Temperature dependent behaviour of a barrel-type HTS dynamo

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- HTS dynamo-type flux pumps: working principles
- The barrel dynamo design
- Current pumping performance
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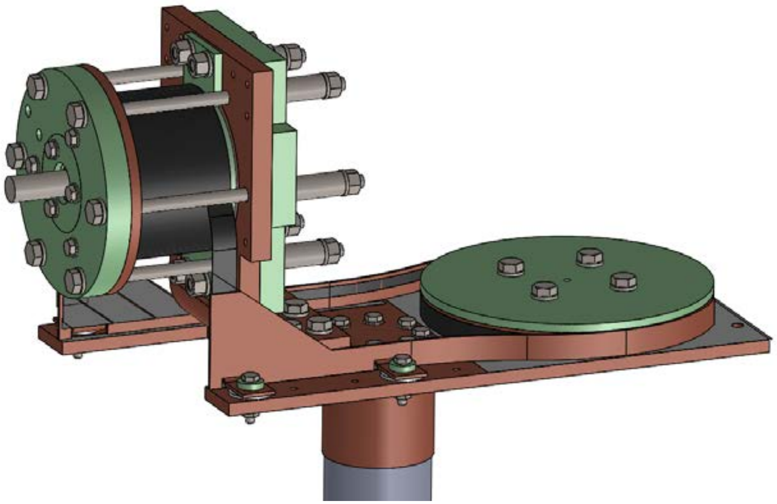
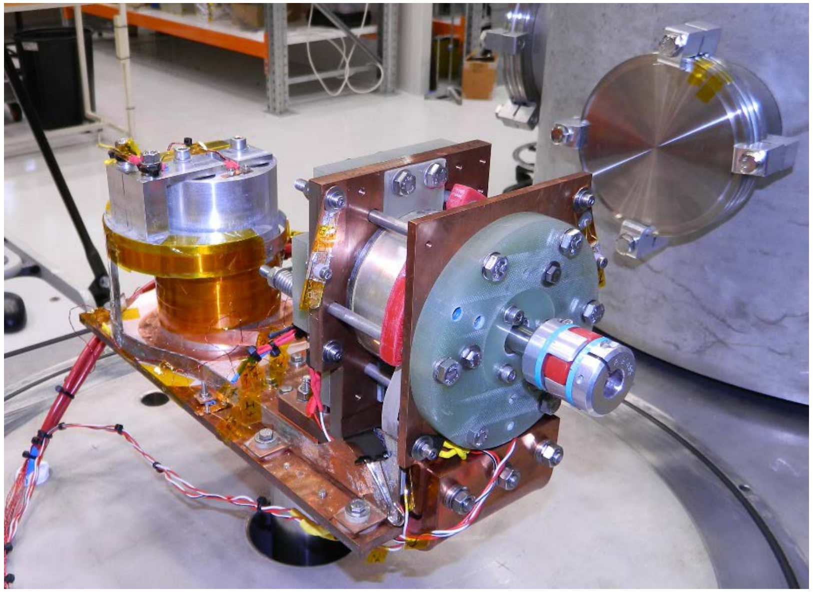
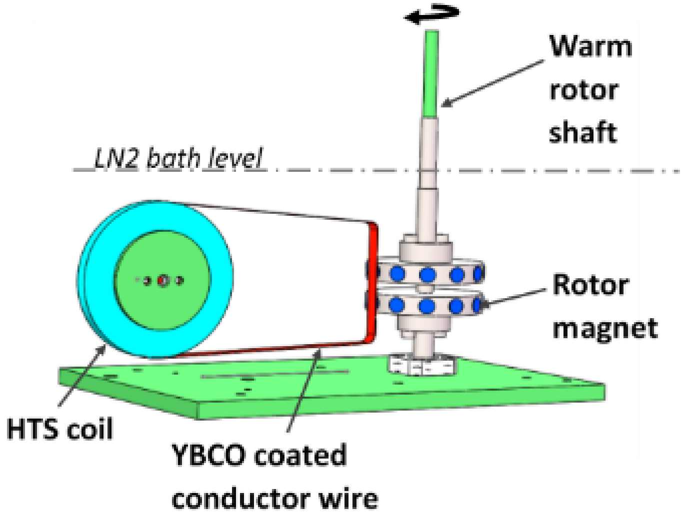


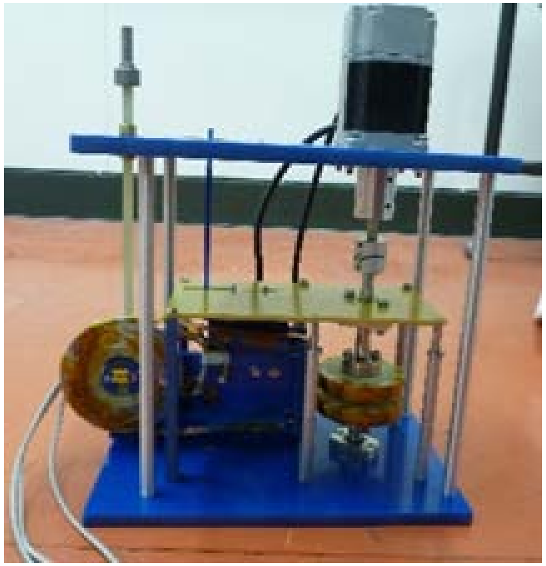


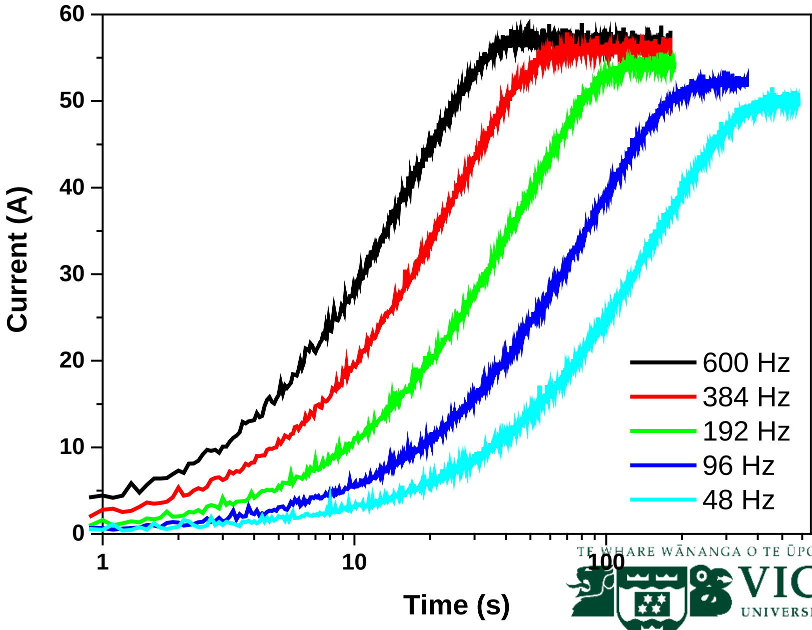
Simple HTS dynamo with single stator wire

Eliminating the current leads – Dynamo-type HTS flux pumps



- Rotating permanent (Nd-Fe-B) magnets move across a coated conductor
- PMs mounted in homo-polar orientation
- Flux penetrates YBCO film and induces a DC current to flow in series connected superconducting coil

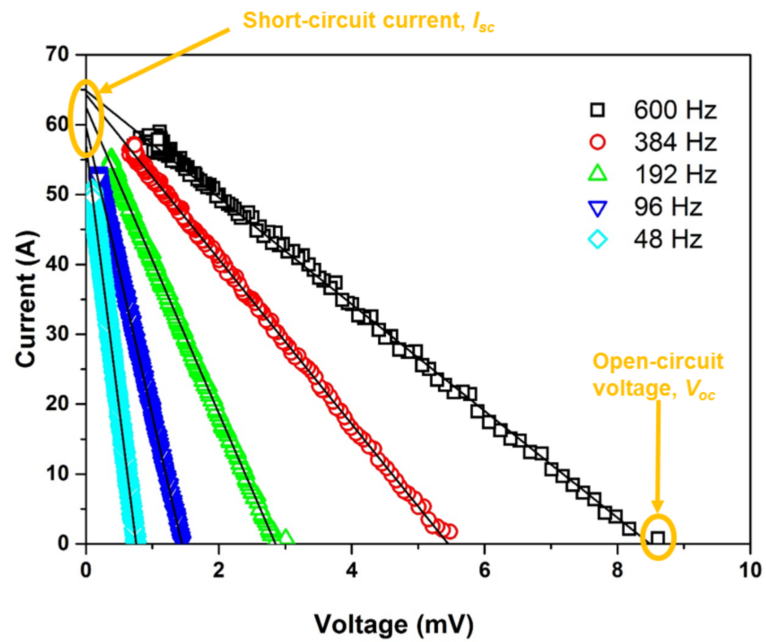


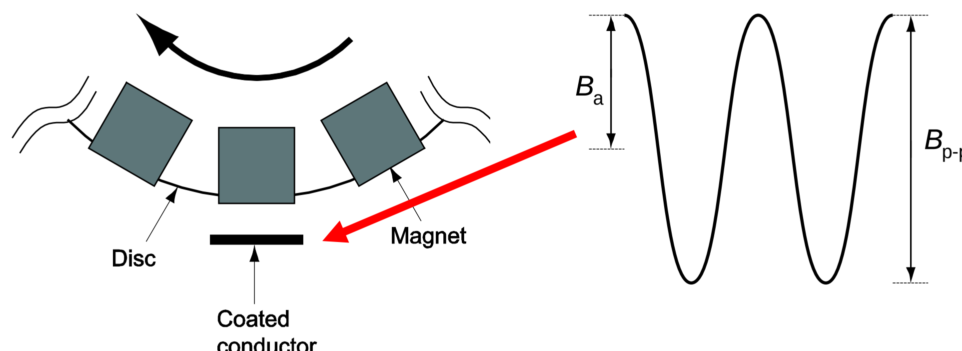


Hoffmann *et al.,* IEEE TAS **21**(2011)1638; Jiang *et al.,* Appl. Phys. Lett.**105**(2014)112601 (2014)

Effective Internal resistance of dynamo

- Gradient of *I-V* curve gives internal resistance, R_d of the flux pump.
- R_d varies with rotor frequency!
- Attributed to ***dynamic resistance*** due to time varying field at stator wire as the wire carries DC current.

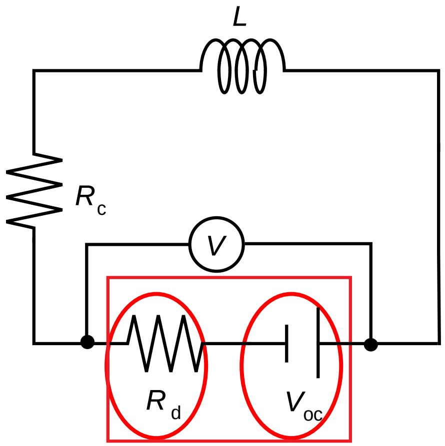




Jiang et al. Apl. Phy. Lett. **105**(2014)112601

Oomen et al. SUST**12** (1999)382-387

Frequency dependence of output at 1mm flux gap

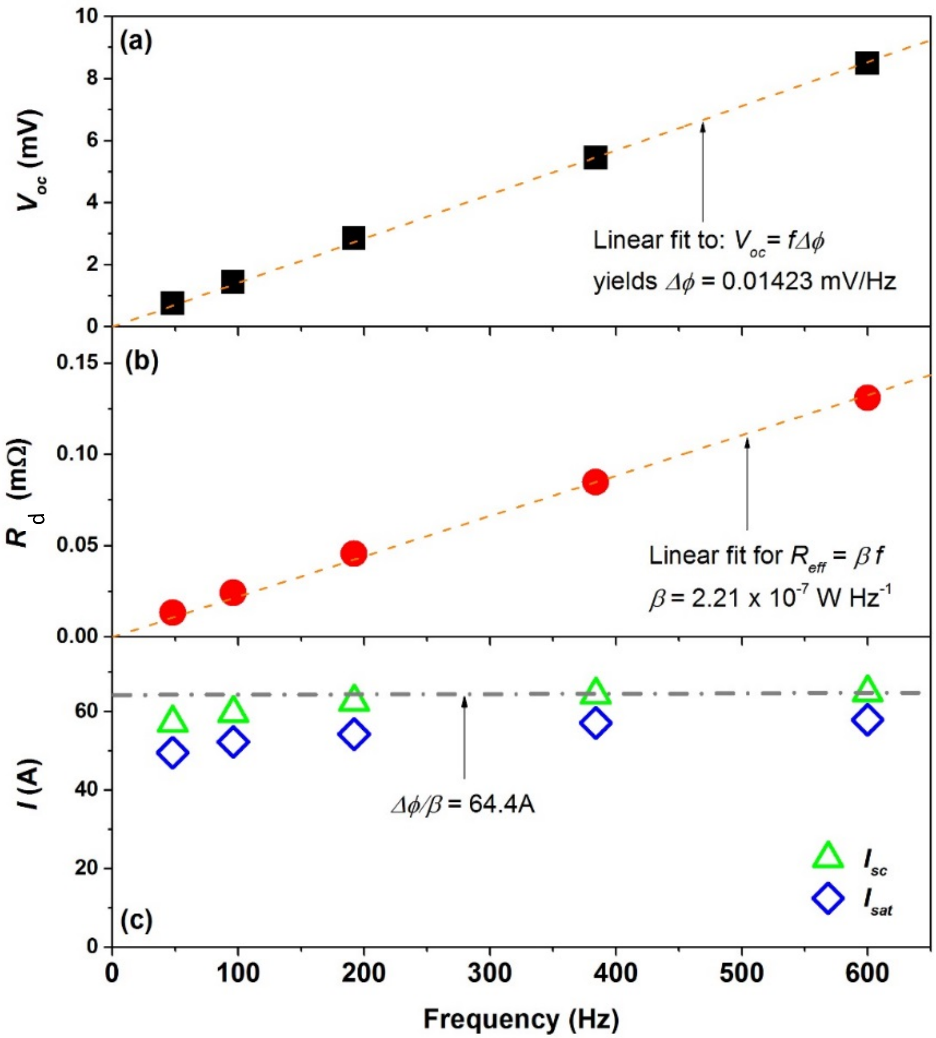


Dynamo type -Flux pump

- ❑ V_{oc} due to partial rectification effect.
- ❑ Both V_{oc} and R_d are proportional to f.
- ❑ Short-circuit current, I_{sc} determined by

$$I_{sc} = \frac{V_{oc}}{R_d}$$

→ I_{sc} independent of frequency



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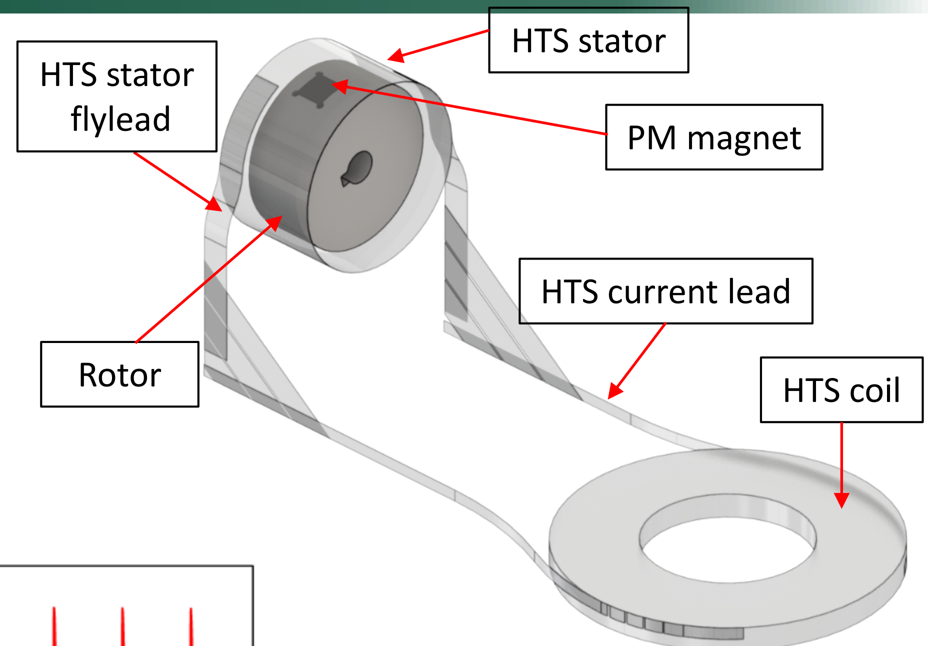
Barrel-type HTS dynamo with continuous cylindrical stator

The barrel dynamo

- Can we reduce voltage pulse if a ‘continuous’ stator is used (e.g. cylinder)
- This geometry has been previously demonstrated in LTS (Nb foils)
- Is the normal soldered joint a problem?



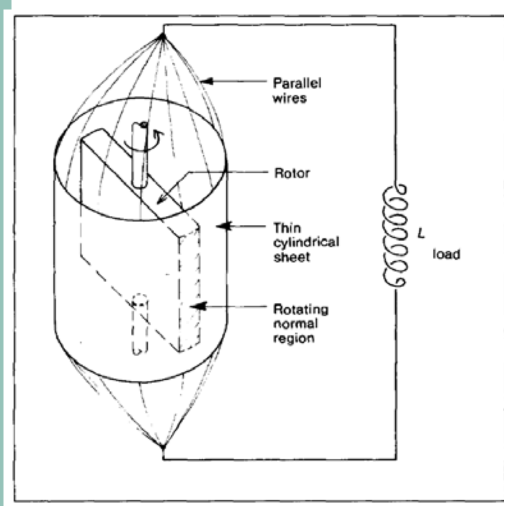
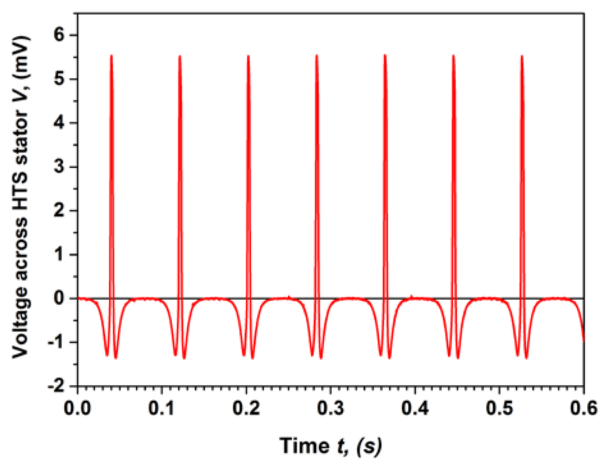
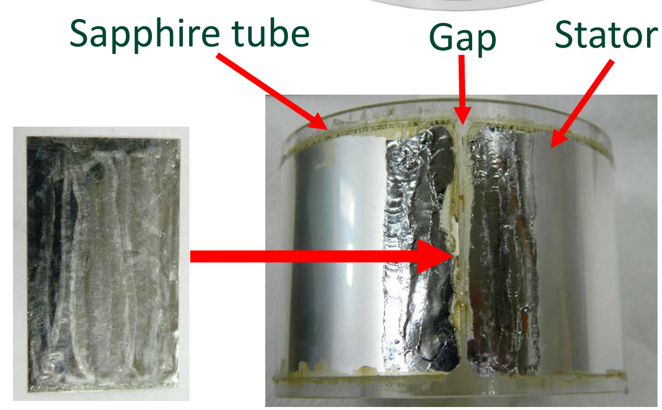


Fig. 7 dc dynamo with cylindrical sheet



Voltage wave form



HTS Strip

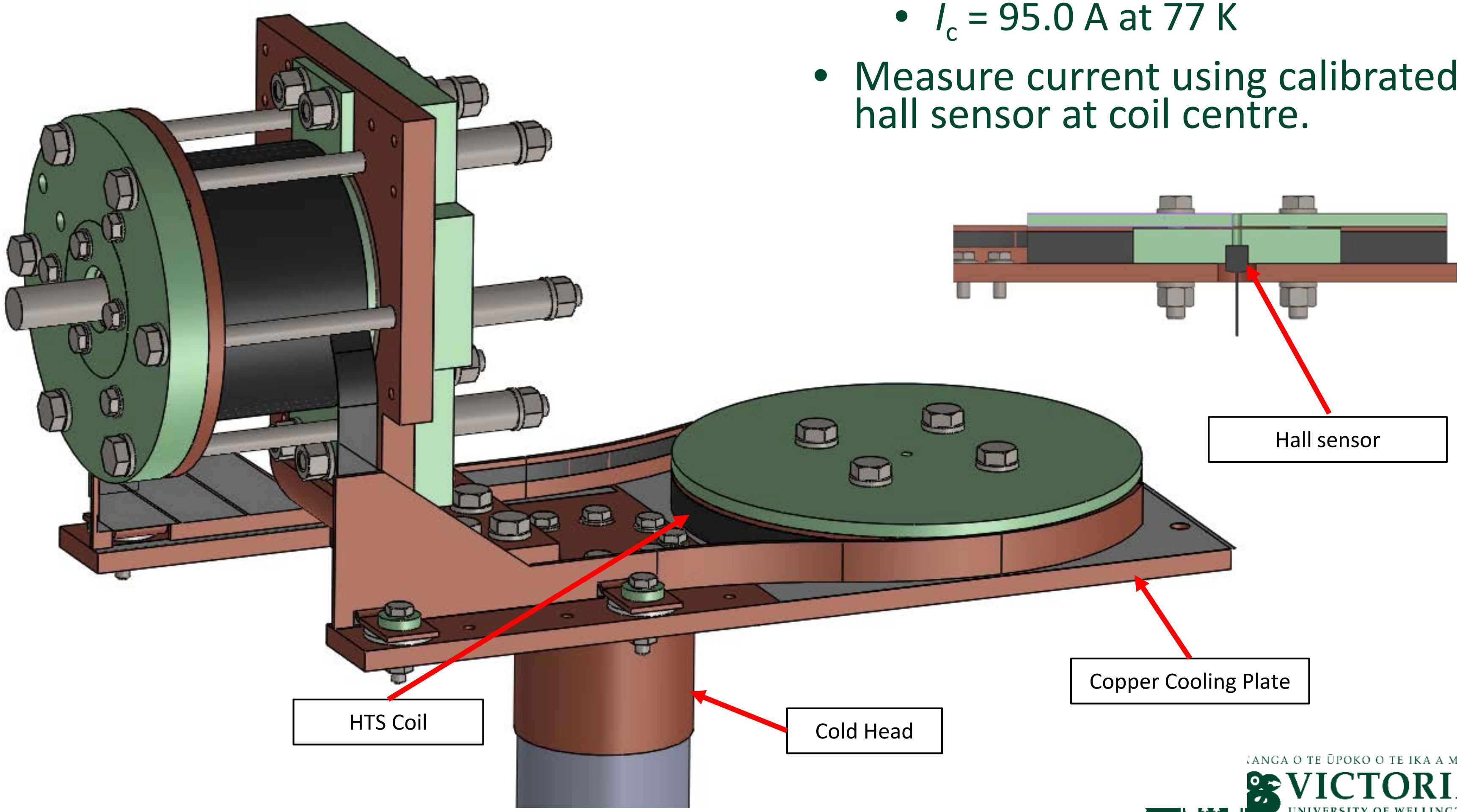
van de Klundert and ten Kate, *Cryogenics* **195**(1981)195-206

Vacuum cryostat enables variable temperature operation

Temp. in stator : 30 K – 80 K

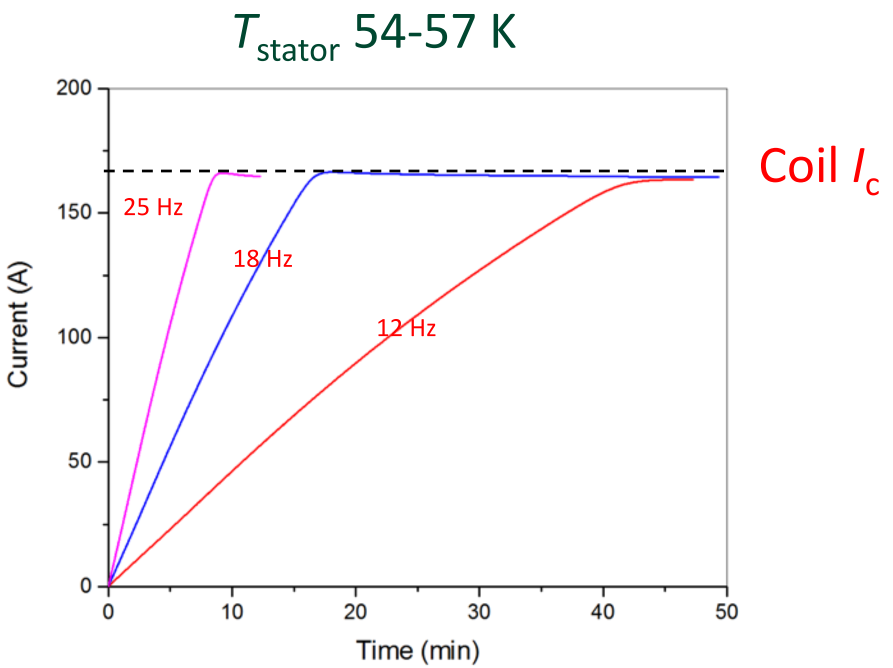
Temp. in coil> 50 K

- Series connected to 1G double pancake coil
  - L = 1.97 mH,
  - I_c = 95.0 A at 77 K
- Measure current using calibrated hall sensor at coil centre.



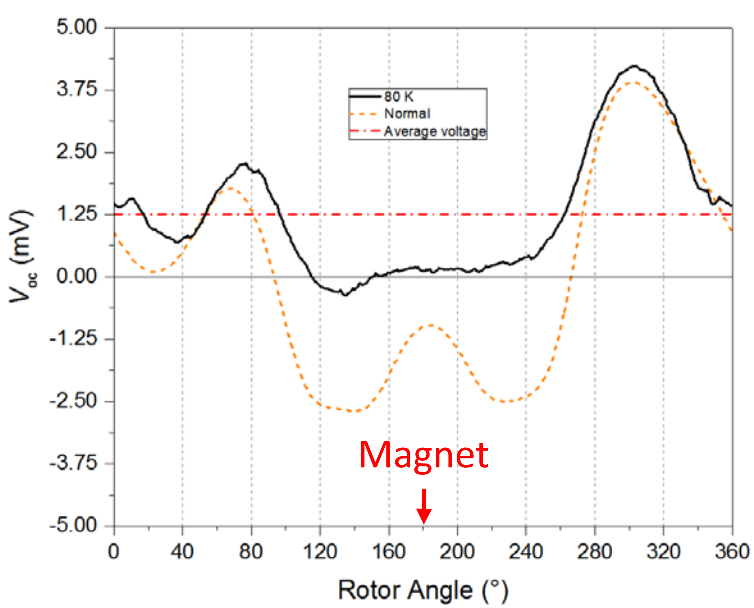
Ramping a coil

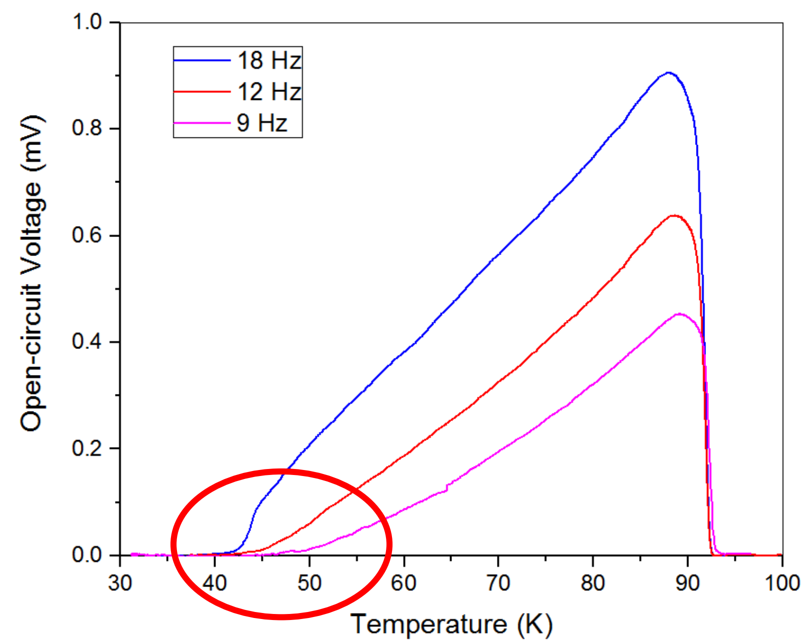
- It takes a long time to charge the coil….
  - *L/R* is large …
- Current limited by I_c of coil ~170 A.
- Total series resistance, R_c < 0.3 μΩ (obtained from decay curve)



Open circuit voltage

- Device generates an open-circuit voltage
- Function of speed and temperature
- Shielding currents become important at low *T*

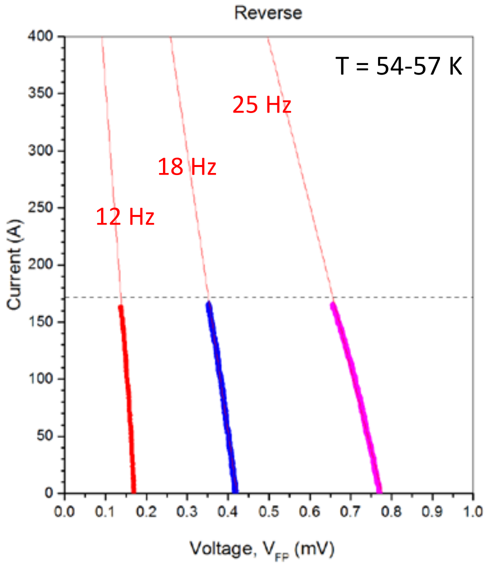




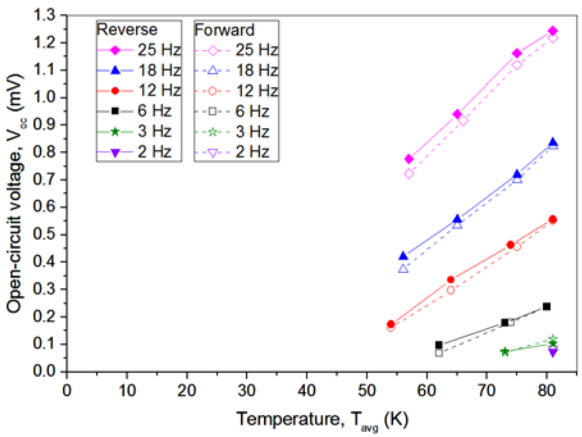
I-V curves – it still has an internal resistance

- Linear *I-V* plot – implies constant internal resistance
  - due to ac loss in stator –
  - Intercept on *y*-axis is short-circuit current

➢ Need a coil with higher I_c, and preferably a lower L.

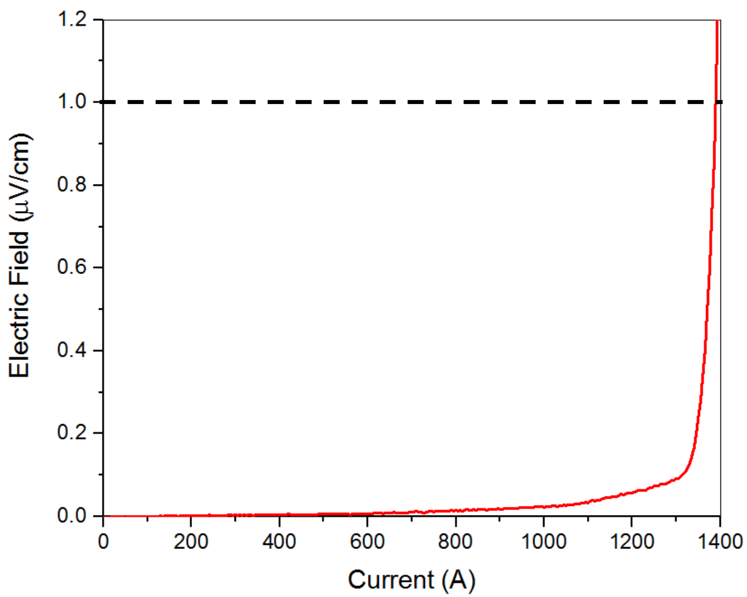


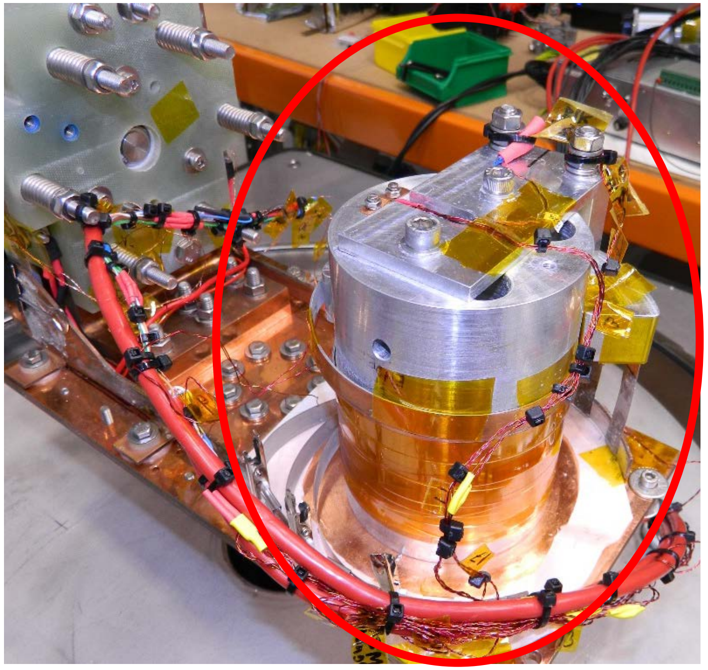
Coil I_c



A very different test coil……

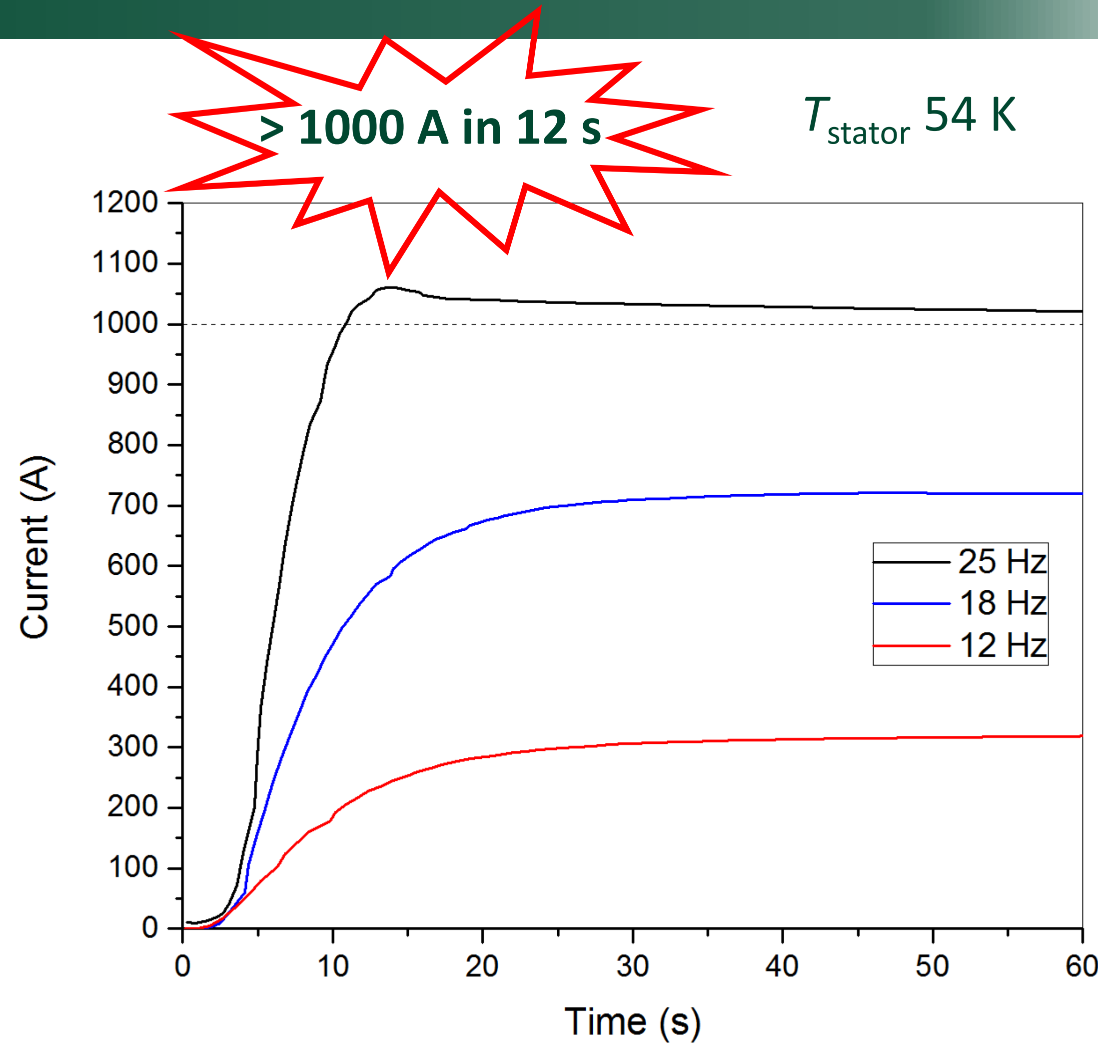
- Single layer solenoid
  - Wound from 3 *10 mm Fujikura CC wires ‘wound in hand’
  - $I_c \approx 1400$ A @ 77K
  - $L = 2.8$ µH
- Conduction cooling via central Al core





It works!

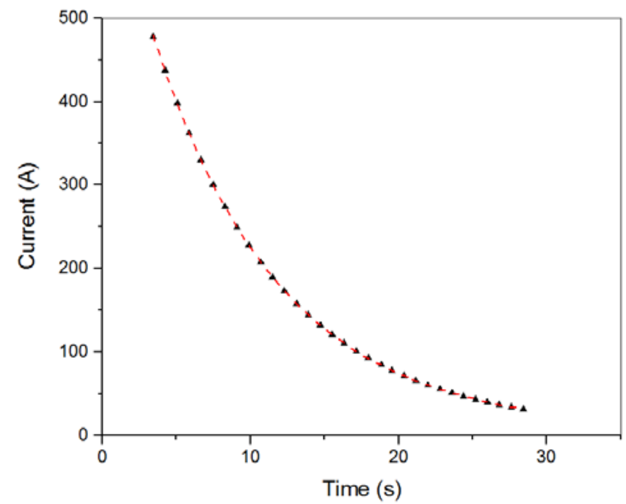
- **Highest output current ever reported for HTS flux pump!**
- *L*/*R* ~ 5 s.



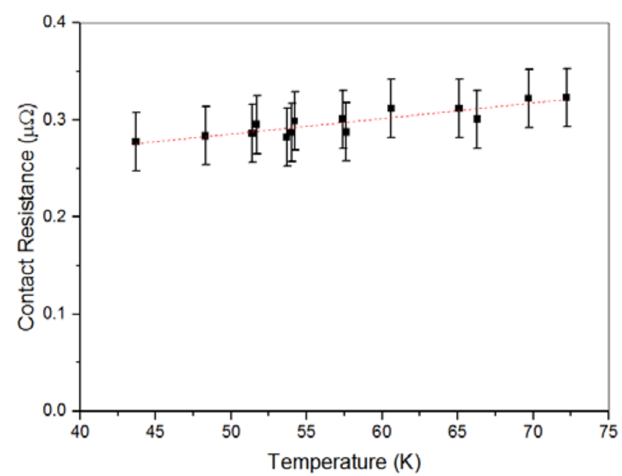
Normal-Conducting Resistance

- Normal-conductive contact resistance R_c from solder joints in the circuit.
- R_c measured using exponential current-decay fit:

$$I_{Coil}(t) = I_0 \cdot \exp\left(-\frac{t \cdot R_c}{L}\right)$$

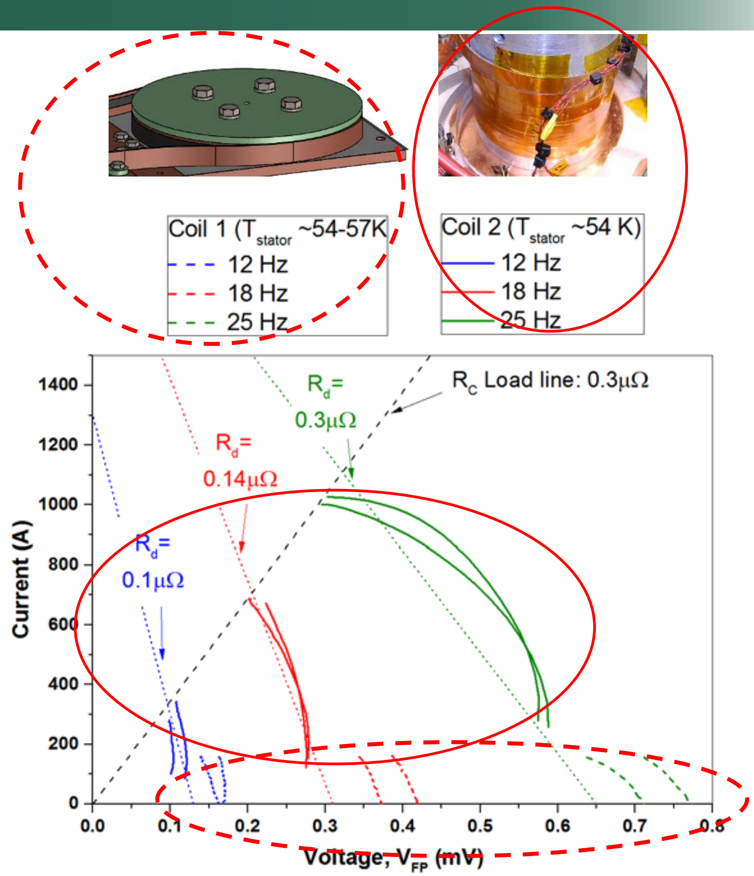


- R_c for various stator temperatures over 40 – 75 K and is generally constant.
- $R_c \leq 0.3\mu\Omega$.
  - Low solder resistances due to
    - Joint overlap + quality
    - Low temperature
    - 3 parallel paths through coil



I-V relation is independent of coil

- *I-V* output from dynamo is similar for both coils
  - Dynamo acts as an independent source regardless of load.
- Thermal stability an issue
  - Some temperature variation for DPC measurements
  - Apparent non-linearity in *I-V* relation
  - Maybe due to insufficient cooling of flying current leads?
- Internal resistance of dynamo, R_d < 0.3 μΩ.
  - Comparable to circuit (joint) resistance
- Open-circuit voltage V_{oc} < 1 mV.
- Short-circuit current I_{sc} > 2kA



f, Hz	V_{oc} (mV)	I_{sc} (kA)	R_d (μΩ)
12	0.13	**1.3**	0.10
18	0.31	**> 2**	0.14
25	0.65	**> 2**	0.30

Summary & conclusions

- We have demonstrated an HTS dynamo-type flux pump with continuous cylinder of coated conductor stator, operating temperatures down to < 45 K!
- The HTS dynamo acts as an independent voltage source (with an internal resistance) regardless of load.
- The cylindrical stator geometry greatly reduces voltage pulse amplitude compared to single wire geometries.
- We have achieved actual currents of ***> 1 kA*** so far using a low inductance coil. This is the highest output current ever reported for HTS flux pump!
- Further work is underway to optimise experimental cooling system and coil design. Actual outputs of > 2 kA appear feasible.

The End

Extra slides

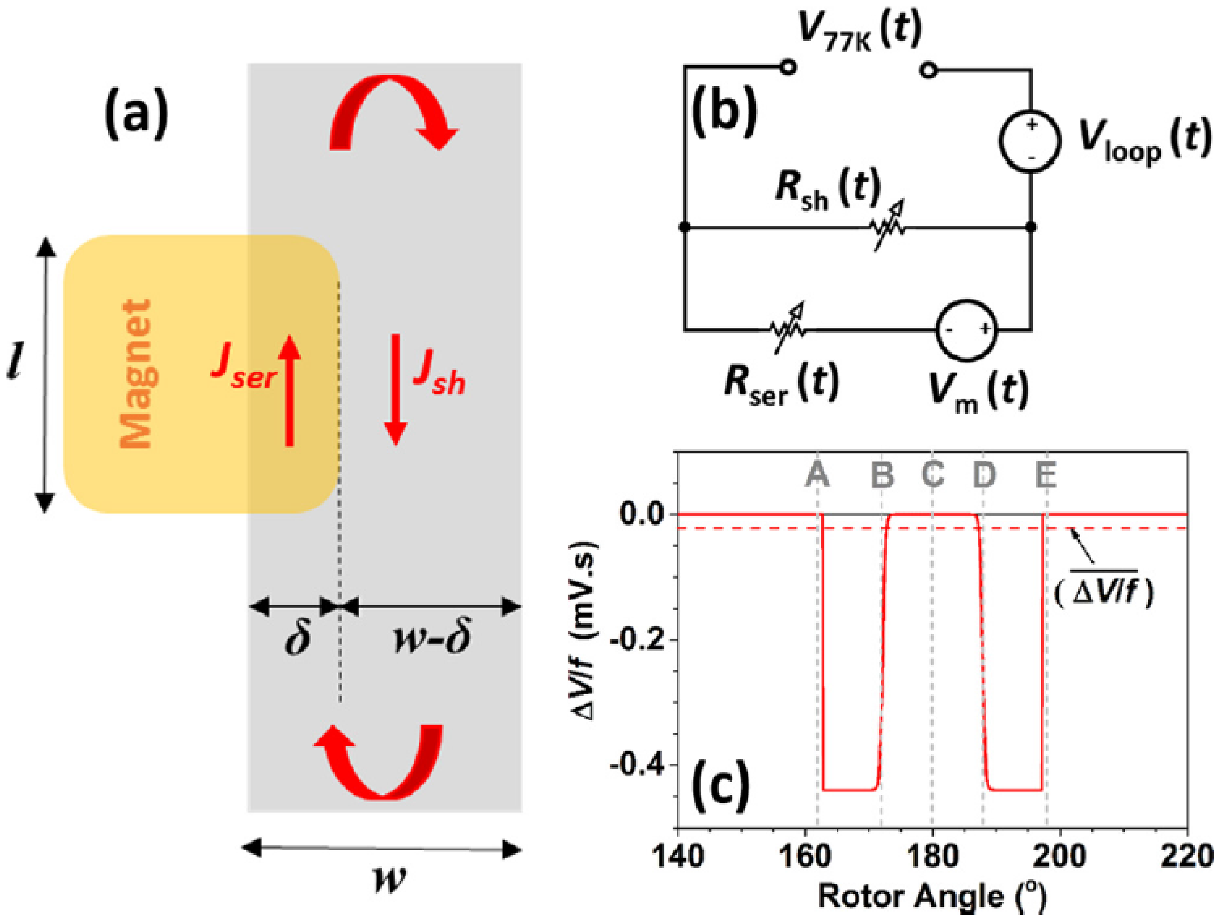
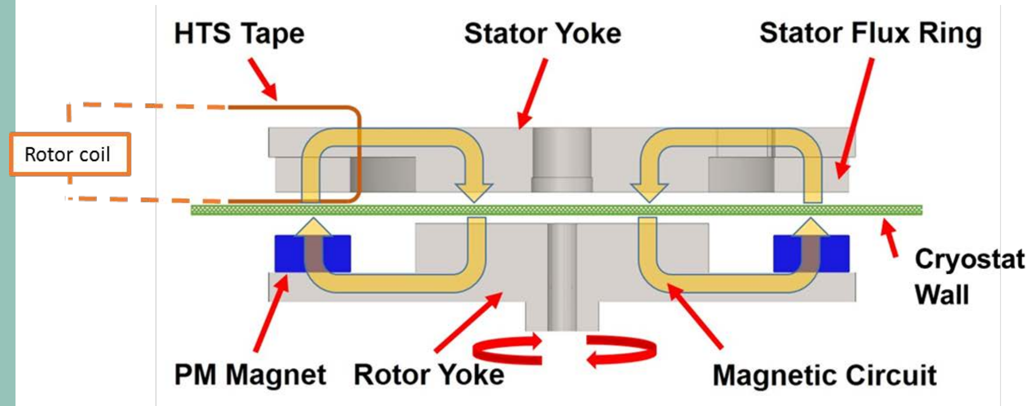


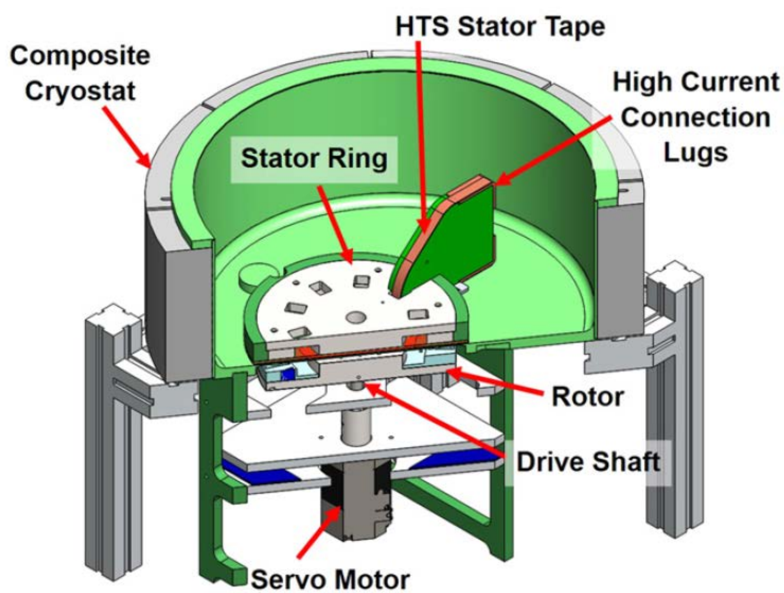
FIG. 4. (a) Schematic diagram illustrating circulating eddy currents in the HTS coated conductor wire as the rotor magnet passes over the stator. (b) Equivalent circuit which describes the effect of shunt leakage current path due to the circulating current. (c) Plot of Equation (7) for an idealized 10 mm × 10 mm square magnet operating at a flux gap of 1.5 mm, with $B_\perp = 0.2\,\mathrm{T}$ and $n = 23$.

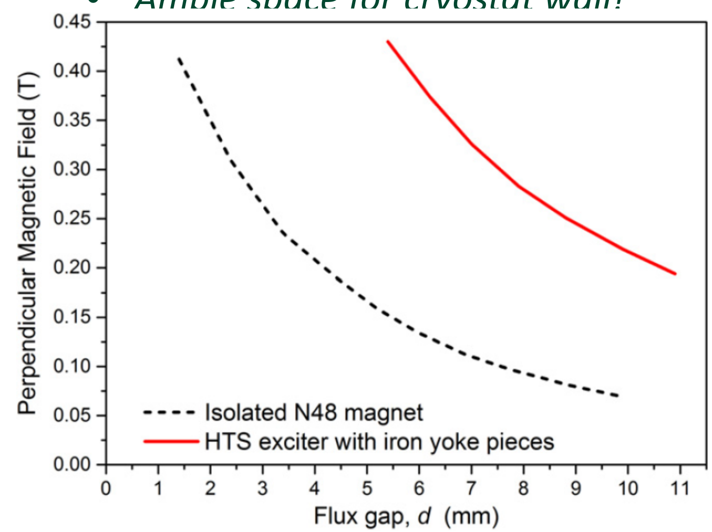
$$R_{\mathrm{sh}} = \frac{l\rho_{sh}}{w-\delta} = \frac{lE_0|\boldsymbol{J}_{\mathbf{sh}}|^{n-1}}{(w-\delta)\,J_c{}^n}$$

Pumping through the cryostat wall – Gen 2 design



- Optimise dynamo design by placing rotor magnets outside cryostat.
- But need to increase field strength to penetrate HTS sheet
- Achieved using magnetic iron circuit to focus flux at stator
- Enables flux gap to increase to >10 mm.
  - *Ample space for cryostat wall!*





Bumby et al. SUST ***29*** *(2), 024008 (2016)*
Jiang et al. IEEE Trans. Appl. Supercond. ***26****(2)* (2), 4900706 (2016)

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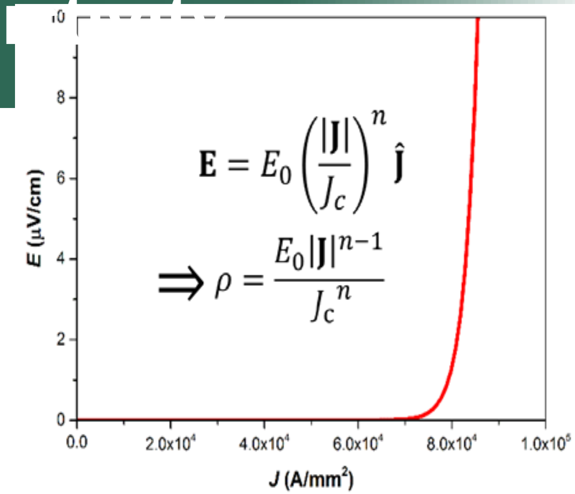
Origin of DC voltage – non-linear resi

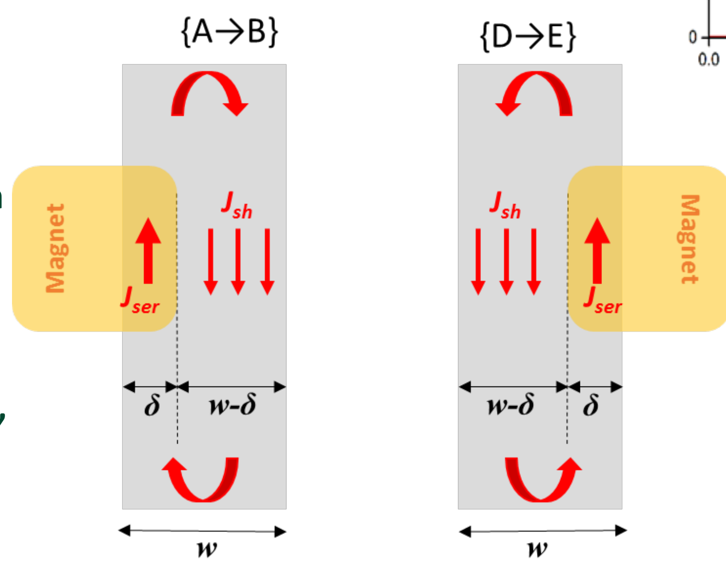


- Coated conductor has highly non-linear local resistivity.
  - *Resistivity increases with |**E**| and |**J**|*

- Partial rectification occurs when $J_{ser} > J_{sh}$
  - Occurs when $\delta < w - \delta$
  - $\rho_{ser} \gg \rho_{sh}$

  - emf across magnet spot is 'short-circuited' at these times.

- This leads to a time-averaged DC voltage in the <u>opposite direction</u> to the emf peak as the magnet crosses stator.



Magnet direction →
Note that $J_{sh} < J_{ser}$ when $\delta < w\text{-}\delta$

Charge continuity requires:

$$I_t = \delta J_{ser} + (w - \delta) J_{sh}$$

Bumby et al. Appl. Phys. Lett. ***108*** *122601 (2016)*

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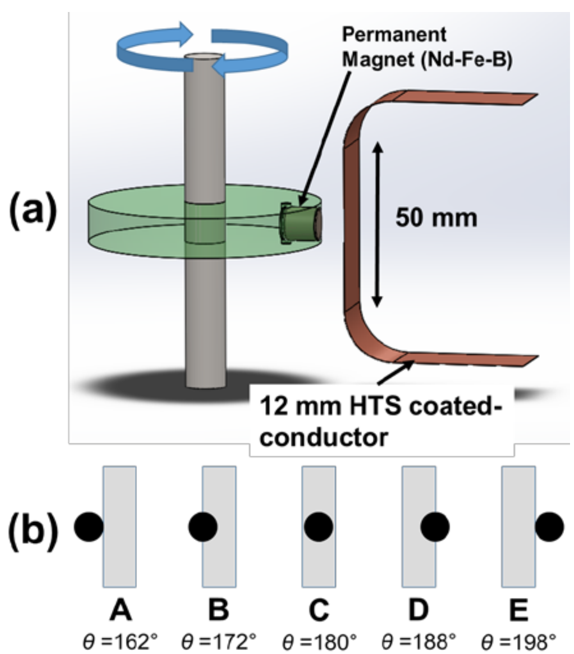
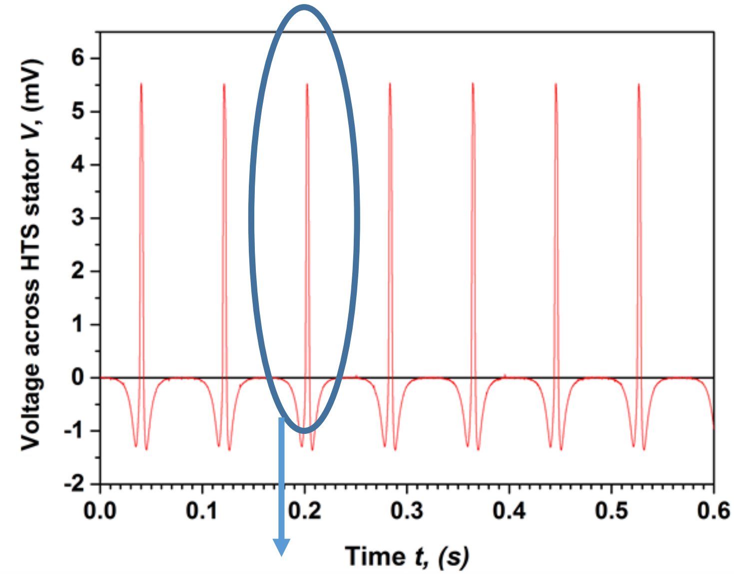
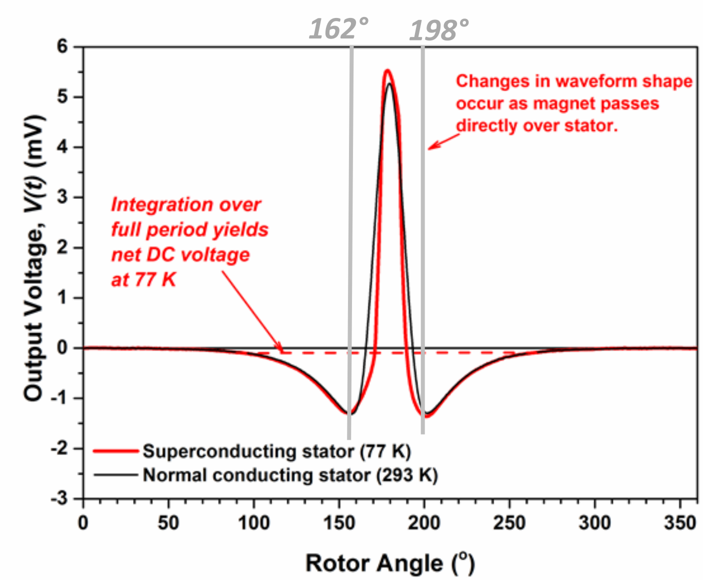
How does it work?

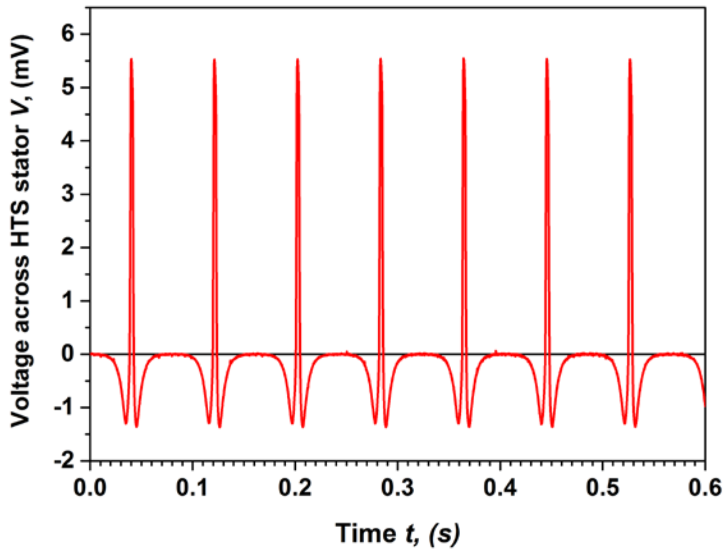
- Use single magnet on rotor to resolve waveform versus magnet position.
- Effect observed <u>only</u> during period that magnet is directly above stator wire

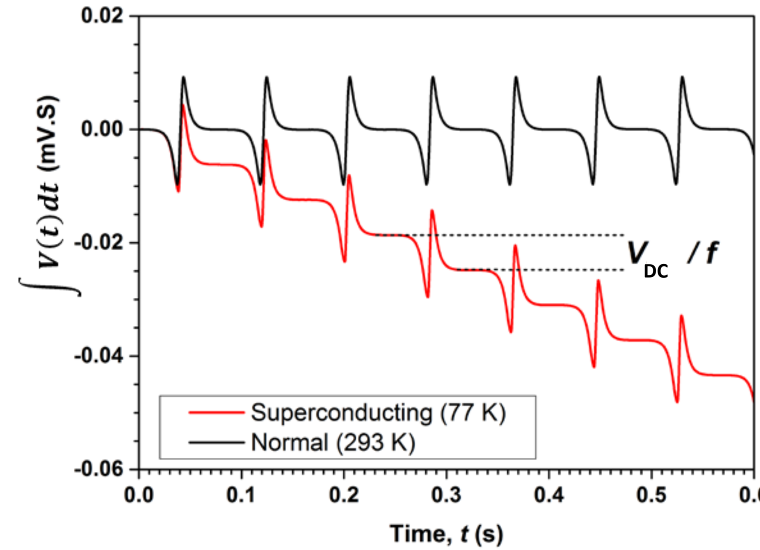


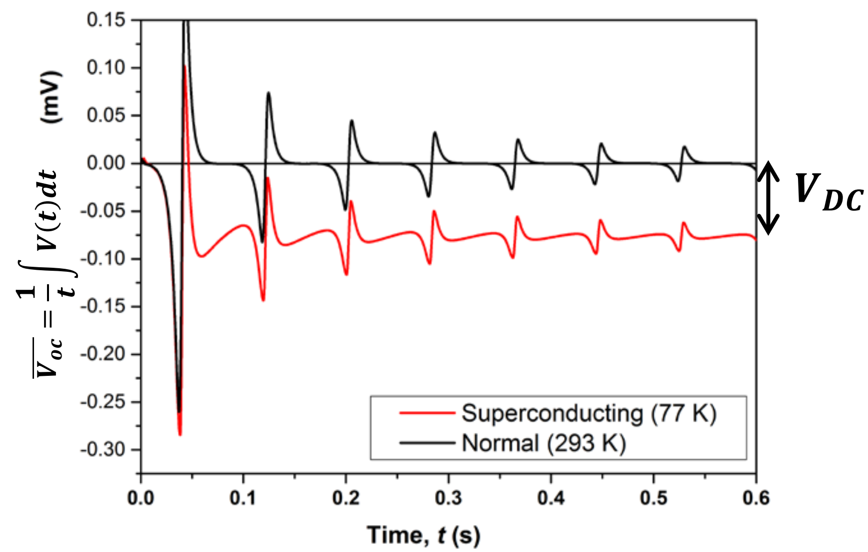




Integrals – the action happens as the magnet crosses the stator







- Series-connected inductance (coil) integrates waveform
- This time-averages AC waveform to DC values)
- Partial rectification occurs!

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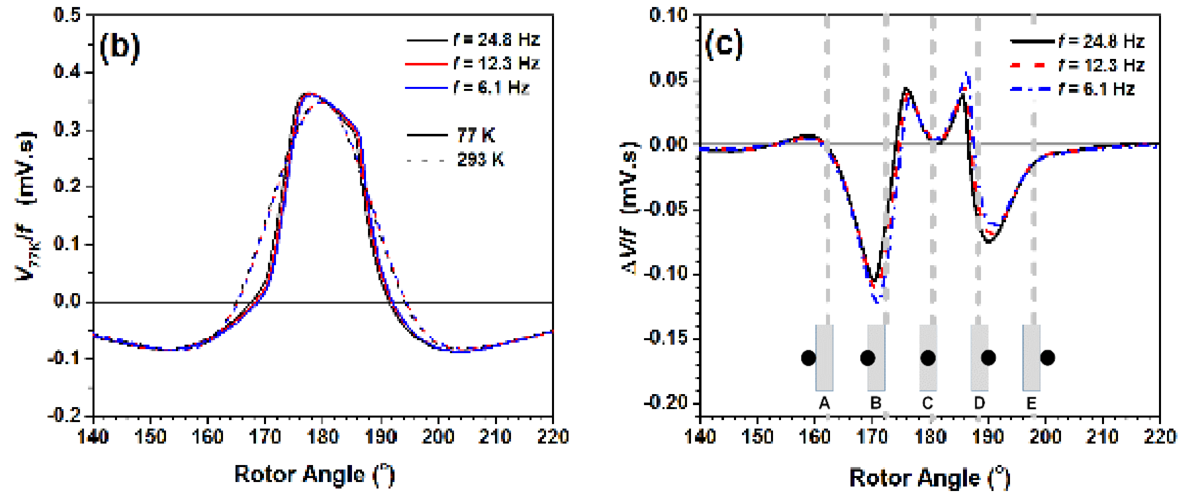
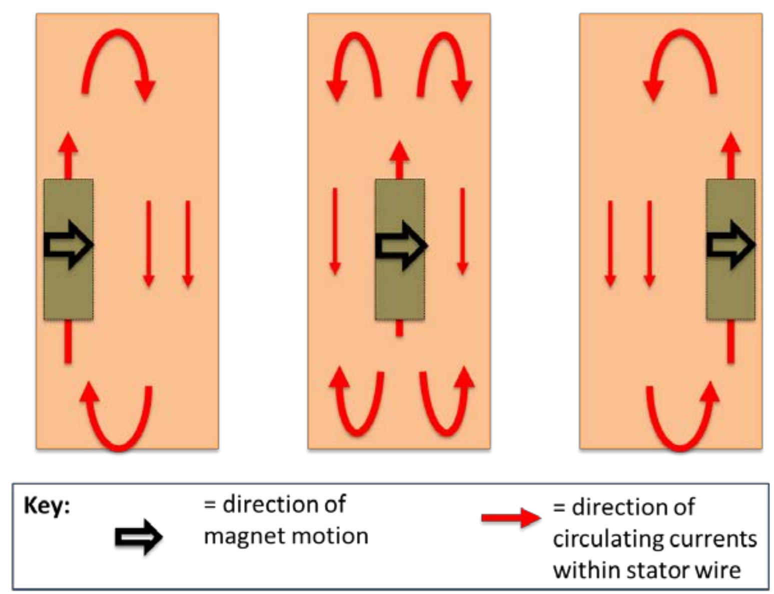
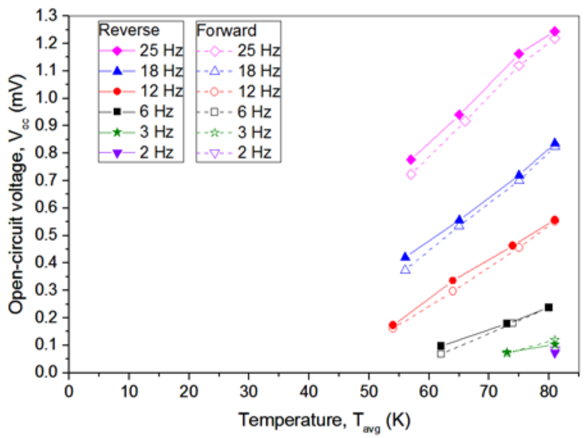
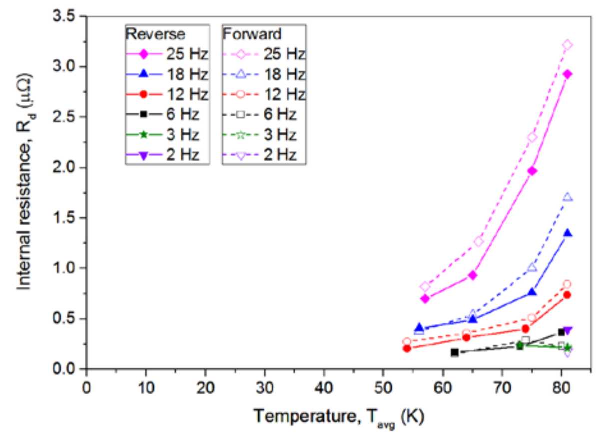
Origin of DC voltage?

- Action happens as magnet crosses coated conductor wire
- Normalised waveforms are a function of rotor angle only (independent of *f*).
- Rotor magnet imposes inhomogeneous local field across stator
  - Circulating currents flow back around high field region






Open-circuit voltage, V_{oc} (mV)
Temperature, T_{avg} (K)
Reverse
25 Hz
18 Hz
12 Hz
6 Hz
3 Hz
2 Hz
Forward
25 Hz
18 Hz
12 Hz
6 Hz
3 Hz
2 Hz


Internal resistance, R_d ($\mu\Omega$)
Temperature, T_{avg} (K)
Reverse
25 Hz
18 Hz
12 Hz
6 Hz
3 Hz
2 Hz
Forward
25 Hz
18 Hz
12 Hz
6 Hz
3 Hz
2 Hz