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Extended Cases of Laboratory Generated Gravitomagnetic Field Measurement Devices

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Abstract

A method is described for creating a measurable unbalanced gravitational acceleration using a gravitomagnetic field surrounding a superconducting toroid. A gravitomagnetic toroid for unbalanced force production has been experimentally realized as quite impractical. However recent advances in nanorod superconducting wire technology has enabled a new class of SMES devices operating at current densities and magnetic field strengths sufficient to develop measurable gravitomagnetic fields, while still maintaining mechanical integrity. It is proposed that an experimental SMES toroid configuration uses an absolute quantum gravimeter to measure acceleration fields along the axis of symmetry of a toroidal coil, thus providing experimental confirmation of the additive nature of the gravitomagnetic fields, as well as the production of a linear component of the overall acceleration field. In the present paper relativistic enhancement of this effect is also explored, as well as alternating current (AC) operations of the superconducting toroid to create gravitational waves. Lorentz force concerns are also addressed in **Appendix**.

Keywords

Gravitational, Gravitomagnetic, Lense-Thirring, Superconducting Magnetic Energy Storage, SMES, Nanorods, Nanowires

1. Introduction

When Forward [1] first proposed a gravitomagnetic toroid for unbalanced gravitational force production in 1962 any experimental realization was quite impractical. However recent advances in high temperature superconducting (HTSC) nanorod wire (nanowire) technology, described recently by Rieken and Bhargava *et al.* [2], have enabled a new class of superconducting magnetic energy storage (SMES) devices operated at current densities and magnetic field strengths sufficient to develop measurable gravitomagnetic fields, while still maintaining mechanical integrity. In the present study, it is proposed that an experimental SMES toroid configuration uses a set of standard accelerometers to measure acceleration fields along the axis of symmetry of a toroidal coil, thus providing experimental confirmation of the additive nature of the gravitomagnetic fields, as well as the production of a linear component of the overall acceleration field. See Figure 1 for details.

In the instantiation of Forward's gravitational generation coil described in this paper superconducting electron flow provides the change in mass current in the toroid.

2. Background

In this section, we provide summaries of enabling developments in high current density nanorod conductors, as well as the overall design and use of Superconducting Magnetic Energy Storage (SMES) devices, which are emerging as an alternate approach to energy storage that does not require chemical energy technologies.

2.1. Superconducting Nanorods

New developments in nanomaterial processing of superconductors [2] [3] have led to the discovery of nano-tubular superconductors Rieken and Bhargava *et al.* which have a T_c at 92 K. A uniqueness of the nano-tubular and other geometric structures of high temperature superconducting (HTSC) makes for a practical wire form without using the melt texturing techniques which make for brittle

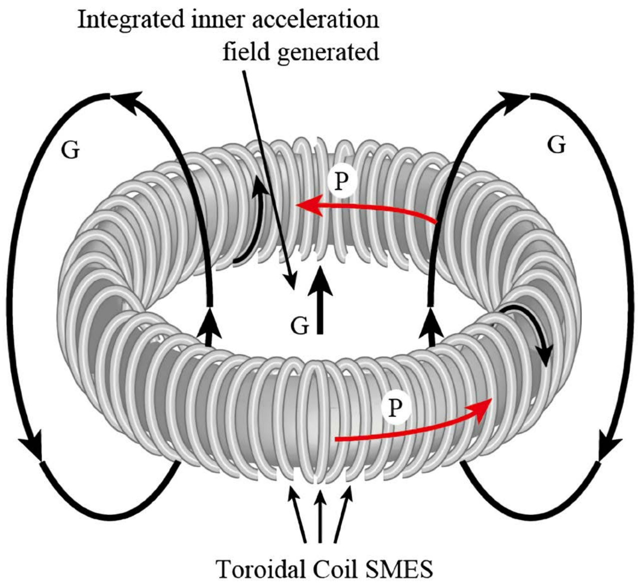


Figure 1. Gravitational force generation coil from Forward 1962 [1] with an inspiralling mass current, with a vector potential P, creating gravitomagnetic field G, which is additive in the center.

thin films that are also difficult to shape into wire. Another aspect of these new HTSC materials is negation of post oxygenation at high temperatures. The elimination of this requirement makes room temperature forming and application of HTSC materials practical. The process has been demonstrated to be a low-cost and mass production method of superconductors which is scalable and without vacuum or cleanroom requirements, Rieken and Bhargava *et al.* [2]. These developments have led to the commercialization by True 2 Materials PTE., LTD (T2M) in Singapore, of a new HTSC wire using standard wire making practices.

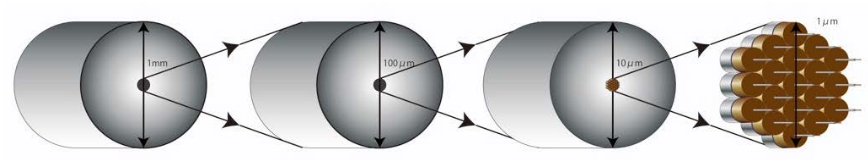
Although the critical temperature of the wire is 92 K, operation at 77 K in liquid nitrogen is more reasonable due to safety issues with gases and nitrogen's inertness, non-explosive and non-flammable, as a cryogenic liquid. Currently T2M prototype wire is in the millimeter range and approaching the micron range. However, development of an HTSC wire, or filament at nanometer scale is on the roadmap [3] of T2M. The estimated diameter of the wire used in this study, currently theoretical, is 200 nm O.D. including insulation and a 30 nm O.D. HTSC core, with the total weight of the wire at approximately 0.001 g/m.

Individual wires make up a 19 nano filament cable of 1 micron diameter as shown in **Figure 2(a)** illustrate the compactness of the nano cable design. This allows the scaling up of the critical current limit, quenching aside, without adding significant weight to the toroidal coil. The individual nano filament as described in **Figure 2(b)** as illustrated is composed of a core (a), core sleeve (b), a highly-insulated sleeve (c) with good heat transport properties and a high strength giga-pascal (GPa) outside sleeve (d) which also possesses good heat transport properties at low temperatures. The main consideration for a candidate of the materials used in this study would be of carbon composition.

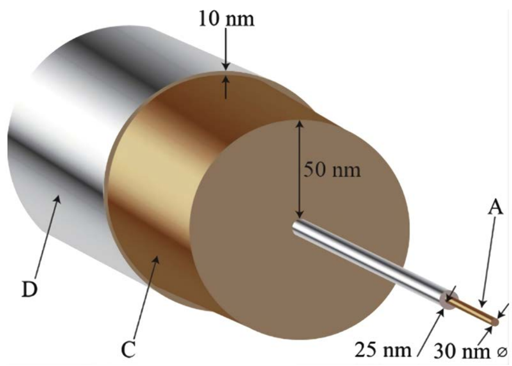
To meet the 250 MA/m^2 required in this study thousands of filaments may be required, even with current flow between 2000 A/mm^2 to as high as 20,000 A/mm^2, although higher currents should be obtained by decreasing temperatures from 77 K to 4 K. This would allow many different cable packing designs giving designers greater freedom in energy flow design. As such the description above may be possible within practical limits due to the size and weight of each filament. Progress and work on development of a geometrical superconductor has been accomplished, however still under study, which may have high enough current densities to overcome thousands of Tesla of internal magnetic field, thereby overcoming the problems of quenching. This is partially accomplished due to the geometry of the material and near perfect crystal alignment enhancing flux trapping due to a ferromagnetic component. It is also considered and still under study that vortex quantum effects, *i.e.* quantum entanglement, are also playing a role in reducing or elimination of quenching.

2.2. Superconducting Magnetic Energy Storage

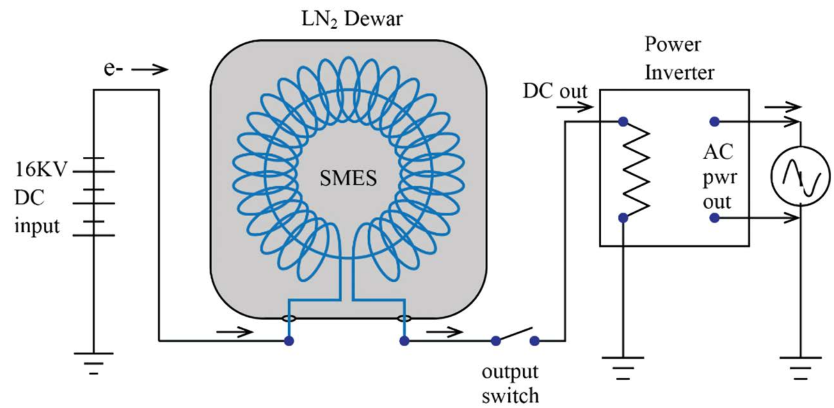
Superconducting Magnetic Energy Storage (SMES) devices are an emerging battery replacement technology [4]. A typical application is shown in **Figure 2(c)**.



(a)



(b)



(c)

Figure 2. (a) Representation of multiple filaments in a cable where each 1 micron yields 19 nano filaments; (b) Detailed illustration of a nano wire filament; (c) SMES in an Energy Storage Application.

The device is fed by a DC current, developing a magnetic field, typically in a toroidal geometry coil. When the need for emergency power is detected, an output switch is activated that provides DC current out, which may be converted to AC power by a power inverter.

Given the recent advances in nanowire as described in Section 2.1, these devices are poised for remarkable improvements in capability in the very near term. With these coming improvements in this technology, and the similarity in geometry with the Forward design of Figure 1, the present paper will study this technology at its limits for possible reapplication as a DC or low frequency gravitomagnetic generator.

3. Gravitomagnetic Force Equation for Toroid Mass Flow

As developed in Forward 1962 Ref. [1] the linear force G_f developed by gravitomagnetic force in the mass flow toroid of **Figure 1** is given by Equation (1):

$$G_f = \left(\frac{\eta}{4\pi}\right)\left(N\dot{T}r^2/R^2\right) \tag{1}$$

where η is gravitomagnetic permeability, $\eta = \eta_o \eta_r$.

Single electron mass flow shown in **Figure 3** is given by mass momentum in Equation (2):

$$T_e = p_e = (\Omega \times r) m_e \tag{2}$$

where Ω = angular rate, angular velocity is $v = \Omega \times r$ in the classical case [5].

Change in mass flow for the single electron flow shown in **Figure 3** is given by Equation (3):

$$\dot{T}_e = \dot{p}_e = a \cdot m_e = (\Omega \times v) m_e \tag{3}$$

This is equivalent to centripetal force shown in Equation (4):

$$\dot{T}_e = F_e = m_e v^2/r = m_e a_e = m_e\left(\omega^2 r\right) \tag{4}$$

where ω is the angular rate, given in Equation (5):

$$\omega = 2\pi/t_p = \frac{\mathrm{d}\theta}{\mathrm{d}t} \tag{5}$$

We now consider the same circular motion, but in a relativistic regime. Relativistic circular motion [6] can be described by Equation (6):

$$\bar{u} \cdot \bar{a} = 0 \rightarrow \alpha^2 = \gamma^4 \cdot a^2 \tag{6}$$

which reduces to Equation (7) for the relativistic acceleration of circular motion:

$$\alpha = \gamma^2 \cdot v^2/r \tag{7}$$

From Equation (4), mass flow change (force) for a relativistic electron is therefore expressed as follows:

$$\dot{T}_e = m_e\left(v^2/r\right)\gamma^2 \tag{8}$$

where m_e is rest mass and gamma γ is defined [7] as Equation (9):

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}} \tag{9}$$

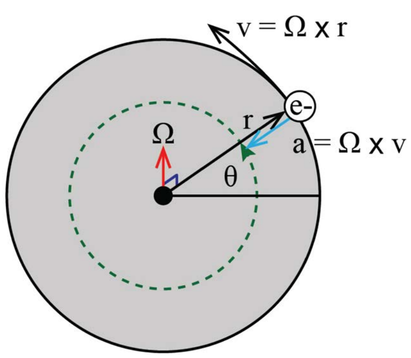


Figure 3. Electron orbit around one loop of SMES toroid.

Effects go as gamma squared. Numerical solutions are described in **Table 1**. Relativistic cases will be explored further in Section 7.

4. Current in Idealized SMES

We now attempt to estimate the possible currents enabled by the emerging technology of Section 2.1 as it relates to the core geometry constraints described in **Figure 4**, a toroid with torus geometry. We start with the assumptions needed to calculate the number of turns N.

From Equation (1) the torus assumptions made in **Figure 4** can be factored into Equation (10) as follows:

$$G_f = \left(\frac{\eta_o \eta_r}{4\pi}\right)\left(N\dot{T}r^2/R^2\right) \quad (10)$$

where:

G_f = gravitomagnetic force;

η_o = absolute gravitomagnetic permeability;

η_r = relative gravitomagnetic permeability;

N = number of turns in the coil of the torus;

$\dot{T}$ = change in mass flow;

r = cross section radius of torus;

R = centerline radius of torus.

For the purposes of describing an idealized case with a realistic geometry we develop a description of a device bounded by a 10 meter toroid centerline diameter, shown in **Figure 4** and **Figure 5**, and with a cross-sectional diameter of 1 meter, as shown in **Figure 4**. We furthermore define 16 sectors as shown in **Figure 5** for possible AC operation described further in Section 8.

Table 1. Relativistic parameters for uniform circular motion of an electron (SI units).

Velocity (relative to speed of light)	Gamma squared, γ^2 (unitless)	Relativistic acceleration, a (m/s^2)	Per electron predicted force developed, $\dot{T}_e$ (N)
$0.5c$	1.3	$5.9(10)^{16}$	$5.4(10)^{-14}$
$0.9c$	5.3	$7.7(10)^{17}$	$7.0(10)^{-13}$
$0.99c$	50	$9.1(10)^{18}$	$8.3(10)^{-12}$
$0.999c$	500	$9.0(10)^{19}$	$8.2(10)^{-11}$
$0.9999c$	5000	$9.0(10)^{20}$	$8.2(10)^{-10}$
$0.99999998c$	25,000,000	$4.5(10)^{24}$	$4.1(10)^{-6}$

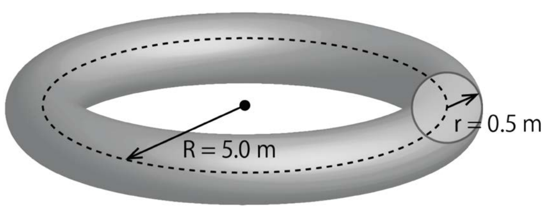


Figure 4. Toroid with a torus shaped core geometry, idealized case.

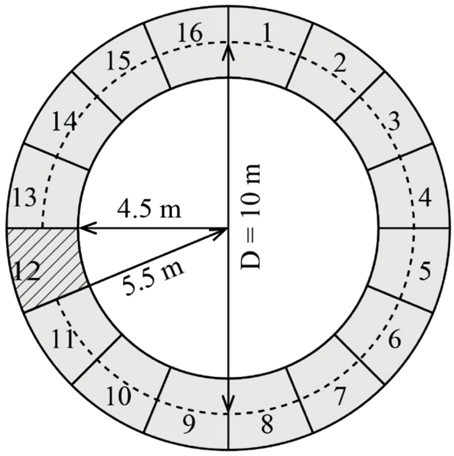


Figure 5. Torus section definition.

We further add additional assumptions regarding to what extent conductors are wrapped around the toroid shaped device to determine constraints on the number of conductive loops that can be accommodated using the technology described in Section 2.1. As shown in **Figure 6** via cross section we assume here a conductor winding depth of 0.5 m.

The segmented share of the inside of cross section C_s is 1/16th of the overall inner circumference as given in Equation (11) as follows:

$$C_s = 2\pi r_i / 16 = 1.57 \text{ m} \tag{11}$$

with a depth D the minimum inner loop cross sectional area can be described in Equation (12) as follows:

$$A_{sec} = D \cdot C_s = 0.5 \text{ m} \times 1.57 \text{ m} = 0.785 \text{ m}^2 \tag{12}$$

This area is shown packed with conductors in **Figure 7**. Windings are depicted as packed in depth and along sector circumference.

Assuming each nanowire conductor has a diameter d_c of 100 µm, then the cross-sectional area of each conductor will be given by Equation (12) as follows:

$$A_c = \pi r^2 = 7.854 \times 10^{-9} \text{ m}^2 \tag{13}$$

For packing the conductors in a cross sectional area described in **Figure 7**, assume as a worst case rectangular area described by the shortest edges such that a number of conductors in depth, N_d, may be packed in one dimension, with the number of conductors, N_{cs}, packed in the other dimension. These packing counts may be calculated in Equation (14a) and Equation (14b) as follows:

$$N_d = D_c / d_c = 0.5 \text{ m} / 100 \text{ µm} = 5000 \tag{14a}$$

$$N_{cs} = C_s / d_c = 1.57 \text{ m} / 100 \text{ µm} = 15700 \tag{14b}$$

The total number of windings by sector will therefore be the product of N_d and N_{cs}:

$$N_{sec} = N_d \cdot N_{cs} = 5000 \times 15700 = 78500000 \tag{15}$$

And with 16 sectors the total number of windings for the entire toroid will be:

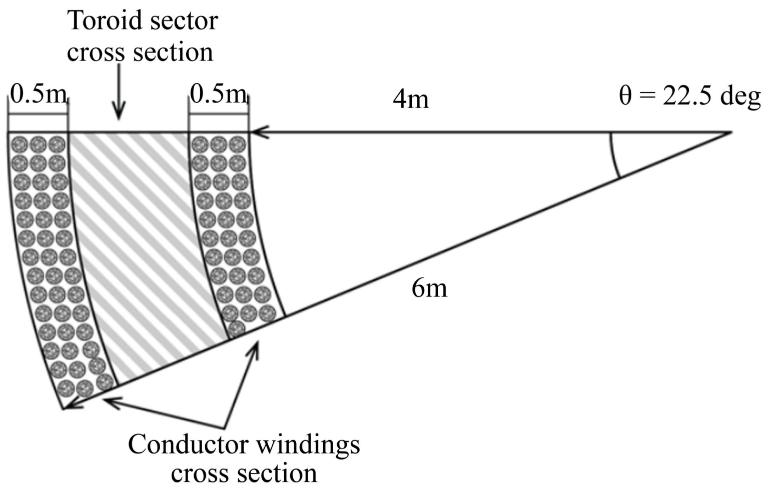


Figure 6. Conductor cross section in each sector.

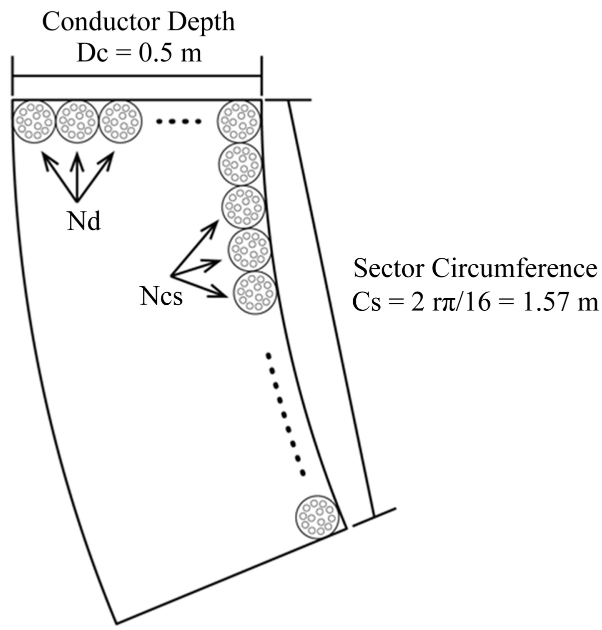


Figure 7. Conductor packing in each sector.

$$N = 16N_{cs} = 1.256\times10^{9} \tag{16}$$

what is $\dot{T}$ with the forgoing assumptions?

In this idealized case electrons circulate about a coil of circumference c_r, or slightly larger, as described by Equation (17):

$$c_r = 2\pi r = 3.14\text{ m} \tag{17}$$

Non-relativistic case

Consider two cases, the first a non-relativistic case. Assume further a supply voltage of 16 KV, resulting in 16 KeV of kinetic energy for each electron, which corresponds with the upper limit of a non-relativistic case, where $v = 0.25c$, so that $\gamma = 1.06 \sim 1.0$.

Then from Equation (4) for non-relativistic circular motion, the vector change in DC current flow is:

$$\dot{T}_e = m_e v^2 / r \tag{18}$$

which for a single electron has the following values:

m_e = mass of the electron = 9.11 × 10^{-31} kg;

v = velocity of the electron = 0.25c = 0.75 × 10^8 m/s;

r = 0.5 m for the assumed geometry.

And where the angular acceleration of the electron is:

$$a_e = v^2 / r = 1.125 \times 10^{16}\ \text{m/s}^2 \tag{19}$$

Thus, change in mass flow represents centripetal acceleration in the case of circular motion:

$$\dot{T}_e = m_e \cdot a_e = 10.25 \times 10^{-15}\ \text{N} \tag{20}$$

Equation (20) corresponds to the change in mass flow for one electron in one loop of coil. Total mass flow change is therefore the mass flow change per electron times the number of electrons:

$$\dot{T} = \dot{T}_e \cdot N_e \tag{21}$$

what is the number of electrons N_e in one loop in motion (part of the mass flow) at a given time for an assumed velocity of v = 0.25c? N_e in one loop can be described by the current I times the period of a single loop circulation Δt:

$$N_e = I \cdot \Delta t \tag{22}$$

where the period of an orbit can be described by:

$$\Delta t = c_r / v = 2\pi r / v = 41.89\ \text{ns} \tag{23}$$

what is the possible current inside the idealized device for the case where the entire winding is in series? We make the assumption about max current to stay below critical current density of 250 MA/m^2 as described in Section 2.1.

Current is limited by the maximum permissible current density and the cross section of the conductor t:

$$I = J \cdot A_c \tag{24}$$

where J is material dependent. For the nanowire assumed in Ref. [2], J = 250 MA/m^2. Cross sectional area A_c = 7.854 × 10^{-9} m^2 as given in Equation (13). Therefore, maximum current for this conductor diameter is I = 1.96 Amps.

Expanding on Equation (22) the number of electrons N_e in circulation in one loop may be calculated by noting that there are 6.2415 × 10^{18} electrons per Coulomb:

$$N_e = \left(\frac{\text{electrons}}{\text{Coulomb}}\right) I \left(\frac{\text{Coulombs}}{\text{sec}}\right) \cdot \Delta t = 5.12 \times 10^{11}\ \text{electrons} \tag{25}$$

5. Forces in Idealized SMES

Expressing Equation (21) as force per electron times the number of electrons in motion in one loop:

$$\dot{T} = \dot{T}_e \left(\frac{\text{Newtons}}{\text{electron}} \right) \cdot N_e \left(\#\text{electrons} \right) = 5.248 \text{ mN} \tag{26}$$

Thus, each loop experiences about 5 mN of integrated centripetal force ($\dot{T}$) due to the electrons in circulation within.

We now describe the scale factor to couple this force to the gravitomagnetic effect.

Revisiting Equation (10) which describes the overall linear force developed at the center of the toroidal coil, total gravitomagnetically developed force will be:

$$G_f = (\eta_o \eta_r)\left(N\dot{T}r^2 / 4\pi R^2 \right) = (\eta_o \eta_r)(5248 \text{ N}) \tag{27}$$

where known variables have been grouped on the right and unknown variables have been collected on the left. This raises the question what are the correct values for η_o and η_r ?

If η_o goes as G/c as does gravitomagnetic potential (Ref. [8], Equation (1.5)), then:

$$\eta_o = -G/2c = 1.11 \times 10^{-19} \tag{28}$$

In this case $G_f = (\eta_r) 5.8 \times 10^{-16}$. Values of η_r are experimentally unknown at this time. However if values of η_r track values of μ_r then values as high as $\eta_r = 10^6$ may be possible, yielding $G_f = 5.8 \times 10^{-10} \text{ N} = 0.58 \text{ nN}$.

Even with very sensitive measurement apparatus this would be a very difficult measurement. However, with additional current or winding count a device scaled up from the idealized case considered in this paper may someday achieve a measurable DC gravitational field, even in the non-relativistic case considered in this section.

6. Stored Energy in an Idealized SMES

What is the stored energy in the idealized torus for the non-relativistic case of Sections 4 and 5? The total energy is the sum of E_k, the kinetic energy of all of the particles in motion within the coil, and the contained magnetic field energy E_m:

$$E_T = E_k \cdot E_m \tag{29}$$

where kinetic energy E_k in all loops from all electrons in each loop is:

$$E_k = NN_e \left(\frac{1}{2} m_e v^2 \right) = 1.65 \text{ MJ} \tag{30}$$

where winding count N is defined in Equation (16) and electrons per loop N_e is defined in Equation (25). Velocity assumed here is the essentially non-relativistic case of $v = 0.25c$.

Magnetically stored energy is the primary purpose of SMES devices and is where most of the energy is contained. For a coil the magnetically stored energy E_m is related to the inductance of the coil [9]:

$$E_m = \frac{1}{2} L\left(I^2\right) \tag{31}$$

For a circular cross sectioned torus shaped toroidal coil with an air core ($\mu_r = 1$) the inductance may be approximated as follows [10]:

$$L \cong 0.007975 \frac{d^2}{D} N^2 \ \mu\text{H} = 1.26 \times 10^{15} \ \mu\text{H} = 1.26 \times 10^9 \ \text{H} \tag{32}$$

which yields a stored magnetic energy E_m of 2.4 GJ. Thus $E_T \sim E_m$ since $E_m \gg E_k$. For SMES applications this is equivalent to $E_m = 2.4 \times 10^6$ kW seconds = 670 kW hr.

However, in Equation (31) this calculation assumes that $\mu = \mu_o$, *i.e.* $\mu_r = 1$. An alternate formulation may be used for $\mu \neq \mu_o$ of the form:

$$L = \frac{N^2 \mu A}{l} \tag{33}$$

which is depicted in **Figure 8**. Where in this case [11]:

$$\mu = \mu_o \mu_r \tag{34}$$

$$A = \pi r^2 = 0.785 \text{ m}^2 \tag{35}$$

Assuming a modest $\mu_r = 600$ (equivalent to soft iron) then $L = 3.0 \times 10^{13}$ H. Assuming a current $I = 1.96$ A to keep below the critical current density of the material of Reference [2] then from Equation (31) the contained energy of the coil will be:

$$E_m = \frac{1}{2} L\left(I^2\right) = 5.76 \times 10^{13} \ \text{J} = 5.76 \times 10^8 \ \text{kW} \cdot \text{hr} \tag{36}$$

Therefore:

$$E_T = E_k + E_m \sim E_m = 5.76 \times 10^8 \ \text{kW} \cdot \text{hr} \tag{37}$$

For comparative purposes, an electric auto battery requires an energy storage of 120 kW hours for a range of 320 miles. Therefore idealized non-relativistic reference device under analysis is some 6 orders larger than required for use as an automotive battery. Thus an automotive scale device could be sized at 10 cm × 10 cm × 2 cm.

Table 2 covers a range of other permeability cases for the SMES application.

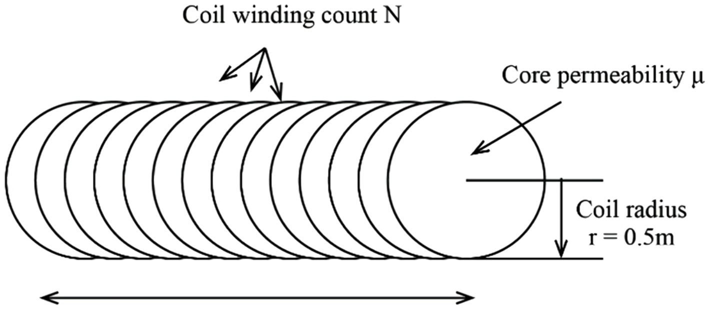


Figure 8. Geometry determining inductance.

Table 2. SMES Inductance and Contained Magnetic Energy as a function of core magnetic permeability.

Core Permeability (μ_r vs μ_o)	Inductance (H)	Stored Magnetic Energy (J)
1	$1.26(10)^{11}$	$2.4(10)^{11}$
600	$3.0(10)^{13}$	$5.76(10)^{13}$
100,000	$5.0(10)^{15}$	$9.6(10)^{15}$
1,000,000	$5.0(10)^{16}$	$9.6(10)^{16}$

In the case of the ~10 PetaJoule (PJ) example, this instantiation of the device could supply 1.0 Gigawatt (GW) of power for 10 million seconds, or over 115 days, providing substantial mission power between charges.

However, these numbers also point out that such devices should be operated with the greatest of care and concern for safety. This is mitigated by the very gradual quenching characteristics of the nanowire materials described in Section 2.1 [2].

7. Relativistic Operation in an Idealized SMES

We now consider an idealized case of relativistic motion for the electrons within the SMES torus to examine possible improvements in performance for this case. What is a reasonable relativistic energy limit for electrons in this application? For present purposes, we use Lawrence Berkley National Labs recently developed Laser Plasma Accelerator, which accelerates electrons to 4.25 GeV within a length of only 9 cm [12].

Converting to Joules, for this case the energy of a single electron E_e would be [13]:

$$E_e = 4.25\times10^{9}\ \text{eV}\times1.6\times10^{-19}\ \text{C/e}\times1\ \text{J/C} = 6.8\times10^{-10}\ \text{J} \tag{38}$$

This represents the total kinetic energy of the electron:

$$E_e = m_e c^2 (\gamma - 1) \tag{39}$$

where m_e is the rest mass of an electron. If solved for γ Equation (39) gives γ = 8293.

Because the electrons are traveling in matter, albeit superconducting matter, even for our idealized case we may assume some energy losses due to domain boundary scattering and Bremsstrahlung radiation. For the purposes of our idealized case we will assume average γ = 5000 < 8293.

We now revisit the gravitomagnetically induced DC gravitational force developed at the center of the SEMS torus as given in Equation (1):

$$G_f = \left(\frac{\eta}{4\pi}\right)\left(N\dot{T}r^2/R^2\right) \tag{1}$$

where η is gravitomagnetic permeability, which is defined as $\eta = \eta_o\eta_r$.

And from Equation (28) we have:

$$\eta_o = -G/2c = 1.11\times 10^{-19} \tag{28}$$

And where η_r may take values over a range yet to be experimentally determined, but if similar to μ_r may range in value from 1 to 1,000,000 [14].

Here N = 1.256 × 10^6 turns, r = 0.5 m, and R = 5.0 m, all of which are the same geometry assumptions as the non-relativistic case. What is not the same will be the change in mass flow $\dot{T}$:

$$\dot{T} = \dot{T}_e \cdot N_e \tag{21}$$

$\dot{T}$ will be different because both $\dot{T}_e$ and N_e will change due to the relativistic motion of the electrons.

N_e will be decreased because the faster circulation time results fewer electrons in motion within each loop at the same time due to their higher velocity:

$$N_e = I \cdot \Delta t \tag{22}$$

where the period of an orbit can be described by:

$$\Delta t = \frac{c_r}{v} = \frac{C_r}{C} \tag{40}$$

since in this case $v \sim c$. Therefore Δt will be reduced from 41.89 ns for the non-relativistic case to 10.47 ns in this relativistic case. This reduces N_e from 5.12×10^{11} electrons as calculated in Equation (25) to just 1.28×10^{11} electrons in this relativistic case.

This reduction in N_e will be more than compensated by the γ^2 growth in the change in mass flow per electron as measured from the rest frame. Because we are assuming γ = 5000 the increase in measurable force will be a factor of 25,000,000, over 7 orders of magnitude. This is expressed in Equation (41) as follows:

$$\dot{T}_e = m_e a_e = m_e\left(\gamma^2 v^2/r\right) = m_e\left(\gamma^2 c^2/r\right) \tag{41}$$

for a relativistic case of circular motion. This yields a $\dot{T}_e$ of 4.1×10^{-6} N for a single electron, a force (or change in mass flow) of a $\dot{T} = N_e\dot{T}_e$ of 5247 N for all the mass flow change in an entire loop, and a gravitational force developed from the gravitomagnetic effect in the center of the SMES torus of $G_f = 5.8 \times 10^{-10}$ N if $\eta_r = 1$, or G_f = 5.8 mN if $\eta_r = 1000000$. For a 1 kg test mass in the center of the torus an acceleration of 0.057 m/s^2 would be observed, or 5.8 mG. This is well within the measureable range of absolute quantum gravimeters [15] and it should be possible to establish an upper bound for η_r using a device similar to this idealized relativistic case.

Thus, although relativistic operation does nothing to improve current or inductance, and therefore accrues no benefit for storing energy, it would theoretically provide quite a dramatic improvement in gravitational force generation.

8. Alternating Current (AC) Operation in an Idealized SMES

We now return to the notion that our idealized torus may be built in sectors as seen in **Figure 9**, and while in the cases of DC operation it is possible to place all

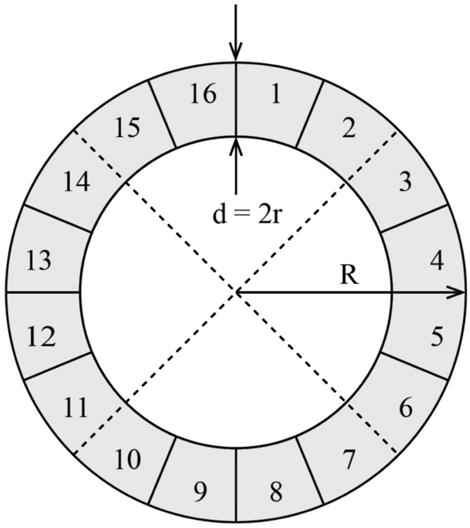


Figure 9. Torus sector assignments for AC operation.

sectors in series, in order to create a quadrupole moment of mass flow these sectors, shown in **Figure 10**, the sectors must be powered in parallel. This means that 32 Amps will be required to provide 2 Amps to each of 16 sectors.

Returning for a moment to the DC case, from Equation (27) we have shown when all sectors are energized in the same rotational direction, that $G_f = (\eta_r) 5.8\times10^{-16}\ \text{N}$, where worst case is $\eta_r = 1$. In this case $G_f = (\eta_r) 5.8\times10^{-16}\ \text{N}$. In this case for a 1 kg test mass m_t from Newton's 2nd law:

$$a_f = G_f / m_t = 5.8\times10^{-16}\ \text{m/s}^2 \tag{42}$$

In Earth's gravitational field g of 9.8 m/s^2 this is equivalent to a relative strain of:

$$h_f = a_f / g = 5.9\times10^{-17} \tag{43}$$

For AC (Alternating Current) operation, powering sectors 15, 16, 1, and 2 as well as 7 through 10 with "inspiralling" current, while simultaneously powering sectors 3 - 6 and 11 - 14, with "outspiralling" current, as shown in **Figure 10**, and then periodically reversing, will create a quadrupole modulated gravitational field as depicted in **Figure 11**.

From **Figure 9** and **Figure 10** only half of the coil is energized in one direction at a time, so $+a_h \sim 1/2a_f$. Therefore, in the non-relativistic case total amplitude of the quadrupole GW wave is:

$$a_{gw} = |-a_h| + |+a_h| = \frac{1}{2}a_f + \frac{1}{2}a_f \sim a_f \tag{44}$$

Then by similarity $h_{gw} = 5.9\times10^{-17}$ for the non-relativistic case.

From Section 7 for the relativistic case:

$$h_f = a_f / g = 5.9\times10^{-11}\eta_r \tag{45}$$

Even assuming a worst case $\eta_r = 1$, this value of h_f should be detectable by

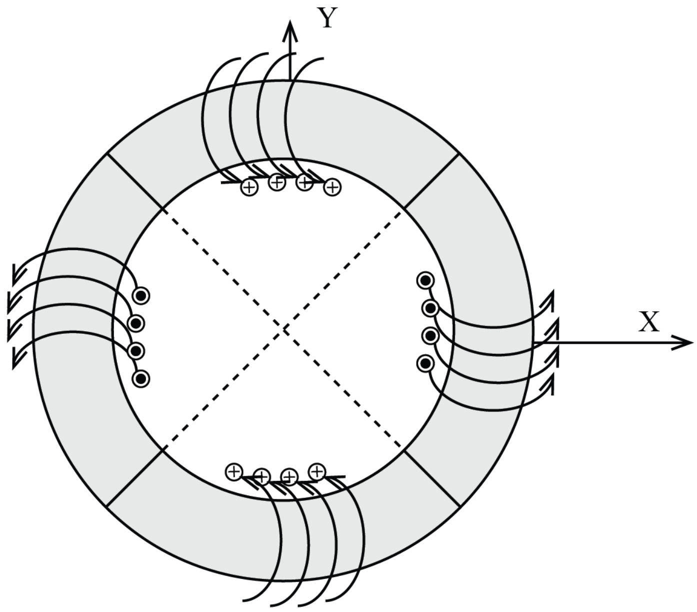


Figure 10. Quadrupole generation via torus alternating current (AC).

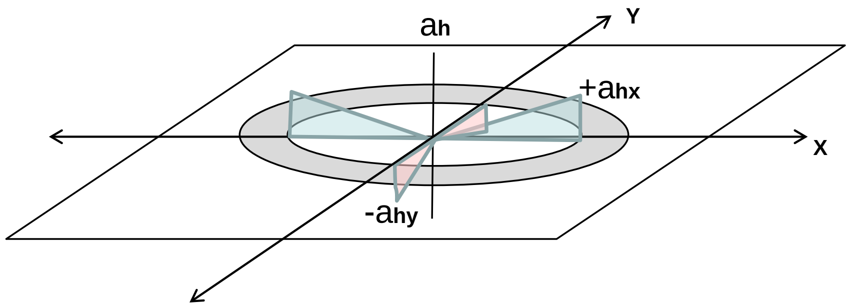


Figure 11. Gravitational potential map during AC operation.

LIGO if operated at a 1 Hz quadrupole oscillation rate. In accordance with Martynov *et al.* [16], LIGO sensitivity at 1 Hz is $h > 10^{-23}$ Hz.

9. Conclusion

An argument is made for using SMES to gravitomagnetically create an unbalanced force, possibly of measurable amplitude. Sector partitioned actuation of a similar SMES device may also be used to generate gravitational waves. Further research would be required to determine to what extent SMES devices could be operated into relativistic regimes to enhance relative mass flow change in the rest frame.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix, Lorentz Forces inside an Idealized SMES

Due to the large magnetic fields developed in SMES devices Lorentz forces are a major design constraint. In this appendix, we explore how nanowires based on weaving together the nanotube fibers described in reference [2] should have sufficient tensile strengths to allow some of the energy storage levels described in **Table 2** of this paper without the need for additional structural elements.

In accordance with reference [17] Lorentz forces developed in the idealized SMES device can be described on a per electron basis as shown in Equation (A1):

$$F_e = qv \times B \tag{A1}$$

where:

$q = q_e = e = 1.6 \times 10^{-19}$ C = elementary charge, the charge per electron;

$v = 0.25c = 0.75 \times 10^8$ m/s for non-relativistic case ($v \sim 1c = 3 \times 10^8$ m/s in relativistic case);

B = magnetic field in the core of an idealized SMES device.

See **Figure A-1** for a depiction of the Lorentz force developed by the motion of a single electron in one loop of an SMES device.

What is B in this case? As described by reference [18] magnetic field strength inside a torus coil is given by (A2):

$$B = \left(\frac{\mu NI}{2\pi R}\right) \tag{A2}$$

where here we will assume values earlier developed for the idealized SMES:

$\mu = \mu_r \mu_0$ magnetic permeability;

$\mu_{\square}$ = 1.26 × 10^{-6}, vacuum magnetic permeability;

μ_r = 600, a moderate value for relative permeability, the equivalent of an iron core;

N = 1.256 × 10^9, the number of loops given in Equation (16);

I = 1.96 Amps in the idealized case of Equation (24);

R = radius of torus, assumed to be 5.0 m, from **Figure 4**.

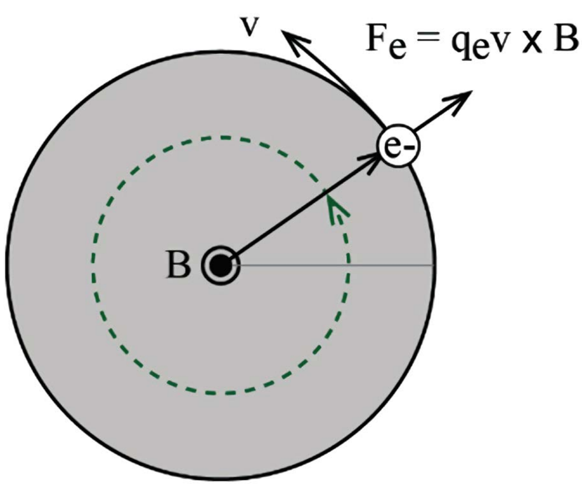

Figure A-1. Lorentz Forces due to Electron orbit in one loop of SMES.

This gives a magnetic field of $B = 600 \times 1.26 \times 10^{-6} \times 1.26 \times 10^{9} \times 1.96/10\pi = 59000\ \text{T}$ in the core of the SMES. The inner most winding loop of the SMES device will experience this field strength. Ideally this field will drop linearly until the field is zero at the outside of the torus. Field orientation inside the core of a torus is depicted in **Figure A-2** for in spiraling current with velocity v_e:

With the worst case magnetic field the electron Lorentz force will be:

$$F_e = qv \times B = 1.6 \times 10^{-19} \times 0.75 \times 10^{8} \times 5.9 \times 10^{4} = 7.1 \times 10^{-7}\ \text{N/electron}$$

In a non-relativistic case the number of electrons per loop is given in Equation (25) as $N_e = 5.12 \times 10^{11}$ electrons/loop.

Lorentz Force developed in a single loop due to the electrons in motion within that loop is given as follows for a worst case magnetic field:

$$F = F_e N_e = 7.1 \times 10^{-7}\ \text{N} \times 5.12 \times 10^{11} = 363500\ \text{N} \quad \text{(A3)}$$

As shown in **Figure A-3** this force is spread over the entire conductor loop circumference and across its cross-sectional area. The force application area can therefore be given as:

$$A_{fa} = C_r d_c = 3.14 \times 10^{-4}\ \text{m}^2 \quad \text{(A4)}$$

where:

C_r = loop circumference, which on average is 3.14 m from Equation (17);

d_c = conductor diameter assumed to be 100 µm.

Lorentz pressure, or Lorentz force per unit area using the above values is given by:

$$P_L = F_e N_e / A_{fa} = 363500\ \text{N} / 3.14 \times 10^{-4}\ \text{m}^2 = 1.16 \times 10^{9}\ \text{Pa/loop} \quad \text{(A5)}$$

Equation (A5) gives Lorentz pressure for a worst case magnetic field, but the average pressure on a loop will be half of that, or 1.16×10^9 Pa. Over a depth of N_d = 5000 loops the average Lorentz pressure per loop $P_L = 0.58 \times 10^9$ Pa, zero

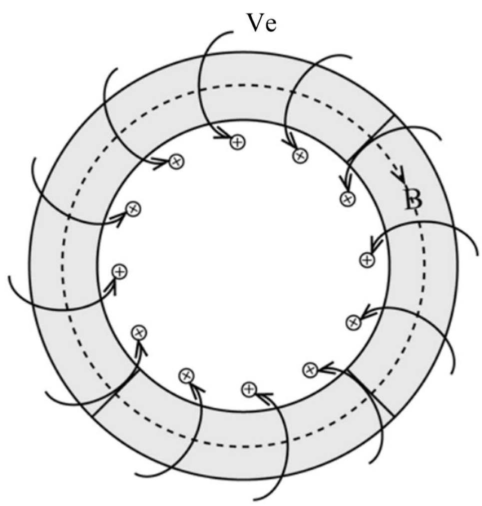

Figure A-2. Magnetic field in an SMES torus core.

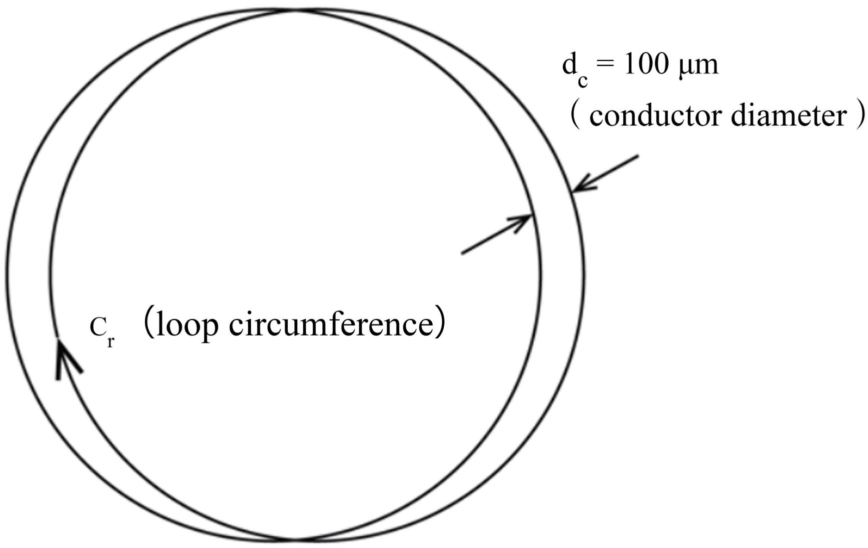

Figure A-3. Application area of Lorentz force for a single conductor loop in an SMES torus.

on the outside, 1.16×10^9 Pa on the inner loop, and shrinking linearly going from inside to out.

For the materials in reference [2], the actual containment tensile strength of the conductors T_{sn} = 260 GPa > 1.16 GPa, so for the reference architecture $T_{sn} > P_L$. For an improved performance case where a d_c = 1 μm diameter nanowire conductor composed of woven nanotube fibers as shown in **Figure 2(a)**, there would be more pressure per unit area, however if total current in all 19 filaments is limited to the original 1.96 A, then

$$T_{sn} = 260\text{ GPa} > 116\text{ GPa} = P_L \quad \text{(A6)}$$

Thus there would still be better than a factor of two margin for tensile strength, even in this more tightly packed case. It is therefore possible to build the SMES using this dense packing factor to withstand Lorentz forces at 1.96 A without the need for supplemental structural elements.

Nomenclature

h = Planck's constant

N = total loop count

Ω = angular rotation rate vector (rad/sec)

η_r = gravitomagnetic permeability

r = toroid cross section radius (m)

R = toroid radius (m)

v_e = velocity, electron

μ = magnetic permeability

Acronyms

HTSC—high temperature superconductor

LIGO—laser interferometer gravitational-wave observatory
LN2—liquid nitrogen
SMES—superconducting magnetic energy storage
SC—superconductor
T2M—True 2 Materials PTE, LTD