Experimental results from the SPECTOR device at General Fusion

Stephen Howard
Michel Laberge, Russ Ivanov, Peter O’Shea, Ken Jensen, Adrian Wong,
Curtis Gutjahr, Patrick Carle, William Young, Neil Carter, Ryan Zindler,
Alex Mossman, Meritt Reynolds, Aaron Froese.

General Fusion Inc, Burnaby, British Columbia, Canada
General Fusion (GF) is operating a new sequence of plasma devices called: SPECTOR (Spherical Compact Toroid)

• Standard operation as a spherical tokamak.
• Similar to smaller scale version of HIST (1/2.5), Pegasus (1/3.75), or NSTX (1/7 scale by major radius) etc.
• Plasma start-up only uses fast coaxial helicity injection (CHI) from long Marshall gun.
• Convex outer wall design (D-shaped) expected to have good plasma stability during compression.
• Operating 1 lab-only device (Spector 1), and 2 mobile systems for out-of-lab compression tests (Spector 2, 3)

➢ Here is a brief tour
Lab-only version (Spector 1)

Spector 1 vessel has good diagnostic access on flux conserver.
Mobile versions (Spector 2, 3)

Flux Conserver only has diagnostic access on top plate to allow for uniform implosion of spherical vessel.

Vacuum system, DAQ/computer control system, and other reusable components are protected by reinforced shipping containers and steel blast shields on roof.

Spector 2, 3 will be the 13th, 14th MTF compression tests completed by General Fusion.
SPECTOR Overview

Machine Geometry & Operating parameters
SPECTOR forms spherical tokamak plasmas by coaxial helicity injection into a flux conserver
- Major, minor radius \( R = 12 \text{ cm}, \ a = 8 \text{ cm} \)
- Vessel radius = 19 cm (interior)
- \( \lambda_{\text{Taylor}} = 23.9 \text{ m}^{-1} \)
- Current in axial shaft \( \leq 500 \text{ kA} \) [crowbarred] creates pre-existing toroidal field before formation plasma
- Density range = \( 5 \times 10^{19} \) to \( 5 \times 10^{20} \text{ m}^{-3} \)
- Poloidal Flux in CT = 30 mWb
- Toroidal Flux in CT = 300 mWb
- Toroidal plasma current = 250 kA
- Total magnetic energy in CT = 120 kJ
- Best magnetic lifetime of
  - 800 us (FWHM)
  - 1700 us until termination
- Peak \( Te > 400 \text{ eV} \)

- Circuit parameters
  - Formation: \( C_F = 3.2 \text{ mF}, \ V_F = 18 \text{ kV} \) max
  - Shaft: \( C_S = 2.5 \text{ mF}, \ V_S = 18 \text{ kV} \) max
  - \( L_S = 1.27 \mu\text{H}, \) Diodes max 25 kV, 600 kA
Spector uses a fast CHI formation process (Marshall gun bubble-out)

- Contours show average poloidal flux $\Psi(r,z)$
- Color scale show plasma pressure
- Oscillations happen just after CHI bubble-out, but calm down by 50 $\mu$s
- Key parameters of simulation:
  - Initial 30 mWb vacuum poloidal gun flux (aka bias flux),
  - Pre-existing 450 kA current on center shaft before plasma is formed
  - Final 70 mWb poloidal CT flux after dynamo (factor of 2.3x amplification)
Diagnostics (equatorial view)

Visible spectra
Thomson Beam

Ion Doppler

Center shaft B probes (12 total)

VUV spectra

Ion Doppler

IR interferometry FIR Polarimetry
Diagnostics (poloidal view)

Visible Light chords (4 toroidal positions)

Outer wall B probes (17 total), measure [Bpol, Btor]
Other diagnostics beyond the scope of this talk

- Dual wavelength IR interferometry (1330, 1550 nm, 2 chords)
- Visible survey spectrometers (3 in use on Spector 1)
- Liquid Scintillator (Gamma + Neutron detector, PSD)
- VUV spectrometer (50 nm to visible)
- X-ray pinhole camera, with Phantom high speed video

- Filtered X-ray photodiodes (in development)
- 4-chord FIR Polarimeter system (in development)
Formation occurs with a pre-existing Toroidal field

Externally driven currents
- **Shaft Current** (428 kA peak)
- **Form Current** (700 kA peak)

Electrode Voltages
- **$V_{\text{preTor}}$** (peak 12 kV)
- **$V_{\text{form}}$** (peak 16 kV)

Shot 6266 chronology

<table>
<thead>
<tr>
<th>time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CT Workshop 2016
Formation occurs with a pre-existing Toroidal field

Extremely driven currents
--- Shaft Current (428 kA peak)
--- Form Current (700 kA peak)

Electrode Voltages
--- \( V_{\text{preTor}} \) (peak 12 kV)
--- \( V_{\text{form}} \) (peak 16 kV)

Shot 6266 chronology

<table>
<thead>
<tr>
<th>time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 1 sec</td>
<td>DC bias magnets turn on. ( \Psi_{\text{Gun}} = 13.6 \text{ mWb} )</td>
</tr>
</tbody>
</table>
Formation occurs with a pre-existing Toroidal field

Electrode Voltages

- $V_{\text{preTor}}$ (peak 12 kV)
- $V_{\text{form}}$ (peak 16 kV)

Externally driven currents

- Shaft Current (428 kA peak)
- Form Current (700 kA peak)

DC magnets

Shot 6266 chronology

<table>
<thead>
<tr>
<th>time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 1 second</td>
<td>DC bias magnets turn on. $\Psi_{\text{Gun}} = 13.6$ mWb</td>
</tr>
<tr>
<td>- 234 $\mu$s</td>
<td>Deuterium is puffed</td>
</tr>
</tbody>
</table>
Formation occurs with a pre-existing Toroidal field.

Electrode Voltages

- $V_{\text{preTor}}$ (peak 12 kV)
- $V_{\text{form}}$ (peak 16 kV)

Externally driven currents

- **Shaft Current** (428 kA peak)
- **Form Current** (700 kA peak)

Shot 6266 chronology

<table>
<thead>
<tr>
<th>time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 1 second</td>
<td>DC bias magnets turn on. $\Psi_{\text{Gun}} = 13.6 \text{ mWb}$</td>
</tr>
<tr>
<td>- 234 $\mu$s</td>
<td>Deuterium is puffed</td>
</tr>
<tr>
<td>- 110 $\mu$s</td>
<td>Shaft circuit fires, creates vacuum $B_{\text{Tor}}$</td>
</tr>
</tbody>
</table>
Formation occurs with a pre-existing Toroidal field

DC magnets
Gas

Vacuum Toroidal B before plasma

Plasma Breakdown

Externally driven currents
--- Shaft Current (428 kA peak)
--- Form Current (700 kA peak)

Electrode Voltages
--- $V_{preTor}$ (peak 12 kV)
--- $V_{form}$ (peak 16 kV)

Shot 6266 chronology

<table>
<thead>
<tr>
<th>time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 1 second</td>
<td>DC bias magnets turn on. $\Psi_{Gun} = 13.6$ mWb</td>
</tr>
<tr>
<td>- 234 $\mu$s</td>
<td>Deuterium is puffed</td>
</tr>
<tr>
<td>- 110 $\mu$s</td>
<td>Shaft circuit fires, creates vacuum $B_{Tor}$</td>
</tr>
<tr>
<td>$t = 0$</td>
<td>Formation fires, plasma breaks down. $I_{shaft}$ crowbarred at 400 kA</td>
</tr>
</tbody>
</table>
Formation occurs with a pre-existing Toroidal field

Electrode Voltages
- $V_{\text{preTor}}$ (peak 12 kV)
- $V_{\text{form}}$ (peak 16 kV)

Externally driven currents
- Shaft Current (428 kA peak)
- Form Current (700 kA peak)

Shot 6266 chronology

<table>
<thead>
<tr>
<th>time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 1 second</td>
<td>DC bias magnets turn on. $\Psi_{\text{Gun}} = 13.6$ mWb</td>
</tr>
<tr>
<td>- 234 $\mu$s</td>
<td>Deuterium is puffed</td>
</tr>
<tr>
<td>- 110 $\mu$s</td>
<td>Shaft circuit fires, creates vacuum $B_{\text{Tor}}$</td>
</tr>
<tr>
<td>$t = 0$</td>
<td>Formation fires, plasma breaks down. $I_{\text{shaft}}$ crowbarred at 400 kA</td>
</tr>
<tr>
<td>+ 35 $\mu$s</td>
<td>Form current peaks 700 kA. Fast Marshall gun bubble-out (CHI) has pushed flux into upper chamber</td>
</tr>
</tbody>
</table>
Formation occurs with a pre-existing Toroidal field

Electrode Voltages

- $V_{\text{preTor}}$ (peak 12 kV)
- $V_{\text{form}}$ (peak 16 kV)

Externally driven currents

--- Shaft Current (428 kA peak)
--- Form Current (700 kA peak)

Shot 6266 chronology

<table>
<thead>
<tr>
<th>time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 1 second</td>
<td>DC magnets turn on. $\Psi_{\text{Gun}} = 13.6$ mWb</td>
</tr>
<tr>
<td>- 234 µs</td>
<td>Deuterium is puffed</td>
</tr>
<tr>
<td>- 110 µs</td>
<td>Shaft circuit fires, creates vacuum $B_{\text{Tor}}$</td>
</tr>
<tr>
<td>$t = 0$</td>
<td>Formation fires, plasma breaks down. $I_{\text{shaft}}$ crowbarred at 400 kA</td>
</tr>
<tr>
<td>+ 35 µs</td>
<td>Form current peaks 700kA Fast Marshall gun bubble-out (CHI) has pushed flux into upper chamber</td>
</tr>
<tr>
<td>+ 90 µs</td>
<td>Form current ends.</td>
</tr>
</tbody>
</table>
Formation occurs with a pre-existing Toroidal field

**Electrode Voltages**
- $V_{\text{preTor}}$ (peak 12 kV)
- $V_{\text{form}}$ (peak 16 kV)

---

**Shot 6266 chronology**

<table>
<thead>
<tr>
<th>Event</th>
<th>time</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC magnets turn on. $\Psi_{\text{Gun}} = 13.6$ mWb</td>
<td>- 1 second</td>
</tr>
<tr>
<td>Deuterium is puffed</td>
<td>- 234 $\mu$s</td>
</tr>
<tr>
<td>Shaft circuit fires, creates vacuum $B_{\text{Tor}}$</td>
<td>- 110 $\mu$s</td>
</tr>
<tr>
<td>Formation fires, plasma breaks down. $I_{\text{shaft}}$ crowbarred at 400 kA</td>
<td>$t = 0$</td>
</tr>
</tbody>
</table>
| Form current peaks 700 kA
Fast Marshall gun bubble-out (CHI) has pushed flux into upper chamber | + 35 $\mu$s |
| Form current ends. | + 90 $\mu$s |
| End of CT toroidal plasma current. | $t = 1.7 \text{ ms}$ $1700 \mu$s |
Current and Voltage over duration of shot

Shot 6266

Externally driven currents
- Shaft Current (428 kA peak)
- Form Current (700 kA peak)

Electrode Voltages
- $V_{\text{preTor}}$ (peak 12 kV)
- $V_{\text{form}}$ (peak 16 kV)
B Poloidal near center shaft (0.9 Tesla peak)

B poloidal

Externally driven currents
--- Shaft Current (428 kA peak)
--- Form Current (700 kA peak)
Toroidal B field shows internal plasma crowbar

- B toroidal at surface of shaft
- Only axial current in shaft
- Internal poloidal current persists ~450 µs after formation pulse ends

- External formation current ends.
- Externally driven currents
  - Shaft Current (428 kA peak)
  - Form Current (700 kA peak)
Toroidal B field shows internal plasma crowbar current.

Plasma crowbar current

External current

Shot 6266

B Toroidal on Inner Shaft

Z = 201

\( \phi = 0 \)

R = 9 mm

Tesla

kA

ms

CT Workshop 2016
Behavior of B poloidal varies across radius

0.35 T
Calm and relatively flat
Fluctuations begin, Decay accelerates
B poloidal near Outer Wall

0.9 T
Always has fluctuations and steady decay
B poloidal near Center Shaft

Shot 6266
B Poloidal on Outer Wall
- $Z = 145, \phi = 0, R = 137$ mm
- $Z = 227, \phi = 0, R = 183$ mm
- $Z = 227, \phi = 45, R = 183$ mm
- $Z = 227, \phi = 90, R = 183$ mm
- $Z = 227, \phi = 135, R = 183$ mm
- $Z = 227, \phi = 180, R = 183$ mm
- $Z = 227, \phi = 225, R = 183$ mm
- $Z = 227, \phi = 315, R = 183$ mm
- $Z = 321, \phi = 0, R = 184$ mm
- $Z = 404, \phi = 0, R = 140$ mm

Shot 6266
B Poloidal on Inner Shaft
- $Z = 201, \phi = 0, R = 9$ mm
- $Z = 201, \phi = 180, R = 9$ mm
- $Z = 276, \phi = 0, R = 9$ mm
- $Z = 276, \phi = 90, R = 9$ mm
- $Z = 276, \phi = 180, R = 9$ mm
- $Z = 276, \phi = 270, R = 9$ mm
Spector geometry allows equilibrium reconstruction

The primary variation in magnetic structure is due to the overall slope of \( \lambda(\psi) \), given by \( \alpha \). Here are 3 example cases of GS equilibria (calculated by Corsica) that span the set of possibilities for this linear \( \lambda \) profile model. Contours of \( |B_{pol}| \) from are plotted. \([\Psi_{CT} = 30 \text{ mWb, } I_{shaft} = 450 \text{ kA}]\)

**Wall values for \( |B_{pol}| \) uniquely determine \( \lambda(\psi) \) to first order.**

**Peaked** \( \alpha = +1 \)

**Flat** \( \alpha = 0 \)

**Hollow** \( \alpha = -1/3 \)

\( |B(\text{in})|/|B(\text{out})| \)

- 1.6 T
- Flat 1.0 T
- Hollow 1.1 T
- Peaked 0.8 T
- |B(\text{in})|/|B(\text{out})| = 2.0
- |B(\text{in})|/|B(\text{out})| = 3.5
- |B(\text{in})|/|B(\text{out})| = 4.27
Corsica Shows Extended Poloidal Flux Amplification

- Flux amp of 1.84x is similar but less than 2.3x from 3D VAC
- Corsica fits to experimental data also show $\lambda(\psi)$ profile as being always peaked $\alpha > +0.5$, increasing with time
Fluctuations near shaft could be signature of dynamo process.

- $n = 1$ and $n = 2$ spatial modes as large as 5%, 9% of $n = 0$
- $n = 0$ has temporal fluctuations.
- $n = 2$ becomes low amplitude $\sim 1\%$ in final decay phase.
Outer fluctuations begin after half-way point

Here is a different shot where the transition is very clear and abrupt

Very Calm $\delta B/B_0 = 0.1\%$ during $\Psi_C$ dynamo

Fluctuations begin at $t = 721 \mu s$ when dynamo turns off $\delta B/B_0 > 3\%$

Decay rate increases

Shot 6562

-- B pol at $z = 227$, $\phi = 45$, $r = 183$ mm
Visible light emissions may imply change in Transport

Total visible emission decreases with time in first 1/2 of shot

Brightness of Li II at 548.3 nm increases in decay phase (with $B_{pol}(t)$ for comparison)

Edge fluctuations in second phase seem to be increasing transport of Li from wall deeper into CT plasma.
Retractable Lithium evaporation sticks (GF patent pending) deposit a fresh coat of ~2 μm of Li over 20 min. Stainless mesh basket holds liquid Li in place by surface tension, evaporates when above 400 C. Stick depletes after ~10 coatings. Cools back to room temperature (Li solidifies) and retracts upward before shots begin.

Lithium coating:
- Reduces ion and electron recycling coefficient
- Bigger improvement with D plasmas, still helps He.
- Minimizes other wall-sourced impurities.
Lithium Gettering increases $T_e$ and plasma lifetime

After first 80 min total of Li gettering with 2 sticks
~320 mg, ~8 micron layer deposited on walls.
This show prompt effect on Deuterium plasmas repeated under similar conditions

Effect due directly to Li coating:
- Core $T_e$ increased by from 200 eV to 350 eV (1.73x)
- CT Total Life increased by 1.44x.

Further improvements occurred with continued shooting, optimization
Detail of Thomson Collection Optics

TS laser system
532 nm
10 ns pulse
1.5 J per pulse
1 pulse per plasma shot
3 collection points
Upgrade to 6 collection points soon.
Core $T_e > 400$ eV has been measured

TS ensemble of 10 recent (consecutive) Deuterium shots [error bars show st.dev. of scatter within measurement set]

Data is consistent with parabolic-like $T_e(r)$ profile during calm period at $t = 403 \mu s$. 

- $r = 12 \text{ cm}$
  - $T_e = 435 \text{ eV } +/- 38$
  - at time = 403.7us
  - best fit to 10 shot ensemble

- $r = 13 \text{ cm}$
  - $T_e = 348 \text{ eV } +/- 40$
  - at time = 403.7us
  - best fit to 10 shot ensemble

- $r = 17 \text{ cm}$
  - $T_e = 220 \text{ eV } +/- 18$
  - at time = 403.7us
  - best fit to 10 shot ensemble
Conclusions for MTF

• MTF compression test of Spector plasma looks promising.
• Adiabatic spherical compression $T \sim 1/R^2$
  - $R_0/R_{\text{min}} = 4 \Rightarrow T_e$ increases from 400 eV to 6.4 keV
  - $R_0/R_{\text{min}} = 5 \Rightarrow T_e$ increases from 400 eV to 10 keV
• Still subscale on density, magnetic energy, won’t get $Q > 1$ yet…
• Starting to explore fusion relevant physics.