Next-Step in Heavy-Ion Fusion: Integrated Beam Experiment (IBX)

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Presented to

March 18-19, 2003

OFES Budget Planning Meeting

Gaithersburg, Maryland

There are compelling reasons why heavy-ion fusion is part of the OFES fusion portfolio:

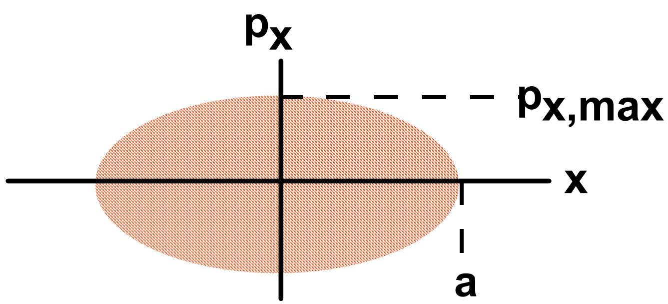
- **1979 Foster Committee:** "...heavy-ion accelerators have great promise as reactor candidates because of their inherently high efficiency, developed repetitive pulse technology,..."
- **1982 JASON Review:** "We conclude that the uncertainties in coupling physics for high-energy heavy ions are minimal."
- **1985 National Academy of Sciences (Happer) Review:** "Heavy-ion beams may well be the best eventual driver for energy applications."
- **1990 Fusion Policy Advisory Committee (Stever)** recommended parallel development of inertial and magnetic fusion (about $30M/year for HIF).
- **1993 Fusion Energy Advisory Committee (Davidson, Conn):** "We recognize the great opportunity for fusion development afforded the DOE by a modest heavy-ion driver program that leverages off the extensive target program being conducted by Defense Programs..."
- **1996 FESAC (Sheffield):** "In agreement with previous reviews, we consider the heavy ion accelerator to be the most promising driver for energy applications."

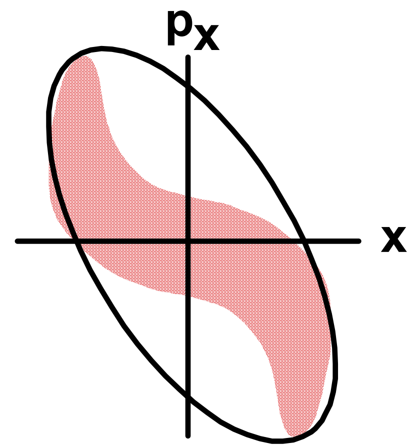
The heavy-ion-fusion (HIF) program's objective is to provide a comprehensive scientific knowledge base for inertial fusion energy (IFE) driven by high-brightness heavy-ion beams.

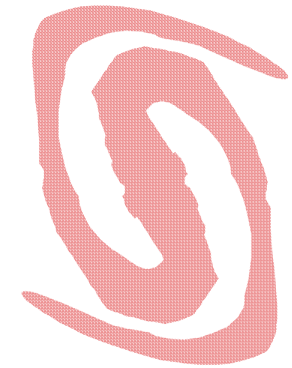
↓

The next step in heavy ion fusion should make an essential advance towards this objective.

The primary measure of beam quality (focusability) is the emittance ε (product of beam radius a and divergence angle p_x/p_z) and associated beam brightness $B \sim I / \varepsilon^2$ (current density per unit solid angle)







an extreme case

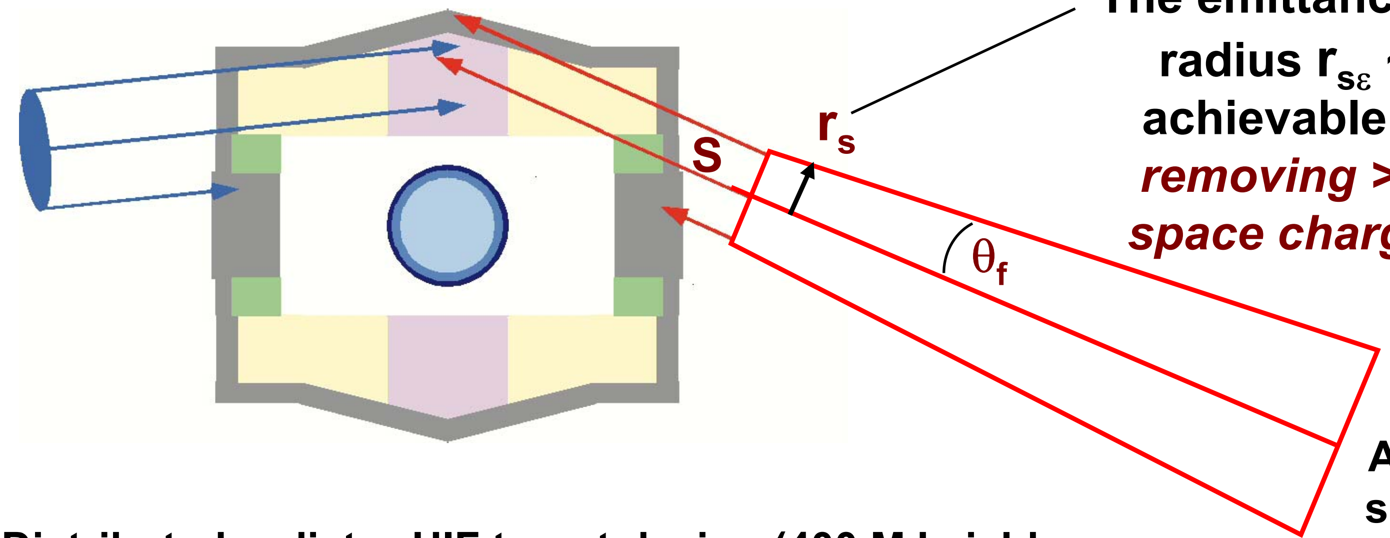
In an ideal accelerator (forces linear in x, y, z) the normalized emittance $\varepsilon_n = \beta\gamma\,\varepsilon = a\,p_{x,max}/mc$, and the normalized brightness x pulse width $B_n\,\tau = I\,\tau / \varepsilon_n^2$ is conserved (Liouville's theorem).

Nonlinear applied and space-charge fields lead to distortions of phase space
→larger equivalent space area
→macroscopic emittance growth, brightness decreases

Along the accelerator, we measure emittance growth or brightness degradation due to non-ideal effects with respect to the normalized values ε_n and $B_n\,\tau$

Hitting a target requires high-brightness beams and plasma neutralization of beam space charge in the target chamber

Example: target emittance-limited beam intensity on target $S_\varepsilon = B\,T_{ion}\,\theta_f^2\,\pi^{-1}$ = 5×10^{14} W/m^2 requires a normalized $B_n\,\tau \sim 4\times10^6$ A·s/(m^{2}rad^2) at T_{ion} = 4 GeV, $\beta\gamma$ = 0.3, τ = 9 ns, at focusing convergence angle $\theta_f = 10^{-2}$ rad. Existing injectors are capable of $B_n\,\tau > 4 \times 10^7$, more than 10 x the target requirement.



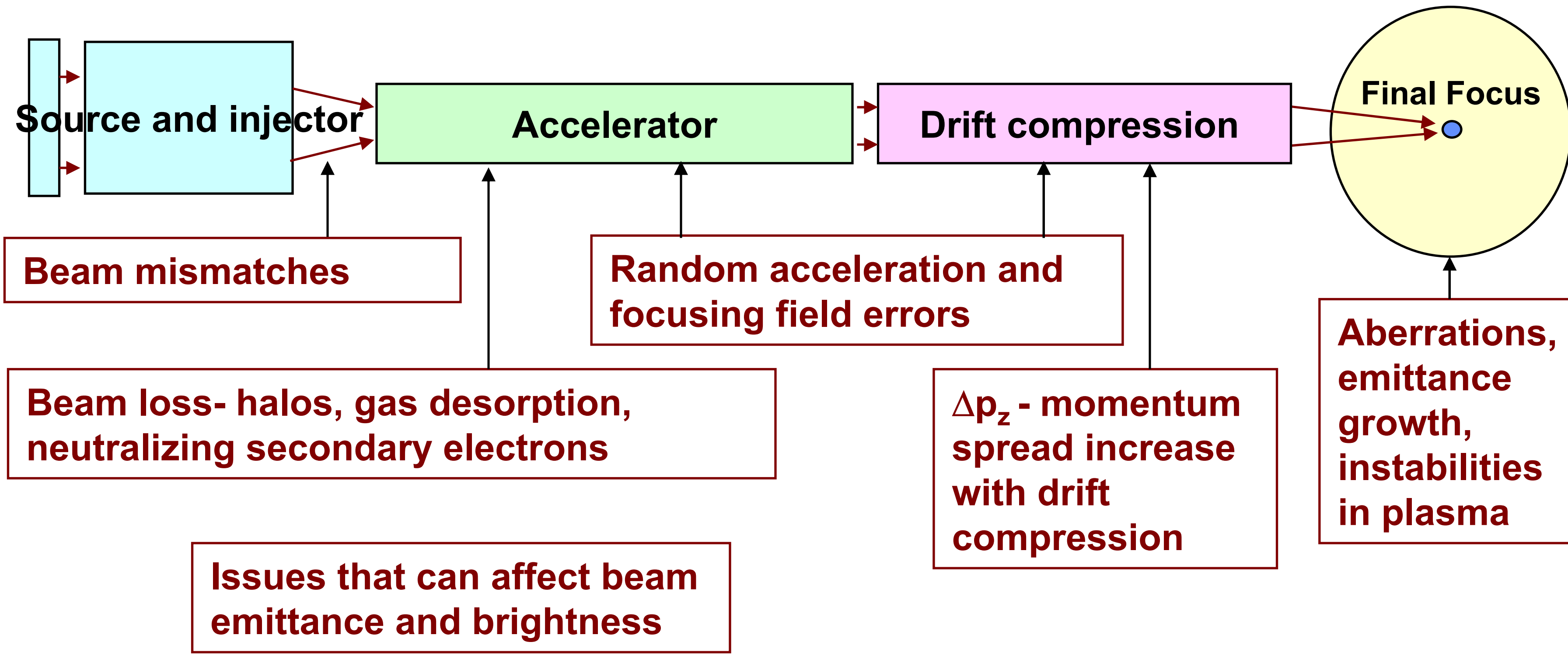
The emittance-limited focal spot radius $r_{s\varepsilon} \sim \varepsilon / \theta_f \sim 1$ mm is achievable *only with plasma removing > 95% of the beam space charge in the chamber.*

Distributed-radiator HIF target design (400 MJ yield @ 7 MJ, 4 GeV Bi, 120 beams, by Callahan-LLNL)

Aiming errors, residual space charge, focusing aberrations contribute an additional 1 mm to the focal spot

Key question: how much degradation in beam brightness (increase in focal spot) will the beam accumulate passing through accelerator, drift compression, and final focus regions?

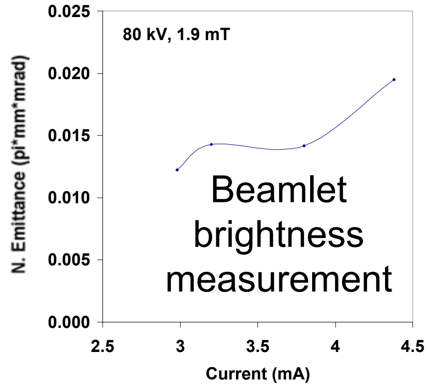
Beam emittance can grow 3 x, (brightness degrade by 10 x) over all regions and still focus on the target



Current experiments in the VNL are addressing key issues affecting beam brightness in selected regions

Source-Injector test facility

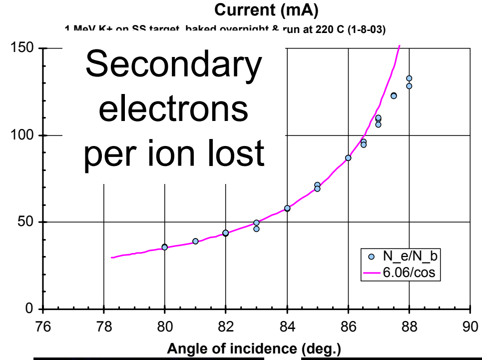
(STS)



Injector Brightness: source brightness, aberration control with apertures, beamlet merging effects

High Current Experiment

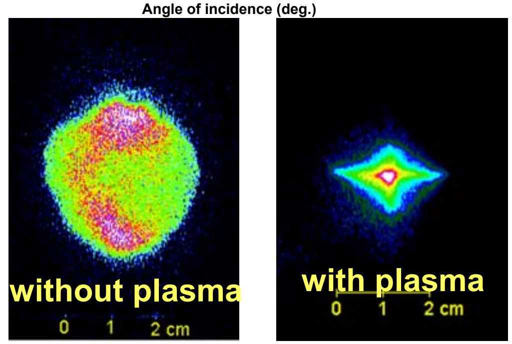
(HCX)



Transport: envelope control sensitivity, halos, gas and secondary electron effects

Neutralized Transport Experiment

(NTX)



Focal spot images

Focusing: aberration control, plasma control techniques and diagnostics

Understanding how the beam distribution evolves passing sequentially through each region requires an integrated experiment

→The beam is collisionless, with a "long memory"

→Its distribution function --- and its focusablity --- integrate the effects of applied and space-charge forces along the entire system

NOW → **NEXT**

STS-injection

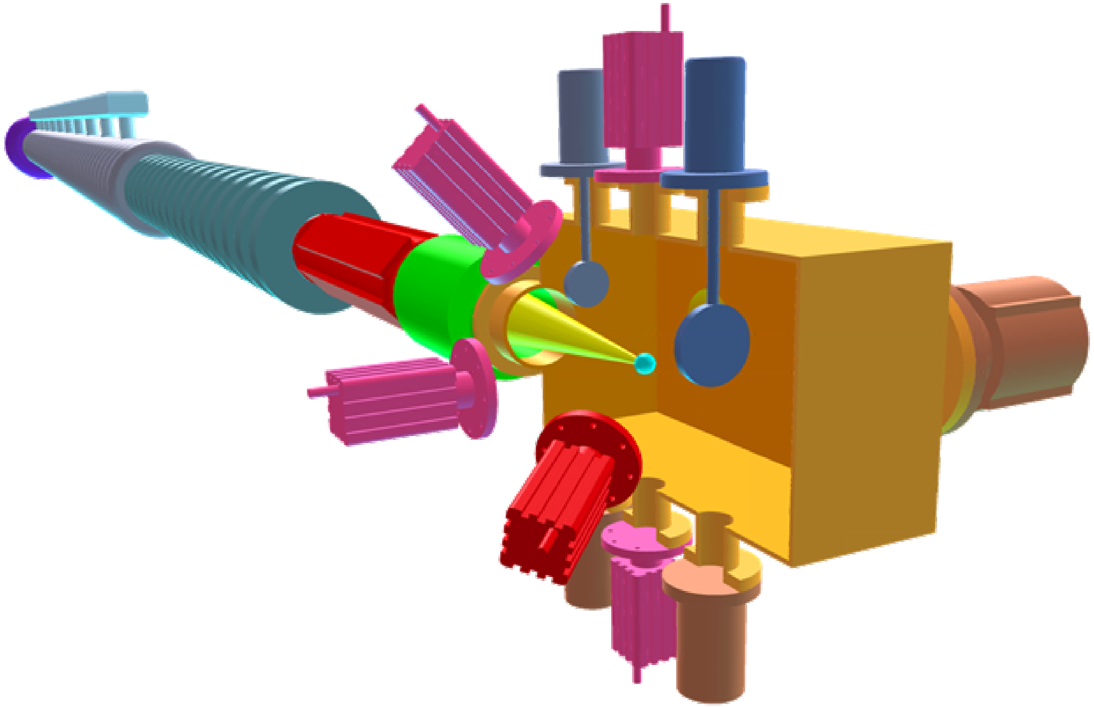
HCX-transport

NTX-focusing

Combine these elements and add acceleration and drift compression

An source-to-target integrated beam experiment which sends a high current beam through injection, acceleration, drift compression, and final focus

IBX mission: Provide integrated source-to-target physics experiments with a high-current heavy ion beam of IFE-relevant brightness to optimize target focusing.



→ **An IBX capability for integrated acceleration, compression and focusing of high-current, space-charge-dominated beams would be unique- not available in any existing accelerator in the world.**

Key physics issues to be addressed define requirements for the IBX

- **Key physics issues and balance of cost and risk, indicate the following constitute an appropriate Proof-of-Principle step for heavy ion fusion:**

→ injection of a single high current heavy-ion beam (> 200 mA for gas/electron effects)
→ acceleration to a sufficient energy (> 5 MeV for > 10 x longitudinal bunch compression)
→ focusing into a well-diagnosed plasma-neutralizing chamber.

- **Further HIF steps will require scaling up the ion kinetic energy and the number of beams to drive targets.**

→ IBX is the right next step to provide the most information at minimum cost needed to design any future HIF steps.

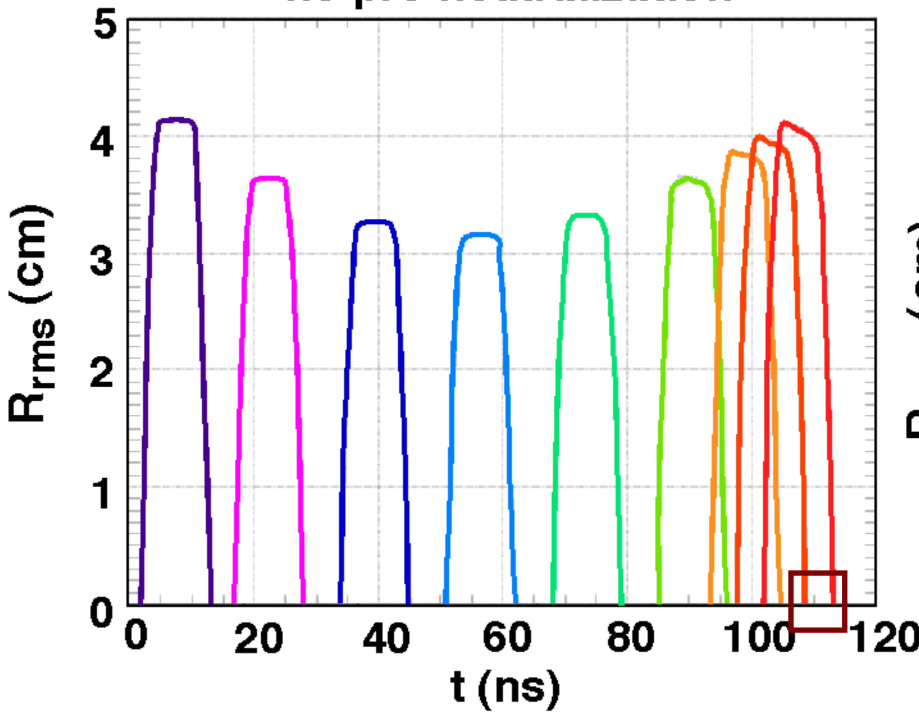
IBX physics objectives that must be integrated to achieve the mission

1) Demonstrate longitudinal bunch control in integrated experiments
   - measure longitudinal perturbations & effect on beam head and tail
   - measure fundamentals of longitudinal wave propagation
2) Measure beam brightness degradation during transport
   - halo production, slight errors in magnet alignment or strength, image forces, etc.
   - temperature anisotropy, 2-stream instabilities
3) Determine impact of gas and electron effects on beam brightness degradation
4) Determine limits on drift compression
5) Test theories/simulations of neutralized beam focusing
6) Develop integrated beam models for predictive focal spot capability

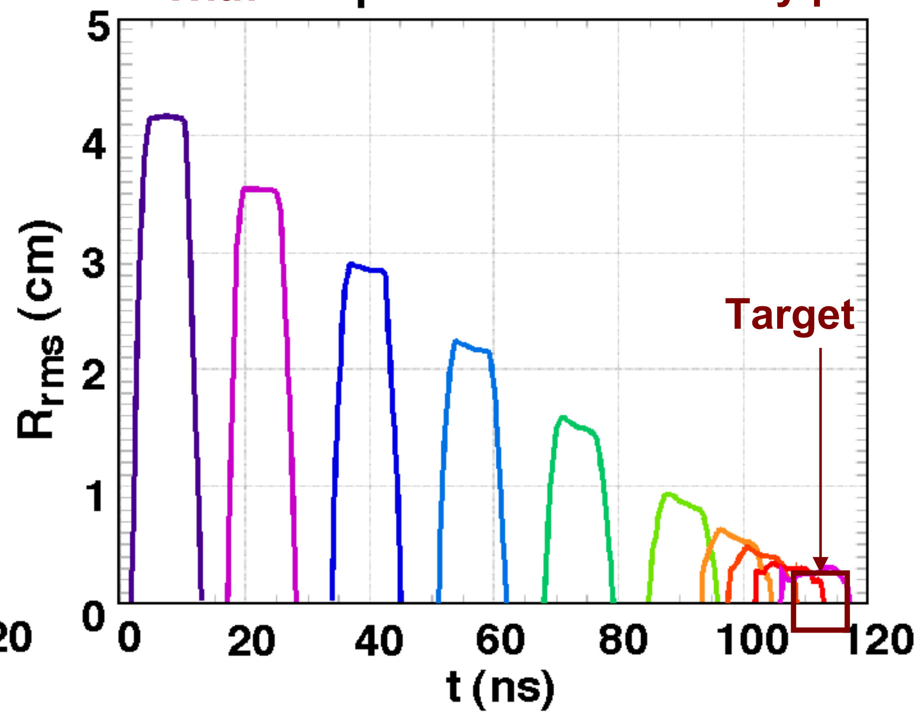
Example of important physics issue: plasma neutralization of beam space charge in focusing chamber

Example: simulations of time histories of a driver 2.5 GeV Xenon beam radius at selected points over a 6 meter focal length

no pre-neutralization



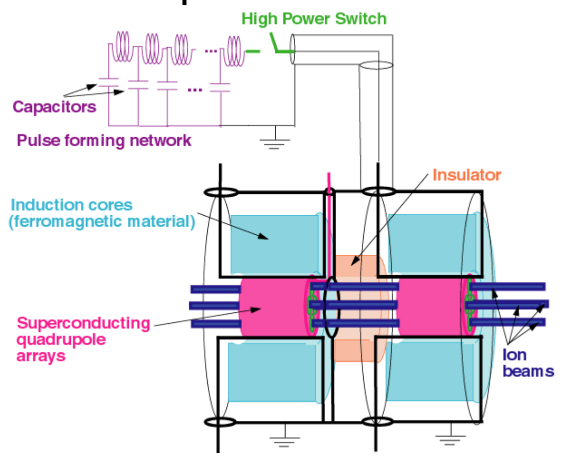
With full pre-neutralization by plasma



Without plasma in the chamber, the ion kinetic energy and linac voltage, length and cost would have to increase by 2 to 3 x to recover the 2 mm focal spot for the target

Example of important physics issue: drift compression of bunch length by factors of 10 to 30

Induction acceleration is most efficient at τ_{pulse} ~100 to 300 ns



Bunch tail has a few percent higher velocity than the head to allow compression in a drift line

Target capsule implosion times require beam drive pulses ~ 10 ns

Drift compression line

Final Focus

The beam must be confined radially and compressed longitudinally against its space-charge forces

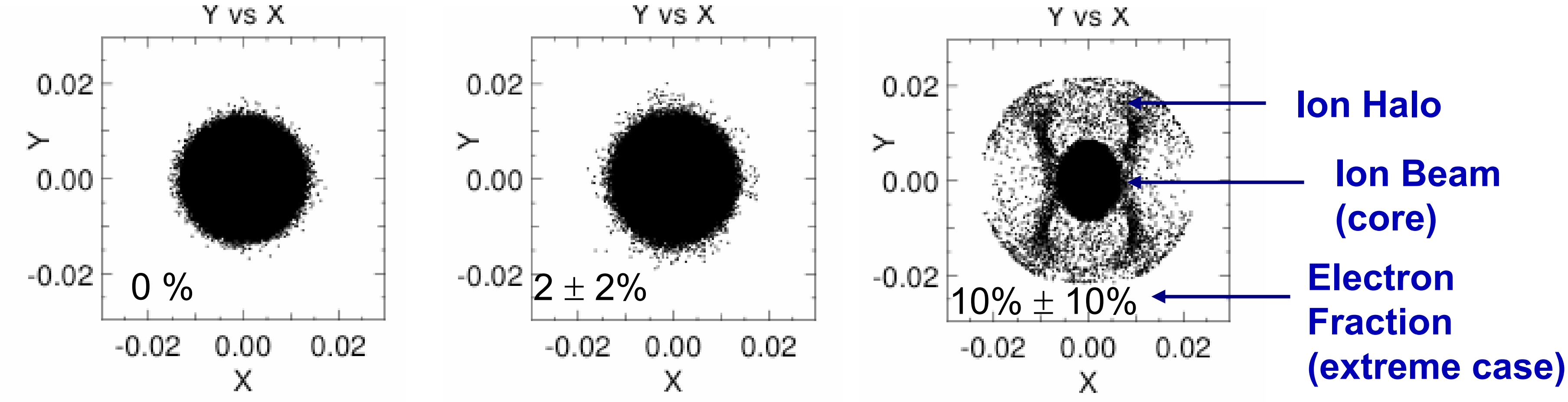
Issues:

1. Matching beam focusing and space-charge forces during compression.
2. Longitudinal beam heating due to compression
3. Chromatic focus aberrations due to velocity spread

Example of important physics issue: beam loss in high intensity accelerators -a current world research topic (GSI-SIS-18, LANL- PSR, SNS)

- **Gas desorption** Gas desorbed by ions scraping off on the channel wall can limit average beam current.

- **Electron cloud effects** Ingress of wall-secondary electrons from beam loss and from channel gas ionization. WARP (below) and BEST simulations indicate incipient halo formation and electron-ion two-steam effects begin with electron fractions of a few percent.



- **Random focusing magnet errors** Gradient and displacement errors can also create halos and beam loss.

IBX will need existing and new diagnostics

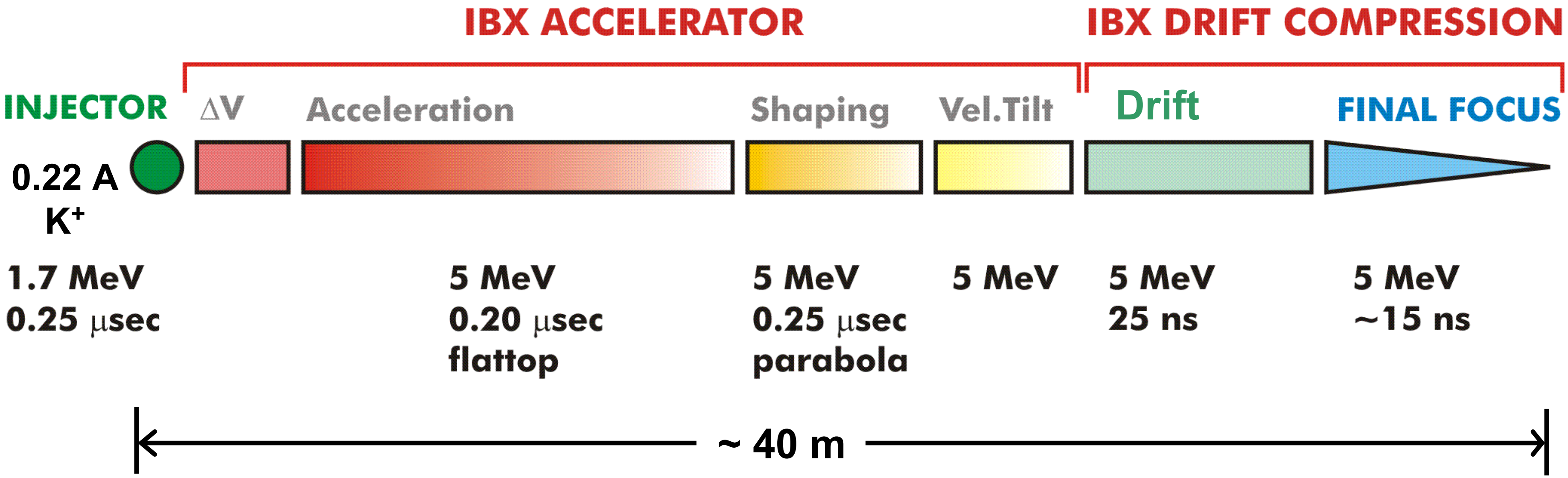
- **Existing diagnostics**
  - -slit scanner
  - -Faraday cup
  - -inductive and capacitive beam monitors
  - -optical scintillator
  - -electrostatic energy analyzer
  - -secondary electron and beam scrape-off monitors
- **Diagnostics under development for current experiments**:
  - -scintillator-based optical diagnostics
  - -pepper-pot techniques
  - -electron-beam potential probe
  - -multiple-channel slit scanner

Needed for machine operation (commissioning)

- **New diagnostics we need to develop**
  - -improved beam energy spectrometer for longitudinal pz, Δpz
  - -compact and non-intercepting diagnostic techniques
  - -low-intensity halo profile diagnostics
  - -dynamic vacuum measurements for repetitive pulses

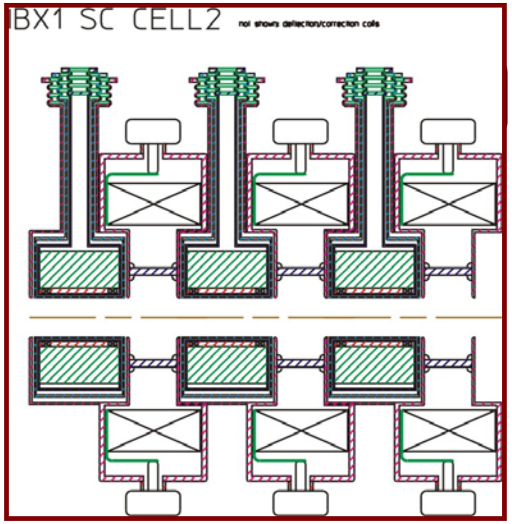
Needed for physics experiments

We have a reference case IBX design to guide detailed physics analysis:



Key machine features:

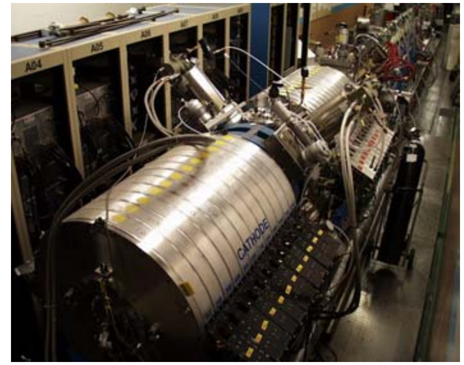
- 100 kV per induction gap (330 kV/m ave.)
- Agile waveform control for longitudinal physics
- NbTi superconducting magnets for focusing
- Cold bore with in-channel cryo-pumping
- 5 Hz pulse rate capability for short periods




PROPOSED SITE for the
INTEGRATED BEAM EXPERIMENT (IBX)
HIF-VNL
EXPERIMENTAL
FACILITIES,
NTX and HCX
HIF-VNL
OFFICE BUILDING
BERKELEY LAB

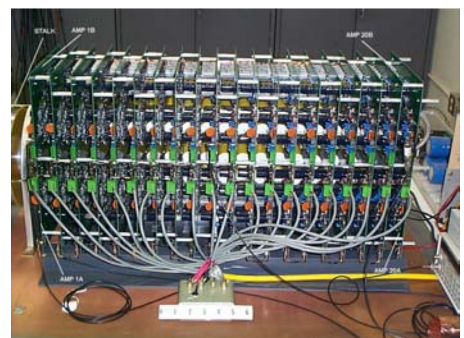
IBX designs assume enabling technology close to HCX, ETA, RTA, DARHT, and SBIR experience.

HCX superconducting transport magnets [85 T/m] (TESTED)



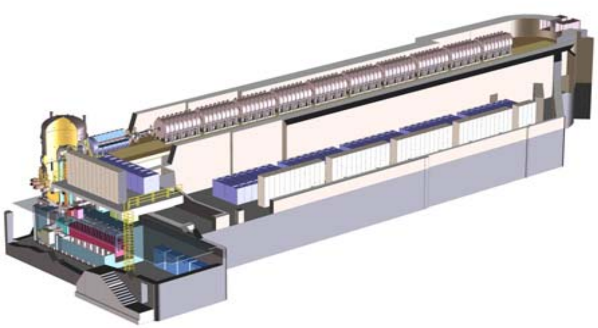
RTA injector, 1 MV, 300 ns

ETA-II cell modification for RTA (100KV, 250ns FWHM



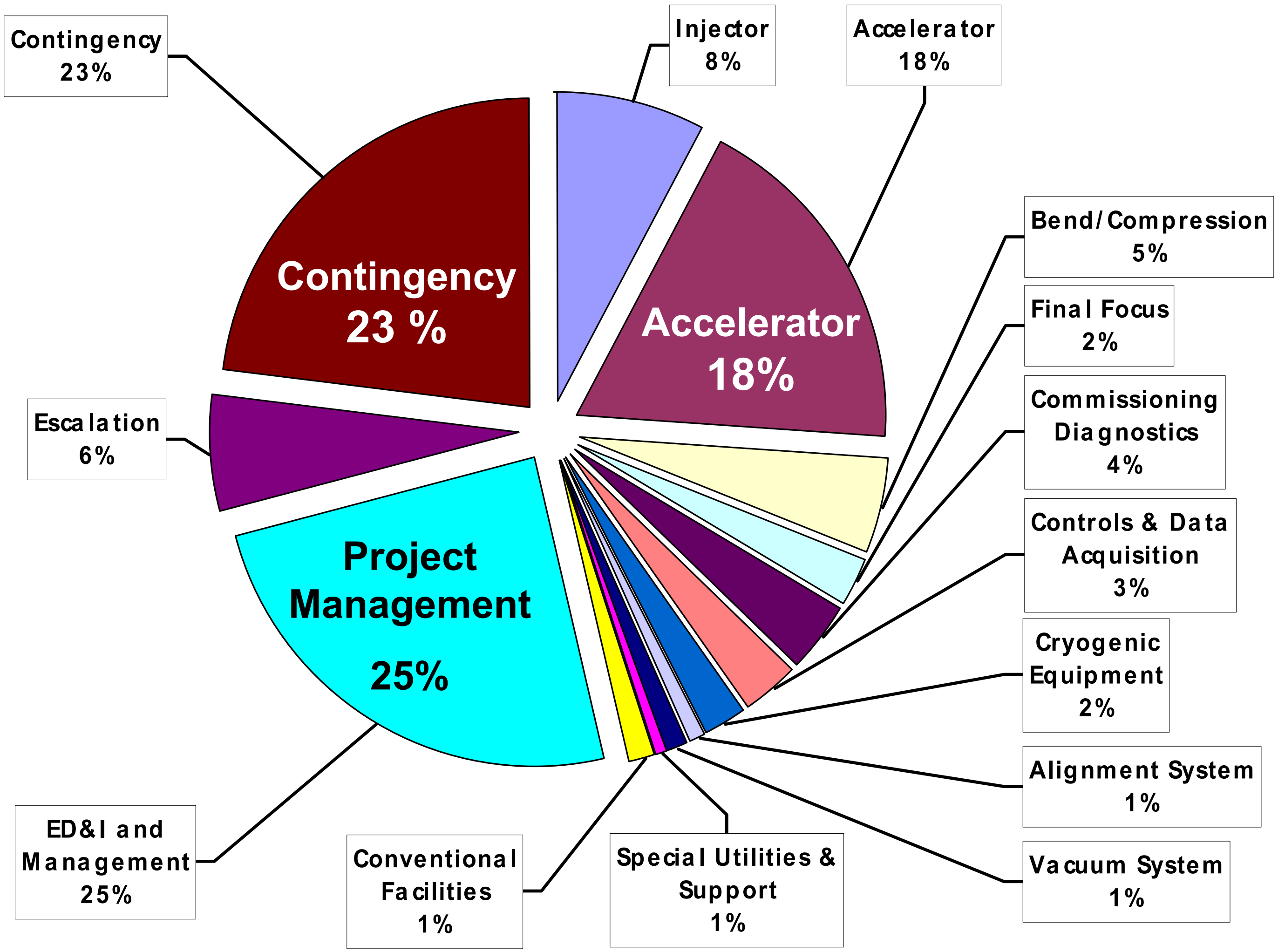
First-Point Scientific Induction SBIR: Regulation Modulator (MOSFET-based linear solid state amplifier-to be installed on HCX)

Key enabling technology for longitudinal beam control



DARHT ***/ 2 micro-sec, 20 MeV***
(useful LBNL actual cost data for cores & pulse-forming networks)

We periodically estimate IBX cost to evaluate design sensitivities:



Cost breakdown
In % of TEC
TEC= $60- 70 M
TPC= $72- 82 M
including 12 M$
R&D (in FY02 $)

For 1 beam, 0.25 μsec, NbTi superconducting magnets, 5 MeV

A timely IBX is critical to the HIF schedule for ETF/Demo decision

(Slide I presented 1/13 to FESAC Devpath panel)

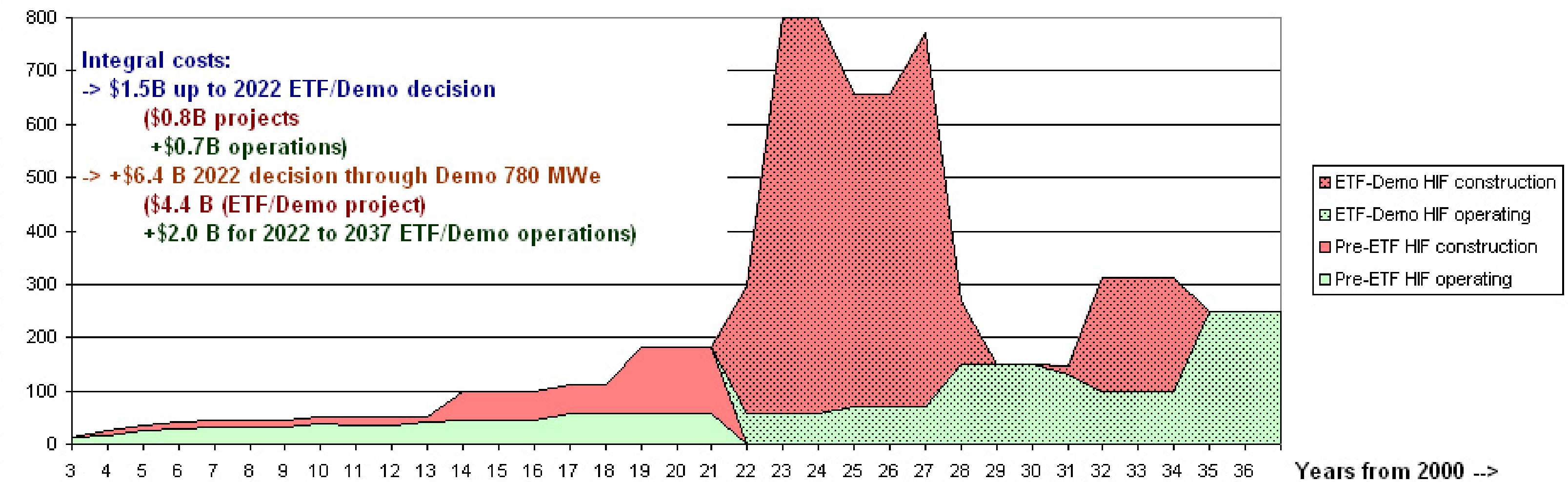
Years - 2000: 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47

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

Costs in $ M/ yr of 02 $



Years from 2000 -->

Conclusions

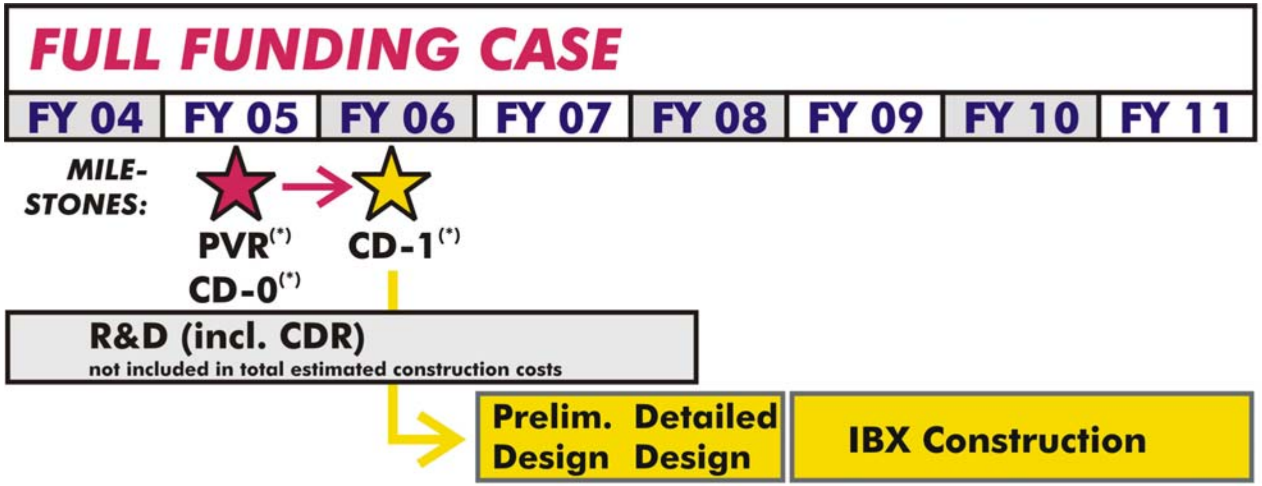
▪Key beam physics issues in heavy ion fusion affect the ultimate beam brightness and focusability for IFE targets: effects of injector current density limits, envelope control, centroid steering, gas and electron cloud effects, transport magnet errors, and final focus plasma neutralization.

▪The key physics issues for HIF define the mission and physics objectives for the next step. An integrated beam experiment (IBX) is the right next step for heavy-ion fusion to evaluate the overall beam brightness evolution from source to target at minimum cost.

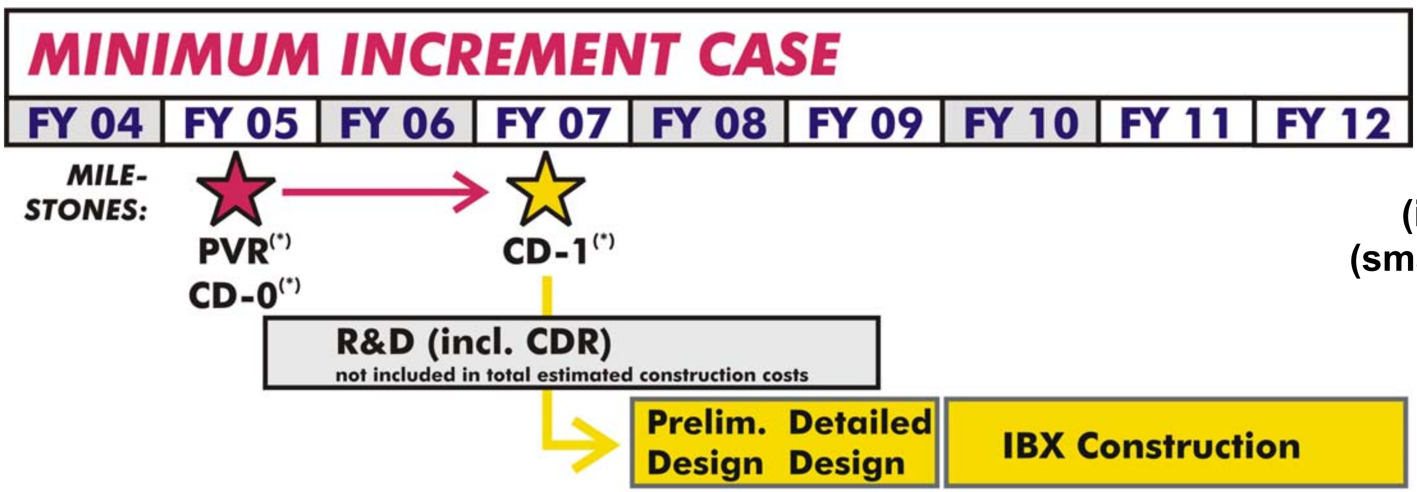
▪Current modest-scale experiments on focusing, transport and injectors are providing important physics information for the IBX physics design and in the development of integrated beam models.

▪A timely start of IBX is required if HIF is to be a viable candidate fusion approach for ETF/Demo.

Backup Viewgraphs



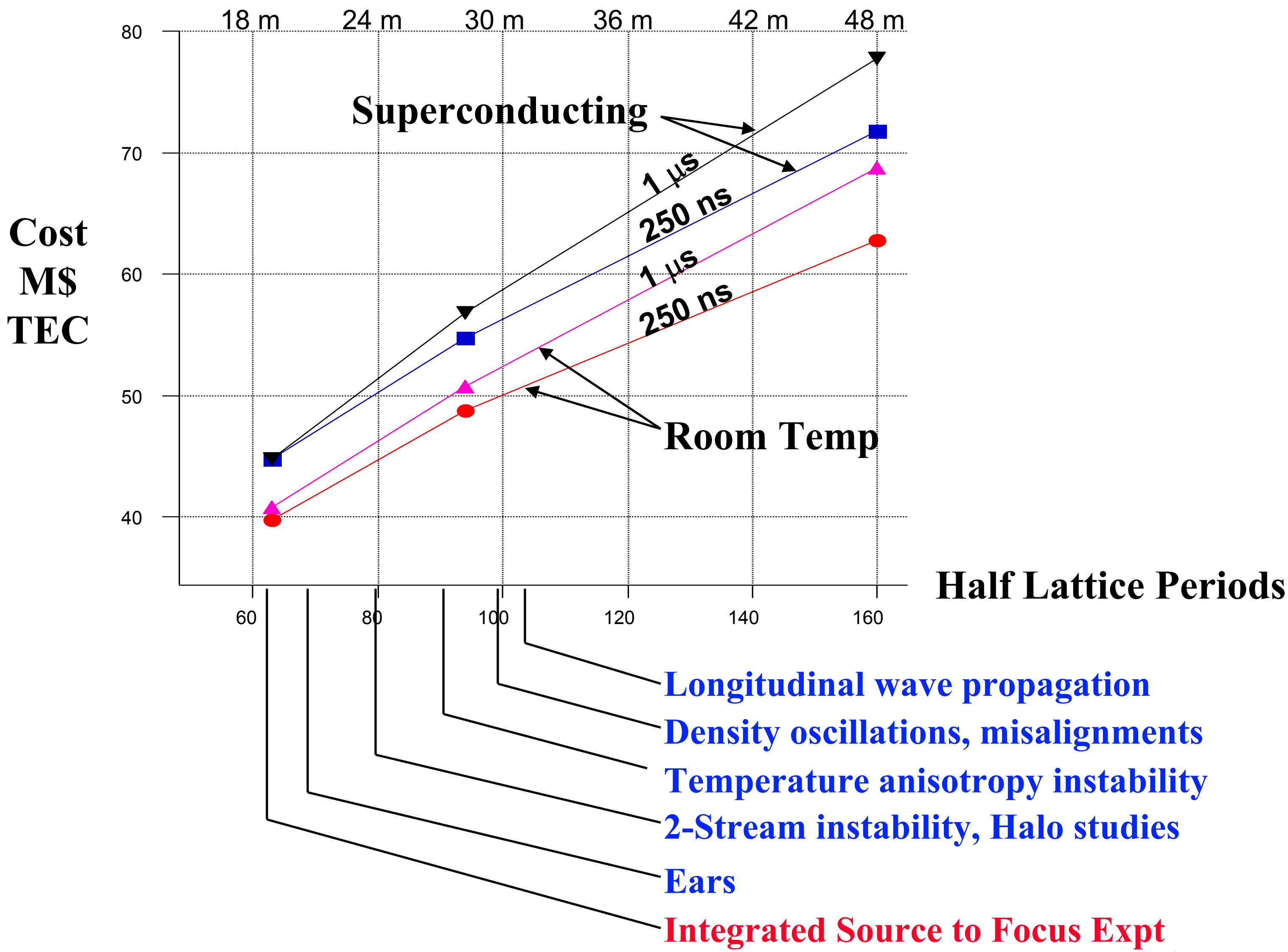
Full R&D in FY04
PVR in FY05
CDR in FY06
Project-Construction Start FY09



PVR in FY05
Less R&D in FY06
(increases project risk)
(small-scale R&D in FY05)
CDR delayed to FY07
Project-Construction Start FY10

(*) PVR ... PHYSICS VALIDATION REVIEW
CD-0 ... MISSION NEED JUSTIFICATION
CD-1 ... CONCEPTUAL DESIGN REVIEW

Physics Available vs. Cost



Scope of an IBX PVR

I. Justification of Mission Need

- Assessment of scientific issues of driver
- Demonstration of uniqueness of physics regime
- Survey of current accelerators
- Physics objectives

II. Justification of Approach

- Survey of alternate options
- Assessment of cost / risk / capability of alternative approaches

III. Justification of Reference Design

- Plausibility to meet physics objectives
- Plausibility to meet cost target

For a PVR, we will evaluate several alternative IBX designs to seek the minimum cost, maximum flexibility, and minimum risk for the mission.

Examples:

- **Compare cost and capability of room temperature versus superconducting magnets, and warm versus cold bore for vacuum pumping**
- **Evaluate alternative acceleration schedules to maximize flexibility (e.g., longer pulses at lower acceleration gradients using the same injector for enhanced halo, beam loss, electron cloud and wave transit time experiments.)**
- **Alternative drift compression experiments (quad and solenoid drift lines, application of fast correction elements)**
- **Alternative final focus experiments (different plasma configurations, final focus with quads, solenoids, and assisted pinch)**

One specific source-to-target configuration for the mission will be required for the PVR and CDR, but modest operating hardware additions to enable additional experiments (e.g., injector upgrades, bends, advanced focus magnets) will also be identified.

Scope needed for an IBX Physics Validation Review

PHYSICS CAPABILITES FOR RANGE OF NEEDED EXPERIMENTS: JUSTIFICATION OF DESIGN SELECTED FROM OPTIONS FOR THE PROPOSED MISSION

"Dynamic Aperture" – necessary clearance to vacuum wall
- electron production & dynamics, halo production, mismatch to focusing system, alignment tolerances, gas desorption

Experiment parameters & flexibility needed ($\Rightarrow$ Specs for Diagnostics)
- Electron dynamics, gas desorption instability (burst mode), longitudinal wave dynamics, halo production, steering, drift compression, focus, neutralization expts, instabilities (two-stream, temp. anisotropy), pulse length limits, etc.

Injector design, beam dynamics, flexibility, and diagnostics

Design of sections for beam "catching", matching, velocity tilt imposition shaping, compression, focus

ENGINEERING / COST

Basic engineering design - mechanical & electrical

Technology options: Focusing magnets (superconduction / room temp), induction module pulsers (spark gap/solid state/ thyratron), injector choices

R&D program outline

Path from CD0 to CDR

Costing basis

Uniqueness of the IBX experiments

In other accelerators (high energy physics, nuclear physics, light sources, spallation neutron source accelerators, etc) space charge is a perturbation.

HIF beam dynamics are space–charge–dominated.

HIF beam physics is non-neutral plasma physics.

IBX is unique:

- ☞ **Only ion accelerator space-charge-dominated from source to end**
- ☞ **Only experiment studying integrated drift compression / final focus / neutralization system**
- ☞ **Unique beam distribution function due to space charge, and beam production and acceleration methods**

We will coordinate all sources of data and modeling for vacuum and electron effects

- Put increased emphasis on gas/electron experiments with four magnetic quads and new diagnostics in HCX this spring

- Collaborate with GSI to extend ion energy range for data, models, and wall materials (add annex for this to new US-German agreement on cooperation in dense plasma science)

- Coordinate other related accelerator research on gas/electron cloud issues: PPPL/LANL-PSR collaboration, LLNL/LBNL/ORNL-SNS collaborations.

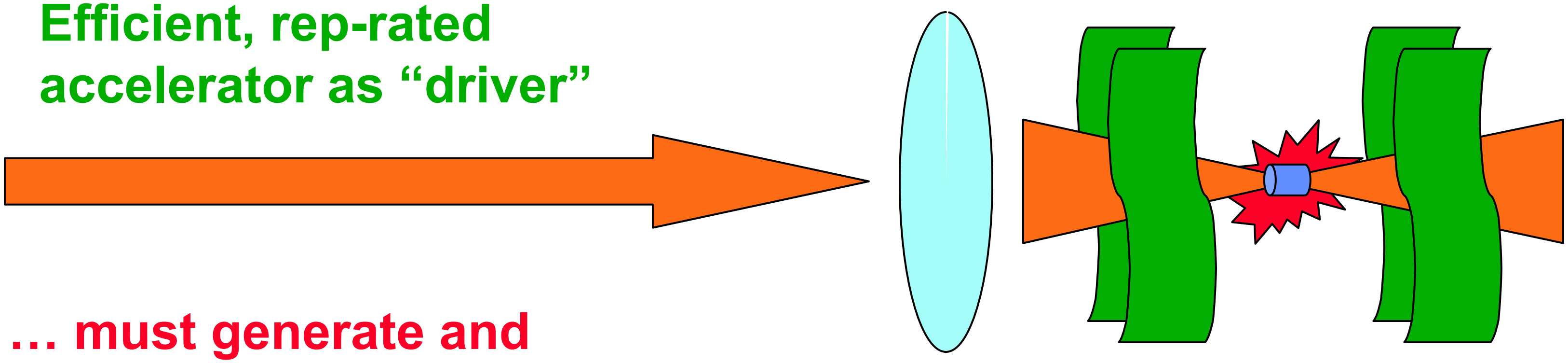
- Add a 5 Hz burst-mode and longer pulse-mode capabilities to IBX so that both vacuum and electron effects can be addressed for IRE and drivers.

The promise of Heavy Ion Fusion - and the challenges

Final magnetic lens that is robust to the effects of target explosions

Fusion chamber that uses neutronically thick liquids to minimize need for special materials

Efficient, rep-rated accelerator as “driver”



… must generate and preserve high quality in uniquely “space charge dominated” beams that exhibit collective behaviors

… must focus and compress the beams into small spots in space and time

… must tailor the chamber environment to achieve correct beam neutralization

IBX will enable study of key HIF beam physics issues at an affordable cost

The IBX will be designed with inherent flexibility to perform a variety of beam dynamics experiments

Injector	Δv	Accelerator	Δv/pulse shape	Drift compression	Final focus	Cham-ber

Constant half-lattice period and **flexible waveform generators** allow a number of options to explore longitudinal and transverse beam physics

Short pulse operation (~ 250 ns) offers a variety of compression schedules:

1. Constant current -- simplest waveform (no Δv) in accelerator
   -- maximizes drift compression; this schedule used at end of driver
2. Constant bunch length -- after initial Δv, no further Δv needed in accelerator
   -- this schedule used in beginning of driver
3. Parabolic pulse -- minimizes manipulations in pulse shaping section
4. Bunch compression -- demonstrates compression in accelerator
   -- this schedule used at intermediate energies in driver

Long pulse operation (~10 μs) allows drifting beam studies (with ears)

1. Examine electron and gas desorption issues

Use of **aperturing** and **different source sizes** allows a **range in perveances** through accelerator, final focus, and chamber

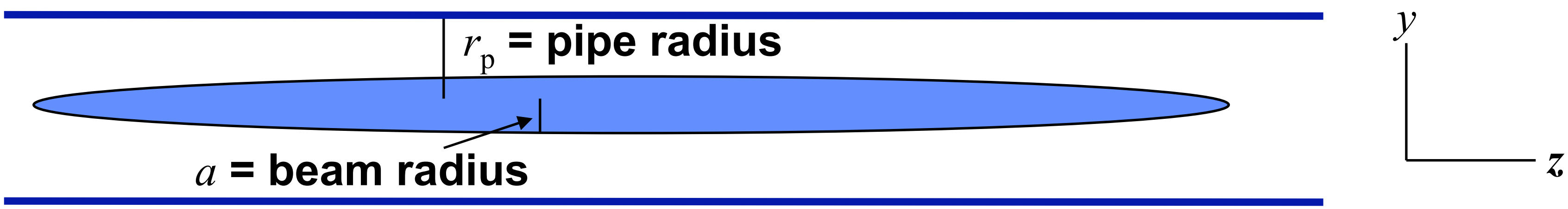
Use of **different plasma sources** allows study of chamber **neutraliz. techniques**

Two or more **time dependent focusing** elements will allow study of chromatic aberration mitigation techniques

Various final focusing schemes (quad, plasma lens, solenoid) can be tested

Can the longitudinal temperature be controlled during acceleration, compression, and confinement?

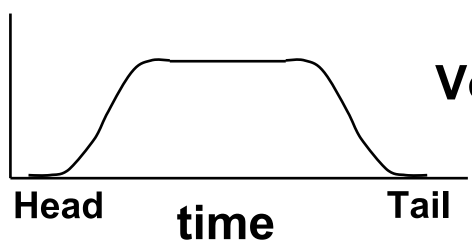
In addition to accelerating and compressing the beam, the induction cells must confine the beam against its own space charge



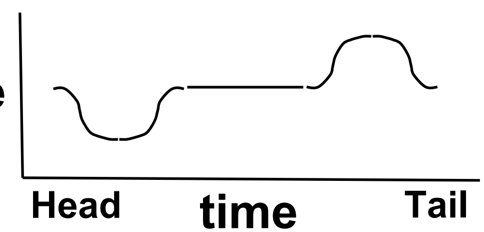
Longitudinal space charge field proportional to z-derivative of line charge

To confine beam longitudinally, "ears" are applied to beam at each gap.

Line charge density



Voltage



At each gap, small voltage errors (for acceleration, compression, and confinement), will generate waves, which can increase the longitudinal temp.

Short-pulse diagnostics issues.

Use solid-shield (heliax) cable for high bandwidth, improved noise immunity.

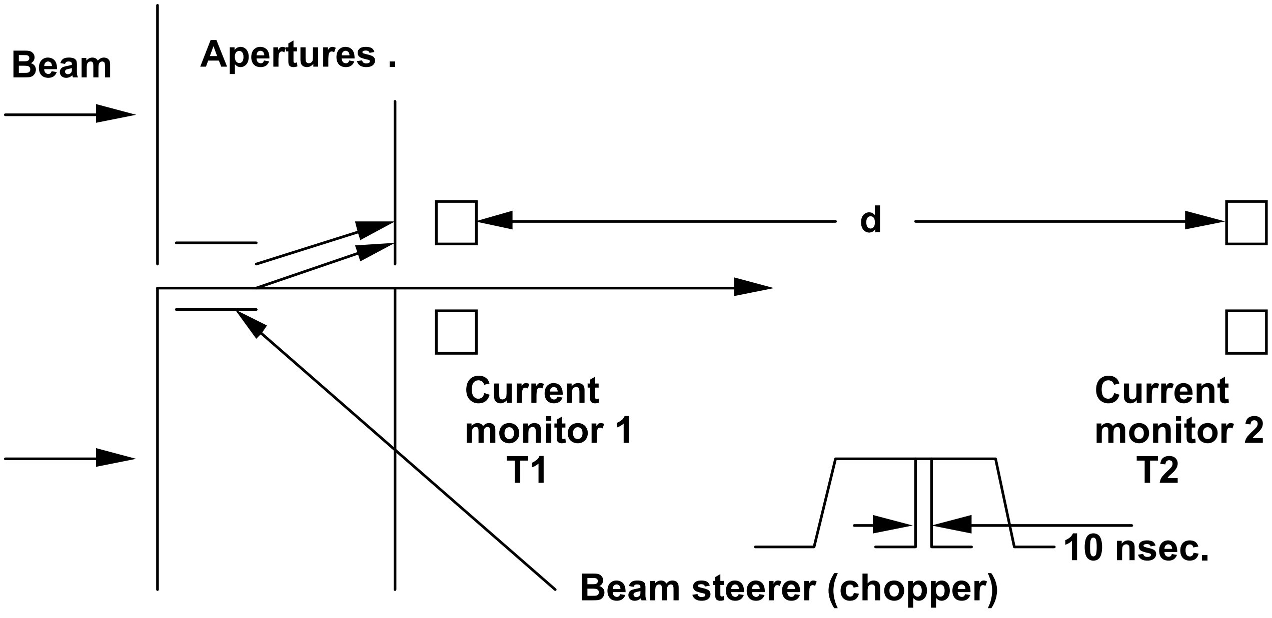
Improve shielding of diagnostics and data acquisition, especially in the presence of spark gaps. Electrical noise encourages use of optical diagnostics. Problems due to acceleration gaps don't appear severe, based on experience on RTA, DARHT.

Data acquisition bandwidth needs to be upgraded ($).

Diagnostic design needs to be oriented toward high bandwidth (cables, capacitance, design of coupling circuit).

Examples – e-beam Faraday cups, x-ray bow probe.

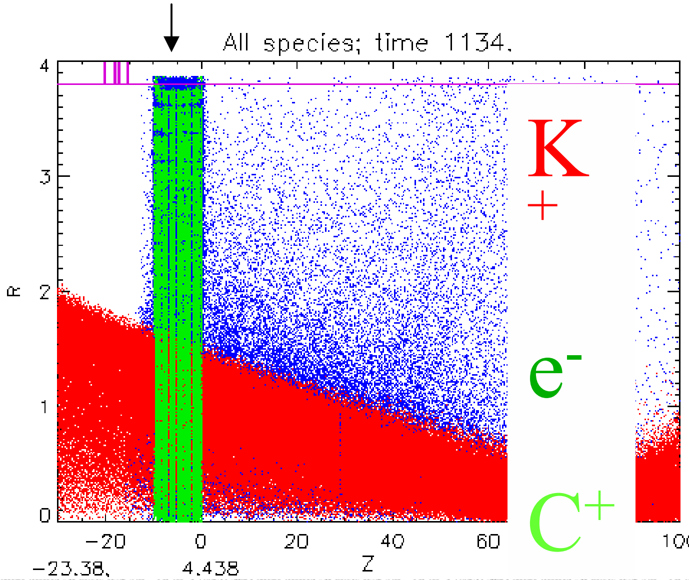
Proposed time of flight beam energy diagnostic for IBX.

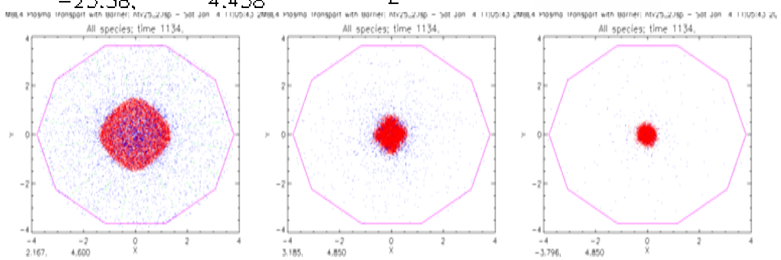


- At the point of measurement beam apertured to a pencil.
- A short slice (~10 ns) is chopped off the beam.
- The time-of-flight of the beam is measured to +- 0.5 ns.
- At a distance of 10 m at 10 MeV the energy can be determined to about 0.14%.
- Flexible placement of the initial aperture.

3d Warp-LSP NTX simulation with plasma plug neutralization

3×10^{9} cm^{-3} plasma plug only



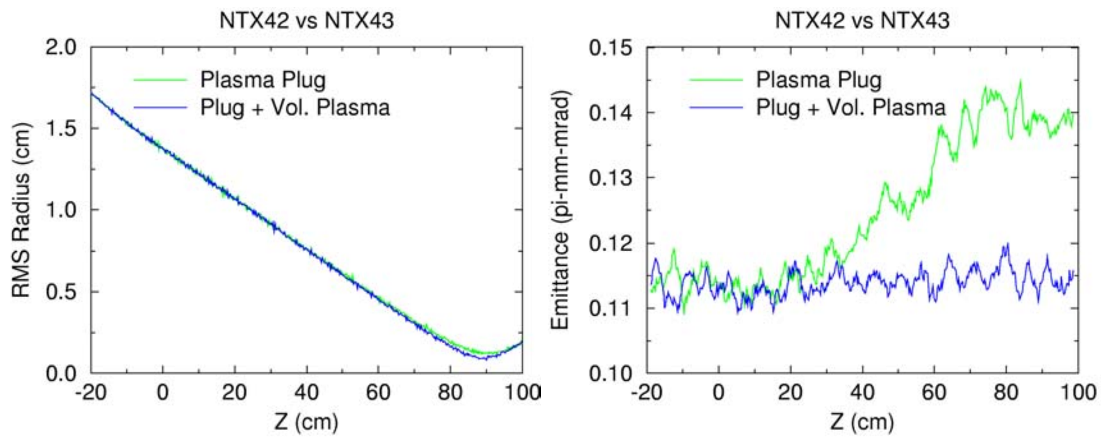


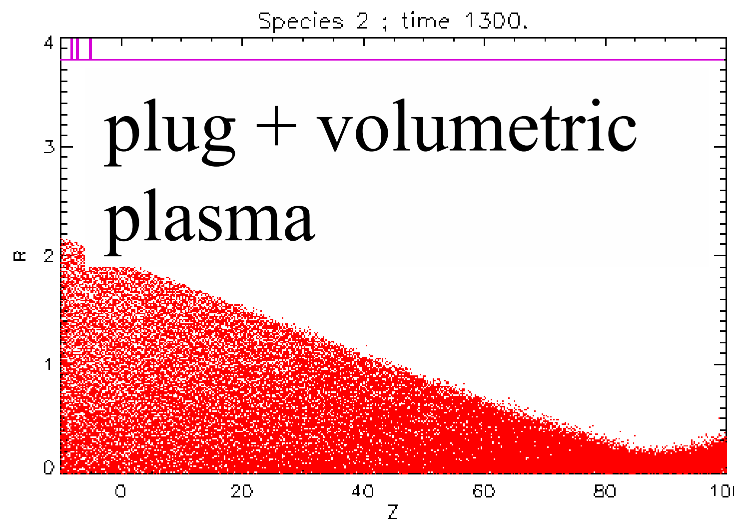
z= 0 cm z=50 cm z=80 cm

25-milliamp, 300 keV K^+ beam

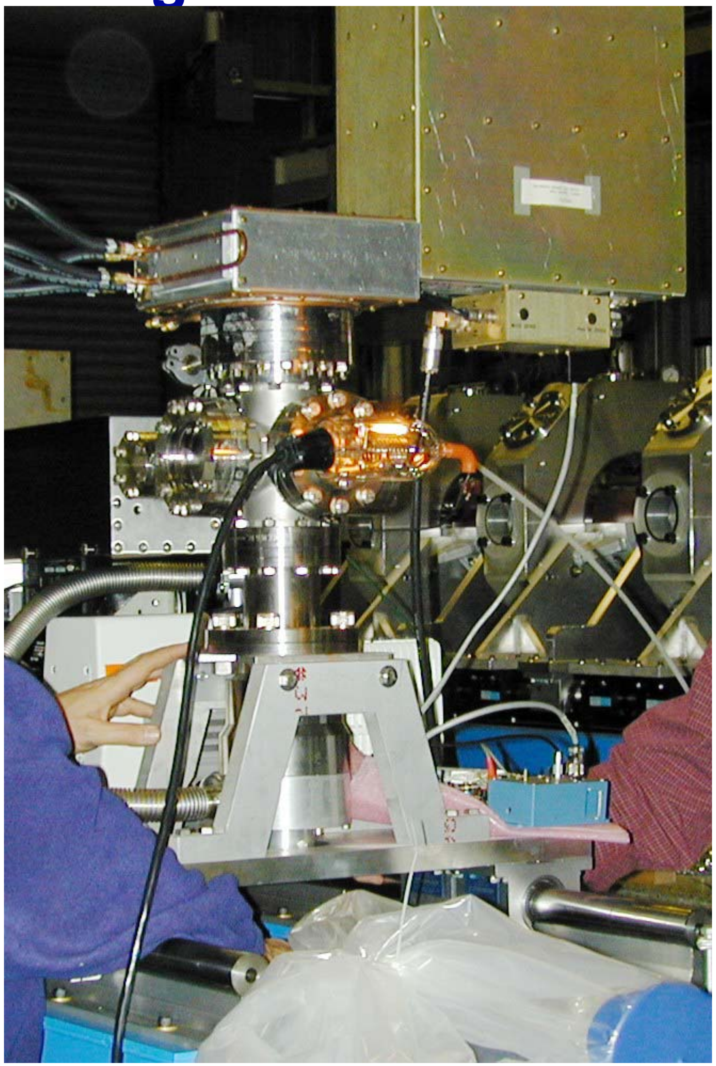
- **1.3-mm RMS spot size with plug**
- **0.9-mm RMS spot size with plug + volumetric**

2d Comparison with volumetric plasma





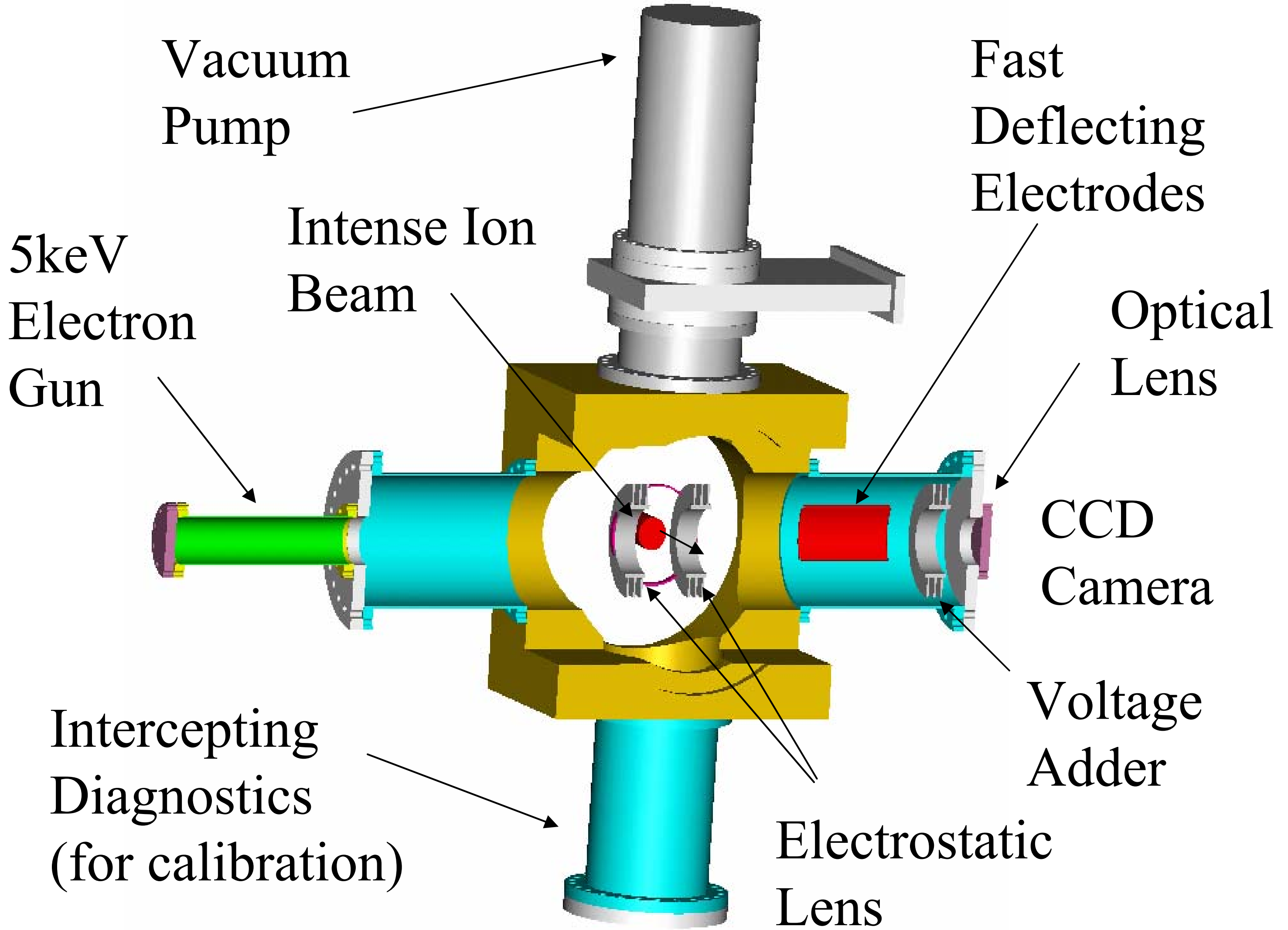
Argon RF Plasma Source for Beam Neutralization



Argon RF plasma source developed at PPPL and delivered to LBNL in December, 2002. Characterization and integration with NTX to be completed by March, 2003.

- Base pressure between shots ~ 5×10^{-7} Torr.
- 5 ms bursts of 50 psi Argon.
- RF Frequency = 17.6 MHz.
- Net power = 3.5 kW.
- Plasma density > 10^{11} cm^{-3}.
- Repetition rate ~ 1/3 Hz.

Non-intercepting beam profile diagnostic: electron beam deflection measures beam potential (NTX).



The Robust Point Design shows that a multi-beam induction linac driver can meet detailed target and focusing requirements.

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

- **The goal of this 18 month effort was self-consistency, not optimization for cost**
- **There are opportunities to optimize this approach to reduce driver cost and CoE**

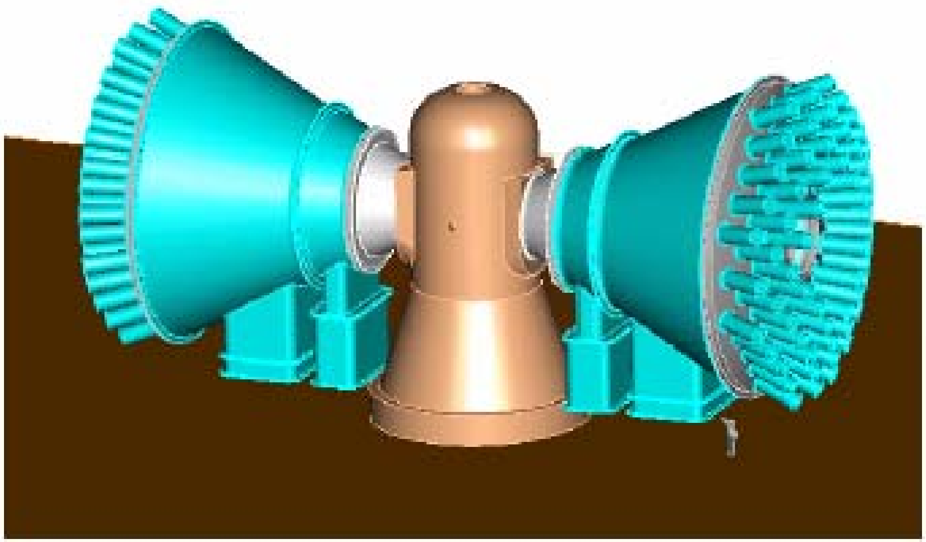


Fig. 3. An isometric view illustrating the coupling of final focus magnet array with the chamber.

(Figure by Tom Brown, PPPL)