Proton Driver with Superconducting Magnets (proposal for R&D)

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Outline

- Introduction
- AC superconducting applications
- AC superconductors LTS and HTS
- Proton driver dipole magnets
- Advantages of superconducting accelerator
- Directions for R&D
- Summary

Introduction

Is it possible to build fast (15Hz) cycling superconducting accelerator?

- **NUKLOTRON, JINR, Dubna – superconducting magnets, 2Tesla, 1 Hz**
- **GSI, Germany, Darmschtadt - two stages, 2T-4T, 1Hz (prototyping)**
- **Super-GM project, Japan – 50-60 Hz applications**
- **HTS 1MVA power transformer, 145A, 6.9 kV, 60Hz**
- **New AC superconductors**
- **HTS Current leads - 2 kA, 50 Hz**
- **HTS transmission lines projects**
- **Resonance power supply with IGBT**

SC Magnets
at Fermilab

AC superconducting applications

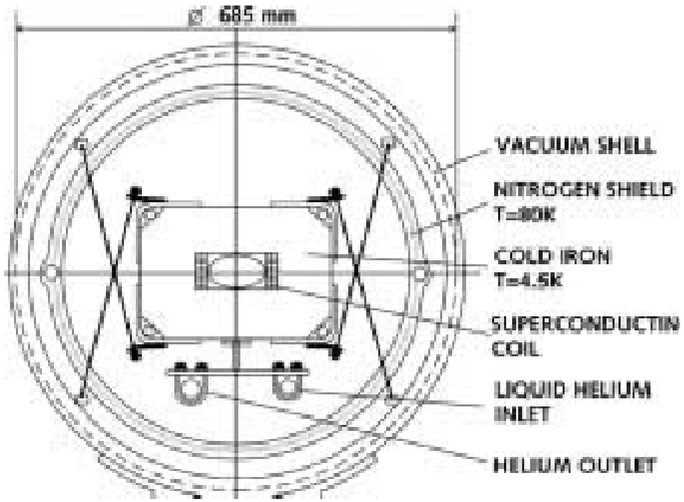


Fig. 1. Cross section of the Nuclotron dipole including its cryostat.

TABLE I
MAIN PARAMETERS OF THE MAGNETS

	80KDP1	80KDP2
Aperture size (mm)	112x56	108x52
Magnetic induction (T)	2	2
Yoke length (mm)	1370	1370
Yoke size (mm)	292x205.5	292x203.4
Yoke gap size (mm)	153x61.7	153x59.6
Yoke temperature (K)	80	80
Mass at 80K (kg)	500	500
Mass at 4.6K (kg)	14	23
Coolant	two-phase *He*	two-phase *He*
Winding		
Number of turns	16	16
Height (mm)	56	56
Number of layer	2	2
He channel diameter (mm)	4	4
Spacer thickness between the half-windings (mm)	-	2.34
SC cable length (m)	62	62
Cable		
Type	hollow composite	hollow composite
Tube diameter (mm)	5	5
External diameter (mm)	7	6.7
Number of strands	31	31
Strand diameter (mm)	0.5	0.5
Twist pitch of strands (mm)	47	47
Superconductor	50%Nb-50%Ti	50%Nb-50%Ti
Number of SC filaments	2970	2970
Filament diameter (μm)	6	6
Twist pitch of filaments (mm)	7	7

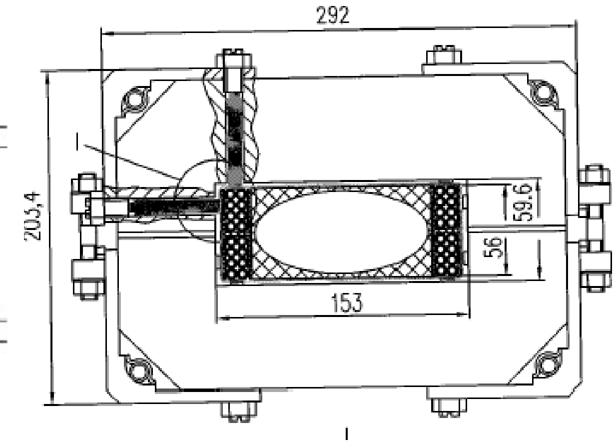
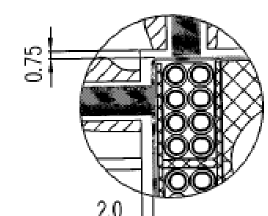


Fig. 1. Magnet 80KDP1 during assembly.



Abstract—Two new prototype dipole magnets for the proposed new fast cycling ($f = 1$ Hz) synchrotron at GSI in Darmstadt have been designed, fabricated and tested. The magnets are based on a window frame iron yoke cooled by liquid nitrogen and a superconducting winding made from a hollow NbTi composite superconductor cable cooled with forced two-phase helium flow at $T = 4{,}5$ K. The cold mass of the magnet is separated from the yoke by a small vacuum gap of 0.75 mm to 2.5 mm. A decrease of ac power losses by a factor of 2.3 in comparison with a standard Nuclotron dipole is obtained. The design features of two prototype dipoles as well as the test results are presented.

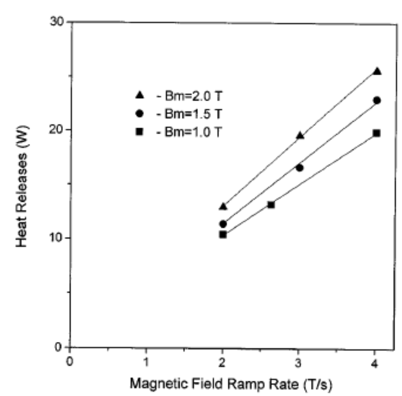


Fig. 5. Heat releases in the winding as a function of the magnetic field ramp rate.

Bm=2T, dB/dt=4T/s, f=1Hz, P=16W/m magnet length

Iq=7400A

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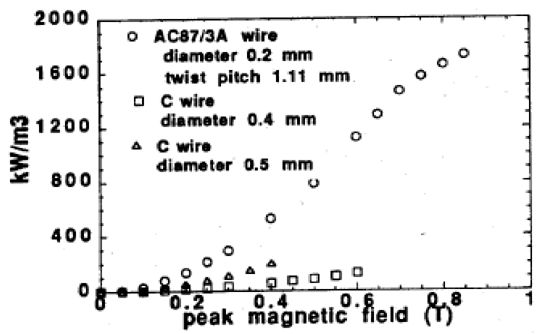
AC LTS superconductors

SC Magnets
at Fermilab

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 3, NO.1, MARCH 1993

ABSTRACT - Superconducting wires for 50-60 Hz applications must have very small diameters, in order to obtain intrinsic stability and low AC losses. kA-class conductors are made of a large number of these elementary wires.
New concepts are developed in the latest GEC ALSTHOM's conductors, which make them more industrial, and give them particular quench properties, leading to self-protection against burning or breakdown.
Experimental results are presented.

Fig. 2 Losses in transversal magnetic field

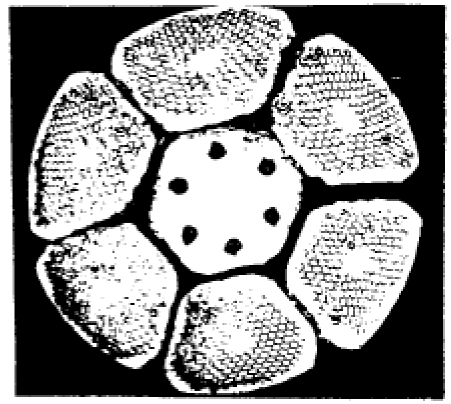


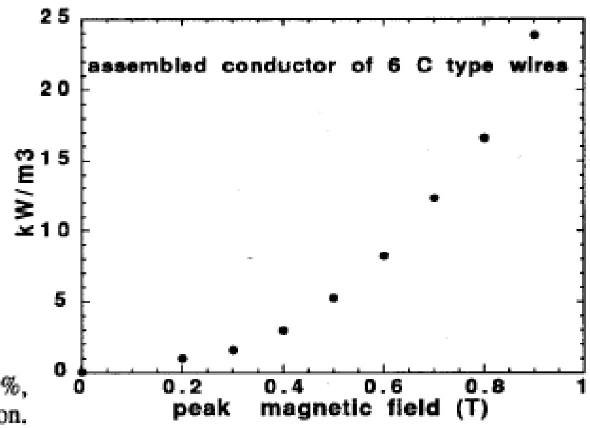
- ***Critical currents***

Critical current densities are reduced of ~ 20 %, compared with those of the sub-wires before deformation. However, due to the compacted form and to the non-insulation of the sub-wires, the overall cross section is reduced and the averaged critical current density is appreciably higher than in a classical assembled strand.

B (T)	Ø 0.4 mm	Ø 0.5 mm
0	384	514
0.2	310	410
0.5	202	270
1	115	170
1.5	74	110
2	50	76

Table 1. DC critical currents (A) of C-type wires.





AC losses of the test coil

1kW/m3 = 1 mW/mm^2-m

The typical diameter of a C-wire is 0.5 mm. Each of its 6 superconducting sub-wires contains 186252 NbTi 0.16 µm diameter filaments in a Cu-30 % wt Ni matrix, and is totally copper-free. The central non superconducting wire is made of Cu filaments in a CuNi matrix, designed for quench behaviour optimization.

- ***Fabrication***

The fabrication process is made possible by the excellent metallurgical behaviour of the NbTi/CuNi composites : the sub-wires are twisted and assembled at a chosen diameter, in the form of a classical strand ; this strand is then compacted and reduced by cold drawing, possibly completed by twisting . The sub-wire twist pitch lengthes are 1.12 and 1.75 mm for the Ø 0.5 and 0.4 C-wires respectively. The C-wire twist pitch lengthes are 5.6 and 8.75 mm respectively. As seen later, the drastic deformation of sub-wires do not seriously reduce their critical current densities or their consistency.

The lengthes and costs involved in the processing are largely reduced, when the assembling is made at a relatively high sub-wire diameter, because the sub-wire final reduction is performed by cold drawing of the relatively large C-wire.

CONCLUSION

C-type wires are industrial products with a typical diameter of 0.5 mm, presenting intrinsic performances (critical current density, stability, AC losses) similar to those of classically optimized wires of 0.2 mm diameter. They benefit besides of the "transfer propagation mode", which offers propagation velocities of several km/s, and is therefore exploited for passive protection.

C-type wires are used as the basic elements of various assembled conductors.

Owing to complementary components of the conductor, any local quench initiation is rapidly transformed into a "mass quench", also exploited for passive protection.

These principles have been successfully experimented on 50 Hz superconductors. A first approach suggests that they are also applicable to various low T_c magnets.

AC Current leads

SC Magnets
at Fermilab

IEEE Trans. on Magnetics, Vol.32, No.4, 1996, p.2671

Y.Yasukawa, et.al.

TABLE I

MAJOR DESIGN PARAMETERS FOR 2kA HTS CURRENT LEAD

Parameter	Value
Rated Current/Rated Voltage	2 kA rms/6.6 kV
Cooling Method	Copper : Cold Nitrogen Gas HTS :Heat Conduction
Whole Length of current lead	1322 mm
HTS Material	$(Bi_{1-x}Pb_x)_2Sr_2Ca_2Cu_3O_y$
Dimension of Copper Section	Area :400 mm^2, Length :855 mm
Dimension of HTS element	18.5 mm × 4.1 mm × 130 mm
Number of HTS element for each pole	12

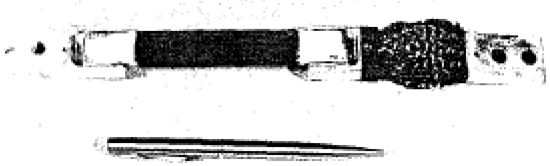


Fig. 1. Photograph of slab–shaped HTS element

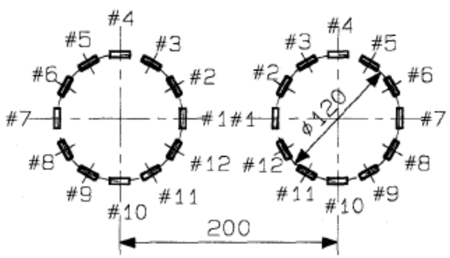
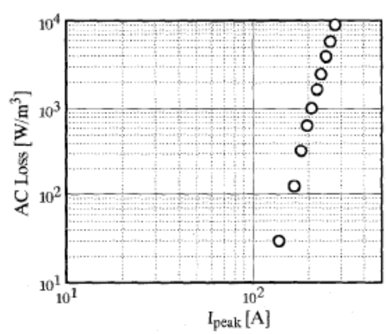
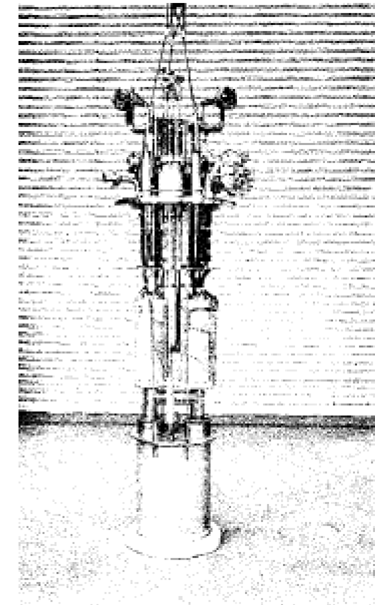


Fig. 5. Placement of HTS elements

Abstract—**High–temperature–superconductor (HTS) current leads are suitable for AC applications because of lower AC loss during operation as well as their lower thermal conductivity. We have designed, fabricated and tested a 2 kA HTS current lead system. It is composed of copper leads for the higher temperature region and HTS elements (BSCCO–2223) for the lower temperature region. The copper section is cooled with cold nitrogen gas, while the HTS section is cooled by solid state heat conduction. Tests demonstrated the current lead system can successfully conduct a current of 2000 Arms at 50 Hz. In order to investigate to evaluate the performance of the current lead system, measurements such as the steady state boil–off rate of cooling gas at various operating currents and the characteristics of current sharing in each HTS element were made. Tests of a.c. behavior in HTS elements were also carried out.**



We have demonstrated that our newly developed 2 kA HTS current leads for AC applications can stably conduct a current of 2000 Arms. AC losses and joint resistances were assessed in the a.c. operation mode. Measured data obtained for temperature distribution in HTS were in good agreement with the calculated results. The helium boil–off rate obtained for our current leads at 2000 Arms was 86 % of the value obtained when using conventional copper leads. We have also obtained the current sharing characteristics that the ratio of the maximum current to the minimum current is about 2:1.



Photograph of 2 kA HTS current lead system

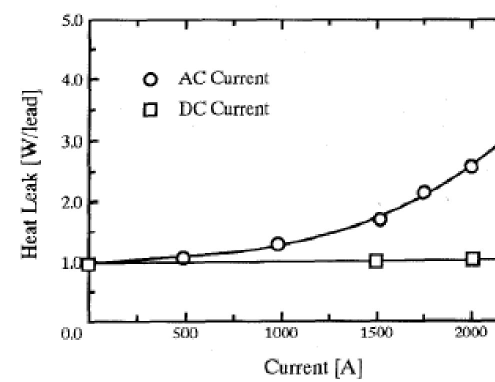


Fig. 7. Heat leak of AC and DC current modes at 4.2 K

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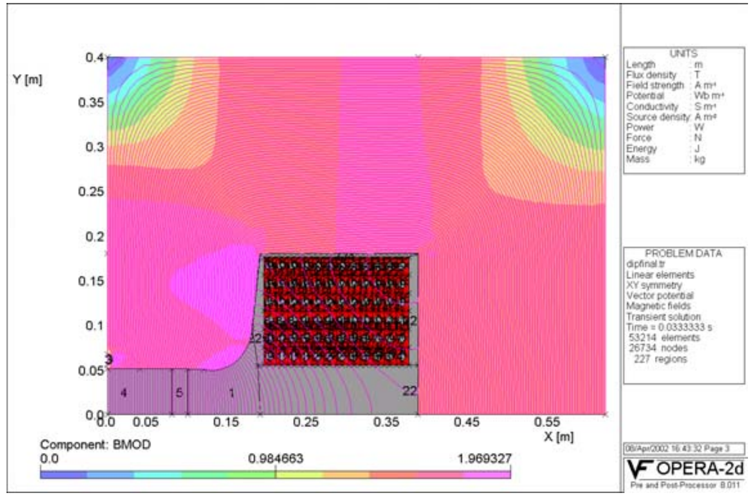
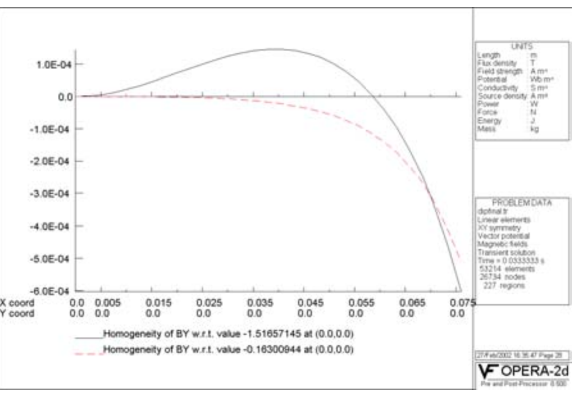
SC Magnets at Fermilab

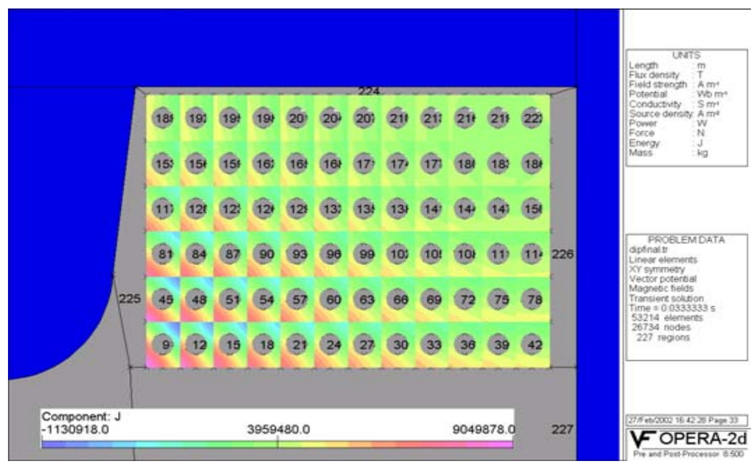
Proton Driver Dipole Magnet

Magnetic field	1.5 T
Air gap	101.6 mm
Field homogeneity	± 0.05 %
Magnet length	5.72 m
Repetition rate	15 Hz
Maximum current	5170 A
Average power	115 kW
Conductor 20.2 mm x 15 mm, 10 mm dia.	





Number of turns/pole	24
(three conductors in parallel)	
Lamination thickness	0.35 mm
DC Resistance	4.7 mOhm
Inductance	18 mH
Number of water circuits	12
Water pressure drop	10 bar
Water flow	1.7 l/s
Water temperature rise	17 C



Operational cost of electricity:

20 years

7900 hours/year

0.1$/kWh including efficiency

115 kW/magnet

~ 25 magnets

Magnets cost 27.3 M$

Electricity 45.4 M$

SC Magnets
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Superconducting Dipole Magnet

Main Issue:

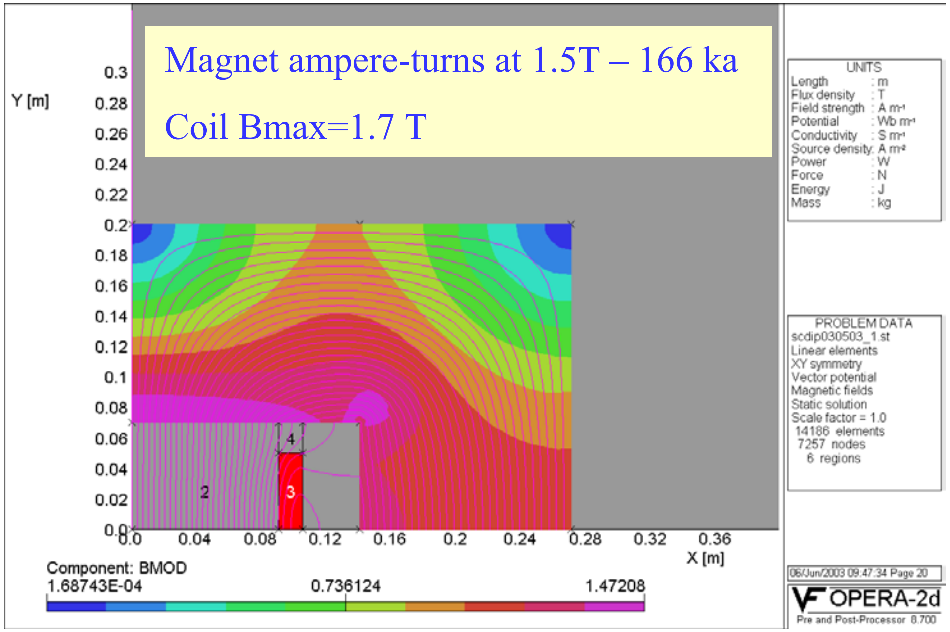
Superconducting cable and winding with low eddy current losses

Magnet Parameters:

Magnetic field	**1.5 – 3.0 T**
Frequency	**15 Hz**
Air gap	**100 – 150 mm**
Length	**5.72m – 2.86 m**
Superconductor	**NbTi/CuNi or HTS**
Iron/air core	**room temperature**
Cooling	**LHe forced flow**

Superconductor AC losses < 3.3 kW/m^3 at 15 Hz and 0.5 mm dia.
Losses for 1.5 T magnet 1.2 W/m for NbTi/CuNi ALSTHOM superconductor with 0.16 um filaments

Hysteresis losses can be effectively reduced by decreasing a filament size up to ~ 0.2 um



Eddy current losses effectively reduced by using high resistive CuNi matrix and small twist pitch 1.5mm for sub-wire and 6-8mm in 0.5mm wire.

Careful optimization needed between SC cable, cooling pipes/channels and construction elements to reduce heat load up to reasonable value

Advantages of superconducting synchrotron

- **Field x Frequency – Accelerator Magnets Record**
  3 T x 15 Hz = 45 !
- **Field x Frequency x Field Volume – World Record**
  4.5 m3 !
- **Possible cost savings**
- **Higher magnetic field**
- **Larger aperture for larger luminocity**
- **Shorter tunnel**
- **Smaller magnets**
- **Lower wall power**
- **New technology for industry**
- **Investments in AC superconductors**
- **Young people education and experience**

SC Magnets
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Directions for R&D

- **Superconducting Proton Driver Preconceptual Design.**
- **Superconducting Proton Driver Design Study with cost analysis.**
- **AC superconductors choice, tests.**
- **AC cables design, manufacturing and tests.**
- **Dipole and quadrupole AC magnets design, model tests.**
- **Test stand with AC current leads and power supply design and manufacturing.**
- **Proton Driver Cryosystem**
- **Proton Driver Power Supply**

Summary

The goal of this proposal is to initiate Superconducting Proton Driver discussion, design study and R&D.

- **Superconducting AC magnets on the frontier of superconducting technology.**
- **These magnets and technology are the good and feasible step to 60 Hz industrial applications: synchronous generators, motors, transformers, transmission lines which supported by DOE funds.**
- **Fermilab needs new and high technology project to continue be a world leader in superconducting magnets and has resources for this task.**