Elements of a Heavy Ion Fusion R&D roadmap/options

B. Grant Logan, Heavy Ion Fusion Science Virtual National Laboratory*

Program Advisory Committee review December 8, 2010 at LLNL

The NAS-IFE charges…

- Assess the prospects for generating power using inertial confinement fusion;
- Identify scientific and engineering challenges, cost targets, and R&D objectives associated with developing an IFE demonstration plant; and
- Advise the U.S. Department of Energy on its development of an R&D roadmap aimed at creating a conceptual design for an inertial fusion energy demonstration plant.

A subpanel on Fusion Target Physics will assess the current performance of fusion targets associated with various ICF concepts in order to understand: 1. The spectrum output; 2. The illumination geometry; 3. The high-gain geometry; and 4. The robustness of the target design.

…and NIF implosion data prompt us to re-examine target options and R&D steps towards a Heavy Ion IFE Demo.
We have started a preliminary HIF plan for NAS, but it is still not complete.

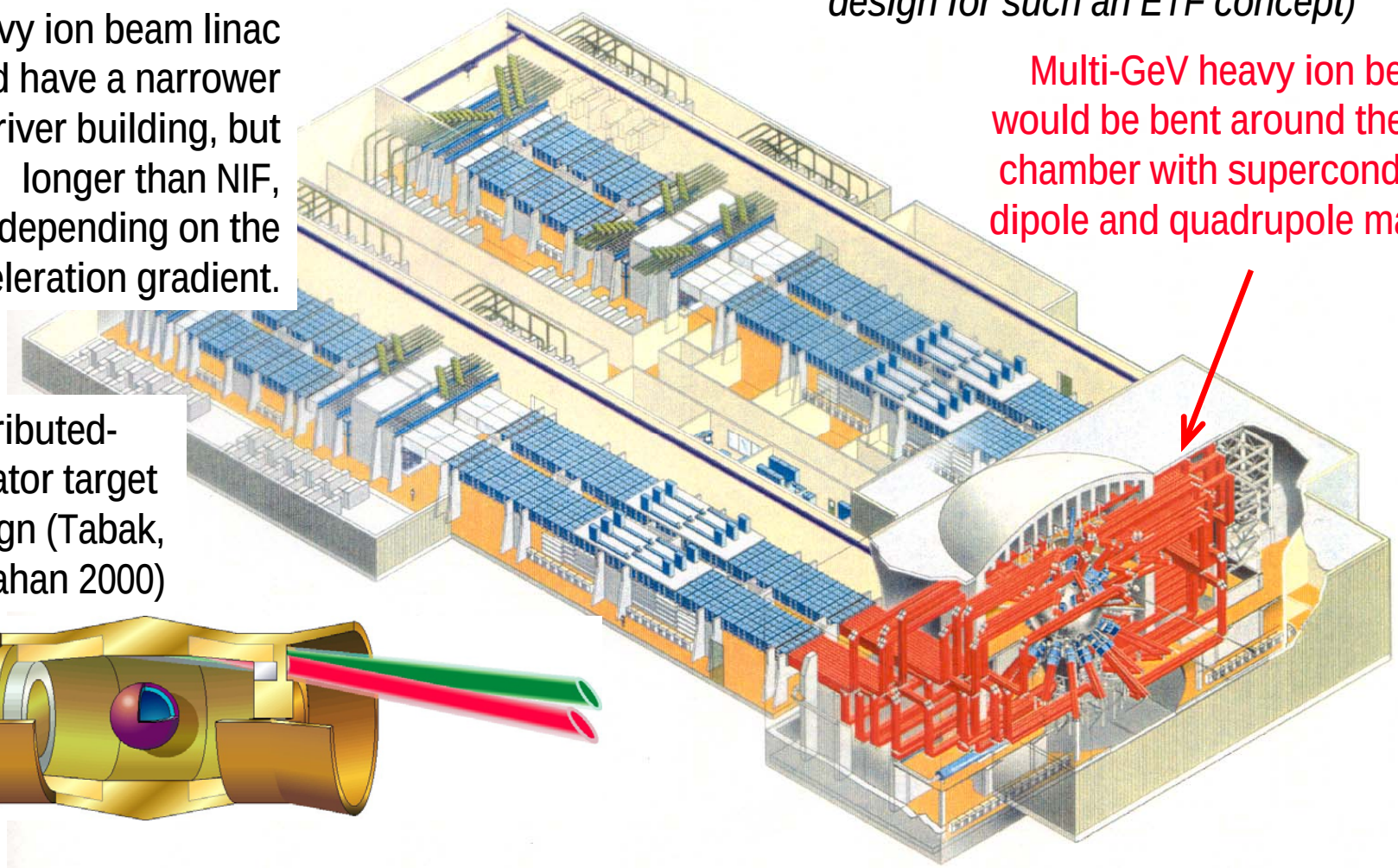
*This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Berkeley and Lawrence Livermore National Laboratories under Contract Numbers DE-AC02-05CH1123 and DE-AC52-07NA27344 , and by the Princeton Plasma Physics Laboratory under Contract Number DE-AC02-76CH03073.

A single-shot ignition-scale facility for indirect drive heavy ion fusion using a two-sided hohlraum (as below) would need a similar energy of 1-2 MJ, and a similar number of beams (100-200), as NIF. A heavy-ion-accelerator for a single shot ignition test would ~ same cost for a 5 Hz Engineering Test Facility→ upgrade the ignition test facility to 5 Hz for 150 MW fusion for an ETF.

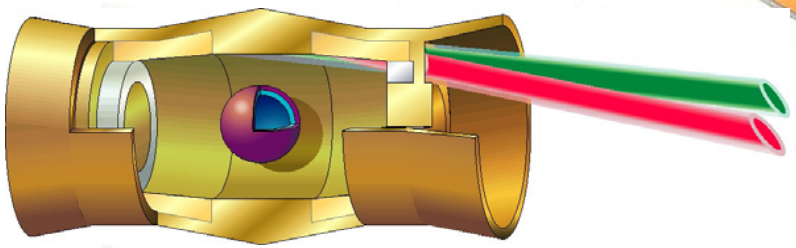
(We have not yet attempted a engineering design for such an ETF concept)

A heavy ion beam linac would have a narrower driver building, but longer than NIF, depending on the acceleration gradient.

Multi-GeV heavy ion beams would be bent around the target chamber with superconducting dipole and quadrupole magnets.



Distributed-radiator target design (Tabak, Callahan 2000)



(A look back…..)

An Engineering Test Facility for Heavy Ion Fusion – Options and Scaling *

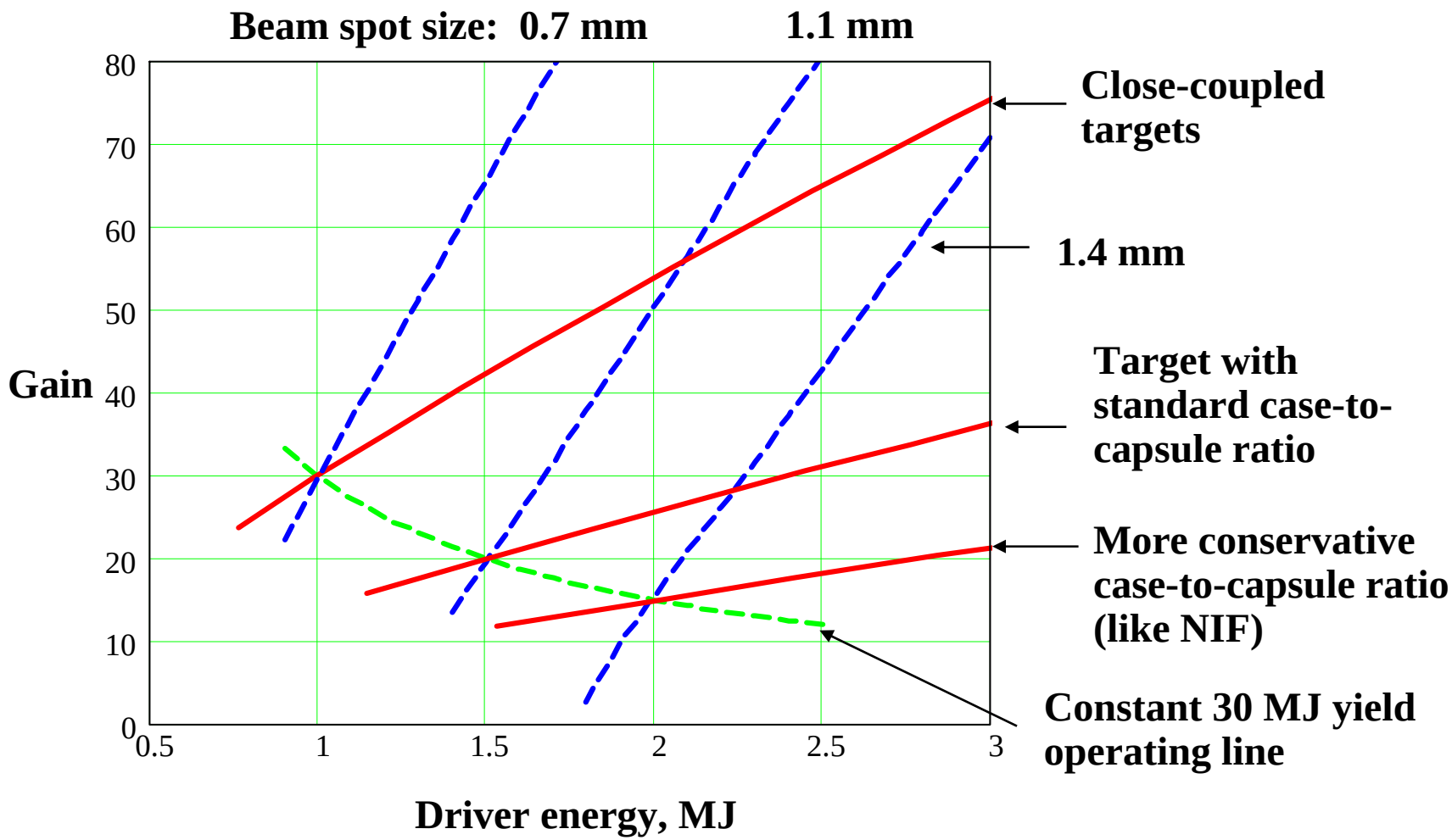
W.R. Meier, D.A. Callahan-Miller, J.F. Latkowski,
B.G. Logan, J.D. Lindl
Lawrence Livermore National Laboratory

P.F. Peterson
University of California, Berkeley

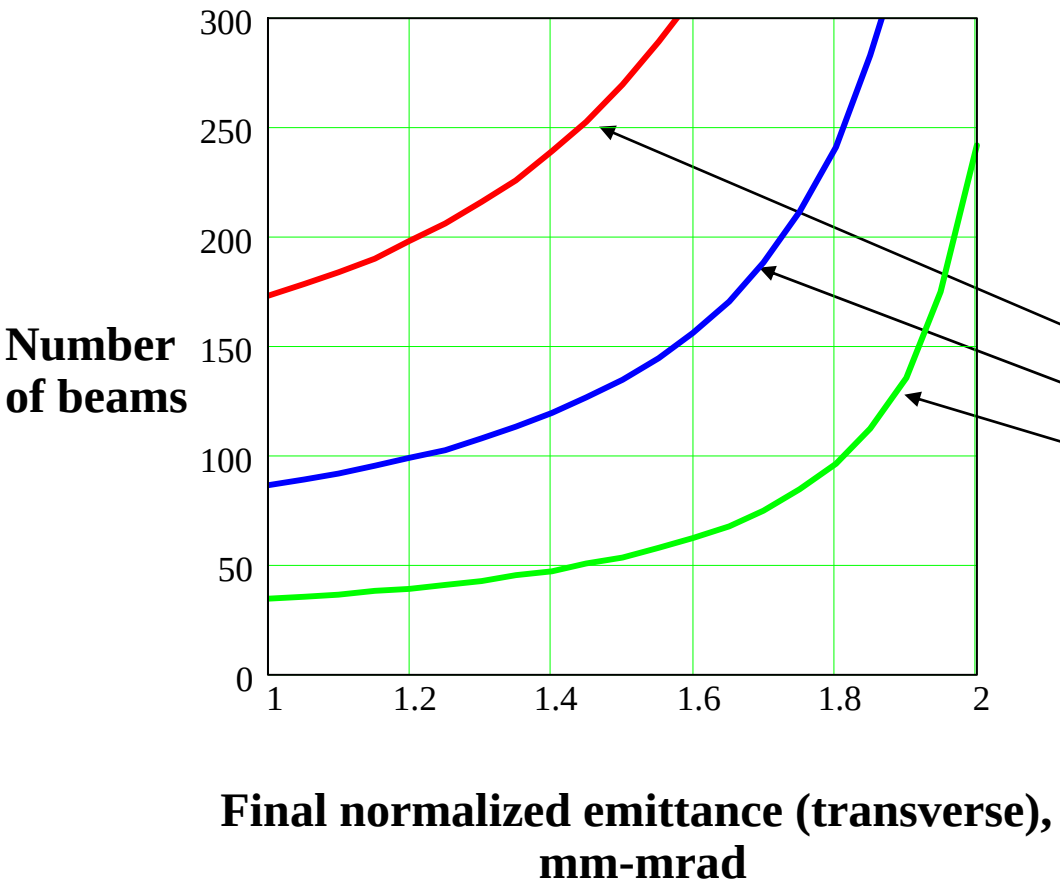
14th Topical Meeting on the Technology of Fusion Energy
October 15-19, 2000

*** This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.**

Driver energy and focusability will limit range of targets that can be investigated



Relationship between number of beams, emittance and neutralization for a given spot size



Assumes
Cs^{+1}
Ed = 2 MJ
Rspot = 1.4 mm
$\delta P/P$ = 0.1%

Neutralization:
90%
95%
98%

Example:
ε_n =1.6 mm-mrad
f_n = 95% neutralization
requires ~ 160 beams

Chamber dynamics can be investigated at reduced scale (Per Peterson)

- For thick liquid wall chambers, there are a variety of non-dimensional parameters to scale various effects (e.g, surface flux, impulse loading, neutron induced motion)

- Scaling as $(\text{yield})^{0.37}$ is proposed. The 0.37 scaling coefficient is midway between the 0.24 needed to preserve impulse loading and 0.5 needed to preserve debris induced thermodynamics and is close to the 0.4 needed to preserve neutron induced motion.

- For a 30 MJ ETF, all dimensions are reduced by

  $L/Lo = (30/350)^{0.37} = 0.4$

- By varying the target yield about this design point, different chamber dynamics effects can be more closely matched

Target fabrication and injection system requirements will be demanding

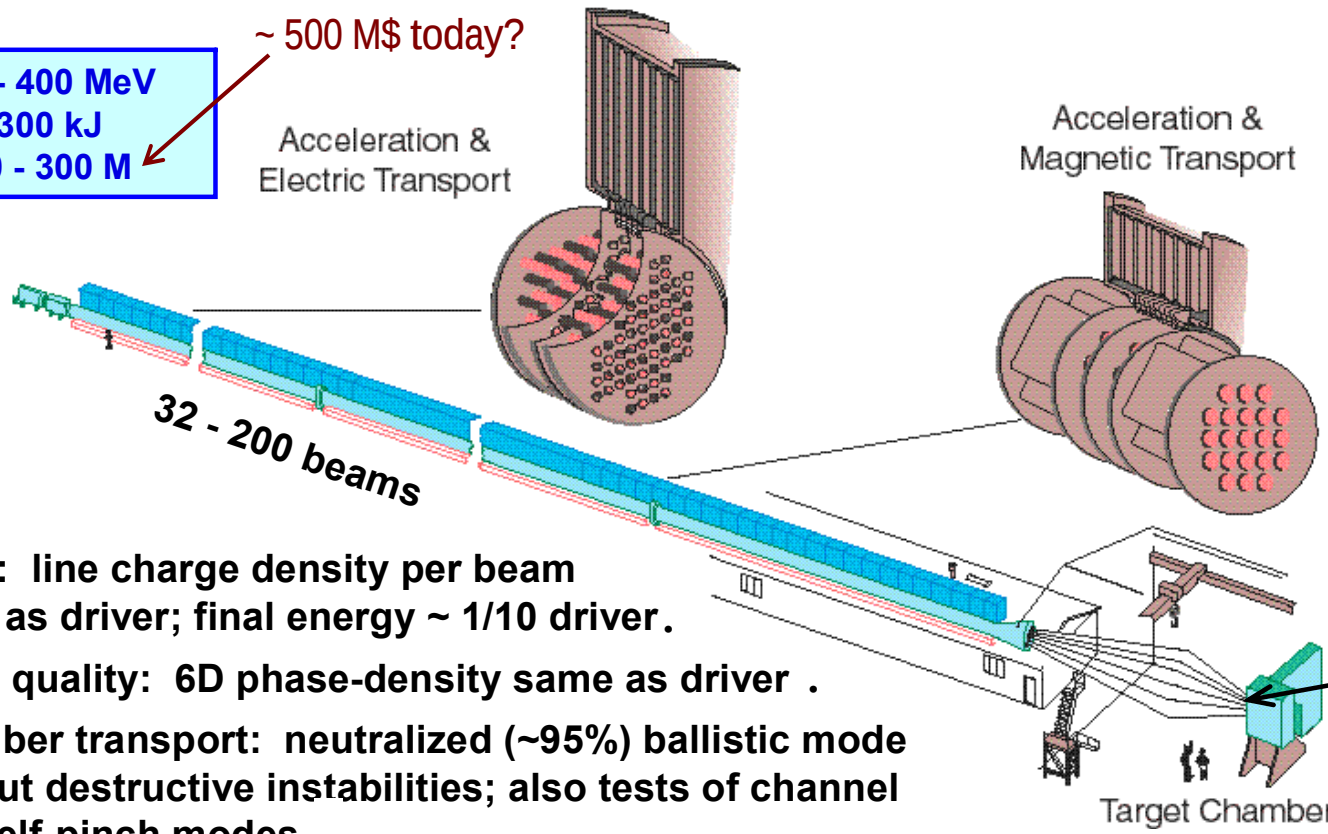
- Target fabrication requirements will range from single-shot tests to batch mode to steady production
- Rep-rate and surface quality requirements will exceed commercial systems because capsules are smaller
- Because chamber scaling preserves the relative effects of inertia an gravity, the scaled targets will follow the same scaled injection trajectory, and the precision at shorter length should improve.
- Target size scaling with yield ($Y^{0.34}$) is close to chamber/ injector scaling $Y^{0.37}$

Heavy ion beam focal spot sizes increase with lower 200- 400 MeV ion energy, while focal spot sizes needed for a 10 kJ-scale implosion target experiment are < 0.5 mm: we propose R&D for shorter focal length magnets with two stages of focusing to enable Heavy-Ion Driven Implosion eXperiments (HIDIX) using an 10-kJ-scale accelerator.

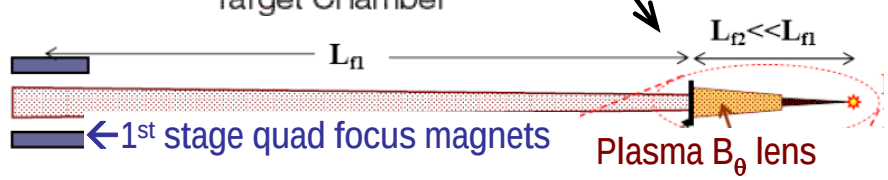
~ 200 - 400 MeV
~ 30 - 300 kJ
~ $150 - 300 M

~ 500 M$ today?

We will improve description of the IRE/HIDIX capability in the next month or two.



Integrated Research Experiment (IRE) concept considered at Snowmass 2002 with two-stage focusing.



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

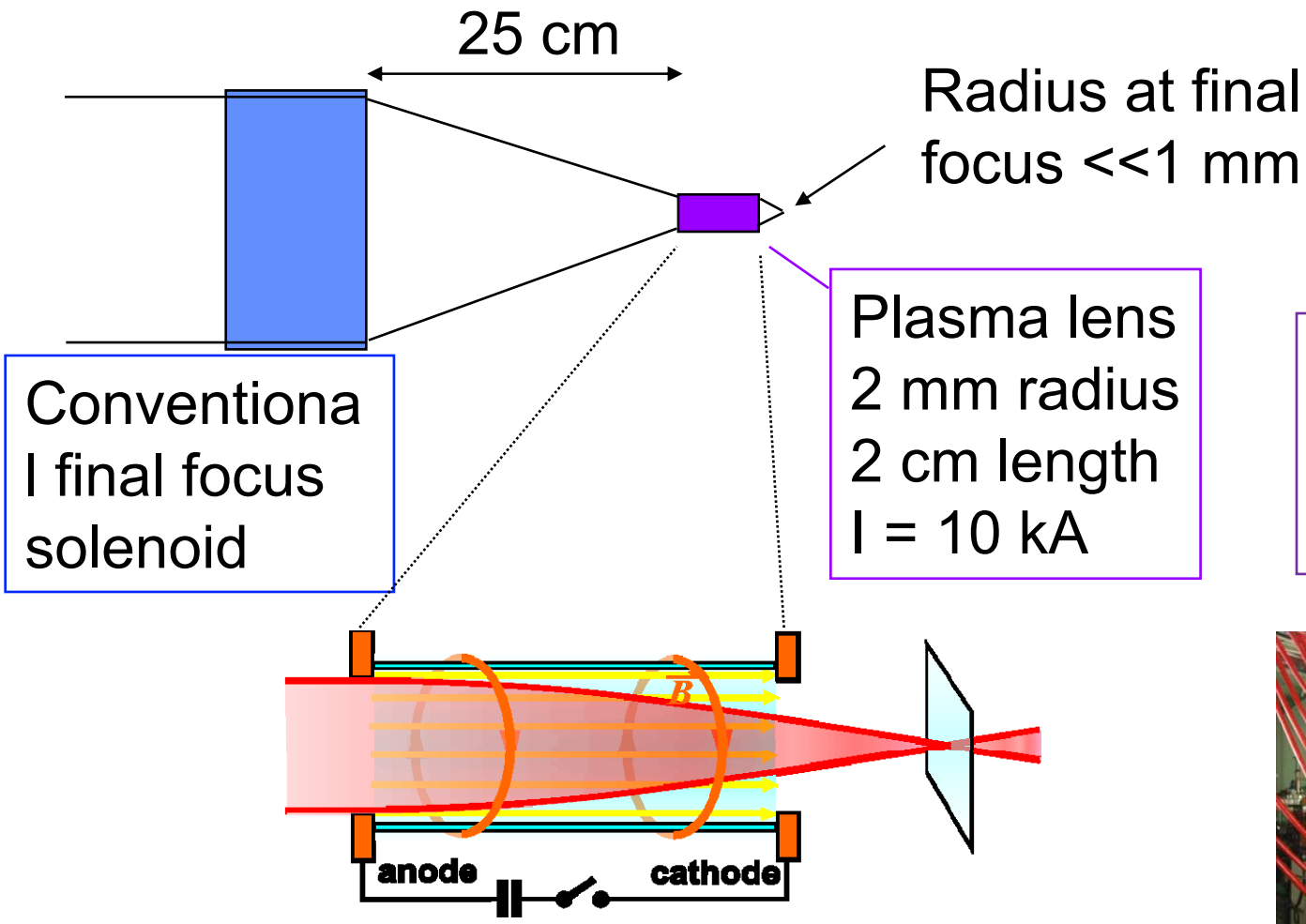
Beam quality: 6D phase-density same as driver .

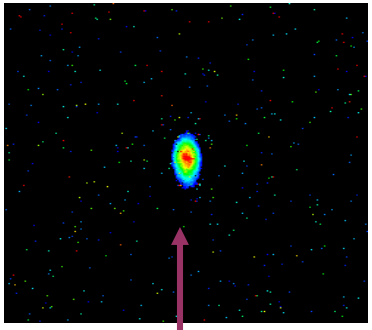
Chamber transport: neutralized (~95%) ballistic mode without destructive instabilities; also tests of channel and self-pinch modes .

Chamber technology: test driver/chamber interface .

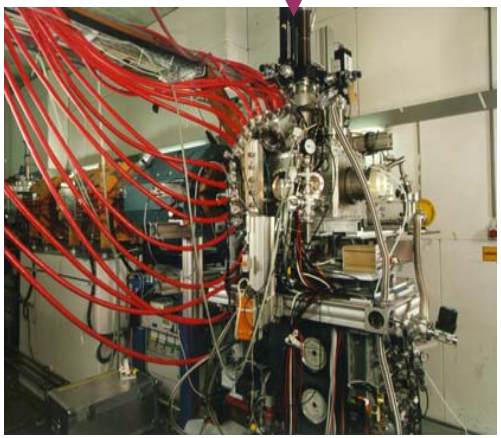
Target temperature: 50 - 100 eV .

NDCX-II experiments can explore two-stage focusing, using a miniature "B_θ" plasma lens.

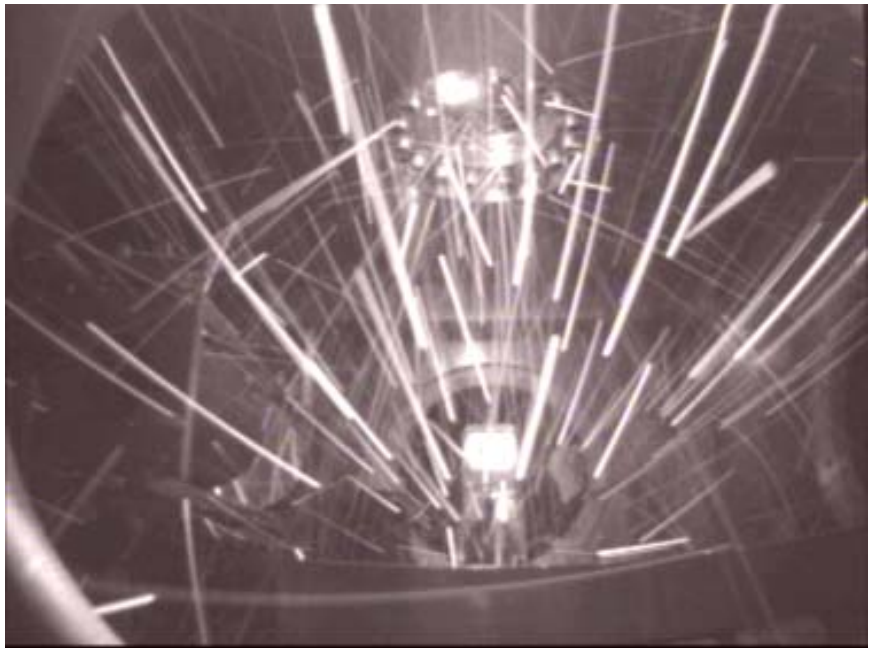




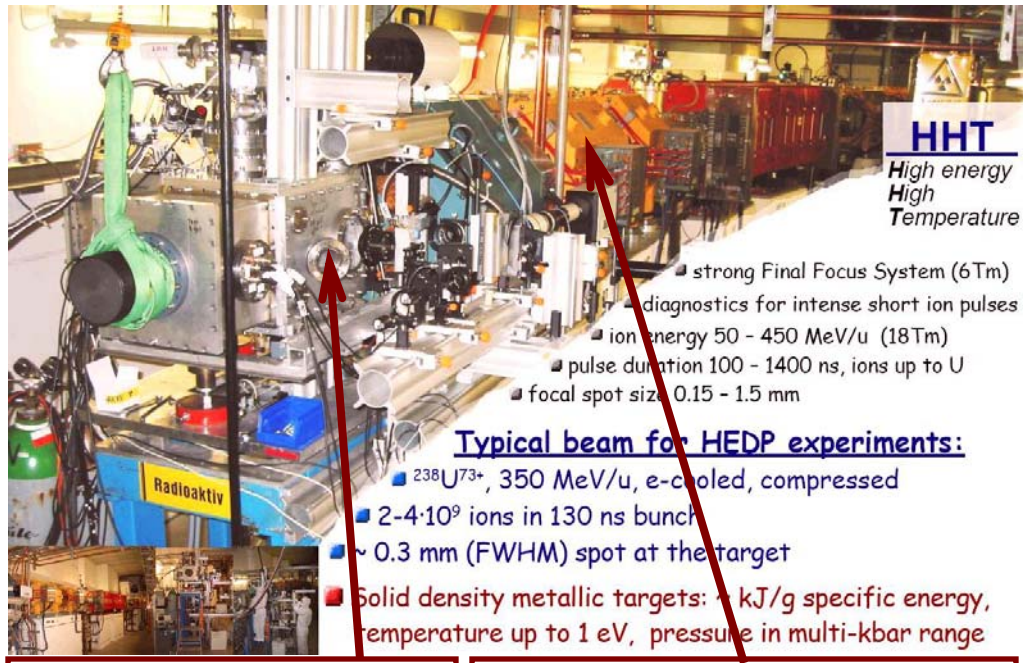
E.g.: GSI plasma lens (240 kA)→ 400 μm spots @ 10 π mm-mr, 80 GeV U



LBNL targets have been heated with~ 0.3 A of 83 GeV U^{+73} ions focused to 150 micron radius spots on target at GSI



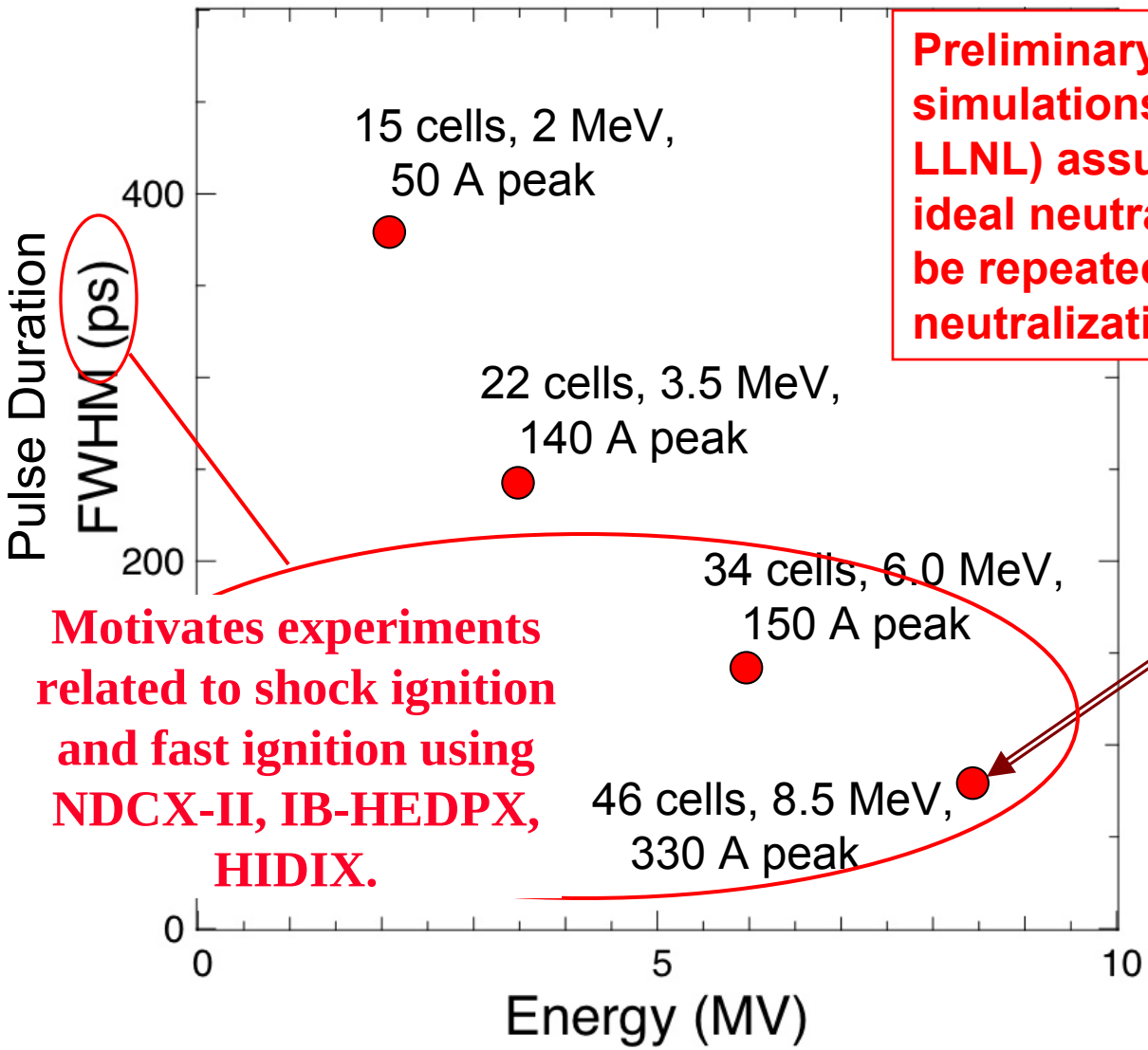
Visible ms camera frame showing hot target debris droplets flying from a VNL gold target (~ few mg mass) isochorically heated by a 130 ns, 50 J heavy ion beam to ~ 1 TW/cm^2 peak and 1 eV in joint experiments at GSI, Germany.



Diagnostic optics

Final focus magnets

Simulations show compressed pulse duration in NDCX-II varies ~ inversely with kinetic energy—the same could be true for an IRE/HIDIX



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.

Motivates experiments related to shock ignition and fast ignition using NDCX-II, IB-HEDPX, HIDIX.

We have 50 ATA cells to use, and could be added in < 2 years!

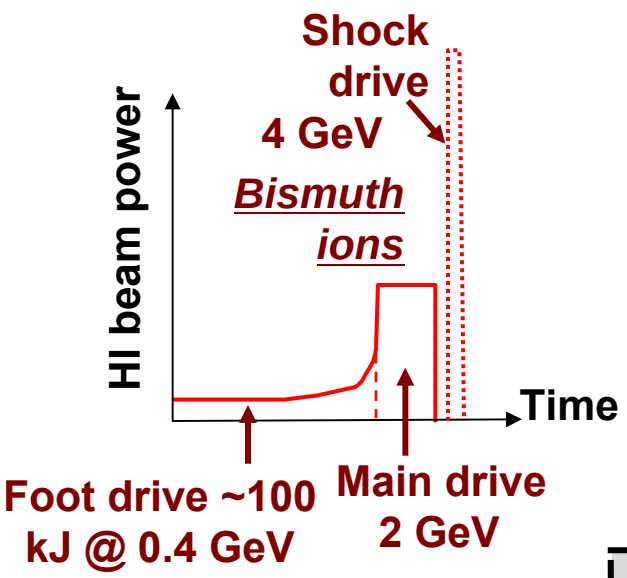
Work plan in heavy ion fusion target design (next few months)

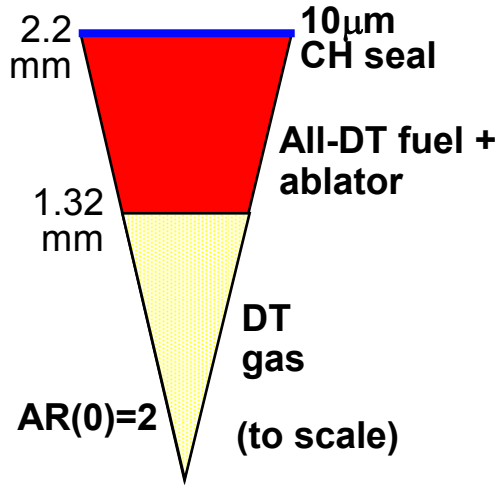
- **A backup plan to use NIF beams to test polar-drive with shock ignition (lower implosion velocity, lower convergence ratio, more tolerant of mix) can be also considered for HIF (John Perkins)**

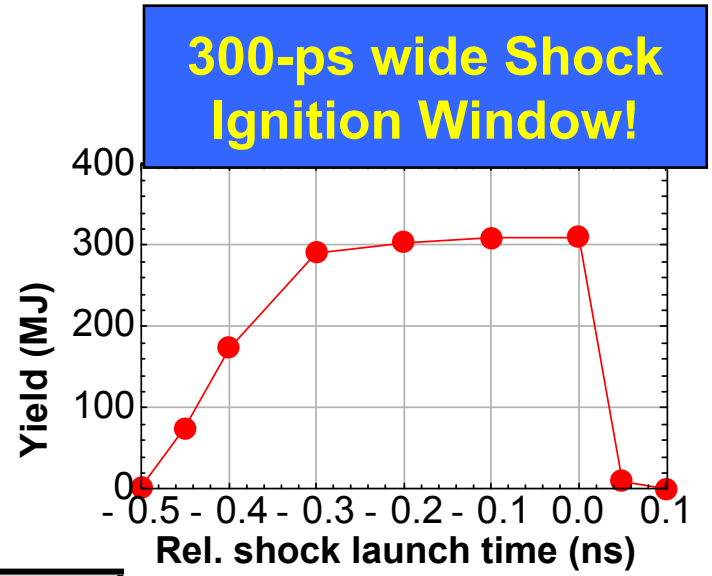
- **Our plan is to assess time dependent beam pointing in 2-D polar drive/shock ignition with heavy ion beams after a successful design is first found for NIF.**

- **The X-target is another potential HIF solution that has even less fuel convergence and is even more robust to RT mix. Explore several ways to increase the gain.**

HIDIX might test shock heating in polar drive geometry at Omega scale energy. [Slide below shows an example of heavy ion shock ignition (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 = $r_{shell\text{-}in}(0)/r_{HS}(t_{ign})$

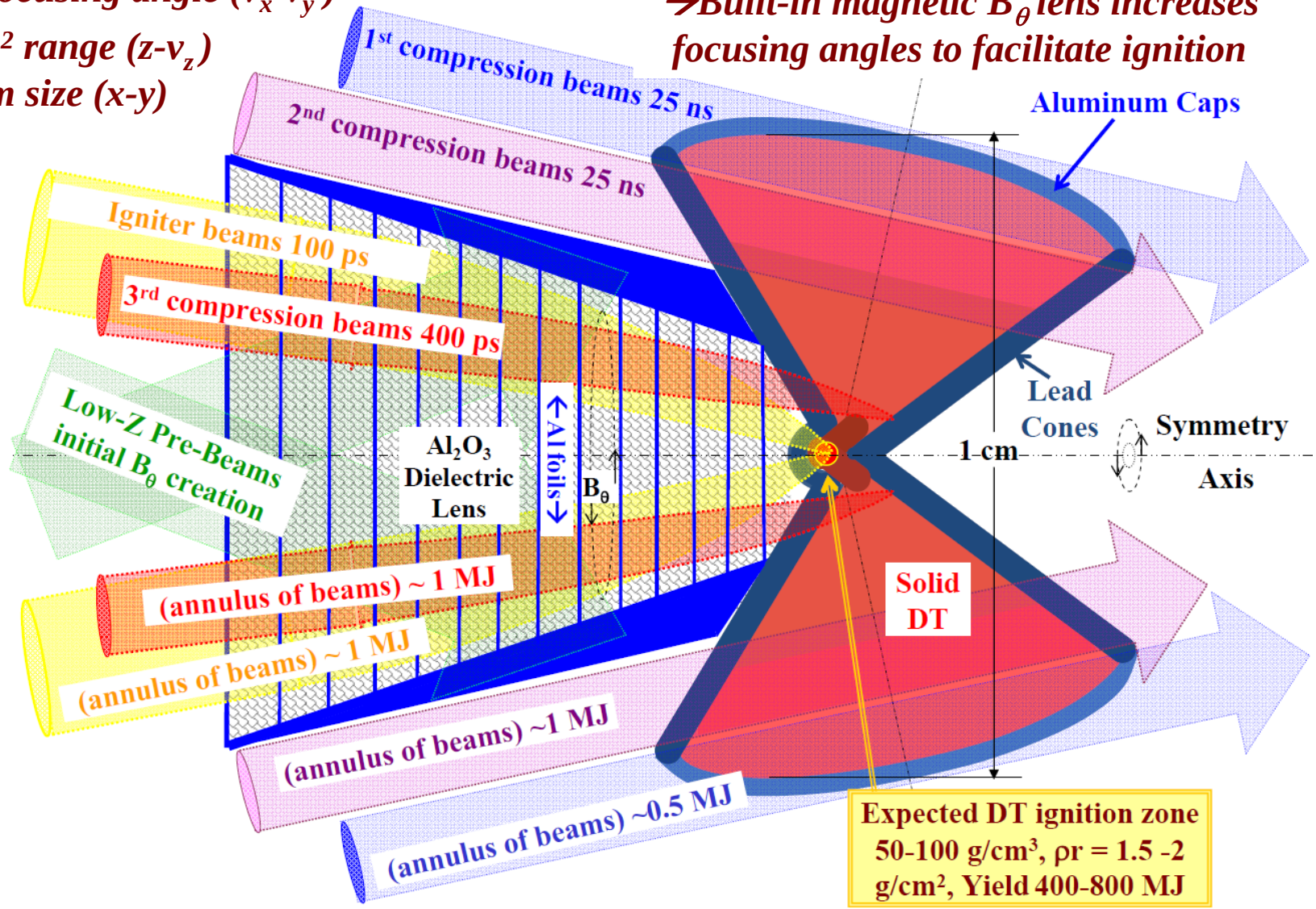
If self focusing can be validated, the X-target potentially enhances 6-D phase space (x, v_x, y, v_y, z, v_z) admittance sufficient for fast ignition→ facilitates accelerator design!

Big 1-rad focusing angle (v_x-v_y)

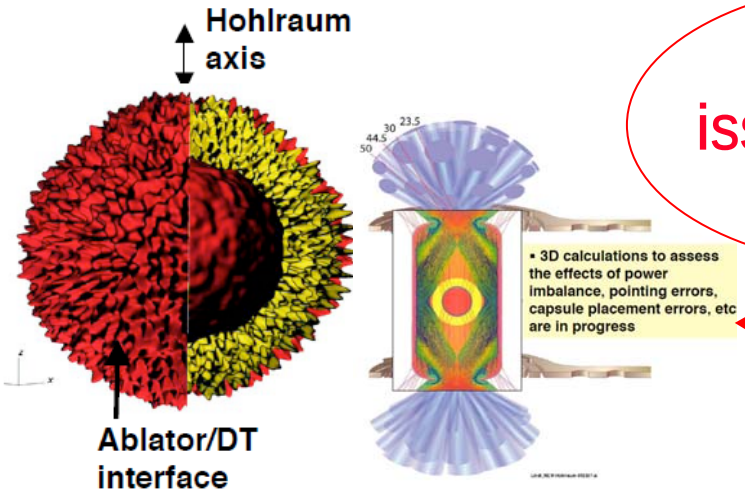
Big 1-g/cm^2 range (z-v_z)

Big 1-cm size (x-y)

→Built-in magnetic B_θ lens increases focusing angles to facilitate ignition



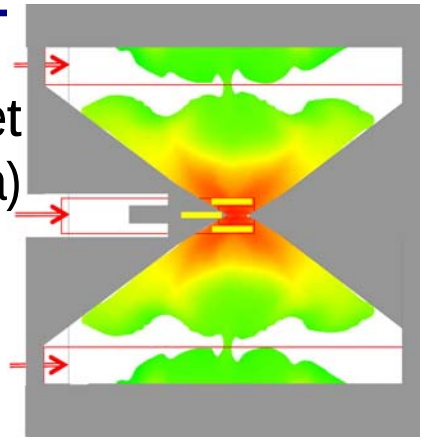
The X-target requires a different R&D path for HIF



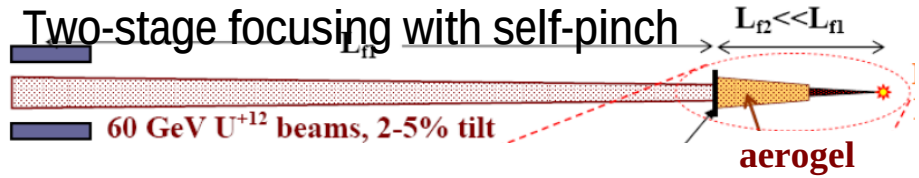
3-D HYDRA simulation of NIF hot spot

Different key issues→ different R&D paths!

X-target (2-D Hydra)



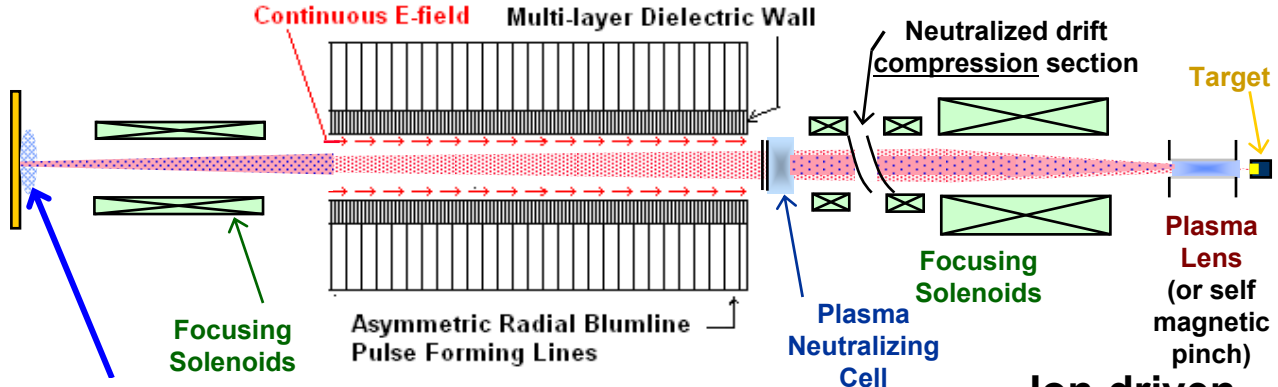
Two-stage focusing with self-pinch



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.

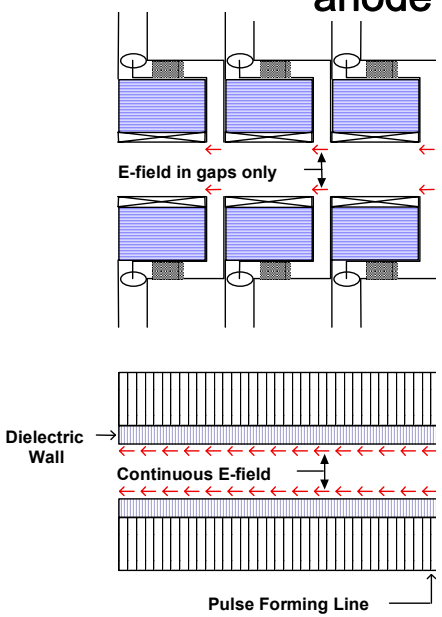
Potential driver collaboration with LLNL's Beam Research Program (George Caporaso): advanced, high gradient, high current DWA option

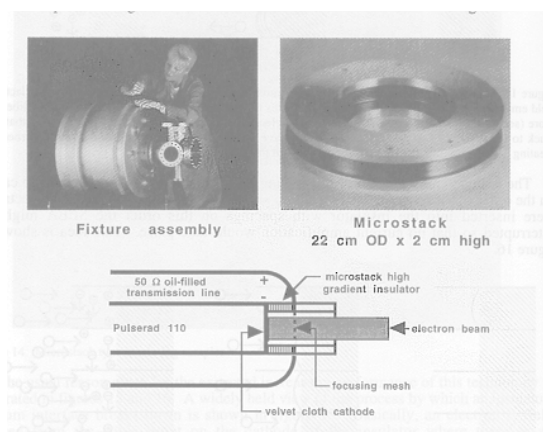


Short-pulse UV laser driven thermal/photo anode ion source

Dielectric Wall Accelerator ~20-30 MV/m

Ion-driven Target





A 30 m-long, 600 MV Dielectric Wall linac might also be a high gradient buncher to compress RHIC or FAIR HI beams from 100 ns down to 100 ps for fast ignition experiments.

With the new 100 TW compressor, the GSI Z-6 laboratory will have the capability to explore the laser driven magnetic lens concept in the near future

(Slide from Markus Roth, TU-Darmstadt)

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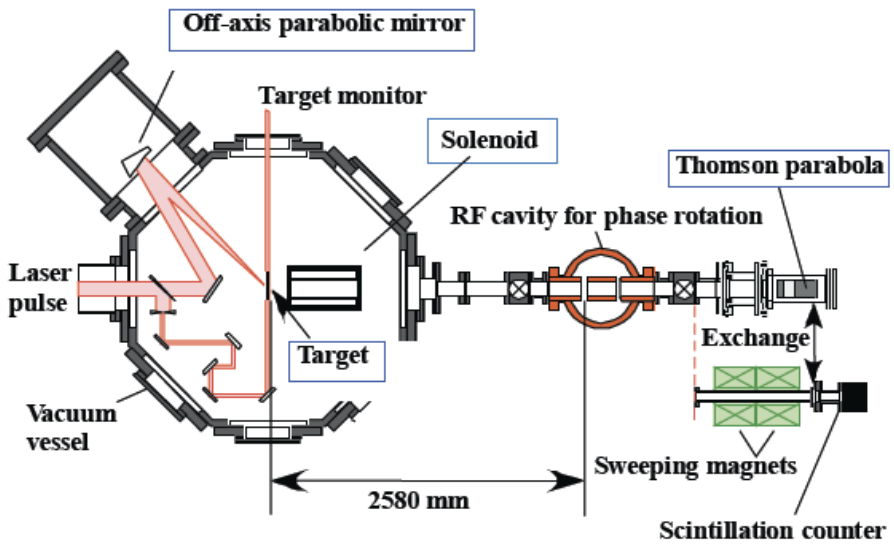
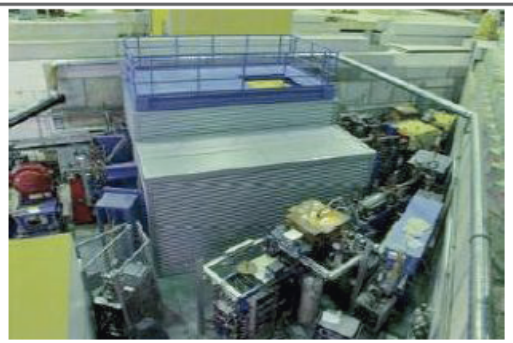
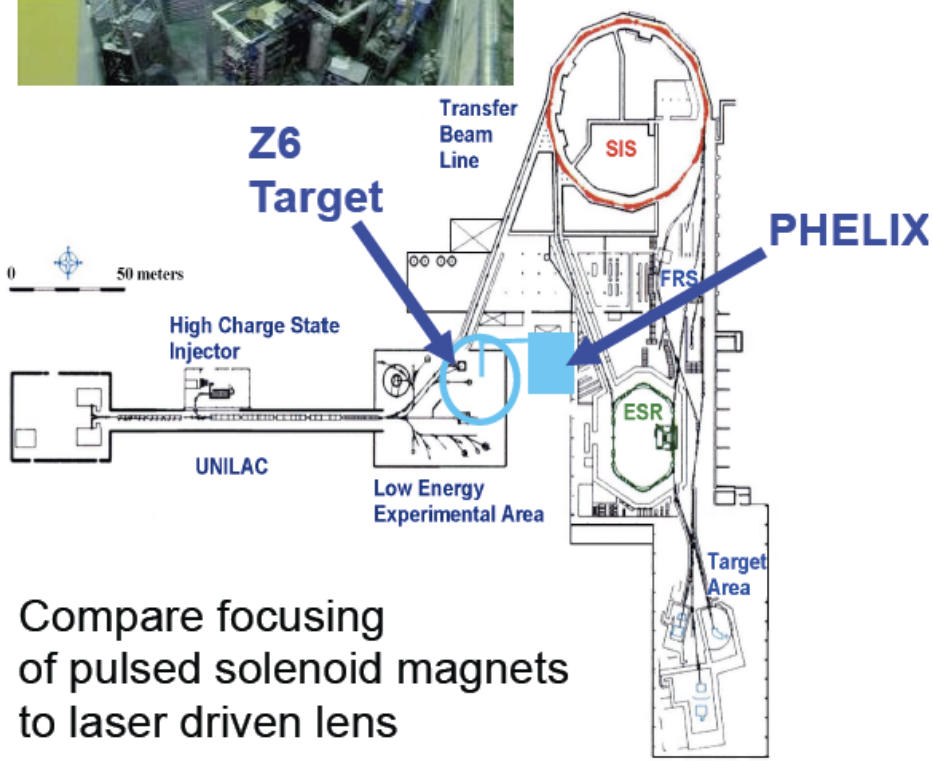
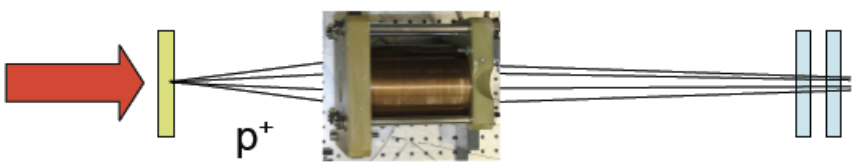
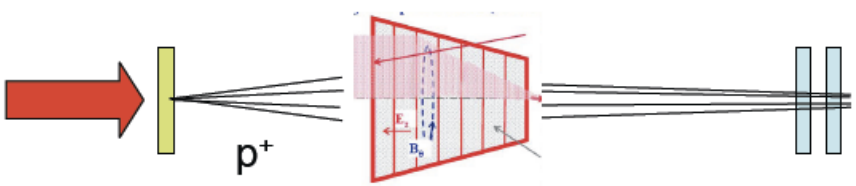






Solenoid





Compare focusing of pulsed solenoid magnets to laser driven lens

HELMHOLTZ GEMEINSCHAFT

GSI

Facility for Antiproton and Ion Research in Germany GmbH i.G.

Planckstraße 1
64291 Darmstadt

www.fair-center.eu

2010-11-11

Opportunity for International Collaboration on Heavy Ion Fusion Research using FAIR

Managing Directors:
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FAIR will provide intense heavy ion beams that can be used to explore hydrogen compression and heating, and to test new focusing optics using the world's highest energy and intensity heavy ion beams.

We encourage consideration of this opportunity for the benefit of heavy ion fusion research.

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E-Mail: b.sharkov@gsi.de

Darmstadt, November 11th, 2010

Boris Y. Sharkov
FAIR Scientific Director

Darmstadt, November 11th, 2010

B. Grant Logan

B. Grant Logan
US Heavy Ion Fusion Science
Virtual Natural Laboratory

Potential collaboration at LANL

- Following a meeting with LANL's accelerator division November 16-17, an MOU defining areas of collaboration on accelerator R&D using LANSCE facilities in support of heavy ion fusion is under preparation (Kurt Schoenberg)

Conclusions

•For different target options, specific R&D plans to an HIF-ETF/Demonstration Plant would be tailored to address different target and driver requirements and different technical risks.

→We keep options for HIF IRE/ETF open for now.
→All HIF target options could use low cost liquid protected chambers.
→Collaborations can enhance HIF R&D for accelerators and focusing.
→Near term plans based on NDCX-I-II, HCX, IB-HEDPX would not change.

Backup Slides

Timeline for research and development to determine the feasibility of power from heavy ion fusion

Fiscal Year	2008 → 2012	2013 → 2017	2018 → 2022	2023 → 2027	2028 → 2032
Integrated single beam experiments to maximize pressure in planar targets	8 → 14	25 → 15	15 → 10	5 → 5	
NDCX-I (to 10 kBar)		(at PPPL) 5			
NDCX-II[1] (to 1 MBar)					
IB-HEDPX[1] (to 10 MBar)	1	15 /yr @2.5yr	10		
		"Phase I"	Key decision (CD2 for HIDIX)		
Accelerator driver R&D for multiple-beam experiments	0.2 → 2	13 → 20	30 → 145	→115	→120
Enabling accelerator R&D (HCX-II)[2]	1	9 → 12	15	→ 20	→ 20
Enabling target R&D (design/fab/inj)	0.2 → 1	2 → 3	10	→ 15	→ 20
Long-path accelerator science (e.g.. UMER and Paul-Trap)	0.5 → 1	2 → 2	5		
Heavy Ion Driven Implosion Experiment (HIDIX) for symmetry (to 100 MBar)		2 → 5	120 x 6 yr	80	
			Key Decision (CD2 for HIFTF)		
Heavy Ion Fusion Nuclear Science and Technology[3]		2 → 5	10	→60	→350?
Cryo DT target and fuel cycle				→ 30	→ 30
Enabling liquid chamber R&D		2 → 5	10	→ 20	→ 20
Heavy Ion Fusion Test Facility (HIFTF) ~100 MJ yield x 5 Hz +400 MJ single shot				10 → 20	300 x 8 yr ? →
(All costs in M $ per year) Total HIF	8 → 16	40 → 40	55 → 165	180	470?

Preliminary draft (to be revised); decision criteria TBD

[1] Not including NDCX-II and IB-HEDPX operating & diagnostic support for HEDLP users
[2] Includes multiple beam injectors, transport, and final focus arrays needed for HIDIX
[3] Does not include MFE nuclear science and technology that maybe useful to HIF

Design | Construction | Operation/R&D

Some Phase I criteria for first five years (FY13 through FY17?) has been argued for laser IFE, but HIF criteria need to be tailored to HIF issues.

Target Design:

•Develop high-gain target designs based on at least 2-D codes, for FTF and a Prototype Reactor that demonstrate that the projected target gains are sufficient to meet the hG > 10 requirements for a viable IFE system.

•Obtain experimental results from existing facilities that provide confidence in the target design.

Driver:

•Develop sub-scale driver modules that demonstrate performance and lifetime of operation that scales to a prototype driver line for FTF.

Sub-scale components (including final) that are suitable for FTF lifetimes and damage threats spectra

Criteria for "passing Phase 1"

•Driver and target combination meets projected technical and economic requirements for an Engineering Test Facility.

•*Sub-fullscale tests are promising for the driver meeting performance criteria (efficiency, durability) and must at a minimum demonstrate 2 days of continuous operation (48 hours) without damage and with precise control of critical parameters (energy, pulse shape). The demonstrated driver technologies must be of sufficient size and nature to be directly scalable to a full size system.*

•Credible pre-conceptual designs for a complete FTF system (target fabrication, target engagement, optics, reaction chamber, tritium breeding, power conversion)

•Credible scale-up path from FTF to an economically and technically attractive full scale reactor. This includes

a. Sufficient η G where η is the projected driver efficiency and G is the gain.

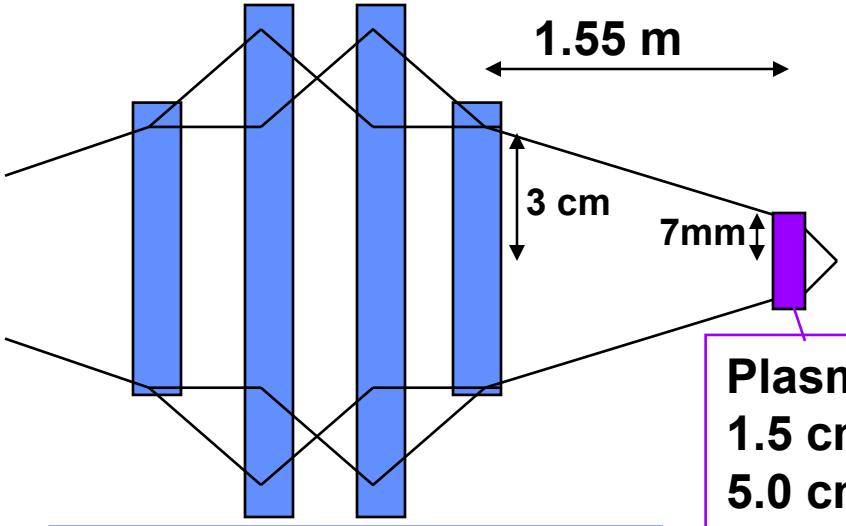
b. Cost of electricity of overall approach (driver, reaction chamber, target technologies)

•Premium will be assigned to lower overall costs for the FTF.

•An external review committee will be required to evaluate progress against these criteria

•Ignition on some facility is a pre-requisite.

A "double focus" (quads+ plasma lens may be used to reduce spot size to ~0.5 mm) in an IRE (John Barnard Snowmass 2002)



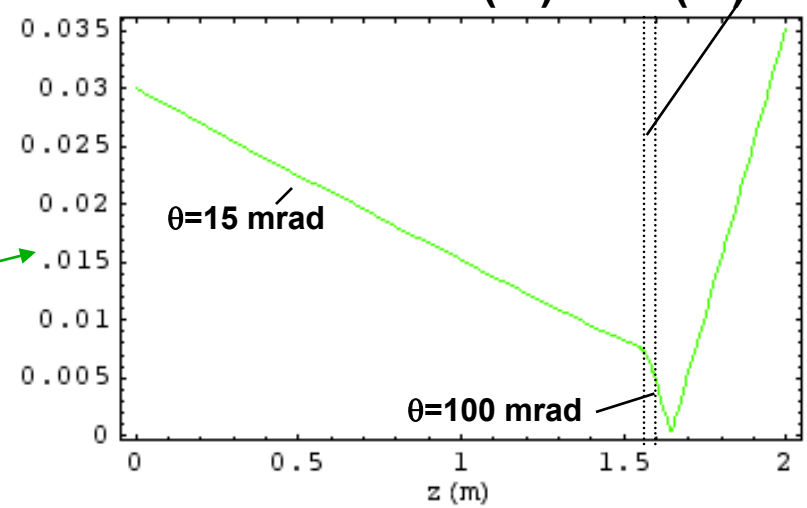
Radius at final focus ~0.5 mm

Plasma lens
1.5 cm radius
5.0 cm length
400 kA

Conventional final focus using quadrupoles

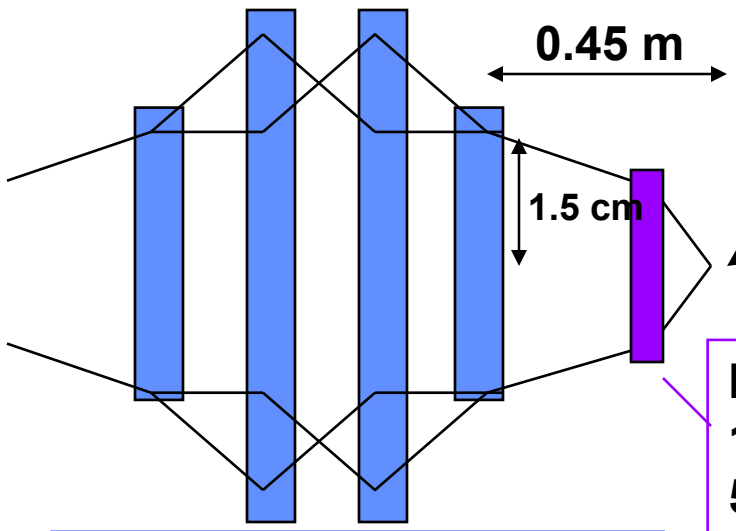
Plasma lens

Beam radius (m) vs. z(m)



Envelope plot for T=450 MeV Xe^{+}
Unneutralized perveance = 10^{-3}
99.5% neutralized
Stripped at plasma lens to Xe^{+26}
Normalized emittance =4 mm-mrad

A "double focus" could be tested on IBX (John Barnard, Snowmass 2002)



Radius at final focus ~ 1.0 mm

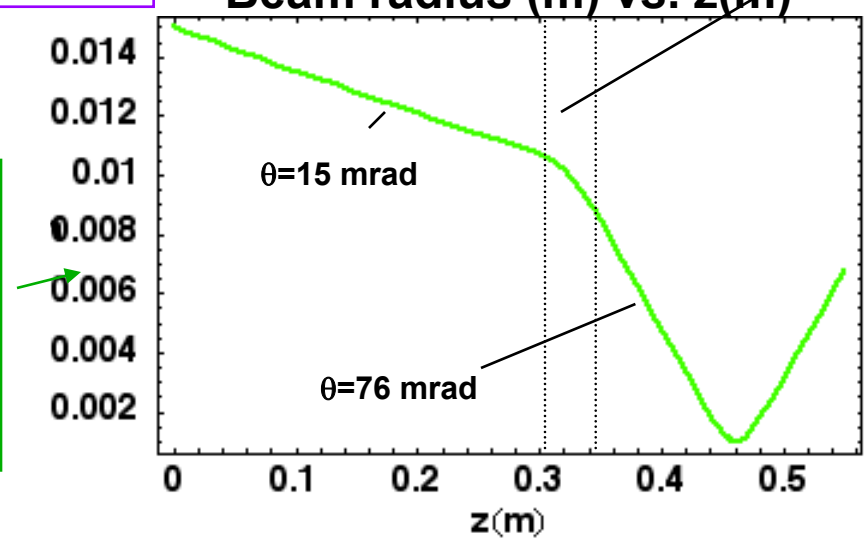
(Now same point for NDCX-II, and IB-HEDPX)

Plasma lens
1.5 cm radius
5.0 cm length
400 kA

Conventional final focus using quadrupoles

Plasma lens

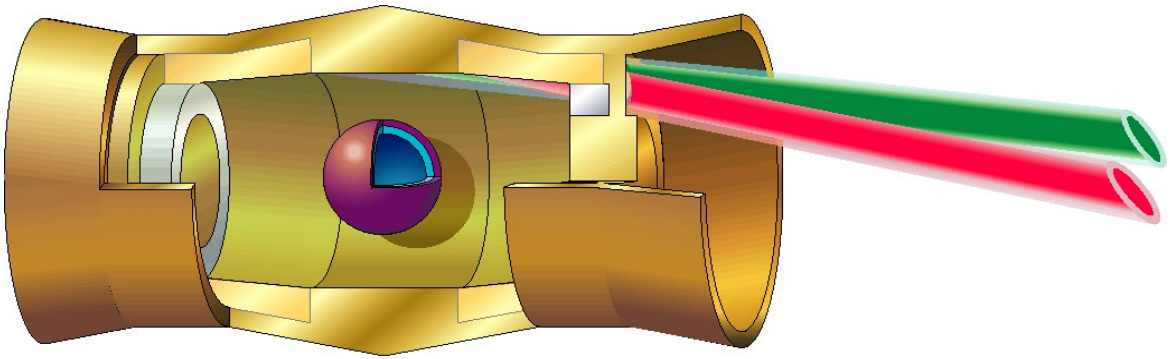
Beam radius (m) vs. z(m)



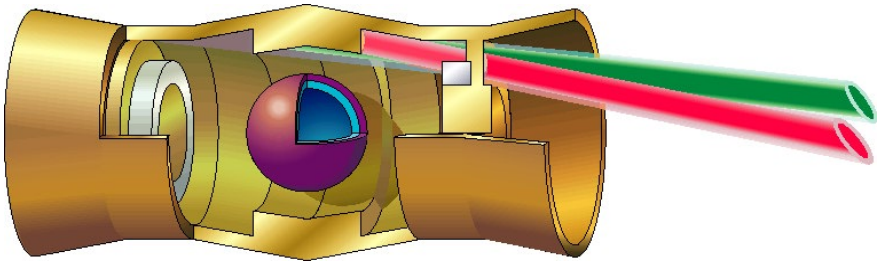
Envelope plot for T=10 MeV K^+
Unneutralized perveance = 10^{-3}
97.1% neutralized
(No stripping assumed in plasma lens)
Normalized emittance =1.6 mm-mrad

Distributed radiator target designs have been developed at LLNL

Standard hohlraum-to-capsule radius ratio design (HCR = 2.1)



Close-coupled design (HCR = 1.6)



Hohlraum is smaller – requires smaller beam spot size

Because induction linac cost was insensitive to beam energy, and because the IRE spot size was > 2mm, a 5.5 MJ ETF was assumed for the 2003 FESAC Dev-Path Panel

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

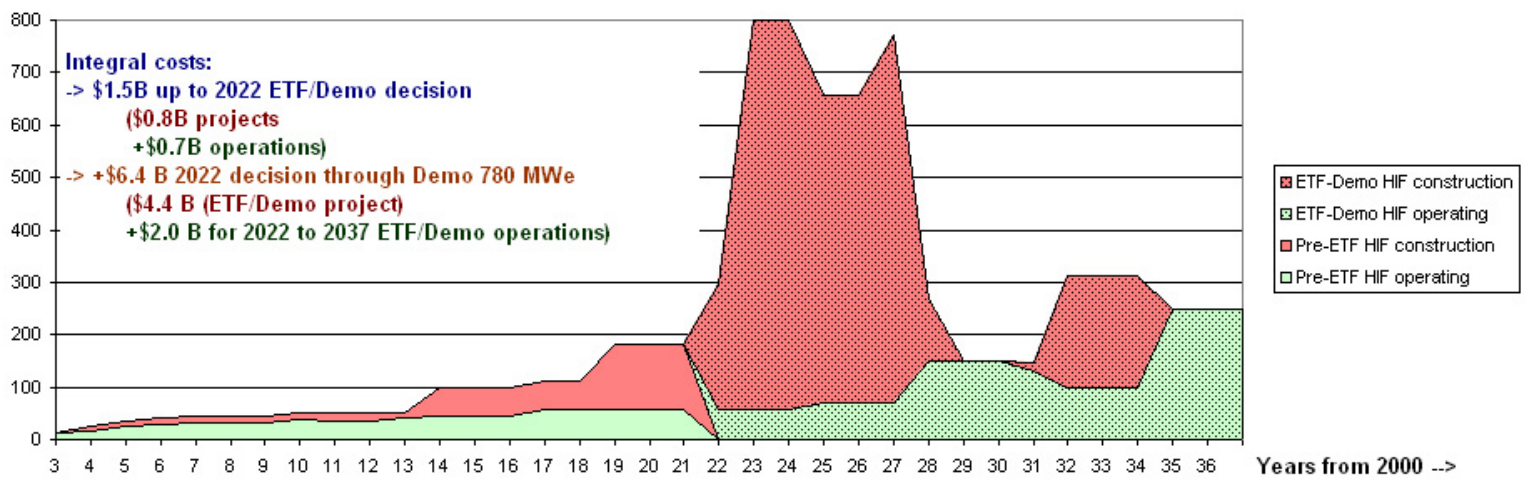
ETF/DEMO cost based on $2.8 B 7 MJ RPD driver

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



The idea of using heavy ion beams for fast ignition is as old as the heavy ion program itself

ASSESSMENT OF POTENTIAL FOR ION-DRIVEN FAST IGNITION

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MAX TABAK,‡ MARKUS ROTH,§ L. JOHN PERKINS,‡ and GEORGE CAPORASO‡

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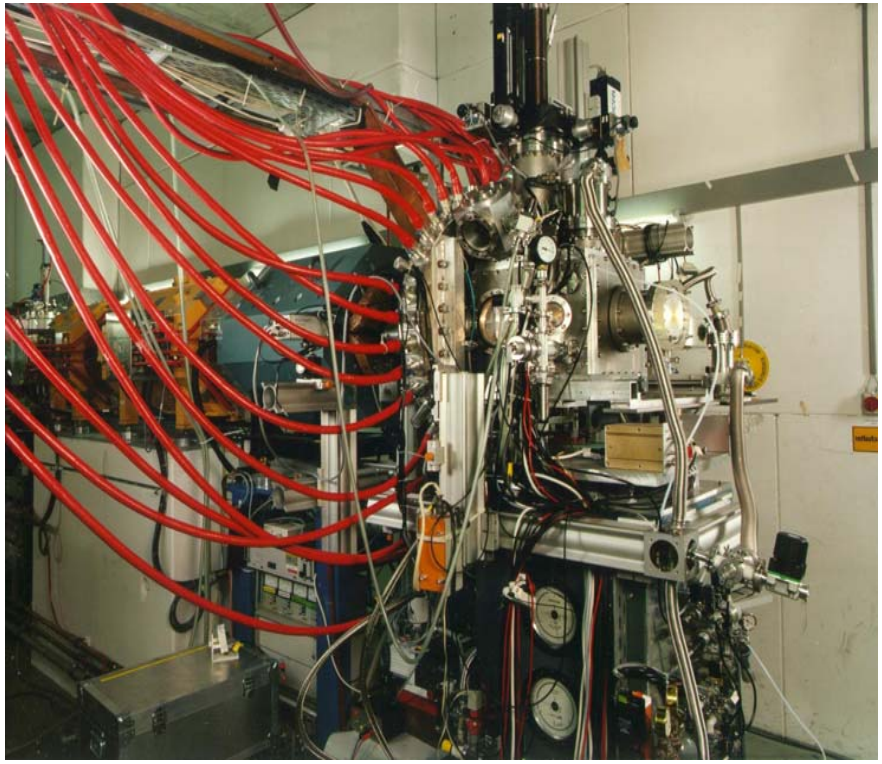
(1) A. W. Maschke, Proceedings of the 1975 Particle Accelerator Conference, page 1875, IEEE report NS-22, June 1975.

(2) M. Tabak, et al., Phys. Plasmas 1, 1626 (1994)

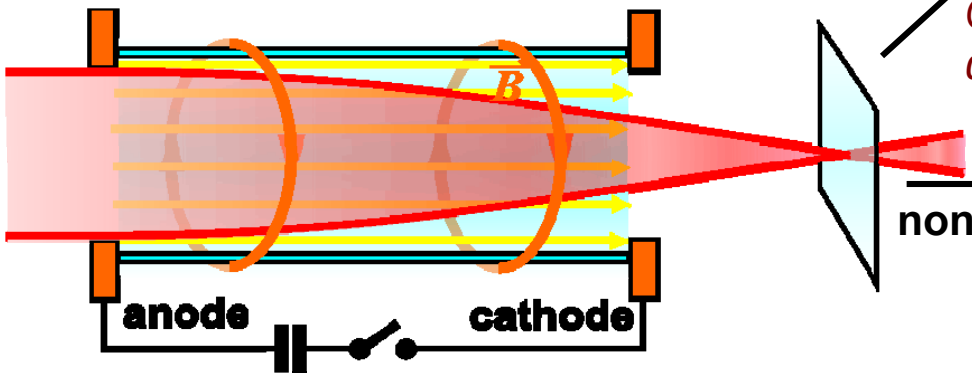
(3) M. Tabak, et. al. 1997 Int. HIF Symposium (Heidelberg) paper

(4) B. Grant Logan, et. al. "Assessment of Potential for Ion Driven Fast Ignition" Fusion Science and Technology Vol. 49, No.3, April 2006, p.399

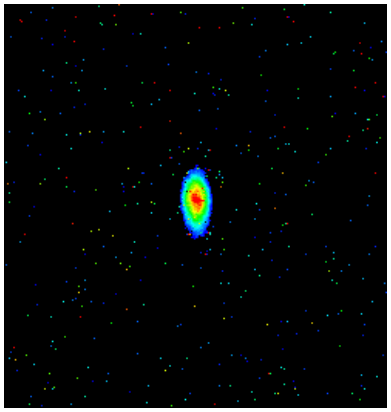
Near term experiments [NDCX-II and Heavy-Ion-Driven-Implosion-eXperiment (HIDIX)] can explore optimizing two-stage focusing with using B_θ lens like the plasma lens that was used for target experiments at Helmholtzzentrum für Schwerionenforschung (GSI)



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

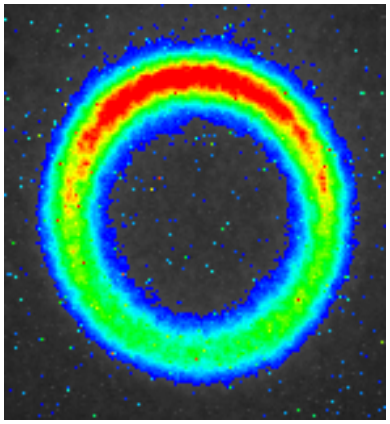


linear B-field



Can be time-dependent

nonlinear B-field

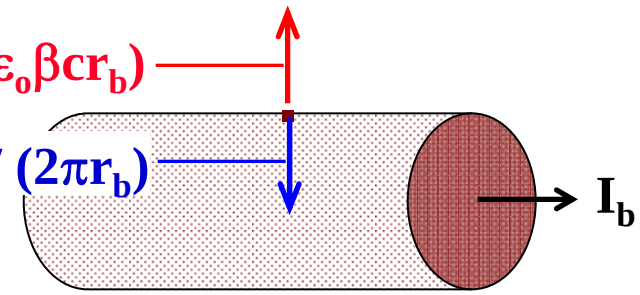


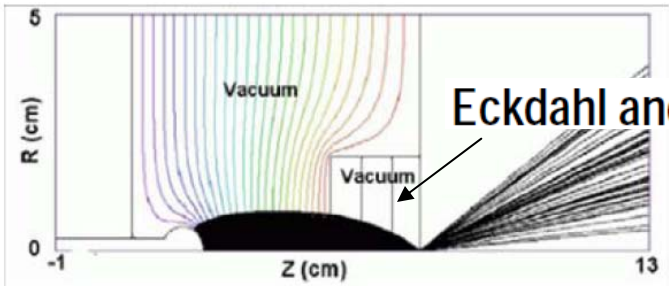
We should *engineer* a B_θ self-pinch built into target assembles, replacing a plasma lens z-current with a net ion beam current.

Step 1: Reduce E_r force on B_θ-forming pre-beam using transverse grids/foils

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

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



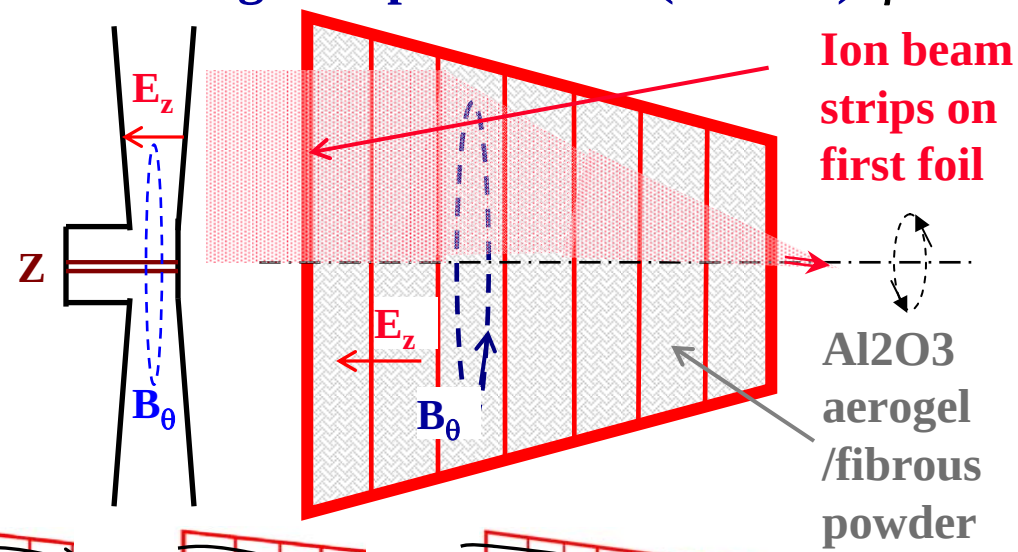


Eckdahl and Humphries

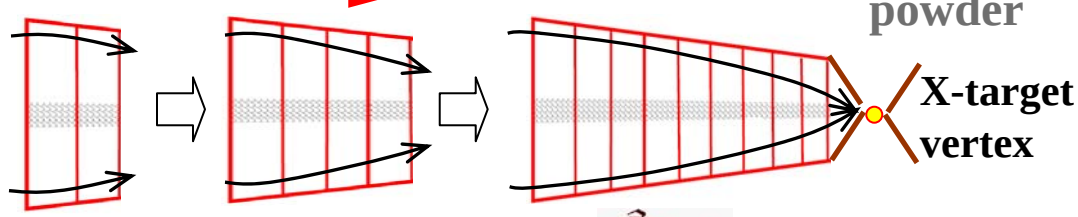
Figure 5. 14-MeV beam focused by anode foil, with additional grids to short out the residual space-charge fields.

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

Step 2: Impede return current with dielectric or magnetic insulation, *until* desired B_θ for focusing lens is *frozen*-into plasma for igniter beam



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



All heavy ion fusion R&D plan options for NAS will exploit 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, heavy ions can drive targets efficiently, and injected HIF targets can be protected against hot IFE chamber gas.** ***Facilitates target injection.***

(e) **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, economy of scale @ 2 GWe, direct conversion of neutron energy at high yields → < 3 cts /kW$_e$hr***

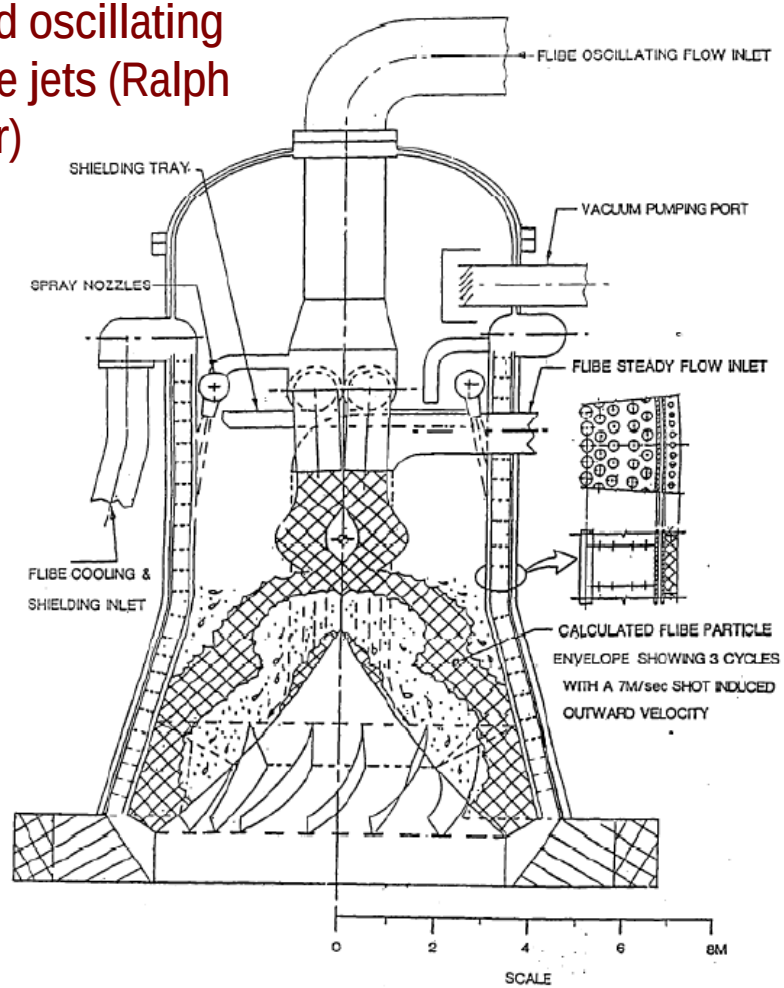
All prudent HIF development plans have called for a series of R&D steps with increasing beam energy and cost, each step addressing key requirements and risk issues for the next higher cost step:

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 Demonstration Plant]

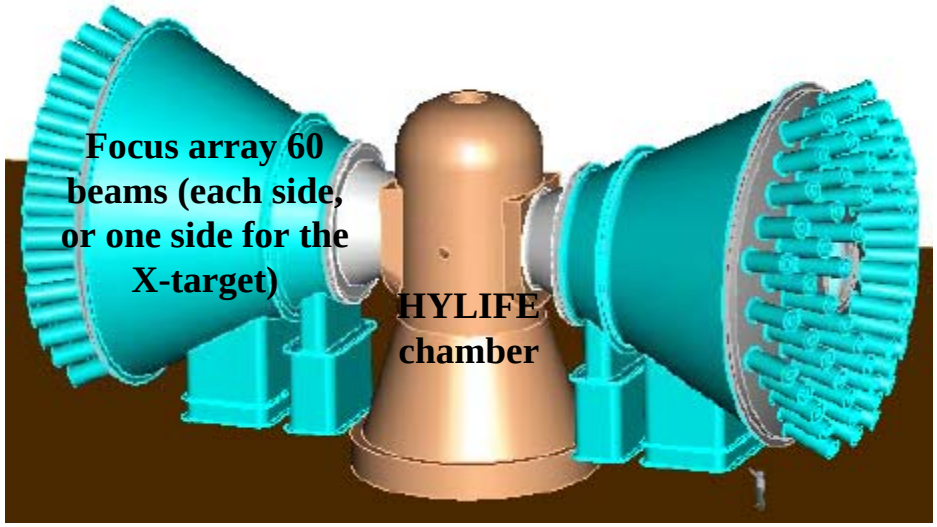
Risk management: The National Ignition Campaign (NIC) experience makes clear that achieving ignition will require mastering precision beam symmetry, balance, pointing and pulse shaping with laser techniques that will not all carry over to heavy ion driven targets→ Given high cost of Step 3, acceptable 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.

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)



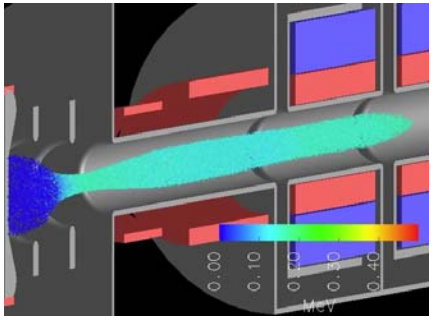
Indirect drive, polar direct drive, and X-targets could be all adapted to use liquid chambers and compatible focusing optics.



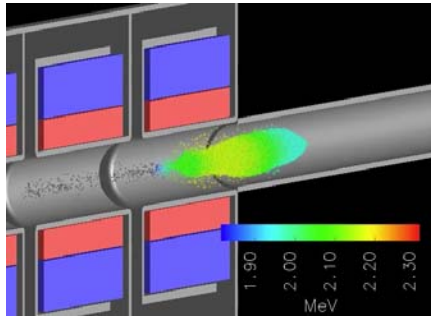
NDCX-II now under construction will provide a test bed for HIF beam manipulations over the next five years (Alex Friedman)

- 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, and compressed to sub-ns.
- 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

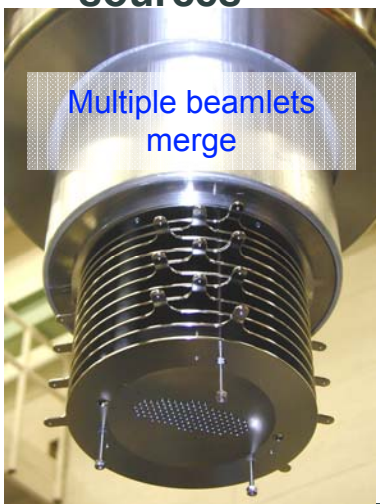


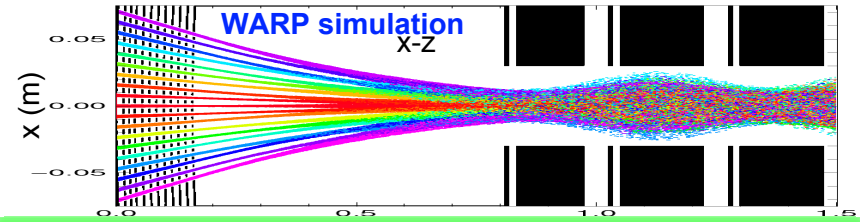
Ref: A. Friedman, et al., *Phys Plasmas*, in press (2010)

	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

Need for driver-scale beam experiments: Sources, injection, matching, transport. Must preserve brightness in the presence of high space charge <u>at ≈ 5 Hz.</u> The beam is susceptible to beam-gas, e-cloud effects.

(a) High current, low emittance, surface ionization sources and **<u>multi-aperture gas</u>** sources

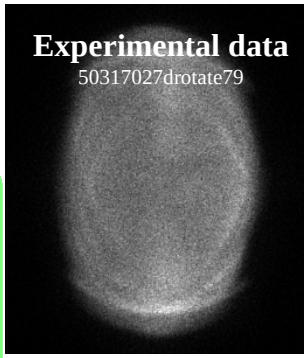




Remaining issues: Compact **arrays & gas load, matching, reliability, lifetime.**

Neg. ions? Higher charge states?

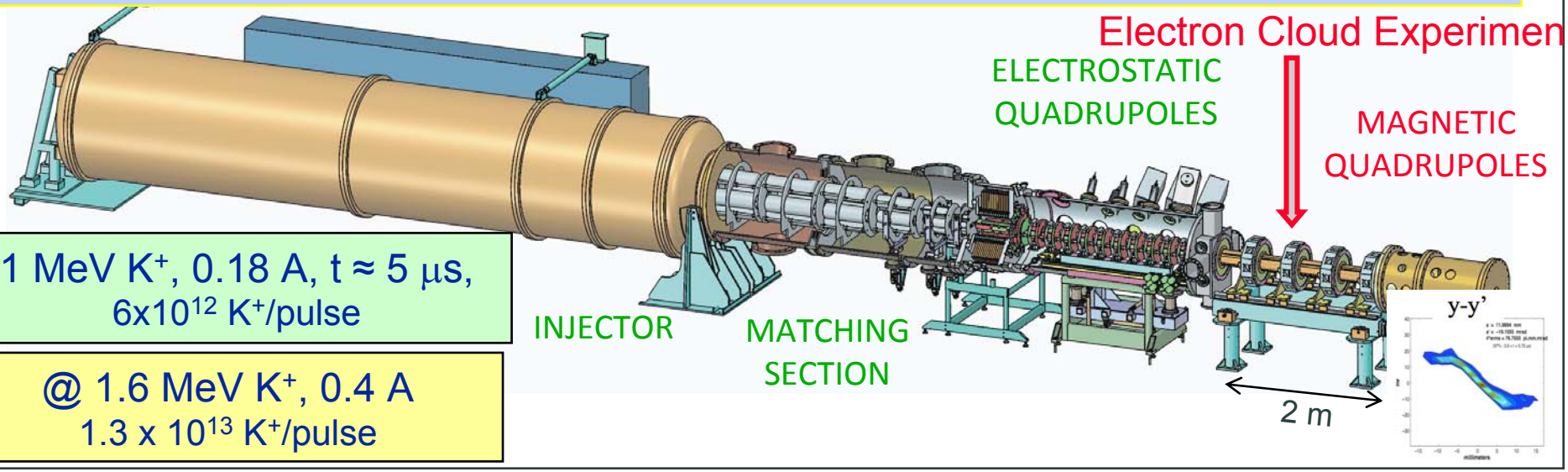
<u>Study at 5 Hz (driver repetition rate)</u>



<u>Energy</u>	<u>Current</u>
0.4 MeV	71 mA
1.6 MeV	568 mA

ε_n < 1 mm•mrad

(b) **Injection, matching, transport** (HCX): explore & control e-cloud, halo-induced gas build-up

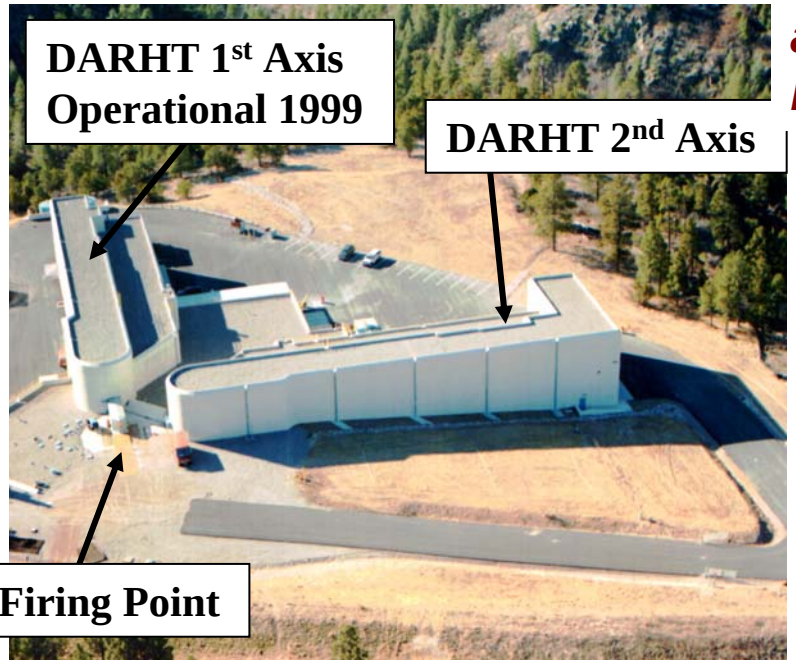


1 MeV K^+, 0.18 A, t ≈ 5 μs, 6×10^{12} K^+/pulse

@ 1.6 MeV K^+, 0.4 A
1.3×10^{13} K^+/pulse

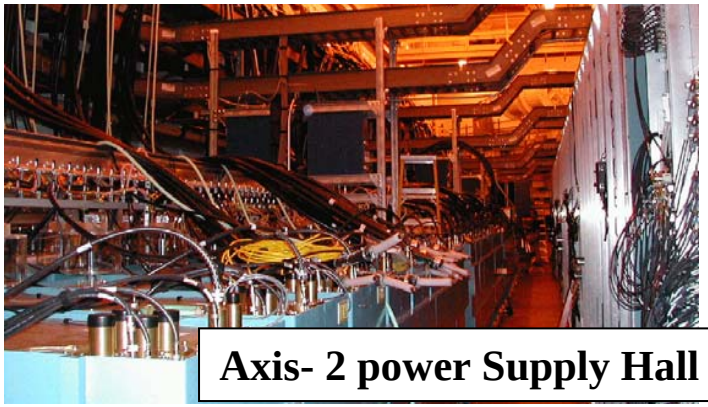
DARHT-II: a state-of-the-art induction accelerator @ >50 kJ/ electron beam pulse. Technology *relevant to induction linac drivers for fusion!*

The DARHT 2nd Axis Project was a collaborative effort among LANL, LBNL, and LLNL



2nd Axis accelerator
1.6 μs, 17 MeV, 2 kA

1st Axis accelerator
.06 μs, 19 MeV, 2 kA



Axis- 2 power Supply Hall

An ion bunch must be compressed to a small volume against its thermal pressure and space charge forces

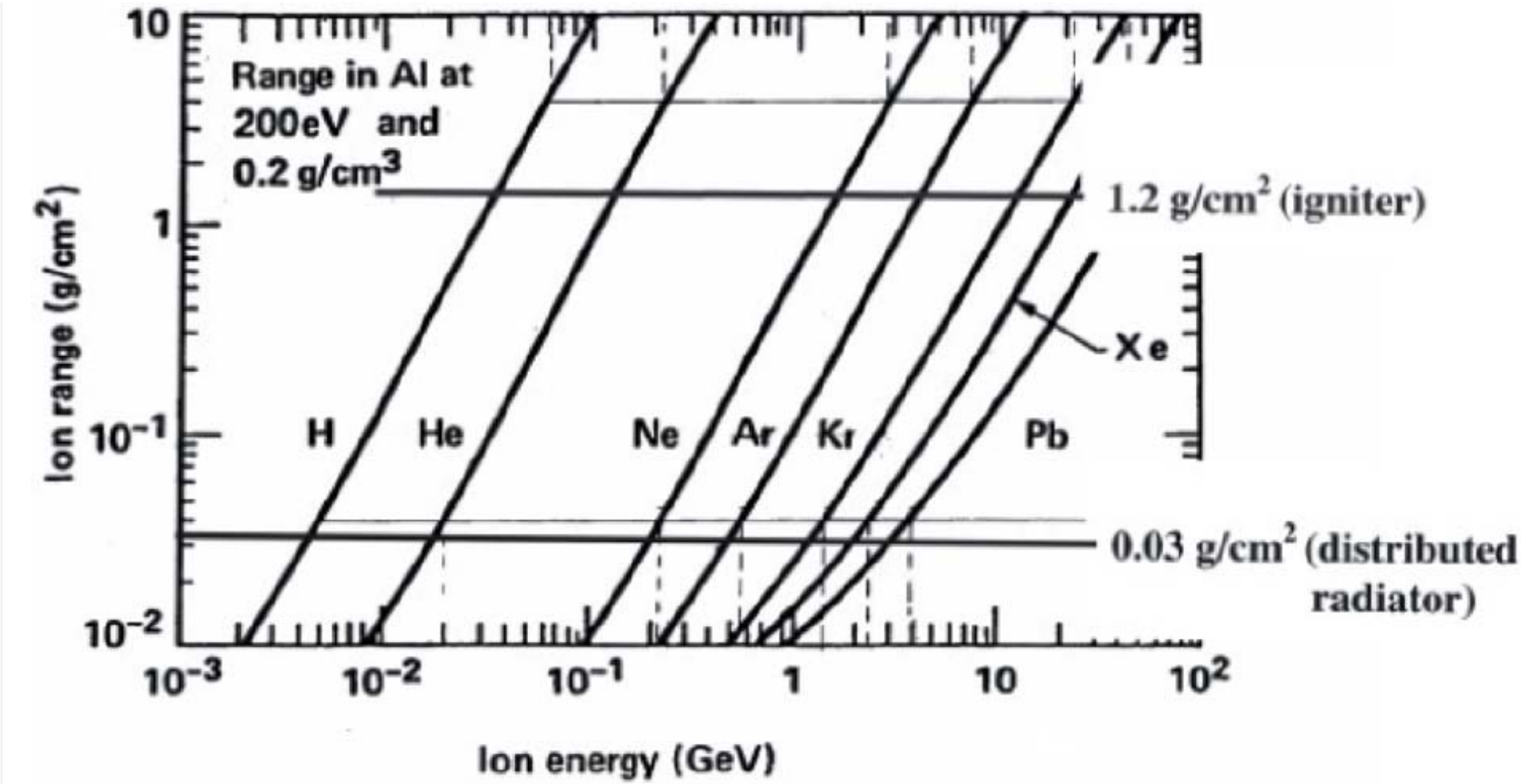
(From Boris Sharkov, ITEP. IFSA Plenary, 2007, Kobe, Japan)

Central issue for heavy ion fusion accelerators: high beam space charge!

Goal of HIF science :

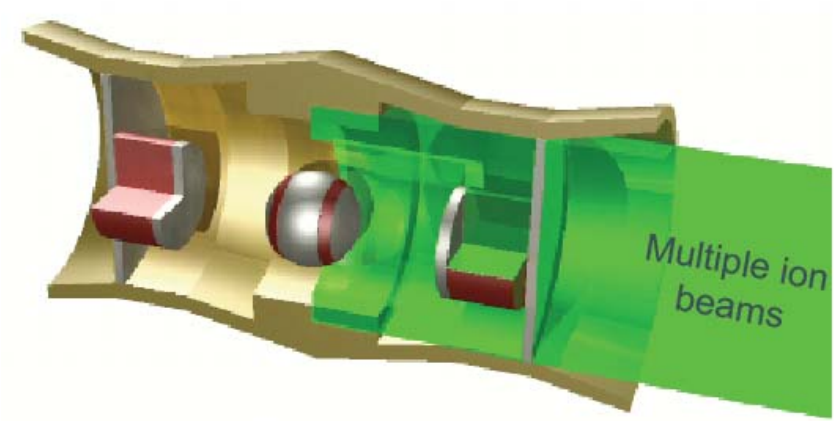
explore limits to beam brightness that lead to lowest energy to drive targets !

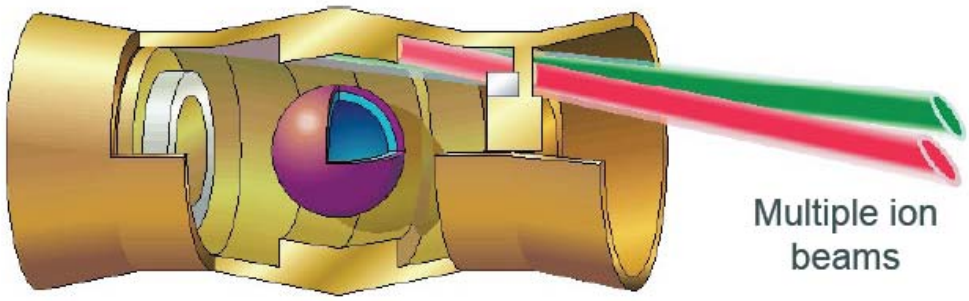
Either higher mass ions for targets with *given* ion range, or targets that allow higher range: enable delivery of energy at higher kinetic energies→ lower beam currents→ easier transport and focusing!



HIF option: indirect drive two-sided hohlraum

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

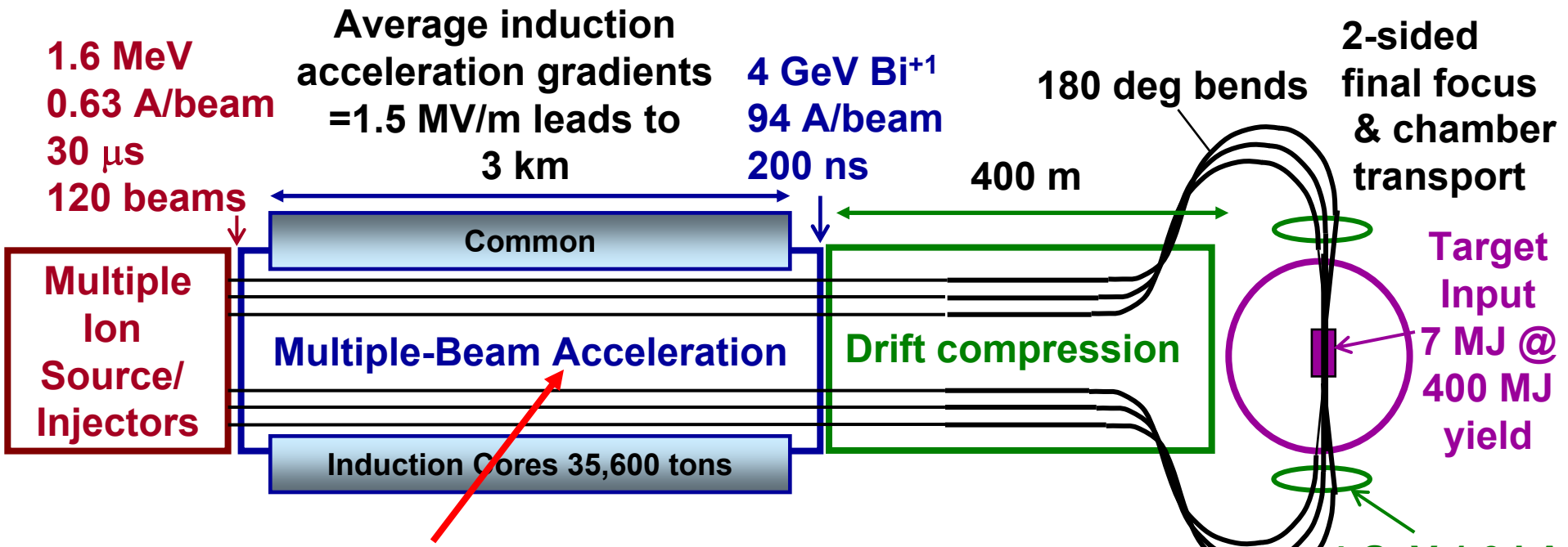
Gain = 68,

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.)

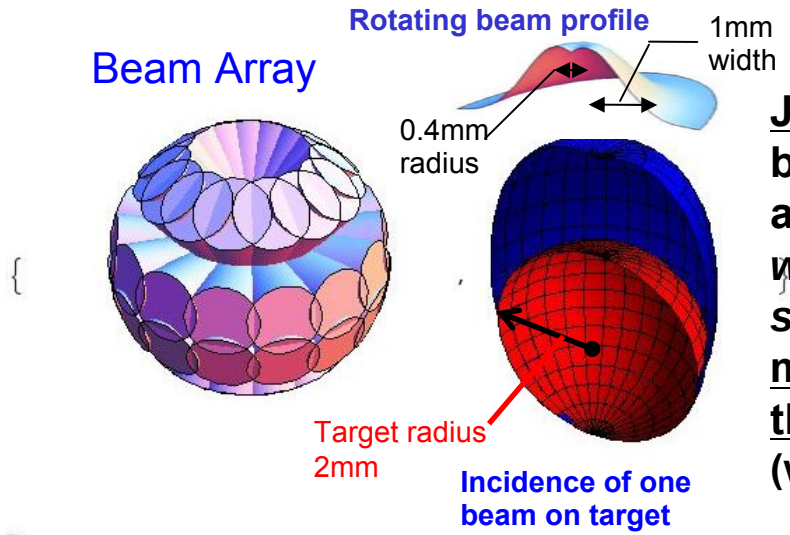


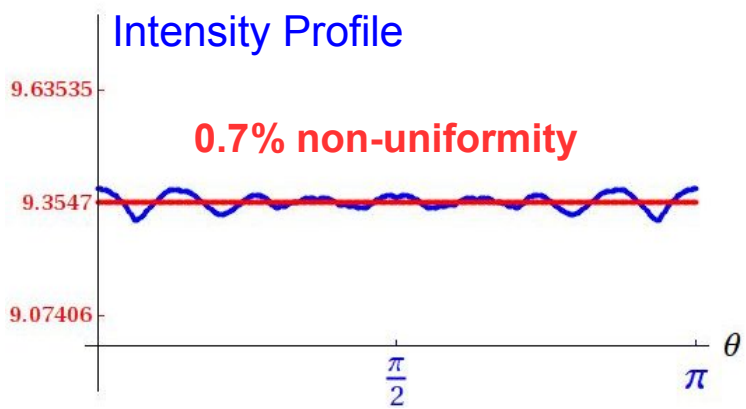
Compact quad-array transport $I_{tot} \sim (\text{core } R_{ic})^2 a_b^{-1}$ → enables more beams in one linac → induction linac efficiency > 30%

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).

HIF option:
Direct drive, polar geometry (likely needs late shock ignition due to 2-D asymmetries of the hot spot)

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).

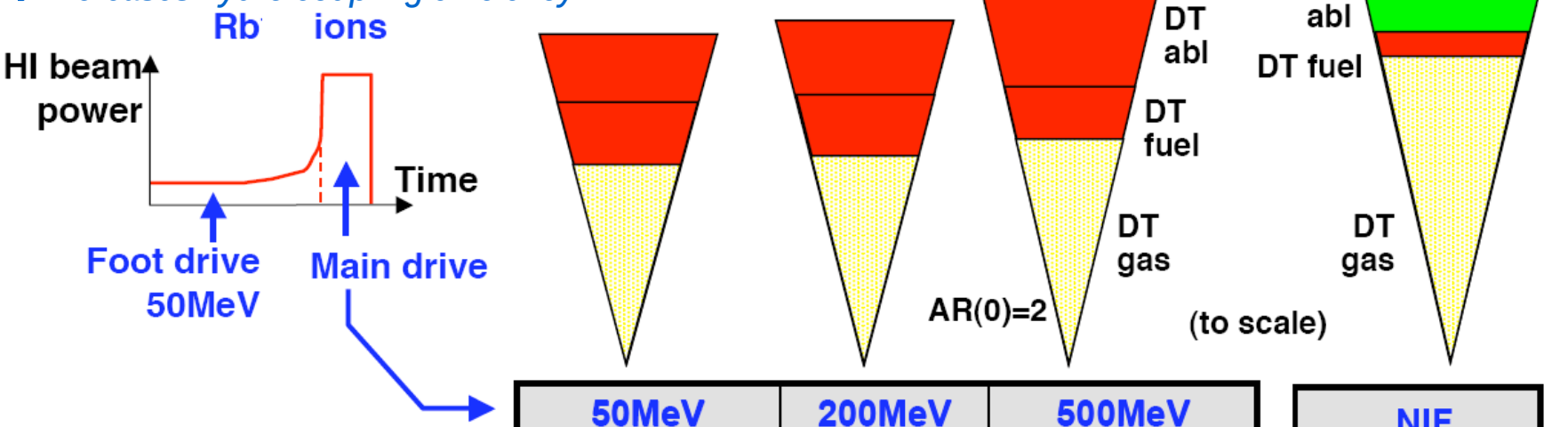
4 polar angles only, *not 4π!*

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)

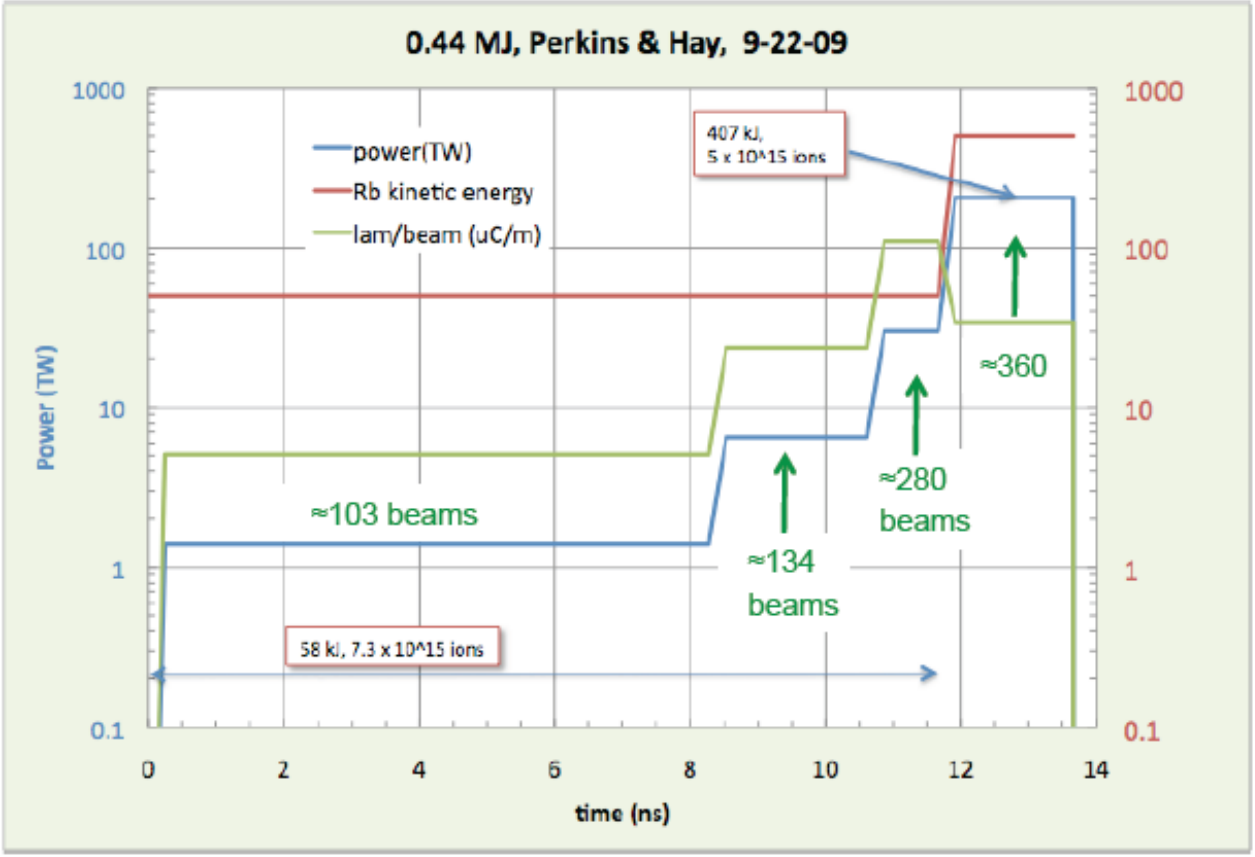
John Perkins surveyed 1-D designs for HIF direct drive in February 2009 giving the same fusion yield as NIF (20 MJ yield)

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

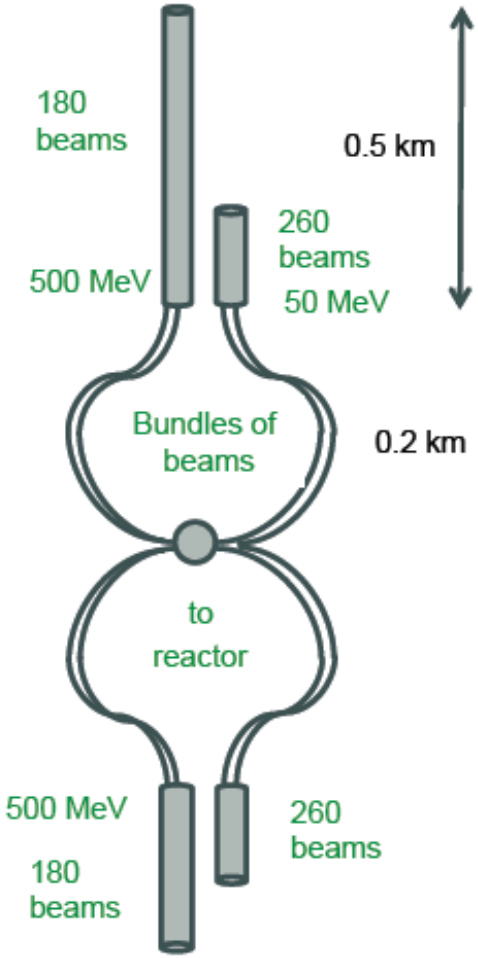


	50MeV	200MeV	500MeV	NIF
$m_{ablator}/m_{fuel}$	1.8	2.1	3.0	18
Driver energy (MJ)	0.32	0.36	0.44	1.3
Peak drive power (TW)	175	195	205	320
Yield (MJ) / Gain	24.7 / 77	21.6 / 60	20.8 / 47	20.0 / 15
$\eta_{absorbed}$ / η	0.97 / 0.10	0.91 / 0.10	0.88 / .09	0.16 / 0.02
In-flight aspect ratio	25	27	25	32
Convergence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

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→

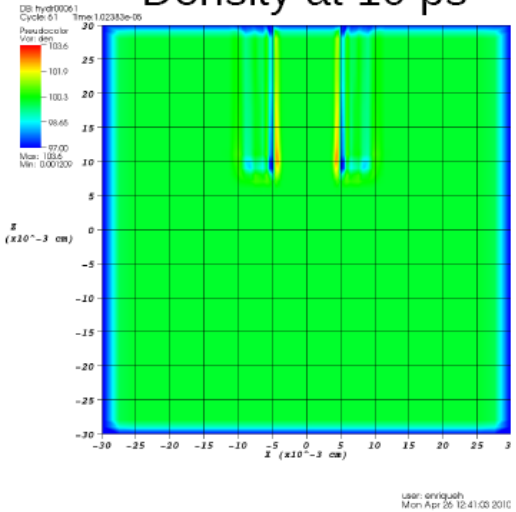
HIF option: Hydro-(direct drive) + Fast/Shock Ignition: the X-target

Mark Hermann proposed use of hollow ion beams for fast ignition (2001APS talk). HYDRA-2-D confirms shock ignition @ 500 kJ, 60 GeV U, 100 ps (Henestroza, 4/26/2010)

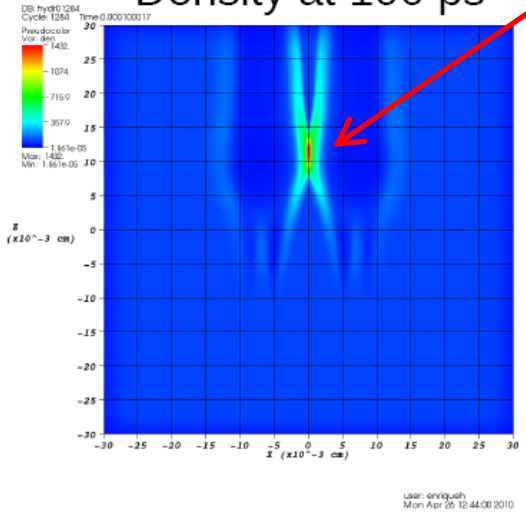
Initial density @ 100 g/cm^3 compresses under the Bragg peak to >1400 g/cm^3!

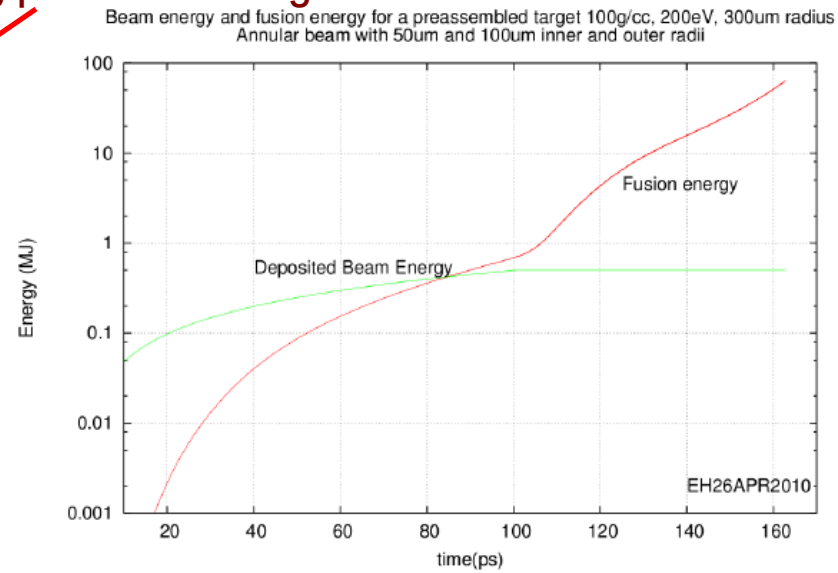
The annular beam is moving from top to bottom

Density at 10 ps

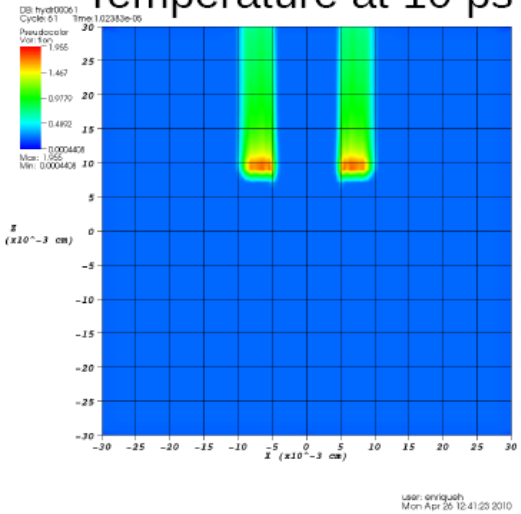


Density at 100 ps

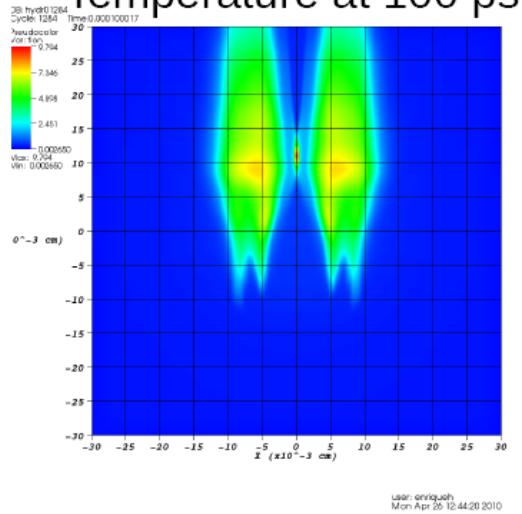




Temperature at 10 ps



Temperature at 100 ps

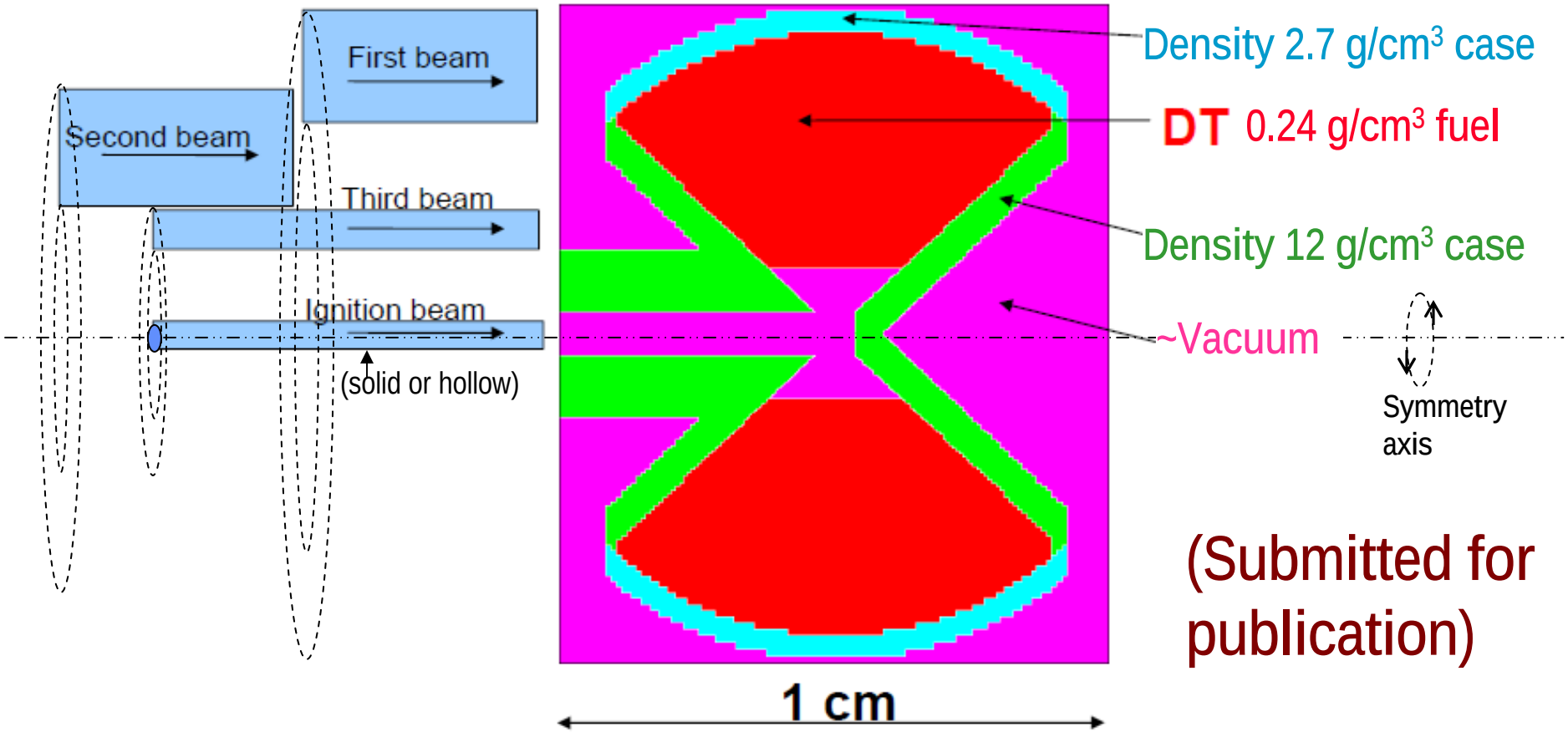


The energy, annular size, and beam pulse length have been chosen to produce the right temperature and density (ρR) to ignite the fuel, conditions which are reached at the end of the pulse.

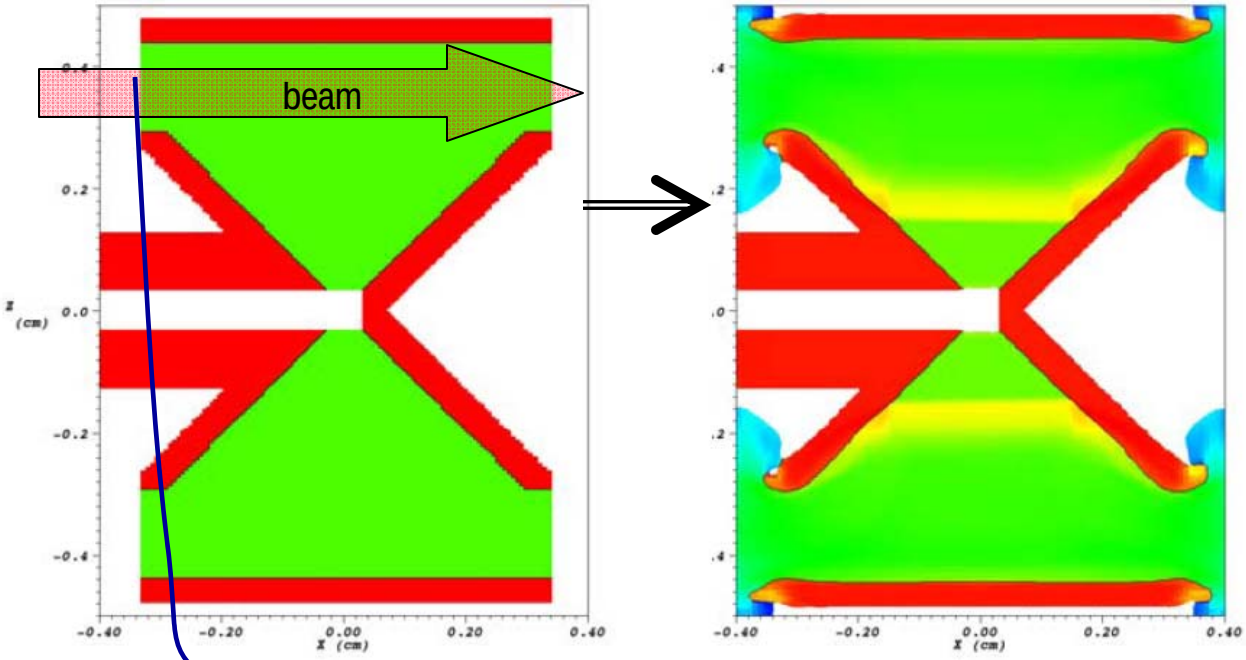
Several integrated 2-D runs at various peak ρ confirm E_{ign}~$1/\rho^2$→gains >>100 coming soon!

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

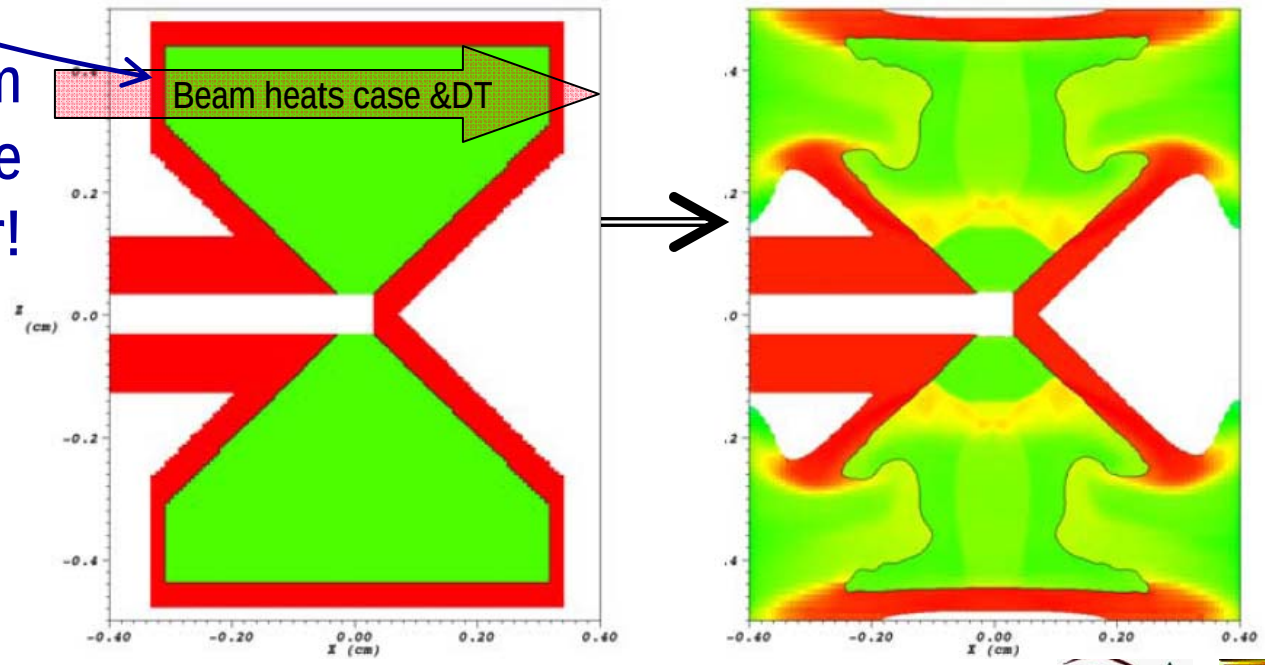


(Submitted for publication)

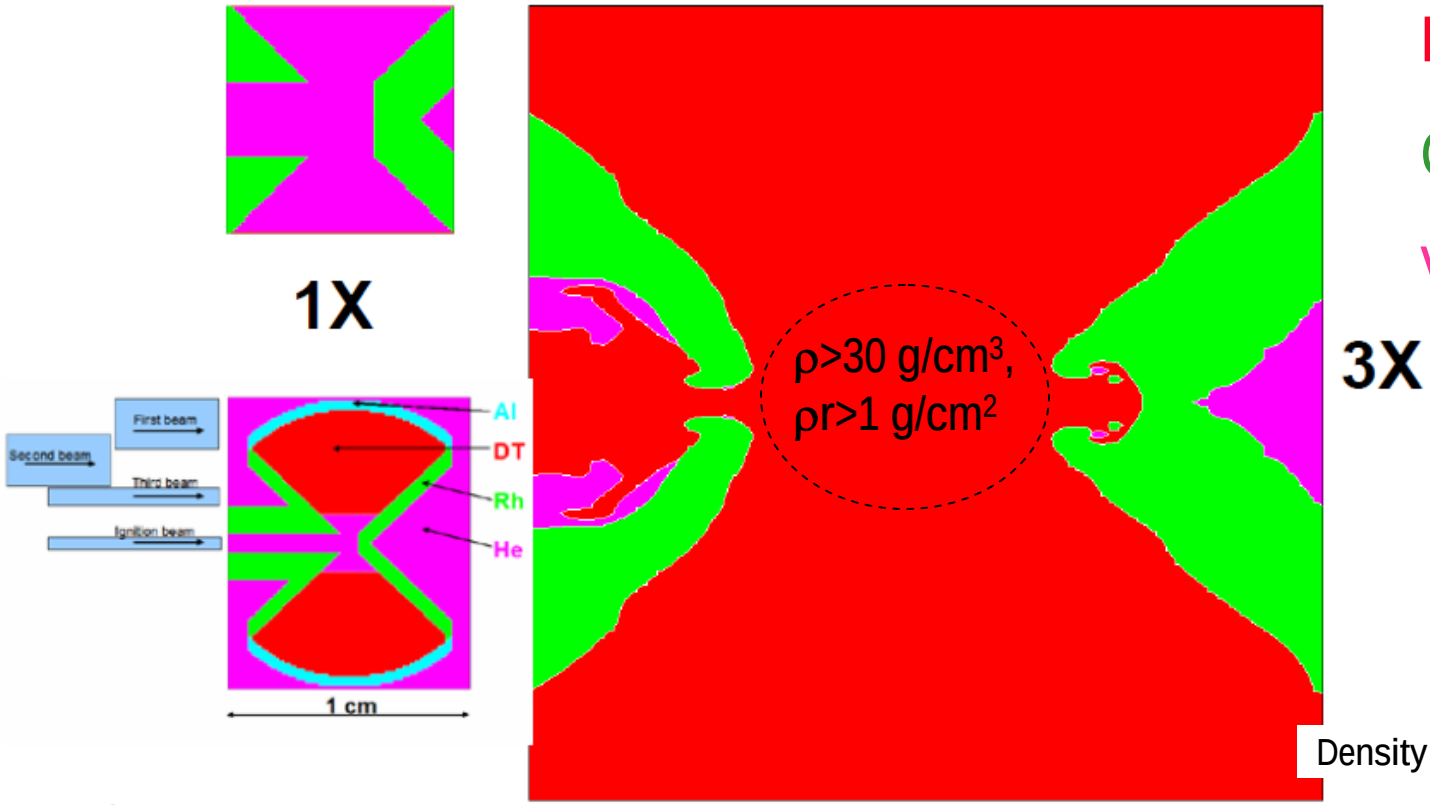


Quasi-hemispherical fuel compression is improved during the foot drive by optimizing the <u>expansion of the beam heated case as well as the DT</u>

Adding beam caps to the case→ better!



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

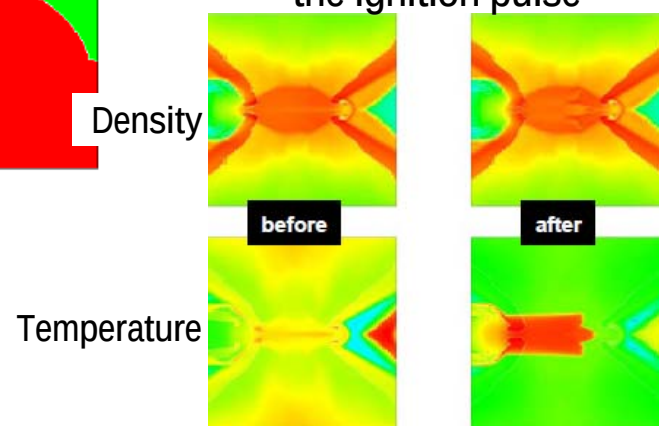


DT

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.

Interesting parallels between heavy ion fast ignition and laser fast ignition:

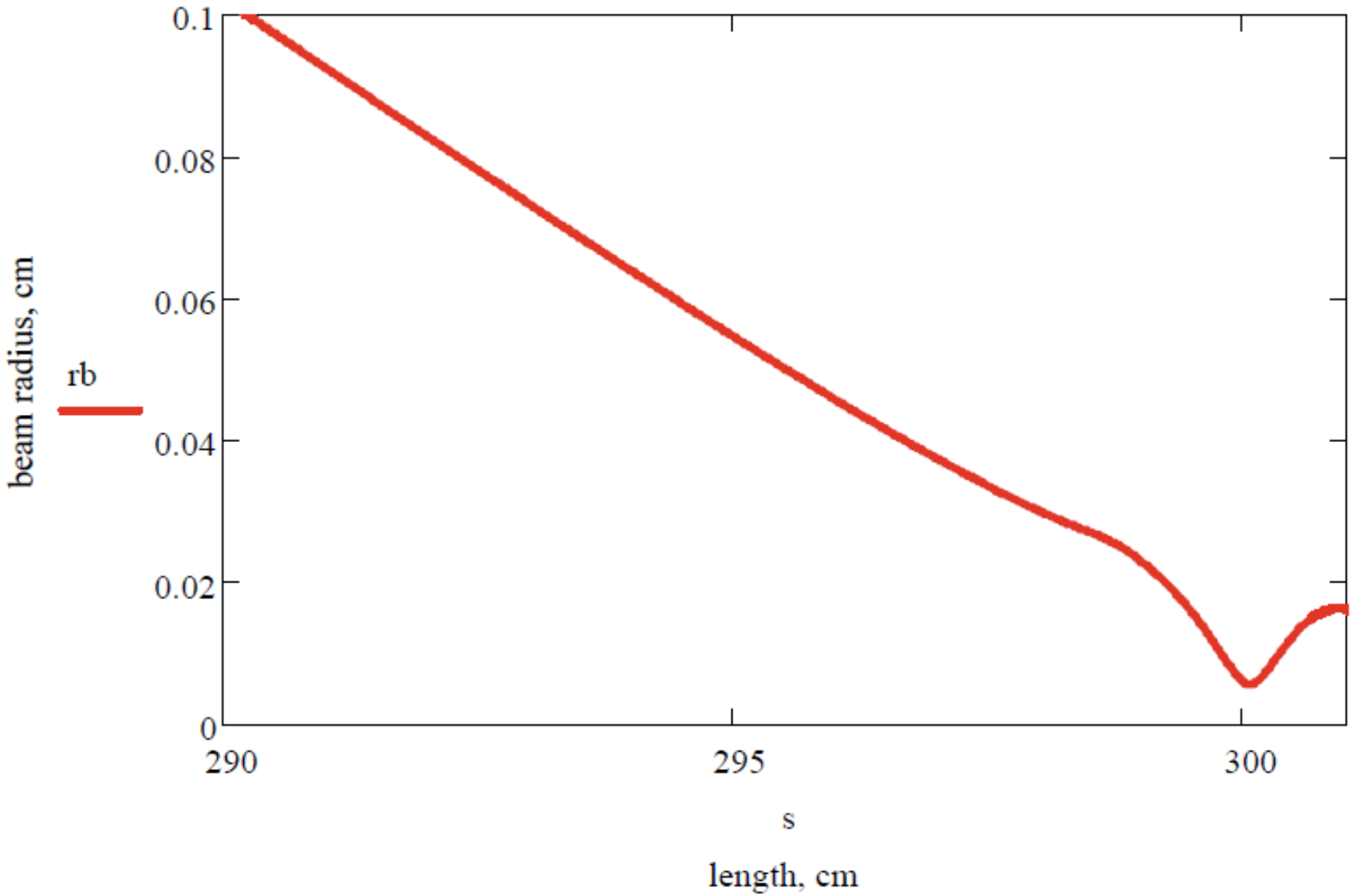
- **Many studies indicate a difference in scales: E_{ign} ~ 1 MJ (HI-FI), vs 100 kJ (Laser FI); 100 ps for HIFI, vs, 10 ps for laser FI, 100 μm r_{spot} (HIFI), vs 10 μm (laser FI) *but both HIFI and laser FI R&D need*:**

- **use chirped beams to get the short pulses (velocity chirp for HI-FI, frequency chirp for laser FI);**

- **need to develop near-target-local means to reduce rspot of the particle beams into the DT ignition zone by factors of 5-10;**

- **E.g., self magnetic pinch for both HIFI and laser FI are being investigated using the same PIC codes (WARP and LSP)**
- **Need benchmark experiments at different facilities: (e.g. Large heavy ion ring accelerators GSI, IMP, RHIC, etc for HIFI pinch experiments.**

Recent LSP simulation by Dale Welch (Voss Scientific) showing self pinching of a 60 GeV U beam stripping on plasma ~1 cm from a target



Second-stage focusing using B_θ:

Near-term: Plasma Lens

Longer term: Engineer beam-generated lens

R&D Needs for X-target HIF→ many opportunities for collaboration.

- **Sub-ns igniter pulses**: ***longitudinal emittance growth limits***. **Study in NDCX-II, and at GSI with added bunchers.**
- **Self-pinching: develop diagnostics to *measure net beam currents* under conditions when charge neutralization exceeds current neutralization. NDCX-II, RHEPP, GSI-FAIR**
- **Hydro coupling efficiency in X-cone tampers: e.g., test compression in X-cone geometry using the beam wobbler planned @ GSI/FAIR**
- **Stripping-induced beam emittance at driver scale beam perveance. Measure emittance stripping $Li^{+1} \rightarrow Li^{+2}$ in NDCX-II at high currents.**
- **Dynamic gas control with multiple beams. Rebuild 2 MV, high beam current HCX-II @ 5 Hz rep rate to benchmark vacuum/beam loss models.**
- **Ion fast ignition -rebuild surplus HEP/NP accelerator hardware for MJ U-igniter (cost ~ 300 M$?).**

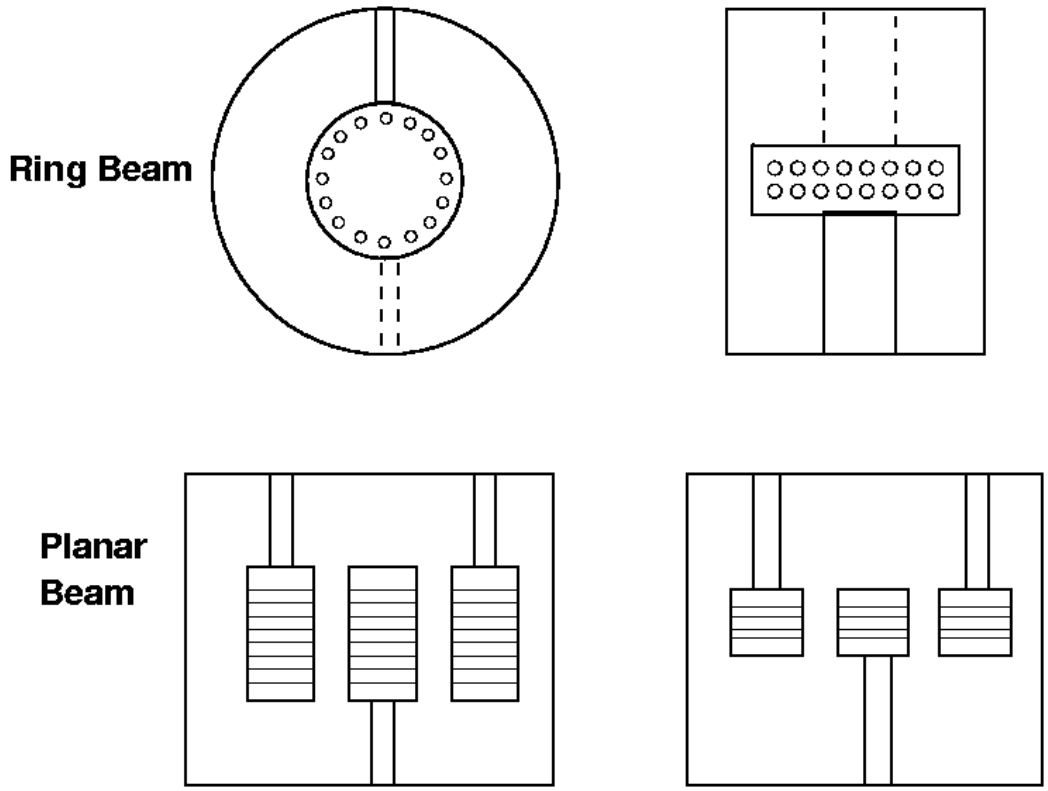
A low-β RF linac concept: q/A~1/20, 1μC, 20 MV, 200ns source→1ns target was developed by the RF-Linac Group at the Accelerators for HEDP Workshop October 2004: *Could this be a front-end feeding 30MV/m SC-RF sections to 1g/cm^2 ion range for an X-target driver? (~10X more parallel beamlines than for induction needed, but maybe 20X shorter?).*

Example from a previous 2004 heavy ion accelerator workshop to consider for the coming spring workshop; *(see Peter Seidl [PASeidl@lbl.gov]*

The RF Linac Group

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

Interdigital H–mode resonator configurations



Workshop on Accelerators for Heavy Ion Fusion: Motivation

- **The upcoming US National Academy review of Inertial Fusion Energy will include Heavy ion Fusion, as specified in the 2010 Fusion Reauthorization Bill passed by Congress.**

- **There has been considerable advances in high intensity ion accelerator technology since the first workshop that motivated the HIF program 30 years ago.**

- **There are new target designs for heavy ion fusion which may expand the accelerator options for heavy ion drivers**

We invite LANL participation!

Conclusion: Many R&D needs for heavy ion fusion→ Many opportunities for high leverage-using many facilities

- ***Longitudinal emittance growth limits*. study in NDCX-II, and at GSI.**
- **Engineered B_θ lens for two stage focusing: NDCX-II, RHEPP, GSI-FAIR, laser-produced proton beams.**
- **Heavy Ion Direct Hydro coupling efficiency: e.g., test compression in X-cone geometry using the beam wobbler planned @ GSI/FAIR.**
- **Dynamic gas control at high ave. current. E.g., rebuild high beam current HCX-II @ 5 Hz rep rate to benchmark vacuum models.**
- **Ion fast/shock ignition -rebuild large accelerator facility hardware for MJ-igniter (cost ~ 300 M$, 1/10 the cost of NIF).**
- **Higher gradient linacs for heavy ion drivers.**

On 12-12-03, SLAC Director Burt Richter wrote to the DOE Fusion Energy Advisory (FESAC) panel considering fusion development:

"The Office of Science funds heavy ion fusion (HIF) while Defense Programs funds the laser and pulsed-power applications. This has had the unfortunate result of putting the vast majority of inertial fusion funding into lasers and pulsed-power while a whole series of review panels, going back to the late 1970's, have consistently indicated that HIF has the most promise as a source of energy. Here is a brief list:…"

1. **The 1979 Foster Committee**
2. **The 1983 Jason Report (JSR82-302)**
3. **The 1986 National Academies of Sciences Report of March**
4. **The 1990 Fusion Policy Advisory Committee report (Stever Panel)**
5. **The 1993 Fusion Energy Advisory Committee (Davidson Panel)**
6. **The 1996 FESAC report (Sheffield Panel)**

…..."

(Copy of Richter letter and past reviews are available upon request)

Beam requirements at linac output for X-target range 1.3 g/cm2 (mix of Al and DT) vs ion mass

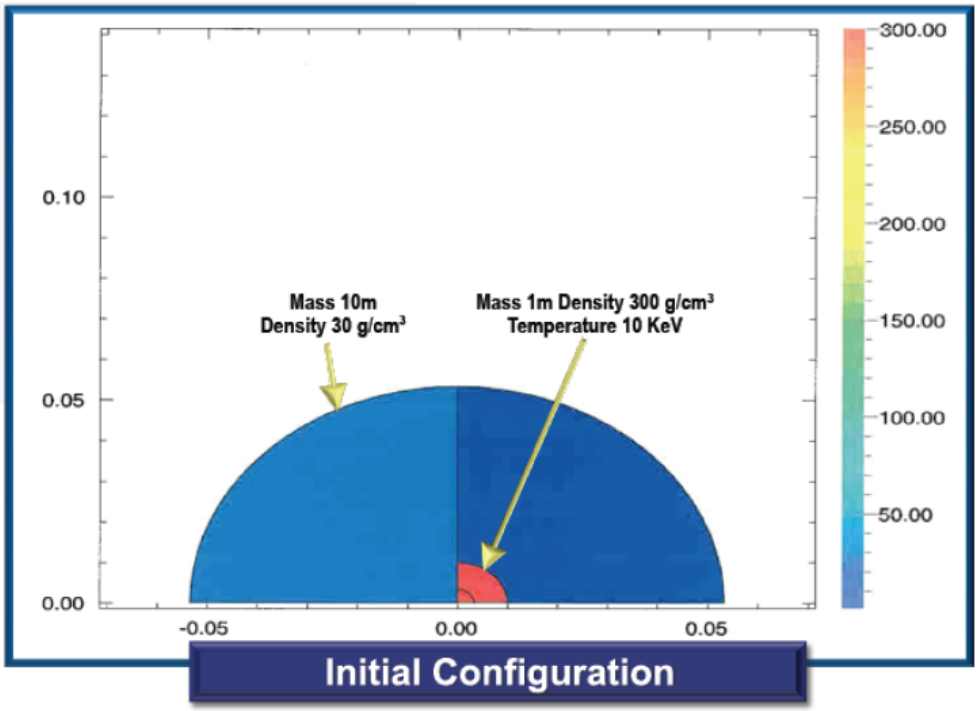
	Ion KE for 1.3 g/cm^2 range	Ion beta	Bunch length (m) @ final $\tau := 5\cdot 10^{-9}$ s	radial E_r space charge field @ beam edge (V/m
U	$T_b(r_c, f_{ao}, 238, 92, F_{ib}) = 6\times 10^{10}$	$\beta(60\cdot 10^9, 238) = 0.62$	$\tau\cdot\beta(60\cdot 10^9, 238)\cdot c = 0.92$	$\frac{4\cdot 6\cdot 10^4\cdot T_b(r_c, f_{ao}, 238, 92, F_{ib})^{-1}}{\tau\cdot\beta(60\cdot 10^9, 238)\cdot c\cdot 4\cdot\pi\cdot\varepsilon_o\cdot a_b} = 1.8\times 10^6$
Cs	$T_b(r_c, f_{ao}, 132, 55, F_{ib}) = 2.6\times 10^{10}$	$\beta(26\cdot 10^9, 132) = 0.56$	$\tau\cdot\beta(26\cdot 10^9, 132)\cdot c = 0.84$	$\frac{4\cdot 6\cdot 10^4\cdot T_b(r_c, f_{ao}, 132, 55, F_{ib})^{-1}}{\tau\cdot\beta(26\cdot 10^9, 132)\cdot c\cdot 4\cdot\pi\cdot\varepsilon_o\cdot a_b} = 4.4\times 10^6$
Rb	$T_b(r_c, f_{ao}, 85, 37, F_{ib}) = 1.3\times 10^{10}$	$\beta(13\cdot 10^9, 85) = 0.51$	$\tau\cdot\beta(13\cdot 10^9, 85)\cdot c = 0.77$	$\frac{4\cdot 6\cdot 10^4\cdot T_b(r_c, f_{ao}, 85, 37, F_{ib})^{-1}}{\tau\cdot\beta(13\cdot 10^9, 85)\cdot c\cdot 4\cdot\pi\cdot\varepsilon_o\cdot a_b} = 9.2\times 10^6$
K	$T_b(r_c, f_{ao}, 39, 19, F_{ib}) = 4.4\times 10^9$	$\beta(4.4\cdot 10^9, 39) = 0.45$	$\tau\cdot\beta(4.4\cdot 10^9, 39)\cdot c = 0.68$	$\frac{4\cdot 6\cdot 10^4\cdot T_b(r_c, f_{ao}, 39, 19, F_{ib})^{-1}}{\tau\cdot\beta(4.4\cdot 10^9, 39)\cdot c\cdot 4\cdot\pi\cdot\varepsilon_o\cdot a_b} = 3.1\times 10^7$
Na	$T_b(r_c, f_{ao}, 22, 11, F_{ib}) = 1.7\times 10^9$	$\beta(1.7\cdot 10^9, 22) = 0.38$	$\tau\cdot\beta(1.7\cdot 10^9, 22)\cdot c = 0.57$	$\frac{4\cdot 6\cdot 10^4\cdot T_b(r_c, f_{ao}, 22, 11, F_{ib})^{-1}}{\tau\cdot\beta(1.7\cdot 10^9, 22)\cdot c\cdot 4\cdot\pi\cdot\varepsilon_o\cdot a_b} = 8.5\times 10^7$

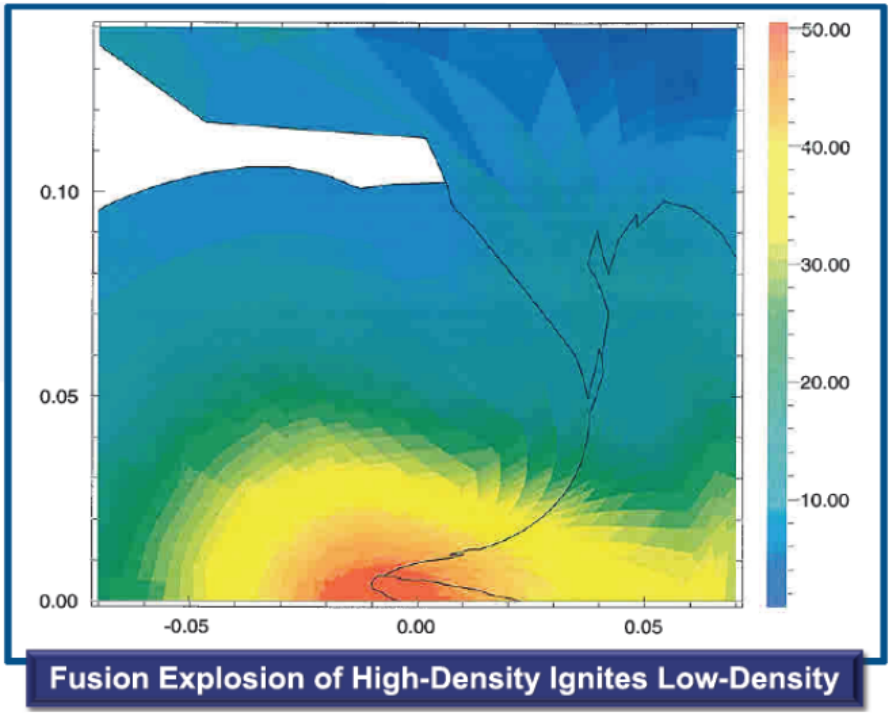
	Linac length (m) @ 30 MV/m	Charge (μC) per bunch for 60 kJ/beam (3.6 MJ total for 60 beams, q=1 ions)	Peak line charge density (μC/m) for simple triangular λ(z) bunch	and longitudinal E_z~dλ/dz field (V/m), for $a_b :=$
U	$\frac{T_b(r_c, f_{ao}, 238, 92, F_{ib})}{30\cdot 10^6} = 2010$	$\frac{(6\cdot 10^4)\cdot 10^6}{T_b(r_c, f_{ao}, 238, 92, F_{ib})} = 1$	$2\cdot\frac{(6\cdot 10^4)}{10^{-6}}\cdot\frac{T_b(r_c, f_{ao}, 238, 92, F_{ib})^{-1}}{(\tau\cdot\beta(60\cdot 10^9, 238)\cdot c)} = 2.2$	$\frac{4\cdot 6\cdot 10^4\cdot T_b(r_c, f_{ao}, 238, 92, F_{ib})^{-1}}{(\tau\cdot\beta(60\cdot 10^9, 238)\cdot c)^2\cdot 4\cdot\pi\cdot\varepsilon_o} = 3.9\times 10^4$
Cs	$\frac{T_b(r_c, f_{ao}, 132, 55, F_{ib})}{30\cdot 10^6} = 858$	$\frac{(6\cdot 10^4)\cdot 10^6}{T_b(r_c, f_{ao}, 132, 55, F_{ib})} = 2.3$	$2\cdot\frac{(6\cdot 10^4)}{10^{-6}}\cdot\frac{T_b(r_c, f_{ao}, 132, 55, F_{ib})^{-1}}{(\tau\cdot\beta(26\cdot 10^9, 132)\cdot c)} = 5.5$	$\frac{4\cdot 6\cdot 10^4\cdot T_b(r_c, f_{ao}, 132, 55, F_{ib})^{-1}}{(\tau\cdot\beta(26\cdot 10^9, 132)\cdot c)^2\cdot 4\cdot\pi\cdot\varepsilon_o} = 1.1\times 10^5$
Rb	$\frac{T_b(r_c, f_{ao}, 85, 37, F_{ib})}{30\cdot 10^6} = 439$	$\frac{(6\cdot 10^4)\cdot 10^6}{T_b(r_c, f_{ao}, 85, 37, F_{ib})} = 4.6$	$2\cdot\frac{(6\cdot 10^4)}{10^{-6}}\cdot\frac{T_b(r_c, f_{ao}, 85, 37, F_{ib})^{-1}}{(\tau\cdot\beta(13\cdot 10^9, 85)\cdot c)} = 11.9$	$\frac{4\cdot 6\cdot 10^4\cdot T_b(r_c, f_{ao}, 85, 37, F_{ib})^{-1}}{(\tau\cdot\beta(13\cdot 10^9, 85)\cdot c)^2\cdot 4\cdot\pi\cdot\varepsilon_o} = 2.4\times 10^5$
K	$\frac{T_b(r_c, f_{ao}, 39, 19, F_{ib})}{30\cdot 10^6} = 174$	$\frac{(6\cdot 10^4)\cdot 10^6}{T_b(r_c, f_{ao}, 39, 19, F_{ib})} = 11.5$	$2\cdot\frac{(6\cdot 10^4)}{10^{-6}}\cdot\frac{T_b(r_c, f_{ao}, 39, 19, F_{ib})^{-1}}{(\tau\cdot\beta(4.4\cdot 10^9, 39)\cdot c)} = 34$	$\frac{4\cdot 6\cdot 10^4\cdot T_b(r_c, f_{ao}, 39, 19, F_{ib})^{-1}}{(\tau\cdot\beta(4.4\cdot 10^9, 39)\cdot c)^2\cdot 4\cdot\pi\cdot\varepsilon_o} = 9.1\times 10^5$
Na	$\frac{T_b(r_c, f_{ao}, 22, 11, F_{ib})}{30\cdot 10^6} = 74$	$\frac{(6\cdot 10^4)\cdot 10^6}{T_b(r_c, f_{ao}, 22, 11, F_{ib})} = 27.2$	$2\cdot\frac{(6\cdot 10^4)}{10^{-6}}\cdot\frac{T_b(r_c, f_{ao}, 22, 11, F_{ib})^{-1}}{(\tau\cdot\beta(1.7\cdot 10^9, 22)\cdot c)} = 95$	$\frac{4\cdot 6\cdot 10^4\cdot T_b(r_c, f_{ao}, 22, 11, F_{ib})^{-1}}{(\tau\cdot\beta(1.7\cdot 10^9, 22)\cdot c)^2\cdot 4\cdot\pi\cdot\varepsilon_o} = 3\times 10^6$

Ignition across a giant density step→ gain 1000?

(John Nuckolls, IFSA Plenary Talk, September 7, 2009)

LLNL-PRES-416563

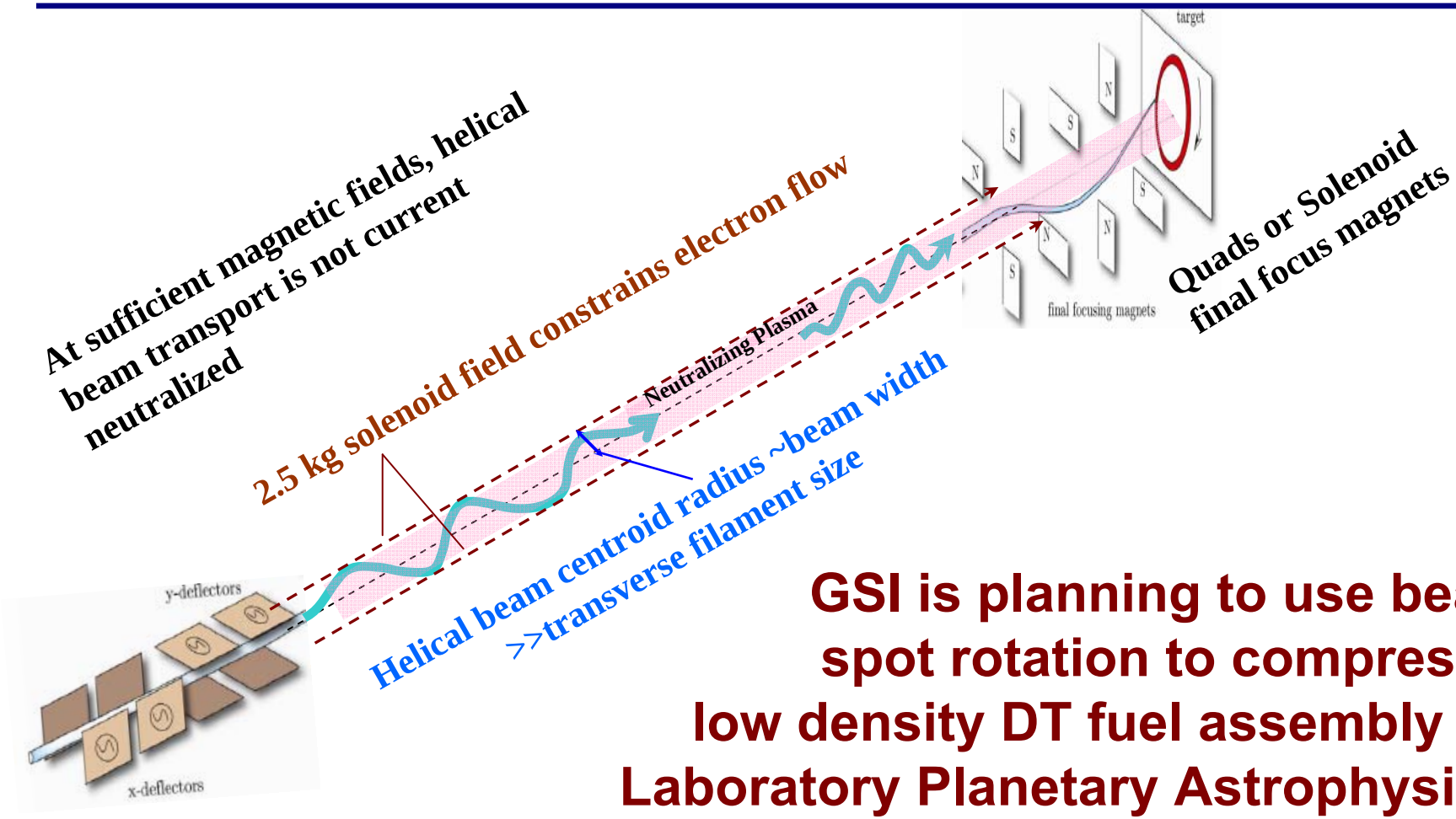




JHN-2009-008IFSA 22

Dec. 2009: John Nuckolls encouraged Grant Logan and John Perkins to find a way to use efficient heavy ion beams to assemble this sort of hemispherical target with large fuel mass to get large yields ~ 1 GJ

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

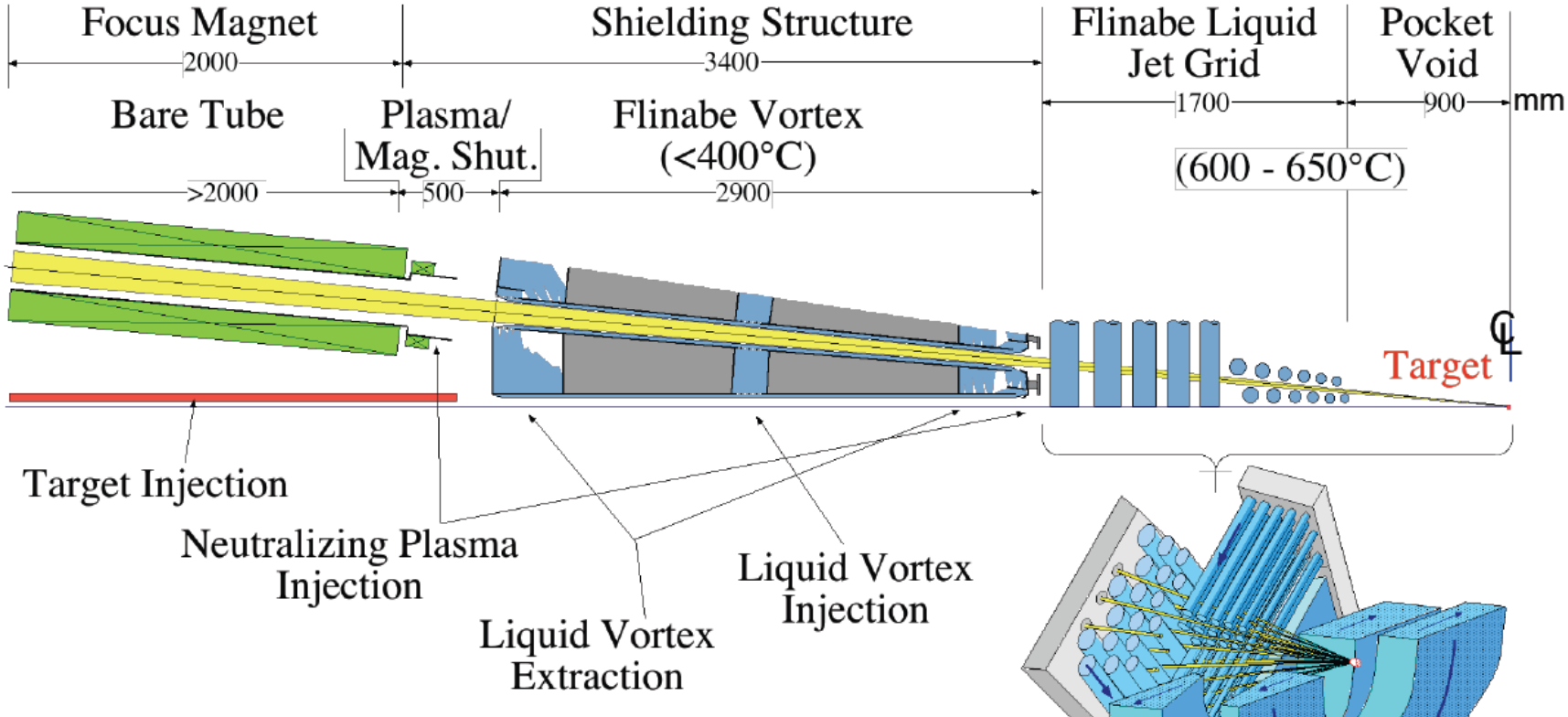


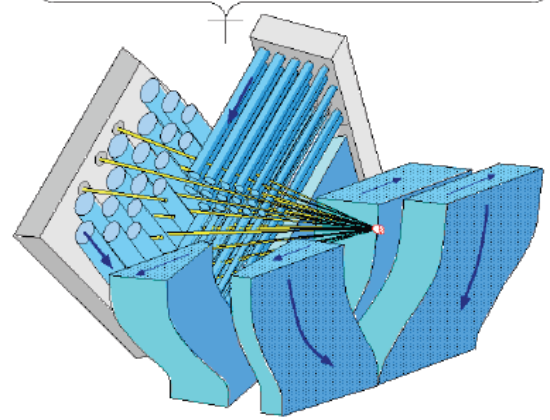
GSI is planning to use beam spot rotation to compress a low density DT fuel assembly for Laboratory Planetary Astrophysics, but this technique can also be applied to low density fuel compression for high gain fast ignition.

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

<u>thick liquid protected chamber</u>

For 120 beams with 10 mr focusing angles, neutron diffusion through "Swiss cheese" set the minimum focal length at 6 meters in the RPD design. *With fewer beams and 5 mr focusing angles, shorter focal lengths < 3 meters would be possible.*





Schematic Liquid Jet Geometry

Magnet lifetimes, which are limited by dose to the insulators and neutron fluence to the superconductor, exceed the plant lifetime;
Insulator & superconductor lifetimes (in years) are:
Last magnet: 230/260
2nd magnet: 410/1580 **(Jeff Latkowski, LLNL)**
3rd magnet: 100/610

RPD

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.

	Time Scale (Phenomena Duration)			
Spatial Volume	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)

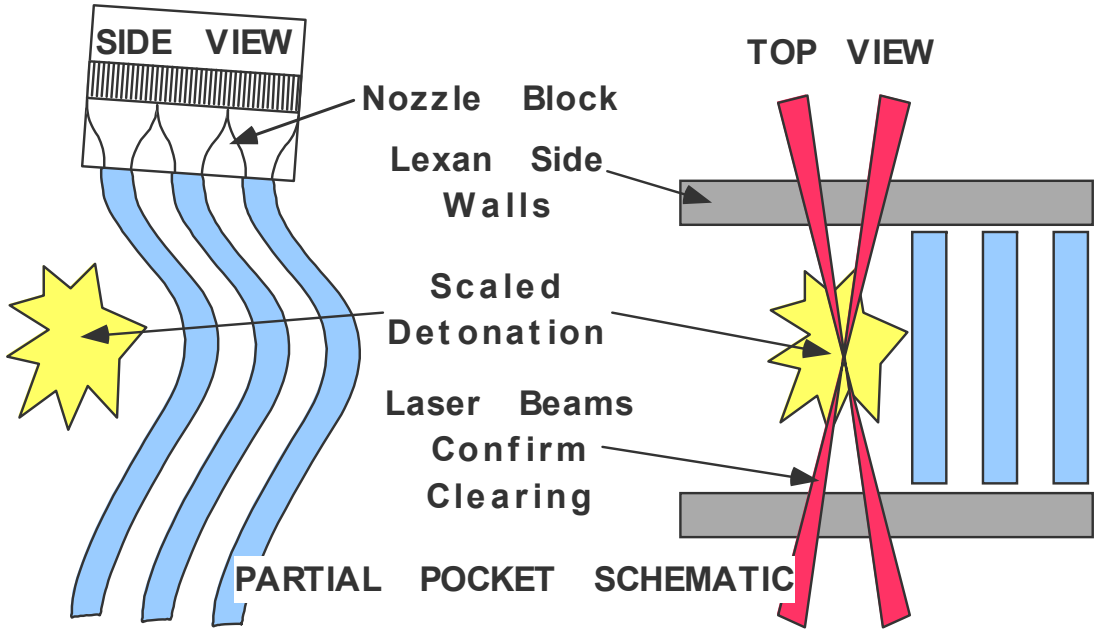
- Example: UCB facility studies single jets and few jets (partial pockets).
- Transient flow into large vacuum vessel
- 4.0 m^3 supply tank, 10-cm diameter supply line
- Jet velocities to 13 m/s
- Flow rates to 40 kg/s for over 1 minute
- Water used to simulate Flibe (allows Re, Fr and We number matching 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 D x 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	$\underline{2.20 \times 10^5}$	0.99×10^5	2.43×10^5	$\underline{2.43 \times 10^5}$
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	$\underline{7.3}$	7.3	$\underline{7.3}$
Working Fluid	Flibe	Water	Water	Flibe	Water

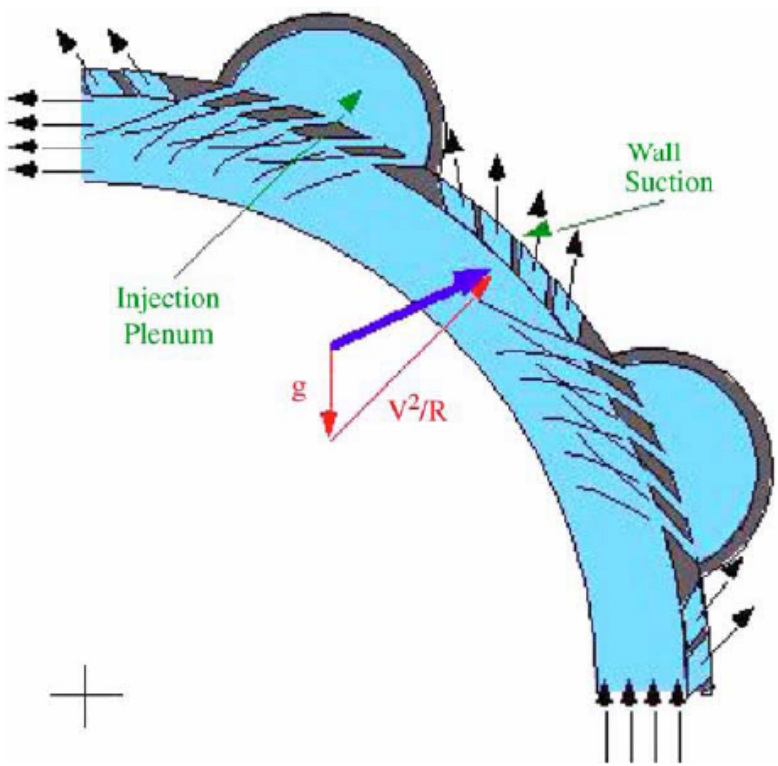
Partial pocket experiments (Per Peterson, UCB)

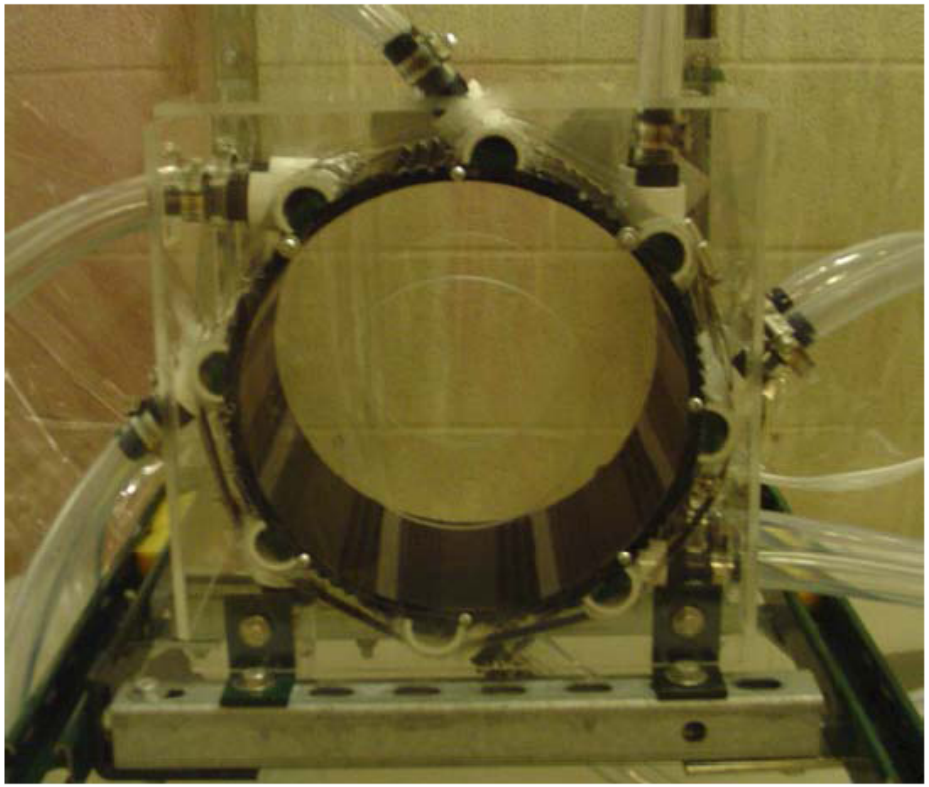
- 1/4-scale partial pocket multiple-jet experiments to study:
  - Jet (various configurations) disruption by scaled fuel-oxidizer detonation
  - Shock propagation and droplet/slug generation from multiple colliding jets
  - Forced clearing of droplets confirmed by laser-beam diagnostic



- 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

US Heavy Ion Fusion Science Virtual National Laboratory: Organization and Research Scope

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

HEDLP/IFES outlook, 5 years

(From Ed Synakowski to FESAC, March 2010)

- **National Ignition Facility (NIF) will have ignited**. FES will have a leadership role in developing IFES and astrophysical science experiments on NIF and on HEDLP facilities nationwide, in partnership with NNSA.
- FES, through its development of coordinated marches using the wide range of HEDLP facilities available, will be resolving fundamental questions of nature and pursuing science essential to assessing the viability of IFE. This range of scales can be levered in a scientifically sensible way
- For IFES, key questions to be pursued by FES include the multiscale physics challenges of advanced ignition concepts and the science of different drivers on the target
- Matter in Extreme Conditions Instrument (MECI) project at SLAC will be producing unique research on matter in extreme conditions relevant to fusion, planetary and astrophysical science, equations of state…
- National Drift Compression Experiment-II (NDCX-II) at LBNL will be assessing the issues surrounding the viability of heavy ion fusion.

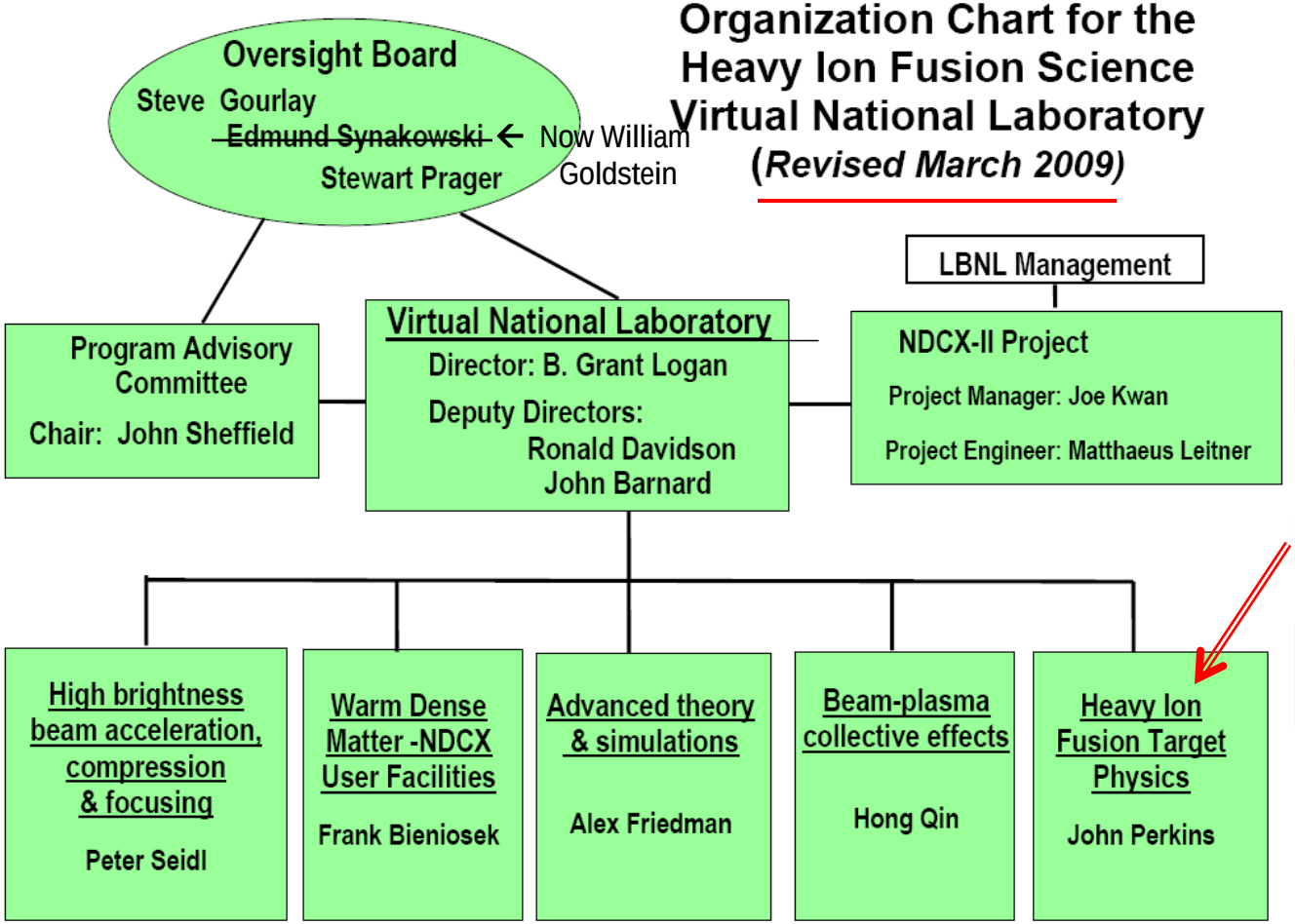
The NAS study and NIF ignition campaign results will have a large impact on the specifics of what we ask FESAC.

The research scope of the HIFS-VNL was revised March 09 to strengthen beam science related to IB-HEDPX and heavy ion fusion target physics.

The revised VNL research scope, including use of NDCX-I and II, addresses research opportunities identified in the Jan 2009 FESAC HEDLP report.

Organization Chart for the Heavy Ion Fusion Science Virtual National Laboratory

(Revised March 2009)



Stephen Gourlay — Date 3/11/09

Edmund Synakowski — Date 3/17/09

Stewart Prager — Date 3/10/09

(New VNL laboratory director endorsements will be needed October 2010 for the next 5-year renewal of the VNL covering FY12-FY16)

An extension of the MOA was signed last month to cover the next five years FY 2011 through FY2015

The Regents of the University of California,
Lawrence Berkeley National Laboratory

A. Paul Alivisatos, Director
Lawrence Berkeley National Laboratory

September 10, 2010
Date

Stephen A. Gourlay, Director
Accelerator and Fusion Research Division

September 10, 2010
Date

Lawrence Livermore National Security LLC

Tomas Diaz de la Rubia
Deputy Director for S&T
Lawrence Livermore National Laboratory

9/16/10
Date

William H. Goldstein
Associate Director, Physics and Life Sciences Directorate
Lawrence Livermore National Laboratory

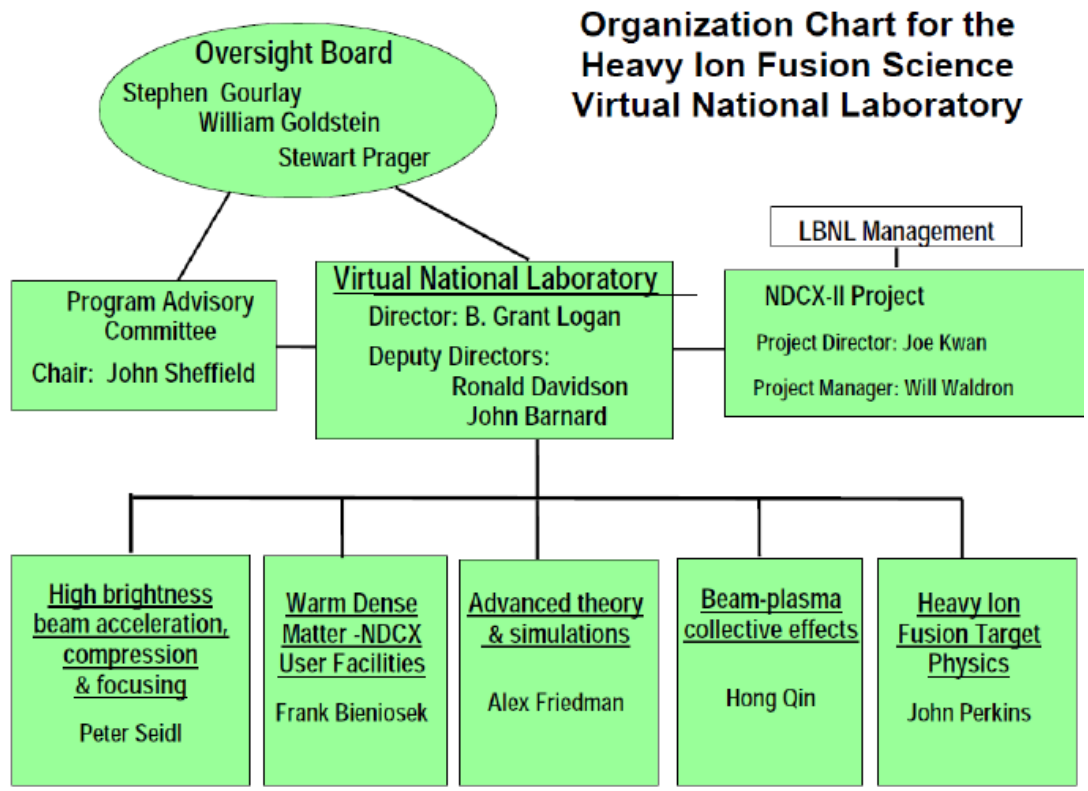
9/13/10
Date

The Trustees of Princeton University,
Princeton Plasma Physics Laboratory

Stewart Prager, Director
Princeton Plasma Physics Laboratory

9/8/10
Date

Organization of the Heavy Ion Fusion Sciences Virtual National Laboratory



The Heavy Ion Fusion Science Virtual National Laboratory (HIFS-VNL) is governed by a MOA, signed by the lab directors. The previous MOA (below) was signed by Steven Chu in October 2005

a) **Background:** The Laboratories desire and are committed to collaborate as a Heavy-Ion Fusion Science Virtual National Laboratory (HIFS-VNL) in the conduct of heavy-ion-driven high energy density physics and fusion science, and to promote more rapid progress in these areas through technical management integration of the Laboratories' scientific staff, equipment, and experimental facilities.

The Regents of the University of California,
Lawrence Berkeley National Laboratory

Steven Chu, Director
Lawrence Berkeley National Laboratory

Date: 22 Sept 2005

William A. Barletta, Director
Accelerator and Fusion Research Division

Date: 22 Sept. 2005

The Regents of the University of California,
Lawrence Livermore National Laboratory

Michael R. Anastasio, Director
Lawrence Livermore National Laboratory

Date: October 17, 2005

William H. Goldstein
Physics and Advanced Technology Directorate

Date: October 2, 2005

The Trustees of Princeton University,
Princeton Plasma Physics Laboratory

Robert J. Goldston, Director
Princeton Plasma Physics Laboratory

Date: October 26, 2005

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.

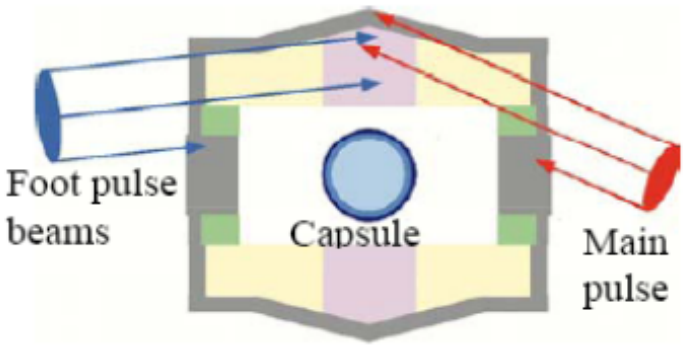


Fig. 1 Large-angle distributed radiator target.

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

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

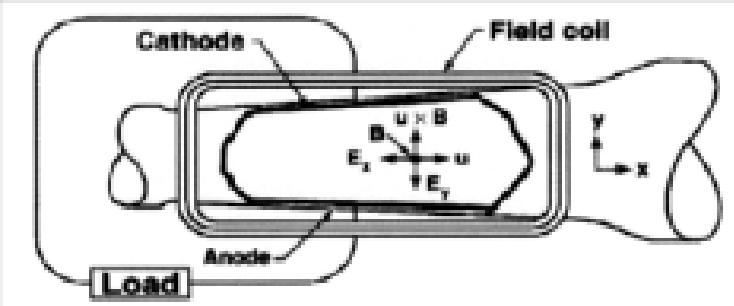
Michael Hay, VNL seminar July 27, 2010

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

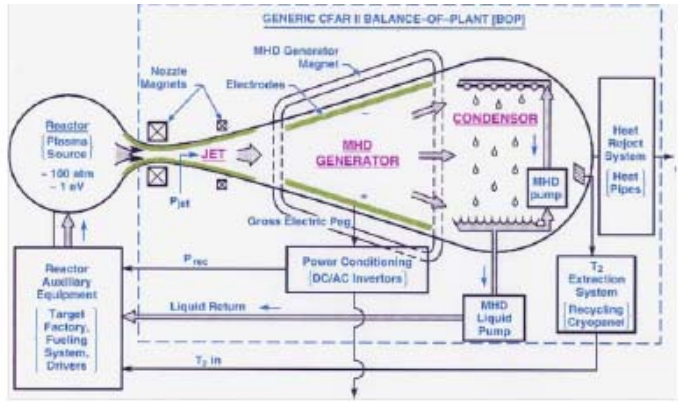
	0.44 MJ target			3.7 MJ target		
Pedestal No.	Power [TW]	Rb Ion KE [MeV]	Q at R(0)	Power [TW]	Hg Ion KE [GeV]	Q at R(0)
1	1.4	50	0.475	2.5	0.22	0.032
2	6.5	50	2.21	16	0.22	0.204
3	30.2	50	10.26	82	0.22	1.05
4 (main)	205	500	0.22	660	2.225	0.027

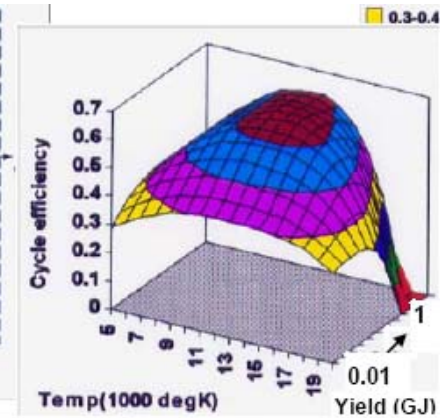
See also: P.A. Seidl, E.P. Lee, R.O. Bangerter, and A. Faltens. HIFAN-1768, (2010).

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



Schematic diagram of a dc magnetohydrodynamic generator. (Rosa)





Momentum :

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

Energy :

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

Continuity :

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

Load Factor :

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

Electric Power Density :

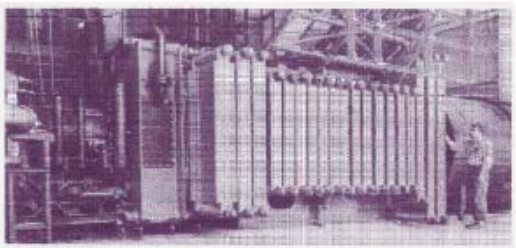
$$j \cdot E = -\frac{K(1-K)\sigma u^2 B^2}{1 + (\omega\tau^2)}$$

Magnet cost, Energy Density :

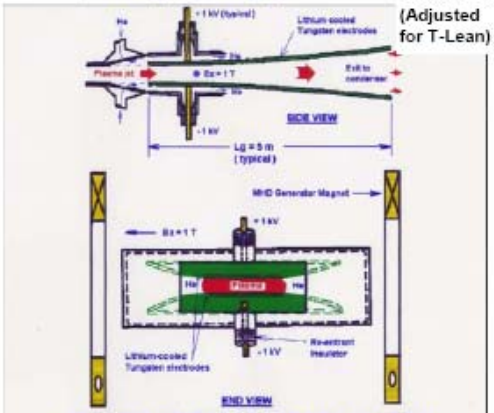
$$\text{Magnet Cost} / m^3 \sim B^2 / (2\mu_o)$$

where ρ = mass density , u = velocity, x = distance along channel, p = pressure, j = current density, B = magnetic field, E = electric field, σ = electrical conductivity, $\omega\tau$ = Hall parameter, h = specific enthalpy, f = friction due to mass inflow from wall transpiration cooling, qr = heat loss / m^3 due to radiation losses, A = channel area.

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



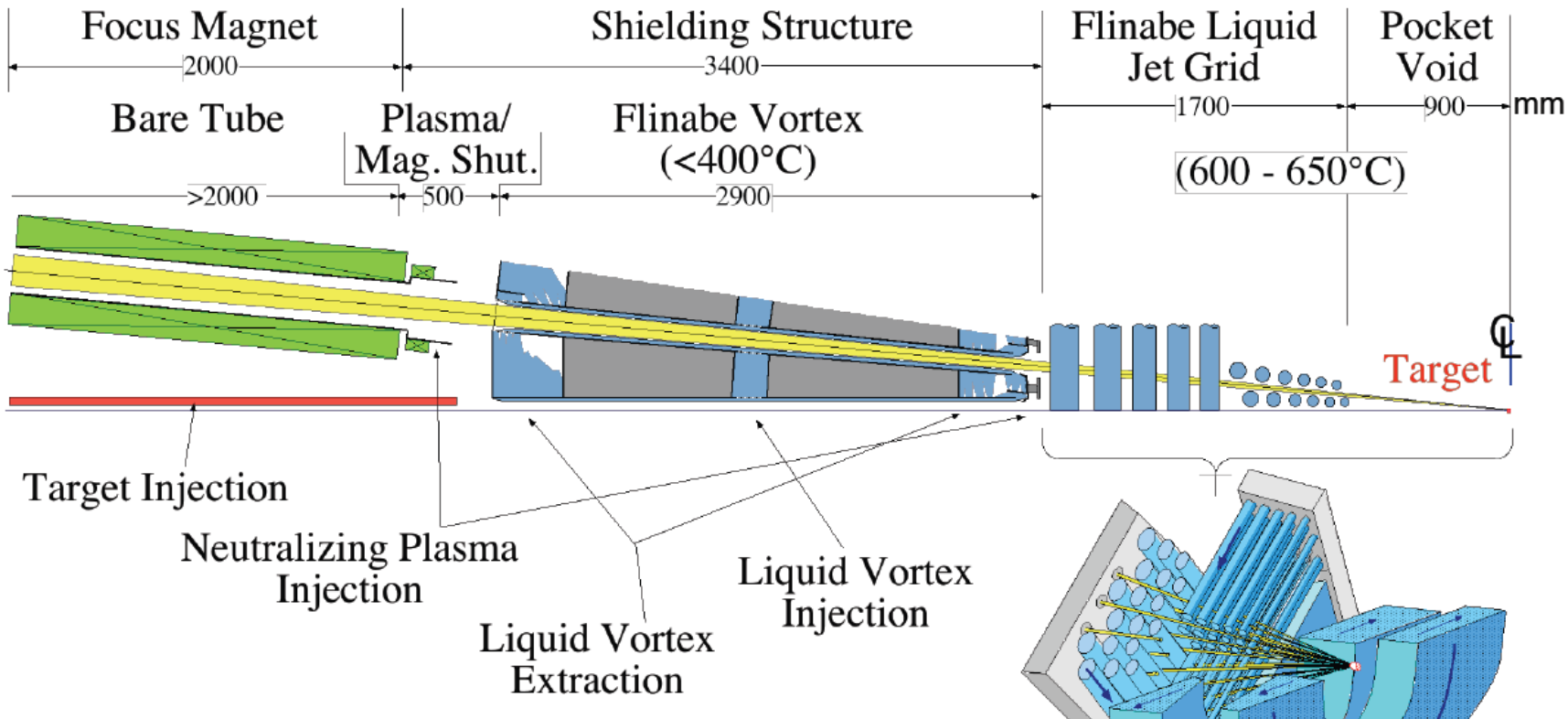
THE AVCO MARK V "ROCKET GENERATOR"
(from Rosa, MHD Energy Conversion, 1968)
Temp ~ 3000 deg K
Conductivity ~ 100 mhos/m
Velocity ~ 1000 m/s
Efficiency ~ 10% (of chemical)
Power (above unit) ~ 20 MWe

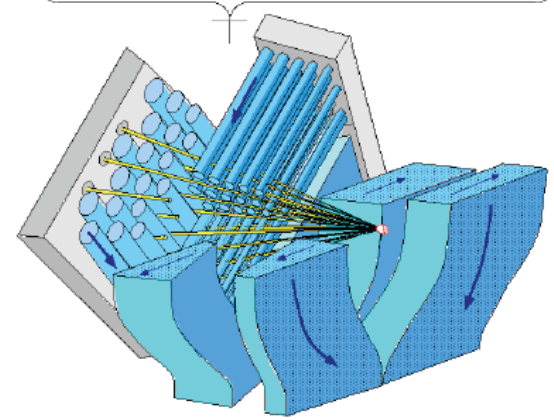


TYPICAL" CFARII MHD GENERATOR
Temp ~ 12000 deg K, Conductivity ~ 500 mho/m
Velocity ~ 10000 m/s, Efficiency ~ 80%(of kinetic)
Power (comparable size to MarkV) ~ 2000 MWe

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

For 120 beams with 10 mr focusing angles, neutron diffusion through "Swiss cheese" set the minimum focal length at 6 meters in the RPD design. *With fewer beams and 5 mr focusing angles, shorter focal lengths < 3 meters would be possible.*



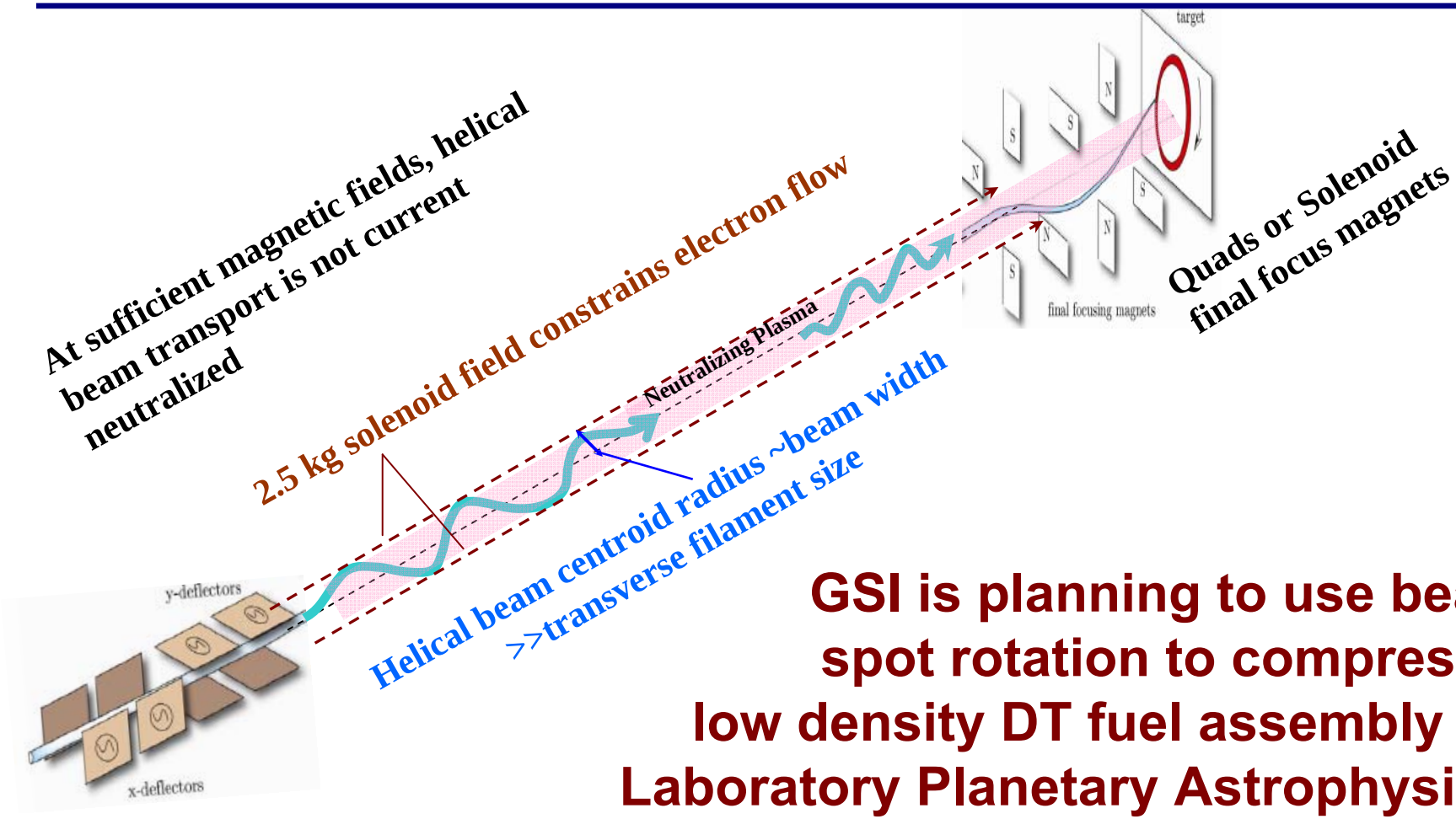


Schematic Liquid Jet Geometry

Magnet lifetimes, which are limited by dose to the insulators and neutron fluence to the superconductor, exceed the plant lifetime;
Insulator & superconductor lifetimes (in years) are:
Last magnet: 230/260
2nd magnet: 410/1580 **(Jeff Latkowski, LLNL)**
3rd magnet: 100/610

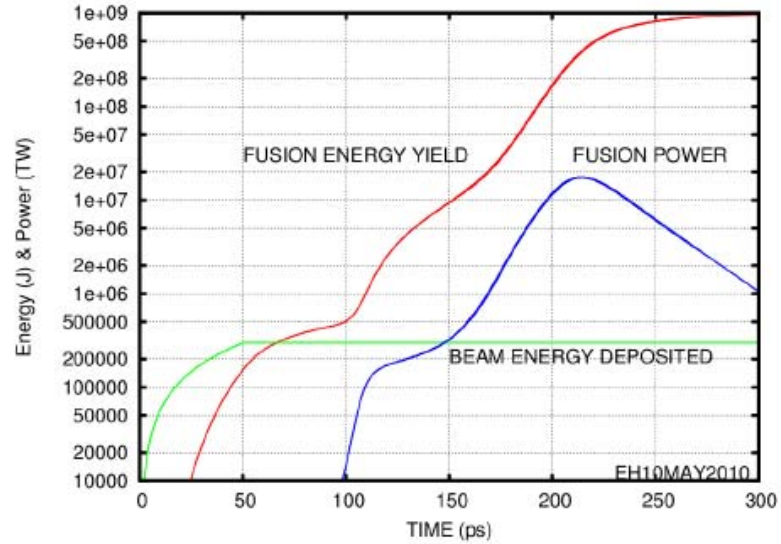
RPD

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

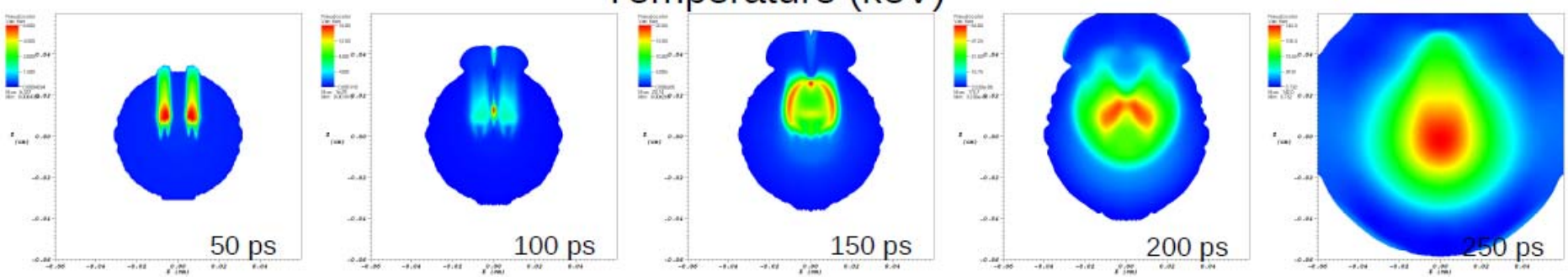


GSI is planning to use beam spot rotation to compress a low density DT fuel assembly for Laboratory Planetary Astrophysics, but this technique can also be applied to low density fuel compression for high gain fast ignition.

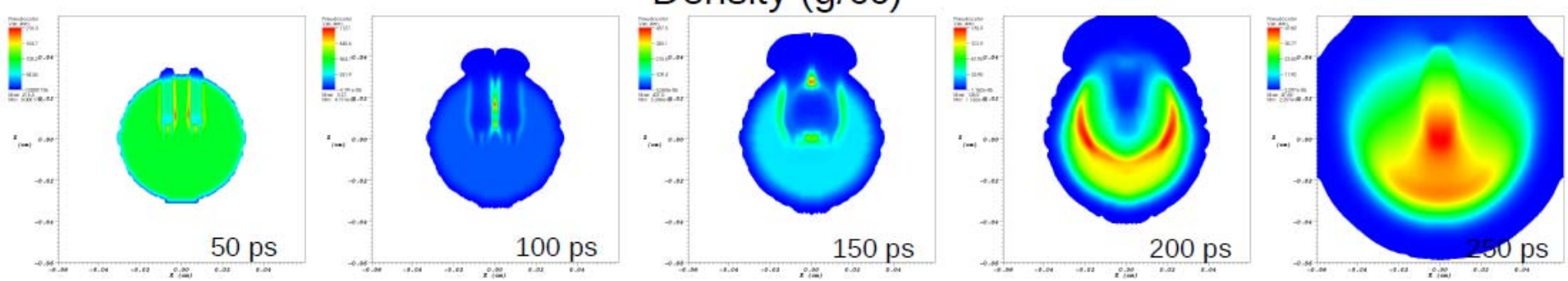
Heavy Ion Fast Ignition (HIFI) example:
60 GeV U annular beam , 300 kJ, 50 ps, 50/100 μm inner/outer radius.
Initial compressed fuel is a 300 μm radius sphere at temperature 200 eV and density 100 g/cc.
Total yield is 1 GJ (~30% burn fraction)



Temperature (keV)



Density (g/cc)



R&D Needs for X-target HIF→ many opportunities for collaboration.

- **Sub-ns igniter pulses**: ***longitudinal emittance growth limits***. **Study in NDCX-II, and at GSI with added bunchers.**
- **Self-pinching: develop diagnostics to *measure net beam currents* under conditions when charge neutralization exceeds current neutralization. NDCX-II, RHEPP, GSI-FAIR**
- **Hydro coupling efficiency in X-cone tampers: e.g., test compression in X-cone geometry using the beam wobbler planned @ GSI/FAIR**
- **Stripping-induced beam emittance at driver scale beam perveance. Measure emittance stripping $Li^{+1} \rightarrow Li^{+2}$ in NDCX-II at high currents.**
- **Dynamic gas control with multiple beams. Rebuild 2 MV, high beam current HCX-II @ 5 Hz rep rate to benchmark vacuum/beam loss models.**
- **Ion fast ignition -rebuild surplus HEP/NP accelerator hardware for MJ U-igniter (cost ~ 300 M$?).**

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

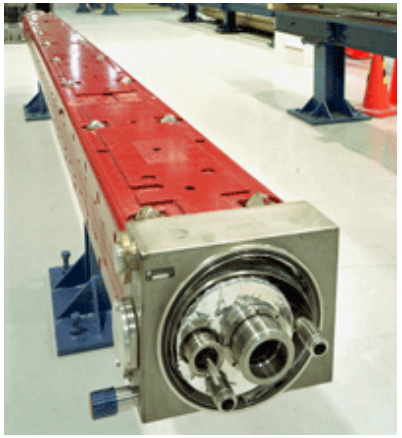
$50M IB-HEDPX would provide a full capability (p>1 Mbar) for HEDP users as an upgrade from NDCX-II. Note this CD-0 (Dec05) calls for NDCX-II as a prerequisite. →NDCX-II commissioning will satisfy this pre-requisite in FY12.

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.

By adding a DT fuel compression system, bunching, and e-cooling or laser cooling of ions in the rings, Fermilab's Tevatron / Main Injector as well as other major synchrotrons such as RHIC, might be examined as to how they might be used to accelerate ~ 0.5 MJ of 50 to 100 GeV heavy ions for a fusion-scale fast ignition experiment

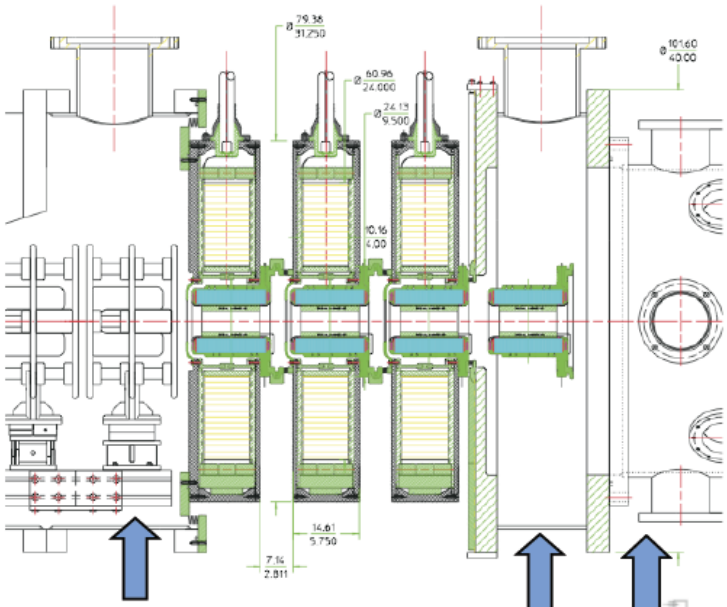
1.3 miles

An informal open workshop would be useful to explore these and other options for a high energy HIF related fast ignition target experiment.



→GSI plans a cryo-H_2 compression experiment using FAIR's 80 kJ, 100 ns, 200 GeV beam and a wobbler like slide 13.

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:

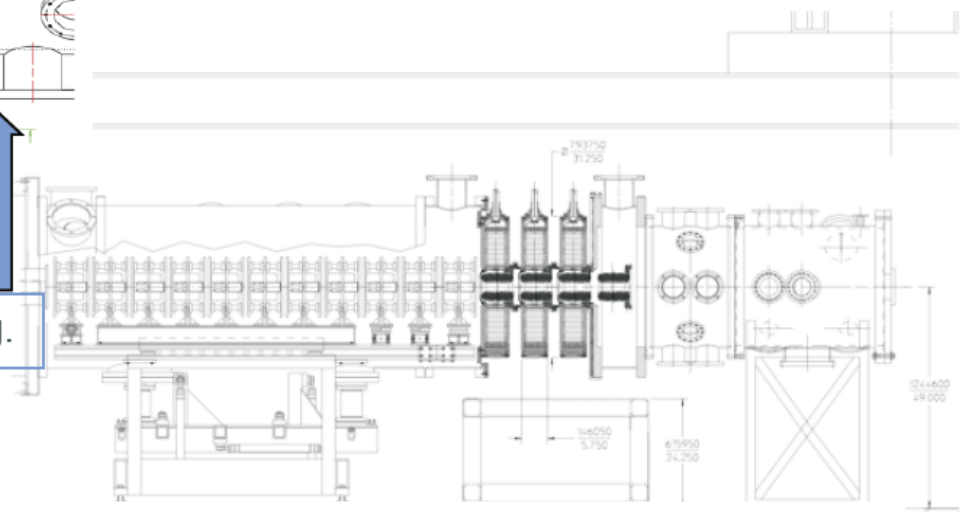
- Better Alignment
- Better Match to Existing Lattice
- Better Engineering for Improved Experimental Control
- Extendable to Longer Lattice
- Interfaces with Different Induction Cells
- Improves Diagnostics Access

New Diagnostic: sliding quad & diagnostic access:

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

Diag.

Diag.



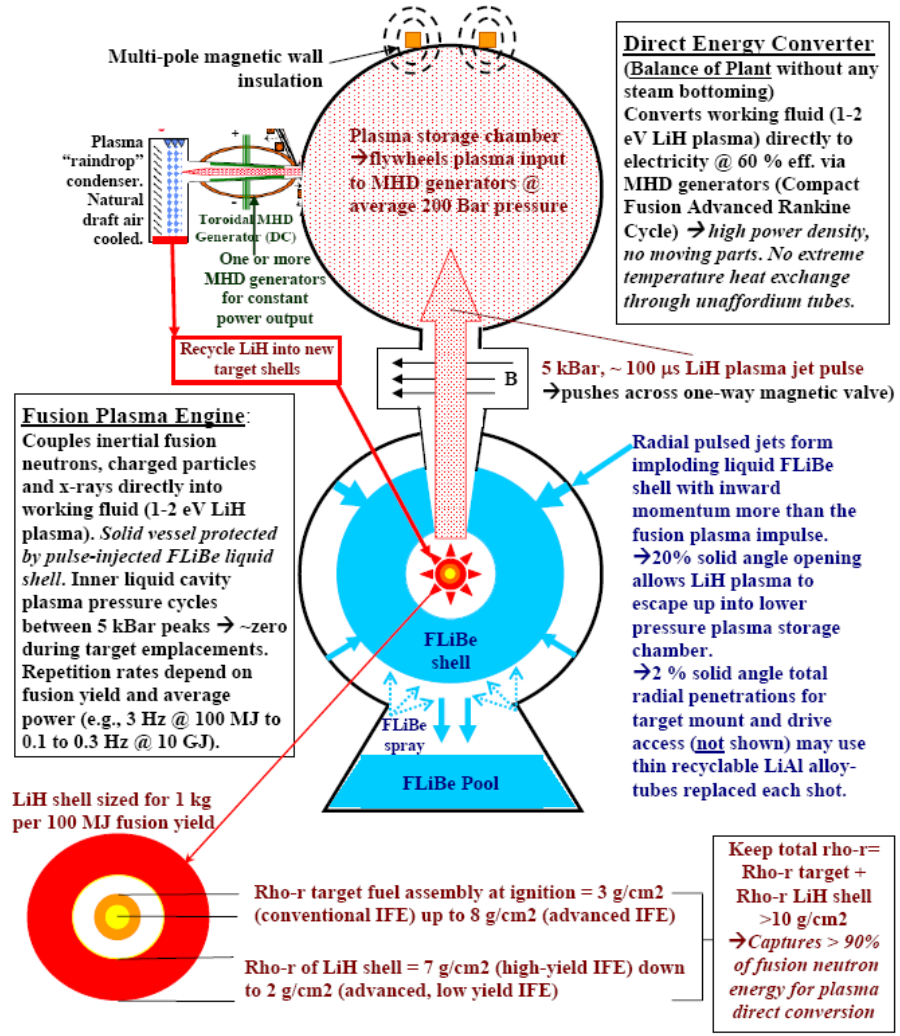
Simplified and optimized magnet transport line design can provide a scalable foundation for future quadrupole experiments beyond gas/electron experiments.

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.