The Heavy Ion Path to Fusion Energy

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- **Schedule of HIF steps to Demo**
- **Cost of projects and operating program**
- **Critical decision points**
- **Decision criteria**
- **Chamber/materials**
- **Reliability/Availability**
- **Target physics/diagnostics**
- **Fusion technology/tritium use**

Reference material used in preparing this talk

- **Long Range HIF Plan** (Snowmass White Paper, describes R&D needs for heavy-ion accelerator, target and chamber R&D. 44 pages. Defines goals and criteria of HIF steps **consistent with 1999 FESAC report on Criteria, Goals and Metrics**) *Authors: 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*

- **An Updated Point Design For Heavy Ion Fusion** (Self-consistent power plant design for a multi-beam induction linac, final focus and chamber propagation, and distributed radiator target. Submitted for publication Fusion Science and Technology, 8 pages. **Meets Table 2 of FESAC Goals/Metrics report criteria for commercial plants.** Used as scaling basis for HIF ETF/DEMO) *Authors: S.S. Yu, W.R. Meier, R.P. Abbott, J.J. Barnard, T. Brown, D.A. Callahan, P. Heitzenroeder, J.F. Latkowski, B.G. Logan, S.J. Pemberton, P.F. Peterson, D.V. Rose, G-L. Sabbi, W.M. Sharp, D.R. Welch.*

- **IBEAM heavy-ion systems code** (MathCAD model used for sizing and costing HIF IRE, ETF/Demo steps. 100 pages) *Author: Wayne Meier*

- **HIF component cost and reliability reports** (1) "Fusion Energy Research Program Industrial Team Support Final Report", an HIF-sponsored technology study1995-1999 on capacitors, cores, solenoids, switches, insulators, quads, pulsers, chamber issues, system design, scaling laws, and costing. *Participants were Westinghouse, Maxwell, Northrop Grumman, SAIC, TRW, and University of Wisconsin (Will Waldron has a copy)* (2) **"**Reliability/Availability considerations for a VLHC", Laboratory of Nuclear Studies Cornell University report 2/12/1999, *G. Dugan*. (3) "Reliability Analysis for the Quench Detection in the LHC Machine" Proceedings of EPAC 2002, Paris, France, *A.Vergara Fernandez., CERN and Universitat Politechnica de Catalunya, Barcelona, Spain, R. Denz, F. Rodriguez Mateos, CERN, Geneva.* [(2) and (3) used for HIF SC magnet reliability estimates here]. "Illustrative Demo Availability Analysis and Data Base" 9-30-02 document from *John Sheffield*.

Strategy elements for the HIF path to fusion energy

1. **Integrated Beam Experiment (IBX)** Test integrated ion beam models for acceleration, longitudinal compression, and neutralized ballistic focusing with a source-to-target, a proof-of-principle level experiment. ***In parallel, HIF target and chamber feasibility R&D for an HIF-IRE decision.***

2. **Leverage NIF for most HIF target physics** ***(5 of 6 IFE physics tasks listed in the 1999 FESAC Goals and Metrics report)***
   - compressing the fuel with low entropy (in indirect drive)
   - demonstrating sufficient irradiation symmetry (in indirect drive)
   - demonstrating sufficient target stability (in indirect drive)
   - obtaining a sufficiently large hot spot to achieve ignition and burn
   - including adequate diagnostics to accomplish the above

3. **HIF-Integrated Research Experiment** ***(for the 6th FESAC physics task)***
   - demonstrating sufficient coupling of driver energy into target

   plus IRE- program technology R&D (for the FESAC technology tasks)

   - ion accelerator technologies
   - pulsed power technologies
   - target fabrication and injection
   - chamber and maintenance technologies
   - tritium systems
   - safety & environment

Strategy elements for HIF path to fusion energy (Cont.)

4. **Minimize Demo schedule with one accelerator, one site in two stages:**
   (a) test HIF chamber, target and fusion technologies (ETF stage), and
   (b) demonstrate commercial potential for HIF (Demo stage).
   →Exploits driver-chamber separability: one accelerator drives sequential upgrades of chamber and target components. Driver cost and beam requirements for ETF targets similar for Demo targets.

5. **Indirect-drive targets with thick-liquid-protected chambers: minimize fusion technology and materials development cost and schedule**
   →Indirect drive target physics comes earliest in NIF
   →Liquid-chamber hydro-testing relatively inexpensive
   →Low tritium inventory in Flibe at recoverable concentrations (<1 g)
   →Fission-tested steels can be used for HYLIFE structures-(Zinkle)

6. ***Interweave periodic target optimization (single shots) and with chamber/fusion technology test runs (bursts/ low average power). Chambers inexpensive enough ($50M) to build parallel/replace.***

Development prior to ETF/DEMO decision

Target physics specific to *accelerator-driven* hohlraums:

- Z (2 MJ of x-ray driven hohlraums): test shims for P4 symmetry control.
- IFE Target Test Facility ($40M/4): HIF-target materials, fab, injection R&D
- NIF (1 to 5 MJ laser driven hohlraums): test x-ray symmetry/shims in HIF model hohlraums. Test HIF-ETF capsule yield tailoring (see below).
- IRE (45 kJ of 450 MeV Xenon ions): foot-pulse x-ray symmetry with ion range-shortening in ¼ scale no-yield hohlraum) with 2-stage focusing (GSI-type plasma lens or high field cusp magnet). Test target tracking and 100 μr (10^{-4} dB/B) beam steering on injected diagnosable targets.

Liquid chamber test facilities (part of HIF-IRE program-see Baker's facility list)

- Hydraulics Integrated Test Facility ($10M facility specific to HIF)
- Flibe Integrated Loop Test Facility ($6M/2, shared with Z, MFE)
- Flibe Chamber Test Facility ($6M/2, shared with Z, MFE alternates)
- X-ray ablation testing in Z (in program funding line)

ETF/DEMO target and chamber development

<u>Target physics</u> specific to *accelerator-driven* hohlraums: <u>ETF/DEMO</u> (5.5 MJ of 4 GeV Bismuth ions): test target fab/injection, 120-beam balance, pointing, pulse-shaping with series of near-full size hohlraums with 2 mm focal spots and capsules tailored for different yields:

1. No-yield capsules for tuning ion beams for x-ray symmetry (use plastic capsules doped for x-ray imaging and for “cold” chamber tests in 1. below.
2. Low yield (~50 MJ) for low average fusion power chamber/tritium cycle tests (use thinner DT layers and thicker ablators),
3. Full yield capsules (280 MJ for DEMO) to produce 780 MWe net (75% of commercial plant power).

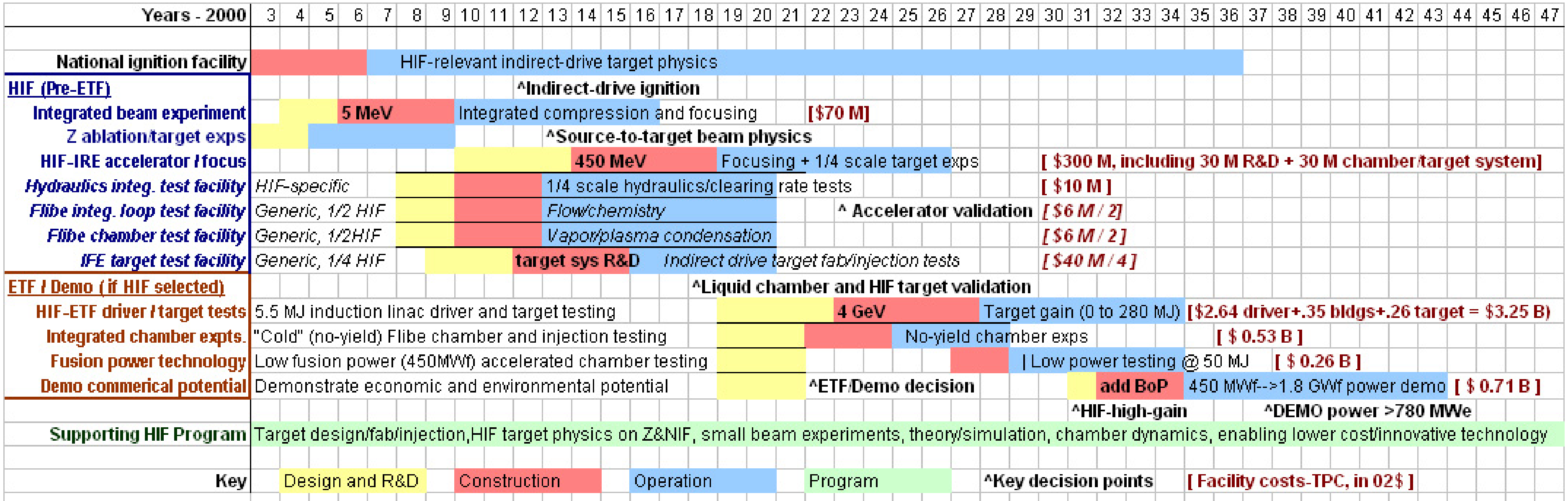
<u>Integrated chamber testing</u> (see Per Peterson’s talk) in three test phases:

1. “Cold” (no-yield) hydro/loop/tritium testing with no-yield target injection (conducted during ETF driver construction and early target physics tests)*
2. “Hot” testing with low average fusion power (~450 MWf-ave) -integrated with ETF low (~50 MJ) target testing*
3. Demo operation with energy conversion @ 75% commercial power level (280 MJ x 6.4 Hz = 1.8 GWf → 88% scale-size HYLIFE-II chamber)

*Notes: (a) We are still considering the pros and cons of chamber test phases 1 and 2 being done with a reduced 40% scale chamber- if so constructing both 40% and 88% scale chambers in parallel would increase cost by ~$50M (<1%).

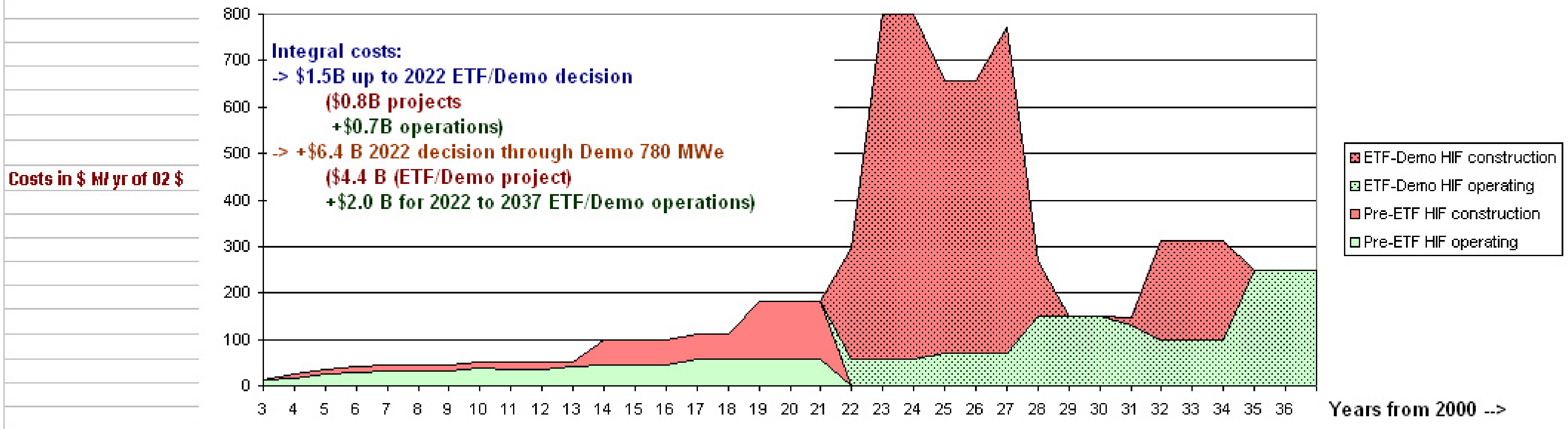
(b) There are 10 or more empty beam tubes that can be used for target-viewing ports. NIF will develop and qualify radiation-hard target diagnostics that operate within 20cm rail-inserted cylinders @ 4 meters from maximum credible NIF yields.

Steps and schedule to a heavy ion fusion DEMO with critical decision points



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

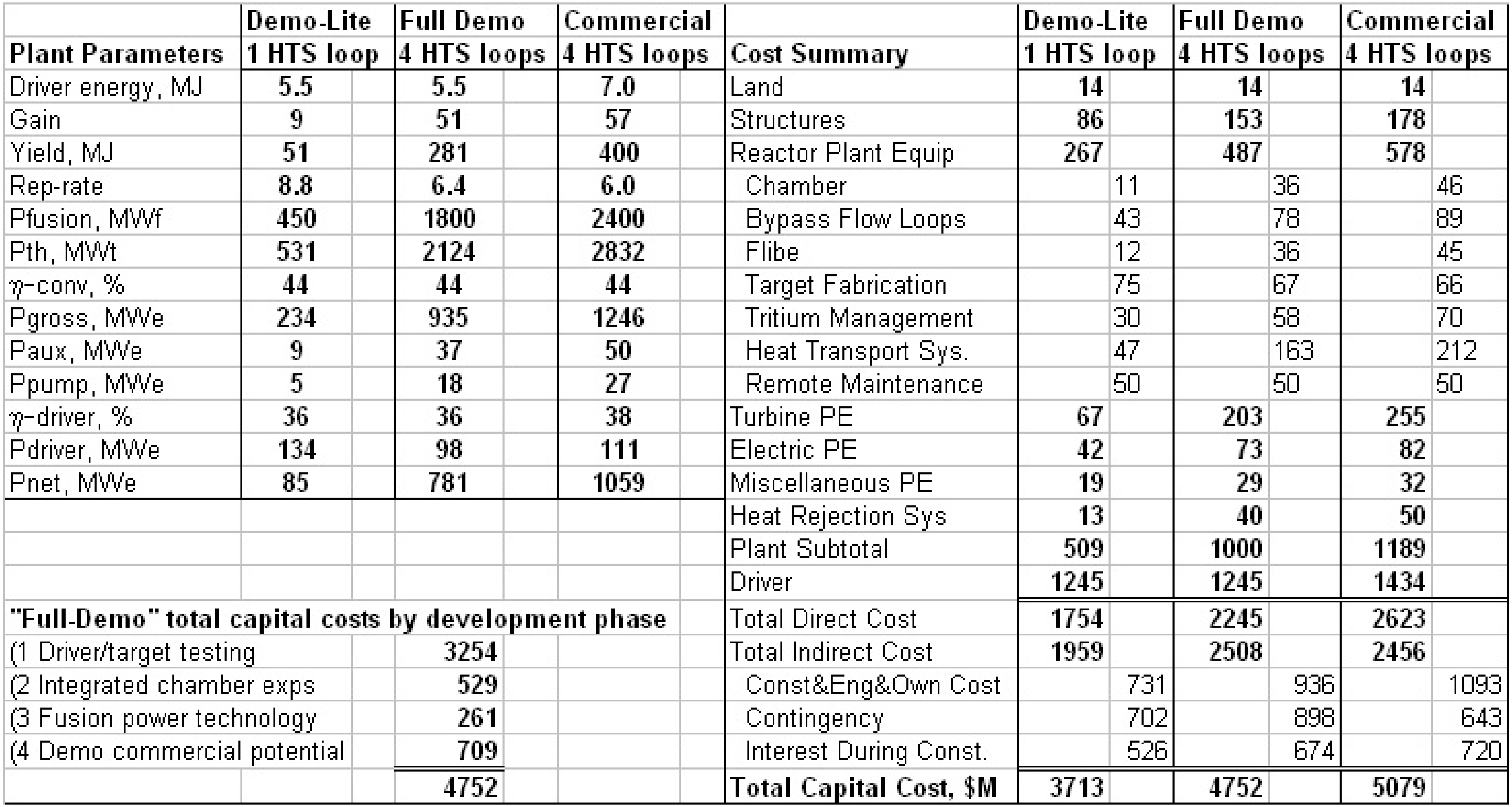
Total annual HIF program cost including facility constructions- based on RPD multi-beam MQ linac, q/A =1/200



Integral costs:
-> $1.5B up to 2022 ETF/Demo decision
($0.8B projects
+$0.7B operations)
-> +$6.4 B 2022 decision through Demo 780 MWe
($4.4 B (ETF/Demo project)
+$2.0 B for 2022 to 2037 ETF/Demo operations)

HIF ETF/DEMO parameters and costs by system and development phase

(from Wayne Meier's system analysis, based on the recent RPD HIF power plant design)



Plant Parameters	Demo-Lite 1 HTS loop	Full Demo 4 HTS loops	Commercial 4 HTS loops
Driver energy, MJ	5.5	5.5	7.0
Gain	9	51	57
Yield, MJ	51	281	400
Rep-rate	8.8	6.4	6.0
Pfusion, MWf	450	1800	2400
Pth, MWt	531	2124	2832
η-conv, %	44	44	44
Pgross, MWe	234	935	1246
Paux, MWe	9	37	50
Ppump, MWe	5	18	27
η-driver, %	36	36	38
Pdriver, MWe	134	98	111
Pnet, MWe	85	781	1059

"Full-Demo" total capital costs by development phase	
(1 Driver/target testing	3254
(2 Integrated chamber exps	529
(3 Fusion power technology	261
(4 Demo commercial potential	709
	4752

Cost Summary	Demo-Lite 1 HTS loop		Full Demo 4 HTS loops		Commercial 4 HTS loops	
Land	14		14		14	
Structures	86		153		178	
Reactor Plant Equip	267		487		578	
Chamber		11		36		46
Bypass Flow Loops		43		78		89
Flibe		12		36		45
Target Fabrication		75		67		66
Tritium Management		30		58		70
Heat Transport Sys.		47		163		212
Remote Maintenance		50		50		50
Turbine PE	67		203		255	
Electric PE	42		73		82	
Miscellaneous PE	19		29		32	
Heat Rejection Sys	13		40		50	
Plant Subtotal	509		1000		1189	
Driver	1245		1245		1434	
Total Direct Cost	1754		2245		2623	
Total Indirect Cost	1959		2508		2456	
Const&Eng&Own Cost		731		936		1093
Contingency		702		898		643
Interest During Const.		526		674		720
Total Capital Cost, $M	3713		4752		5079	

The HIF-IRE will test linac availability thru modular construction, robotic replacement, with few-% off-line and on-line spares (Logan/Waldron)

Approach: ETF linac driver 5.5 MJ @ 4 GeV sufficient to drive 2GW fusion DEMO. Estimate unavailability (UA's) = # of components of type n x mean time to replace (MTTR -in hours) divided by mean time to failure (MTTF-in hours), for four basic linac components : superconducting quadrupole focusing magnet arrays (treated as factory module units), factory-built induction modules, and online replaceable clusters of redundant switches and capacitors. Assume failures are infrequent enough that one can neglect overlapping failures: then UA ~ N_n x MTTR/MTTF. Assume only robotic replacement of factory-built modular components with spare units for any failure (no hands-on due to tritium contamination and ion loss induced activation). MTTF's bounded by closest related component databases: e.g., CERN and Tevatron magnet failure rate experiences, power industry databases for lifetime of transformers, IGBT power controllers, and capacitors.

Component 1

Superconducting quads

UA per quad array $UA_1 := \frac{24}{10^6}$

Tot. # of quad arrays per linac $N_1 := 10^3$

$N_1 \cdot UA_1 = 0.024$

Replace whole array as a unit with factory-built spare arrays

100-quad sc magnet arrays

(wired as one factory module)

Component 2

Induction Modules

UA per module $UA_2 := \frac{10^{-1}}{10^5}$

Tot. # of modules $N_2 := 2 \cdot 10^4$

$N_2 \cdot UA_2 = 0.02$

Whole accelerator module (core/ housing/ insulator) replaced with spare units, inc.100 built-in-linac spares.

Induction modules

Component 3

All solid state switches

UA per 10^9 W module $UA_3 := \frac{10^{-2}}{10^5}$

Tot. # of 10^9W modules $N_3 := 10^5$

$N_3 \cdot UA_3 = 0.01$

Online replacement w/spare solid state modules inc. 10X magnetic compression

Switching modules

Component 4

Energy storage caps

UA per 10^4 J cap module $UA_4 := \frac{10^{-2}}{10^4}$

Tot. # of 10^4 J modules $N_4 := 10^4$

$N_4 \cdot UA_4 = 0.01$

Online "switch-out" replacement of redundant built-in spare cap modules

Cap modules

Availability (with 15% scheduled maintenance)

$$A := (1 - 0.15) \cdot \left(1 - \sum_{n=1}^{4} N_n \cdot UA_n \right) \qquad A = 0.8$$

Tritium use during HIF-ETF-fusion chamber tests

- **ETF target optimization testing: About 10^4 shots (no-yield to 280 MJ)→3×10^5 MJ or 10^{-2} MW-yr over 7 years of intermittent target tests.**

→~ 0.5 g T burned, ~ 50 g for unburned T recovered in inventory

- **Low-power HIF fusion power technology test phase:**
  - **T burned in liquid Flibe chamber : 450 MWf at 1% to 30% (est. 5% average capacity over 6 yr of low-power testing) = 22 MW-yr = 7.2 kg T.**
  - **Neutron losses during low power test phase thru 160 beam ports @15 mr half-angle each < 1 % of 4π solid angle, equiv to potential loss of < 75 g T that would otherwise be bred, easily covered by any TBR >1***
  - **T-inventory = 0.5 g in saturated Flibe, ~100 in structures, 200 g in target factory (assuming cold assembly) ~ 300 g total**

→ Total T procurement for low-power ETF test phase = 50+300=350 g T.

*W.R. Meier, et. al, Fus. Tech. **39,** p 671, 2002 reported TBR=1.23 (40%-scale ETF), 1.26 (power plant) for Flibe. Slightly lower for Flinabe, but still >1.

Decision criteria for HIF-IRE: current experiments and the IBX must provide the accelerator physics basis for proceeding to an IRE

Current research milestones through FY04:

- **HCX- quadrupole fill factors, halo loss, electron/gas effects**
- **NTX-geometric FF aberrations and plasma neutralization**
- **STS 500-insulator tests, merging-beamlet experiment**
- **Integrated modeling methods.**

IBX-goals for an IRE decision:

- **Transport with low emittance growth for aperture fill factors > 0.5 and for > 40 - 80 lattice periods**
- **Acceleration gradients useful to an IRE**
- **Final focus to near-emittance-size spots after > 5 x longitudinal bunch compression, consistent with integrated models.**

Decision criteria for an HIF-IRE: other requirements

- Peer-reviewed/published HIF target designs with adequate gain.

- Compact multi-beam injectors with normalized emittance < 1 π mm-mr, and overall ave. current density > 30 A/m^2 adequate for IRE

- End to end simulation of a full scale driver.

- Affordable technology for ion induction linacs: low loss cores (<\$5/kg), high gradient insulators (<0.01\$/V), solid state pulsers (<\$10^{-5}/W), SC quad arrays (<\$10/kA-m).

- Feasibility (plausible pathways) shown for low cost HIF target fabrication and injection

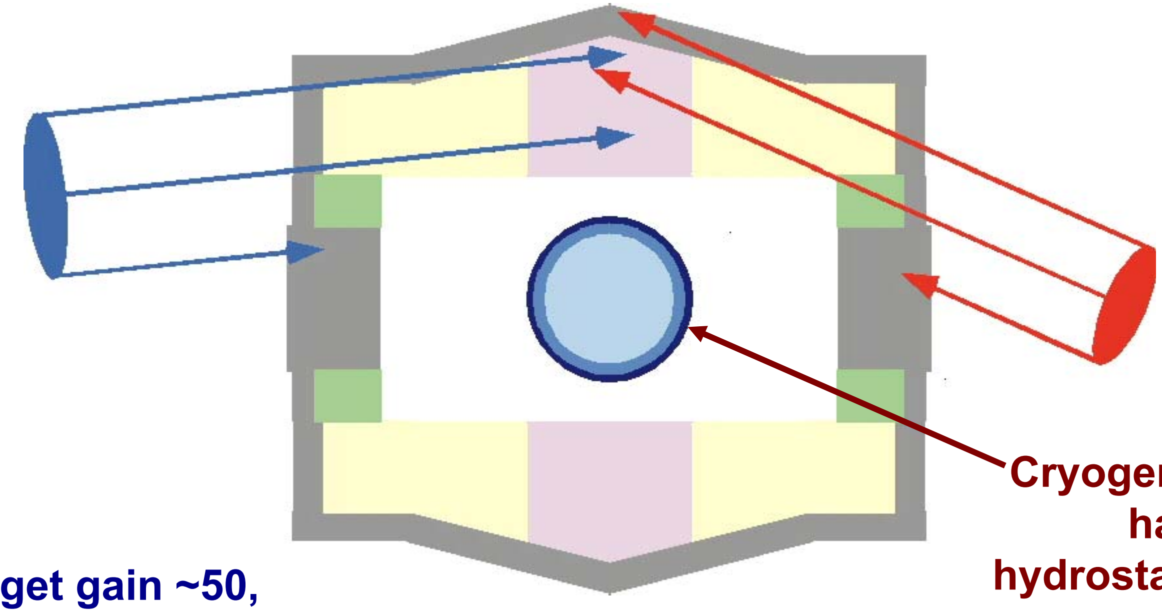
- Credible power plant concepts with feasibility data for long-lasting chambers and final focus interfaces compatible with driver and target requirements.

Decision criteria for HIF-ETF/DEMO

- Adequate target physics data from NIF and other ICF facilities on implosion symmetry and capsule/fuel layer smoothness for indirect-drive
- IRE accelerator component cost, reliability, cost and efficiency that project to meet corresponding HIF-ETF/DEMO requirements (Slides 8 and 9)
- IRE tests of ion beam steering, injected target tracking, and beam-target coupling under relevant chamber environment and time scales.
- IRE and other ion beam data that resolve beam chamber propagation and interaction with ETF targets (beam balance, symmetry, imprint, filamentation, chamber plasma/gas)
- Sufficient data-base for HIF hohlraum target materials and mass-manufacturing methods to project meeting ETF target factory cost, precision, and tritium inventory requirements.
- Adequate projected life and quench-avoidance of superconducting final focus magnets based on pre-conceptual ETF/DEMO shielding designs, and available neutron/gamma damage data for superconducting magnets.
- Scaled liquid chamber experiments demonstrating hydrodynamically-equivalent shock impulse mitigation and chamber clearing rates for ETF/Demo.
- Systems studies that show HIF power plants that can meet Table 2 of FESAC Goals/Metrics report criteria for commercial plants

Backup Slides

Reference HIF target design guides design optimization and fabrication R&D

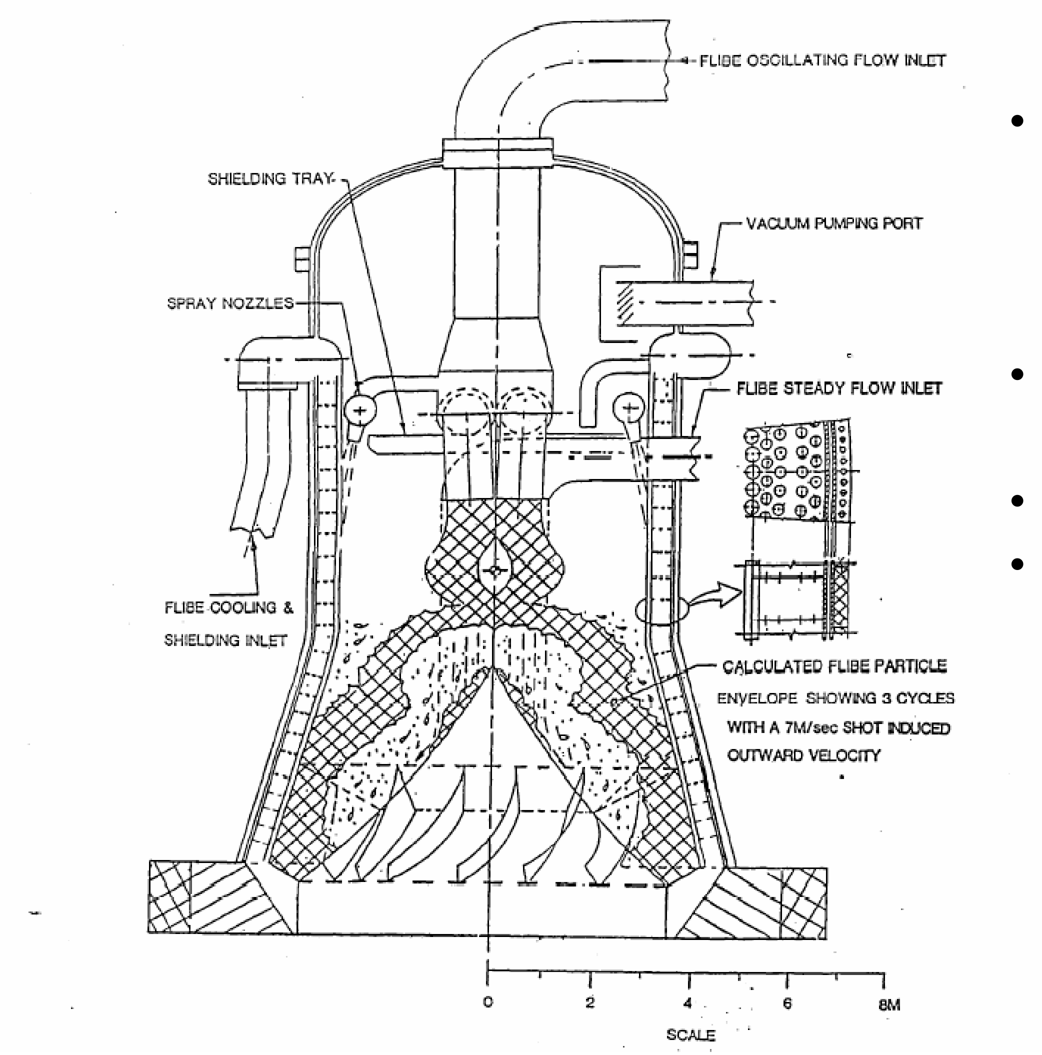


Cryogenic DT fuel capsule has robust 2-D hydrostability (requires less convergence ratio, peak density, and ablator/ice smoothness than NIF)

- Target gain ~50,
- 7 MJ,
- 40% of energy in foot pulse beam (blue)
- 24 degree maximum half angle for main pulse beams (red)
- Main pulse ion range 0.035 g/cm2 (2.5 GeV Xenon or 4 GeV Bismuth)
- Foot pulse at ~75% range.

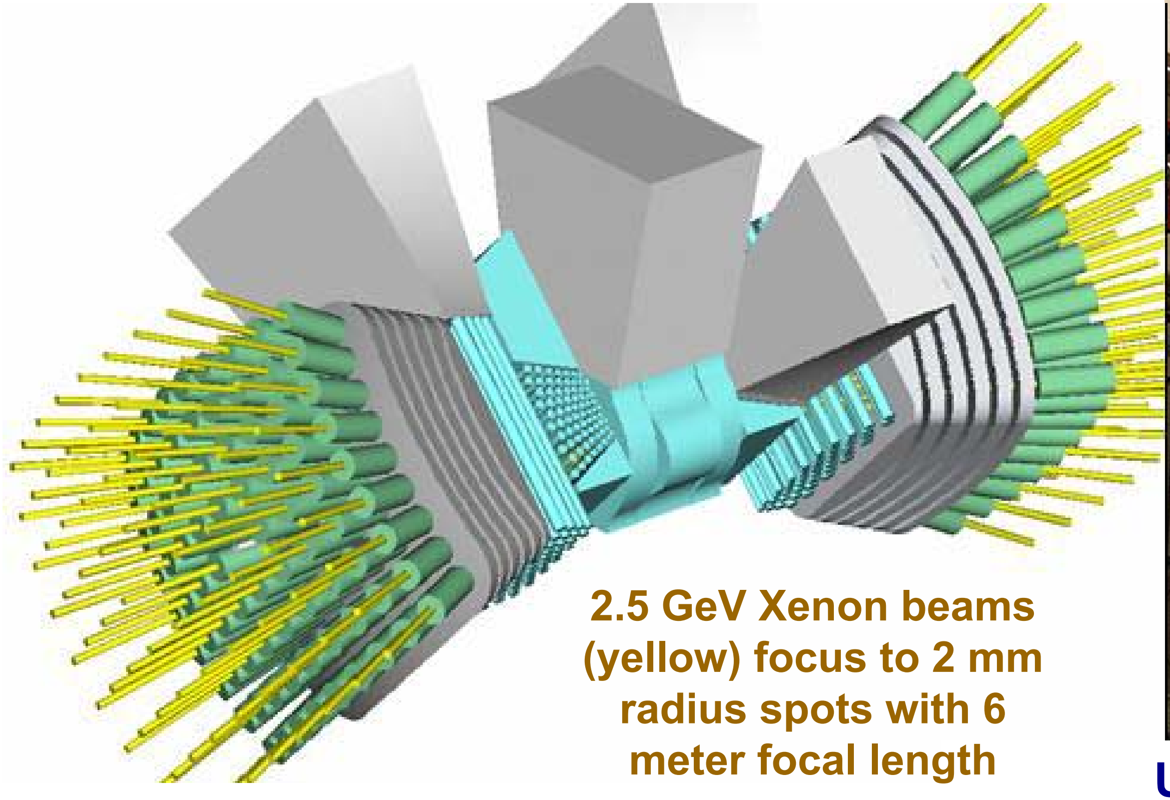
-->Fabrication issues: mass production methods/cost, activation of suitable high-opacity, high z hohlraum materials

Thick liquid walls allow major chamber structures to last many years



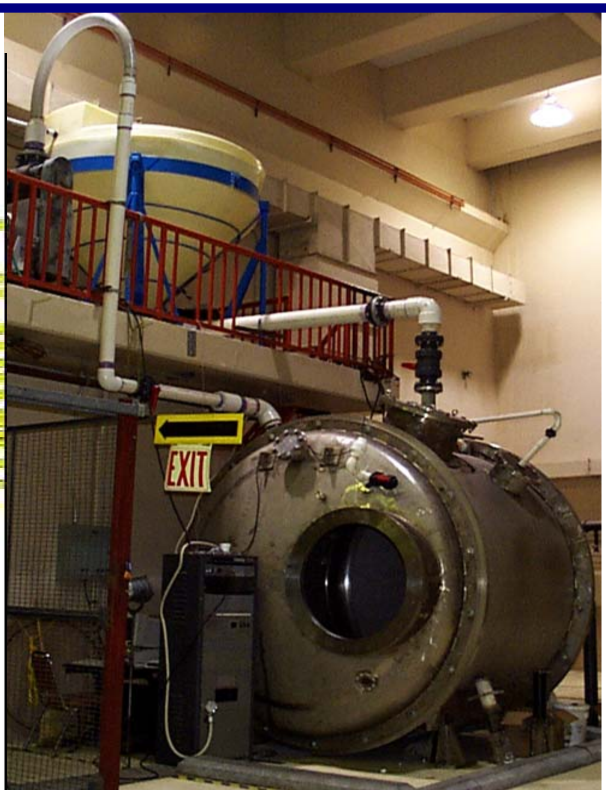
- A thick liquid pocket protects chamber structures from direct exposure to x-rays, ions, debris and neutrons.
- Liquid is molten salt – flinabe for point design
- Effective shielding thickness is 56 cm
- Oscillating jets dynamically clear droplets near target (clear path for next pulse).

With indirect drive targets, chamber walls can be protected from neutron damage by thick liquid jets



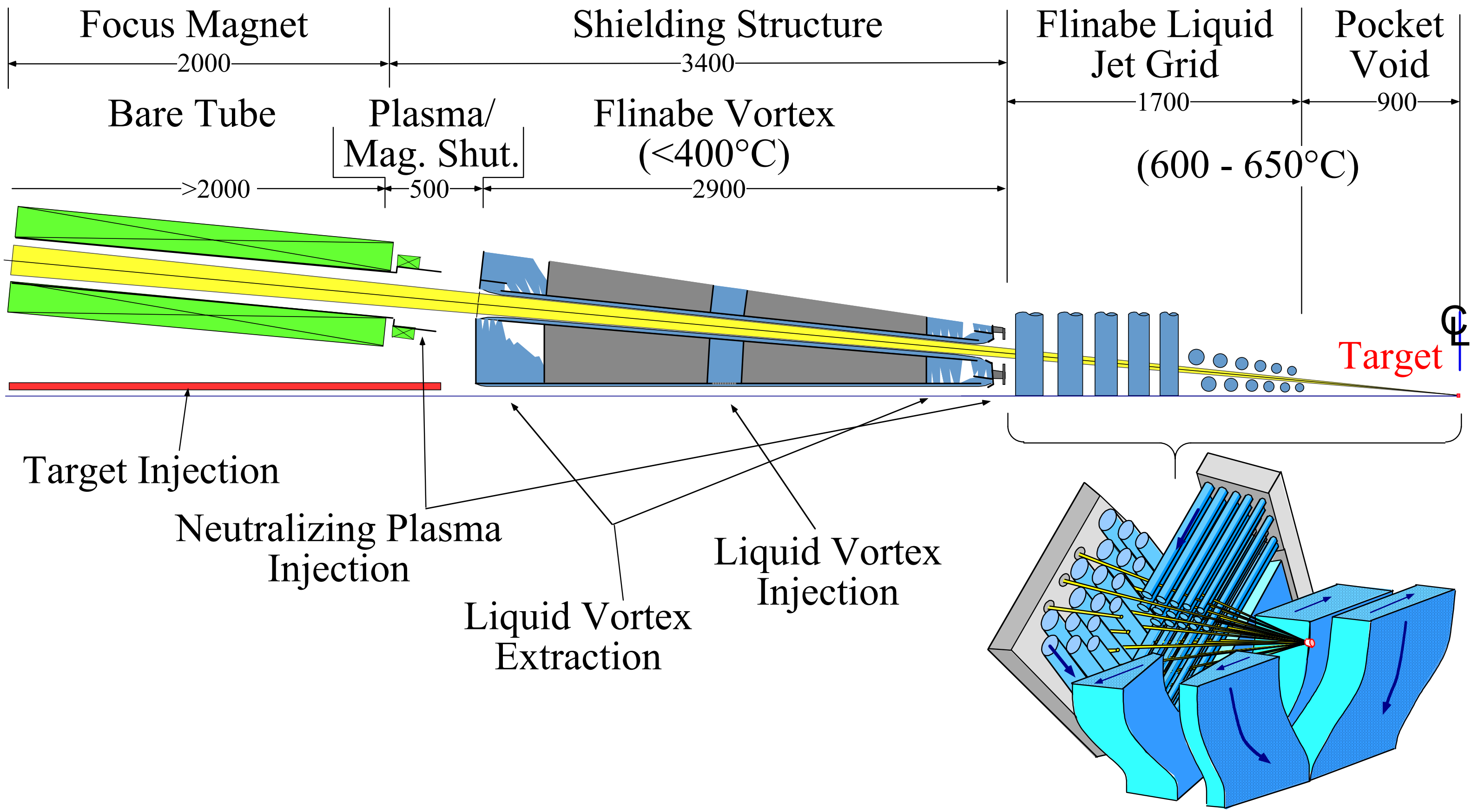
2.5 GeV Xenon beams (yellow) focus to 2 mm radius spots with 6 meter focal length

A 160-beam HYLIFE-II chamber cutaway view showing the focus magnets (in green) and molten-salt-Flibe jets (in light blue). This chamber is designed for 30 year lifetime.



UCB facility studies hydrodynamically- equivalent single jets and few jets (partial pockets) relevant to liquid chamber (HYLIFE-type) HIF chambers.

The Robust Point Design (RPD) beam line

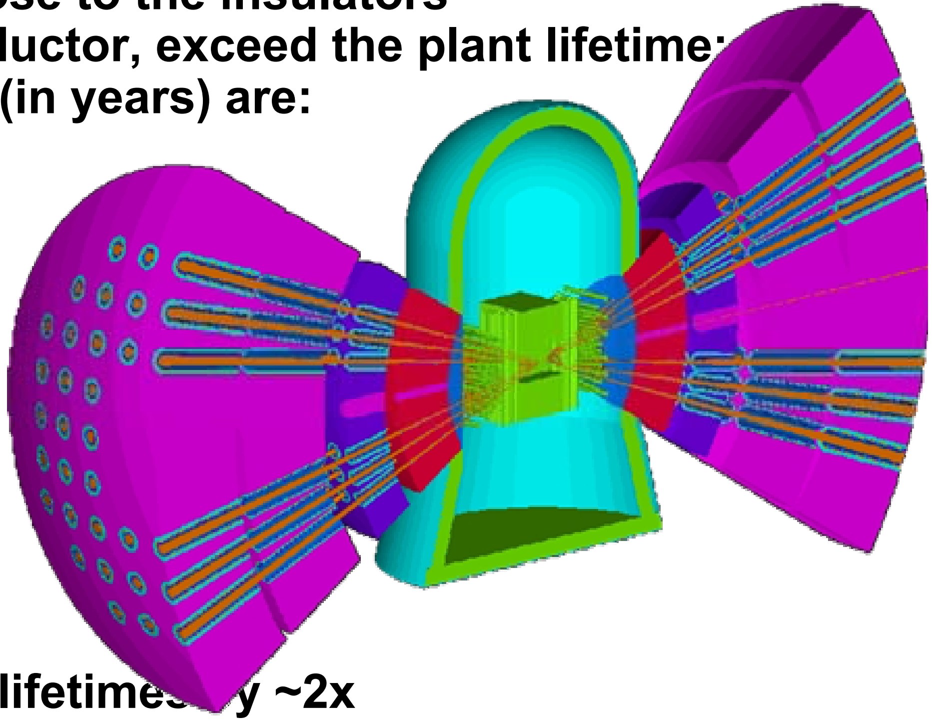


Schematic Liquid Jet Geometry

Recent magnet shielding & activation results are quite promising

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



Waste disposal ratings are significantly reduced from previous work: 1.7, 0.5, 0.4 (^{94}Nb)

Increasing liquid stand-off distance in vortices (from 1 → 5 mm) will reduce lifetimes y ~2x

Optimizing shielding to increase neutron effectiveness (at cost of gamma-ray shielding effectiveness) should enable all magnets to qualify for disposal as low-level waste; adequate margin exists for magnet lifetime to exceed plant life.

The 5.5 MJ ETF/Demo driver may drive a reduced (40%) scale chamber in addition to the 88% scale Demo chamber

- ETF/DEMO “multi-use” chamber =88% of RPD power plant size for 0 to 280 MJ yields
- Operation must alternate between target physics (Flibe drained out for some target shots) and low-power fusion testing
- Requires more -radiation-hardened diagnostics and other modifications for target physics tests in a “hot” chamber
- Reduced-scale chamber =40% of RPD chamber size for 0 to 50 MJ yields (reduced DT-fill target capsules)
- Separate larger chambers single-shot target physics (less activated, more diagnostics) and for later Demo operation.
- Requires a 120-beam magnet “switchyard” for quick beam switching (not yet designed).

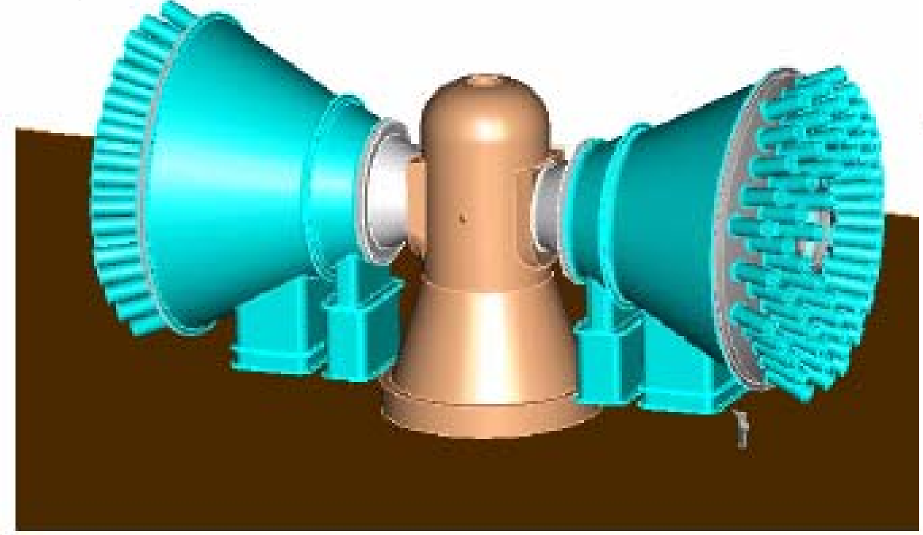


Fig. 3. An isometric view illustrating the coupling o final focus magnet array with the chamber.

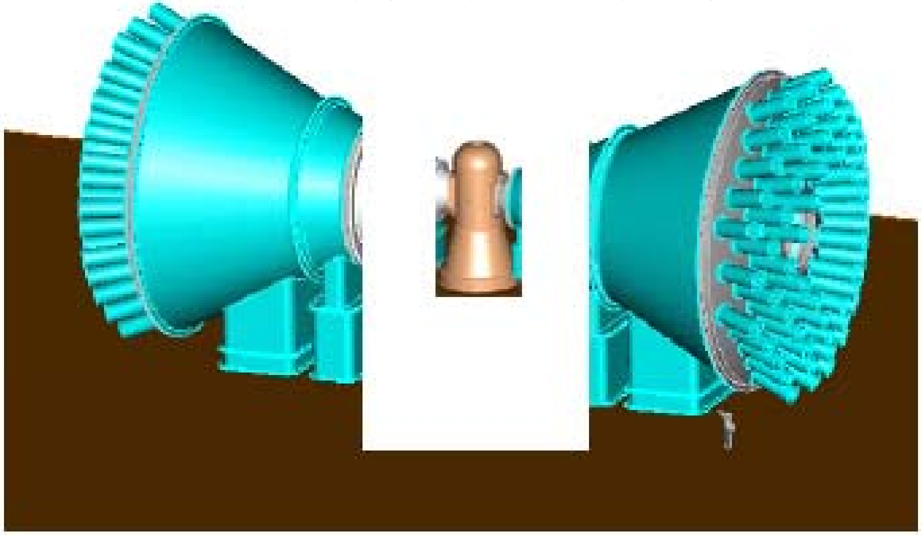
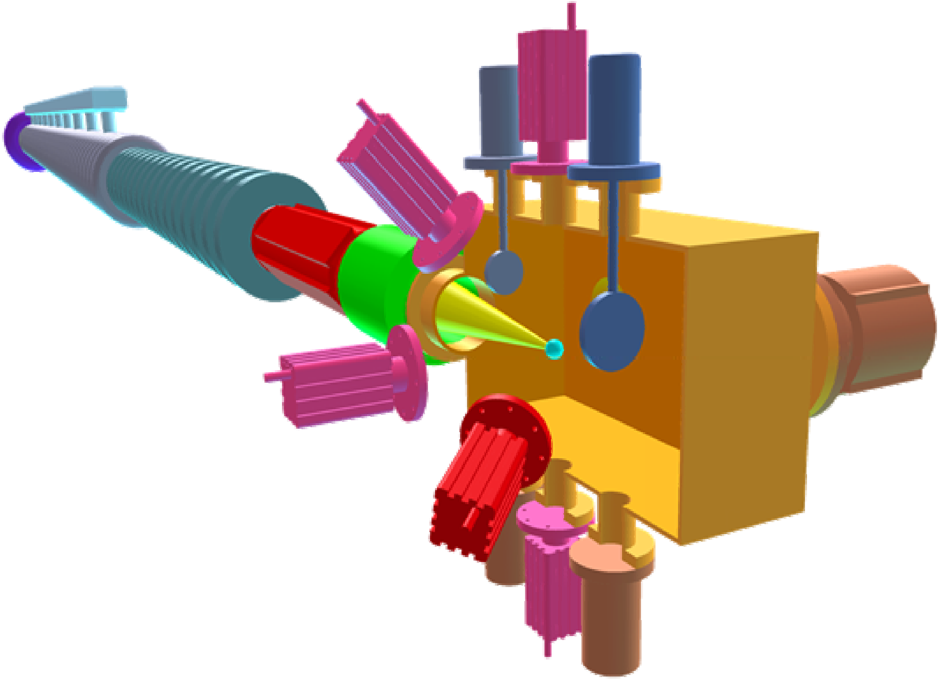


Fig. 3. An isometric view illustrating the coupling of final focus magnet array with the chamber.

The Integrated Beam Experiment (IBX) will provide the first source-to-target fusion-relevant beam physics

- A proposed $50 M Proof-of-Principle experiment ~5-10 MeV.
- Test acceleration, longitudinal compression, final focus and chamber transport.
- Candidate PoP facility in the OFES program beginning FY04-05 as funding permits.



→The IBX, along with aggressive technology development,

will provide the basis for an optimized IRE

Goal: Integrated Research Experiment (IRE) for both ion-specific target physics and driver prototype technology

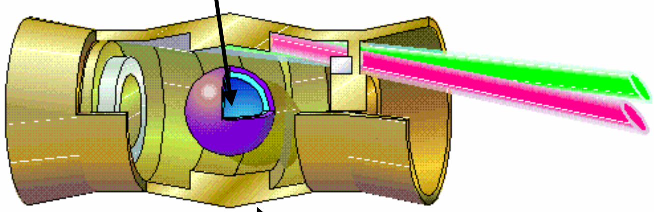
IRE: High intensity beam physics: multiple-beam effects, long-term transverse and longitudinal dynamics, etc...

HIF Target Design (LLNL-OFES)

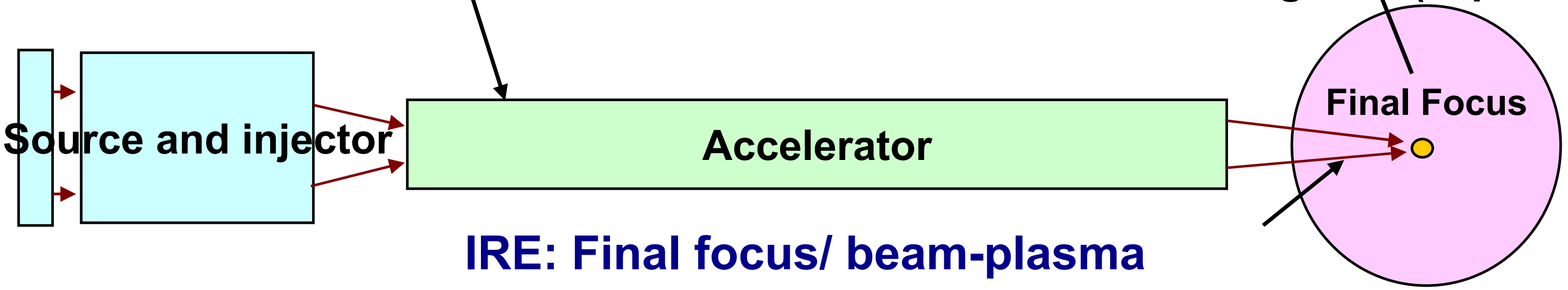
Injection/fabrication R&D (VLT-OFES)

Capsule hydrostability/ DT burn (NIF-DP)

IRE: Beam-target interaction, accelerator driven hohlraum symmetry experiments

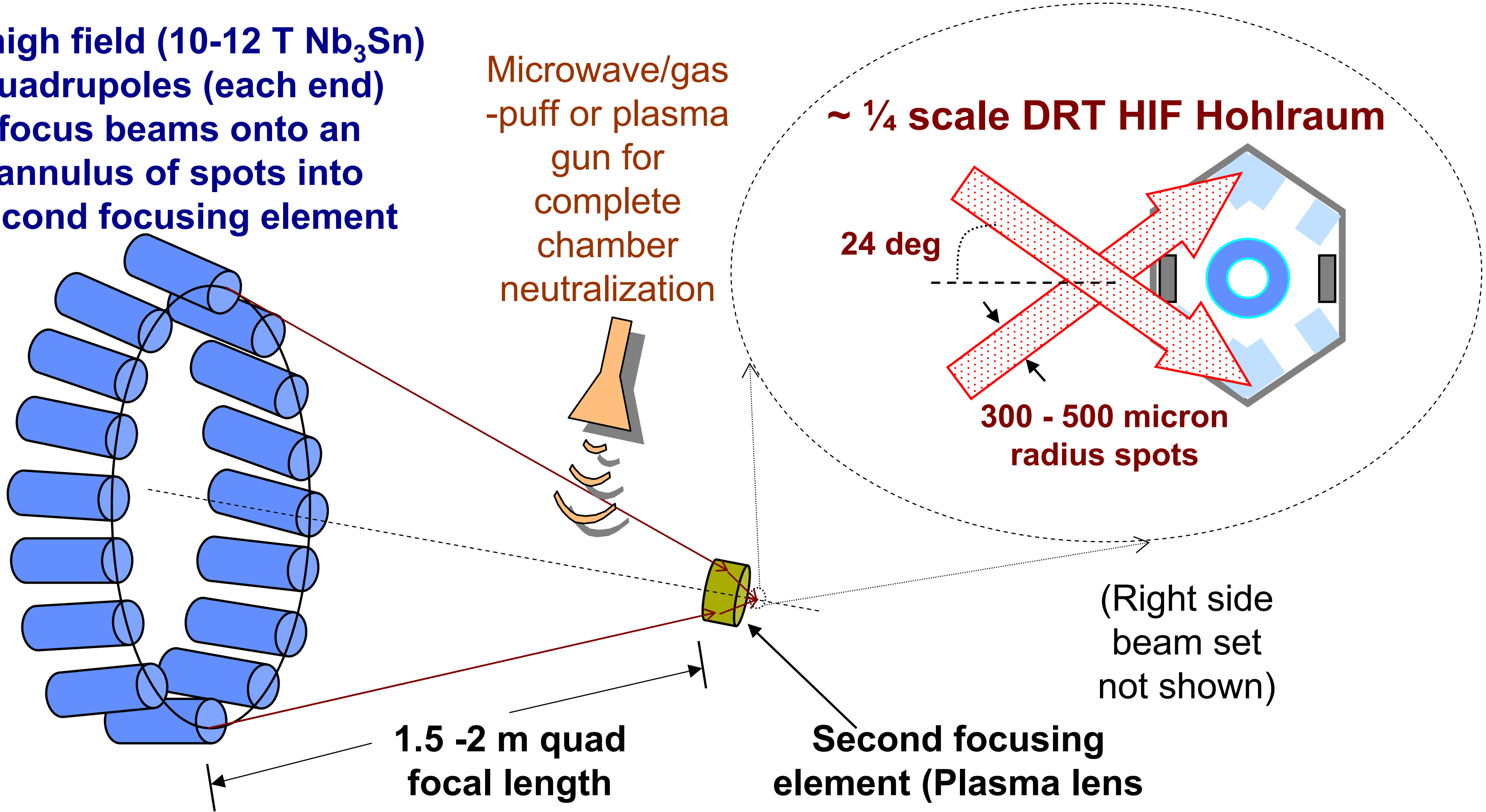


Target (expanded view)



IRE: Final focus/ beam-plasma neutralization, to reduce ion energy and save money

2nd IRE experiment tests multi-beam coordination for basic P2 hohlraum asymmetry due to range shortening



16 high field (10-12 T Nb_3Sn) quadrupoles (each end) focus beams onto an annulus of spots into second focusing element

Microwave/gas -puff or plasma gun for complete chamber neutralization

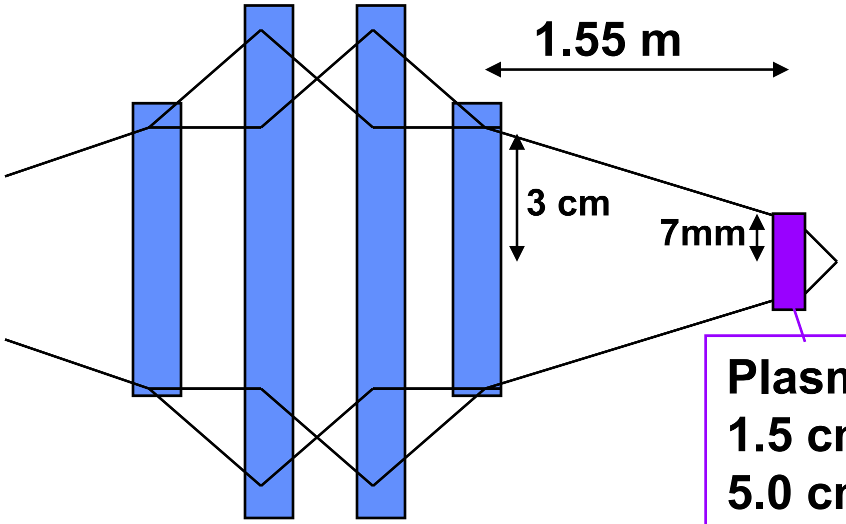
~ ¼ scale DRT HIF Hohlraum

(Right side beam set not shown)

1.5 -2 m quad focal length L_{f1}

Second focusing element (Plasma lens or cusp magnets) with short $L_{f2}< 0.1L_{f1}$

A “double focus” (quads+plasma lens may be used to reduce spot size to ~0.5 mm)



Radius at final focus ~0.5 mm

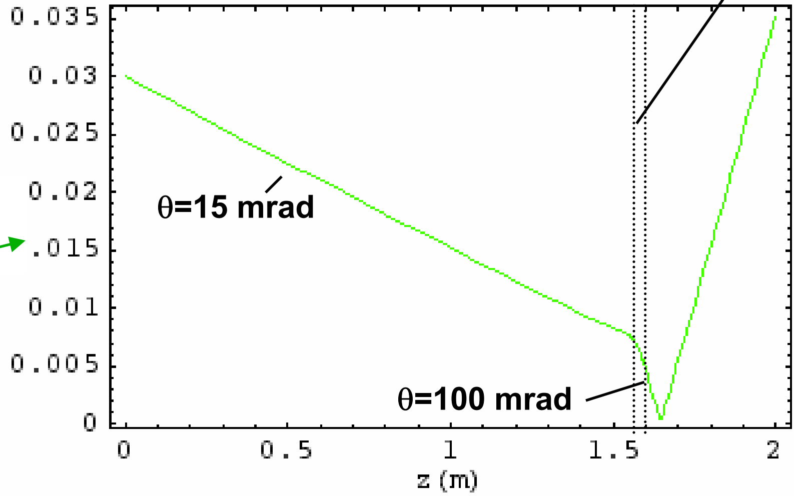
Plasma lens
1.5 cm radius
5.0 cm length
400 kA

Conventional final focus using quadrupoles

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

Plasma lens

Beam radius (m) vs. z(m)



An IRE accelerator that matches the 1/4 scale target will have 1/4 range and 1/4 spot radius of a distributed radiator target foot beam

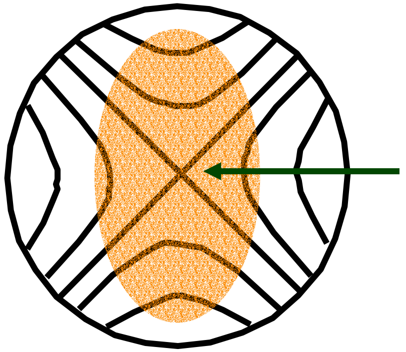
Xe^{+1} (A=131) at 450 MeV
Total pulse energy = 45 kJ
Pulse duration = 6.25 ns

13 beams required to reduce final perveance to below 10^{-3}
16 beams required for symmetry
64 beams increases cost modestly but reduces perveance to 2×10^{-4} if needed

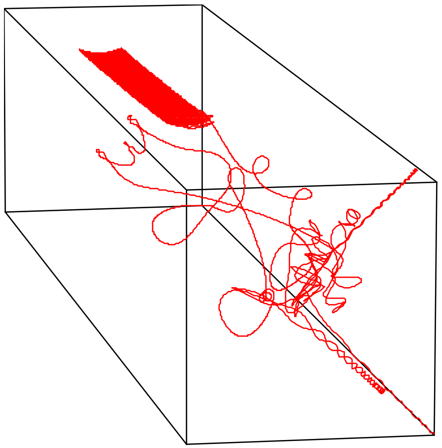
Total HIF-IRE Project Costs	With today's technology/ costs (TPC)	Projected cost with ~$30-50 M R&D to improve technology/ component costs	Final beam perveance
64 beams	$820 M	$280 M	2×10^{-4}
16 beams	$675 M	$230 M	8×10^{-4}

NTX will test focusing over this range of final beam perveances

We are studying sources, sinks, and dynamics of electrons



Electrons can trap into beam space-charge and quadrupole magnetic fields



Electron lifetime ~ time to drift out the ends of a magnetic quadrupole

$n_e = n_e(\text{beam-gas}) + \text{ion flux to wall} \times e^-\text{'s per incident ion} \times e^- \text{ lifetime}$

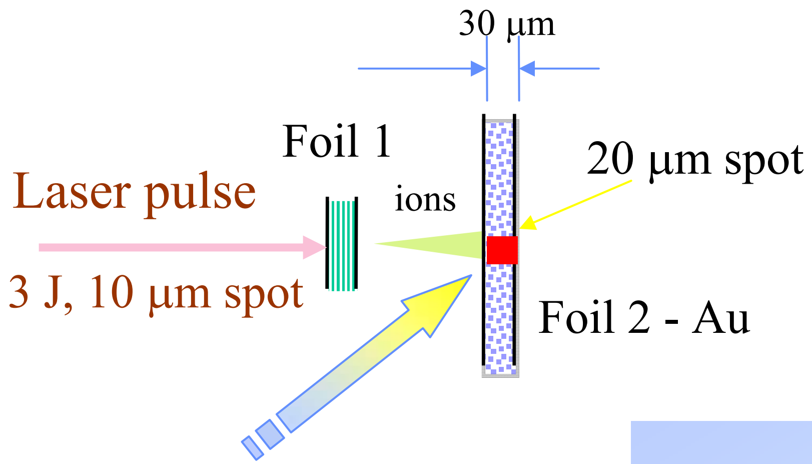
- **beam halo**
- **charge exchange**
- **scattering**

- **secondaries**
- **ionization of neutrals from wall**

- **trapping**
- **detrapping**
- **pulse duration**

Experiments on HCX exploring these issues are planned to begin this summer

Warm dense matter experiments relevant to HIF can be produced with laser-generated heavy ion beams



20 fs x-ray pulse from all optical Thompson source

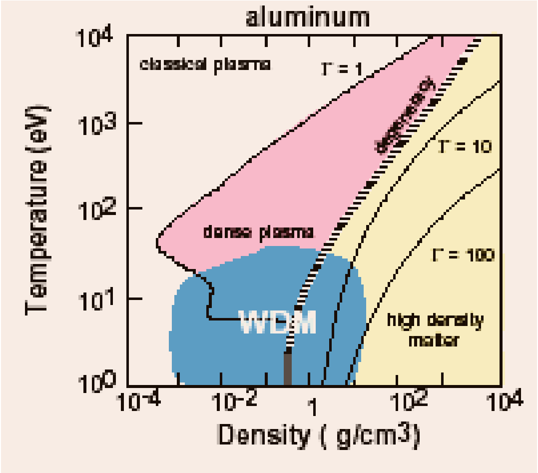
1 laser beam - 3 J

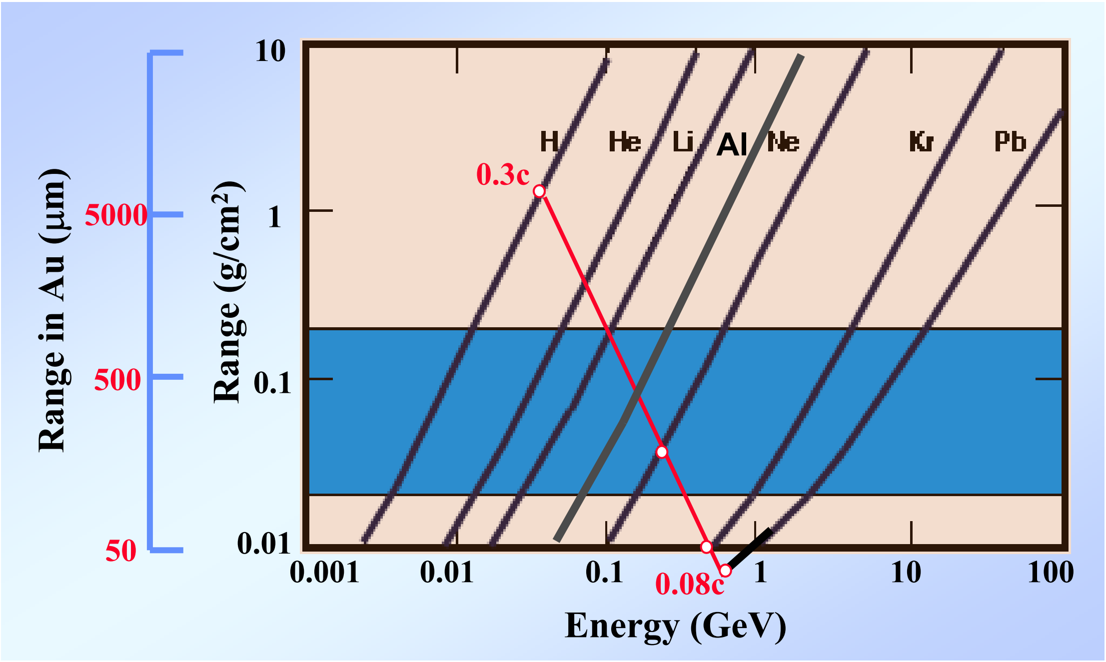
==> ~0.3 J heavy ions @ 3-5 MeV/n

==> ~10 ^{5} J/cm^2 in ~1 ps

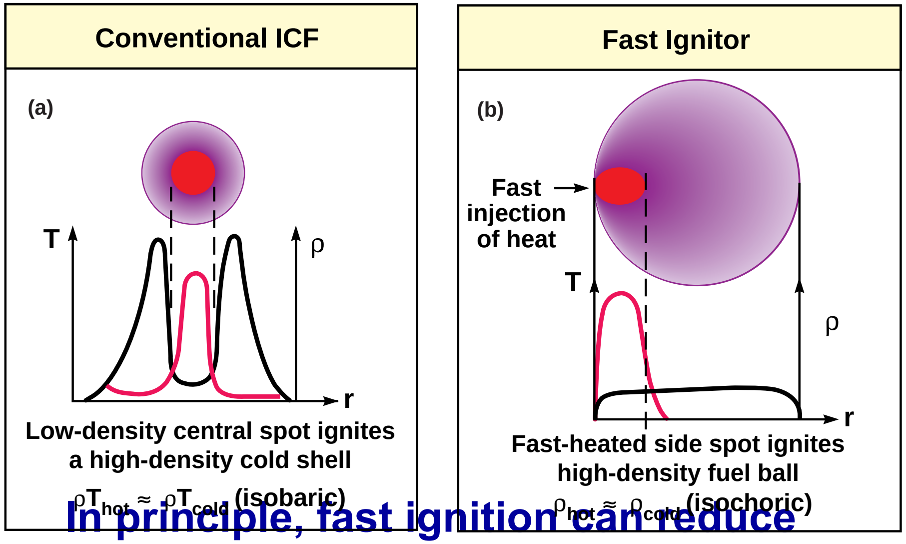
==> 10 ^{5} TW/cm^2

==> ~5x10 ^{5} cal/g ==> ~50 eV





Fast ignition *might* benefit heavy ion fusion in a variety of ways: higher gain or lower drive energy, lower peak ion power (for fuel compression), less required ion bunch longitudinal compression and bigger spots (allow higher longitudinal and transverse emittance), and more room for shielding final focus magnet arrays.



Low-density central spot ignites a high-density cold shell

$\rho T_{hot} \approx \rho T_{cold}$ (isobaric)

Fast-heated side spot ignites high-density fuel ball

$\rho_{hot} \approx \rho_{cold}$ (isochoric)

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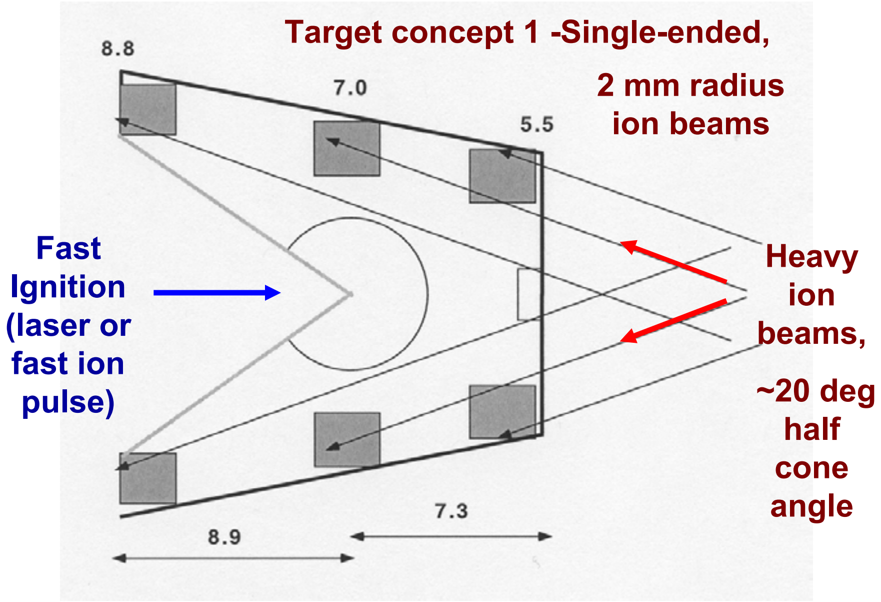
In principle, fast ignition can reduce total drive energy for any driver used to supply the dominate energy for fuel compression (as long as the igniter beam energy < 1 MJ)



Target concept 1 -Single-ended,

2 mm radius ion beams

Fast Ignition (laser or fast ion pulse)

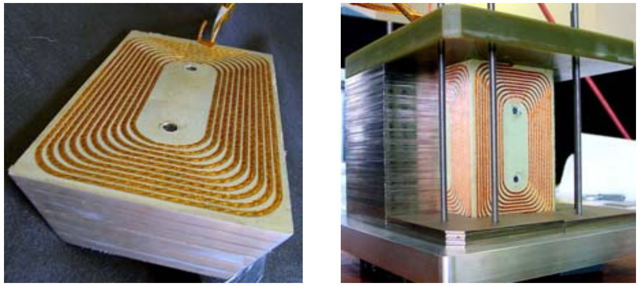
Heavy ion beams, ~20 deg half cone angle

Recent work by Debra Callahan (LLNL), used analytic target models to estimate ion beam requirements to drive three hohlraum geometries at 150 and 120 eV

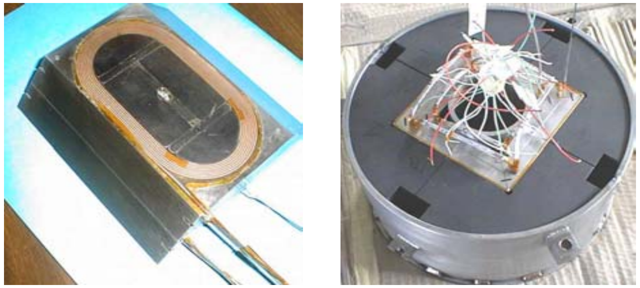
Superconducting magnet development FY01-02

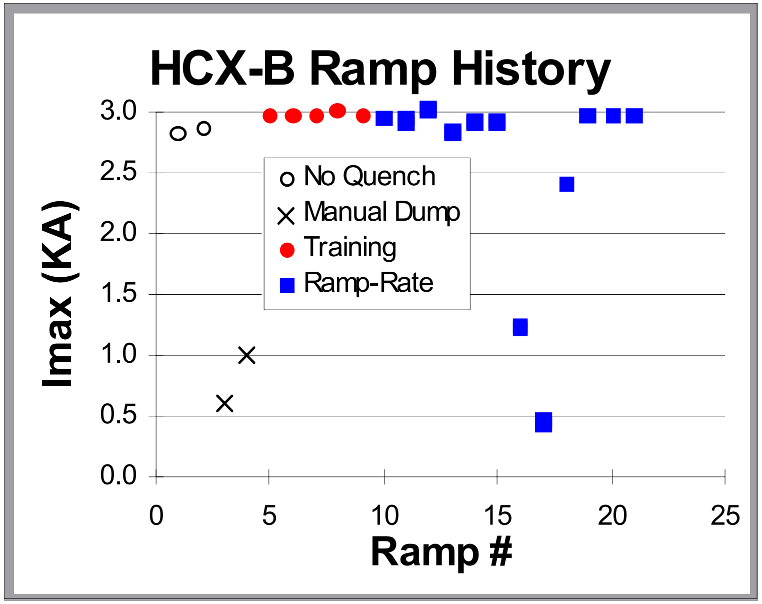
Four prototypes fabricated and tested

AML



LLNL



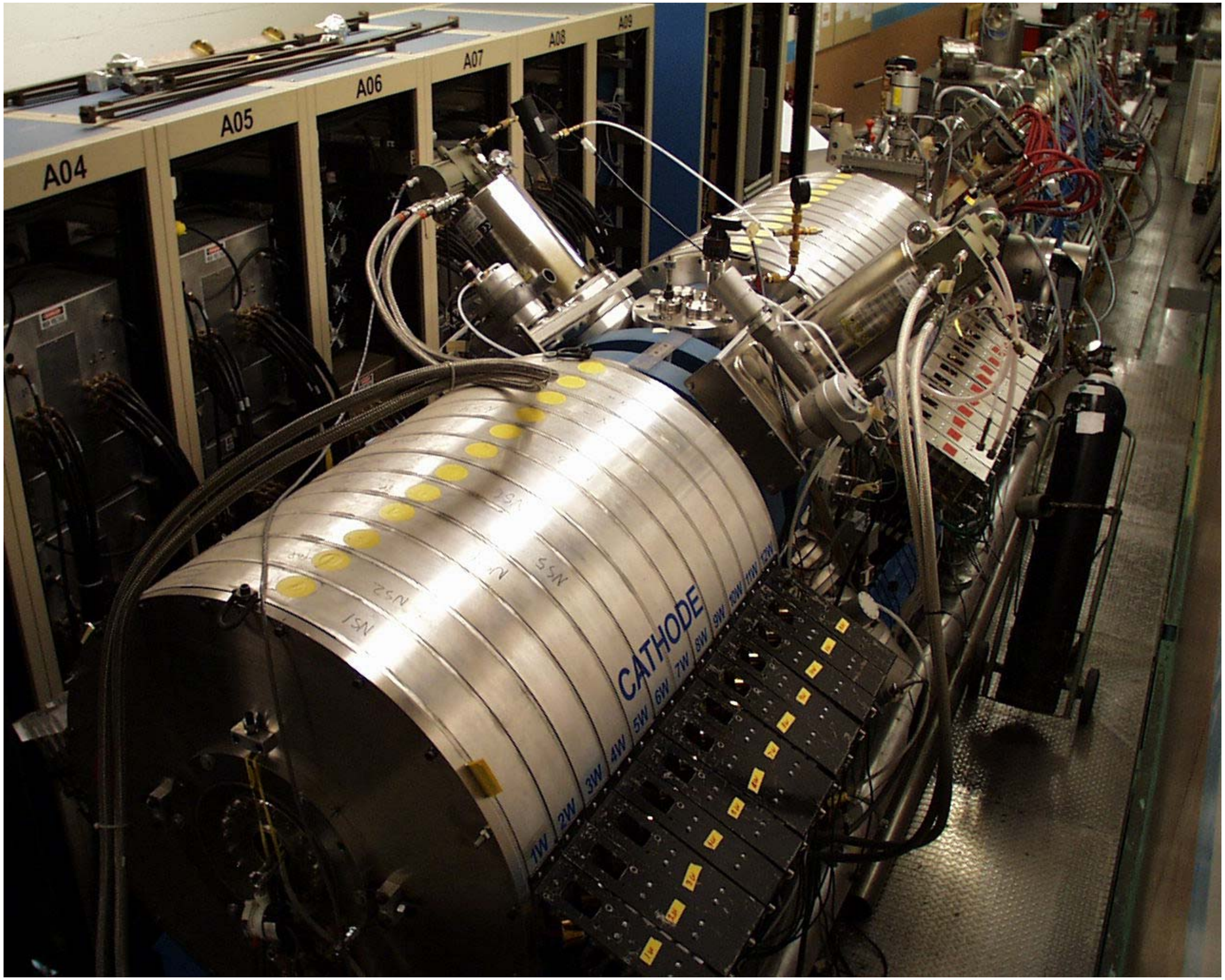


The LLNL design was selected for further development (December 2001)

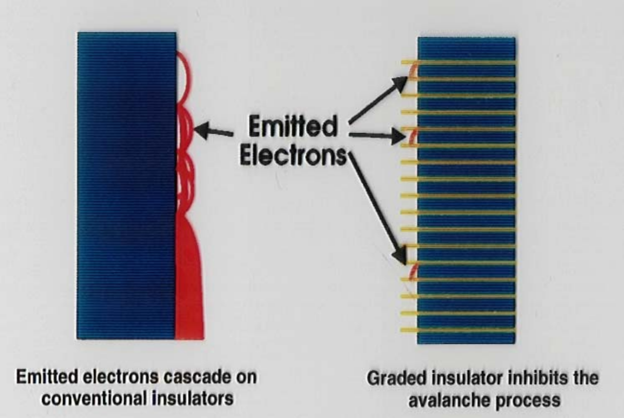
A cryostat housing two quads, and one optimized prototype magnet are being fabricated in FY02

ETA-II Cell Modification

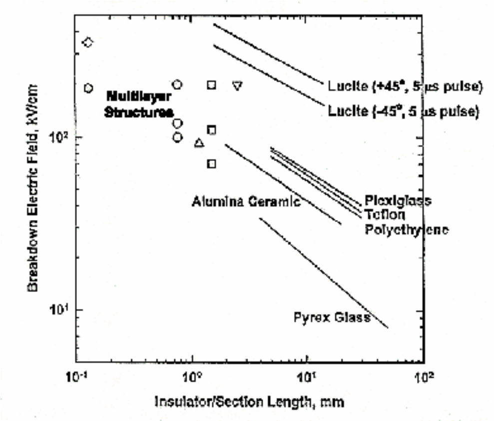
The RTA Injector (1 MeV, 1 KA, 375 ns) is a working example of a short-pulse induction-driven injector



LLNL and Allied Signal Insulator Development

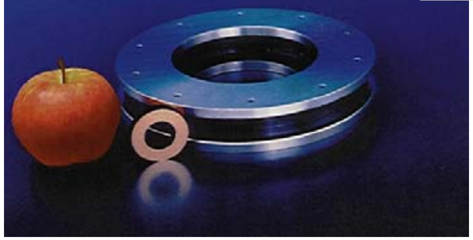


Closely spaced conductors are believed to inhibit the breakdown process



The effect scales inversely with spacing of the conductive planes

The ability to manufacture these structures is being perfected



Insulator Test Cell

Beam Dump

The technology has been demonstrated with beam on ETA-II (175 kV/cm in a high radiation field with no breakdowns)

Induction is used to accelerate high peak currents (up to 1 kA) by inducing longitudinal electric fields in a sequence of gaps

The electric field in the gap does three things:

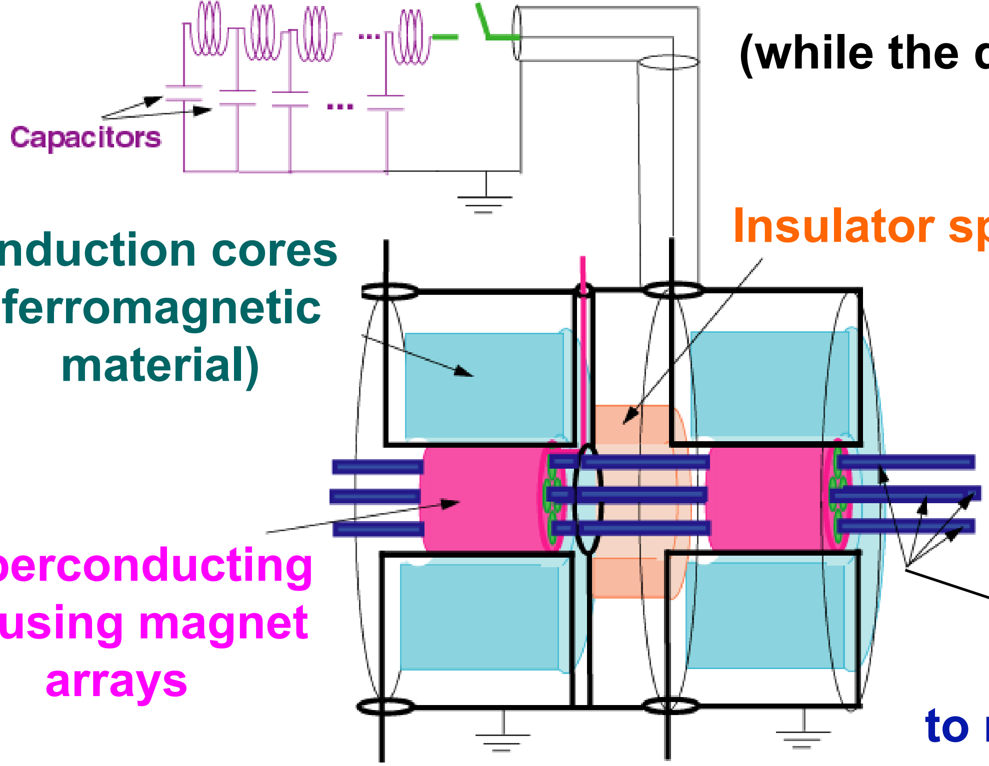
Accelerates the beam

Compresses the beam

Confines the beam longitudinally

(while the quadrupoles confine beam transversely)

Pulse forming network



Insulator spans acceleration “gap”

Induction cores (ferromagnetic material)

Superconducting focusing magnet arrays

Multiple ion beams can share common cores to reduce cost, improve efficiency