High Acceleration Mass Drivers

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Abstract

After testing an early, simplified mass-driver (35 gravity acceleration) a second, designated MD2, was designed and is now operating. MD2 is of axial geometry, with individually powered drive coils of 13.1 cm diameter. Timing is derived through the interruption of light beams by the moving armature (bucket). Electric power is provided by the resonant discharge of sector capacitor banks through silicon-controlled rectifiers in a two-phase, quadrature circuit. The bucket flies in vacuum, guided by passive dynamic eddy-current magnetic forces, those currents flowing in strip conductors lining the inside of a nonconducting vacuum pipe. The initial length of MD2 is 2.5 m, divided equally into acceleration and deceleration. Nominal acceleration is 5000 m/sec^2. For routine testing an ohmic bucket is used. Quantitative measurements are obtained with a solid bucket carrying two superconducting coils with a current density of 25 kA/cm^2. A cryogenic station for cooling the bucket to liquid helium temperature is connected to the vacuum pipe. The test program, now begun, will concentrate on guidance and acceleration forces, measurement of drive shielding losses, and possible couplings of drive forces into modes of oscillation.

Introduction

A Mass-driver linear motor combines acceleration by mutual inductance gradient dM/dx, control of drive-circuit timing by position-sensing, magnetic flight, intermediate energy storage by sector capacitors, separation of load and armature (bucket) and recirculation of the bucket. These essentials, and the term "mass driver" to describe them were first combined 5 years ago, and were published in the Proceedings of the first Princeton Conference (1974) on Space Manufacturing/Space Colonies (O'Neill, 1977).[1] A deeper understanding of mass-driver component optimization and of methods for performance calculation was obtained in studies carried on at the NASA-Ames Research Laboratory in 1976 and 1977, and in work during the intervening year.[2]

By the autumn of 1976 our understanding had progressed to the point where a first model was appropriate. This model, "MD1", was then built in the early months of 1977, and was demonstrated at the 1977 Princeton/AIAA Conference (Fine, 1977). Though successful, it was simplified and primitive. It lacked magnetic flight, used an ohmic rather than a superconducting bucket, and employed a single-phase, half-wave drive system with one capacitor per drive coil, triggered by mechanical switches. This model was featured in a "NOV A" public television broadcast in 1978 called "The Final Frontier".

By the close of the 1977 NASA-Ames Study the basic circuit design of an efficient mass-driver had reached a point we might describe as "asymptotic"; it has changed very little in the subsequent years, and will only change if a substantial new insight occurs. The electrical design is based on a two-phase system, the two phases being in quadrature. The spacing between coils is equal to the distance from one coil plane to the peak of the *dM/dx* curve (Figure 1).

The two bucket coils are separated by eight times the spacing between drive coils. With that arrangement the bucket coil currents are in the same sense, which will permit the simple application of active magnetic steering as the bucket moves through the accelerator.

Geometry of MD2

By mid-1977 it became clear that the next step in development should be primarily the experimental verification of theory rather than its further elaboration. At that time a division of responsibility was agreed on: MIT would concentrate on the superconducting bucket, its cryogenic cooling station, and guidance measurements, while Princeton would concentrate on the accelerator. All parameters of MD2 affecting the interface

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[1] Paper presented at the 30th Congress of the International Astronautical Federation, Munich, F.R.G., 16-22 September 1979.

[2] See Chilton *et al.*, 1977; Arnold *et al.*, 1979a,b,c; and Kolm, 1977.

between bucket and accelerator were settled in joint design meetings during the Autumn of 1977, and the first half of 1978 was devoted to detailed design and the selection of components.

MD2 combined for the first time all the essential elements of an operational mass-driver with the exception of bucket recirculation and payload handling. It operates on a single-shot rather than a continuous basis; therefore its energy is stored in a supply capacitor bank (not to be confused with the sector capacitor banks) rather than being obtained from a d.c. source.

A lucky windfall occurred in 1978: a large number of components, including silicon-controlled rectifiers with high ratings for voltage and current and capacitors, became available on a surplus basis. These components, the property of Princeton University, were obtained from the dismantling of the Princeton-Pennsylvania 3 GeV proton synchrotron, and were made available to us through the courtesy of Professor M. G. White, its Director during the years of design, construction and operation of that synchrotron.

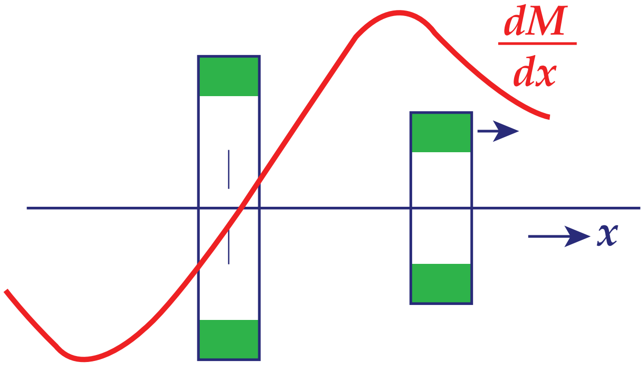


Figure 1 — The mutual inductance gradient as a function of drive coil position, for axial mass drivers.

The components now on hand will permit the extension of MD2 through versions we designate as MD3 and MD4, the last being of total length 18 m. That development is indicated by Table 1.

Table 1 — Mass-driver nominal performance and terminology

		Nominal Peak Velocity	
Name	Total Length, m	m/s	mph
MD2	2.5	112	250
MD3	10	224	500
MD4	18	300	670

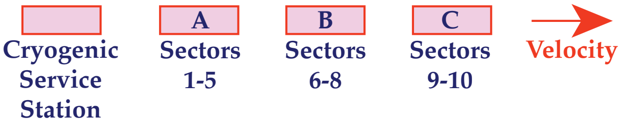
Each model will be developed from the previous one by the addition of higher-velocity acceleration and deceleration sections between pre-existing lower-speed sections, which will be moved apart to accommodate them. The earliest stage, MD2, is in most respects the most difficult to design and build: it must include the transition from rest to and from a speed adequate for magnetic flight, and accommodation to a velocity varying rapidly over a distance of only a few drive coils. The nominal parameters of MD2 and MD3 are given in Table 2.

Table 2 — Nominal parameters for mass-drivers MD2 and MD3

			Ringing Frequency		
Sector	Position, m	Velocity, m/s	rad/s	Hz	Ringing Period, us
1	0.05	22.4	1,428	227	4,400
2	0.20	44.7	2,856	455	2,200
3	0.45	67.1	4,283	682	1,467
4	0.80	89.4	5,711	909	1,100
5	1.25	111.8	7,139	1,136	880
6	1.80	134.2	8,567	1,363	733
7	2.45	156.5	9,994	1,591	629
8	3.2	178.9	11,420	1,818	550
9	4.05	201.3	12,850	2,045	489
10	5.00	223.6	14,280	2,273	440

*With caliber D = 13.06 cm; bucket/drive coil diameter ratio a = 0.514; acceleration *a* = 5000 m/s; drive coil spacing l_m = 2.46 cm; and injection velocity from the cryogenic service station *u0* = 0 m/s.

The physical arrangement and drive-coil inventory for MD2 and MD3 are shown in Figure 2.



Sectors	Coils	End Coils	Section Total
1-3	19	4	—
4	14	0	—
5	18	4	59
6	22	4	—
7	26	0	—
8	30	4	86
9	35	4	—
10	39	4	82
1-10	—	—	227

Figure 2 — Configuration of mass-driver two and three acceleration sections

The cryogenic service station is shown in Figure 3, and the cross-section of the accelerator and light-beam system in Figure 4. MD2 consists of the cryogenic service station plus acceleration and deceleration sections A (sectors 1-5) with 59 drive coils in each.

Electrical Design

The two-phase quadrature drive system is energized in groups of four drive coils per phase resonating with a sector capacitor bank. These controlled pulsed electromagnetic fields provide the drive force required to accelerate the superconducting bucket, which possesses its own constant magnetic field. In MD2 sectors 1-5 of each phase resonate with a common sector capacitor bank rather than individual capacitors for each sector. Figure 5 shows a representative segment of the drive circuit for one phase. Strip line is used extensively to minimize lead inductances.

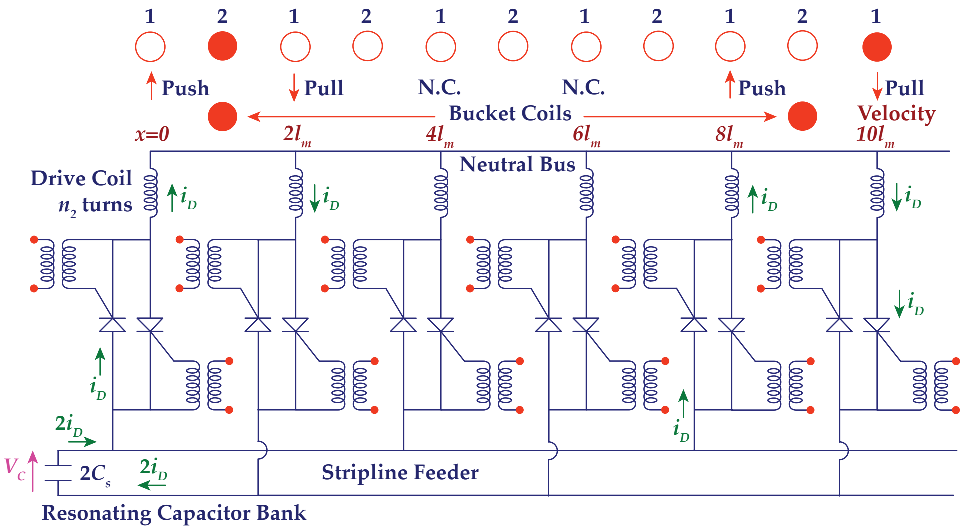


Figure 5 — Six drive coils of phase 1, shown at the time of peak positive current; at this time there is zero current in phase 2. Four coils are excited, one to pull and one to push each of the two bucket coils. Spacing I.. is chosen equal to the separation between a drive and bucket coil at peak gradient dM/dx. SeRs are triggered through pulse transformers for electrical isolation between the drive circuit and the electronic triggering circuitry.

At the high-speed end of MD2 the parameters relevant to the SCRs are given in Table 3.

Table 3 — Main Parameters at the Midpoints of the Higher Speed Sectors of MD2

Parameter	Sector 4	Sector 5	Units
Ringing frequency	6.8	9.3	10^3 rad/s
Capacitor bank	2100	2040	uf
Capacitor voltage	641	668	volts
Number of turns	8	6	
Peak current	4610	6315	amps
di/dt	31.6	58.6	amps/us
DV/dt	4.4	6.1	volts/us
i^2t	19,500	27,000	amp^{2}sec
Firing offset	6.7	7.6	mm
Recharge time	170	150	us

For 500 g acceleration and an assumed 20% loss of drive, mainly due to field-shielding by the guideway, the SCRs must stand off 670 V and switch 6300 amps. The parameter *di/dt* is significant in preventing excessive temperature rise at a "hot spot" occurring on localized regions over the silicon chip during turn-on switching. The parameter i^2t determines the total input of heat to the chip during its short pulse, and must be limited to avoid thermal shock.

The logic circuits that set the order and timing of drive coil firings (each coil must be supplied with four independent half-cycles of current oscillation, two of each sign) receive their timing signals from optical triggers (Figure 4) located before each drive coil.

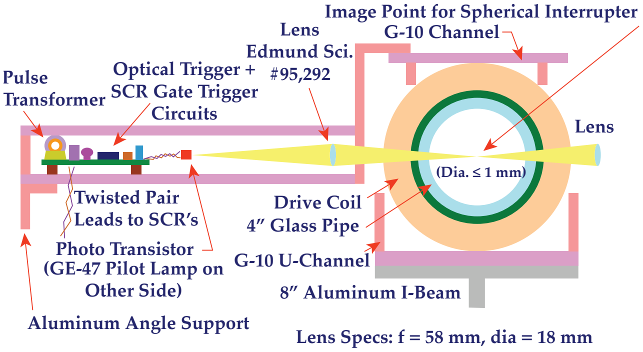


Figure 4 — Optical Trigger

One output of the logic circuits feeds a current amplifier (Figure 6) that triggers a particular SCR through a ferrite-core pulse transformer. All low-level circuitry up through the pulse transformer is within a shielded enclosure.

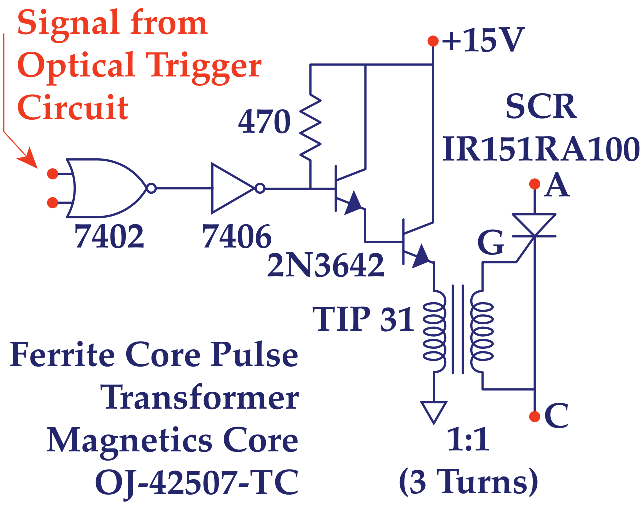
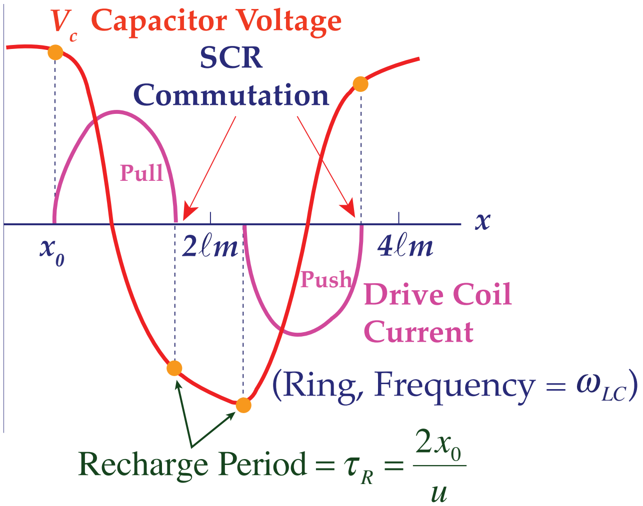


Figure 6 — SCR Trigger Current Amplifier

A high-current, high-speed full-wave recharge circuit must restore each sector capacitor to full voltage during brief (typically 100-150 *u*sec) periods between half-cycles of drive-coil oscillation. For that reason the oscillation period is chosen to be approximately two-thirds of $4\ell_m/u$, where *u* is the bucket velocity (Figure 7). Design of the recharge circuit was a major task of early 1979, and we are indebted to the NASA-Lewis Research Center for technical advice and documents that were most helpful for that design.



x_0 = Firing Offset

$$x_0 = \frac{1}{4}\left(\frac{4\ell m}{\mu} - \frac{2\pi}{\omega_{LC}}\right)$$

u = Local Bucket Velocity
Current Waveform
in One Drive Coil During
Transit by One Bucket Coil

Figure 7 — Bucket and cryogenic station

A non-cryogenic ohmic bucket was designed in order to permit convenient testing of the accelerator without the need for vacuum or liquid helium. The ohmic bucket can sustain a current adequate for 500 g for more than 0.2 sec, without heating by more than 40°C from an initial temperature of -200°C (liquid nitrogen temperature). For comparison, the transfer time (end to end) for MD4 (18 m) will be nominally 0.12 sec.

Bucket and Cryogenic Station

The cryogenic module comprises a 3.25 in. (82.55 mm) o.d. bucket with two 44 kA-turn coils made with 0.028 inch (0.71 mm) diameter niobium-titanium multi-filamentary cable in a copper matrix, impregnated with lead alloy for thermal inertia, as well as the service station to refrigerate, energize and eject the bucket (Figure 3). The station is housed in a 6 in. flanged pyrex cross which connects to the 4 in. pyrex tube of the mass driver itself. The bucket is refrigerated by being forced against a copper braid cradle attached to the bottom of a liquid helium reservoir which protrudes into the cross from above. The bucket is energized inductively by turning off two superconducting coils which are also attached to the helium reservoir, and which have maintained the correct flux linkage through the bucket coils during their cool-down through the critical temperature. Once charging is completed, the clamping pressure is released and the bucket is injected into the mass driver by means of two normal-conductor pulse coils surrounding the horizontal branches of the cross (Fine et al., 1979).

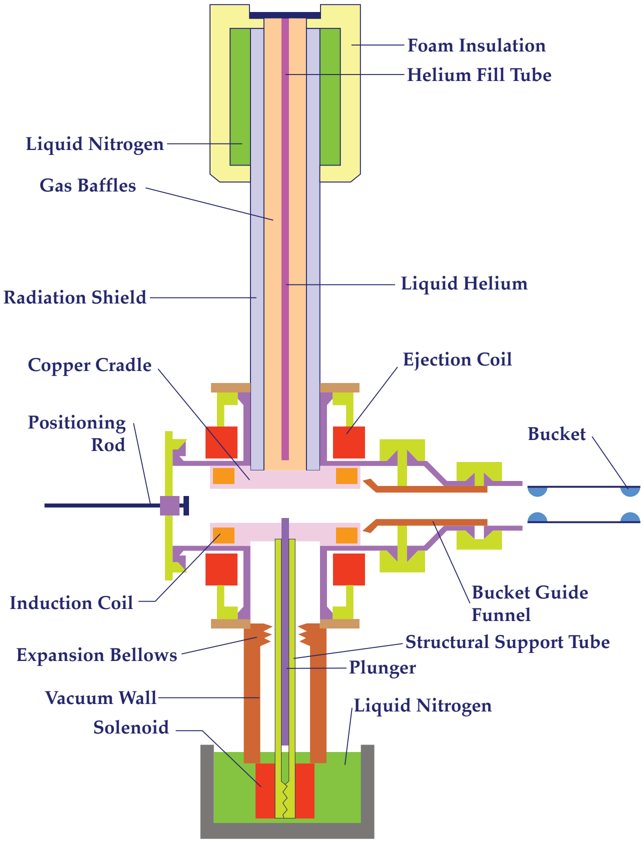


Figure 3 — Cryogenic Service Station

A liquid nitrogen reservoir made of foam plastic surrounds the bottom termination of the cross to reduce heat input from the stabilizing support, and also to serve as 77 K heat station for the electrical leads to the superconducting charging magnets which form an integral part of the massive copper cradle.

External components include a manipulation plunger for positioning the bucket, which passes through a vacuum seal in the horizontal termination of the cross, and two ejection coils which surround the horizontal arms of the cross. These coils are sufficiently large to permit accurate adjustment of their position for the purpose of aiming the ejection trajectory. A guide funnel with teflon knife-edge skid surfaces ensures smooth transition of the bucket into the accelerator tube.

Radiation shielding is provided to reduce the dominant source of heat input, which is interception of black body radiation from room temperature surroundings. A conduction-cooled liquid nitrogen shield surrounds the major exposed area, that of the helium reservoir, thereby reducing heat input from 2 W to 9 mW. The relatively small area of the bucket itself remains exposed to permit inspection. One watt represents a liquid helium boil-off rate of 1.4 liter/hour.

Enthalpy utilization requires baffles to extract vapor enthalpy during cool down as well as steady-state operation. Vapor enthalpy represents about fifty times as much refrigeration as the latent heat of evaporation of liquid helium. The baffle system is thermally connected to the massive structure to be cooled down, but at the same time does not provide excessive conduction to room temperature during steady-state operation.

The bucket has a 3.25 in. o.d. and 8 inch length. The coil forms are aluminum, welded to a thin-walled aluminum connecting tube. Each coil has about 340 turns of 0.028 inch (0.711 mm) diameter multi-filamentary niobium-titanium cable in a copper matrix, with a copper/superconductor ratio of about 2. The cable will carry 130 amp, for a total of 44 kA-turns. The central field intensity will be about 0.78 tesla, and the field at the windings will be about 1 tesla. At such a low field it should be possible to operate at twice the current density we are designing for conservatively.

The superconductor is impregnated with woods metal, the solid of highest heat content except for water ice. Warming from 4 to 10 K, it will absorb an enthalpy of 34 x 10^{-3} J/g; its specific heat at 4 K is 0.62 x 10^{-3} J/g-degree. For comparison, liquid helium at 25 atmosphere has a specific heat of 1.7 J/g-degree. The windings are surrounded by copper hoops 0.125 in. thick to serve as bearing surface for heat transfer and as eddy current shields to protect the windings against field fluctuations caused by ripple (higher harmonics in the drive frequency), and the starting transient when the first drive coil is energized.

A subsequent bucket, of long thermal time constant, will contain high pressure super-critical helium. For this purpose, the coils will be encased in pressure vessels and connected by small diameter tubular stringers serving as reservoirs. A spring-loaded expansion chamber will have to be provided to prevent the permanently sealed charge from developing excessive pressure when the bucket is warmed to room temperature. To determine the trade-off between pressure vessel strength and vessel size we have calculated the volume expansion ratio which must be provided as a function of the maximum tolerable room temperature pressure P_{300}. for two values of cold pressure P_4. 2.5 atmosphere, which is barely above the critical pressure of 2.25, and 20 atmosphere, where improved thermal stability is provided.

The low temperature pressure P_4 has very little effect on the required expansion ratio providing a room temperature pressure as high as 150 atmosphere can be accommodated. This requires an expansion ratio of only 7.

The coil containment-vessel wall-thicknesses were calculated for a stress level of 30,000 psi. Total mass of each coil will be 385 g. A "bicycle rim" cross section has several advantages. One of them is shared with the bicycle: it represents the optimum containment of a high pressure torus. Hoop stress is contained by the thick-walled tire band, while bursting force is contained by the semi-circular inner rim, a semi-torus. The cross section also places the current centroid as far outward as possible without making the coil excessively wide compared to the inductance length. The alpha ratio is 5.1.

The expansion chamber must permit a 7-fold volume increase of the supercritical helium and must also incorporate an elastic diaphragm or bellows, spring-loaded to prevent the pressure from falling below 2.25 atmosphere, the critical pressure at 4 K. If the spring were to operate progressively to absorb the entire expansion energy, it would have prohibitive mass. For example, 0.11. expansion over an average pressure of 100 atmosphere entails an energy of 10 liter-atmosphere or 1 kJ. A spring weighs about 0.18 kg/J of energy storage capacity and would therefore have a mass of 180 kg in order to absorb the expansion energy. Fortunately it is not necessary for the spring to follow the entire expansion. A bi-stable, snap-over diaphragm which snaps at a pressure above 2.25 atmosphere will serve the purpose.

Construction of accelerator

The accelerator/decelerator MD2 is located at Jadwin Laboratory, the Physics Department of Princeton University (O'Neill and Snow, 1979; Snow, 1979). The status of the construction of MD2 as of June 1979 is shown in Figure 8.

Figure 8 — High acceleration model mass-driver model MD2. The large stack of electrolytic capacitors stores the energy for the recharging circuit. The power line capacitors resting on the floor are in the sector capacitor banks. Components, including especially these capacitors, are in many cases much larger than necessary because they were obtained from decommissioned equipment. MD2 is designed for extension through versions MD3 and MD4 to an eventual length of 18 m or more.

In addition to a small permanent staff (W. R. Snow, L. Hagopian and W. Werosta) at Princeton responsible for the construction of MD2, a large part of the construction has been carried out by student volunteers and by students working intensively during summer periods between University semesters. At MIT the cryogenic station and superconducting bucket were constructed by K. Fine, P. Mongeau and F. Williams.

Applications

The mass-driver has two primary applications in our view: the first is as a stationary launching device (catapult) to be located either in orbit or on the surface of a natural or artificial satellite, for the purpose of launching payloads at high velocity to a precise point in space. The second application is as a general-purpose reaction engine, powered by any source of electricity, and using as reaction mass any material which is available and which can be rendered harmless from the viewpoint of the space environment.

Acknowledgements

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