

# Impact of Stator Ring Width on Output of a Dynamo-type HTS Flux Pump

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## HTS Flux Pumps

Flux pumps are a type of brushless exciter that provide a contactless method of energizing supercurrents in superconducting coils. Using these devices, traditional non-superconducting metal current leads and their associated heat leaks can be done away with, thereby improving cryogenic efficiency and significantly reducing the cost of systems incorporating superconducting magnets. Flux pumps also provide a low-power means of stabilizing the current and field of high-temperature superconductor (HTS) coils, which decay slowly due to finite resistances of normal-conducting joints and the inductance of the coil.

The device considered in this work is a superconducting dynamo consisting of a circular array of magnets mounted on a rotor that passes the magnets across an HTS superconducting stator wire. During operation in the superconducting state, a time-averaged dc voltage is produced which can be used to energize the field in a connected superconducting coil. The parameter investigated here is the width of the iron stator yoke ring on which the HTS wire is mounted.

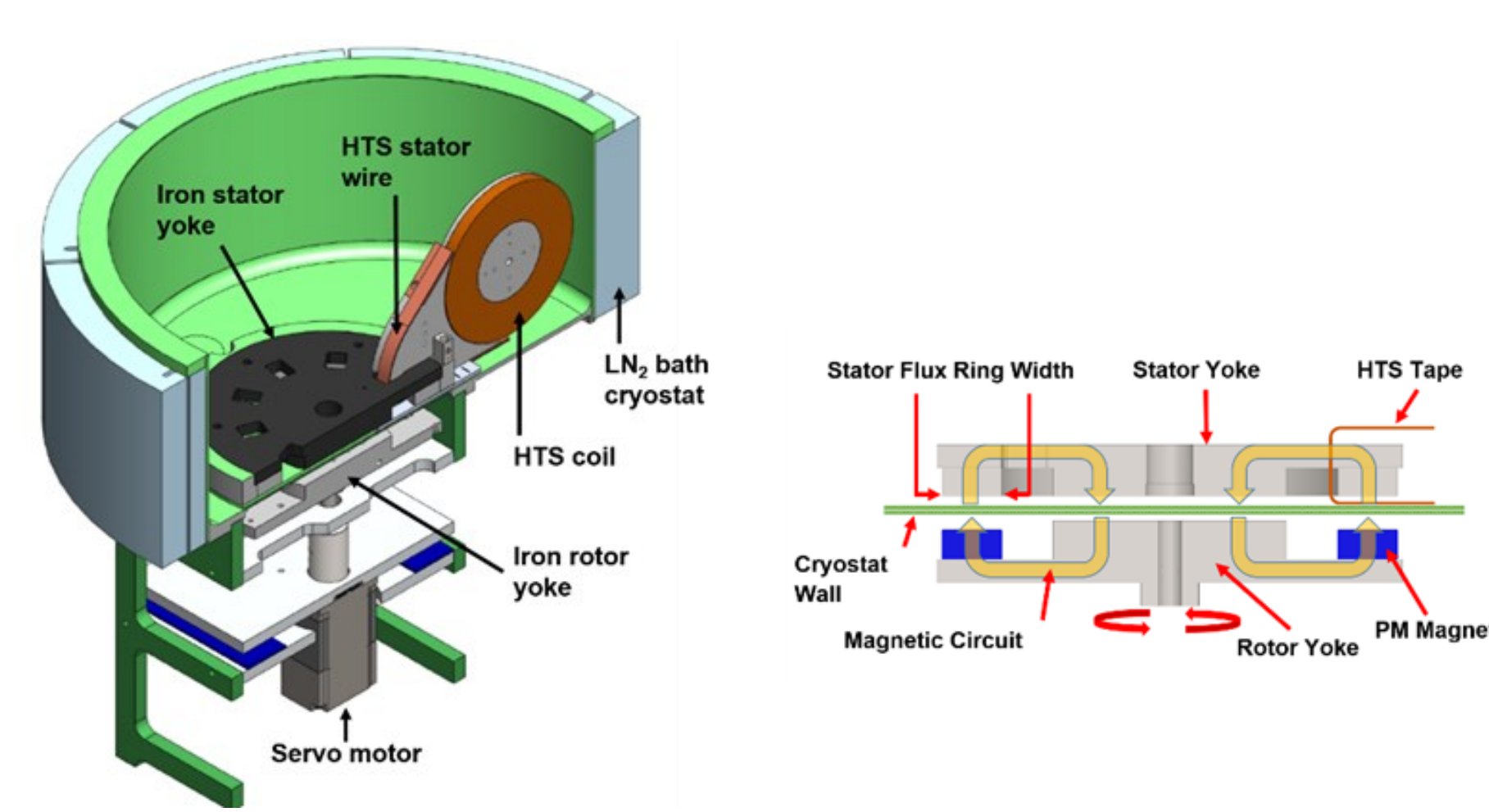


Fig. 1. Cutaway view of the external-rotor dynamo-type HTS flux pump, the liquid nitrogen cryostat bath and HTS coil.

Fig. 2. Section showing the magnetic circuit formed between the rotor and stator.

Fig. 3. Schematic showing the arrangement of the iron stator yoke, rotor magnets and 12 mm wide HTS stator wire.

The overall design of the flux pump features a cylindrical ring-shaped iron stator yoke immersed in a liquid nitrogen bath (see Fig. 1). Three yokes with ring widths  $\Delta r$  of 25 mm, 12.5 mm and 6.25 mm were trialled in this study, corresponding to full, half and quarter lengths of the rotor magnets respectively (see Fig. 2 and Fig. 3). A 12 mm wide Superpower 2G HTS coated conductor stator wire (SCS12050) is wrapped around the yoke and soldered to an HTS double pancake coil, forming a closed circuit (see Fig. 2). An iron rotor, holding an array of nine N42 (6.35 x 12.5 x 25 mm) Nd-Fe-B magnets is located outside of the cryostat opposite the stator. The magnets are arranged with their magnetization vectors pointing through the flux gap  $d$  (and cryostat wall) towards the stator. Rotation is achieved with a servo motor.

## Magnet Fields

The magnetic field at the stator wire was simulated using Opera finite element analysis software for the different stator yoke ring widths  $\Delta r$  and flux gaps  $d$  with the magnet centred above the wire. The perpendicular field component  $B_y$  over the wire area is plotted in Fig. 4 for a flux gap of 5 mm.  $B_y$  along orthogonal line cuts passing lengthwise and widthwise through the middle of the wire are shown in Fig. 5(a) and (b) respectively.

The field follows a bell-shaped profile across the centre width of the wire, in the direction around the stator ring, and increases slightly in magnitude as the ring width is reduced. The changes in field along the length of the wire are more pronounced. As the ring width is reduced the profile becomes hat-shaped, peaking at the edges of the ring due to flux concentration effects. The decay of  $B_y$  at the centre of the wire with increasing flux gap is shown in Fig. 5(c).

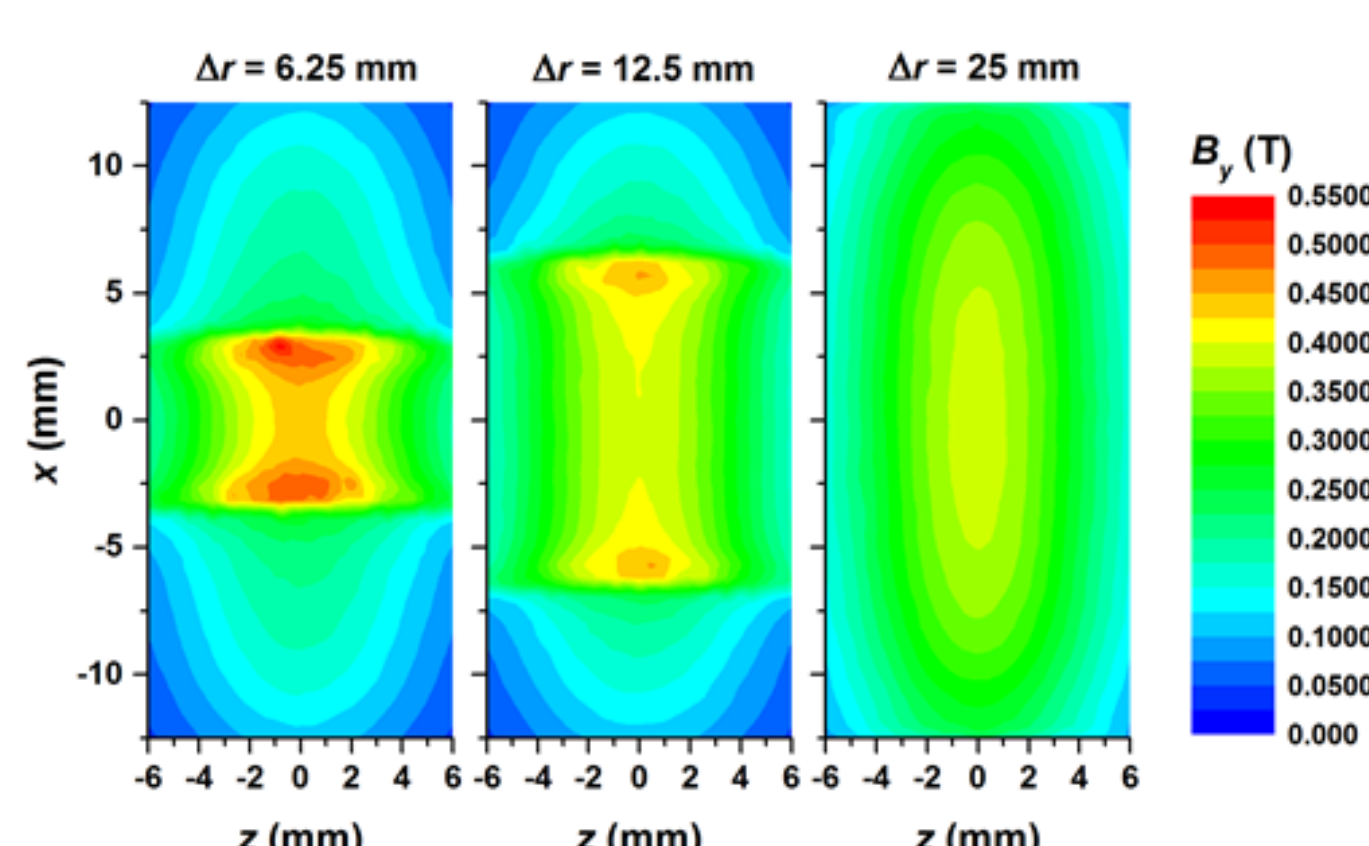


Fig. 4. Perpendicular component of the magnetic field calculated over the stator wire for the different ring widths (in the x-direction) with the magnet located 5 mm above the wire.

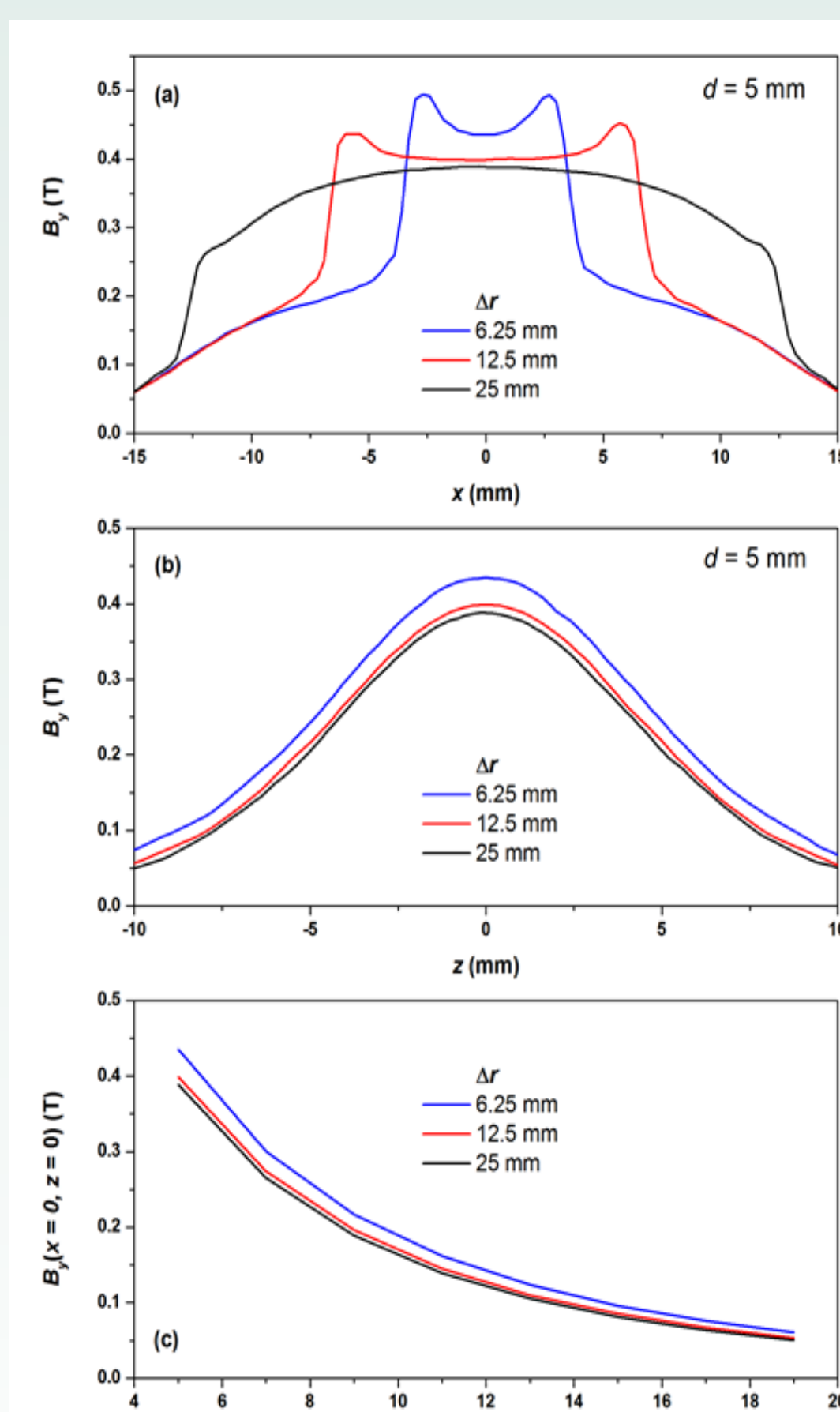


Fig. 5. Calculated perpendicular magnetic field  $B_y$  for different ring widths (a) along the centre length the stator wire, and (b) along the centre width of the stator wire. The magnet is located 5 mm above the centre of the wire. (c)  $B_y$  at the centre of the wire vs the flux gap.

## Dynamo HTS Flux Pumps

The voltage produced by the flux pump  $V_{FP}$  can be parametrized by an open circuit voltage  $V_{oc}$  and an effective internal resistance  $R_d$  according to  $V_{FP} = V_{oc} - IR_d$ . The current  $I$  delivered by the flux pump connected to a coil of inductance  $L$  by contact resistance  $R_c$  is shown in Fig. 6 and leads to the short circuit current,  $I_{sc}$ .

These parameters allow the performance of a flux pump to be predicted for any given HTS coil implementation.

The coil current is plotted as a function of the output voltage  $V_{FP}$  in Fig. 8. The device parameters  $I_{sc}$ ,  $V_{oc}$ , and  $R_d$  are given by the  $I$ - &  $V$ -axis intercepts and the gradient respectively. The values are plotted as functions of  $\Delta r$  in Fig. 9. The frequency dependence in  $V_{oc}$  and  $R_d$  is attributed to eddy currents induced in the iron yoke and/or in the stabilising layers of the HTS stator.

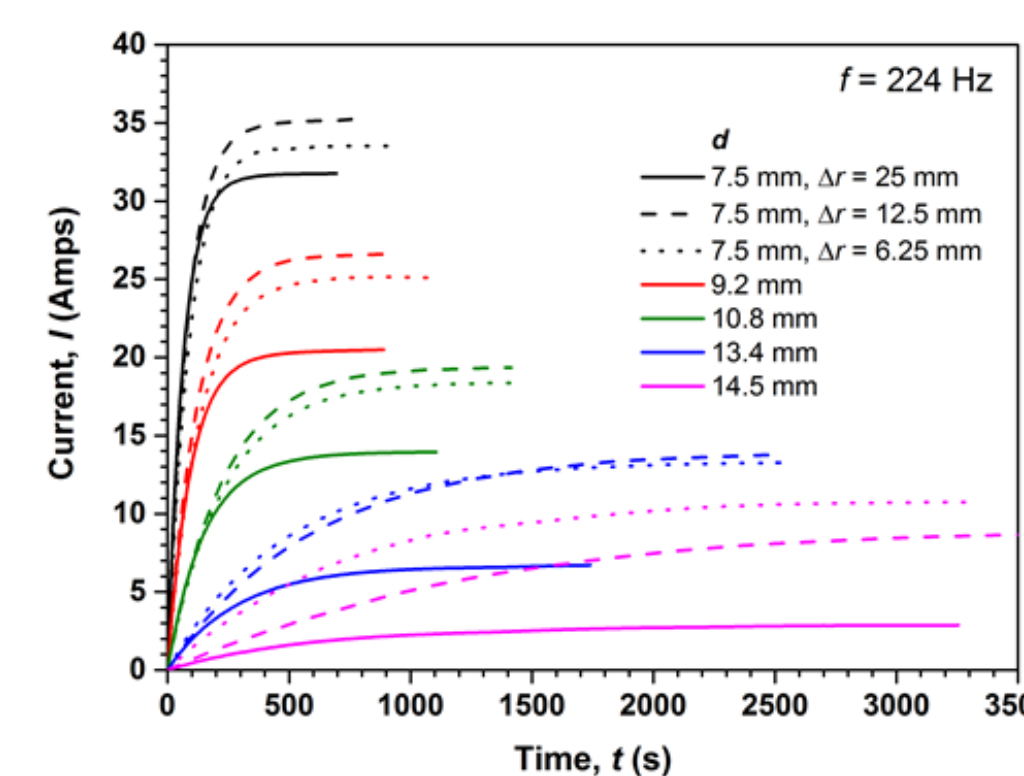


Fig. 7. Coil current vs the flux pump running time for different stator ring widths  $\Delta r$  and flux gaps  $d$ . The operating frequency  $f$  is 224 Hz.

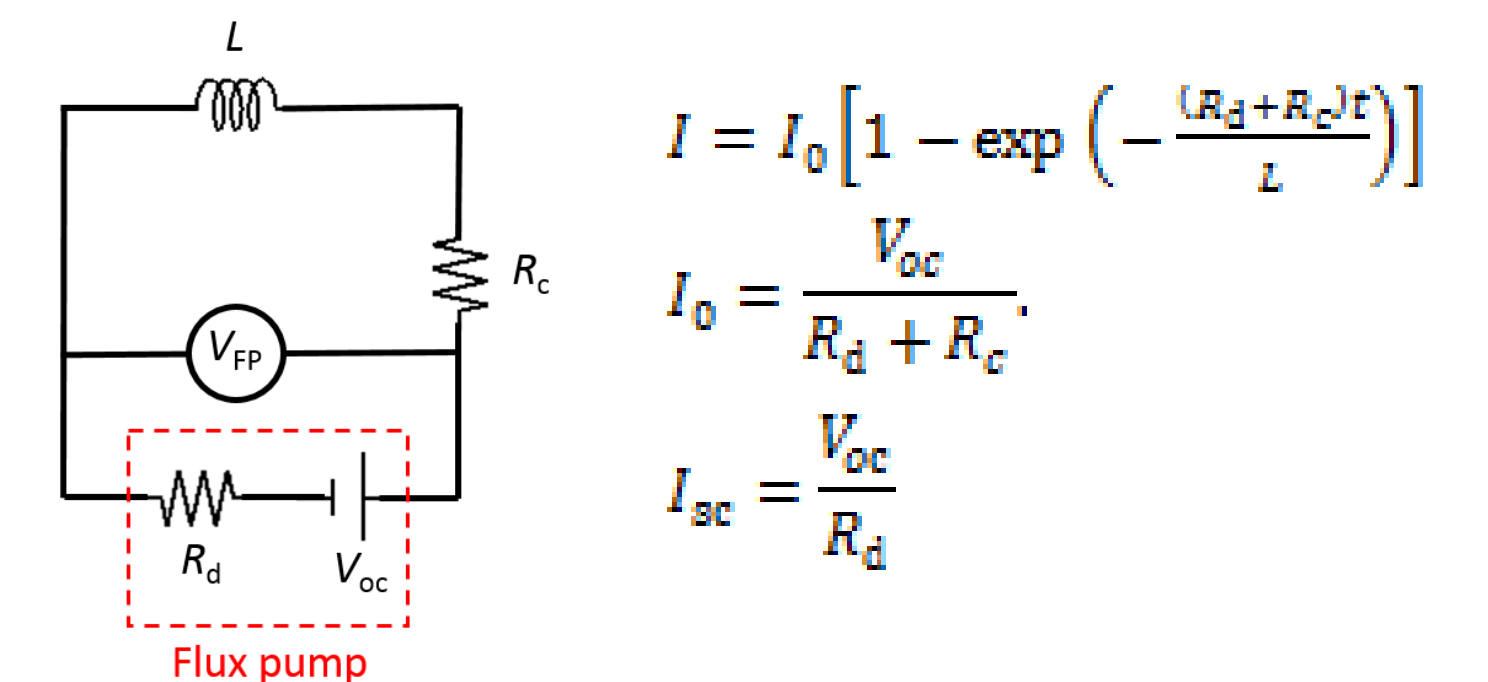


Fig. 6. HTS flux pump circuit model, consisting of an open circuit voltage  $V_{oc}$  and internal resistance  $R_d$ , connected to a coil of inductance  $L$  via joints with combined resistance  $R_c$ .

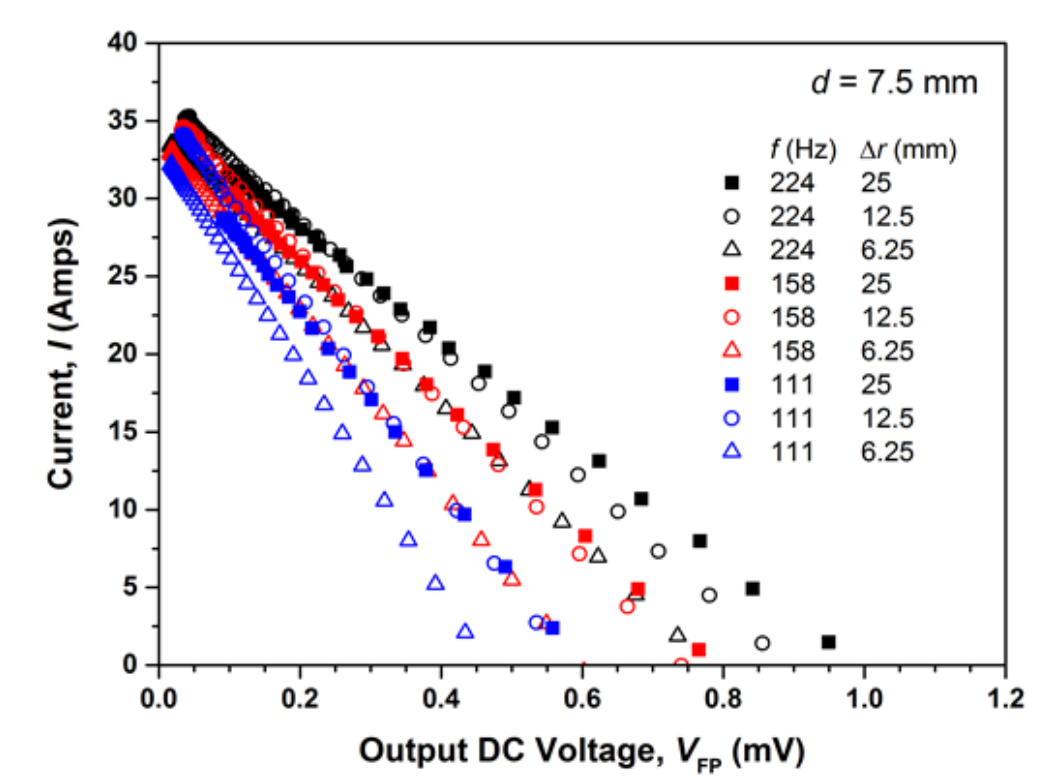


Fig. 8. Current vs dc output voltage for different operating frequencies  $f$  and stator ring widths  $\Delta r$ . The flux gap  $d$  is 7.5 mm.

## Discussion

Fig. 9(b), (c) and (d) show the device parameters are relatively insensitive to the size of the stator yoke ring width. The largest changes from the four-fold increase in  $\Delta r$  are 25 – 30 % increases in  $R_d$  and  $V_{oc}$  at the closest flux gap of 7.5 mm. An explanation for this insensitivity is that the total magnetic flux increases only slightly with ring width (see Fig. 9. (a)). From a practical standpoint this implies that thinner stator rings, advantageous in terms of weight, thermal mass, and iron-losses, can be employed with little impact on electrical performance.

Linear relationships are found between the device parameters and the calculated perpendicular field at the centre of the stator wire, as shown in Fig. 10. The linear fits to  $R_d$  and  $V_{oc}$  extrapolate to a threshold field between 0.075 and 0.12 T which has been interpreted as the field at which flux fully penetrates the HTS stator. The slopes of the fits to  $R_d$  and  $V_{oc}$  decrease with decreasing ring width in a similar manner such that the resulting  $I_{sc}$  values nearly occur on a common line.

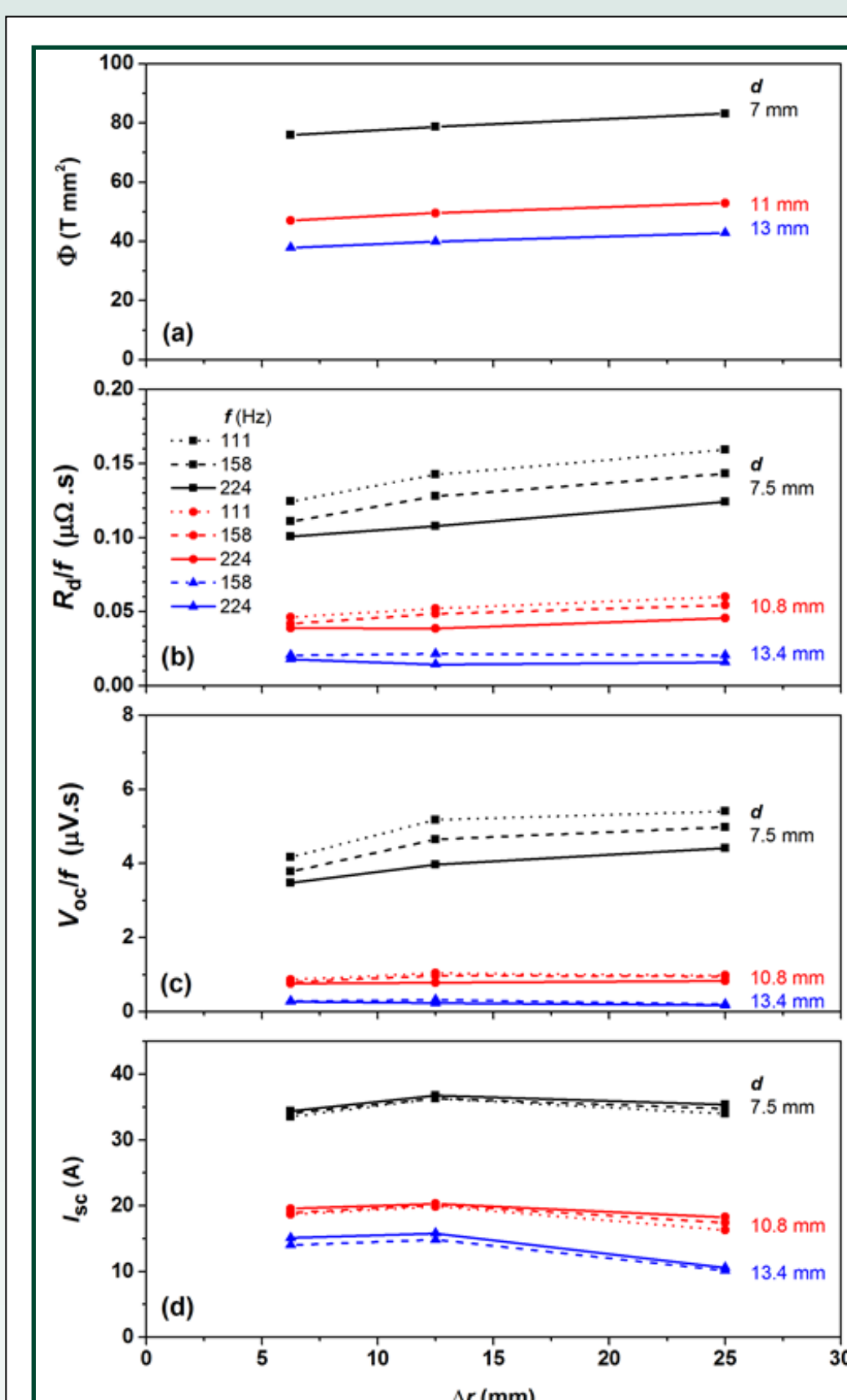


Fig. 9. (a) Calculated flux, (b) frequency normalised dynamic resistance, (c) frequency normalised open-circuit voltage, and (d) short circuit current for different frequencies  $f$  and flux gaps  $d$  versus stator ring width  $\Delta r$ .

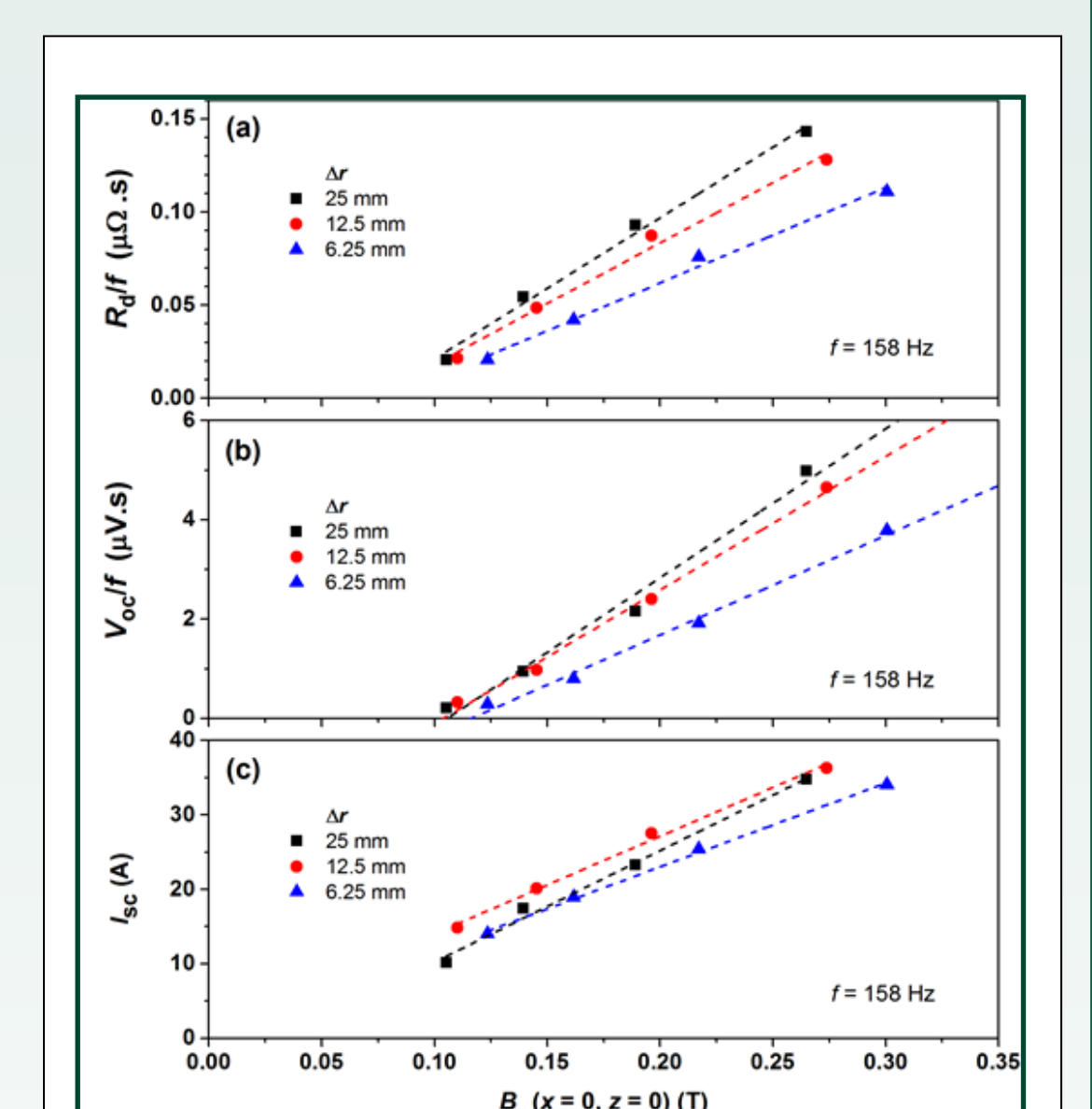


Fig. 10. The measured device parameters (a)  $R_d/f$ , (b)  $V_{oc}/f$ , (c)  $I_{sc}$ , versus the maximum perpendicular field  $B_y$ ,  $f = 158$  Hz.

In this work the effect of the width of the iron stator yoke ring on the performance of a dynamo type HTS flux pump was investigated. Only a small increase in the open circuit voltage and internal resistance with width at the smallest flux gap was observed. The short circuit current was found to be independent of stator yoke width. As in other studies, the performance of the device was found to correlate with the peak field at the centre of the stator wire, which is mostly governed by the size of the flux gap. These results imply that thinner stator yoke rings can be utilised in HTS dynamos with little impact on device performance.