National Heavy-Ion Fusion Program Portfolio*

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Outline

- Motivation/requirements/challenges for heavy-ion fusion

- Integrated program approach to address key HIF issues

- Current research

- Next steps needed for heavy-ion driver development:
  - Integrated Beam Experiment (IBX)
  - Integrated Research Experiment (IRE)

- Budget needs for balanced portfolio to provide basis for a heavy-ion driven Engineering Test Facility (ETF)

Heavy Ion fusion is pursued for these reasons:

- Present high energy accelerators exhibit MJ beam energy, high efficiency and durability (particle energies are too high for targets).
- Heavy-ion beams are compatible with indirect-drive targets for which the NNSA program contributes much of the target physics.
- Heavy-ion beams with indirect drive are compatible with long-lasting, thick-liquid-protected chambers.
- Hohlraums can protect fragile cryogenic fuel capsules during injection into hot chambers.
- Clear bore magnets used to focus the beams can avoid line-of-sight damage from target debris, neutrons, and gammas.
- Power plant designs show attractive economics and environmental characteristics for heavy-ion fusion at a few GeV energy.

Nominal top-level requirements for heavy-ion fusion

☞**Competitive cost-of-electricity < 5 cents per kWehr with acceptable environmental/safety characteristics, requiring:**

- **Multiple heavy-ion beams with range ~ 0.03 g/cm2 capable of delivering a total ion beam power ~0.5 PW for ~10 ns into r < 2 mm spots at ~ 5 Hz pulse rate for > 10^9 shots, with efficiencies > 20%, and direct capital cost < 1 B$.**

- **Manufacture of 500,000 heavy ion targets per day with gain > 50 at < 30 cents/target cost using materials that meet accident dose, waste management, and recyclability criteria.**

- **Long life chambers and final focusing magnets (> 3 x 10^8 shots) with low T inventory (<15 g for <1 rem worst case accident dose), and < 0.1 m^3 of long-term radioactive waste disposal per year.**

Significant challenges to realize heavy-ion fusion

Driver: HIF requires well-focused beams of sufficient power to drive high-plasma-energy density experiments and IFE targets

- **Beam quality for focus- emittance growth, electron/gas interactions at high current, evolution of beam distributions over long pathlengths**
- **Maximum-average beam current densities achievable in injection, transport and acceleration experiments for future multi-beam arrays**
- **Longitudinal bunch compression with velocity-tilt after acceleration**
- **Beam perveance (beam space charge potential over ion kinetic energy) and neutralization limits to final focus and chamber transport**
- **Multiple-beam interactions -electrostatic and magnetic beam-beam coupling in the accelerator, and when converging together in the chamber**
- **Need innovation and $ for accelerator component R&D for the IRE and drivers: compact multiple-beam injectors, compact superconducting transport magnet arrays, agile waveform solid state pulsers, low cost/ low loss ferromagnetic core materials, high gradient and low cost insulators.**

Challenges (Continued-heavy-ion driver)

- HIF driver Issues are more economic than basic feasibility: e.g. halo ion losses may be reduced with larger gaps between beam and pipe wall, at expense of larger focusing magnets and induction cores.

- Most uncertain current issue is achievable focal spot size consistent with bunch compression, focal length, target gain, chamber gas, ion stripping, and plasma neutralization.

→At present budgets, we address many of these issues cost-effectively through separate specialized experiments using existing equipment.

→Achievable focal spot size depends on cumulative beam quality changes integrated along entire path from source to target

→Need more-integrated experiments and modeling, more technology development to reduce IRE and driver costs→ more $

Challenges- heavy-ion chamber/final focus magnets

- **Rapid chamber clearing** (vapor and droplets) consistent with required pulse rates, ion beam propagation and focusing

- **Final focus magnet** (and other interface structures) shielding/ activation /and waste generation

- Management of **target debris in beam-lines**

- **Recovery of hohlraum materials** from chamber

- **Safety**- measure/understand potential release/mobilization of activated fluorine and hohlraum components from Flibe spills in worst-case accidents

Challenges – heavy-ion targets, design and fabrication

- Identify and develop methods for low cost mass manufacture

- Identify acceptable hohlraum materials (high opacity cocktails for hohlraum walls, low density high-Z foams for radiators, ability for recovery and recycle from the chamber)

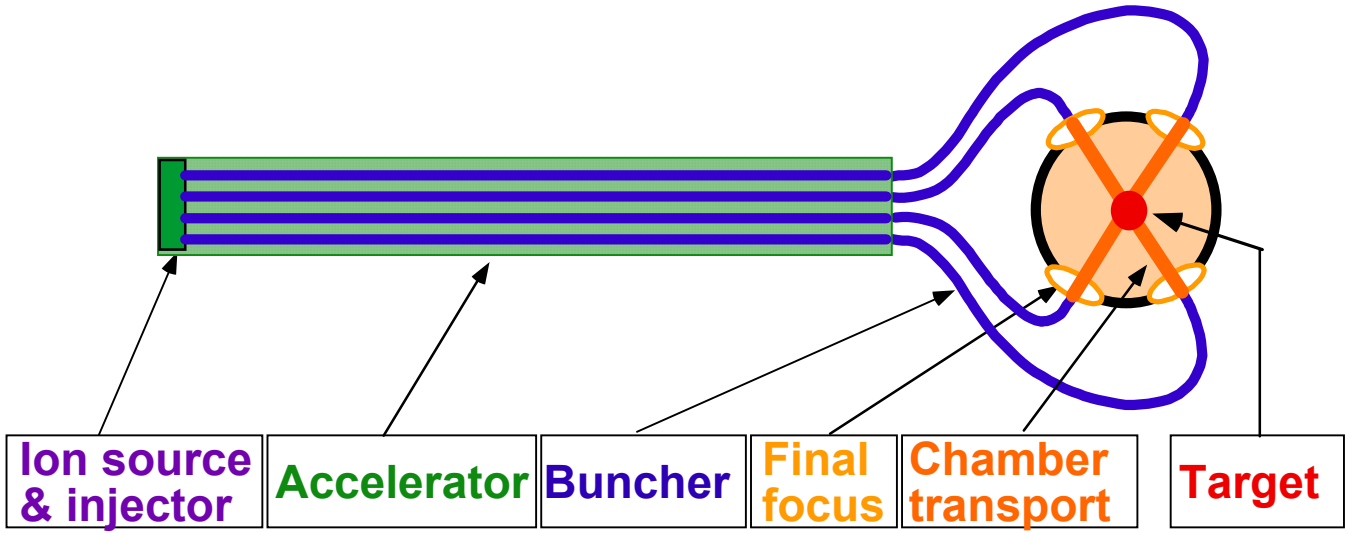
- Low vulnerable tritium inventory in the target factory (reduce time for filling and beta-layering)

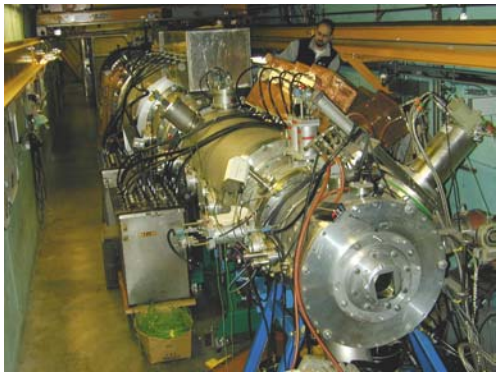
- Optimize target designs for higher gain, larger spot size, larger tolerance for aiming errors, single-ended illumination, simpler components for manufacturing

- Methods to inject and track HIF targets, and with small-angle ion beam steering/correction at 5 Hz repetition rates

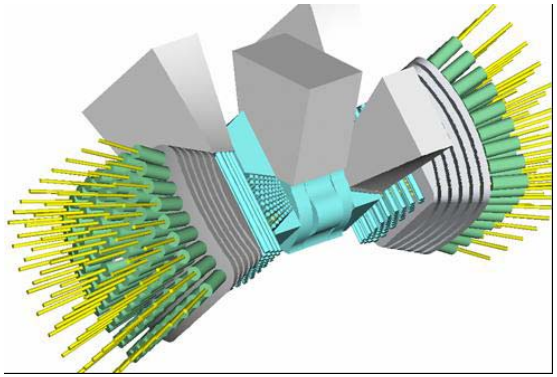
Integrated program approach to address key HIF issues

Success of heavy-ion fusion depends on an integrated program to achieve accelerators, chambers and targets *that work together*

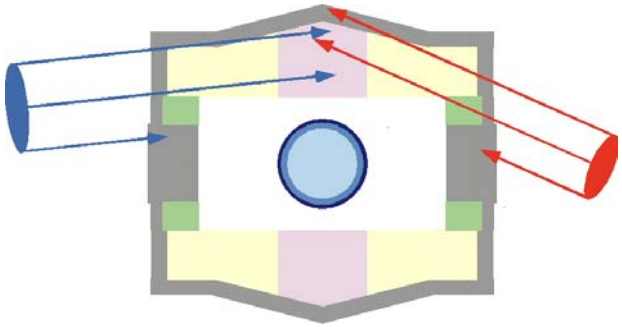




Beams at high current and sufficient brightness to focus



Long lasting, low activation chambers that can withstand 300 MJ fusion pulses @ 5 Hz



High gain targets that can be produced at low cost and injected

Although separately funded from OFES science and technology divisions, HIF driver, chamber and target groups work together

- **Intense ion beam science and enabling accelerator technology:**
  - We implemented an innovative management structure-the HIF Virtual National laboratory with LBNL, LLNL and PPPL
  - with support from UMd, NRL and SNL, MRC, and MIT

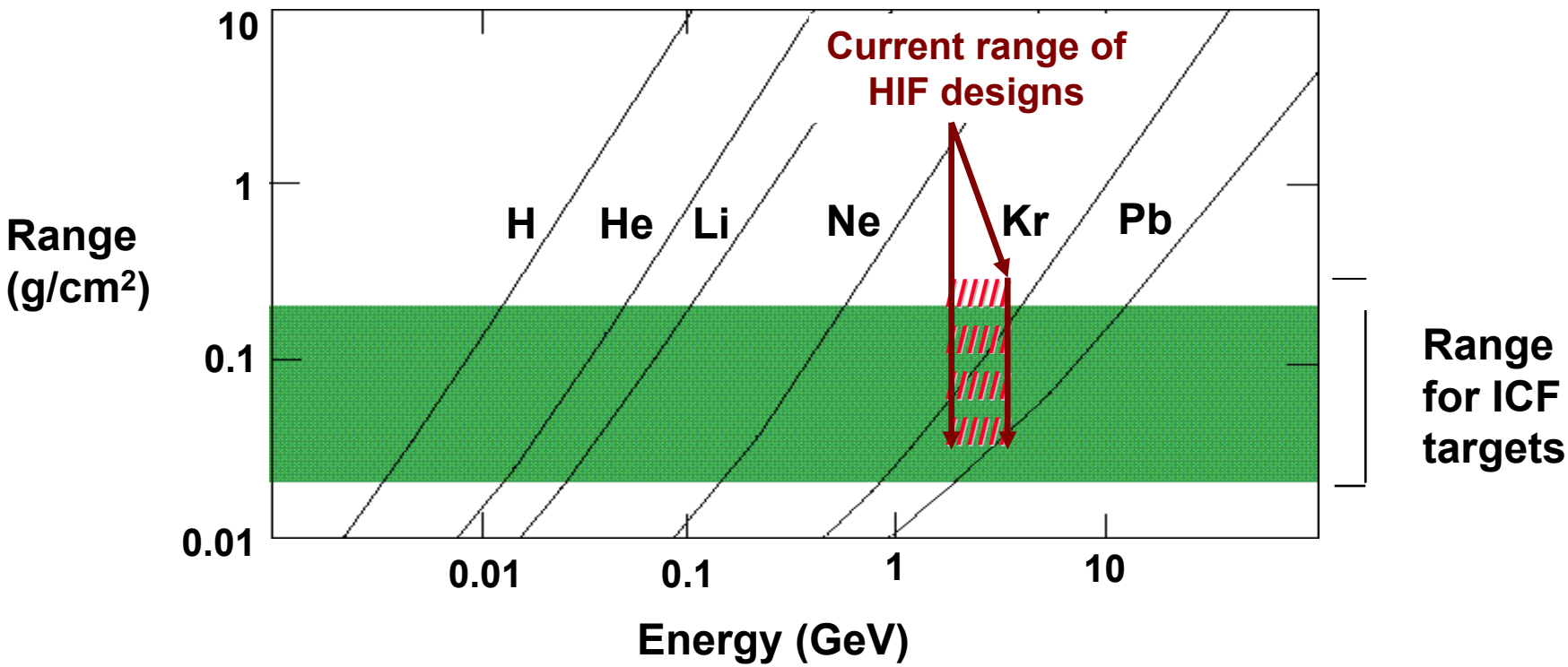
- **We work together with groups working on heavy ion chambers and targets:**
  - Virtual Lab for Technology : HIF chamber R&D, systems analysis
  - LLNL/GA/LANL : HIF target science and technology.

A balanced HIF program devotes most effort to highest confidence approach, with innovation on promising power plant alternates.

Accelerator	Target	Focusing	Chamber
Induction Linac	Indirect Drive, Distributed Radiator	Ballistic, Neutralized	Thick-Liquid-Protected Wall
RF Linac + Storage Ring	Indirect Drive, Hybrid Target	Ballistic, Vacuum	Thin-Liquid-Protected Wall
Induction Recirculator	Indirect Drive, Fast ignition	Pinch Modes	Solid Dry Wall
Dielectric Wall Accelerator	Direct Drive, Aspherical		Granular-Solid Flow Protected Wall

Approach: heavier ions →higher voltage →lower current beams

- Collective effects are reduced with heaviest ions →more energy/particle →fewer particles (~10^{15} total ions).
- Cost tradeoff with lower mass ions →lower voltage, lower cost accelerators. Compromise with 2.5 GeV Xenon.
- Modern superconducting magnets can adequately confine the beam against its space charge forces during acceleration.



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:

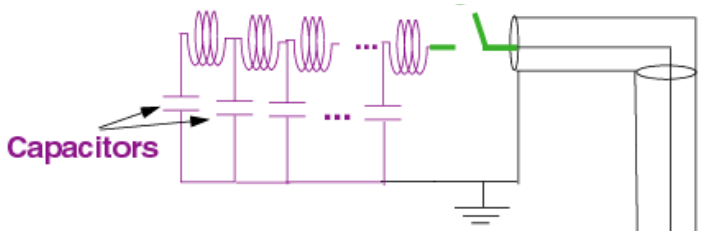
Accelerates the beam

Compresses the beam

Confines the beam longitudinally

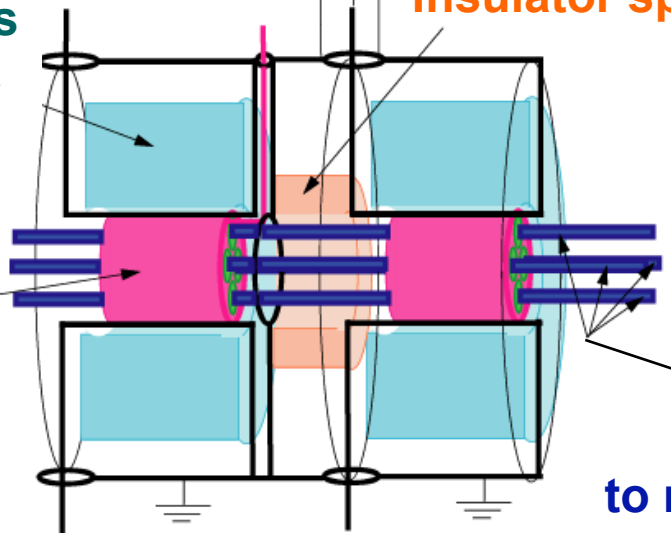
(while the quadrupoles confine beam transversely)

Pulse forming network



Insulator spans acceleration "gap"

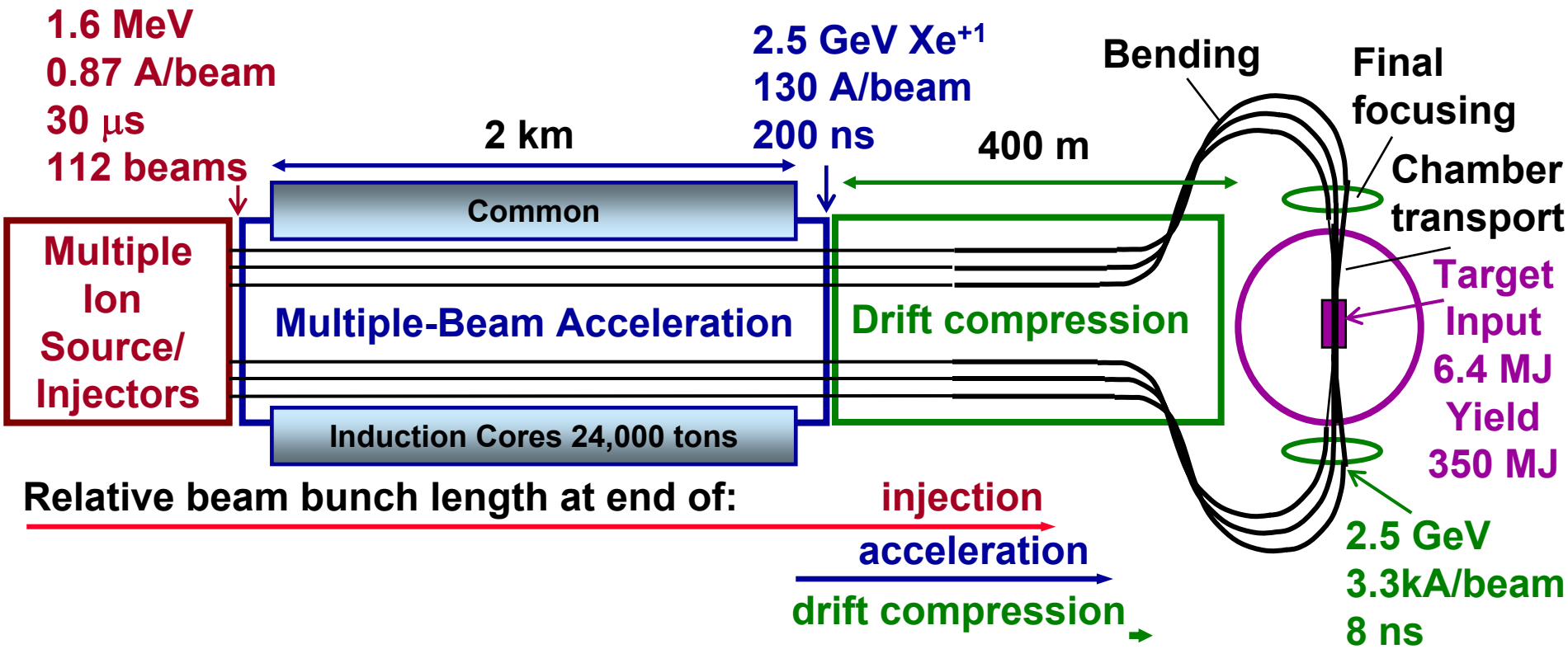
Induction cores (ferromagnetic material)



Superconducting focusing magnet arrays

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

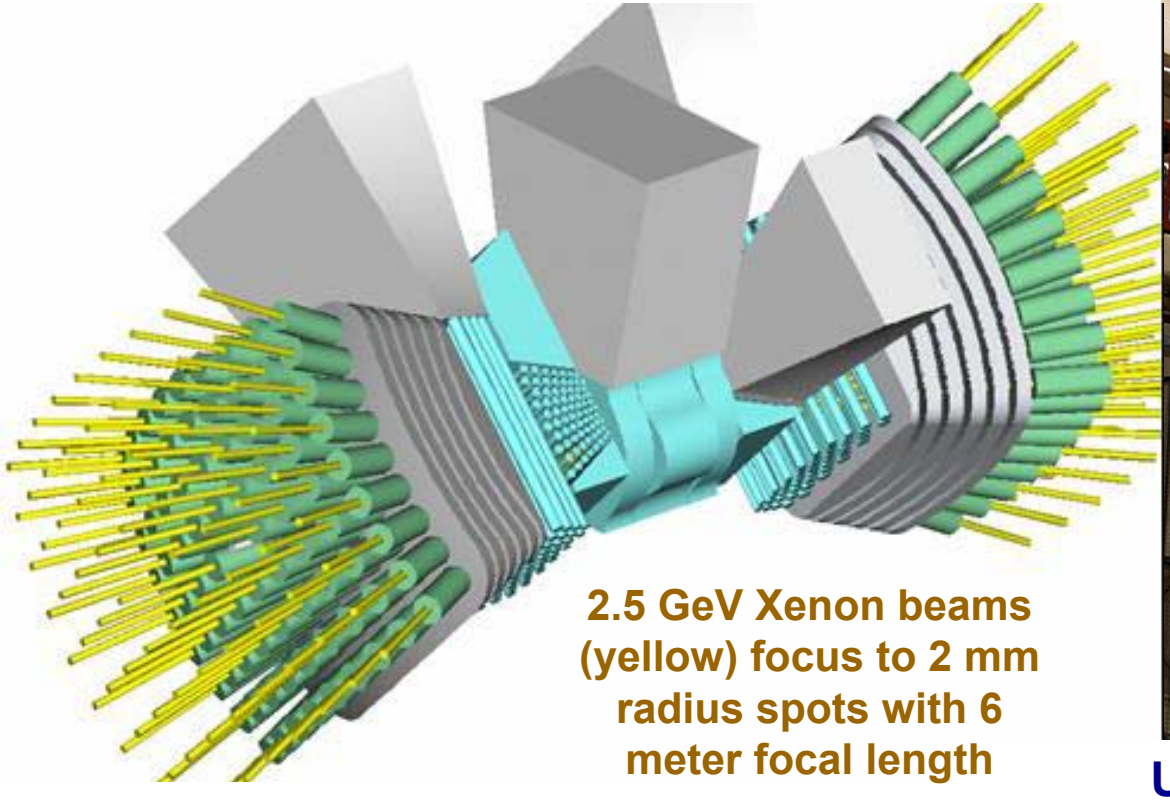
Reference 112-beam quad-focused driver: 6.4 MJ, 2.5 GeV Xe^{+1}, 24,000 tons induction cores, $720M hardware, $1 B direct,$2.1 B tot capital cost



Bunch length compression is integral part of HIF concept

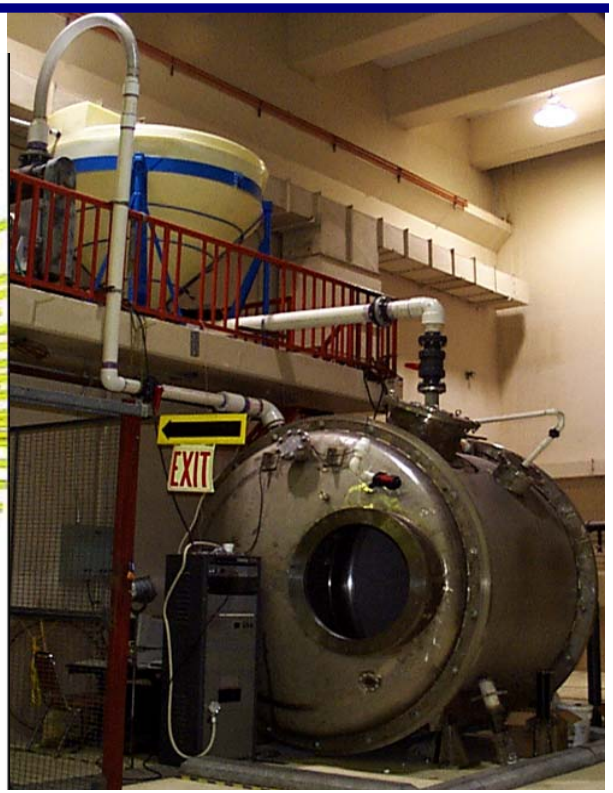
Within accelerator, average induction pulse ~300 ns
Target requires pulse duration of ~10 ns

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



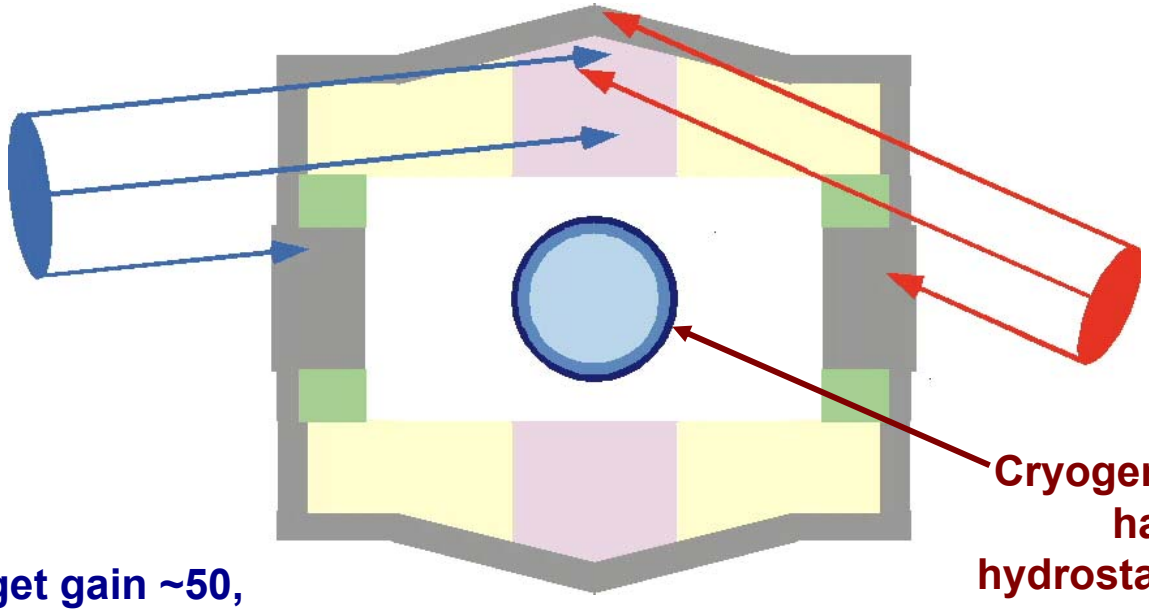
2.5 GeV Xenon beams (yellow) focus to 2 mm radius spots with 6 meter focal length

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.

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,
- 6.4 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 equivalent)
- Foot pulse at ~75% range.

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

HIF policy on fast ignition: continue to update assessments on potential impact for HIF

Approach – Heavy Ion Fusion Strategy

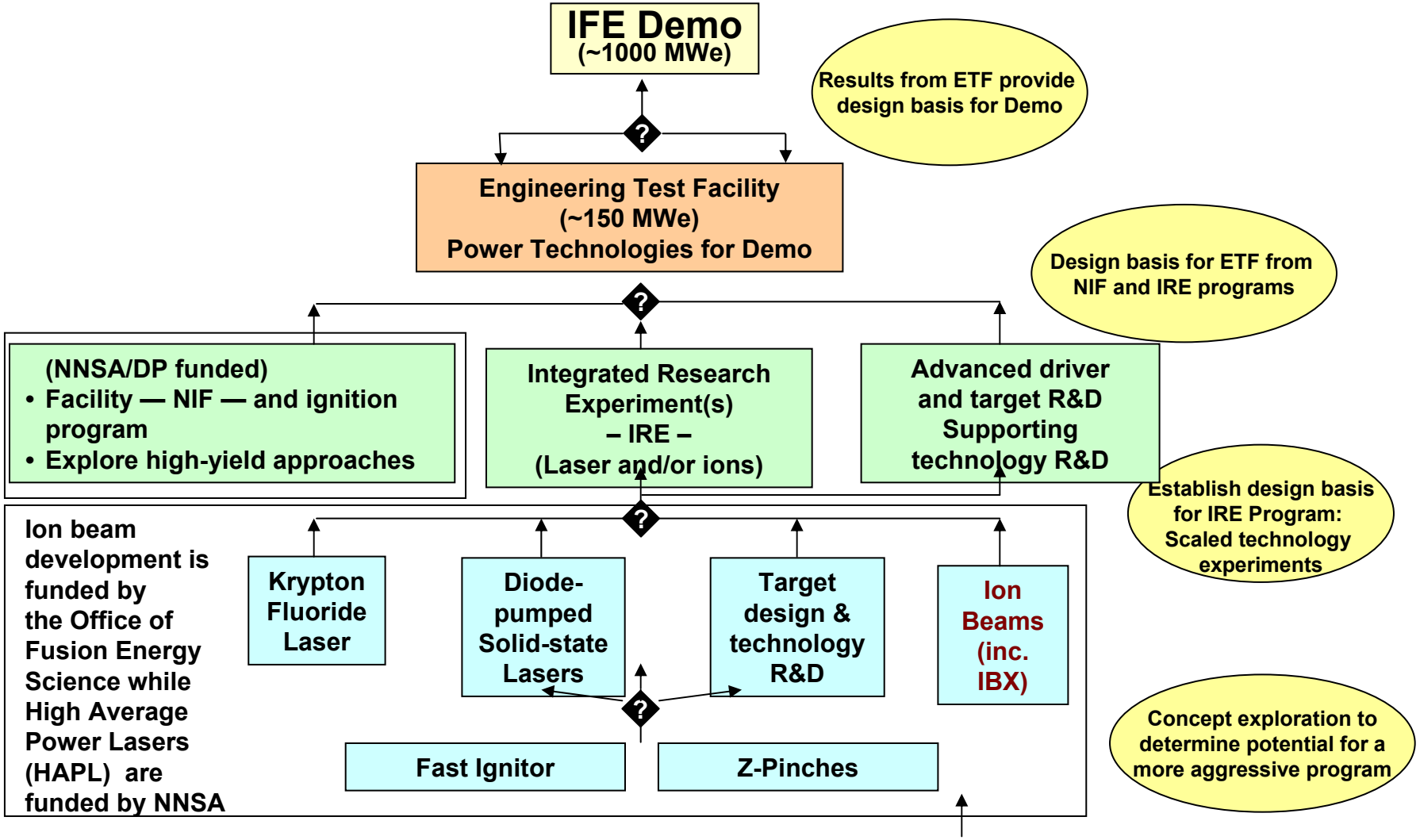
Present: Attack important physics in short experiments
~ 1 amp level at ~ 0.5-1 MeV

Next: Integrated Beam Experiments (**IBX**) ~ $50M
Single beam (possibly upgradeable to 4-9)
Source to target physics
~5-20 MeV

Longer Term: Integrated Research Experiments (**IRE**) ~$200-300M
Multiple Beams (32-64) with driver technology
Source to target physics
200-800 MeV

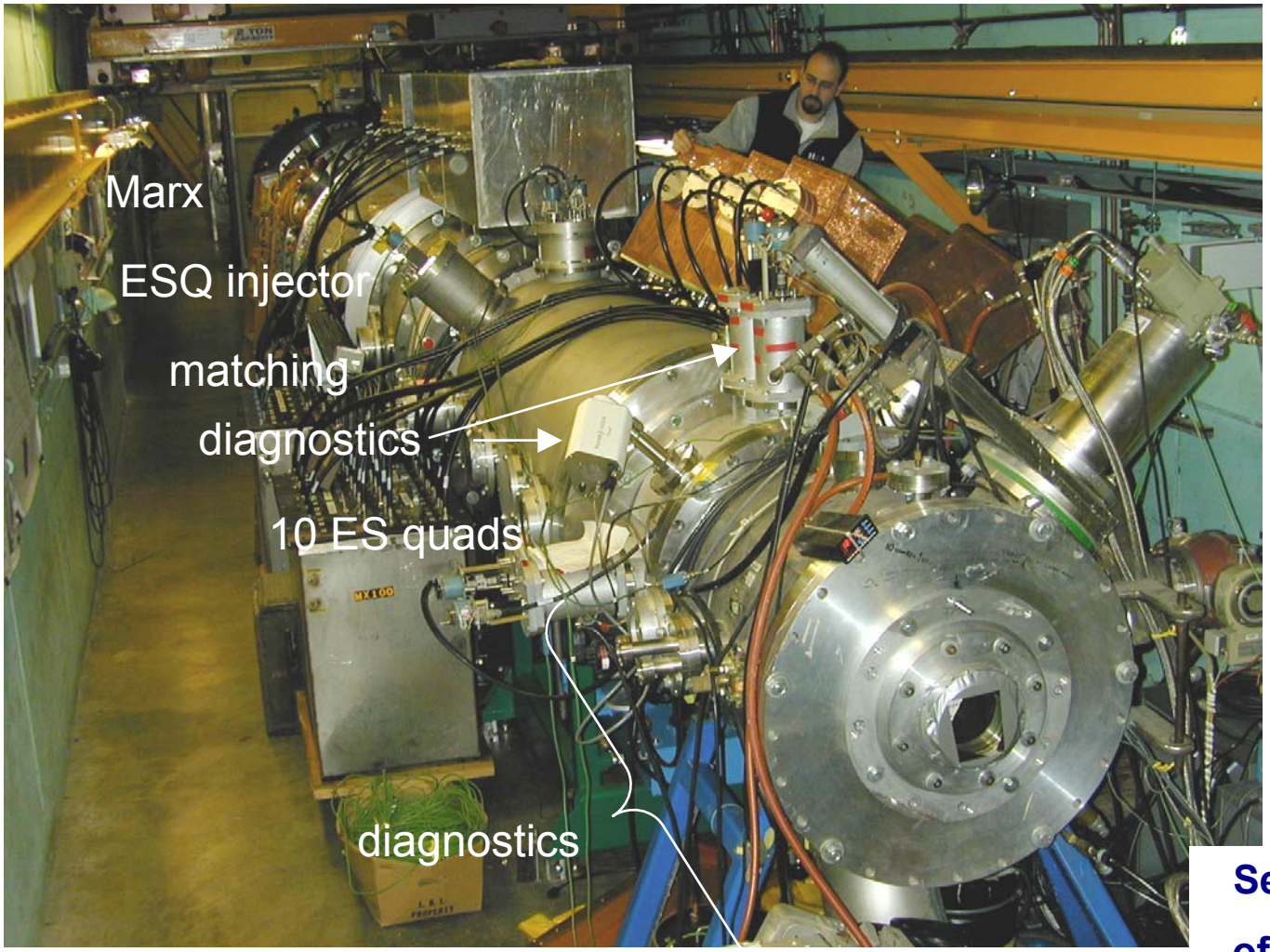
Then, after NIF: Engineering Test Facility (**ETF**) ~$2-3B
(***NIF=National Ignition Facility***)
Full-scale engineering test
Upgradeable from IRE to driver prototype
Test many chambers with 1 accelerator

IBX will complete the proof-of-principle-level phase of research for HIF. The following heavy-ion IRE, together with NIF and other R&D, would provide the basis for an ETF



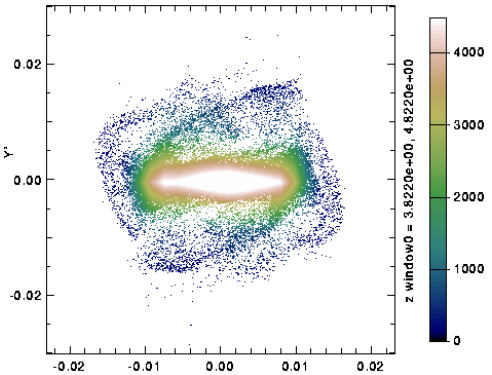
Current Research

High Current Experiment (HCX) began operation January 11, 2002.



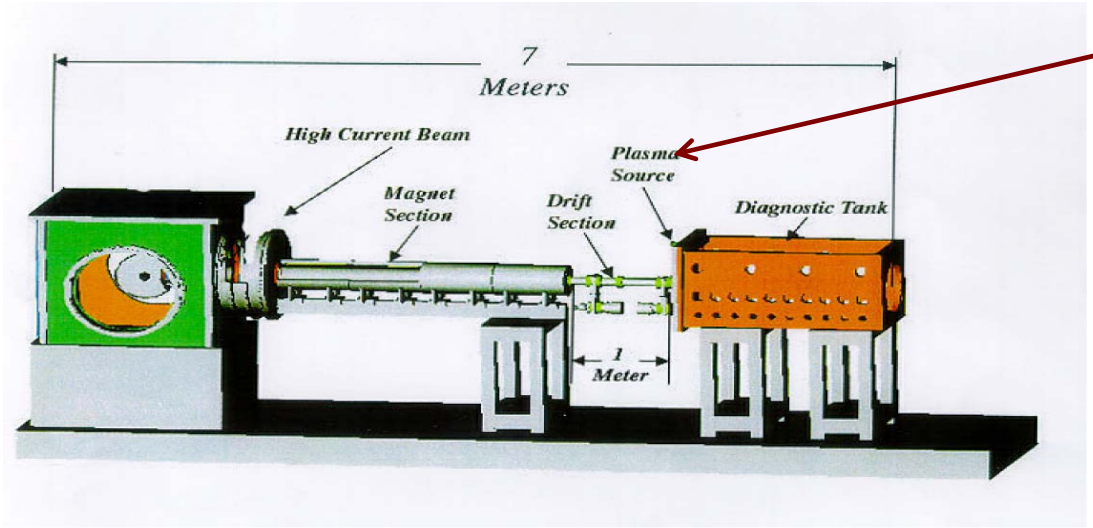
Transport

- aperture limits
- electrons
- gas effects
- halo formation
- steering

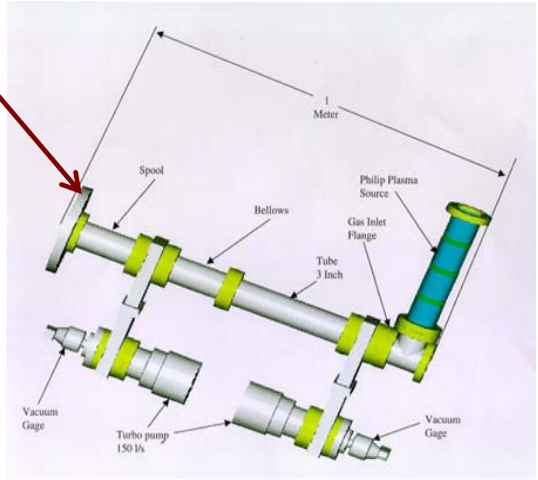


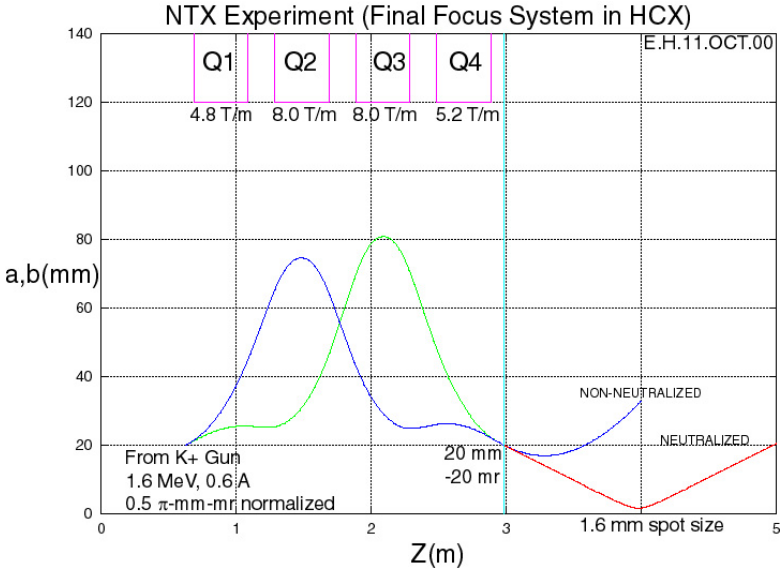
Self-consistent simulation of HCX beam phase space

The Neutralized Transport Experiment (NTX) will study ballistic final focus with plasma neutralization



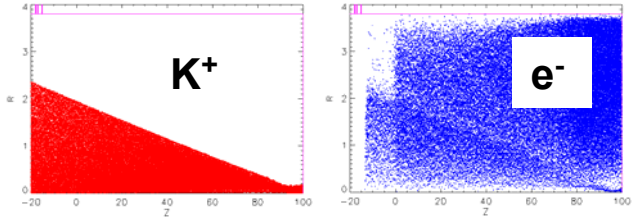
PPPL ECR plasma source



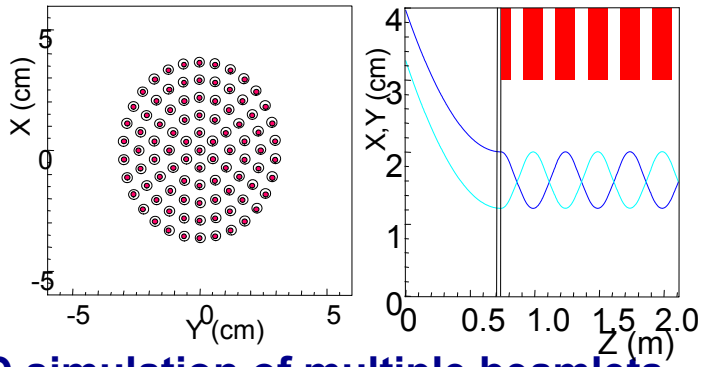


NTX gun has achieved design current 80mA @ 0.4 MeV and very low measured emittance $\varepsilon_N \leq 0.1\ \pi$ mm-mr.

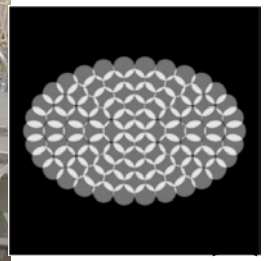
Simulations predict 99% neutralization



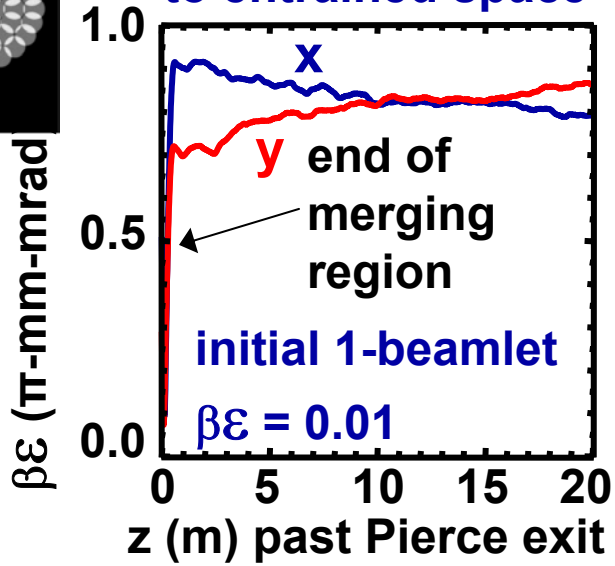
Research on high-brightness sources and injectors commenced on LLNL test stand completed Dec 2001



3-D simulation of multiple beamlets



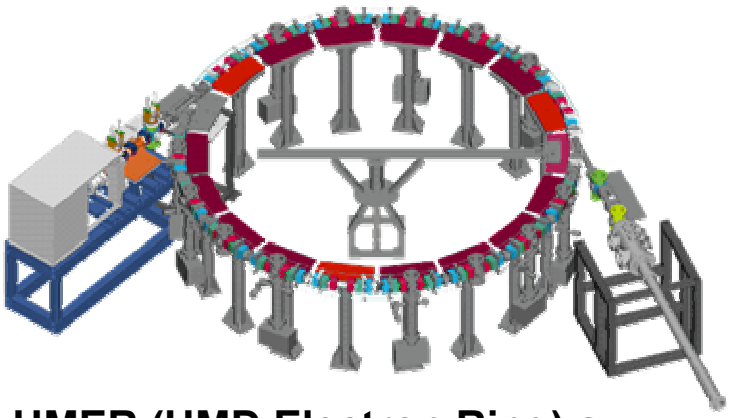
emittance grows due to entrained space



New STS500 KV facility at LLNL will explore a new compact injector concept useful for all future experiments, as well as feasibility of high-brightness plasma sources.

University of Maryland Work

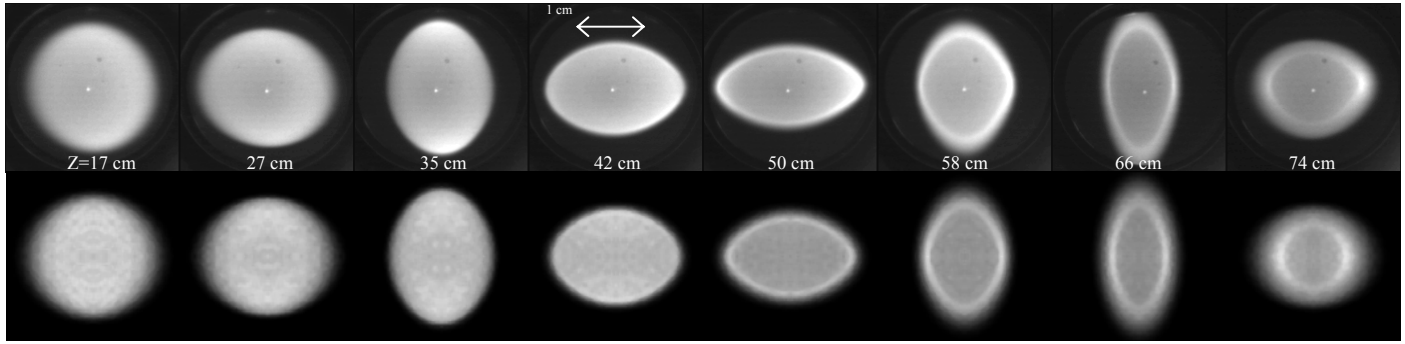
- Equipartitioning in HIF-scale beams.
- Mechanisms for growth of energy spread.
- Benchmarking of HIF computer codes
- Effects of skew quadrupoles, and beam-based corrections to skew quad errors.
- Exploring collimation and wave propagation over long-scale lengths.
- Generation of Perturbations; Studies of Instabilities, mixing and dissipation.



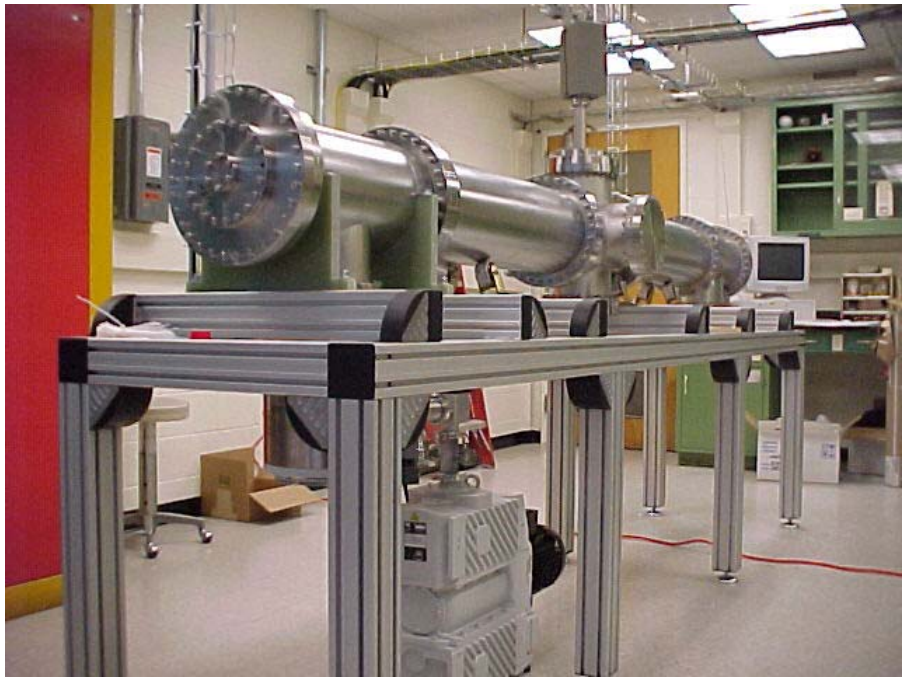
UMER (UMD Electron Ring) a low-cost research platform for intense beam physics at very high intensity with strong focusing and dispersion.

Experiment

WARP Simulation



Objective: Simulate collective processes and transverse dynamics of intense charged particle beam propagation through an alternating-gradient quadrupole focusing field using a compact laboratory Paul trap.

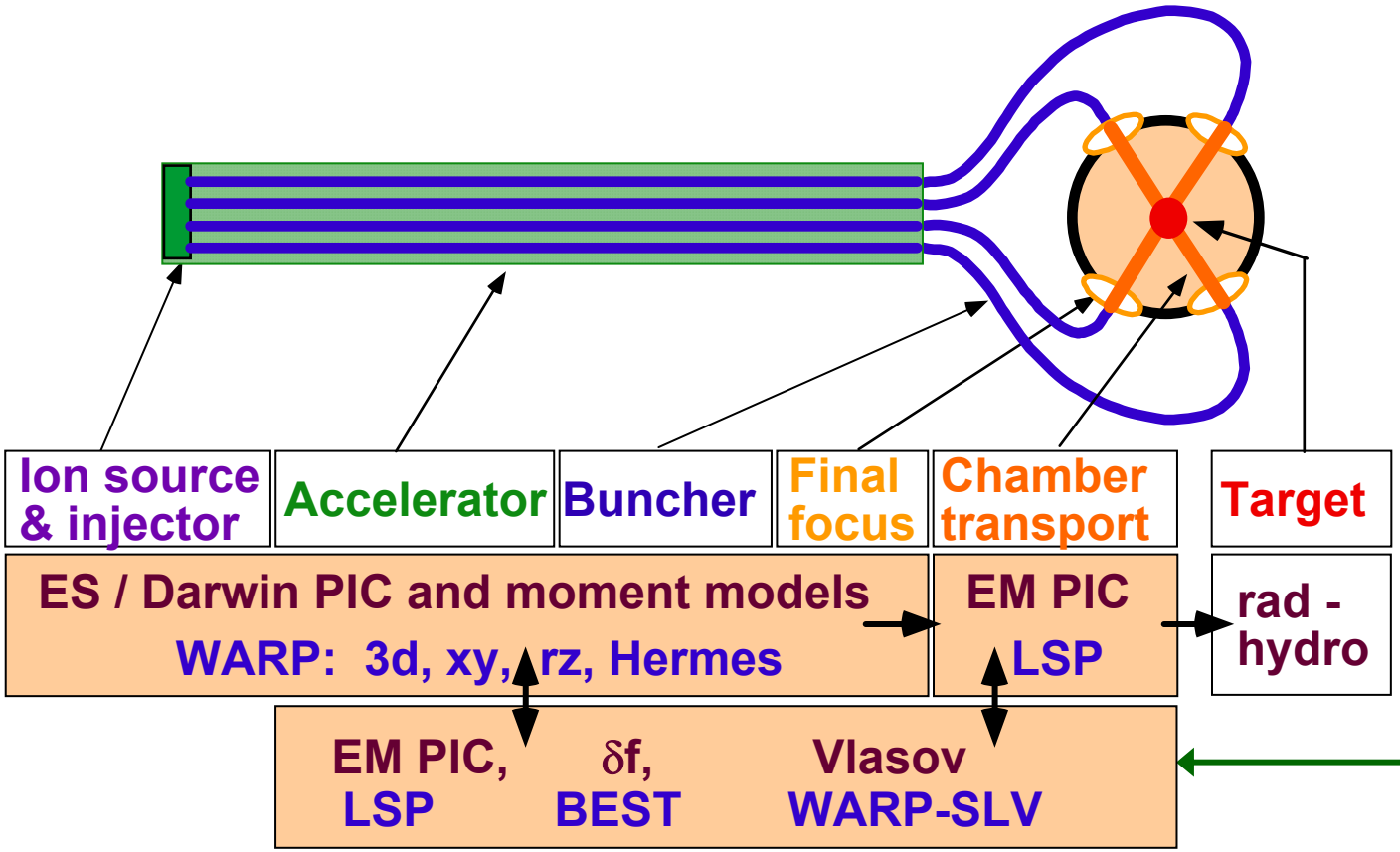


Paul Trap Simulator Experiment vacuum chamber.

Approach: Investigate dynamics and collective processes in a long one-component charge bunch confined in a Paul trap with oscillating wall voltage

Laboratory preparation, procurement, assembly, bakeout, and pumpdown of PTSX vacuum chamber to 5.25×10^{-10} Torr (May, 2002).

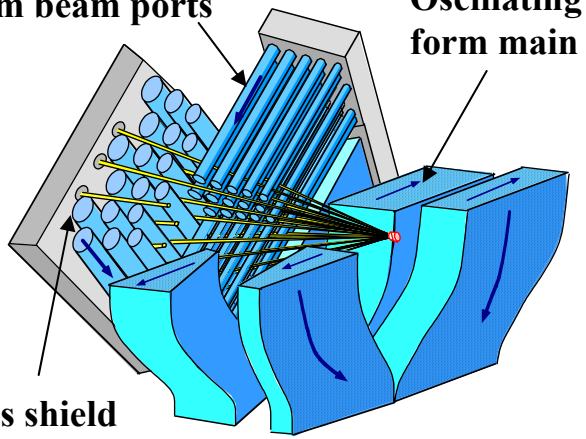
The heavy-ion program relies strongly on theory and advanced computing to model beams from source to target

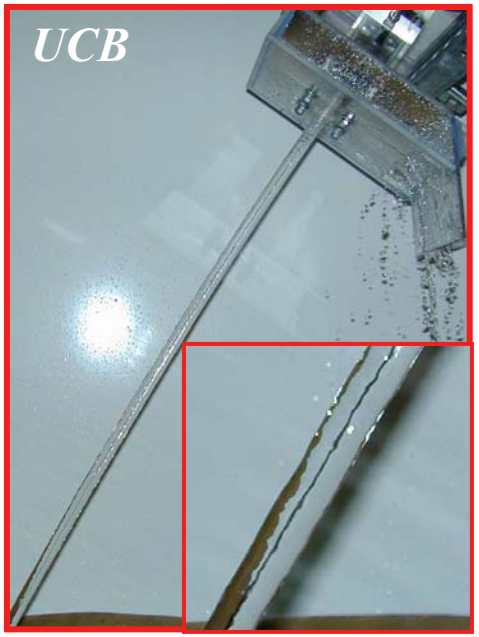


Track beam ions consistently along entire system

Study instabilities, halo, electrons, ..., via coupled detailed models

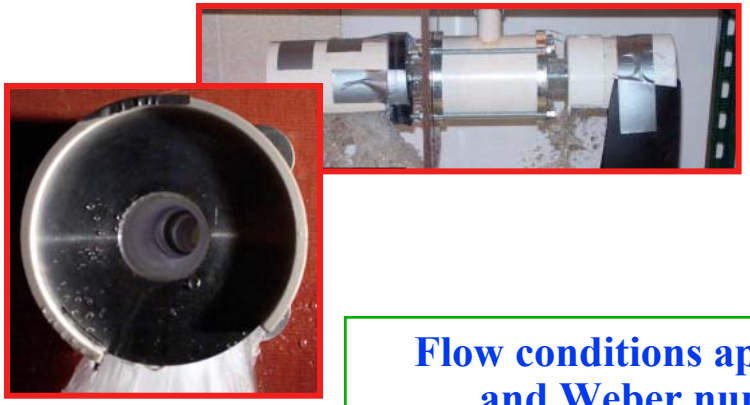
Current research on thick-liquid protected chambers





Highly smooth cylindrical jets

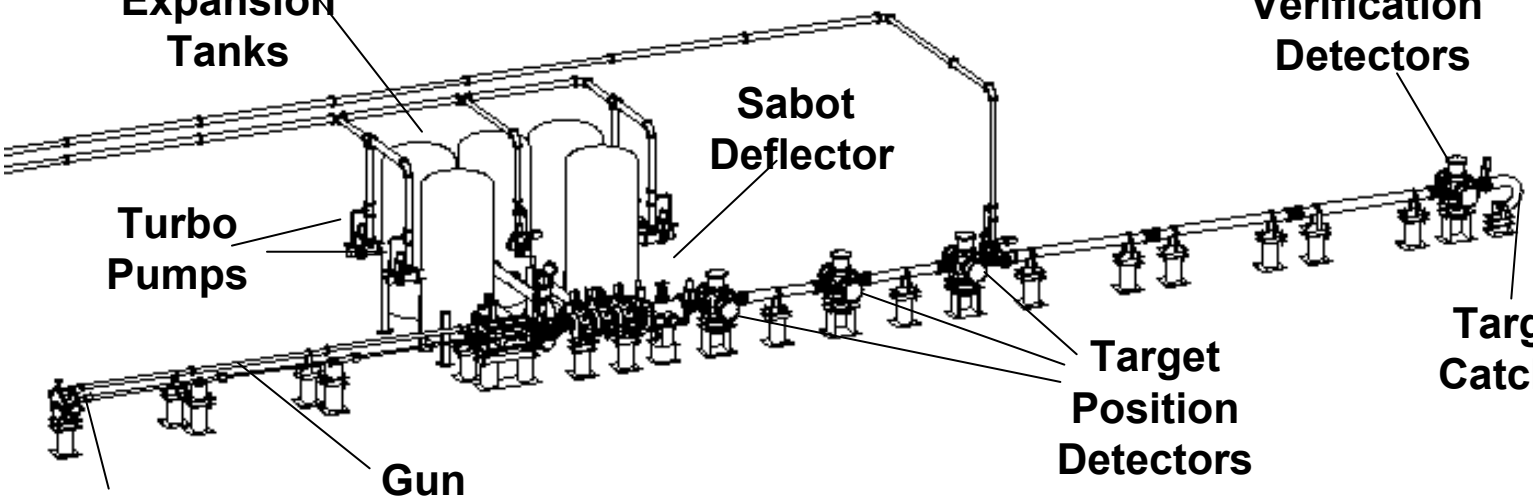
Slab jet arrays with disruptions



Vortices

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

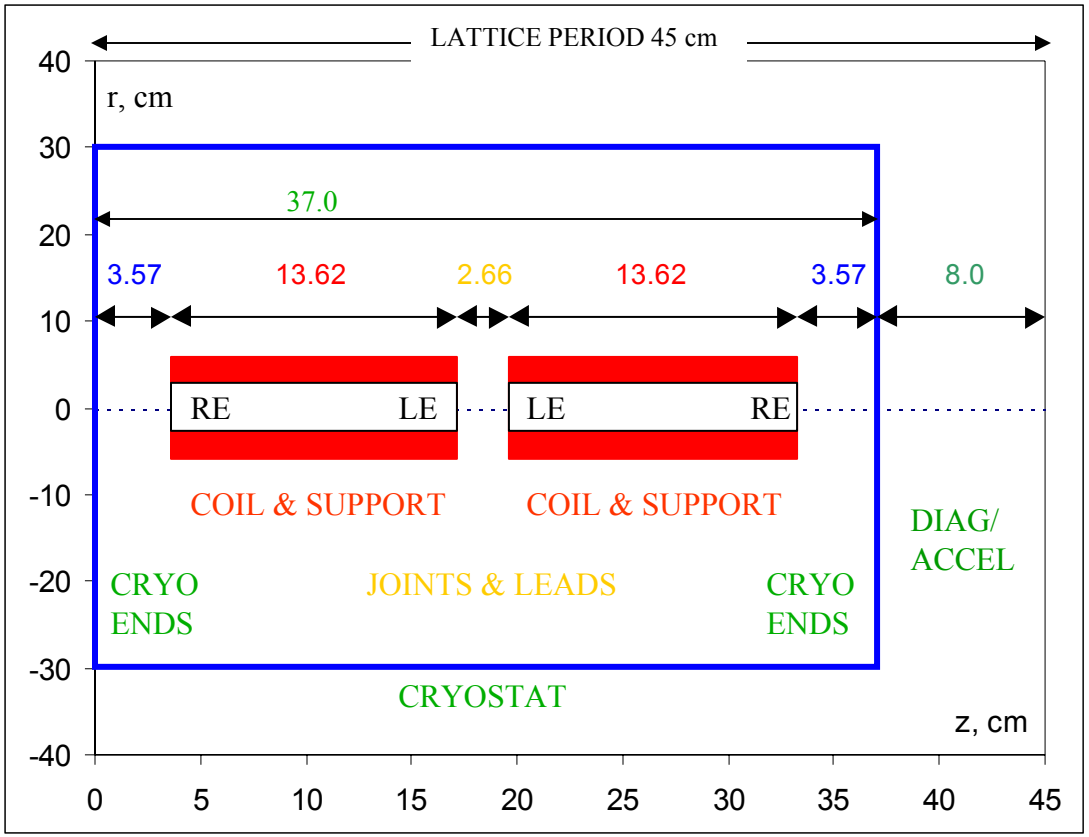
Injection System procurement is underway

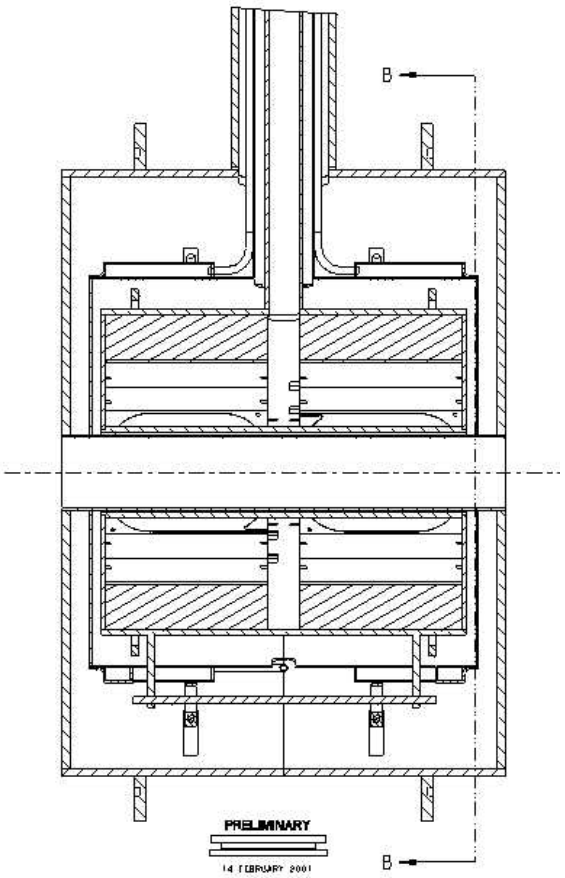


Serves both heavy ion and laser driven target designs

Phased approach - single shot with single-axis tracking (CY02) then rep-rated and full tracking (CY03)

LLNL Cryostat Design for 2 quads per unit suitable for use in HXC experiments





Next steps needed for heavy-ion driver development:

- **Integrated Beam Experiment (IBX)**
- **Integrated Research Experiment (IRE)**

Roles of the IBX and IRE in heavy-ion fusion strategy

IBX (~ $50 M): Use existing technology to expedite integrated beam physics: measurements and simulations of beam distribution evolution through injection, acceleration, drift compression, final focus and chamber propagation with plasma neutralization.

→ The role of the IBX is to increase confidence that the next step, the IRE, will be able to compress and focus beams to >TW/cm^2/beam sufficient to drive a variety of important ion chamber and target experiments.

IRE (~$250 M): Prototype multiple beam technology, efficiency, rep-rate at unit costs that scale to competitive power plant requirements. Drive several experiments: multiple beam chamber transport, target injection @5Hz bursts, foot-beam coupling and symmetry in hohlraums @ 100 eV.

→ The role of the IRE is to provide the basis for an ETF through improved accelerator technology integrated with chamber and target experiments (no-yield). *The IRE thus gives a key focus for heavy-ion chamber and target research in the program over the next 8-10 years.*

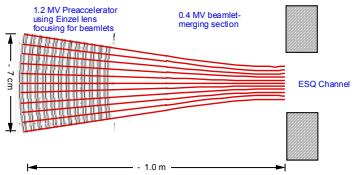
Our next-step vision

Larger Beam Brightness → Smaller Focal Spots → Higher Target Gain

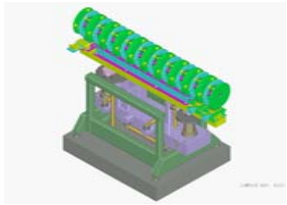
$B = I_{beam} / (\pi\, \varepsilon_x\, \varepsilon_y)$ → W/cm2 → smaller spots r_f → lower $E_{driver} \sim r_f^3$

NOW (next three years)

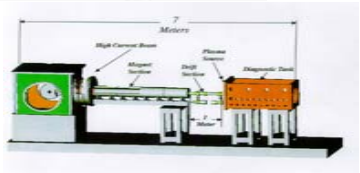
Brighter sources/ injector



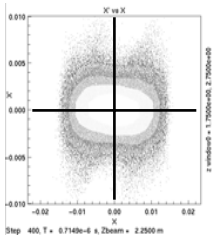
Maximum <J >, B_n Transport



Beam neutralization → min ε-limited focus r_f

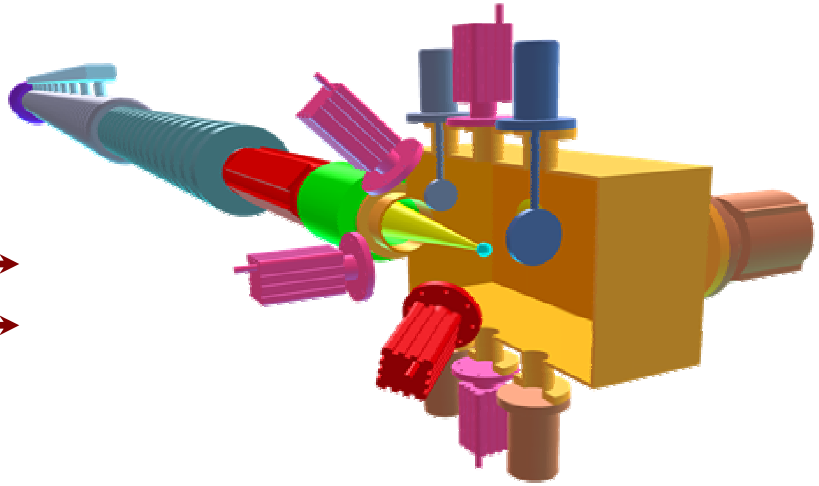


Theory/simulations



NEXT STEP

Integrated beam experiment (IBX)

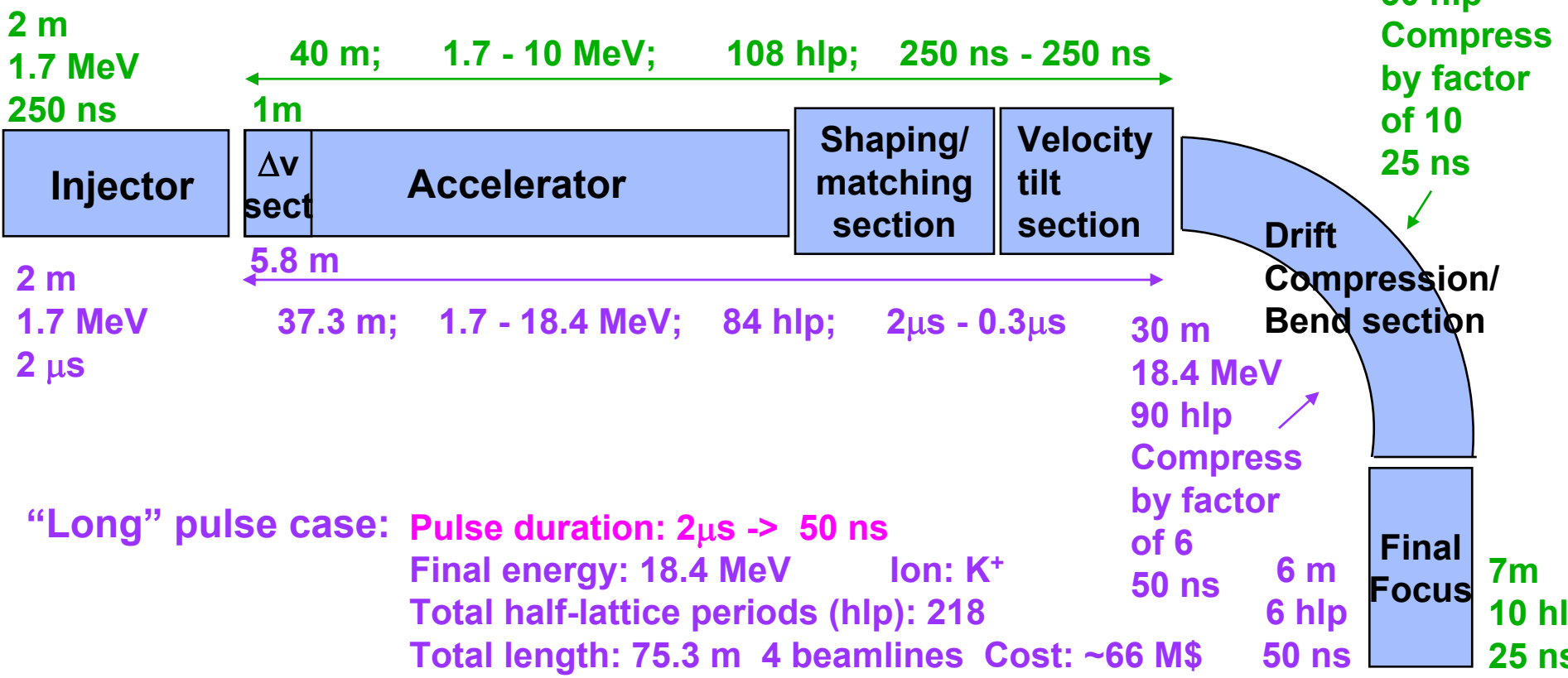


Injection, acceleration, drift compression and final focus to test source-to-target integrated models

IBX workshop considered two cases for IBX

Short pulse case:

Pulse duration: 250 ns -> 25 ns
Final energy: 10 MeV Ion: K^+
Total half-lattice periods (hlp): 148
Total length: 64 m 1 beamline Cost: ~38 M$



"Long" pulse case:

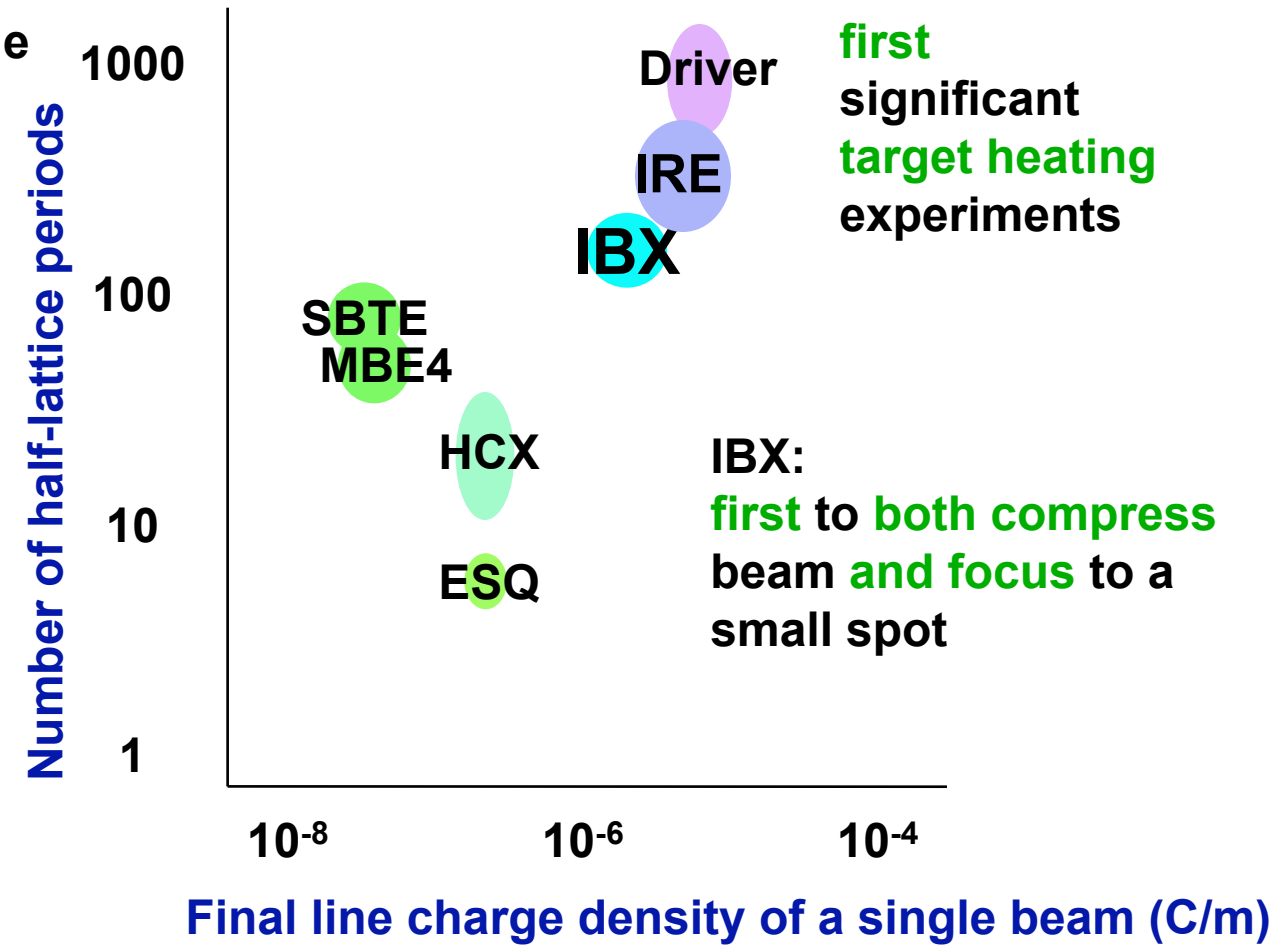
Pulse duration: 2μs -> 50 ns
Final energy: 18.4 MeV Ion: K^+
Total half-lattice periods (hlp): 218
Total length: 75.3 m 4 beamlines Cost: ~66 M$

IBX is a logical step in a progression of HIF experiments

SBTE:
stability of space-charge dominated beams

MBE-4:
multiple beams and simple pulse compression

HCX and ESQ:
line charge comparable to initial line charge in driver; electron effects



IRE:
first significant target heating experiments

IBX:
first to both compress beam and focus to a small spot

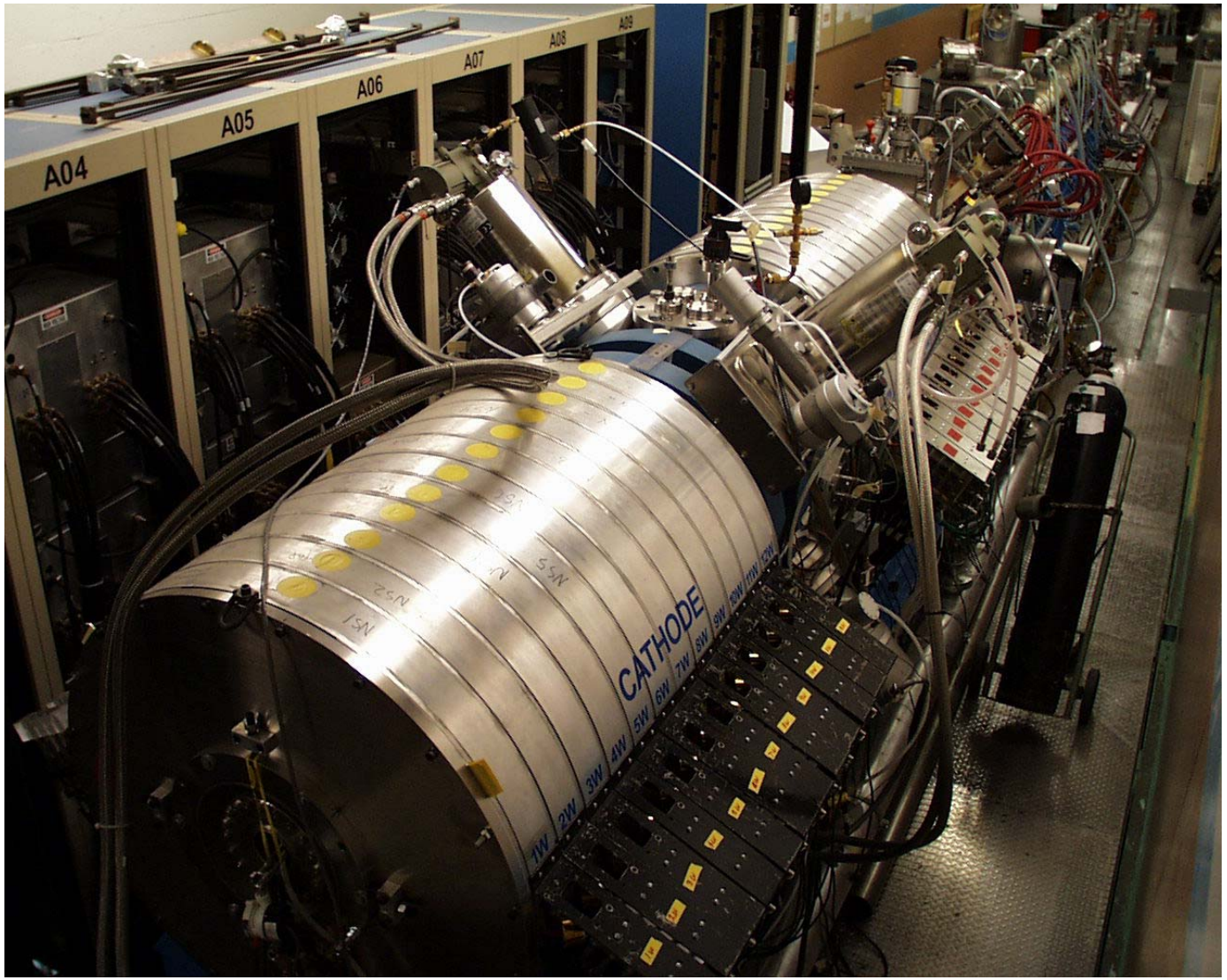
We believe we can build a suitable, science-driven IBX using technology within our experience base

- Experience with a short-pulse injector RTA (Relativistic Two-Beam Accelerator) in Bldg 58 at LBNL

- Experience with 2 microsec induction modules for a 20 MeV, 80 kJ induction linac DARHT (Dual Axis Radiographic Hydrotest Facility)

- Experience with compact, high gradient superconducting quadrupoles

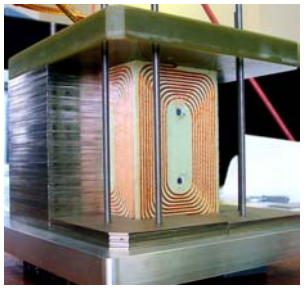
The RTA Injector (1 MeV, 1 KA, 375 ns) is a working example of a short-pulse induction-driven injector



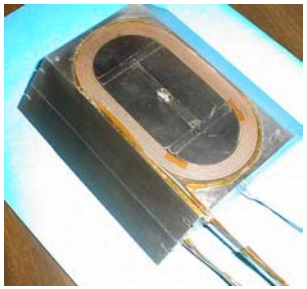
Superconducting magnet development FY01-02

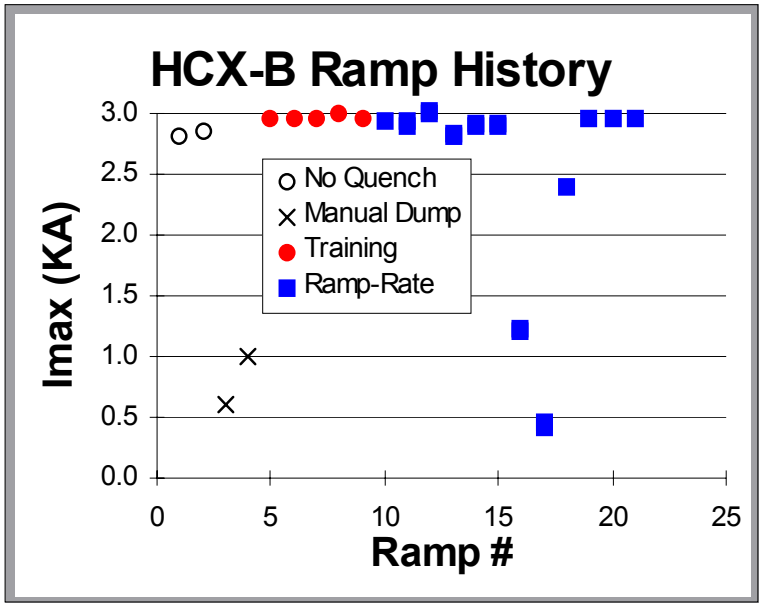
Four prototypes fabricated and tested

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

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

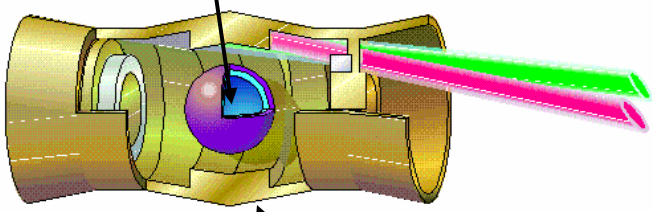
HIF Target Design (LLNL-OFES)

Injection/fabrication R&D (VLT-OFES)

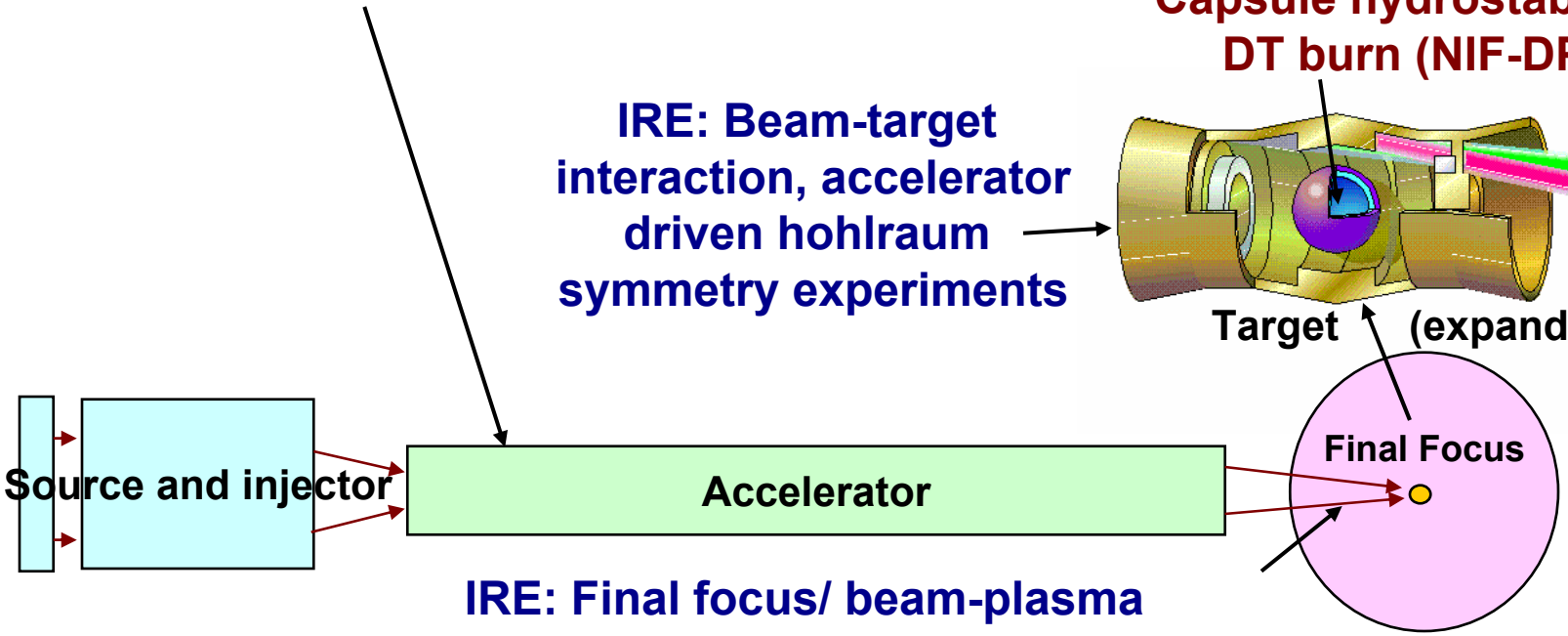
Capsule hydrostability/ DT burn (NIF-DP)

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

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

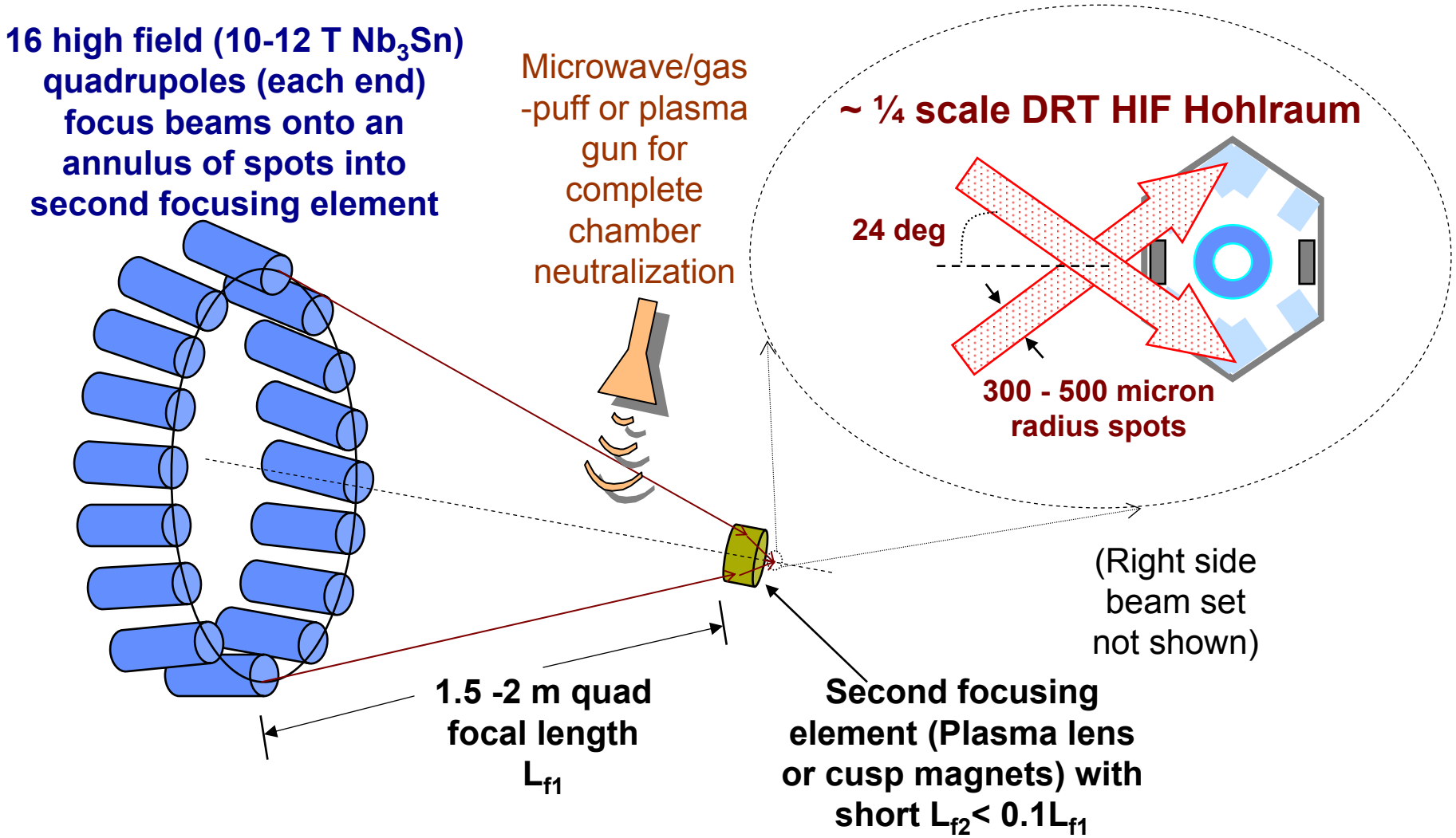


Target (expanded view)

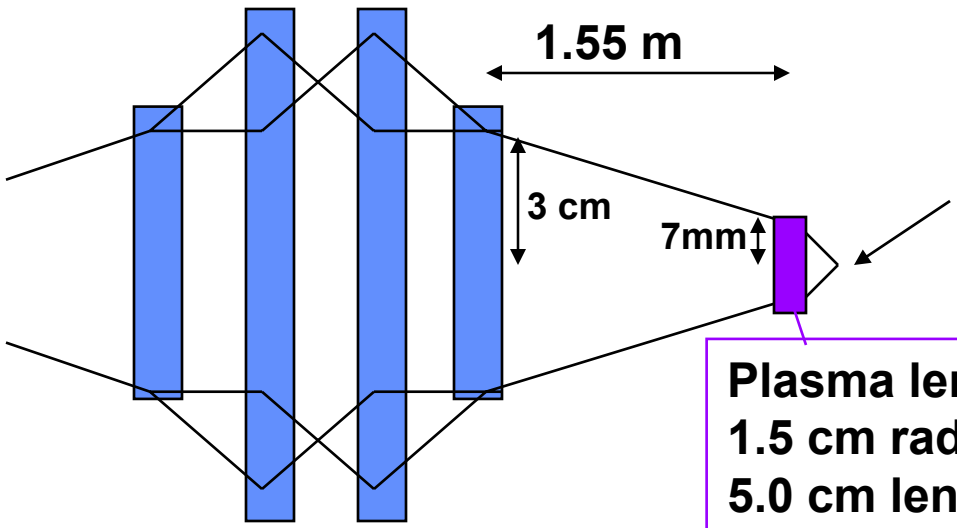


IRE: Final focus/ beam-plasma neutralization, to reduce ion energy and save money

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



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



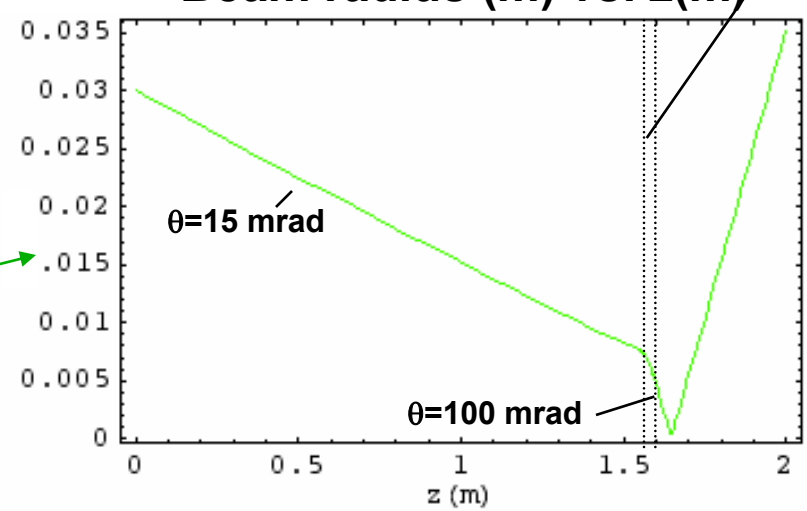
Radius at final focus ~0.5 mm

Plasma lens
1.5 cm radius
5.0 cm length
400 kA

Conventional final focus using quadrupoles

Plasma lens

Beam radius (m) vs. z(m)



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

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

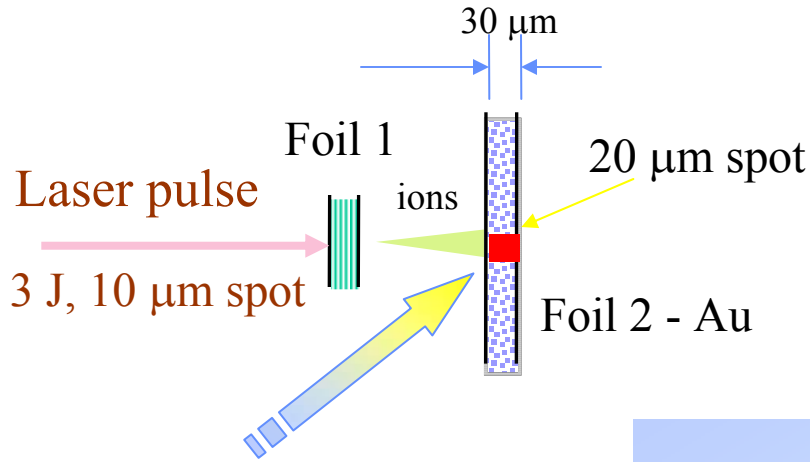
Heavy-ion Integrated Research Program needs:

- Innovation in design and funds for advanced technology development to reduce costs for the IRE by about ~3x from present technology projections.

- Expanded heavy-ion chamber and target R&D aimed to support integrated target shooting and chamber tests using the IRE that are important to provide confidence in the ETF.

- Explore heavy-ion beam target interaction physics at full power-plant intensities (several 10^{14} W/cm^2) using laser-produced, high brightness ion micro-beams, as a timely supplement to the IRE.

Laser-generated heavy ion beams can enable warm dense matter experiments in the nearer term before the IRE.



20 fs x-ray pulse from
all optical Thompson source

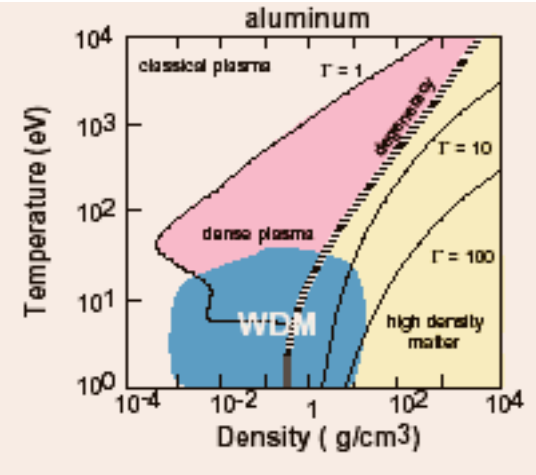
1 laser beam - 3 J

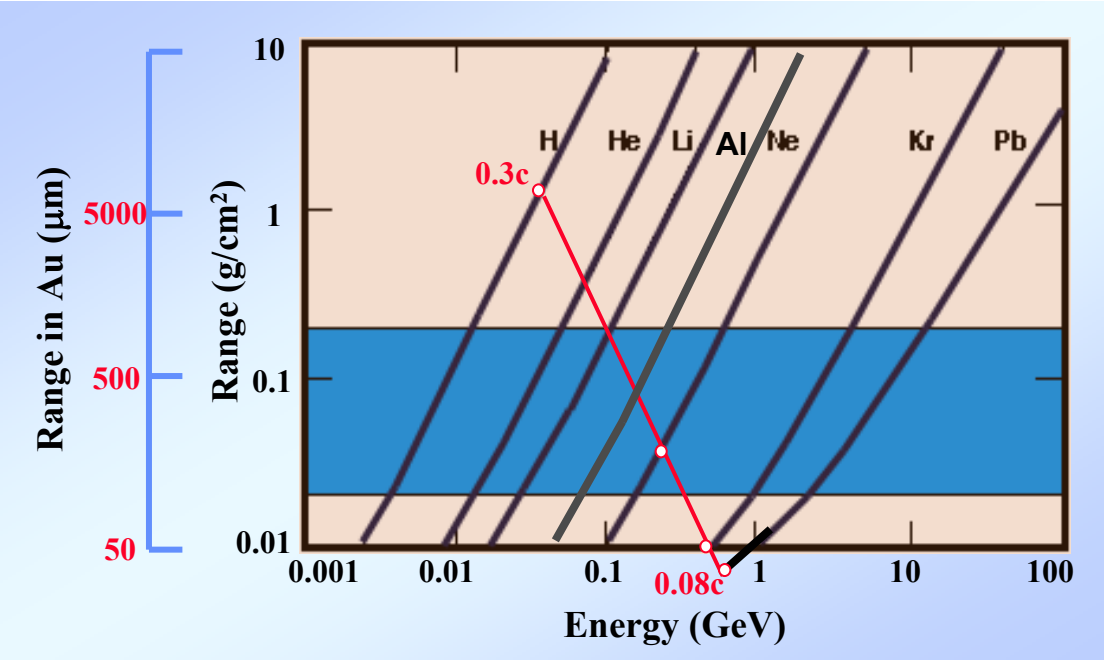
==> ~0.3 J heavy ions @ 3-5 MeV/n

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

==> 10^5 TW/cm^2

==> ~5×10^5 cal/g ==> ~50 eV





Decision criteria for IBX→IRE and for IRE→ETF

Prerequisites for IBX

1. Good HIF-VNL science output in FY02 and 03 (Peer-reviewable scientific results -publishable experimental results with supporting simulations) from HCX, NTX and STS100.
2. Measurements with 4 HCX magnetic quads that electron effects can be tolerated with negligible impact on high current ion transport for at least short times < 1 μsecond into the pulse)
3. Measurements of focusable beam quality through 4 NTX quads at high perveance (> 10^{-4}).
4. Trial end-to-end simulation of an IBX example with idealized beams that demonstrates our scheme for integrated modeling (e.g., WARP through acceleration and drift compression, passing distribution "seamlessly" into LSP for final focus/chamber).
5. Δ ~ 6M$ increase in VNL budget to support preconceptual IBX design and pre-project engineering for a FESAC review.

IBX followed by three years of IRE technology R&D would address these metrics for an HIF-IRE decision:

- Transport with low emittance growth for aperture fill factors > 0.5 and for > 40 - 80 lattice periods

- Average acceleration gradient > 0.5 x $E_{ion}/(eL_{bunch})$ V/m

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

- Final focus to near-emittance-size spots after > 5 x longitudinal bunch compression, beam perveance > 2 x 10^{-4}, and >90% plasma neutralization.

- End to end simulation of a full scale driver

- Affordable technology for an IRE: low loss cores, high gradient insulators, solid state pulsers, SC quad arrays.

Requirements for IRE and ETF for any IFE approach

Requirements to qualify IRE for each approach:

- Resolve key PoP driver issues that are specific to each approach
- Publish adequate gain IFE target designs with 2-D hydostability for plausible beam non-uniformities
- Plausible pathways for target fabrication and injection
- Chamber design concepts compatible with target illumination geometry, final focus and beam propagation

Requirements to qualify ETF for each approach:

- Adequate NIF target physics data
- IRE-level confirmation of scaling for ETF driver cost and lifetime at rep-rate, for adequate efficiency at minimum ηG
- Test injection of prototype ETF targets in simulated fusion chamber environment (could be separate facility)
- Final focus lifetime data for sufficient # of shots under prototypical ETF conditions
- Experiments that resolve specific issues of beams driving ETF targets (e.g., beam balance, symmetry, imprint, filamentation, chamber plasma/gas interaction)

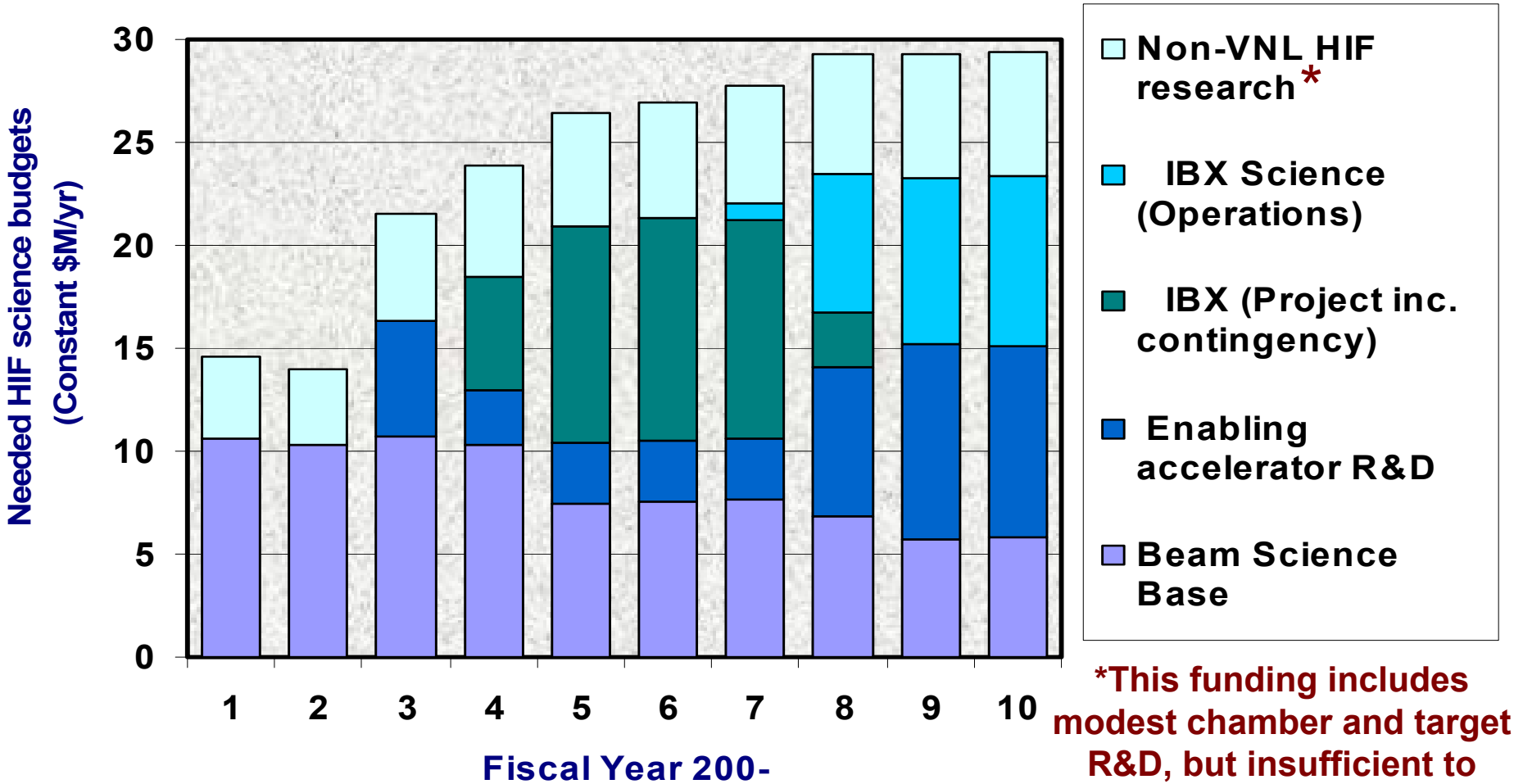
Additional specific requirements for an HIF-ETF

1. IRE tests showing focal spot size predictive capability with multiple beams and plasma neutralization over 2- 4 meter focal lengths (Exp1).
2. Demonstrate multi-beam precision/coupling into scaled hohlraums that validate codes incorporating ion range shortening (Exp2).

Budget needs for balanced portfolio to provide basis for a heavy-ion driven Engineering Test Facility (ETF)

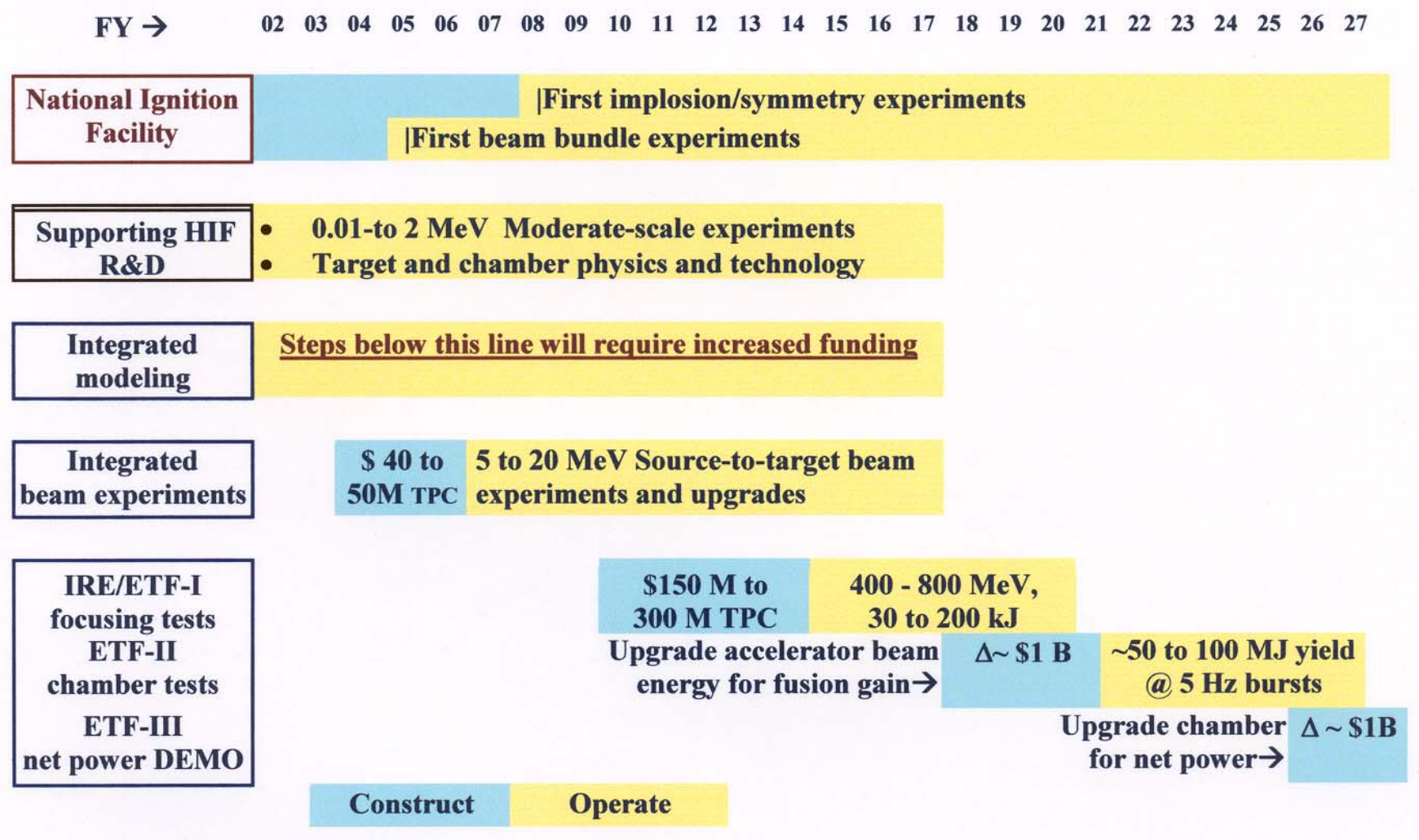
Extended National HIF Phase I (Proof-of Principle) Plan

[Assumes $45 M IBX with growth of national HIF to ~27M/yr]



*This funding includes modest chamber and target R&D, but insufficient to enable IRE/ETF by FY10.

Long- range HIF strategy to expedite an ETF



→ The expedited ETF schedule shown here would require faster IBX construction (3-yr vs. 5-yr), and more accelerator, chamber, and target support, than in the $27 M/yr plan.

My principles for HIF program balance so as to maximize overall progress towards the goal of IFE:

1. Keep support for driver, chamber and target R&D balanced so that all essential decision criteria can be met for advancement to next levels in the IFE roadmap at the same time, whatever the funding level and time between steps.

2. Strive to increase percentage of total program funding for advanced, innovative (high risk/high payoff) alternatives towards ~20 % assuming budgets grow, (or even higher percentage if real budgets continue to decline for 3 more years).

3. Advance enabling technology and science together by selecting new technologies that can be tested near-term and applied to near-term experiments if successful.

4. Keep annual construction costs for major facilities (e.g., IBX and IRE) under 50 % of total program costs, to support effective use of the facilities when completed, and to expedite following steps.