Eagleworks Laboratories
Advanced Propulsion

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NASA JSC
The Challenge of Interstellar Flight

• Voyager 1 mission:
  – 0.722 t spacecraft launched in 1977 to study outer solar system and boundary with interstellar space.
  – After 33 years, Voyager 1 is currently at 116 Astronomical Units (AU) from the sun travelling at 3.6 AU per year,
  – no spacecraft launched to date will overtake Voyager 1.

• If Voyager 1 were on a trajectory headed to one of the Sun’s nearest neighboring star systems, Alpha Centauri at 4.3 light years (or 271,931 AU), it would take ~75,000 years to traverse this distance at 3.6 AU/year.
DAEDELUS

- Project Daedalus sponsored by British Interplanetary Society in 1970’s to develop robotic interstellar probe capable of reaching Barnard’s star, at ~6 light years away, in 50 years.
- The resulting spacecraft was 54,000t,
- 92% fuel for fusion propulsion system.
- ISS is ~450t

Picture courtesy of Adrian Mann, www.bisbos.com, used with permission
ISS picture courtesy of NASA (STS-135 fly-around)
IS THERE ANOTHER WAY??
Hyper-fast interstellar travel...

- Is there a way within the framework of physics such that one could cross any given cosmic distance in an arbitrarily short period of time, while never locally breaking the speed of light (11th commandment)?

Images courtesy NASA
Inflation: Alcubierre Metric

**Warp Metric:**

\[ ds^2 = -dt^2 + (dx - v_s f(r_s) dt)^2 + dy^2 + dz^2 \]

**Shaping Function:**

\[ f(r_s) = \frac{\tanh(\sigma(r_s + R)) - \tanh(\sigma(r_s - R))}{2 \tanh(\sigma R)} \]

**York Time:**

\[ \theta = v_s \frac{x_s}{r_s} \frac{df(r_s)}{dr_s} \]

York Time is measure of expansion/contraction of space

**Energy Density:**

\[ \frac{1}{8\pi} G^{00} = -\frac{1}{8\pi} \frac{v_s^2 (y^2 + z^2)}{4r_s^2} \left( \frac{df(r_s)}{dr_s} \right)^2 \]

Appealing Characteristics

- Proper acceleration in the bubble is formally zero.
- MCC clocks synchronized with onboard clocks.
  (Coordinate time = proper time)
- Flat space-time inside the bubble.
  (divergence of phi = 0)

Unappealing characteristic
(square peg, round hole)
Bubble Topology Optimization

York Time magnitude decreases

Energy density magnitude decreases

“bubble” thickness decreases

Surface plots of York Time & $T^0_0$, $\langle v \rangle = 10c$, 10 meter diameter volume, variable warp “bubble” thickness
Bubble Oscillation Optimization

\[ ds^2 = -c^2 dt^2 + \frac{a^2(t)}{e^{2kU}} dX^2 + dU^2 \]

\[ \frac{dX}{dt} = \frac{ce^{kU}}{a(t)} \sqrt{1 - \frac{dU^2}{c^2 dt^2}} \]

\[ \frac{dU}{dt} \Rightarrow 1, U = 0 \quad \therefore \frac{dX}{dt} \Rightarrow 0 \]

\[ \gamma \approx e^U \quad \phi \approx U \quad \frac{d\phi}{dt} \approx \frac{dU}{dt} \]

Oscillate the bubble intensity
Warp Field Interferometer

- Warp Field Interferometer developed after putting metric into canonical form\(^1\):

\[
ds^2 = \left( v_s^2 f(r_s)^2 - 1 \right) \left( dt - \frac{v_s f(r_s)}{v_s^2 f(r_s)^2 - 1} dx \right)^2 - dx^2 + dy^2 + dz^2
\]

- Generate microscopic warp bubble that perturbs optical index by 1 part in 10,000,000

- Induce relative phase shift between split beams that should be detectable.

Interferometer and Test-article Setup

- Laser
- Iris
- Beam splitter
- 2 Polarizers (jointly used for intensity control)
- Off-axis mirror
- Along-axis mirror
- Test article
- Low-voltage power supply
- High-voltage power supply
- Computer for interference image capture and test article power cycling
Fabry-Perot Interferometer

Example: Michelson-Morley Interferometer image for Sodium source

- Consists of two reflecting, highly parallel surfaces, called an Etalon
- The interference pattern is created within the Etalon
- Multiple reflections in the Etalon reinforce the areas where constructive and destructive interference occurs
- Allows for much higher-precision measurements of fringes (image averaging without software)

Example: Fabry-Perot Interferometer image for Sodium source (note doublet)
Data Analysis

FFT of single pixel

FFT of entire imager at frequency of interest
Isolated Lab

Panel Overview
Primary/Auxiliary
Feed Air
Isolator pressure
Height control pressure
FFT of imager data at frequency of interest

isolated

not isolated
Open-air etalon Implementation

Frequencies of interest

Inactive

Active
### Newport Broadband Amplitude Modulator

- **Model**: 4102NF
- **Type**: Broadband Amplitude Modulator
- **Operating Frequency**: DC-200 MHz
- **Wavelength Range**: 500-900 nm
- **Material**: MgO:LiNbO$_3$
- **Maximum $V_{\pi}$**: 195 V @ 633 nm
- **Maximum Input Power**: 2 W/mm$^2$ @ 532 nm
- **Aperture Diameter**: 2 mm
- **RF Bandwidth**: 200 MHz
- **RF Connector**: SMA
- **Input Impedance**: 10 pF
- **Maximum RF Power**: 10 W
- **Connector**: SMA

### Thorlabs High-Speed Avalanche Detector

- **Model**: APD210
- **Rise Time**: 0.5 ns
- **Supply Voltage**: +12 to +15 V
- **Current Consumption**: 200 mA
- **Max. Incident Power**: 10 mW
- **Spectral Range**: 400 – 1000 nm
- **Frequency Range**: 1-1600 MHz
- **Maximum Gain**: 2.5x10$^5$ V/W

### Agilent Technologies Infiniium DSO9254A 2.5 GHz Oscilloscope

- 2.5 GHz bandwidth across all 4 analog channels
- 20 GSa/s max. sample rate
- Standard 20 Mpts memory per channel, upgradeable to 1 Gpts
Original Matthew Jeffries concept from mid 1960’s, rendered by Mark Rademaker

Matthew Jeffries is the artist that created the familiar Star Trek enterprise look
Updated concept based on Dr. White’s theoretical findings, rendered by Mark Rademaker with artwork and inputs from Mike Okuda
Forward Plan

• Explore the $d\phi/dt$ dependency in future test devices
  – The idea of an optimized space warp needs vacuum energy, and large $d\phi/dt$ - **both of these conditions are present in the q-thruster technology also being explored in the lab.**
  – Use the q-thruster physics models to guide design of RF frequency test devices to be evaluated in the warp field interferometer, the Fabry-Perot Interferometer, and the time of flight experiment.
Q-Thrusters For Space Exploration
Q-Thruster Background

- A Q-thruster is a form of electric propulsion
- Through the use of electric and magnetic fields, a Q-thruster pushes quantum particles (electrons/positrons) in one direction, while the Q-thruster recoils to conserve momentum
  - This principle is similar to how a submarine uses its propeller to push water in one direction, while the submarine recoils to conserve momentum
- Based on test and theoretical model development, expected thrust to power for initial flight applications is 0.4N/kW (~7x Hall)
  - 0.4 N/kW enables power-constrained HEO SEP missions to close without needing chemical kick stages and very long transit times.
  - 0.4N/kW coupled with persistent power (e.g. NEP) enables rapid transit missions throughout the solar system.
RF Q-thruster Concept Animation

Application of high frequency RF power to an air dielectric in the q-thruster increases quantum particle density

Q-thruster pushes virtual particles with electric and magnetic fields – quantum particle thruster

Conservation of Momentum

Particles accelerated to the right results in thrust applied to the system to push it to the left.
RF Q-thruster Plume Diagnostics

Simple ballistic pendulum in wake will deflect, but deflection will be too small to measure due to diffuse plume.

Q-thruster produces diffuse wake outside thruster body producing little recoil (e.g. thruster can be IVA).

Placing a small q-thruster in the plume instrumented with a strain gauge will be better coupled with the wake and the ballistic displacement will be measurable.

I don’t “feel” the wake
Recent experimental campaigns show theory and experiment correlate well [\(\sim 20\%\)]

- Net Measured Force: \(\sim 60\) microNewtons
- Quality Factor Q: \(\sim 22000\)
- Power: 2.6W
- Newtons per kW: 0.023N/kW
- Predicted Force: 49 microNewtons
- Predicted Q: 21817
- Predicted Newtons per kW: 0.019N/kW
Team Continuing to Enhance Understanding & Performance

Freq: 1,932.612 MHz (TM211?)
Q= 7,376
Power: 17.08W

Output Forces are NET

200V, 29uN

196.0 Sec.

April 21, 2014 Data Run-2 Thrust

04/16/2014 Paul March - Eagleworks Lab

200V, 29uN

44.2uN

196.0 Sec.

Table Floated
Q-thruster Physics Data

- JSC collaborating with DoD and Industry to explain test results from prototypes at Boeing Phantomworks, Lockheed-Martin Skunkworks, Cannae, etc.
- JSC derived q-thruster physics models provides consistent explanation of test device performance.

**2004 Test Article**

- Thrust: ~4 mN
- Specific Force: ~0.4N/kW

**2005 Test Campaign**

- Thrust: ~3 mN
- Specific Force: ~0.3N/kW

**2012 Test Article**

- Thrust: ~vaccum fluctuation density increased from \(1 \times 10^{-56}\) to \(> 1 \times 10^{-14}\)

**SFE Test Article at JSC**

- In 2013, Boeing/DARPA sent Eagleworks Lab an SFE test article for testing and evaluation.
- Evaluation of the test article in and out of a Faraday Shield performed from Feb through June 2013.
- There is a consistent transient thrust at device turn-on and turn-off that is consistent with Q-thruster physics.
- The magnitude of the thrust scaled approximately with the cube of the input voltage (20-110uN).
- The magnitude of the thrust is dependent on the AC content of the turn-on and turn-off pulse.
- Specific force of transient thrust was in the \(1-20\) N/kW range.

**Cannae Test Article at JSC**

- Both the slotted and null-cavity test article generated continuous thrust from 30-40 micro-Newtons.
- The operating hypothesis is that the RF feed system for both test articles is potentially a \(\frac{1}{4}\) wave coaxial q-thruster with a very high quality factor enabled by the large resonance volume which serves as a matching network.
- NASA and Cannae will continue to partner working towards implementing a Phase Lock Loop-enabled test article. In parallel, NASA will consider other RF resonance geometries (numerical analysis of fields).

**Microwave Thruster Device**

- SPR Ltd. Has produced several Microwave test articles. Claims are they produce thrust with just electric power input.
- Seasonal theoretical model has been developed for Q-thruster and may be visible by scientific community soon.
- Thrust measured against Q-thruster models and analysis suggests this may be a microwave version of a quantumvacuum plasma thruster.
- Overproduces non-thermal plasmas that cannot be turned off and thereby thrust is uncontrolled.
- Microwave Q-thrusters would be minimized to suppress radiation.
- Thrust magnitude increased over multiple test devices from 10 to 30mN.
- If Q-Thruster theory accounts for measured force, then microwave test articles may have ability to reach \(100\)N/kW.
- Chinese university claimed to have duplicated EM Drive tests, but no way for U.S. to evaluate credibility (so we have ignored it).

**Unreal Results?**

- Overall: Yes, points against Unreal.
- Could be Q-Field or Q-thruster devices.
- Both devices use RF energy which is currently not practical.
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Q-THRUSTER + 2MW NUCLEAR POWER IS MISSION ENABLING

POSSIBLE MISSIONS TO MARS, THE OUTER SOLAR SYSTEM, AND BEYOND WITH Q-THRUSTERS
300 kW SEP Mars

- 70t stack departs from DRO
- 300kW SEP
- 0.4N/kW Q-thrusters
- 50-day stay in Deimos orbit around Mars
- Total mission duration of 788 days and 2AU maximum distance from the sun.
2MW NEP Mars

- 90t spacecraft
- 2MW power
- 0.4N/kW (800N)
- 246 day mission with 70 day stay at Mars

- 90t spacecraft
- 2MW power
- 4N/kW (8000N)
- 140 day mission with 90 day stay at Mars
2MW NEP Jupiter

- 0.4 N/kW
  - 194 days

- 4 N/kW
  - 61 days

- 90t spacecraft
  - 50t cargo, 20t power, 20t propulsion

- 2MW power
Saturn

0.4 N/kW
263 days

4 N/kW
86 days

- 90t spacecraft
  - 50t cargo, 20t power, 20t propulsion
- 2MW power
Uranus

0.4 N/kW
399 days

4 N/kW
129 days

- 90t spacecraft
  - 50t cargo, 20t power, 20t propulsion
- 2MW power
Neptune

0.4 N/kW
492 days

4 N/kW
160 days

- 90t spacecraft
  - 50t cargo, 20t power, 20t propulsion
- 2MW power
Pluto

0.4 N/kW
518 days

4 N/kW
167 days

- 90t spacecraft
  - 50t cargo, 20t power, 20t propulsion
- 2MW power
1000 AU

0.4 N/kW
5.6 years

4 N/kW
1.8 years

- 90t spacecraft
  - 50t cargo, 20t power, 20t propulsion
- 2MW power
Proxima Centauri

0.4 N/kW
122.5 years

4 N/kW
29.9 years

- 90t spacecraft
  - 50t cargo, 20t power, 20t propulsion
- 2MW power
Solar System & Beyond Summary

time of flight in **days** to reach the location

<table>
<thead>
<tr>
<th>Destination</th>
<th>0.4 N/kW</th>
<th>4 N/kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mars</td>
<td>66</td>
<td>22</td>
</tr>
<tr>
<td>Jupiter</td>
<td>194</td>
<td>61</td>
</tr>
<tr>
<td>Saturn</td>
<td>263</td>
<td>86</td>
</tr>
<tr>
<td>Uranus</td>
<td>399</td>
<td>129</td>
</tr>
<tr>
<td>Neptune</td>
<td>492</td>
<td>160</td>
</tr>
<tr>
<td>Pluto</td>
<td>518</td>
<td>167</td>
</tr>
<tr>
<td>1000 AU</td>
<td>2106 (5.6 years)</td>
<td>664 (1.8 years)</td>
</tr>
<tr>
<td>Proxima Centauri with brake</td>
<td>122.5 years</td>
<td>29.9 years</td>
</tr>
</tbody>
</table>

initial mass = 90 tons
Next Steps for Q-Thruster Development

- Develop IV&V breadboard implementation for testing at multiple NASA centers (TRL 3-4 ~ FY14/15)
  - Objective is to test thruster prototype at GRC and JPL for independent validation of performance.
  - Also discussing testing at JHU APL utilizing Cavendish balance approach
GODSPEED!

“READY FOR CREW”