Heavy Ion Fusion Program Plans*

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

- Motivation
- Current research
- Next Steps and performance metrics

Presented at the Fusion Snowmass Conference
Snowmass, Colorado, Monday, July 15, 2002

*This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Berkeley and Lawrence Livermore National Laboratories under Contract Numbers DE-AC03-76SF00098 and W-7405-Eng-48, and by the Princeton Plasma Physics Laboratory under Contract Number DE-AC02-76CH03073

Outline /Summary

- The program to develop heavy-ion fusion is an integrated effort on accelerator drivers, chambers and targets.

- We have a current program designed to maximize scientific productivity in the near term, with major results to be completed by the end of FY04.

- An Integrated Beam Experiment (IBX) is the next step. The IBX, with enabling technology improvement, would provide the basis for an optimized Integrated Research Experiment (IRE) in parallel with NIF target experiments.

- There is a strong strategic rationale for heavy-ion fusion.

A strong strategic rationale for heavy-ion fusion:

- High energy accelerators have energy > MJ, intensity > 10^{20} W/cm^2, high efficiency, durability and rep-rate. However, particle range is too high for targets and peak power too low- we need heavy-ions with the correct range at higher peak power.

- Heavy-ion beams are compatible with indirect-drive targets.

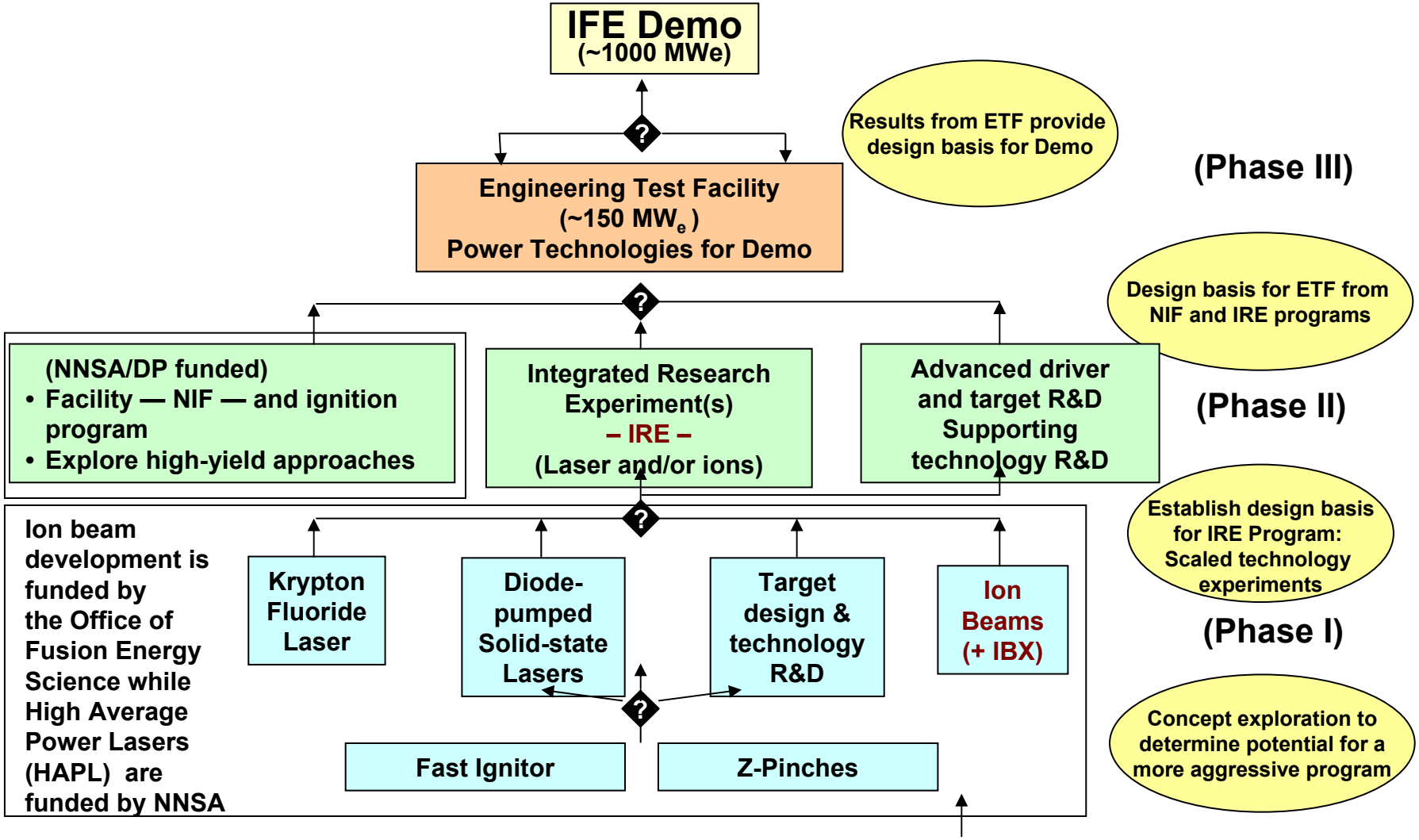
- Indirect drive is compatible with long-lasting (30-yr), thick-liquid-protected chambers.

- Hohlraums can protect fragile cryogenic fuel capsules during injection into hot chambers.

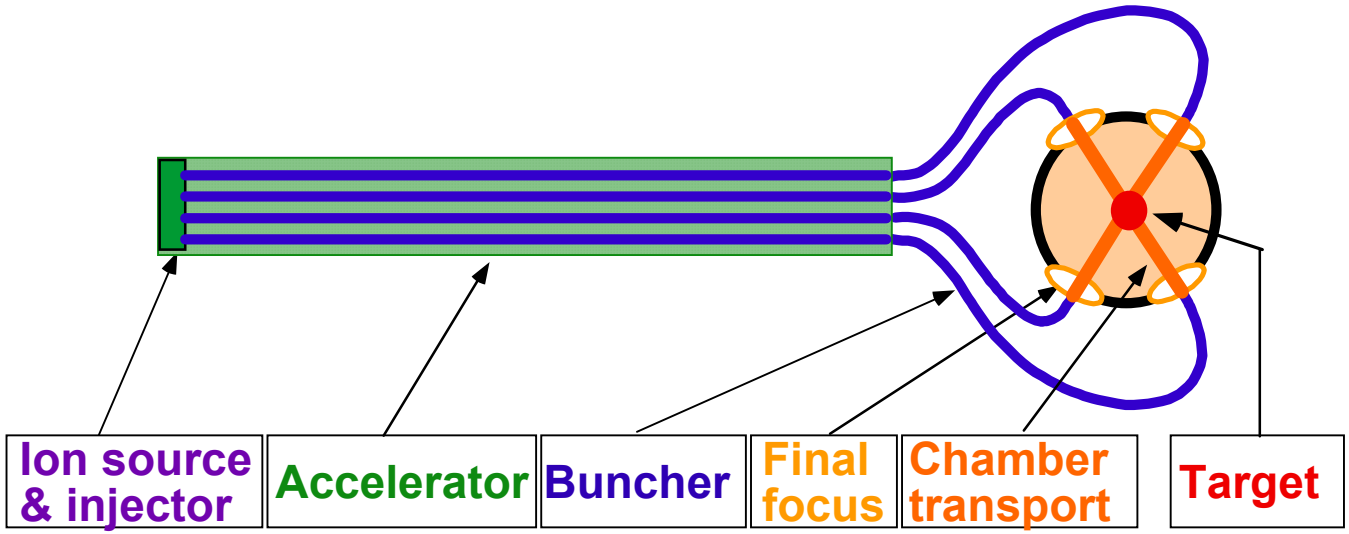
- Focusing magnets can achieve long life by avoiding line-of-sight damage from target debris, neutrons, and gammas.

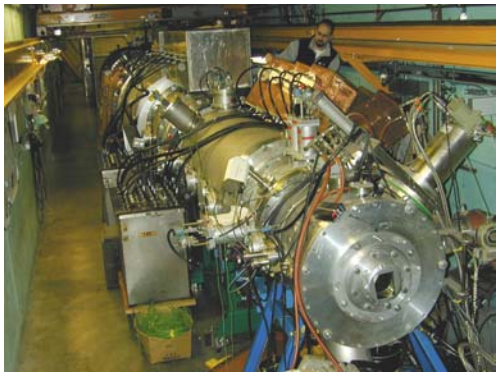
- Power plant designs show attractive economics and environmental characteristics.

The heavy-ion fusion program strategy follows the 1999 roadmap for the development of inertial fusion energy

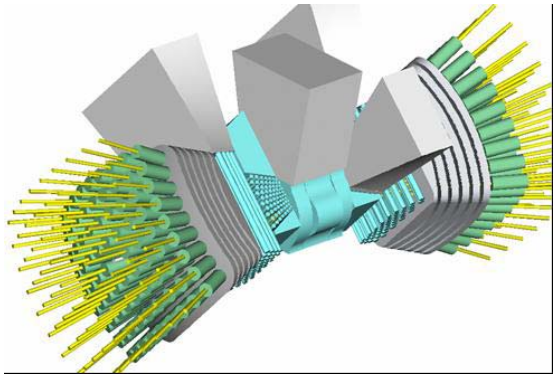


Heavy-ion driver, chamber and target groups are working together to develop an integrated approach to fusion energy.

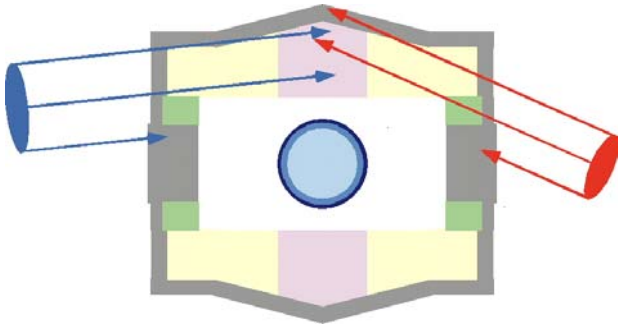




Beams at high current and sufficient brightness to focus



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, MIT, SLAC and others.

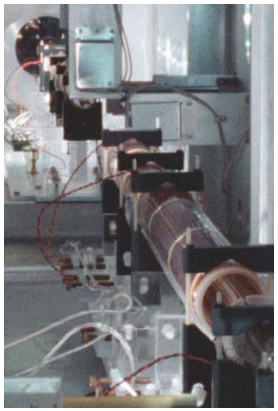
- **We work together with groups working on heavy ion chambers and targets:**
  - Virtual Lab for Technology : HIF chamber R&D, systems analysis
  - LLNL/GA/LANL : HIF target science and technology.

Heavy-ion fusion has made much progress

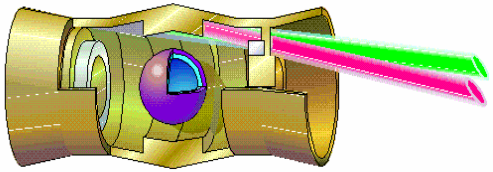
→ Experiments and simulations have verified beam dynamics equations at correct dimensionless parameters with low beam currents of a few mA.

Multiple Beam Experiment→

Scaled final focus experiment→



→We have published high gain target designs with more than adequate stability and gain for heavy-ion fusion.

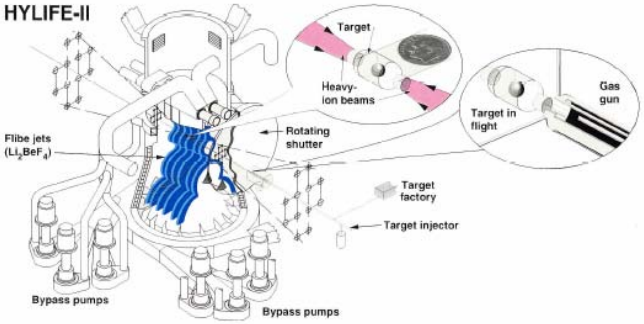


Distributed radiator target

→Experiments support feasibility of liquid chambers

Oscillating water jet arrays→ with scaled disruptions

→Heavy ion power plant studies (Osiris, Prometheus-H, HYLIFEII) show attractive economics and environmental



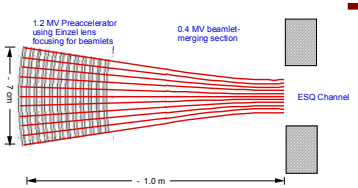
Significant challenges remain

- **Beam quality**- emittance growth, electron/gas interactions at high current, evolution of beam distributions over long path lengths.
- **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
- **Improved accelerator technology** for the IRE and drivers: compact multiple-beam injectors and superconducting magnet arrays, solid state pulsers, low cost/loss ferromagnetic core materials, high gradient/low cost insulators.
- **Heavy-ion targets** that can be mass produced at low cost and injected
- **Heavy-ion liquid chamber** at power-plant scale allowing >5 Hz pulse rates

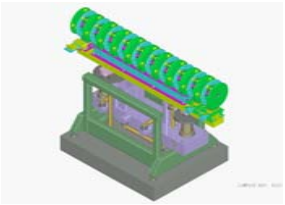
The phase I heavy-ion driver plan consists of experiments on sources, transport and focusing followed by an integrated beam experiment.

NOW (next three years) → **NEXT STEP**

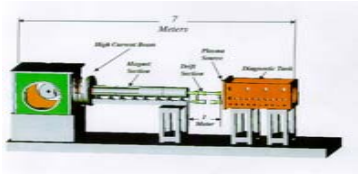
Brighter sources/ injector



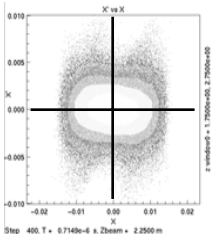
Maximum <J >, B_n Transport



Beam neutralization → min ε-limited focus r_f

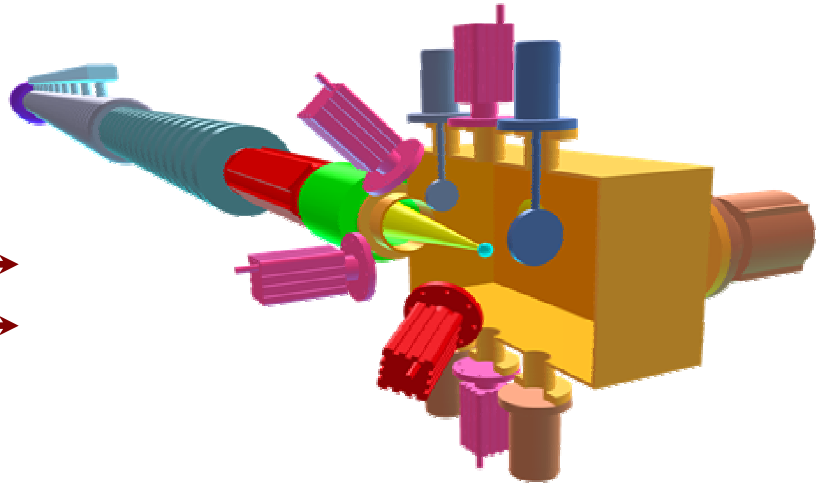


Theory/simulations



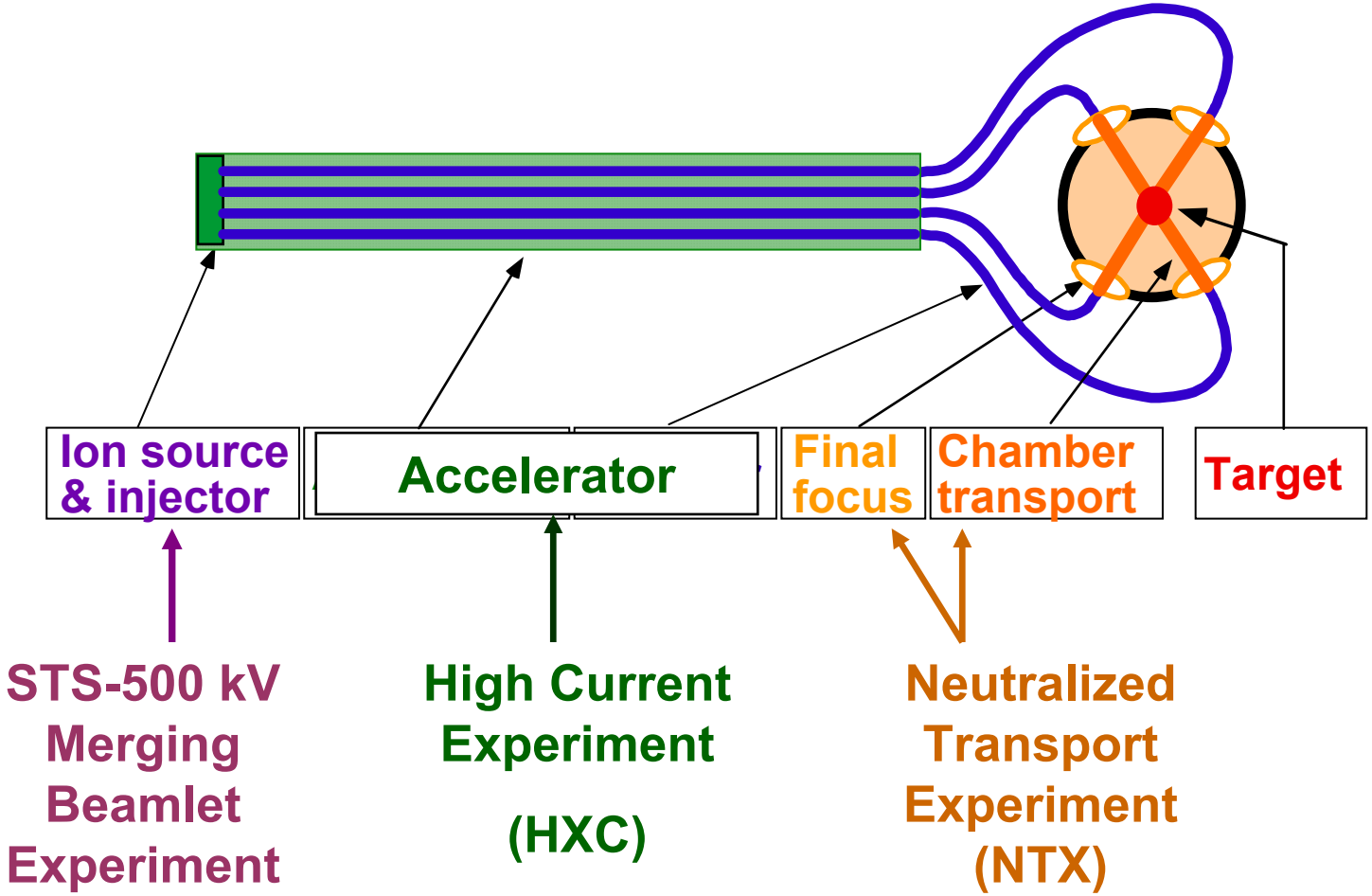
Supporting theory, scaled experiments, chamber and target R&D

Integrated beam experiment (IBX)

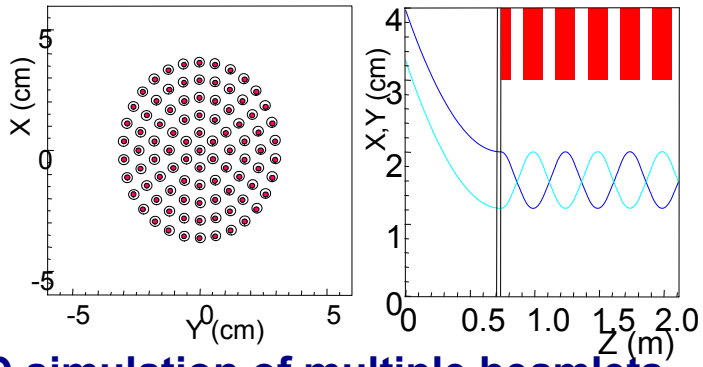


Injection, acceleration, drift compression and final focus to test source-to-target integrated models

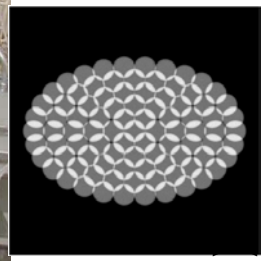
By FY04, we will complete major milestones in three experiments at higher beam currents (0.1 to 1 A) to benchmark models in injector, accelerator, and final focus regions



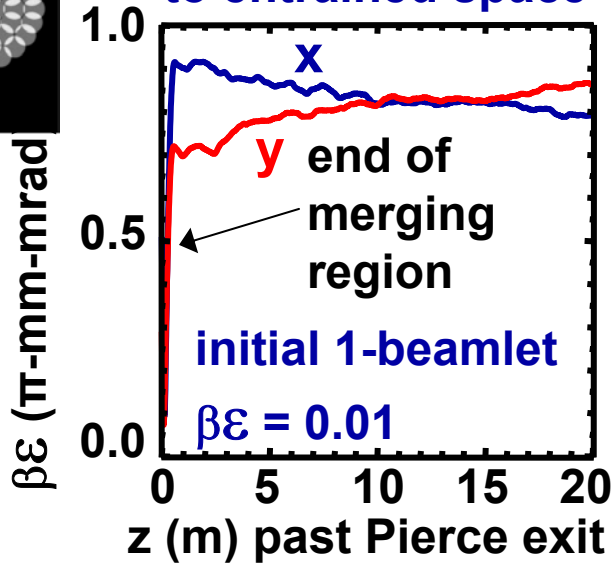
Research on high-brightness sources and injectors commenced on LLNL test stand completed Dec 2001



3-D simulation of multiple beamlets

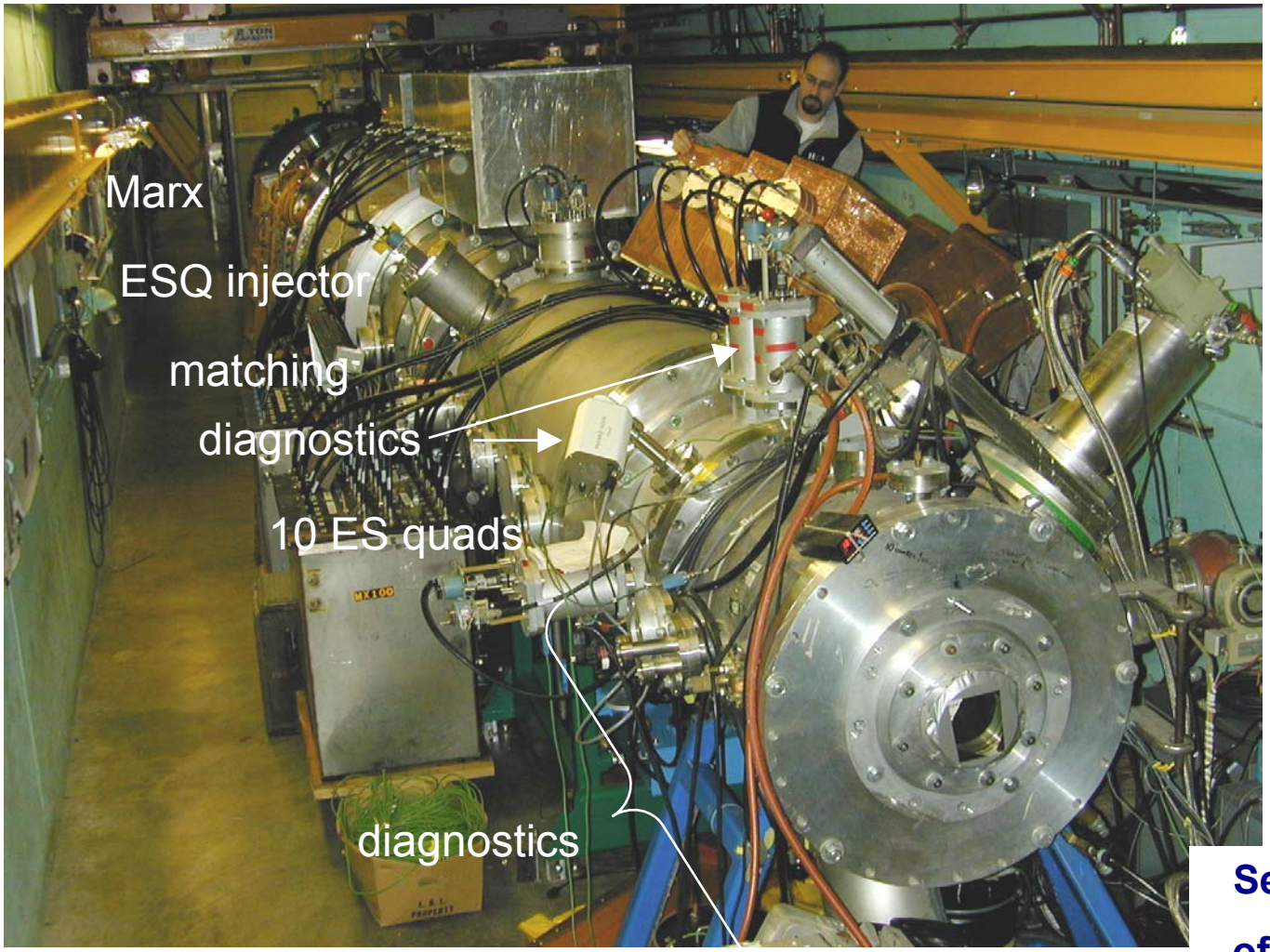


emittance grows due to entrained space



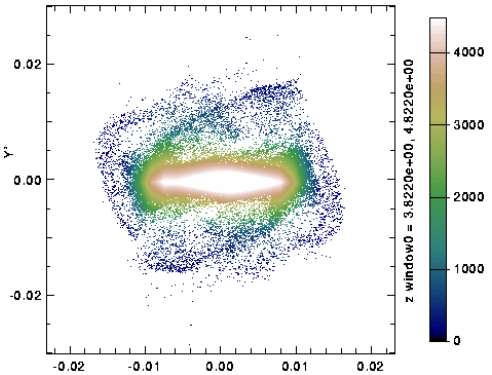
New STS500 KV facility at LLNL will explore a new compact injector concept useful for all future experiments, as well as feasibility of high-brightness plasma sources.

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



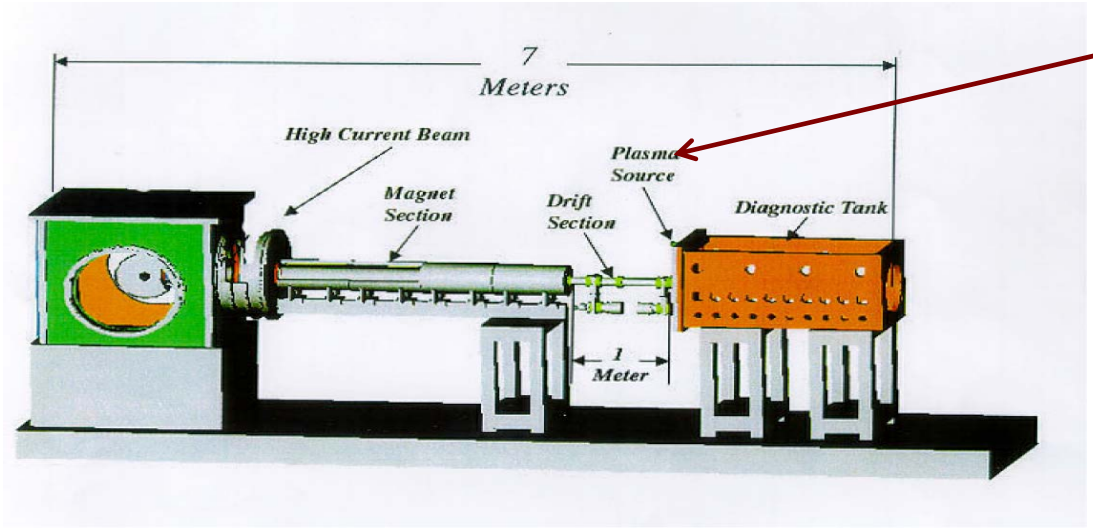
Transport

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

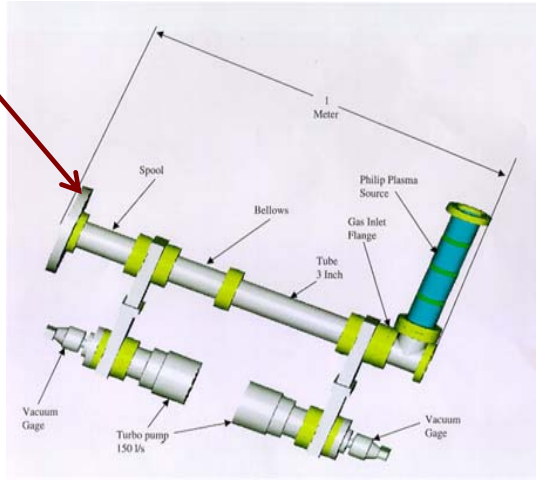


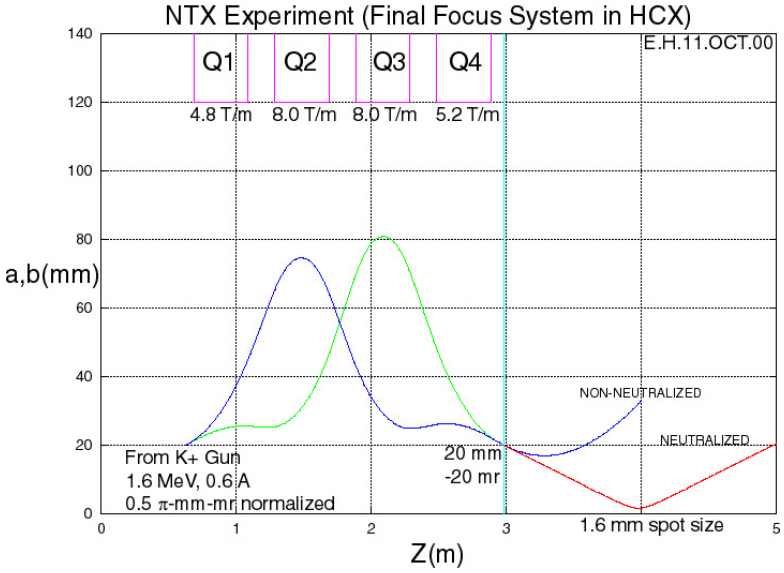
Self-consistent simulation of HCX beam phase space

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



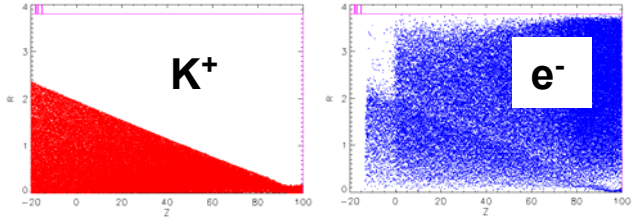
PPPL ECR plasma source



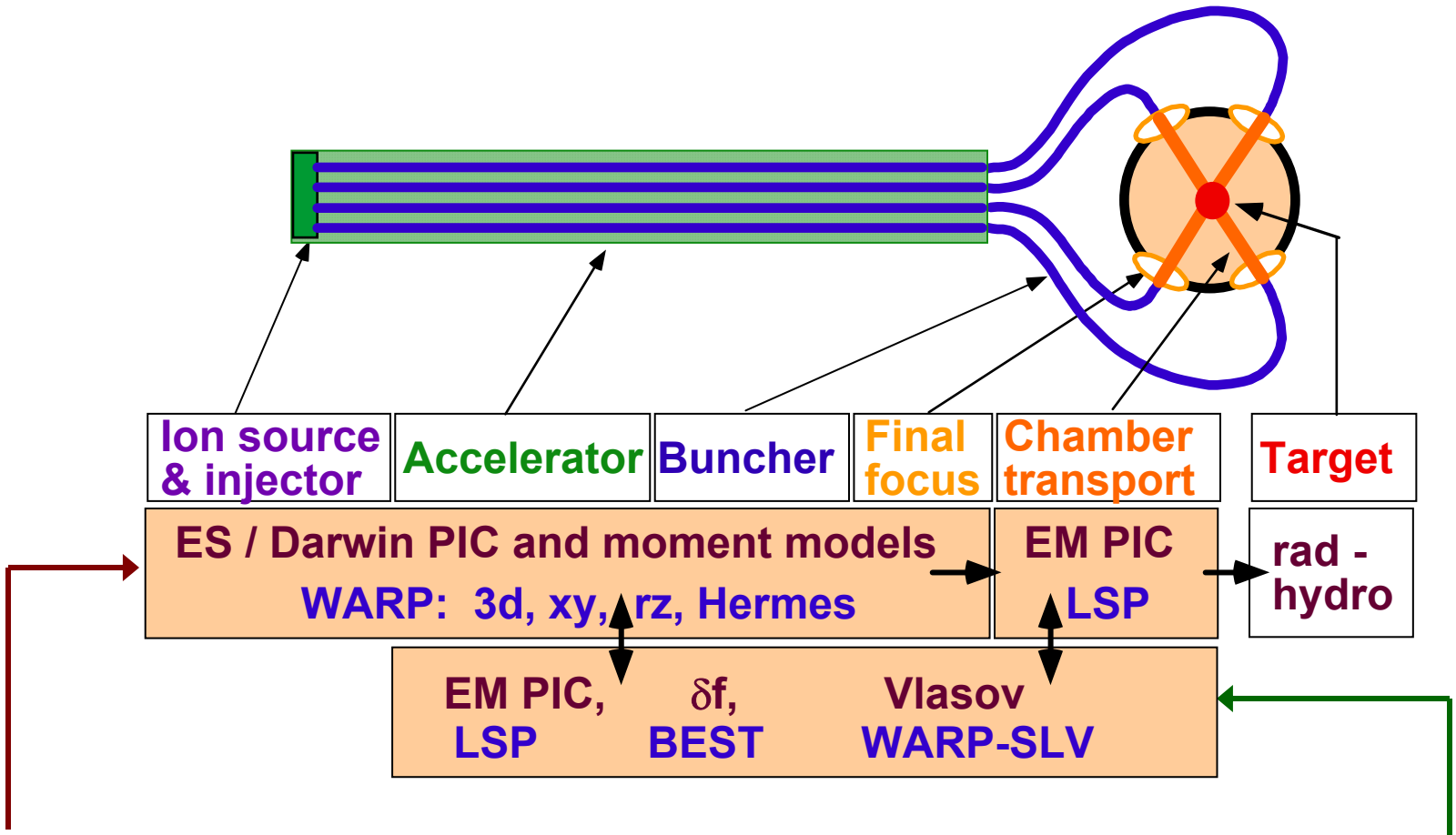


NTX gun has achieved design current 80mA @ 0.4 MeV and very low measured emittance $\varepsilon_N \leq 0.1\ \pi$ mm-mr.

Simulations predict 99% neutralization



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

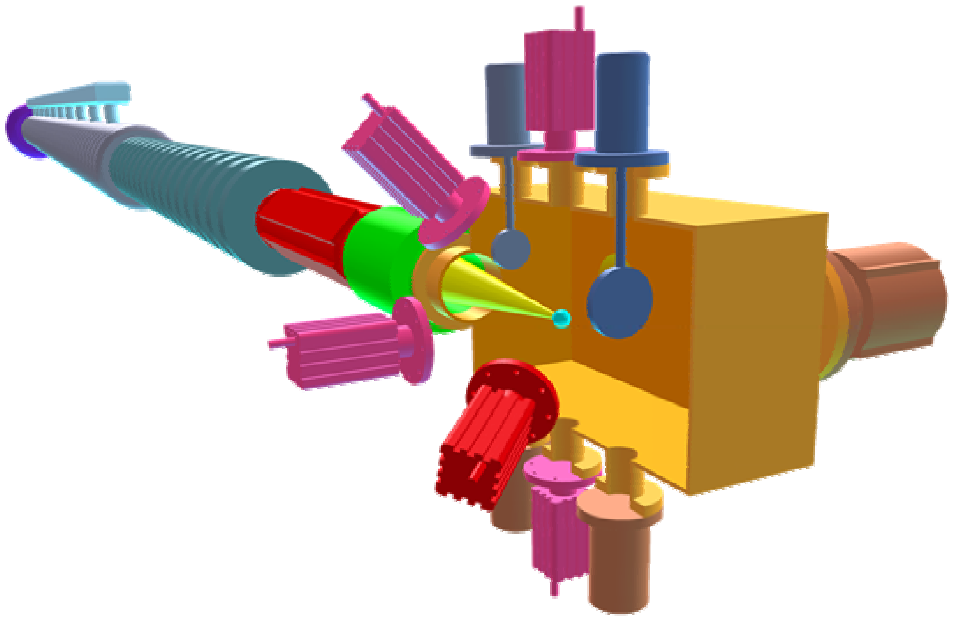


Track beam ions consistently along entire system

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

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.



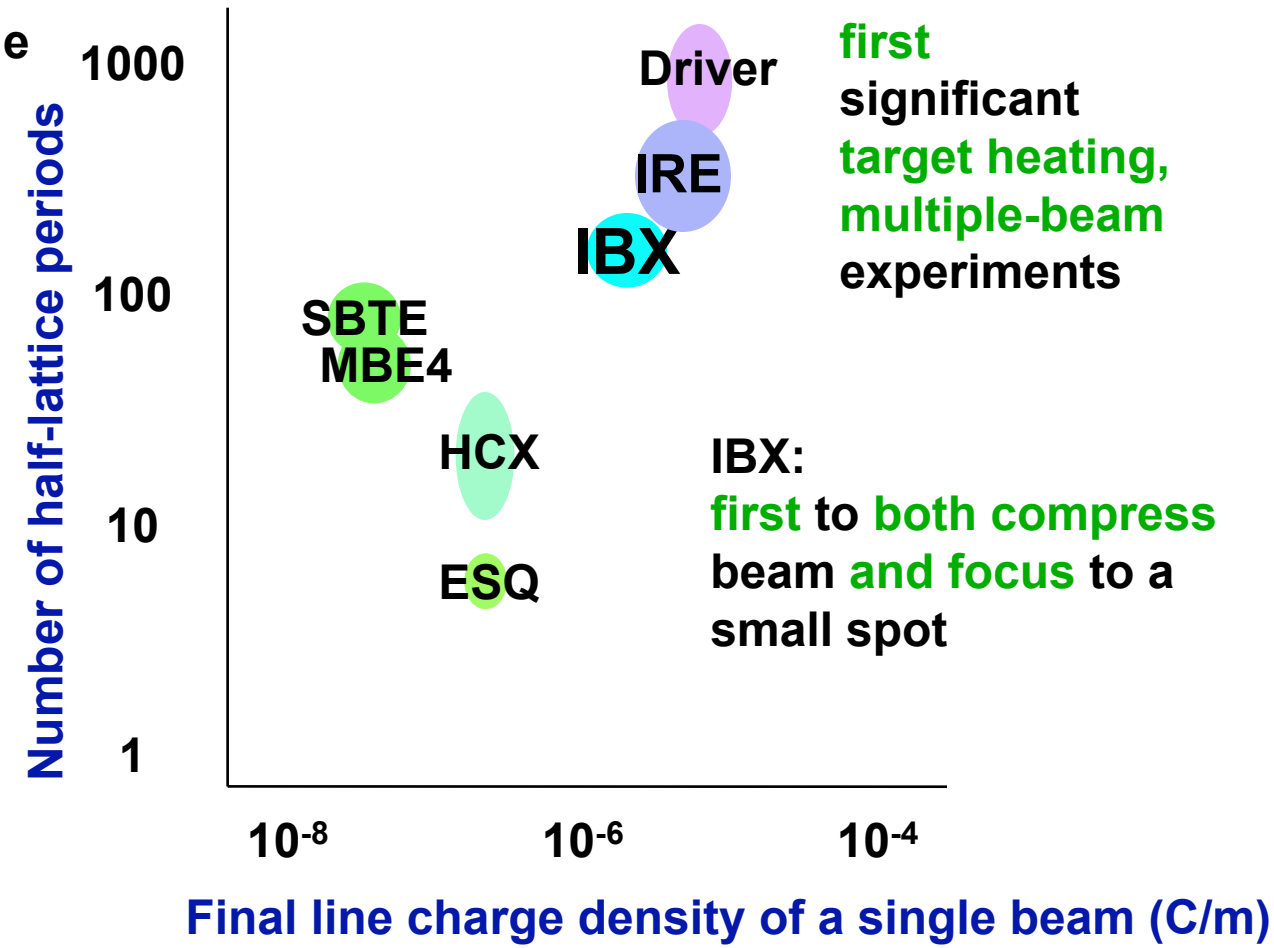
→The IBX, along with aggressive technology development, will provide the basis for an optimized IRE

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, multiple-beam experiments

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

The IBX and IRE have complementary roles in the HIF strategy

IBX (~ $50 M):

- **Validate integrated models for beam quality evolution from source to target.**
- **Use existing technology at modest scale to expedite the schedule.**

→Increases confidence for IRE beam focusing to >TW/cm2/beam sufficient to drive a variety of important ion chamber and target experiments.

IRE (~$250 M):

- **Provide basis for ETF: improved accelerator technology, multiple-beam dynamics, integrated chamber and ion target experiments.**
- **Use prototype multiple beam technology, efficiency, rep-rate at unit costs that scale to competitive power plant requirements.**

Current experiments and the IBX would 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.

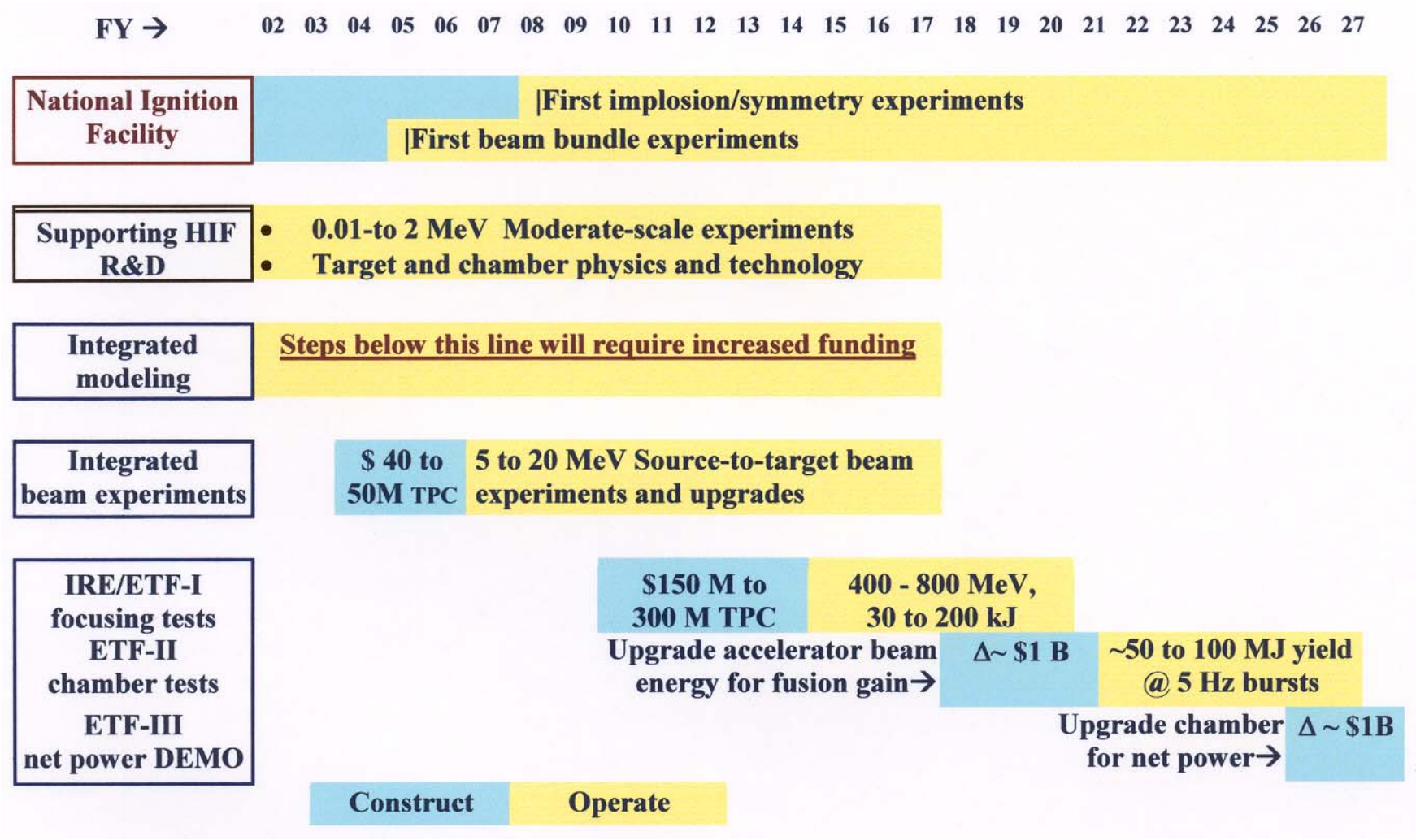
IBX-goals for an IRE decision:

- 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.

In addition to the current HIF experiments and IBX achievements, a heavy-ion IRE construction decision would require:

- 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 multiple beam linacs: low loss cores, high gradient insulators, solid state pulsers, SC quad arrays
- 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.

With sufficient funding, it would be possible to demonstrate heavy-ion fusion energy in the next 25 years



Backup slides

Approach – Heavy Ion Fusion Strategy

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

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

Longer Term: Integrated Research Experiments (**IRE**) ~$200-300M
Multiple Beams (>16) 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 scientific mission

- **Well-diagnosed experiments that benchmark integrated beam dynamics models through injection, acceleration, longitudinal drift compression, and final focus. Sufficient beam current to study gas/electron interactions.**

- ***The crucial integration role of the IBX is to test the ability to maintain high beam brightness (focusability) from source to target, and thereby improve the ability to predict the final focal spot size.***

→IBX would address important integrated beam physics years earlier than the IRE, which could lead to more-optimum IRE designs.

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

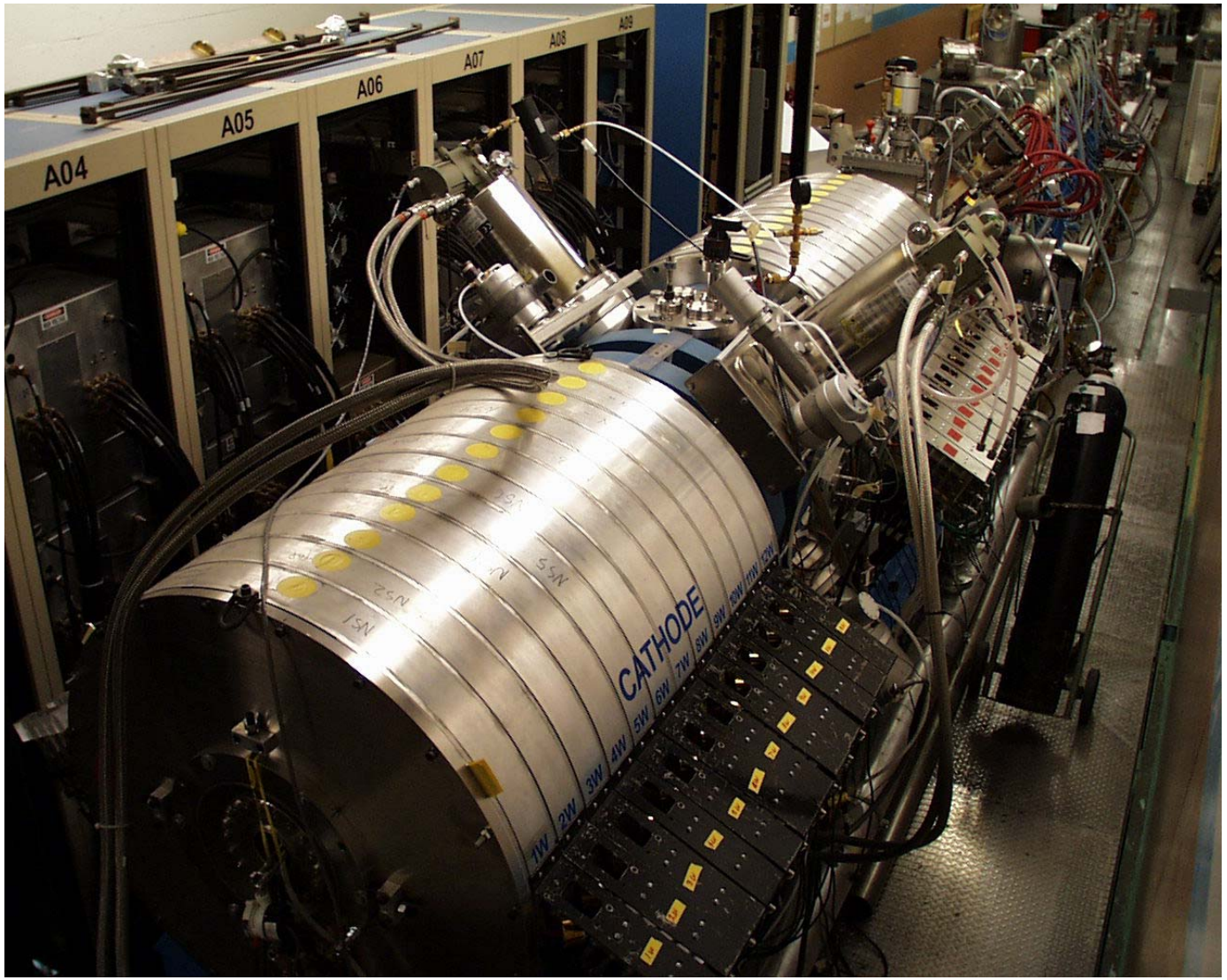
- Experience with a short-pulse injector RTA (Relativistic Two-Beam Accelerator) in Bldg 58 at LBNL

- 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

→While sufficient to enable beam physics experiments at high current in IBX, further development of these technologies for multiple beams, lower cost, and 5 Hz pulse rates would be required to enable the follow-on IRE.

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

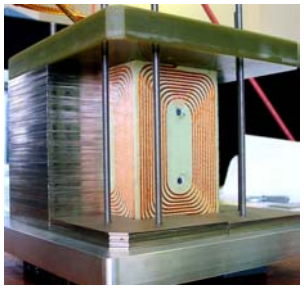


ETA-II Cell Modification

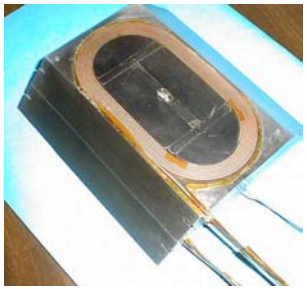
Superconducting magnet development FY01-02

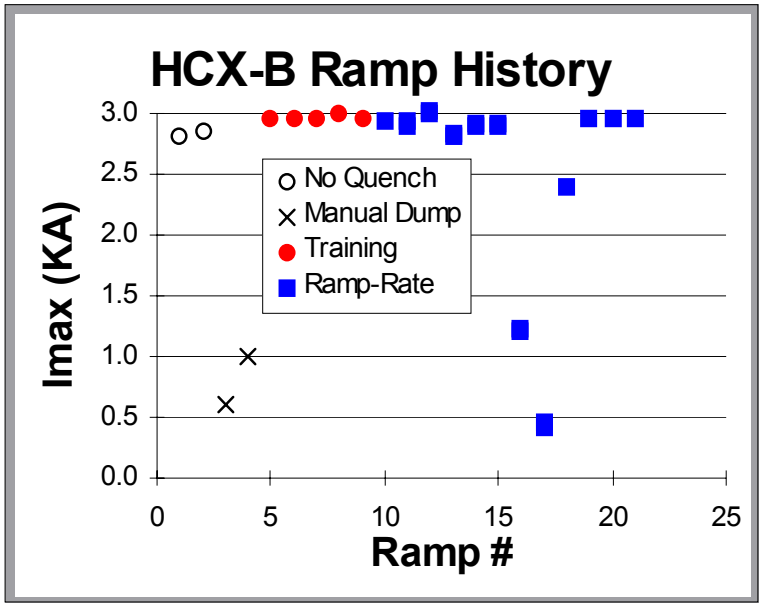
Four prototypes fabricated and tested

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

The HIF-VNL Program Advisory Committee reviewed the new HIF plan Feb 14-15, 2002 and endorsed it.

HIF-VNL PAC Committee

Mike Campbell (Chair)
Marshal Rosenbluth, (UCSD)
Richard Hawryluk, (PPPL)
George Caporaso, (LLNL)
Ingo Hoffman, (GSI)
Dave Hammer (Cornell)
John Sheffield (ORNL)
Bill Foster (FNAL)
Mike Mauel (Columbia)
Bruce Hammel (LLNL)
Mike Norman (UCSD)
Steve Obenschain (NRL)

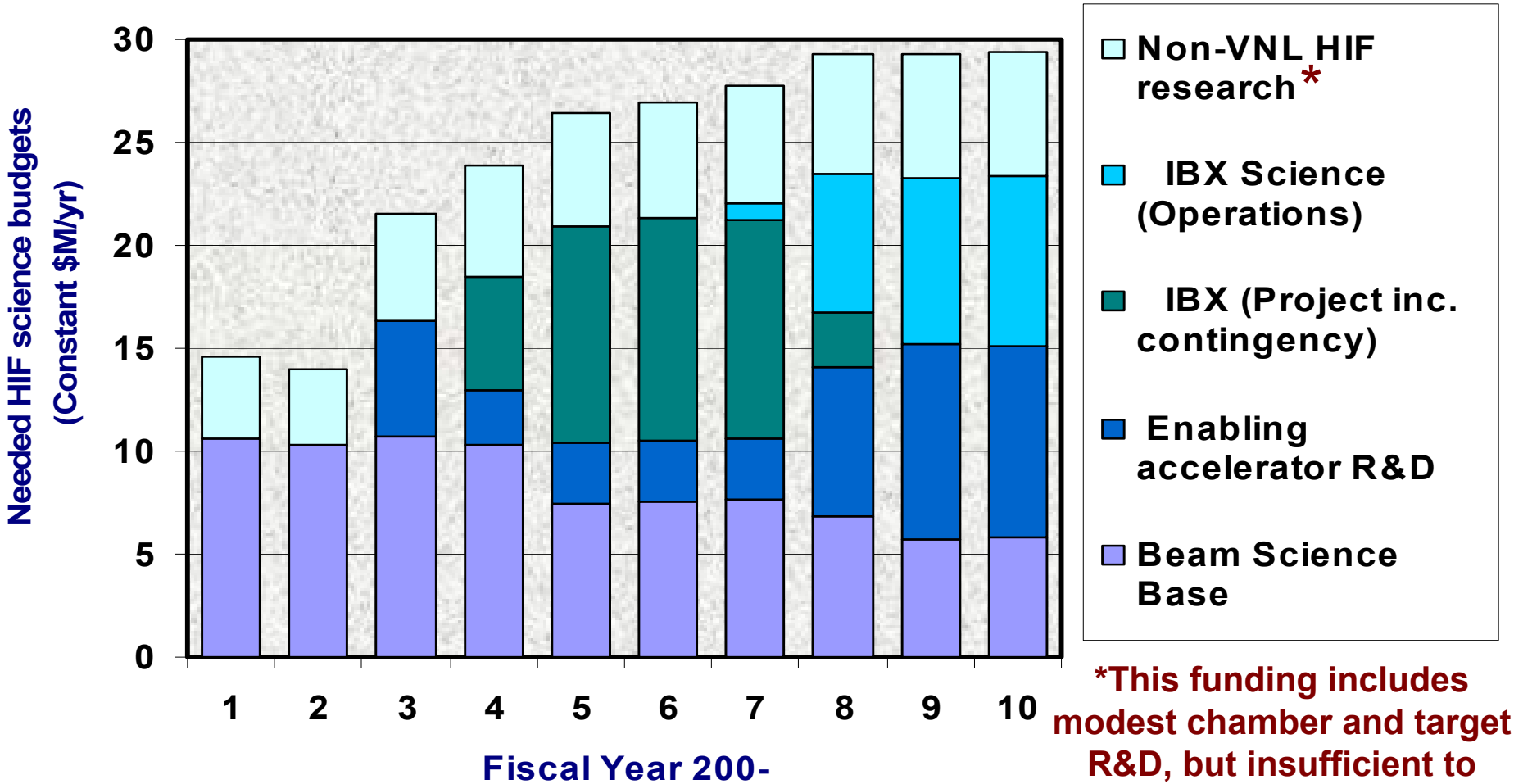
Excerpts from the PAC report:

"The committee endorses the three-year program plan described in the review. We believe the technical choices and balance are correct. All of the three experimental activities (Injector/source, High Current experiment (HCX), and Final Focus (NTX)) as well as the simulation and modeling component are required to justify an IBX".

"The committee feels that the IBX is the appropriate next step in the HIF program. It is realistic both in budget and technical scope".

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

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

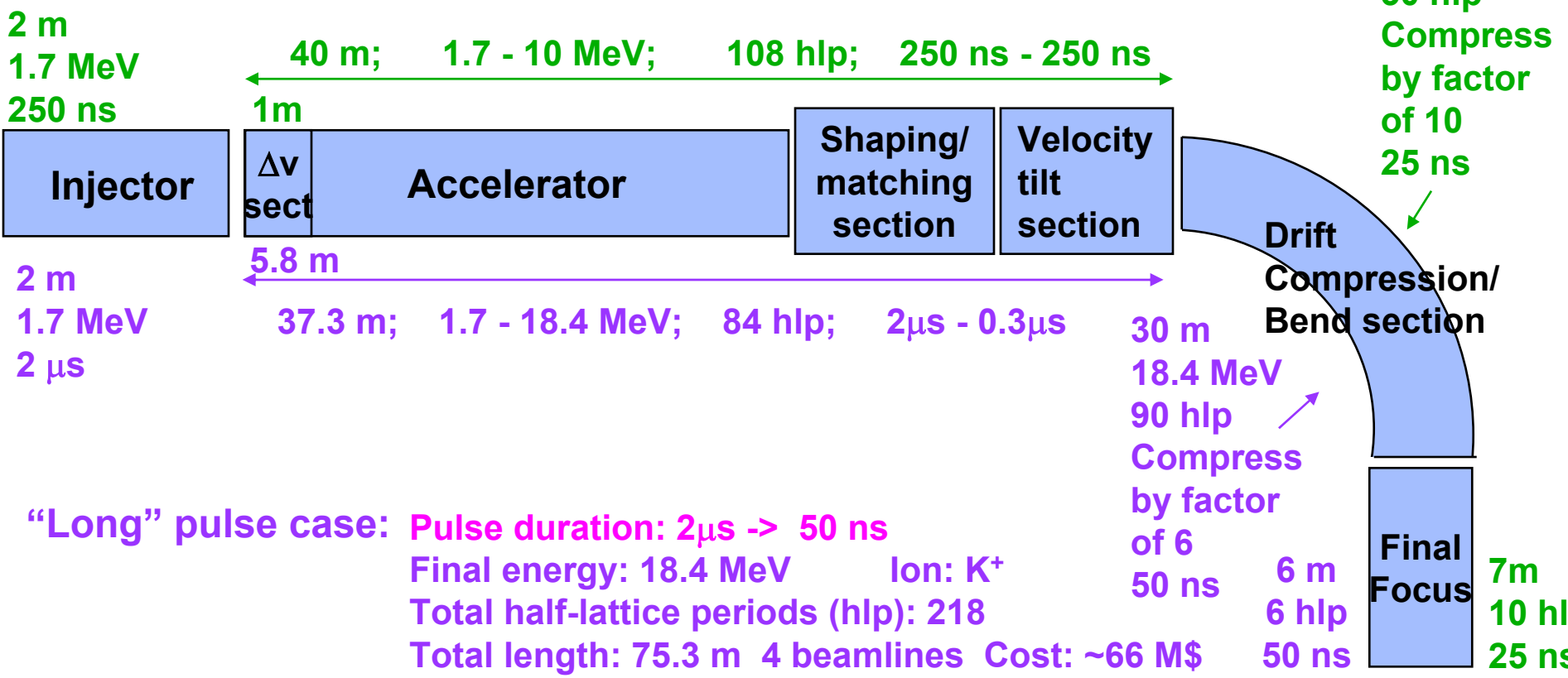


*This funding includes modest chamber and target R&D, but insufficient to enable IRE/ETF by FY10.

IBX workshop considered two cases for IBX

Short pulse case:

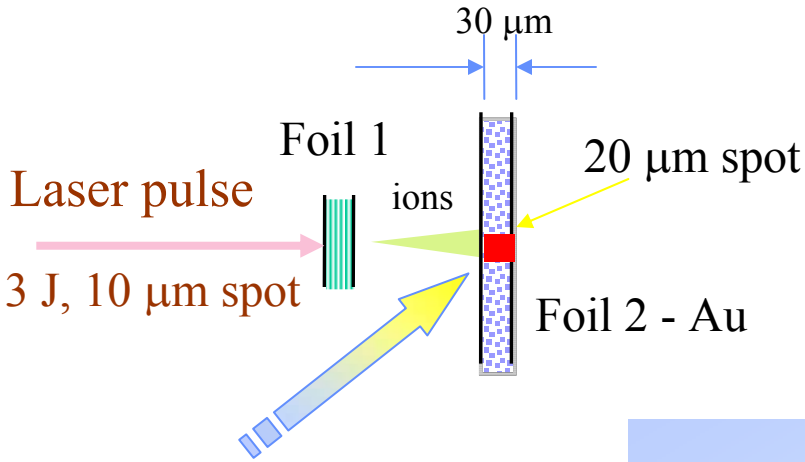
Pulse duration: 250 ns -> 25 ns
Final energy: 10 MeV Ion: K^+
Total half-lattice periods (hlp): 148
Total length: 64 m 1 beamline Cost: ~38 M$



"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$

Laser-generated heavy ion beams may enable warm dense matter experiments in parallel with beam dynamics experiments in IBX.

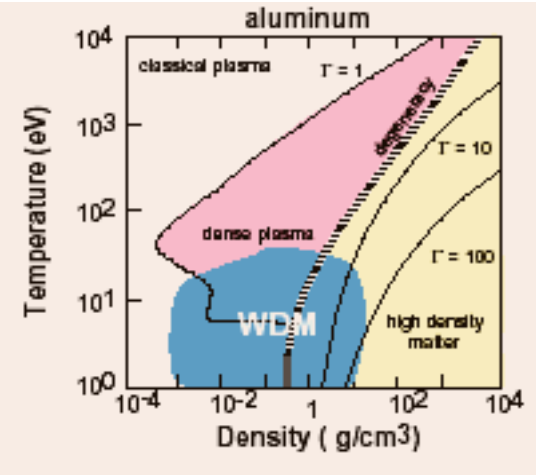
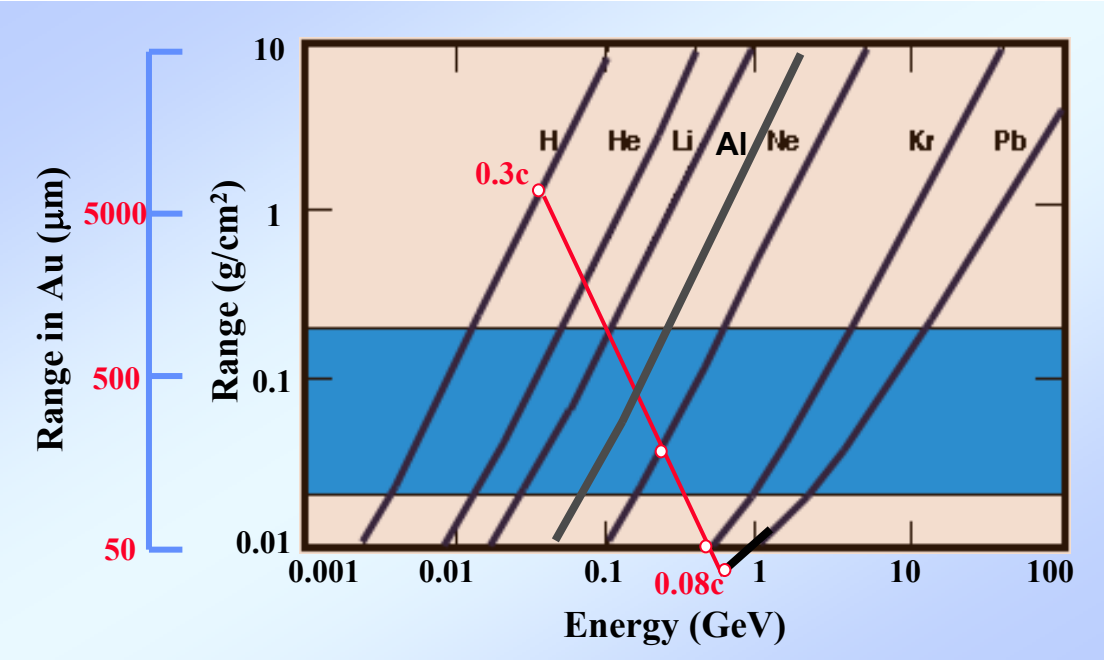


20 fs x-ray pulse from
all optical Thompson source

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