The Place of the IBX and the IRE in the HIF-VNL Program Plan

C.M. Celata

for the HIF Virtual National Laboratory

Snowmass Fusion Summer Study, July 2002

All Stories about Heavy Ion Fusion Begin with the Target ...

Target Requirements:

3 - 7 MJ ÷ ~ 10 ns ⇒ *~ 500 Terawatts*

Ion Range: 0.02 - 0.2 g/cm^2 ⇒ *1- 10 GeV*

⇓

For A ~ 200 →

~ 10^{16} ions

1-2 kA / beam

~ 100 beams

Multiple intense beams with long initial pulse length are necessary.

So What Do We Have to Understand?

Intense Beam Physics

- Stability, waves, phase space changes, nonlinear dynamics

Beam Manipulations

- Beam production, acceleration, longitudinal compression, bending, focusing, chamber transport

Multiple-Beam Interactions

Pulse-length Limits

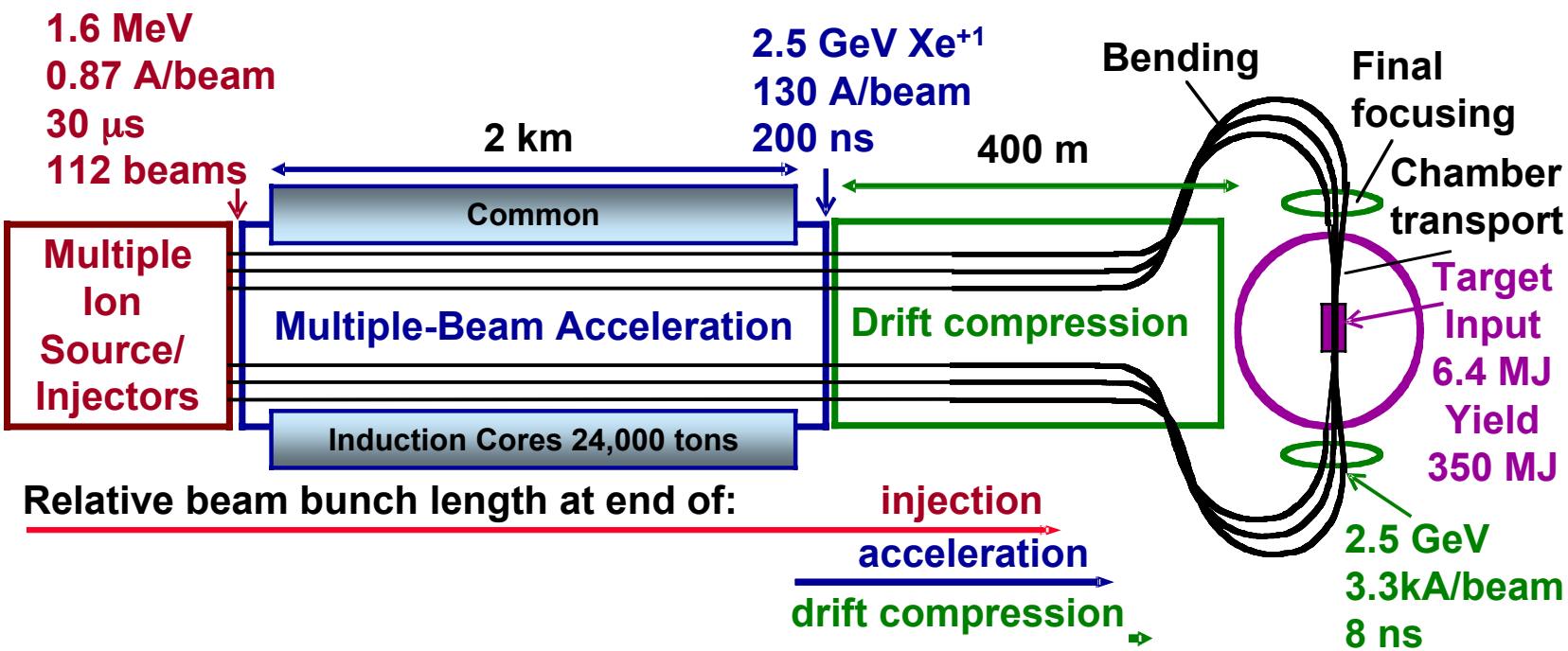
Technology

Emittance

Beam loss

Cost, reliability

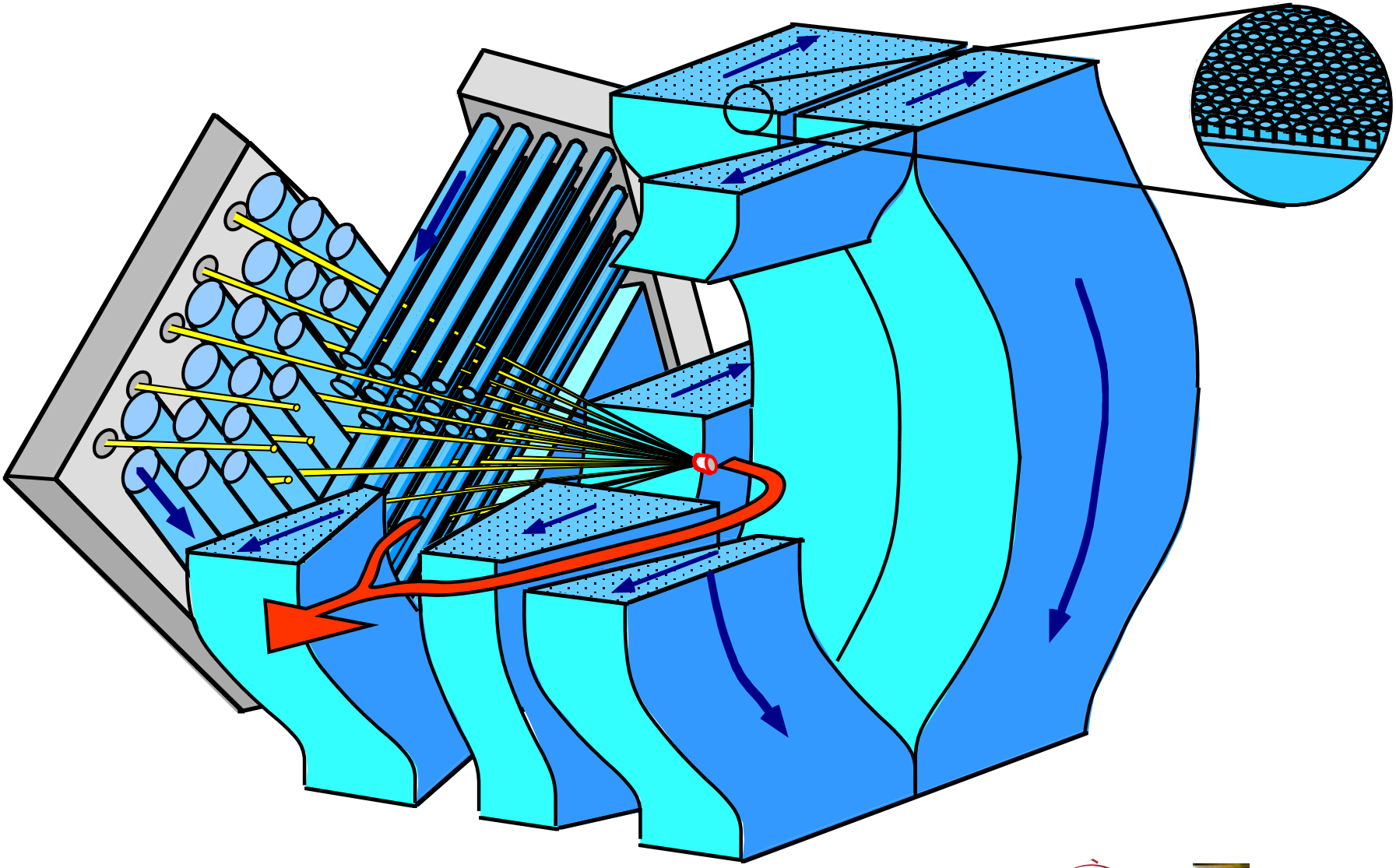
Schematic of a Driver Showing Beam Manipulations



Bunch length compression is integral part of HIF concept

Within accelerator, average induction pulse ~300 - 1000 ns
Target requires pulse duration of ~10 ns

Multiple beams converging on target (one half cut away)



The Approach of the "80's & 90's – Maximizing Physics for Low $

Small scaled experiments

The Choice

Intense, but:

		Driver
Low energy	(≤ 1 MeV)	~3 GeV
Small radius	(initial I ~ μA - 10's of mA)	~ 0.5 - 1 A
Short pulse	(~ 1-2 μs)	~ 10 - 20 μs
1 – 4 beams		~ 100

↓

Cheap

But very valuable for physics investigations.

Physics Investigated at Low Energy and Current

- Intense beam stability
- Focusing limits
- Effect of image charges, mismatch, nonuniform density, misaligned centroid, etc.
- Production of intense beams & initial acceleration

  1-2 MeV, 0.5 - 1 A single-beam injector
- Longitudinal compression, transverse combining of beams, final focus

Present Experiments Have Larger Current, Enabling Electron Physics

Present experiments have higher current (larger radius), similar to the driver at low energy ⇒ **high space charge potential**.

0.1 - 0.5 A

0.4 - 1 MeV

space charge potential ~ few kV

High Current Experiment (HCX) –

electron production coefficient, electron orbits

Neutralized Transport Expt. (NTX) –

neutralization by plasmas after the final focus

Much More Nonlinear Physics Is Also Being Explored

HCX

aperture limits (fringe fields, images, halo)

pulse length limits (also LLNL 500 kV test stand)

halo production

steering

…

NTX

perveance limits of final focus

aberration correction with intense beams

experiment funding scale: ≤ $2 M/yr

So What is Missing for Proof-of-Principle?

Beam Manipulations:

Explored all (except final drift compression) but not in series

– *Not* ***integrated*** –

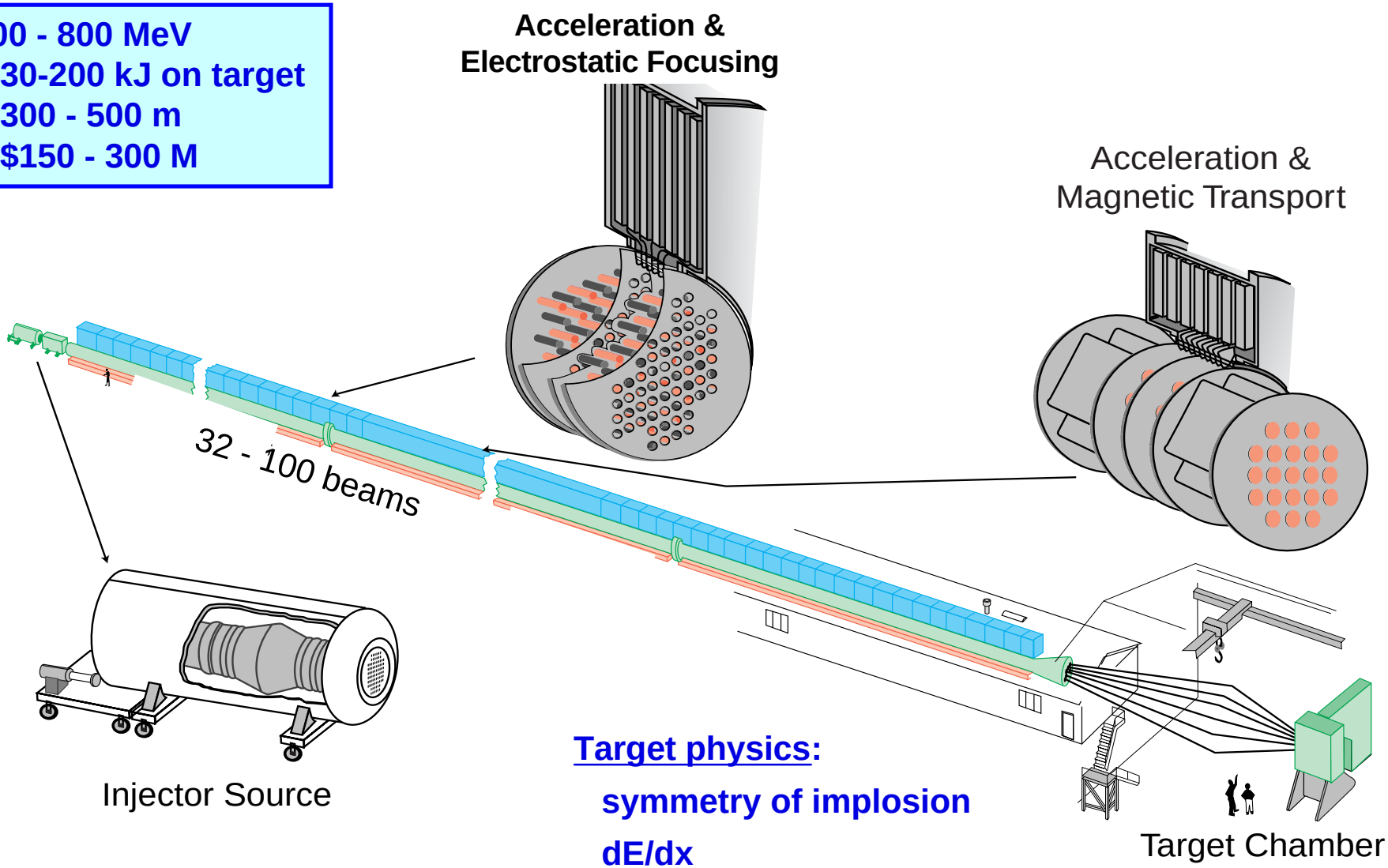
example: We have studied focusing of beams from source, but driver beam will have different distribution function.

Missing Physics:

- Long length-scale physics
  longitudinal physics (wave speeds and growth rates low)
- Physics at high energy
  inductive effects, stripping in chamber
- Multiple Beam studies

Until Recently, the IRE Was to Be the Next Step

400 - 800 MeV
~ 30-200 kJ on target
~ 300 - 500 m
~ $150 - 300 M



Target physics:

symmetry of implosion

dE/dx

But This Is a Large Step ...

In:

$$$

Technology (funding profile not up to development needs)

Experimental & physics scale

A very large step is a normal step in accelerator physics.
The biggest problem with this step is that it is impossible to make.

The HIF Program Derived the IBX by Intensive Program Examination

- **Science Workshop** (May 2001)
  - Listed, reviewed, and prioritized all issues
  - Integrated intermediate-scale experiment suggest by G. Logan. Discussion of possible science goals.
- **Study Groups** (3 months)
  - 2 straw designs (E. Lee & J. Barnard)
  - Design questions / Programmatic issues

    Transport issues, injector, acceleration limits, multiple beams vs. single, drift compression-final focus-chamber transport goals, costing, science value vs. an IRE
- **IBX Workshop** (October 2001)

The IBX Workshop Produced the IBX Scientific Mission & Parameters

Participants iterated on the following questions:

- What can be done at intermediate scale (~$50M, 70 m length)?
- Is it worth doing?
  evaluation used Science Workshop prioritization extensively
- What parameters are needed to accomplish the scientific mission?

Answer:

> A modest increase in accelerator length and energy can make possible an experiment which integrates all the beam manipulations of a driver and enables investigation of much physics flagged as important by the Science Workshop.

This IBX Could Do Important New Physics for a Modest Increase in Resources

*Highest priority from Science Workshop

- Longitudinal wave production & propagation*
- Longitudinal/transverse coupling
- Effects of electrons on the ion beam during transport*
- Halo production*
- Evolution of beam head and tail*
- Long length scale emittance growth (much greater sensitivity)
- Upstream correction of beam aiming for final focus
- Acceleration limits
- Integrated demonstration of drift compression, final focus, chamber transport !*

New!

Parameters were Chosen to Match Scientific Goals

5 - 20 MeV	Perveance low enough for focusing, but aggressive (10^{-4} - 10^{-3})
0.5 - 1 A (at 0.5 -1 MeV)	Space charge potential ~ driver (for studies of electron effects, including neutralized focusing
0.2 - 2 μs pulse	Reduced cost
1? 4? 9? beams	Reduced cost. Make upgradeable for 4 or 9?
Present technology	Reduced cost & risk

IBX Length & Relevant Frequencies for Transverse Physics

If IBX has ~ 50 lattice periods, this is

~ 15 plasma periods

~ 10 centroid oscillation or internal mode periods

~ 10, 14 mismatch periods (2 modes)

~ 1.4 depressed betatron periods

~ 5% of number of driver lattice periods

So can study

internal modes - density oscillations

mismatch (impacts halo formation)

steering*

Miss anything related to single particle orbit frequency, or spread of tunes (e.g., phase-mix damping)

Costing of the IBX is Very Preliminary, but Based on Realistic Groundwork

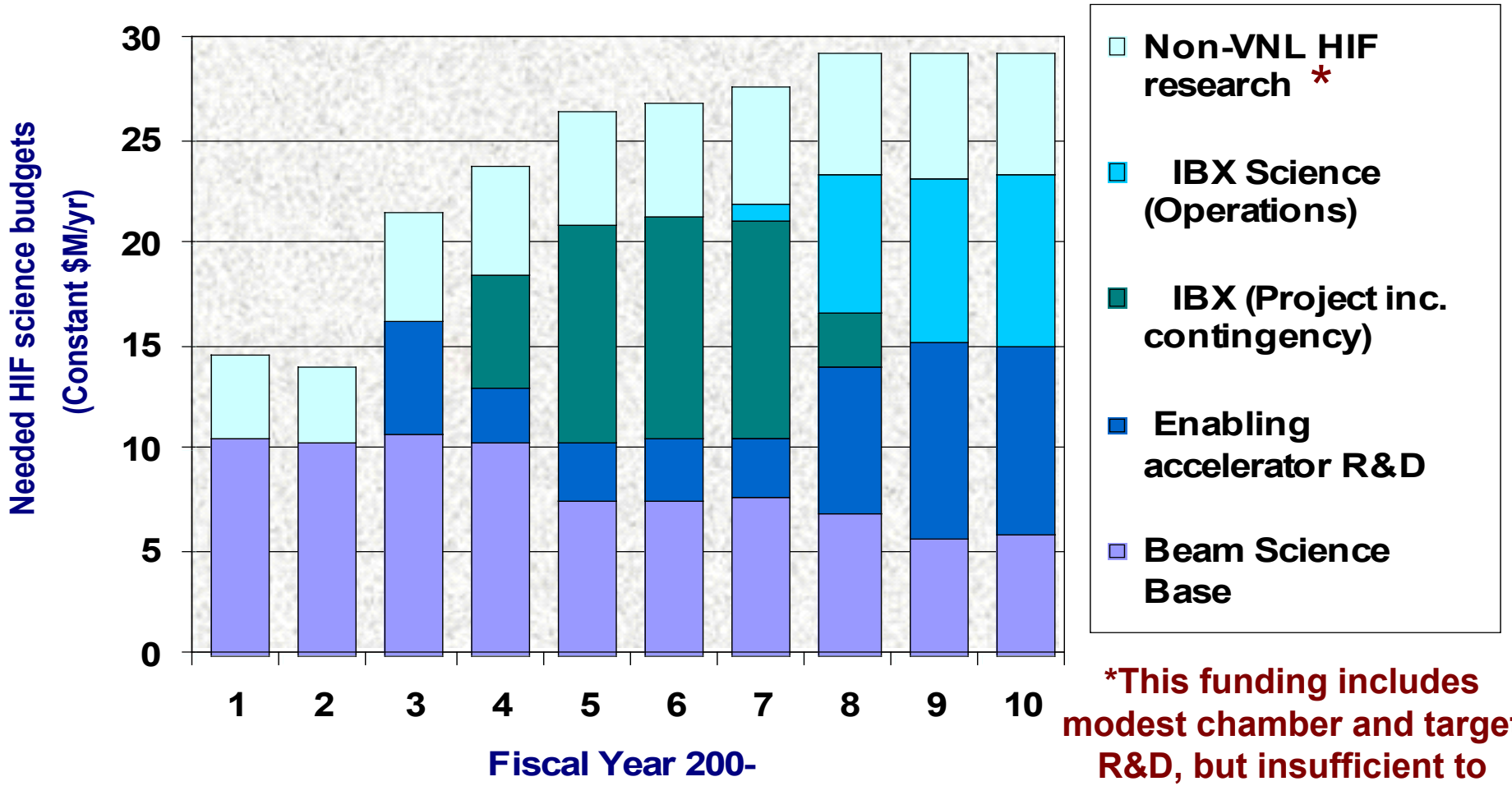
Based on:

- Bottoms-up design and costs of the 2nd arm of the DARHT accelerator
- Engineering drawings for designs for ILSE experiment
- Costs from HIF small-scale experiments
- Vendor quotes
- Prototype costs (e.g. magnets)

$\Rightarrow$ **$45 M** (Construction)

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.**

What the IBX Can't Do – The Mission of the IRE

IRE will:

Do the physics which requires high kinetic energy, large number of beams, or long accelerator

	IBX	IRE	Driver
Final energy	5 - 20 MeV	400 - 800 MeV	3-10 GeV
# of Beams	1 - 9	32 - 64	100 - 200
Length (focusing pds)	70 - 100	300 - 500	~ 1500

Physics for the IRE

- **Multiple beam physics**

  inductive effects at high energy

  interaction with neutralizing electrons in chamber

- **Effect on longitudinal stability of interaction of beam with induction cores & drive circuitry (beam loading)**

- **Effect of electron accumulation in pulse**

- **Long length scale emittance growth**

  retest of physics on IBX with high sensitivity

- **Beam–target interaction physics & implosion symmetry**

Other Goals Necessary for Proof-of-Performance

- Prototype multiple beam technology
- Demonstrate electrical efficiency of accelerator & reliability
- Show costs which scale to favorable COE

Value of the IBX to the IRE

IBX would:

- Obtain data to optimize aperture, pulse length, final focus design
- Prototype technology in an integrated system
- Prototype diagnostics
- **Benchmark computer design codes**

For the IRE:

Reduced risk
Increased capability
Reduced cost
Ability to design experiments at end of accel. with confidence

Summary

- When the present experiments are completed, HIF will have finished testing the physics which can be tested at small scale.

- For a modest increase in funding, giving a modest increase in length and energy, an intermediate-scale experiment, the IBX, would give access to new and important physics and provide an integrated test of all driver beam manipulations.

- The IBX would provide data to optimize the IRE, lower risk and cost, and improve planning capability for this experiment.

- The IRE would investigate physics of high energy and high current, and multiple beams, and demonstrate the viability and reliability of technology, as well as providing cost scaling.