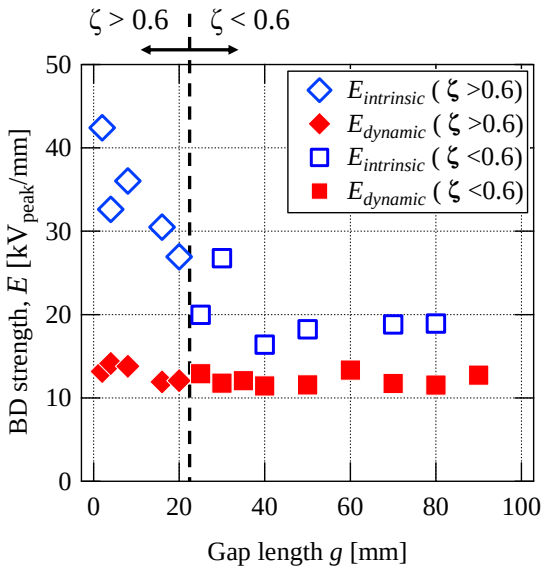

Fig. 12. Gap length dependence of intrinsic BD strength $E_{intrinsic}$ and dynamic BD strength $E_{dynamic}$ at sphere-plane electrode by KIT. Sphere diameter ϕ = 50 mm [12].

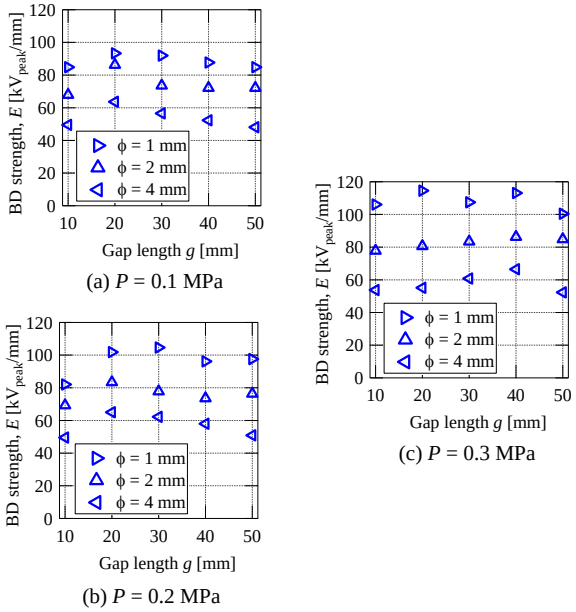

Fig. 13. Gap length dependence of intrinsic BD strength $E_{intrinsic}$ for different tip diameter and LN_2 pressure at tip-plane electrode by TH Köln [14].

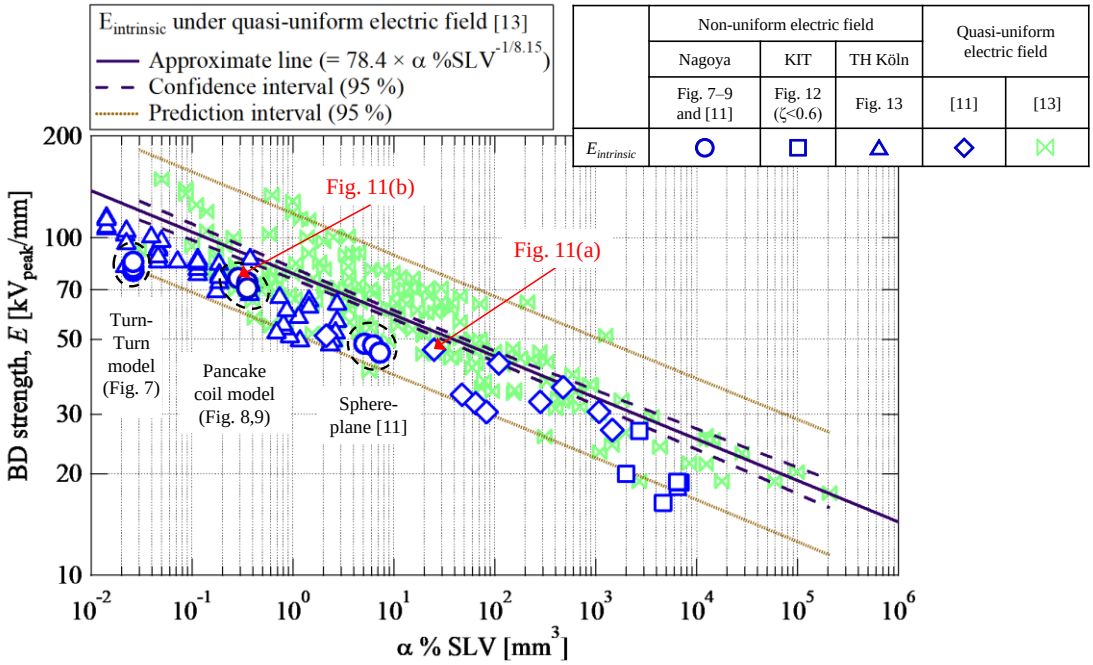

Fig. 14. Volume effect of intrinsic BD strength $E_{intrinsic}$ in LN_2 under quasi-uniform and non-uniform electric field.

IV. Conclusion

In this paper, we designed and fabricated a Turn-Turn model and a pancake coil model for the practical RSFCL and investigated the intrinsic and dynamic BD characteristics ($E_{intrinsic}$, $E_{dynamic}$) under non-uniform electric field in LN_2. Experimental results revealed the followings:

1) $E_{dynamic}$ with transient bubbles in LN_2 is lower than $E_{intrinsic}$ without bubbles.
2) $E_{intrinsic}$ and $E_{dynamic}$ can be estimated by the calculation of α%SLV in terms of the volume effect, regardless of the quasi-uniform/non-uniform electric field.
3) Based on $E_{intrinsic}$ and $E_{dynamic}$, the reliable and rational insulation design of RSFCL can be expected.

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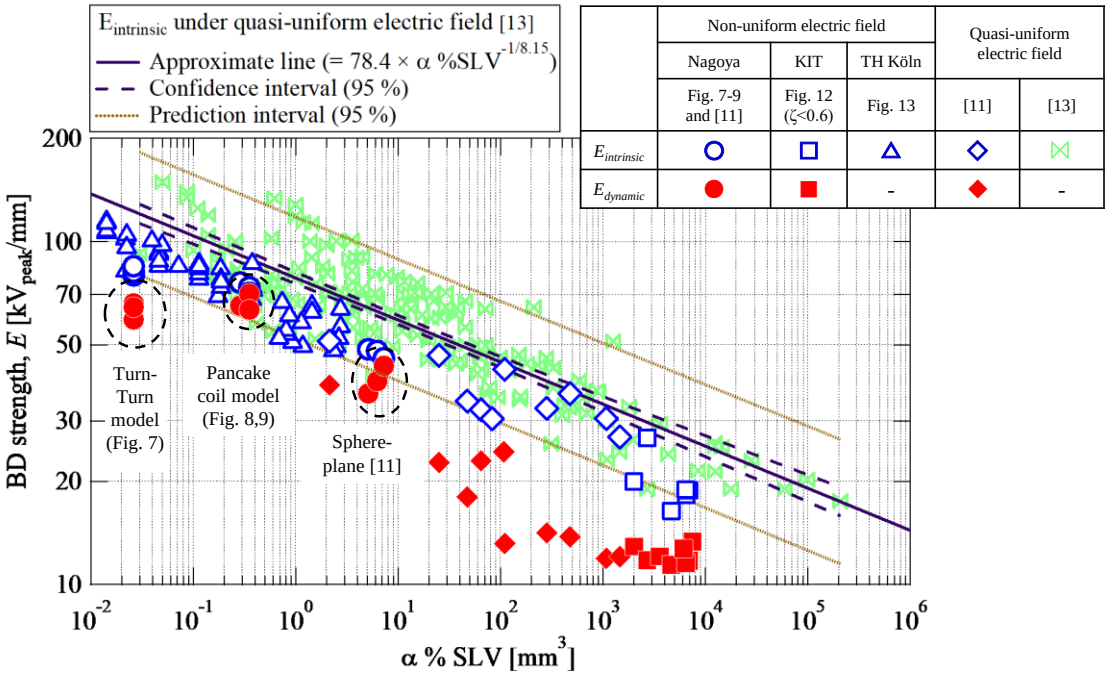

Fig. 15. Volume effect of intrinsic BD strength $E_{intrinsic}$ and dynamic BD strength $E_{dynamic}$ in LN_2 under quasi-uniform and non-uniform electric field.

REFERENCES

[1] A. Morandi, "Fault current limiter: an enabler for increasing safety and power quality of distribution networks," *IEEE Trans. Appl. Supercond.*, vol.23, no.6, 5604608, 2013.

[2] J. Bock, A. Hobl, J. Schramm, S. Krämer, and C. Jänke, "Resistive superconducting fault current limiters are becoming a mature technology," *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, 5600604, 2015.

[3] G. Angeli, M. Bocchi, M. Ascade, V. Rossi, A. Valzasina, and L. Martini, "Development of superconducting devices for power grids in Italy: update about the SFCL project and launching of the research activity on HTS cables", *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, 5600406, 2017.

[4] M. Moyzykh, D. Sotnikov, D. Gorbunova, and S. Samoilenkov, "Superconducting fault current limiter for Moscow 220 kV city grid," *European Conference on Applied Superconductivity 2017*, 1LO1-02, 2017

[5] N. Hayakawa, Y. Maeno, and H. Kojima, "Fault current limitation coordination in electric power grid with superconducting fault current limiters," *IEEE Trans. Appl. Supercond.*, vol. 28, No.4, 5602304, 2018.

[6] M. Hara, D. J. Kwak, and M. Kubuki, "Thermal bubble breakdown characteristics of LN_2 at 0.1 MPa under a.c. and impulse electric fields," *Cryogenics*, vol.29, pp.895–903, 1989.

[7] I. Sauers, R. James, A. Ellis, E. Tuncer, G. Polizos, and M. Pace, "Effect of bubbles on liquid nitrogen breakdown in plane-plane electrode geometry from 100-250 kPa," *IEEE Trans. Appl. Supercond.*, vol.21, no.3, pp.1892–1895, 2011.

[8] M. Blaz and M. Kurrat, "Influence of bubbles in pressurized liquid nitrogen on the discharge behavior in a homogeneous electric field," *IEEE Trans. Appl. Supercond.*, vol.23, 7700804, 2013.

[9] N. Hayakawa, T. Matsuoka, H. Kojima, S. Isojima, and M. Kuwata, "Breakdown characteristics and mechanisms of liquid nitrogen under transient thermal stress for superconducting fault current limiters," *IEEE Trans. Appl. Supercond.*, vol. 27, No.4, 7700305, 2017.

[10] N. Hayakawa, T. Matsuoka, K. Ishida, H. Kojima, S. Isojima, and M. Kuwata, "Pressure dependence and size effect of LN_2 breakdown characteristics under transient thermal stress," *IEEE Trans. Appl. Supercond.*, vol. 26, No.3, 7700604, 2016.

[11] N. Hayakawa, K. Ishida, M. Mimbu, H. Kojima, S. Isojima, and M. Kuwata, "Volume effect of dynamic breakdown strength in LN_2 for insulation design of resistive superconducting fault current limiters," *IEEE Trans. Appl. Supercond.*, vol. 28, No.4, 5600804, 2018.

[12] S. Fink, H.–R. Kim, R. Mueller, M. Noe, and V. Zwecker, "AC breakdown voltage of liquid nitrogen depending on gas bubbles and pressure," *Int. Conf. on High Voltage Engineering and Application*, 7035445, 2014.

[13] N. Hayakawa, S. Nishimachi, H. Kojima, and H.Okubo, "Size effect on breakdown strength in sub-cooled liquid nitrogen for superconducting power apparatus," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 5, pp. 2565–2571, 2015.

[14] C. Humpert, H. Seufert, R. Brustle, F. Kasten, G. Pfeiffer, and R. Schumacher, "Breakdown characteristics of liquid nitrogen in non-uniform electric fields," *Int. Conf. on Properties and Applications of Dielectric Materials*, No. 384, 2018