Briefing for the National Academy review of Inertial Fusion Energy

Heavy Ion Fusion

B. Grant Logan

Director, U.S. Heavy Ion Fusion Science Virtual National Laboratory,
a collaboration of LBNL, LLNL, and PPPL heavy ion research

San Ramon, California

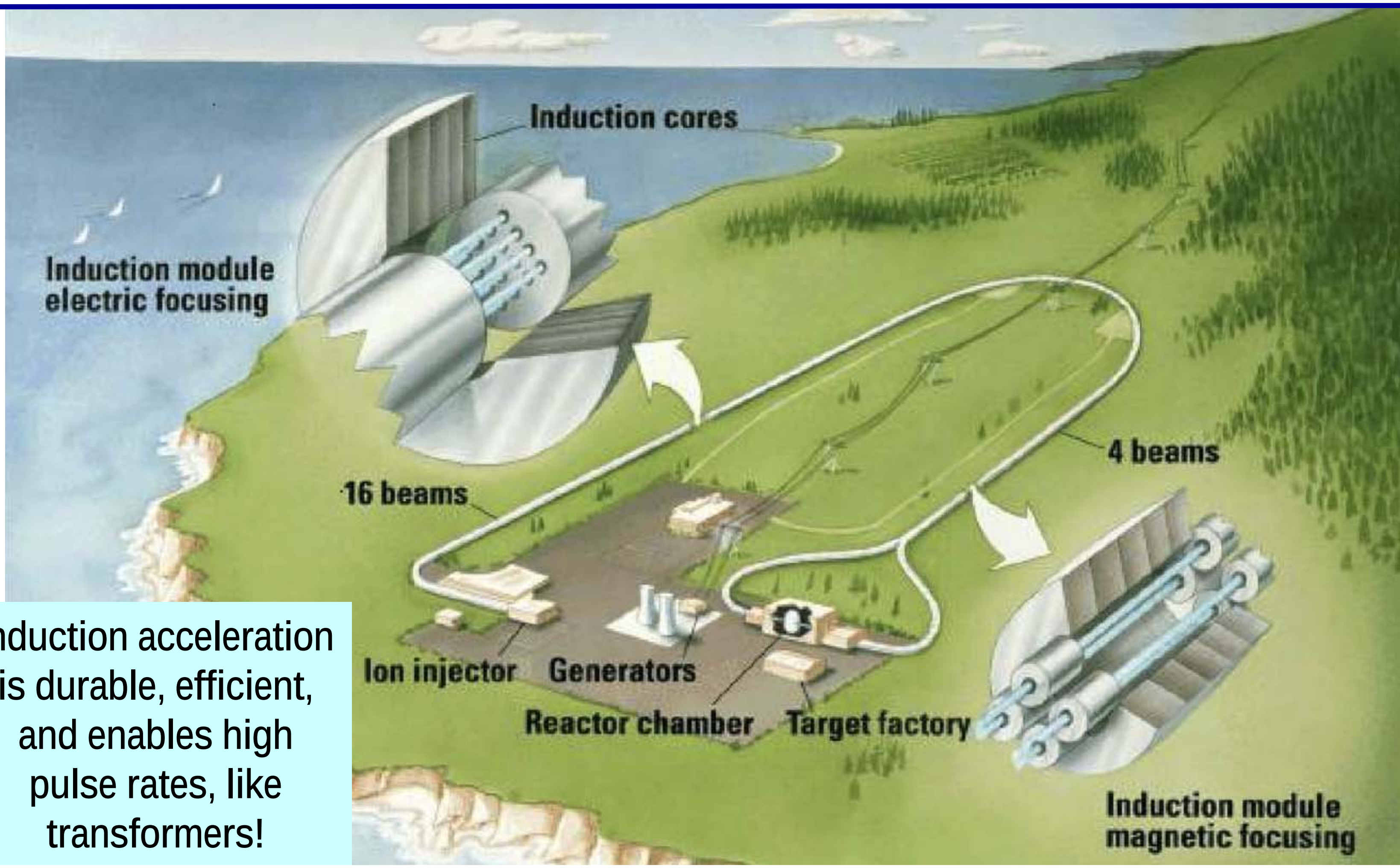
January 29, 2011

*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.

Outline

- Motivation and relevant prior work.
- Scientific and engineering challenges.
- Strategy of phased approach of R&D to ETF/Demo.
- R&D elements proposed for first five years, and deliverables.
- Roadmap-timeline and estimated resource needs per year.
- Potential collaborations.
- Conclusions.

Heavy ion fusion driver concept: heavy ion $dE/dx \sim Z^{1\text{-}2}$ enables ~10 GeV to stop in targets. Induction acceleration with superconducting magnets enables high peak beam currents, 100's of TW peak power.



Induction acceleration is durable, efficient, and enables high pulse rates, like transformers!

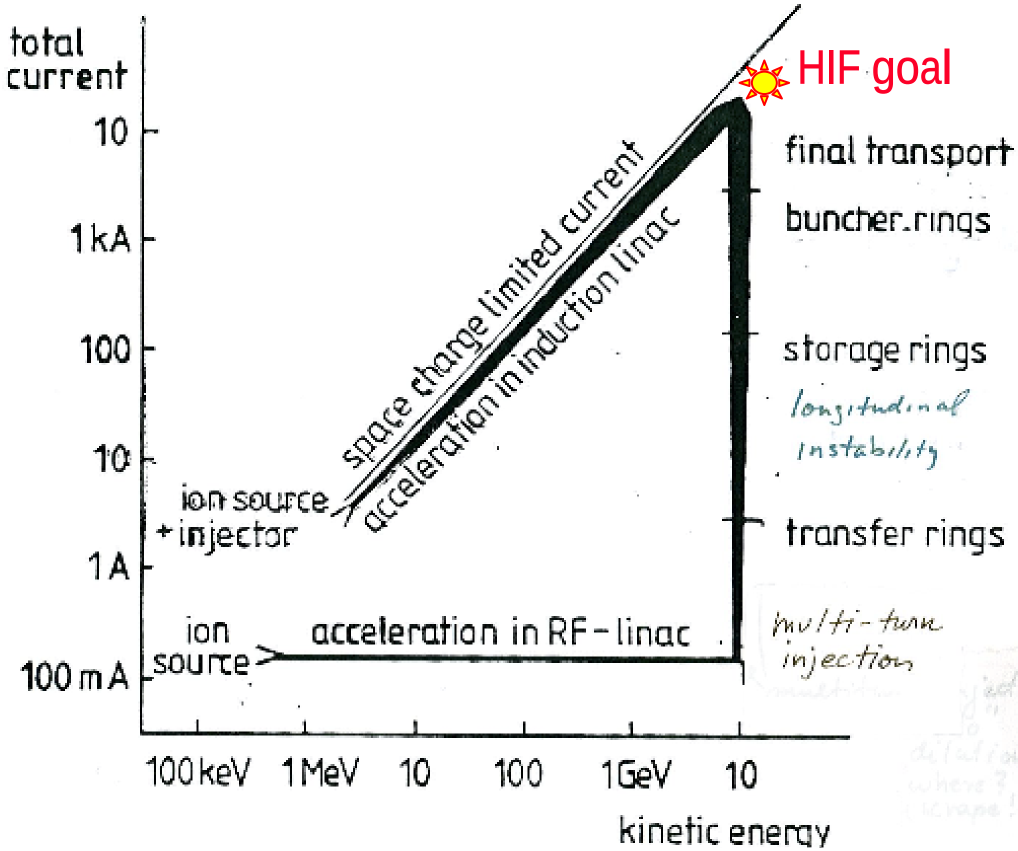
Heavy ion accelerators of multi-MJ fusion scale would be comparable in scale to today's large NP accelerators like GSI-FAIR, RHIC →economical for 1-2 GW_e baseload power plants.

Heavy ion fusion is an IFE option because of long-recognized advantages:

- **Established accelerator base:** High energy particle accelerators of MJ-beam energy scale have separately exhibited intrinsic efficiencies, pulse-rates, average power levels, and durability required for IFE.
- **Liquid Chambers:** Heavy ion beams can propagate through the vapor pressure of thick-liquid-protected target chambers with 30 yr lifetimes.
- **Robust final optics:** Focusing magnets for ion beams avoid direct line-of-sight damage from target debris, neutron and gamma radiation.
- **Target injection:** Heavy ions can penetrate metal cases surrounding cryogenic-DT fuel, protects HIF targets injected into hot IFE chambers.
- **Competitive economics:** projected in several power plant studies and with no high level radioactive waste.

John Nuckolls, et. al.'s seminal 1972 Nature article on laser fusion…. <u>also sparked interest for heavy ion fusion</u>→ *in the world's high energy accelerator community and some weapons-lab scientists.*

Early workshops in the 70's identified induction and RF linac candidate drivers. Later, storage rings were also considered at GSI and Russia (ITEP).



A new HIF workshop is being organized this spring To rekindle interest of the accelerator community

70's and 80's HIF workshops <u>had broad participation from</u>:

LBNL
LLNL
LANL
FNAL
ANL
BNL
SLAC
Rutherford
CERN

Even though target design details were classified at the time, the accelerator scientists were confident they could design fusion-scale accelerators to deliver the required energy and peak power for HIF, with more efficiency, pulse rate, and durability than lasers.

A number of driver, focusing, chamber, and target options have been considered for heavy ion fusion.

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

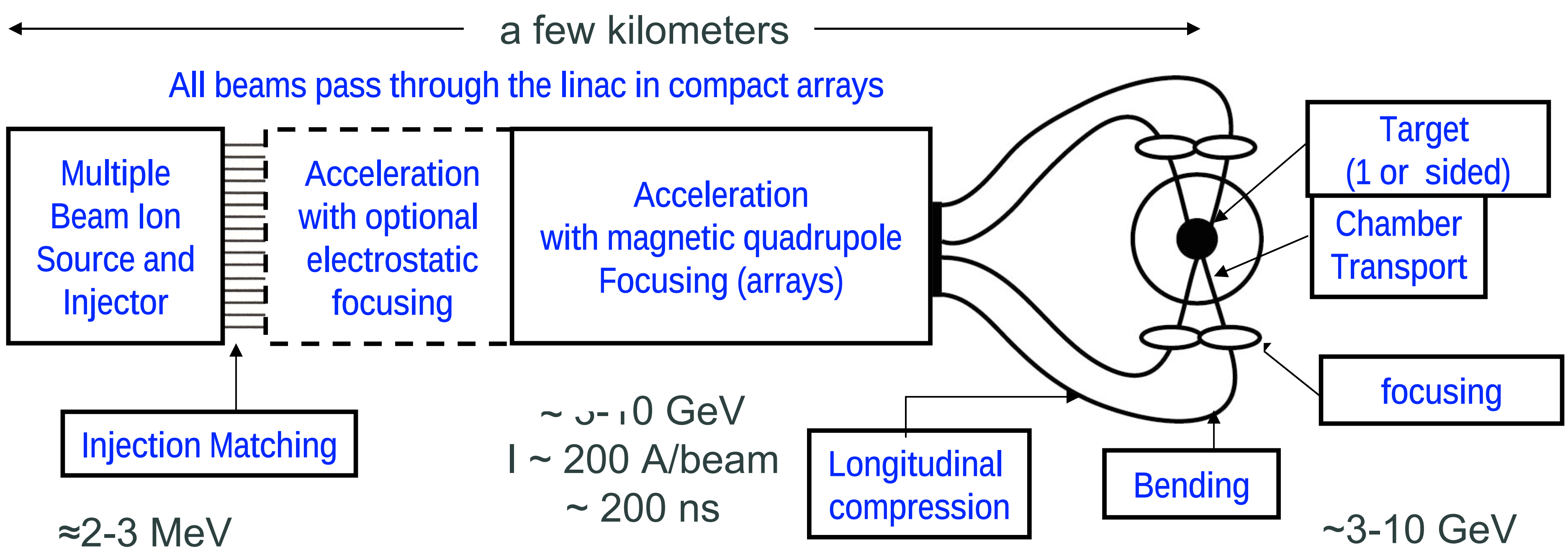
Focusing
- Ballistic, Neutralized
- Ballistic, Vacuum
- Self Pinch, 2-stage

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

US effort has focused on induction linacs, ballistic neutralized focusing, thick liquid protected chambers, and indirect drive targets. We believe induction linacs and thick liquid chambers can be applied to several target options.

Multiple-beam induction linac driver for heavy ion fusion

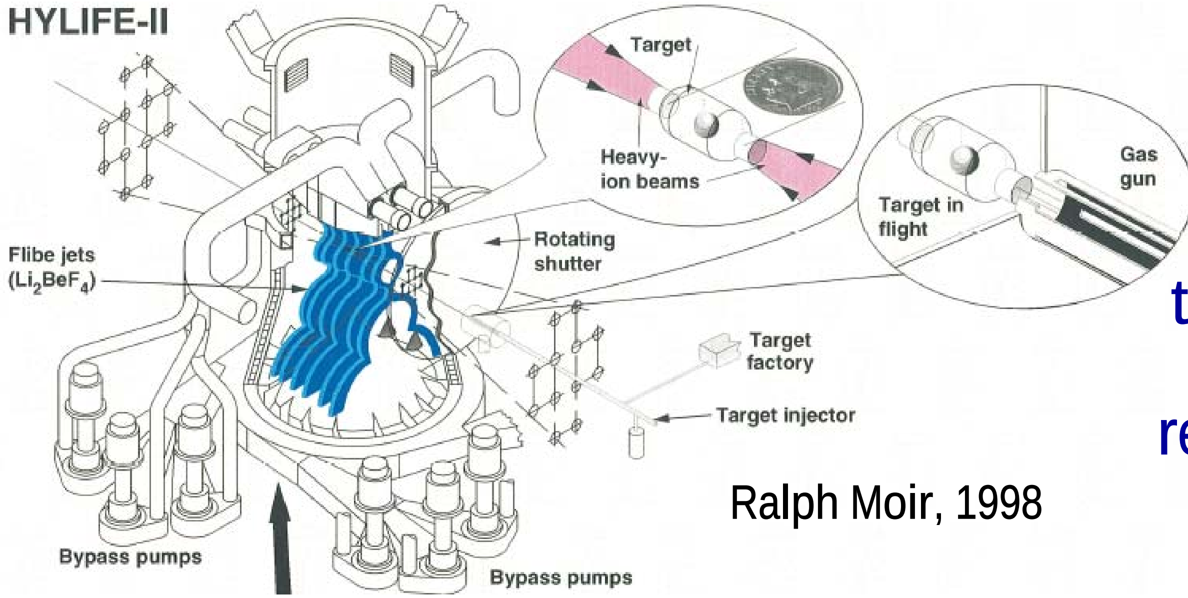


≈2-3 MeV
~1 A/beam
~ 20 μs
A ≥ 133
q = 1 *

~3-10 GeV
~4000 A/beam
~10 ns

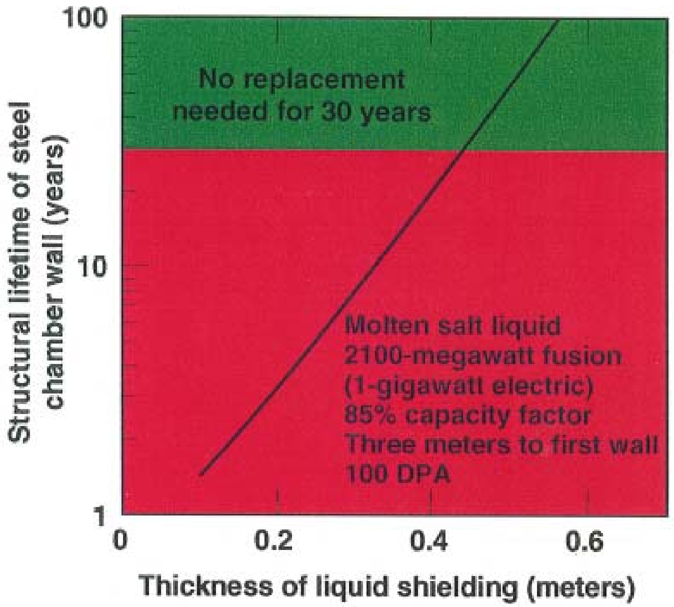
Power amplification to the required 10 TW per beam is achieved by acceleration and longitudinal bunching of mildly-relativistic ions.

HIF chambers:

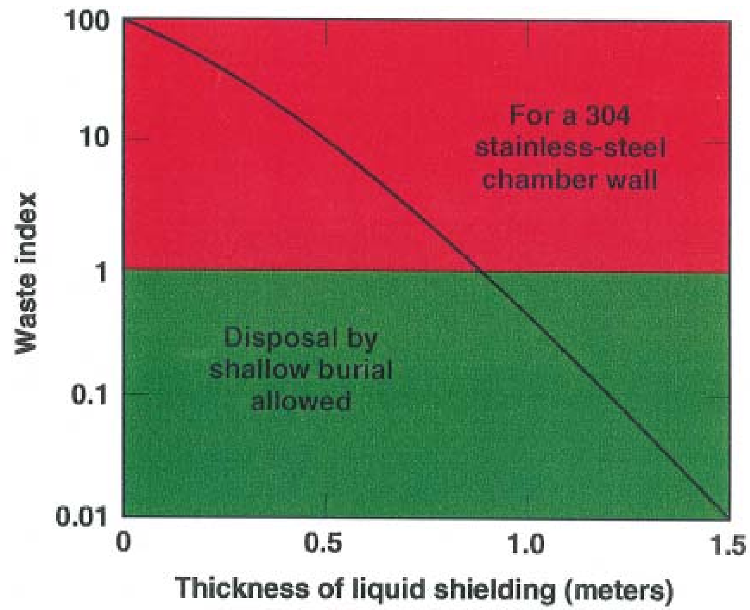


Ralph Moir, 1998

thick liquid-protected walls to avoid structural-wall replacements and high level radioactive waste…
…is still our goal!



Sumer Sahin, R. W. Moir, A. Sahinaslan, and H. M. Sahin, "Radiation damage in liquid-protected first-wall materials for IFE-reactors," *Fusion Technology*, **30**, 1027–1035 (1996).

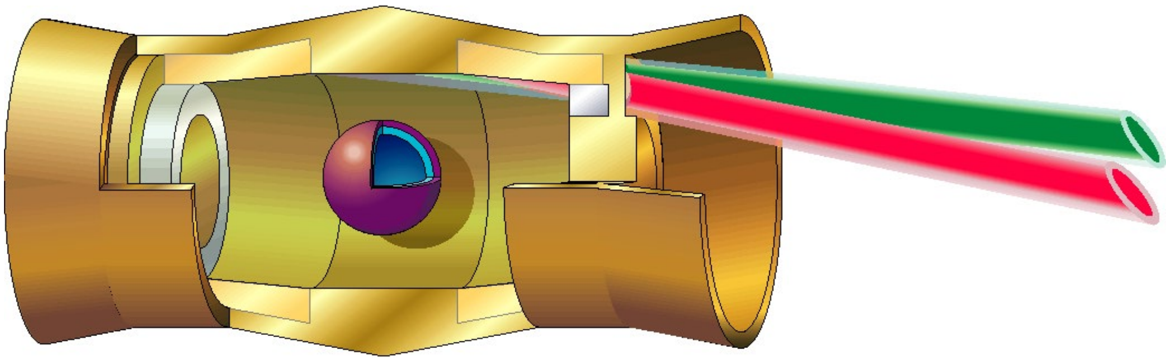


J. D. Lee, "Waste Disposal Assessment of HYLIFE-II Structure," *Fusion Technology*, **26**, 74 (1994).

Indirect-drive, distributed radiator HIF target designs were developed in 2-D calculations at LLNL (1998 -2000)

Standard hohlraum-to-capsule radius ratio design (HCR = 2.1) Gain 60 @ 6 MJ

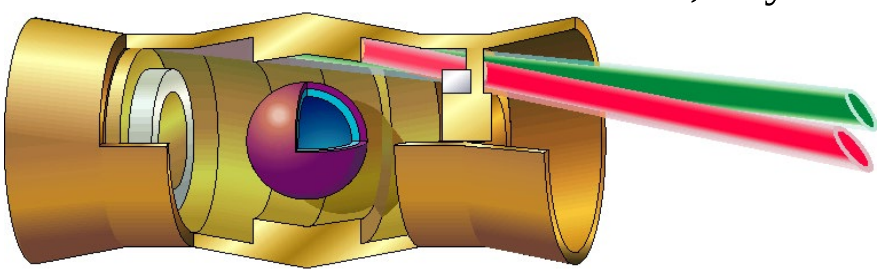
M. Tabak and D. Callahan-Miller, Phys. Plasmas **5** (1998)



(Drawn at same scale)

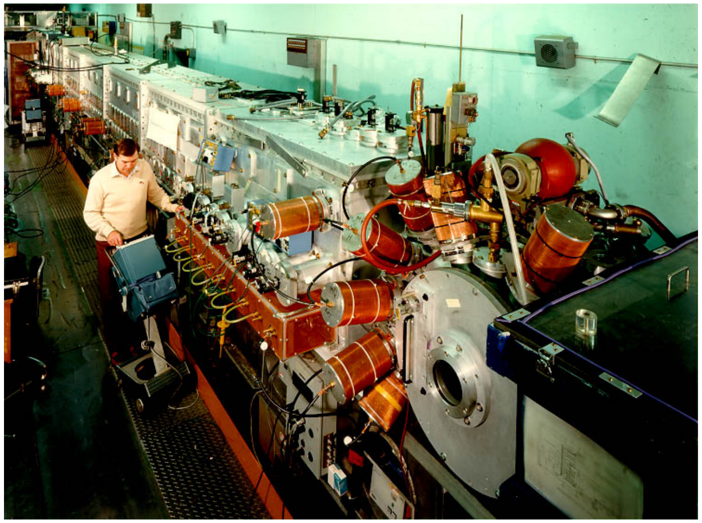
Close-coupled design (HCR = 1.6) Gain 130 at 3.3 MJ

D. Callahan-Miller and M. Tabak, Phys. Plasmas **7** (2000)



Hohlraum is smaller – requires smaller beam spots

Single-Beam Transport Experiment (SBTE) 1986



10-20 mA
120 kV
86 electric quadrupoles
15 m long

Established attractive scaling of transportable current.

Multiple-Beam Experiment with 4 beams (MBE-4) 1987

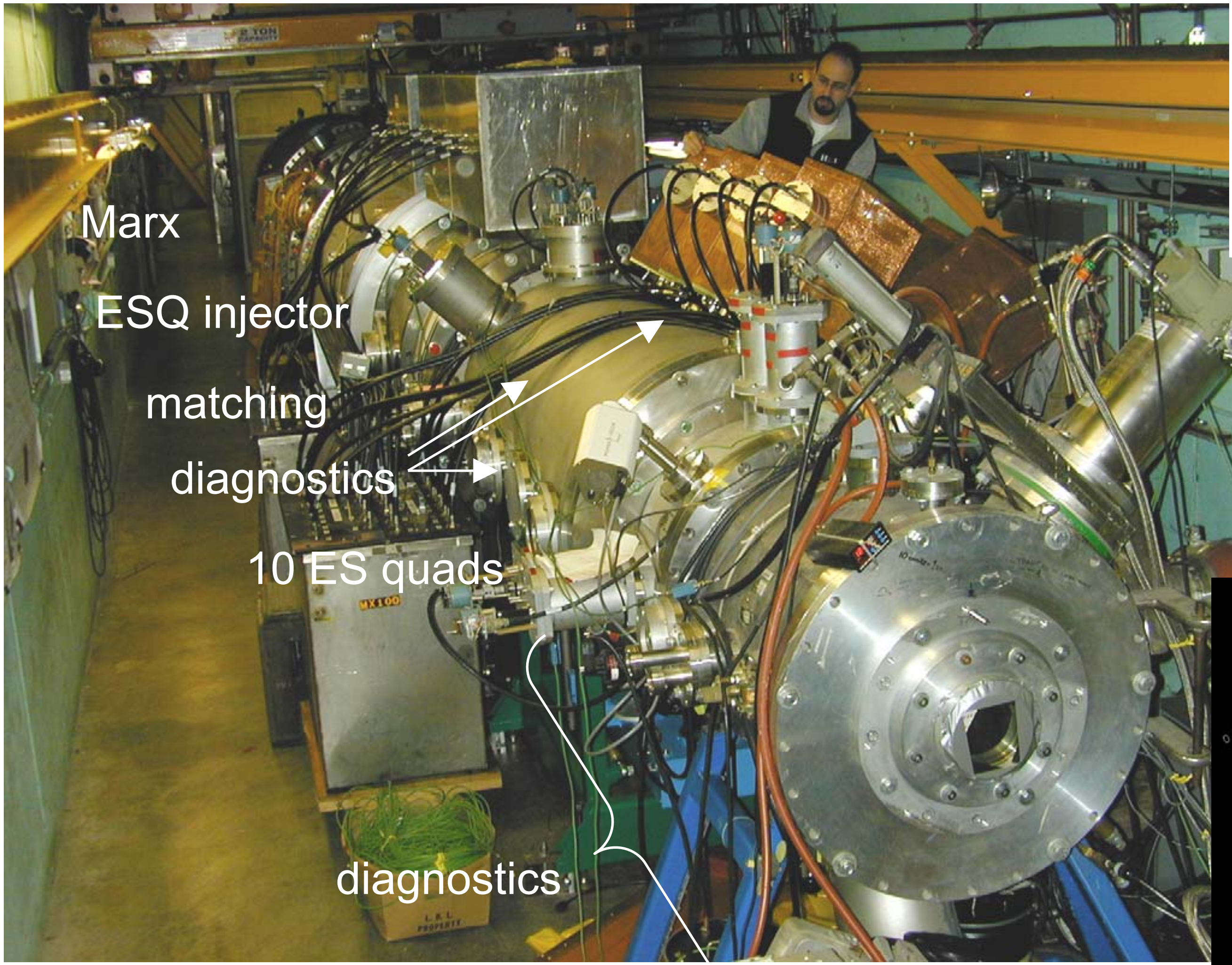
10-90 mA/beam,

200-900 keV

Addressed:

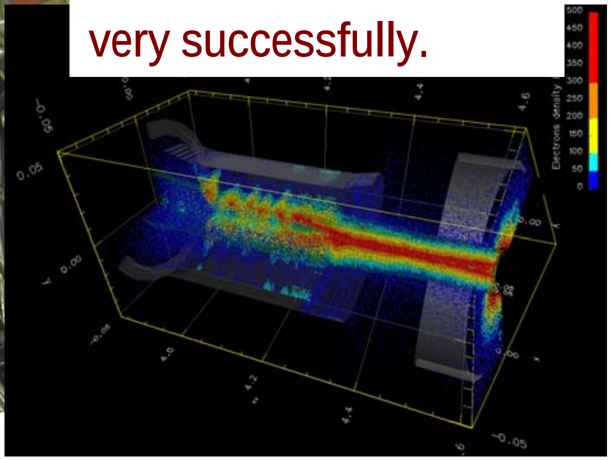
Acceleration
Current amplification
Longitudinal confinement
Multi-beam transport

The High Current Experiment (HCX) (2002-2005) studied driver-like beam transport (up to 1 A) and e-cloud effects.



The ion beam filled a large fraction of the aperture. Important for driver economics.

3-D WARP (particle simulations) modeled interaction of secondary electrons with the HCX ion beams very successfully.



Experiments for compact high current beam injectors for HIF were completed in 2004.

→ Measured beam brightness of an RF-driven Argon plasma source

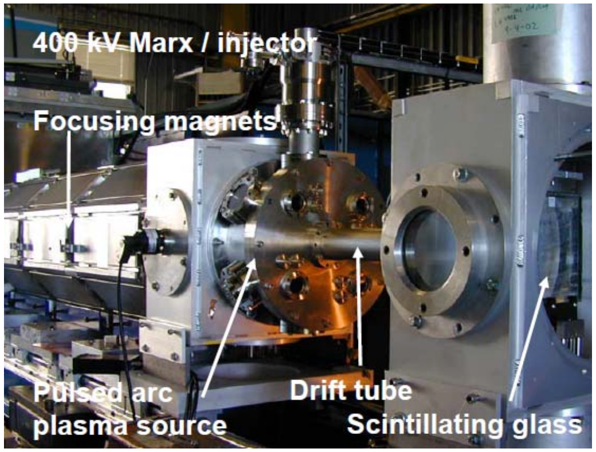
→ Multiple beamlets were merged into a high brightness composite beam for compact HIF injectors

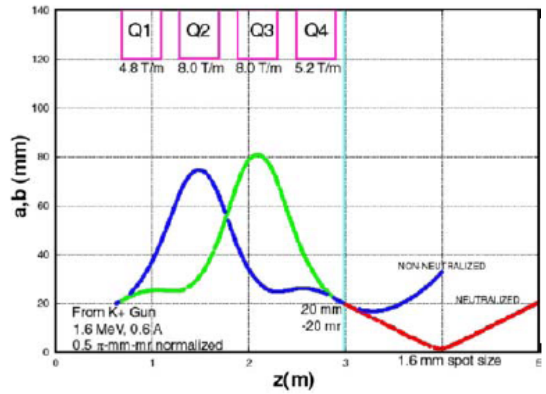
Two LLNL injector test stands

STS-100 Source test stand
(now in operation again at PPPL)

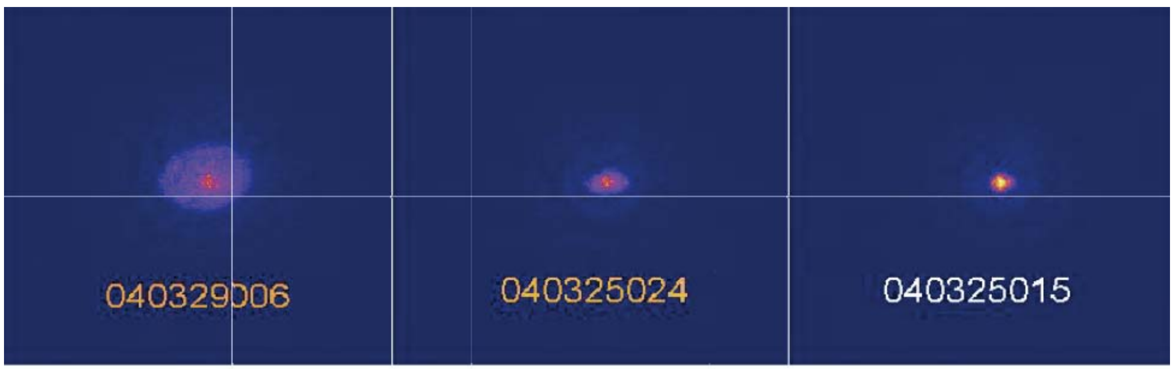
STS-500 Injector test stand

In 2004, the Neutralized Transport Experiment (NTX) achieved greatly reduced focal spot sizes by neutralizing the space charge of intense ion beams with background plasma in the target chamber.





Envelope simulation of NTX focusing with and without plasma



Neither plasma plug nor volumetric plasma.

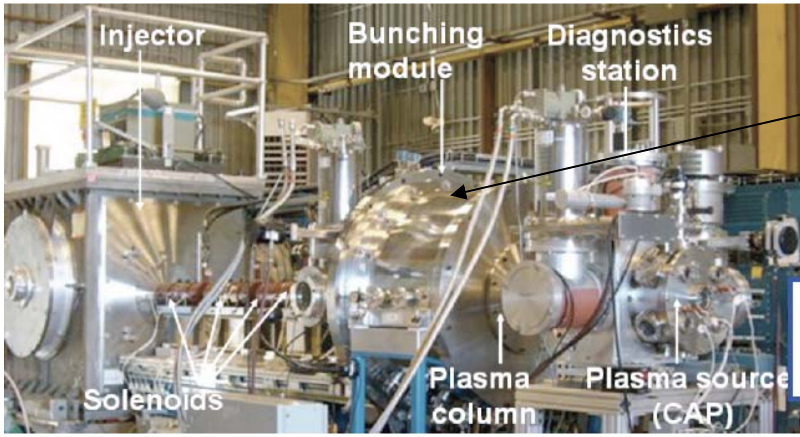
Plasma plug.

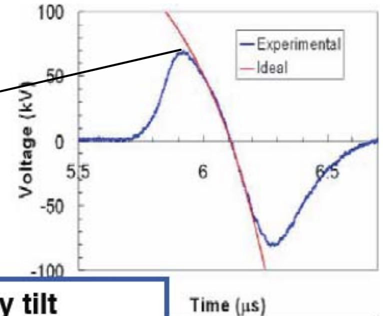
Plasma plug and volumetric plasma.

Ion species: K^+
Energy: $E_0 \leq 400$ keV
Current: $I_0 < 80$ mA
Beam radius: $r_b \sim 1\text{-}2$ cm
Temperature: $T_b \sim 0.2$ eV

P. Roy, et. al, Physics of Plasmas, 11, 2890, 2004.

After NTX showed improved transverse focusing with neutralizing plasma, we added a head to tail velocity ramp for improved longitudinal compression (Neutralized Drift Compression Experiment-I)

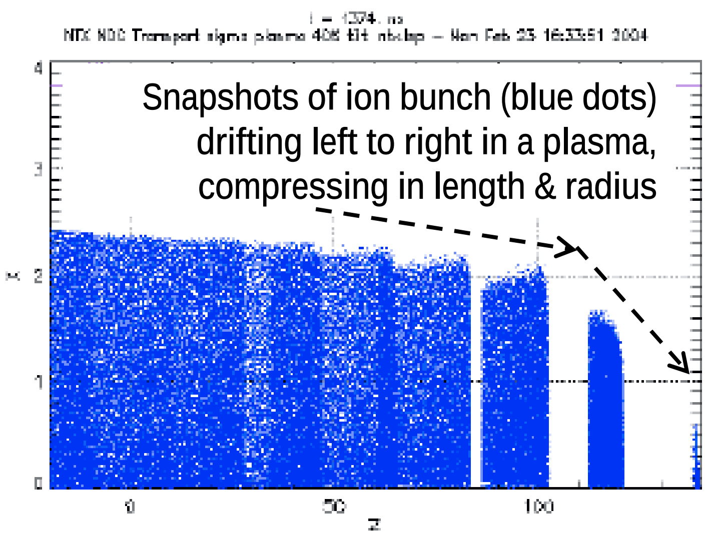


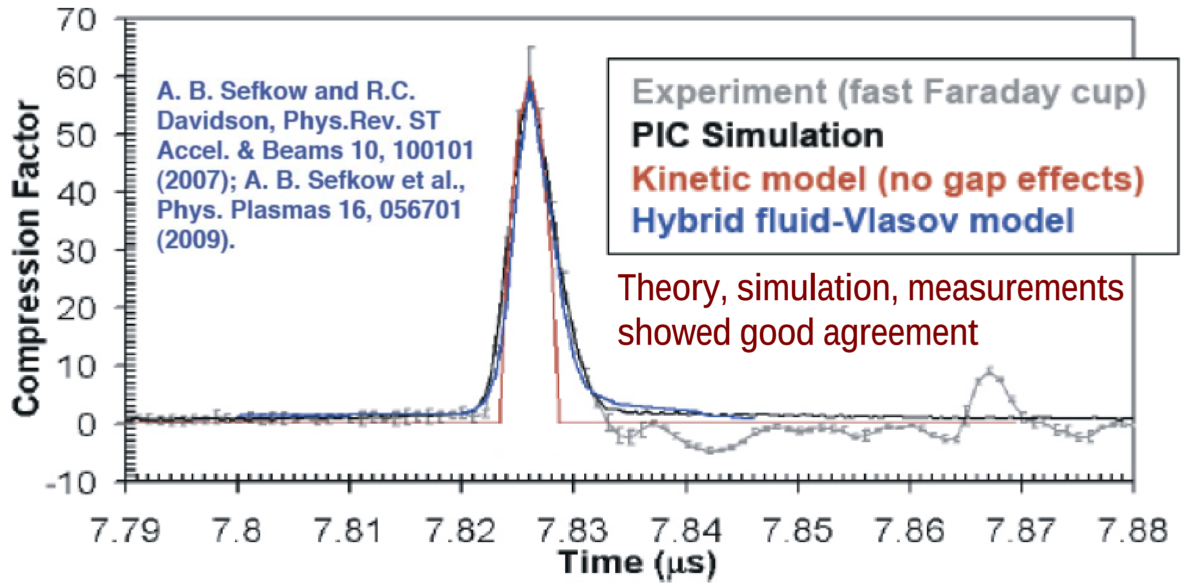


Velocity tilt accelerates tail, decelerates head

(Like chirped pulse compression)

*** P. K. Roy, S. S. Yu et al. ,Phys. Rev. Lett. 95, 234801 (2005).**

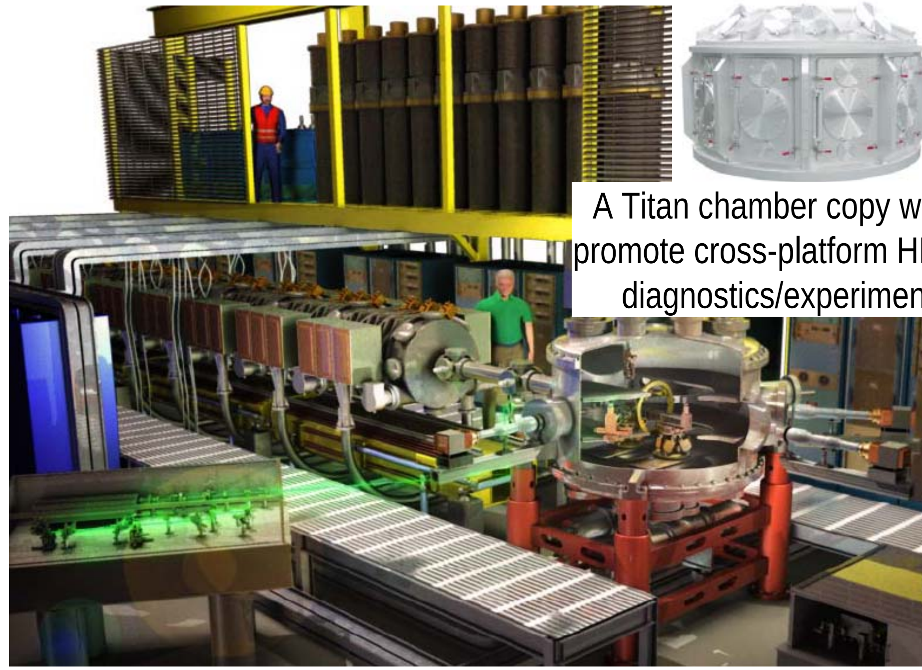




Pre-project simulation of the concept Mar 2004 led quickly to 60 X compression of peak current by May 2005

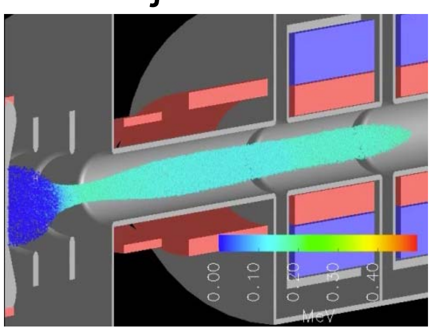
In addition to NDCX-I, NDCX-II will explore more intense compression and focusing physics needed for heavy ion fusion.

- 11 M$ construction began July 2009, to be completed in March of 2012 (ARRA project)
- 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

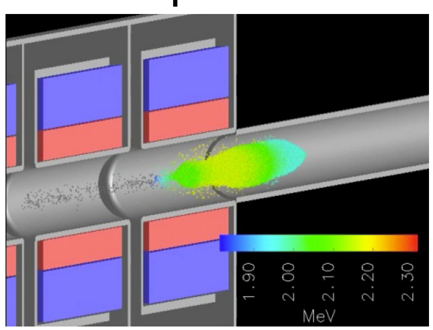


A Titan chamber copy would promote cross-platform HEDLP diagnostics/experiments

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

Scientific and engineering challenges for heavy ion fusion

Longer term HIF-ETF/ DEMO issues, such as cost of mass-manufactured targets, precision of tracking, injection and beam-target coupling and target gain at 5 Hz, depend on the type of target which we will select at the end of the first five year phase.

The following slides describe top-level issues we plan to address in the first five years.

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

HIF targets require ~ 100 beams for pulse shape and symmetry. Each beam must be compressed to a few kA and focused to ~ 1mm radius spots on target.
→100's of kV space charge potential @ initial 5 cm radius can be neutralized in chamber plasma before reaching the target.

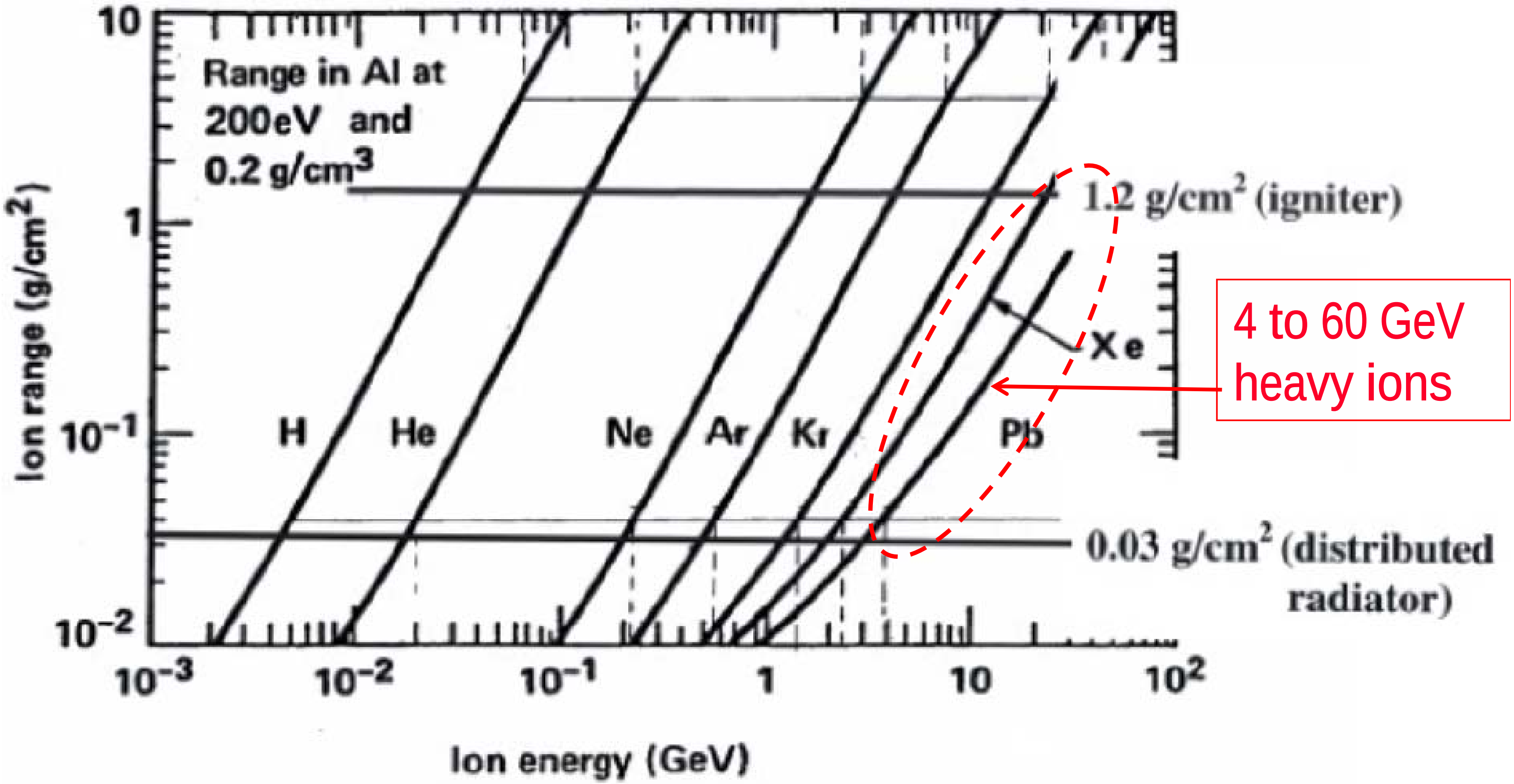
(Figure from Boris Sharkov, ITEP-IFSA Plenary talk, 2007, Kobe, Japan)

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 ion kinetic energies→ lower beam currents→ less space-charge effect on focus!

Heavy ion stopping in very dense target plasma is calculable, measured, predictable



Significant scale up of accelerator energy and peak power @ *relevant ion target range* is needed for an HIF driver.

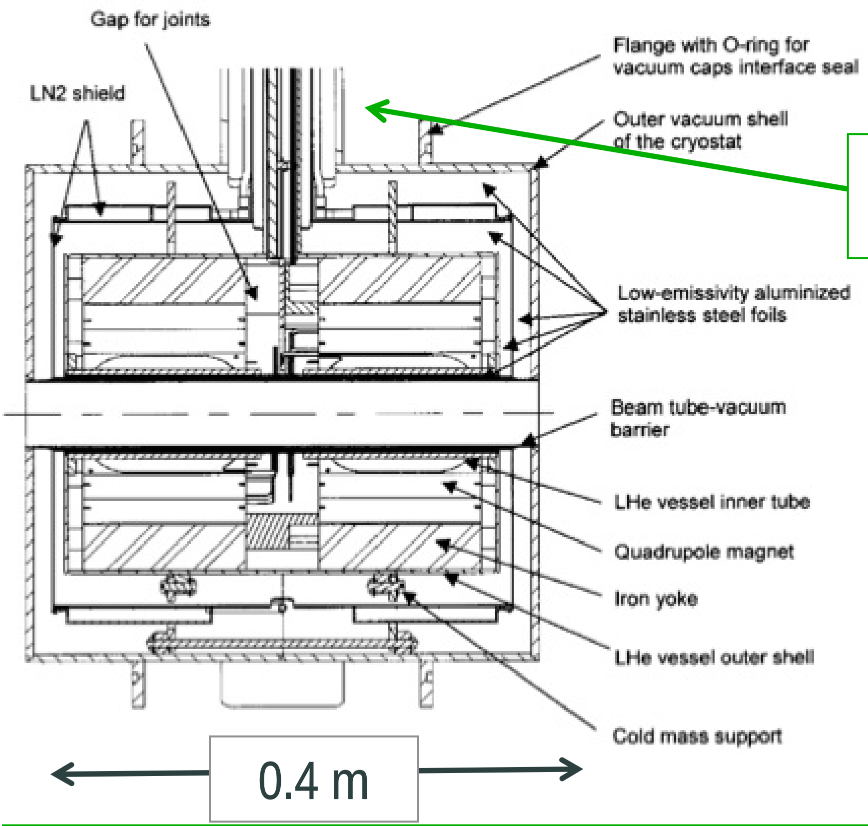
	NDCX-II	GSI-SIS18	LHC	HIF driver
Ion energy	1.2→ 6 MeV (Li+)	70 GeV (U^{28+})	14 TeV (p)	10 GeV (Pb^+)
Beam power	0.1 to 1 GW (50Ax2MeV →150Ax6MeV)	350 MW (in 130 ns)	1 TW (100 μs dump)	4 TW / beam X100 beams (in 8.2 ns)
Beam energy	0.08 to 0.25 J	45 J	100 MJ (total dump)	6 MJ
Space charge $\Delta\phi$/KE (final)	High 5×10^{-2}	Very Low 10^{-9}	Negligible	High to low 10^{-1} to 10^{-5}
Ion range	Low (~ 3 μm foil) 0.0001 g/cm^2	High (> WDM target) 10 g/cm^2	Way too high for IFE 10,000 g/cm^2	IFE target requirement 0.03 -1 g/cm^2

Heavy ion accelerator driver R&D needs

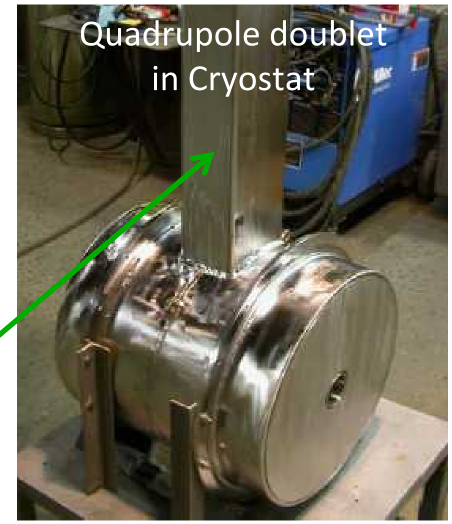
- Long-life ion sources in compact arrays
- Longitudinal and transverse emittance growth @ high beam current
- Waveform control with beam-to-module and beam-to-beam couplings
- Longitudinal-transverse equilibration of high space charge beams
- Beam loss control (halo scraping, field errors, gas and e-clouds)
- Low-loss accelerator cores and durable, high peak power pulsers
- Value engineering of integrated modules with compact magnet arrays
- Bending and focusing of beams with momentum spread, high current
- Compact, radiation resistant final focus magnets
- Durable plasma sources for beam neutralization in the target chamber

We need to restart superconducting magnet array development for heavy ion fusion. Challenges are compactness, field quality, and cost.

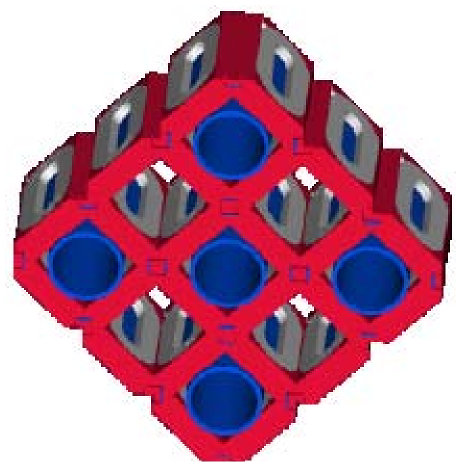
Prototypes reached 100% I_{ss} after a few quenches.
Flat coils, room temperature bore (59 mm f)



Long, narrow chimney for high current leads



Measured low field error: <0.5% at R= 25 mm (integrated) $G(I_{ss})$ = 132 T/m.

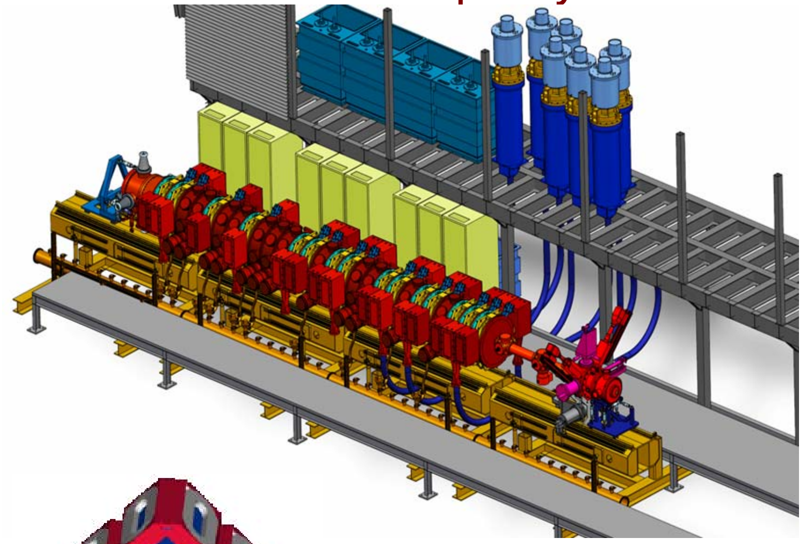


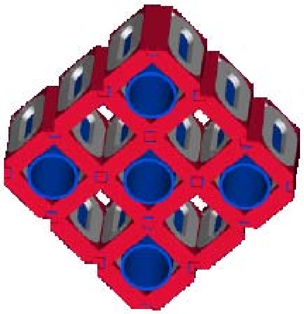
part of a **focusing array**

Driver cost has long been a concern for HIF; we need value-engineering and reliability data for *ensembles of components*

Most recent study published→ S. Yu, W. Meier, et. al., "An updated point design for heavy ion fusion" Fusion Science and Technology, 44, 266 (2003).

NDCX-II is an example of a linearly-modular accelerator that can be quickly assembled on rails





←Factory magnet array modules →faster magnet reliability development!

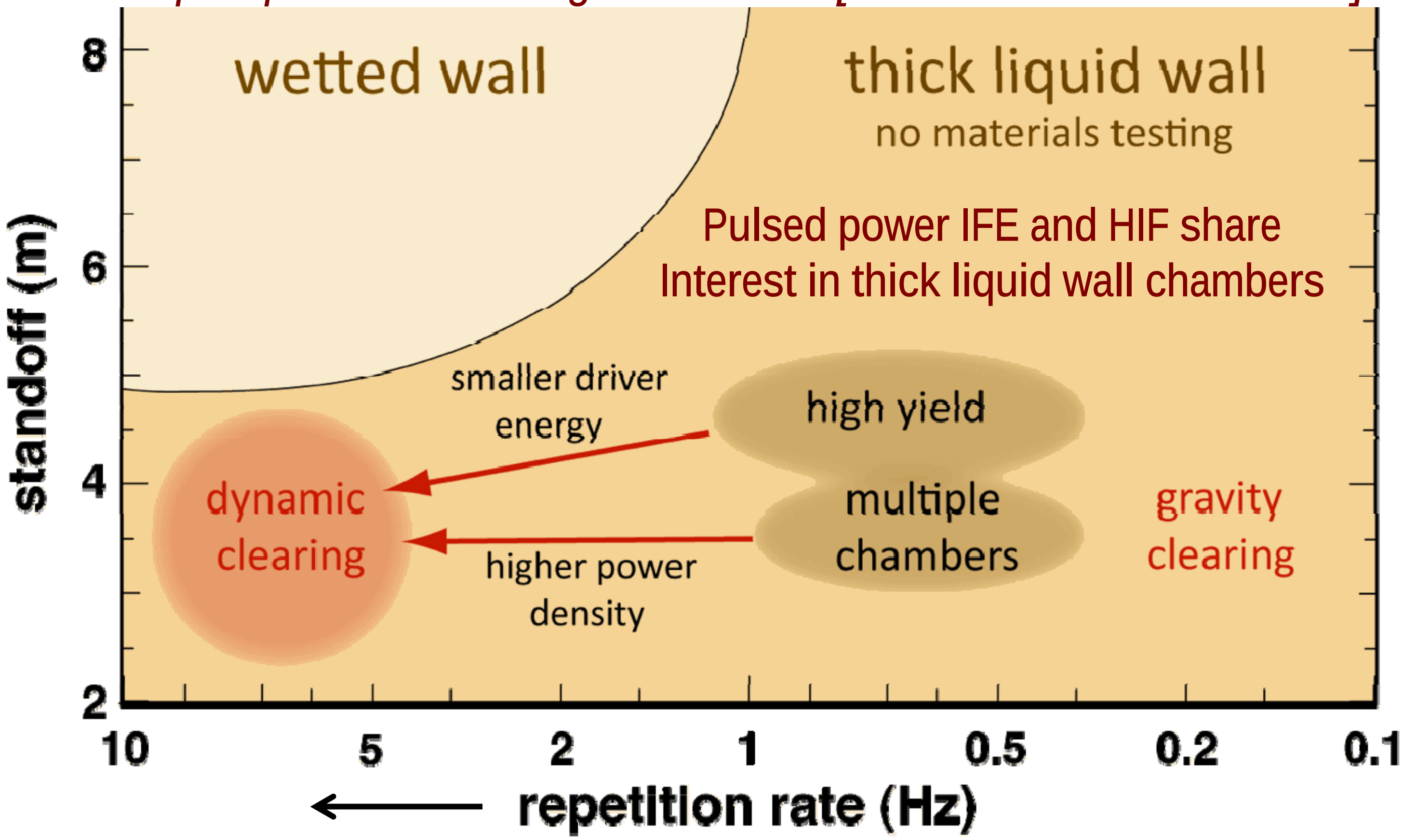
Table IV. Summary of Power Plant Parameters

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

We need value-engineering on component costs, but the total driver cost here is ~3 X the component costs →We also need to investigate the use of factory-built truck-size integrated accelerator modules that can be shipped and quickly installed.

Heavy ion targets would typically produce ~100 MJ of hot target plasma and soft-x-rays →*requires first wall protection*. Beams can propagate through the vapor pressure of hot liquid-protected chamber walls (vapor pre-ionization can actually help beam focusing).

Per Petersen (UCB), showed that liquid-protection parameter space has multiple options for IFE target chambers. [SEAB MFE-IFE review 1999]



The HIF program can't contribute expertise to develop 200-dpa first wall materials, *but the program can restart hydro-equivalent water jet experiments cost-effectively.*

Strategy: a three-phase approach of HIF R&D to an IFE Demo

The HIFS-VNL supports the ICF Community's consensus views

- Demonstration of laboratory ignition will establish that the physics underpinning IFE exploitation is fundamentally sound.
- IFE is a field in which the US is a clear world leader – academically, technologically and industrially.
- We have an opportunity to capitalize on this leadership position over the next few years~~,~~ and leverage prior substantial defense program investment.
- Recent action by the DOE to propose a new IFE development program and secure a stable home for IFE is timely and very welcome.
- Moving forward, the IFE program needs to focus on the requirements of an operating power plant, with design choices managed at a systems-level.
- The inherent modularity and separability of IFE provides significant benefits when considering power plant development, operations , and evolution.
- Taking advantage of significant prior research, future development activities in this program need to include IFE scale science and technology development and demonstration.
- IFE is a national scale program requiring a coordinated effort by academic, Laboratory, and industrial partners.
- A phased program with competition and unambiguous selection criteria is needed

Proposed heavy ion fusion strategy: Three R&D phases to HIF-ETF/Demo

PHASE I: first 5 years: Integrated single beam accelerator experiments, benchmarked simulations, enabling technology development (e.g., magnet arrays), scaled liquid chamber experiments), target designs for several target options, systems analysis.

→ *Deliverable:* validation of selected heavy ion accelerator and target approach for Phase II & III

Decision

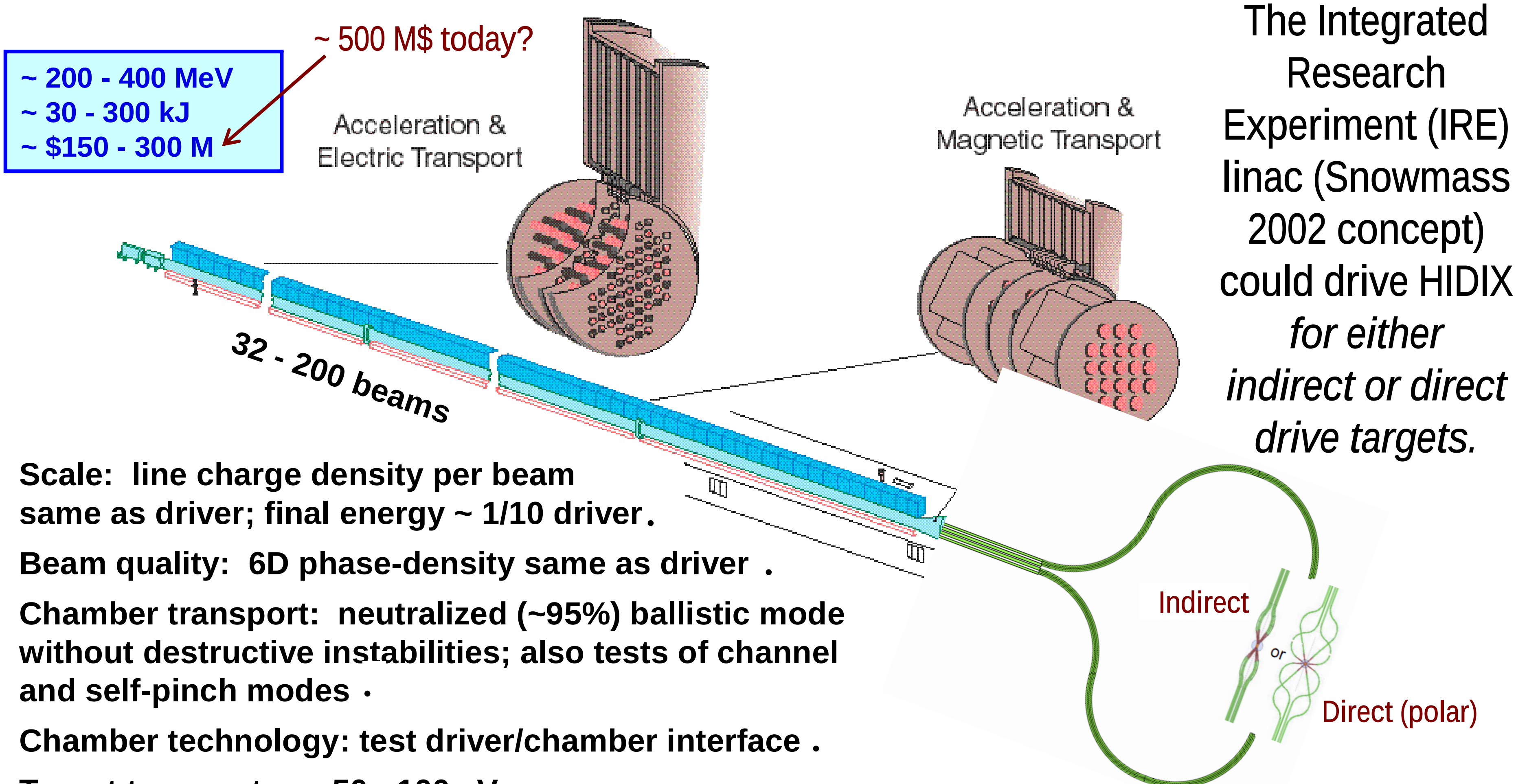
PHASE II: Next 10 years: Construct and operate 10-kJ-scale Heavy-Ion-Driven Implosion Experiment (HIDIX), supporting liquid chamber, target fabrication, and injection R&D for 5 Hz burst-mode experiments on HIDIX. Continued technology development for Phase III.

→ *Deliverable:* validation of integrated multiple-beam accelerator, chamber & target design for Phase III

Decision

PHASE III: Next 20 years: Construct 2-3 MJ HIF ignition test facility for single shot tests, then burst mode, using accelerator designed for 5 Hz. If successful, add nuclear systems to upgrade to 150 MW average-fusion-power level HIF-ETF/DEMO.

Phase II: Heavy Ion Driven Implosion eXperiment (HIDIX) will enable learning control of 10-kJ-scale target implosions (symmetry, pulse-shaping, shock-timing with multiple heavy ion beams). NDCX-II and HCX- 5Hz Phase I data will be needed for HIDIX, with HIDIX data in turn needed for Phase III.



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

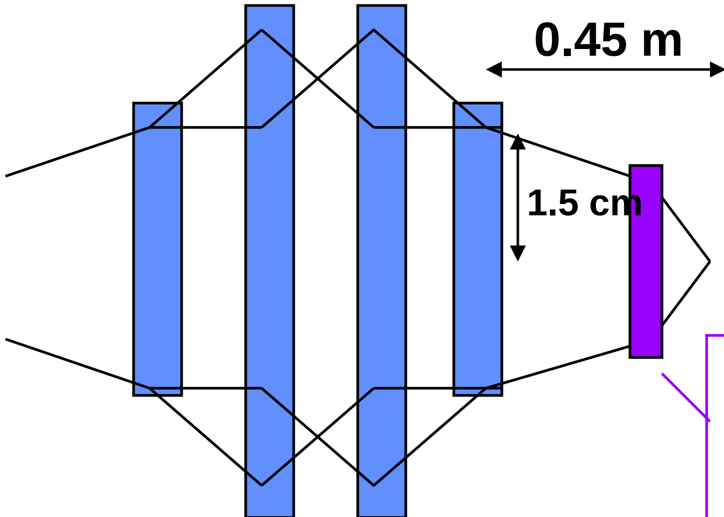
Beam quality: 6D phase-density same as driver .

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 .

One option to enable HIDIX to drive < 1 mm target spot radii is two stage focusing.



Radius at final focus ~ 1.0 mm

Plasma lens
1.5 cm radius
5.0 cm length
400 kA

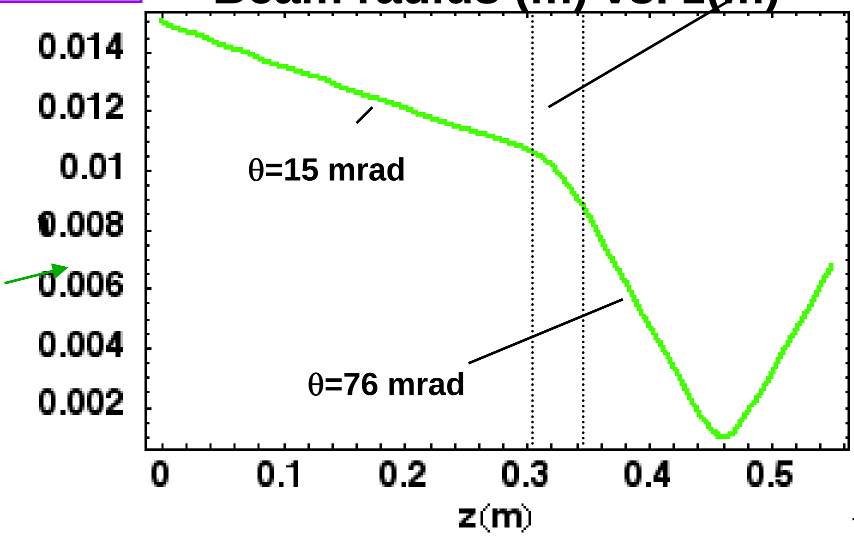
Conventional final focus using quadrupoles

(We plan to test two-stage focusing on NDCX-II)

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

Plasma lens

Beam radius (m) vs. z(m)



Phase III: We did a systems study in 2000 for an HIF- ETF (DEMO)

An engineering design, cost and schedule for an HIF-DEMO is not available, but should be done after the first five year phase, once we have made an informed choice of target.

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

R&D elements proposed for first five years, and deliverables

Elements of proposed five year HIF Phase I research portfolio

- **Experiments and modeling of beam processes:**
  - Neutral and non-neutral drift compression, bending, and final focus (NDCX-II with extensions).
  - emittance evolution, electron clearing, and dynamic vacuum control in quads (at 5 Hz on HCX).
  - Long-path-length beam evolution (university expt's UMER and Paul Trap)
- **Key accelerator technologies:**
  - SC magnet arrays design and prototype development suitable for HIF and HIDIX.
  - Insulator, pulsed power R&D toward a prototype accelerator module for HIDIX.
  - Scaled liquid jets and vortex experiments with hydrodynamic modeling.
- **Beam and plasma injection processes:**
  - Durable beam injector and higher-density plasma sources (100 kV test stand; NDCX-I at PPPL).
  - Multiple beam injector modeling and prototype development for HIDIX.
- **Target designs** (both IFE DEMO and HIDIX scale)
  - with input from NIF and Omega data
  - iterated with HIDIX and HIF-DEMO accelerator design
  - using models improved with NDCX-II data.
- **Design studies for both HIDIX and HIF-DEMO** based upon data obtained from above.

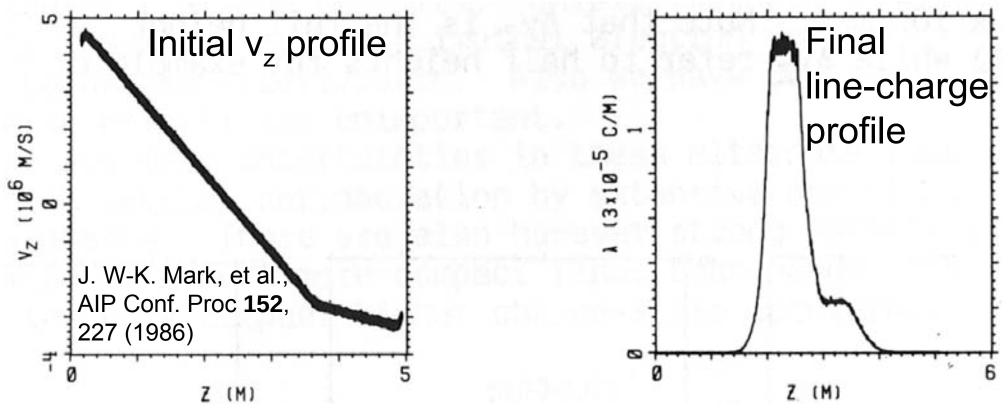
5-year phase I research:

NDCX-II

We propose using NDCX-II to study …

- how well space charge can "stagnate" the compression to create a mono-energetic beam at final focus.

- how well the beam current can be controlled during drift compression for target pulse-shaping

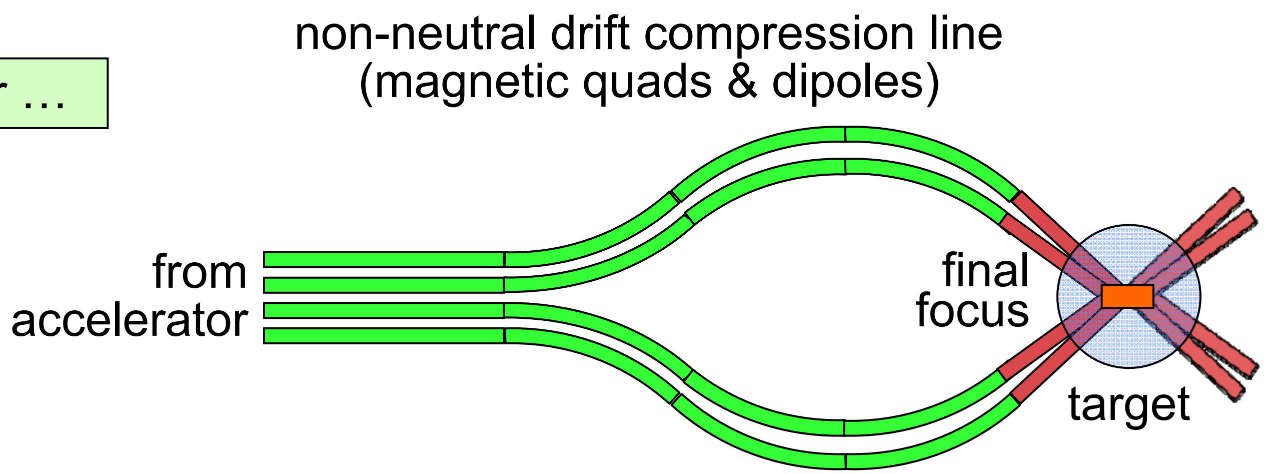


- how well can we compress a beam while bending it:
  - "achromatic" design, so that particles with all energies exit bend similarly
  - or, leave some chromatic effect in for radial zooming
  - emittance growth due to dispersion in the bend
- Compare neutralized and vacuum @ final focus (solenoids vs quadrupoles)

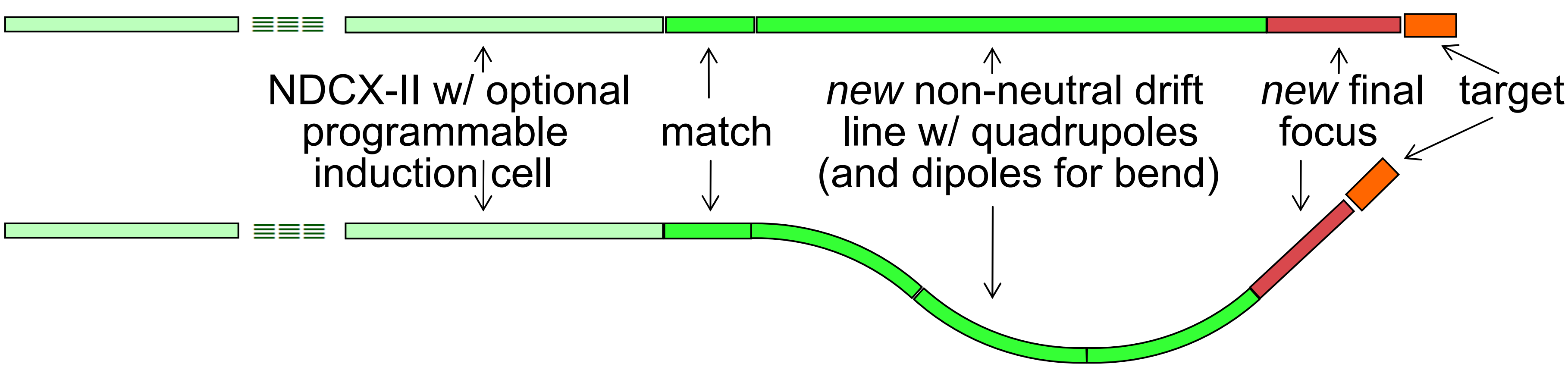
Most dimensionless parameters (perveance, "tune depression," compression ratio, etc.) will be similar to, or more aggressive than, those in a driver.

Experiments on NDCX-II can explore non-neutral compression, bending, and focusing of beams in driver-like geometry

In a driver …

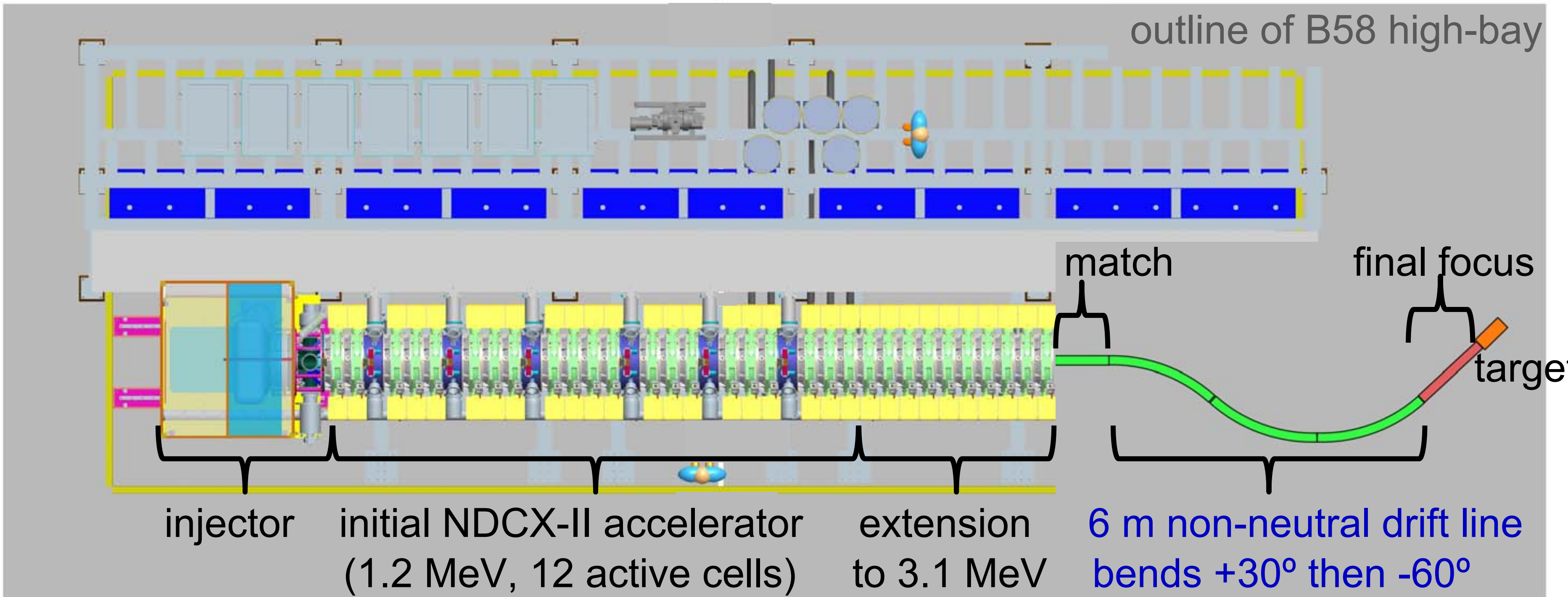


On NDCX-II, two configurations to test …



Non-neutral drift / bend / focus experiment in LBNL's Building 58

… will serve to validate our "achromat" concept (ions of all energies exit bend similarly) and quadrupole focusing onto a target, for space-charge-dominated beams



For a head-to-tail velocity tilt of +/- 5% :

- Pulse length of 0.6 m decreases to 0.083 m, with stagnation beyond the bend end at 6.5 m
- Current of 0.5 A increases to 3.6 A

Pipe radius = 3.0 cm

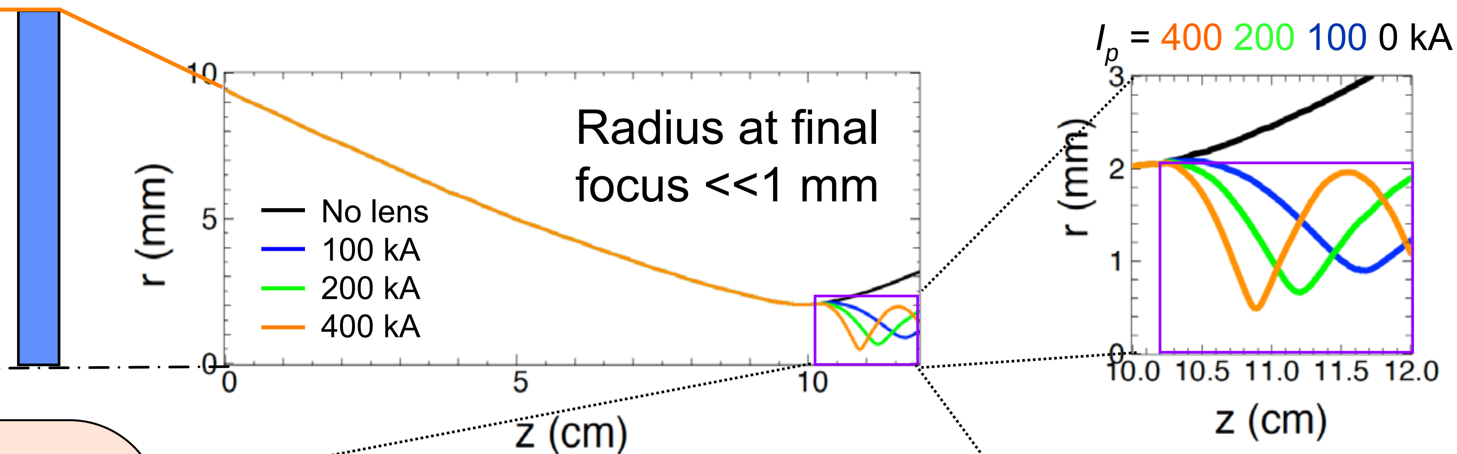
30 water-cooled DC magnetic quads w/ iron poles:

Quad spacing = 20 cm, L_{eff} = 13.33 cm

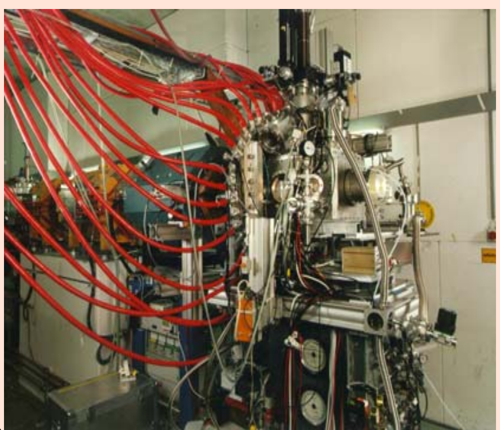
Bend field 0.173 T continuous (combined function)

NDCX-II experiments can explore two-stage focusing, using a second-stage "B $_\theta$" plasma lens

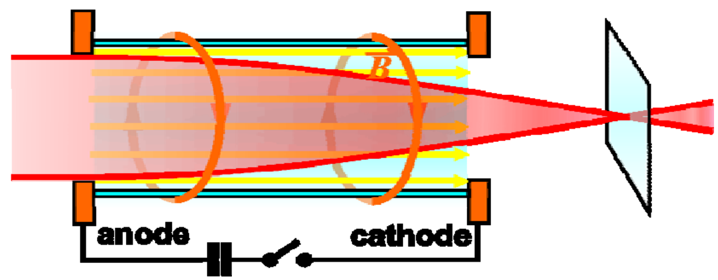
Conventional final focus solenoid (FFS) or quadrupoles



GSI plasma lens
(I_p=240 kA)

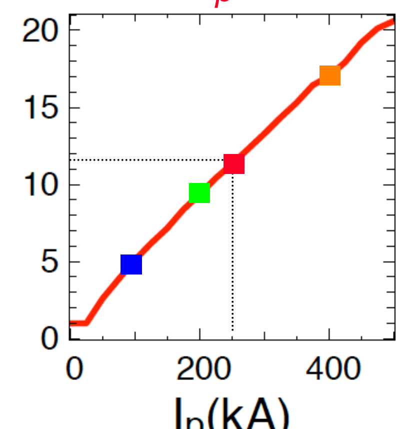


Windowless plasma lens



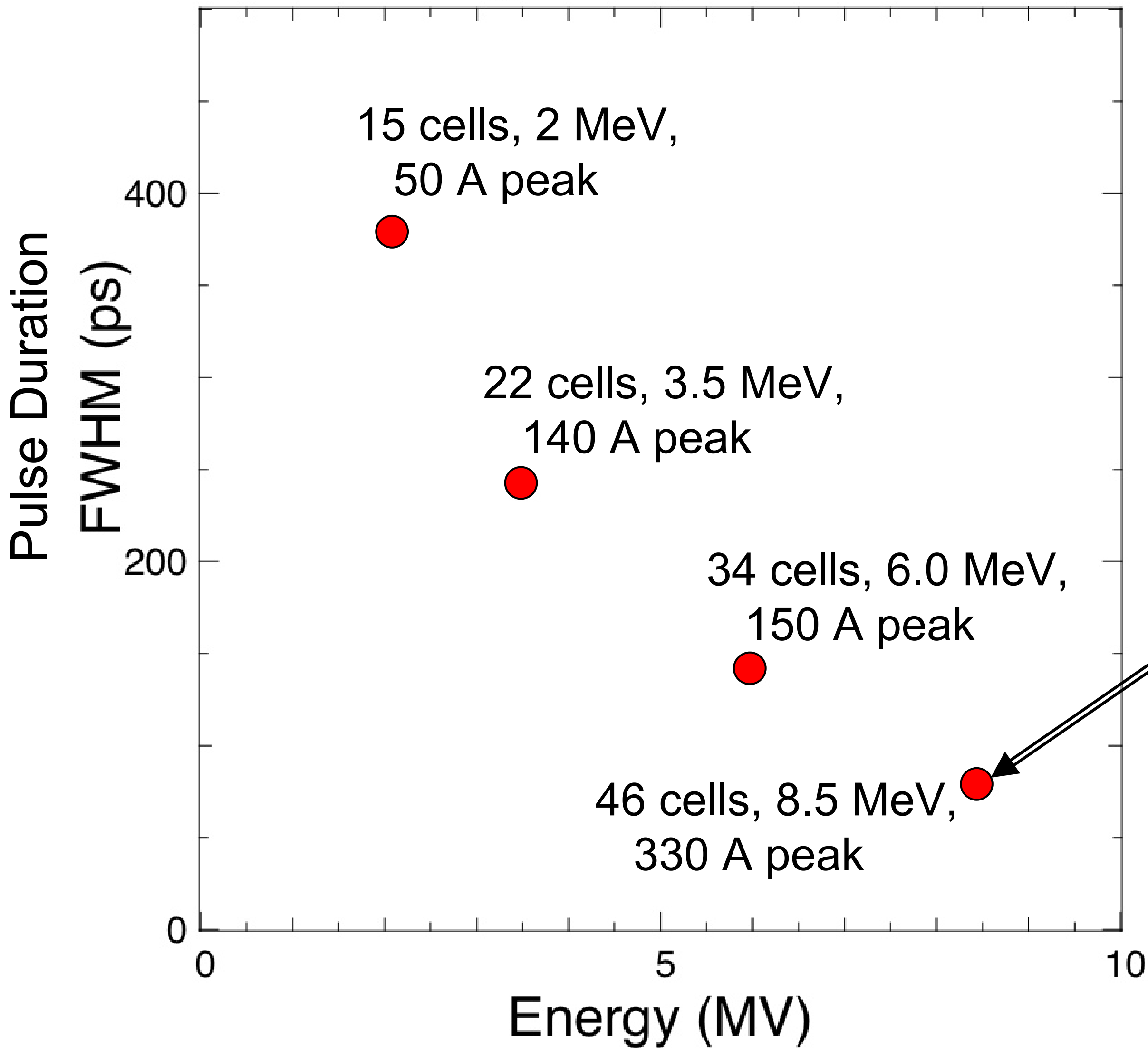
2 mm radius
0.5-1.5 cm length
I_p = 100-500 kA

Fluence increase
>10x at I_p=250 kA



(incident beam from Warp NDCX-II simulation, post-FFS; used ideal B $_\theta$ & neutralization)

WARP simulations of compression to sub-ns pulses on NDCX-II will be compared with measurements to understand longitudinal physics limits.



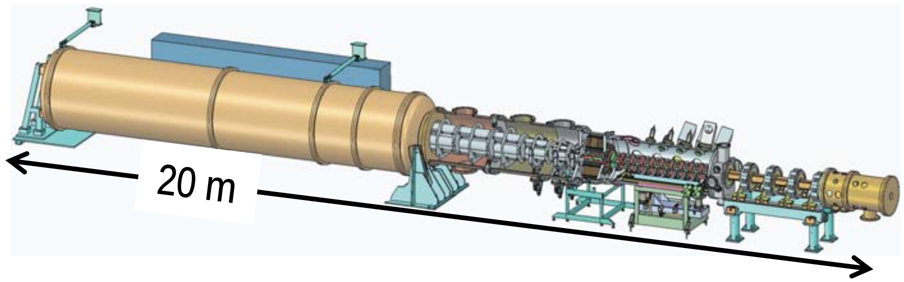
Motivates short pulse experiments related to shock ignition and fast ignition using NDCX-II, IB-HEDPX, HIDIX.

We have 50 ATA cells to extend NDCX-II in < 2 years

5-year phase I research:

HCX
modified for 5 Hz operation

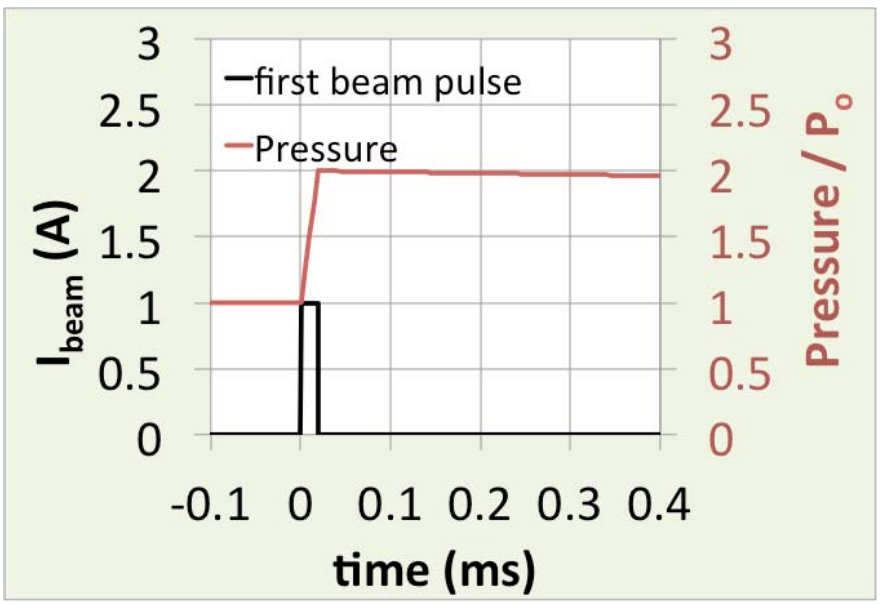
We propose modifying HCX to 5 Hz to obtain data needed to design dynamic pressure control for HIDIX (Phase II) and for HIF drivers:



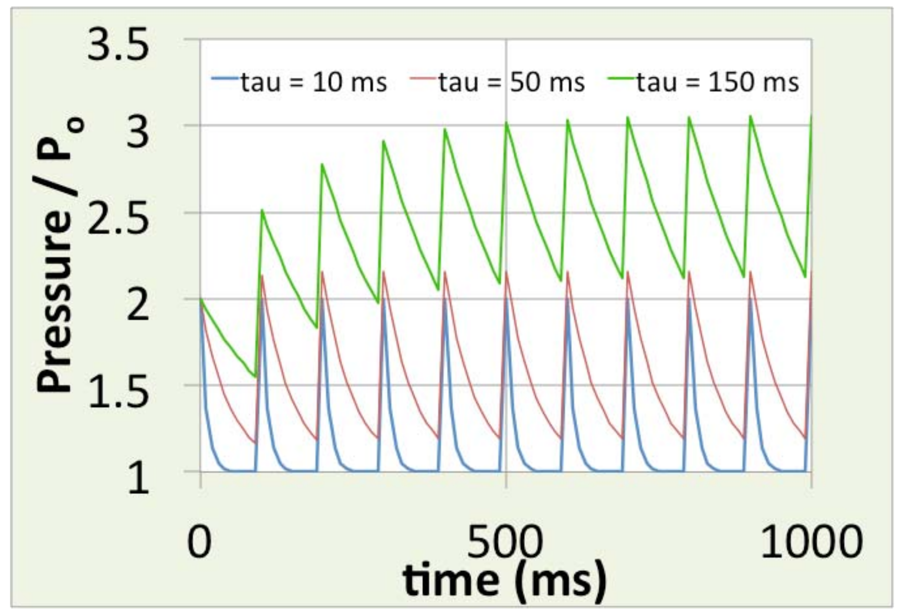
We can modify the existing

HCX facility in Bldg. 58, LBNL

Sources and sinks determine the steady state pressure: Gas desorption from ionized gas, beam ions (halo) striking the wall, removal of gas by vacuum pumping. Eg:, Turner, 2006, J. Vac. Sci. Technol. A 14(4).



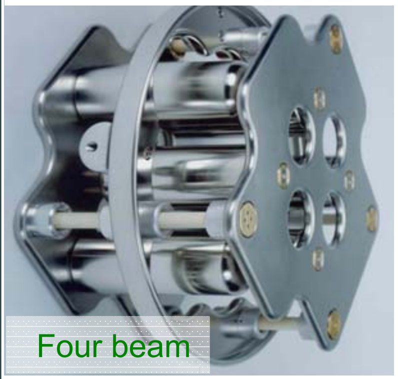
The beam pulse will create a burst of pressure, which may affect the tail of the same pulse



The decay time of the pressure burst will determine the effect on the steady state vacuum pressure

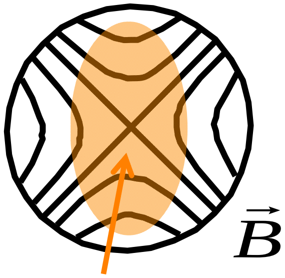
Proposed rep-rate experiments: What is the beam loss from vacuum and beam halo?

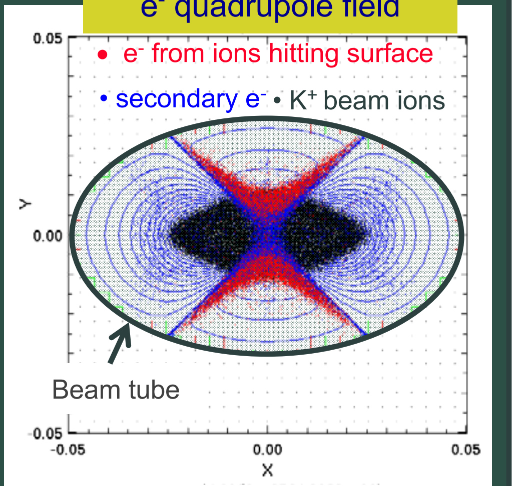
Establish operating limits of **electric quadrupoles at driver scale:**
Full voltage, beam rep-rate, current and pulse length



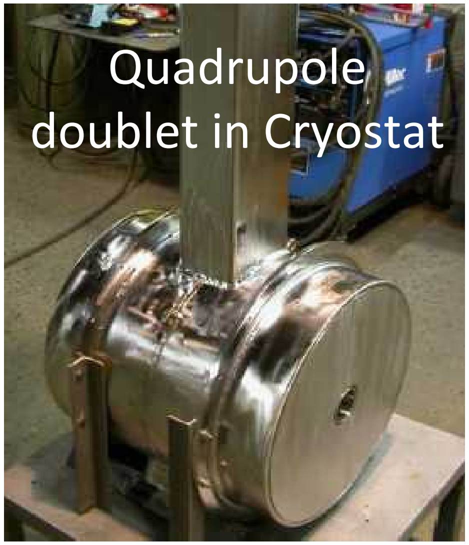
Magnetic quadrupoles

- unwanted e⁻ linger due to ExB
- Cold bore to help with pumping?
    - desorption and sticking coefficients





An extreme example we tested previously.



Relevant atomic cross sections are greatest at low energy. Key experiments are possible with modest enhancements to existing HCX equipment.

σ_s, **stripping**, eg: $Cs^+ + A^o \rightarrow Cs^{2+} + A^o + e^-$

σ_{RCX}, **resonant charge exchange**, eg: $Cs^+ + Cs^o \rightarrow Cs^o + Cs^+$

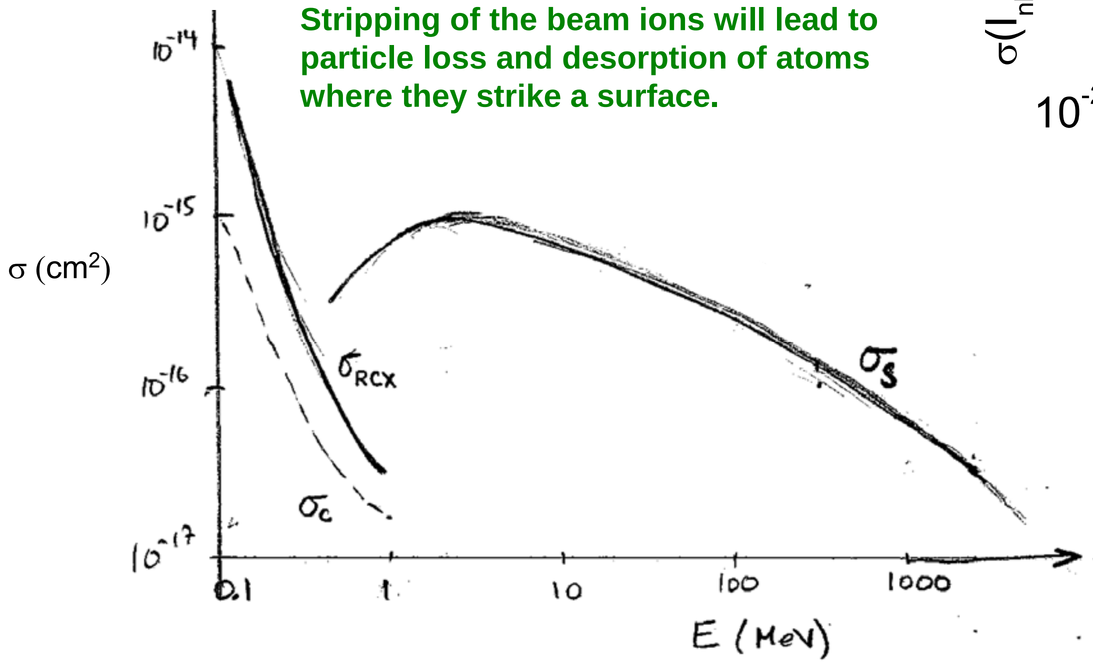
σ_c, **capture**, eg: $Cs^+ + A^o \rightarrow Cs^o + A^+$

σ_I, **ionization**, eg: $Cs^+ + A^o \rightarrow Cs^+ + A^+ + e^-$

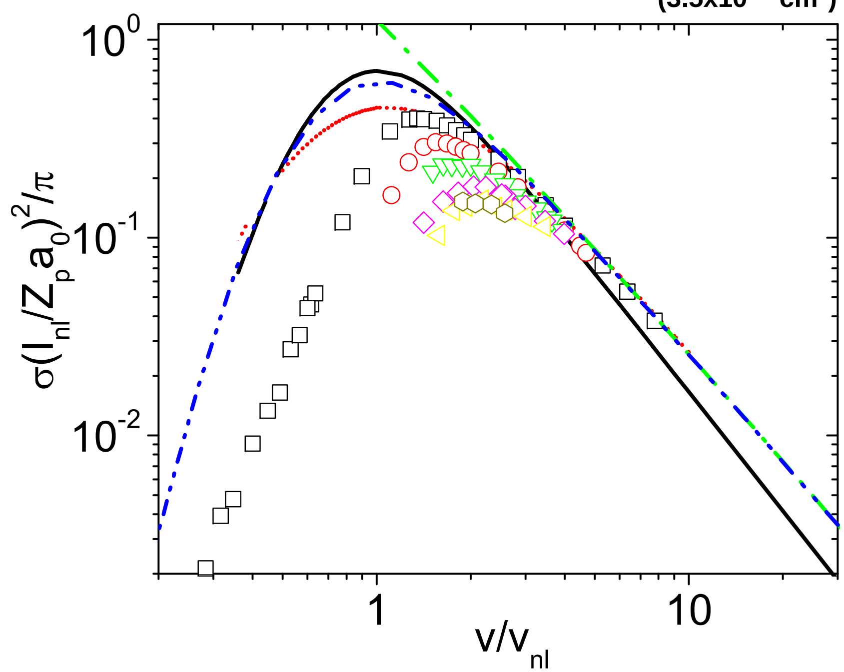
σ_{IS}, **intra-beam scattering**, eg: $Cs^+ + Cs^+ \rightarrow Cs^{2+} + Cs^o$
$Cs^+ + Cs^+ \rightarrow Cs^{2+} + Cs^+ + e^-$

(Dunn, 1979, ≈ 2×10^{-16} cm^2)
A^o, a neutral gas atom (or molecule)

Stripping of the beam ions will lead to particle loss and desorption of atoms where they strike a surface.



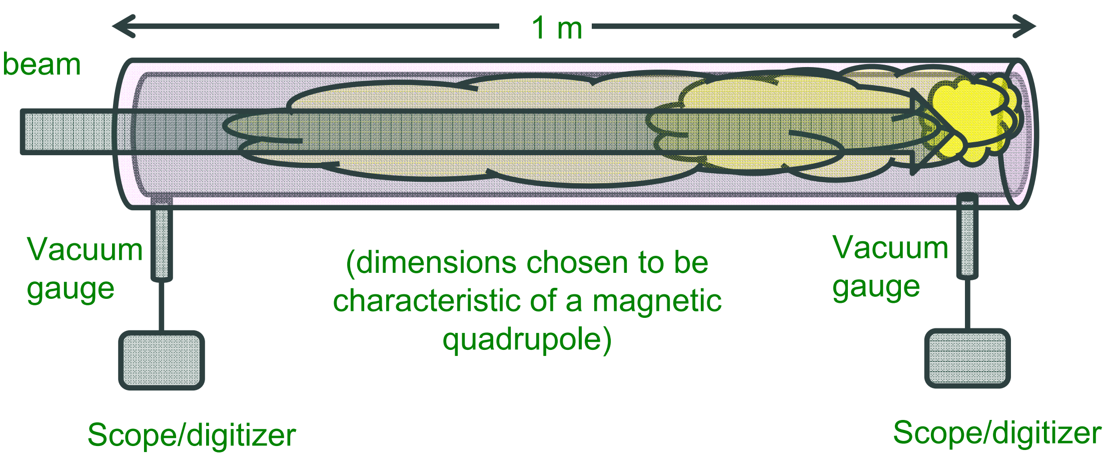
Ionization (of background gas) (3.5x10^{-16} cm^2)

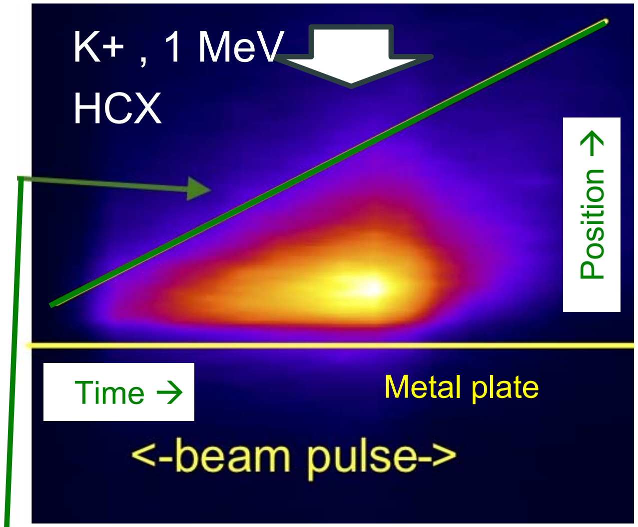


Kaganovich et al., New J. Phys. 8 (2006) 278

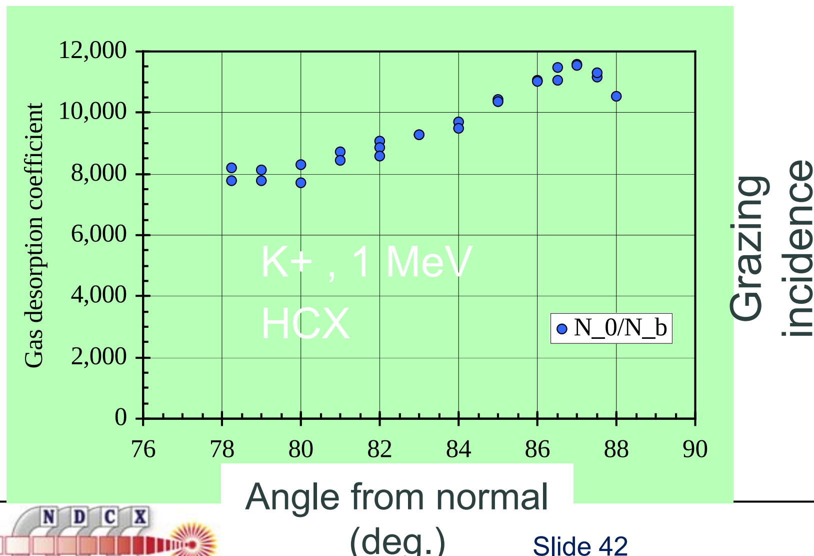
Experiments with intense beams at driver rep rate will quantify effects of beam-gas and electron clouds, enabling driver design optimization.

Example: Rep-rated beam loss and halo induced desorption.





$v_{cloud} \approx 1.5$ mm/μs, mostly H_2

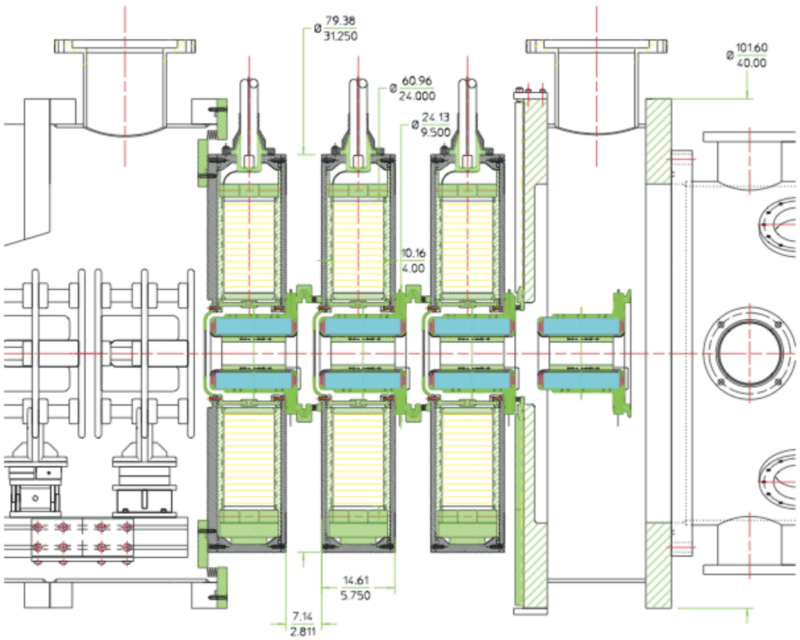


Q: Would a cold bore in the magnetic quadrupoles reduce the vacuum pressure?

Depends on desorption per ion, sticking coefficients.

Experiment with cold bore and beam screen

Upgraded HCX magnetic transport line – scalable for future transport experiments



Benefits:

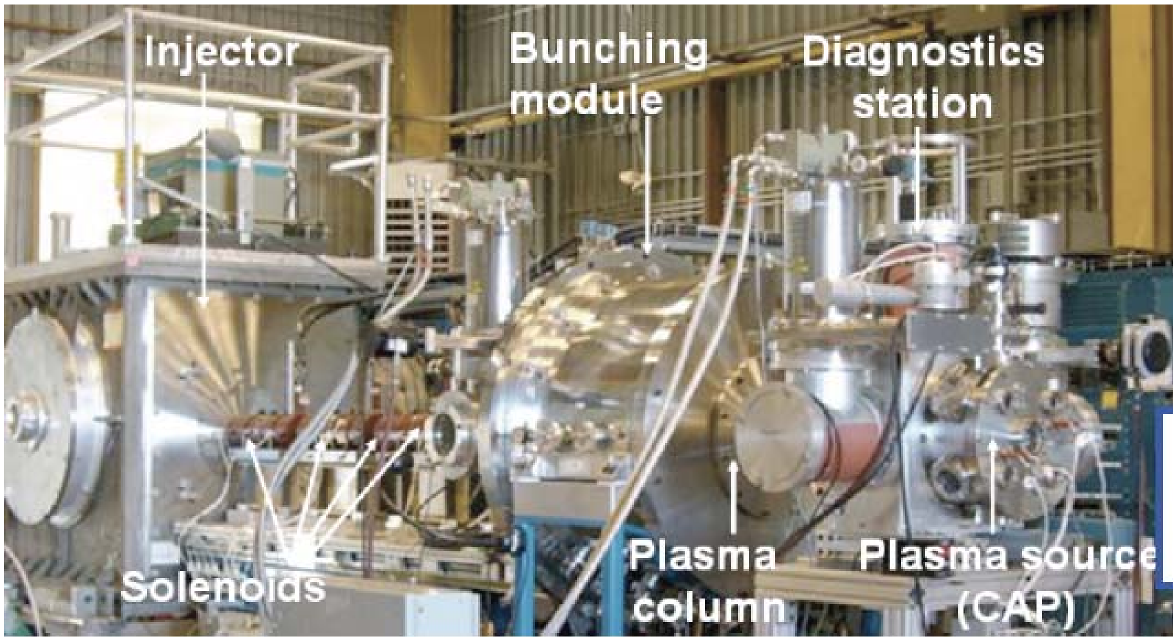
- **Better Match to Existing Lattice**
- **Extendable to Longer Lattice**
- **Interfaces with Different Induction Cells**
- **Improves diagnostics access**
- **Induction cores between quads can sweep out unwanted electrons**

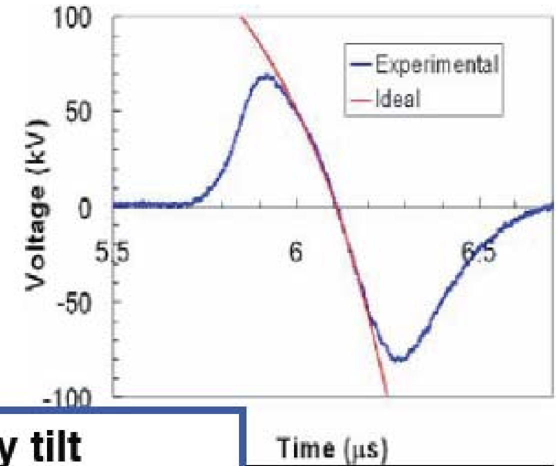
Simplified and optimized magnet transport line design can provide a scalable foundation for future quadrupole experiments beyond gas/electron experiments.

5-year phase I research:

NDCX-I
Technology R&D
Target Design

The NDCX-I will be moved to PPPL to continue optimizing beam compression and focusing methods and new plasma sources.



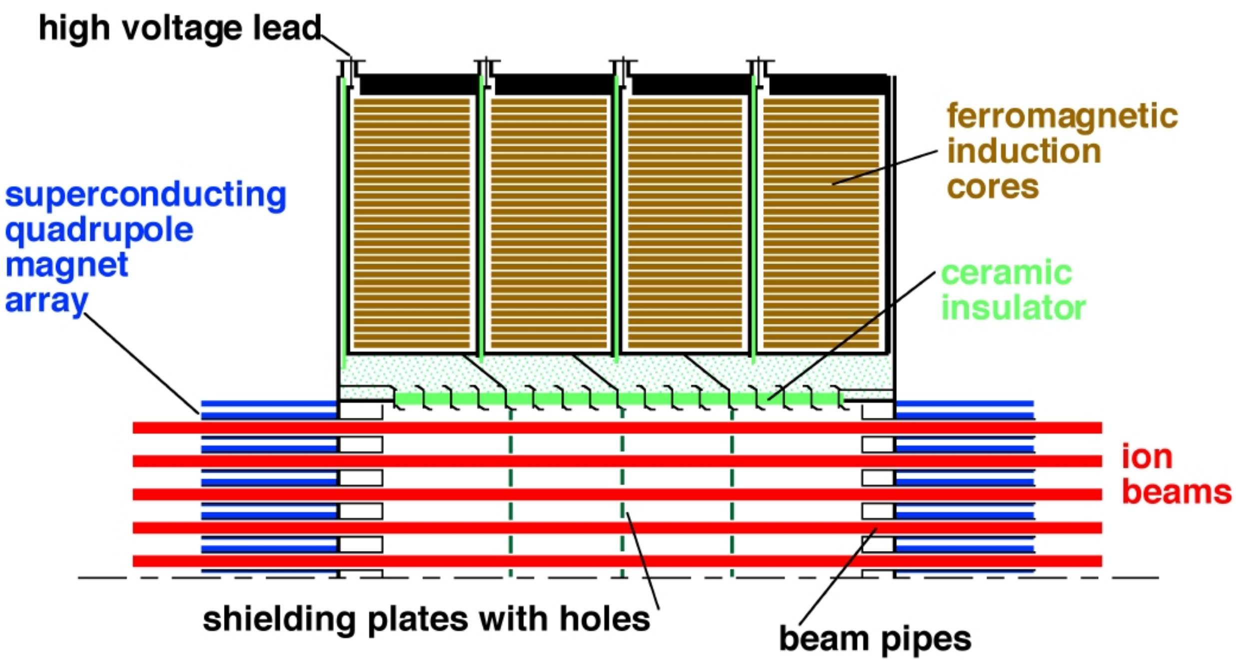


Velocity tilt accelerates tail, decelerates head

(Like chirped pulse compression)

- Provide the HIFS-VNL with a facility for developing and testing advanced systems and concepts before they are deployed on NDCX-II.
- Study beam-plasma interactions and instabilities and constraints on the plasma parameters.
- Explore Final focusing schemes such as the Robertson lens and collective focusing.
- Characterize the effects of the solenoid misalignment and identify methods for optimizing the transport element alignment.
- Measure the effects of aberrations on longitudinal focusing and on optimal simultaneous longitudinal/transverse focusing.

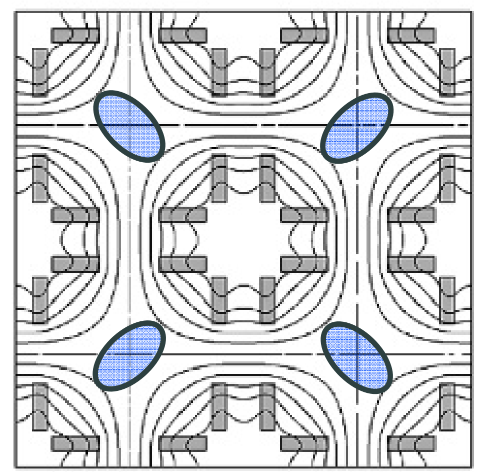
The Phase I research we propose should allow us to design and build an HIF driver prototype module



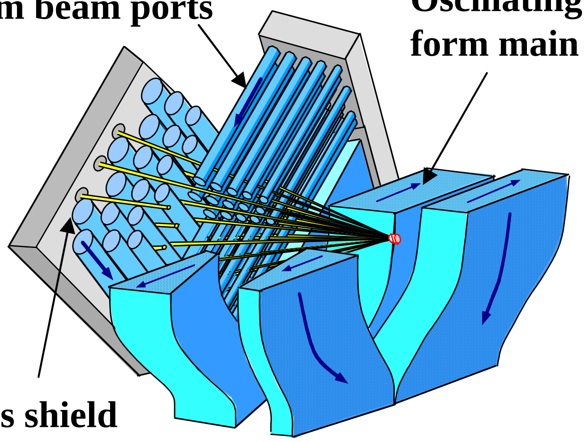
The beam quality at the target will be affected by: beam-gas, beam-beam interactions, electron clouds, beam-core loading...

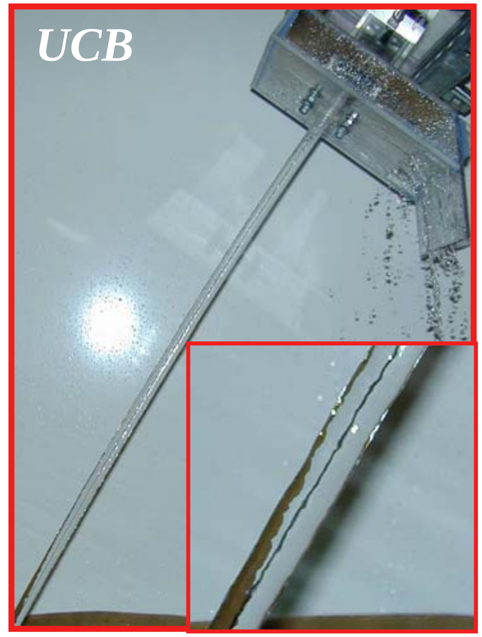
Electrostatic quadrupole array

Superconducting array coils share flux with neighboring cells. Enhances field ≈30%



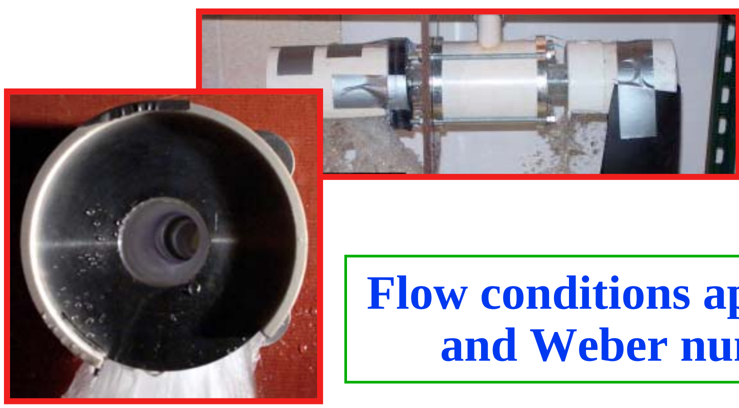
A wide array of hydrodynamically-equivalent water jet experiments are proposed to validate the HIF-IFE DEMO beamline design and to design an experimental HIDIX chamber. (Per Peterson, UCB)





Highly smooth cylindrical jets

Slab jet arrays with disruptions

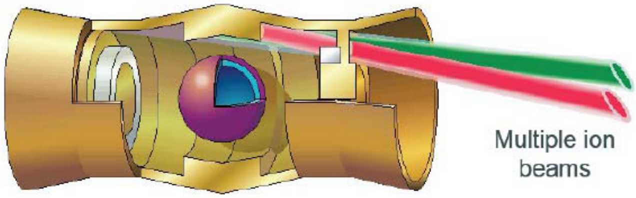


Vortices

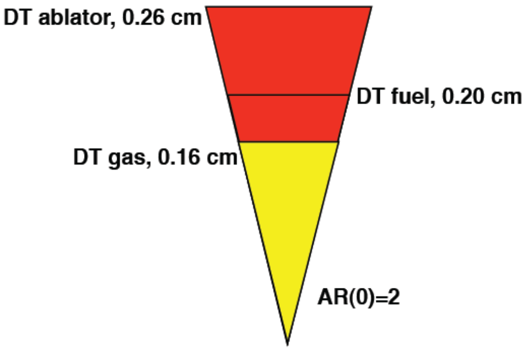
Flow conditions approach correct Reynolds and Weber numbers for HYLIFE-II

We propose to triple the present HIF target design effort in Phase I to 3 FTE to allow a target selection for Phase II .

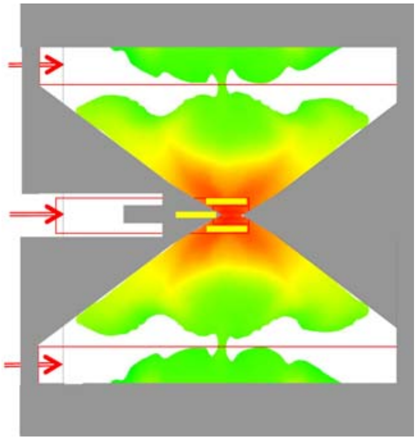
- Indirect drive (2-sided hohlraum) *2-D Lasnex design (2002):* 7 MJ, 3→ 4 GeV Bi^{+1} , gain 68.
  Two-sided illumination, like NIF-most studied.



- Heavy-ion direct drive *1-D Lasnex design (2010):*
  3 MJ, 3 GeV, Hg^{+1} ion beams, gain ~150.
  Future 2-D design planned for polar drive illumination, with tamper & shock ignition assist.



- X-target hydro-drive with FI *2-D Hydra design (2010):*
  3 MJ compression+3 MJ ignition, all 60 GeV U beams, gain 50. One-sided illumination (to be published)

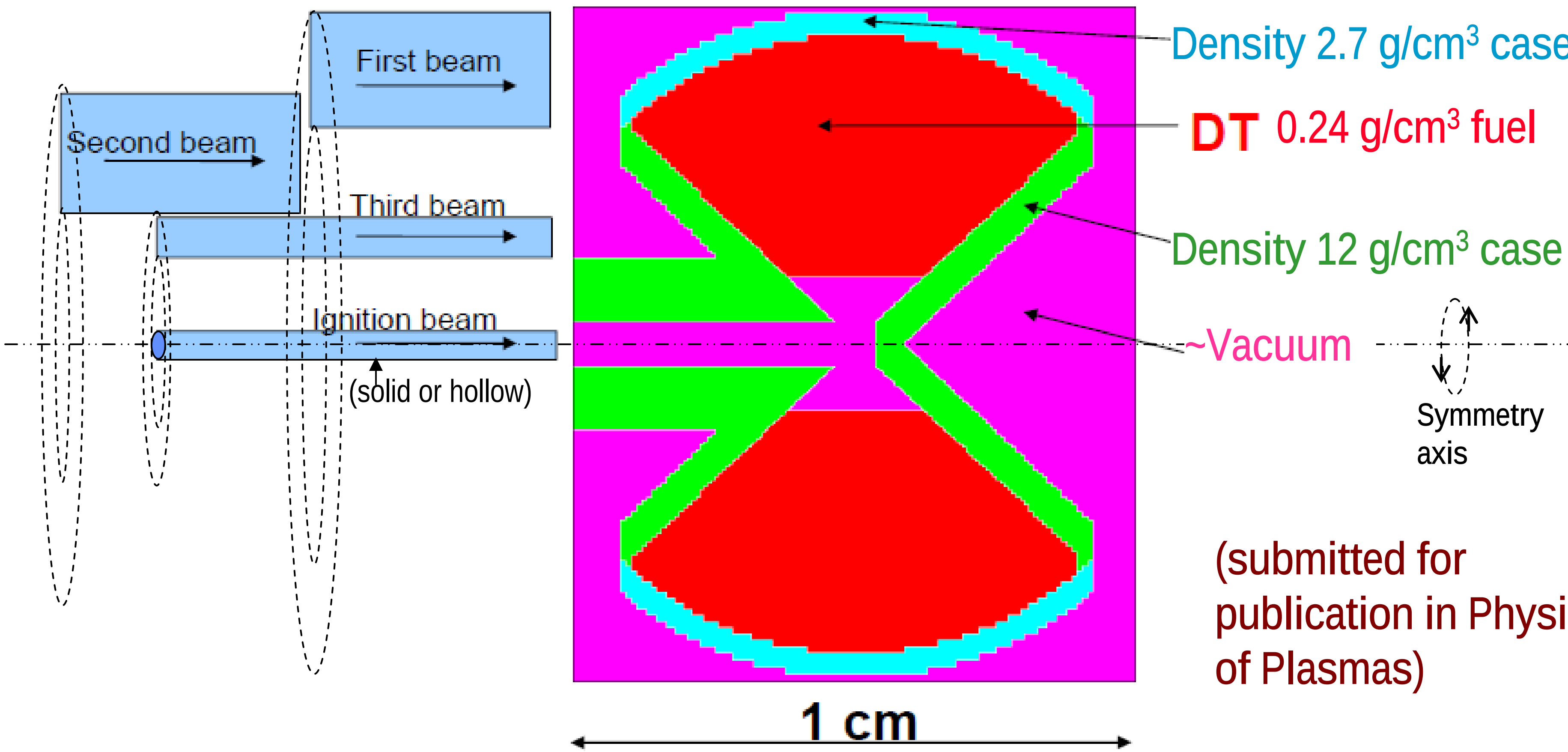


→All three options are intended to use multiple-beam linac drivers with thick-liquid-protected chambers to mitigate material neutron damage risks.

Opportunity: powerful unclassified target codes (E.g. HYDRA) allow more laboratories to participate in 2-D target designs for heavy ion fusion.

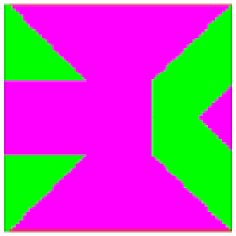
Example: X-target: gain 50 @ 6 MJ drive, 1.3 g/cm2 ions, one-sided beam illumination, robust RT stability. (Enrique Henestroza, LBNL, August 2010)

1st, 2nd, 3rd and 4th ion beams are many beams with overlapping spots <u>modeled as annuli</u>

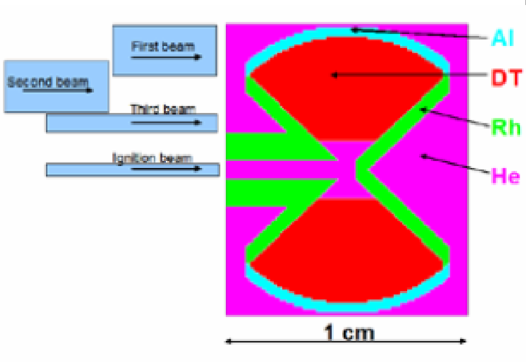


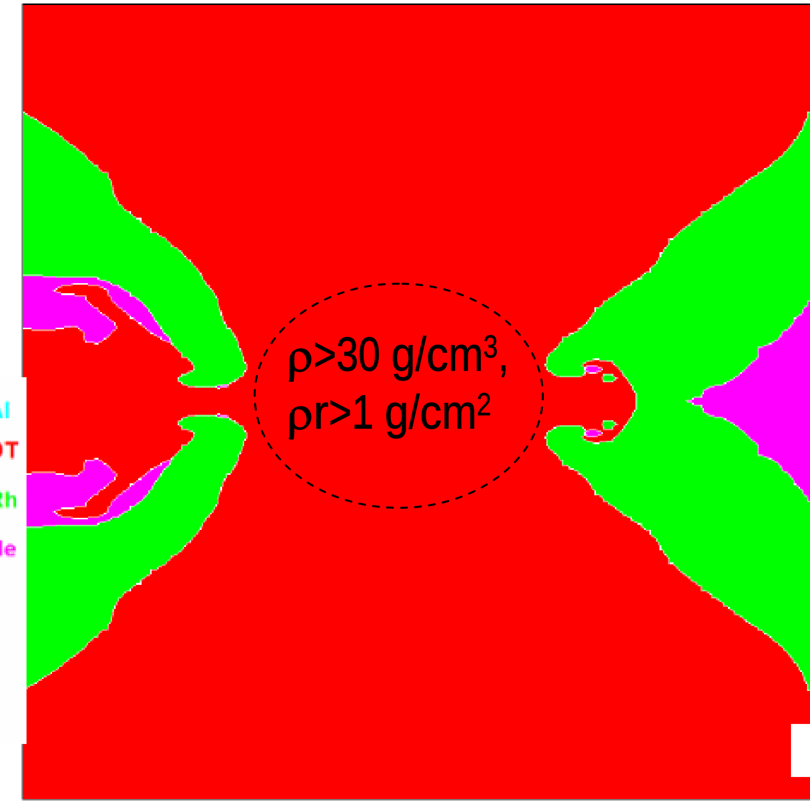
(submitted for publication in Physics of Plasmas)

DT and case metal material distributions at initial time and after compression with low convergence $r_o/r_{ig} \sim 5$, before injection of the ignition beam, *show small RT mix effects*.



1X





3X

DT

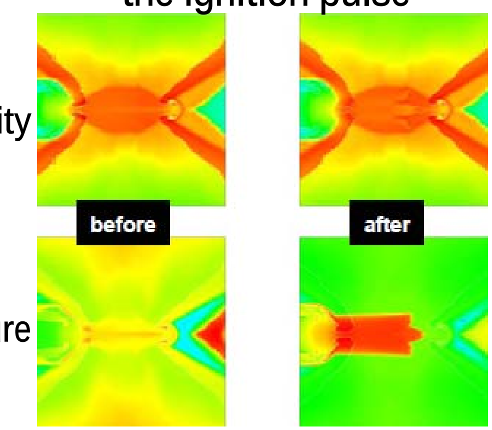
Case

Void

Density and temperature before and after the ignition pulse

Density

Temperature



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

Systems analysis in Phase I: benchmark accelerator beam brightness models with NDCX-II data, update target designs, assess accelerator designs, risks and costs.

Target designs will be updated with NIF and Omega data, and driver codes will be improved to select a target for Phase II and III.

HIF Target option	Indirect-Drive (2-sided) hotspot ig.	Tamped polar-direct-drive w/ shock ignition	Single-sided-direct drive w/ fast ignition*
Total beam energy *(energy in peak drive)*	7 MJ *(5 MJ -main)*	3 MJ *(1 MJ-shock)*	6 MJ *(3 MJ-igniter)*
Peak drive power	*0.5 PW*	*2 PW*	*15 PW*
Ion / K.E.	Bi^{+1} / 3 & 4 GeV	Hg^{+1} / 3.5 GeV (all)	Rb^{+1} / 13 GeV (all)
Linac length and gradient	3 km @ 1.5 MV/m	2 km @ 2 MV/m	4 km @ 3 MV/m
Driver total capital cost-B$	3 $B	2 $B	2 $B
Target gain (linac efficiency)	60 (40%)	100-200 (1D) (35%)	50-100 (35%)

From left to right→ decreasing target maturity; increasing peak power (more accelerator risk).

→ decreasing implosion velocity, aspect ratio and convergence (less target risk).

* We have yet to work out an igniter beam focusing design.

Examples: all cases have 120 beams total (none optimized), vacuum drift compression, neutralized ballistic chamber focus, with pulse lengths/ accelerator gradients chosen to minimize induction linac core mass.

Phase I (5-year) Deliverables

- **HIF Target designs (one or more) for HIF DEMO and HIDIX qualified in 2-D with RT multi-mode stability, and accelerator designs that are consistent with the target requirements.**
- **Sufficient data from NDCX-II beam compression, bending, and final focusing, and from HCX @ 5 Hz, to validate accelerator models used to design HIDIX (phase II) and HIF-DEMO-(Phase III) accelerators.**
- **Scaled water jet and vortex experiments with benchmarked hydro models that can be used to design liquid chambers for 5 Hz for HIDIX and HIF-DEMO.**
- **Engineering studies showing credible accelerator cost reduction methods, including component cost and reliability improvements sufficient so that reasonable HIF DEMO costs can be projected.**

HIF roadmap-timeline with estimated resource needs per year

R&D roadmap to determine the feasibility of heavy ion fusion energy *(#'s=M$/yr)*

Fiscal Year	2009	2013	2014	2018	2019	2023	2024	2028	2029	2033
Integrated single beam HEDP/IFE exps. to maximize pressure in planar targets	7 M$/yr →	15	25 →	20	20 →	20	15 →	15		
NDCX-I (to 10 kBar)	7(@lbl	1 (@ PPPL) →		5					Optimize plasma	
NDCX-II[1] (to 1 MBar)		12 →	13						Drift, bend & focus	
NDCX-II+→IB-HEDPX[1] (to 10 MBar)		1	10	13 →	11 →	6			Upgrade to 8 MV	
Intl. Collab. Exps. @ FAIR, LANSCE...		1	→	2 →	4 →	9	→	10	High KE ions	
(each row includes theory/sim and equipment support)			<5-yr Phase I >		Key decision (CD2 for HIDIX)					
Accelerator driver R&D for 5 Hz, multiple-beam target experiments	0.6 →	2.5	11 →	14	25 →	100	100 →	90		→90
5 Hz accelerator R&D (inc. HCX-II)[2]		1.5	8	8	15 →	15	15			
Exp. target R&D (design/fab/inj.)	0.3 →	0.5	1	2	2.5					
Long-path accelerator R&D(UMER,PT)	0.3 →	0.5	2 →	2	2.5					
Heavy Ion Driven Implosion Experiment (HIDIX) (5Hz, 100 MBar)				2 →	5	80 x 6 yr		80		
							Key Decision (CD2 for HIFTF)			
Heavy Ion Fusion Nuclear Science and Technology[3]	0.4	1.5 → 3		→ 5 →	20	→ 30→40		→ 75		→310?
5Hz HIF target design, fab, inj., tracking	0.3 →	1	2 →	2.5	10 →	15	20 →	30		
Enabling liquid chamber R&D	0.1	0.5 → 1	→	2.5	10 →	15	20 →	30		
Heavy Ion Fusion Test Facility (HIFTF) ~100 MJ yield single shot and 5 Hz							10 →	15	250 x 8 yr ?	→
Fiscal Year	2009	2013	2014	2018	2019	2023	2024	2028	2029	2033
(All costs in M $ per year) Total HIF[1]	8 →	19	38 →	40	65 →	150	155	180		400?

[1] Budgets include HEDLP relevant to HIF, but not operations & diagnostic support for grant-funded 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 may be applicable to HIF

Design	Construction	Operation/R&D

The Snowmass 2002 white paper was used during the 2003 and 2004 FESAC reviews, and is available for more specific detail on tasks, costs and schedule needed for HIF 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

Potential collaborations on HIF

Workshop on Accelerators for Heavy Ion Inertial Fusion

LBNL, May 23-26, 2011

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
- Induction accelerators
- RF accelerators (including linacs, synchrotrons, storage rings, cyclotrons)
- Superconducting magnets
- Chamber and chamber - driver interface
- Technology development (e.g.: insulators, high-voltage pulsed power, RF systems, vacuum systems)

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

Registered office: Darmstadt

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.

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

Darmstadt, November 11th, 2010

Boris Y. Sharkov
FAIR Scientific Director

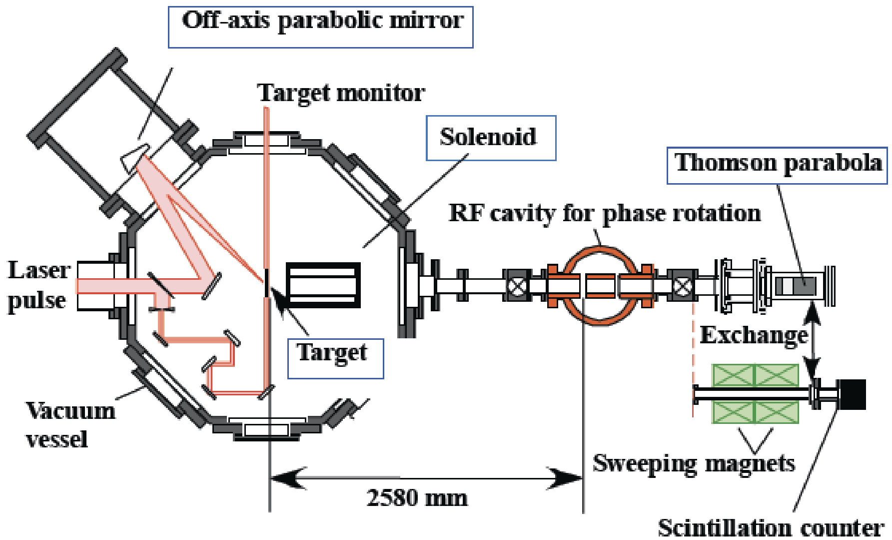
Darmstadt, November 11th, 2010

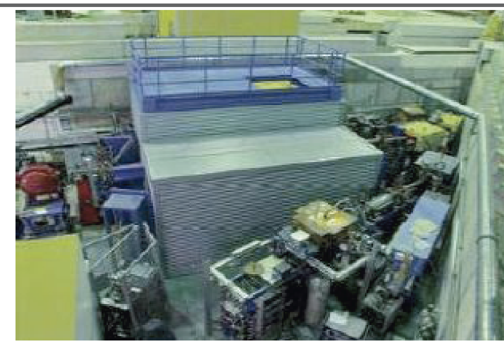
B. Grant Logan

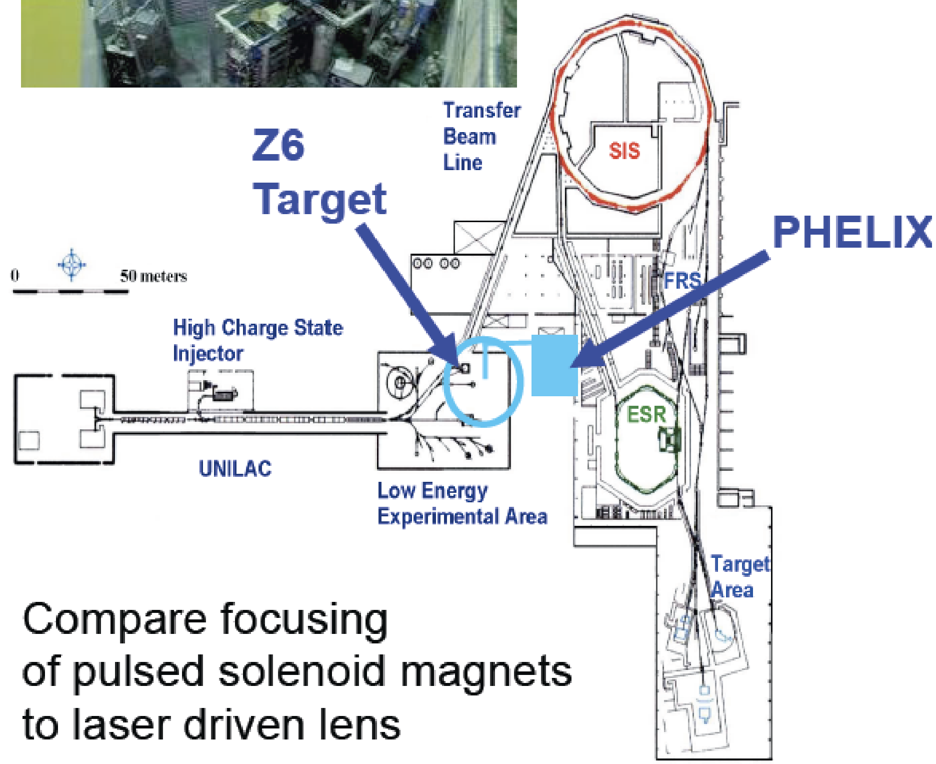
B. Grant Logan
US Heavy Ion Fusion Science
Virtual Natural Laboratory

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)*

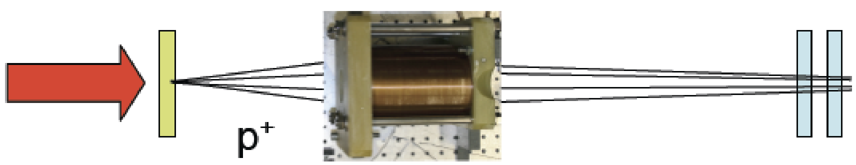
TECHNISCHE UNIVERSITÄT DARMSTADT

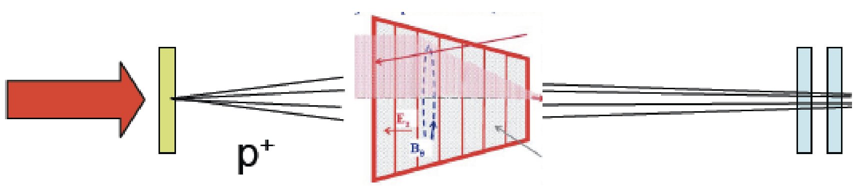






Solenoid



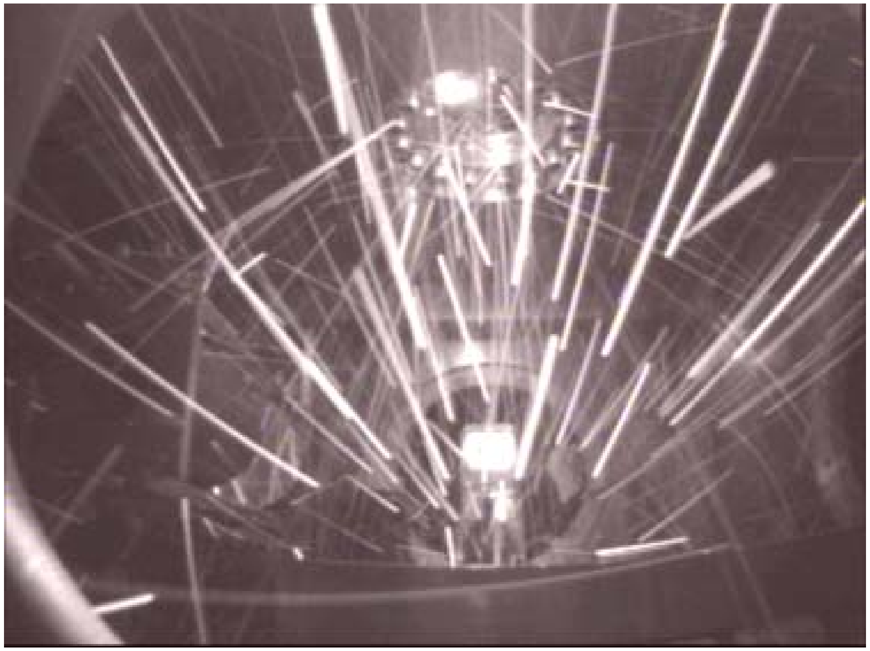


Compare focusing of pulsed solenoid magnets to laser driven lens

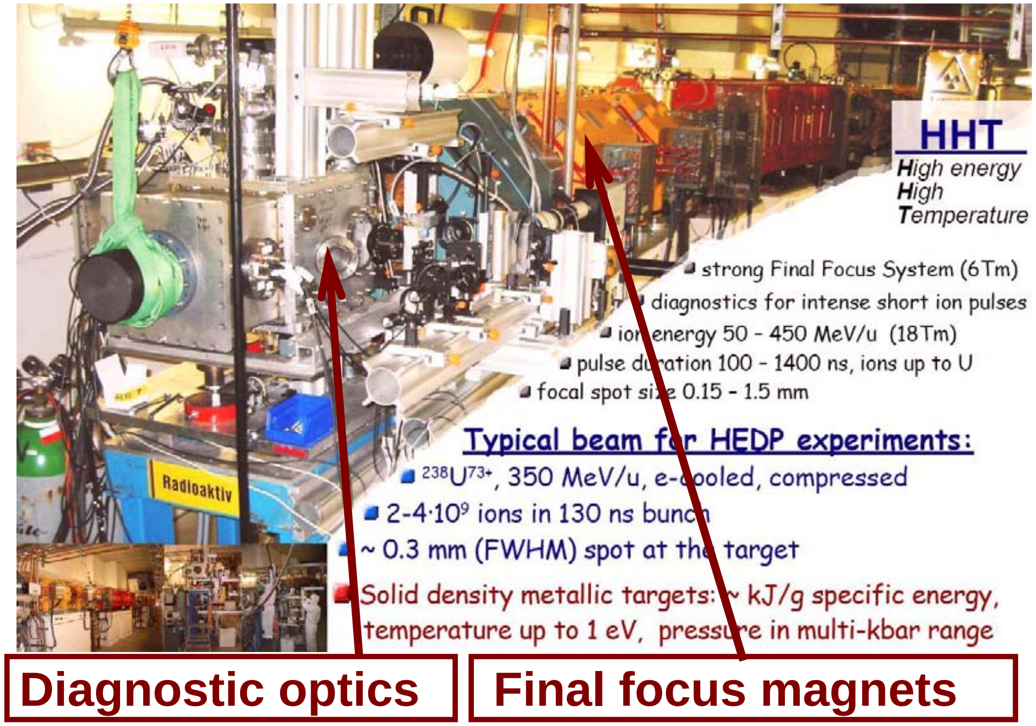
HELMHOLTZ GEMEINSCHAFT

GSI

VNL 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 new FAIR upgrade of GSI's accelerator will allow joint cryo hydrogen compression experiments relevant to heavy ion fusion with much more (80 kJ) of uranium beam energy.

US-Japan collaboration on heavy-ion fusion has benefited both nations for more than a decade.

Since 1997, we have had a series of workshops that have identified and enabled areas of collaboration with the HIFS VNL

Recent areas of collaborative research:

K. Takayama (KEK), induction acceleration, recent collaborative book, "Induction Accelerators", [Springer: NY] (2010)

K. Horioka, Y. Oguri, J. Hasegawa, (Tokyo Institute of Technology), Warm Dense Matter and ion stopping in heated material

S. Kawata (Utsunomia University), Target concepts, RT stabilization techniques

T. Sasaki (Nagoka University), Diagnostics for NDCX-II

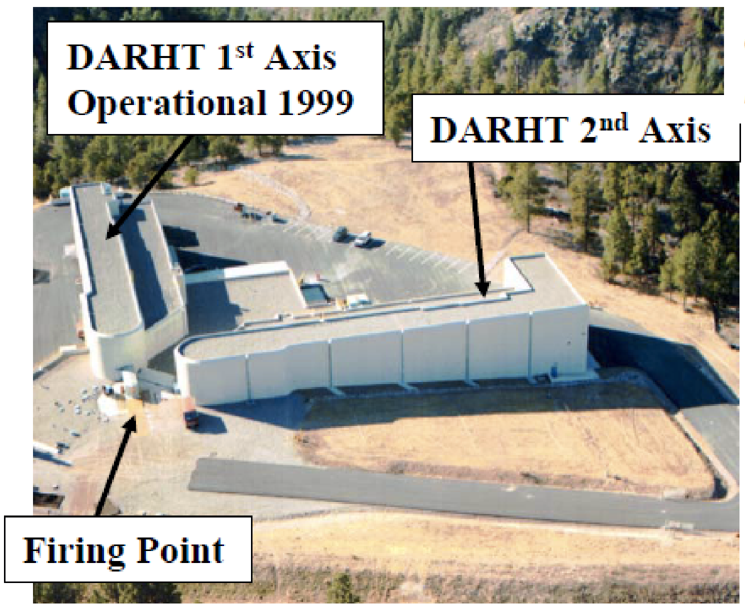
S. Ohtsubo (Hiroshima University), Beam stability using Paul Traps

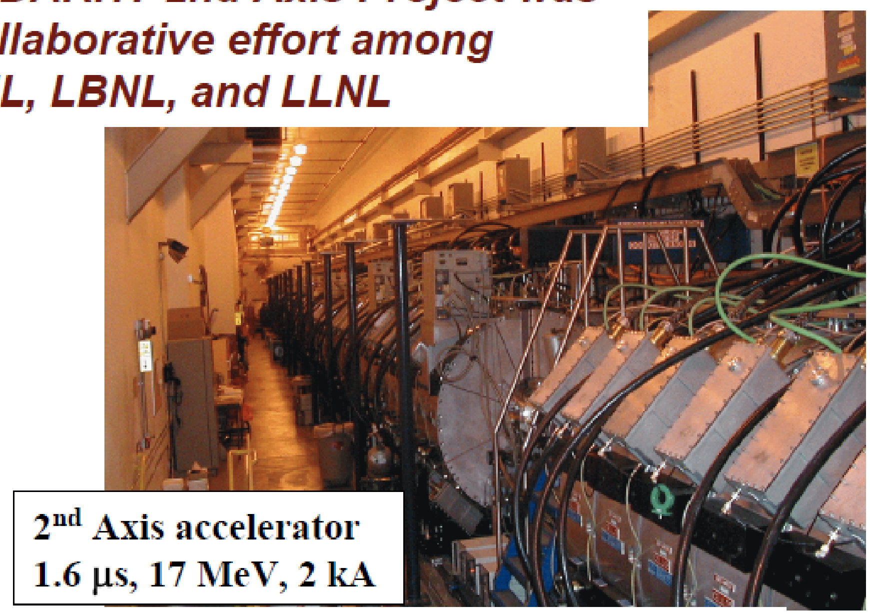
Potential HIF collaboration at LANL

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 (this message was approved by Kurt Schoenberg)

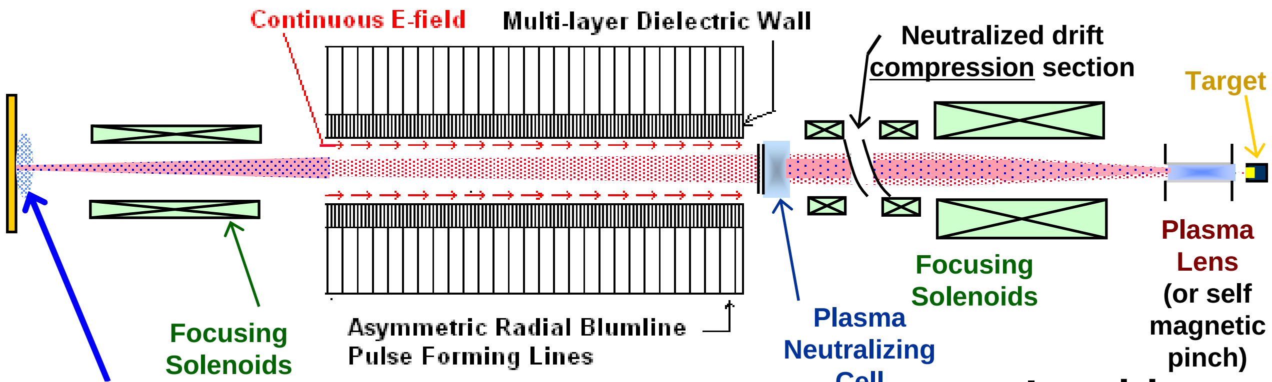
DARHT-II: a state-of-the-art induction accelerator @ >50 kJ/ electron beam pulse. Technology *relevant to induction linac drivers for fusion!*

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





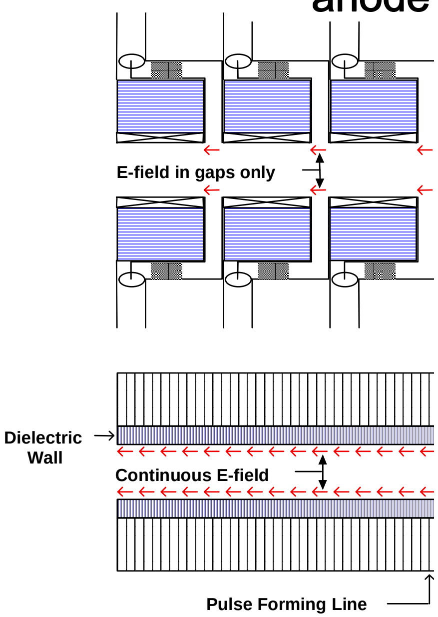
Potentially fruitful driver collaboration with LLNL's Beam Research Program (George Caporaso): advanced, high gradient, high current DWA option

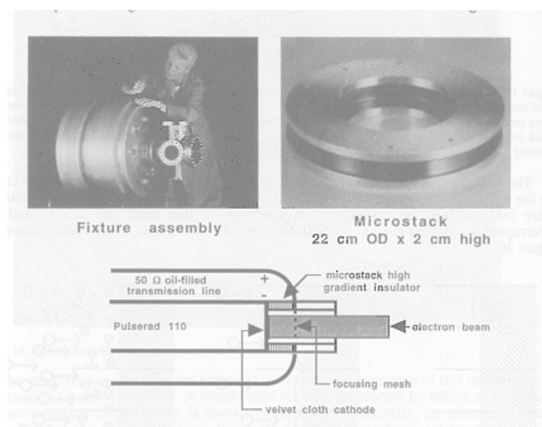


Short-pulse UV laser driven thermal/photo anode ion source

Dielectric Wall Accelerator ~20-30 MV/m

Ion-driven Target

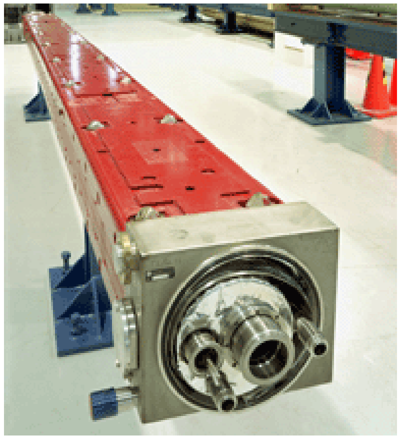




A 30 m-long, 600 MV Dielectric Wall linac might also be a high gradient buncher to compress RHIC or FAIR HI beams from 100 ns down to 100 ps for fast ignition experiments.

Retirement of large high energy accelerators may soon free up thousands of large superconducting magnets that could be reconfigured to do fusion-scale heavy ion target experiments cost-effectively. We need to re-engage the accelerator community.

The upcoming HIF accelerator workshop will enable us to explore options for target experiments relevant to ion-driven fast ignition.



→GSI plans a cryo-H_2 compression experiment using FAIR's 80 kJ, 100 ns, 200 GeV beam and a wobbler like slide 30.

Conclusion- heavy ion fusion offers an attractive option for inertial fusion energy.

- Heavy ion fusion can build on long-recognized HIF advantages of durability, efficiency, robust chamber/final focus, and merits expanded research.
- Existing facilities and NDCX-II can study beam compression and focusing relevant to HIF and HIDIX, cost-effectively.
- New unclassified-code capabilities for HIF target design should yield more robust targets for IFE, and should help attract world intellectual effort into HIF.
- Our proposed five year Phase I R&D is generic to all HIF target options; thus the choice of HIF target can be informed with data from Phase I, NIF, and Omega.
- We have opportunities to develop collaborations with the US and world accelerator community on technology development and on experiments to compression and focusing of beams to high peak power.

Backup Slides

A balanced HIF R&D portfolio to support the HIF roadmap requires :

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

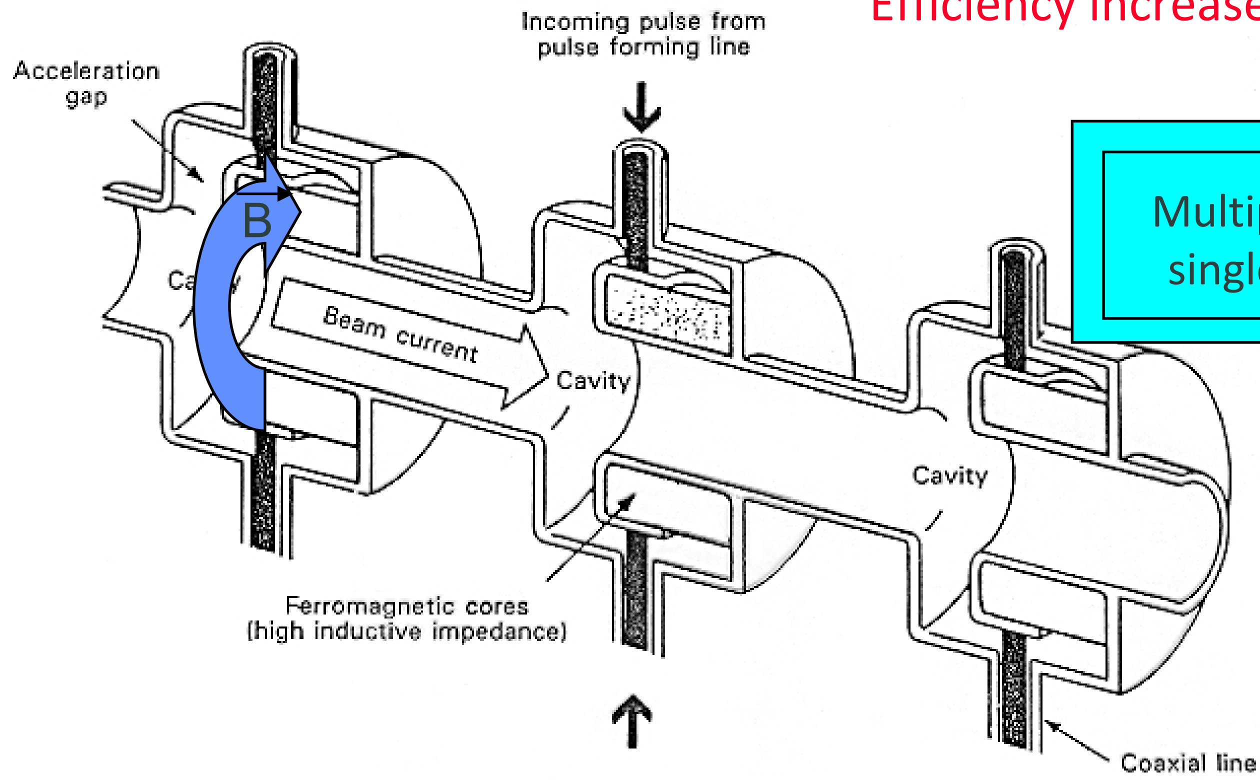
- Tritium breeding
- Radiation shielding
- Liquid protection

•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

->We seek a balanced near-term HIF program.

Induction acceleration efficiently accelerates high current beams



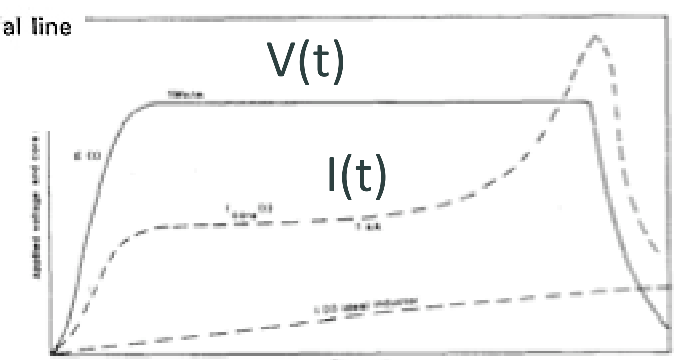
Schematic cutaway of an induction Linac

Efficiency increases as beam current increases

$\Downarrow$

Multiple beams within single induction core

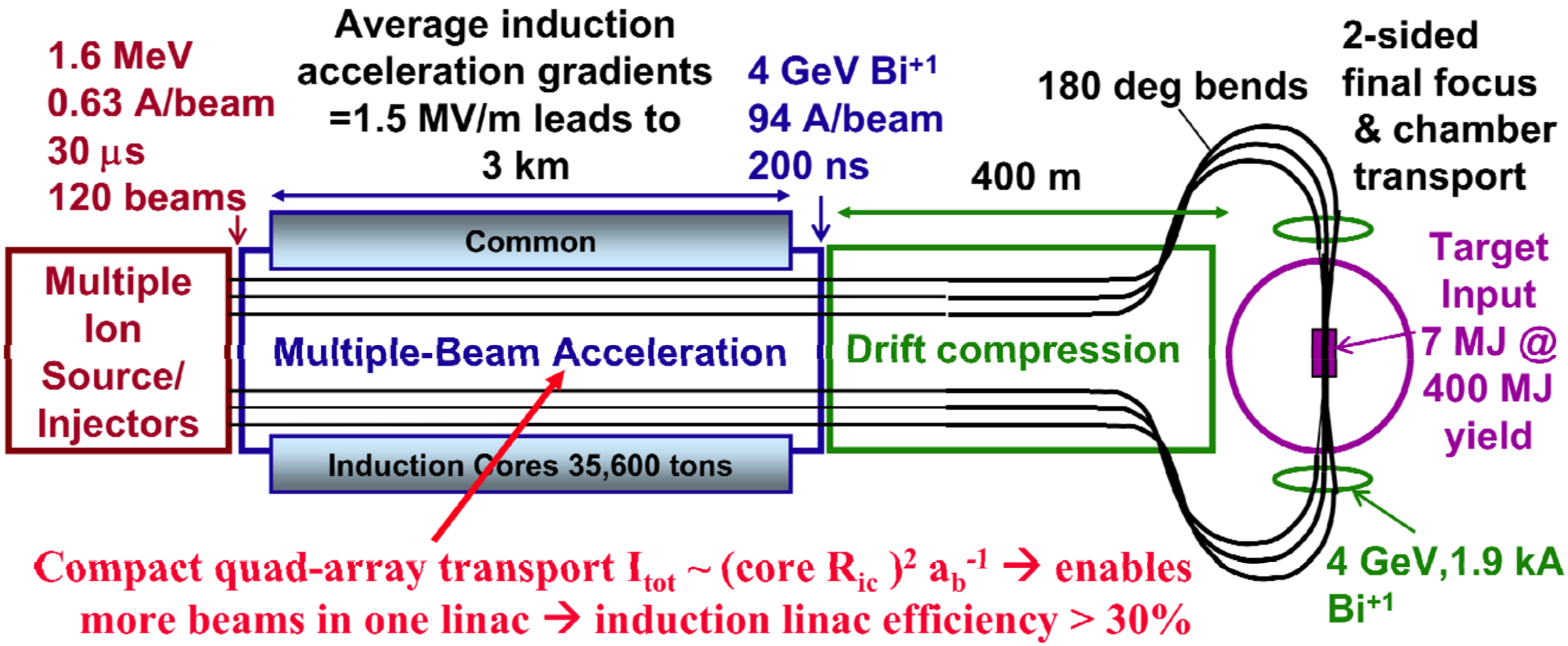
$$V = \frac{\Delta B \cdot area}{\tau}$$



Approximate Form of Core Excitation Current

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.)

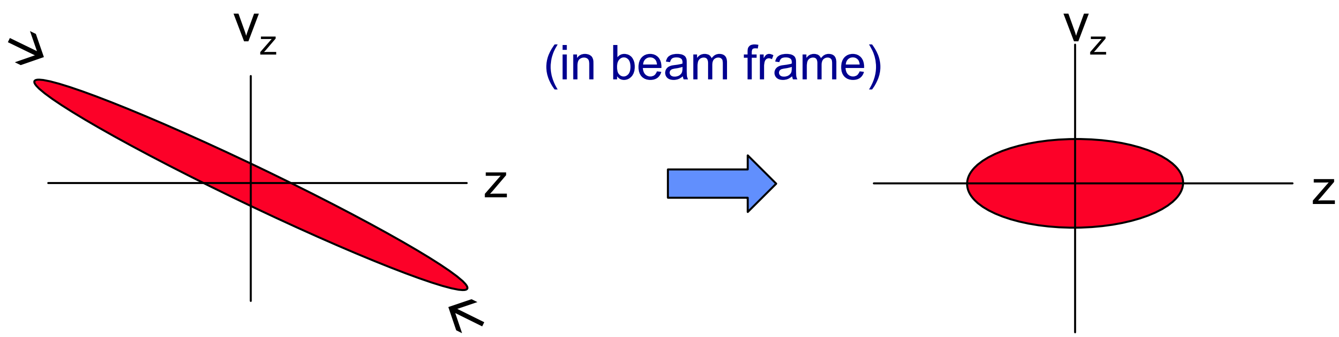


10th-of-a-kind cost 2.8 B$ (driver cost) estimated-see Ref. - S.S Yu, W.R. Meier et al., *Fusion Science and Technology*, **44**, No.2, 266 (2003).

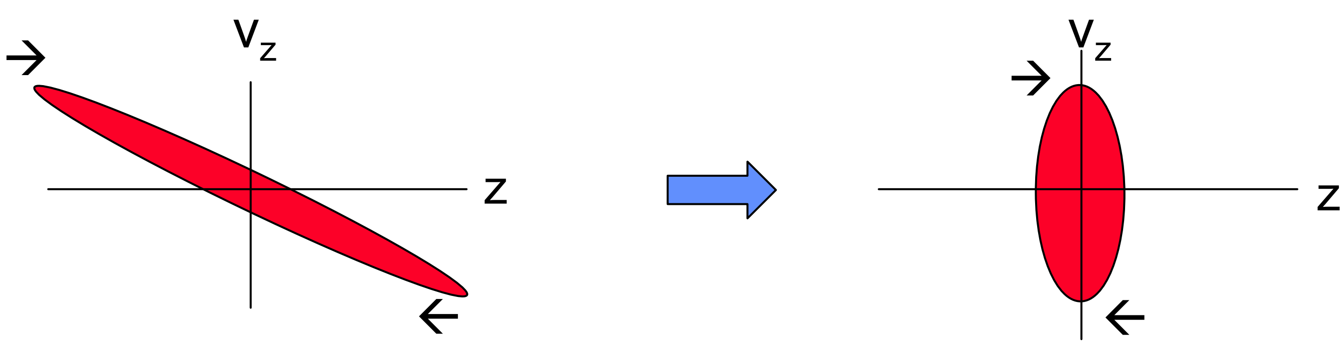
The drift compression process is used to shorten an ion bunch

- Induction cells impart a head-to-tail velocity gradient (“tilt”) to the beam
- The beam shortens as it “drifts” down the beam line

- In non-neutral drift compression, the space charge force opposes (“stagnates”) the inward flow, leading to a nearly mono-energetic compressed pulse:

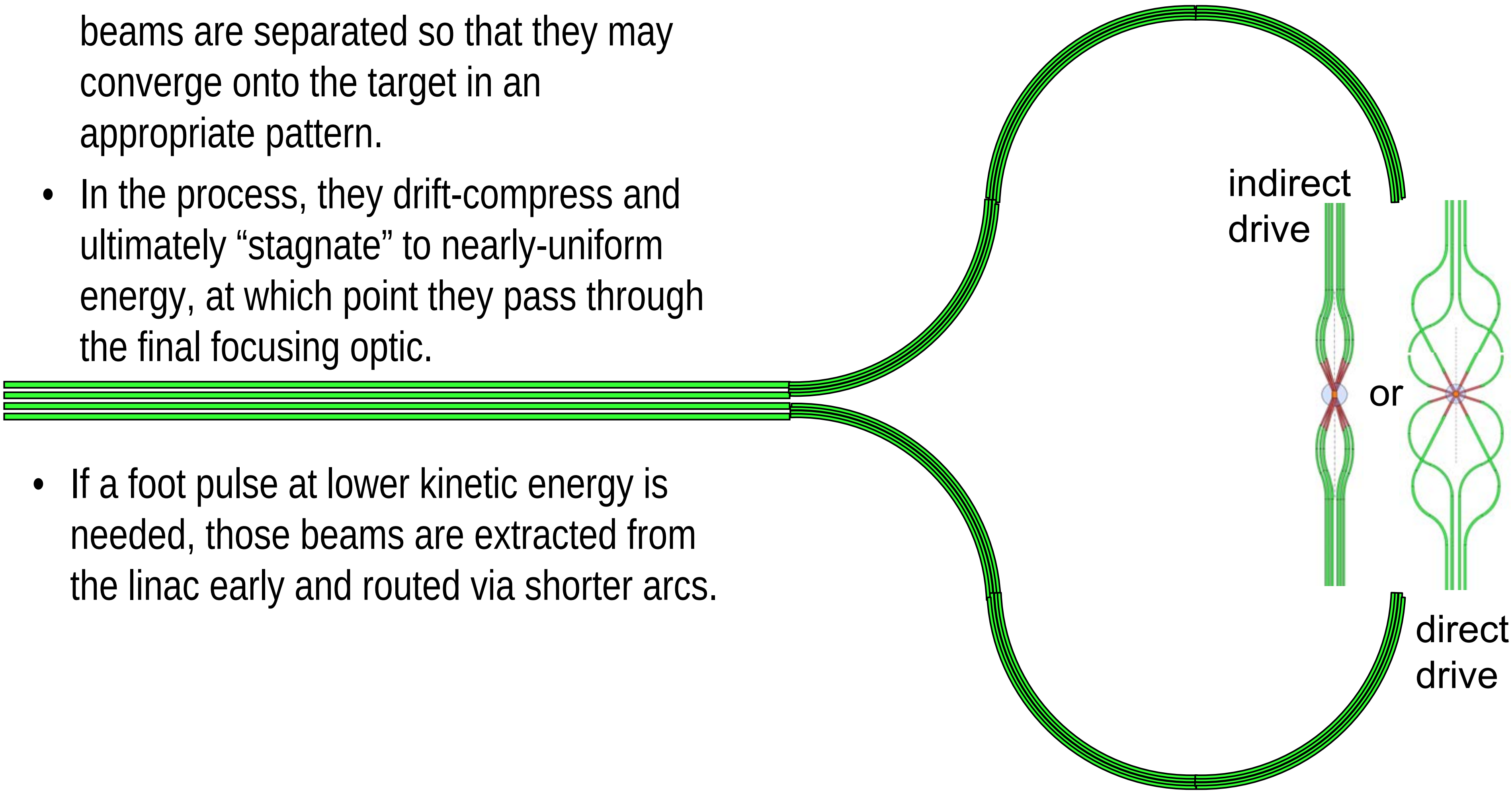


- In neutralized drift compression, the space charge force is eliminated, resulting in a shorter pulse but a larger velocity spread:



NDCX-II experiments can model the final sections of a driver

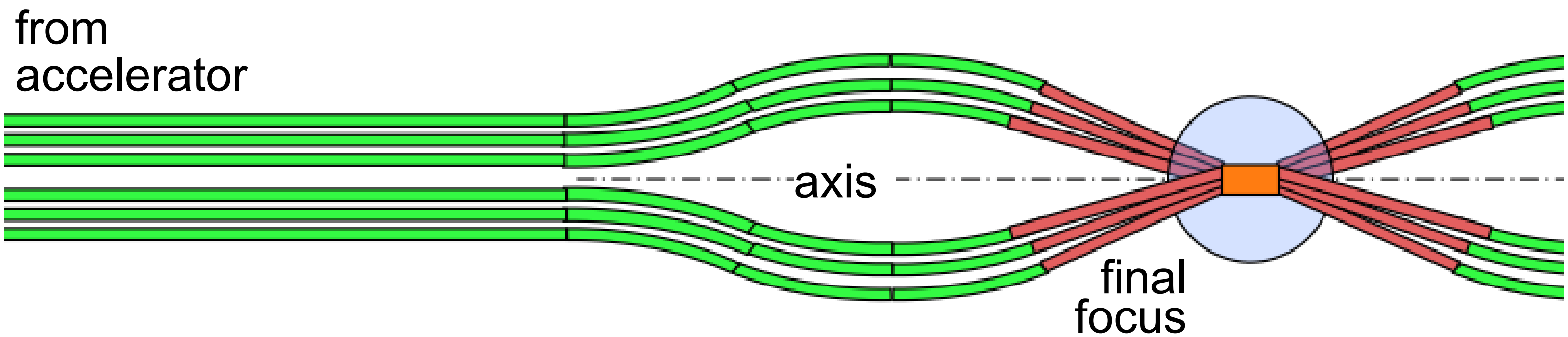
- In the final section of the driver, the beams are separated so that they may converge onto the target in an appropriate pattern.
- In the process, they drift-compress and ultimately "stagnate" to nearly-uniform energy, at which point they pass through the final focusing optic.



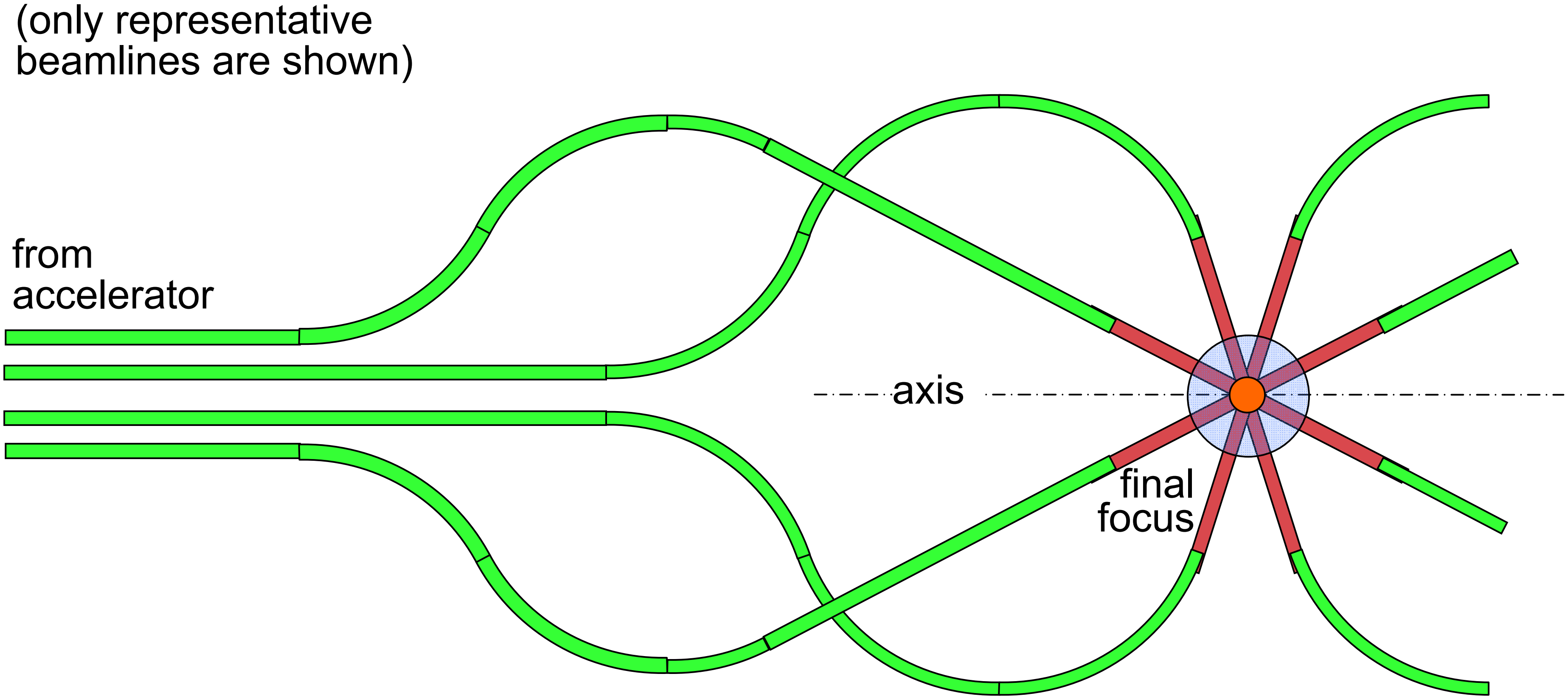
- If a foot pulse at lower kinetic energy is needed, those beams are extracted from the linac early and routed via shorter arcs.

Schematic of final beamlines for ion hohlraum drive

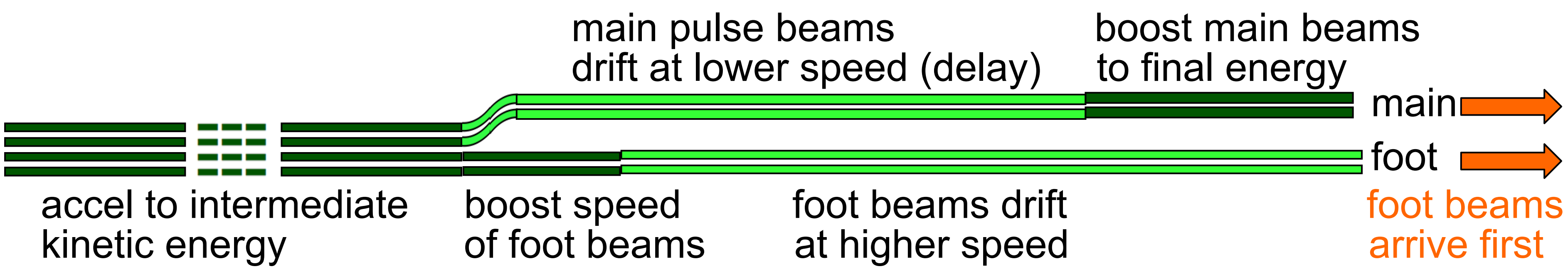
(only representative
beamlines are shown)



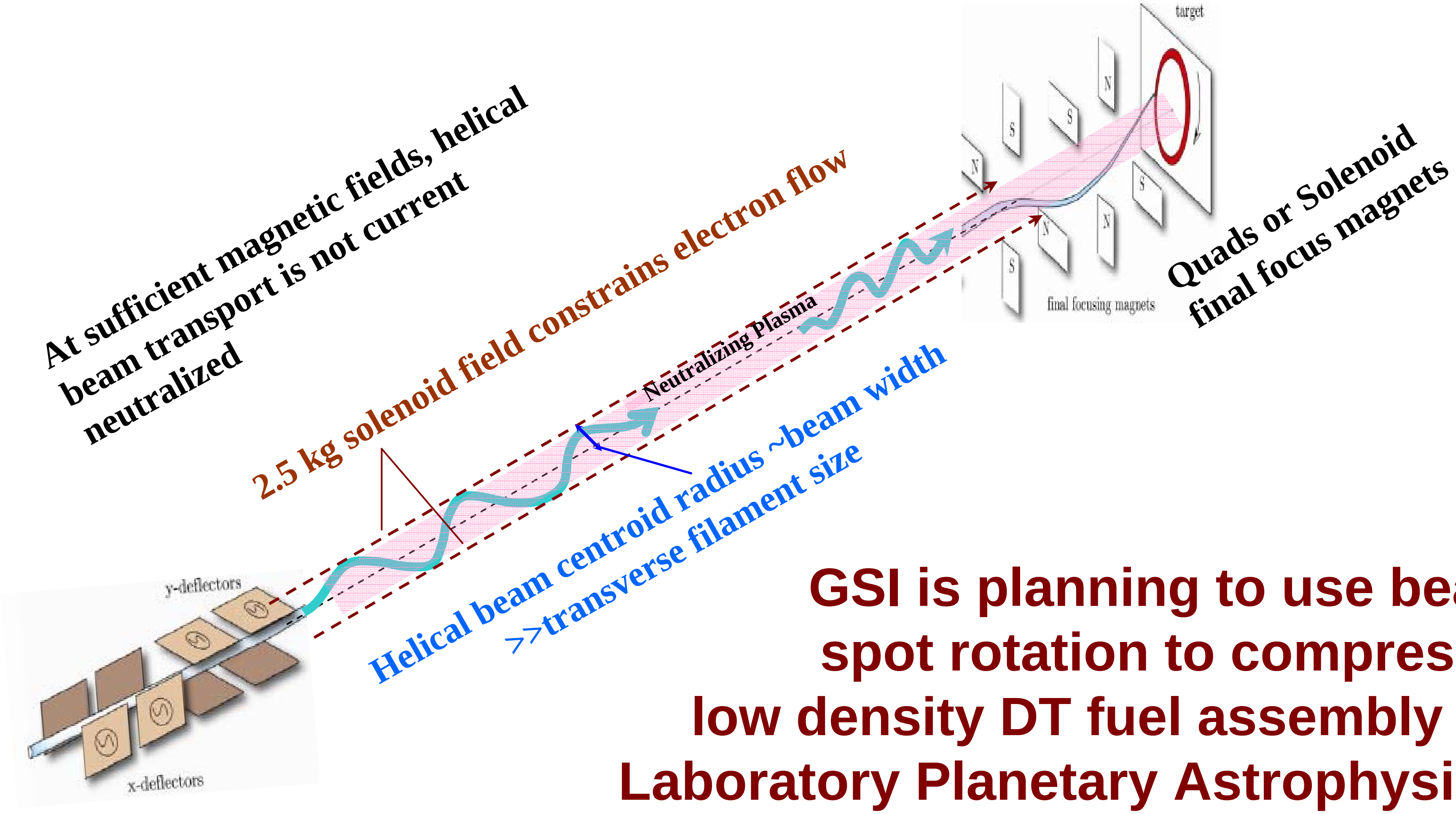
Schematic of final beamlines for ion direct drive



If two linacs are used, or for a single-sided target, delay between foot and main pulses can be inserted in a nearly linear system



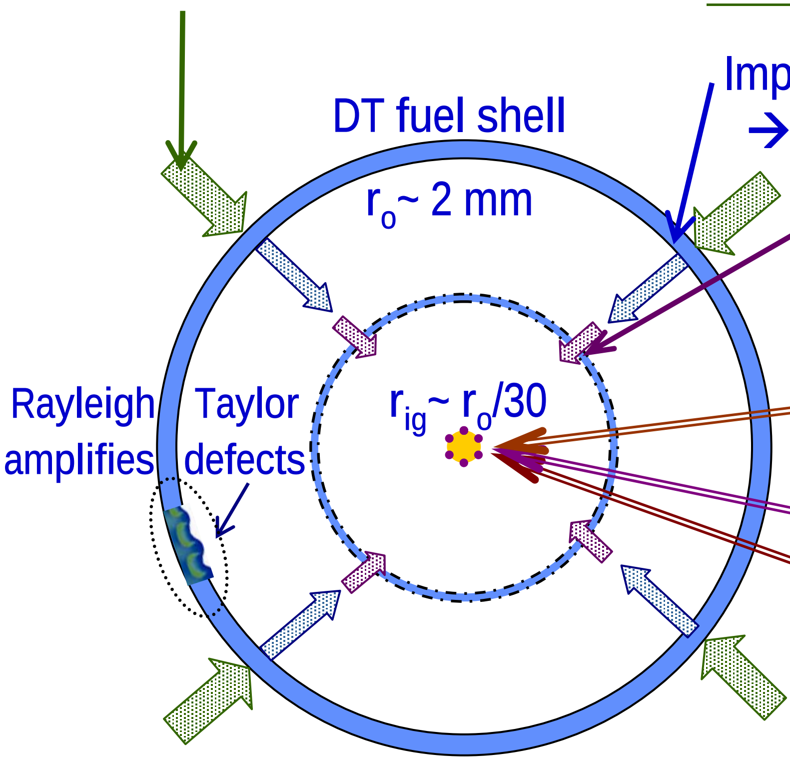
PPPL is exploring the use of *rotating helical beams on NDCX-II→IB-HEDPX, and effects on Weibel instabilities.*



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.

HIF target ignition requires petawatt power input. More target design is needed since target stability and accelerator risks are not congruent. NIF and Omega results next several years should inform our designs.

3 - 6 MJ / 300- 600 TW ion beam drive energy / power (direct or indirect), 10-20 ns.



Implosion / DT fuel shell KE ~ 5 to 20% of ion beam drive → ~100 to 200 kJ.

Optional 400 to 800 TW peak direct drive for 0.5 ns @ implosion midpoint can create Gbar shock which spherically converges to add~ 2 PW for ignition.

Spherical convergence amplifies shell $P\dot{V}$ rate in ~ 100 ps stagnation to ~ 2 PW → *hot-spot ignition,*

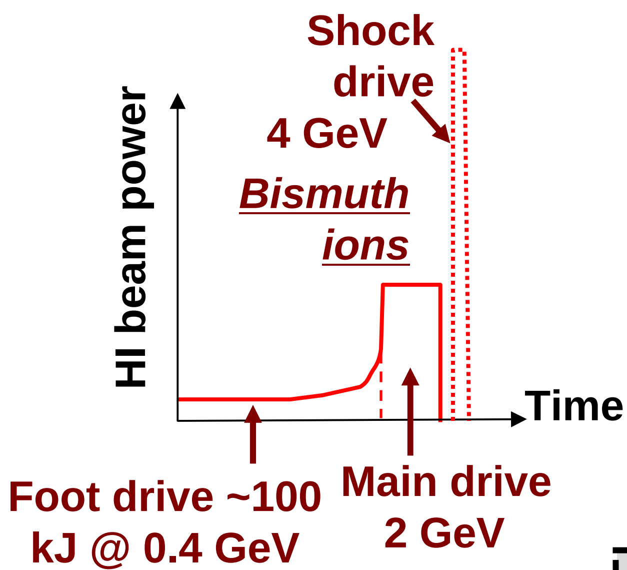
or, with ~2 PW converged shock →shock ignition,

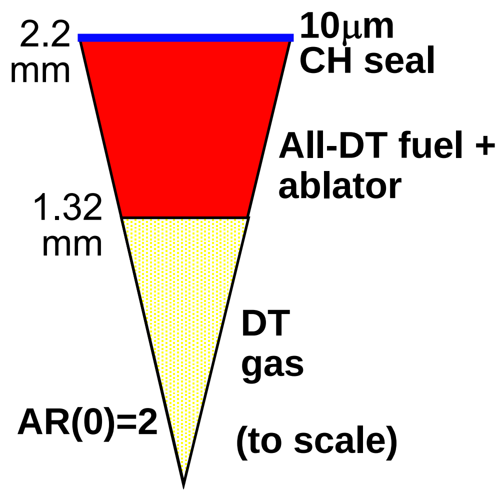
or, with ~2 PW direct electron or ion beam heating into r_o/30 spot →fast ignition in 20 ps (laser) to 100 ps (ion)

Ignition energy scaling: $E_{ig} \sim r_{ig}^3\, \rho_{DT}\, x10^9$ J/g ~ ρ_{DT}^{-2} @ $\rho_{DT} r_{ig}$ > 0.5 g/cm^2 @ 10 keV.

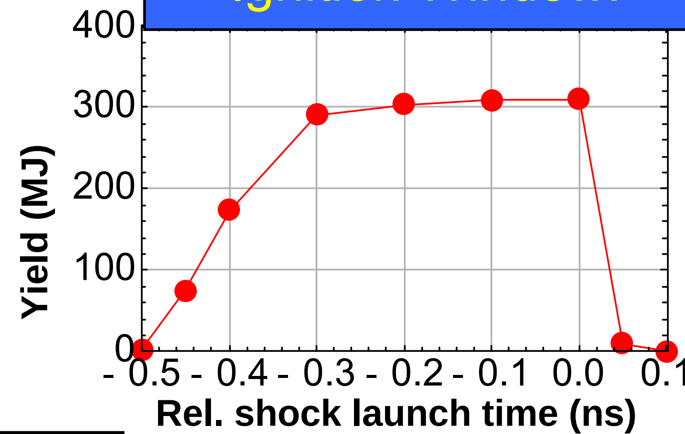
Risk tradeoff: High spherical convergence →amplifies shell final ρ, $P\dot{V}$→ reduces ignition energy but ..also *amplifies defects (Rayleigh-Taylor instability growth factors)→can quench ignition.* Shock and fast ignition →less convergence →more robust, but need *higher peak drive power*.

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)]





300-ps wide Shock Ignition Window!

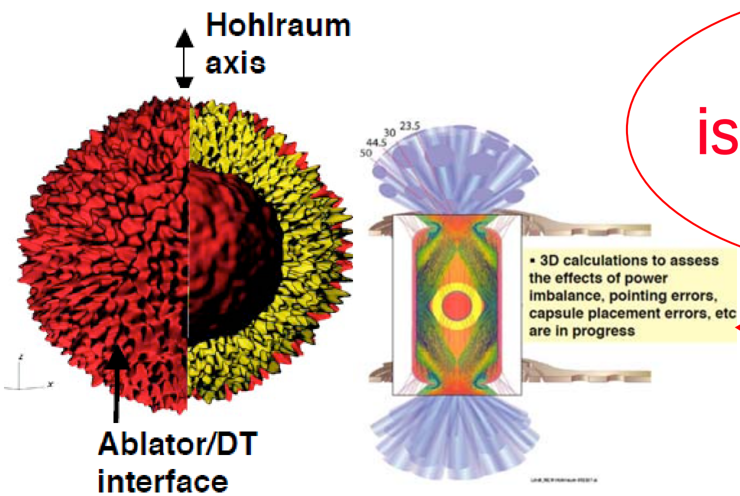


	Hotspot Ignition 1D	Shock Ignition 1D
Driver energy (MJ)	2.60	1.49 + 0.8 (sh)
Peak drive power (TW)	500	200 + 1250 (sh)
Yield (MJ) / Gain	317 / 122	310 / 136
Convergence ratio	28.4* (17.0**)	30.9* (18.5**)
In-flight aspect ratio	14.0	8.7

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 = $r_{shell\text{-}in}(0)/r_{HS}(t_{ign})$

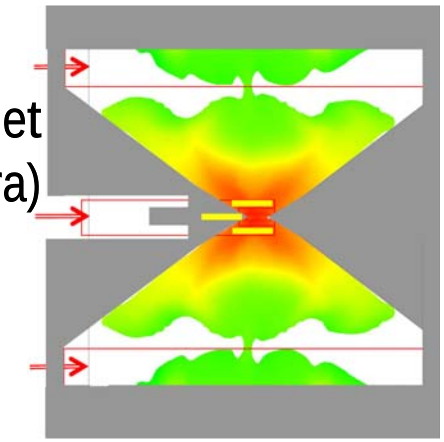
The X-target has different risks and R&D path for HIF

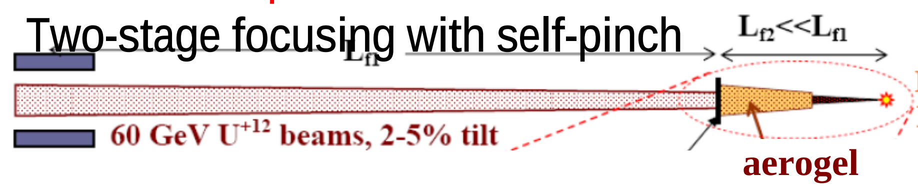


3-D HYDRA simulation of NIF hot spot

Different key issues→ different R&D paths!

X-target (2-D Hydra)

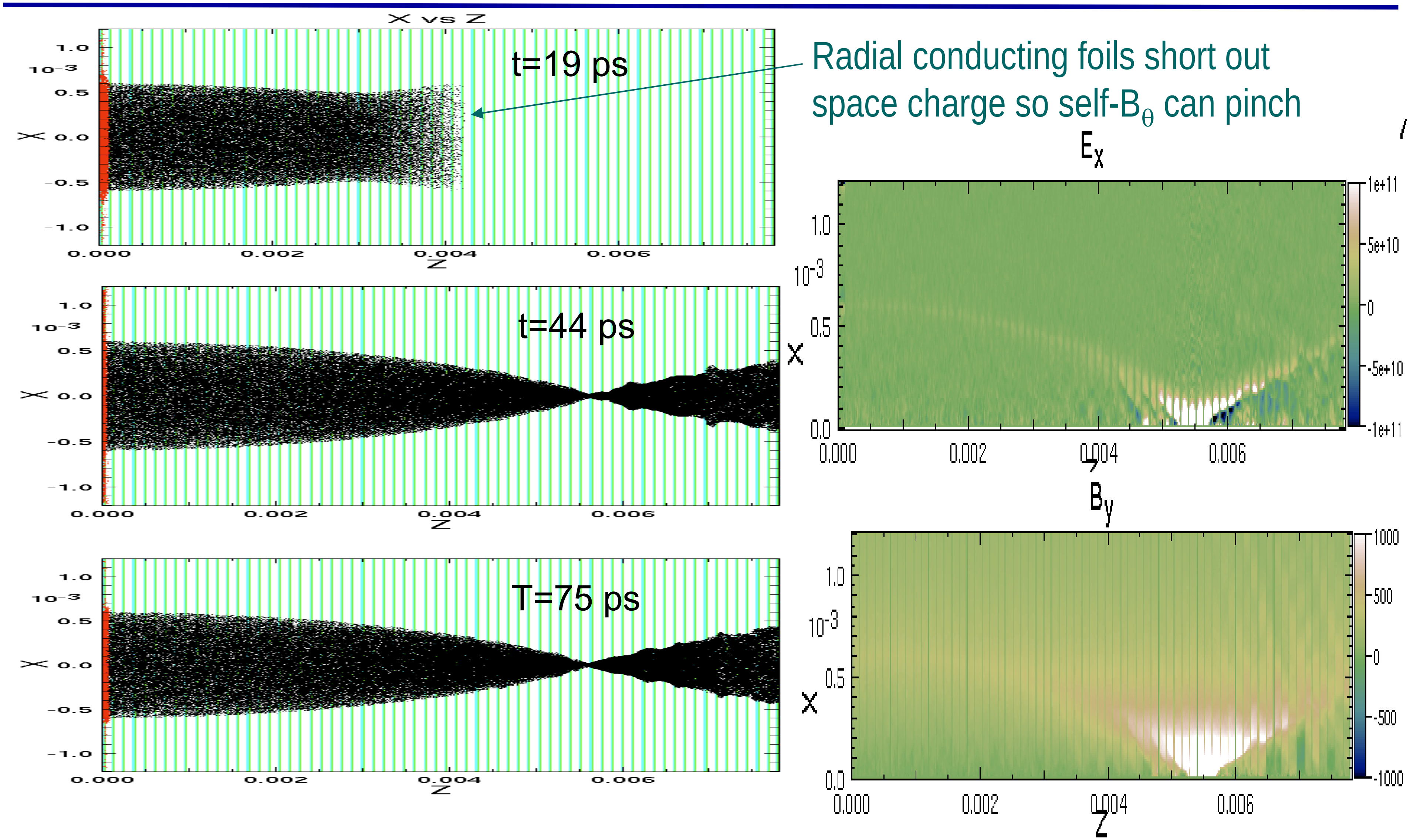




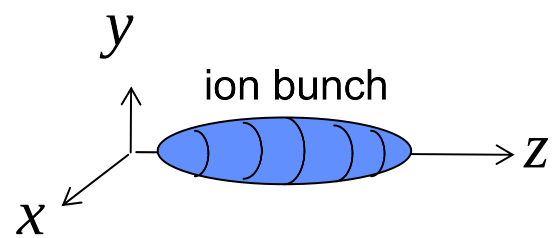
Any hot spot ignition for direct or indirect drive will need precision cryo beta layering, 100 nm-smooth capsules, precision time-dependent beam power and pointing control, RT-mix <0.5 r_{hs} → *A NIF- equivalent heavy-ion beam ignition test would be required to validate an HIF fusion test facility (ETF).*

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.

WARP simulations are making progress on self-pinching of heavy ion igniter beams. (R.H. Cohen, A. Friedman, D.P. Grote, J.L. Vay, Jan. 27,2011



For ion beams, the target imposes requirements on the 6D phase space density



The IFE target requires:

a minimum energy E,

a maximum radius r_{spot}

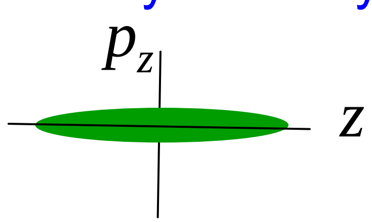
a maximum pulse duration Δt

a maximum momentum spread $\Delta p_z/p_z$ and angular spread $\Delta\theta_x$ and $\Delta\theta_y$

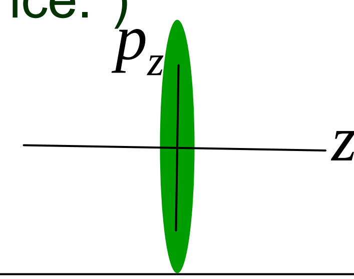
constrained to satisfy r_{spot} and Δt requirement.

Thus, there is an overall requirement on the average density in the 6D phase space, x, y, z, p_x, p_y, p_z.

Beam transport is governed by Hamilton's equations, so the *microscopic* phase density is exactly conserved. For transport systems that have nearly linear forces ($F_x \sim x, F_y \sim y, F_z \sim z$) , there is no differential rotation in phase space, so that the *average* phase space density is nearly conserved. (Area in 2D projection = "emittance.")



At injector, beam is long (and large radius) with little spread in momentum; At target, beam is short and small, with larger spread in momentum



Estimates of allowable emittance growth (due to imperfections in transport system) depend on specific target requirements

At injection, ion mass and charge, space charge limited flow, voltage breakdown limit, and diode optics limits, together with diode voltage determine initial phase space density.

Systems codes give good estimates of the initial phase space density at the injector (dN/dU_injector) and the final phase space requirement at the target (dN/dU_target), so the margin for errors can be determined.

	Rad. Drive (RPD) foot	Rad. Drive (RPD) main	Polar Direct Drive foot	Polar Direct Drive shock	X-target com-pressor	X-targ. igniter (ent. to 2^{nd} foc)
Pulse energy (MJ)	2.4	5.2	2	1	3	3
Ion mass (amu)/ ion energy (GeV)	209/ 3.3	209/ 4	201/ 3.5	201/ 3.5	85/ 13	85/ 13
Final pulse Δt (ns)	6.5	9.3	20	0.5	20	0.2
Final spot radius (mm)	1.7	1.9	1.9	2.2	0.45	3.1
(dN/dU_injector/ dN/dU_target)^(1/3)	2.6	3.8	5.2	2.1	4.6	4.5

Induction linear accelerators have operated at high current and high repetition rate

- **Astron – 0.8 kA, 60 Hz**
- **ATA – 10 kA, 5 Hz, 1 kHz (burst mode),**
- **SILUND-2 (former USSR) – 1 kA, 50 Hz**
- **DARHT-II – 2 kA, < 1 Hz**
- **These accelerated e$^-$**

- **Many RF proton and ion accelerators operate at a repetition rate exceeding HIF requirements, but at much lower current.**

Linear Accelerators: SNS, SLAC, LANCE,

Circular machines: Fermilab, RHIC, LHC.

Filling of synchrotrons and storage rings can take >> 1 second, but revolution frequency is fast.

Induction linacs should satisfy lifetime, availability, and reliability requirements*

Principal components:

•Induction cores – metallic glass tape wound into a core; experience at 10^8 pulses with no degradation; Possible effects of magnetorestrictive abrasion of insulation easily obtainable in short term experiment (e.g. 100 Hz for 1.5 years)

•Induction cavities – stainless steel and aluminum – no known limit

•Insulators – ceramics at voltage gaps – no known limit when operated well below breakdown thresholds

•Switches – thyratrons – lifetimes 10^9 to 10^{10} pulses according to manufacturers;

•Pulse forming networks – lumped and distributed elements; capacitors meet 10^9 to 10^{10} lifetime requirements from manufacturers

•Superconducting quadrupole magnets are DC and are used with the Tevatron, RHIC, and the LHC (for example)

•Ion source – continuously replenishible source a current subject of research

→Redundancy of cores, modulators, etc. essential in achieving reliability

*** Typical accelerator-based X-ray sources (ca 2002) have an availability of over 93 %; the average reliability of cryogenic facilities is higher than 99% [1]**

[1] L. Hardy, "Accelerator Reliability - Availability," Proc. EPAC 2002, http://accelconf.web.cern.ch/Accelconf/e02/PAPERS/WEXLA001.pdf

Accelerator reliability: The availability of high-repetition rate accelerators >90%.

- LCLS (commissioning, 2008-09) average availability: >92% ***Wienands, SLAC (2009)***
- Hardware availabilities of 70% - 90% have been reached at large energy frontier machines and as high as >98% at synchrotron light sources. ***S. Suhring, JLAB (2003)***

- SNS: reliability >90% ***Henderson, SNS (2007)***
- 1 MW, 1 GeV protons, 60 pps for 24 hours (2010), no interruptions.
- Tevatron: ≈1000 magnets installed. 6 failures during 2003-08. ***Dixon (2008)***

SNS Linac

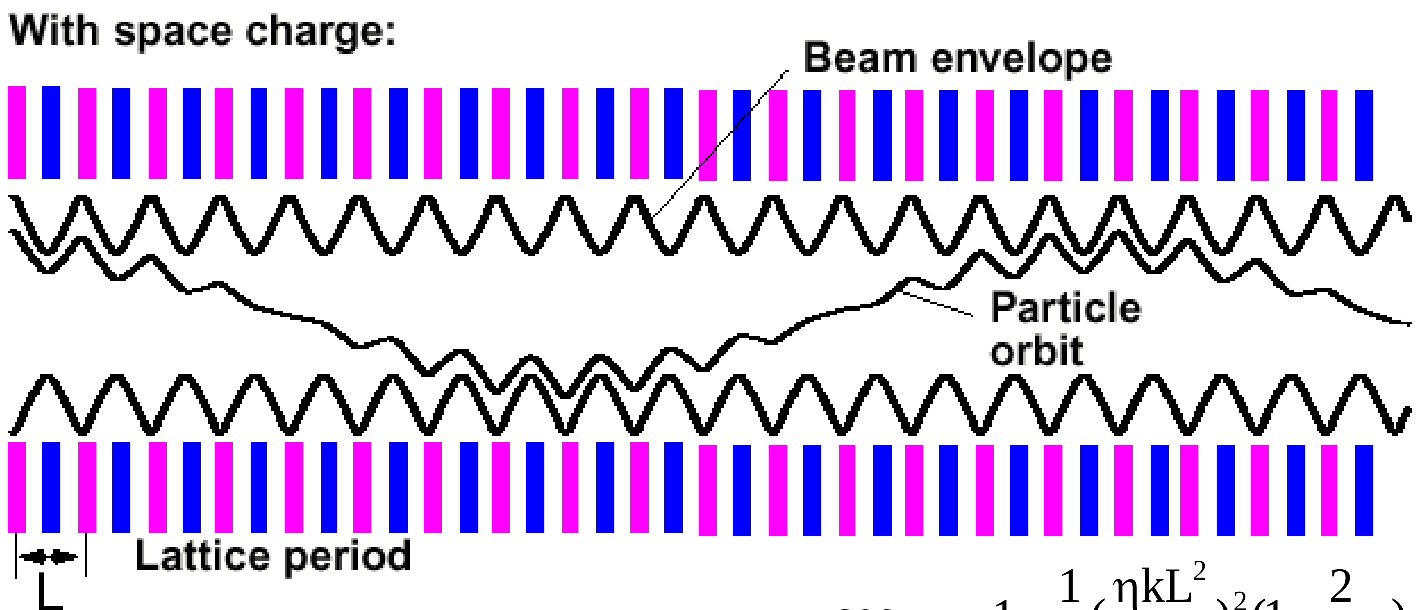
Except at the target, beam is space-charge dominated.
Depressed phase advance $\sigma << \sigma_o$. $\sigma \approx 0.1$ Unusual!

Transverse envelope

$$\mathbf{a}'' = -\mathbf{k}\mathbf{a} + \frac{\varepsilon^2}{\mathbf{a}^3} + \frac{2\mathbf{K}}{\mathbf{a}+\mathbf{b}} \qquad K \equiv \frac{q\lambda}{2\pi\varepsilon_0 m c^2 \beta^2 \gamma^3} \approx \frac{q\lambda}{4\pi\varepsilon_0 E_{kin}} \qquad k = \frac{qE'}{mv^2}, \quad \frac{qB'}{mv}$$

For HIF,

$$\frac{2\mathbf{K}}{\mathbf{a}+\mathbf{b}} >> \frac{\varepsilon^2}{\mathbf{a}^3}$$



$$\cos\sigma_o = 1 - \frac{1}{2}\left(\frac{\eta k L^2}{4}\right)^2\left(1 - \frac{2}{3}\eta\right)$$

$$K\left(\frac{2L}{2a}\right)^2 = 2(\cos\sigma - \cos\sigma_o)$$

For quadrupoles, $\sigma_o \leq 85^o$

longitudinal occupancy = η

Opportunities for R&D Using the PPPL 100 kV Test Stand

HEDLP solicitation proposal funding awarded to PPPL to use the versatile STS-100 equipment to perform VNL heavy-ion-beam research

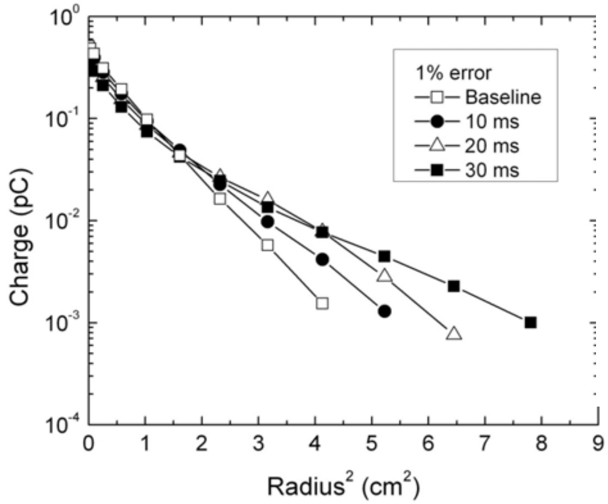
Research Topics:

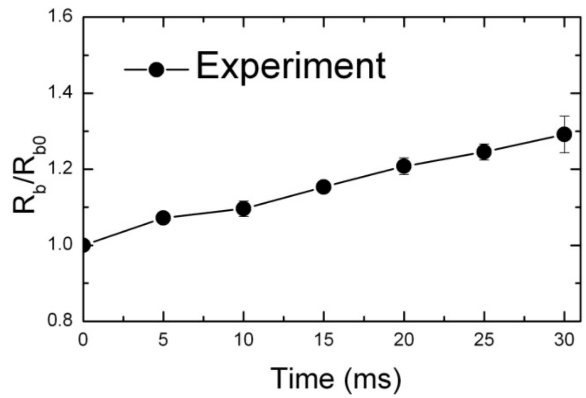
- Advanced plasma source development for NDCX-I and NDCX–II.
- Investigate plasma injection into multi-Tesla solenoidal magnetic field.
- Study negative and positive ion beams extracted from ion-ion plasmas.
- Perform advanced studies of short-pulse, high current density, ion extraction from aluminosilicate ion sources.
- Magnetic insulation.

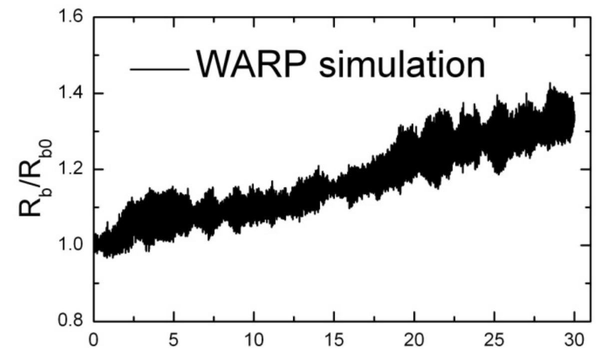
The STS-100 previously at LLNL.

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

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







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

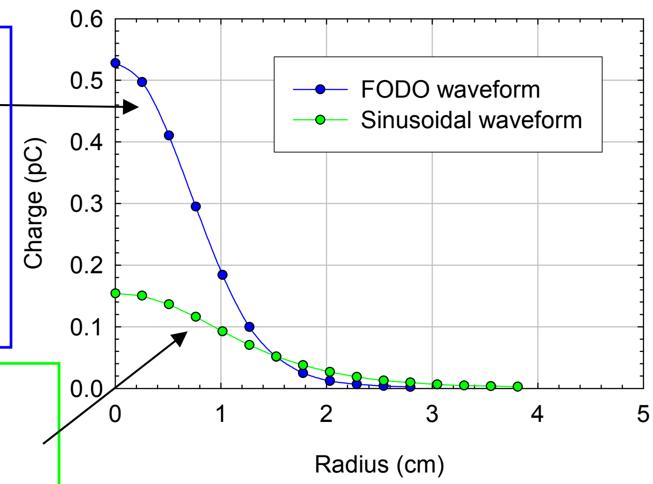
FODO

R_b = 1.0 cm

kT = 0.08 eV

s = 0.45

45% less emittance



Sinusoidal

R_b = 1.5 cm

kT = 0.17 eV

s = 0.16

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

s is the normalized intensity.

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

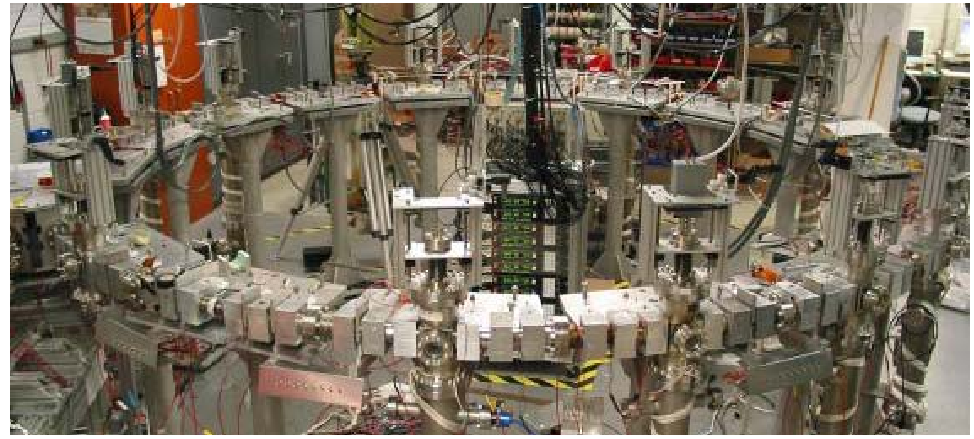
University of Maryland Electron Ring (UMER):
Scaled experiments using low-energy, high-current electron beams

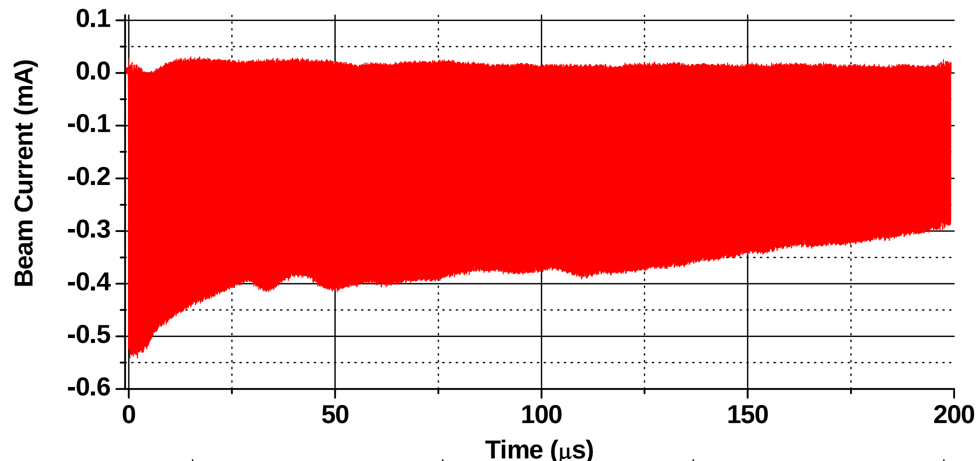
Goal: To demonstrate transport over long distance for intense beams of relevance to drivers for HIF and HEDP.

Status: Recently exceeded 1000 turns with longitudinal induction focusing

Ongoing Work:

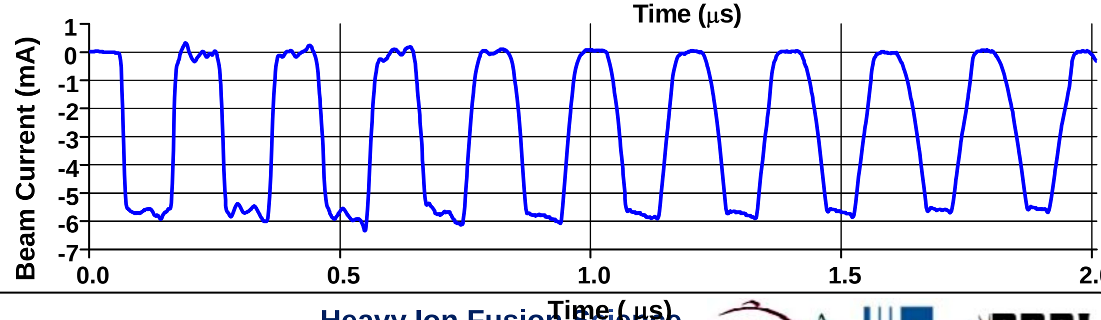
- Extending focusing to higher-current beams
- Designing acceleration stage
- Halo, emittance growth, and other topics





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

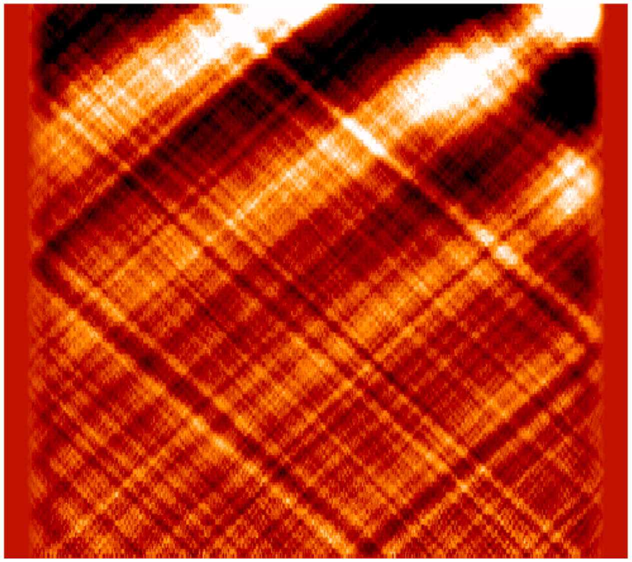
6 mA beam,
$k/k_o = 0.629$
10 - 100 Turns with ***no*** longitudinal focusing



Multiple beams in driver introduce significant new physics

- Transverse deflections arise from self-fields in accelerating gaps
  - Can shield transverse electric field via plates-with-holes
  - But plates allow cavity modes to develop; use wires (?)
  - Magnetic forces may be comparable for large N_{beams}
- Longitudinal waves obey $v_{wave} = 1/2\, g^{1/2} \omega_p (a_0 b_0)^{1/2}$; $g = 1/(4\pi\varepsilon_0)\log(r_w^2/a_0 b_0)$
- They can be driven unstable by module impedance ("resistive wall")
  - Convective growth, head-to-tail
  - Inductive field in multi-beam system slows space-charge waves on beams near center of cluster (destabilizing)
  - But spread in wave speed among beams is probably stabilizing
  - Also stabilize by capacitance, feedforward
  - May have to avoid $g < 0$ on any beam

observing station



time in beam frame

Considerations for a scaled multi-beam experiment using electrons

- Goal would be to explore transverse deflections & wave propagation in a regime where magnetic and inductive effects are significant
- UMER is 10 kV (β = 0.2), 100 mA, a ~ 0.5 cm, 32 cm LP, 40 ns = 2.4 m, 36 LP's total; could go up to β = 0.4 w/ upgrade
- Magnetic forces are down from electric forces by β^2 but are not shielded by plates-with-holes; so are comparable when $N\beta^2 \sim 1$
- This implies need for ~12 to 25 UMER beams
- Waves propagate ~ 1 beam diameter / period; could shorten beam, so to propagate ~ 1 m would require ~ 3x UMER length
- Vacuum of 10^{-8} needed to avoid poisoning K $\Rightarrow$ challenging pumping
- Resolving 10 cm wavelength (~ tip?) implies that diagnostics need ~ 2ns time resolution
- Crude cost estimate; if UMER was ~ \$3M, then cost might be:

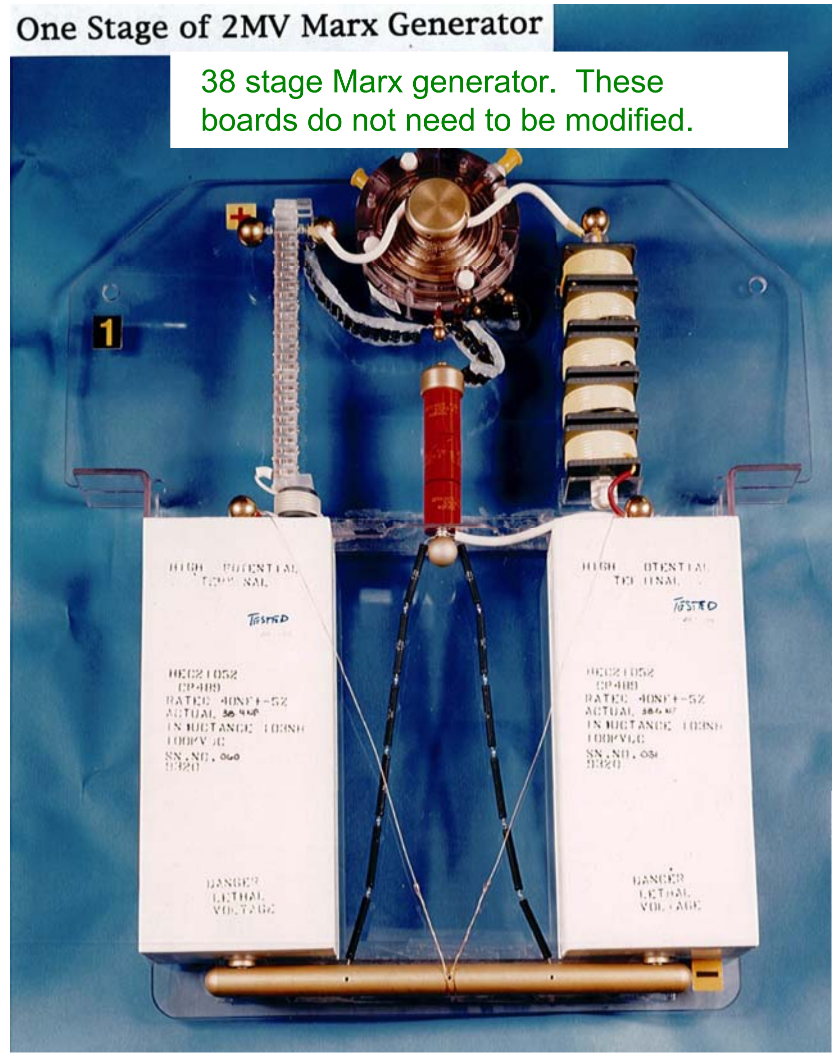
  \$3M x (15 beams) x (multibeam savings 1/3) x (length factor 3)

  $\Rightarrow$ \$45M with very large error bars

Most accelerators operate at a repetition rate exceeding HIF requirements, but at much lower current.

- **Experiments at 5-10 Hz are needed to explore gas buildup, beam-gas collisions, electron clouds, and to develop techniques to maintain low emittance.**

- **With modifications,**
- **HCX is capable of doing such experiments.**



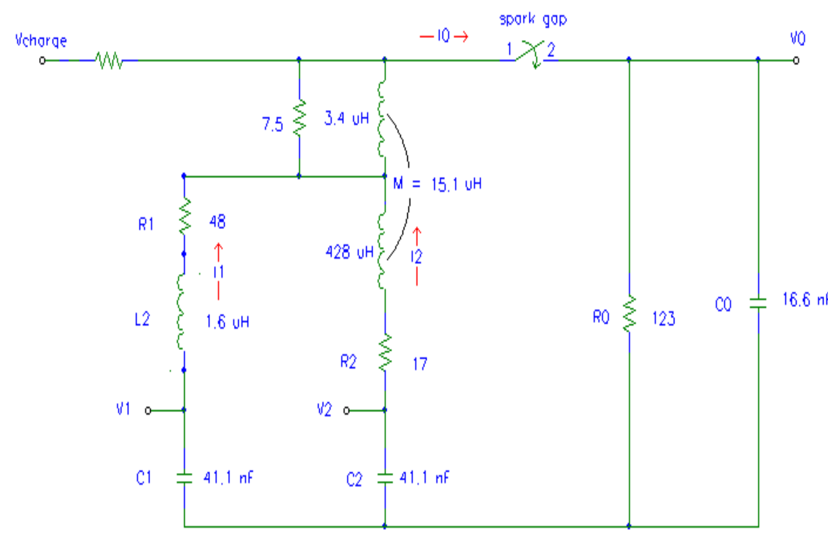
38 stage Marx generator. These boards do not need to be modified.

Modification of HCX injector for 5 Hz operation

•Acquire two charging power supplies; eg Glassman 8 kW, 270 mA peak.

•**(PS/SH030P270: $17.25k)**

•Reduce $R_{charging}$ → x Ω



Charging path resistors are low enough, heating is acceptable, the power supply is adequately protected.

Technology goals for a HIDIX accelerator

- Multiple-beam arrays (≤ $10/kA•m)
- Cast insulators (≤ $0.01/V)
- Ferromagnetic materials ($5-10/kg)
- Pulsers (≤ 10-5 $/W, ≤ $20/J)

Symposium on Accelerators for America's Future, Oct 26-28. 2010

Chairs: **Walter Henning, Argonne Distinguished Fellow, ANL and Charles Shank, Director, LBNL (Retired)**

Purpose: **…examine the challenges for developing and deploying accelerators to meet the nation's needs in:**

- **Discovery Science**
- **Medicine and Biology**
- **Energy and Environment:**
  - **ADS (SCRF, FFAGs), HIF, HTS, Terahertz-to-Infrared light source (algal fuel R&D)**
- **National Security**
- **Industrial Applications and Production**

Goals:

- **identify needs of stakeholders**
- **seek crosscutting challenges…**
- **identify the areas of accelerator R&D that hold greatest promise**
- **provide guidance to bridge the gap between basic accelerator research and technology deployment**

Accelerator physicists from a variety of areas of expertise have expressed interest…

Ingo Hofmann	(GSI, Frankfurt U.) High current and intensity beam dynamics
R. Garnett	(LANL) – RF and induction accelerators
G. Sabbi	(LBNL) superconducting magnet arrays for HIF
B. Sharkov	(GSI, FAIR Scientific Director) Heavy ion fusic

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.

Registered office: Darmstadt

Darmstadt, November 11th, 2010

Boris Y. Sharkov
FAIR Scientific Director

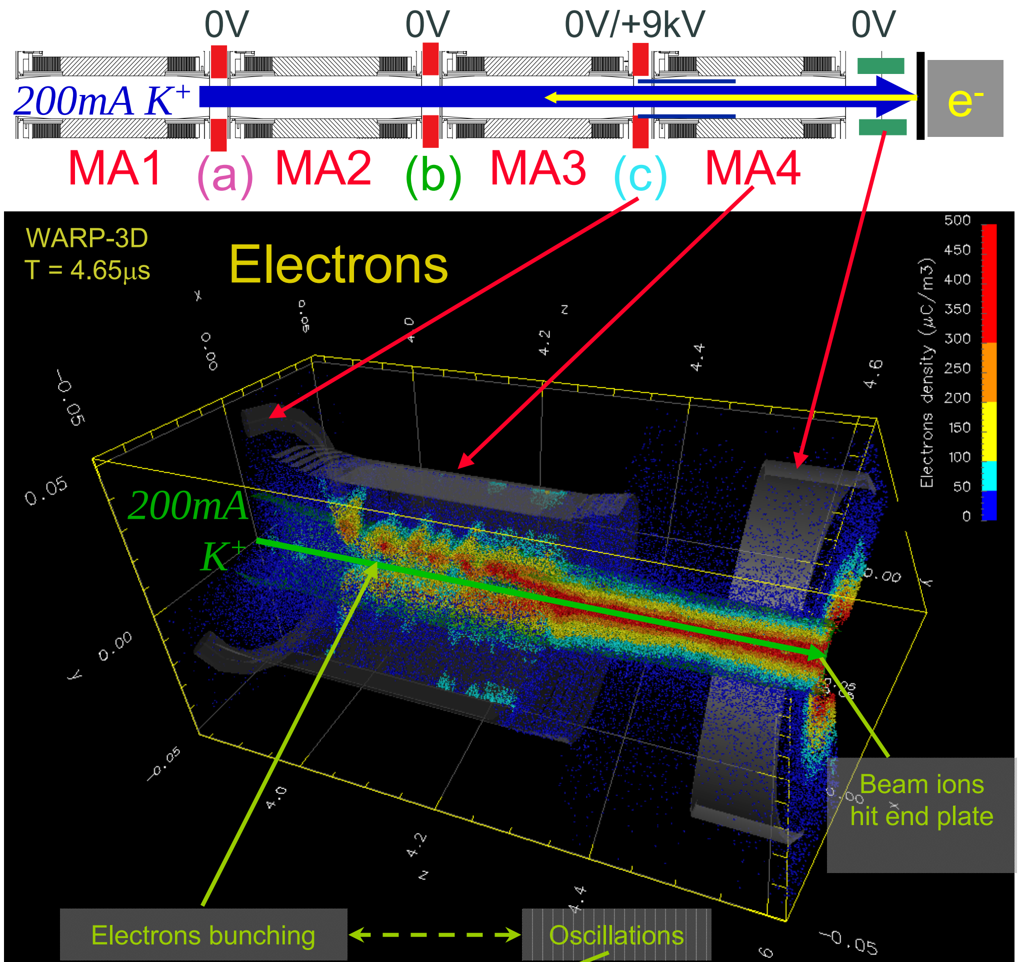
Darmstadt, November 11th, 2010

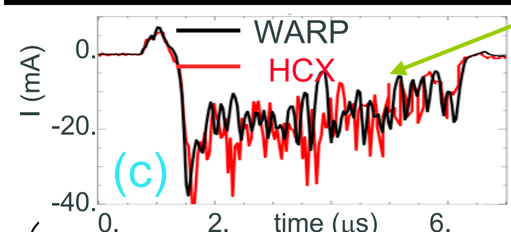
B. Grant Logan

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

- DOE HEP, **General Acc**
- DOE NP, **Assoc. Director of Science for Nuclear Physics, Tim Hallman**
- & seeking participation from CERN, FNAL , BNL, SNL…

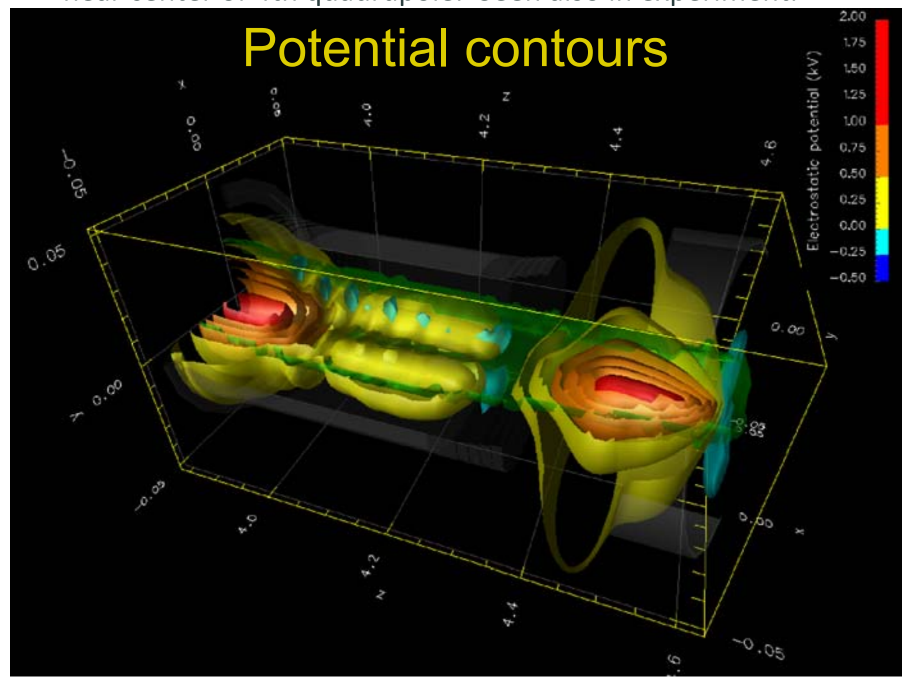
3-D Particle simulations modeling interaction of secondary electrons with intense ion beams in HCX were very successful.



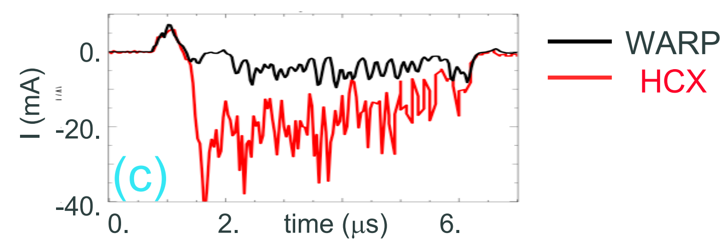


~6 MHz signal in (C) in simulation AND experiment

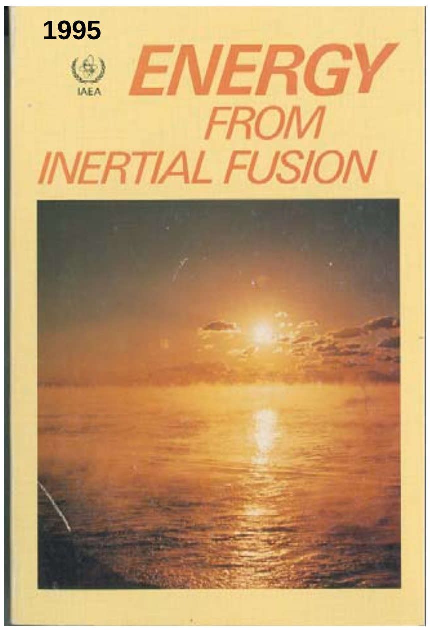
Simulation discovered oscillation (λ~5 cm) growing from near center of 4th quadrupole. Seen also in experiment.



1. Good test of secondary module - no secondary electrons:



Heavy ion targets typically expect to produce ~100 MJ of hot target plasma and soft-x-rays →requires first wall protection. Beams can propagate through the vapor pressure of hot liquid-protected chamber walls (pre-ionization can actually help beam focusing)→ *We seek methods to create and clear liquid layers at 5 Hz that are thick enough to attenuate neutrons for 30-yr wall life.*



Chapter 3.4: Reaction Chamber Systems, page 200 (Kulcinski, et. al.,)

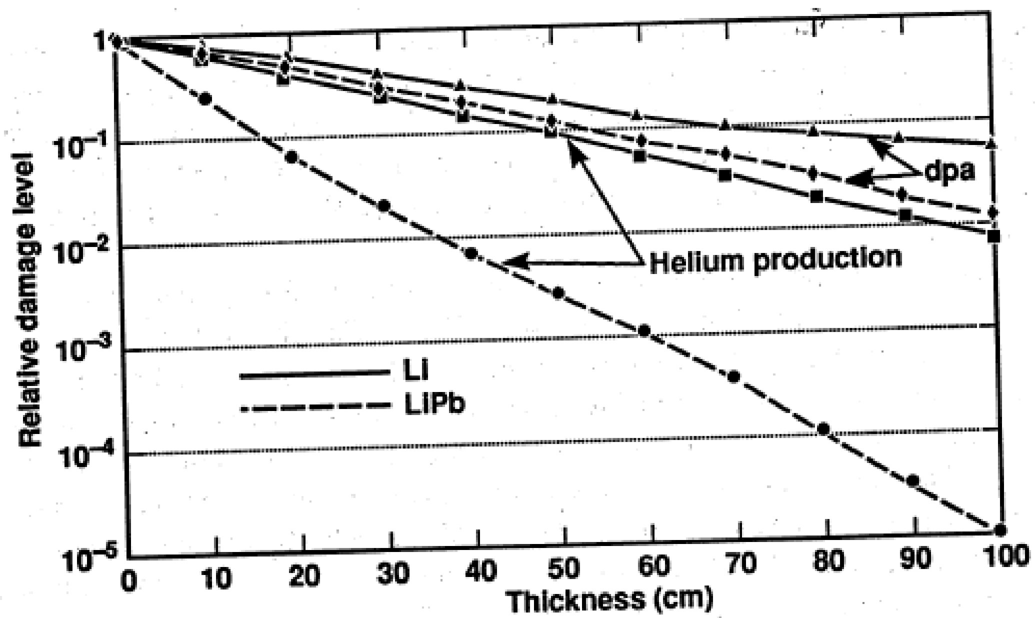
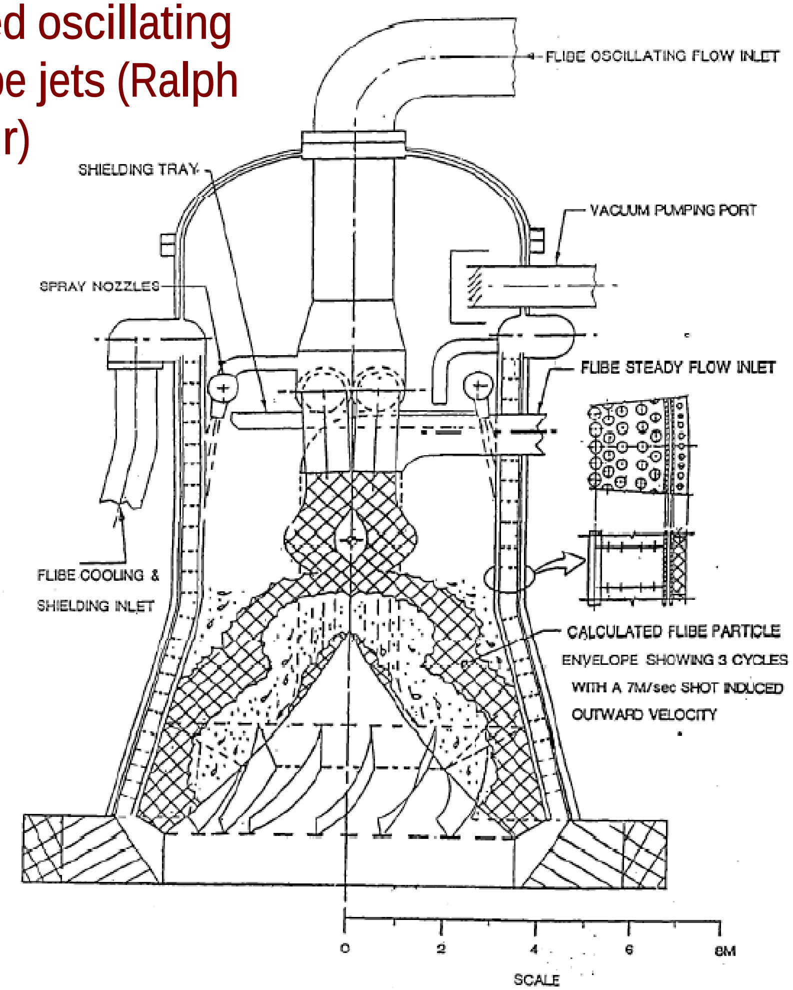


FIG. 3.4.8. The use of lithium, LiPb alloys or other lithium bearing materials between the IFE target and the first structural wall can significantly reduce the radiation damage and prolong the useful life of IFE reactor materials.

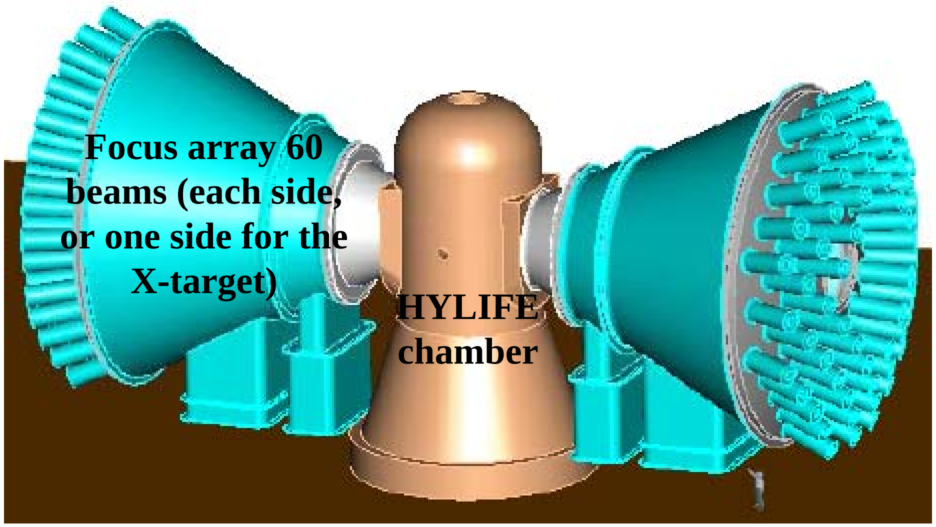
The HIF program can't contribute expertise to develop 200-dpa first wall materials, *but the program could restart hydro-equivalent water jet experiments cost-effectively.*

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.

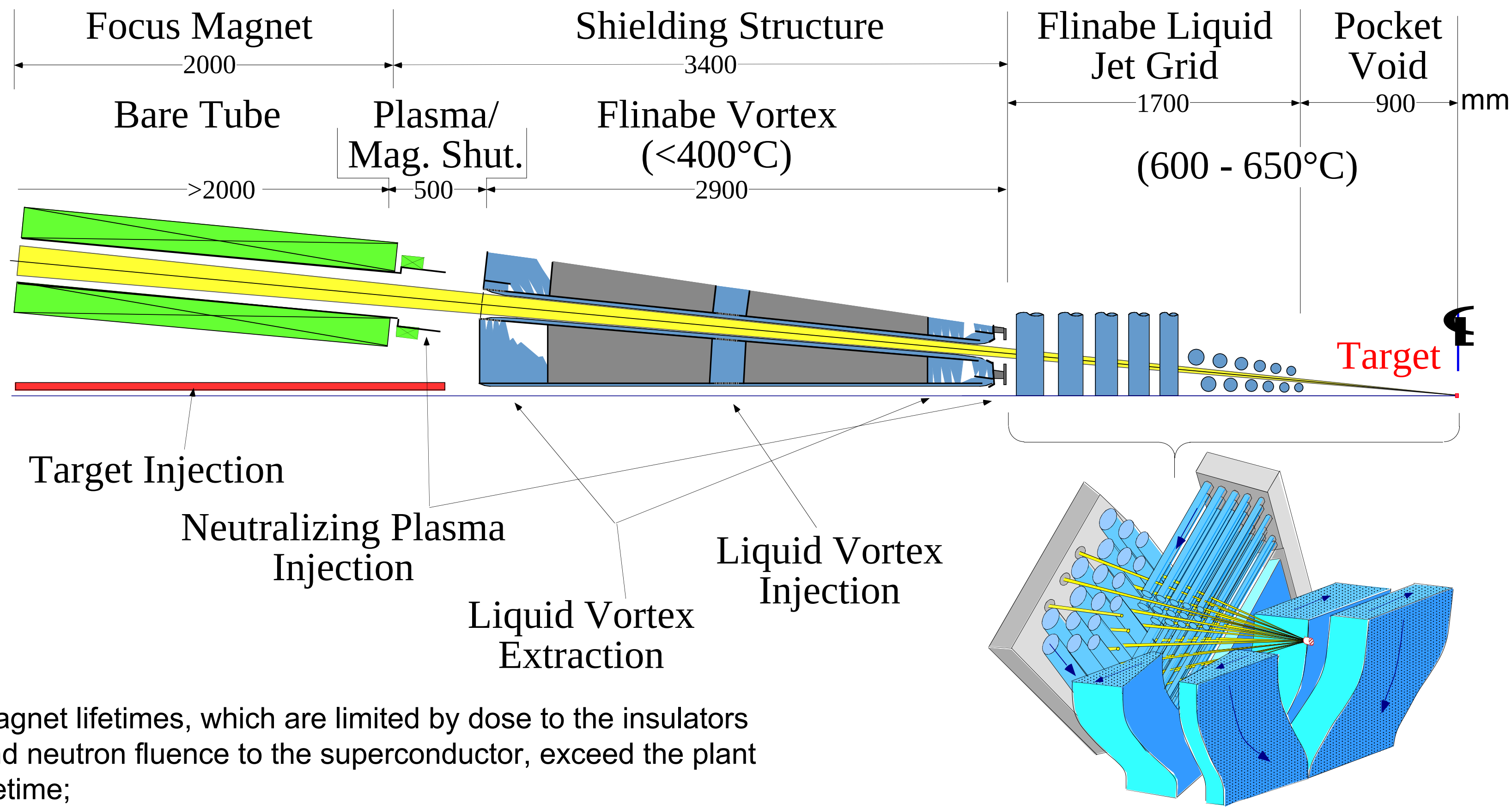
HYLIFE-II chamber used oscillating Flibe jets (Ralph Moir)



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



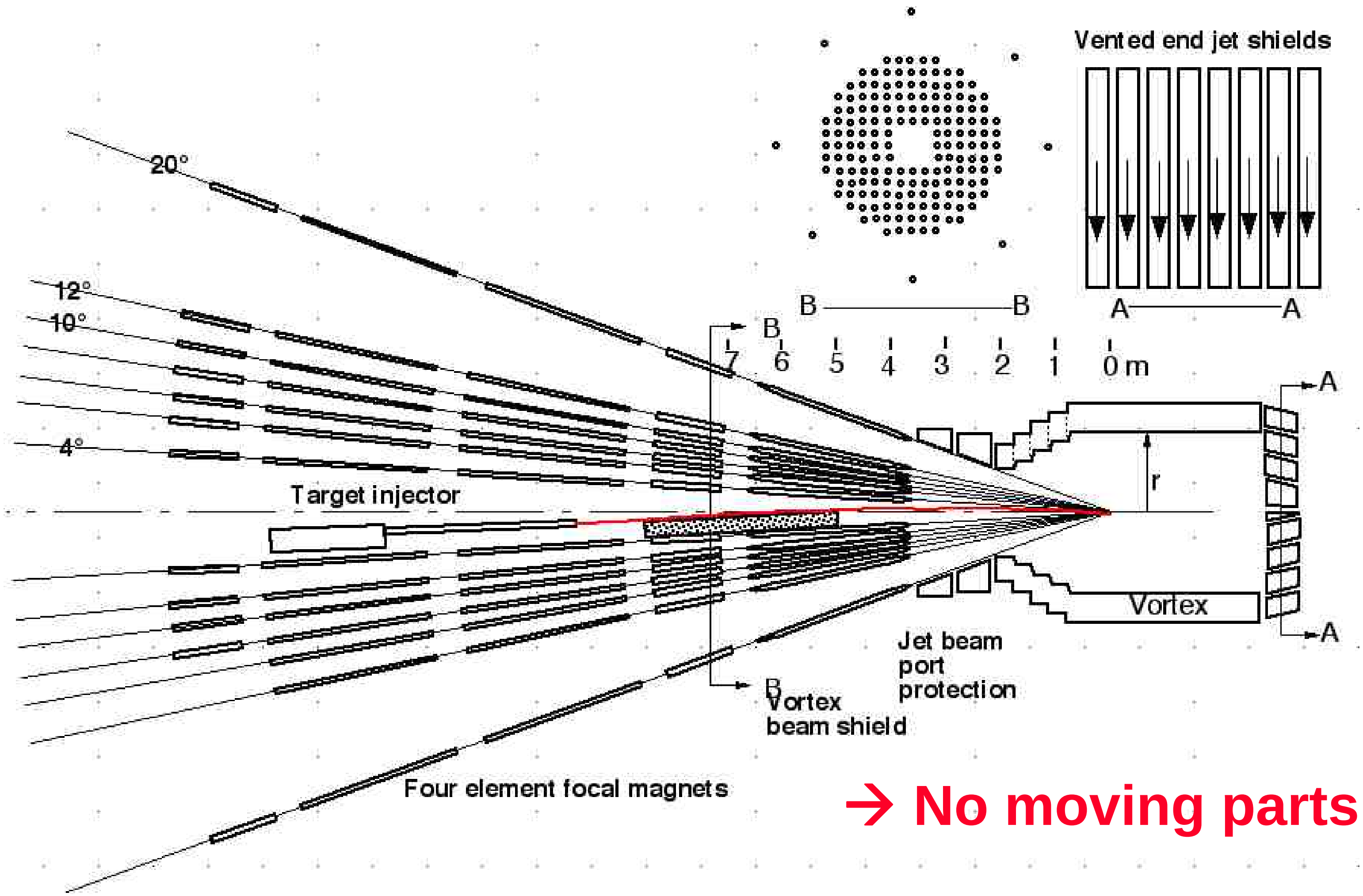
Design beam line for HIF illustrates liquid wall protection



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
3rd magnet: 100/610

Liquid jets and a vortex chamber protect solid structures for the life of the plant (R. Moir Dec. 6, 2010, for single sided targets)

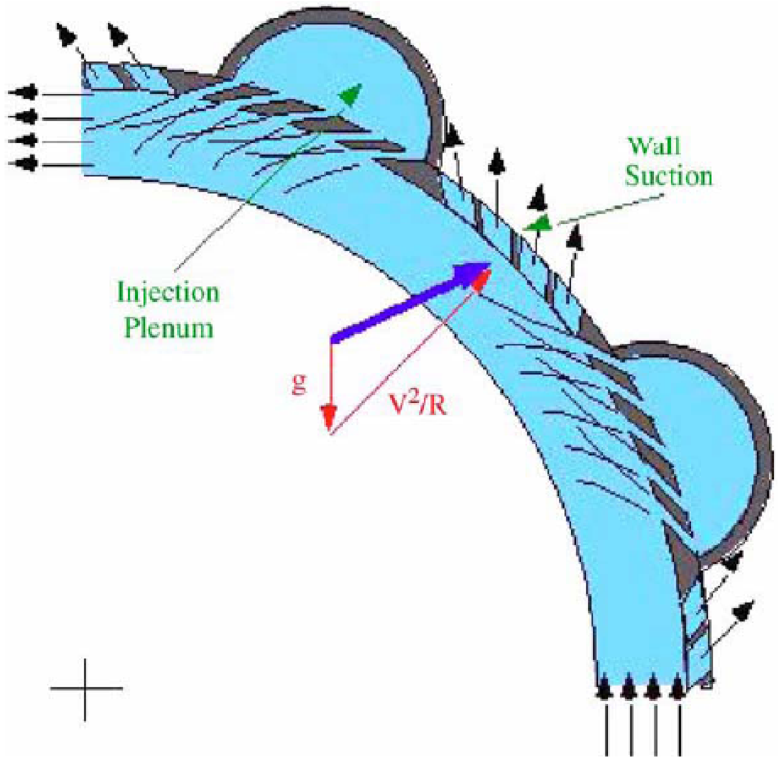


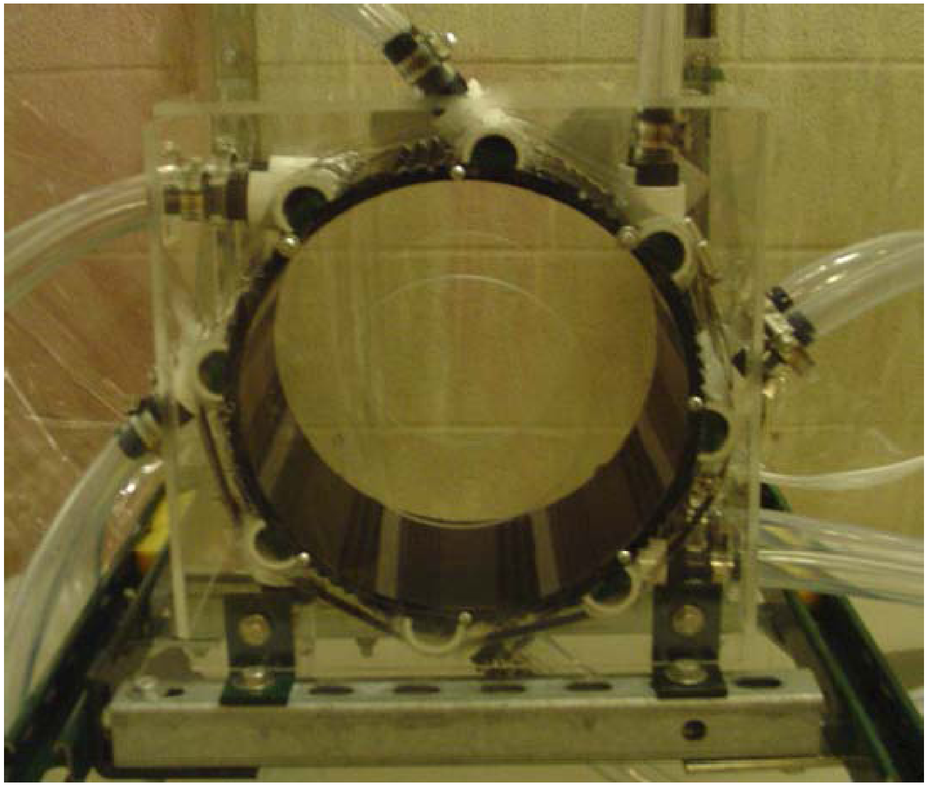
→ No moving parts!

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)

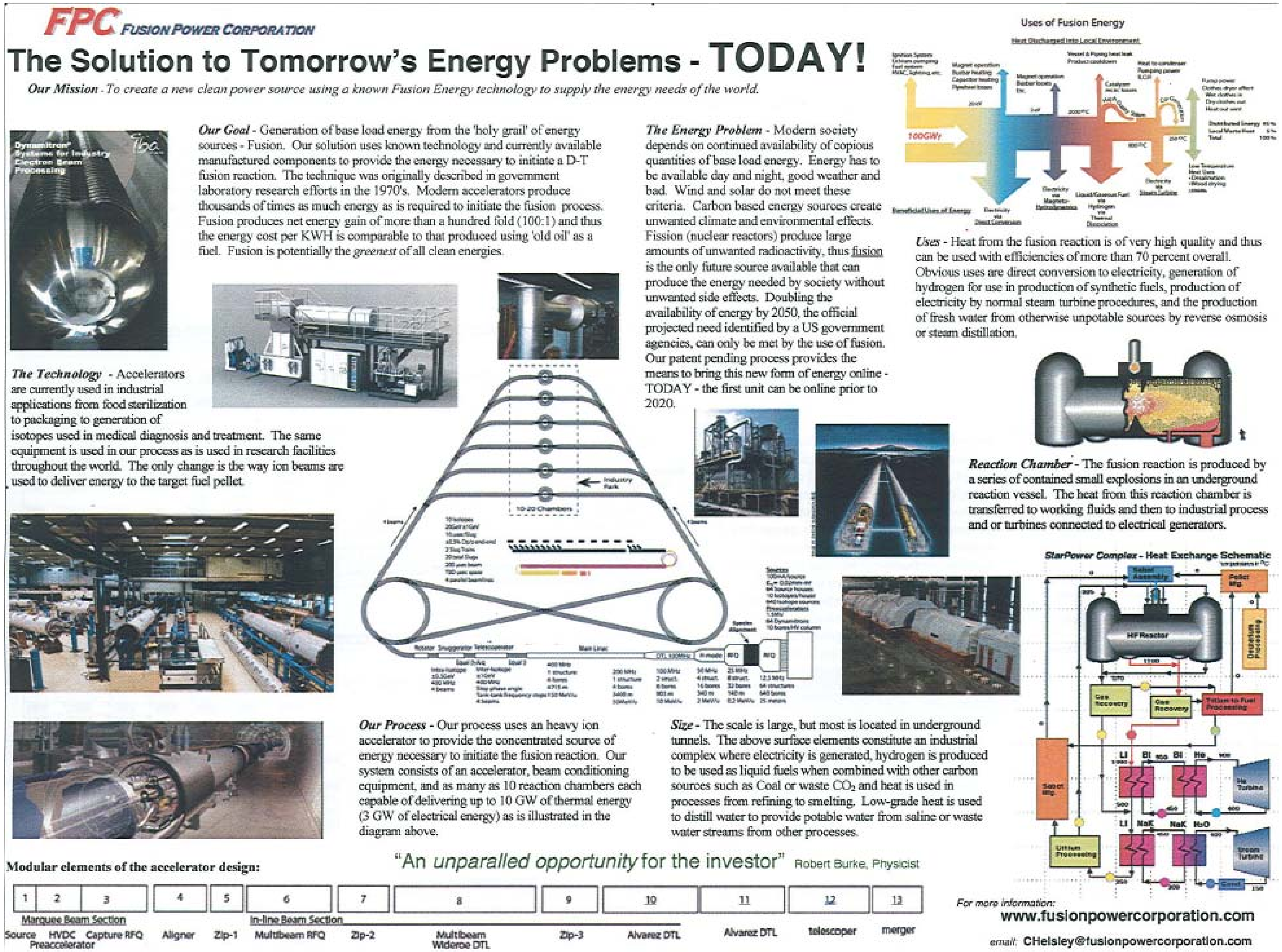
UC Berkeley worked on modeling and experiments in support of vortex chamber concept





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

Robert Burke has advocated exploiting the economy-of-scale for very large heavy ion drivers (20 MJ), multiple chambers → 30 GW_e



FPC FUSION POWER CORPORATION

The Solution to Tomorrow's Energy Problems - TODAY!

Our Mission - To create a new clean power source using a known Fusion Energy technology to supply the energy needs of the world.

Our Goal - Generation of base load energy from the 'holy grail' of energy sources - Fusion. Our solution uses known technology and currently available manufactured components to provide the energy necessary to initiate a D-T fusion reaction. The technique was originally described in government laboratory research efforts in the 1970's. Modern accelerators produce thousands of times as much energy as is required to initiate the fusion process. Fusion produces net energy gain of more than a hundred fold (100:1) and thus the energy cost per KWH is comparable to that produced using 'old oil' as a fuel. Fusion is potentially the *greenest* of all clean energies.

The Technology - Accelerators are currently used in industrial applications from food sterilization to packaging to generation of isotopes used in medical diagnosis and treatment. The same equipment is used in our process as is used in research facilities throughout the world. The only change is the way ion beams are used to deliver energy to the target fuel pellet.

The Energy Problem - Modern society depends on continued availability of copious quantities of base load energy. Energy has to be available day and night, good weather and bad. Wind and solar do not meet these criteria. Carbon based energy sources create unwanted climate and environmental effects. Fission (nuclear reactors) produce large amounts of unwanted radioactivity, thus fusion is the only future source available that can produce the energy needed by society without unwanted side effects. Doubling the availability of energy by 2050, the official projected need identified by a US government agencies, can only be met by the use of fusion. Our patent pending process provides the means to bring this new form of energy online - TODAY - the first unit can be online prior to 2020.

Uses of Fusion Energy

Uses - Heat from the fusion reaction is of very high quality and thus can be used with efficiencies of more than 70 percent overall. Obvious uses are direct conversion to electricity, generation of hydrogen for use in production of synthetic fuels, production of electricity by normal steam turbine procedures, and the production of fresh water from otherwise unpotable sources by reverse osmosis or steam distillation.

Reaction Chamber - The fusion reaction is produced by a series of contained small explosions in an underground reaction vessel. The heat from this reaction chamber is transferred to working fluids and then to industrial process and or turbines connected to electrical generators.

StarPower Complex - Heat Exchange Schematic

Our Process - Our process uses an heavy ion accelerator to provide the concentrated source of energy necessary to initiate the fusion reaction. Our system consists of an accelerator, beam conditioning equipment, and as many as 10 reaction chambers each capable of delivering up to 10 GW of thermal energy (3 GW of electrical energy) as is illustrated in the diagram above.

Size - The scale is large, but most is located in underground tunnels. The above surface elements constitute an industrial complex where electricity is generated, hydrogen is produced to be used as liquid fuels when combined with other carbon sources such as Coal or waste CO_2 and heat is used in processes from refining to smelting. Low-grade heat is used to distill water to provide potable water from saline or waste water streams from other processes.

"An *unparalled opportunity* for the investor" Robert Burke, Physicist

Modular elements of the accelerator design:

1, 2, 3 — Marquee Beam Section: Source, HVDC Preaccelerator, Capture RFQ; 4 Aligner; 5 Zip-1; 6 In-line Beam Section: Multibeam RFQ; 7 Zip-2; 8 Multibeam Wideroe DTL; 9 Zip-3; 10 Alvarez DTL; 11 Alvarez DTL; 12 telescoper; 13 merger

For more information:
www.fusionpowercorporation.com
email: CHelsley@fusionpowercorporation.com

HIFS-VNL budgets ($M as spent) by lab and by year

FY	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
LBNL	5.0	5.6	5.6	5.7	6.0	5.4	4.7	4.7	4.7	4.6
LLNL	4.5	3.6	3.3	3.2	2.7	2.5	2.1	2.1	2.1	2.1
PPPL	1.1	1.1	1.2	1.2	1.6	1.1	0.9	1.0	1.0	1.0
Total VNL	10.6	10.3	10.1	10.1	10.3	9.0	7.7	7.8	7.8	7.7