hz gas/e-cloud effects in the linac, nor beam emittance with space charge & tilt in the drift/bend lines.)

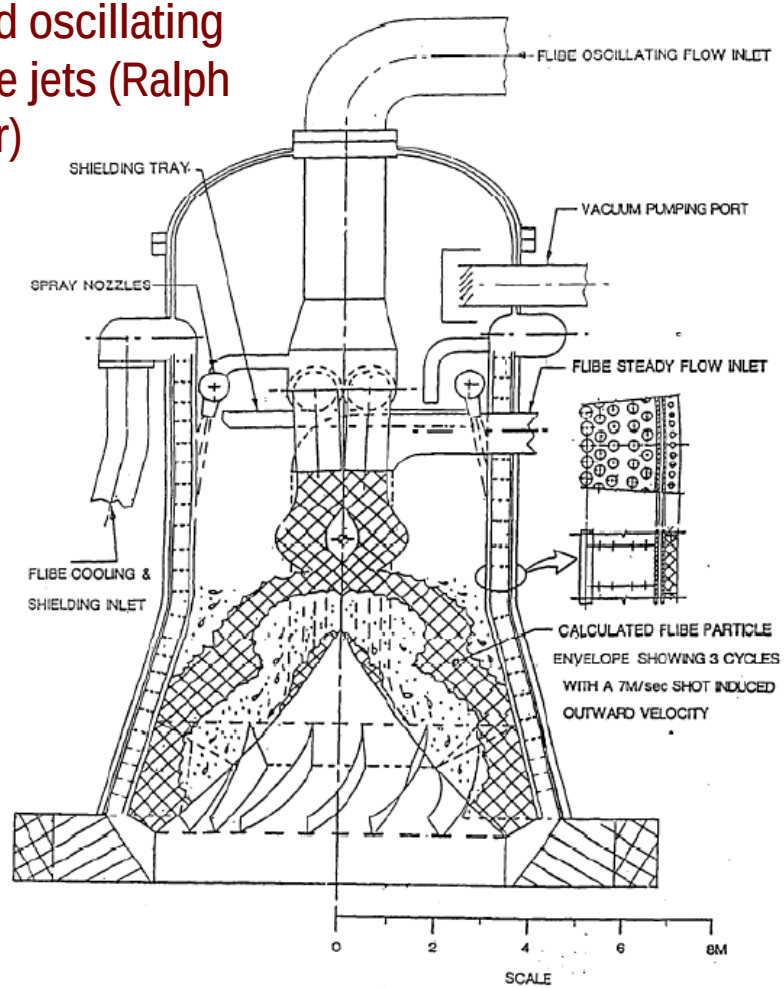


Compact quad-array transport $I_{tot} \sim (\text{core } R_{ic})^2 a_b^{-1}$ → enables more beams in one linac → induction linac efficiency > 30%

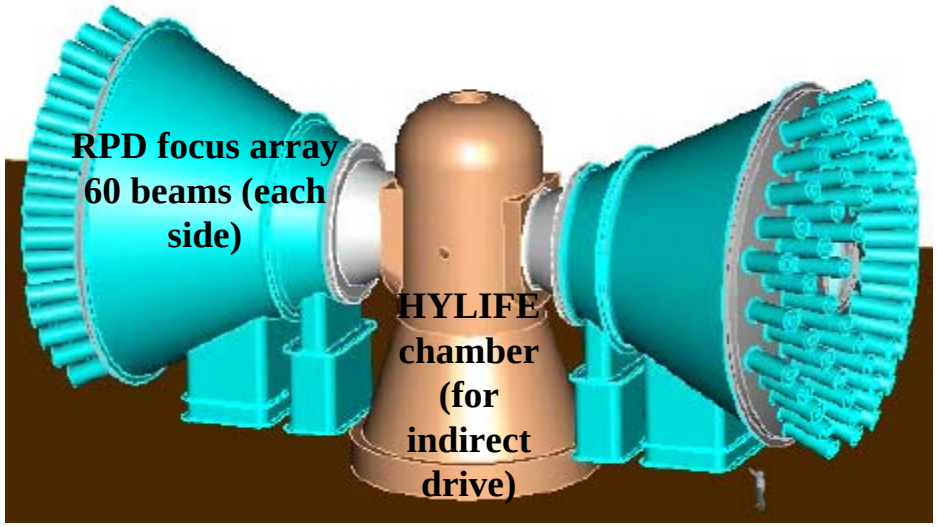
10th-of-a-kind cost 2.8 B$ (driver cost) estimated-see Ref. - S.S Yu, W.R. Meier et al., *Fusion Science and Technology*, **44**, No.2, 266 (2003).

Thick liquid protected chambers lower R&D cost compared to solid first wall materials R&D. Ion beam propagation and final focusing magnets are compatible with high temperature Flibe vapor.

HYLIFE-II chamber used oscillating Flibe jets (Ralph Moir)



Double sided hohlraum illumination requirements led to 60 beams X 400 m X two-sides of drift/180 deg bend transport lines between the linac driver and the target chamber.



Our Snowmass 2002 plan addressed all HIF-IFE technology areas in the requested NAS review for indirect drive targets with illumination geometry similar to NIF:

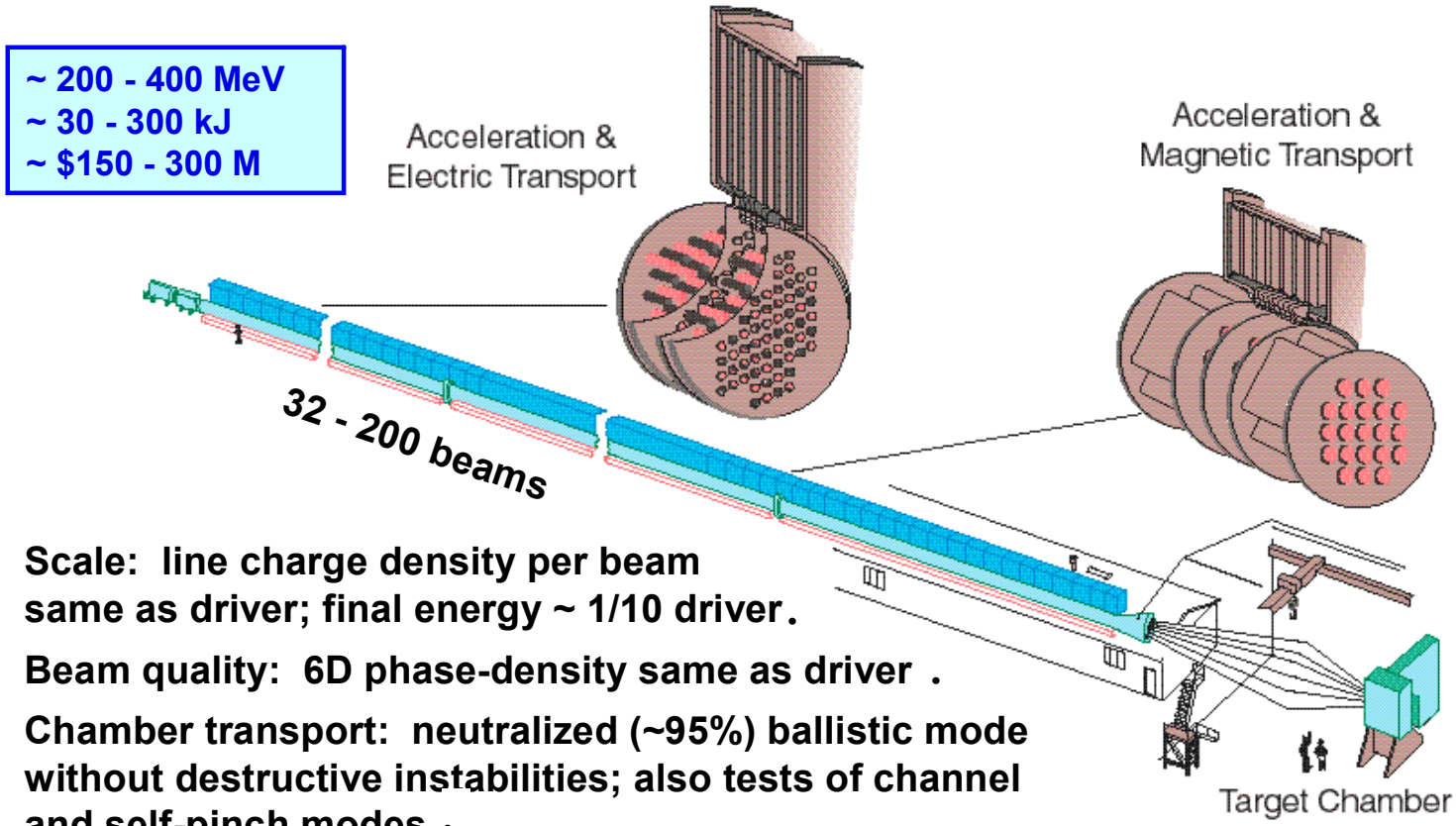
*Heavy Ion Fusion White Paper -- Strategic Plan and Research Needs for Heavy-Ion Fusion Energy Development: An Integrated Research Program, G. Logan et al.,(2002)

Fiscal year	04	05	06	07	08	09	10	11	12	13	14	15	16
1. Accelerator R&D	24	31	34	34	34	37	37	37	80	80	80	80	80
Integrated modeling	3	4	4	4	4	4	4	4	5	5	5	5	5
Supporting science	10	7	7	7	7	7	7	7	7	7	7	7	7
IBX construction		10	14	14	12								
IBX operating						14	14	14	7	7	7	7	7
IRE construction									55	55	55	55	55
Enabling accelerator	8	7	6	6	6	6	6	6	6	6	6	6	6
Advanced accelerator	3	3	3	3	5	6	6	6					
2. HIF target physics	3	3	3	3	3	3.5	3.5	3.5	6	6	6	10	10
HIF target design	1.4	1.4	1.4	1.4	1.4	1.5	1.5	1.5	2.5	2.5	2.5	5	5
HIF target exps.	1.6	1.6	1.6	1.6	1.6	2.0	2.0	2.0	3.5	3.5	3.5	5	5
3. HIF target/chamber	8	8	8	8	8	9.5	9.5	9.5	14	14	14	20	20
HIF target fab/ inj	4	4	4	4	4	5	5	5	9	9	9	12	12
HIF chamber	4	4	4	4	4	4.5	4.5	4.5	5	5	5	8	8
Total HIF R&D budget	35	42	45	45	45	50	50	50	100	100	100	110	110

A near-term 5yr plan for IB-HEDPX + other VNL R&D for HIF for NAS might resemble this dotted section of the 2002 plan, moved forward 8 years (not yet any IRE)

We are re-evaluating the role of the heavy-ion Integrated research experiment (IRE) to include 10 kJ scale implosion target experiments

The figure below depicts an earlier concept presented at Snowmass 2002 for a development accelerator called the Integrated Research Experiment. Such a driver is needed to do Gekko-XII or Omega-scale (10- kJ-scale) heavy-ion-driven implosion experiments (HIDIX).



Scale: line charge density per beam same as driver; final energy ~ 1/10 driver.

Beam quality: 6D phase-density same as driver .

Chamber transport: neutralized (~95%) ballistic mode without destructive instabilities; also tests of channel and self-pinch modes .

Chamber technology: test driver/chamber interface .

Target temperature: 50 - 100 eV.

The HIDIX requirements for hohlraum drive are reproduced below from the RPD 2003 final publication

This "large-angle distributed radiator target" (illustrated in Fig. 1) is driven by ion beams that enter in four cones at angles of 6, 12, 18 and 24 degrees. Target physics considerations (i.e. radiation symmetry) require that the beams in the early part of the pulse shape come in at the shallowest angles.

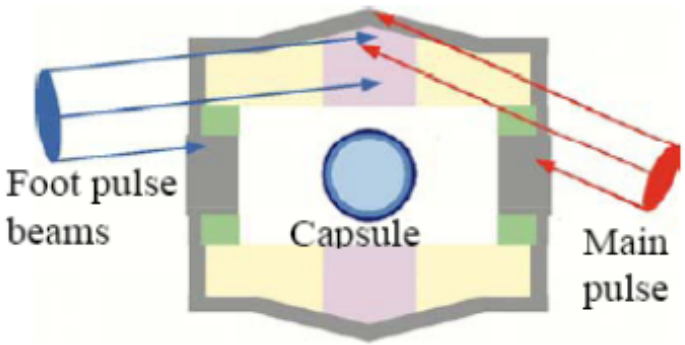


Fig. 1 Large-angle distributed radiator target.

Two beneficial side effects came from this requirement. First, the shallow angle foot beams can have a 30% larger beam spot size than the large angle main pulse beams (2.3 mm vs. 1.8 mm). This is helpful for beam focusing since the foot beams do not benefit from the extra neutralizing plasma near the target created by photoionization. Second, the difference in the ion kinetic energy between foot and main pulse beams was reduced (3.3 GeV foot and 4 GeV main vs 3 GeV foot and 4 GeV main) due to the longer path length in the converters for the main pulse beams.

These requirements call for a HIDIX linac @ 3.3 GV, 3 km length, with 48 beams delivering 1.77 MJ of foot beam energy, and drift lines directing 24 beams to each side of the target. This HIDIX example would cost ~ 0.6 that of RPD, or about 2 B $ total driver cost, using the IBEAM systems code. The spot size for the foot beams was barely met with 6 meter focal lengths at 3.3 GeV for Bismuth ions, so lower mass ions for shorter, lower voltage linacs cannot be used for that focal length (we tried Xenon ions at 2 GeV and failed). A shorter focal length, eg., 2 m for HIDIX might allow use of 1.7 GeV Xenon, reducing length and cost by 40%, or, the number of foot beams increased to >100 to keep the same focal length and beam perveance at final focus.

We need to find a way to get IRE/HIDIX beam spot sizes down to < 500 micron in radii in order to reduce the energy and cost required to test ¼-scale hohlraum ion drive symmetry

Table I. Beam and Pulse Shape Requirements

Block	No. of Beams	Power, TW	Pulse width, ns	Energy, MJ
A (foot)	16	70	6.5	0.46
B (foot)	16	20	38.3	0.77
C (foot)	16	53	10.1	0.54
D (main)	24	120	13.7	1.64
E (main)	48	388	9.3	3.61

III. DRIVER

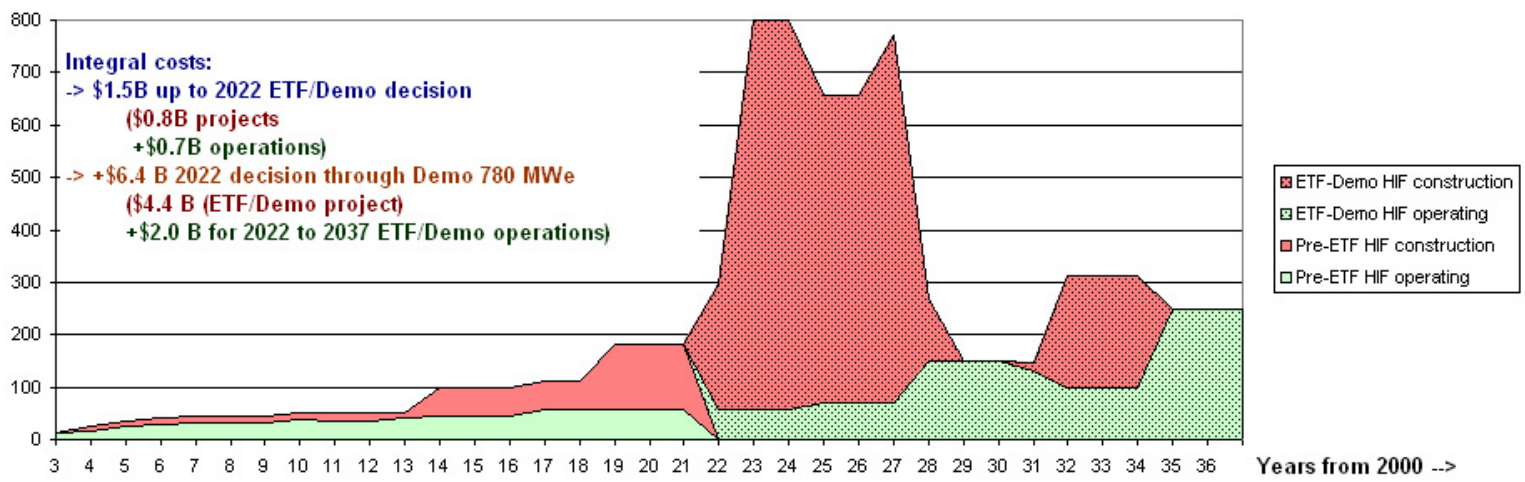
Snowmass 2002 HIF development plan for the FESAC Dev-Path Panel

(Slide presented Jan 13,2003 to FESAC Fusion Dev-Path panel)

ETF/DEMO cost based on $2.8 B RPD driver

Years - 2000	3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47
National ignition facility	HIF-relevant indirect-drive target physics
HIF (Pre-ETF)	^Indirect-drive ignition
Integrated beam experiment	5 MeV; Integrated compression and focusing; [$70 M]
Z ablation/target exps	^Source-to-target beam physics
HIF-IRE accelerator / focus	450 MeV; Focusing + 1/4 scale target exps; [$300 M, including 30 M R&D + 30 M chamber/target system]
Hydraulics integ. test facility	HIF-specific; 1/4 scale hydraulics/clearing rate tests; [$10 M]
Flibe integ. loop test facility	Generic, 1/2 HIF; Flow/chemistry; ^ Accelerator validation; [$6 M / 2]
Flibe chamber test facility	Generic, 1/2HIF; Vapor/plasma condensation; [$6 M / 2]
IFE target test facility	Generic, 1/4 HIF; target sys R&D; Indirect drive target fab/injection tests; [$40 M / 4]
ETF / Demo (if HIF selected)	^Liquid chamber and HIF target validation
HIF-ETF driver / target tests	5.5 MJ induction linac driver and target testing; 4 GeV; Target gain (0 to 280 MJ); [$2.64 driver+.35 bldgs+.26 target = $3.25 B)
Integrated chamber expts.	"Cold" (no-yield) Flibe chamber and injection testing; No-yield chamber exps; [$ 0.53 B]
Fusion power technology	Low fusion power (450MWf) accelerated chamber testing; | Low power testing @ 50 MJ; [$ 0.26 B]
Demo commerical potential	Demonstrate economic and environmental potential; ^ETF/Demo decision; add BoP; 450 MWf-->1.8 GWf power demo; [$ 0.71 B]
	^HIF-high-gain; ^DEMO power >780 MWe
Supporting HIF Program	Target design/fab/injection,HIF target physics on Z&NIF, small beam experiments, theory/simulation, chamber dynamics, enabling lower cost/innovative technology
Key	Design and R&D; Construction; Operation; Program; ^Key decision points; [Facility costs-TPC, in 02$]

Total annual HIF program cost including facility constructions- based on RPD multi-beam MQ linac, q/A =1/200



HIF option:
Direct drive, polar geometry
(may need shock ignition)

We revisited heavy ion direct drive (ablative rocket regime) in 2008

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

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

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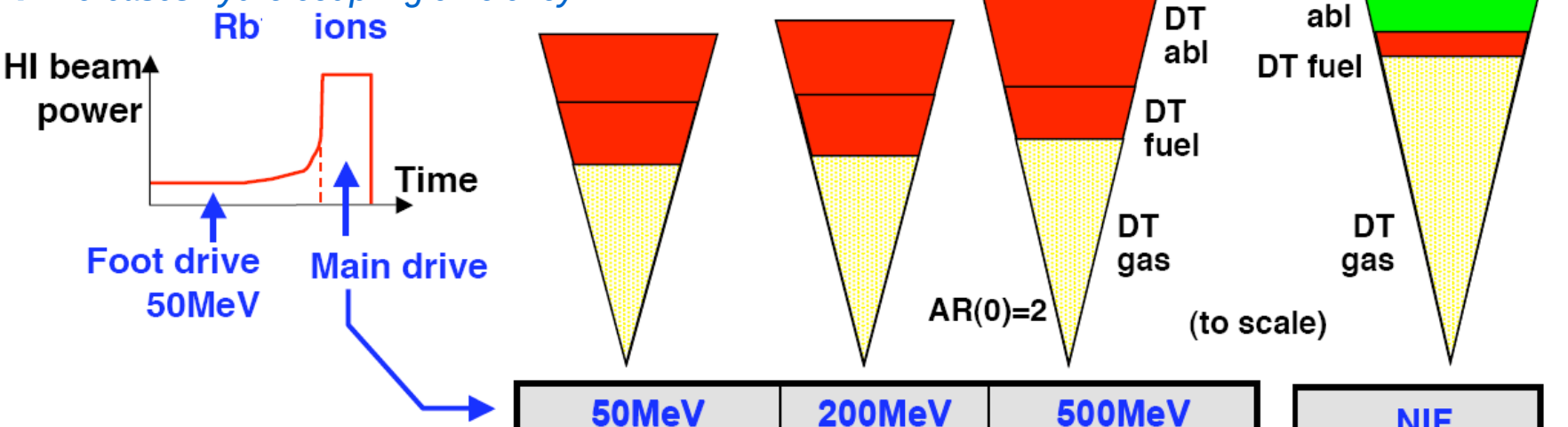
(Received 16 May 2008; accepted 4 June 2008; published online 9 July 2008)

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 Perkins surveyed 1-D designs for HIF direct drive in February 2009 giving the same fusion yield as NIF (20 MJ yield)

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

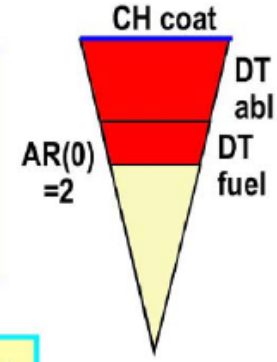


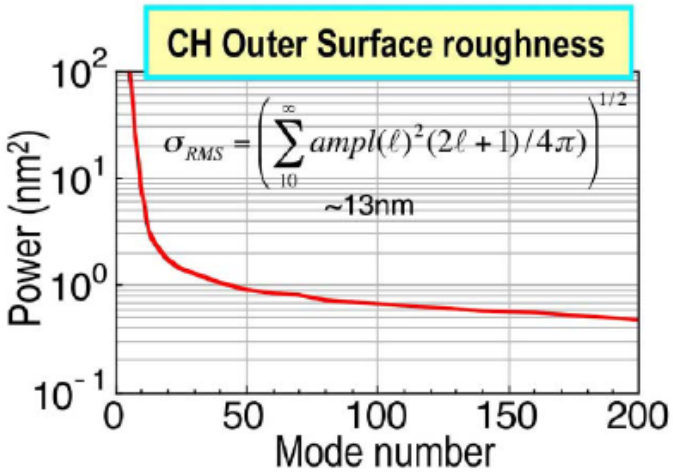
	50MeV	200MeV	500MeV	NIF
$m_{ablator}/m_{fuel}$	1.8	2.1	3.0	18
Driver energy (MJ)	0.32	0.36	0.44	1.3
Peak drive power (TW)	175	195	205	320
Yield (MJ) / Gain	24.7 / 77	21.6 / 60	20.8 / 47	20.0 / 15
$\eta_{absorbed}$ / η	0.97 / 0.10	0.91 / 0.10	0.88 / .09	0.16 / 0.02
In-flight aspect ratio	25	27	25	32
Convergence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

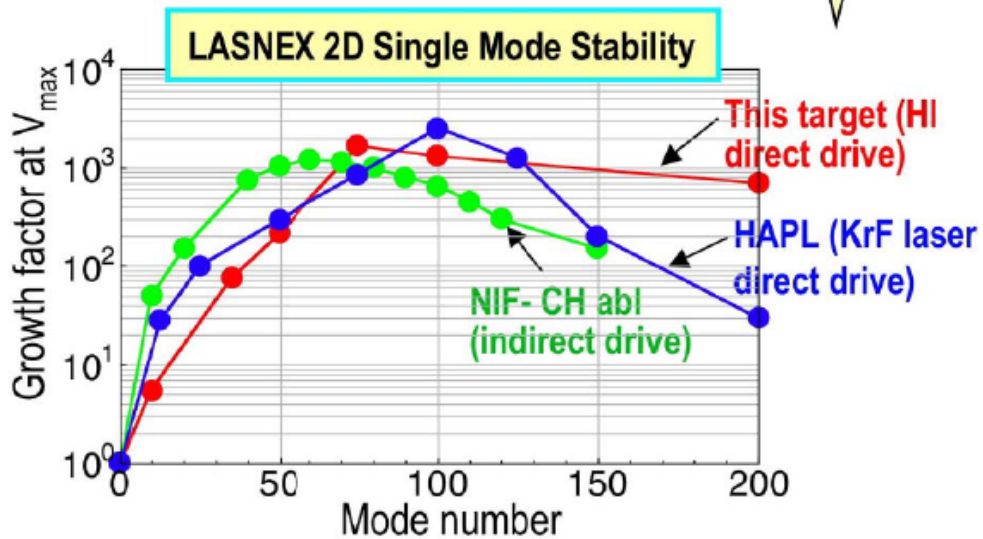
Low aspect ratio targets are expected to be robust to shell breakup: heavy ion direct drive targets have been evaluated for 2-D Rayleigh Taylor growth factors (John Perkins, 2009)

Implosion stability should be good because of :

(a) ablation stabilization (but less at higher mode numbers)
(b) no ablator/fuel mix , (c) low Atwood numbers,
(d) low inflight aspect ratios (big fat shells)

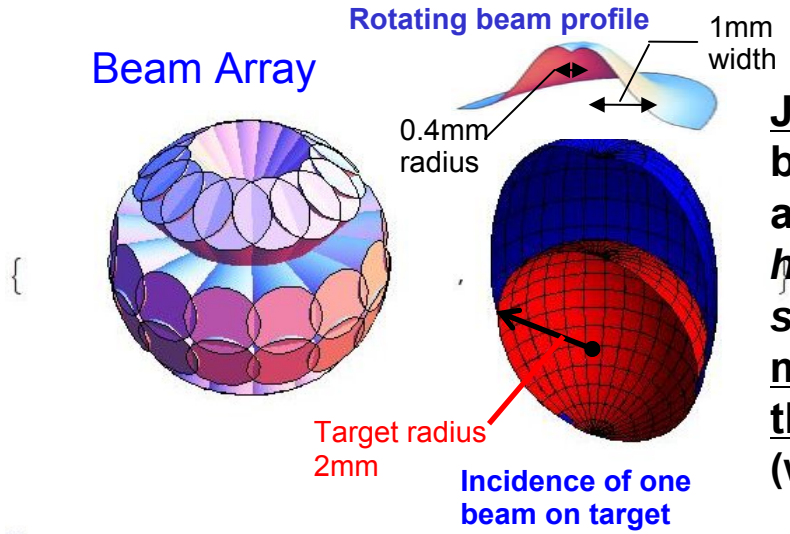


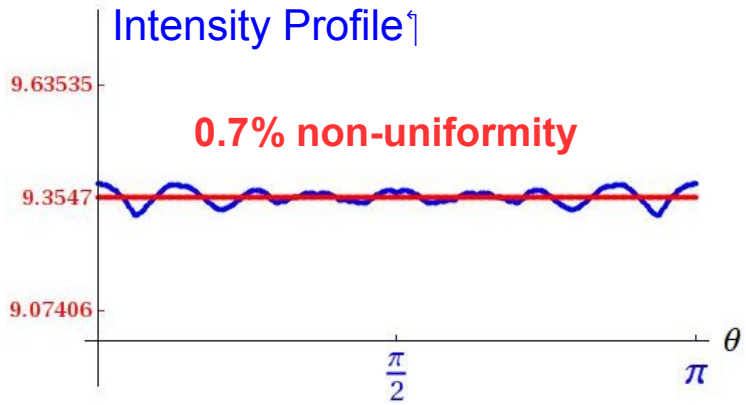




⇒ Even with linear (unsaturated) growth, perturbations are unlikely to penetrate shell at late time

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

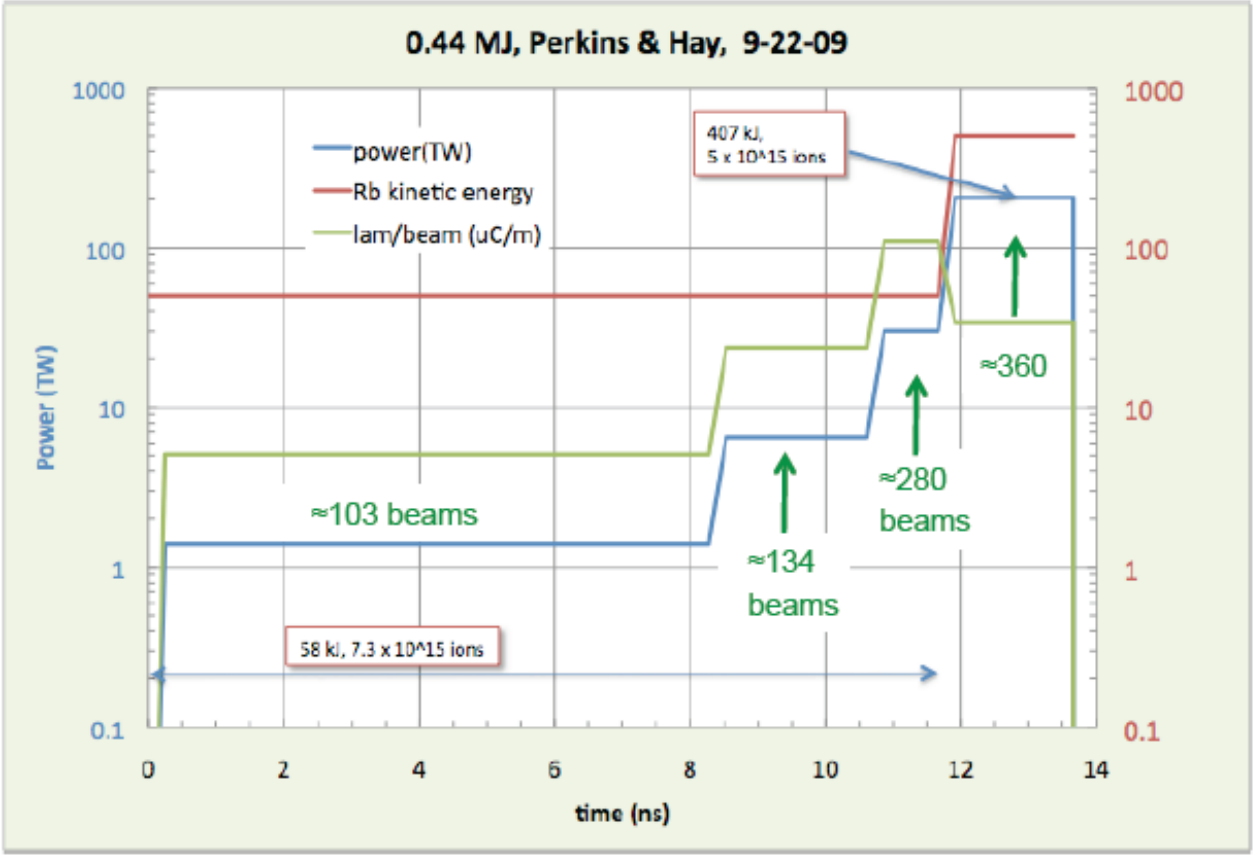
Just four annular rings of beams (15 each, 60 total) at ±37.3° and ±79.3°, *with hollow, rotated beam spot projections* give a maximum deviation from the mean of 0.7% (with 21% spilled intensity).

4 polar angles only, *not 4π!*

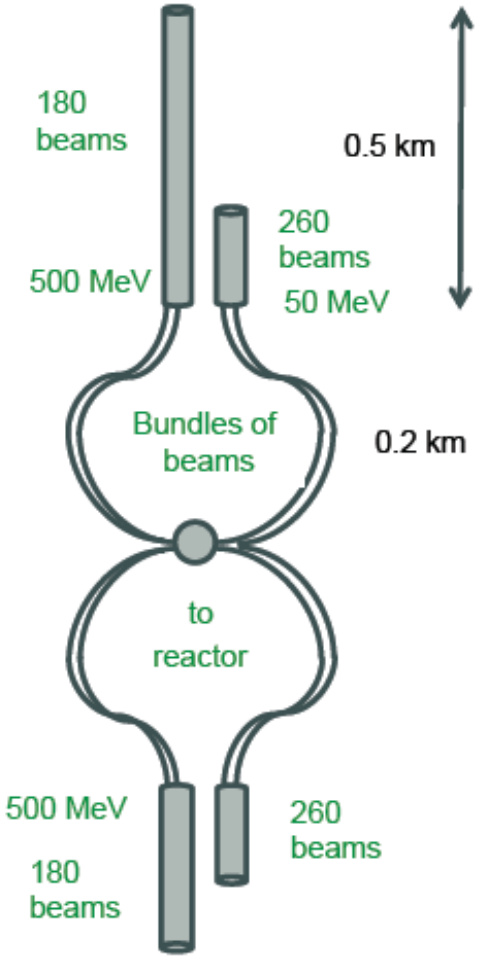
40 beams total give less than 1.4% and 32 beams total still give about 2%. With smaller ring radii the spill can be reduced, but unwanted radial incidence increases (RT instabilities). Smaller widths are desirable.

(To be published in Physics of Plasmas)

The high beam space-charge (perveance) required to drive the small (< 1 MJ) scale direct-drive targets requires too many beams



Four multi-beam linacs with electrostatic quadrupoles, followed by an un-neutralized (190 m), then neutralized drift compression section (30 m).



Issues include: Phase space constraints for the 50-MeV foot. Complexity of chamber interface (≈877 beams). Chromatic corrections.

Simon Yu proposed four linacs to drive the 0.44 MJ target→

Moving to higher-energy ion species can mitigate accelerator challenges and simultaneously improve capsule performance

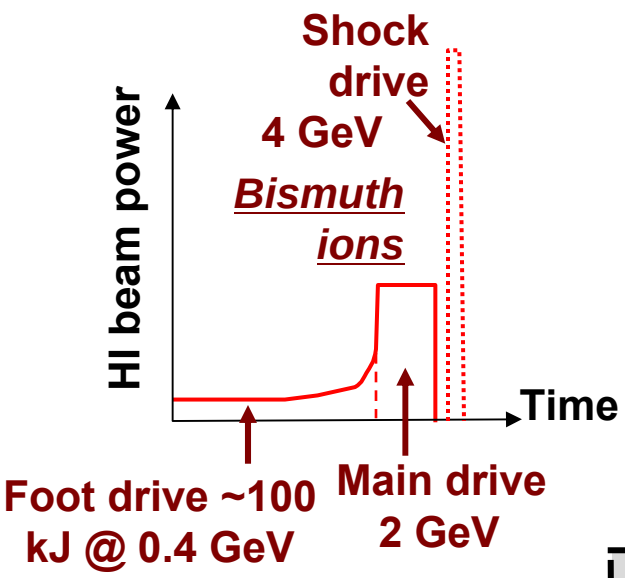
Michael Hay, VNL seminar July 27, 2010

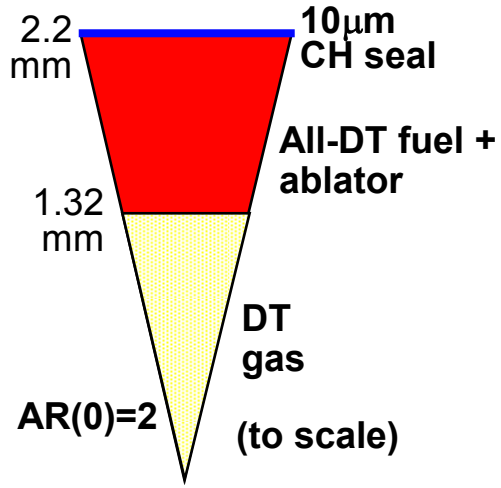
Bare perveance $Q = \lambda/V \sim P/KE^{5/2}$

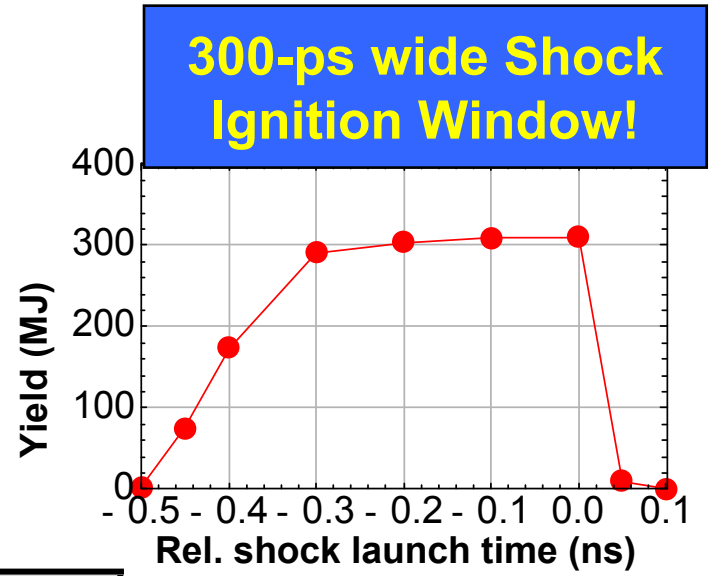
	0.44 MJ target			3.7 MJ target		
Pedestal No.	Power [TW]	Rb Ion KE [MeV]	Q at R(0)	Power [TW]	Hg Ion KE [GeV]	Q at R(0)
1	1.4	50	0.475	2.5	0.22	0.032
2	6.5	50	2.21	16	0.22	0.204
3	30.2	50	10.26	82	0.22	1.05
4 (main)	205	500	0.22	660	2.225	0.027

See also: P.A. Seidl, E.P. Lee, R.O. Bangerter, and A. Faltens. HIFAN-1768, (2010).

HIF target option: direct drive in polar geometry + shock ignition (for thick liquid chambers and higher gains) (J. Perkins, LLNL Jan2010)







	Hotspot Ignition 1D	Shock Ignition 1D
Driver energy (MJ)	2.60	1.49 + 0.8 (sh)
Peak drive power (TW)	500	200 + 1250 (sh)
Yield (MJ) / Gain	317 / 122	310 / 136
Convergence ratio	28.4* (17.0**)	30.9* (18.5**)
In-flight aspect ratio	14.0	8.7

Not optimized, nor 2-D polar yet.
→*May use outer heavy metal tampers allowing higher 3 GeV ions.*

* Conventional definition CR = $r_{shell\text{-}out}(0)/r_{HS}(t_{ign})$ ** Using CR = $r_{shell\text{-}in}(0)/r_{HS}(t_{ign})$

Future plans for heavy ion direct drive target design

1. **Build off larger LLE, RAL, CEA, LLNL design efforts for laser polar direct drive and shock ignition and use that larger effort as a guide seeking heavy-ion polar drive solutions.**

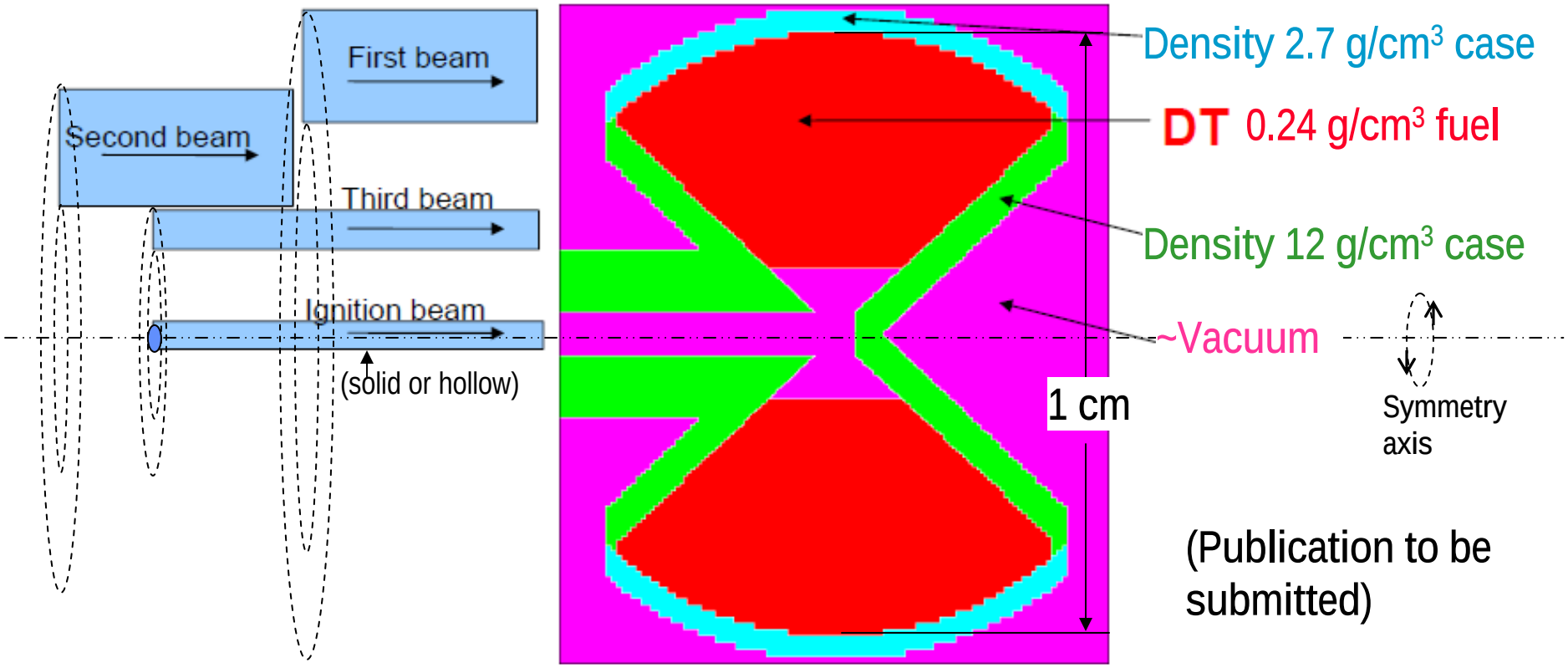
2. **Optimize shock-ignited heavy-ion direct drive target performance consistent with beam focusing geometry**

3. **Perform 2D calculations of heavy-ion polar drive for application to thick liquid protected chambers**

HIF option: Hydro-drive + Fast/Shock Ignition: the X-target

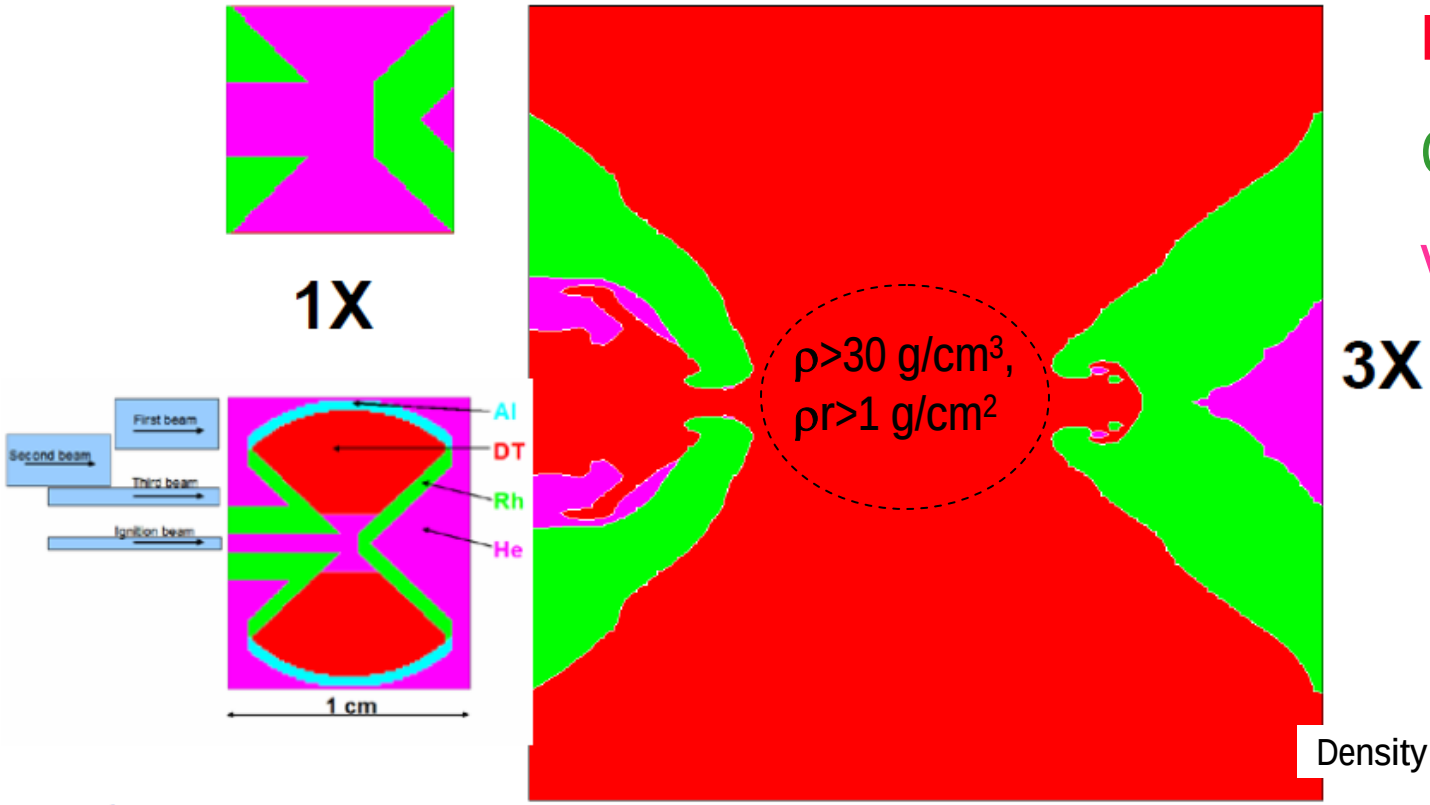
The X-target: First full-physics rad-hydro implosion calculations using HYDRA in 2-D give gains equivalent to indirect drive: 3 MJ compression + 3 MJ fast ignition→300 MJ yield, all 60 GeV U beams, for one-sided beam illumination, robust RT stability. (E. Henestroza, August 2010)

1st, 2nd, 3rd and 4th beams are many beams with overlapping spots modeled as annuli



(Publication to be submitted)

Material distribution at initial time and just before injection of the ignition beam, showing very small mix effects.

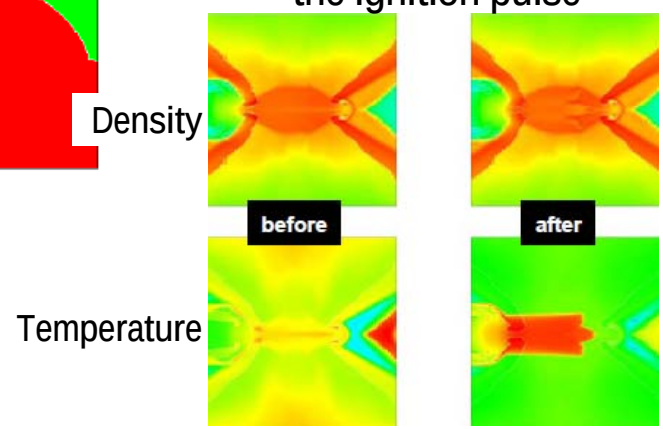


DT

Case

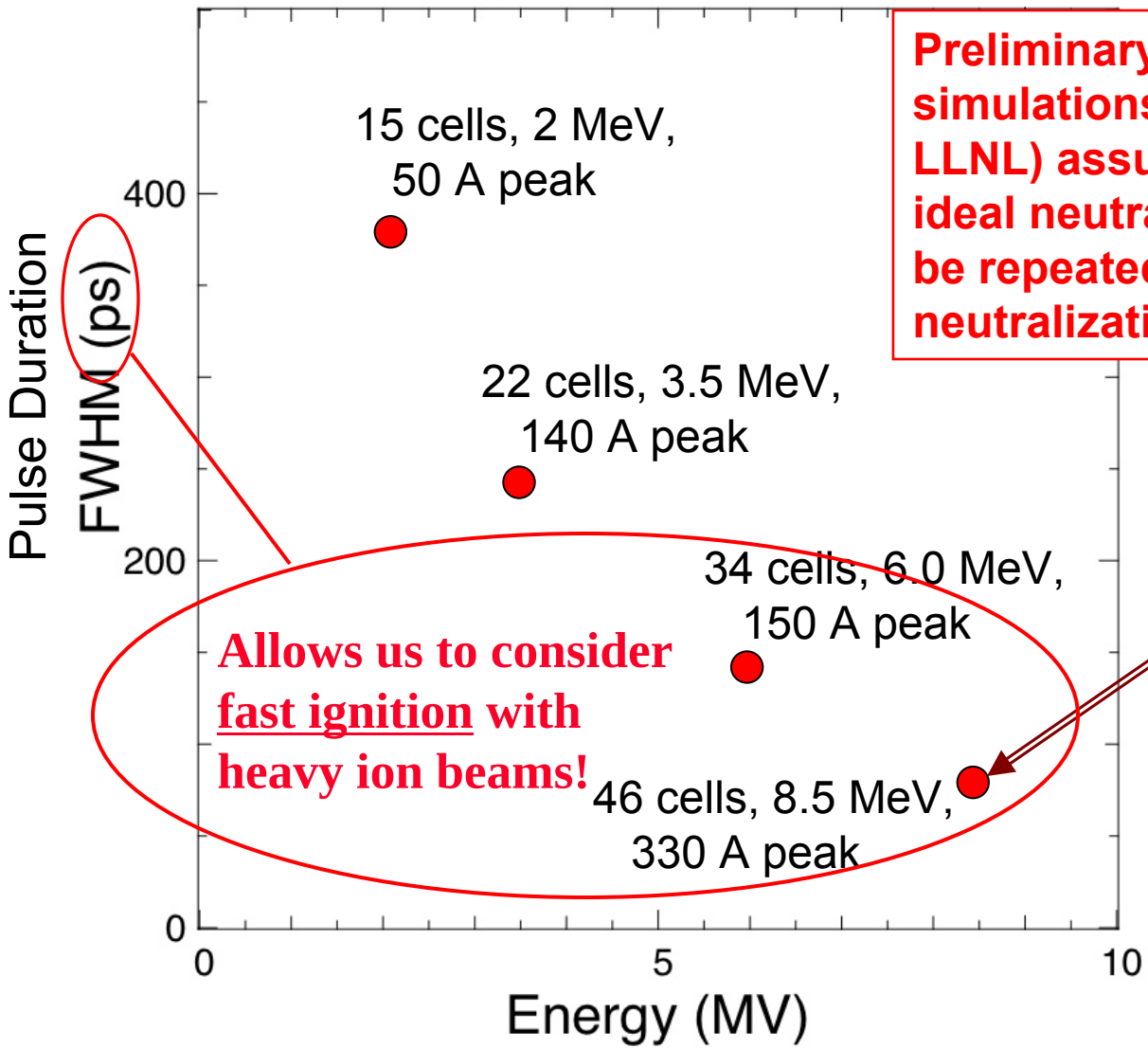
Void

Density and temperature before and after the ignition pulse



Near term plans include sub-ns pulses for the third ring of beams, seeking ρ_{DT}>100g/cm3, & hollow ignition beam for shock heating.

Simulations show compressed pulse duration in NDCX-II varies ~ inversely with kinetic energy, assuming ideal neutralization.

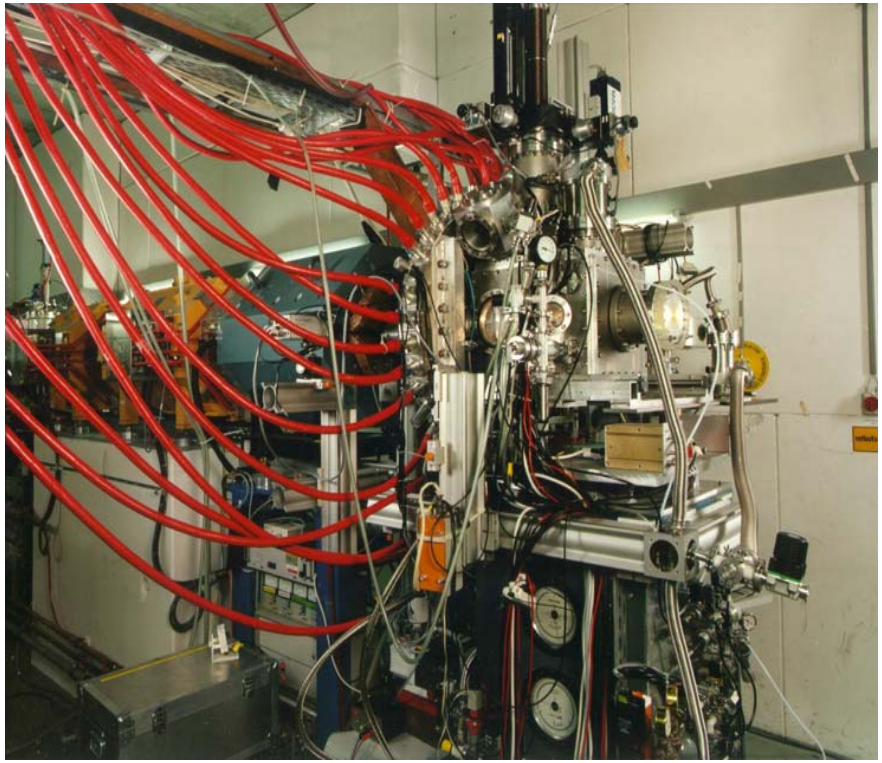


Preliminary results of Warp PIC simulations (Friedman, Grote LLNL) assuming jitter errors with ideal neutralization. These will be repeated with full plasma neutralization physics models.

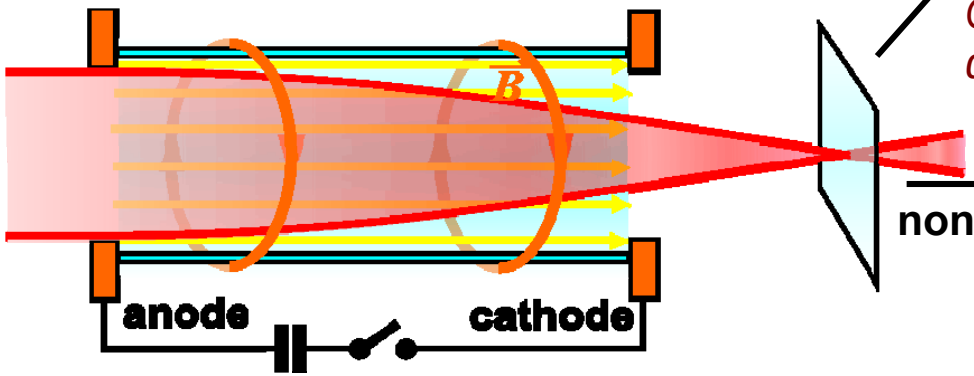
Allows us to consider fast ignition with heavy ion beams!

We have 50 ATA cells to add in < 2 years!

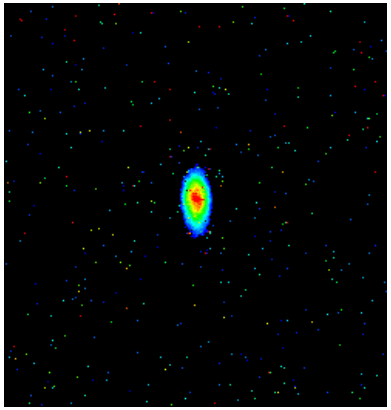
Near term experiments (NDCX-II-IBX) can explore optimizing two-stage focusing with drift velocity tilt using B_q lens like the GSI plasma lens



400 μm focal beam spots @ 10 π mm-mr normalized beam emittance achieved

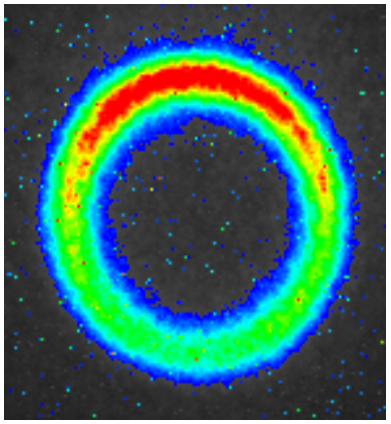


linear B-field



Can be time-dependent

nonlinear B-field

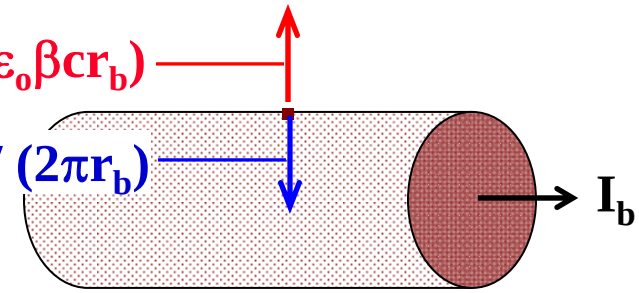


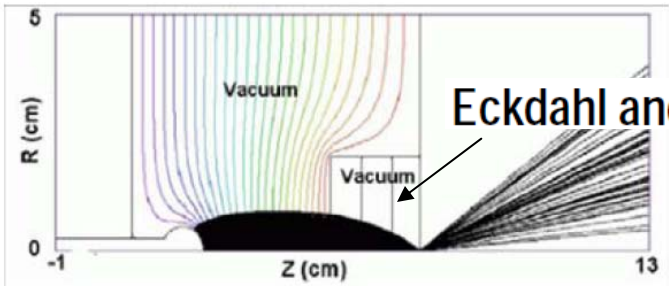
We should *engineer* a B_θ self-pinch built into target assembles, replacing a plasma lens z-current with a net ion beam current.

Step 1: Reduce the E_r force using transverse grids/foils

$$qE_r = I_b / (2\pi\varepsilon_o\beta c r_b)$$

$$q\beta c B_\theta = (\mu_o I_b) / (2\pi r_b)$$



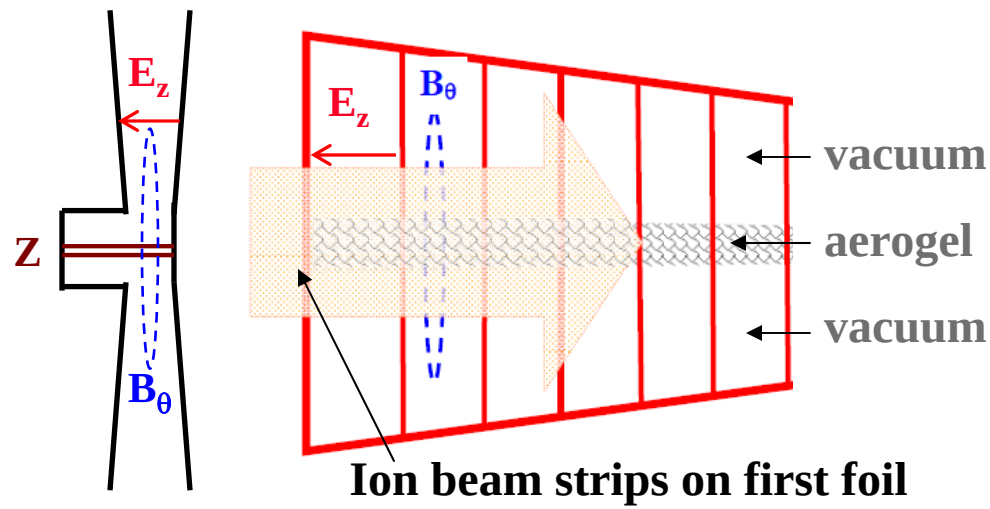


Eckdahl and Humphries

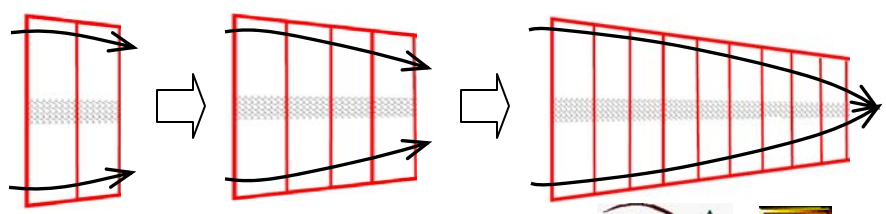
Figure 5. 14-MeV beam focused by anode foil, with additional grids to short out the residual space-charge

Ratio of space charge force (outward) ~ 1 / magnetic pinch force (inward) β^2

Step 2: reduce the return current with magnetic insulation (see S. Humphries *Charged Particle Beams*, p 351) at large r, with resistive aerogel plasma at small r

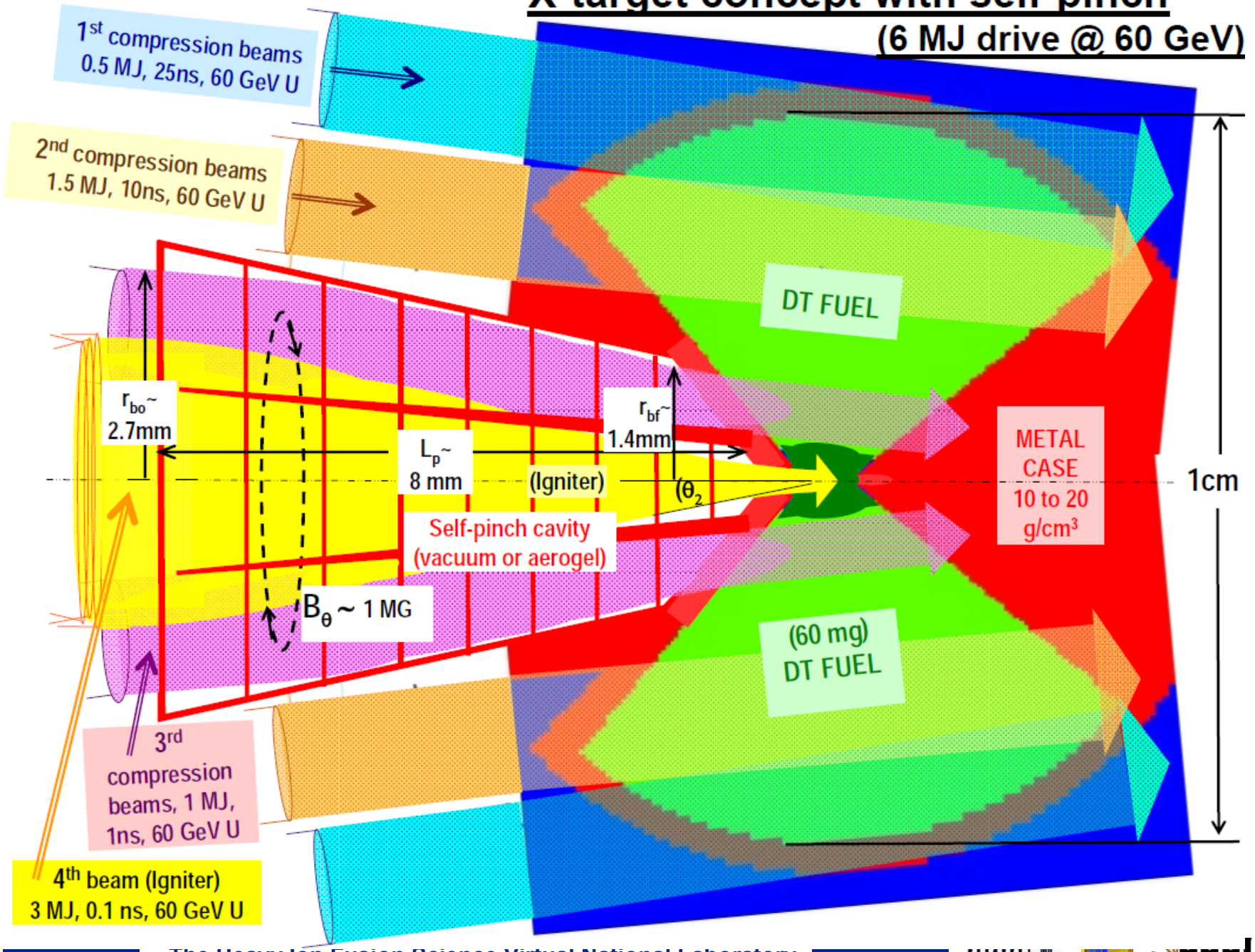


Step 3: Adjust the pinch cavity length to bring pinch into X-vertex

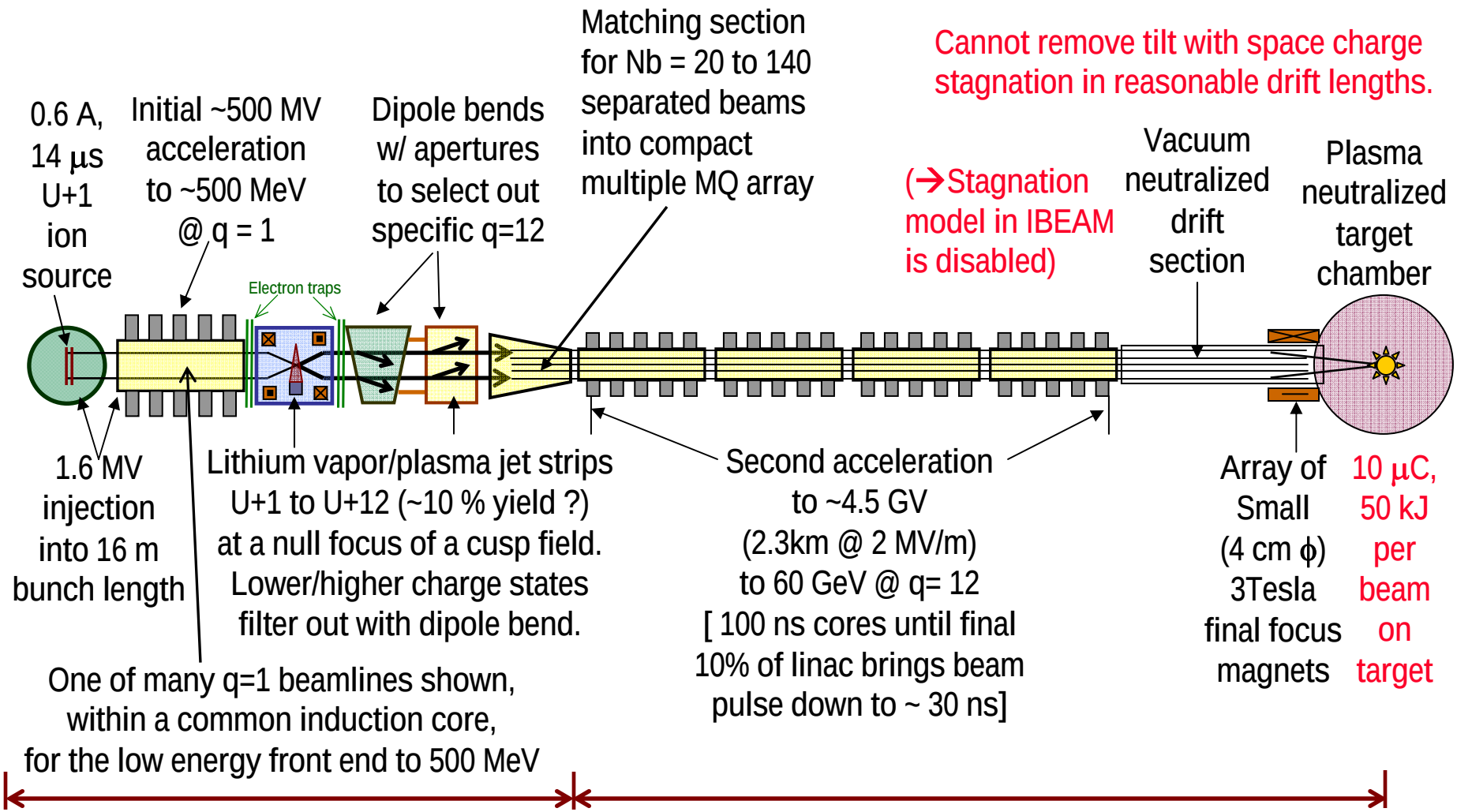


X-target concept with self-pinch

(6 MJ drive @ 60 GeV)



Concept for an X-target induction linac driver with stripping @ 500 MV, feeding U+12 ions into a 5 GV multiple-beam X-target induction linac



This front end model is not yet in IBEAM, which assumes a U+12 ion source.

IBEAM models and costs this main linac section, + a CL injector for U+12, vacuum drift and ballistic neutralized final focus.

IBEAM predicts significantly lower cost drivers due to $(\beta\gamma)^2$-4X greater transport efficiency for 60GeV U^{+12} vis-a-vis RPD

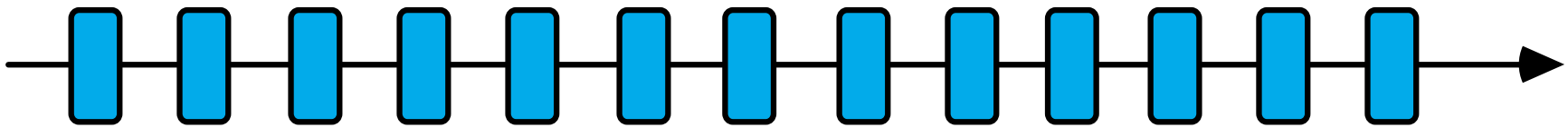
All cases: U^{+12} multiple beam SC quad linac, 2.5 km, 2 MV/m, 100 ns*, 3T* MQ, Inj. @4 μs, 2.5A	18 beams 0.9 MJ	36 beams 1.8 MJ	72 beams 3.6 MJ	144 beams 7.2 MJ
Ion KE (GeV) Current/beam @ ff (kA) (for igniter beams)	All @ 60 0.33 (10.9)	All @ 60 0.33 (10.9)	All @ 60 0.33 (10.9)	All @ 60 0.33 (10.9)
Compression beam spot radius (mm) @ L_f (m) (Igniter beams-@ second stage focus L_{f2}(cm))	0.68 @ 4 m, (0.1 @ 1.7 cm)	0.68 @ 4 m, (0.1 @ 1.7 cm)	0.68 @ 4 m, (0.1 @ 1.7 cm)	0.68 @ 4 m, (0.1 @ 1.7 cm)
*Inner core radius (cm) *Outer core radius (cm)	19 57	23 61	30 68	40 78
Final focus array angle	5.8 deg	8.9 deg	13.2 deg	19.0 deg
Core mass (tons)	7,000	7,900	9,200	11,100
Linac efficiency (%)	19	28	38	47
Linac total capital cost (inc. indirect) (B$)	0.60	0.74	0.98	1.4

½ of RPD!

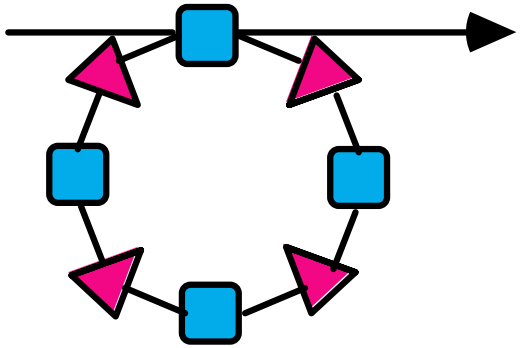
*Optimized for minimum driver cost

Comparison of driver options (Induction vs RF linac vs Recirculator) may need to be revisited for 60 GeV

E.g., Recirculators (induction synchrotrons) might be reconsidered if the number of beams is small (~< 10 @ 60 GeV), and if vacuum OK.



- **Length is reduced—fewer accelerating modules (etc.) are needed.**
- **Individual modules are smaller & driven less hard.**

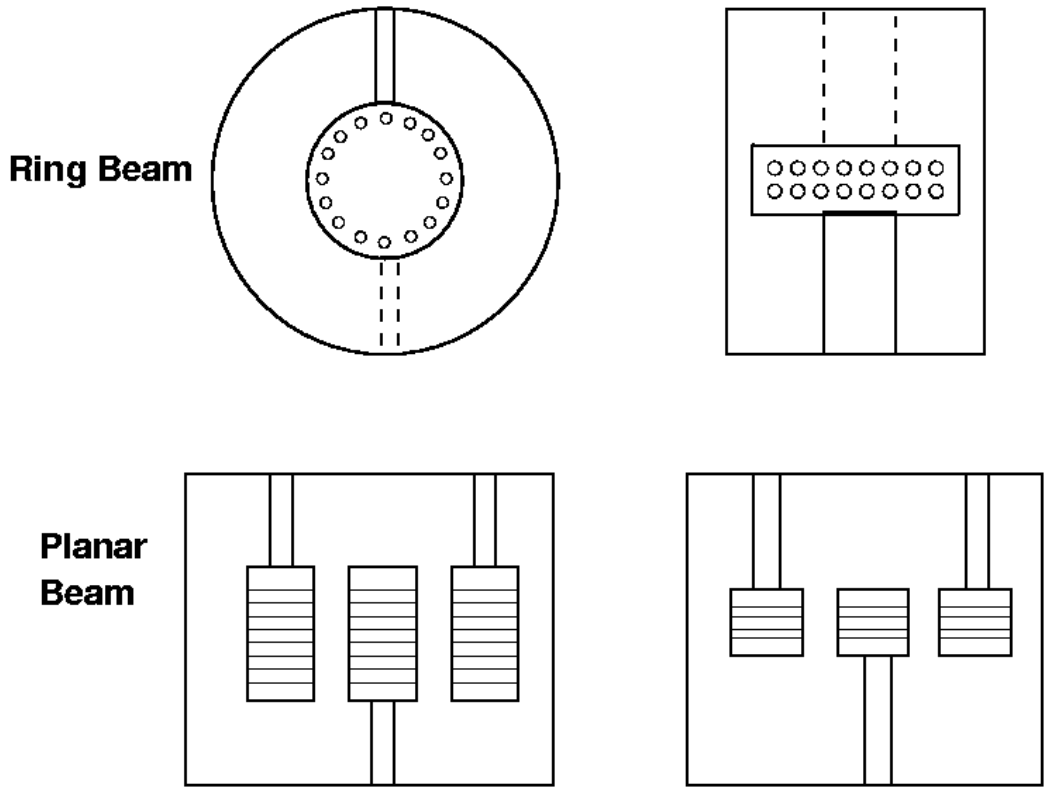


A low-β RF linac concept: q/A~1/20, 1μC, 20 MV, 200ns source→1ns target was developed by the RF-Linac Group at the Accelerators for HEDP Workshop October 2004: Could this be a front-end feeding 20MV/m SC-RF section to 1g/cm^2 ion range for an X-target driver? (~10X more parallel beamlines than for induction needed, but maybe 10X shorter).

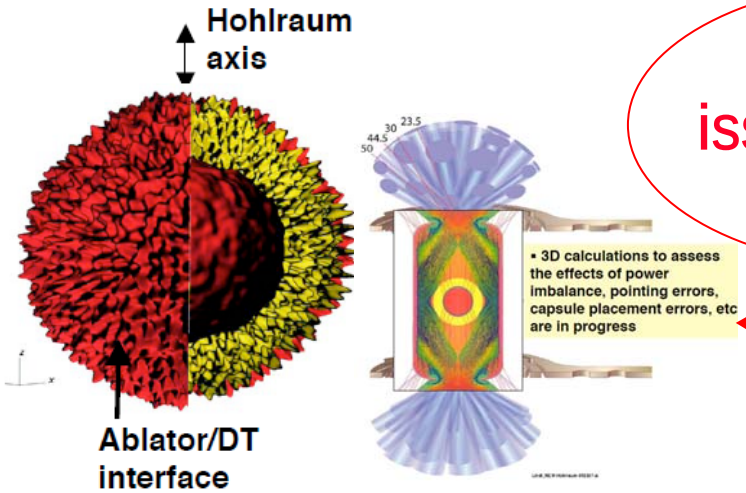
Interdigital H–mode resonator configurations

<u>The RF Linac Group</u>

John Staples, Andy Sessler,
Joe Kwan, Rod Keller, LBNL
Paul Schlossow, Tech-X
Peter Ostroumov, ANL
Wieren Chou, FNAL
Bill Herrmannsfeldt, SLAC



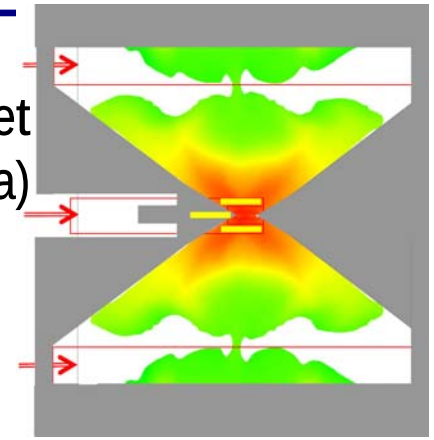
The X-target requires a different R&D path for HIF



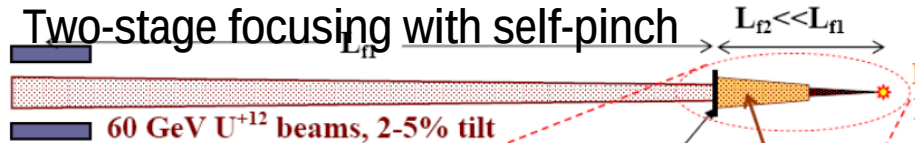
3-D HYDRA simulation of NIF hot spot

Different key issues→ different R&D paths!

X-target (2-D Hydra)



Two-stage focusing with self-pinch



Any hot spot ignition for direct or indirect drive will need precision cryo beta layering, 100 nm-smooth capsules, precision time-dependent beam power and pointing control, RT-mix <0.5 r_{hs}→ *A NIF- equivalent heavy-ion beam ignition test would be required to validate an HIF fusion test facility (ETF).*

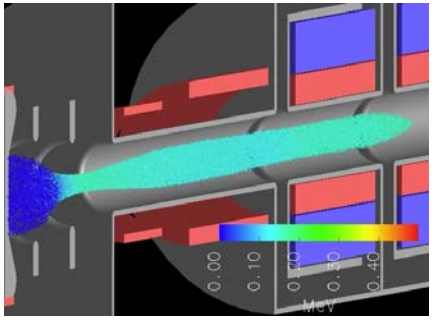
HI-fast ignition (or shock ignition) for X-target requires R&D to develop sub-nanosecond pulses and 200 μm focal spot radii → experiments and modeling on NDCX-II, IB-HEDPX, GSI-FAIR, RHIC, IMP facilities.→ Success of relevant-physics experiments could lead to ~ 2MJ HI-FI ignition test facility upgradeable to high average fusion power.

Elements of proposed initial five year HIF R&D plan common to all HIF target options: NDCX-II, IB-HEDPX, HCX-II, NDCX-I (moved to PPPL), Long-path scaled experiments, and scaled liquid chamber R&D. The choice of target defining the IRE/HIDIX and HIF ignition/ETF can be decided after completing the five year phase.

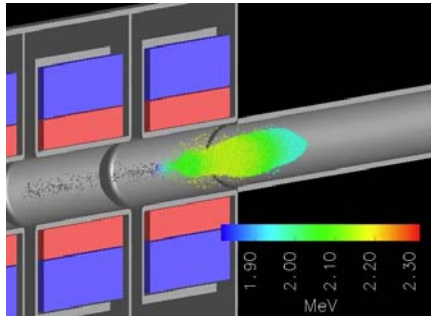
NDCX-II now under construction will enable higher energy heavy-ion driven beam experiments for warm dense matter and heavy ion fusion

- 11 M$ construction began July 2009, to be completed in March of 2012
- Rapid initial bunch compression allows re-use of 70-ns pulsed power sources from the ATA accelerator
- Detailed 3-D simulations using the Warp code confirmed the physics design & set engineering requirements
- rapid initial bunch compression could reduce front end length and cost for HIF drivers

During injection



Entering final compression



Ref: A. Friedman, et al., *Phys Plasmas*, in press (2010)

	NDCX-I	NDCX-II (baseline)
Ion species	K^+ (A=39)	Li^+ (A=7)
Ion energy	300-400 keV	(1.5 MeV) → > 4 MeV
Focal radius	1.5 - 3 mm	(0.5 mm)
Pulse duration	2 - 4 ns	~(1 ns) → < 200ps
Peak current	~ 2 A	~ (10 A) → > 100 A

Justification of Mission Need CD-0 for the Integrated Beam High Energy Density Physics Experiment (IB-HEDPX)

The overall IB-HEDPX program addresses a critical issue for high energy density physics in the near term, and inertial fusion energy in the long term, namely, the integration of the generation

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IB-HEDPX + smaller experiments are proposed to be part of an "affordable" five year plan FY13-18 for both HEDP and for HIF-IFE

→*a* 300 M$, 10 kJ heavy-ion IRE/Heavy Ion Driven Implosion eXperiment (HIDIX) would follow this five-year phase.

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in Year 1 and 2, is necessary R&D to assess the performance requirements of injection, acceleration and focusing of short pulses needed for the IB-HEDPX.

APPROVAL

This Justification of Mission Need for the IB-HEDPX Project is satisfactory and Critical Decision 0 (CD-0) is approved and the Project is authorized to proceed with Conceptual Design activities.

Submitted by:

Francis Thio — 12/1/2005 Date

Y. C. Francis Thio
Program Manager
Research Division
Office of Fusion Energy Sciences

Approved by:

12/1/05 Date

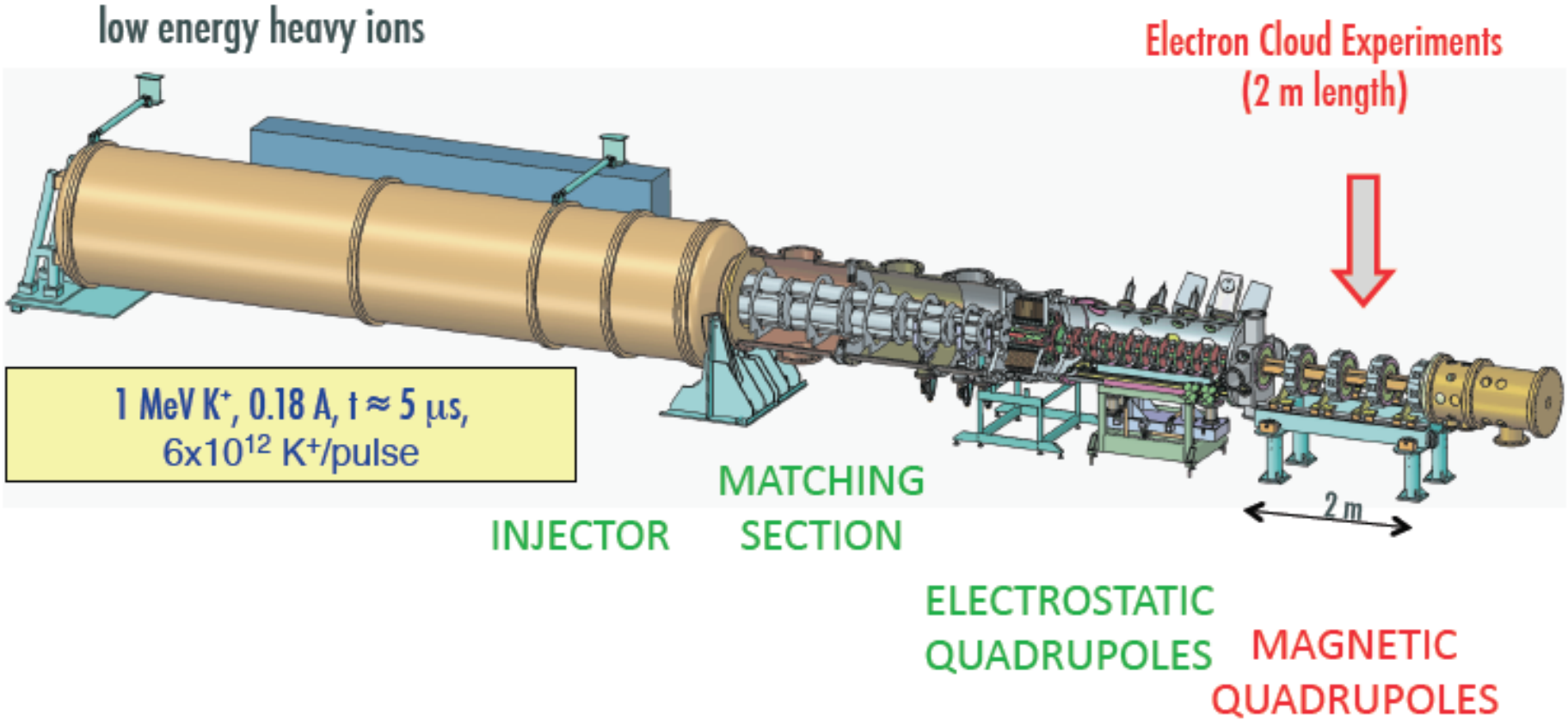
N. Anne Davies
Associate Director for Fusion Energy Sciences
Office of Science

$50M IB-HEDPX would provide a full capability (p>1 Mbar) for HEDP users as an upgrade from NDCX-II. Note this CD-0 (Dec05) calls for NDCX-II as a prerequisite. →NDCX-II commissioning will satisfy this pre-requisite in FY12.

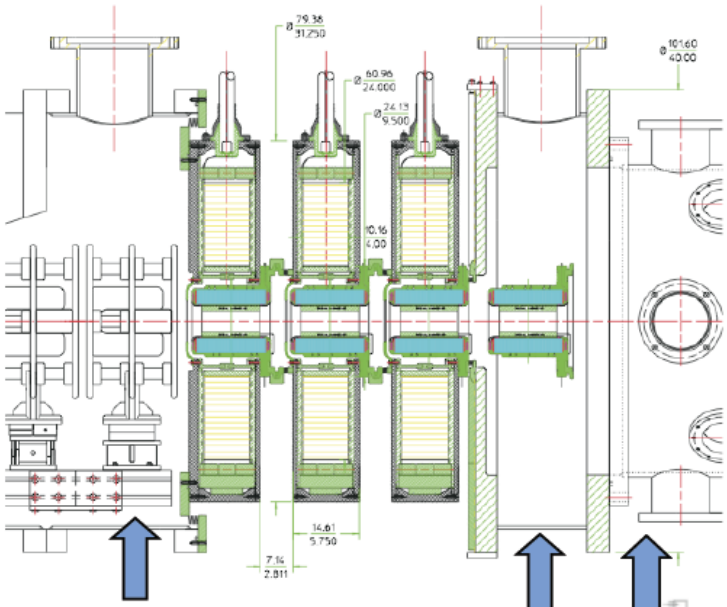
NDCX-II is constructed as a modular system on rails, for future expandability. We possess <u>50 ATA cells, sufficient for an upgrade to 8-10 MV</u>, with an eastern extension of the B58 high bay: ~$20 M + $30 M (LCLS-HED-scale) user area ~ $50M.

Injection, matching, low-energy transport at driver scale

…needs to be continued at 5 Hz to evaluate gas and e-cloud mitigation techniques to be used in an IRE/HIDIX



In the proposed national HIF plan, an improved HCX would address key driver beam transport and gas/e-cloud control for both HIF hohlraums as well as for direct drive and X-targets (slide from Peter Seidl's VNL-PAC talk of Dec 8.)



Benefits:

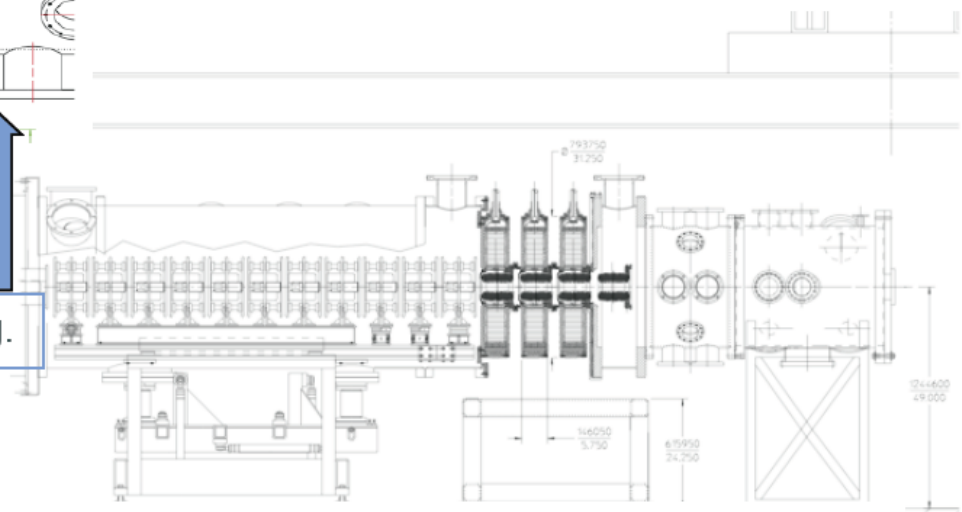
- Better Alignment
- Better Match to Existing Lattice
- Better Engineering for Improved Experimental Control
- Extendable to Longer Lattice
- Interfaces with Different Induction Cells
- Improves Diagnostics Access

New Diagnostic: sliding quad & diagnostic access:

1. double slit,
2. optical,
3. Faraday cups,
4. current transformers

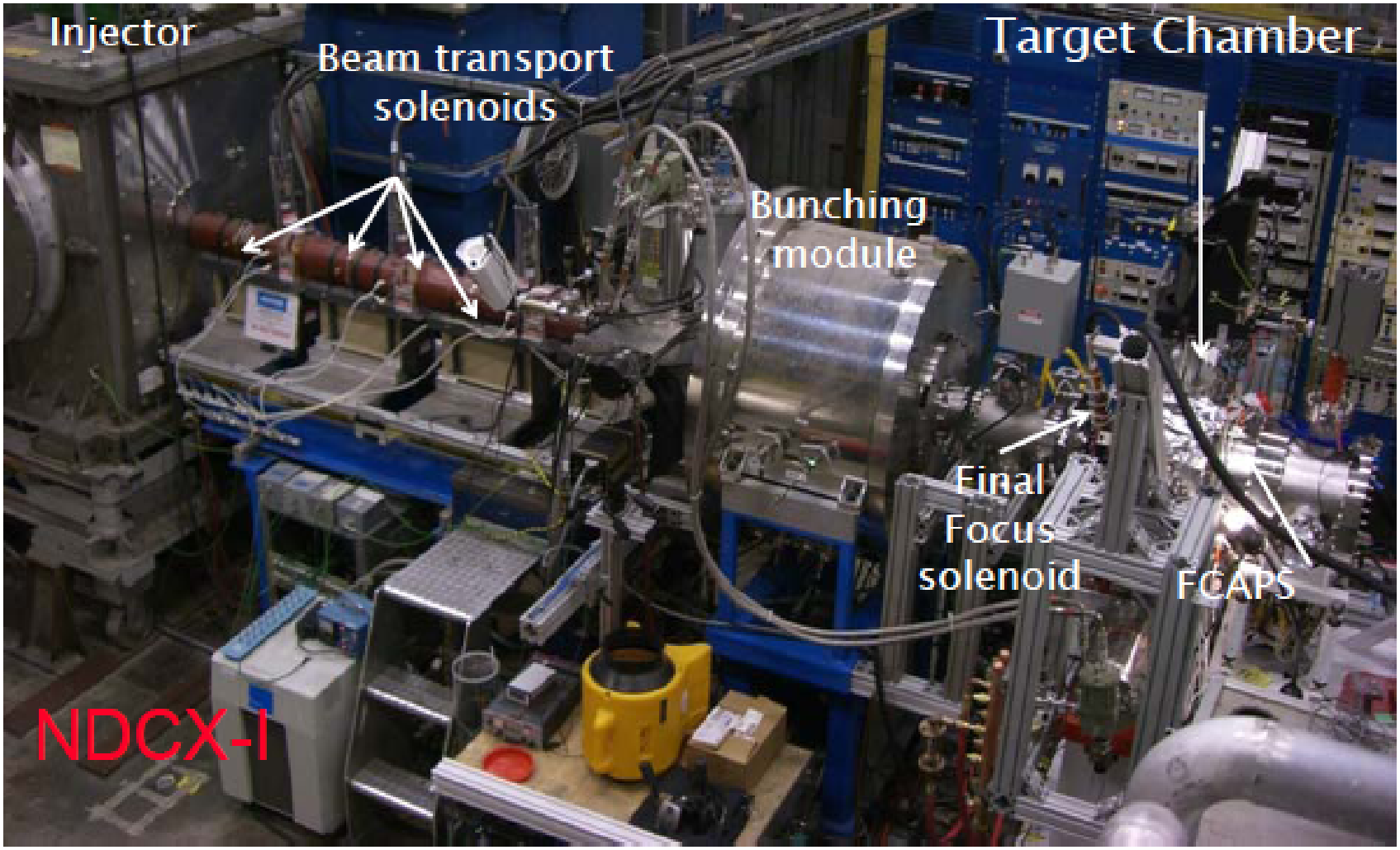
Diag.

Diag.

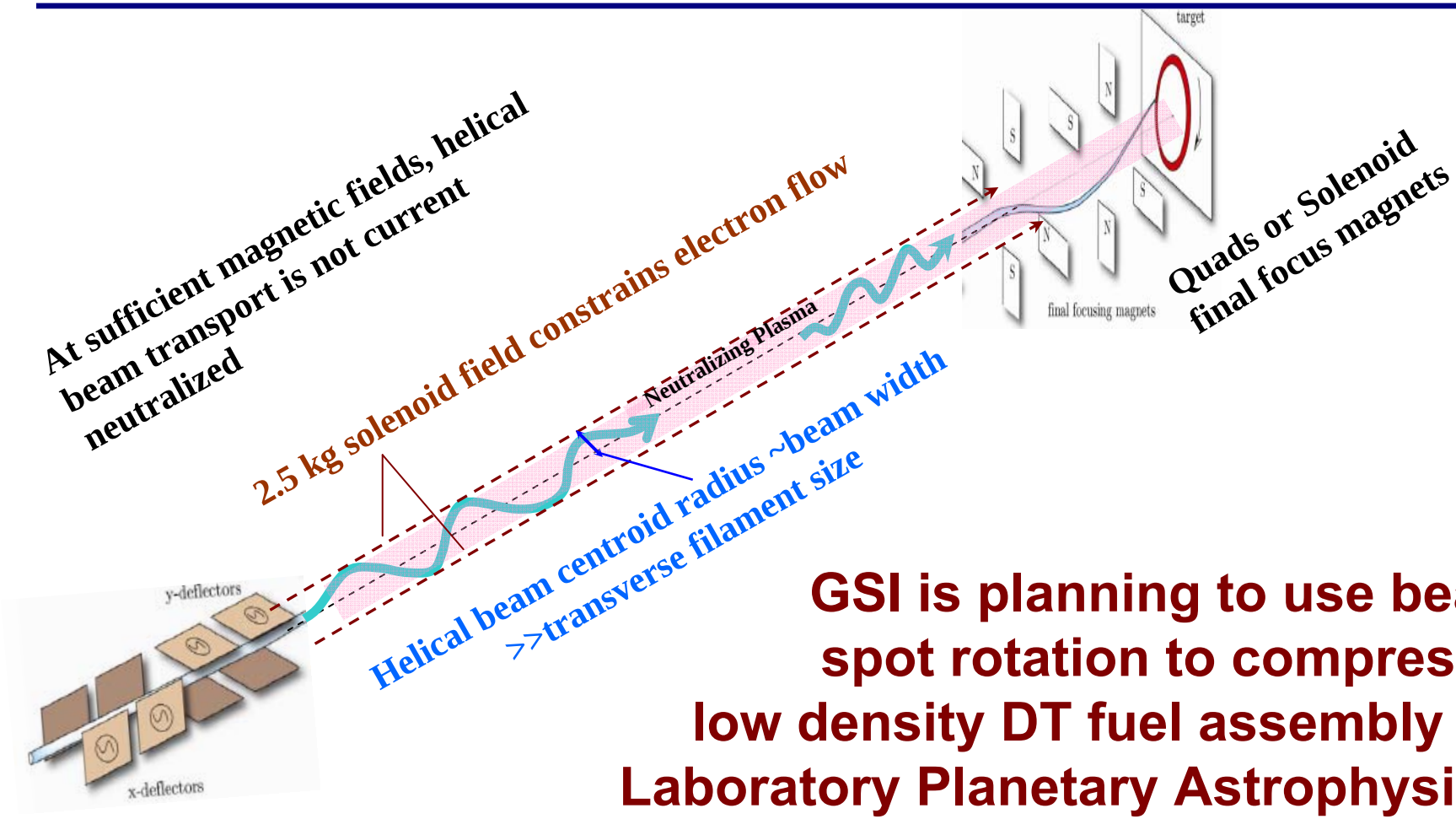


Simplified and optimized magnet transport line design can provide a scalable foundation for future quadrupole experiments beyond gas/electron experiments.

All HIF target options need neutralized beams at least within the target chamber, and there is much more research needed to optimize beam neutralization and compression than can be completed before NDCX-I has to be moved to make room for NDCX-II. We propose moving NDCX-I to PPPL when funding permits.



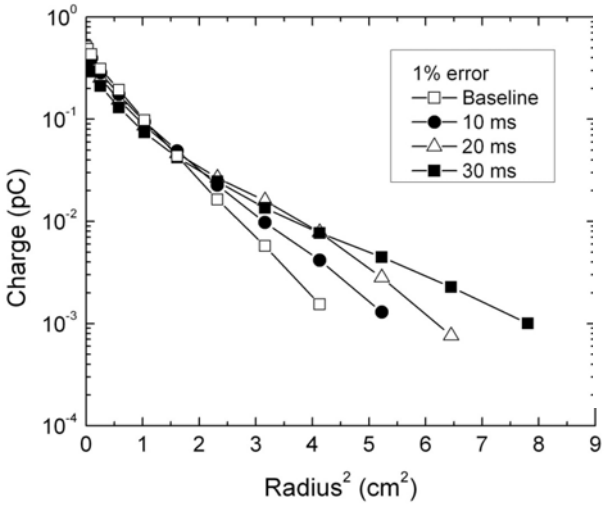
PPPL is exploring the use of *rotating helical beams on NDCX-II→IB-HEDPX, and effects on Weibel instabilities.*

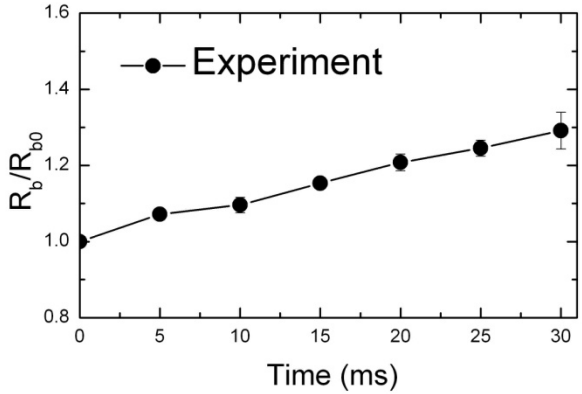


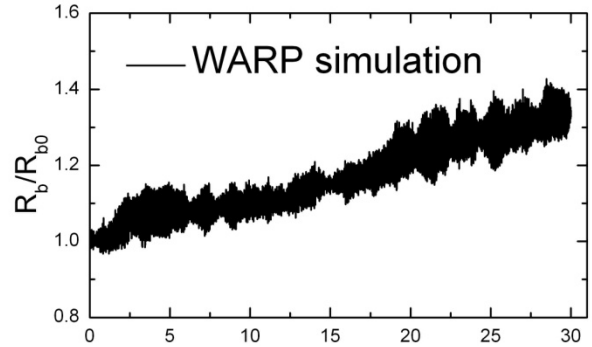
GSI is planning to use beam spot rotation to compress a low density DT fuel assembly for Laboratory Planetary Astrophysics, but this technique can also be applied to low density fuel compression for high gain fast ignition.

Improved Capability to Study High-Intensity Beams Will Enable PTSX to Better Study Emittance Growth Over Large Equivalent Propagation Distances Relevant to HIF Drivers

Experiments on PTSX using moderate density beams demonstrate noise-induced profile broadening, and therefore emittance growth, over 1800 lattice periods. WARP simulations corroborate this.







Changing from sinusoidal waveforms to FODO waveforms increases the normalized intensity, enabling PTSX to perform experiments studying the combined effects of lattice noise and space-charge on long-distance beam propagation.

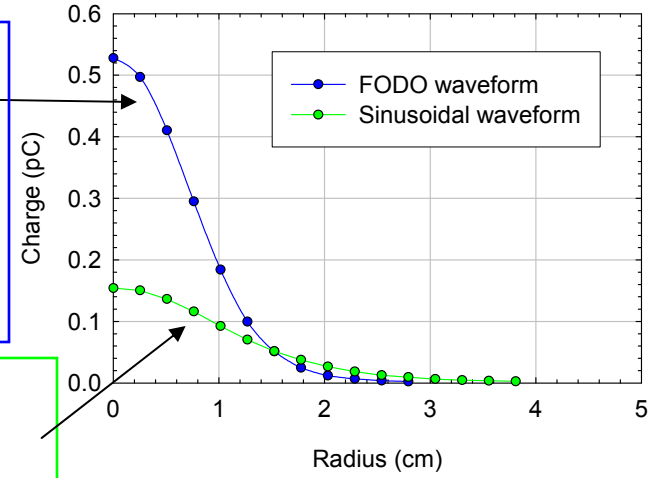
FODO

R_b = 1.0 cm

kT = 0.08 eV

s = 0.45

45% less emittance



Sinusoidal

R_b = 1.5 cm

kT = 0.17 eV

s = 0.16

$$s \equiv \frac{\omega_p^2}{2\omega_q^2} < 1$$

s is the normalized intensity.

Here, ω_p is the plasma frequency and ω_q is the average transverse focusing frequency.

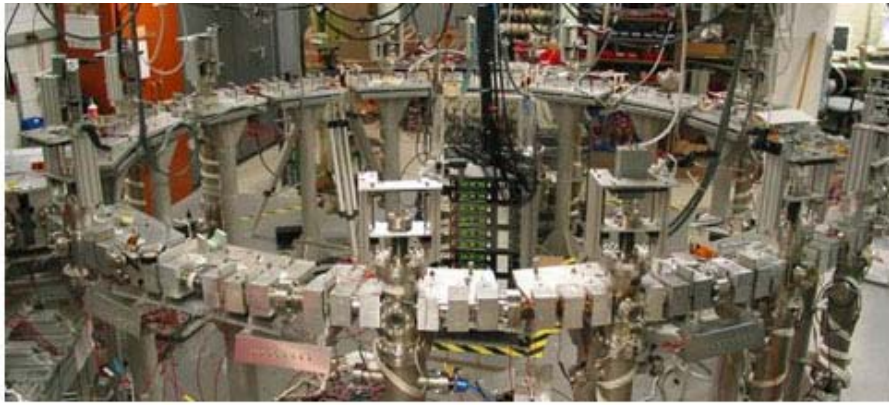
University of Maryland Electron Ring (UMER):
Scaled experiments using low-energy, high-current electron beams

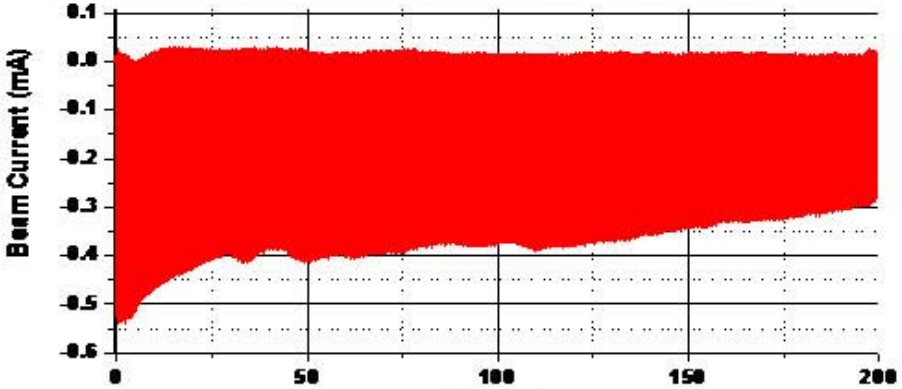
Goal: To demonstrate transport over long distance for intense beams of relevance to drivers for HIF and HEDP.

Status: Recently exceeded 1000 turns with longitudinal induction focusing

Ongoing Work:

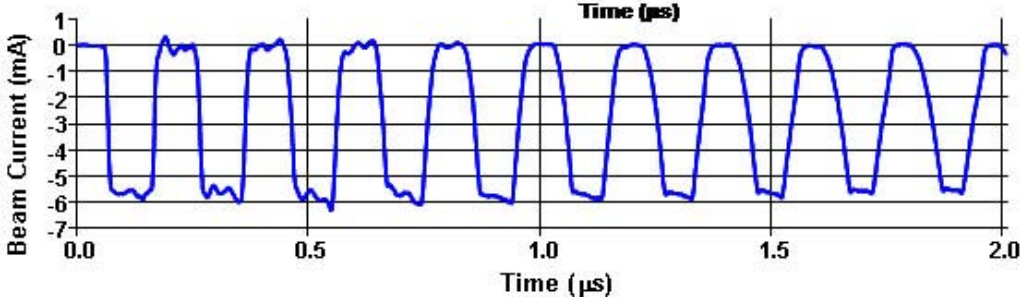
- Extending focusing to higher-current beams
- Designing acceleration stage
- Halo, emittance growth, and other topics





0.6 mA beam,
k/k_o = 0.851
>1000 Turns
with longitudinal focusing;

6 mA beam,
k/k_o = 0.629
10 - 100 Turns with ***no*** longitudinal focusing



Most critical accelerator R&D goals to achieve in the 5-year period of FY13-18 to enable IRE/HIDIX (*success for HIF on-ramp decision*):

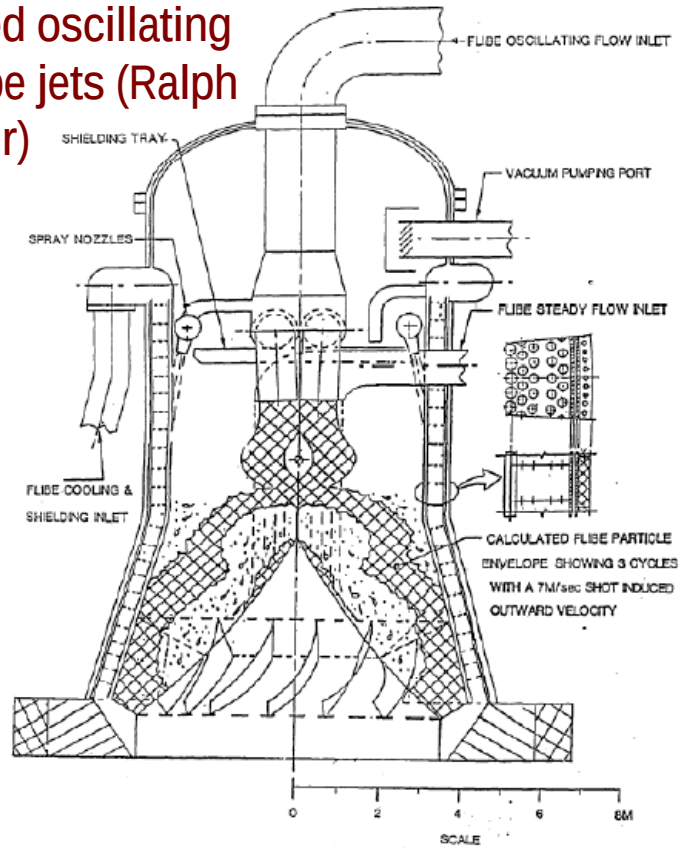
- **10 MBar in IBX (using two-stage focusing)**
- **Beam 6-D phase space density (brightness) consistent with HIF target requirements.**
- **Space charge neutralization and focusing of ion beams with compression tilt and compatible with cryogenic targets.**
- **Transport beam arrays compact enough (>0.1A/cm^2 ave. @ β>0.2) to support induction linac efficiencies ηG > 10 at full driver scale.**
- **Beam loss < 10^{-5}/m due to gas/electron cloud effects at driver scale current and pulse rates for longer than vacuum equilibration times.**

Proposed HIF R&D common to all HIF target options:

thick liquid protected chamber

Although HIF can in principle use any type of fusion chamber, thick-liquid-protected chambers are preferred: lower cost R&D compared to solid first wall materials R&D, and ion beam propagation and final focusing magnets are compatible with high temperature Flibe vapor.

HYLIFE-II chamber used oscillating Flibe jets (Ralph Moir)



Ref. - S.S Yu, W.R. Meier et al., *Fusion Science and Technology*, **44**, No.2, 266 (2003).

Robust Point Design power plant parameters

Driver energy, MJ	7.0
Target gain	57
Target yield, MJ	400
Pulse rep-rate, Hz	6.0
Fusion power, MW	2400
Thermal power, MWt	2832
Conversion efficiency, %	44
Gross electric power, MWe	1246
Auxiliary power, MWe	50
Pumping power, MWe	27
Driver efficiency, %	38
Driver power, MWe	110
Net electric power, MWe	1058
Driver cost, $B	2.78
Other plant costs, $B	2.27
Total power plant cost, $B	5.05
COE, ¢/kWeh	7.18

Costs need to be updated, but not expected to be out of line with other IFE concepts

Per Peterson proposes cost-effective scaled liquid chamber R&D

P.F. Peterson Fusion Technology, Vol 39, No. 2, pp.702-710, 2001 "In fortuitous cases, systems can have many spatial and temporal boundaries where the coupling between phenomena is weak. When the coupling at such boundaries is weak, in experiments it becomes much easier to artificially replicate the boundary forcing and initial conditions to study subsets of phenomena. Thick-liquid IFE target chambers have a surprisingly large number of such spatial and temporal boundaries where substantial phenomena decoupling occurs."

Table 1. Representative experimental facilities for studying coupling in subgroups of IFE phenomena. For each time scale, energy, mass and momentum fluxes are negligible or strongly unidirectional between the specified spatial volumes.

Spatial Volume	Time Scale (Phenomena Duration)			
	Nanosecond	Microsecond	Millisecond	Quasi-Steady
Capsule	NIF/Omega	Z / NIF / Shock Tube	Flibe Cond.	—
Hohlraum/Convertors	HCX/IRE			—
Beam Paths	HCX/IRE			Flibe Cond.
Pocket Void/Vent Paths	—			—
Ablation Layers	Cross-section			
Condensing Region	—	Shock Tube		—
Pocket Liquid	Cross-section	Liq. Relax.	Water Exp.	—
Magnets/Solid Shielding		—	—	Mech./Activ.
Chamber Structures		—	—	Chem./Mech./ Activ./Safety
Coolant Recirc./Heat Recovery/Chemistry Control	—	—	—	Flibe Chem./Safety
Accelerator	HCX/IRE	—	—	—
Target Injection	—	—	Gas Gun	—
Target Fabrication	—	—	—	Target Fab.
Balance of Plant	—	—	—	Safety

Liquid chamber hydraulics experiments can be performed in university-scale facilities (Per Peterson, UCB)

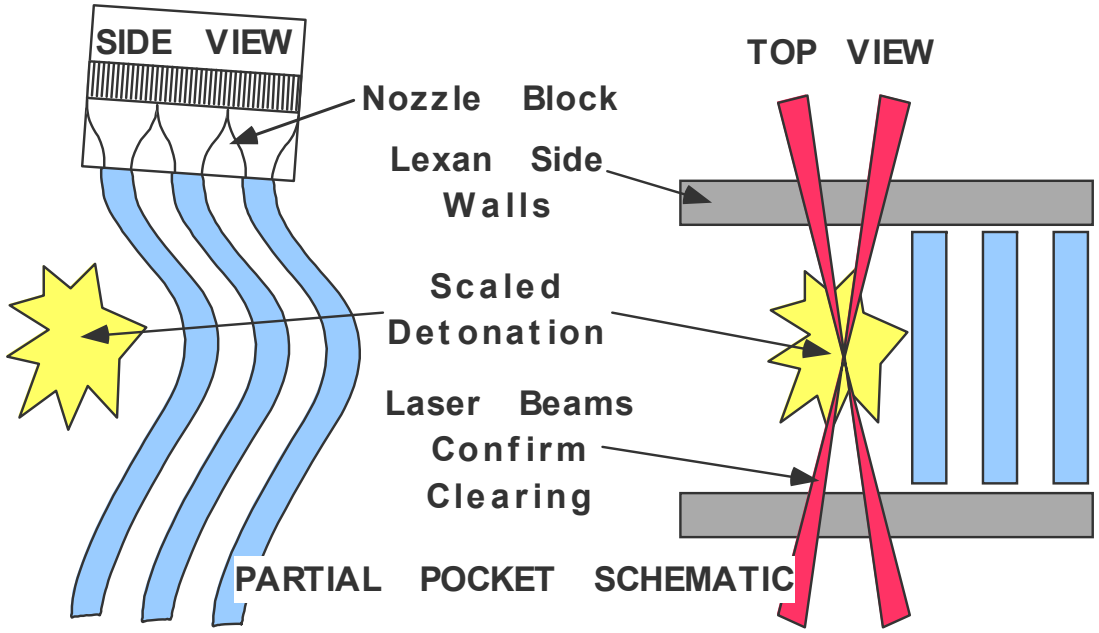
- Example: UCB facility studies single jets and few jets (partial pockets).
- Transient flow into large vacuum vessel
- 4.0 m^3 supply tank, 10-cm diameter supply line
- Jet velocities to 13 m/s
- Flow rates to 40 kg/s for over 1 minute
- Water used to simulate Flibe (allows Re, Fr and We number matching at 1/2 to 1/4 geometric scale)

Thick liquid experiment scaling (Per Peterson, UCB)

	Single/Few Jet			Integral System	
	HYLIFE	Single Jet	Partial Pocket	HYLIFE	HITF
Geometric Scale	1.0	0.24	0.24	1.0	0.44
Volumetric Flow (m^3/s)	0.84	0.017	0.16	75	9.5
Oscillation Freq. (Hz)	6.0	27.0	12.2	6.0	9.0
Nozzle Velocity U (m/s)	12.0	13.0	5.9	12	8.0
Number of Jets	1	1	10	~90	~90
Jet Dimensions Dx W (cm)	7.0 x 100	1.62 x 8.1	1.62 x 16	various	various
Pumping Power (kW)	360	2.2	21	32,000	2,400
Storage Tank Size (m)	N/A	4.0	4.0	N/A	300
Flow Duration (sec)	□	230	25	□	31
Jet Reynolds Number† Re	2.43×10^5	2.20×10^5	0.99×10^5	2.43×10^5	2.43×10^5
Jet Weber Number† We	1.03×10^5	0.39×10^5	0.08×10^5	1.03×10^5	0.26×10^5
Froude Number† Fr	7.3	36.0	7.3	7.3	7.3
Working Fluid	Flibe	Water	Water	Flibe	Water

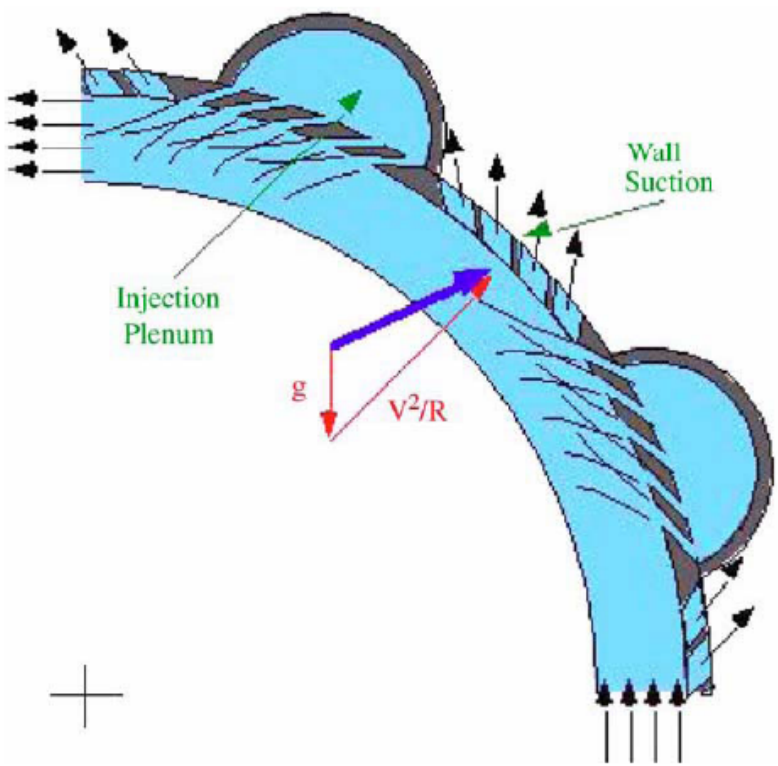
Partial pocket experiments (Per Peterson, UCB)

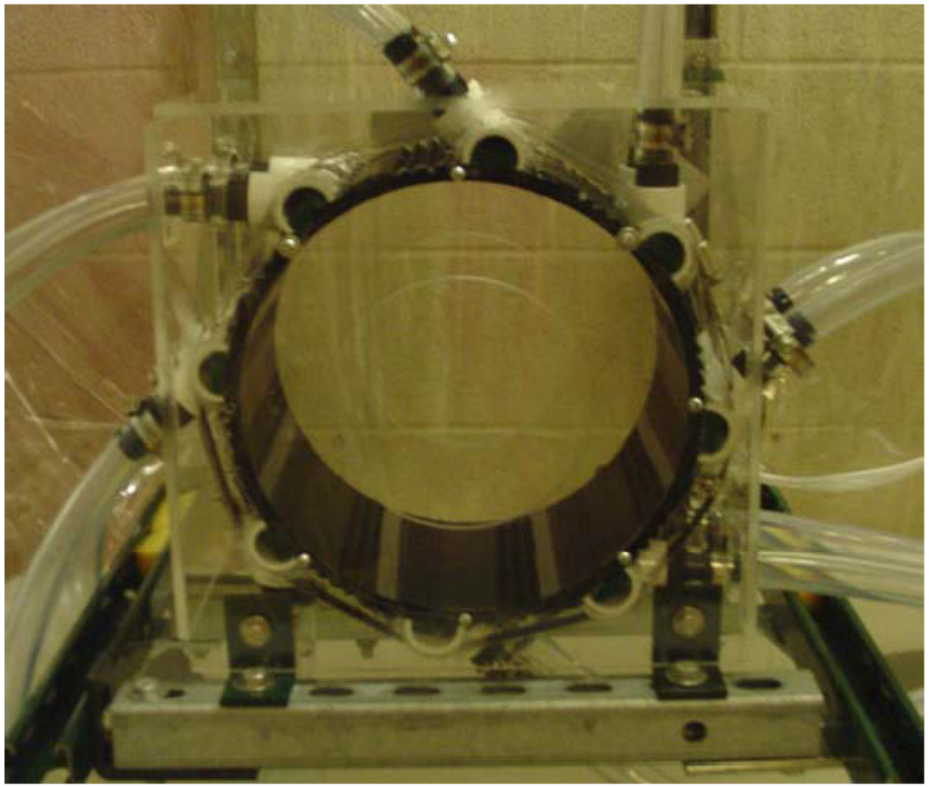
- 1/4-scale partial pocket multiple-jet experiments to study:
  - Jet (various configurations) disruption by scaled fuel-oxidizer detonation
  - Shock propagation and droplet/slug generation from multiple colliding jets
  - Forced clearing of droplets confirmed by laser-beam diagnostic



- Supports Phase-II Hydraulics Integral Test Facility (HITF) design

UC Berkeley worked on modeling and experiments in support of vortex chamber concept





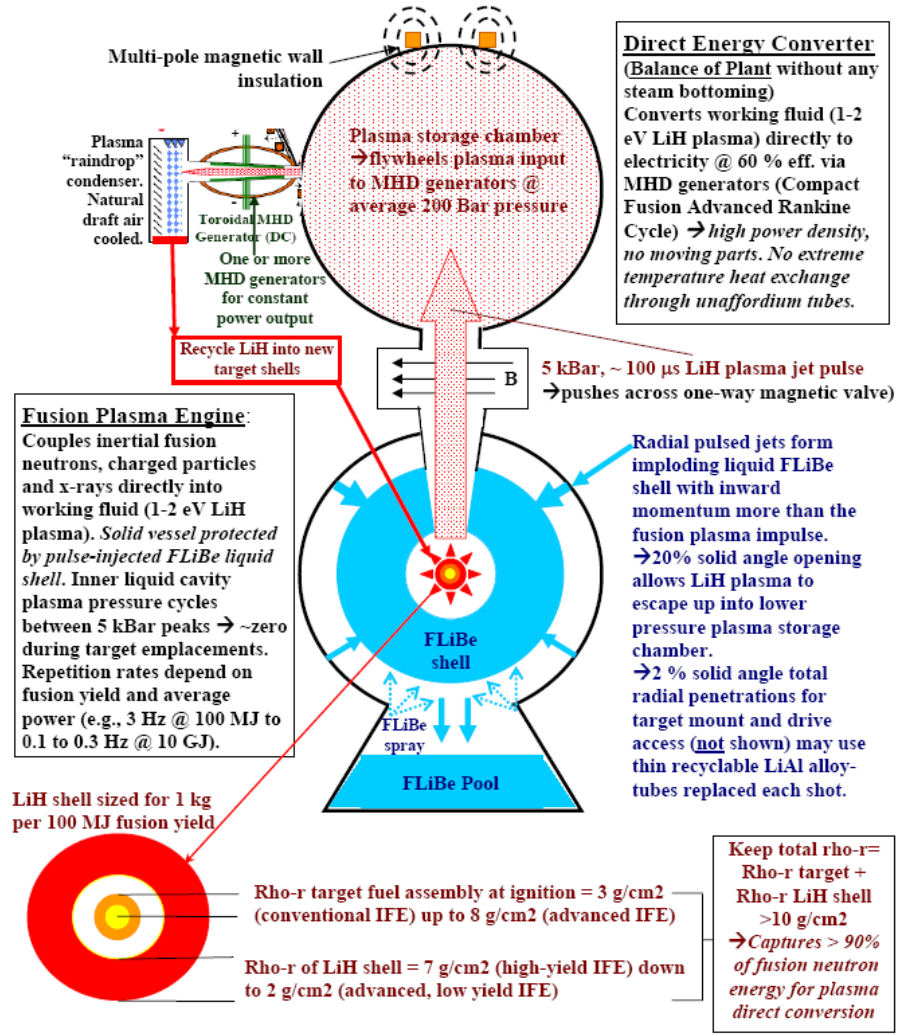
Per F. Peterson, Philippe M. Bardet, Christophe S. Debonnel, Grant T. Fukuda, Justin Freeman, Boris F. Supiot

High energy density plasma *(energy conversion!)*

"Subsidies or taxes should not be counted on to sustain non-carbon alternatives in the long term, if those alternatives cannot become competitive with coal" ←Steven Chu

An IFE driver, target factory, chamber and primary coolant loop must total less than 3 cts/kW$_e$hr (< ~1 B$) to replace a coal boiler and CO_2 scrubber, *if the IFE Balance-of-Plant also costs $1B.*

What if the working fluid for an IFE engine (laser, heavy ion, or pulsed power) could capture 100 MJ of target yield/kg, including most neutron energy, for direct MHD conversion to electricity @ 60% efficiency and for less than 0.5 cts/kW$_e$hr cost?



Interested? Email John Perkins or myself, re 2-pg white paper. Join us in this exploration.