Accelerators to make Electricity– An Overview of Heavy-Ion-Driven Fusion

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Talk Outline

Fusion for Commercial Energy Production
  – Advantages of fusion
  – How do you do it?
  – Why use an accelerator?
  – What does the system look like?

What Physics Do We Do?
  – How and why we use computers
  – An example

Where are we, and where are we going?
  – Status & plans
A small metal or plastic capsule (about the size of a pea) contains fusion fuel. Radiation (light, X-rays, ions, or electrons) rapidly heats the surface of the fuel capsule. Fuel is compressed (imploded) by rocket-like blowoff (ablation) of the surface material. With the final driver pulse, the fuel core reaches about 1000 times liquid density and ignites at 100,000,000 degrees. Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.
Fusion is an attractive energy source

- Plentiful fuel
- No radioactive waste from reaction
- No chain reaction
- No CO\textsubscript{2} & no air pollution
- Relatively short half-life for components

Deuterium–Tritium Fusion Reaction

\begin{align*}
\text{Deuterium} & \rightarrow \text{Tritium} \\
\text{4 MeV} & \rightarrow \text{14 MeV} \\
\text{Alpha Particle} & \rightarrow \text{Neutron} \\
\text{He}^4 & \rightarrow \\
\text{ENERGY MULTIPLICATION} & \text{About 450:1}
\end{align*}
Heavy Ion Fusion Uses “Indirect Drive”

Ion Beams $\Rightarrow$ x-rays

X-rays symmetrize in hohlraum

Requires $\sim 500$ Terawatts (!!) (3 - 7 MJ in $\sim 10$ ns)

Ion Range $\Rightarrow$ 1-10 GeV
Heavy Ion Accelerators are a Good Choice for a Fusion Driver

HEP / NP accelerators already have:

- Long life
- High pulse repetition rates
- High electrical efficiency (~ 30%)
- Present systems comparable to requirements in:
  - complexity
  - cost
  - ion energy
So why is it hard?

New Physics Regime for Accelerators

Target Requirements:

500 Terawatts
1-10 GeV

\[
\downarrow
\]

For \( A \sim 200 \) →

\(~ 10^{16} \) ions
\(~ 100 \) beams

Beam particles interact-- this dominates the physics.
Schematic of a Heavy Ion Fusion Driver

- **Multiple Beam Ion Source & Injector**
  - ~2-3 MeV
  - ~1 A/beam
  - ~20 µs

- **Acceleration with quadrupole focusing**
  - ~3 GeV
  - ~200 A/beam
  - ~200 ns

- **Longitudinal compression**
  - ~3 GeV
  - ~4000 A/beam
  - ~10 ns

- **Target Chamber Transport**

- **Focusing**

- **Bending**

A few kilometers
An Artist’s Conception of a Heavy Ion Fusion Power Plant
The First Wall is Protected by Neutron-thick Molten Salt (FLiBe)

Crossing jets form beam ports

Vortices shield beamline penetrations

Oscillating jets form main pocket

(One Half Cut Away)
The Physics is almost all classical-- but it isn’t simple!

\[ \frac{v}{c} \leq 0.2 \implies \text{Maxwell + Newton is enough} \]

But:

Particle interactions \implies Nonlinear forces

Nonlinear external forces:
- focusing field errors
- image forces from beam pipe wall
- magnet fringe field forces
- electrons
- interactions with other beams

\implies Beam Heating, Waves, Instabilities
Particle-in-Cell Simulation Codes are Needed for Self-Consistent Calculations

For ~ 60,000 - 1,000,000 particles:

**Calculate forces on each particle**

\[
\vec{F} = q(\vec{E}_{\text{quad}} + \vec{E}_{\text{particles}})
\]

**Move Particles**

\[
\Delta \vec{x} = \vec{v}\Delta t
\]

**Calculate new velocities after timestep \( \Delta t \)**

\[
\begin{align*}
\vec{F} &= ma \\
\frac{\Delta \vec{v}}{\Delta t} &= \frac{\vec{F}}{m}
\end{align*}
\]

**PIC Algorithm**

64 processors, 10 hours \( \Rightarrow \)

\( x \sim 300 \)
Neutralization competes with stripping in the target chamber
3-D BPIC simulation of beam propagating through Flibe

beam ions
Flibe ions
electrons

at 27.6 ns; 10 GeV,
210 AMU, 3.125 kA,
$5 \times 10^{13}$/cm$^3$ BeF$_2$
Reduction of spot size using plasma plug and volume plasma

- Non-neutralized: FWHM=6.6 mm
- Plasma plug: FWHM=2.2 mm
- Plasma plug & Volume plasma: FWHM=1.5 mm

6 mA
Plasma density = $2 \times 10^{11} / \text{cm}^3$

95% neutralized
Accomplishments of Past HIF Experiments

- Ion Sources & Injector
- Acceleration with electric focusing
- Acceleration with magnetic focusing
- Longitudinal compression
- Bending
- Chamber Transport
- Scaled Final Focus

Single Beam Transport Experiment

Multiple Beam Expt
Current Experiments use Driver-Scale Beams

Ion Sources & Injector  Acceleration with electric focusing  Acceleration with magnetic focusing

Chamber Transport  Longitudinal compression  Bending

focusing
The IBX mission is to demonstrate integrated source-to-focus physics

- Injector
- Accelerator: 40 m (10 MeV)
- Drift: 15 m
- Compression: 250 ns → 25 ns
- Ion: K⁺ (1 beamline)
- Neutralization
- Final Focus
- 7 m
- 25 ns
- Total half-lattice periods: 148
- Total length: 64 m

$60 - 70 M TEC over 4 yrs + $10 M R&D for 6 MeV
After IBX: The Integrated Research Experiment (IRE) will test all components & physics for an ETF

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

**Target physics:**
- Rayleigh-Taylor instability
- dE/dx

**Injector Source**

**Target Chamber**
Heavy Ion Fusion -- Peaceful Power for the Poor