Helical Engine

David M. Burns, Ph.D.[1]
NASA, Marshall Space Flight Center, Alabama, 35812, USA

A new concept for in-space propulsion is proposed in which propellant is not ejected from the engine, but instead is captured to create a nearly infinite specific impulse. The engine accelerates ions confined in a closed loop to relativistic speeds, and slightly varies their velocity to change their momentum. The engine then moves the ions back and forth along the direction of travel to produce thrust. This in-space engine is intended to be used for long-term satellite station-keeping without refueling or to propel spacecraft across interstellar distances. The engine has no moving parts other than ions traveling in a closed-loop vacuum line, trapped inside electric and magnetic fields.

I. Nomenclature

%c	=	velocity represented as a percentage of the velocity of light in a vacuum
Δv	=	change in velocity
100*x*	=	one hundred times the original value
a	=	acceleration
atm	=	one standard atmosphere of pressure
c	=	velocity of light in a vacuum: 299,792,458 meters/second
cm	=	centimeter
cm^3	=	cubic centimeter
F	=	force
He	=	Helium
kg	=	kilogram
km/s	=	kilometers/second
L	=	length
lbf	=	pound (force)
m	=	mass if used in an equation, or meter if used to denote length
m/s	=	meters/second
mm	=	millimeter: 10^{-3} meters
MW	=	megawatt: 10^6 watts (power)
N	=	Newton (force)
N·m	=	Newton-meter (torque)
ns	=	nanosecond: 10^{-9} seconds
ρ	=	momentum (kg·m/s)
RF	=	radio frequency electromagnetic radiation
s	=	second
T	=	Tesla (magnetic flux density)
t	=	time
v	=	velocity
v_z	=	*z*-axis velocity component, which is aligned with the engine's direction of thrust
W	=	Watt (power)
γ	=	Lorentz factor, an element of Special Relativity defined in Table 1

II. Introduction

Chemical, nuclear, and electric propulsion systems produce thrust by accelerating and expelling propellants. Deep space travel is often a trade-off between thrust and large propellant storage tanks that eventually limit performance. The objective of this paper is to introduce and examine a unique engine that uses a closed-cycle propellant. This in-

[1] Manager, Office of Science and Technology.

space engine is intended to provide long-term station-keeping for satellites without refueling and for traveling interstellar distances at high speed. As opposed to "propellantless drives" such as the EM Drive [1], the proposed Helical Engine relies on well understood physical processes. The key challenge is to determine if the engine can provide meaningful thrust within real world engineering constraints.

As a thought experiment, imagine a box resting on a frictionless surface in a vacuum as shown in Fig 1. The box contains a heavy ring that slides easily on a rod and can be given an initial push to one side using a mechanical spring. Also assume that when the ring reaches an end of the box, the resulting collision is elastic. If the ring is pushed towards the right as shown in Fig 1(a), then box will move left as described by Newton's Third Law of Motion. The box will stop when the ring reaches the right side in Fig 1(b). If the ring has an elastic collision with the right side of the box, the ring will then move towards the left and the box towards the right as shown in Fig 1(c). Now imagine that as the ring travels through the middle of the box in Fig 1(c), the ring's mass is halved. When the modified ring reaches the left side as shown in Fig 1(d), the resulting momentum exchange is half the amount exchanged in Fig 1(b), so the box will continue to slide right at half its peak velocity. The system essentially ejected half of the ring's mass as "propellant." If the ring is returned to its original mass while it is moving through the position shown in Fig 1(a), then the cycle can be repeated.

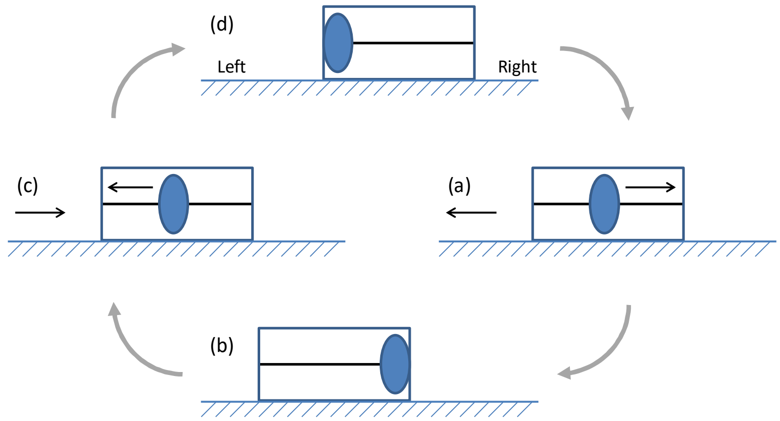

Fig. 1 Thought Experiment.

Each cycle increases the system's velocity, assuming the process used to reduce or increase the ring's mass does not impart a significant momentum change to the box. Even if the box is traveling at 1,000 *km/s* and the ring has a top speed of 10 *m/s* inside the box, the system will accelerate because all components are moving at an initial velocity of 1,000 *km/s* from the perspective of an external observer. Conservation of Momentum applies during the collisions with each end of the box because the ring's mass is constant and there are no external forces acting during these intervals (Fig 1(b) and Fig 1(d)). The ring's mass changes as it travels through the middle of the box (Fig 1(a) and Fig 1(c)), though this does not impact the box's velocity since the ring is traveling at a constant velocity during these phases. The velocity change (Δv) to the box produced in this experiment over one cycle that starts and ends in Fig 1(a) can be represented by Equation 1, where v_z is the starting velocity of the ring with respect to the inside of the box, m_{Box} is the mass of the box, m_1 and m_2 are the mass of the ring when it hits the right and left sides of the box respectively.

$$\Delta v_{Box} = \frac{2 v_z m_{Box}(m_1 - m_2)}{(m_1 + m_{Box})(m_2 + m_{Box})} \tag{1}$$

Note that if the mass of the ring does not change ($m_1 = m_2$), then the net velocity change for the box is zero and momentum is conserved in the box-ring system. The box's acceleration, a, is equal to the velocity change in Equation 1 divided by the time required for the ring to complete a circuit and is shown in Equation 2, where L_{Box} and L_{Ring} are the internal widths of the box and ring, respectively.

$$a_{Box} = \frac{{v_z}^2 m_{Box}(m_1 - m_2)}{(m_1 + m_{Box})(m_2 + m_{Box})(L_{Box} - L_{Ring})} \tag{2}$$

The box's acceleration can be improved by increasing the ring's velocity inside the box, as well as increasing the amount of the ring's mass that is changed. Equations 1 and 2 are not valid when v_z approaches relativistic speeds because relationships for momentum, force, and kinetic energy become more complex.

The ring's momentum is not constant during every point inside the local box-ring system in this thought experiment. Momentum is defined as the product of mass and velocity, and the ring's mass is not constant. The ring requires an external action or force to change its mass, so the thought experiment does not have enough information to evaluate conservation of momentum. If the box and ring continue to accelerate from perspective of an external observer, then the local system's total momentum will increase. Momentum may be conserved in the global sense of the box-ring system and the surrounding environment. Adding or subtracting mass distorts the surrounding space-time environment and requires an external intervention to the local box-ring system. These influences may create a balancing force on the surrounding environment to the acceleration produced by the box and ring, which will conserve momentum at the global level. A method for changing the ring's momentum using external power is presented in the next section, and global conservation of momentum will be revisited in section IV.

III. Implementing Relativistic Momentum Change Using a Particle Accelerator

The proposed engine replaces the solid ring in Fig 1 with a ring of ions rotating in a plane orthogonal to the engine's thrust vector as depicted in Fig 2. The engine varies the rotational velocity of the ions to change their momentum as the ring is moved back and forth inside the engine. To prevent ion velocity changes from negatively impacting the engine's momentum, the radius of rotation for the ions in the ring increases as the ions accelerate and decreases when the ions decelerate. The total number of ions in the engine does not change. The ion's z-axis velocity component is denoted by v_z and is relative to the inside of the engine.

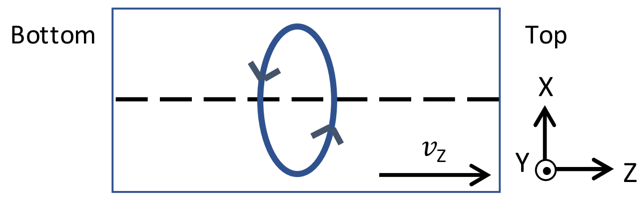

Fig. 2 Diagram of Proposed Engine Operation.

Relationships for momentum, force and kinetic energy are presented in Table 1. Relativistic formulas can be approximated by the classical formulas when an object's velocity is much less than the speed of light [2,3]. γ is the Lorentz factor, an element of Special Relativity [2]. The momentum of each ion (along with other properties, such as length and time) depends on its absolute velocity. The ion's momentum increases faster as a function of its absolute velocity using the relativistic instead of the classical formula because $\gamma \geq 1$.

Table 1 Classical and Relativistic Dynamics.

	Classical	Relativistic	Definitions
Momentum	$\boldsymbol{\rho = mv}$	$\boldsymbol{\rho = \gamma mv}$ using $\boldsymbol{\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}}$	$\boldsymbol{a}$ Acceleration $\boldsymbol{F}$ Force
Force	$\boldsymbol{F = \frac{d\rho}{dt}}$	$\boldsymbol{F = \frac{d\rho^*}{dt}}$ * Must account for direction of travel	$\boldsymbol{KE}$ Kinetic Energy $\boldsymbol{\gamma}$ Lorentz Factor
Force	$\boldsymbol{F = ma}$	$\boldsymbol{F_{\parallel} = \gamma^3 ma}$ Parallel $\boldsymbol{F_{\perp} = \gamma ma}$ Perpendicular	$\boldsymbol{\rho}$ Momentum $\boldsymbol{m}$ Resting Mass $\boldsymbol{c}$ Speed of Light
Kinetic Energy	$\boldsymbol{KE = \frac{1}{2}mv^2}$	$\boldsymbol{KE = mc^2[\gamma - 1]}$	$\boldsymbol{t}$ Time $\boldsymbol{v}$ Velocity

Each ion transfers the z-axis component of its momentum to the top (right side of Fig 2) and then the bottom (left side of Fig 2) of the engine. The ion's z-axis velocity changes at each end are modeled as elastic collisions with the system. Thrust is created because the two momentum transfers are not balanced. The proposed engine attempts to create the momentum difference in these collisions by first accelerating and then decelerating the ions.

Force produced by an ion traveling at a relativistic velocity depends on the ion's direction of travel. Newton's Second Law of Motion can be applied to define force as a change in momentum divided by the amount of time required for that change to occur. The asterisk on the relativistic formula for this method implies there are parallel and perpendicular momentum components that adjust the application of the Lorentz factor accordingly. More force is required to accelerate an object parallel to its direction of travel (proportional to γ^3) than in a direction perpendicular to its direction of travel (proportional to γ). This will be a key relationship that will determine the efficiency of the proposed engine. Relativistic kinetic energy also increases faster than the classical definition as an object's velocity approaches the speed of light.

If an ion rotating in a circle is moved along an axis perpendicular to its plane of rotation, the resulting motion is a helix. Instead of mechanically guiding a fixed ion ring back and forth, a single closed-loop helically shaped beam guide can be used to transport the ions along the optimum path inside the engine. The beam guide is a coiled circular particle accelerator that uses electric and magnetic fields to accelerate and guide ions inside a closed and sealed tubular vacuum line.

A. Implementation Using a Helical Beam Guide

The beam guide is designed to hold the ion's *z*-axis component constant while its absolute velocity is increased or decreased as needed. Fig 3 demonstrates how an ion's *z*-axis velocity component can be held constant while its absolute velocity increases. The radius of curvature increases in proportion to its absolute velocity, so the ion has a longer distance to travel in the *x*-*y* plane as it moves upwards along the +*z*-axis. The engine changes the momentum of ions by increasing and decreasing their rotational velocity around the *z*-axis, which is parallel to the engine's direction of travel. This allows the ion's absolute velocity to be altered without imparting force along the engine's direction of travel.

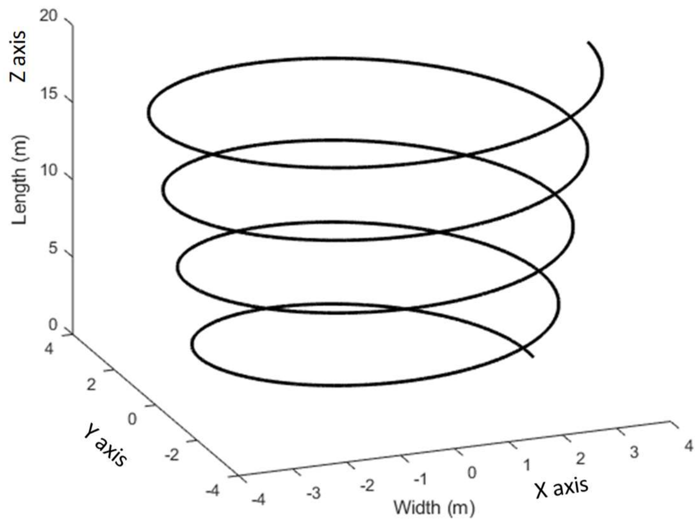

Fig. 3 Increasing Ion Absolute Speed with a Constant *Z*-axis Velocity Component.

The Helical Engine has two concentric helical beam guide "cores." Ions travel toward the top of the engine in an outer core with a constant positive *z*-axis velocity and increasing absolute velocity. This corresponds to the action in Fig 1(a) and is accomplished by accelerating ions using strong electric fields and increasing the radius of rotation. Ions return to the bottom of the engine in an inner core, corresponding to the action in Fig 1(c), with a constant negative *z*-axis velocity and decreasing absolute velocity. This is accomplished by decelerating the ion's rotational velocity using an undulator [4] or similar device to lower the ion's kinetic energy and decrease the radius of rotation. The direction of rotation is the same for both cores. Even if the engine is traveling at a relativistic speed, the system will accelerate because ions are changing momentum according to their own reference frame inside the engine under the General Theory of Relativity.

B. Proposed Helical Engine

An example design is presented in Fig 4(a), where lines represent the path of a single closed-loop beam guide. The green line in the center section of each core identifies the accelerator (outer core) or decelerator (inner core). The radius of rotation changes as needed in the accelerator and decelerator sections to keep the *z*-axis velocity component constant. The ion's velocity on the *z*-axis is reversed in the blue lines at each end so ions can exchange momentum with the engine and the inner and outer cores can connect. Ion absolute velocity (also referred to as the total magnitude of the velocity) is constant in the blue sections of the beam guide.

The beam guide's helical path mimics the path an ion rotating in a ring follows, if the ring is rapidly moved from end to end. Ions travel towards the top of the engine in the outer core in Fig 4(b), which has a radius of curvature that increases in the accelerator region (green line). The beam guide radius of curvature then decreases so it can connect with the inner core. Ions return to the bottom of the engine in Fig 4(c), which has a radius of curvature that decreases in the decelerator region (green line). Ions travel in "bunches" in synchrotrons instead of being equally distributed throughout the volume. It could be possible to set the radius of curvature to the same range for the inner and outer cores, and manipulate the travel time of bunches to avoid collisions.

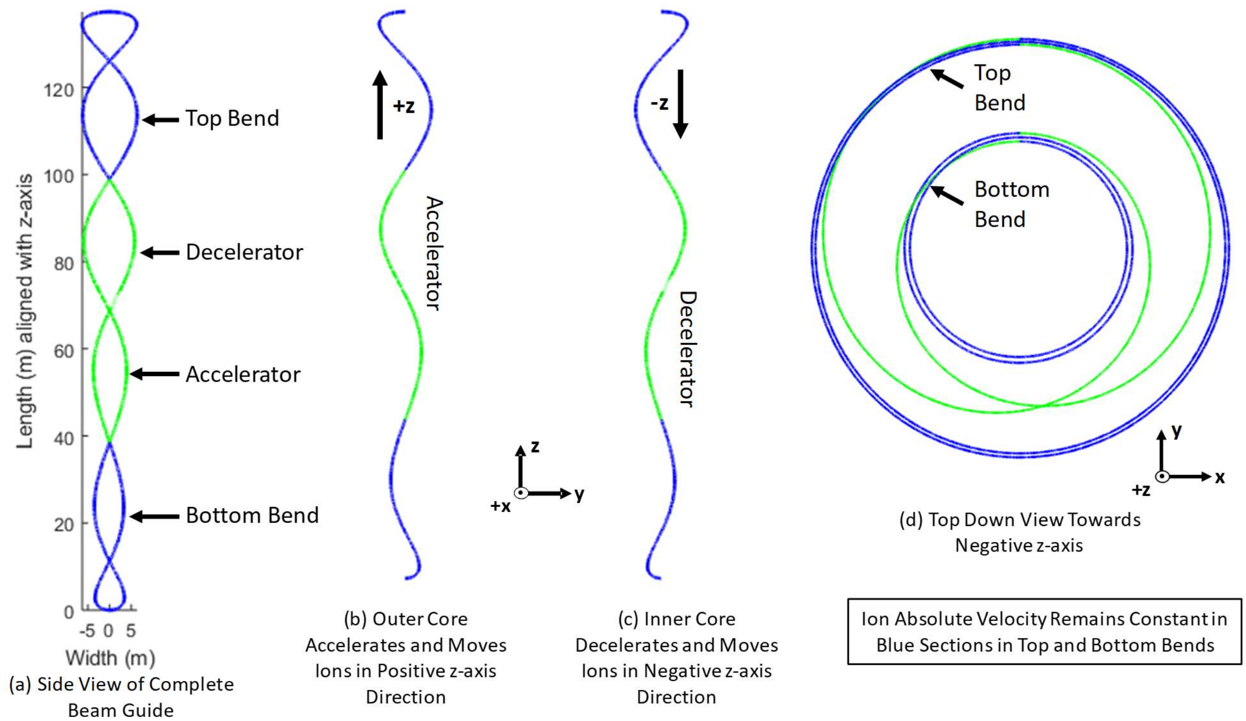

Fig. 4 Side and Top Down Views of a Helical Engine Beam Guide. Ions Accelerate or Decelerate in Green Beam Guide Sections, and Coast in Blue Beam Guide Sections.

C. Relativistic Momentum Transfer Model (RMTM)

The author created a relativistic physics-based model for examining arbitrarily shaped closed-path beam guide structures. The Relativistic Momentum Transfer Model simulates force, mass, energy, and velocity. The model also predicts magnetic, electric, and radiation fields and emissions. A specific implementation of the design architecture depicted in Fig 4 was created and analyzed using RMTM and is presented in Table 2. The *z*-axis roll-out angle is the initial angle of the beam guide in the accelerator region with respect to the *x-y* plane.

Table 2 RMTM Simulation of An Example Design.

Beam Guide		Simulation Output			
Beam Diameter	5 *mm*	Minimum Velocity	99.0 *%c*	Thrust (z-axis)	
Ion Type	Alpha (He++)	ϒ Calculated using Table 1	7.0888	Accelerator	-2.103 x 10^{-8} *N*
Ion Pressure	10^{-11} *atm*	Maximum Velocity	99.05 *%c*	Top Bend	+42.37 *N*
Total Round Trip Length	576.9 *m*	ϒ Calculated using Table 1	7.2648	Decelerator	-2.345 x 10^{-8} *N*
Total Volume	11,328 cm^3	Average Velocity	99.024 *%c*	Bottom Bend	-41.34 *N*
Outer Core Radius		Ion Cycle Time	1,943 *ns*	Total Thrust	1.03 *N*
Minimum	6.5 *m*	Total Number of Ions in Beam Guide	3.029 x 10^{12}		0.231 *lbf*
Maximum	6.527 *m*	Ion Lifetime	10 *hours*	Total Torque	1.226 x 10^{-5} *N·m*
Inner Core Radius		Ion Mass Expended Each Year	1.776 x 10^{-11} *kg*	Power	
Minimum	6.25 *m*	Maximum Magnetic Field	7.18 *T*	Accelerator Power	165 *MW*
Maximum	6.278 *m*	Average Magnetic Field	6.97 *T*	Decelerator Power*	-165 *MW*
Z-axis Roll-Out Angle	70°	Average X-Ray Emissions	5.02 x 10^{-11} *W*	* Decelerator generates power	
Samples in Simulation	2,451,600	RMTM Version: 2.41			

The design presented in Table 2 was predicted to produce approximately 1 *N* of continuous thrust by the RMTM simulator. The relativistic momentum of each ion is higher at the top of the engine than the bottom. The small *z*-axis thrust losses for the accelerator and decelerator regions are due in part to the use of a low pass filter during construction, which was applied to smooth the beam guide structure and avoid discontinuities. Fig 5 was produced by RMTM and shows the system level force and velocity changes resulting from all ions traveling through a complete circuit of the beam guide. Fig 5(a) shows the *z*-axis force and Fig 5(b) shows the resulting system velocity change, assuming an arbitrary system mass of 10,000 *kg*. The time scale used on the bottom axes of Fig 5 indicates the position of ions in the engine. Ions start at the bottom of the engine (time equals zero) and travel through the outer core. Ions transition to the inner core at 971.5 *ns*. Ions complete a round trip when they return to their original starting position at 1,943 *ns*. This scale is also used in Fig 6. The vertical axes show the force or velocity change for each segment in the simulation.

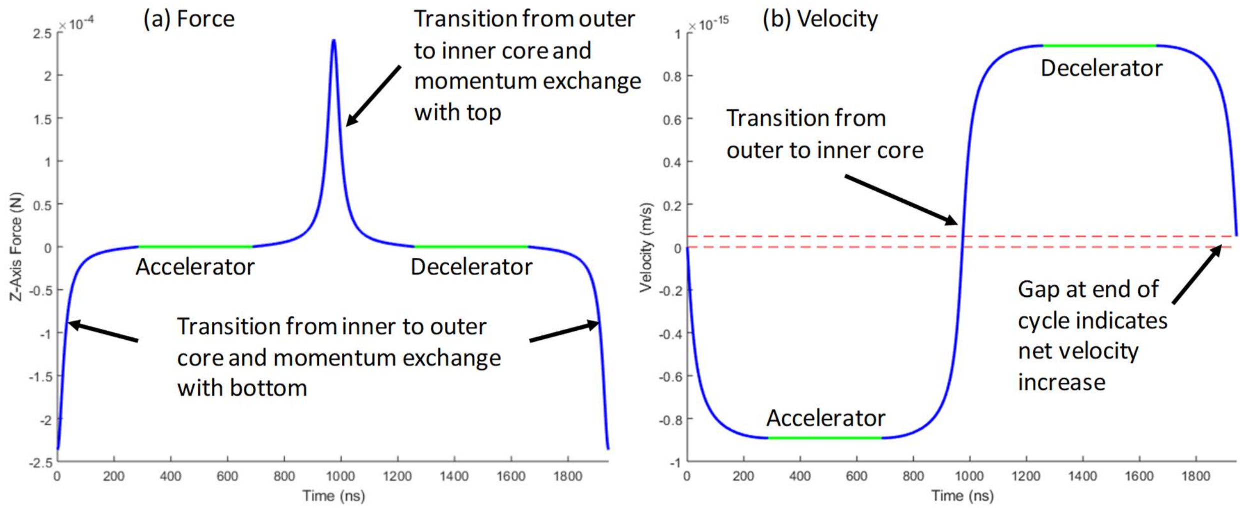

Fig. 5 Effect of all Ions Completing a Single Cycle in the Beam Guide.

Each ion starts at the bottom of the engine and then travels up towards the accelerator region in the outer core, imparting a negative force to the system. The ion's *z*-axis velocity is almost constant inside the accelerator, so only a very small force is transferred to the system. The ion then moves towards the top of the engine and applies a positive force to the system as its *z*-axis velocity is reversed. The ion's *z*-axis velocity is almost constant inside the decelerator, so only a very small force is transferred to the system. The ion then returns to the bottom after exiting the decelerator, which applies a negative force. The velocity change for an ion traveling through a single cycle is small, however the beam guide contains over 3×10^{12} ions that complete over a half million round trip cycles each second.

Each ion applies a force aligned with the *z*-axis when the *z*-axis component of its velocity changes. The *z*-axis velocity component of each ion as it completes a round trip is shown in Fig 6, starting from the bottom of the engine. The ion's *z*-axis velocity is negative when it is moving in the inner core back towards the bottom of the engine because it is then traveling in the negative *z*-axis direction. The ion's absolute velocity in Fig 6 includes all three axis velocity components. As the ion's absolute velocity increases, its relativistic momentum increases non-linearly at a faster rate than the classical formula as predicted by the momentum equations in Table 1.

Regrettably, the accelerator section of the design defined in Table 2 requires 165 *MW* of power for continuous operation. This power can also be approximated using the change in ion relativistic kinetic energy and the amount of time required to make this change. The actual "wall plug" power will depend on many other factors. Fortunately, power produced in the inner core's decelerator is nearly equal to this amount. If all the power collected in the decelerator could be applied to the accelerator, the design described in Table 2 would require less than 10 *watts* to offset momentum and radiation losses for all ions during operation. Additional power would be required to generate control electric and magnetic fields inside the beam guide. Harvesting power in the decelerator is not only important for improving engine efficiency – it also reduces the amount of heat that must be dissipated from the engine during operation.

The engine scales linearly with power. 100*x* the power and 100*x* the ion density, yields 100*x* the thrust without increasing the peak magnetic field. Thrust is scaled by adjusting the ion density (number of ions inside the engine) and power, or ion mass and power – not the velocity of the ions inside the system. The ion velocity range is set when the engine is designed because this range determines the radius of curvature in the beam guide. Replacing ionized Helium with Xenon for example would increase ion mass and increase the available engine thrust.

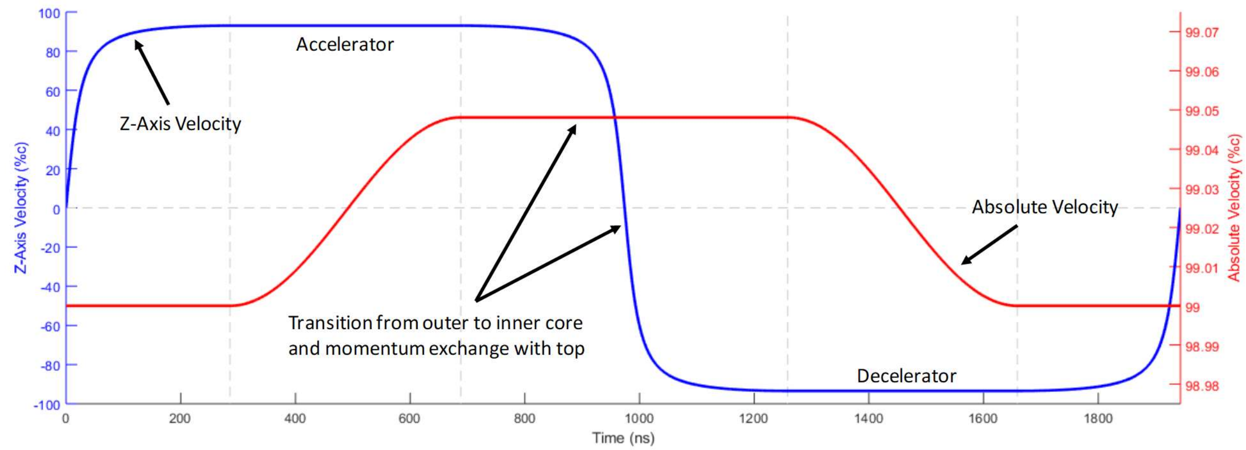

Fig. 6 *Z*-axis and Absolute Ion Velocity (Magnitude) During A Round Trip.

The efficient transfer of energy from the inner to outer core is important if this engine is to become feasible. An initial concept for harvesting energy in the decelerator is to use magnetic undulators tuned to produce RF fields that directly accelerate ions in the accelerator. This approach transfers energy efficiently, avoiding parasitic losses typical with electrical conversion processes. The helical design brings the accelerator and decelerator beam guide sections into proximity, reducing energy transfer path lengths. Additional loops can be added to increase thrust or aid in thermal dissipation. Ions travel in bunches and their position can be accurately controlled. The author proposes to use this precision to position decelerating ions to reinforce accelerating ions in an adjacent section of the beam guide.

Ions in a synchrotron may have lifetimes of 10 hours or more – implying the design presented in Table 2 may require only 17.76 *nanograms* of ionized Helium for each year of continuous operation. Although specific impulse is not strictly appropriate for this class of engine, this ion lifetime gives an equivalent specific impulse of 1.86×10^{17} seconds for the engine design defined in Table 2. Ions in the beam guide could be replenished by injection from a secondary linear accelerator, a technique currently used in synchrotrons. Ion lifetime may be increased by operating the engine continuously because this could gradually eliminate contamination in the beam guide. It is also possible the engine could harvest helium from its surrounding environment or the power generation source. Alpha particles can be produced during radioactive decay.

Modeling indicates the engine architecture will produce measurable torque around the z-axis if the radii of inner and outer cores are not equal. This may be beneficial, and the design could be adapted by substituting electrons for ions in a compact cyclotron/microwave tube assembly to replace satellite reaction wheels. A pair of engines with counter-rotating ions could produce and manage torque.

D. Engine Efficiency

Thrust can be improved by designing the beam guide to operate with higher ion velocity, however the required accelerator power and magnetic field also increase. A strong magnetic field is required to bend the ion's direction of travel so that it remains in the center of the beam guide and does not impact the walls of the vacuum chamber. The accelerator applies an in-line (parallel) force to accelerate ions, which scales proportionally to γ^3. Since the beam guide is curved, most of the momentum exchange at each end of the engine is perpendicular to the ion's direction of travel unless the ion is traveling at an extremely high velocity. As a result, most of the momentum transfer forces in the top and bottom bends are proportional to γ until the ion velocity approaches the speed of light. When ion velocity approaches the speed of light, the γ^3 momentum term in the ends of the engine begins to dominate. Fig 7 shows the effect of increasing the minimum velocity using a constant input power of 165 *MW*. Thrust efficiency increases dramatically for ion velocities at or above 99.99 *%c*, however the peak required magnetic field also increases rapidly. For comparison, the Large Hadron Collider can accelerate ions to 99.9999991 *%c* with a beam guide circumference of 27 kilometers and magnetic fields that exceed 8 *T* [5].

If most of the power in the decelerator can be recovered, then higher average ion velocities may improve overall system efficiency. The total length of the beam guide decreases as the minimum ion velocity increases for a given applied power level because the range of the radius of curvature in the accelerator/decelerator sections decreases. Future designs could alter the ends of the engine to make momentum transfer more of a direct reflection (parallel force). Additional beam guides could be "woven" into the architecture shown in Fig 4 to increase thrust.

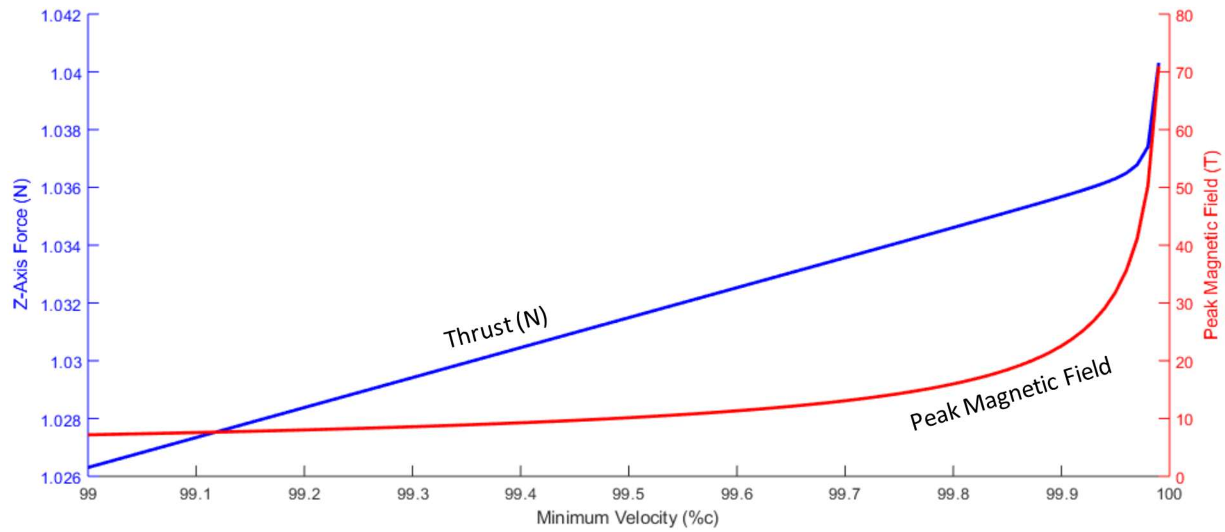

Fig. 7 Thrust and Peak Magnetic Field for a Constant Applied Power of 165 MW.

IV. Conservation of Momentum

The high required power and low resulting thrust seem to imply the principle of conservation of momentum is present, however the engine theoretically continues to accelerate if it has power. There are several ways momentum can be conserved from a global perspective.

The process of increasing and decreasing the ion's relativistic momentum along with producing the required power may distribute the momentum change to the surrounding environment external to the engine. Some process must be used to generate the required power, and this process could conserve momentum in a global sense. This is difficult to quantify, given the current abstract method for modeling the engine's performance.

The ions inside the engine may accumulate an offsetting momentum. For example, the ions may develop spin during each trip around the engine. This spin could eventually lower or even halt engine thrust. Ion spin is dependent on the specific beam guide implementation design and is not currently modelled in RMTM. This is an area where a more detailed model or testing would be very useful. It may be possible to mitigate ion spin by using a pair of counter-rotating Helical Engines that share a single beam guide. This technique could prevent ion spin from accumulating during subsequent round trips through the engine. A pair of counter-rotating Helical Engines could also be used to manage torque.

Another possibility for momentum conservation is beam guide emissions. The beam guide requires strong magnetic fields to bend the ion's direction of travel and high electric fields to alter the ion's velocity. Ions traveling in the beam guide produce x-ray emissions during each circuit. These fields and emissions may radiate energy to the surrounding area that would balance the accelerating engine.

V. Future Work

Anchoring the Relativistic Momentum Transfer Model with relevant test data is essential to continuing the research. Modeling the momentum of charged particles moving at relativistic velocities around an arbitrarily curved path is complex and the magnitudes of velocity and resulting forces span many orders of magnitude. Small round-off errors could propagate into larger errors during each simulation. RMTM has been evaluated using basic checks, such as calculating consistent thrust near boundary conditions; generating zero net thrust for non-helical architectures; and providing stable predictions for a wide range of simulation step sizes. However, RMTM needs to be validated and verified through the testing of helical beam guide shapes in a synchrotron.

The Helical Engine design can be improved based on RMTM simulations. The design currently uses a tapered power distribution profile in the accelerator and decelerator sections. This causes ripples, which account for small negative forces in the accelerator and decelerator as listed in Table 2. If power was applied and removed using a more optimum technique, then there would be less z-axis force losses during transitions in and out of these sections. The engine design could also be improved so that more of the momentum exchange at each end results in parallel instead of perpendicular force based on the ion's direction of travel. This could greatly increase engine power efficiency and improve operation at higher minimum ion velocity. Replacing ions with electrons would greatly decrease engine thrust, but would simplify construction, reduce costs, lower power requirements, and validate the concept.

VI. Conclusions

Producing 1 *N* of thrust using megawatts of power and a space-rated synchrotron is not a compelling reason to build this engine – however the concept can theoretically produce thrust even though the engine is inside an enclosed volume. There are many paths to make the engine more efficient and powerful.

Key benefits: the engine can operate indefinitely without significant refueling; be energy efficient (provided the decelerator energy is harvested); be reliable as ions are the only moving part; and have an extremely high speed. The engine could be powered by solar energy for satellite station keeping or a nuclear reactor for interstellar travel [6]. It may be the only practical long duration interstellar engine based on existing technology. The Helical Engine is possible because of recent innovations: an engine architecture that conserves propellant and offers an opportunity to recover energy used to accelerate ions; lightweight, efficient, space-rated, neutrally-charged particle beam components developed by National Laboratories; space-qualified nuclear reactor technology developed by NASA; and lightweight magnets and high efficiency undulators developed for producing synchrotron radiation in particle accelerators.

Challenges include significant engineering design hurdles and trades. Particle accelerators can produce intense x-rays and are traditionally designed for nuclear chemistry, with magnets, shielding, and detectors often weighing hundreds of tons. There are numerous technical challenges to be addressed before a practical engine can be realized:

a) Efficient power collection and transfer from the decelerator to the accelerator is key to the feasibility of this class of propulsion. This technology is mature for producing low current spectrally pure energy from electrons, but it has not been developed for continually producing high current from heavier ions. The proposed engine architecture requires high current and high efficiency.
b) The design is not proven or optimized, and the author's system level models need to be examined by the particle accelerator technical community. The point design described in Table 2 can be improved, with tradeoffs between applied magnetic field, ion density, power, cycle time, and thrust. Many design parameters are dependent on power, ion chemistry, curvature, and minimum ion velocity.
c) High temperature materials and components, including high efficiency electromagnets. Revolutionary material advances, including superconducting magnets designed and manufactured for the Large Hadron Collider [5], may enable the proposed engine. New particle accelerator designs can be optimized for high current and low mass – suitable for space propulsion but not traditional nuclear chemistry applications. A space-based neutrally charged particle beam missile interceptor was designed and flight-tested by the Los Alamos National Laboratory in 1989 but was not fielded due to a shift in national strategy [7].

The Helical Engine could be an interesting testbed for exploring the relationship of Conservation of Momentum to mass, force, and energy.

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[3] Forshaw, J. R. and Smith, A. G. (2009). Dynamics and Relativity. Great Britain: John Wiley & Sons Ltd.
[4] An Undulator, also known as a wiggler, is a series of alternating magnetic fields that decelerate a charged particle and emit focused energy at a specific design frequency.
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