Heavy Ion Fusion*

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

Fusion Power Associates Annual Meeting and Symposium

December 1-2, 2010

Capitol Hill Club, 300 First Street, Washington, DC

*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.

** HIFS-VNL: A collaboration between Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, and Princeton Plasma Physics Laboratory, USA.

We are very pleased to have the opportunity to describe to the NAS review a research agenda specifically aimed at heavy ion fusion energy.

Our approach is to:

1. **Follow the general HIF development plan logic presented at Snowmass in 2002 as a roadmap for induction linac driver and low cost liquid chamber technology R&D as was used as a guide in the 2003 and 2004 FESAC reports, including updates and recent advances;**
2. **Exploit HEDP advances: next five years use NDCX-I, NDCX-II and its extension to IB-HEDPX to test HIF-relevant beam manipulations;**
3. **Plan modifications of existing facilities (e.g., HCX, NDCX-I) as test beds for dynamic vacuum/e-cloud accelerator R&D @ 5 Hz;**
4. **Defer down-selections on HIF target options until NIF ignition test data becomes available for indirect and direct drive; hot-spot and shock ignition;**
5. **Continue to improve the X-target concept seeking ways to simplify the driver-chamber-target interface for an HIF-ETF/Demonstration Plant;**
6. **Host a spring 2011 workshop on Accelerators for Heavy Ion Fusion to assess advances in accelerator driver technology (Peter Seidl-LBNL);**
7. **Evolve a flexible HIF develop plan that exploits accelerator-lab collaborations and avoids premature downselections.**

Heavy ion fusion has been considered for a variety of driver, focusing, chamber, and target options: downselection is not prudent before NIF ignition.

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

The US has focused on induction linacs, but advances in RF technology warrant re-assessment in the spring 2011 workshop. Any driver with ~ 100 beams, and with liquid chambers, could apply to most target options.

All heavy ion fusion R&D plan options can 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.

(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.

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

(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.

(e) Attractive economics (competitive CoE with nuclear plants) and environmental characteristics (no high level waste; only class-C low level waste).

Early HIF plans, as well as Snowmass and 2003/2004 FESAC plans, called for three steps to an HIF Demo: a ~10-kJ-scale IRE→ single shot ignition tests @ ~1-2 MJ→ ~100 MW_e-average-fusion-power ETF

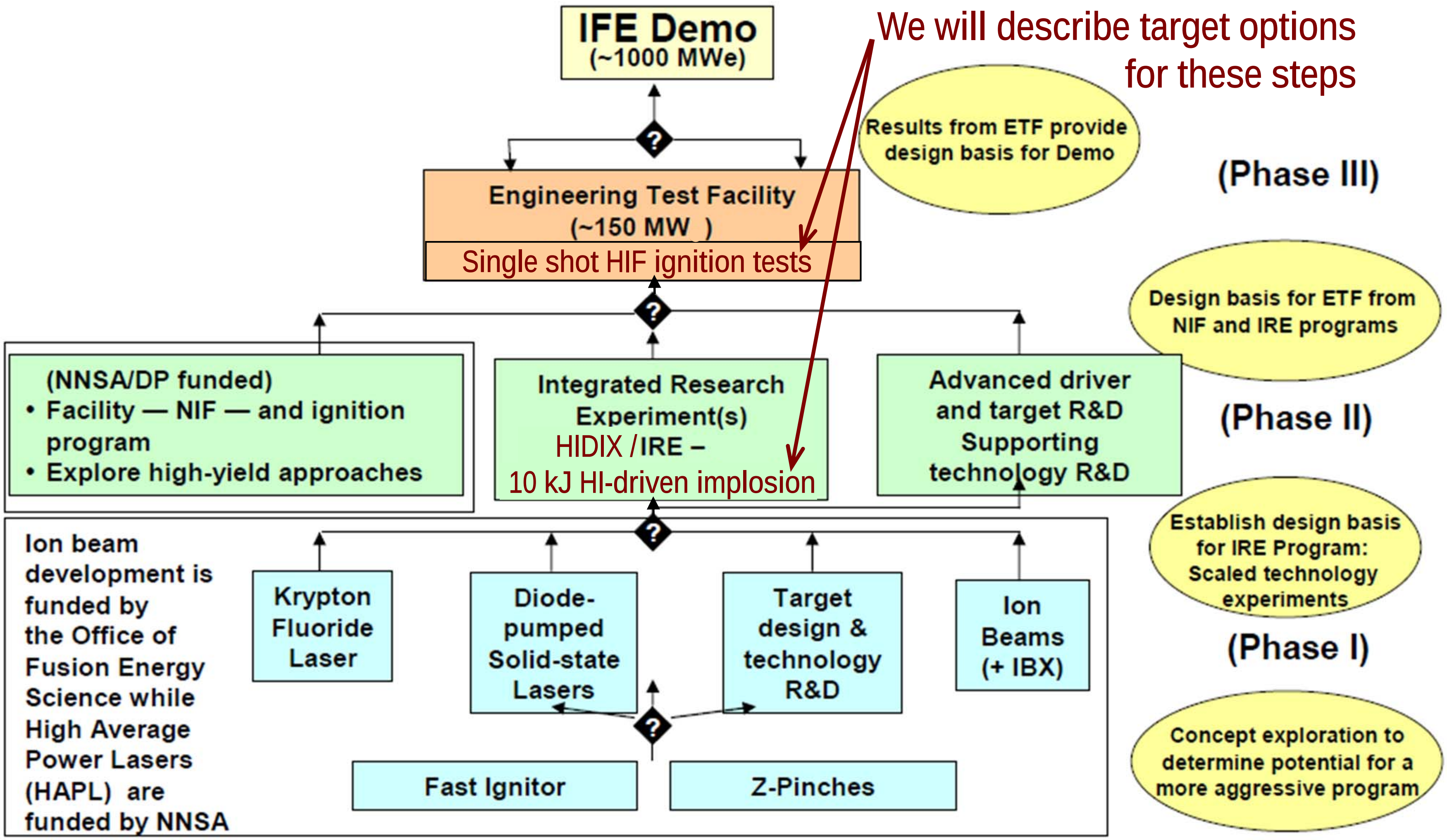


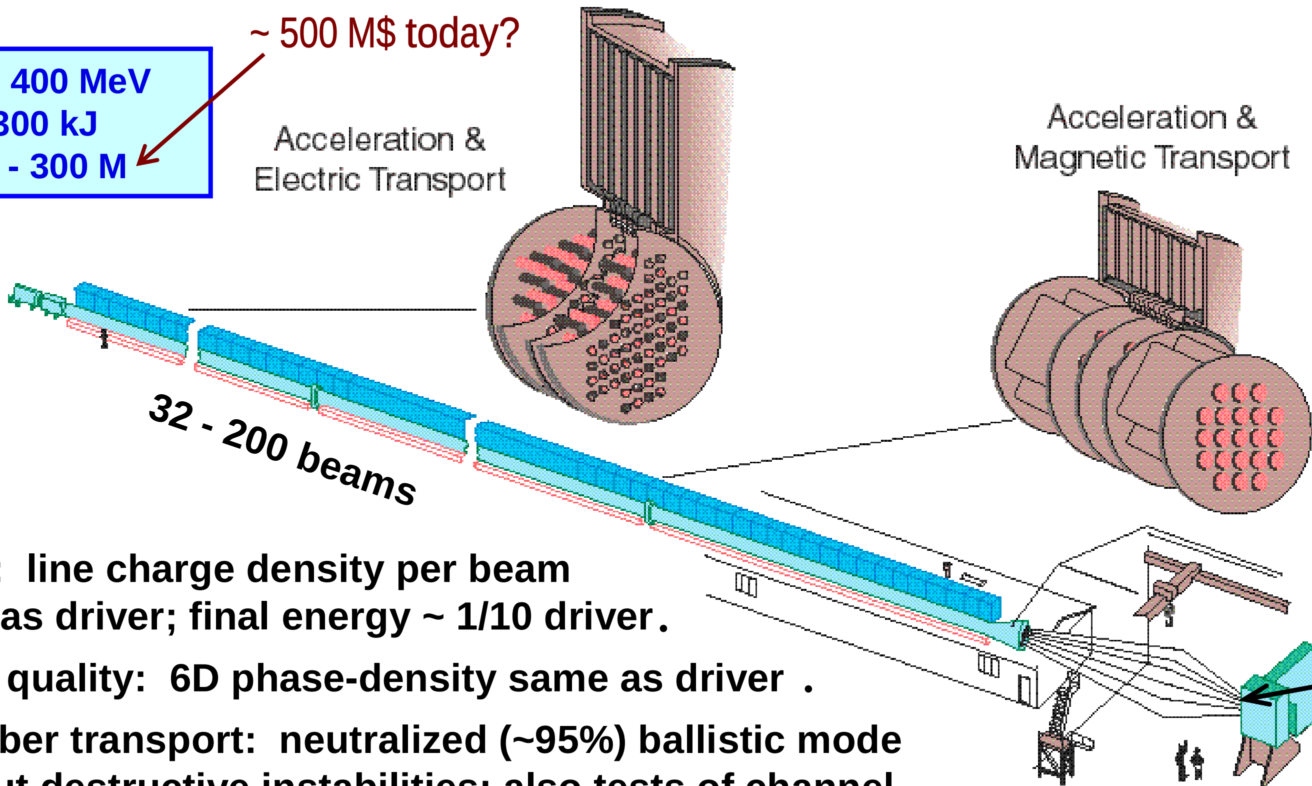
Figure 3. The Inertial Fusion Energy Roadmap

(from 2002 Snowmass Executive Summary for IFE - John Lindl)

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

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

~ 500 M$ today?



IRE concept considered at Snowmass 2002 with two-stage focusing.

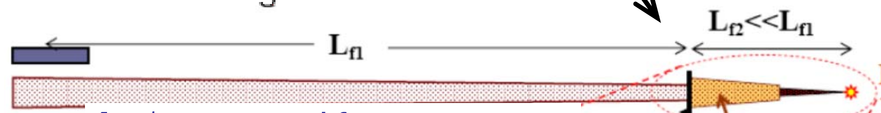
Scale: line charge density per beam same as driver; final energy ~ 1/10 driver.

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 .

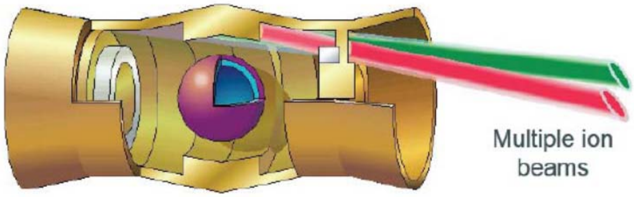


R&D for driver, chamber, and target fabrication are governed by target design requirements.

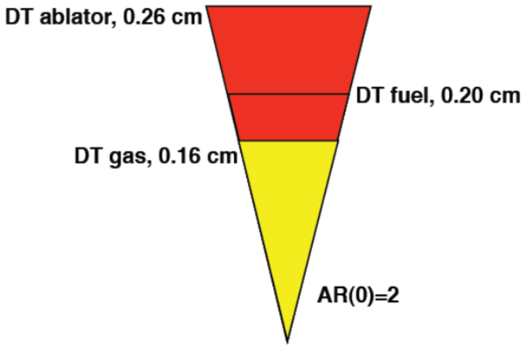
For prudent risk management, HIF should not be limited solely to central hot spot ignition.

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

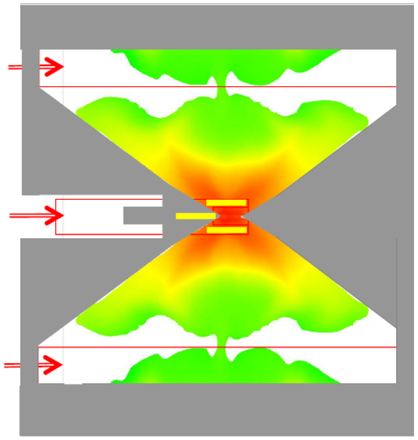
There are three classes of options for heavy-ion-fusion targets (Perkins/Henestroza). Each has several variations. Examples shown have 2-D target designs done or "in the hopper".



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, like NIF.



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, <u>with shock ignition assist</u>.

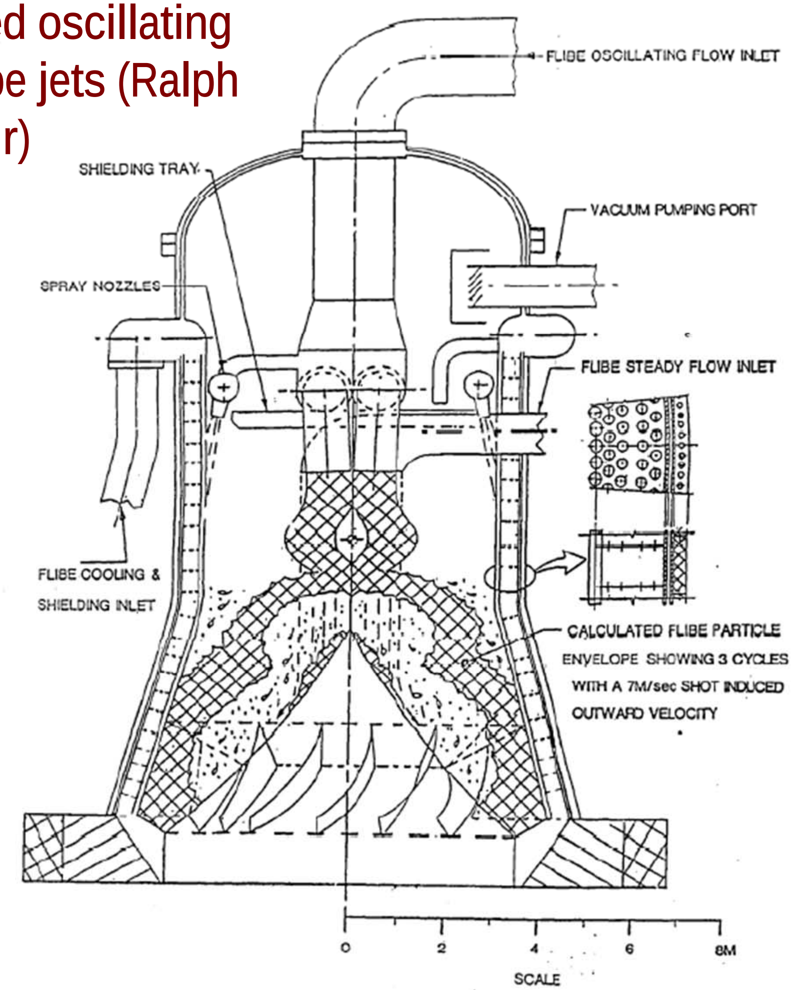


3. **<u>X-target hydro-drive</u> *2-D Hydra design (2010):* 3 MJ compression+3 MJ ignition, all 60 GeV U beams, gain 50. One-sided illumination (publication submitted)**

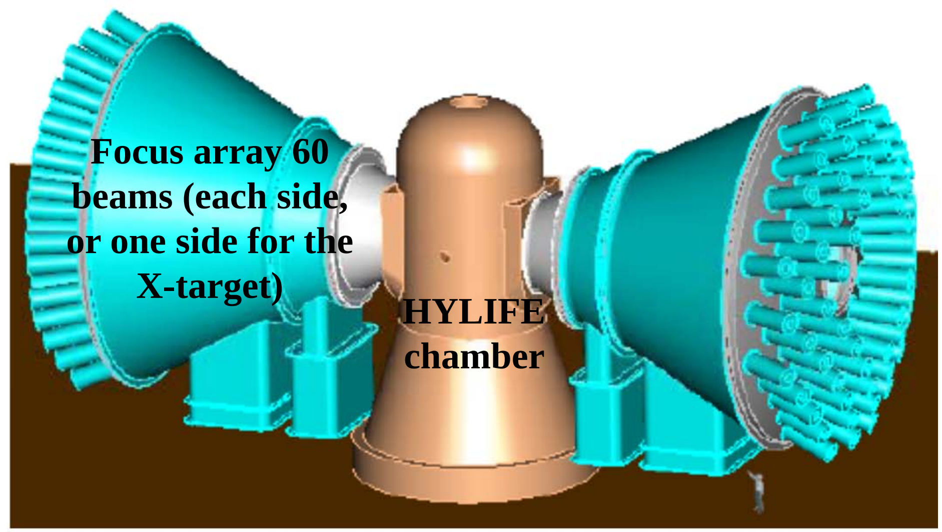
→All three options are intended to use multiple-beam linac drivers with thick-liquid-protected chambers to mitigate material neutron damage risks.

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)



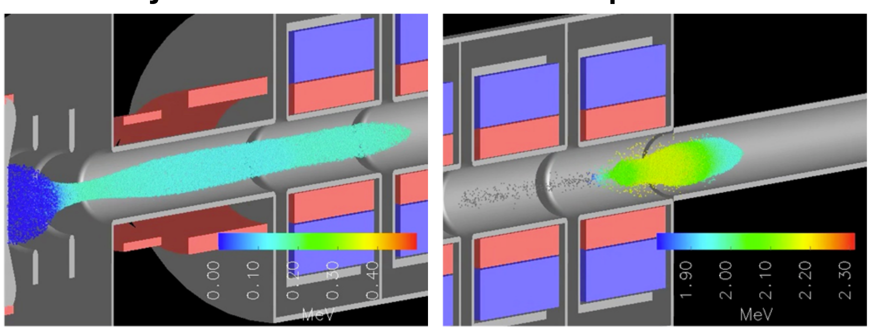
Indirect drive, polar direct drive, and X-targets could all be adapted to use liquid chambers and compatible focusing optics.



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

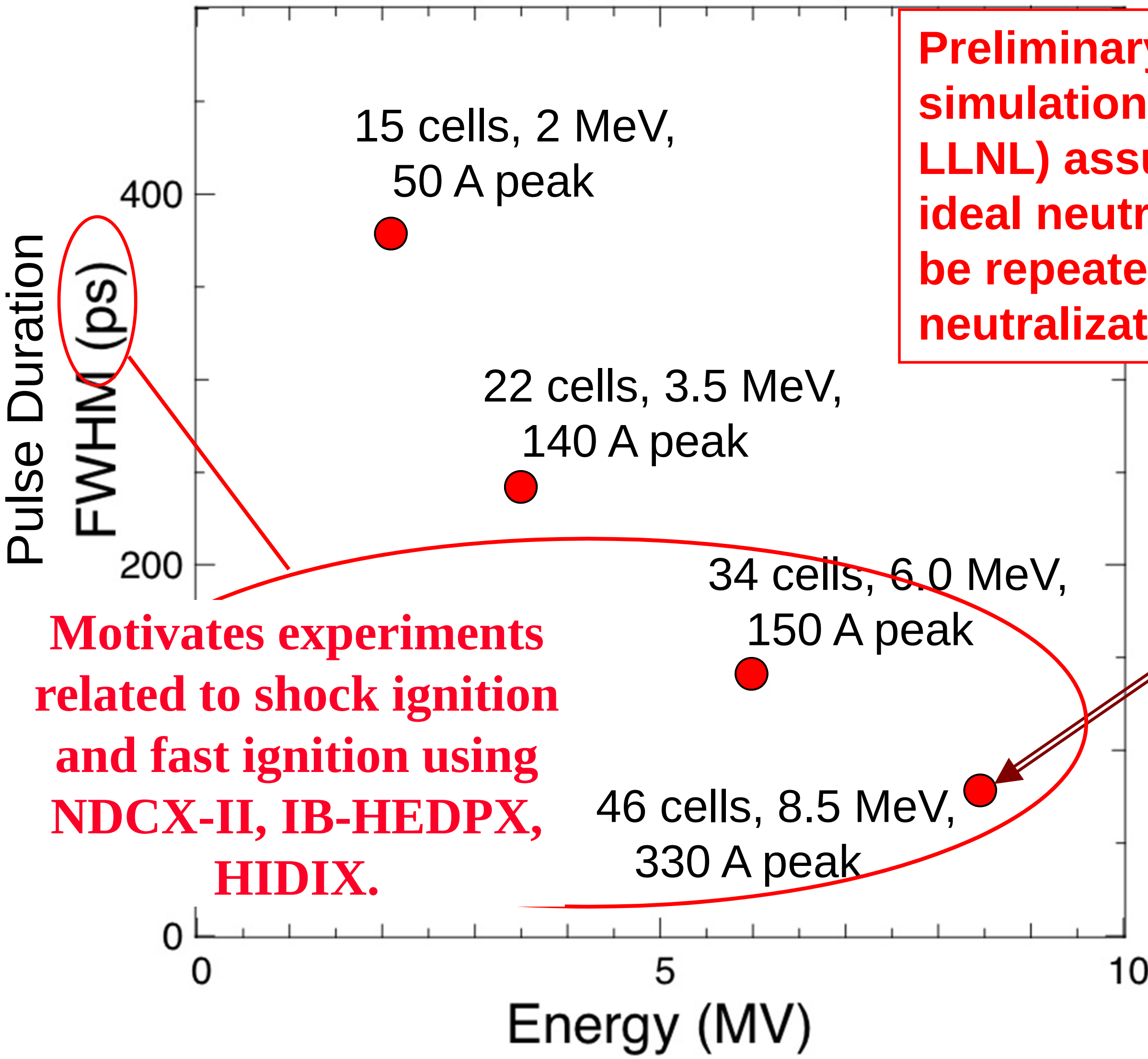
During injection | Entering final compression



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

	NDCX-I	NDCX-II (baseline)
Ion species	**K^+ (A=39)**	**Li^+ (A=7)**
Ion energy	**300-400 keV**	**(1.2 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**

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

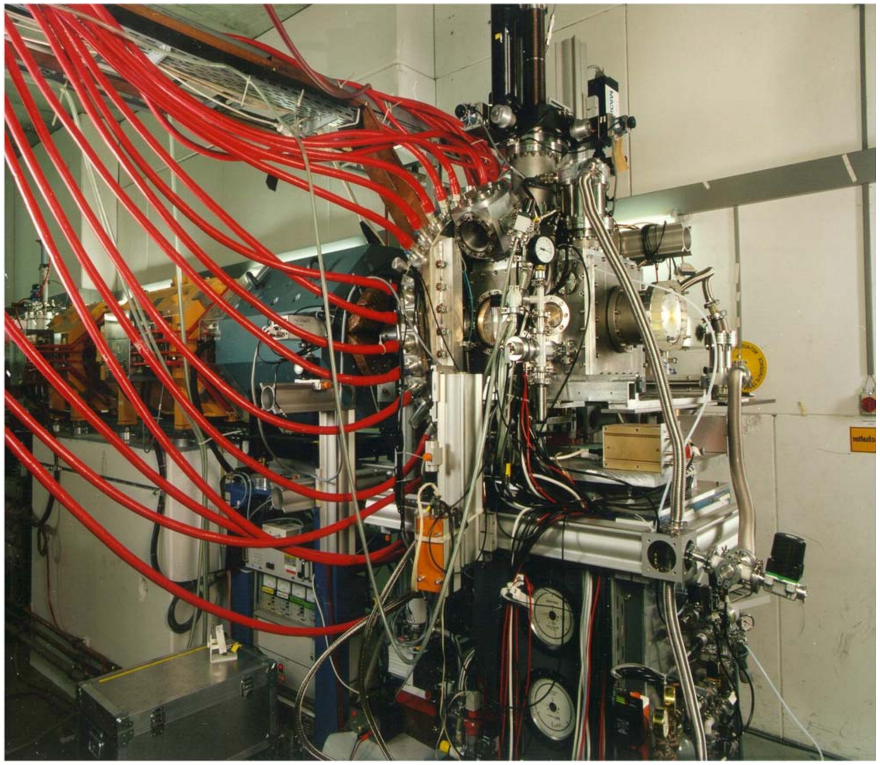


Preliminary results of Warp PIC simulations (Friedman, Grote LLNL) assuming jitter errors with ideal neutralization. These will be repeated with full plasma neutralization physics models.

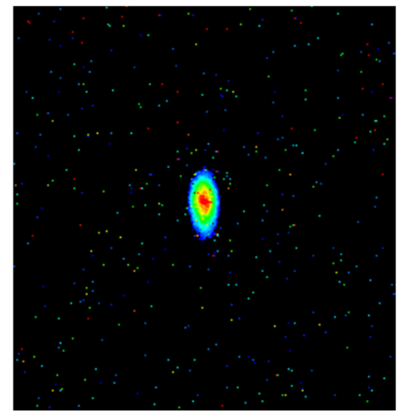
Motivates experiments related to shock ignition and fast ignition using NDCX-II, IB-HEDPX, HIDIX.

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

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

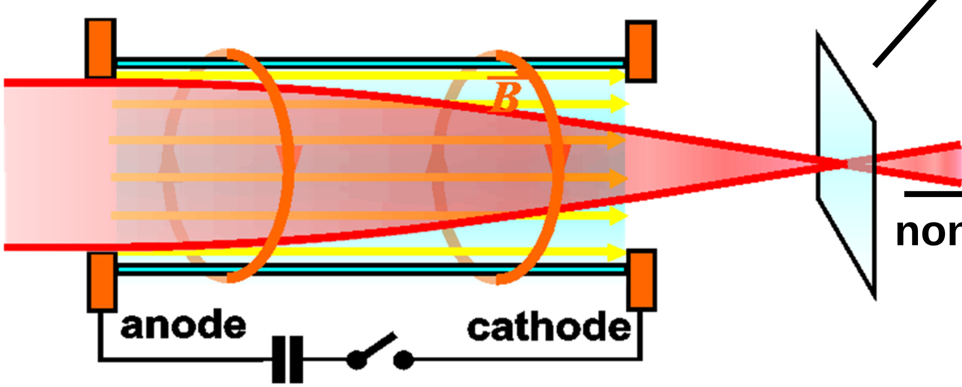


400 μm focal beam spots @ 10 π mm-mr normalized beam emittance achieved

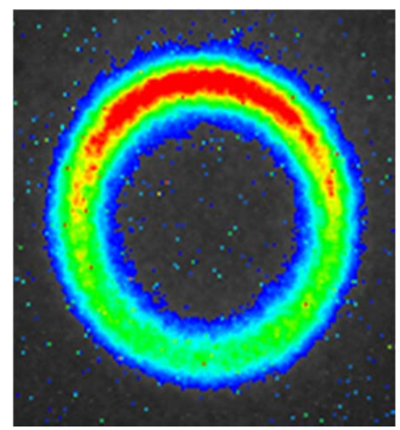


linear B-field

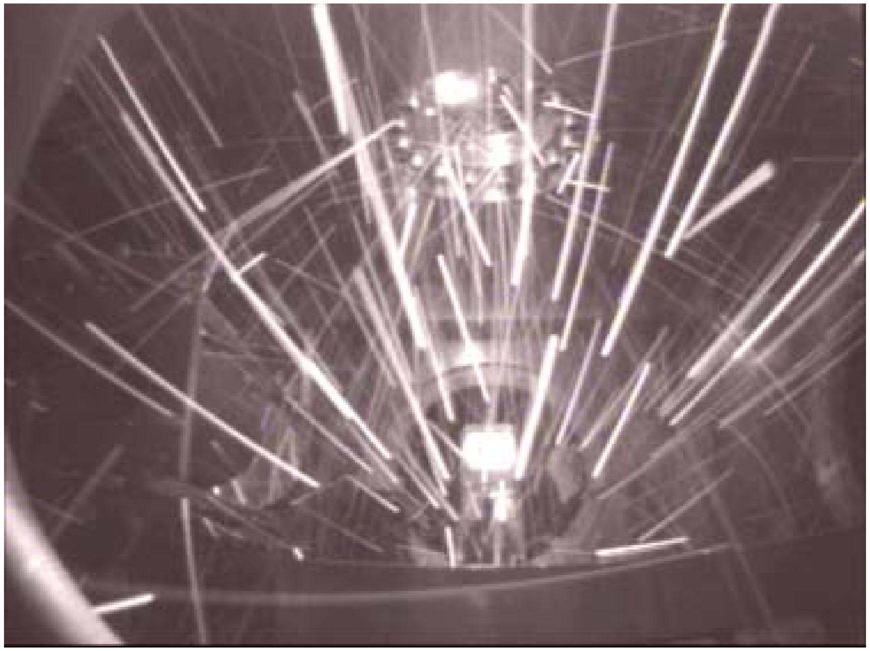
Can be time-dependent



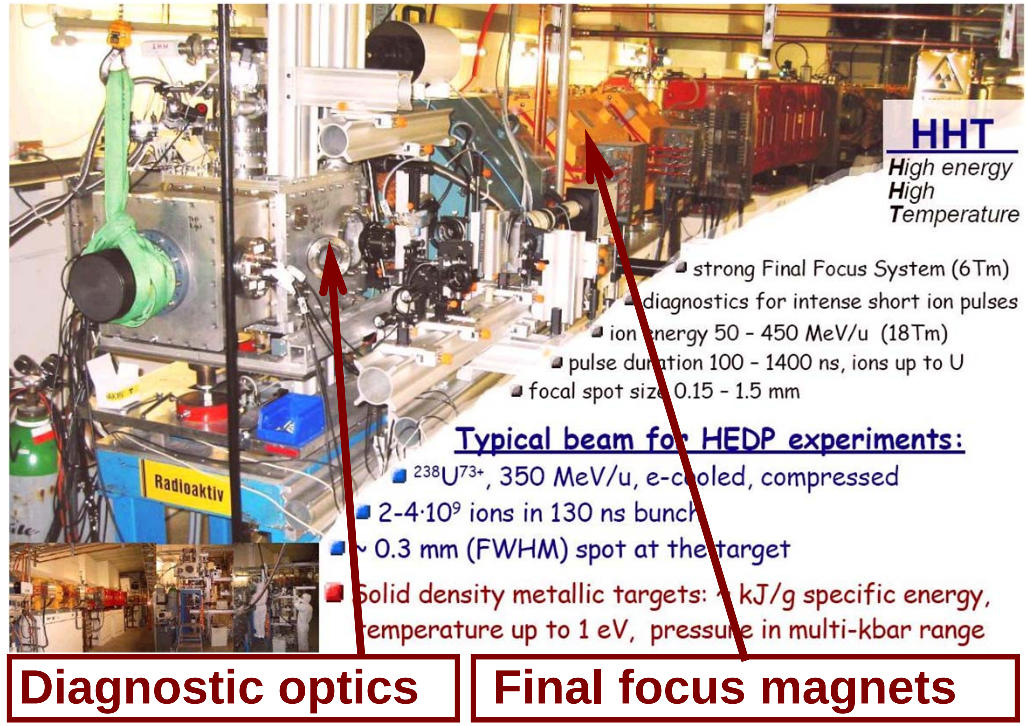
nonlinear B-field



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

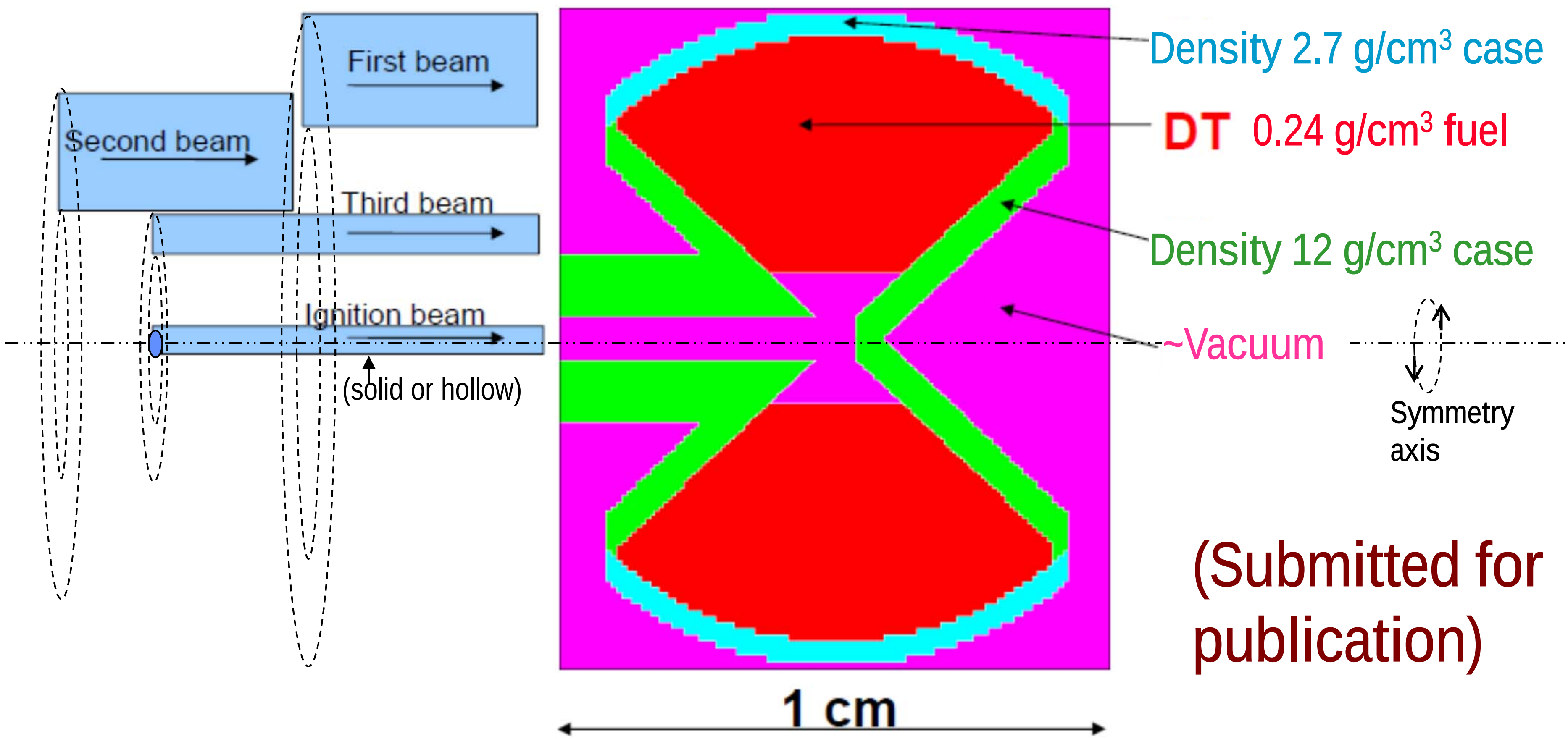


Visible ms camera frame showing hot target debris droplets flying from a VNL gold target (~ few mg mass) isochorically heated by a 130 ns, 50 J heavy ion beam to ~ 1 TW/cm^2 peak and 1 eV in joint experiments at GSI, Germany.



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)

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

Planckstraße 1
64291 Darmstadt

www.fair-center.eu

2010-11-11

Managing Directors:
Professor Boris Y. Sharkov
Dr. Simone G. Richter

Registered office: Darmstadt

Opportunity for International Collaboration on Heavy Ion Fusion Research using FAIR

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.

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

FAIR GmbH
Prof. Boris Sharkov
Scientific Director

Telephone	+49 6159 71-1640
Fax	+49 6159 71-3916
Mobile	+49 174 3281550
E-Mail:	b.sharkov@gsi.de

Workshop on Accelerators for Heavy Ion Inertial Fusion

Bay Area, March/April, 2011(TBD) ***(Contact Peter Seidl [PASeidl@lbl.gov])***

- **There is a growing interest in the development of energy solutions that can provide carbon-free, base-load electricity.**
- **The purpose of the Workshop is to review the status of heavy ion fusion (HIF) research, and to identify the most promising areas of research. We are bringing together experts in these areas:**
- **Fusion target physics**
- **Ion sources**
- **RF accelerators (including linacs, synchrotrons, storage rings, cyclotrons)**
- **Induction accelerators**
- **Superconducting magnets**
- **Chamber and chamber - driver interface**
- **Technology development (e.g.: insulators, high-voltage pulsed power, RF systems, vacuum systems)**

Conclusions

- Heavy ion fusion has a variety of driver, focusing, chamber, and target options: downselection is not prudent before NIF ignition;

- All heavy ion fusion R&D options can exploit long-recognized HIF advantages;

- **We have developed a new target concept, the X-target, that is uniquely suited for accelerator drivers;**

- **Advances in accelerator technology and will be re-assessed in a spring 2011 workshop.**

Backup Slides

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)**

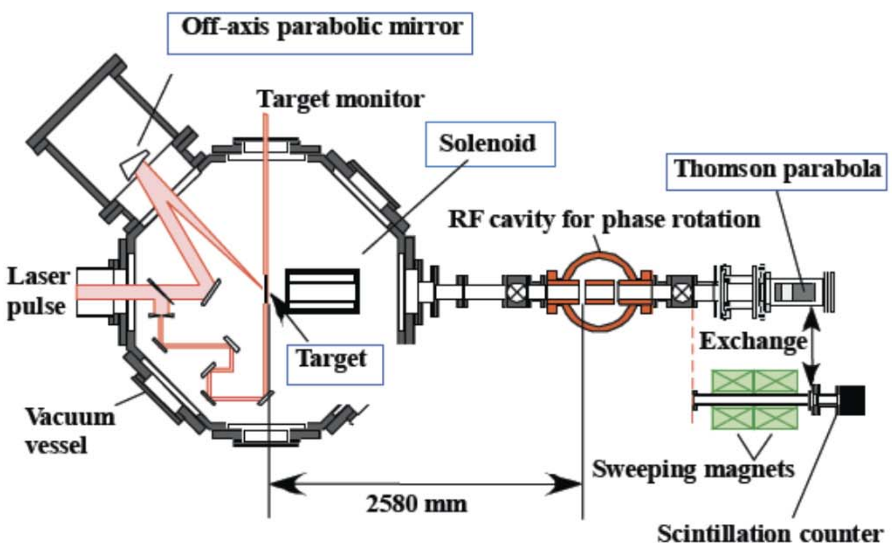
….."

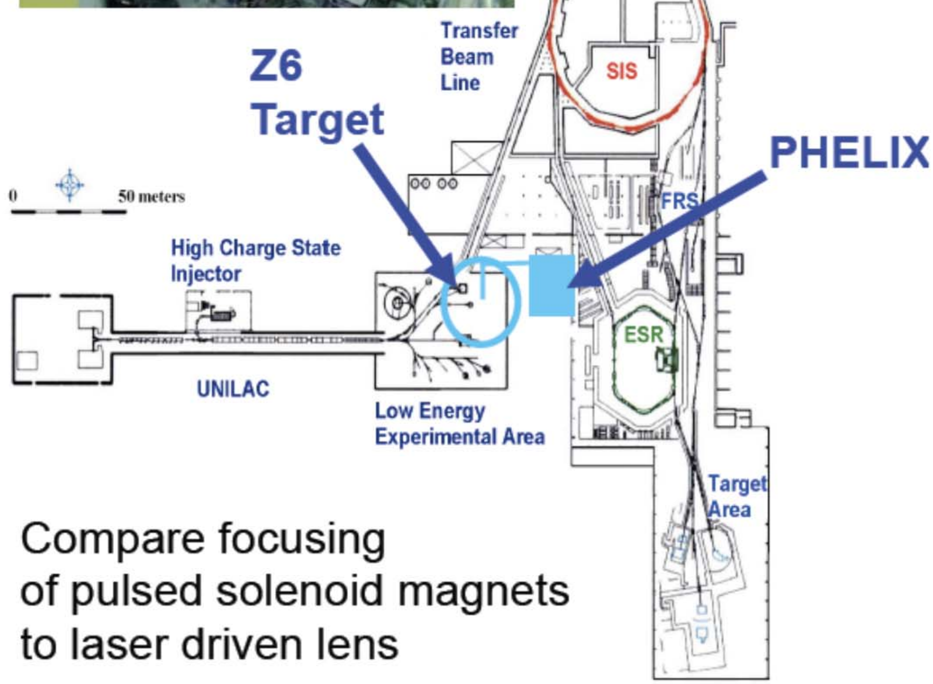
(Copy of Richter letter and past reviews are available upon request)

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

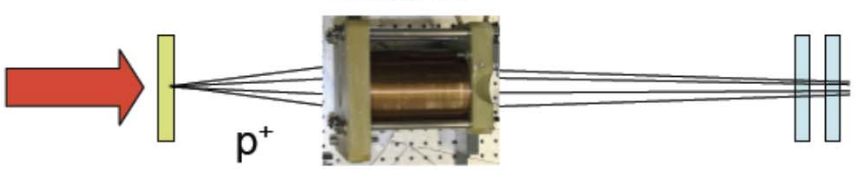
(Slide from Markus Roth, TU-Darmstadt)

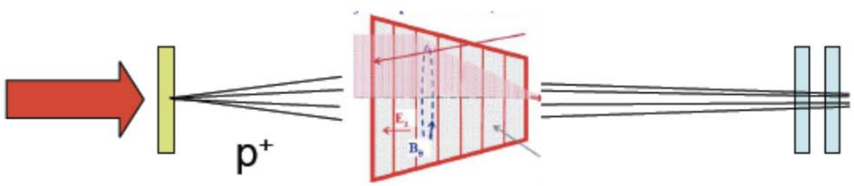
TECHNISCHE UNIVERSITÄT DARMSTADT





Solenoid



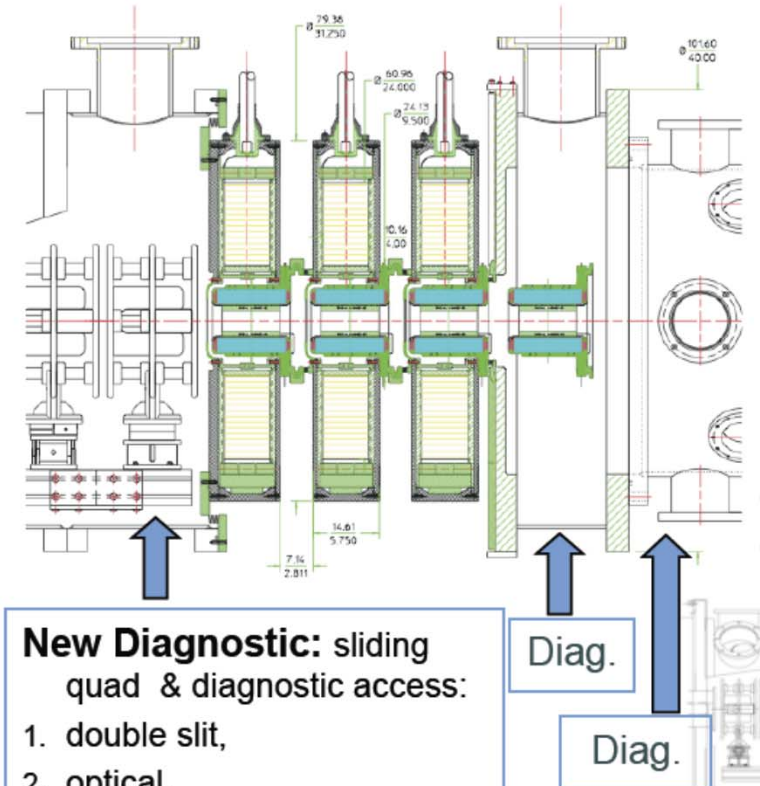


Compare focusing
of pulsed solenoid magnets
to laser driven lens

HELMHOLTZ GEMEINSCHAFT

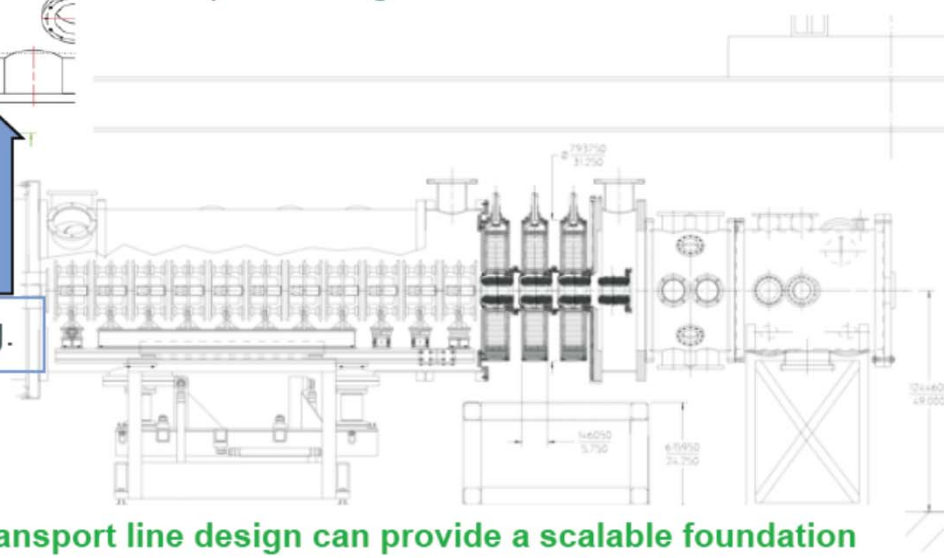
GSI

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



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

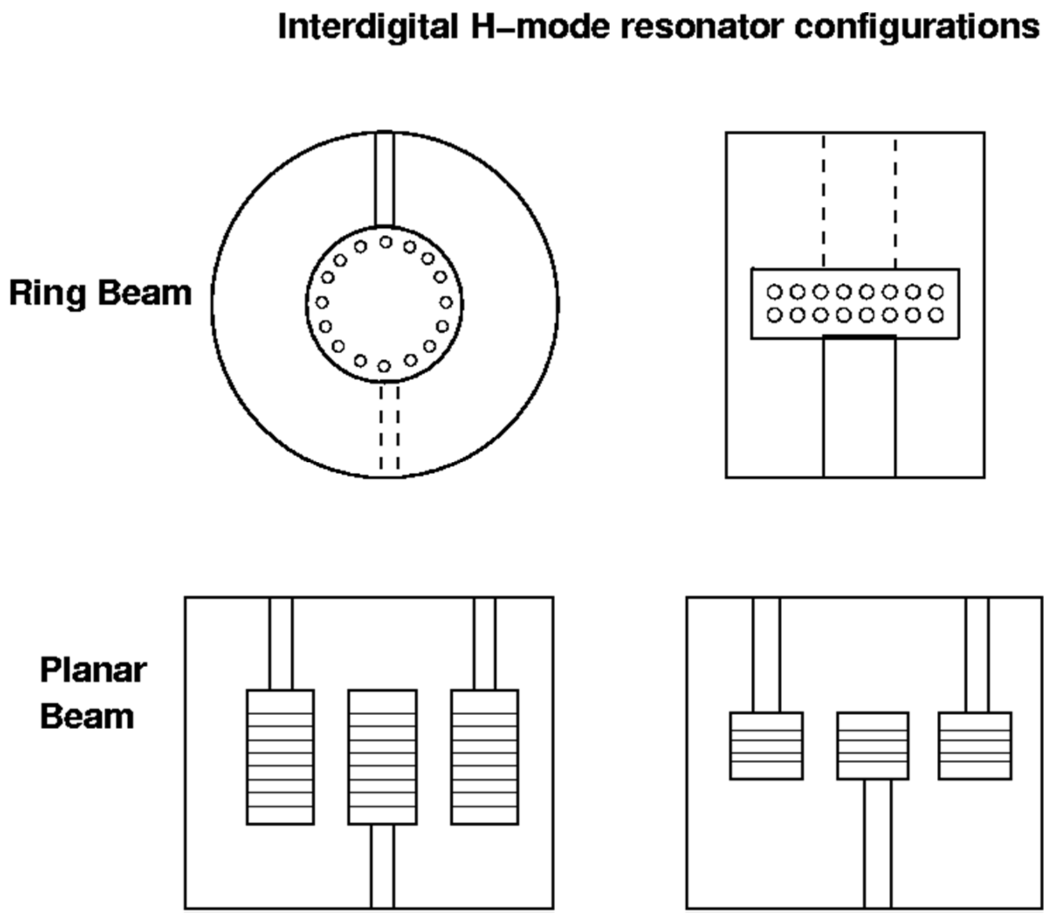
Simplified and optimized magnet transport line design can provide a scalable foundation for future quadrupole experiments beyond gas/electron experiments.

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]*

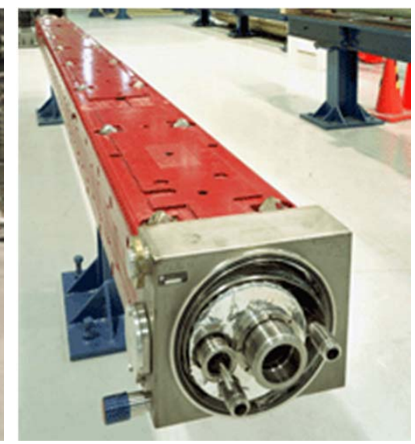
The RF Linac Group

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



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

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.

Addressing the NAS review scope requires a balance of HIF R&D for:

Target physics & design

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

Symmetry, Stability, beam pointing, distribution

Accelerator physics & driver design:

Multi-beam ion sources, injection, matching

Controlling beam-plasma interactions

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

•Advanced plasma source development

•Pulsed power

•Insulators (eg: glassy ceramics, embedded rings)

•Superconducting materials (Nb3Sn)

•Quadrupole, solenoid design

•Focusing arrays

•Reactor materials and components

The Snowmass 2002 white paper was used during the 2003 and 2004 FESAC reviews, and gives more specific detail on tasks, costs and schedule needed for accelerator, target and chamber R&D.

Heavy Ion Fusion White Paper 9-20, 2002

Strategic Plan and Research Needs for Heavy-Ion Fusion Energy Development: An Integrated Research Program

Grant Logan, John Lindl, Jill Dahlburg, Ron Davidson, Ed Lee, (Editors), with contributions by Debra Callahan, Max Tabak, Wayne Meier, Per Peterson, Jeff Latkowski, Dan Goodin, Peter Seidl, Alex Friedman, Simon Yu, Joe Kwan, John Barnard, Christine Celata, Matthaeus Leitner, Gian-Lucca Sabbi, Will Waldron, George Caporaso, Glen Westenskow, and Patrick O'Shea
U.S. Heavy Ion Fusion Virtual National Laboratory, and
U.S. Virtual Laboratory for Technology

Table of Contents	Page

Estimated overall HIF R&D cost and schedule is similar to the 2002-2003 plans, except dates moved forward ~8 years. Projected budget needs higher than in our 20-year science plan to enable more robust technology R&D on accelerator, liquid chamber, target fabrication, and injection.

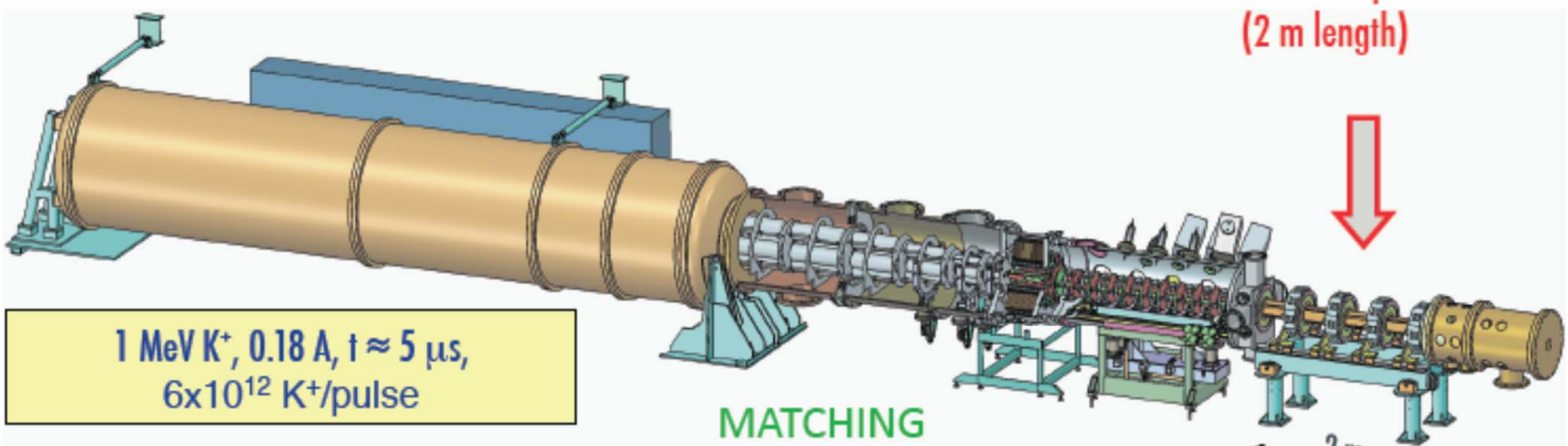
*Heavy Ion Fusion White Paper -- Strategic Plan and Research Needs for Heavy-Ion Fusion Energy Development: An Integrated Research Program, G. Logan et al.,(2002)

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

To be updated to reflect accelerator, target physics progress.

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 (Peter Seidl)

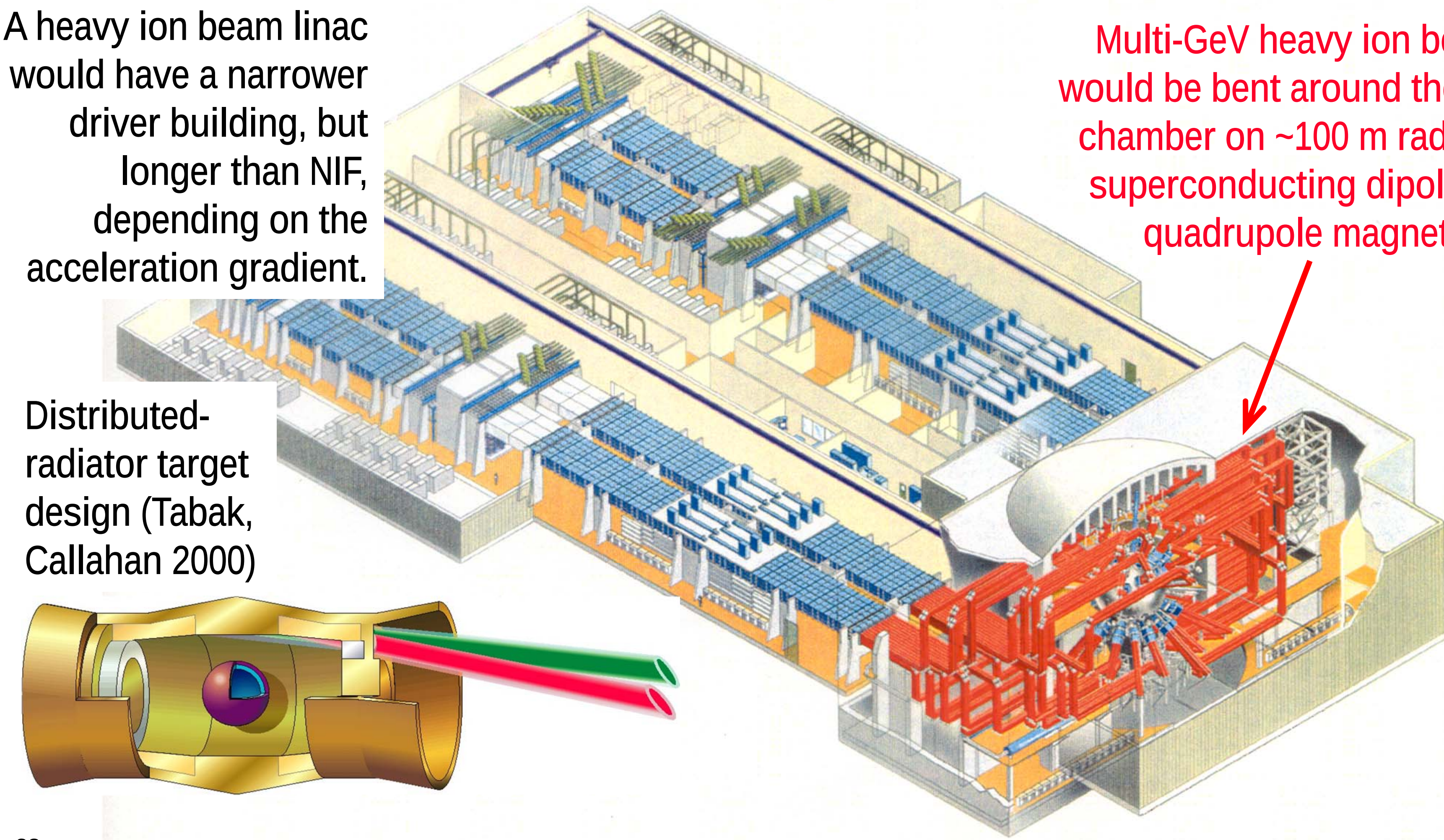
low energy heavy ions



(Peter will give me an updated version)

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 ETF could be an upgrade of the ignition test facility to 5 Hz for 150 MW fusion. (We have not yet attempted a CAD design for any 2000-2003 heavy-ion -ETF facility 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 on ~100 m radii 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 *

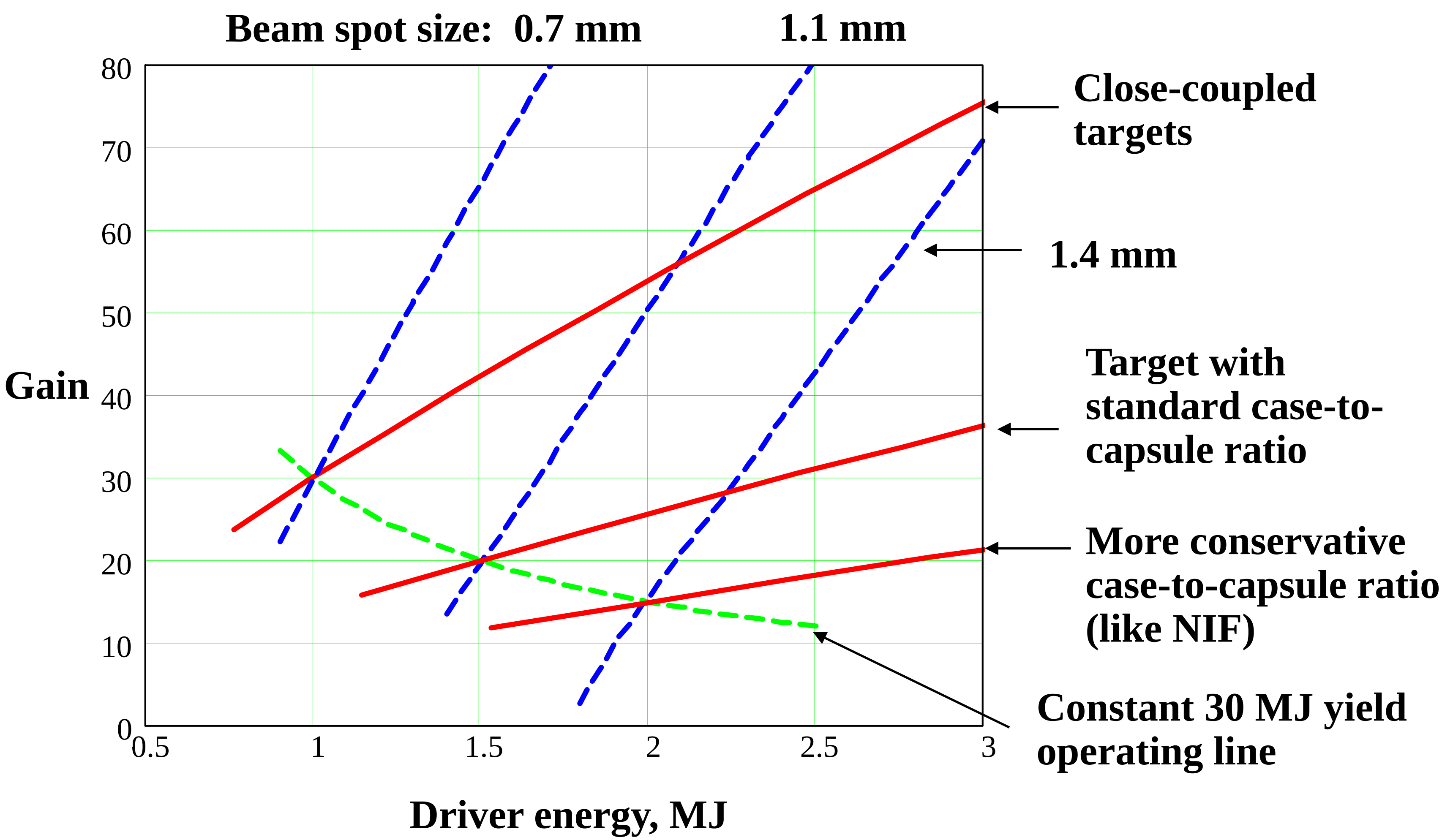
W.R. Meier, D.A. Callahan-Miller, J.F. Latkowski,
B.G. Logan, J.D. Lindl
Lawrence Livermore National Laboratory

P.F. Peterson
University of California, Berkeley

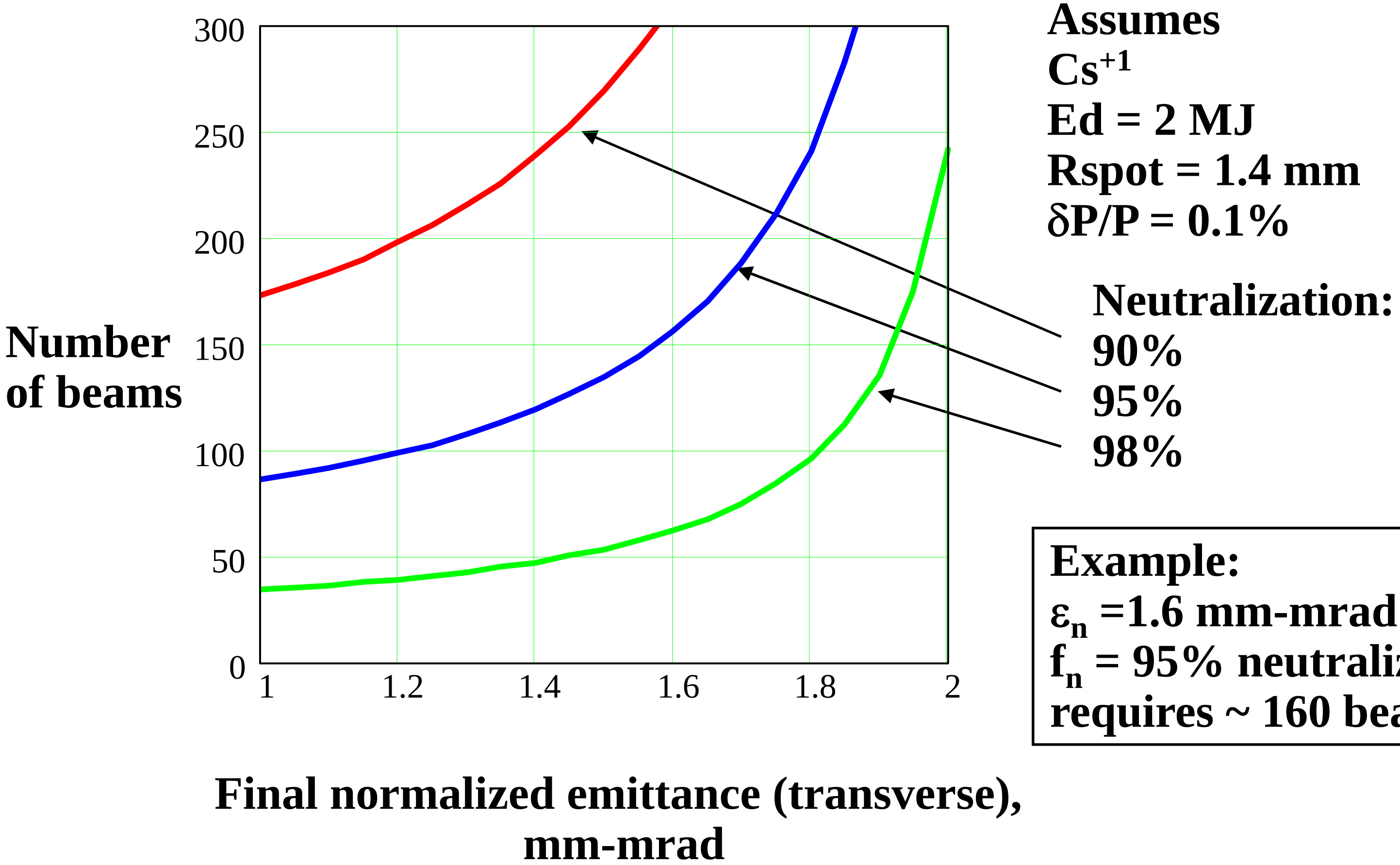
14th Topical Meeting on the Technology of Fusion Energy
October 15-19, 2000

*** 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
$\delta P/P = 0.1\%$

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 $Y^{0.37}$

R&D opportunities for heavy ion fusion:

- **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.**