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Brief History and Classification of Magnetic Flux Compression Generators

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Abstract

Sixty years after the first magnetic flux compression experiments were performed, it is now appropriate to attempt a classification of the various devices that are known collectively as either magnetic flux-compression generators or magnetocumulative generators. This paper summarises the main characteristics on which such a classification of generators can conveniently be based, with emphasis given to the helical form that is undoubtedly the most common type of generator in use today. After indicating various fundamental limitations to generator performance, the paper introduces a number of features on which a possible classification can be based. Typical values are given for the major properties of the different features and the main applications are highlighted.

1. Introduction

Magnetic flux compression experiments were first performed in early 1944, as part of Project Y, the Los Alamos atomic bomb project [1] (see Appendix). The main development of magnetic flux-compression generators dates however from the early 1950s in Russia and the USA, followed in the 1960s by the UK, France, EURATOM (in Italy) and China. Research groups in Japan, Poland, Germany, Romania and more recently in Ukraine, Sweden, South Korea and South Africa have since joined what can be termed the Megagauss Club (named after the relevant Conference), with the best experimental results so far reported being summarised in Table 1.

Table 1 does not include data from laser driven experiments, in which ultrahigh magnetic fields of the order of 300 MG (30 kT) are generated in microscopic volumes [34]. Also omitted is any reference to the production of fields of up to 40 MG (4 kT) where the inferred field was not directly measured to provide undisputable supporting evidence [35,36].

2. Generator Classification

It is convenient to separate magnetic flux compression generators into two groups, depending on the applications for which they are to be used. This leads immediately to a distinction between:

(i) implosive systems, termed Class I or Mk-1, in which the total magnetic field energy is progressively compressed towards the *centre* to provide an ultrahigh magnetic flux density (over

Table 1. Megagauss Club members: best-known achievements

Member	**Magnetic flux density MG (100 T)**	**Energy MJ**	**Current MA**	**Programme start year**	**References**
Russia (USSR)	28	100	>300	1952	[2–4]
USA	$10^{+}/14^{*}$	50	320	1950	[5–8]
France	$10/11.7^{*}$	8.5	24	1961	[9,10]
Japan	$6.2^{\#}$	—	8	1970	[11,12]
Euratom (Italy)	$5.4/7^{*}$	2	16	1961	[13,14]
UK	5	10	20	1956	[15,16]
Romania	$5/7.5^{*}$	0.5	12	1979	[17–19]
Poland	3.5	—	0.8	1973	[20,21]
Germany	$3.1^{\#}$	—	1.2	1975	[22,23]
P R China	—	—	2	1967	[24]
South Korea	—	0.2	2	1999	[25]
Ukraine	—	—	> 1	1993	[26]
Sweden	—	—	0.4	1995	[25]
South Africa	—	—	?	?	[25]

$^{+}$ deduced from X-rays pictures and a numerical simulation code,

* obtained only rarely,

$^{\#}$ indoor experimentation: electromagnetic flux compression / single turn capacitor discharges,

? no data available.

Table 2. Typical data and output of Class I (Mk-1) and Class II (Mk-2) magnetic flux-compression generators

Class	**Final characteristics**	**Driving force**				
		Explosive (solid, liquid, gaseous)		**Electromagnetic**		
		ML [2–4,7]	**DMSWT** [27,28]	**ML** [29,30]	**EG/ DMSWT** [31]	**PL** [32,33]
I(Mk-1)	$B_f = B_0\left(\lambda\frac{S_0}{S_f}\right)$	$\lambda \approx 0.18$ $\frac{S_0}{S_f} \approx 1225$ $B_f \approx 2800\,T$	$\lambda \approx 0.056$ $\frac{S_0}{S_f} \approx 1600$ $B_f \approx 350\,T$	$\lambda \approx 0.6$ $\frac{S_0}{S_f} \approx 440$ $B_f \approx 550\,T$	$\lambda \approx 0.25$ $\frac{S_0}{S_f} \approx 30$ $B_f \approx 45\,T$	$\lambda \approx 0.23$ $\frac{S_0}{S_f} \approx 760$ $B_f \approx 160\,T$
II(Mk-II)	$I_f = I_0\left(\lambda\frac{L_0}{L_f}\right)$ $W_f = W_0\left(\lambda^2\frac{L_0}{L_f}\right)$	$\lambda \approx 0.2 - 0.8$ $\frac{L_0}{L_f} \approx 5 - 16000$ $I_f \approx 320\,\mathrm{MA}$ $W_f \approx 100\,\mathrm{MJ}$	? ? $I_f \approx 27\,\mathrm{MA}$ $W_f \approx 200\,\mathrm{MJ}$	? ? $I_f \approx 11\,\mathrm{MA}$?	—	? ? $I_f \approx 19.5\,\mathrm{MA}$?

ML: metallic liner, DMSWT: dielectric/metallic shock-wave driven transition, EG: electric gun, PL: plasma liner (gas-puff or exploding wire array) B – magnetic flux density, I – current, W – magnetic energy, L – inductance, S – cross-sectional area, l – magnetic flux conservation factor Subscripts o and f indicate initial and final values

100 T or 1 MG), and

(ii) conventional flux-compression generators, termed Class II or Mk-2, in which a high energy (MJ) and a high current (MA) are produced in an *external* load.

Numerous experimental results are available for both generator groups, and these enable various details of their performance to be summarised as in Table 2. When only explosively driven generators are considered, it becomes possible to identify four main operating features that distinguish one generator design form another. These are:

(a) geometric form Each of the two groups of flux-compression generators has been produced in a number of distinct geometrical constructions:

Class I (or Mk-1) — for which the geometry is cylindrical (either imploding or exploding), and

Class II (or Mk-2) — which can have many forms, including cylindrical-coaxial (either imploding or exploding), helical, disk, Archimedes spiral, plate, strip, bellows, spherical (a number of spherical designs have been proposed for generators ranging in size from the very small to the very large used with nuclear explosives). It is possible to construct generators in most of these geometric forms with a shaped geometry, so that the time rate-of-change of the inductance will increase as the generator operation progresses (see note (c)).

(b) explosive charge initiation Initiation of the explosive charge of the generator may be

- surface plane initiated (by a PWG or an exploding wire mesh system)
- line initiated (by a LWG)
- axial initiated (using axial detonators known also as "slappers")
- cylindrical imploding (using a CWG, a system of two LWGs or high precision multipoint detonators)
- spherical imploding (combination of high precision multipoint detonators with PWGs or spherical exploding wire mesh techniques)
- spherical exploding (nuclear)
- etc.

WG implies explosive (shock) wave generators, which are also sometimes termed explosive lenses, where P is for planar, L for linear and C for cylindrical.

(c) time rate-of-change of inductance (dL/dt) The time rate-of-change of the inductance of a magnetic flux-compression generator can obviously either remain constant or be variable as the operation proceeds. This enables generators to be described as either

- *time constant*: plate, bellows, cylindrical-coaxial, single-pitch helical, or
- *time variable*: all generators, including those above when properly shaped (or the multisection variable pitch helical generator)

It is known [37] that the maximum energy multiplication of a generator k, the action Λ and the electromagnetic/chemical energy efficiency η are related by the equation $\Lambda = \eta k$. It was been shown [38] that, if dL/dt is constant, Λ cannot exceed unity, and in more general considerations [37] that only if dL/dt is variable can Λ exceed unity. These limitations on Λ show that two quite different designs can be realised, one that maximises the energy multiplication, but with very low global energy efficiency, and the second with a much higher efficiency, but a limited energy multiplication.

(d) compression time This can be described as either

- *fast*: when it is less than ten microseconds, or
- *slow*: when it is from tens to hundreds of microseconds.

3. Classification of Various Types of Helical Flux Compression Generators (HFCG)

The HFCG is the type of explosive driven generator most commonly adopted in practice. Conventionally it is a Class II device, with a helical coil that is usually multisectional and a cylindrical/coaxial coil-armature system with no shaping. It employs fast crowbarring and a direct feed, with the return current flowing through the armature.

Numerous variations on the basic generator design have appeared, depending on the requirements of the particular application. A thorough study of the literature reveals that the six most important of these are

(a) fast pulse The length of the explosive charge is obviously one of the main factors determining

Table 3. Principal parameters of conventional HFCG designs

Parameter	**Large**	**Medium**	**Mini**	**Micro**
Length (mm)	1000-2500...	500-1500	100-500	< 100
Diameter (mm)	250-500...	100-250	40-100	< 40
Total mass (kg)	200-2000...	10-200	0.2-10	< 0.2
Explosive mass (kg)	20-200...	1-20	0.05-1	< 0.05
Current (MA)	10-50...	1-10	0.1-5	< 0.1
Energy (MJ)	10-100...	0.2-10	0.1-0.5	< 0.1
Compression time (ms)	100-300...	50-200	10-50	< 10

Table 4. Relative numerical modelling and design difficulties for conventional HFCG designs

Type	**Design problems (in order of importance)**	**Main tasks for numerical modelling**	**Overall design difficulty** (1-5 scale)
Large	• cost • magnetic forces! • insulation/voltage breakdown	• coil and armature 2D movement (radial and axial) • contact delays	3-4
Medium	• explosive mass • insulation/voltage breakdown • magnetic forces • energy efficiency	• electric field • 1D (radial) coil dynamics • total resistance	1-2
Mini	• energy efficiency • nonlinear diffusion • armature cracks • 2π clocking	• electric field • total resistance	2-3
Micro	• manufacture • armature cracks • 2π clocking • voltage breakdown • maximum current	• electric field • total resistance • exotic losses (contact point delay, micro-jets, etc)	4-5

the operating time of an FCG. This time can however be much reduced by either two-ended initiation of the explosive charge, as in the Sandia generators [39], or by inductive coupling and late crowbarring, as in the FLUXAR system [37,40].

(b) high efficiency This can be obtained either by dL/dt optimisation [41] or by using a special nested (Matrioshka) design [42,43]. It follows however that because the activity L is limited the energy multiplication cannot be very high.

(c) high voltage Applications where a high-voltage output is required use either an inductive feed with axial initiation [44] or Marxing [45].

(d) high current There are fundamentally two quite different approaches to achieving a high-current output from a generator. One of these is either by shaping the helical coil and/or the armature [46,47] or by using tilted turns [48] while the second is either by parallel 'battery' coupling [46] or the use of a low value of inductive/resistive load.

(e) high energy High energy generators use an optimum dL/dt grading to maintain a constant and high electric field [49] and a high value of inductive/resistive load

Table 5. Applications of conventional HFCG designs

Large	Medium	Mini	Micro
• *Large scale proof of principle experiments*: nuclear fusion; X-ray generators; lasers	• *Most applications* including: emg launchers; lightning simulators; microwave and radiowave emitters; X-ray generators (expendable); lasers; neutrons, electron and ion beam sources; small scale proof of principle experiments; large area detonating systems; electric armour	• Rocket borne applications; • inductively coupled systems (FLUXARS); • special detonator array systems	• *Special applications*: radar jamming; aviation techniques; spacecraft technology; artillery; special autonomous; detonator systems for nuclear weapons, etc.

(f) high energy/current multiplication A very high energy (or current) multiplication can only be achieved by using a chain of inductively coupled generators. Present technology imposes limits to the maximum internal electric field that can be sustained [37] and so restricts the maximum value of the action L that is achievable. This in turn means (Section 2(c)) that a high gain generator inevitably has a low efficiency, and the highest gain reported in the literature of 10^3 [49] was obtained with only some 4 % of the energy stored in the explosive charge being converted into electrical output. The need is therefore clear for a chain of generators with connection between stages, that is achieved by means of air-cored transformers [50], autotransformers [51] or dynamic transformers (flux-trapping technique or FLUXAR systems) [37 and included references].

4. Classification of Designs of Conventional HFCGs

Many laboratories have produced designs of conventional HFCGs, and on the basis of their principal parameters these can conveniently be divided into the four categories identified in Table 3. As can be seen, the range of the parameters in the different categories can overlap somewhat.

Table 4 also provides an indication of the comparative difficulties encountered in the mathematical modelling and design of the four generator categories.

5. Application of Conventional HFCG Designs

The very wide range of diverse applications for which HFCGs have been employed is summarised in Table 5.

6. Conclusions

This paper constitutes an early attempt to classify the very wide range of magnetic flux-compression generators that have been produced over the last fifty years, together with their wide range of applications, all on the basis of a set of well-established operational features.

Appendix

As the first ever magnetic flux compression experiments are only described in a Los Alamos National Laboratory internal report, which is not easily available, the most important excerpts relevant to those historical experiments are presented below (page numbers as in [1]):

"...Also in December (1943), field preparations were started for taking electronic records of objects imploded in a magnetic field. **The first shot of this type, the 'magnetic method', was fired January 4, 1944**, and the results were encouraging. The magnetic method was designed to take advantage of the fact that the motion of metal in a magnetic field alters the field. Thus the inward motion of imploding metal would induce a current in a surrounding coil, and the proper interpretation of this current would give information on the velocity and other characteristics of the implosion. Considerable perfection of the electronic records was needed, however, and this held up the final proof of the method until spring." (pp. 141-143, the highlights are not present in the original)

"...A full scale test (of a plutonium sphere), by the magnetic method, had to be made between April 15 and May 1 (1944)." (p 194)

"Material velocities measured by the electric pin method were in agreement with the theory, while those measured by the magnetic method were lower than predicted" (p. 201)

"Los Alamos had at that time a 'Weapons Physics Division' which had a group named G3-The Magnetic Method headed by E.W.McMillan." (p 228)

"By August 1944 the magnetic method had been established as a practical way of determining the velocity of the external metal surface of an imploding sphere. By integration, the average compression could also be obtained." (p 232)

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