Application of Plasma Phenomena

Lecture 13

2017/5/17
There are alternative

http://www.nextbigfuture.com/2016/05/nuclear-fusion-comany-tri-alpha-energy.html
Field reverse configuration is used in Tri-alpha energy

LANL: design, test
AFRL: Shiva-FRC

*Magneto-Inertial Fusion & Magnetized HED Physics by Bruno S. Bauer, UNR & Magneto-Inertial Fusion Community
**https://en.wikipedia.org/wiki/Field-reversed_configuration
Field reverse configuration is used in Tri-alpha energy
General fusion is a design ready to be migrated to a power plant

https://en.wikipedia.org/wiki/General_Fusion
The performance of a fusion plasma has doubled every 1.8 years like the Moore’s law.
We are really closed!
Outline

• Introduction to nuclear fusion
• Magnetic confinement fusion (MCF)
  – Tokamak
  – Stellarator
• Inertial confinement fusion (ICF)
  – Indirection drive ICF
  – Direct drive ICF
• Innovation idea – MCF + ICF
• Pulsed-power system at NCKU
High energy density plasma is the regime that $p > 1$ Mbar

http://fsc.lle.rochester.edu/hedp.php
A pulsed-power system is much cheaper than a laser facility

<table>
<thead>
<tr>
<th>Facility</th>
<th>Budgets (NTD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OMEGA at University of Rochester</td>
<td>~1.8 billion</td>
</tr>
<tr>
<td>National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL)</td>
<td>~100 billion</td>
</tr>
<tr>
<td>Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory in Berkeley (LBNL)</td>
<td>~3 billion</td>
</tr>
<tr>
<td>Taiwan Photon Source (TPS) at National Synchrotron Radiation Research Center (NSRRC)</td>
<td>~7 billion</td>
</tr>
<tr>
<td>Pulsed-power system at ISAPS, NCKU</td>
<td>~0.002 billion (&lt;0.1 %)!!!</td>
</tr>
</tbody>
</table>
A pulsed-power machine using Marx Generator is being built ISAPS, NCKU

- In a marx generator, capacitors are connected in parallel during charge period and in series during discharge to provide high voltage output.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak current</td>
<td>200 kA</td>
</tr>
<tr>
<td>Rise time</td>
<td>~500 ns</td>
</tr>
<tr>
<td>Total energy</td>
<td>9 kJ</td>
</tr>
<tr>
<td>Power</td>
<td>~10 GW</td>
</tr>
<tr>
<td>Capacitors</td>
<td>1 uF/each</td>
</tr>
<tr>
<td># of capacitor</td>
<td>20</td>
</tr>
<tr>
<td>Voltage</td>
<td>±30 kV</td>
</tr>
</tbody>
</table>
Different wire configurations can be used to generate plasma jets and hard x rays

- x pinch
- multi-wires x pinch
- wire array
- conical-wire array
- inverse-wire array
- radial-wire array
- radial foil
Spatial coherent hard x rays can be generated using x pinches for point-projection x-ray radiography

- x pinch
- The process of an exploded x pinch
- Point-projection x-ray radiography

We are expecting x-ray yields of couple keV, < 1ns, <10 um, ~5 J in total energy generated in our system.

Soft x rays for 3-D x-ray tomographic microscopy can be generated using gas-puff Z pinches.

- Line radiation in the range of 40-15 Å (310-830 eV) with a total energy of 10 J using CO₂ is expected.
- Soft x rays (~520 eV) from synchrotron radiation at Advanced Light Source (ALS) is used for 3-D x-ray tomographic microscopy.
- Single line emission in 41.8 / 32.8 nm is expected using Xenon or Krypton.

Plasma jet can be created for laboratory astrophysics and space science

- A conical-wire array can be used to generate a plasma jet where the flow speed is $\sim 200 \text{ km/s}$ with Mach number up to 20.
- The solar wind is a supersonic plasma flow with Mach number $\sim 5\text{-}10$ and the flow speed $\sim 400 \text{ km/s}$.

Hydrodynamic equations can be written in a dimensionless form

- Dimensional form:
  \[
  \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \, \mathbf{u}) = 0
  \]
  \[
  \rho \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla p
  \]
  \[
  \frac{\partial p}{\partial t} + \mathbf{u} \cdot \nabla p = -\gamma p \nabla \cdot \mathbf{u}
  \]

- Dimensionless form:
  \[
  \tilde{\frac{\partial \tilde{\rho}}{\partial \tilde{t}}} + \nabla \cdot (\tilde{\rho} \, \tilde{\mathbf{u}}) = 0
  \]
  \[
  \tilde{\rho} \left( \tilde{\frac{\partial \tilde{\mathbf{u}}}{\partial \tilde{t}}} + \tilde{\mathbf{u}} \cdot \nabla \tilde{\mathbf{u}} \right) = -\nabla \tilde{p}
  \]
  \[
  \tilde{\frac{\partial \tilde{p}}{\partial \tilde{t}}} + \tilde{\mathbf{u}} \cdot \nabla \tilde{p} = -\gamma \tilde{p} \nabla \cdot \tilde{\mathbf{u}}
  \]

Any two hydrodynamic systems involve identically in a scaled sense if \( f, g, h, \) and \( u^*(\rho^*/p^*)^{1/2} \) are the same.
Interactions between solar winds and planetary magnetic fields or unmagnetized planets will be studied.

- Electrically nonconductive planets
- Electrically conductive planets w/o B
- Electrically conductive planets w/ B

- Ex: moon
- Ex: mars or venus
- Ex: earth

Reconnection can be simulated experimentally using pulsed-power machine

* James L. Burch and James F. Drake, American Scientist 97, 392 (2009)
An Dense-Plasma-Focus (DPF) device is a pulsed-power device that can generate high-energy electrons and ions, x rays, and neutrons.

- A 6 kJ DPF device can generate up to 108 neutrons in each discharge and is a very attractive neutron source.
- It can be a table-top neutron source for Neutron capture therapy of cancer.
Neutral beam source

- Neutral beam injection for heating plasma in Tokamak
  - Jure Maglica, Seminar at University in Ljubljana
  - Ian G. Brown, The Physics and Technology of Ion Sources

- Electric propulsion (plasma thrusters)
  - D. M. Goebel and I. Katz, Fundamentals of Electric Propulsion: Ion and Hall Thrusters
Neutral beam source

• Neutral beam injection for heating plasma in Tokamak
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• Electric propulsion (plasma thrusters)
Hot plasma is confined by the magnetic field in magnetic confinement fusion
Neutral beam injector is one of the main heat mechanisms in MCF

\[ \eta_\perp \propto T^{-3/2} \]
Varies way of heating a MCF device

<table>
<thead>
<tr>
<th>System</th>
<th>Frequency/energy</th>
<th>Maximum power coupled to plasma</th>
<th>Overall system efficiency</th>
<th>Development/demonstration required</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECRF</td>
<td>Demonstrated in tokamaks</td>
<td>28–157 GHz</td>
<td>2.8 MW, 0.2 s</td>
<td>30–40%</td>
<td>Power sources and windows, off-axis CD</td>
</tr>
<tr>
<td></td>
<td>ITER needs</td>
<td>150–170 GHz</td>
<td>50 MW, SS</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Demonstrated in tokamaks</td>
<td>25–120 MHz</td>
<td>22 MW, 3 s (L-mode); 16.5 MW, 3 s (H-mode)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ICRF</td>
<td>ITER needs</td>
<td>40–75 MHz</td>
<td>50 MW, SS</td>
<td>50–60%</td>
<td>ELM tolerant system</td>
</tr>
<tr>
<td></td>
<td>Demonstrated in tokamaks</td>
<td>1.3–8 GHz</td>
<td>2.5 MW, 120 s; 10 MW, 0.5 s</td>
<td>45–55%</td>
<td>Launcher, coupling to H-mode</td>
</tr>
<tr>
<td></td>
<td>ITER needs</td>
<td>5 GHz</td>
<td>50 MW, SS</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Demonstrated in tokamaks</td>
<td>80–140 keV</td>
<td>40 MW, 2 s; 20 MW, 8 s</td>
<td>35–45%</td>
<td>None</td>
</tr>
<tr>
<td>NBI</td>
<td>Demonstrated in tokamaks</td>
<td>None</td>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ITER needs</td>
<td>None</td>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Demonstrated in tokamaks</td>
<td>0.35 MeV</td>
<td>5.2 MW, D−, 0.8 s (from 2 sources)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>−ve ion</td>
<td>ITER needs</td>
<td>1 MeV</td>
<td>50 MW, SS</td>
<td></td>
</tr>
</tbody>
</table>

‘SS’ indicates steady state
Neutral particles heat the plasma via coulomb collisions

1. create energetic (fast) neutral ions
2. ionize the neutral particles
3. heat the plasma (electrons and ions) via Coulomb collisions
Negative ion source is preferred due to higher neutralization efficiency
There are two ways to make negative ions – surface and volume production

• Surface production, depends on:
  – Work function $\Phi$
  – Electron affinity level, 0.75 eV for $\text{H}^-$
  – Perpendicular velocity
  – Work function can be reduced by covering the metal surface with cesium

\[
\text{H} + e^- \rightarrow \text{H}^-
\]
\[
\text{H}^+ + 2e^- \rightarrow \text{H}^-
\]

• Volume production:

\[
\text{H}_2 + e_{\text{fast}}(>20 \text{ eV}) \rightarrow \text{H}_2^*(\text{excited state}) + e_{\text{fast}},
\]
\[
\text{H}_2^*(\text{excited state}) + e_{\text{slow}}(\approx1 \text{ eV}) \rightarrow \text{H}^- + \text{H}.
\]
Two-chamber method of negative ions in volume production with a magnetic filter
Adding cesium increases negative ion current

\[ \text{NEGATIVE ION CURRENT } I_{H^-} \text{ (A)} \]

- **Varc = 70 V**
- **Vb = 2-3 V**
- **Vacc = 50 kV**

**With Cs**
- \( P_A = 1.0 \text{ Pa} \)

**Without Cs**
- \( P_A = 1.4 \text{ Pa} \)
Electrons need to be filtered out since they are extracted together with negative ions.
Acceleration

- Multi-stage acceleration
- Single-stage acceleration

The ITER neutral beam system: status of the project and review of the main technological issues, presented by V. Antoni
NBI system of the LHD fusion machine

- 180 keV and 30 A
- Arc chamber: 35 cm x 145 cm, 21 cm in depth
- Single stage accelerator

Y. Takeiri, etc., Nucl. Fusion, 46, S199, 2006
JT60U NBI system

- JT-60 (Japan-Torus) is a tokamak in Japan.
- 550 keV, 22A
- 2m in diameter and 1.7 m in height
- 3-stage accelerator
Neutralization

• Gas neutralization
  – Collisions between fast negative ions and atoms
    \[ H^- + H_2 \rightarrow H + H_2 + e^- \]
  – Fast ions can lose another electron after neutralized
    \[ H + H_2 \rightarrow H^+ + H_2 + e^- \]

• Plasma neutralization
  – Collisions with charged particles in plasma
    \[ H^- + X(e, Ar, H^+, H_2^+) \rightarrow H + X + e^- \]
  – The efficiencies reach up to 85% for fully ionized hydrogen plasma
Beam dump

![Graph showing neutralisation efficiency vs energy for D, D+, D2+, and D3+ ions.]

(a) 1.6 MeV D°

(b) -1.58 MV

1.6 MeV D°

+1.58 MV
NBI for ITER

- beam components (Ion Source, Accelerator, Neutralizer, Residual Ion Dump and Calorimeter)
- other components (cryo-pump, vessels, fast shutter, duct, magnetic shielding, and residual magnetic field compensating coils)

The ITER neutral beam system: status of the project and review of the main technological issues, presented by V. Antoni
Neutral beam penetration

- Parallel direction
  - Longest path through the densest part of the plasma
  - Harder to be built
- Perpendicular direction
  - Path is short
  - Larger perpendicular energies leads to larger losses
  - Easier to be built

https://www.iter.org
Neutral beam source

- Neutral beam injection for heating plasma in Tokamak
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  - Ian G. Brown, The Physics and Technology of Ion Sources

- Electric propulsion (plasma thrusters)
  - D. M. Goebel and I. Katz, Fundamentals of Electric Propulsion: Ion and Hall Thrusters
Comparison between liquid rockets and ion thrusters

- Liquid rockets
  - $u \sim 4500 \text{ m/s}$
  - $I_{sp} \sim 450 \text{ s}$
  - Energy $\sim 100 \text{GJ}$
  - Power $\sim 300 \text{MW}$
  - Thrust $\sim 2 \times 10^6 \text{ N}$

- Ion thrusters
  - $u \sim 30000 \text{ m/s}$
  - $I_{sp} \sim 3000 \text{ s}$
  - Energy $\sim 1000 \text{GJ}$
  - Power $\sim 1 \text{kW}$
  - Thrust $\sim 0.1 \text{ N}$

https://www.grc.nasa.gov/WWW/k-12/VirtualAero/BottleRocket/airplane/rockth.html
http://propagation.ece.gatech.edu/ECE6390/project/Fall2008/Martographers/Martographers/Propulsion.html
Electric thruster types - electrothermal

- Resistojet
- Arcjet

[Diagram of Resistojet and Arcjet with descriptions]

http://pages.erau.edu/~ericksol/courses/sp300/ch5/propul_ch5.html
Electric thruster types - electrothermal

- **Ion thruster**

  ![Ion thruster diagram]

- **Hall thruster**

  ![Hall thruster diagram]

https://en.wikipedia.org/wiki/Grided_ion_thruster
http://propagation.ece.gatech.edu/ECE6390/project/Fall2010/Projects/group2/hall.gif
Electric thruster types - Electromagnetic

- Pulsed plasma thruster
- Magnetoplasmadynamic thruster (MPD)

http://pages.erau.edu/~ericksol/courses/sp300/ch5/propul_ch5.html
Structure of thruster plume can be complicated
The rocket equation

\[ P_{\text{ini}} = P_{\text{final}} \]

\[ Mv = (M - dM)(v + dv) - dm_p(v_{\text{ex}} - v) \]

\[ Mv = Mv + Md\nu - dM\nu - dMd\nu \]

\[ -dm_p v_{\text{ex}} + dm_p \nu \]

\[ Md\nu = -dm_p v_{\text{ex}} + (dM + dm_p)\nu - dMd\nu \]

\[ Md\nu = -v_{\text{ex}} dm_p \]

\[ M(t) = m_d + m_p \]

\[ \int_{v_i}^{v_f} dv = -v_{\text{ex}} \int_{m_d + m_p}^{m_d} \frac{dM}{M} \]

\[ \text{Thrust} = -v_{\text{ex}} \frac{dM}{dt} \]

\[ \nu_f - \nu_i = \Delta \nu = -v_{\text{ex}} \ln \left( \frac{m_d}{m_d + m_p} \right) \]

\[ m_d = (m_d + m_p) e^{-\Delta\nu/v_{\text{ex}}} \]

\[ \Delta \nu = \left( \text{Isp} \times g \right) \ln \left( \frac{m_d + m_p}{m_d} \right) \]

\[ m_p = m_d \left[ e^{\Delta \nu/v_{\text{ex}}} - 1 \right] = m_d \left[ e^{\Delta \nu/(\text{Isp} \times g)} - 1 \right] \]
The thrust in an ion engine is transferred by the electrostatic force between the ions and the two grids.

\[
\frac{dE(x)}{dx} = \frac{\rho(x)}{\varepsilon_0} = \frac{qn_i(x)}{\varepsilon_0}
\]

\[
E(x) = \frac{q}{\varepsilon_0} \int_0^x n_i(x')dx' + E_{\text{screen}}
\]

**Surface charge:** \( \sigma = \varepsilon_0 E_{\text{screen}} \)

\[
F_{\text{screen}} = \sigma \left( \frac{E_{\text{screen}} + 0}{2} \right) = \frac{1}{2} \varepsilon_0 E_{\text{screen}}^2
\]

\[
F_{\text{accel}} = -\sigma \left( \frac{E_{\text{accel}} + 0}{2} \right) = -\frac{1}{2} \varepsilon_0 E_{\text{accel}}^2
\]

\[
T = F_{\text{screen}} + F_{\text{accel}} = \frac{1}{2} \varepsilon_0 (E_{\text{screen}}^2 - E_{\text{accel}}^2)
\]

\[
F_{\text{ion}} = q \int_0^d n_i(x) E(x) \, dx = \varepsilon_0 \int_0^d \frac{dE}{dx} E \, dx = \frac{1}{2} \varepsilon_0 (E_{\text{accel}}^2 - E_{\text{screen}}^2)
\]
Force transfer

\[ T = -\frac{d}{dt} (m_p v_{ex}) = -v_{ex} \frac{dm_p}{dt} = m_p v_{ex} \]

\[ \dot{m}_p = QM \]

\[ P_{jet} = \frac{1}{2} \dot{m}_p v_{ex}^2 = T^2 \]

\[ T = \frac{dm_p}{dt} v_{ex} \approx \dot{m}_i v_i \]

\[ \dot{m}_i \approx \dot{m}_p = QM = \frac{\#}{t} M = \frac{e \#}{e t} M \]

\[ \dot{m}_i = \frac{I_b M}{e} \]

\[ v_i = \sqrt{\frac{2qV_b}{M}} \quad V_b = \text{grid voltage} \]

\[ b = \text{ion mass flow rate in kg/s} \]

\[ \dot{m}_i = \text{ion mass flow rate in kg/s} \]

\[ T = \sqrt{\frac{2M}{e}} I_b \sqrt{V_b} \quad (\text{Nt}) \]

\[ T = 1.65 I_{b,Amp} \sqrt{V_{b,V}} \quad (mN) \]

\[ I_b = \text{ion beam current} \]
Thrust

\[ F_t = \cos \theta \]

\[ I_b = I^+ + I^{++} \]

\[ T_m = I^+ \sqrt{\frac{2MV_b}{e}} + I^{++} \sqrt{\frac{MV_b}{e}} = I^+ \sqrt{\frac{2MV_b}{e}} \left( 1 + \frac{1}{\sqrt{2}} \frac{I^{++}}{I^+} \right) \equiv I^+ \alpha \sqrt{\frac{2MV_b}{e}} \]

\[ \gamma = \alpha F_t \]

\[ T = \gamma m_i v_i = \gamma \sqrt{\frac{2M}{e}} I_b \sqrt{V_b} \]

\[ T = 1.65 \gamma I_b \sqrt{V_b} \text{(mN)} \]

Ex: 10° half-angle beam divergence, \( I^{++}/I^+=10\% \)  \( \gamma = 0.958 \)

\( I_b = 2A, V_b = 1500V, \text{Xenon, } T=122.4 \text{ mN} \)
Specific impulse (Isp)

\[ I_{sp} = \frac{T}{m_pg} = \frac{v_{ex}}{g} \quad T = m_p v_{ex} \]

\[ I_{sp} = \frac{T}{m_pg} = \frac{v_i}{g} \frac{m_i}{m_p} \quad T \approx m_i v_i \]

- Thruster mass utilization efficiency (ionized versus unionized propellant)

\[ \eta_m = \frac{\dot{m}_i}{m_p} = \frac{I_b}{e} \frac{M}{m_p} \quad \eta_m^* = \alpha m \frac{I_b}{e} \frac{M}{m_p} \quad T = \gamma m_i v_i = \gamma \sqrt{\frac{2M}{e} I_b \sqrt{V_b}} \]

- \( \alpha \) and \( \gamma \) are to consider number of charge per ion.

\[ I_{sp} = \frac{\gamma \eta_m}{g} \sqrt{\frac{2eV_b}{M}} = 1.417 \times 10^3 \gamma \eta_m \sqrt{V_b} = 123.6 \gamma \eta_m \sqrt{V_b} \]

For xenon, \( M_a = 131.29 \)

Ex: 10° half-angle beam divergence, \( I^{++}/I^+ = 10\% \quad \gamma = 0.958 \)

\( I_b = 2A, V_b = 1500V, \) Xenon, 90% propellant utilization, \( I_{sp} = 4127 \) s
Thruster efficiency

- Electrical efficiency of the thruster

$$\eta_e = \frac{P_b}{P_{in}} = \frac{P_b}{P_T} = \frac{I_b V_b}{I_b V_b + P_0}$$

- Ion production efficiency (discharge loss)

$$\eta_d = \frac{\text{Power to produce the ions}}{\text{Current of ions produced}} = \frac{P_0}{I_b}$$

$$P_{\text{jet}} = \frac{1}{2} m_p v_{\text{ex}}^2 = \frac{T^2}{2m_p}$$

$$T = \gamma \sqrt{\frac{2M}{e} I_b \sqrt{V_b}}$$

- Total efficiency

$$\eta_T = \gamma^2 \eta_m \frac{I_b V_b}{P_{in}} = \gamma^2 \eta_m \eta_e$$

Ex: 10° half-angle beam divergence, I^+/I+=10%  \( \gamma = 0.958 \)

I_b = 2A, V_b = 1500V, Xenon, 90% propellant utilization

ion production efficiency: 250EV/ion

$$\eta_e = \frac{2 \times 1500}{2 \times 1500 + 250 \times 2} = 0.857$$

$$\eta_T = 0.958^2 \times 0.9 \times 0.857 = 0.708$$
Ion thruster has the highest specific impulse (Isp)

<table>
<thead>
<tr>
<th>Thruster</th>
<th>Specific Impulse (s)</th>
<th>Input Power (kW)</th>
<th>Efficiency Range (%)</th>
<th>Propellant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold gas</td>
<td>50–75</td>
<td>—</td>
<td>—</td>
<td>Various</td>
</tr>
<tr>
<td>Chemical (monopropellant)</td>
<td>150–225</td>
<td>—</td>
<td>—</td>
<td>N₂H₄, H₂O₂</td>
</tr>
<tr>
<td>Chemical (bipropellant)</td>
<td>300–450</td>
<td>—</td>
<td>—</td>
<td>Various</td>
</tr>
<tr>
<td>Resistojet</td>
<td>300</td>
<td>0.5–1</td>
<td>65–90</td>
<td>N₂H₄ monoprop</td>
</tr>
<tr>
<td>Arcjet</td>
<td>500–600</td>
<td>0.9–2.2</td>
<td>25–45</td>
<td>N₂H₄ monoprop</td>
</tr>
<tr>
<td>Ion thruster</td>
<td>2500–3600</td>
<td>0.4–4.3</td>
<td>40–80</td>
<td>Xenon</td>
</tr>
<tr>
<td>Hall thrusters</td>
<td>1500–2000</td>
<td>1.5–4.5</td>
<td>35–60</td>
<td>Xenon</td>
</tr>
<tr>
<td>PPTs</td>
<td>850–1200</td>
<td>&lt;0.2</td>
<td>7–13</td>
<td>Teflon</td>
</tr>
</tbody>
</table>