NIAC Study of the Magnetic Sail

NIAC Slide Presentation: 11/8/99

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- Performance as Interstellar Mission Brake
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Introduction

- Magsail
 - a large loop of wire
 - generates artificial magnetosphere
 - superconductors cable > min. mass > max. accel.



- move large payloads (solar system and beyond)
- decel. spacecraft from relativistic velocities.

Magsail Theory

- 1. D.G. Andrews and R.M. Zubrin, "Magnetic Sails and Interstellar Travel," 39th Congress of the International Astronautical Federation, IAF-88-553, Bangelore India, Oct. 1988. Published in the Journal of the British Interplanetary Society, 1990.
- - First magsail paper. Results of particle model presented.
- 2. R. M. Zubrin and D. G. Andrews, "Magnetic Sails and Interplanetary Travel," AIAA-89-2441, AIAA/ASME 25th Joint Propulsion Conference, Monterey, CA, July 1989. Published in Journal of Spacecraft and Rockets, April 1991.
 - Presented plasma MHD magsail model, and analytic methods for computing magsail orbits.
 - Self-acceleration D/M= 0.59 ($\mu\rho^2 V^4 R_m/I$)^{1/3}(J/ ρ_m)
- 3. S.G. Love and D. G. Andrews, "Applications of Magnetic Sails," IAF 91-245, 42nd Congress of the International Astronautical Federation, Oct. 1991, Montreal, Canada.
- - Showed value of using magsail as a system for ionospheric planetary aerobraking
- 4. R. Zubrin, "The Use of Magnetic Sails to Escape from Low Earth Orbit," Journal of the British Interplanetary Society, Vol. 46, pp.3-10, 1993.
 - Analyzed potential for magsails to raise orbits by pumping against planetary magnetic poles.

Introduction: Terms

- J_c Critical current density: the maximum current a superconductor can carry before losing its superconductivity divided by the cross-sectional area of current carrying superconducting material, often a filament imbedded in a larger non-superconducting matrix, a thin-film on top of a thick non-superconducting substrate or a fraction thereof. Method by which J_c is measured is not always uniform between labs. The critical current density decreases very rapidly with increasing temperatures and magnetic fields.
- J_e Engineering critical current density: the maximum current a superconducting material can carry before losing its superconductivity divided by the total cross-sectional area of wire, tape, or structure of interest.

Superconductor Trade Study

- Superconductors Needed
 - larger current per unit mass, also store energy
 - J_e(bulk--wire, substrate, insulation, etc.) << J_c (small scale--crystal)
 - Want $J_e > 10^9 \text{ A/m}^2$, $\rho < 8x10^9 \text{ kg/m}^3$
- Best Commercial High Temperature Superconducting Wire-- NOW
 - Barium Strontium Calcium Copper Oxide (BSCCO)
 - Mostly Ag matrix, ~ 9 X 10³ kg/m³
 - Best $J_e = 1.12 \times 10^8 \text{ A/m}^2 @ 77 \text{ K}$ (avg. in 100+ wires, L > 200 m)
 - Best $J_e = 2.3 \times 10^8 \text{ A/m}^2 @ 77 \text{ K} (L= 10 \text{ cm})$)
- Promising YBCO Research
 - Yttrium Barium Copper Calcium Oxide (YBCO)
 - Thin film on Substrate -- $(Yb_2O_3/Y_2O_3/Ni, etc.)$
 - Best $J_c = 3 \times 10^{10} \text{ A/m}^2 @ 77 \text{ K}$ (thin film, $J_e \sim 6 \times 10^8 \text{ A/m}^2 @ 77 \text{ K}$)
 - Best $J_c = 10^{11} \text{ A/m}^2 @ 77 \text{ K}$ (Single Crystal)

Superconductor Trade Study: Predictions for Superconductors

John Cerulli 100 (American Superconductor) 90 80 predicts progress in commercial ² at 77 K self field) b 2 8 2 wire to follow trend, Malozemoff's Law Extrapolate @ 77 K 30 20 (الم 10 $J_{e} = 1.76 \times 10^{8} \text{ A/m}^{2} \text{ in } 2005,$ $J_{a} = 2.1 \times 10^{8} \text{ A/m}^{2} \text{ in } 2010,$ $J_{a} = 2.4 \times 10^{8} \text{ A/m}^{2}$ in 2015 0 ·91 ·92 ·93 ·94 ·95 ·96 ·97 ·90 for BSCCO wires > 100 m

Best $J_e = 2.3 \times 10^8 \text{ A/m}^2 - (10 \text{ cm wires})$

Other HTS materials could lead to greater performance

Malozemoff's Law for BSCCO Bi-2223 (Cerulli)

Superconductor Trade Study: Predictions for Superconductors

Dean Peterson,

(Superconducting Tech. Center, LANL)

- Speculates:
- given adequate funding and continued progress, "..it would not be unreasonable" to reach a

 $J_{\rm e}$ of 10° A/m² in 5 years, $J_{\rm e}$ of 10¹⁰ A/m² in 10 years, $J_{\rm e}$ of 10¹¹ A/m² in 15-20 years

in thin tapes and wires @ 77 K

LANL has made YBCO thick-film tape $J_c = 1.2 \times 10^{10} \text{ A/m}^{2}$, L=1m (plans for 10 m)



Predictions Compared for Two Different Types of Superconducting Wire

Magsail Systems: Coil Configuration

Coil Design Drivers

- J_e increases as Temp. decreases
 - Minimize coil Temp.
- Lower current--easier charging
 - Use multiple coils
- Performance increases as Mass decreases
 - Minimize Mass

Main coil

- Multiple Loops of superconducting wire
- Wedge of MLI
- Silvered-Teflon coating
- White epoxy paint



Cross section of superconducting wire loop wire

Magsail Systems: Coil Configuration

- square cross-section wire
 - ease of manufacture
 - compact size.
- Max. temperatures determined from Thermal Transport Eqn.s
- Ag-Teflon ~ 305.8 K
 - to radiate all solar energy
- Before Ag-Teflon ages (9 months to 4 years),
 - Will be colder

- MLI modeled
 - as several 1 mm thin layers.
 - Energy conducted = Energy radiated
 - Used Fick's Law (Lockheed Correlation)
 - shape factor, A_{sf, to} accounts for heat loss through the sides
 - (k Δ T)/ Δ X = $\epsilon \sigma_{Bc} A_{sf} T^4_{MLI bot}$.

Magsail Systems: Current Injection

- Injection System (Three Sets)
 - Solar (or AMTEC) power source
 - Power supply lines
 - Power controllers
- Shaded by solar arrays at rim
- Superconducting cable w/ many small wires
 - reduces total current needed.
- Loop self-inductance (for Op.M)
 - $L = \phi_{B \text{ coil}}/I = n \phi_{B \text{ one loop}}/I = \mu_0 \Pi R n^2/2$
 - (R=2 x 10⁴ m, B= μ_0 nl/2R, n=#_{coils} tot.current = nI, strand current= I) dl/dt=-(EMF/L)
- 20 km radius magsail
 - L = 1.105 x 10⁴ H
 - Constant EMF = 3.858 V
 - dl/dt = 3.491 x 10⁻⁴ A/s.
- After Margins
 - Solar powered operational magsail -- 15.82 V, 622.8 W
 - AMTEC powered operational magsail -- 8.10 V, 319.0 W.

Power to Inflate in:	1 hour	24 hours
Demonstrator Magsail	58.6 mW	2.44 mW
Operational Magsail	1.40 kW	58.2 W

Magsail Systems: Current Injection Diagram



Magsail Systems: Shroud Lines

- Attach Payload and Control systems to Coil
- Do not take up stress from Coil
- Worst stress on the shroud lines from shifting center of mass to control attitude
 - 2.0 km in an hour one --> 0.556 m/s. KEmax= 6.697 kJ , F= 6.70 N (1.51 lbf)

Use "Hoytethers" -- Tethers Unlimited

- made from Spectra 2000
- anticipated lifetimes of several decades
- 1,820 g per 10,300 m length

Magsail Systems: Magsail Deployment

- Superconducting magsail current could deploy cable by magnetic hoop stresses
- Magnetic deployment time, $T = sqrt (2R_m/a)$ and $a = (nI_{filament}B_m)/(Mass/Circum)$
 - << charge-up time</p>

<u>But</u>

Magsail will not be superconducting until it is deployed and properly oriented

- Could use Normal current
 - Operational Magsail, constant coil mass, 69 % Ag
 - R=20 km, P= 10 kW, 529 coils
 - I_{net} = 4.66 A, T= 1.58 x 10⁶ s (438 hr.)
 - --> Too Long
 - R=2 km, P= 10 kW , 5290 coils
 - I_{net} = 46.6 A, T= 4.98 x 10⁴ s (13.8 hr.)

->But this loses performance ! Self-accel. drops by 4.6 x's

Magsail Systems: Magsail Deployment

• Use Rotating Booms or other non-magnetic deployment systems.

----> Reliable Deployment is a Key issue for Magsails !

Magsail Systems: Distributed power Concept



Magsail Designs

- Radius, R_m
 - 200 m Demonstrator
 - 20 km Near-term "Operational"
- Magnetic Field, B_m
 - 3.25 to 10.00 x 10^{-7} T >> 5.18 x 10^{-8} T
 - avoids solar wind "punch through"
- Eng. Crit. Current Density, J_e
 - Demo --in 10 cm lengths
 - Operation -- not yet available
- Magsail Self-Accel.
 - D/M= 0.59 ($\mu \rho^2 V^4 R_m / I$)^{1/3}(J/ ρ_m)
- Temperature and J_e
 - Demonstrator $J_e \sim 2 x$ value @ 77 K
 - Advanced wires (YBCO,etc.)
 - higher overall J_e,
 - same trend in J_e vs. T (assumed)



Engineering Current Density vs. Temperature For BSCCO (Scaled Relative to Je at 77 K)

Magsail Performance: Definitions

• α - The effective fractional attraction of the Sun in solar gravities

at Constant α:

- $-\alpha /2a = v^{2}/2 \alpha /R$
- Weight Ratio total system mass / coil mass
- Payload Ratio cargo mass / unloaded magsail mass

Magsail Designs: Demonstrator Design

<u>Wire:</u>

•	Coil Temperature:	63.9 K (max)	
•	Current density, J _e :	4.56 x 10 ⁸ A/m ²	
•	Current per filament:	4.60 A	(225 filaments .1 mm x .1 mm)
•	Magnetic Field, B _m :	3.25 x 10⁻ ⁶ T	
•	Radius, R _m :	2.00 x 10 ² m	
ML	<u>L</u>		
•	MLI width:	2.04 mm - 6.62 mm	(min - max)
•	MLI thickness:	13.0 mm	
<u>Per</u>	formance:		
•	Coil Mass:	25.70 kg	
•	Other S/C Mass:	64.3 kg	(without payload)
•	Payload:	10.0 kg	
•	Weight Ratio:	3.90	(Total system mass/ coil mass)
•	Payload Ratio:	0.111	(cargo mass/ unloaded magsail mass)
•	Self-Acceleration:	0.000305 m/s ²	
•	Apoapsis:	1.0267 AU	(@ Constant α)

Magsail Designs: Operational Design

Wire:

•	Coil Temperature :	60.2 K (max)	
•	Current density, J _e :	2.27 x 10 ⁹ A/m ²	
•	Current per filament:	30.17 A	(529 filaments .1 mm x .1 mm)
•	Magnetic Field, B _m :	5.01 x 10 ⁻⁷ T	
•	Coil Stress:	1.51 Mpa	
•	Radius, R _m :	2.00 x 10 ⁴ m	
ML	<u>l:</u>		
•	MLI width:	3.58 mm - 9.93 mm	(min - max)
•	MLI thickness:	18.0 mm	
<u>Per</u>	formance:		
•	Coil Mass:	7.060 x 10³ kg	
•	Other S/C Mass:	3.780 x 10 ³ kg	(without payload)
•	Payload:	1.096 x 10⁴ kg	(To Mars)
•	Weight Ratio:	3.09 (Mars)	(Total system mass/total coil mass)
•	Payload Ratio:	1.011 (Mars)	(cargo mass/ unloaded magsail mass)
•	Self-Acceleration:	3.185 x 10⁻³ m/s²	
•	Apoapsis:	1.5237 AU	(@Constant α)

Magsail Designs: Ultimate Magsail Performance

- J_e Could ultimately rise above 2.27 x 10¹¹ A/m² @ 60.2 K
- Cable Mass density Could ultimately fall below 7 x 10³ kg/m³

When coupled with likely advances in other systems:

Ultimate AMTEC Magsail: Payload Vs Distance: 9.801 x 10³ kg, R_m=20 km

Destination	Distance (AU)	Payload from Earth (kg)	Payload ratio @ Constant α
Mars	1.524	4.600 x 10⁵	46.9269
Jupiter	5.203	1.901 x 10⁵	19.3928
Saturn	9.539	1.706 x 10⁵	17.4026
Uranus	19.191	1.605 x 10⁵	16.3788
Neptune	30.061	1.572 x 10⁵	16.0401
Pluto	39.469	1.559 x 10⁵	15.9008
Kuiper Belt	1,000	1.518 x 10⁵	15.4897
Ort Cloud	10,000	1.517 x 10⁵	15.4749

Maximizing Performance: Modes of Operation

- Constant Alpha
 - Low performance
 - easiest to calculate
- Constant Current
 - Low performance
- Maximum Current
 - Medium performance
 - J_e increases as Temp. drops away from Sun
- Orbit Pumping
 - Very High Performance
 - Magsail turned off during Sunward portion of orbit
- Modified Orbit Pumping
 - Very High Performance
 - Magsail turned off during Sunward portion of orbit
 - Magsail turned off at preset velocity/distance until minimum perihelion reached
 - Trades off Aphelion distance for Speed

Maximizing Performance: Orbit Simulations

Orbit Simulations

- Iteratively calculated by computer code
- Refinements Implemented (vs. previous Constant Alpha calculations)
 - Solar wind speed reduced to 480 m/s
 - Accounted for:
 - Magsail relative motion
 - Changing temperatures
 - Solar wind densities
- Assumed Baseline J @ 77 K
 - 2.30 x 10⁸ A/m² demonstrator magsail
 - 10⁹ A/m² 'Operational' magsail,
 - 10¹¹ A/m² advanced magsail
 - inverse relationship of J_e vs T same as for commercial
 - payload ratio = 1.0
 - Plotted Represenative Cases
 - Const. I, Max. I, Max I Pumped

Maximizing Performance: Orbit for Constant Alpha

- Operational Magsail
 - Constant Alpha
 - No Orbit Pumping
 - Payload ratio = 1.0
- Orbit
 - periapsis = 1.000
 - apoapsis = 1.484 AU



Maximizing Performance: Orbit for Maximum Current

- Operational Magsail
 - Variable α
 - Max. Current
 - No Orbit Pumping
 - Payload ratio = 1.0
- Orbit
 - periapsis = 1.000
 - increases with time
 - apoapsis = 1.614 AU (max)
 - decreases with time
 - Precesses



Maximizing Performance: Orbit for Maximum Current- Pumped

- Operational Magsail
 - Constant α
 - Orbit Pumping
 - Payload ratio = 1.0
- Orbit
 - min. periapsis = 0.5457
 - apoapsis = ∞



Maximizing Performance: Velocity Vs. Speed Compared

- Operational Magsail
 - Maximum Current
 - Not Pumped
 - Pumped
 - Modified Pumping
 - Payload ratio = 1.0
- Pumped Orbits
 - final velocity ~ 5 AU/yr
 - − final apoapsis = ∞
- Could reach vicinity of termination shock/heliopause ~ 100 Au in ~ 30 years



<u>Maximizing Performance</u>: Payload Ratio Vs. Apoapsis



Performance as an Interstellar Brake

Interstellar Mission Brake:

Temp. = 2.7 K Payload Mass = 10⁵ kg Radius =100 km

- Scaled-up Operational Magsail
 - Wire density of 8 x 10³ kg/m³
 - Je = $10^9 \text{ A/m}^2 @ 77 \text{ K}$
 - 0.950 c to 0.582 c in 800 days
- Advanced Magsail
 - Wire density of 7 x 10³ kg/m³
 - Je =10¹¹ A/m² @ 77 K
 - 0.950 c to 0.0056 c in 800 days



Pioneer Astronautics

Time (days)

Magsail Experimental Program:

Conduct tests with Superconducting Wire

Fabricate multistranded magsail cables from wire strands and MLI

- cut larger superconducting wires/tapes into proper size
- bond together 0.1 mm square superconducting wires
- compare heat fusing vs. adhesives.
- test for mechanical properties
- test for J_e
- validate ability to use multi-stranded wire for multiple coil magsails

Simulate deployment systems

Test deployment systems

- 2 D air table
- 3 D KC-135

Conclusions

Magsails !

- Can deliver large payloads in Solar system without propellant
- Reusable
- Can open launch windows by adding flexibility to Keplerian orbits
- Can decelerate interstellar spacecraft from relativistic velocity without propellant
- Near-term superconductors can enable useful magsail -- and the field is advancing

The time to start engineering magsails is Now !