Inertial Fusion Driven by Heavy-Ion Beams*

W M Sharp and the HIFS-VNL team

30 March 2011

Heavy Ion Fusion Science
Virtual National Laboratory

*This work was performed under the auspices of the US Department of Energy by LLNL under Contract DE-AC52-07NA27344 and by LBNL under Contract DE-AC02-05CH11231.

What's the Heavy Ion Fusion Science Virtual National Laboratory?

HIFS-VNL is a consortium formed in 1996 by LBNL, LLNL, and PPPL

LBNL

Grant Logan	Joe Kwan	Frank Bieniosek	Andy Faltens	Enrique Henestroza
Jin-Young Jung	Ed Lee	Steve Lidia	Pavel Ni	Lou Reginato
Prabir Roy	Peter Seidl	Derek Shuman	Jean-Luc Vay	Will Waldron

LLNL

Alex Friedman	**John Barnard**	Dave Grote	Steve Lund	Ron Cohen
Ralph Moir	Art Molvik	Dick More	John Perkins	Bill Sharp

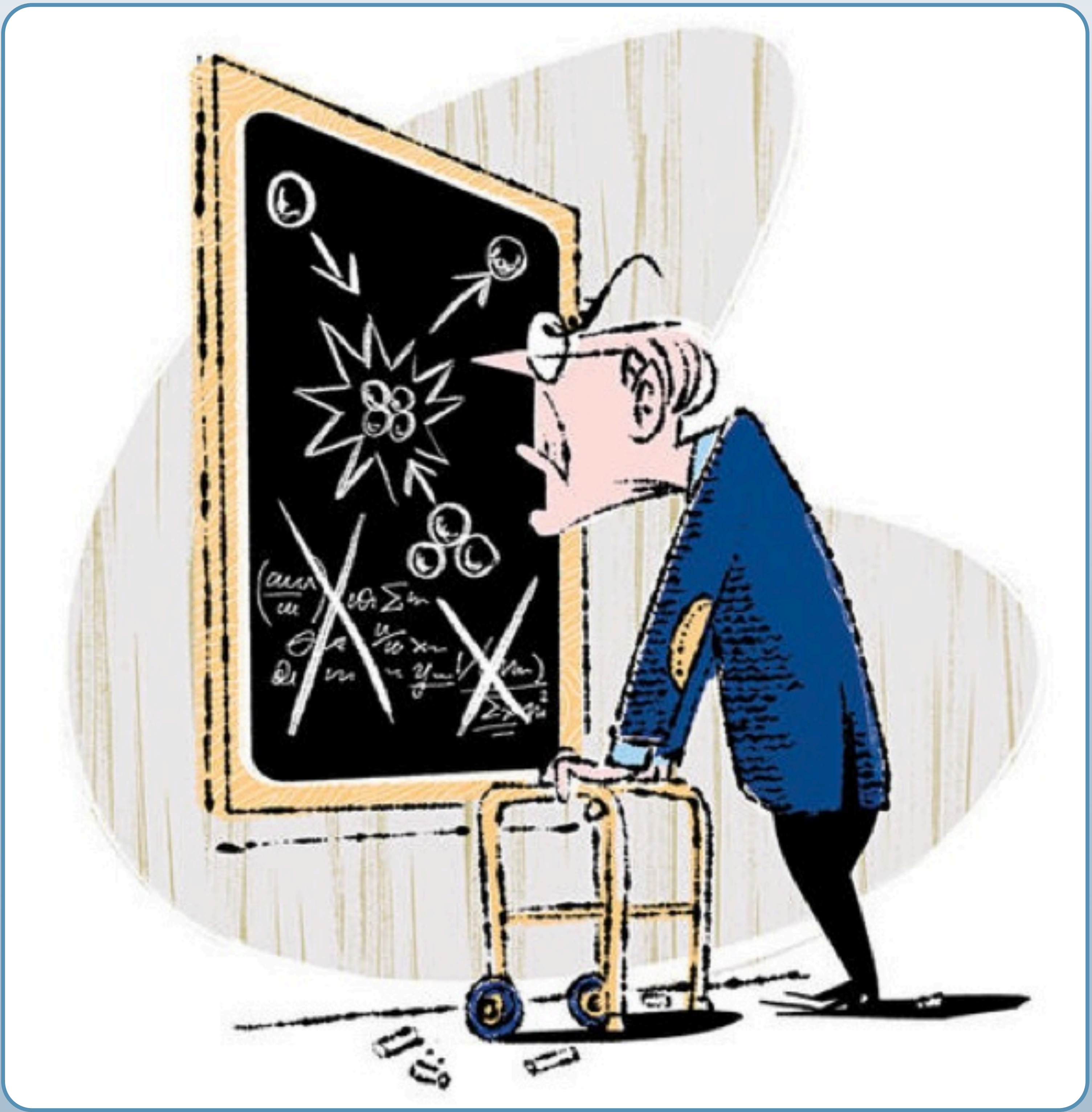
PPPL

Ron Davidson	Bill Abraham	Phil Efthimion	Erik Gilson	Larry Grisham
Igor Kaganovich	Dick Majeski	Hong Qin	Ed Startsev	

plus collaborators around the world...

Stefano Atzeni	Roger Bangerter	Dick Briggs	Michael Dorf	Claude Deutsch
Irv Haber	Dieter Hoffman	Ingo Hofmann	Kazuhiko Horioka	Takashi Kikuchi
Rami Kishek	Alice Koniges	Shigeo Kawata	Hiromi Okamoto	Per Peterson
Boris Sharkov	Ken Takayama	Naeem Tahir	Dale Welch	Simon Yu

Fusion research was named one of the Worst Jobs in Science by *Popular Science*



from Popular Science, 26 January 2009

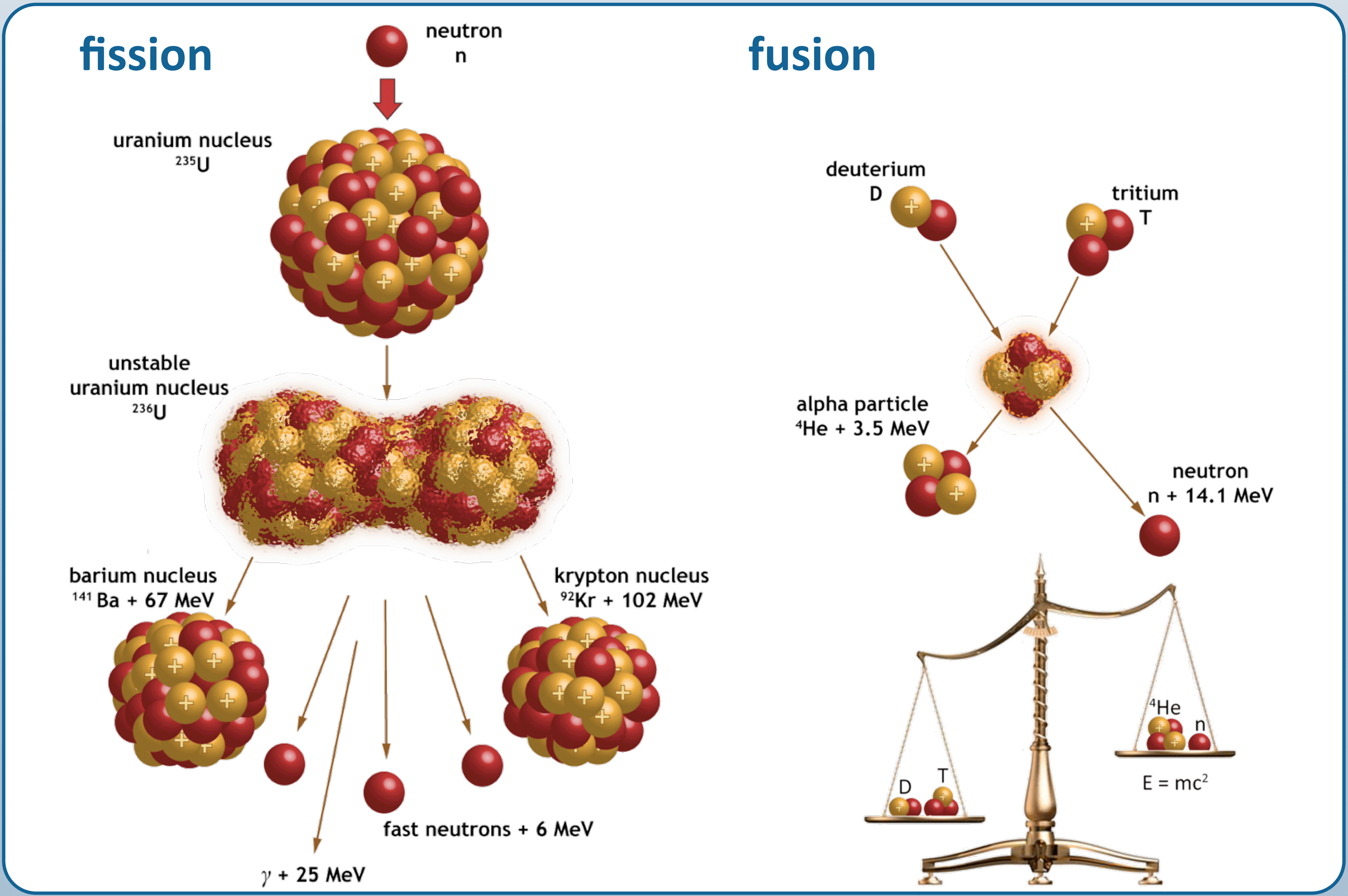
Outline

- motivation
- a fusion primer
- essentials of heavy-ion fusion
- past and present HIF research
- future research directions

fission and fusion both produce energy from nuclear forces

mass is lost when large nuclei split or small ones merge

- this mass converted to energy according to $E = mc^2$
- energy escapes as kinetic energy of particles or nuclei, or as gamma rays



So why is nuclear energy interesting?

carbon-free!

plentiful

- uranium reserves, properly used, could last for centuries
- deuterium in a gallon of sea water equals four gallons of gasoline

versatile

- nuclear energy can produce electricity, hydrogen, synthetic fuels, desalinated water, ...

highly concentrated

- annual fuel requirement for a 1000 MW_e power plant is

2.1×10^6 metric tons of coal - about 21 000 rail cars

10^7 barrels of oil - about 10 super tankers

30 metric tons of UO_2 - about one rail car

0.6 metric tons of deuterium - one pickup truck

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What are the candidate fusion fuels?

the original - primary reactions in the sun

$p^+ + p^+ \longrightarrow D + e^+ + \nu_e$ **+ 0.43 MeV** ~1 keV (10^7 °C) with D = deuterium ($^2H^+$)

$p^+ + D \longrightarrow {}^3He + \gamma$ **+ 5.49 MeV**

the easiest

$D + T \longrightarrow {}^4He + n$ **+ 17.6 MeV** ~10 keV (10^8 °C) with T = tritium ($^3H^+$)

"advanced" fuels

$D + D \longrightarrow {}^3He + n$ **+ 3.3 MeV** ~30 keV (3×10^8 °C)

$\longrightarrow T + p^+$ **+ 4.0 MeV**

$D + {}^3He \longrightarrow {}^4He + p^+$ **+ 18.4 MeV**

"ultimate" fuels

$p^+ + {}^{11}B \longrightarrow {}^4He + {}^4He + {}^4He$ **+ 8.7 MeV** ~50 keV (5×10^8 °C)

$p^+ + {}^7Li \longrightarrow {}^4He + {}^4He$ **+ 17.3 MeV**

$p^+ + {}^9Be \longrightarrow {}^4He + {}^6Li$ **+ 2.1 MeV**

a note on energy units:

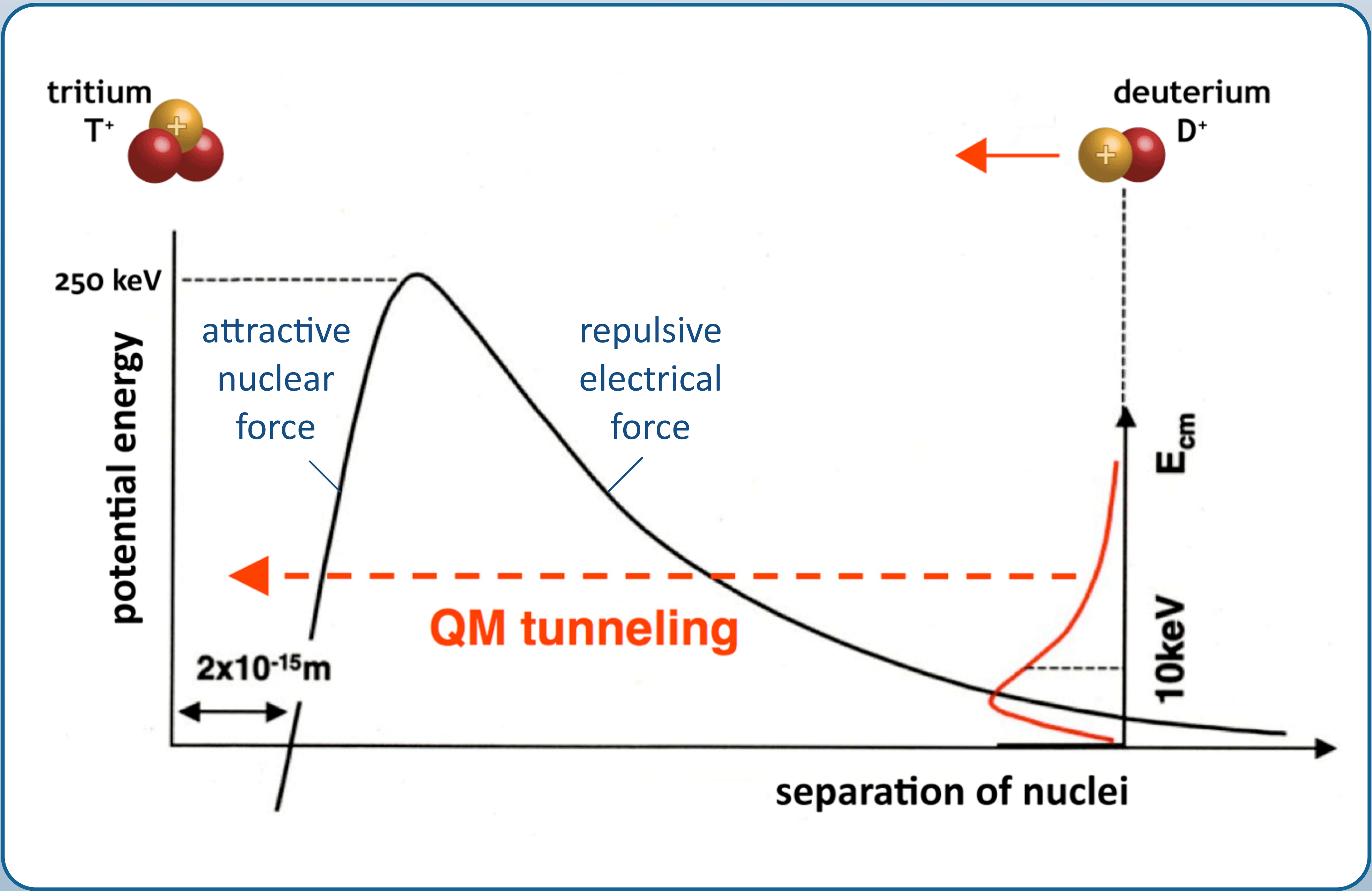
1 eV (electron-volt) = 1.602×10^{-19} Joules . Characteristic of energy changes in *atomic* processes

1 MeV = 1.602×10^{-13} Joules. Characteristic of energy changes in *nuclear* processes

Why has controlled fusion taken sixty years?

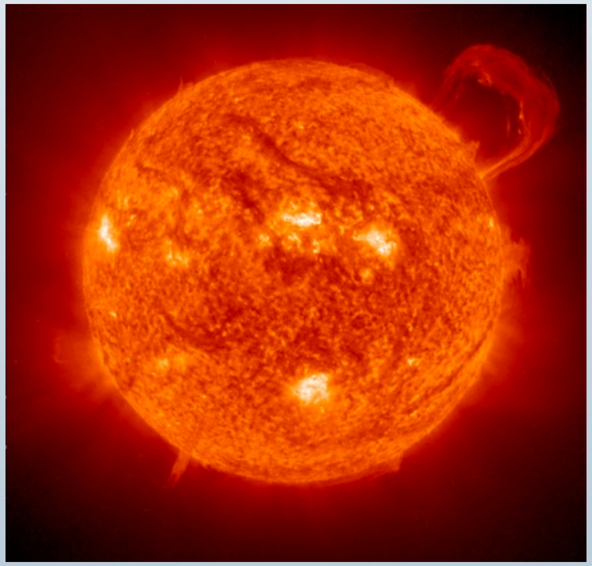
fusion depends on quantum-mechanical tunneling of energetic nuclei

- rate is only appreciable for very energetic ions (> 10 keV or 10^8 ^oC)
- electrons and nuclei dissociate, making a thermal plasma
- holding a D-T plasma together long enough is a major challenge



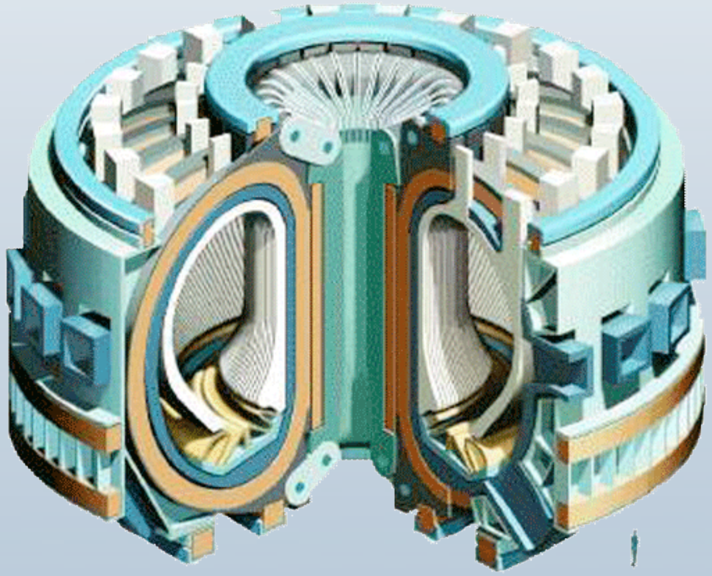
How can we achieve controlled fusion?

three main ways



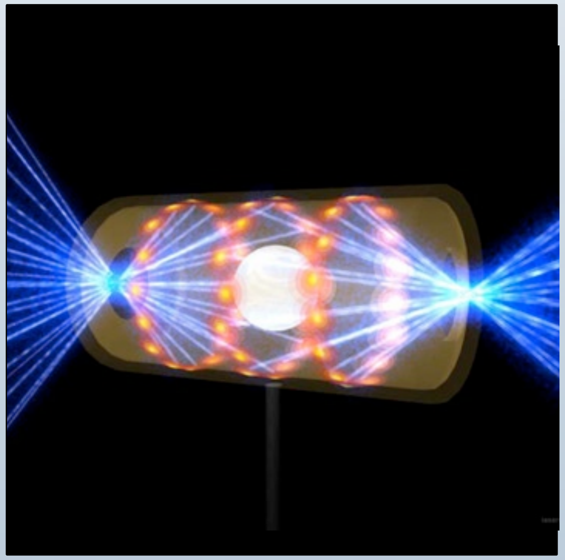
gravitational confinement

"a day without fusion is like a day without sunshine"



magnetic confinement

"...like holding jello together with rubber bands" - Edward Teller



inertial confinement

"A small supernova. Very small" - Ed Moses

	density	temperature	confinement time	status
gravitational	10^4 x solid	1 keV	10^5 years	proven daily
magnetic	10^{-8} x solid	10 keV	seconds	first test 2020
inertial	10^3 x solid	10 keV to ignite	10's of picoseconds	first test 2011

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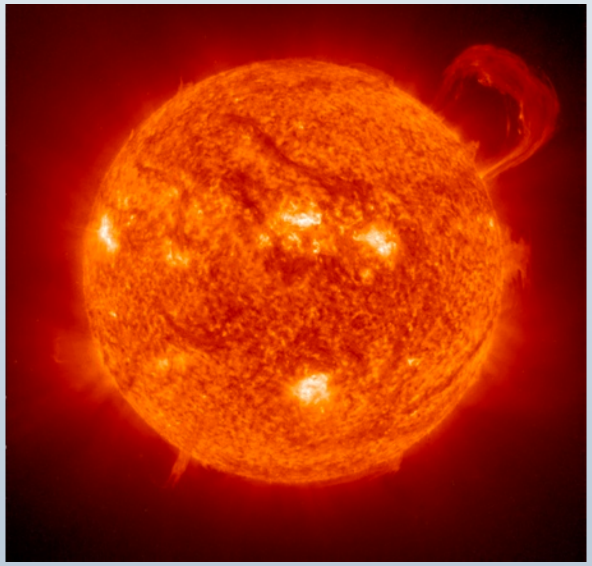
International Thermonuclear Experimental Reactor (ITER) being built in Cadarache, France
first plasma 2019



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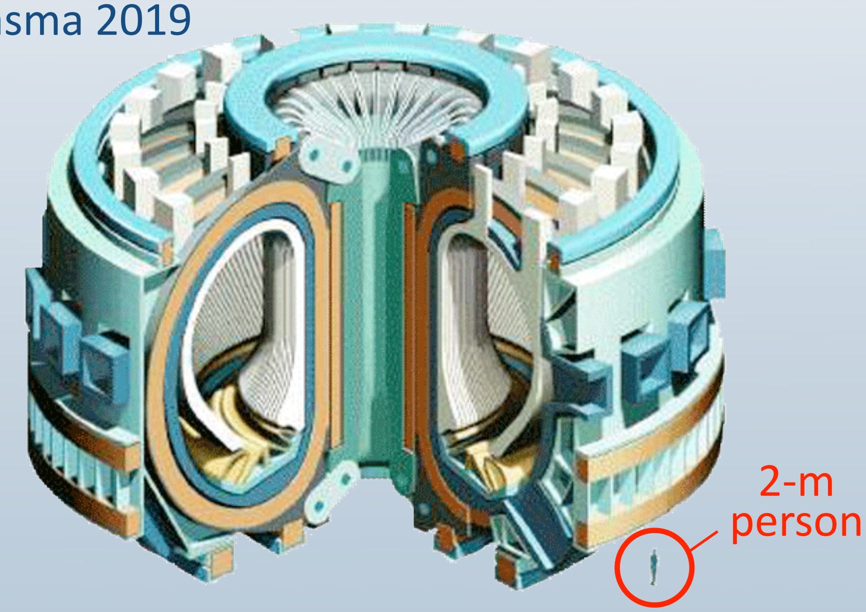

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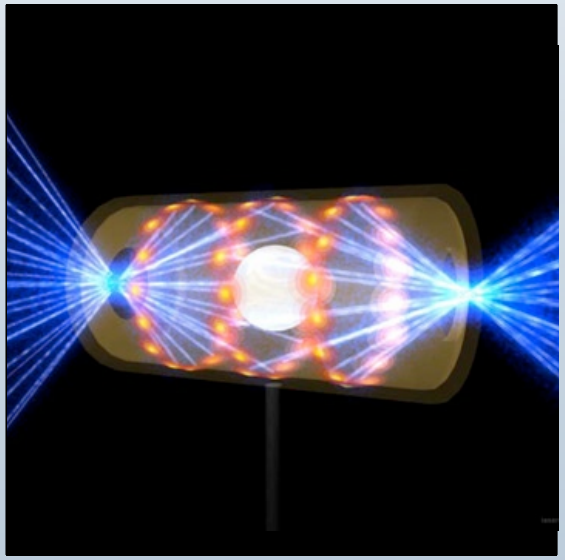

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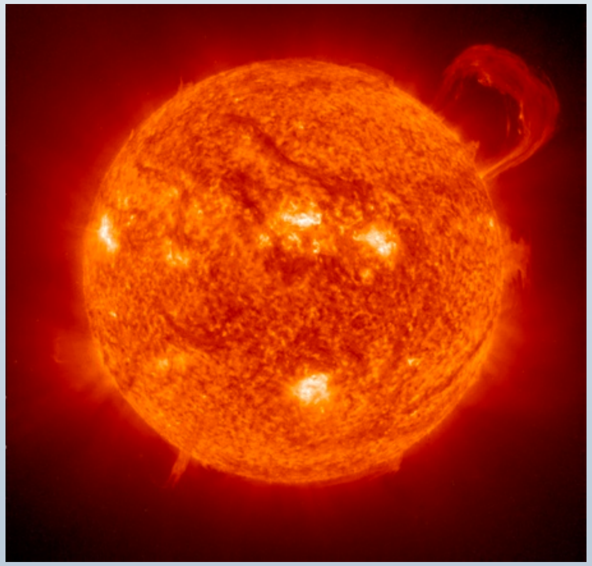

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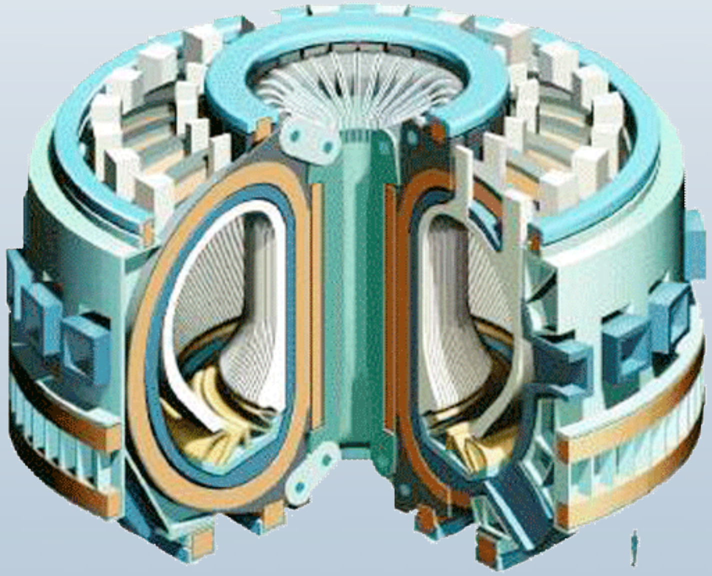

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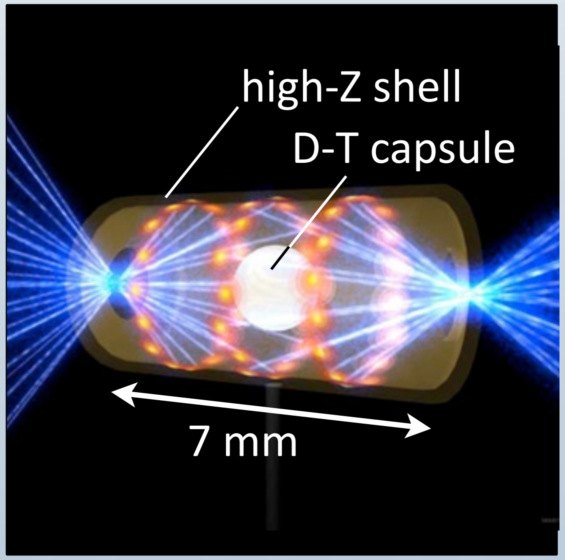
National Ignition Facility (NIF)
completed 2009 in Livermore, CA
2.2 MJ in 192 beams



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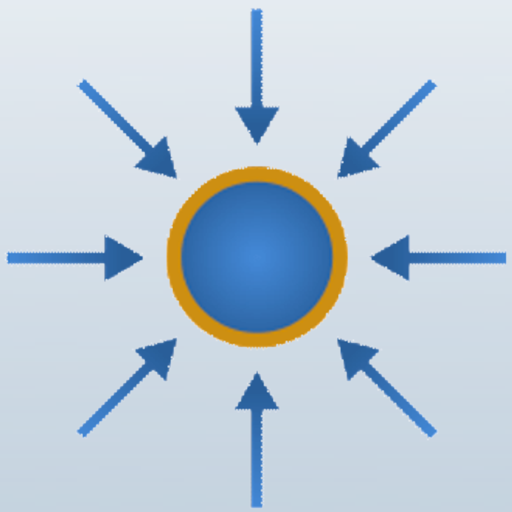
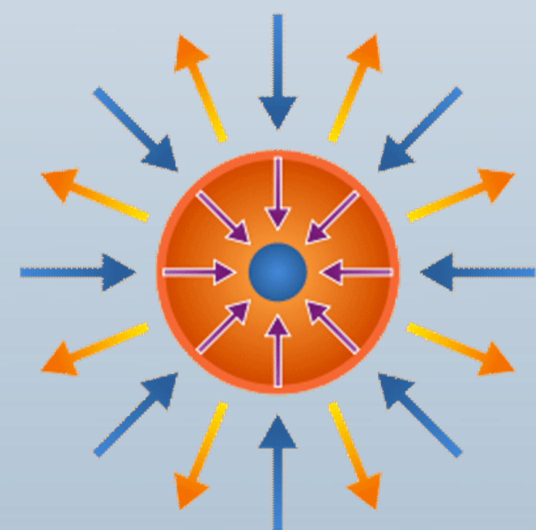
What goes on in the target?

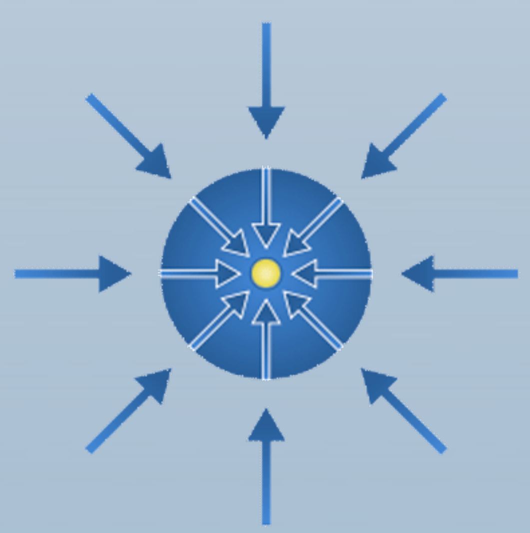


input energy quickly heats surface of fuel capsule



fuel is compressed isentropically by rocket-like blowoff of hot surface material

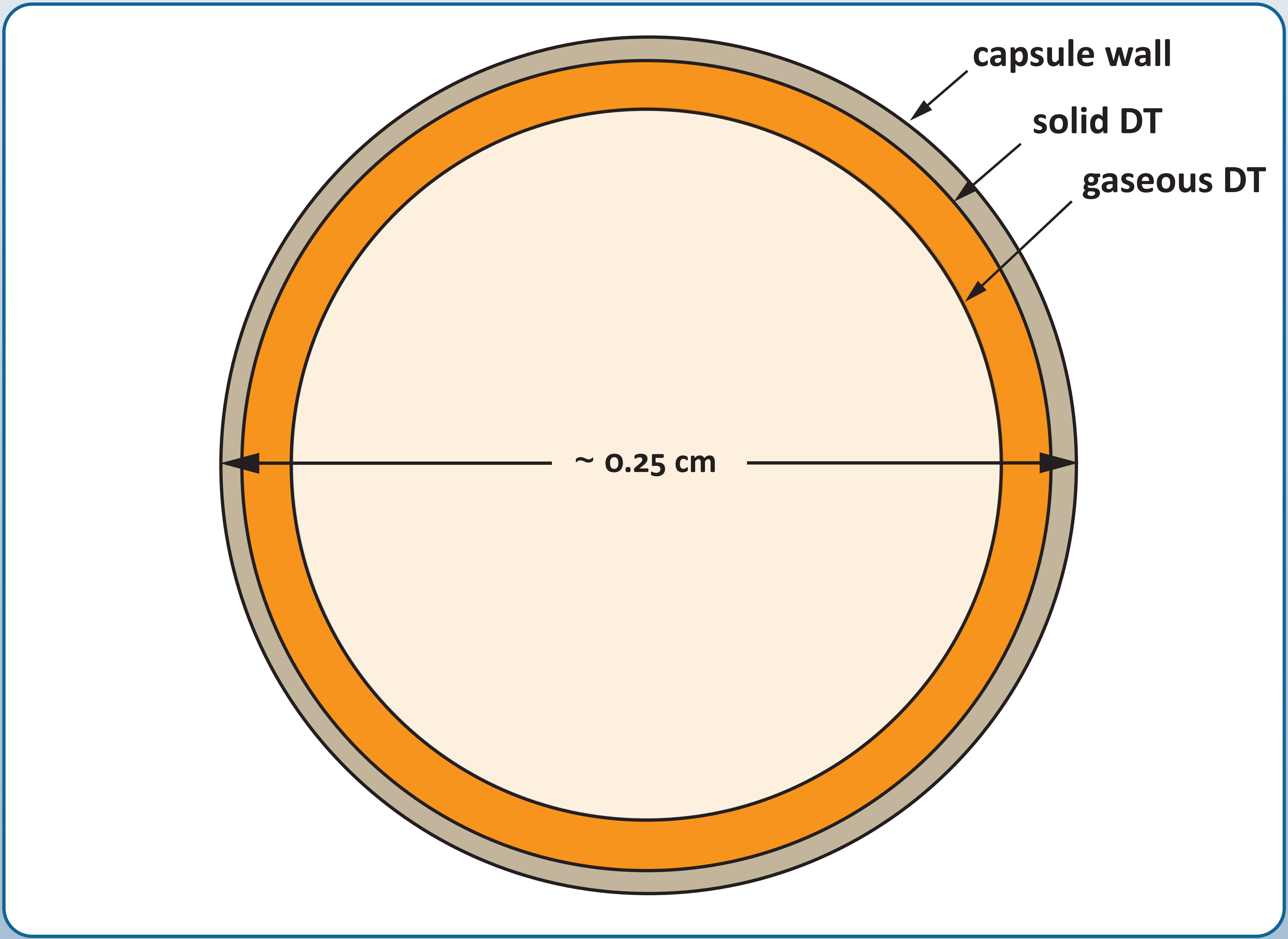
compressed fuel core (“hotspot”) reaches density and temperature needed for ignition



thermonuclear burn spreads quickly through compressed fuel

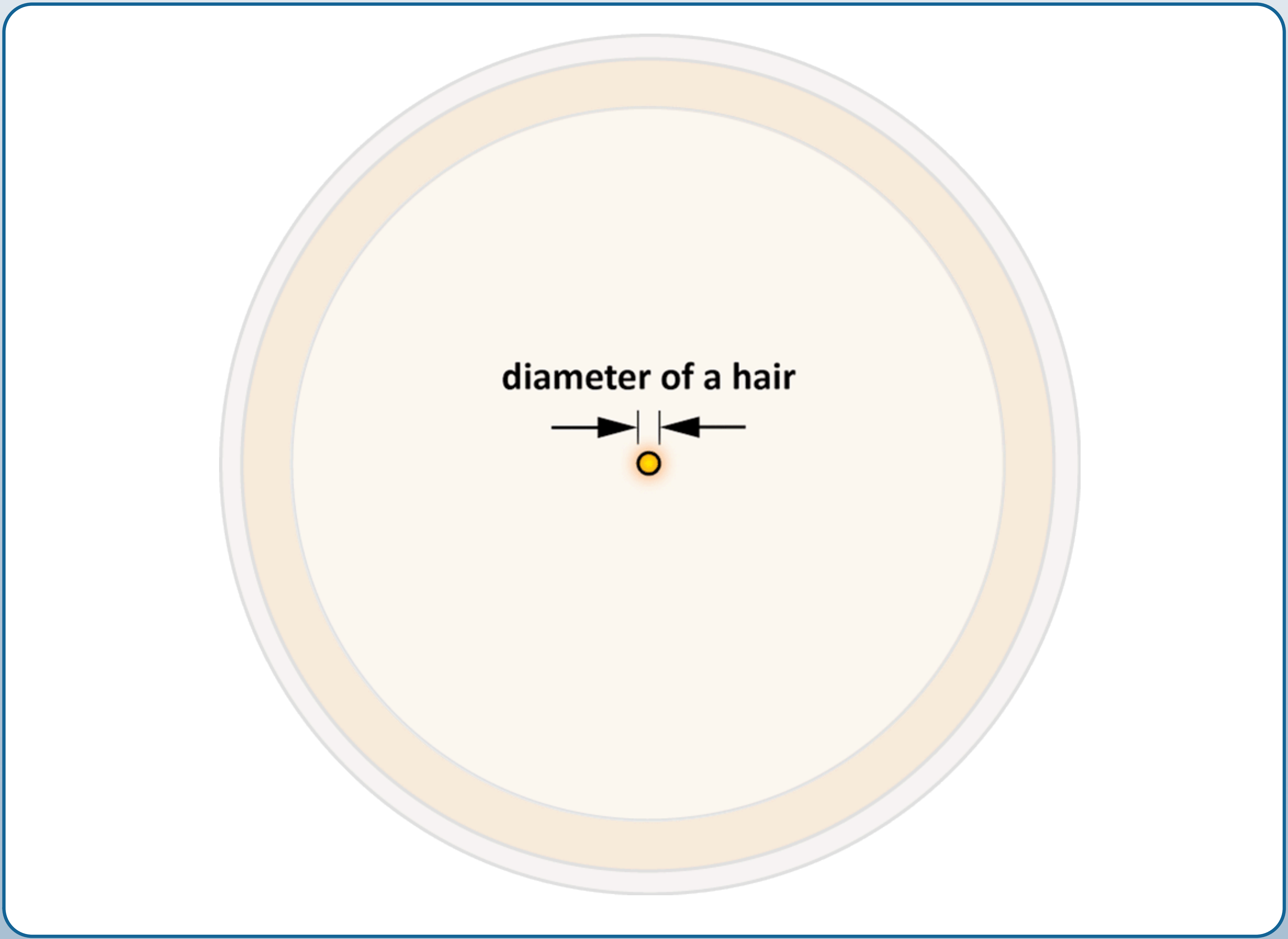
How much compression is needed?

the fusion capsule before compression

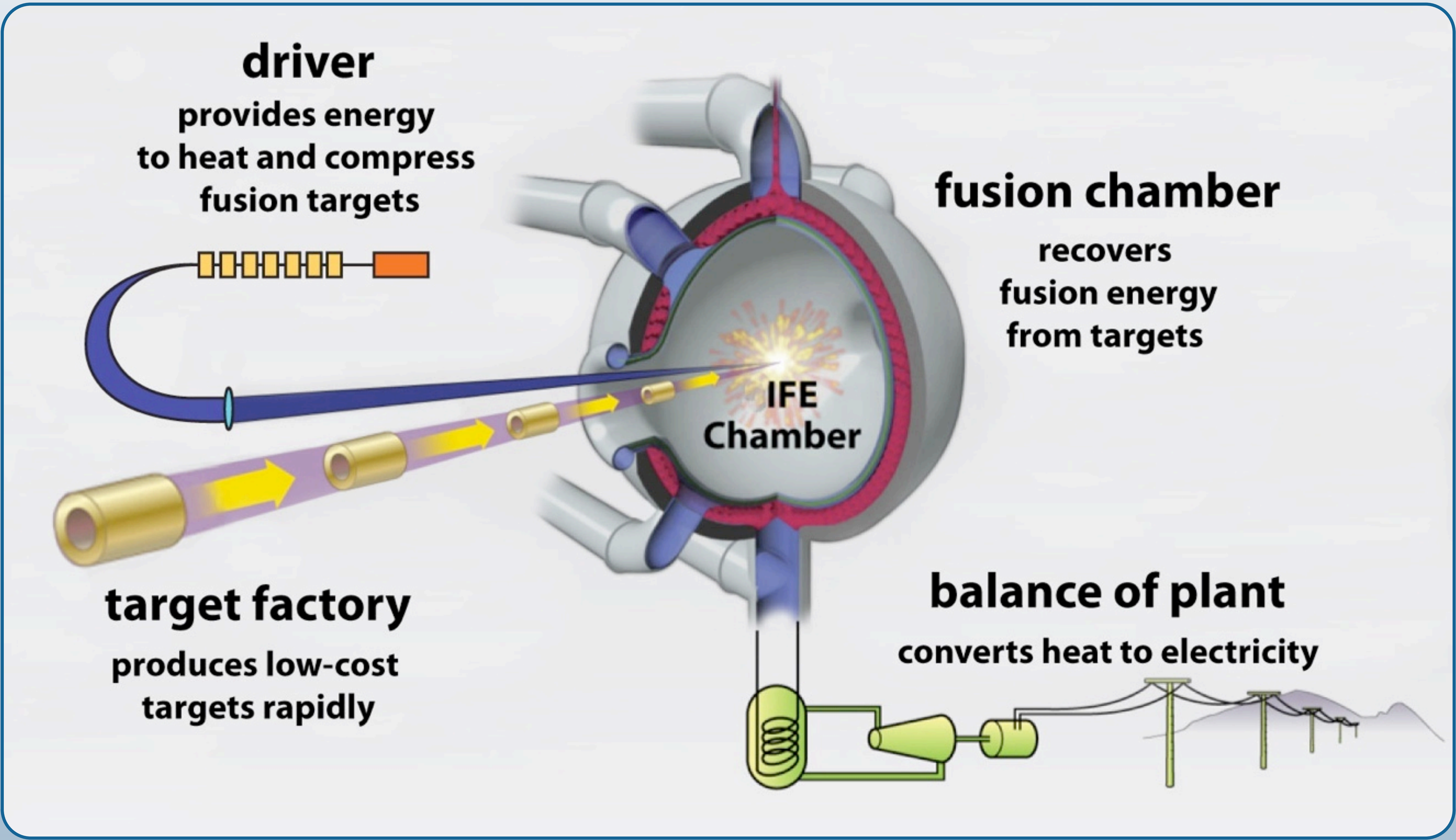


How much compression is needed?

10 ns later after 30:1 compression



What's needed for an inertial fusion energy power plant?



Why is this interesting?

safety

- no possibility of meltdown
- no fissile materials, so reduced proliferation issues
- wastes can qualify for shallow burial (Class-C)

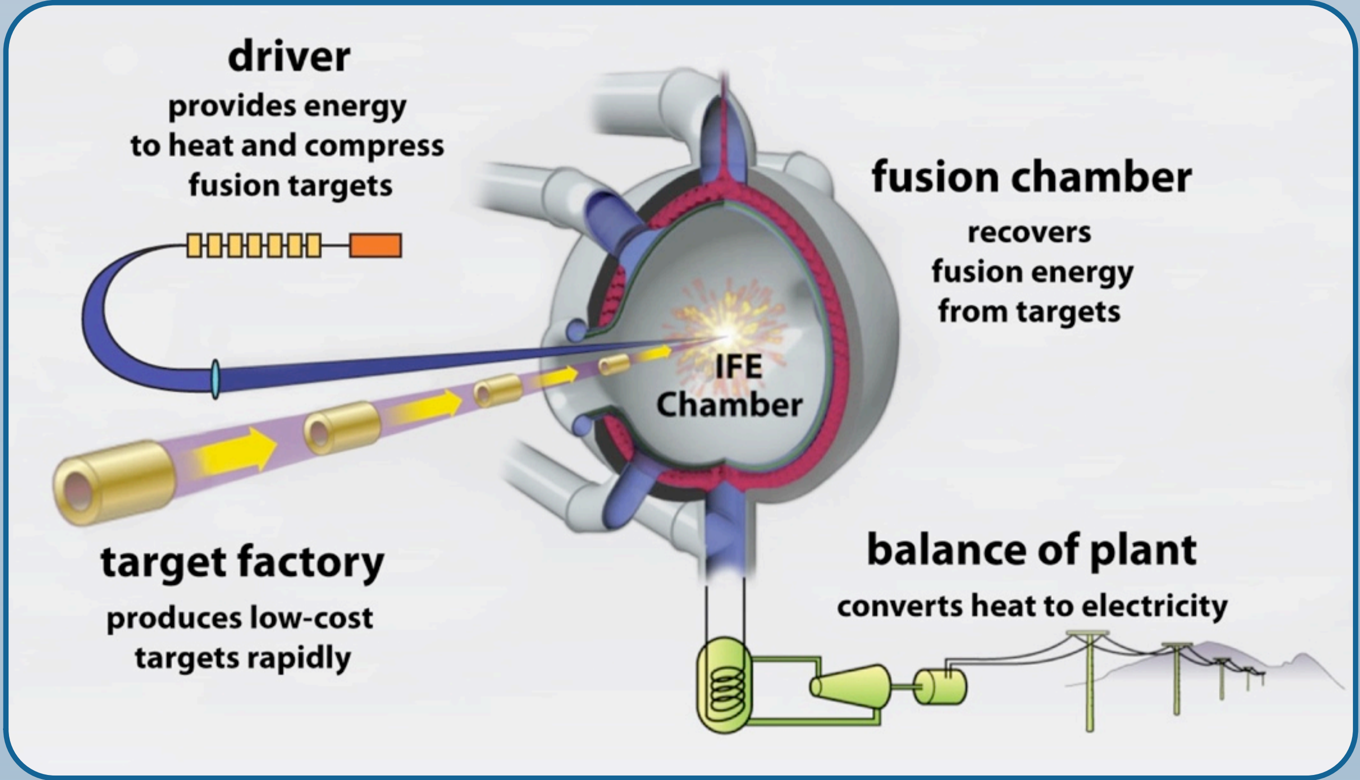
simplicity

- much simpler reactor chamber than a tokamak
- fusion driver is separate from the chamber

flexibility

- many options for driver, chamber, and target
- modular development path

NAS is reviewing IFE programs in anticipation of NIF success



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If laser fusion is expected soon, why bother about heavy-ion fusion?

repetition rate

- NIF can manage 1-2 shots per day
  - a power plant needs 5-10 shots per second, and accelerators can provide 1000s

efficiency

- NIF lasers are less than 1% efficient, and advanced high-repetition lasers may get 15%
  - induction accelerators for ions should get about 40%

robust final optics

- laser final optics are directly exposed to target blast
  - focusing magnets for ions do not intercept the line-of-sight from the target

thick-liquid walls

- laser power-plant concepts call for periodic replacement of the chamber inner wall
  - heavy-ion power-plant concepts use molten Li_2BeF_4 salt (“FLiBe”) to absorb blast

How do you design an HIF power plant?

many interrelated questions must be answered first

- **what target to use?**
  gives the total energy, beam spot size, symmetry requirements
- **what ion species to use?**
  gives the beam energy and total current
- **what type of acceleration to use?**
  determines the complexity, efficiency, and cost of plant
- **what type of transverse focusing to use?**
  transport limits determine the number and radius of beams
- **what type of fusion-chamber transport to use?**
  space-charge, energy spread, and transverse temperature impair beam focusability
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then **you can start designing**

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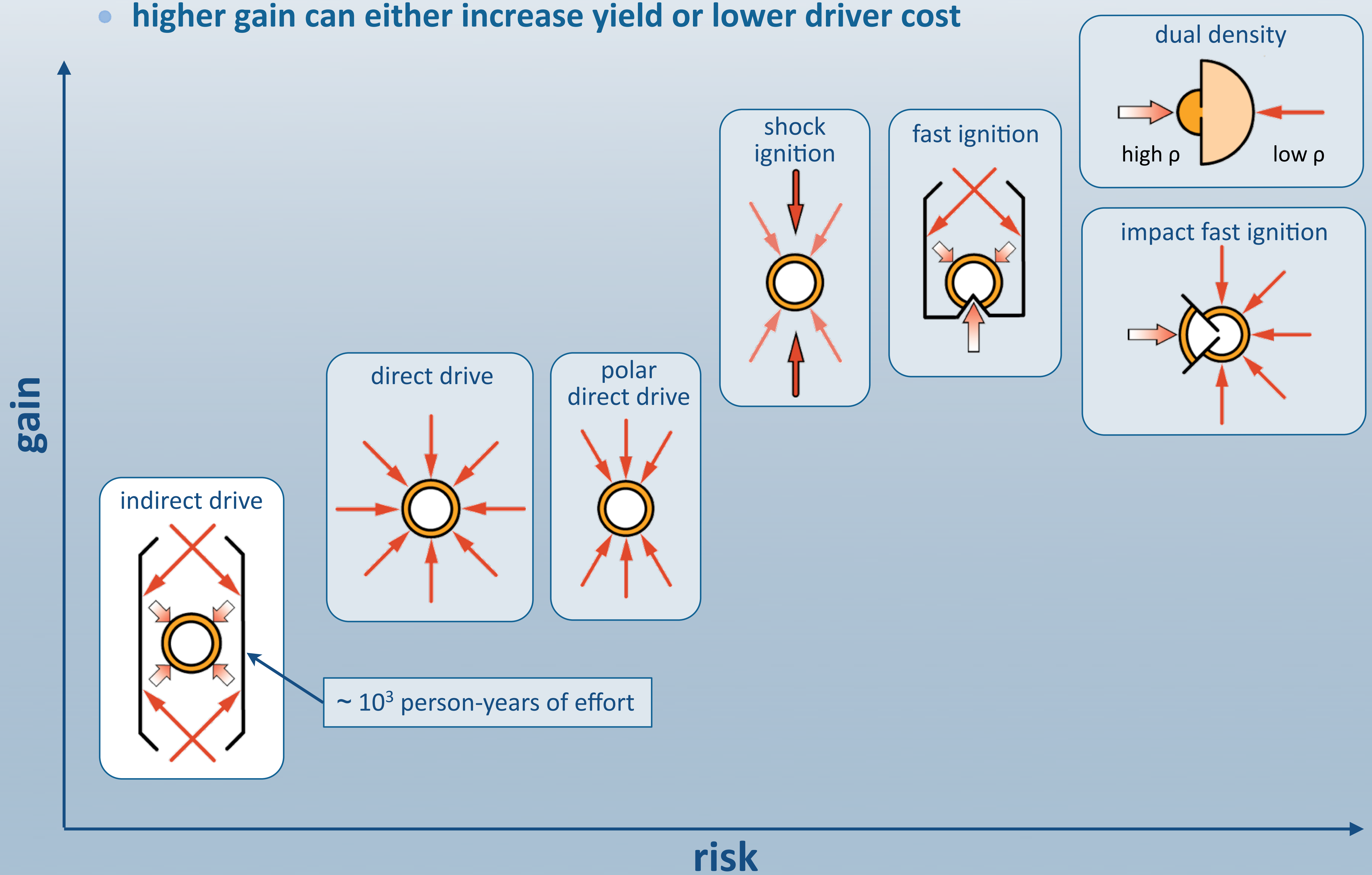
What target to use?

targets range from low-risk / low-gain to high-risk / high-gain

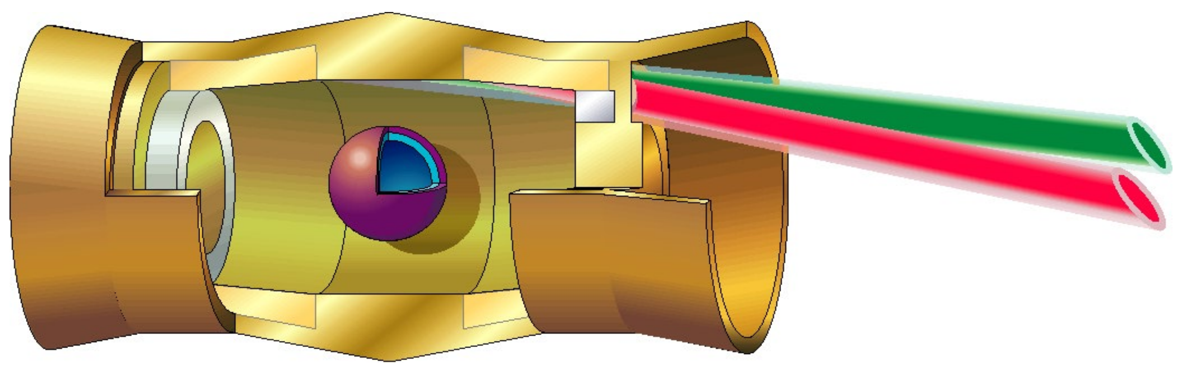
- **higher gain can either increase yield or lower driver cost**



So what would a HIF target look like?

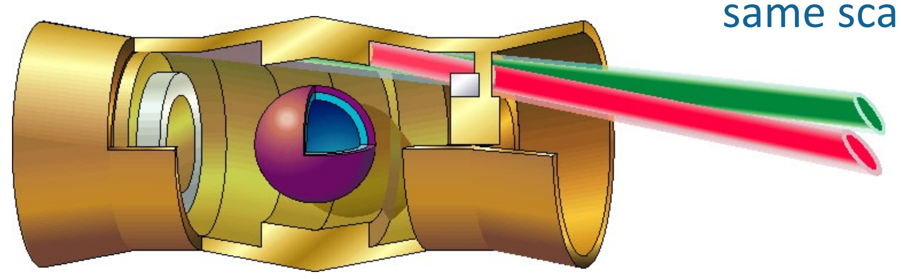
several indirect-drive designs were developed in the 1990s

- two energies are needed to compensate for range-shortening with heating
- beams are aimed around an annulus on each end to give needed symmetry
- early 6-MJ version had a gain of 60



"distributed-radiator" HIF target
from M Tabak and D A Callahan-Miller, Phys. Plasmas **5** (1998)

- smaller 3.3-MJ version had a gain of 130



same scale

"close-coupled" HIF target
from D A Callahan-Miller and M Tabak, Phys. Plasmas **7** (2000)

current work is investigating advanced direct-drive concepts

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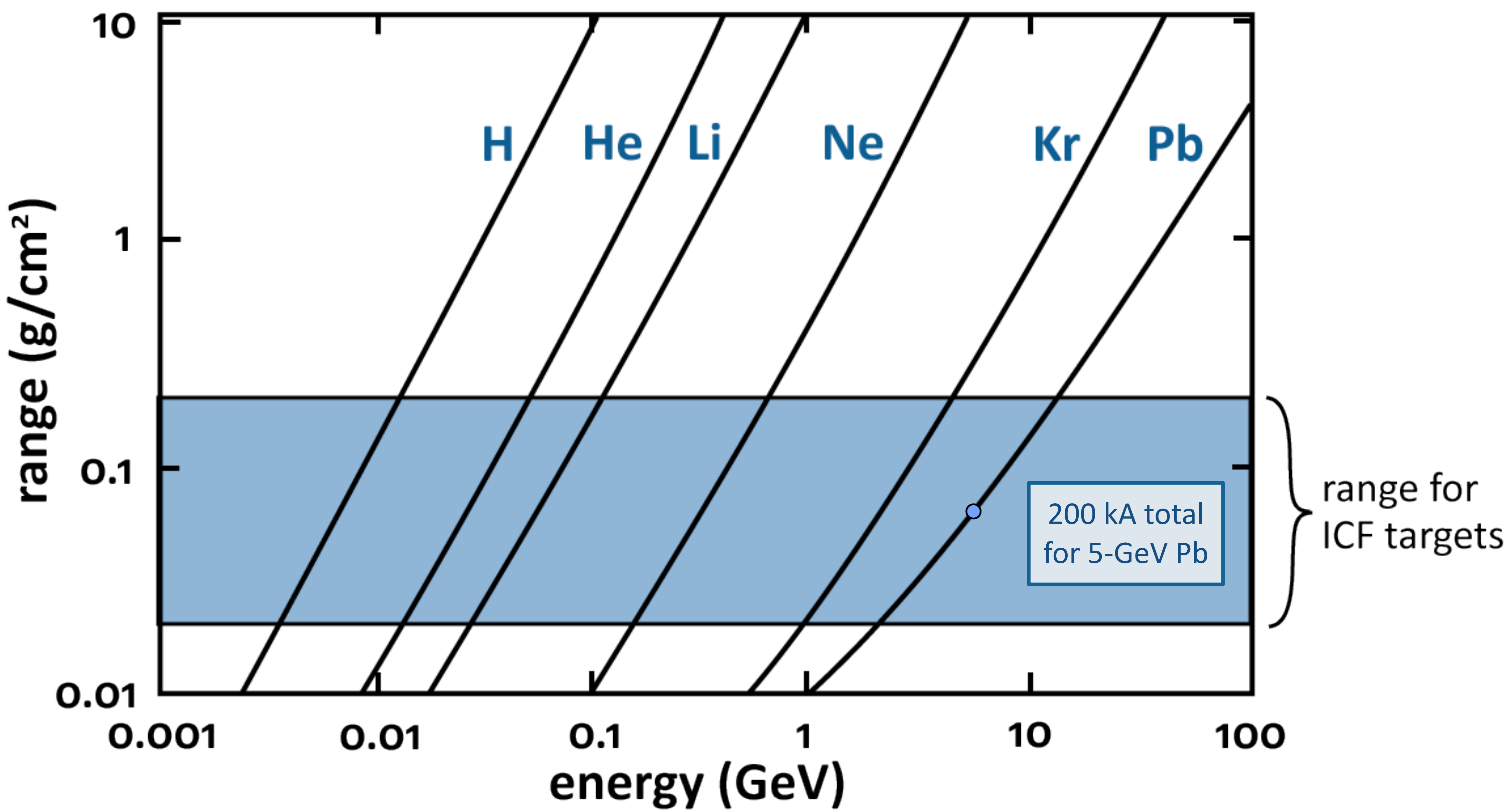
What ion species to use?

going down in ion mass decreases energy but increases current or number of beams

- **for indirect drive**

  (number of beams) x **(current)** x **(deposition time)** x **($\frac{1}{2} m_b v_z^2$)** ≈ **1-10 MJ**



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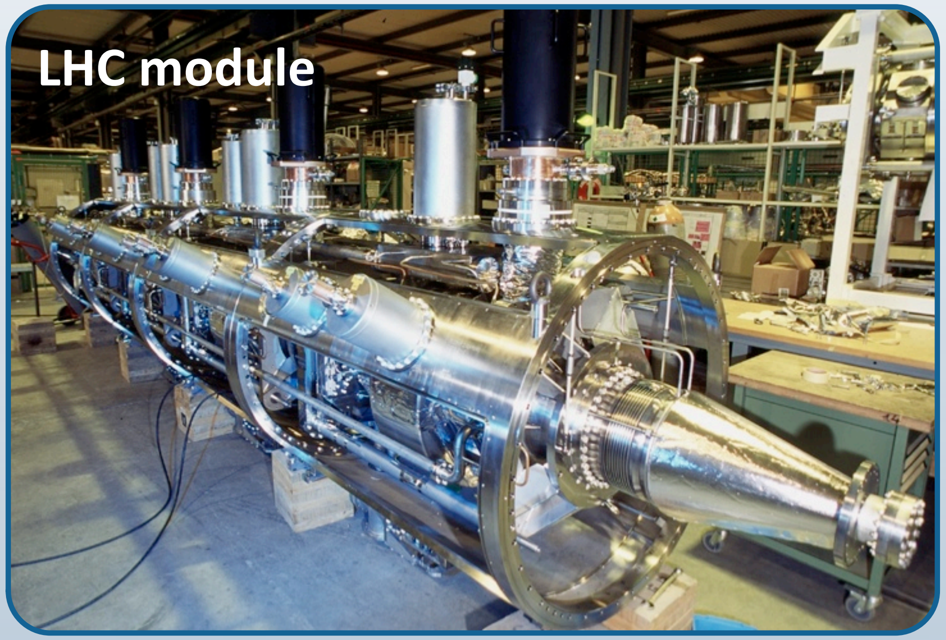
What kind of accelerator to use?

most accelerators are radio-frequency (rf) devices

- rf accelerators can have gradients up to 100 MeV/m

  but

- current is typically limited to less than 200 mA
- beams cannot be shortened during acceleration
- rf drivers need beam storage and stacking



induction accelerators are an attractive alternative

- currents up to 10 kA have been demonstrated
- beams can compressed during acceleration
- absence of resonant structures improves stability

  but

- acceleration gradient typically averages 1 MeV/m
- symmetry on target demands at least 100 beams

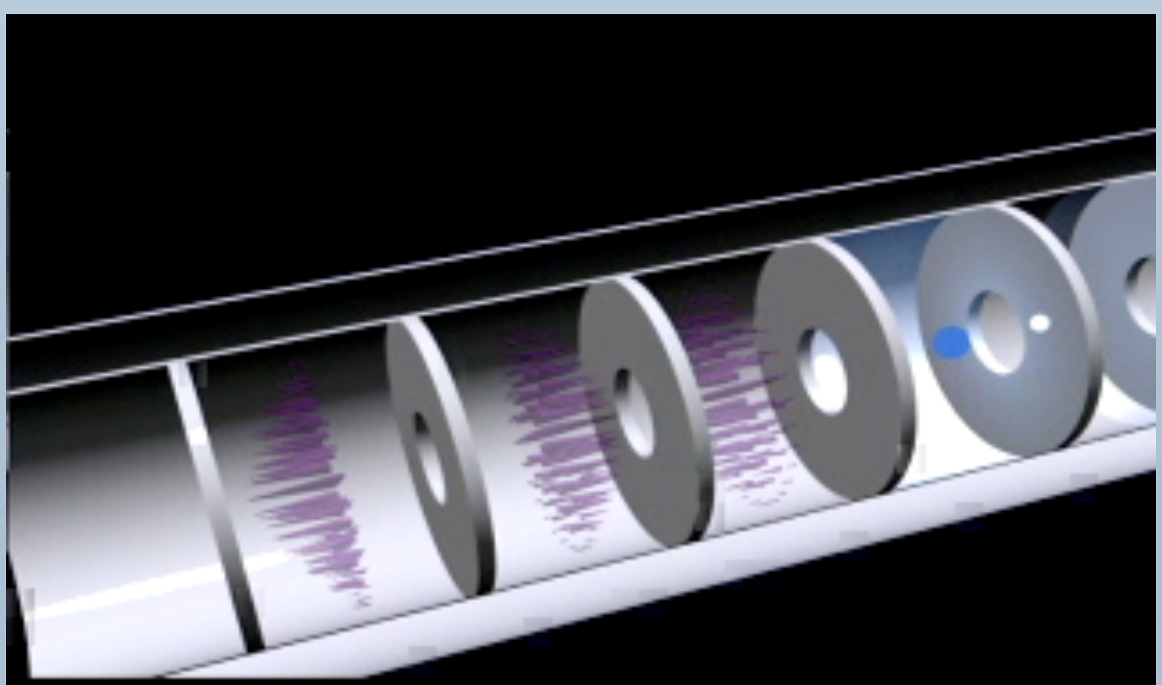
How does an rf accelerator work?

all types of rf accelerators share a simple design concept

- tuned cavities are filled with rf fields
- beams see only accelerating phase of oscillating electric field
- cavity field profile provides automatic control of beam ends

major limitation is low current

- current must be accumulated for 4 ms to provide energy for indirect-drive target
- various stacking schemes have been proposed to achieve 4 x 10^5 compression



from Cornell Wilson Laboratory video material

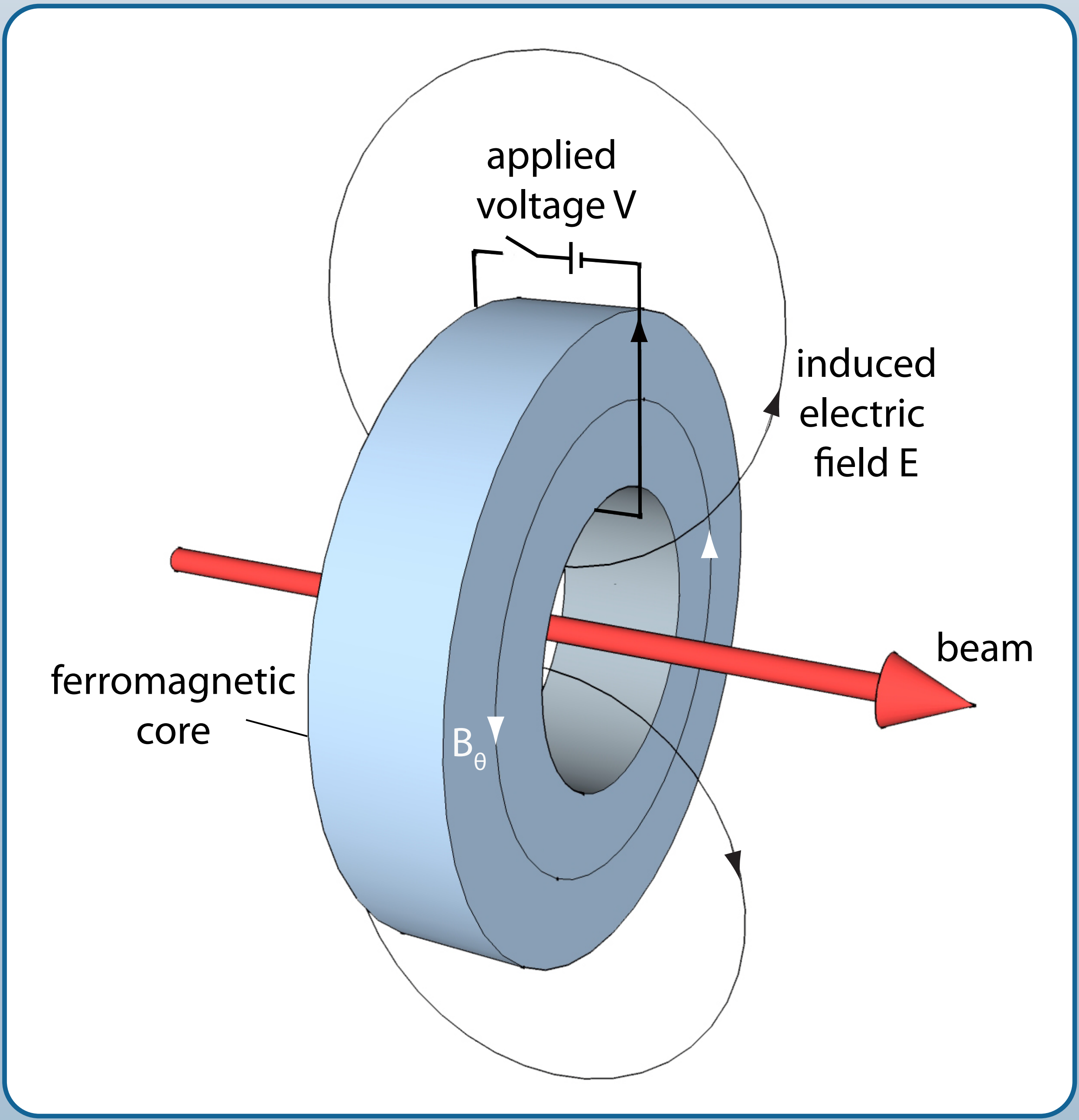
How does an induction accelerator work?

an induction cell works like a transformer

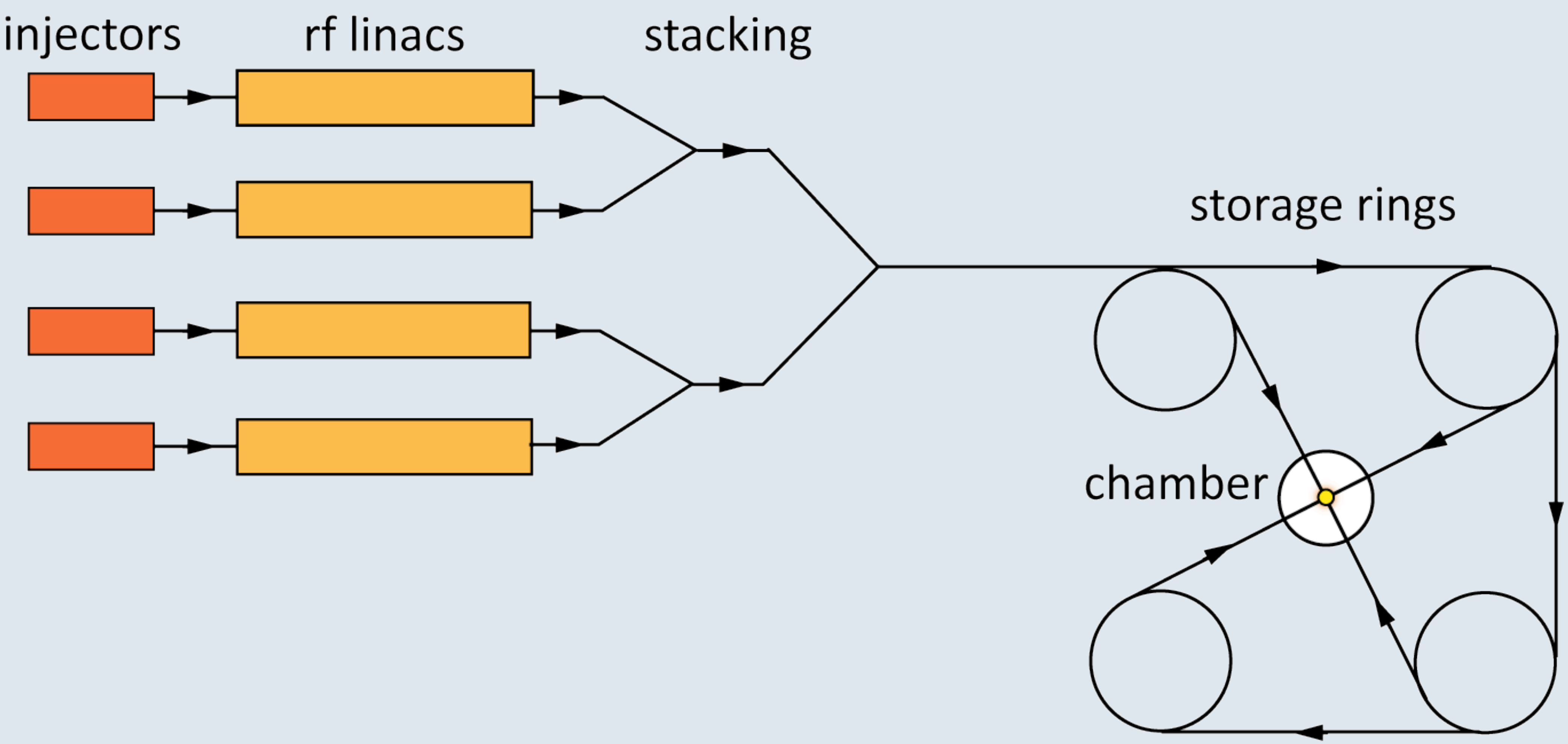
- **beam acts as a "single-turn" secondary**

changing flux in the ferrite core induces an electric field E_z along the axis

applied voltage waveform determines rate of flux change in the core and hence $E_z(t)$



What are some possible layouts for a HIF driver?



multiple rf linacs

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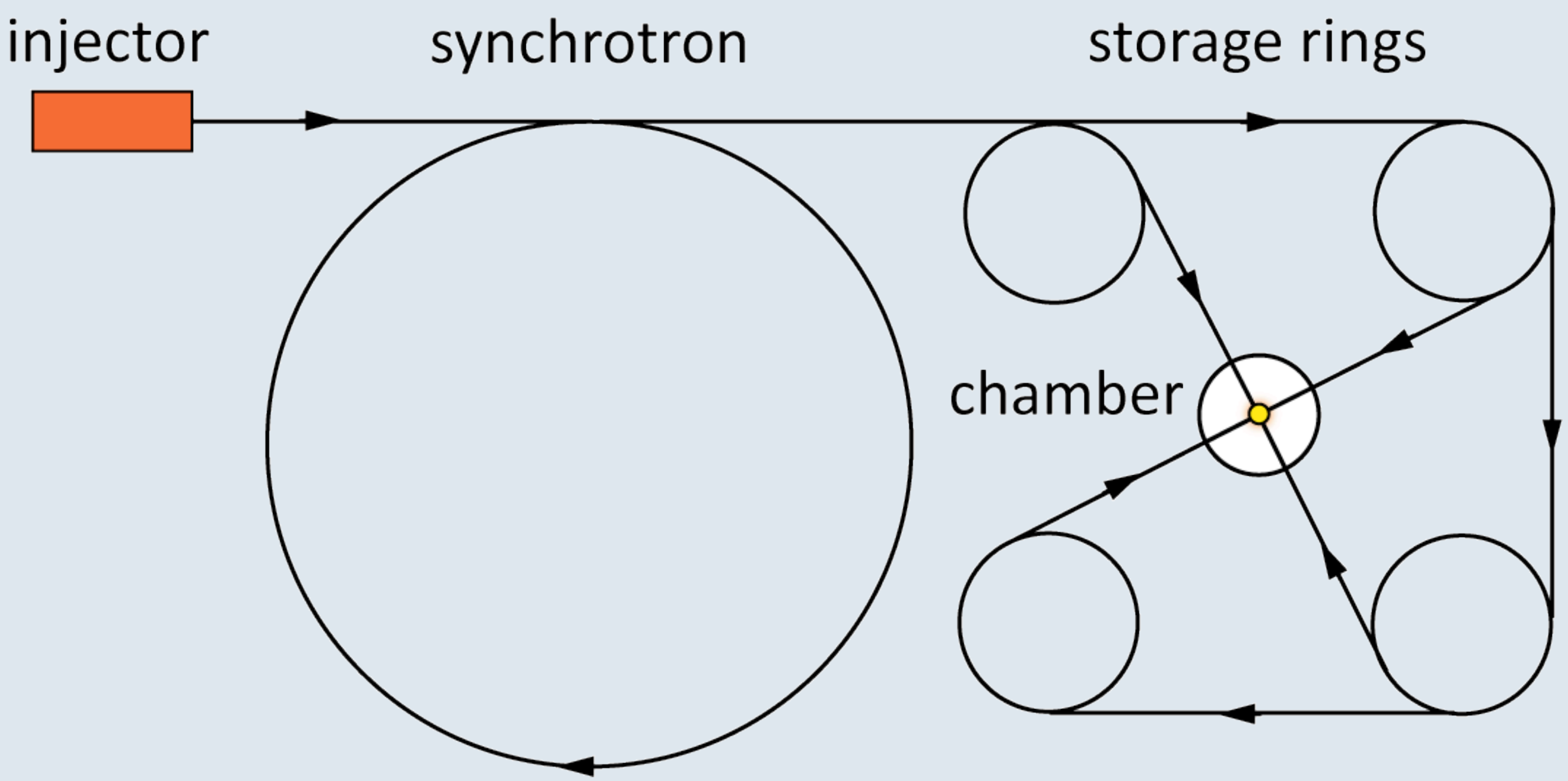

rf synchrotron

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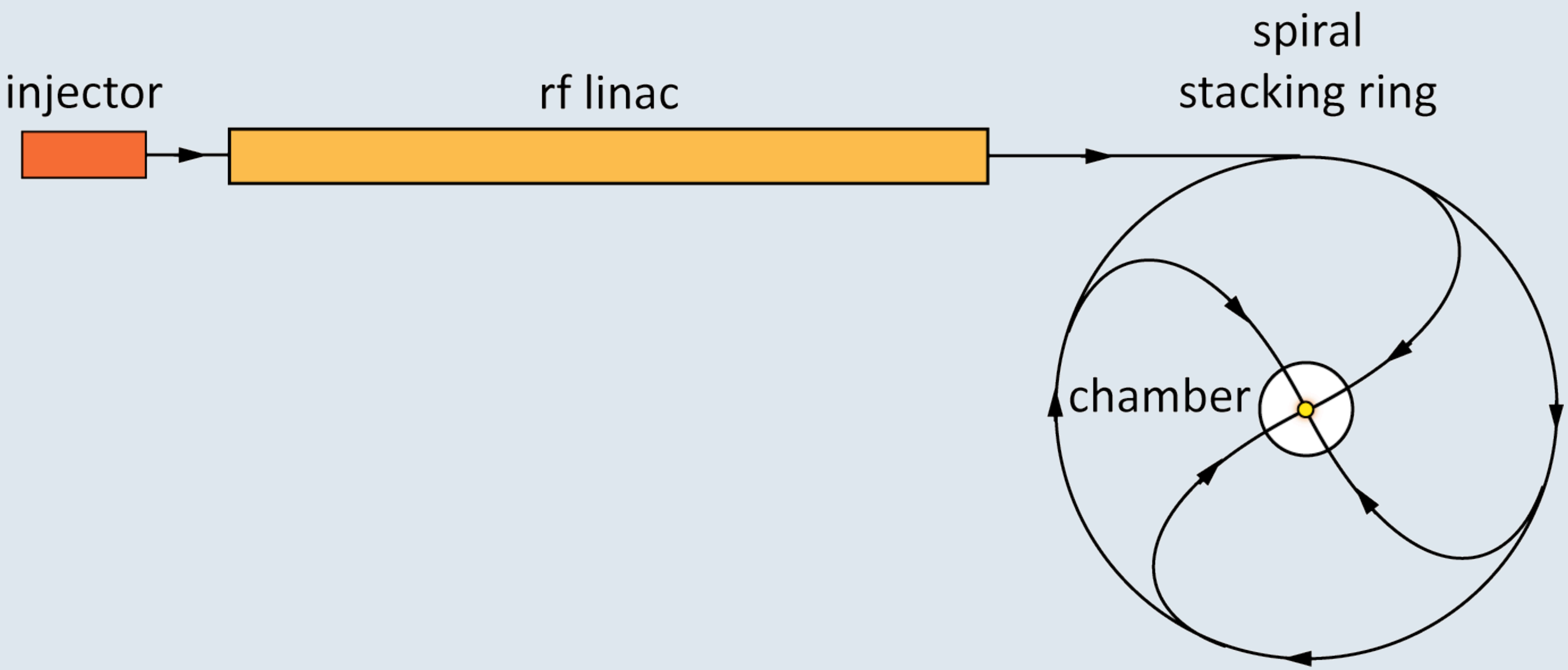

single rf linac plus stacking rings

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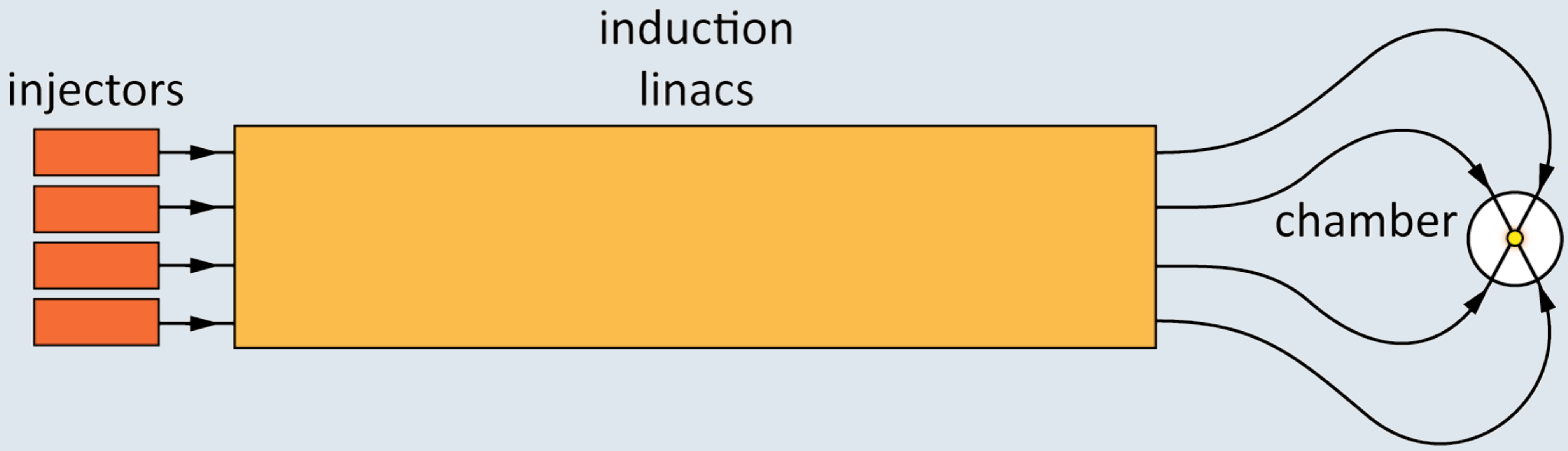

multiple-beam induction linac

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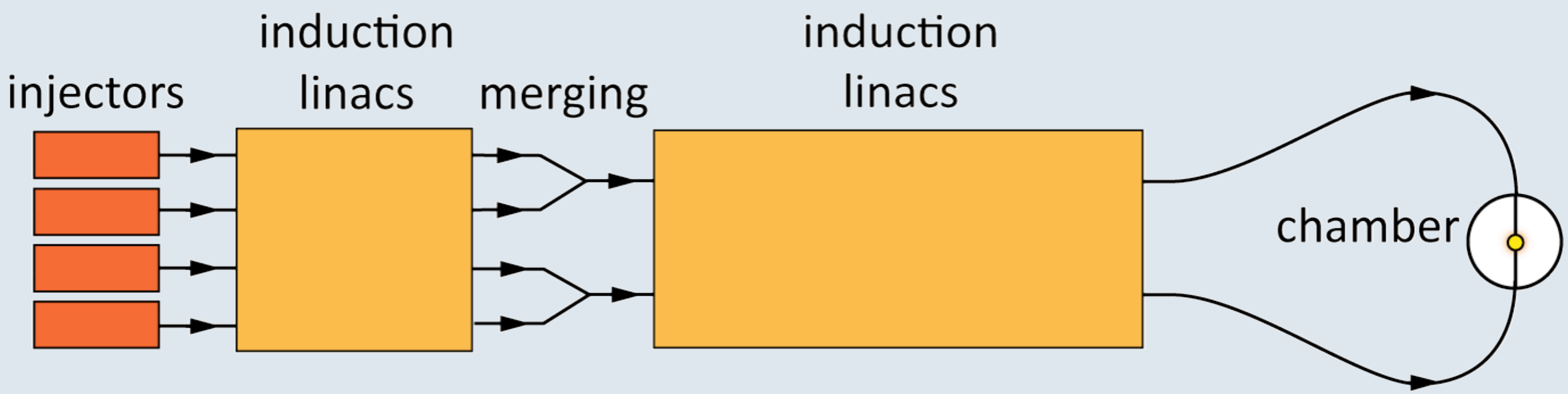

multiple-beam induction linac with merging

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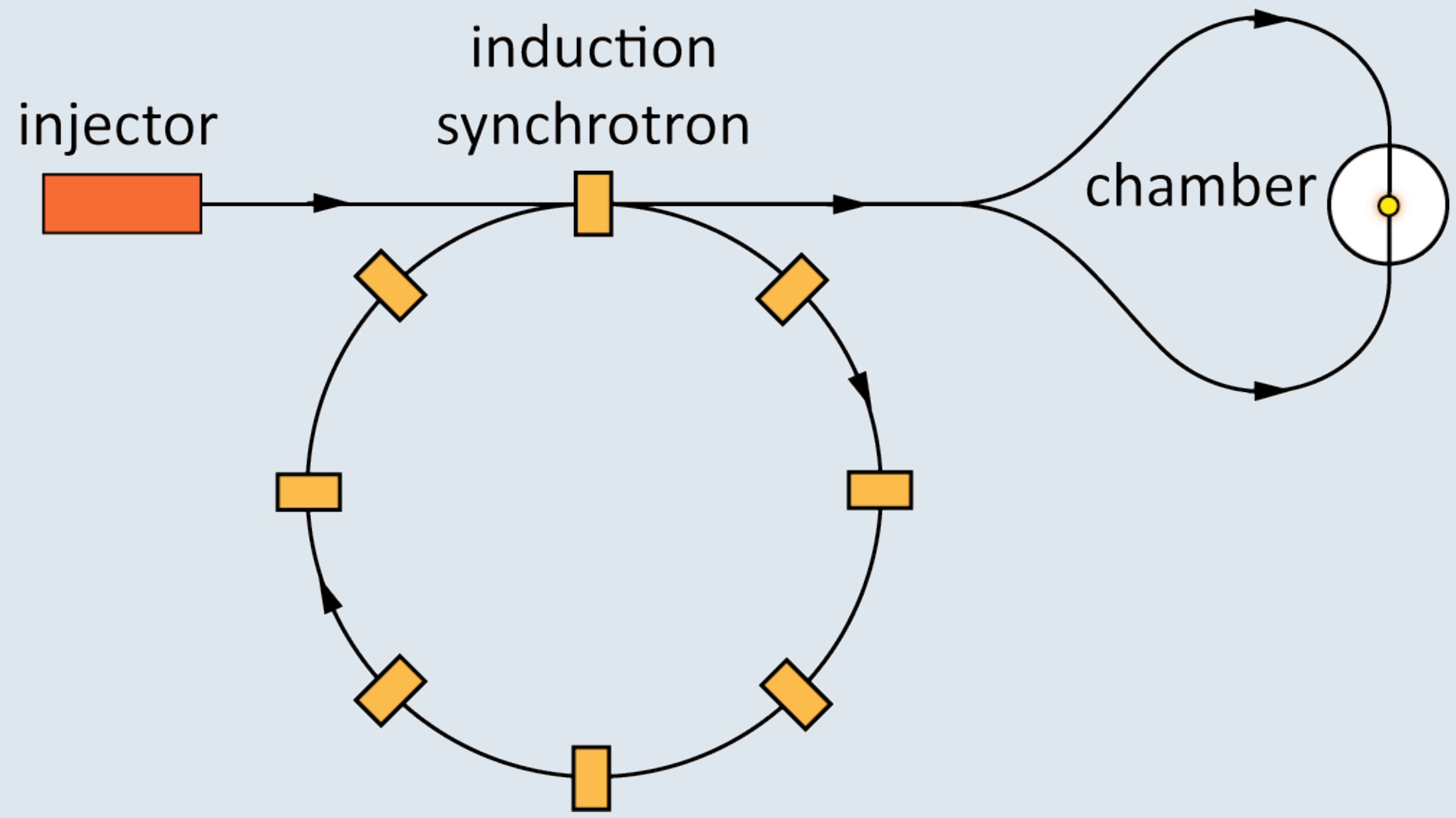
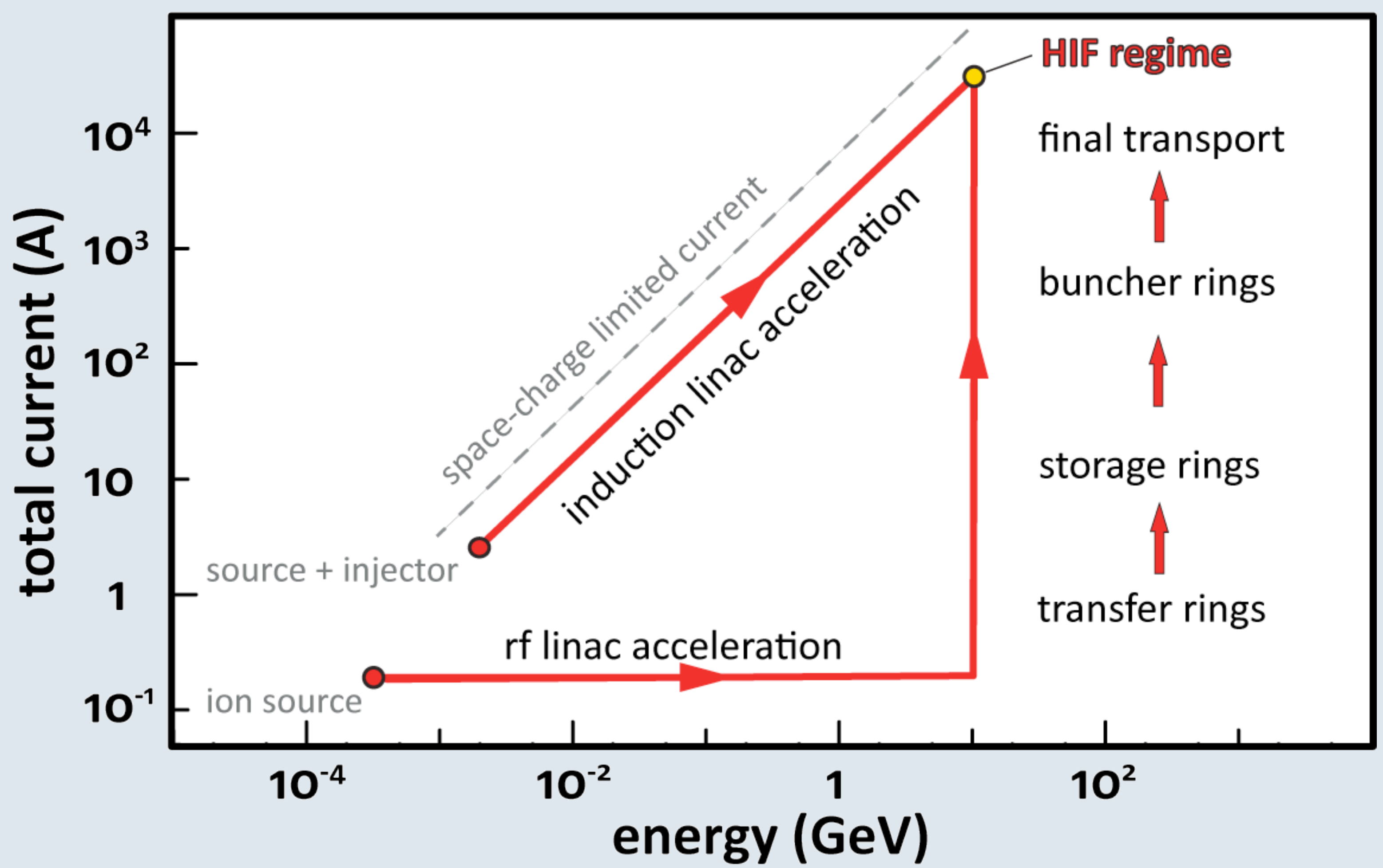


induction "recirculator"

So how do we choose?

both rf and induction accelerators have strengths and weaknesses

- **rf accelerators offer greater familiarity and higher gradients**
- **induction accelerators offer simplicity and higher current**



adapted from S. Atzeni in *Physics of Multiply Charged Ions* (Plenum, 1995)

HIF programs in Europe and Japan favor rf accelerators

US HIF program prefers induction drivers

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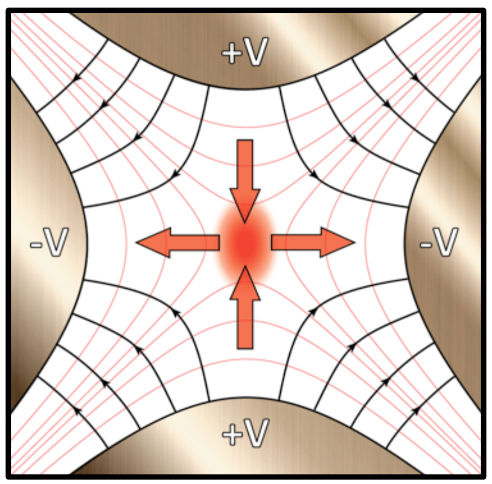
***then* you can start designing**

How does quadrupole focusing work?

quadrupoles squeeze the beam alternately in the two transverse directions

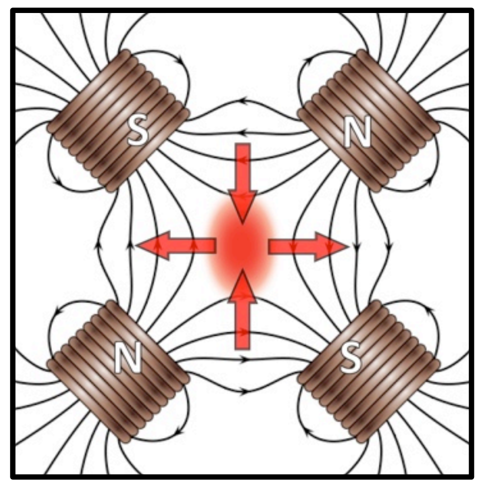
- can use electric or magnetic fields
- electric quads work best at low beam velocity. magnetic quads, at high velocity.

electric quadrupole



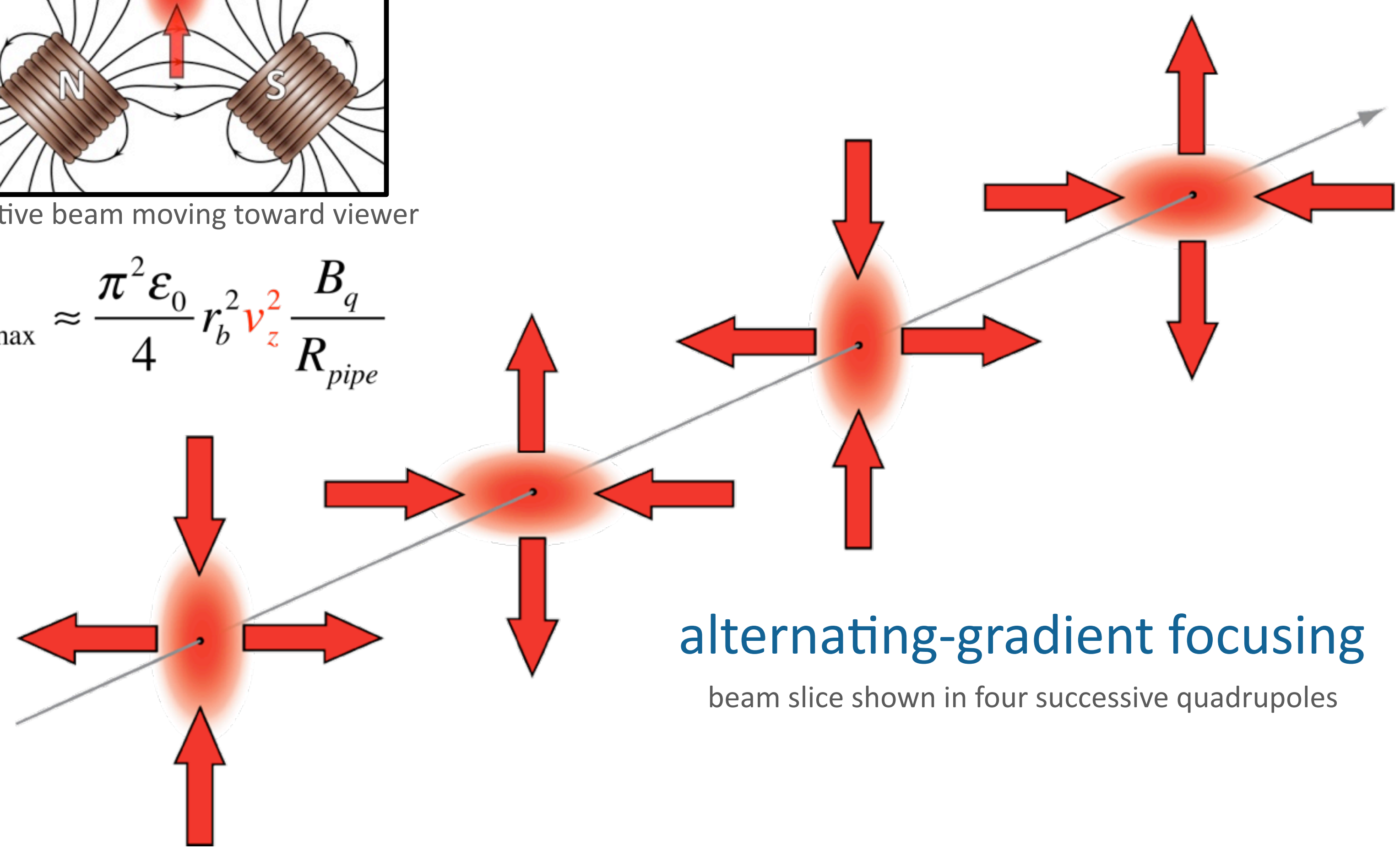
$$I_{\max} \approx \frac{\pi^2 \varepsilon_0}{4} r_b^2 v_z \frac{V}{R_{pipe}^2}$$

magnetic quadrupole



positive beam moving toward viewer

$$I_{\max} \approx \frac{\pi^2 \varepsilon_0}{4} r_b^2 v_z^2 \frac{B_q}{R_{pipe}}$$



alternating-gradient focusing

beam slice shown in four successive quadrupoles

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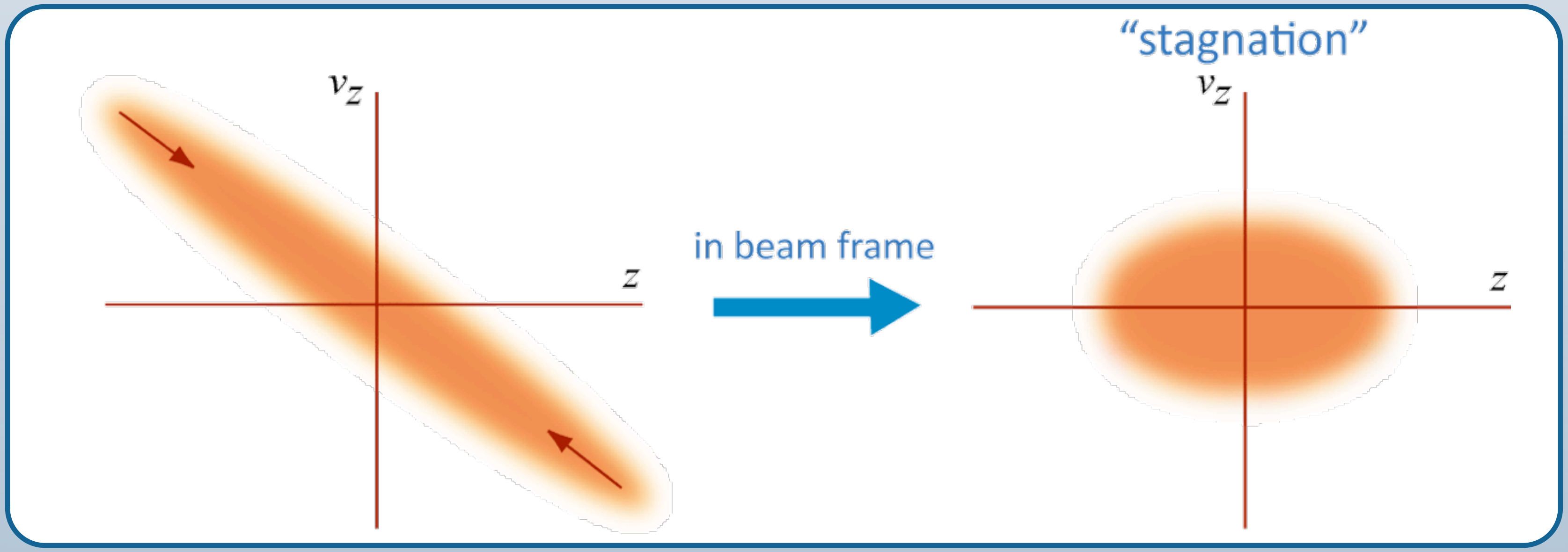
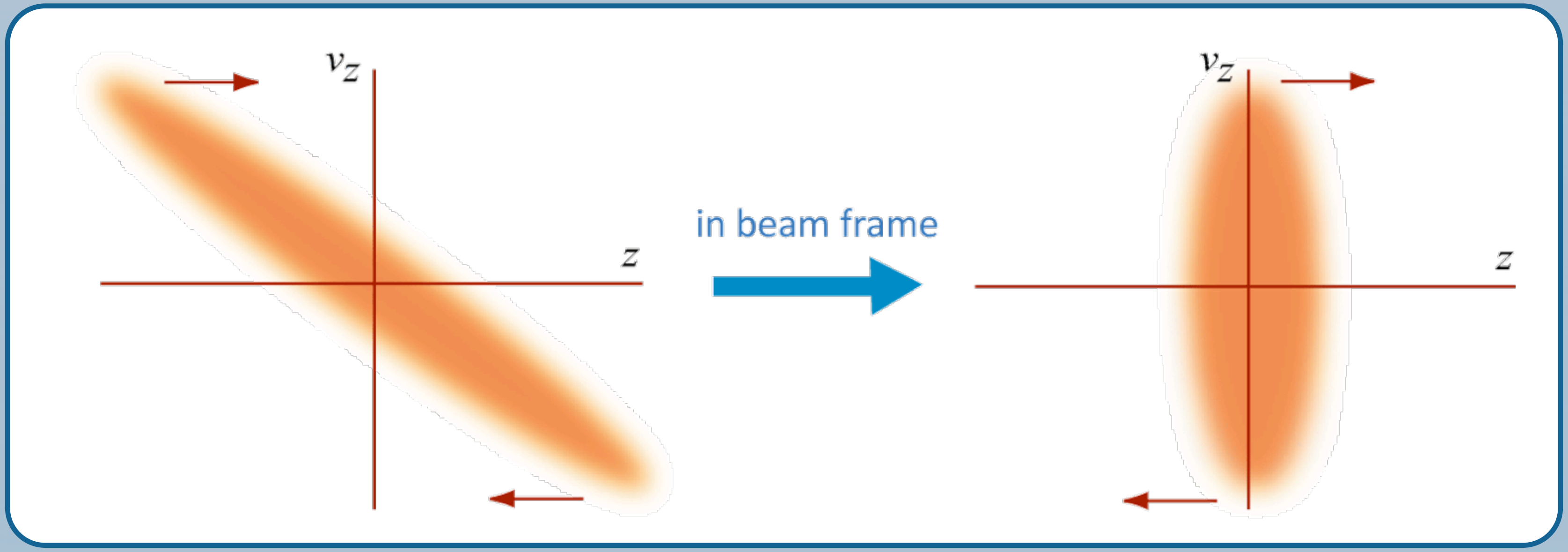
Drift-compression is used to shorten an ion bunch

induction cells impart a head-to-tail velocity gradient ("tilt") to the beam

- **the beam shortens as it "drifts" down the beam line**
- **without neutralization, space charge opposes compression, leading to a nearly mono-energetic compressed pulse**



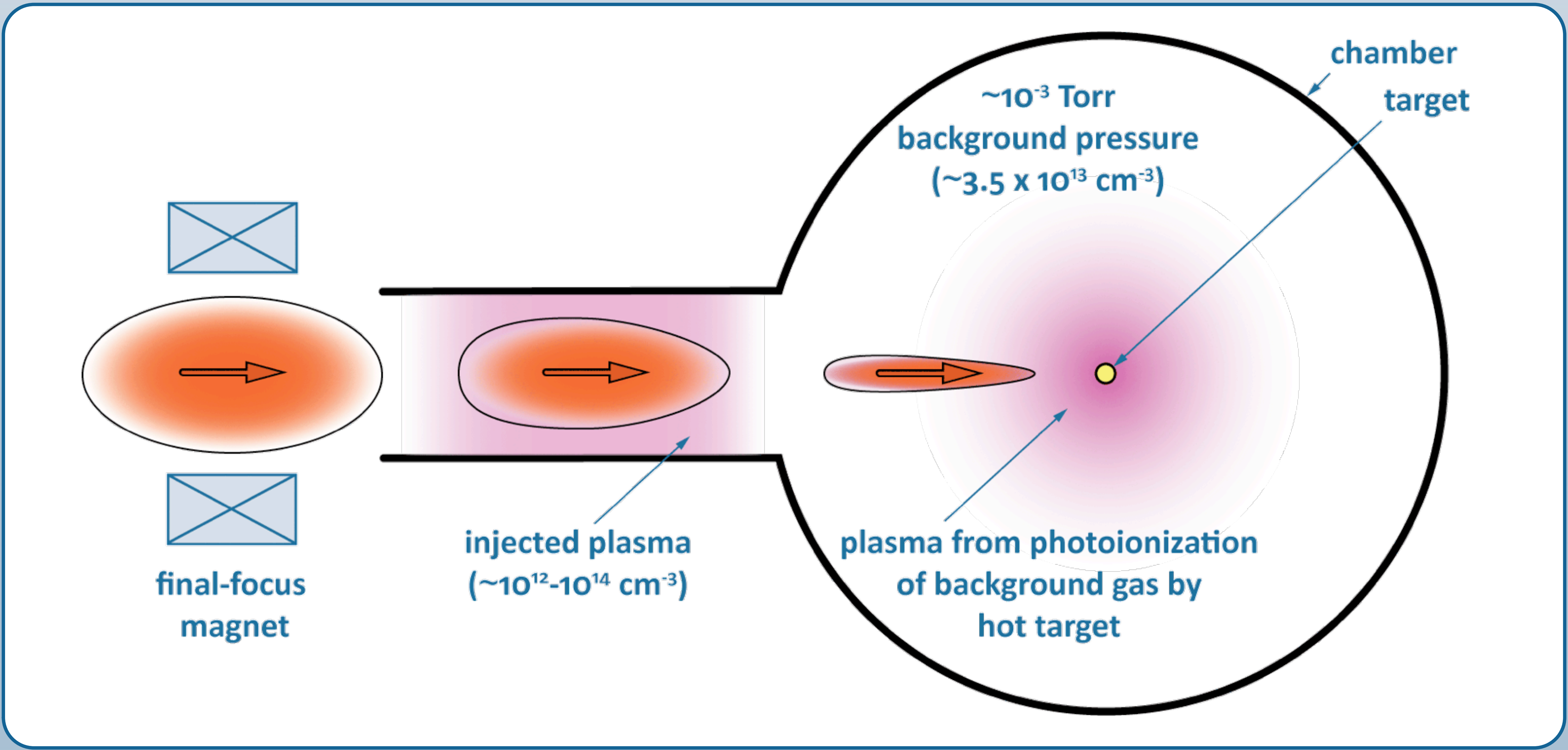
- **in neutralized drift-compression, space charge is eliminated, resulting in a shorter pulse but a larger velocity spread**



How does neutralized compression work?

beam space charge can be neutralized by a sufficiently dense plasma

- plasma density should be 3-10 times beam density
- neutralized beam drags electrons with in into the chamber
- additional neutralization is provided by photoionization plasma around hot target
- increased beam charge state from collisional and photo stripping has minor effect



How do you design an HIF power plant?

many interrelated questions must be answered first

- **what target to use?**
  gives the total energy, beam spot size, symmetry requirements
- **what ion species to use?**
  gives the beam energy and total current
- **what type of acceleration to use?**
  determines the complexity, efficiency, and cost of plant
- **what type of transverse focusing to use?**
  transport limits determine the number and radius of beams
- **what type of fusion-chamber transport to use?**
  space-charge, energy spread, and transverse temperature impair beam focus
- **what type of fusion-chamber protection to use?**
  choice between liquid and solid depends on the target design and number of beams

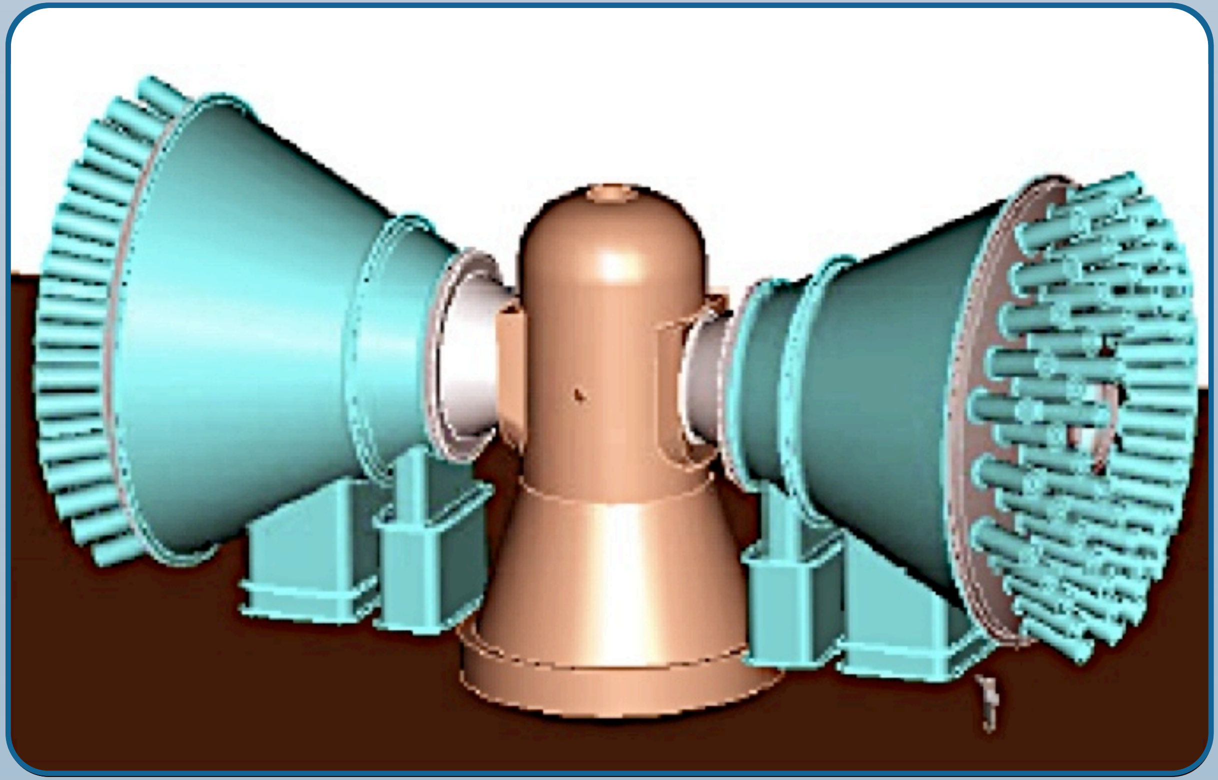
then **you can start designing**

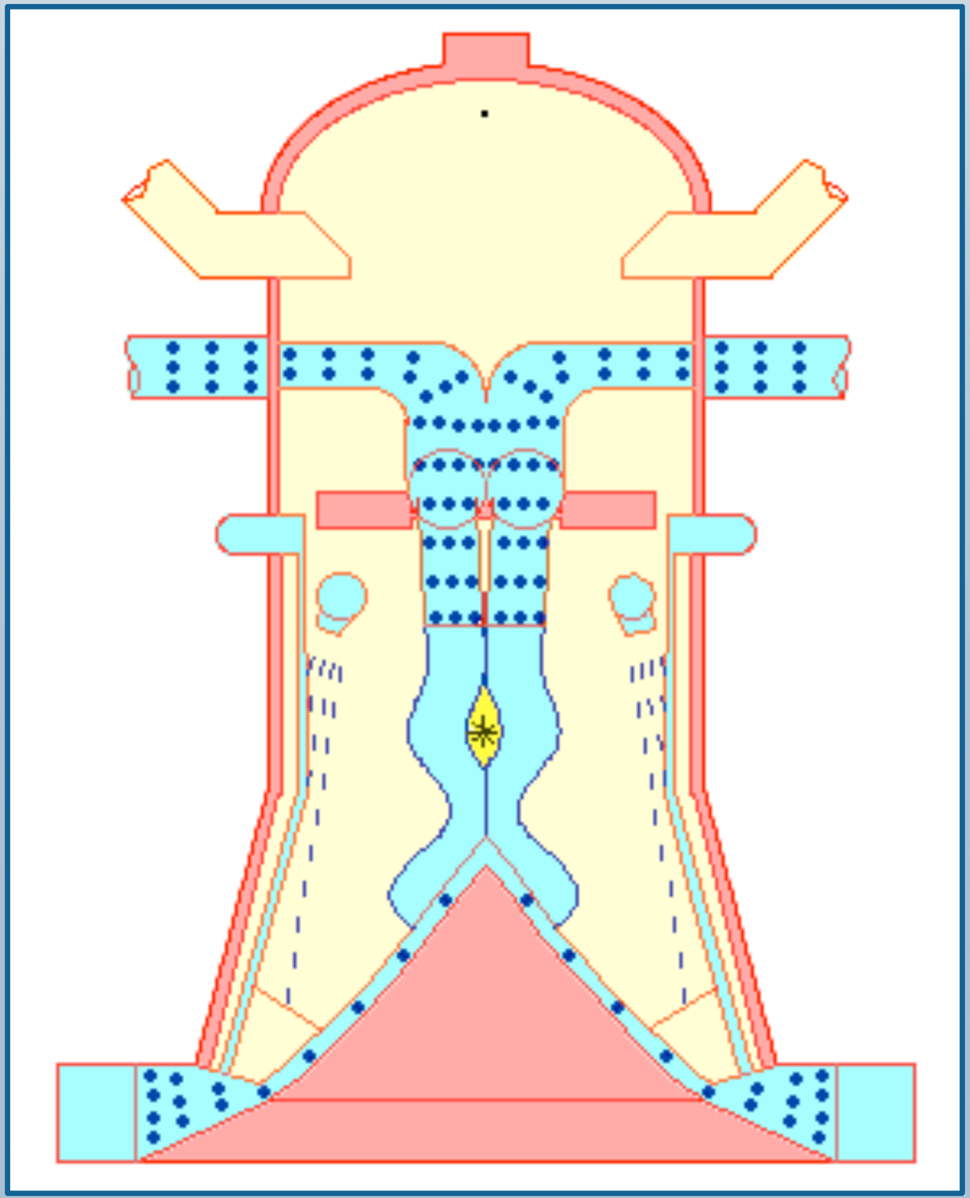
How does a thick-liquid wall work?

curtains of neutronically thick liquid (Li, LiPb, Li_2BeF_4) surround the fusion target

- cavities are formed by oscillating liquid curtains
- targets are injected into cavities
- cavity ends are protected by crisscrossed liquid jets
- ion beams enter cavities through holes between jets
- liquid carries heat to generator
- lithium in liquid breeds tritium for targets
- tritium and debris are removed from fluid

approach was introduced in 1996 HYLIFE-II study





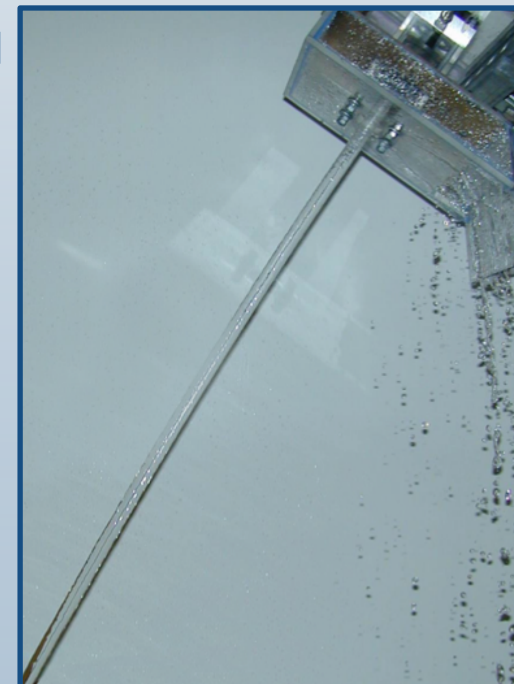
from R W Moir, Fusion Eng. Design **32-33,** 93 (1996)

Liquid FLiBe walls have been studied in scaled experiments

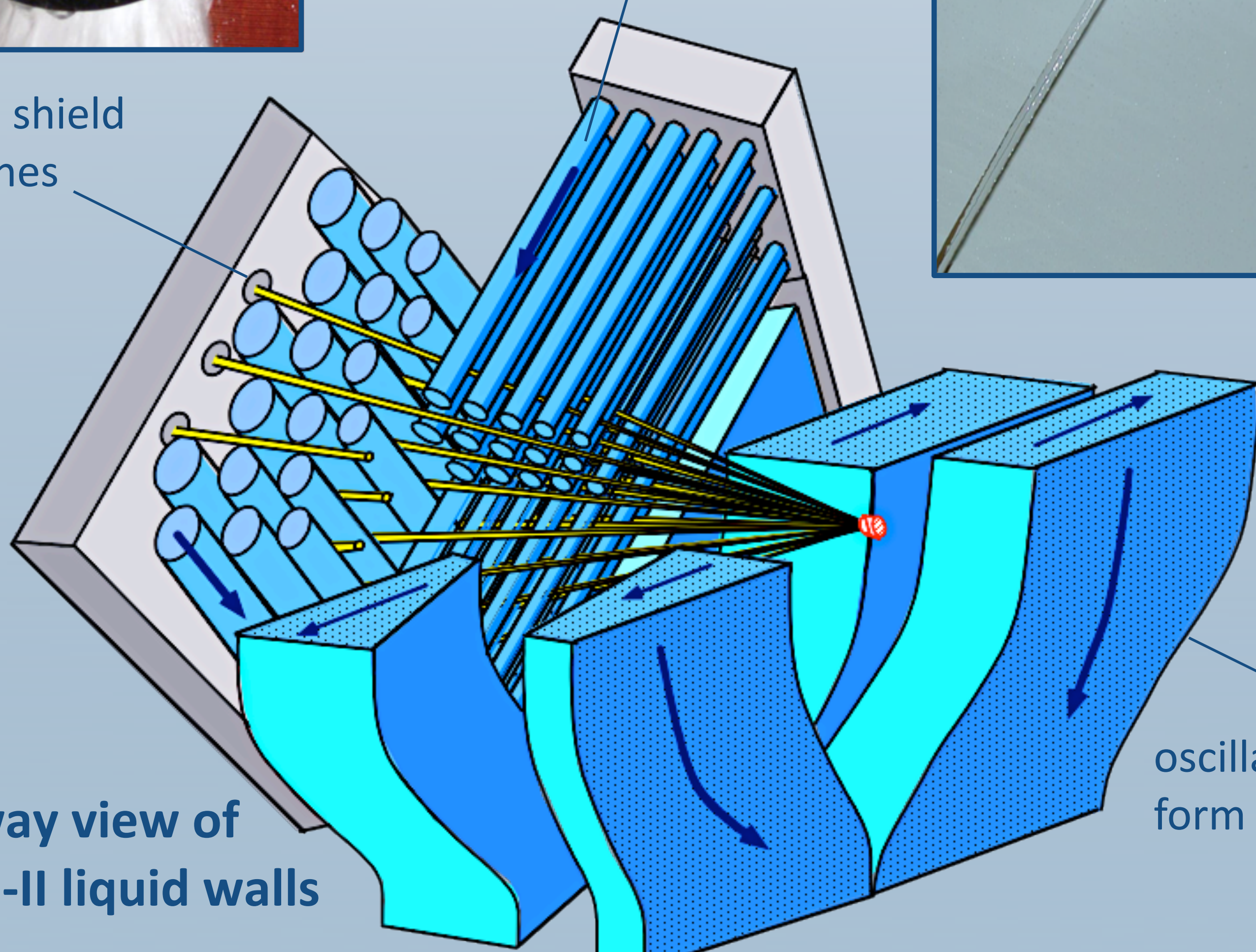
UCB group modeled HYLIFE-II walls with hydrodynamically equivalent water jets

- **flow conditions approach correct Reynolds and Weber numbers of molten FLiBe**
- **jets, curtains, and vortices have all been studied experimentally**

crisscrossed cylindrical jets form beam ports



vortices shield beam lines



oscillating curtains form pocket for target

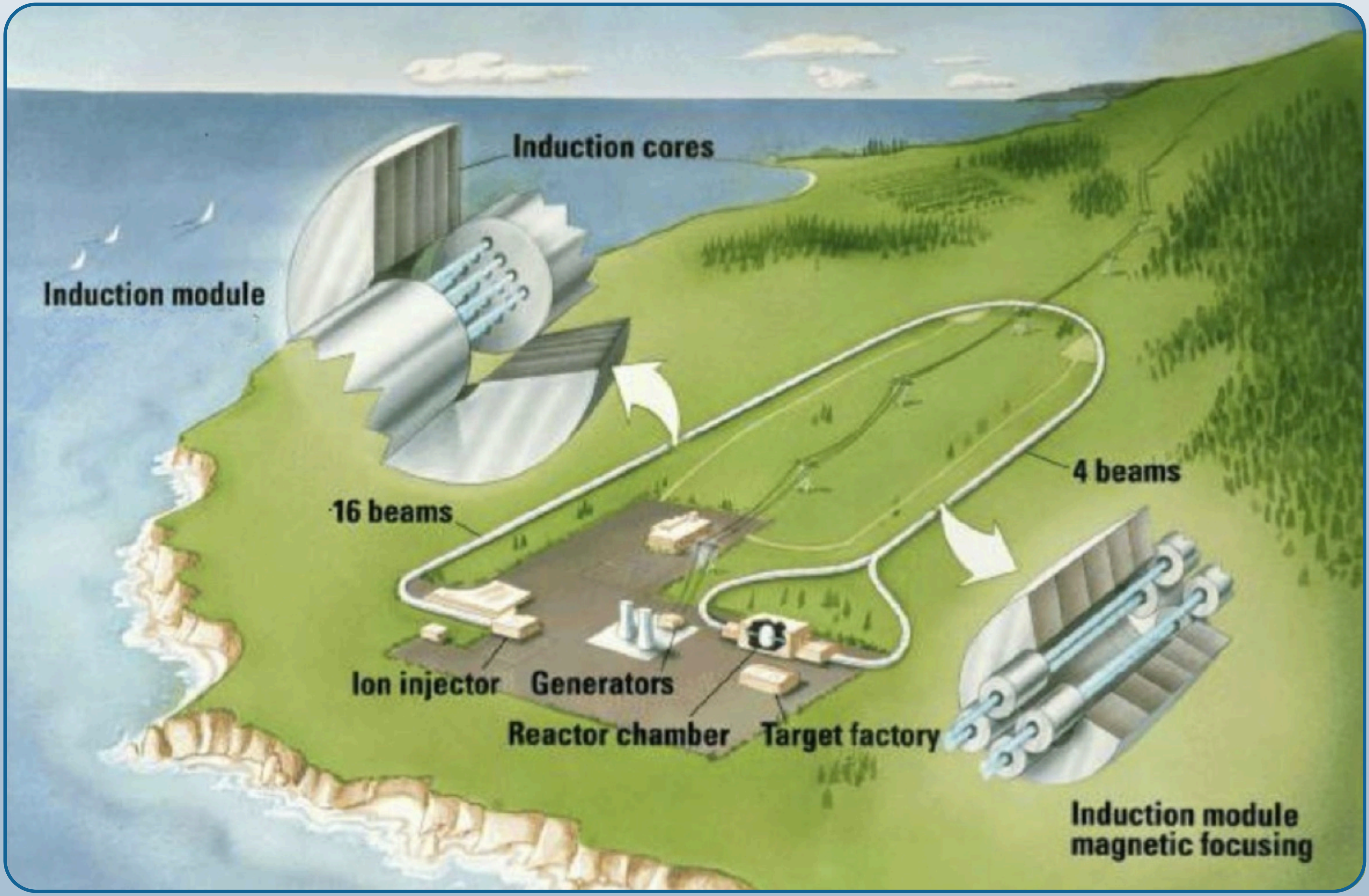
cut-away view of HYLIFE-II liquid walls

Outline

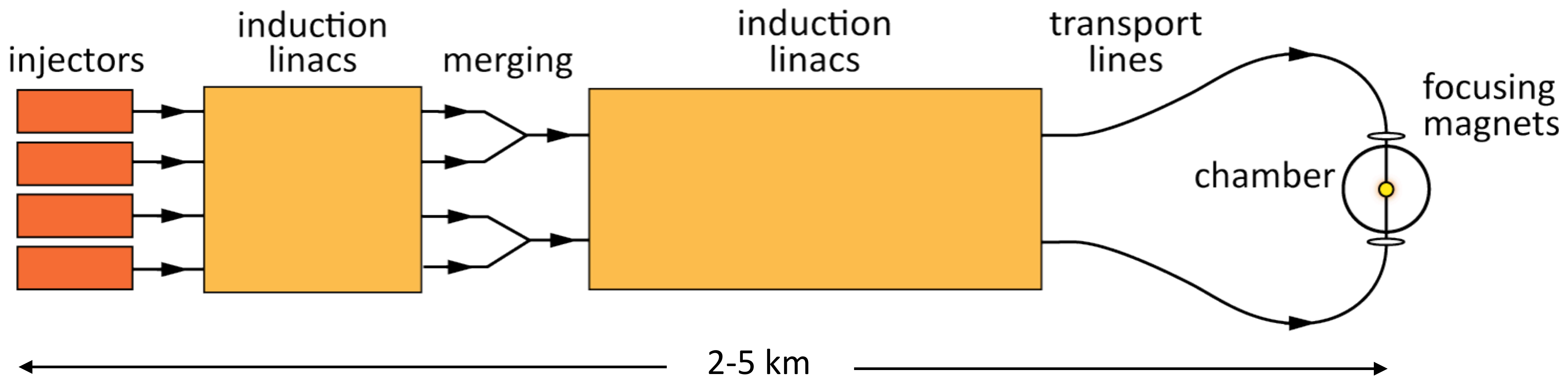
- motivation
- a fusion primer
- essentials of heavy-ion fusion
- **past and present HIF research**
- future research directions

Fanciful picture of an HIF power plant...

artist's conception from the 1980s



Schematic picture of a induction-linac driver



~ 1-3 MeV
~ 1 A/beam x ~ 100 beams
~ 20 µs

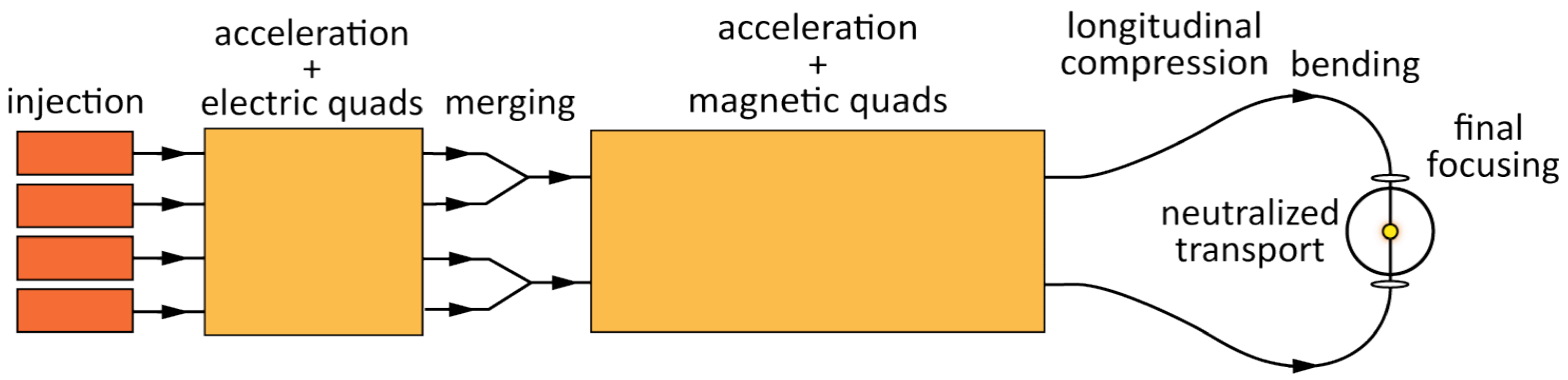
~ 1-10 GeV
~ 200 A/beam
~ 100 ns

~ 1-10 GeV
~ 2000 A/beam
~ 10 ns

beam physics is dominated by space charge

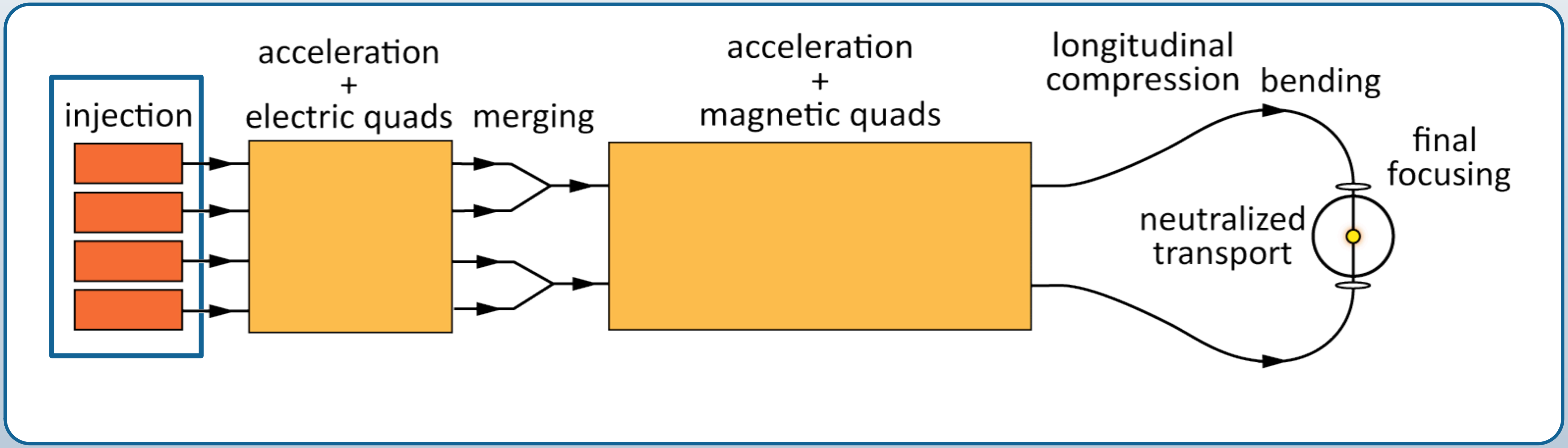
perveance ~ 10^{-4}-10^{-3} tune depression ~ $\sigma/\sigma_0 < 0.1$

Schematic picture of a induction-linac driver



most driver functions have been investigated separately in scaled experiments

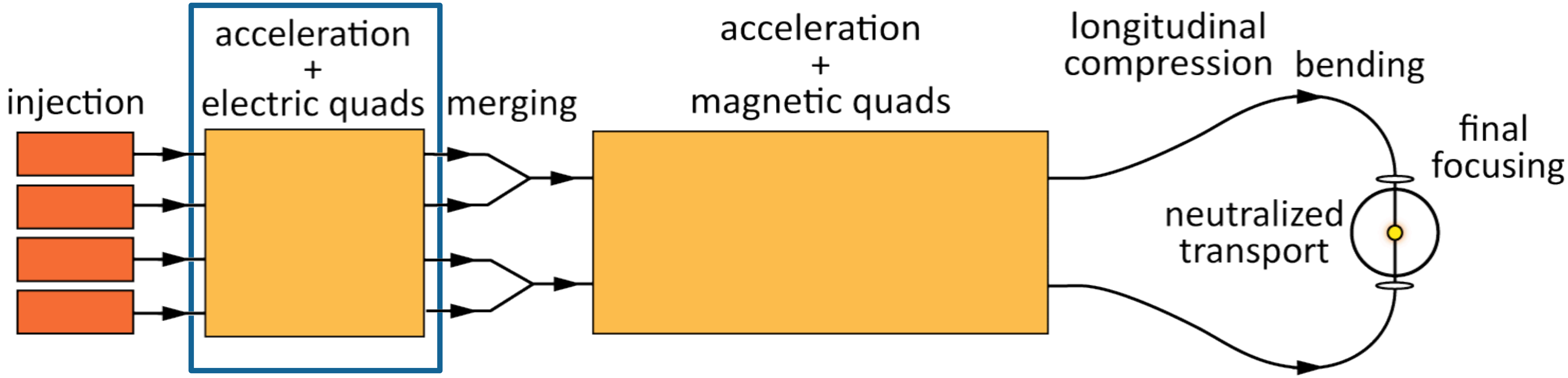
Schematic picture of a induction-linac driver

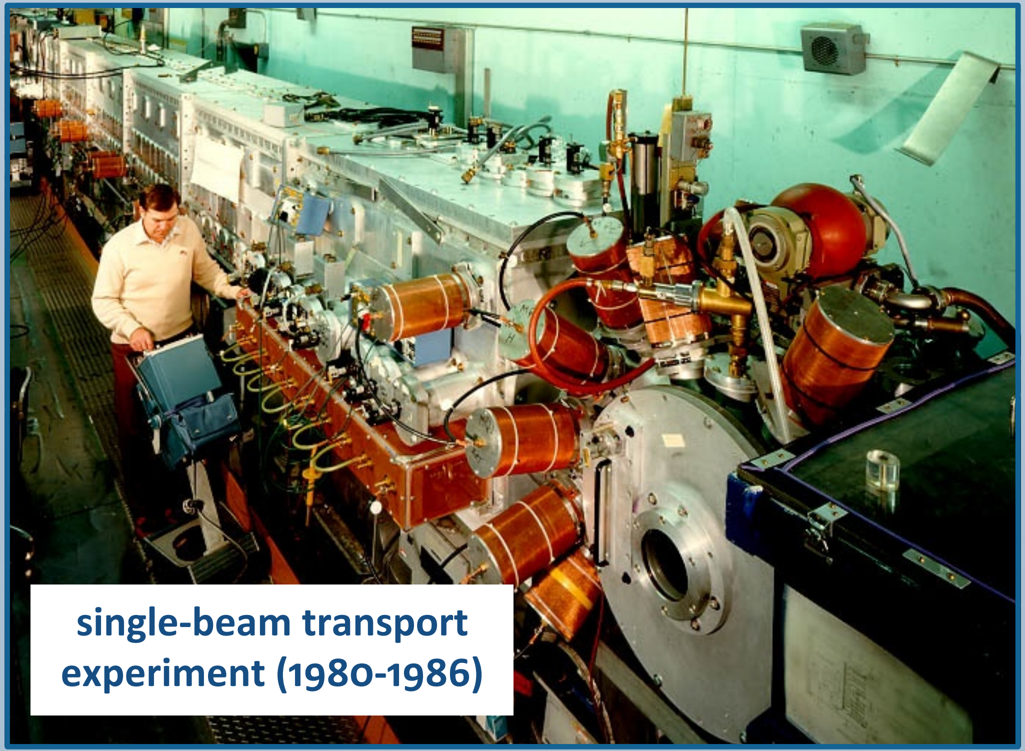


2-MeV injector (1994)

produced low-emittance driver-scale beam

Schematic picture of a induction-linac driver

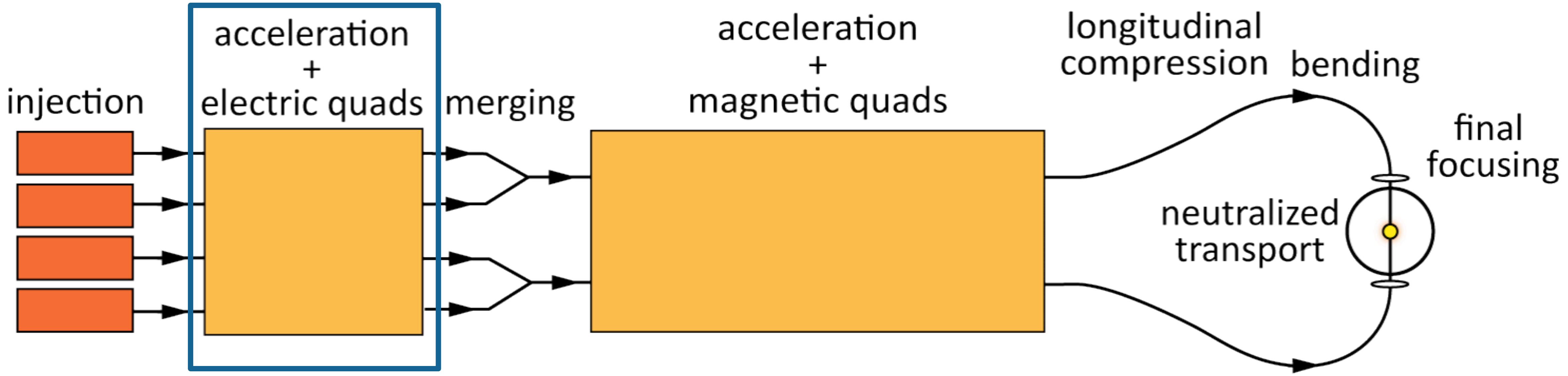


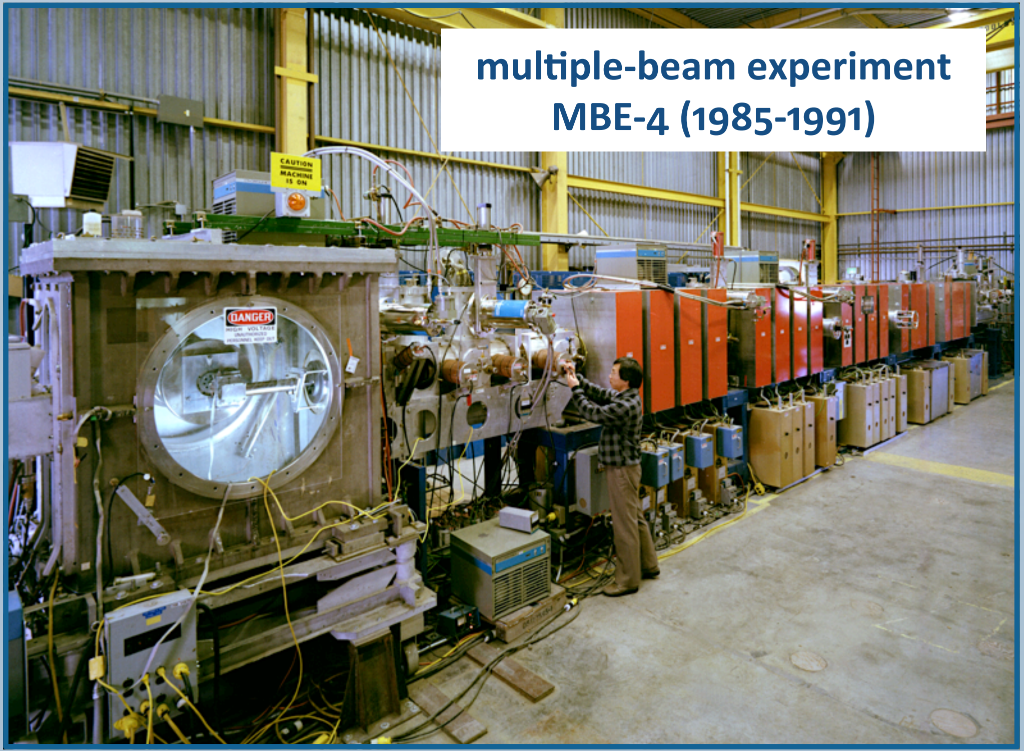


single-beam transport experiment (1980-1986)

established attractive scaling of transportable current through 86 electrostatic quads

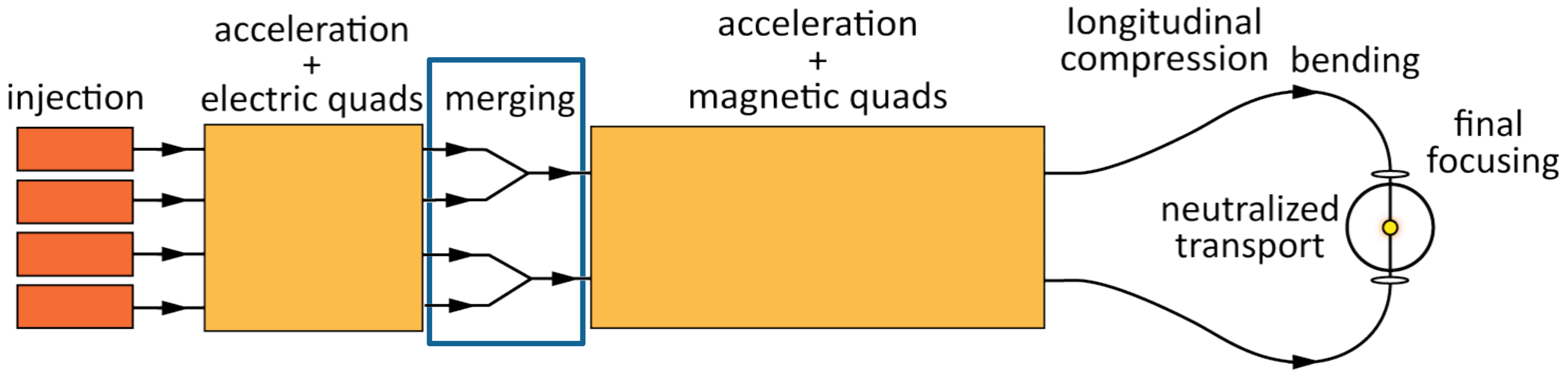
Schematic picture of a induction-linac driver

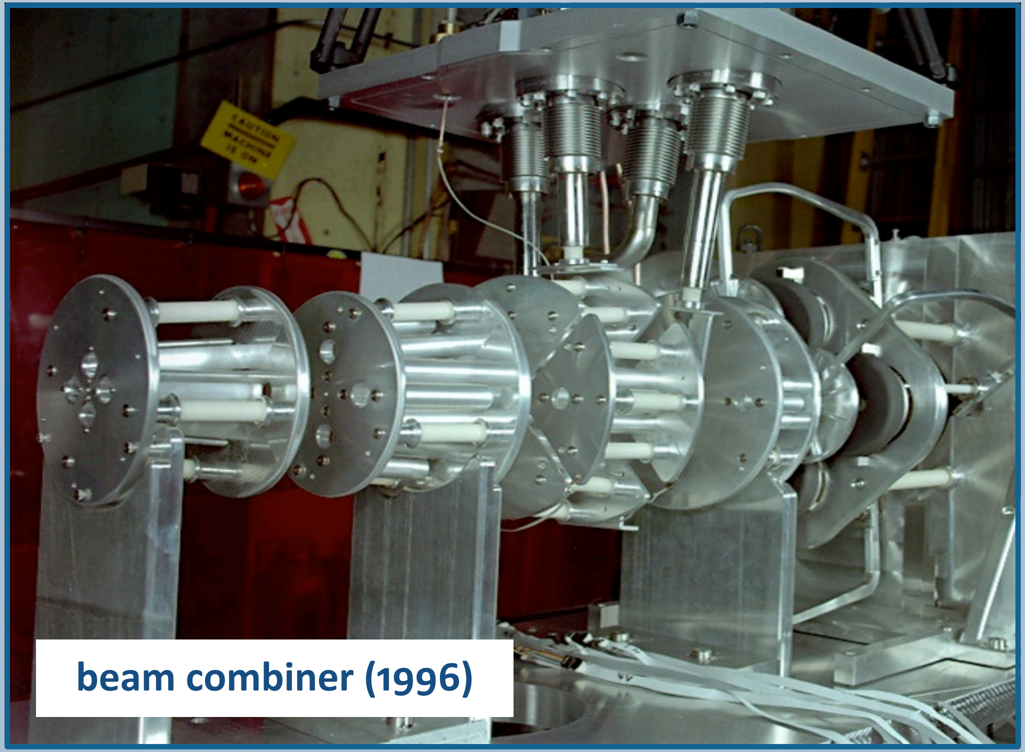




accelerated and compressed four-beams with electrostatic focusing

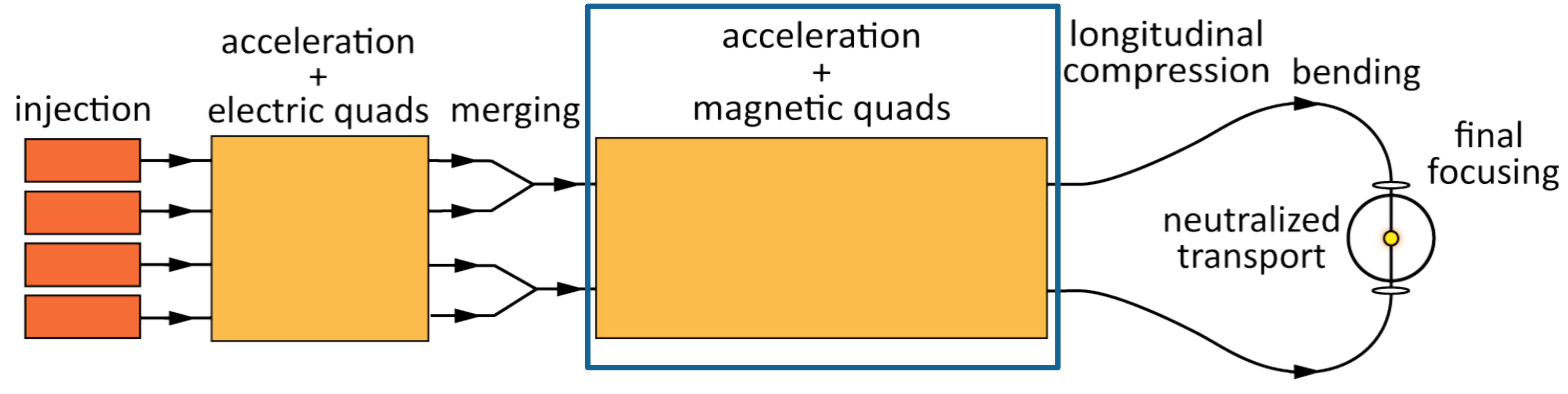
Schematic picture of a induction-linac driver

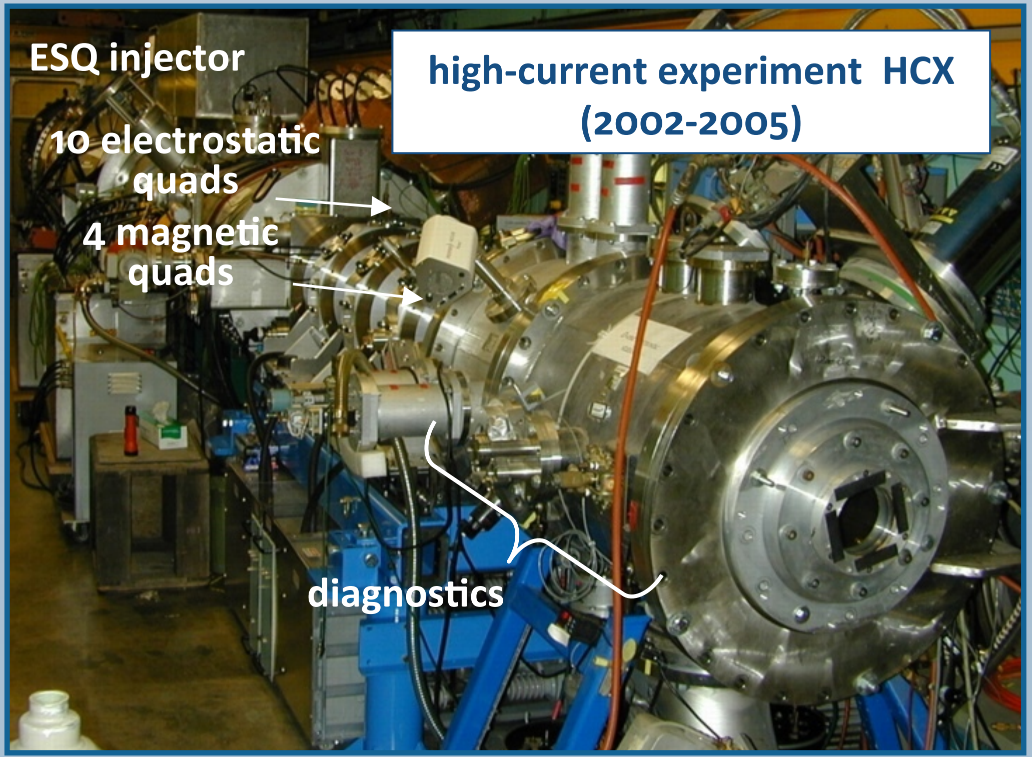




merged four beams with minimal emittance growth

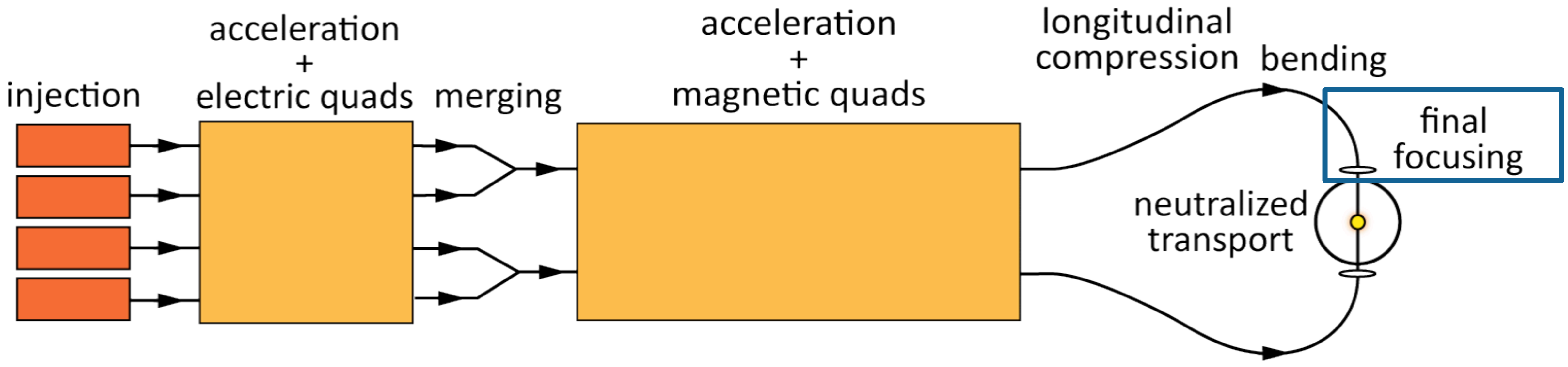
Schematic picture of a induction-linac driver

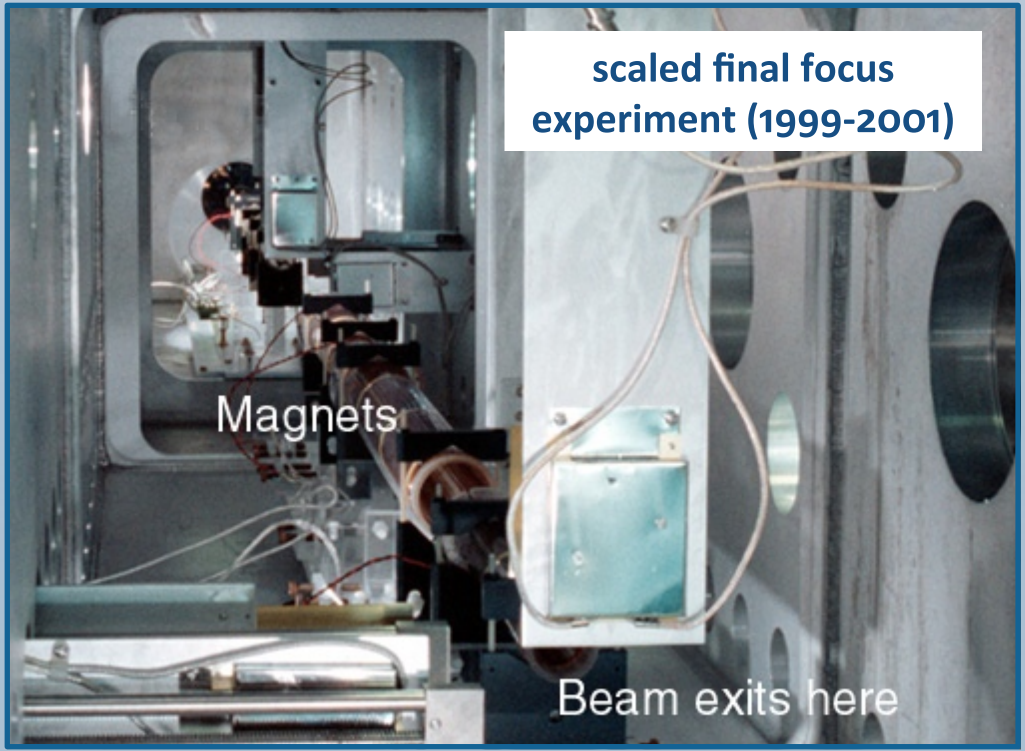




electrostatic and magnetic transport of driver-scale beam filling large fraction of aperture

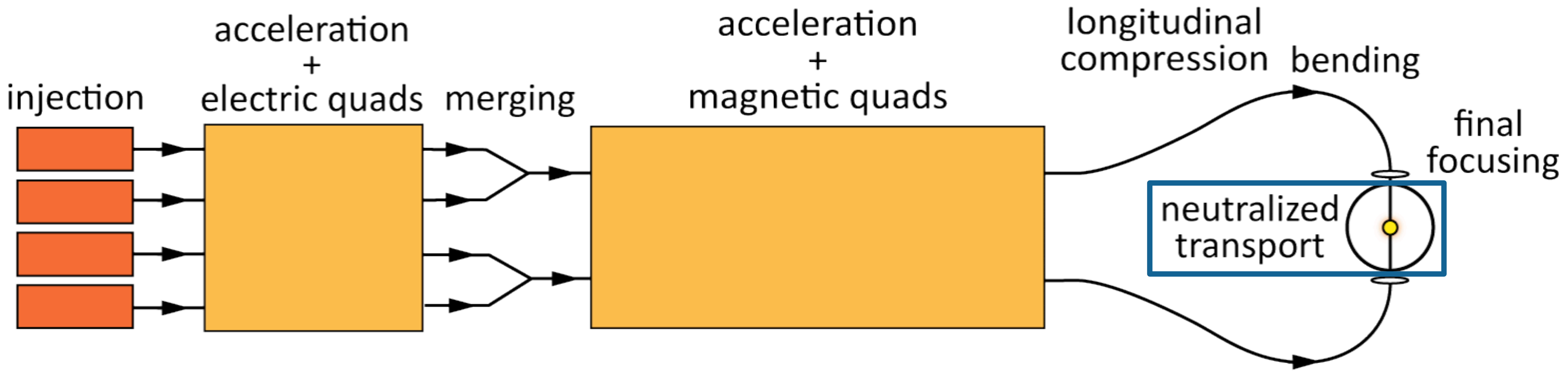
Schematic picture of a induction-linac driver

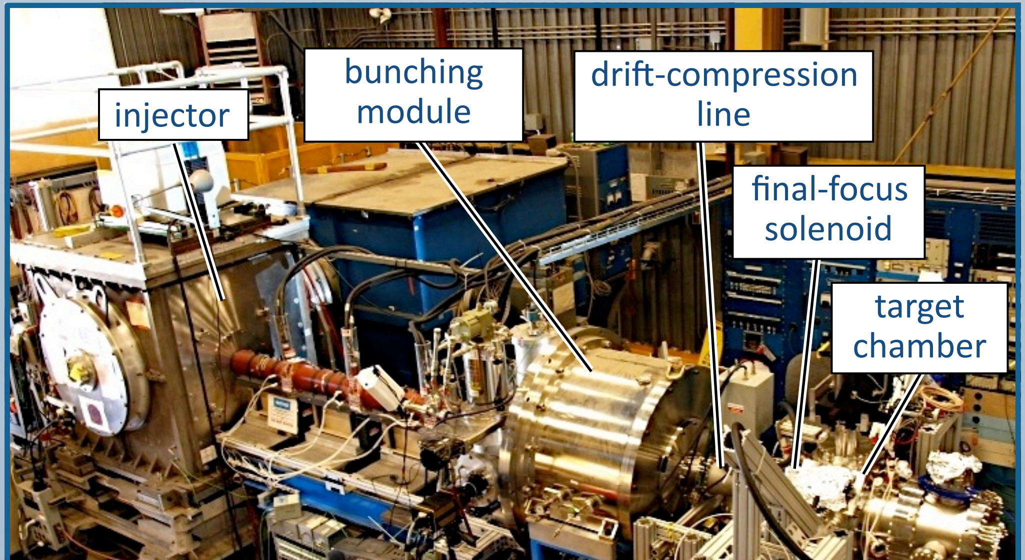




replicated physics of HYLIFE-II focus on reduced scale

Schematic picture of a induction-linac driver

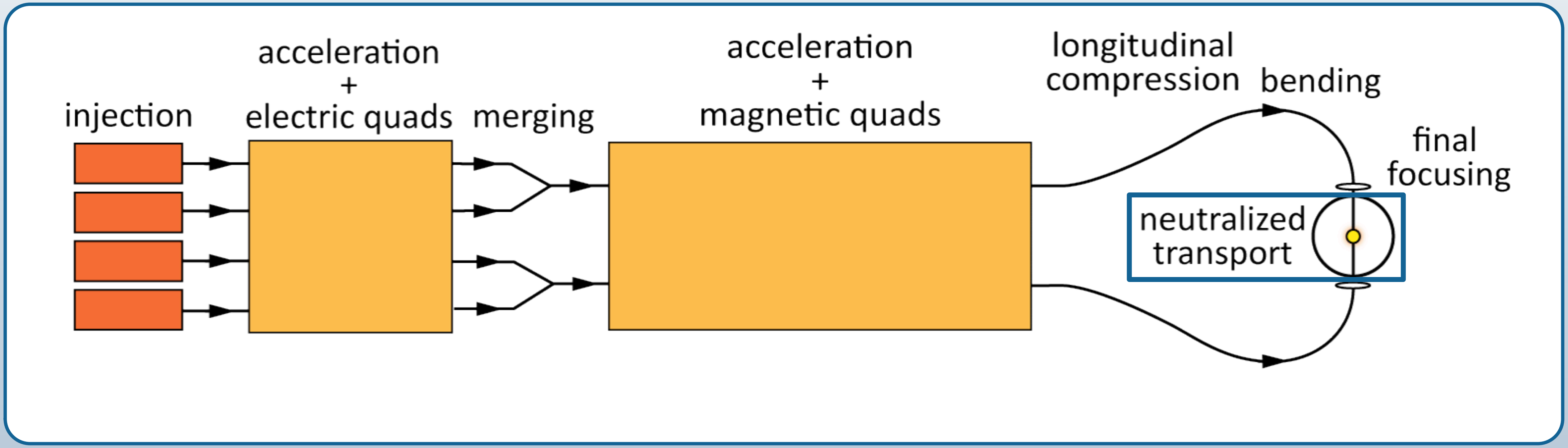


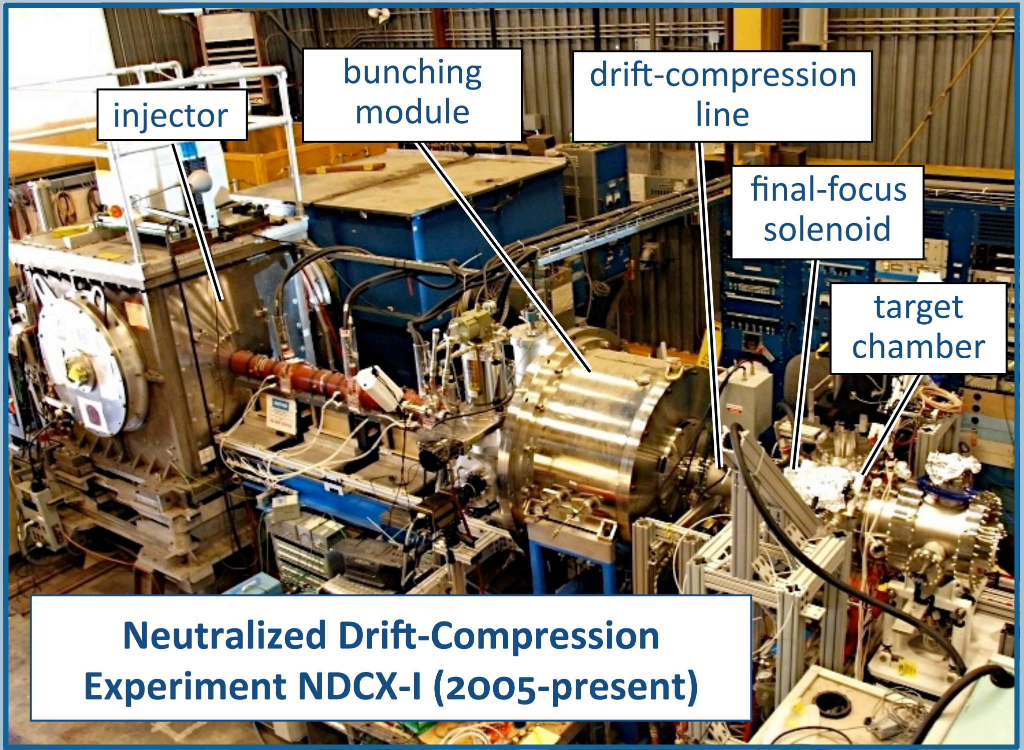


Neutralized Drift-Compression Experiment NDCX-I (2005-present)

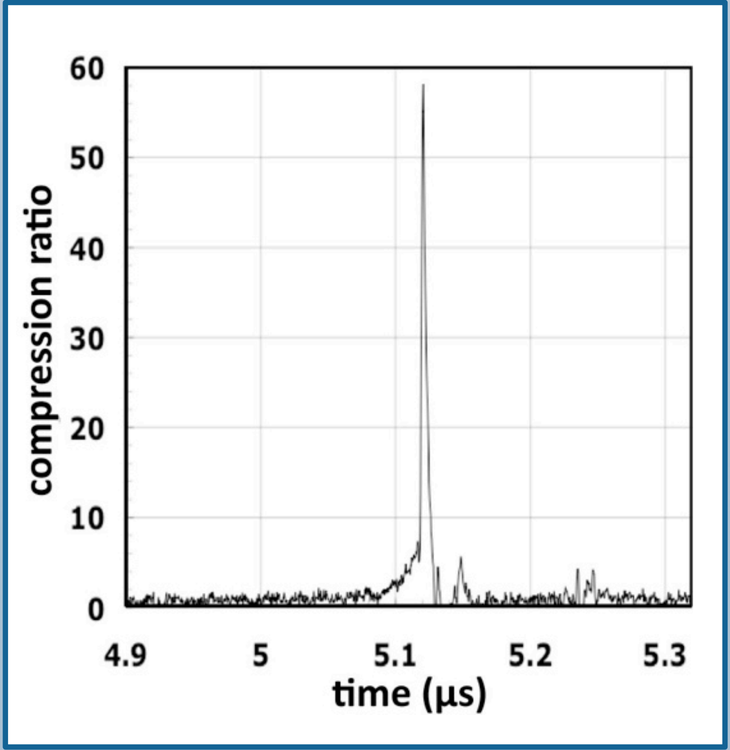
demonstrated neutralized drift compression with current and power amplification routinely above x50

Schematic picture of a induction-linac driver





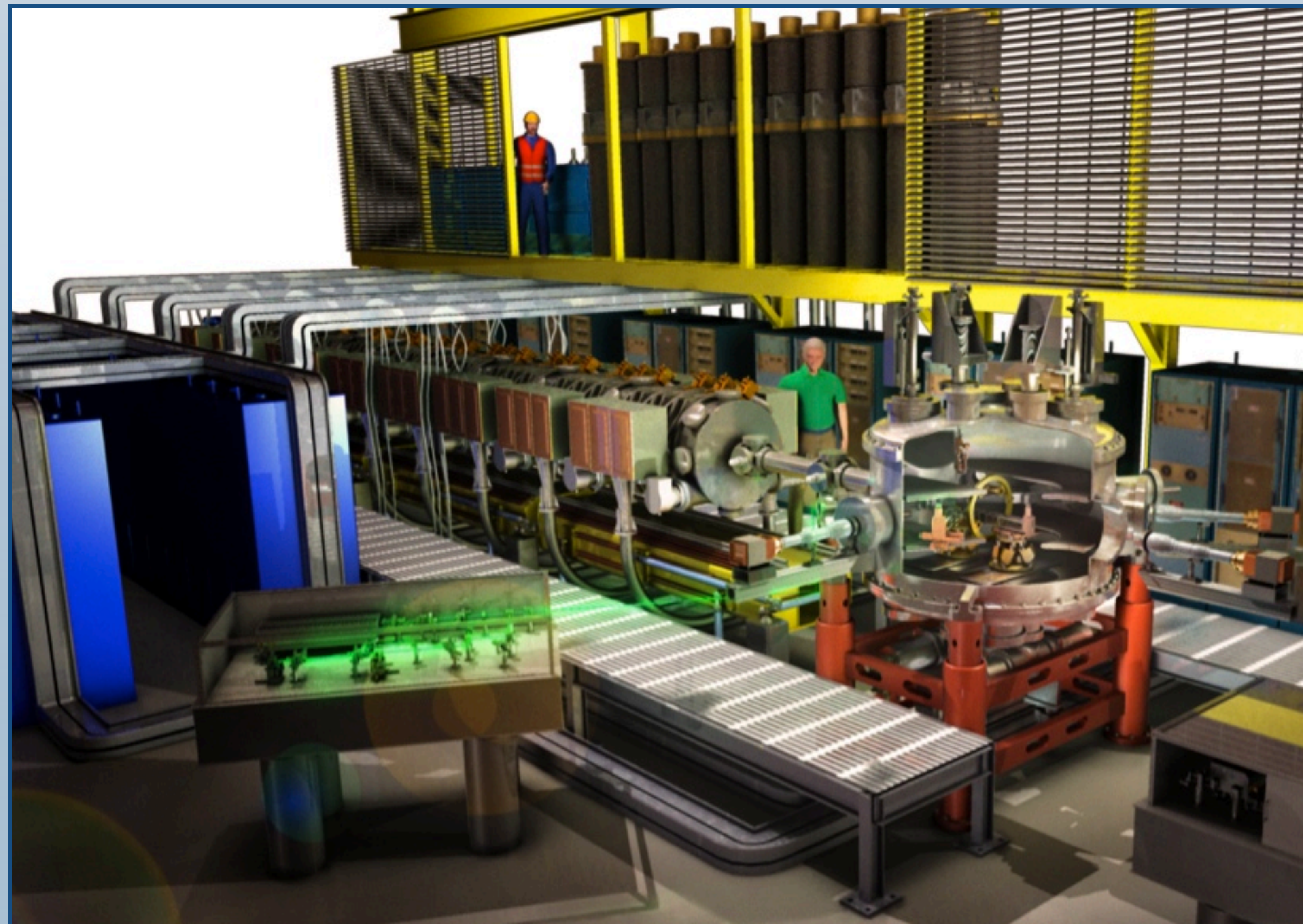
Neutralized Drift-Compression Experiment NDCX-I (2005-present)



The NDCX-II project is well underway

DOE Fusion Energy Sciences office approved NDCX-II in 2009.

- $11 M funding was provided via the American Recovery and Reinvestment Act
- construction of the initial configuration began in July 2009
- project completion is due by March 2012
- commissioning might begin in fall 2011
- HEDP target experiments will follow

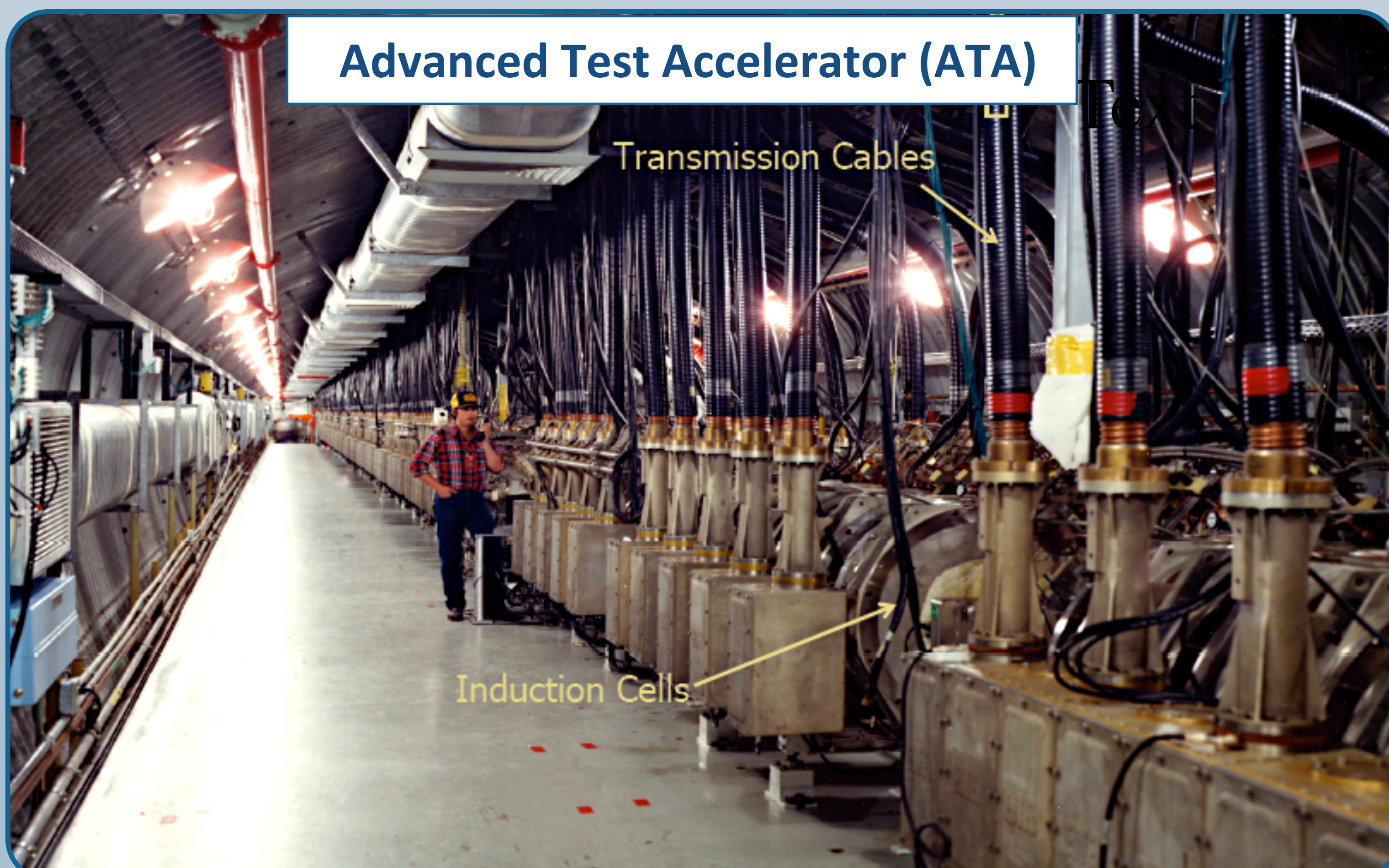


LLNL donated 50 induction cells from the ATA electron accelerator

ferrite cores each provide 1.4 x 10^{-2} Volt-seconds

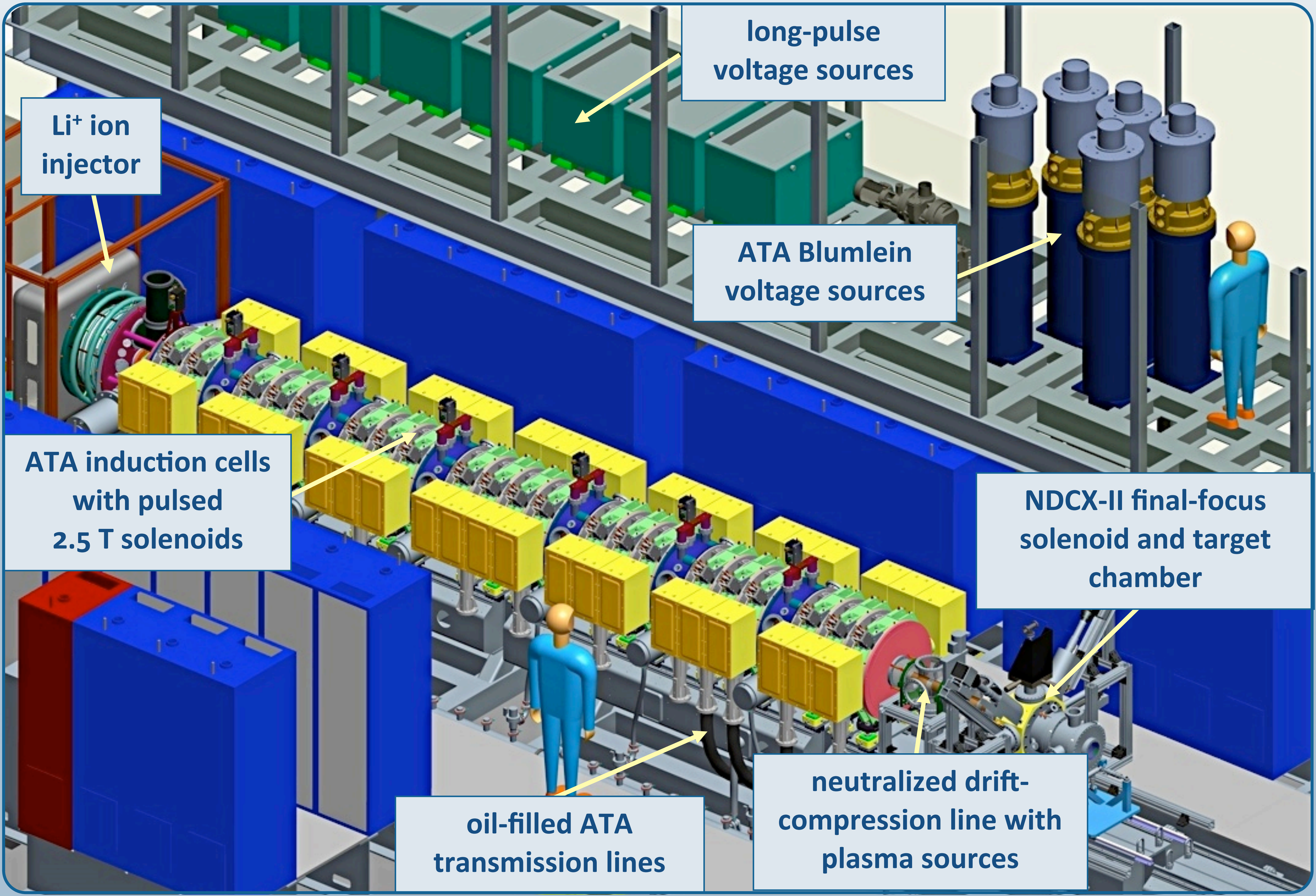
Blumlein voltage sources offer 200-250 kV with FWHM duration of 70 ns

- **NDCX-II needs custom voltage sources < 100 kV at low energy**
- **ion beam requires stronger (3T) pulsed solenoids and other cell modifications**

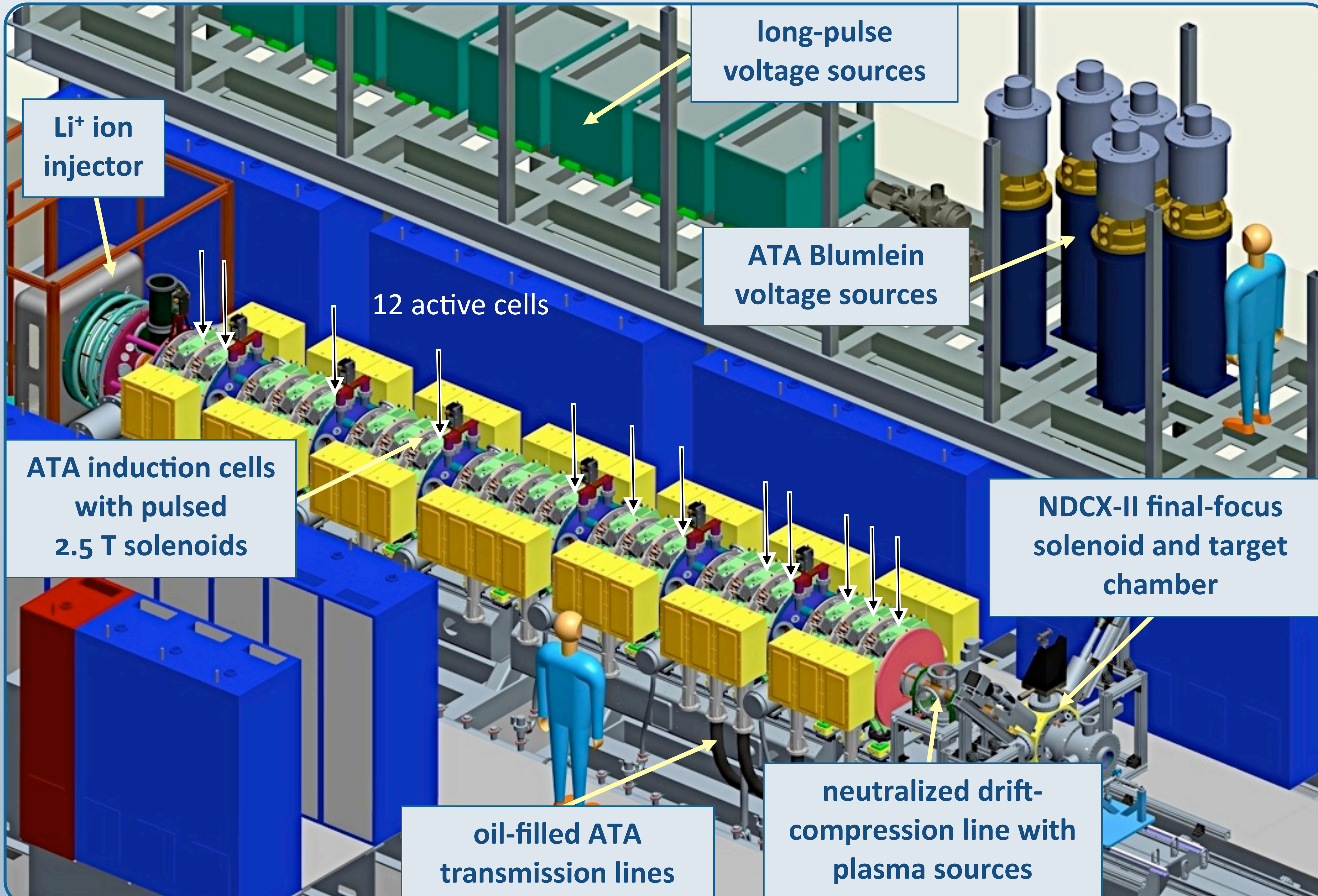


Advanced Test Accelerator (ATA)

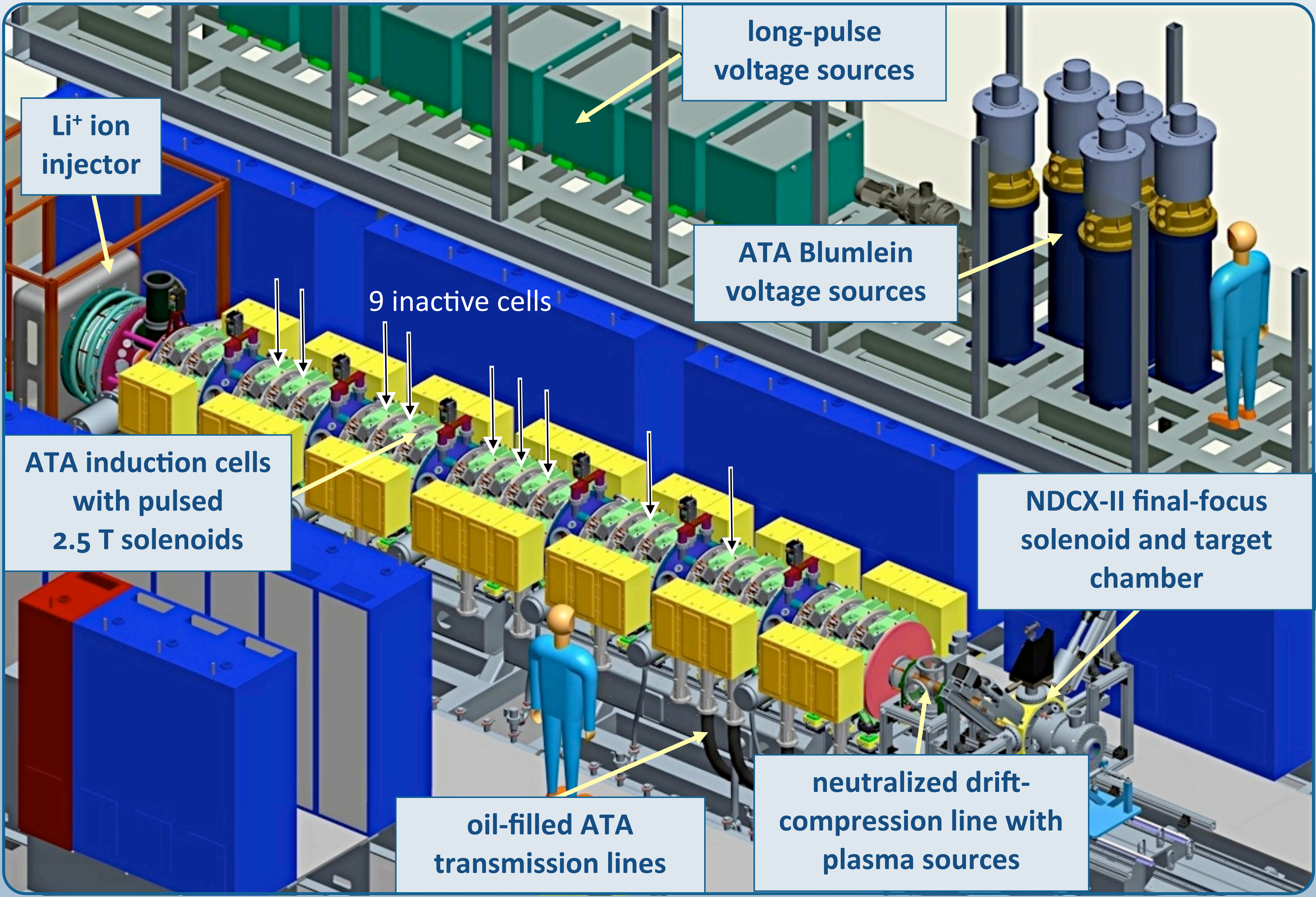
12-cell NDCX-II baseline layout



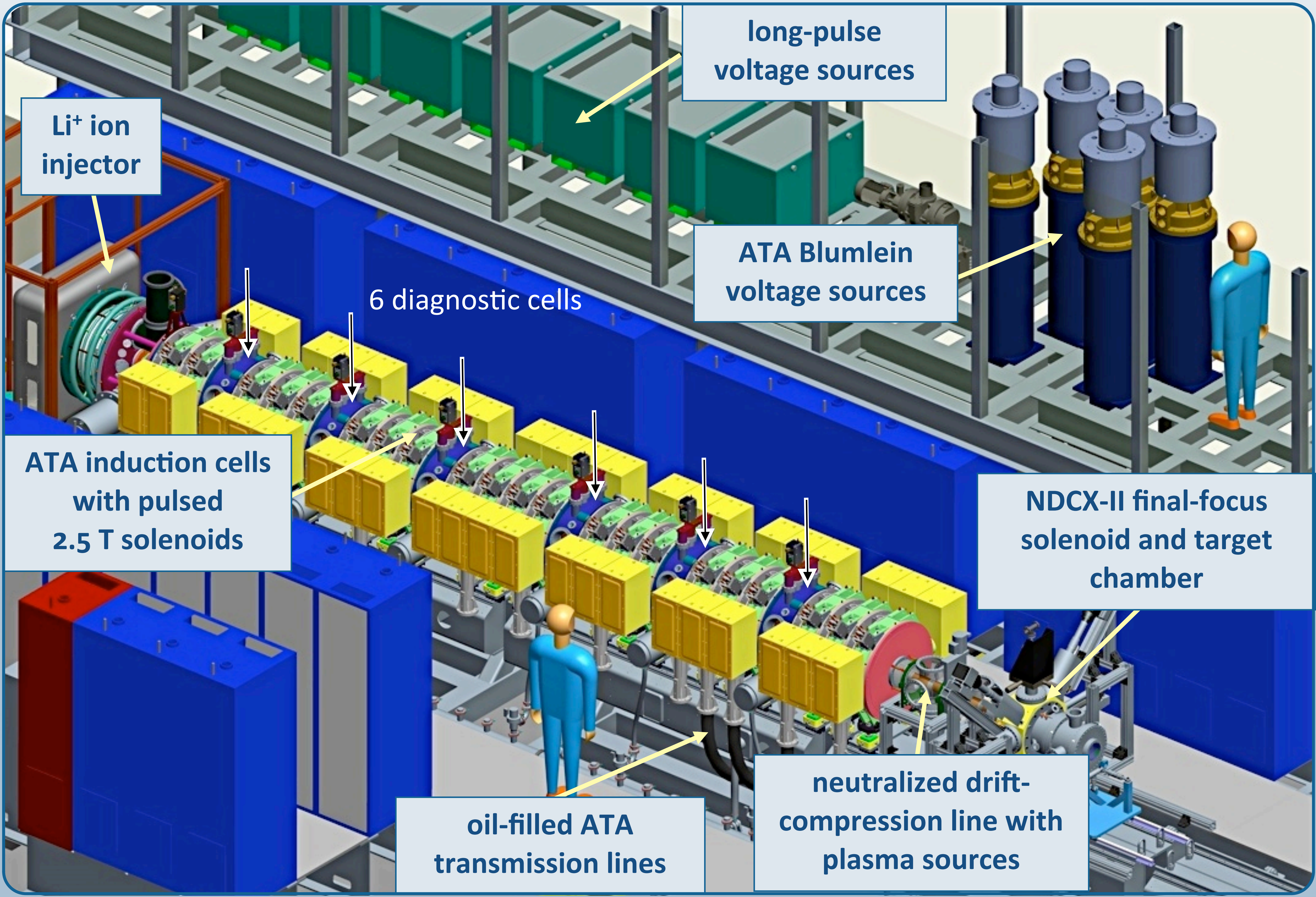
12-cell NDCX-II baseline layout



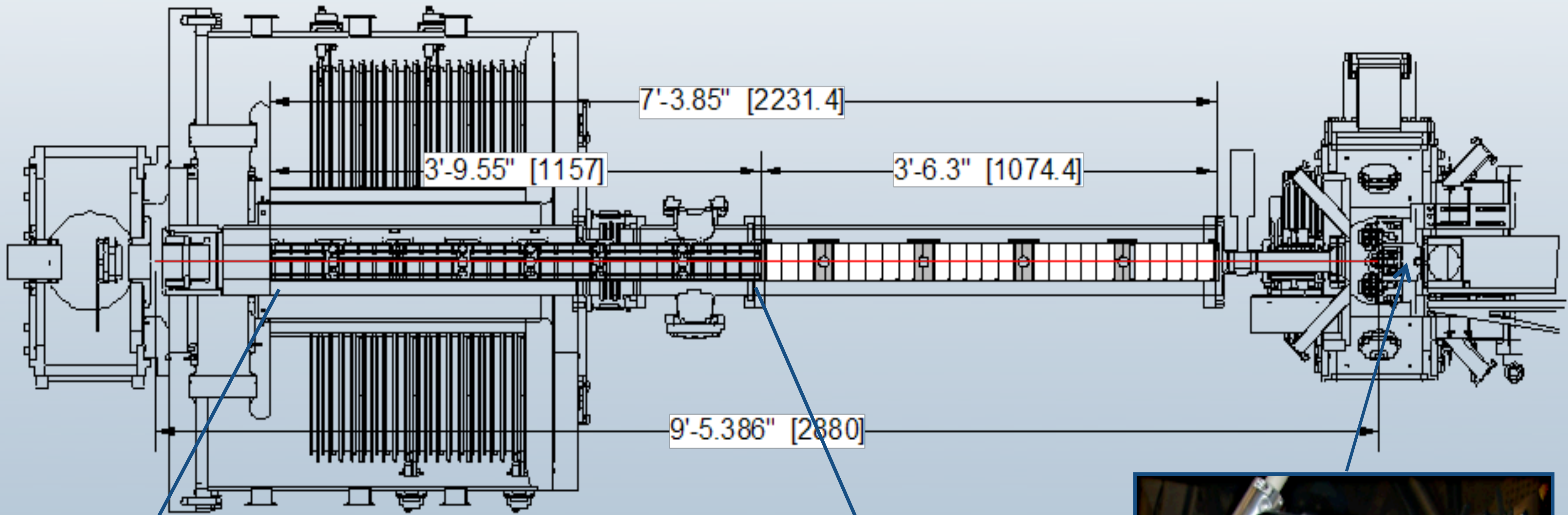
12-cell NDCX-II baseline layout

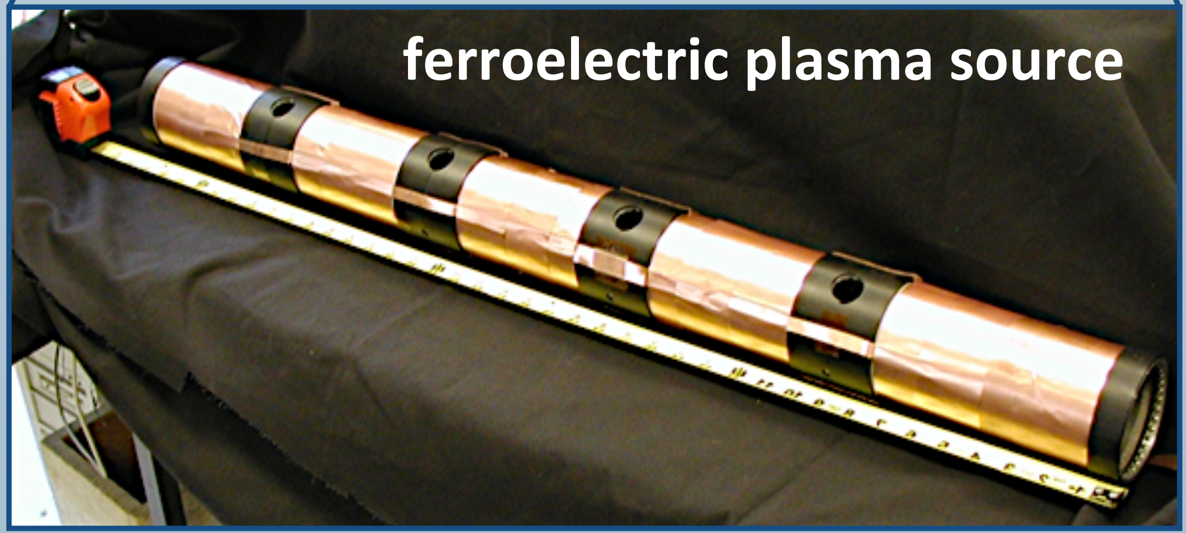


12-cell NDCX-II baseline layout



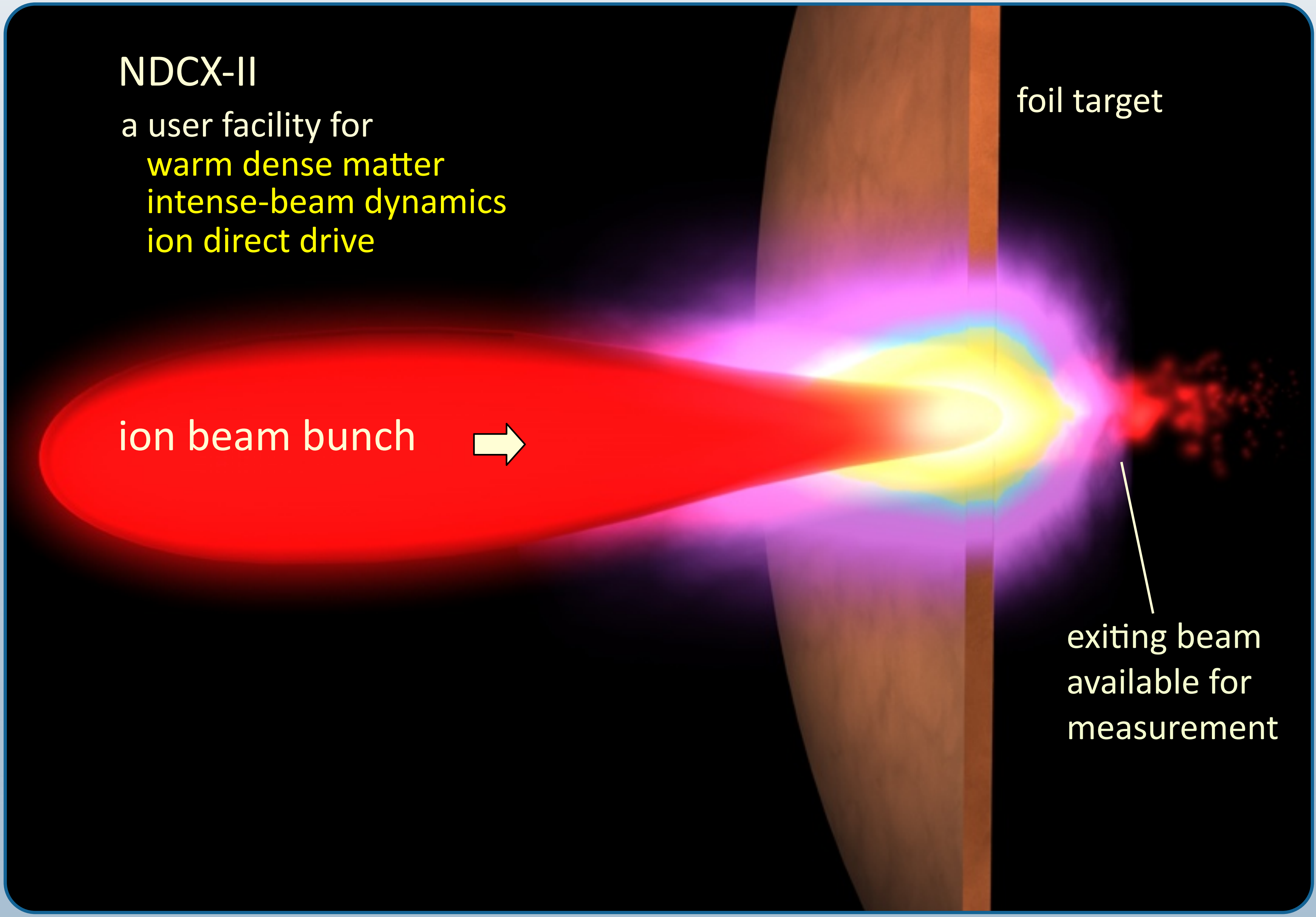
NDCX-II plasma sources will be based on NDCX-I design





developed by E P Gilson at PPPL

NDCX-II will enable WDM experiments near the boiling point of many metals

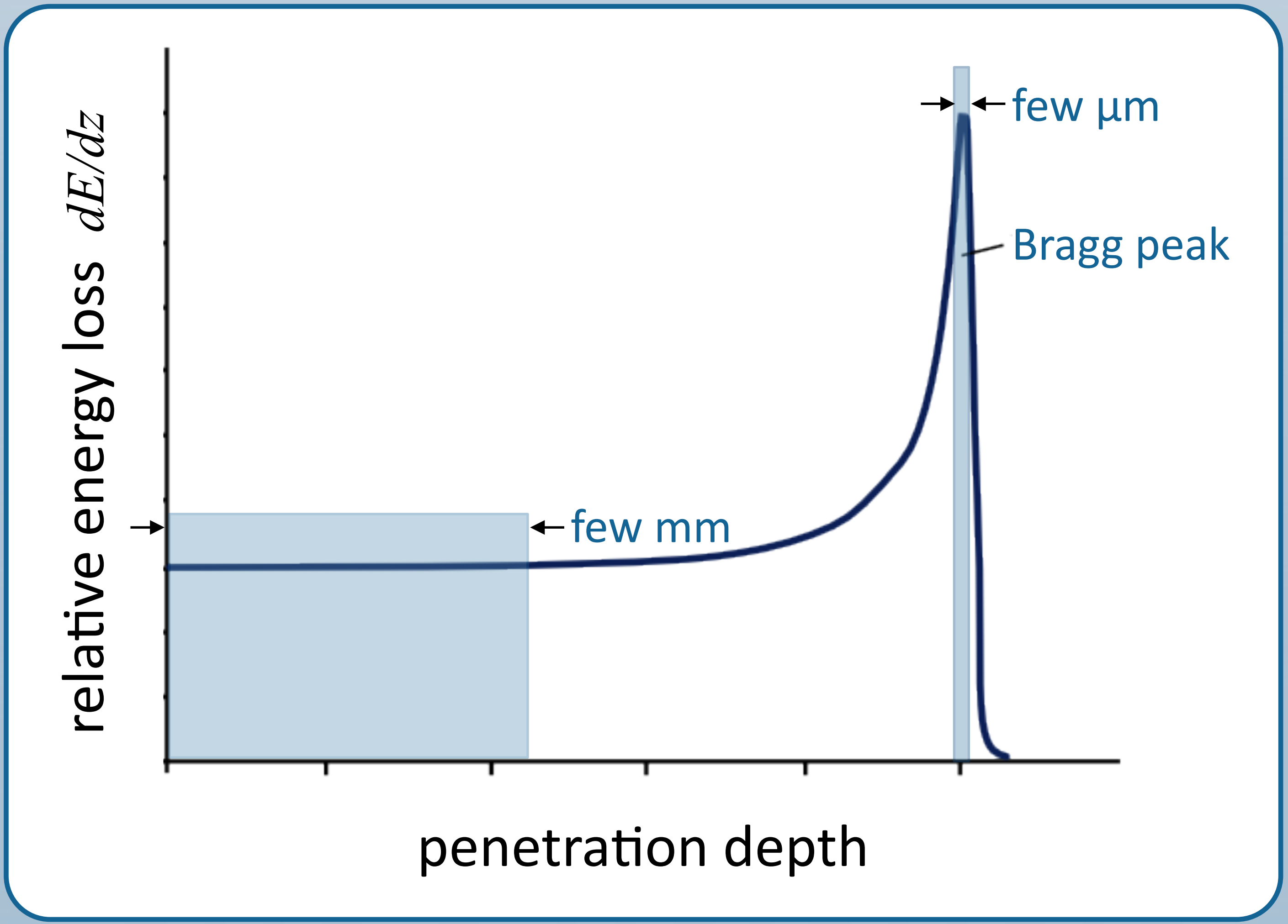


Why use ions to create high energy density?

ion beams are complementary to laser heating

features

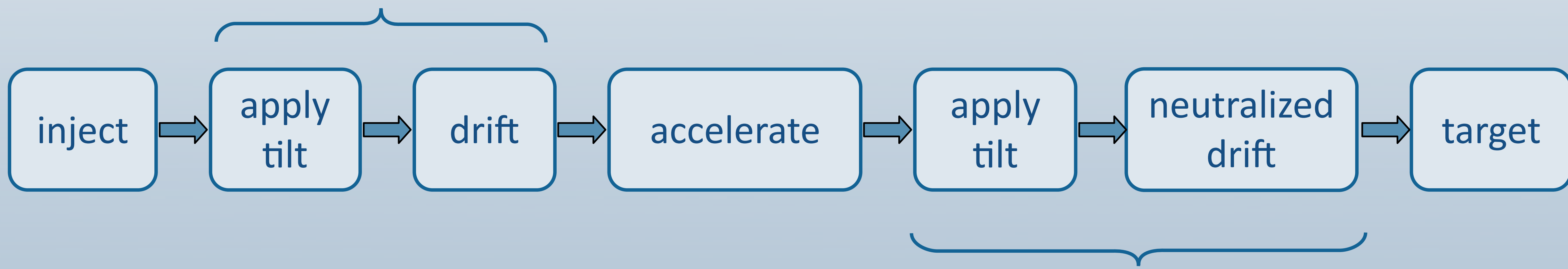
- classical energy deposition without x-rays and electron preheat
- volume deposition rather than surface heating → large heated volume
- possibility of uniform deposition to a few percent
- precisely controlled beam parameters
- high repetition rate → high data rate



Drift-compression is used twice in NDCX-II

initial non-neutral drift-compression for

- **optimum use of induction-core Volt-seconds**
- **early use of 70-ns 250-kV Blumlein power supplies from ATA**



final neutralized drift-compression to the target

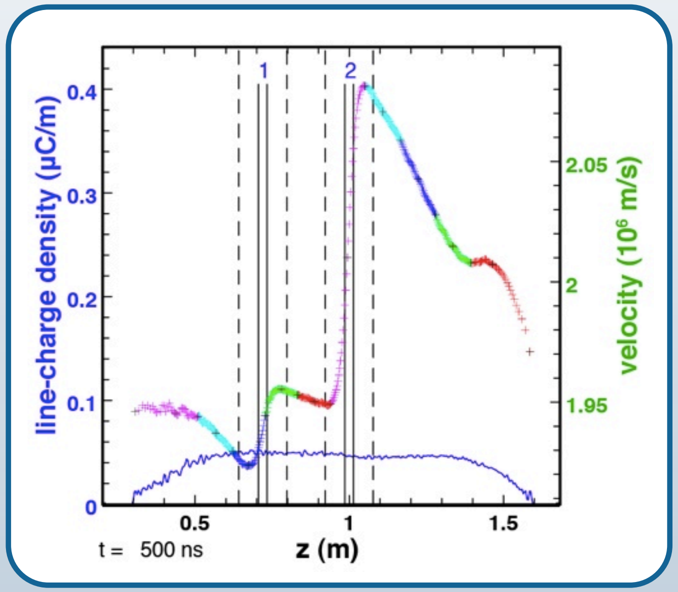
- **plasma electrons move to cancel the beam electric field**
- **requires $n_{\text{plasma}} > n_{\text{beam}}$ for this to work well**

see A. Friedman, *et al.*, *Phys. Plasmas* **17**, 056704 (2010)

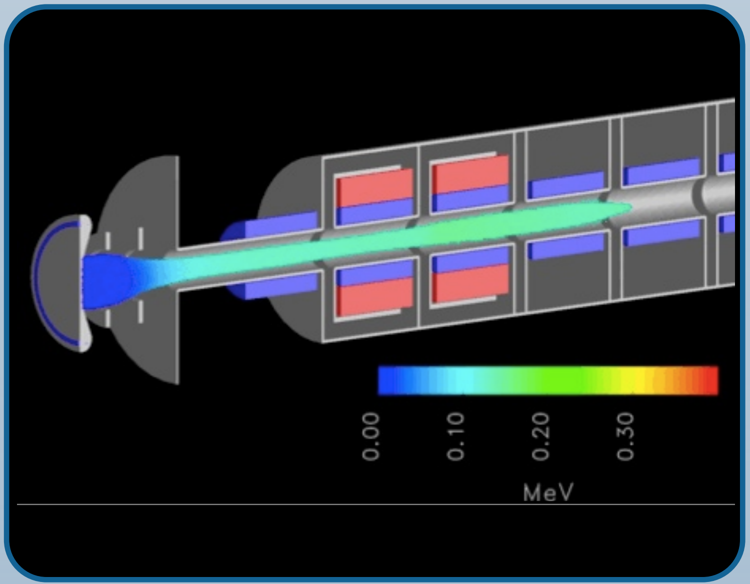
How do you develop a NDCX-II physics design?

lots and lots of simulation

- **ASP** is a new, fast 1-D (z) particle-in-cell code to develop acceleration schedules
  - 1-D Poisson solver with an approximate transverse derivative
  - realistic z profile on acceleration-gap fields
  - many optimization options

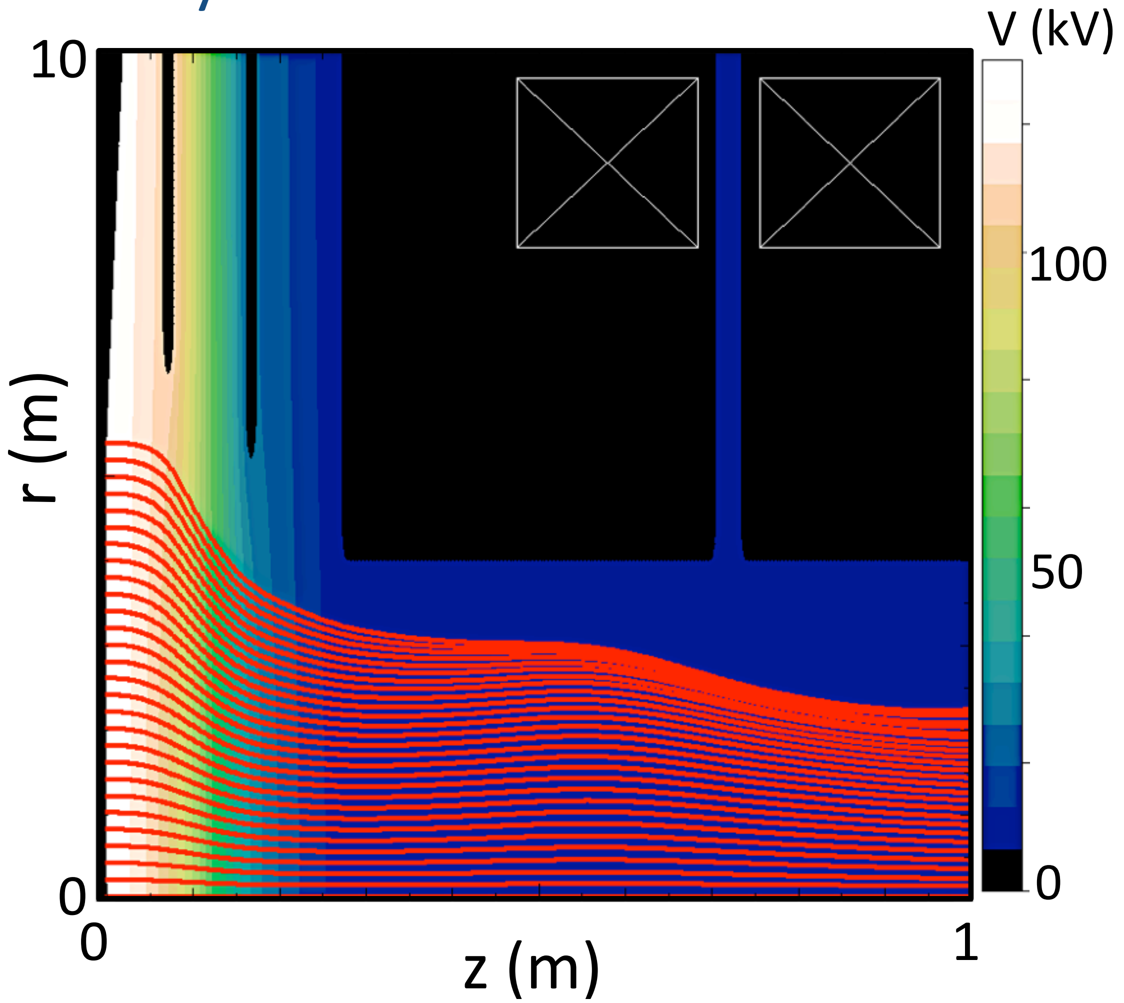


- **Warp** is our full-physics simulation code
  - 1, 2, and 3-D ES and EM field solvers
  - first-principles and approximate models of lattice elements
  - space-charge-limited and current-limited injection
  - cut-cell boundaries for internal conductors in ES solver
  - Adaptive Mesh Refinement (AMR) in ES and EM field solvers
  - large Δt algorithms (implicit electrostatic, large $\omega_c\Delta t$)
  - emission, ionization, secondaries, Coulomb collisions...
  - parallel processing with 1, 2 and 3-D domain decomposition
  - and loads more...



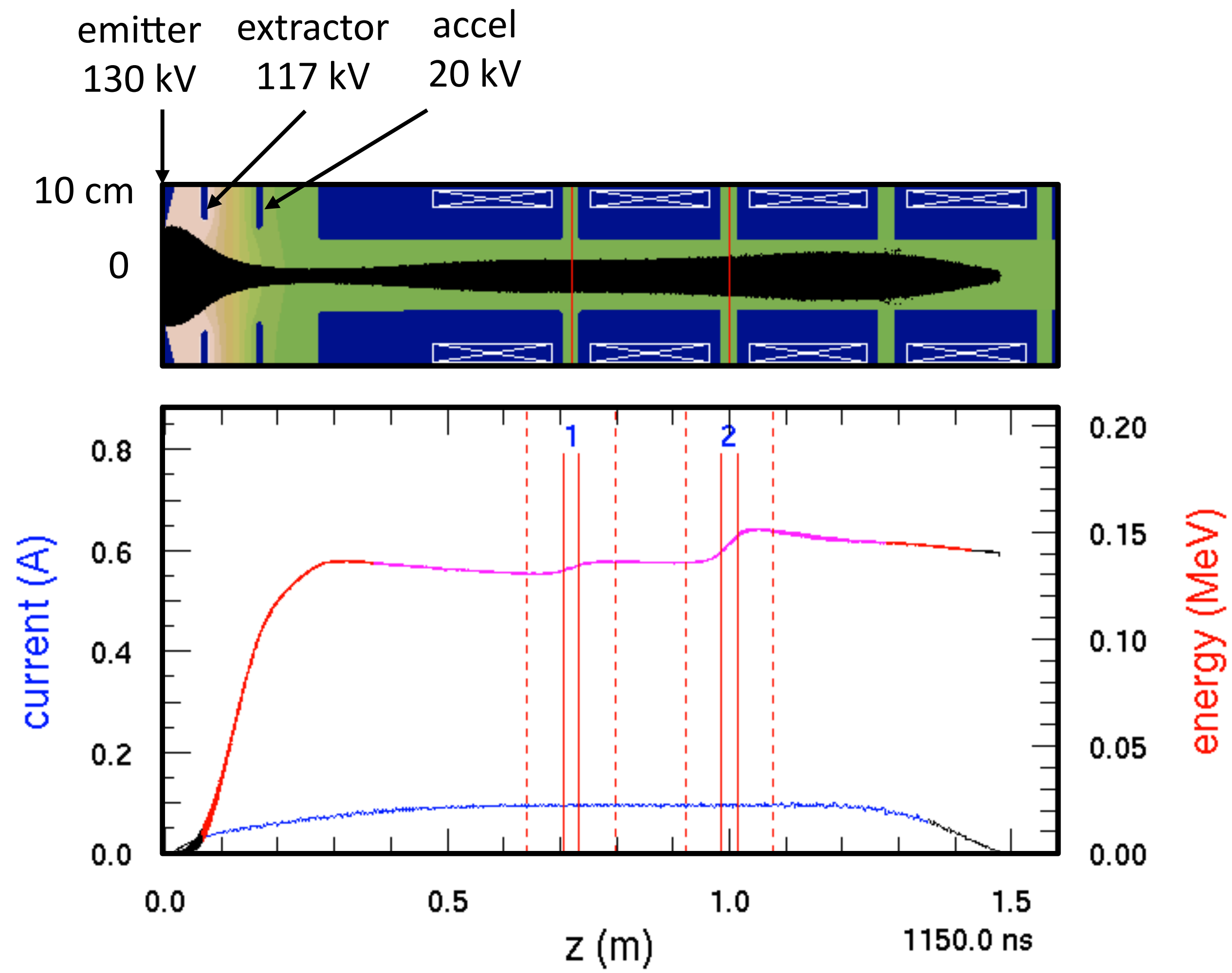
How do you develop a NDCX-II physics design?

first, use Warp steady-flow "gun" mode to design the injector for a nearly laminar flow



1 mA/cm² Li⁺ ion source

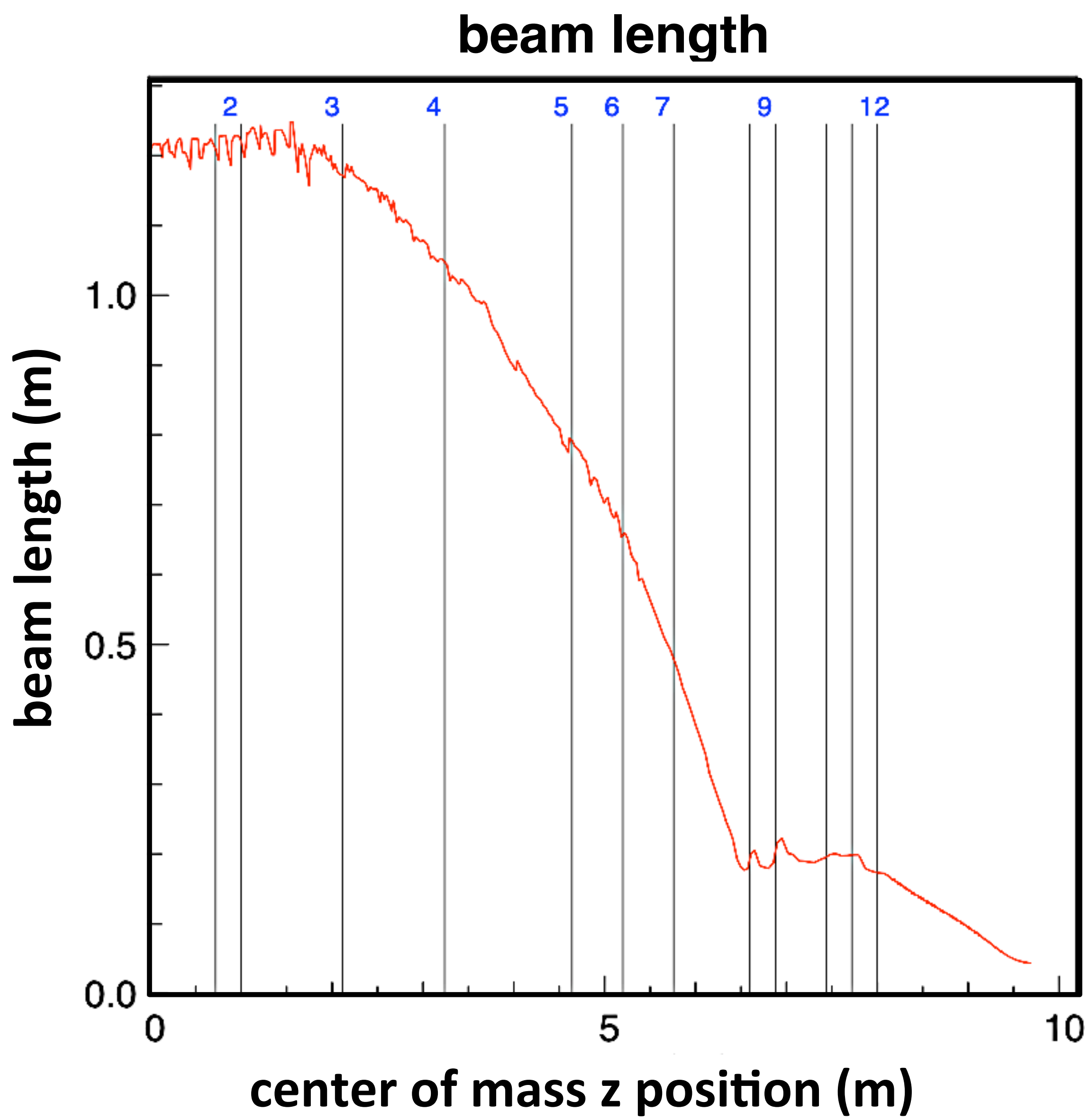
second, carry out a time-dependent *r-z* simulation from the source with Warp

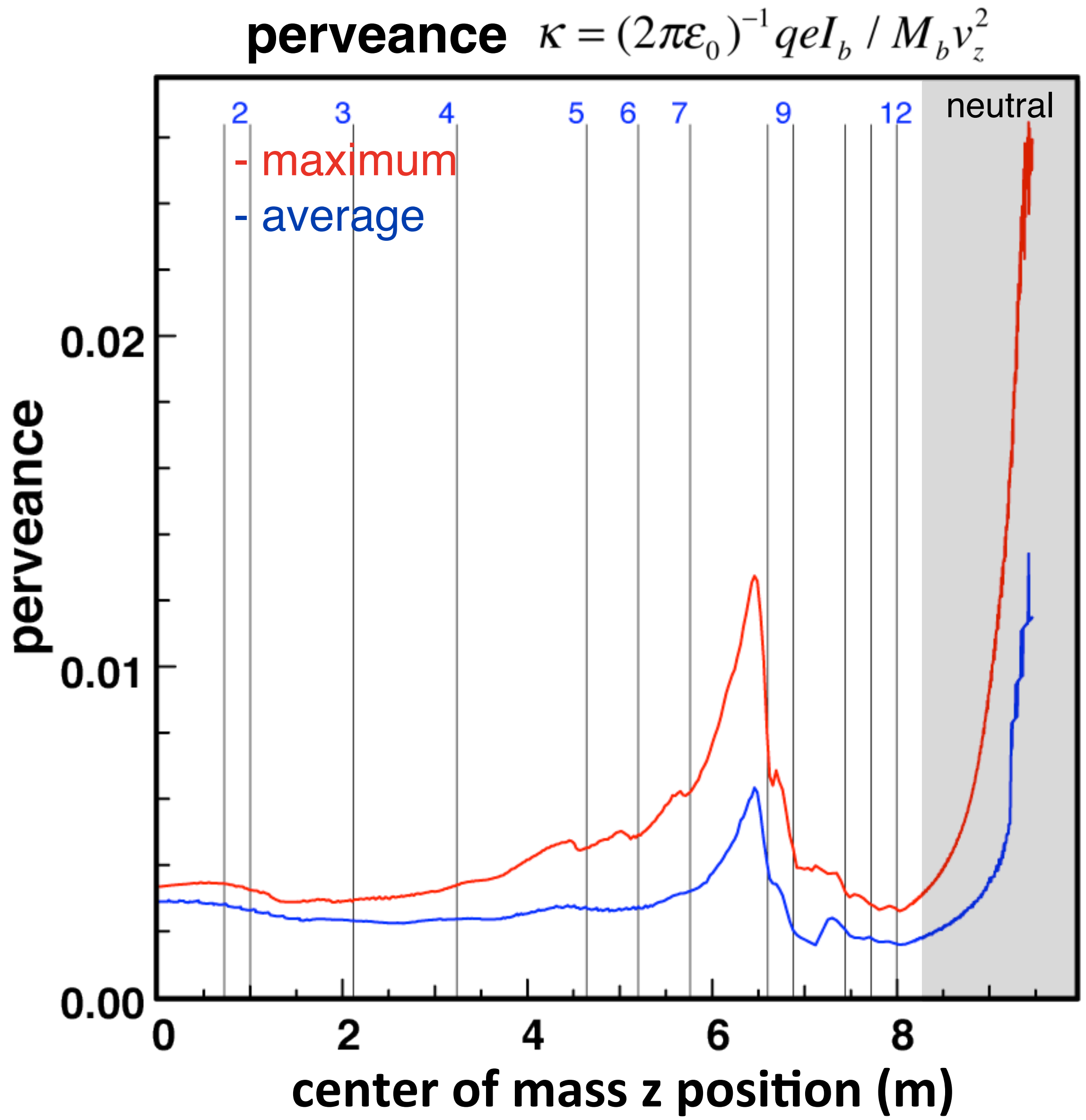


40g-12

How do you develop a NDCX-II physics design?

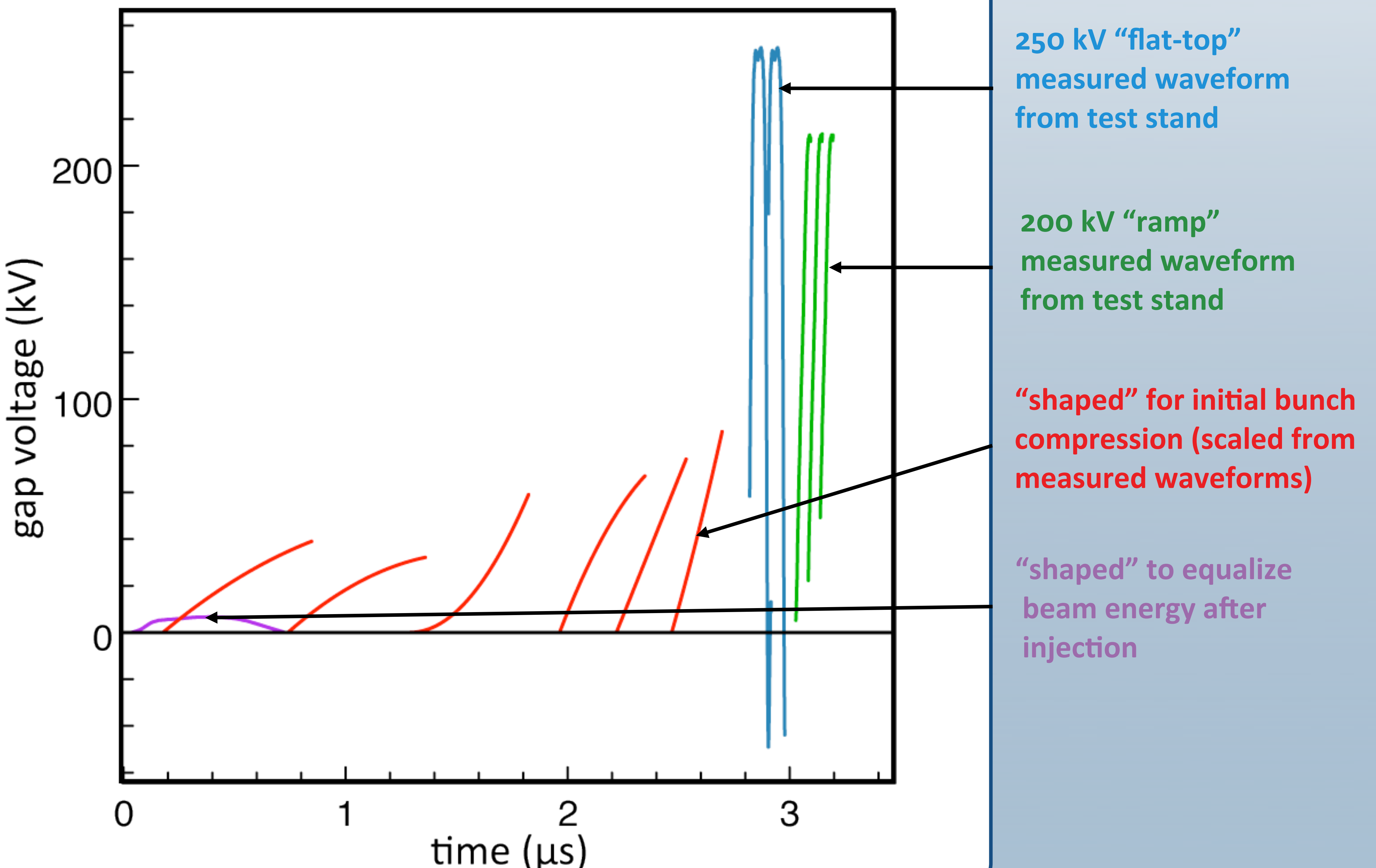
third, iterate with ASP to find an acceleration schedule that delivers a beam with an acceptable final phase-space distribution





How do you develop a NDCX-II physics design?

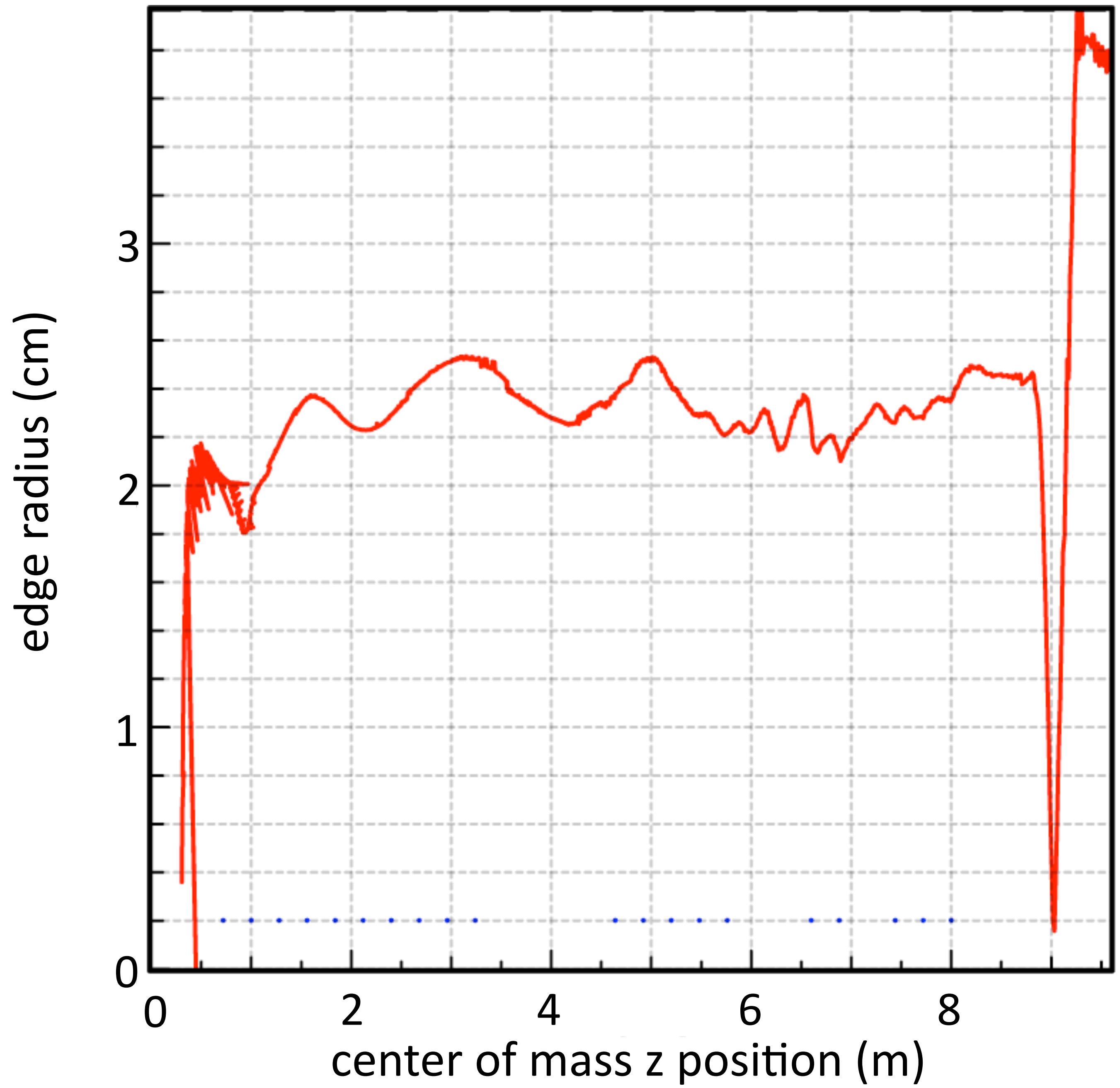
fourth, pass the waveforms back to Warp and verify with time-dependent *r*-*z* simulation



40g.002-12

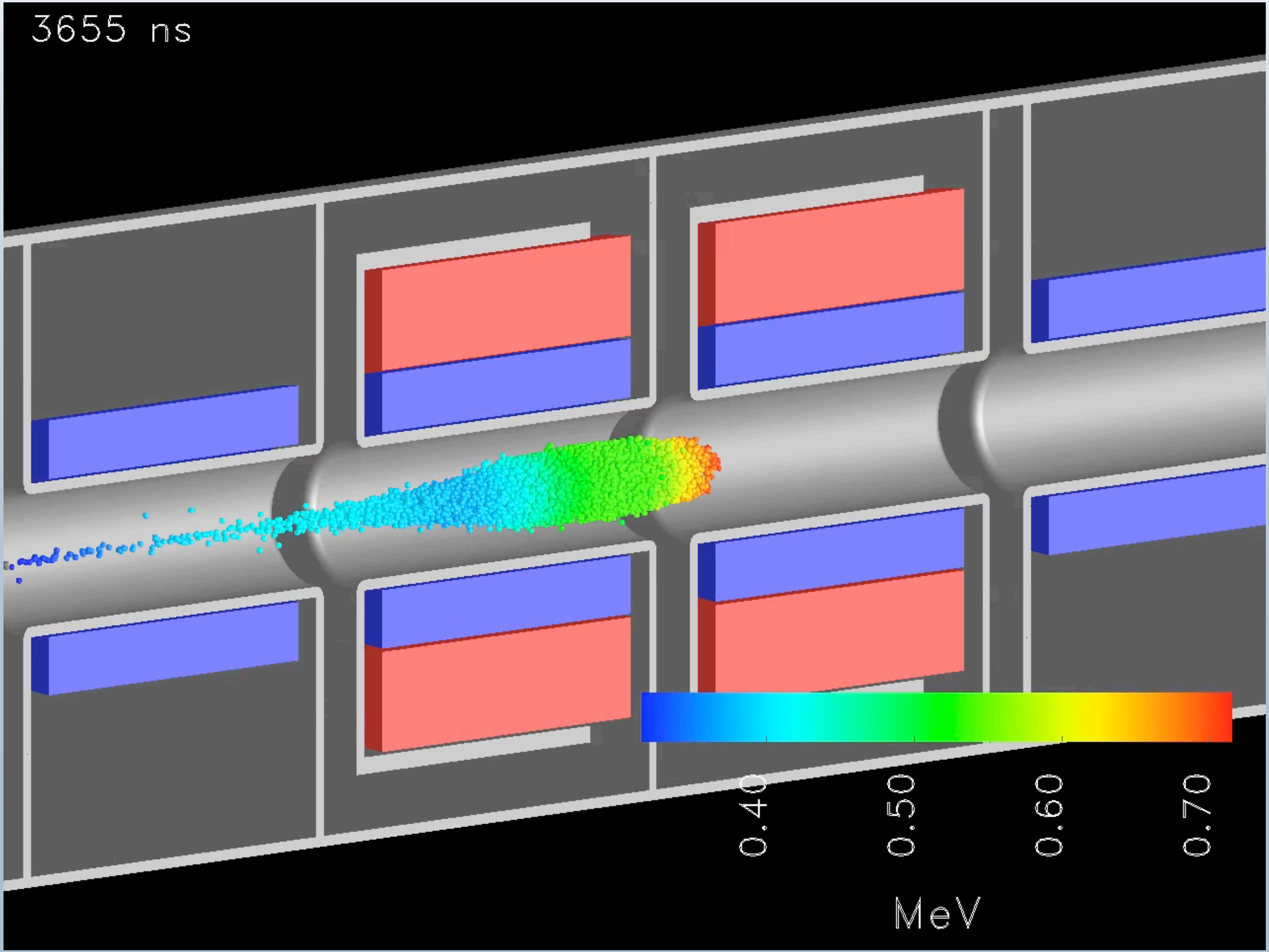
How do you develop a NDCX-II physics design?

fifth, adjust transverse focusing to maintain nearly constant radius



40g.002-12

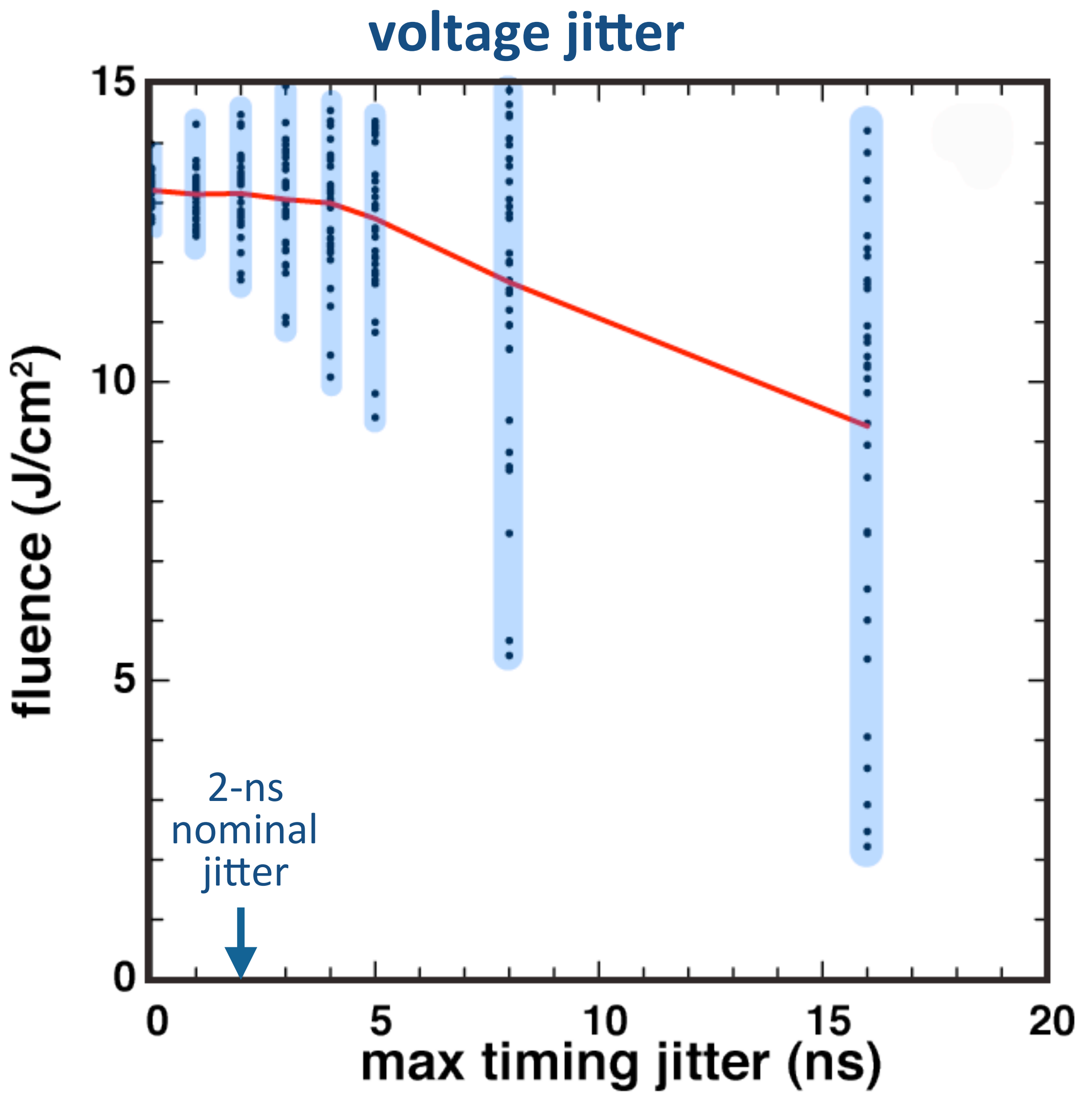
3-D Warp run of 12-cell baseline case with perfectly aligned solenoids



40ga24-12 simulation and movie from D P Grote

How do you develop a NDCX-II physics design?

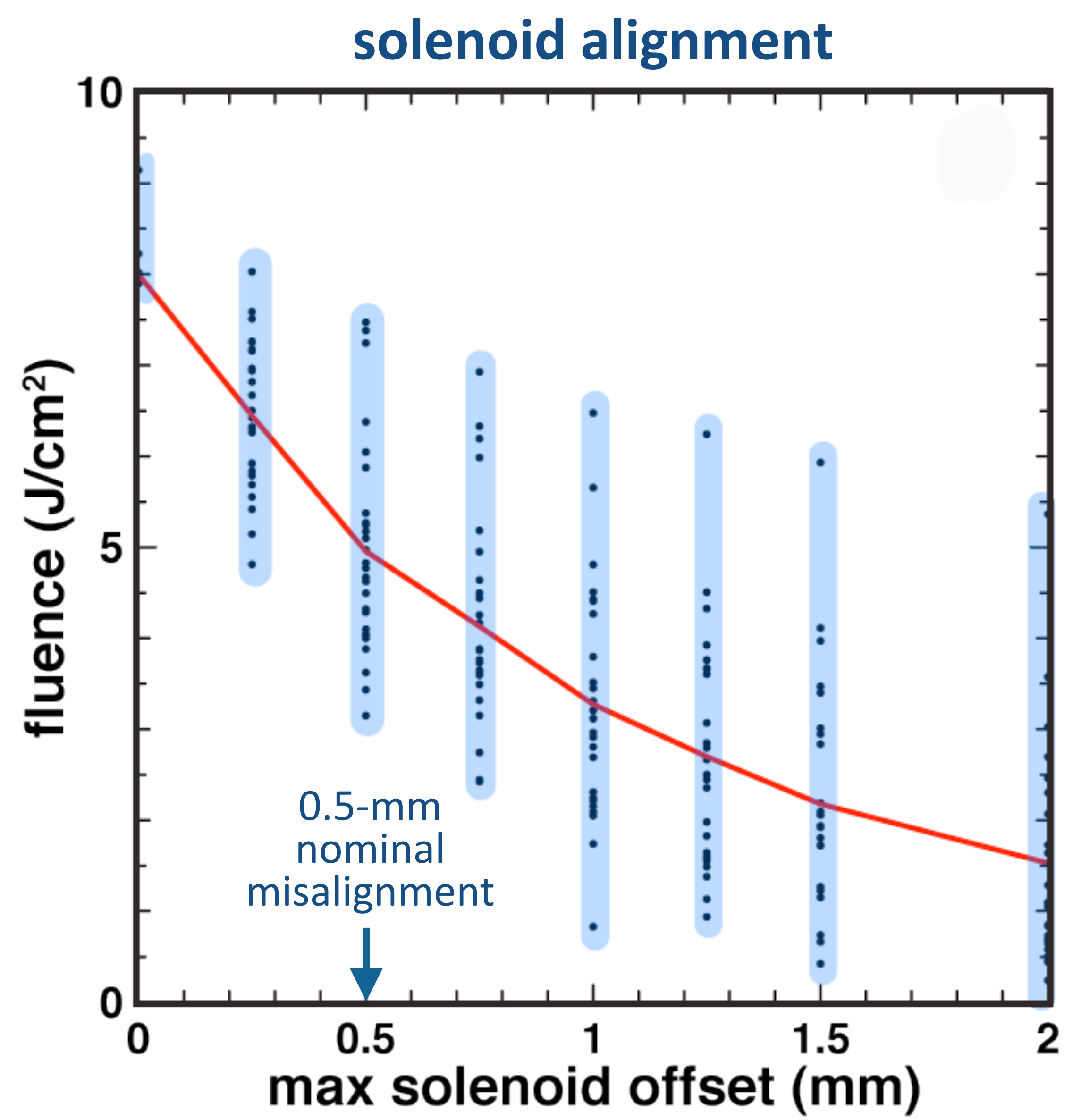
sixth, test sensitivity to random timing error in acceleration waveforms



40g-12 with random timing shifts in acceleration voltage pulses

How do you develop a NDCX-II physics design?

seventh, test sensitivity to random solenoid misalignments

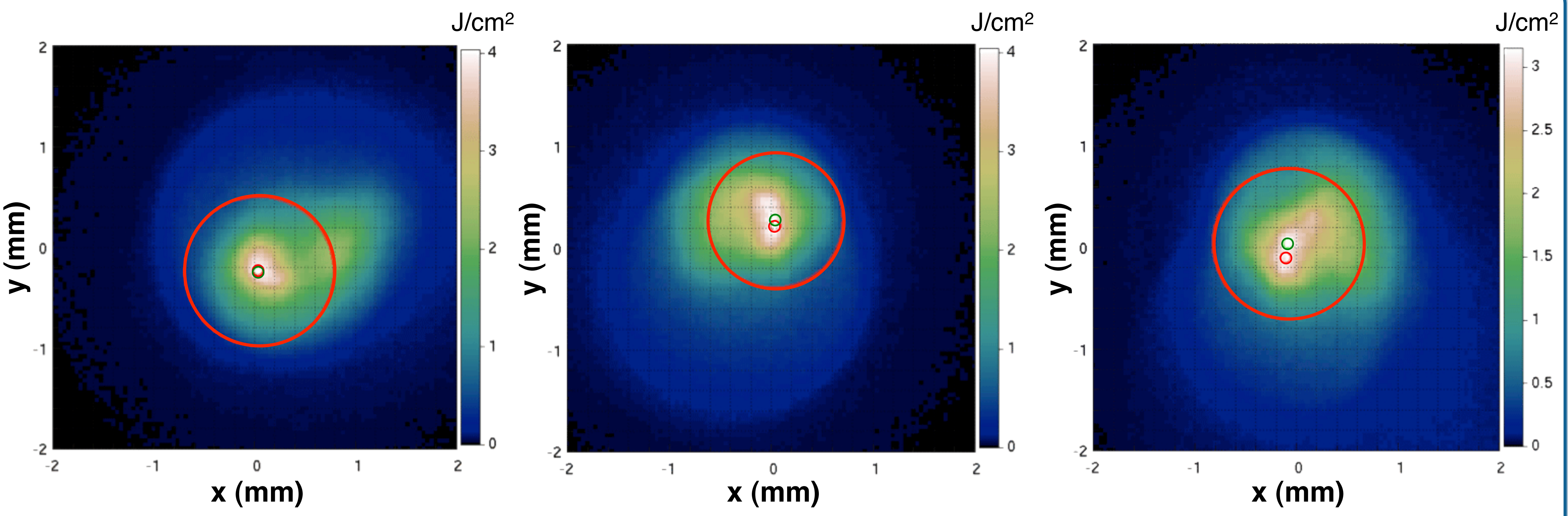


40g-12 with random offsets to both ends of each solenoid

Warp runs illustrate effects of solenoid alignment errors

plots show beam deposition for three ensembles of solenoid offsets

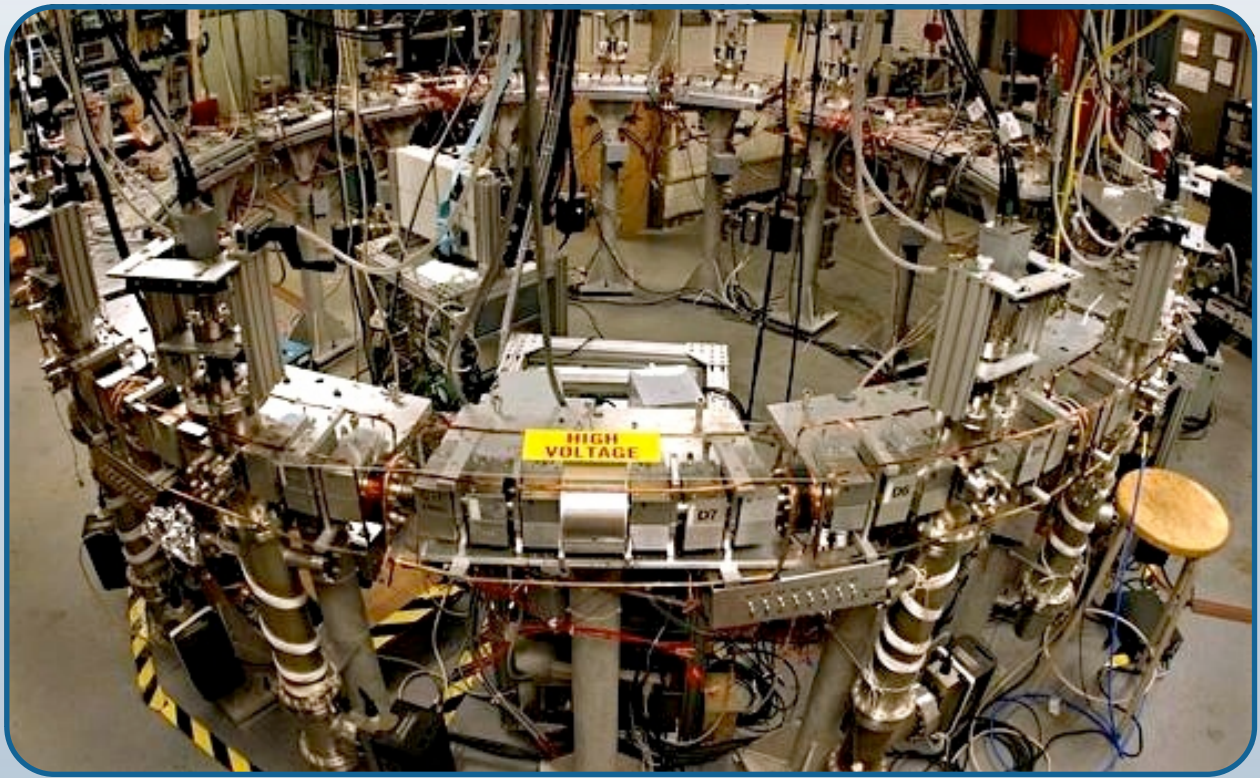
- maximum offset for each case is 0.5 mm
- red circles include half of deposited energy
- smaller circles indicate hot spots



ASP runs show steering can stabilize spot location

see Y-J Chen, *et al.*, *Nucl. Inst. Meth. in Phys. Res. A* **292**, 455 (1990)

Small-scale experiments are studying long-path transport physics

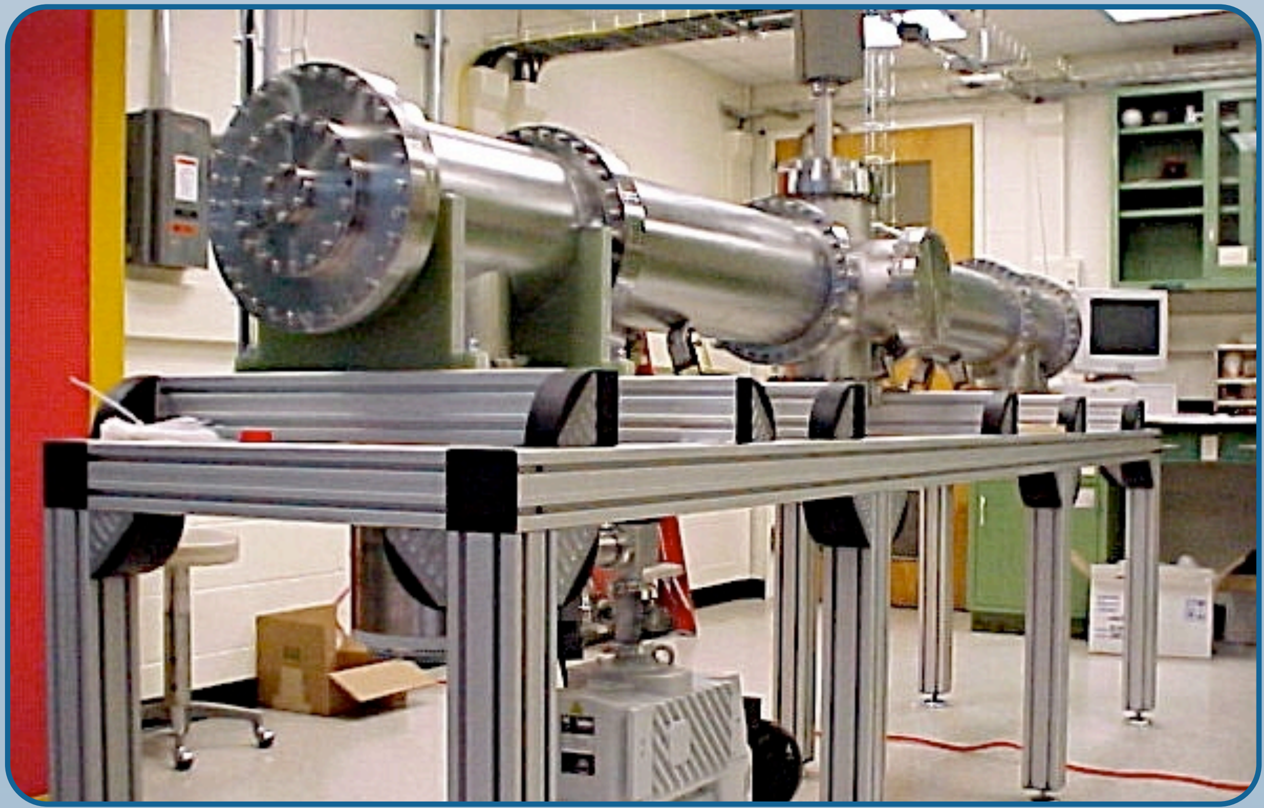


University of Maryland Electron Ring (UMER)

- ring under construction since 1997
- completed in 2008
- low-energy electrons model intense ion beams
- dimensionless space-charge intensity similar to HIF driver
- beam has successfully completed 100s of laps

Paul Trap Simulator Experiment (PTSX)

- operating at PPPL since 2002
- oscillating electric quadrupoles confine ions
- equivalent to 1000s of lattice periods



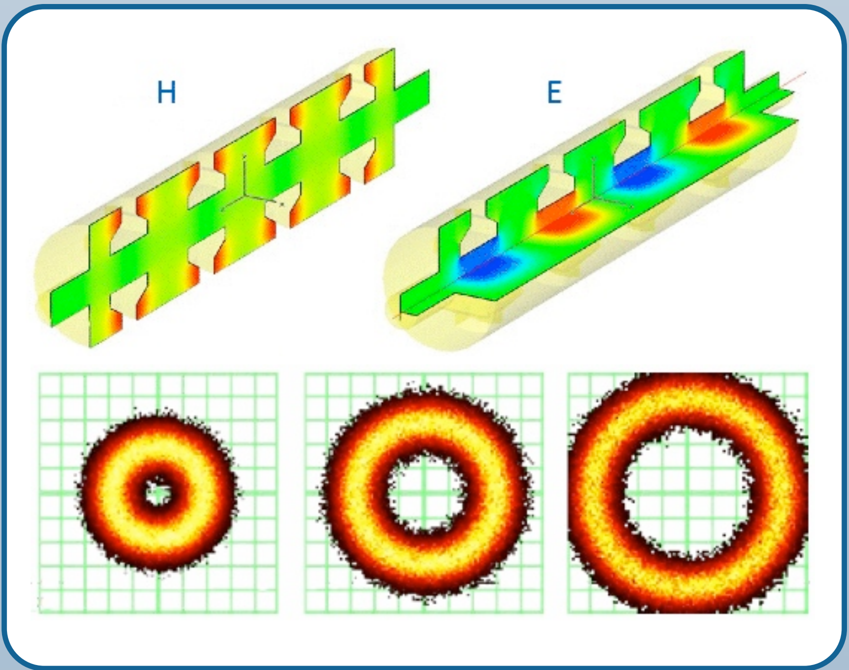
What are other countries doing?

Germany - GSI

- FAIR (Facility for Antiproton and Ion Research) is being built
  - major upgrade of current and energy for existing accelerator complex
  - 5×10^{11} ions at 150 MeV/u in a 50-100 ns pulse
- HEDgHOB program will use FAIR to study high-energy-density physics
- LAPLAS (LAboratory PLanetary Science) will FAIR to study physics of Jupiter-like planets

Russia - ITEP

- TWAC (TeraWatt ACcumlator) is complete
- multiple rings accelerate ions to 200 GeV/ion
- laser ion source for high-charge-state Al, Fe, and Ag ions
- rf “wobbler” developed to produce circular focal spots
  - improves the deposition symmetry
  - could allow use of fewer beams



Japan and China

- numerical work on beam transport, focusing, and target physics
- Paul Trap research at Hiroshima University

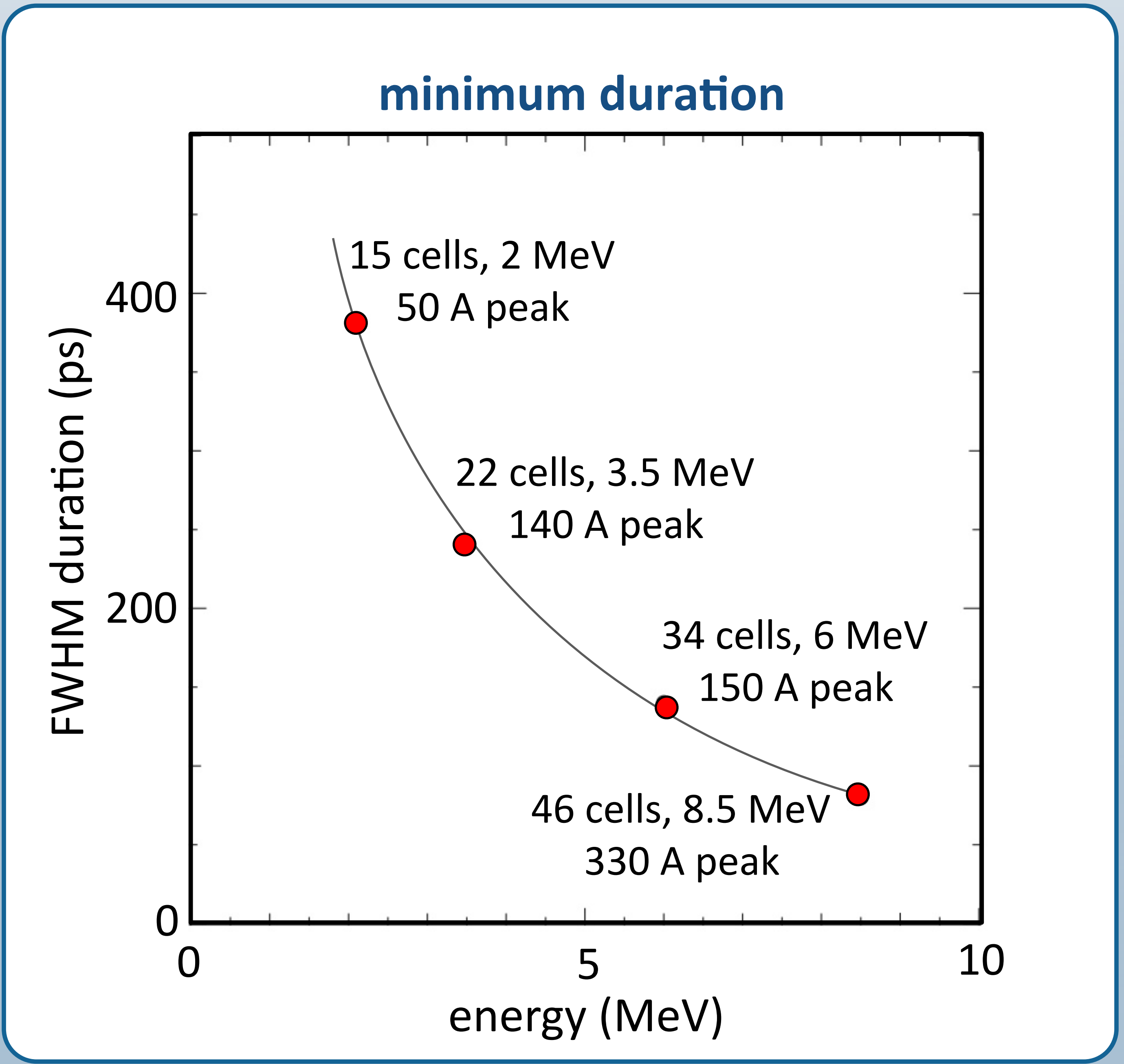
Outline

- motivation
- a fusion primer
- essentials of heavy-ion fusion
- past and present HIF research
- **future research directions**

Upgrades can significantly enhance NDCX-II capabilities

adding cells to NDCX-II will enable investigation of short ion pulses

- short pulses are needed for direct-drive shock ignition
- 50 ATA cells are available



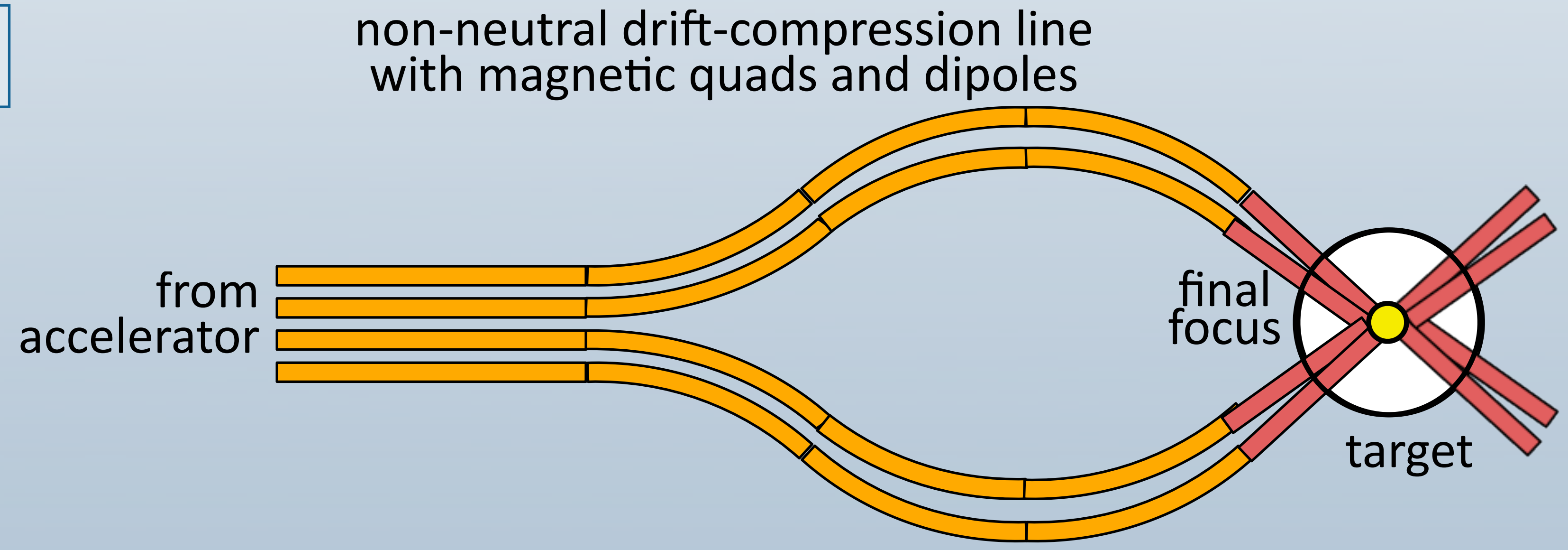
Warp simulations from D P Grote

NDCX-II experiments can model driver-like final transport

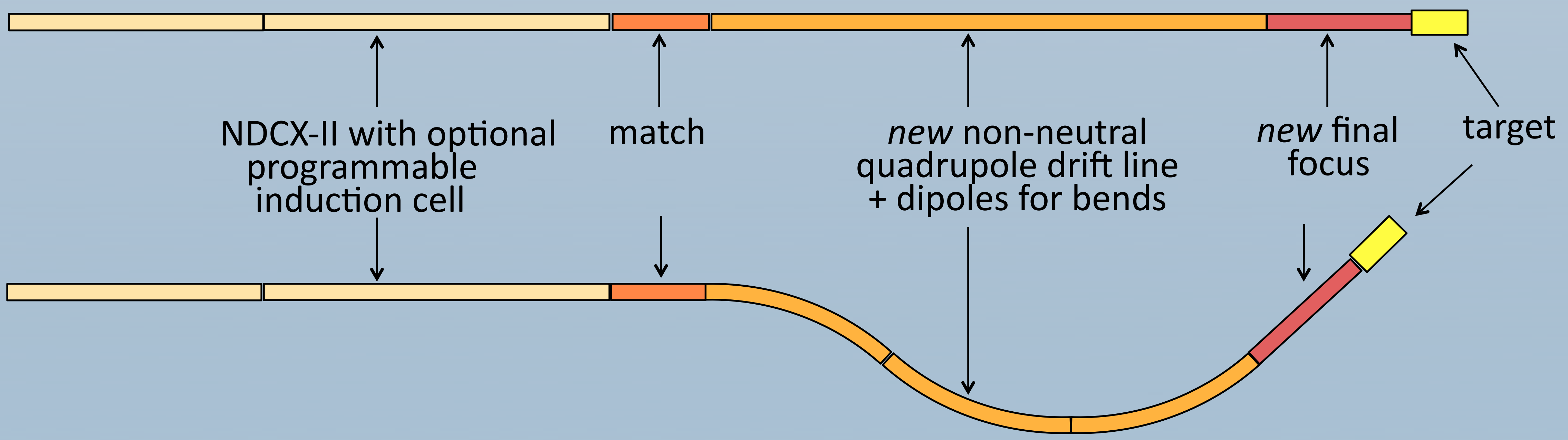
unneutralized driver beams approach target in curving drift-compression lines

- **they pass through final-focusing magnets as they reach stagnation**
- **neutralized transport is used after final focus**

in a driver...



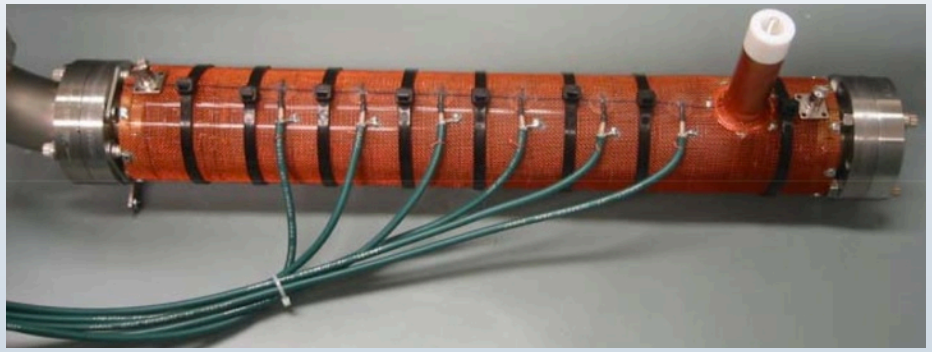
on NDCX-II, two configurations to test...

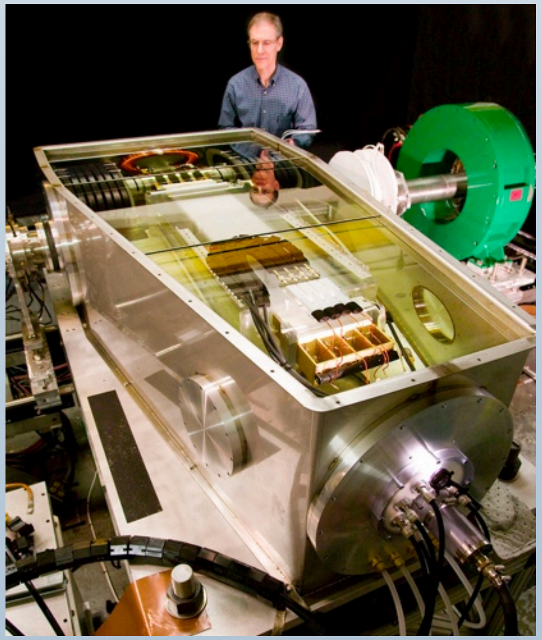


New ideas for improving HIF accelerators are being explored

pulse-line-induction accelerator (PLIA)

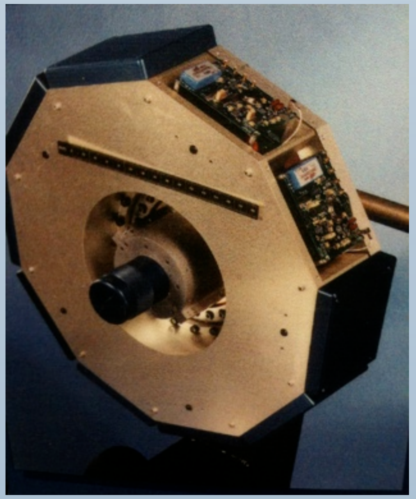
- helical slow-wave structure replaces cores
- gradients of 3-5 MeV/m are theoretically possible
- simplicity and low cost are attractive





dielectric-wall accelerator promises a higher gradient

- uses layered dielectrics to permit gradient up to 30 MeV/m
- electron version has been built
- proton model may find therapeutic use



solid-state pulsers for pulse shaping

- programmable waveforms
- reduced resistive losses

induction accelerators with higher charge state

a LBNL workshop on advanced HIF accelerators is planned for 23-26 May 2011
see **www.regonline.com/HIF11** to register

Take-aways

fusion promises unlimited future energy if a competitive reactor can be developed

inertial fusion has advantages over magnetic confinement

- separation of the driver from the fusion reaction → safety, ease of maintenance
- proof of principle imminent at NIF
- modularity can reduce driver cost
- many, many design options

heavy-ion inertial fusion has advantages over laser drivers

- higher efficiency
- higher repetition rate
- possibility of liquid-protected walls
- robust final optics

much of the physics of HIF drivers has been tested in scaled experiments

- other aspects can be tested on NDCX-II
- full-scale integrated demonstration of HIF driver is still needed

HIF research is entering an exciting period

Fusion...

...still the energy of the future after sixty years