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CONTENTS

PC Codes for the Field Calculation in MHD Superconducting Magnets

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***Abstract* - The paper describes two computer codes for the calculation of magnetic field in superconducting magnets. The codes, based on analytical methods and entirely self-developed by the authors, have been implemented on personal computer. Examples of utilization of the codes to calculate the magnetic field in superconducting magnets under development in the field of magnetohydrodynamic energy conversion (MHD) are given.**

I. Introduction

Analytical methods are useful for calculating the magnetic field in magnets with coils having uncomplicated cylindrical symmetry. They can also apply to more general three-dimensional configurations that may be decomposed in one or more filiform circuits. The implementation of analytical methods on personal computers (PC) may be more convenient than numerical codes, since information can be quickly obtained with more friendly interface.

The Research Unit of the Department of Electrical Engineering of Padova University has wide experience in the development of both two- and three-dimensional analytical methods for calculating magnetic field in superconducting (SC) magnets, with various geometries and for various applications.

In the frame of the Italian research program on MHD superconducting magnets, supported by the National Research Council (CNR), the Unit firstly developed analytical codes to be used in the preliminary design of the SC prototype magnet [1,2]. The second part of the research activity dealt with the development of two new codes and with their implementation on personal computer:

- Code **1**, to calculate magnetic field, inductances and forces in magnets composed of one or more circular coils (solenoids). The code doesn't introduce any approximation, since it takes into account the actual axial lengths and thicknesses of the coils.
- Code **2**, to calculate the magnetic field in magnets composed of one or more coils with any shape and arrangement. The code represents the coils by means of filiform circuits, allowing approximate calculation especially close to the coils.

The computer programs, based on fully-analytical methods, have been entirely self-developed by the Unit; it has been taken great care of ease of use, in order to obtain a friendly interface as regards the data input and the presentation of the results.

The paper describes the characteristics of both the codes and gives some examples of their application for the calculation of magnetic field in MHD superconducting magnets composed of circular coils (disk generators) or saddle coils (linear generators).

II. Code 1

The code allows the calculation of magnetic field and related quantities in magnets composed of solenoids, without any approximation on the shape of the coils.
The computation is performed by means of a vector-potential analytical method based on the Fourier series expansions of coil current density [1].

The code takes into consideration four coil configurations:

A: single solenoid
B: split solenoid
C: two-section solenoid
D: two-section split solenoid

and provides the following outputs:

- components of the flux density in all the regions of the magnet;
- components of the force per unit volume in the coils composing the magnet;
- pressures on the outer surfaces of the coils;
- total forces acting between coils and on the external mechanical structure;
- self and mutual inductances and stored energy.

The computer program is arranged in the following way [3,4]:

Pre-processor

It performs the following tasks:
– choice of the coil configuration;
– introduction of the input data (geometrical and electrical parameters of the magnet solenoids);

- if necessary, editing of the input data;
- viewing of the configuration;
- saving of the configuration.

Main module

It is the main solver of the program and performs the following tasks:
- calculation of the integration constants (if necessary, the number of harmonics used in computations may be controlled);
- calculation of self and mutual inductances;
- calculation of the stored energy.

Field secondary modules

There are four secondary modules to calculate the magnetic field. Each module (one for each configuration) performs the following tasks:
- calculation of the magnetic field on a line along the radial or axial coordinate;
- calculation of the magnetic field on a surface.

Force secondary modules

There are two secondary modules to calculate the electromagnetic forces. Each module (one for configuration A and one for configuration B) performs the following tasks:
- calculation of the distribution of forces per unit volume on a pre-fixed mesh inside the coils;
- calculation of the forces acting on volume elements of pre-fixed sizes;
- calculation of pressures on coil outer surfaces;
- calculation of total forces acting between coils and on the external mechanical structure.

Post-processor

It is called by each secondary module. It performs the following tasks:
- numerical viewing of the results;
- graphical viewing of the results (only for the field modules);
- saving of the results (ASCII file) for subsequent graphical elaboration.

The code can be utilized to map the field in SC magnets for MHD disk generators; in particular:

- to evaluate the peak field on the SC cable in order to keep the SC operation point away from critical conditions;
- to verify whether the magnet meets, in the active MHD region, requirements in regards to the magnitude and the homogeneity of the field;
- to evaluate the flux density in the outer region, even at long distance, (field intensity on measurement apparatus, magnetizable objects and persons).

As an example of application, the code has been utilized in order to calculate the above-mentioned quantities in a SC magnet coupled with a disk generator in a closed cycle MHD experimental facility [5]. The magnet under consideration consists of two circular coils faced each other with the generator placed in the gap between the coils (configuration B, split solenoid).

Fig.1 shows the starting menu of the code, while Fig.2 gives the view of the coil arrangement and dimensions as well as the results in terms of inductances ,and stored energy.

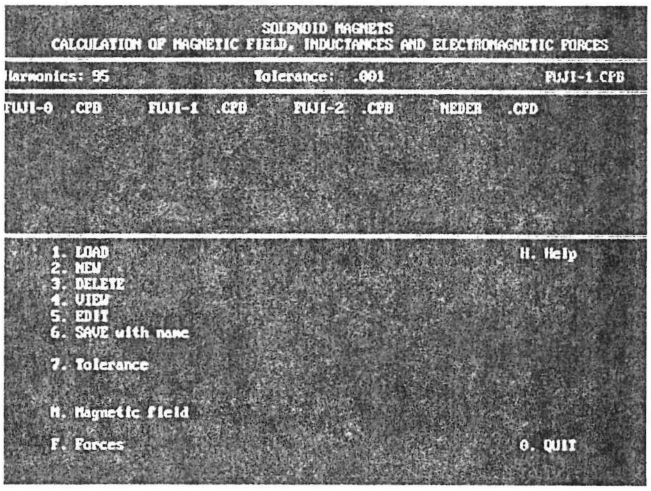

Fig.1 - Starting menu of code 1.

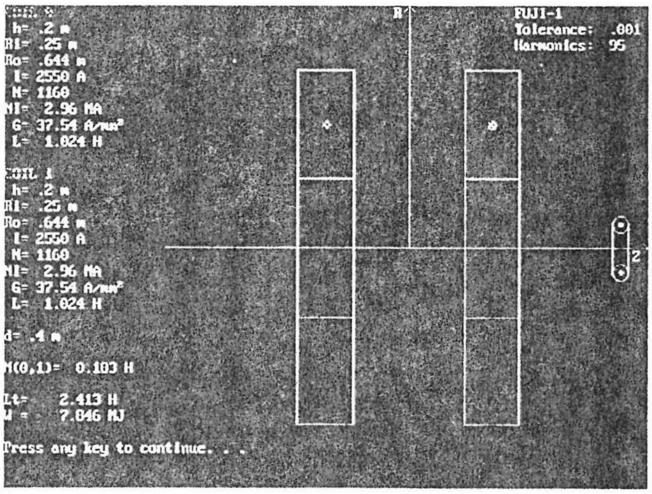

Fig.2 - Code 1: view of a split solenoid configuration.
[h, Ri, Ro, d: dimensions; NI, G: ampereturns and overall current density; L, M, Lt: self, mutual and total inductances; W: stored energy].

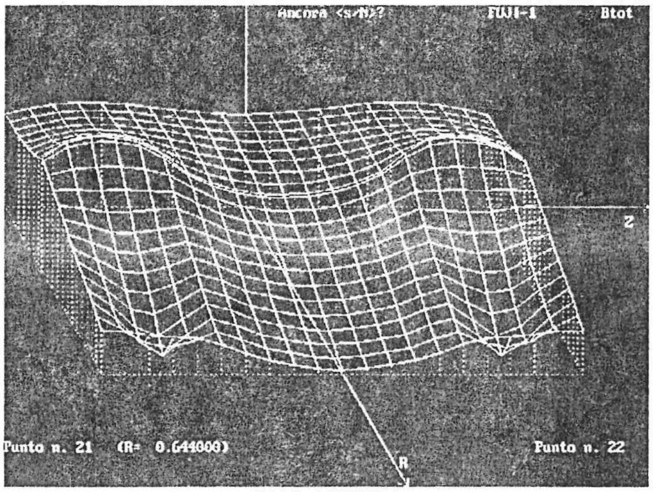

Fig.3 - Code 1: view of the map of the magnetic field for the magnet of Fig.2.

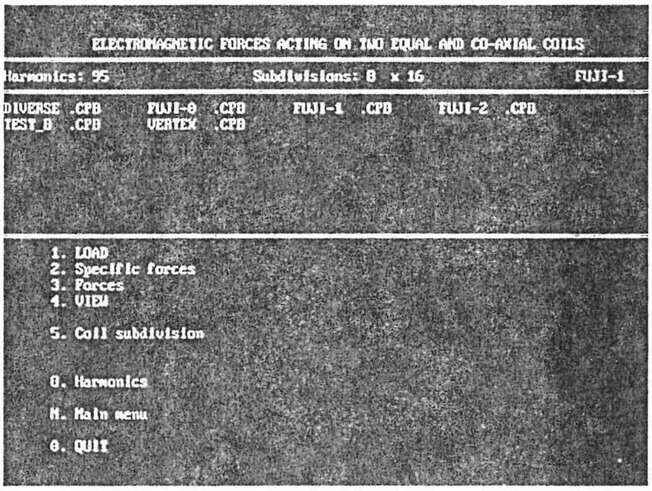

Fig.4 - Code 1: starting menu of the force module.

Fig.3 gives an example of distribution of the module of the flux density, as it is displayed by the program.
Finally, Fig.4 shows the starting menu of the force module while an example of corresponding numerical output is shown in the Appendix.

III. Code 2

The code allows the calculation of magnetic field in magnets composed of several coils, of different geometry and configuration [6]; it is based on a fully analytical approach and lets to rebuild the map of the field outside the superconductor quickly and with good precision.
Each magnet coil is replaced by means of a filiform representation, made of several rectilinear segments connected to originate one or more filiform circuits (called elementary turns), suitably arranged in order to rebuild the geometry of the coil.

Once a suitable fraction of the total ampereturns has been assigned to an elementary turn, the magnetic field produced by the turn is calculated by the sum of the contributions of the rectilinear segments.

The main points of the procedure are:

- determination of the number and position of the elementary turns replacing each magnet coil;
- determination of the rectilinear segments composing each elementary turn;
- rebuilding of the magnetic field by the sum of the contributions of the rectilinear segments.

Elementary turns

The more distant from the coil, the more accurate is the calculation of the magnetic field. In order to improve the precision close to the coil, the coil itself is replaced by more than one elementary turn.
Consider a coil with a rectangular cross section. In the formulations for the field calculation, a surface integral appears: the procedure consists in determining $p \cdot q$ points in the section and then expressing the integral by means of Gauss quadrature formulas. In this way, the field calculation turns into the calculation of the field produced by $p \cdot q$ filiform circuits, each with ampereturns obtainable multiplying the total ampereturns by the relative Gauss weights. In case of non-rectangular section, a bilinear transformation allows to refer anyway to the case of rectangular section.

Rectilinear segments

The adopted procedure involves the generation of a file containing the coordinates of the vertices of the polygonal line originating the filiform circuit. Such a file is automatically generated in the case of standard coils (race track coils, for example), starting from their geometrical parameters. In the case of coils of non-standard geometry, the file may be created by the user by means of a CAD procedure.

Rebuilding of the magnetic field

Consider an elementary turn, made of n rectilinear segments. Two coordinate system are used: a general system, related to the whole coil, and a particular system, related to the n-th segment. The versor components of the particular system with respect to the general one are the elements of the transformation matrix which allows to change from one system to the other. In this way, the field produced by the elementary turn can be determined by the sum of the contributions of all the segments, each contribution being calculated by means of well-known formulations.

The code consists of a main solver, a pre- and a post-processor.
At present, the main solver has been completely implemented and tested. The part of the pre-processors related to magnet composed of so-called standard coils (race track, solenoid and cylindrical saddle coils) has been completed (Fig.5), while the part related to non-standard coils is still under development.

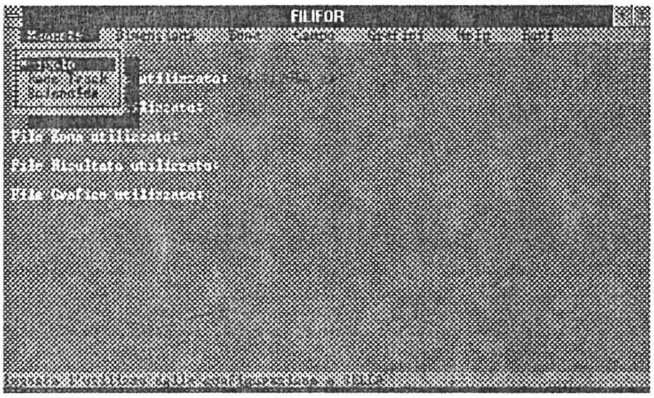

Fig.5 - Starting menu of code **2** (standard coils).

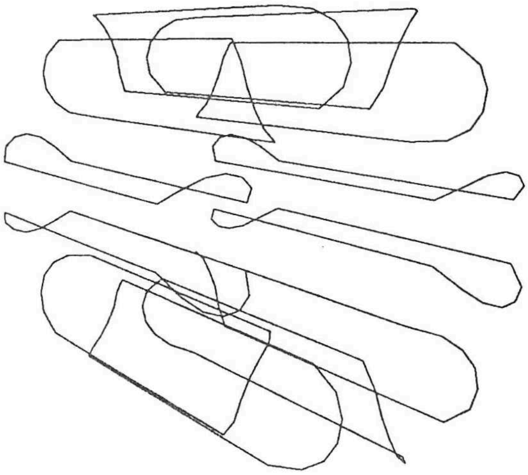

Fig.6 - Filiform representation of the six SC dipoles of the thrusters of Yamato I (one elementary turn per saddle) [7].

The first example of application refers to a configuration with six dipoles (cylindrical saddle coils), utilized in the thrusters of the MHD propulsion ship Yamato I (Fig.6) [7].

Each coil is represented by mean of six elementary turns (Fig.7) with a total of 72 saddle-shaped elementary turns. The number of rectilinear segments composing a single turn is between 10 and 20. The magnetic field has been evaluated in the conduct of a dipole: Fig.8 shows the distribution of the module of the flux density in the middle plane inside the conduct.

The second example of application deals with a magnet composed of non-standard coils (rectangular saddle coils) and refers to the SC MHD prototype magnet under manufacturing at Ansaldo [3,4,6]. Fig.9 shows the filiform representation used in the code: each coil is represented by means of nine elementary turns while the number of rectilinear segments composing a single turn is 56.
The obtained distribution of the field along the magnet axis is shown in Fig.10.

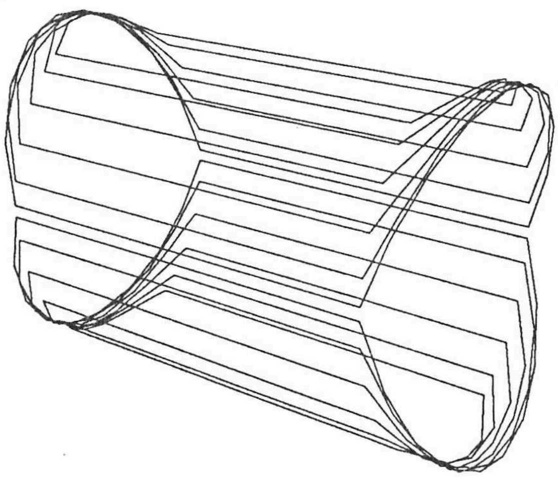

Fig.7 - Filiform representation of a dipole of Yamato I (six elementary turns per saddle).

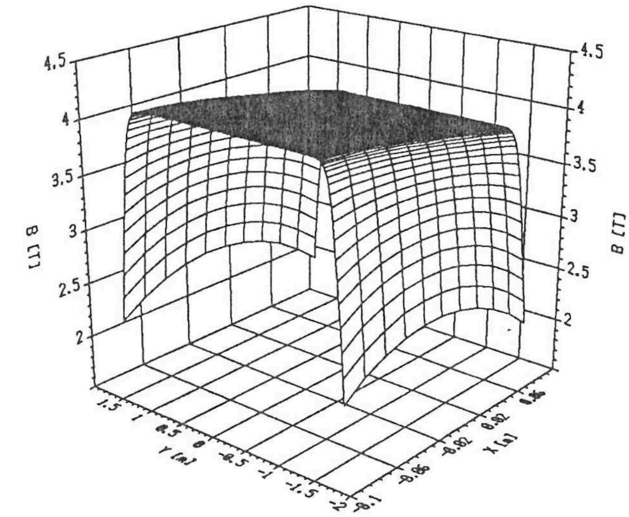

Fig.8 - Flux density distribution in the active region of a dipole of Yamato I (taking into account the contributions of the other five dipoles).

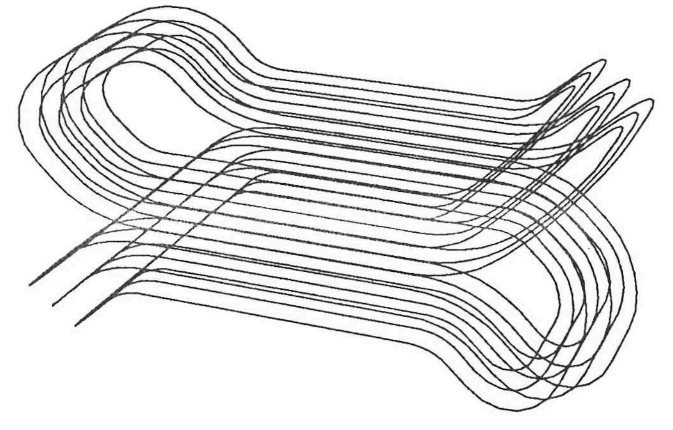

Fig.9 - Filiform representation of the MHD prototype magnet under manufacturing (nine elementary turns per saddle).

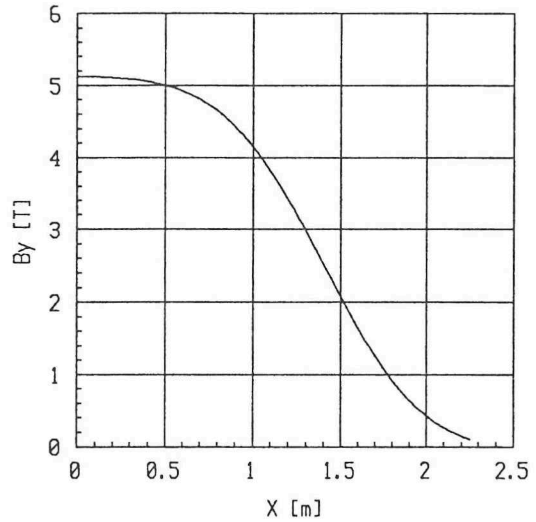

Fig.10 - Flux density distribution in the active region of the MHD prototype magnet.

IV. Conclusions

Due to ease of use and friendly interface as regards the data input and the presentation of the results, PC analytical codes are useful in the preliminary design of SC magnet, the introduced approximations, if present, being counterbalanced by saving in calculation time and costs.

In the frame of the CNR Italian research program on MHD SC magnets, the paper describes two PC codes developed by Padova Research Unit. Some example of application are given with reference to magnets with saddle or circular coils. The obtained results are in good concordance with the ones obtainable by means of numerical codes: in every region of the magnet for code **1** and outside the coils for code **2**.

Appendix

Code **1**: example of numerical output related to the force analysis of the magnet of Fig.2.

FUJI-1

COIL n.	0	COIL n.	1
Axial length h [m]:	.2	Axial length h [m]:	.2
Inner radius Ri [m]:	.25	Inner radius Ri [m]:	.25
Outer radius Ro [m]:	.644	Outer radius Ro [m]:	.644
Current I [A]:	2550	Current I [A]:	2550
Number of turns N:	1160	Number of turns N:	1160
Ampereturns NI [MA]:	2.958	Ampereturns NI [MA]:	2.958
Density G [A/mm2]:	37.538	Density G [A/mm2]:	37.538
Self inductance L [H]:	1.023590	Self inductance [H]:	1.023590

Distance between coils d [m]: .4

Mutual inductance M [H]:	0.183097
Total inductance Lt [H]:	2.413375
Stored energy W [MJ]:	7.846485

Harmonic order: 95

Subdivisions along R: 8
Subdivisions along Z: 16

LEFT COIL - FORCES acting at the center of volume elements 2πR*DR*DZ

Element: DR = 0.4925D-01 DZ = 0.1250D-01

	R (m)	Z+(h+d)/2 (m)	fr (MN)	fz (MN)
1	0.27462500D+00	-.93750000D-01	0.199087D+00	0.940334D-01
2	0.27462500D+00	-.81250000D-01	0.209654D+00	0.868966D-01
3	0.27462500D+00	-.68750000D-01	0.219112D+00	0.761994D-01
4	0.27462500D+00	-.56250000D-01	0.227056D+00	0.632946D-01
5	0.27462500D+00	-.43750000D-01	0.233304D+00	0.498341D-01
6	0.27462500D+00	-.31250000D-01	0.237904D+00	0.372505D-01
7	0.27462500D+00	-.18750000D-01	0.241064D+00	0.263149D-01
8	0.27462500D+00	-.62500000D-02	0.243038D+00	0.169372D-01
9	0.27462500D+00	0.62500000D-02	0.244004D+00	0.828921D-02
10	0.27462500D+00	0.18750000D-01	0.243979D+00	-.788591D-03
11	0.27462500D+00	0.31250000D-01	0.242819D+00	-.112473D-01
12	0.27462500D+00	0.43750000D-01	0.240278D+00	-.233602D-01
13	0.27462500D+00	0.56250000D-01	0.236131D+00	-.365063D-01
14	0.27462500D+00	0.68750000D-01	0.230303D+00	-.492920D-01
15	0.27462500D+00	0.81250000D-01	0.222947D+00	-.599726D-01
16	0.27462500D+00	0.93750000D-01	0.214466D+00	-.670155D-01

....
....

1	0.61937500D+00	-.93750000D-01	-.589007D-01	0.202841D+00
2	0.61937500D+00	-.81250000D-01	-.700459D-01	0.187947D+00
3	0.61937500D+00	-.68750000D-01	-.798552D-01	0.165416D+00
4	0.61937500D+00	-.56250000D-01	-.878048D-01	0.138199D+00
5	0.61937500D+00	-.43750000D-01	-.936827D-01	0.109914D+00
6	0.61937500D+00	-.31250000D-01	-.975821D-01	0.837016D-01
7	0.61937500D+00	-.18750000D-01	-.997998D-01	0.612462D-01
8	0.61937500D+00	-.62500000D-02	-.100675D+00	0.423212D-01
9	0.61937500D+00	0.62500000D-02	-.100431D+00	0.250552D-01
10	0.61937500D+00	0.18750000D-01	-.990710D-01	0.682763D-02
11	0.61937500D+00	0.31250000D-01	-.963817D-01	-.145339D-01
12	0.61937500D+00	0.43750000D-01	-.920250D-01	-.397052D-01
13	0.61937500D+00	0.56250000D-01	-.857013D-01	-.673734D-01
14	0.61937500D+00	0.68750000D-01	-.773132D-01	-.944983D-01
15	0.61937500D+00	0.81250000D-01	-.670730D-01	-.117240D+00
16	0.61937500D+00	0.93750000D-01	-.555125D-01	-.132211D+00

LEFT COILS PRESSURES

	Z+(h+d)/2 (m)	pr (MPa)
1	-.93750000D-01	0.177715D+02
2	-.81250000D-01	0.182767D+02
3	-.68750000D-01	0.187371D+02

4	-.56250000D-01	0.191382D+02
5	-.43750000D-01	0.194729D+02
6	-.31250000D-01	0.197423D+02
7	-.18750000D-01	0.199530D+02
8	-.62500000D-02	0.201137D+02
9	0.62500000D-02	0.202310D+02
10	0.18750000D-01	0.203059D+02
11	0.31250000D-01	0.203338D+02
12	0.43750000D-01	0.203065D+02
13	0.56250000D-01	0.202164D+02
14	0.68750000D-01	0.200607D+02
15	0.81250000D-01	0.198448D+02
16	0.93750000D-01	0.195827D+02

	R (m)	pz (MPa)
1	0.27462500D+00	0.248132D+01
2	0.32387500D+00	0.276201D+01
3	0.37312500D+00	0.296854D+01
4	0.42237500D+00	0.309772D+01
5	0.47162500D+00	0.315007D+01
6	0.52087500D+00	0.313026D+01
7	0.57012500D+00	0.304668D+01
8	0.61937500D+00	0.291086D+01

LEFT COIL - TOTAL RESULTANT FORCES

Frt = 0.158864D+02 MN
Fzt = 0.329500D+01 MN

ACKNOWLEDGMENT

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