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Design and performance of a "squirrel-cage" dynamo-type HTS flux pump

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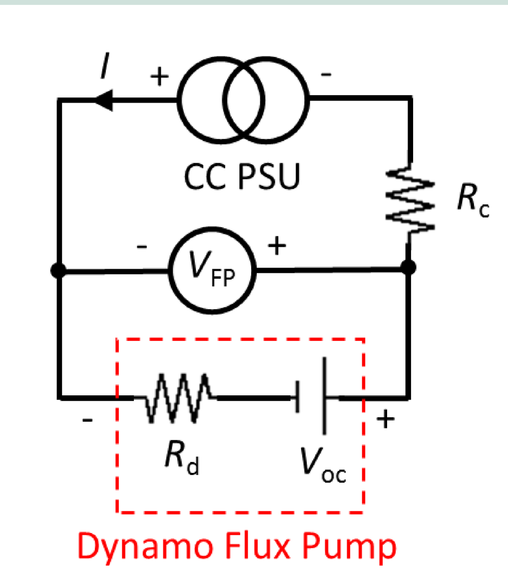
HTS Dynamo Flux Pumps

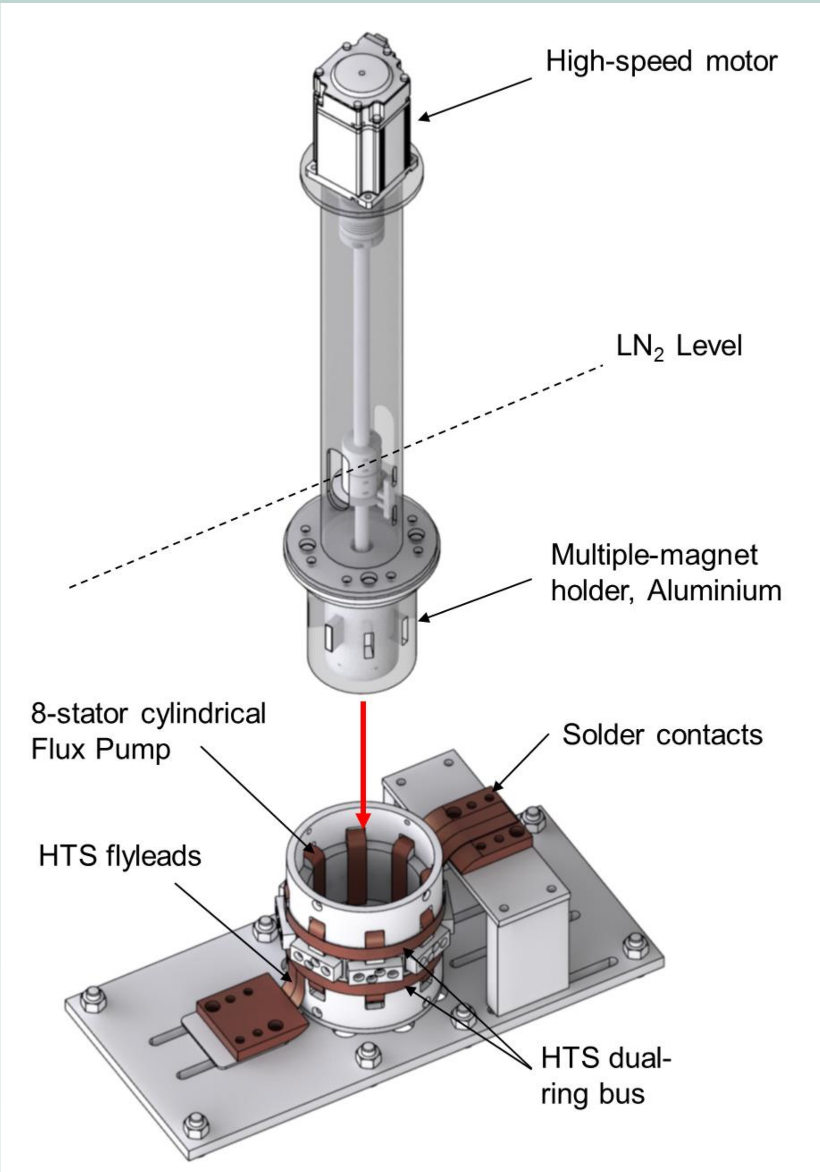
- HTS magnet coils cannot be operated in persistent mode.
- Require DC current injection from external current supply via metal current leads.
  - Conducting current leads bridge between room temperature and cryogenic environment
  - → Parasitic heat load (conduction + dissipation)
- Alternative approach: Dynamo-type HTS flux pumps can inject DC current into a series-connected superconducting coil (inductive load) without physical electrical connections.
  - Employs mechanically-rotating permanent magnets which pass over coated conductor tape (stator wire).
  - Behaves like a DC voltage source: output voltage V_{OC} and internal resistance R_d. [1 – 4]
  - DC voltage arises due to partial rectification of the induced ac output. This is caused by circulating supercurrents which 'short-circuit' the emf in the high field region directly opposite the rotor magnet [4].
- The internal resistance (R_d) of an HTS dynamo limits its maximum output current (I_{sc}). R_d can be reduced by adding additional stator wires in parallel.
  - Here we investigate the effect of changing the ratio of number of rotor magnets to number of stator wires for a cylindrical 'squirrel cage' stator geometry.
  - A programmable DC current supply is used to characterise the output of the dynamo across a range of operating currents and frequencies (see [3]).



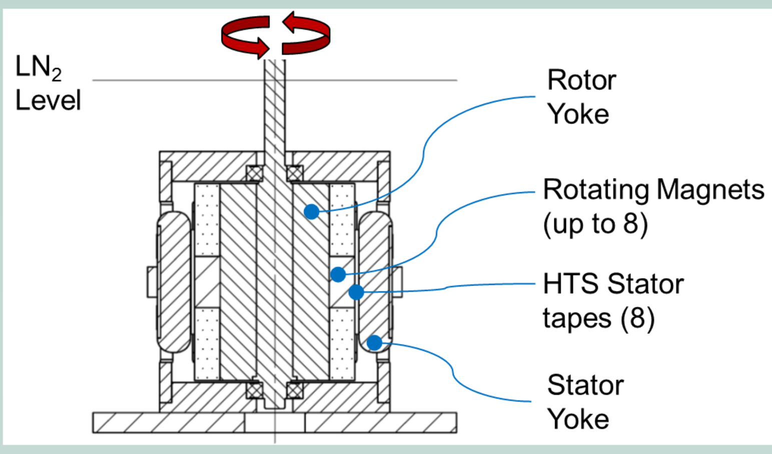
Equivalent circuit diagram showing the measurement setup: Dynamo Flux Pump, comprising open-circuit voltage V_{OC} and effective internal resistance R_d. Also shown is the constant-current power supply (CC PSU) - which is employed as a programmable load - and solder-joint resistance R_c. The dynamo-type flux pump outputs a measured DC voltage V_{FP} whilst driving current I around the circuit.

Design of experimental "squirrel-cage" dynamo

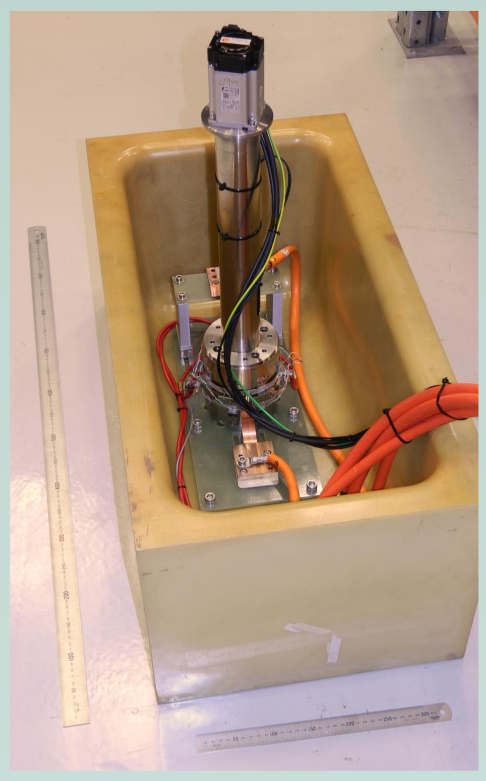
- Design employs a stator geometry of 8 parallel HTS tapes connected at either end by a superconducting ring-bus. The 8 stator tapes are mounted upon a cylindrical iron stator yoke which is arranged co-axially with the rotor.
  - Parallel HTS stator tapes: 12 mm ReBCO coated conductor (Superpower Inc, self-field I_c = 260 A @ 77K).
  - HTS dual-ring bus and flyleads: 10 mm ReBCO coated conductor (Fujikura, self-field I_c = 490 A @ 77 K).



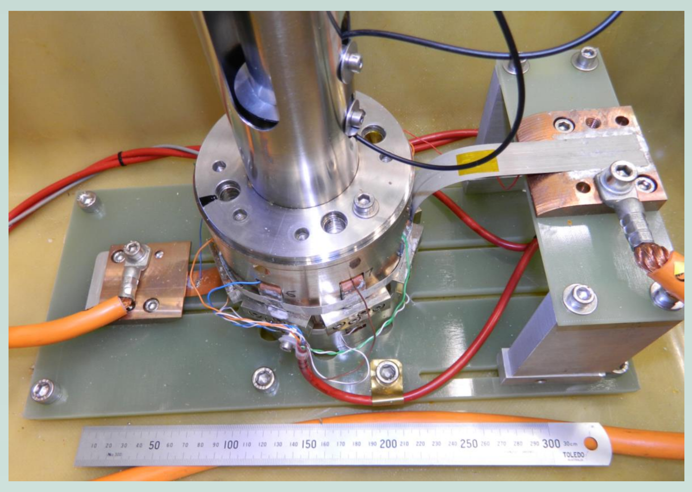
Exploded view of multiple-magnet holder insert with high-speed motor (top), and the cylindrical arrangement of eight HTS stator tapes, dual HTS ring bus, and HTS flyleads (bottom). Two high-current copper terminals (solder contacts) allow connection to the CC PSU. V_{FP} is measured from voltage taps connected to each of the 8 HTS stator wires.



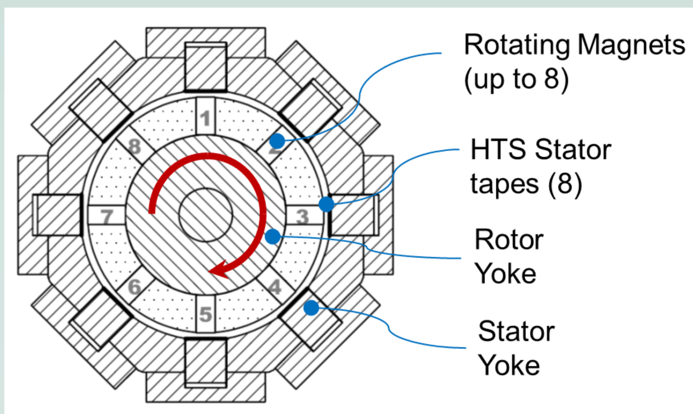
Side-view cross-section. Shaded regions indicate the magnetic circuit path formed by the magnet(s) and the two yokes.



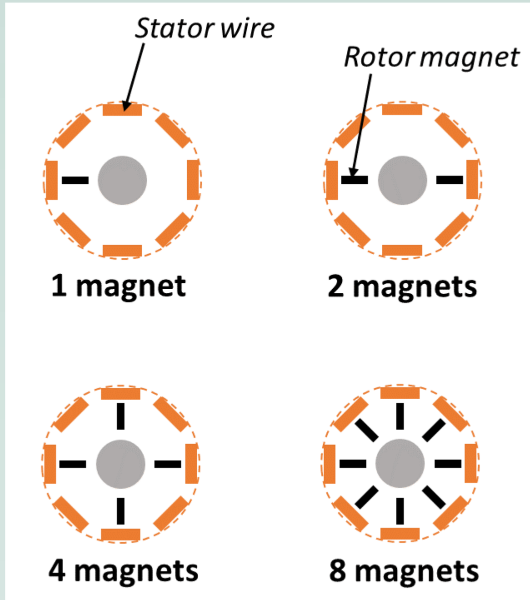
The measurement rig in its liquid nitrogen immersion cryostat. Metal rulers on the ground show the scale: 1 m (left) and 30 cm (bottom).



The completed assembly, showing high-current leads, soldered HTS flyleads, and thin wire stator voltage taps.



Top-view cross-section showing HTS stator tapes, rotor yoke, stator yoke, and 8 locations for Nd-Fe-B magnets (numbered 1 to 8).



Rotor magnet geometries studied using 8 stator wires

Up to 8 rotor magnets can be mounted on the rotor. In this work, symmetric arrangements of n_M=1, n_M=2, n_M=4 and n_M=8 were used, in conjunction with 8 parallel stator wires.

Current-voltage output characteristics

Measuring the I-V_{FP} relationship of the dynamo provides three key parameters which fully describe the output of the dynamo at a given rotor speed:

V_{OC} Is the open-circuit voltage, given by the x-axis intercept.

R_d is the internal resistance due to ac losses [5], obtained from the slope of the linear fit.

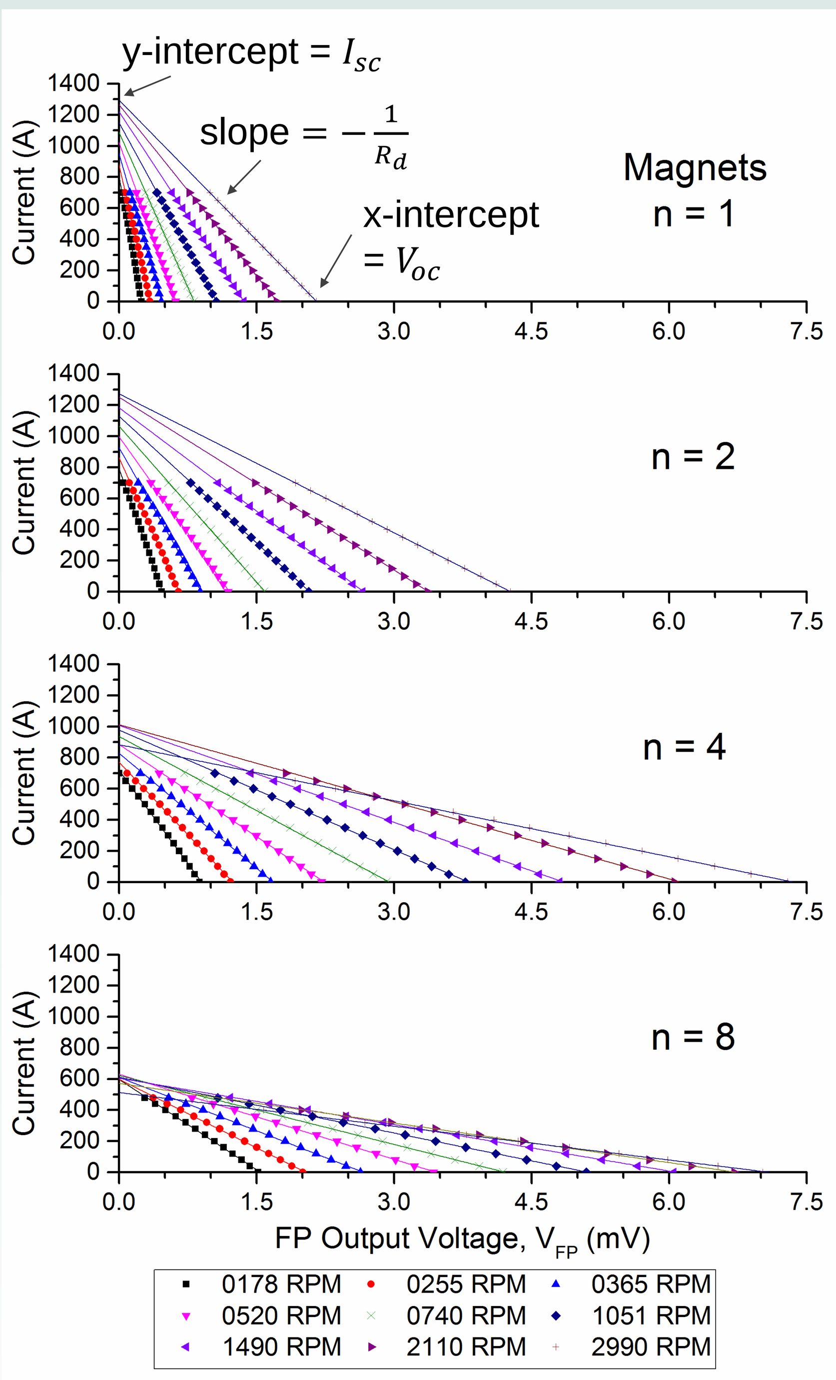
I_{SC} is the short-circuit current (the maximum current that could be delivered into a fully-superconducting load). This is given by the y-axis intercept.

These 3 parameters are related by:

$$I_{SC} = V_{OC} / R_d.$$

For $n_M \leq 4$ we measure output currents up to 700 A. This is the limit of our measurement system. Extrapolations of each line indicate substantially higher currents can be achieved.

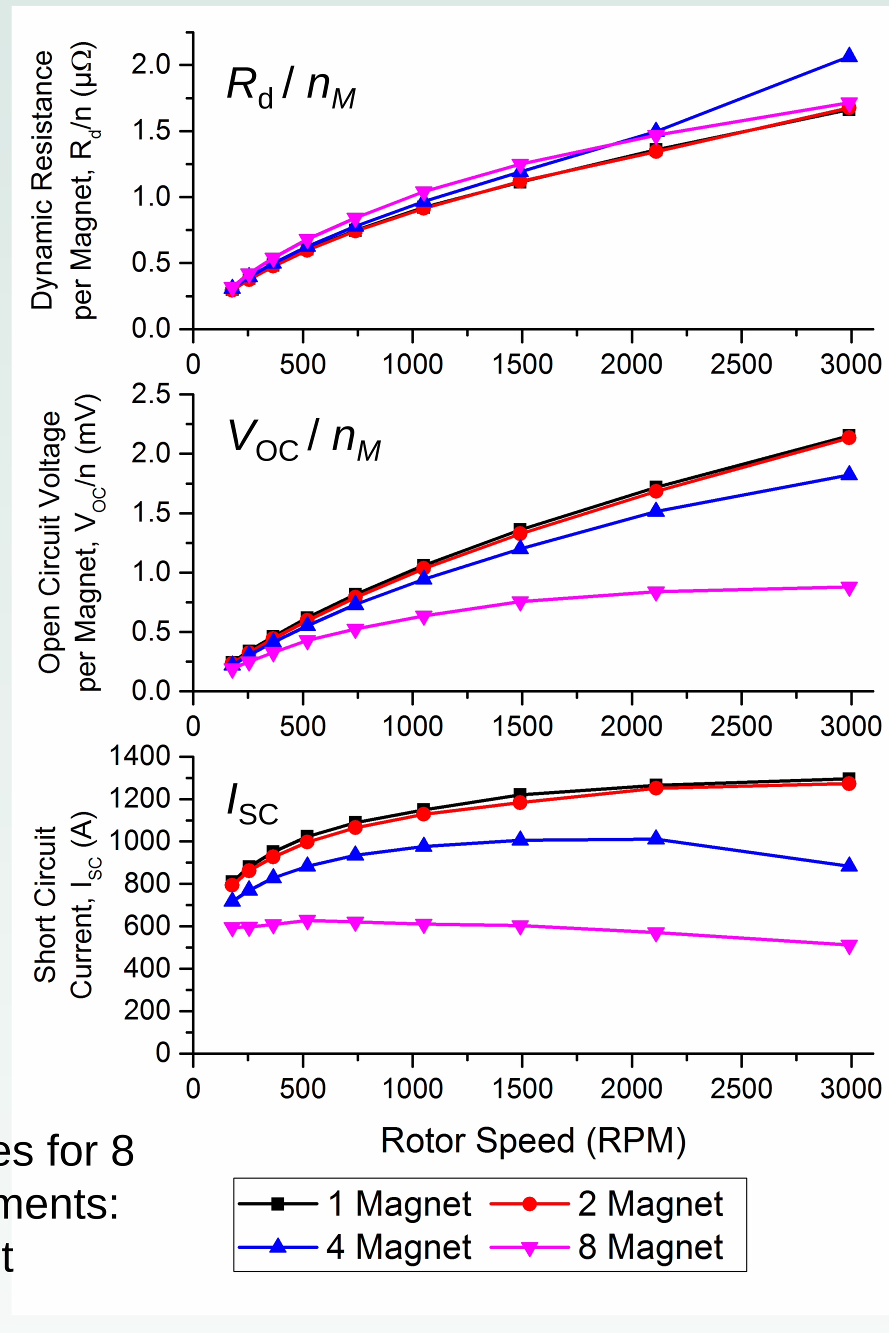
For n_M = 8, the maximum measured output current is reduced and this is exacerbated at higher rotor speeds. This is probably due to the much higher magnet frequencies seen by each stator tape, resulting in local heating of the HTS wire. [6, 7]



Effect of magnet ratio on output parameters

The Flux Pump output is strongly dependent on the ratio of magnet number, n_M to number of parallel stator wires, n_S (= 8 in this work). When $n_M > n_S/2$, the critical current of the superconducting return path is no longer sufficient to fully short-circuit the magnet-driven emf.

- R_d scales linearly with n_M. R_d is also approximately proportional to rotor speed. Thus plotting R_d/n_M collapses all the data onto a single line.
- V_{OC} scales linearly with n_M and rotor speed up to n_M=4. For n_M=8, the DC voltage per magnet is suppressed and saturates with increasing rotor speed.
- $I_{SC} = V_{OC} / R_d$, and is approximately independent of rotor speed [5, 6]. For $n_M \leq 2$, I_{SC} saturates at ~1.3 kA. For $n_M \geq 4$, I_{SC} drops, corresponding to the drop in V_{OC}.



The optimal ratio of magnets to stator wires for 8 stators will depend on application requirements:

- n_M = 4 delivers the highest open-circuit voltage V_{OC} (7.5 mV).
- n_M = 2 delivers the highest short-circuit current I_{SC} (1.3 kA).

Summary

- The HTS dynamo behaves as a simple DC voltage source with open-circuit voltage V_{OC} and internal resistance R_d.
- R_d is proportional to both rotor speed and magnet number. Multiple parallel stator wires lead to low internal resistance of < 3.5 μΩ for all speeds with $n_M \leq 2$.
- To date, the maximum measured current from this device is 700 A, but this is limited by experimental equipment. Linear extrapolations indicate maximum output currents of up to 1.3 kA could be achieved.

References

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[2] C.W. Bumby *et al.* "Development of a brushless HTS exciter for a 10 kW HTS synchronous generator," *Supercond. Sci. Technol.*, **29**, 024008 (2016)
[3] R.M. Walsh *et al.* "Characterization of Current Stability in an HTS NMR System Energized by an HTS Flux Pump," *IEEE Trans. Appl. Supercond.* **24**, 4600805 (2014)
[4] C.W. Bumby *et al.* "Anomalous open-circuit voltage from a high-T_c superconducting dynamo," *Appl. Phys. Lett.*, **108** 122601 (2016).
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[6] C. W Bumby *et al.* "Frequency Dependent Behavior of a Dynamo-Type HTS Flux Pump," *IEEE Trans. Appl. Supercond.*, **27**, 5200705 (2017)
[7] A.E. Pantoja *et al.* "Impact of stator wire width on output of a dynamo-type HTS flux pump," *IEEE Trans. Appl. Supercond.* **26**, 4805208 (2016)