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Frequency Ramping Effects on a Dynamo-type HTS Flux Pump

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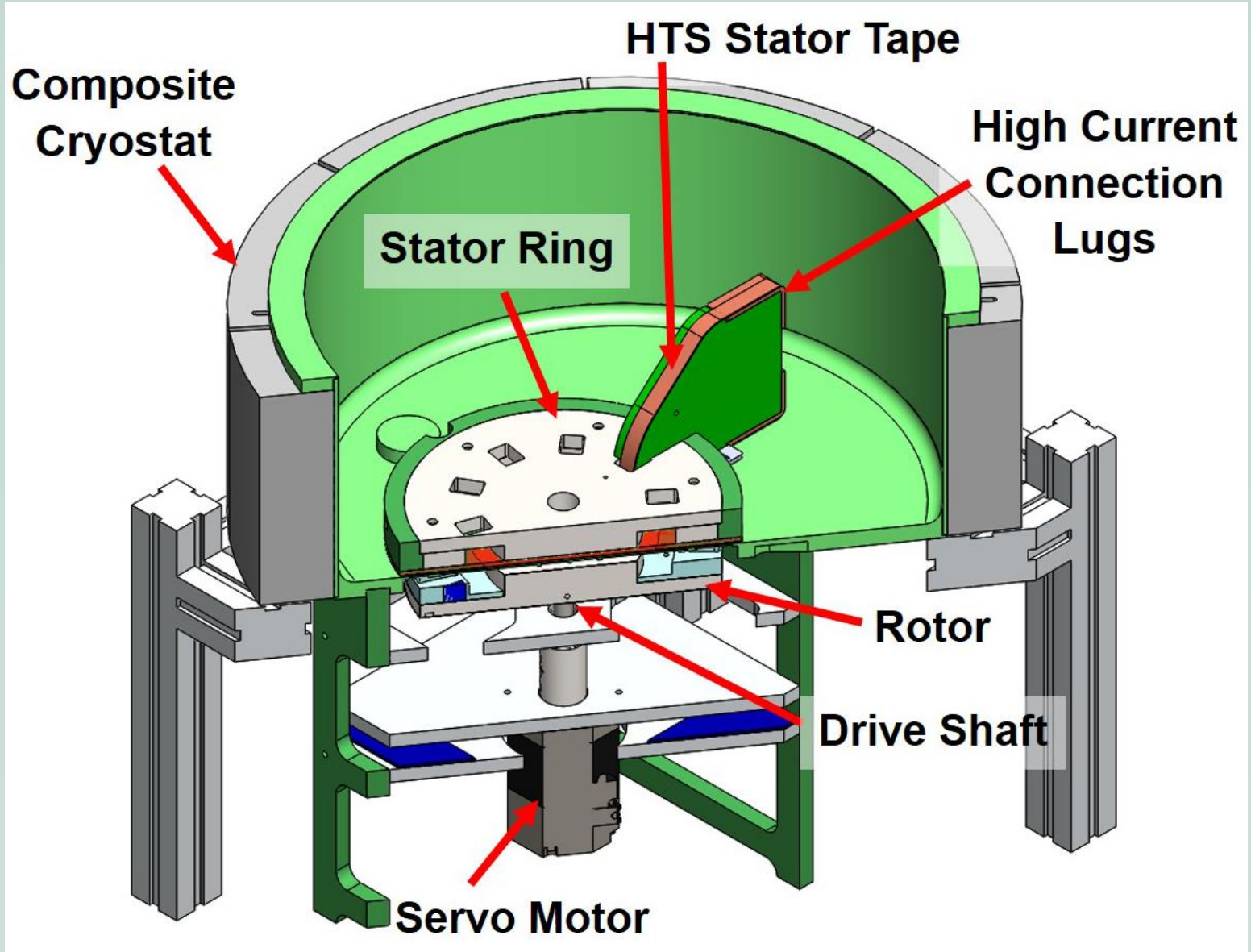
High-Temperature Superconductor Flux Pumps

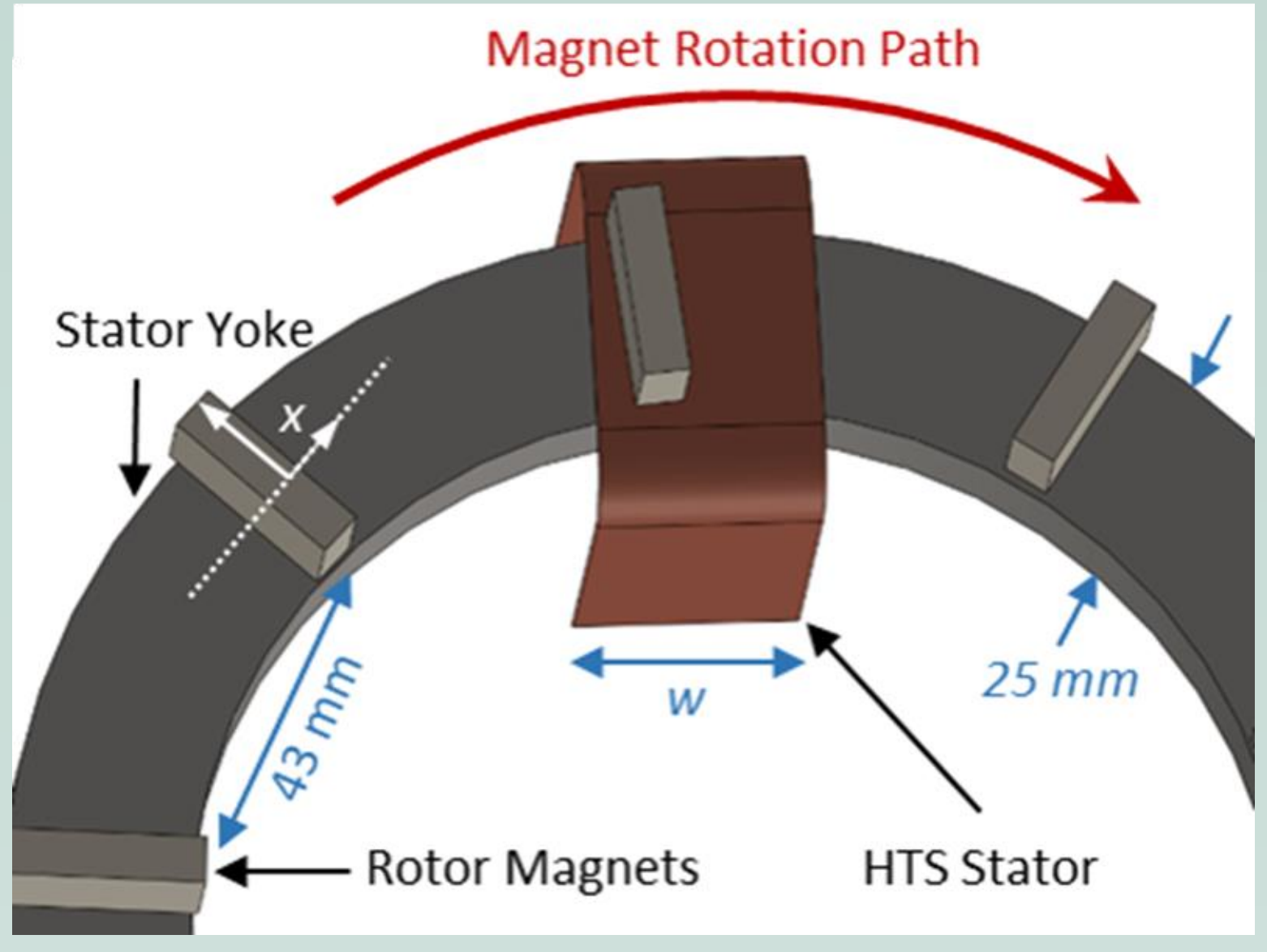
Flux Pumps can create high (> 300 A) DC currents [1] in superconducting coils without large metal current leads bridging the cryogenic superconducting circuit and the room-temperature environment, significantly lowering the heat load on the cryocooler.

We study a dynamo-type flux pump employing 2G ReBCO 46mm wide coated conductor wire at 77 K, 6 Nd-Fe-B magnets on a spinning rotor platter, and a soft ferromagnetic iron yoke. All moving parts are situated outside of the cryogenic environment.

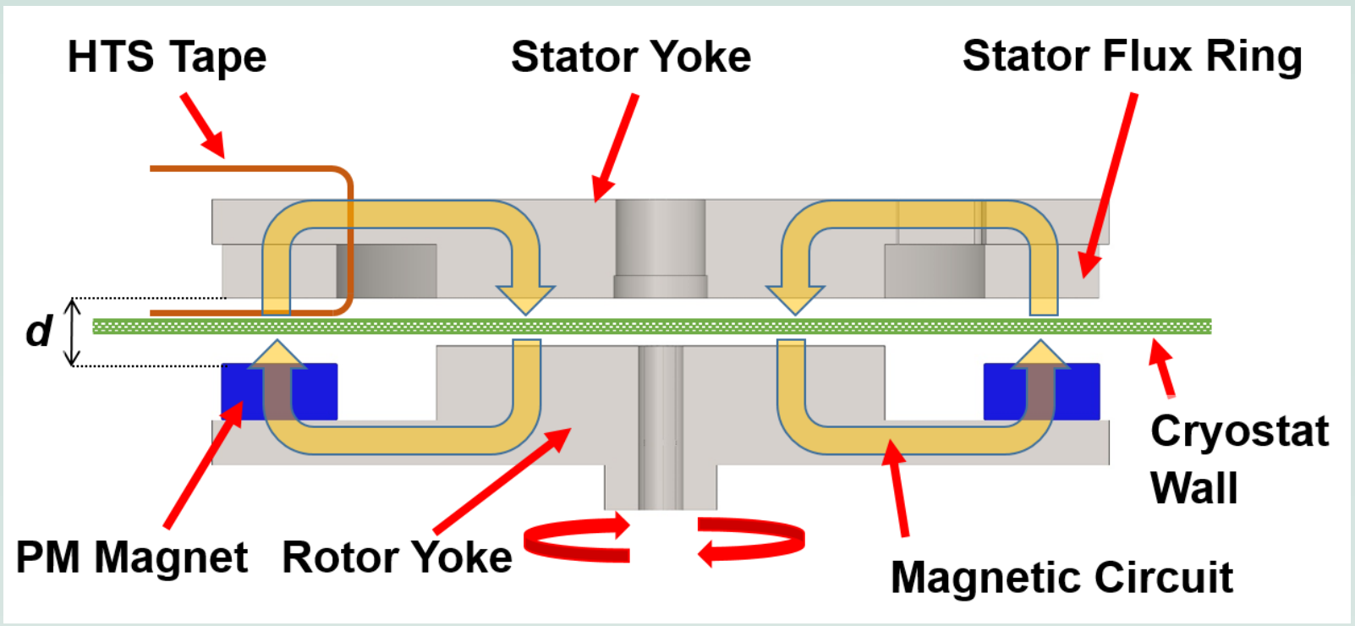
Dynamo-type flux pumps can be modelled as a DC voltage source with an internal resistance, where all output parameters are functions of the frequency of the spinning magnets. Here, we study the effects of frequency f on the net averaged DC voltage generated. Looking at the high-speed waveform trace and its average DC value can be a fast, simple method for understanding the complex frequency behaviour of the Flux Pump, and this can be used to optimise the current control of a superconducting coil.



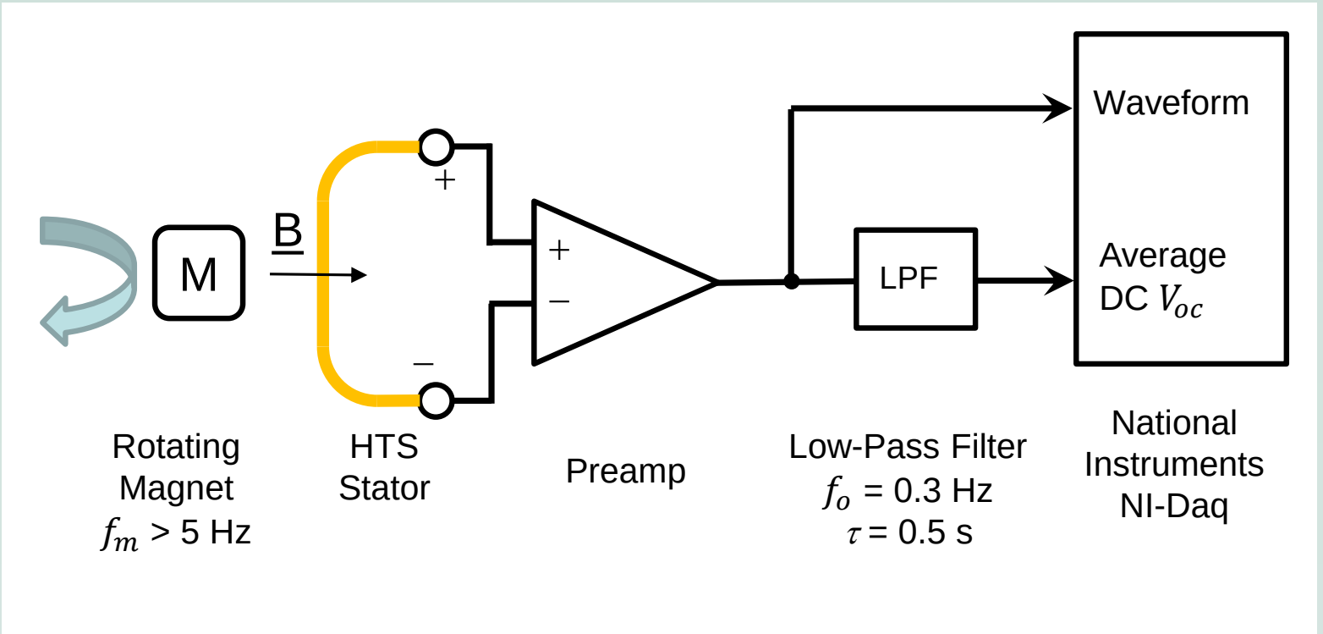
Schematic diagram of the externally-excited HTS rotating flux pump, incorporating iron yokes within rotor, HTS stator, and flux return path.



Schematic of magnet path across w = 46 mm HTS stator wire. 6 magnets were used.



Cross-section of Flux pump showing iron rotor yoke, stator yoke and cryostat wall. The flux gap d = 7.5mm.



Schematic of acquisition circuitry that captures both the high-speed waveform and its average DC value. We create the cyclic-average V_{oc} by using a low-pass filter (LPF) whose cut-off frequency f_o is much lower than the magnet frequency f_m.

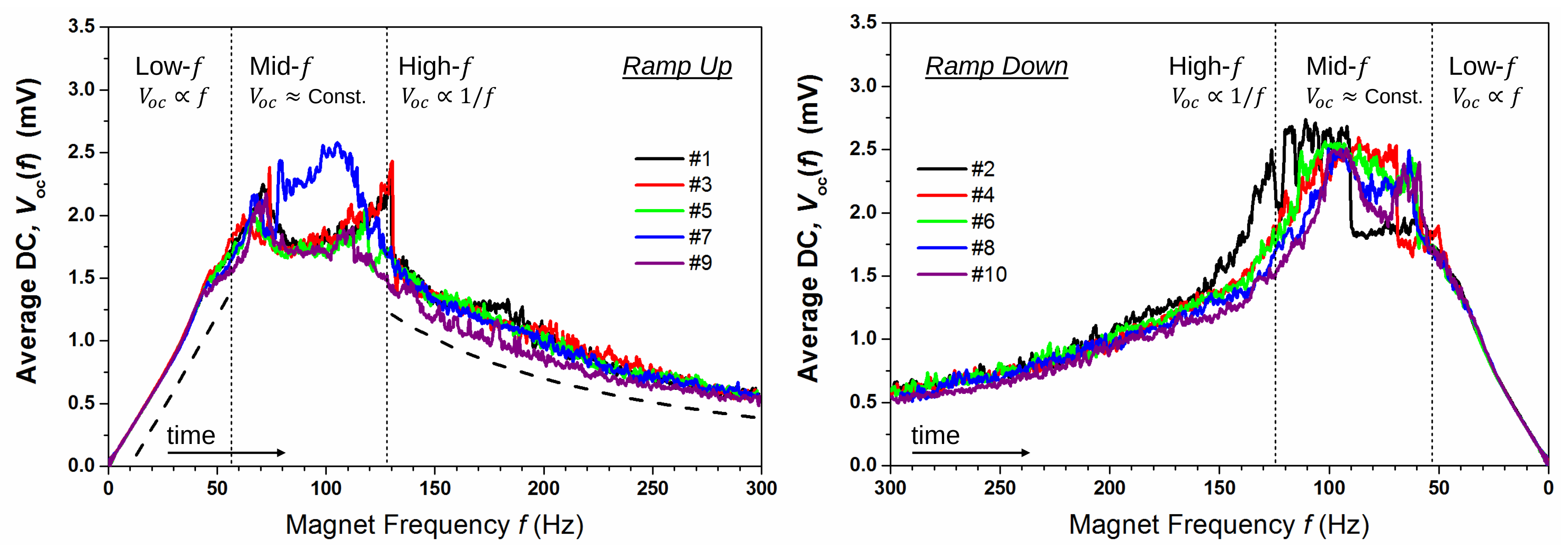
Average Voltage versus Frequency

The average open-circuit DC voltage (V_{oc}) is an important parameter in all dynamo-type flux pumps, as it ultimately determines the maximum current that can be delivered into a load, together with dynamic resistance and normal contact resistance [2].

To measure V_{oc} over all possible frequencies, we slowly ramp the magnets up to maximum speed over 10 minutes, and then slowly ramp it down to zero.

The DC values clearly separate into 3 f regions, Which we classify as Low-f, Mid-f and High-f. Each region shows distinctive $V_{oc}(f)$ behaviour.

- The Low-f region shows simple 'linear' frequency response, V_{oc} proportional to f; while in the High-f region V_{oc} shows a roughly $1/f$ frequency response.
- In the Mid-f region V_{oc} is roughly constant with f, but we observe complex and unstable behaviour where some ramp traces markedly separate from the rest.



Three distinct frequency regions observed in the average DC voltage V_{oc} over consecutive ramp-up and ramp-down runs. Left plot: frequencies ramped up from zero to maximum. Right plot: frequencies ramped down from maximum to zero. The 10 traces are labelled in the order they were taken. In all cases the acceleration/deceleration rate is 0.5 Hz/s. The long-dash lines indicate the simple behaviour of the Low-f and High-f regions.

References

[1] C. W. Bumby et al., "Frequency Dependent Behaviour of a Dynamo-type HTS Flux Pump," Trans. Appl. Supercond, **4**, pp. 5200705, 2017.

[2] Z. Jiang et al., "Dynamic resistance of a high-T_c superconducting flux pump," Appl. Phys. Lett., **105**, 112601, 2014.

[3] C.W. Bumby et al., "Anomalous open-circuit voltage from a high-T_C superconducting dynamo," Appl. Phys. Lett., **108**, 122601 (2016).

[4] C.W. Bumby et al. "Through-Wall Excitation of a Magnet Coil by an External-Rotor HTS Flux Pump," IEEE Trans. Appl. Supercond., **24**, 0500505 (2016).

[5] A.E. Pantoja et al., "Impact of stator wire width on output of a dynamo-type HTS flux pump," IEEE Trans. Appl. Supercond., **26**, pp. 4805208, 2016.

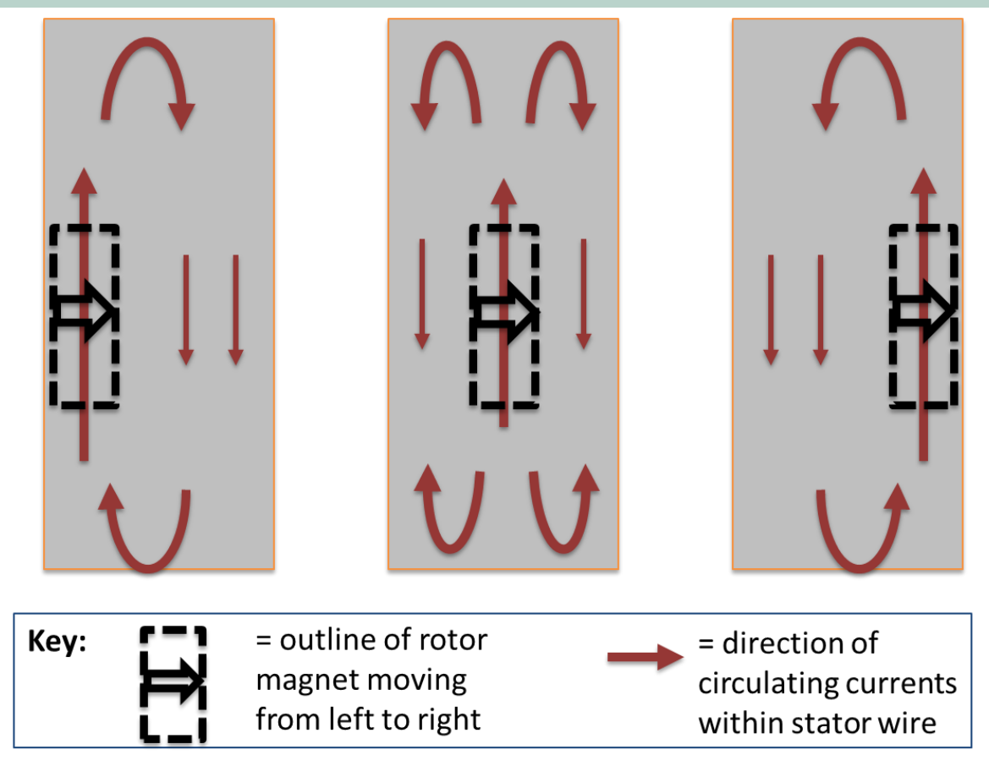
[6] R. A. Badcock et al., "Impact of Magnet Geometry on Output of a Dynamo-Type HTS Flux Pump", IEEE Trans. Appl. Supercond., **27**, pp. 5200905, 2017.

Related works: [183] Tue-Af-Po2.11-01 *Optimising Rotor Speed and Design for an Externally-mounted HTS Dynamo*
[184] Tue-Af-Po2.11-02 *Impact of Stator Ring Width on Output of a Dynamo-type HTS Flux Pump*

Origin of the Observed DC voltage

The DC output voltage V_{oc} arises from time-varying circulating eddy currents within the HTS stator wire. [3]

Such circulating currents form a superconducting shunt path which "short-circuits" the high field region directly beneath the rotor magnet at times when it partially overlaps the superconducting stator wire. This reduces the output voltage during these periods of the rotor cycle, leading to partial rectification of the voltage waveform and resulting in a time-averaged DC voltage.

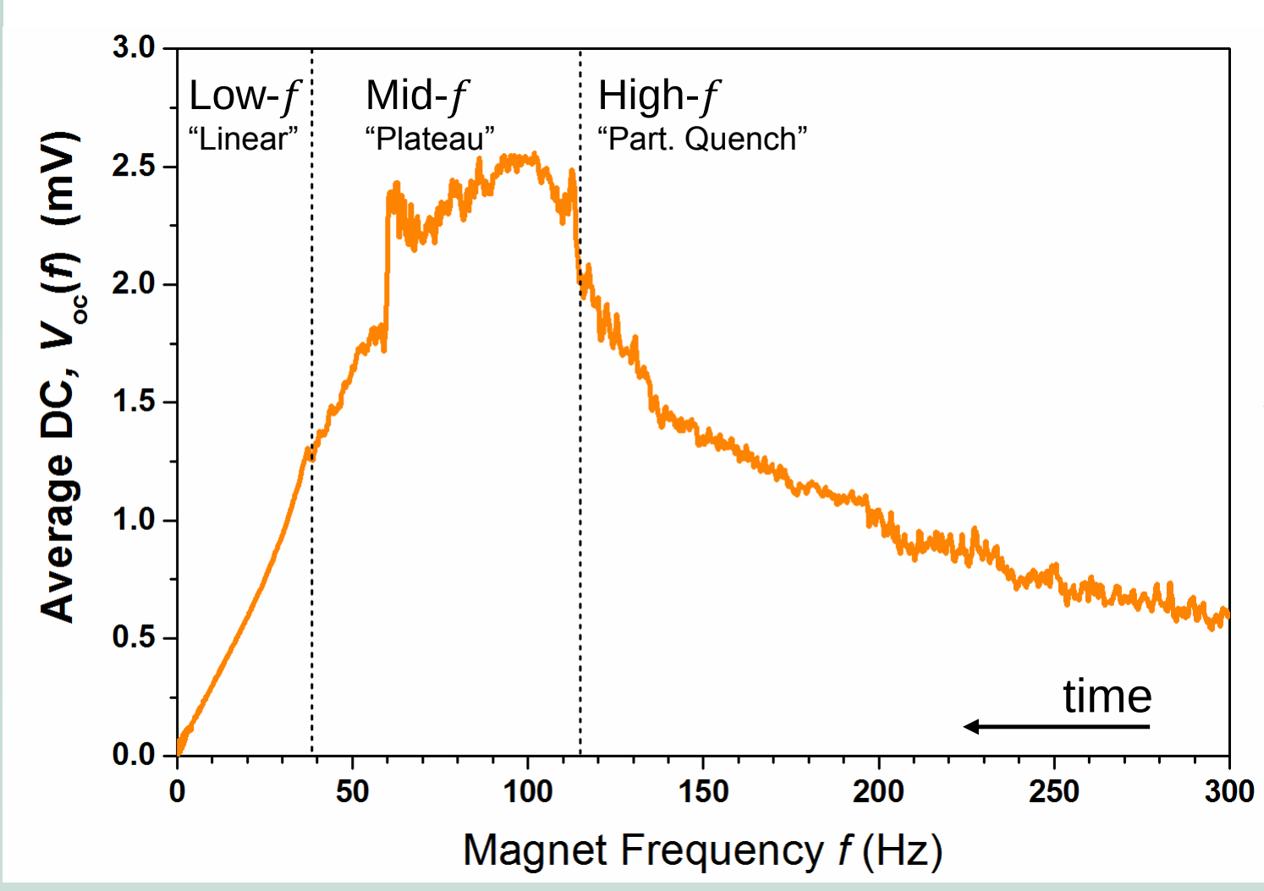


Schematic showing circulating eddy currents flowing around rotor magnet as it passes over 46 mm wide stator wire.

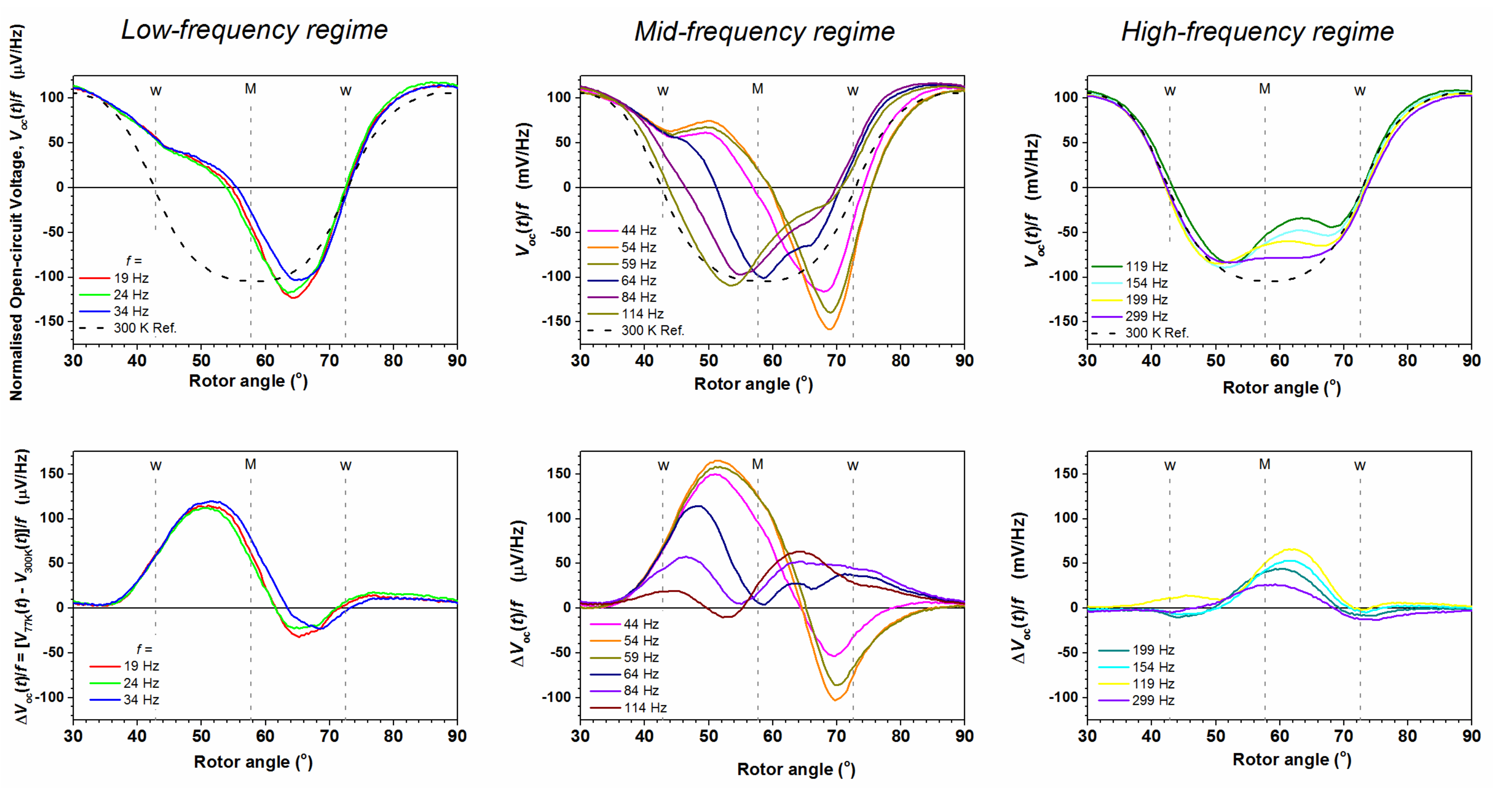
Waveforms versus Frequency

The instantaneous voltage trace waveforms show distinctly different wave shapes in the 3 frequency regions.

On the right is the average DC voltage trace of one ramp-down set, and below we show the resultant waveforms at various spot frequencies.



Left: The average DC value vs. f for the waveforms below.
Note that the time axis has been reversed for clarity.



Plots of instantaneous voltage waveforms split into 3 frequency regions. Waveform magnitudes have been normalised by the magnet frequency f. The angular locations marked 'M' indicate when the magnet is directly over the centre of the HTS stator, and the 'w' denote the width of the 46 mm HTS stator.
Top row: Waveforms at 77K ($V_{77K}(t)$,colour) and 300K reference ($V_{300K}(t)$, black dashed line).
Bottom row: Subtracted voltage $\Delta V_{oc}(t) = V_{77K}(t) - V_{300K}(t)$.

- The 77 K waveforms in the Low-f region are simple, have a well defined f-dependence, and deviate from the 300 K reference waveform only when the magnet is directly above the HTS stator. This is consistent with the simple model of "short-circuiting" eddy currents described above.
- The highest waveform amplitudes are seen in the Mid-f region, and this corresponds to the region where the highest average DC voltage is seen. In this region we also see two complex waveform shapes, which average to different DC values. We classify this Mid-f region as metastable, with the waveform profile depending on the history of the thermal self-heating within the stator.
- In the High-f region, partial quenching of the stator leads to a much reduced voltage trace amplitude, and the wave shapes are similar to that of the Low-f region.

Summary: Three Frequency Regions

Monitoring the average DC voltage V_{oc} and the high-speed voltage waveform is a simple and powerful tool for understanding and optimising the behaviour of this Flux Pump.

f Region	Effect on Average DC	Explanation
Low "Linear" f < 60 Hz	The DC voltage increases proportional to frequency. Simple waveforms.	The EMF in the region beneath the magnet is "short circuited" by circulating currents, leading to partial rectification of the AC waveform.
Mid "Plateau" 60 Hz < f < 130 Hz	The DC voltage is roughly constant with f, but is unstable and can switch between multiple values. Complex waveforms.	The total circulating current in the stator saturates, causing the waveform amplitude to substantially increase.
High "Part. Quench" f > 130 Hz	The DC voltage drops with an approximately $1/f$ dependence, tending towards $V_{oc} = 0$. Simple waveforms.	Partial quenching raises the temperature of the stator, reducing and ultimately eliminating the rectification effect.