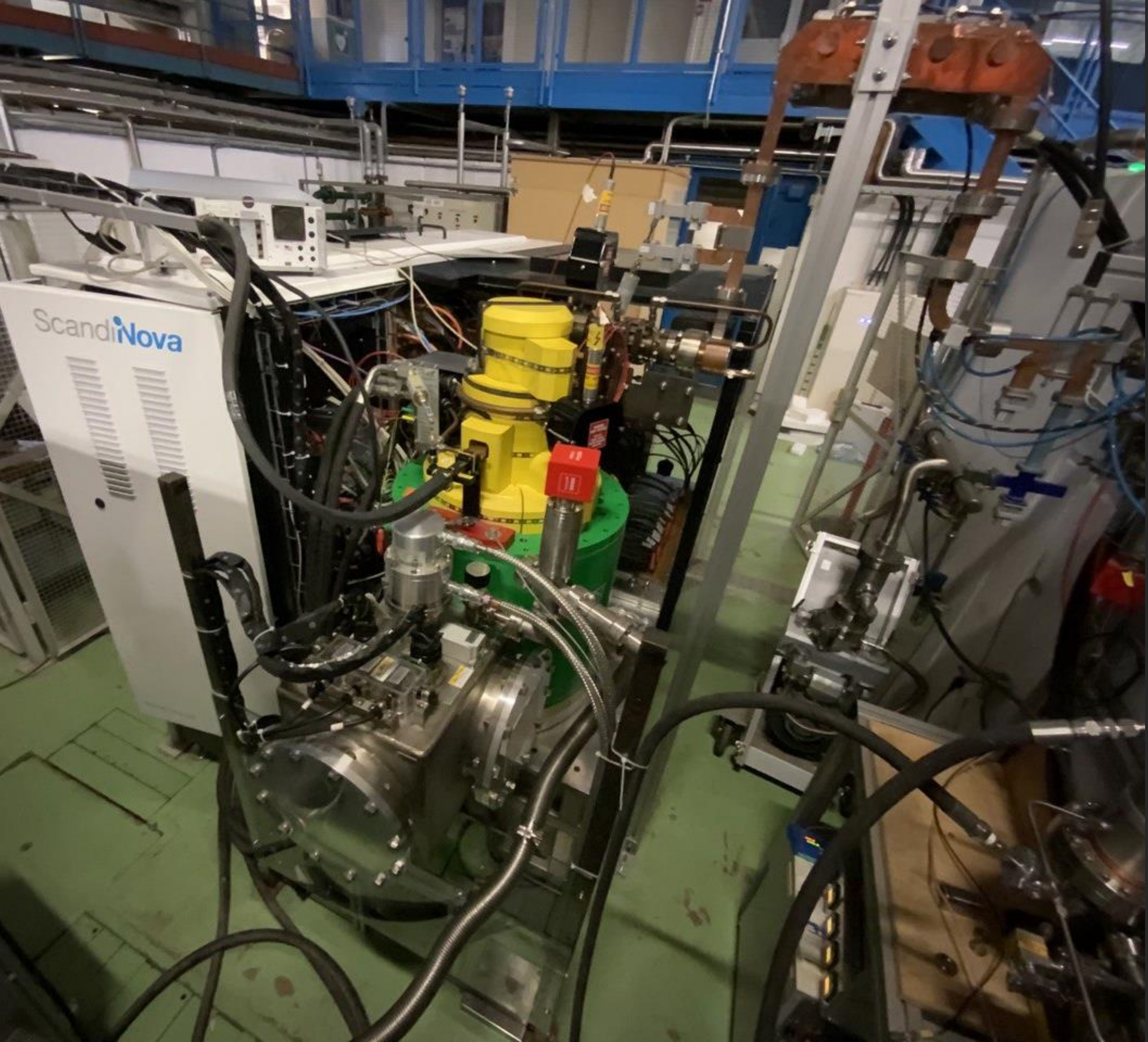


# FIRST OPERATION OF A KLYSTRON FITTED WITH A SUPERCONDUCTING $MGB_2$ SOLENOID

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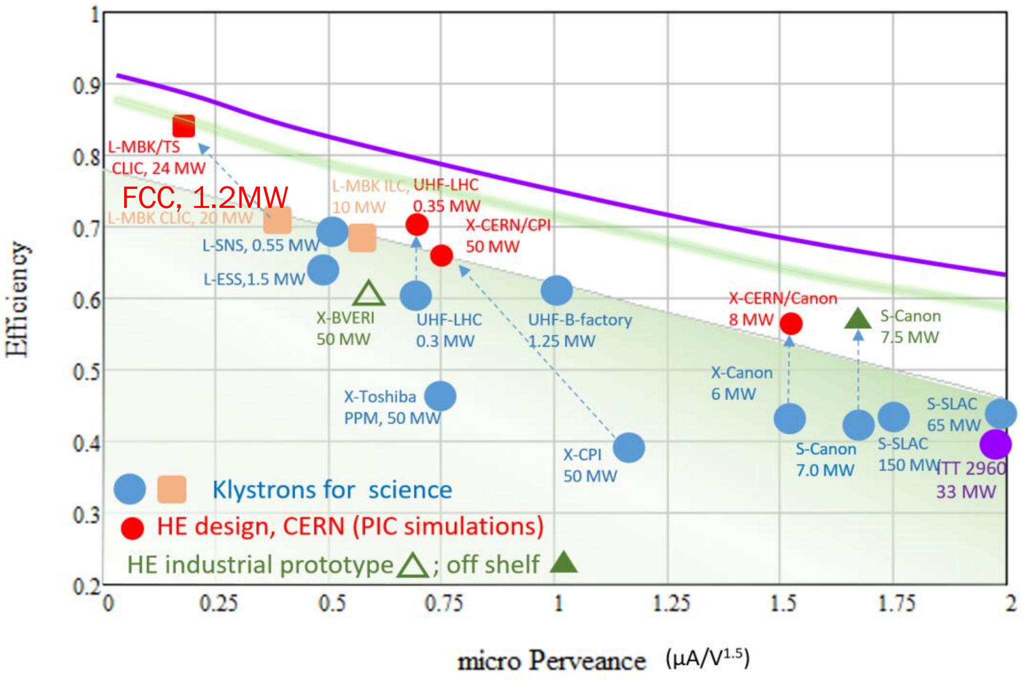
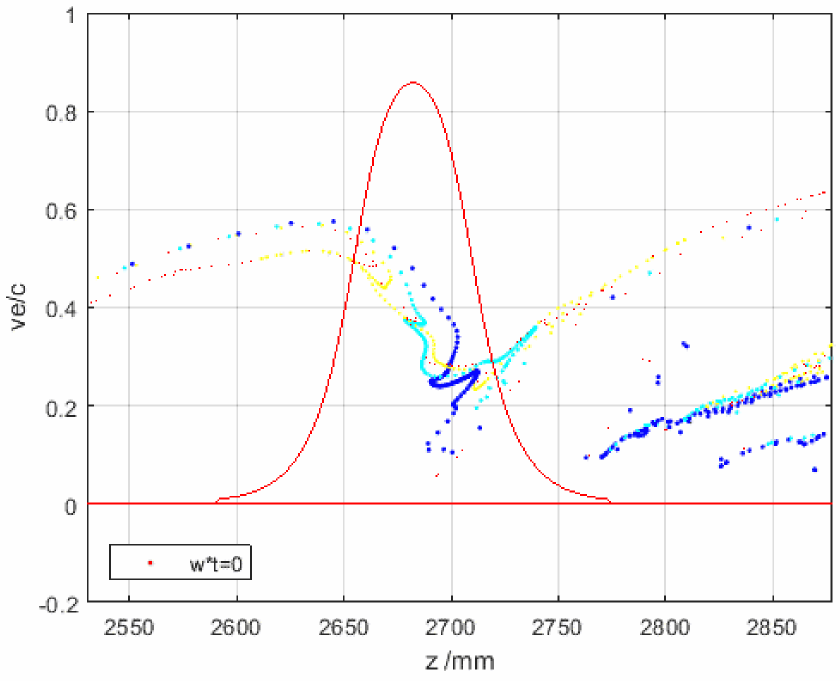
# OUTLOOK

- Motivation
- Cable and magnet manufacturing
- Integration at CERN
- Performance of the klystron system
- Conclusions



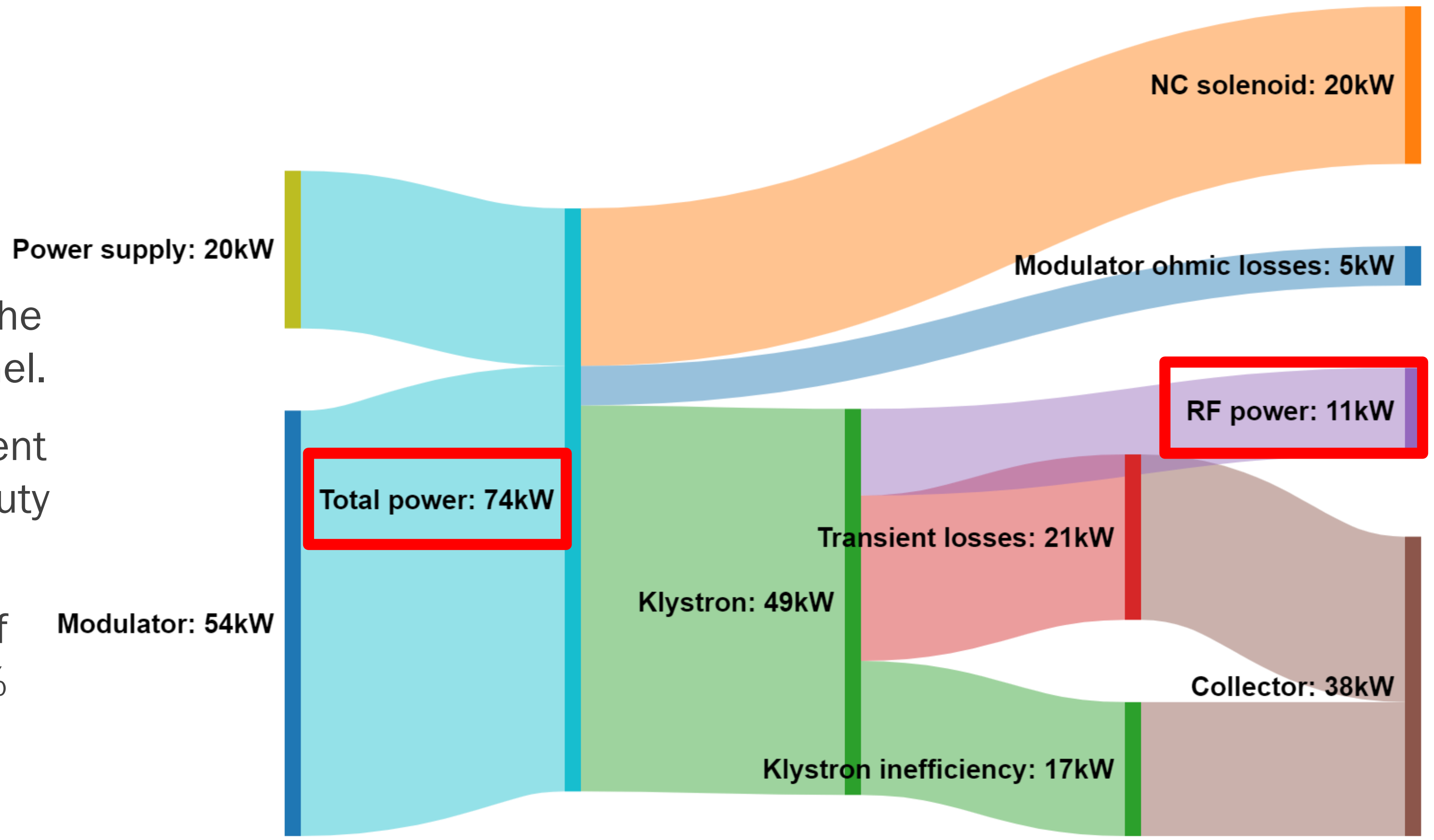

# MOTIVATION

- New projects are rated by their efficiency and sustainability performance
- Recent years have seen tremendous effort to make more efficient klystrons
- Among effects studied: E field expansion in the drift tubes; Ohmic loses; Space charge depression; Bunch saturation; Bunch congregation; Bunch stratification; Radial bunch expansion; Reflected electrons.

*J. Cai and I. Syratchev, "Design Study of X-band High Efficiency Klystrons for CLIC," 2020 IEEE 21st International Conference on Vacuum Electronics (IVEC), 2020, pp. 121-122, doi: 10.1109/IVEC45766.2020.9520585.*

# SOLENOID FOR PULSED KLYSTRONS

- Solenoidal field needed to confine the electron beam in the klystron channel.
- Electromagnet sits at constant current even for pulsed klystrons with low duty cycle
- In the x-band facility consumption of the electromagnet represents ~30% of the total power source




AC power/RF efficiency = 15.2%

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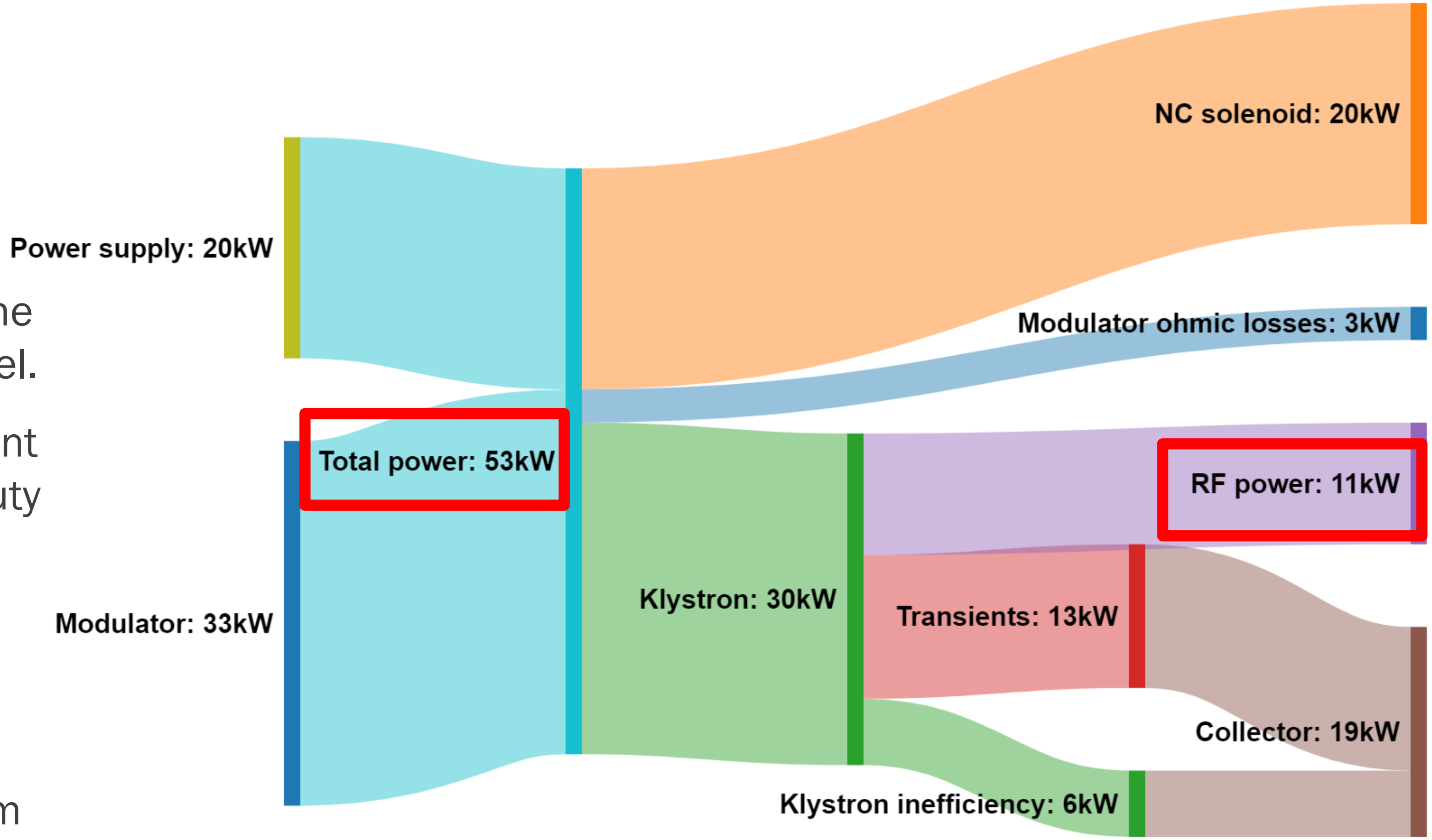
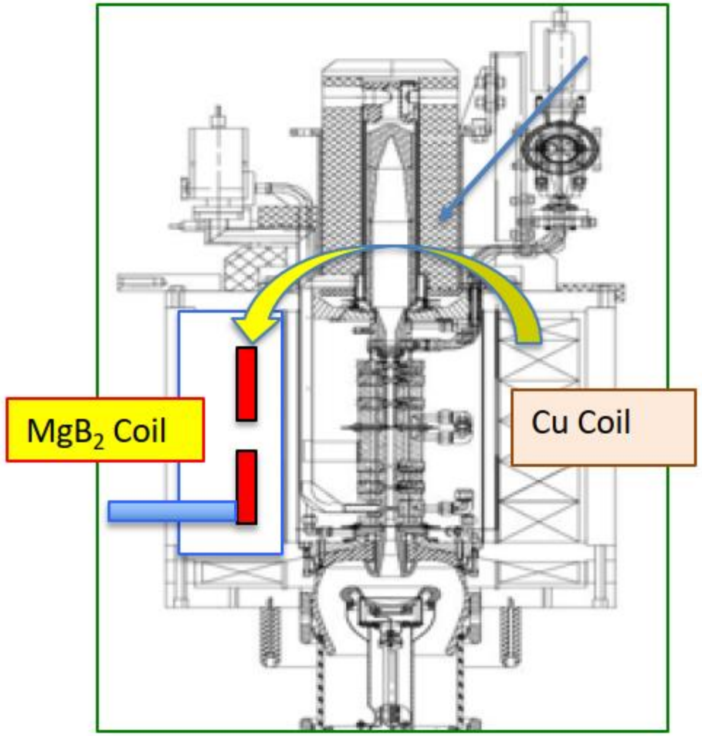
- In the x-band facility consumption of the electromagnet represents ~30% of the total power source
- With a gain in klystron efficiency from 40% to 65% and an optimized pulse we can save 20 KW per RF unit
- The solenoid will then represent 37% of the power`




AC power/RF efficiency = 21.0%

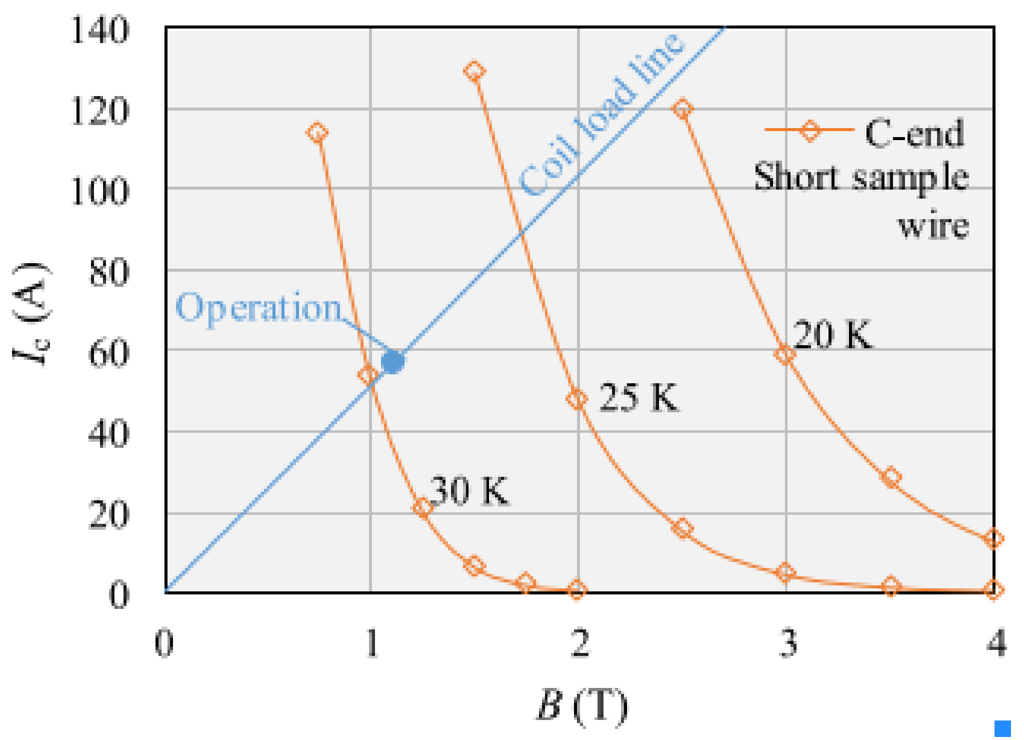
# SOLENOID DESIGN AND CHARACTERISTICS

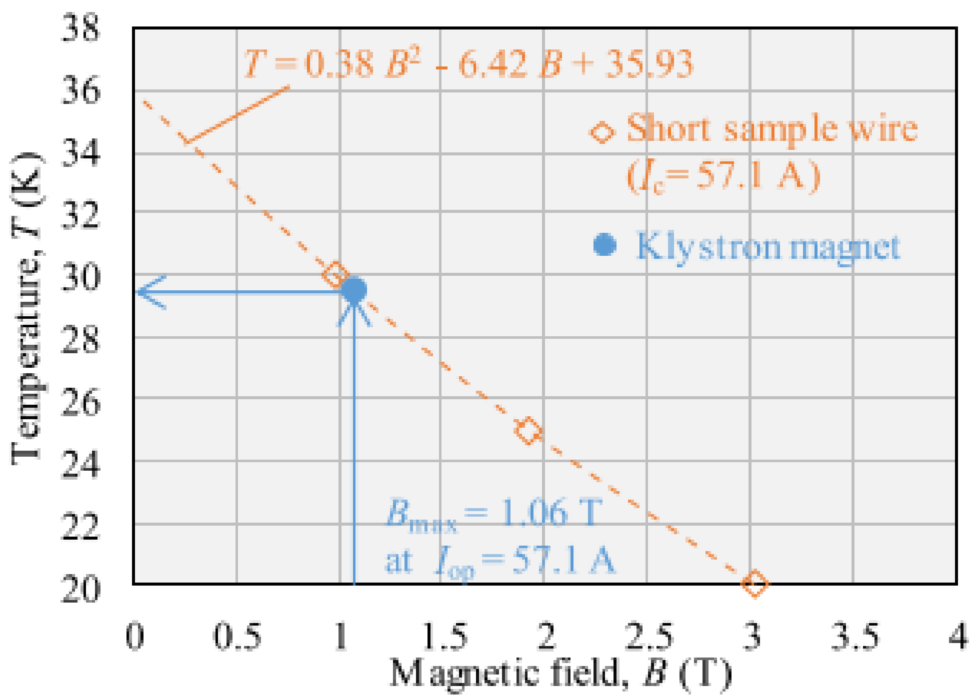
- Proposal from A. Yamamoto (KEK) to build a superconducting solenoid that could be tested and operational on the CERN X-band facility
- The required magnetic field is well below 1T so we can use $MgB_2$ working below 30 K to improve the cryocooler efficiency ad minimize costs



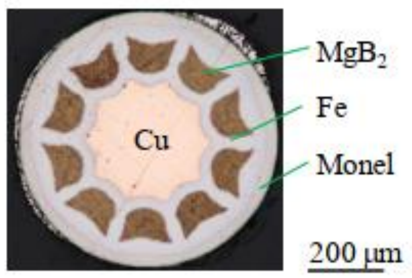

| Coil technology | Unit | Cu | $MgB_2$ |
|---|---|---|---|
| Central field | T | 0.6 | 0.8 |
| Current | A | 2x300 | 57 |
| Voltage | V | 35 | 0 |
| Cooling method | | Water | Cryo-cooler |
| Temp | K | 300 | ~25 |
| Wall plug power | kW | 20 | <3 |

*A. Yamamoto et al., "Applying Superconducting Magnet Technology for High-Efficiency Klystrons in Particle Accelerator RF Systems", IEEE Transactions on Applied Superconductivity, vol. 30, no. 4, pp. 1-4, Jun. 2020.doi:10.1109/TASC.2020.2978471*



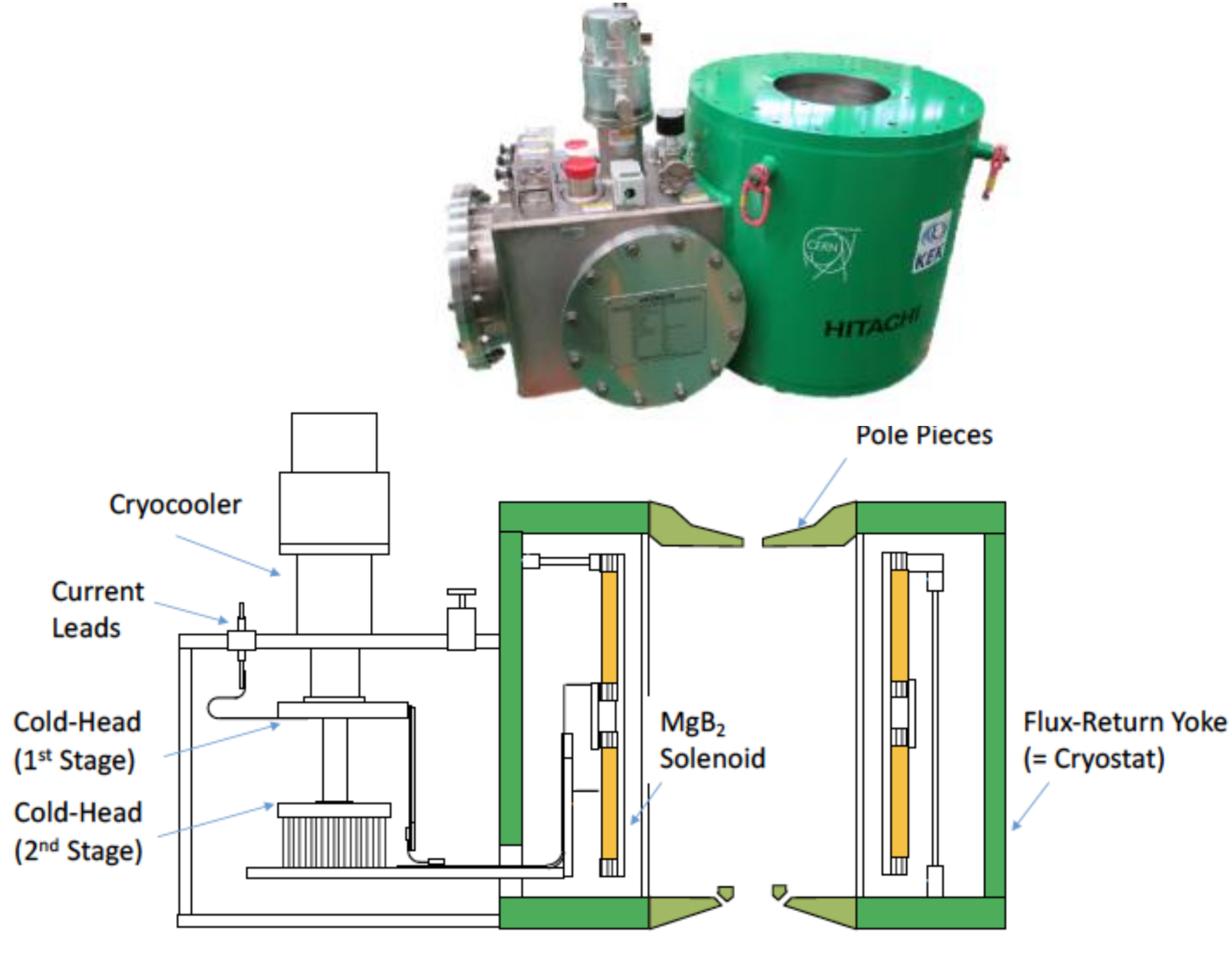

# CABLE AND CABLE TESTS




- 8km $MgB_2$ wire (0,67 mm) manufactured by Hitachi. Based on experience for MRI magnets
- 21 samples measured. Very good homogeneity
- Critical temperature of the cable at the operational point is 29 K.
  - 57.1 A and 1.06 T field in the coil
- Works at 46% of the load-line

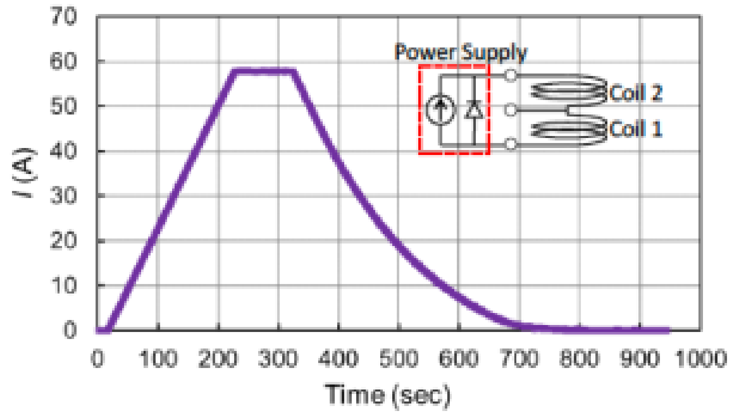
*H. Tanaka et al., "Performance of MgB2 Superconductor Developed for High-Efficiency Klystron Applications", IEEE Transactions on Applied Superconductivity, vol. 30, no. 4, pp. 1-5, Jun. 2020. doi:10.1109/TASC.2020.2970391*

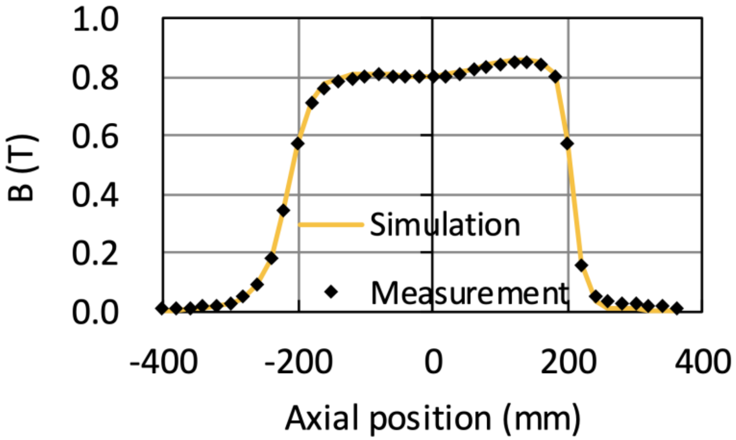
# MANUFACTURING OF THE SC SOLENOID IN HITACHI

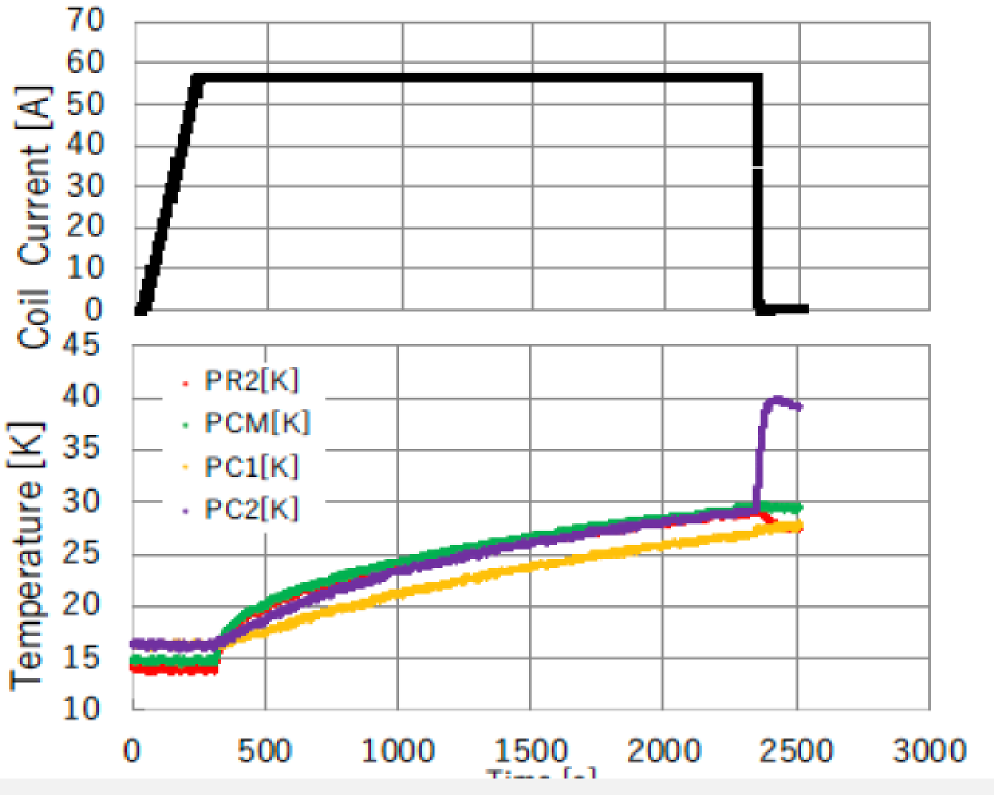



- Wind and react coils (2) in an iron cryostat that serves also as return yoke.
- Passive quench protection

| | | |
|---|---|---|
| Superconductor | MgB2 | |
| Maximum B field | 0.8 | T |
| Current | 57.1 | A |
| Inductance | 7.3 | H |
| Max. field in coil | 1.06 | T |
| Operating temperature | <20 | K |
| Stored energy | 11.8 | kJ |
| Weight | 600 | Kg |
| AC plug power | <3 | kW |



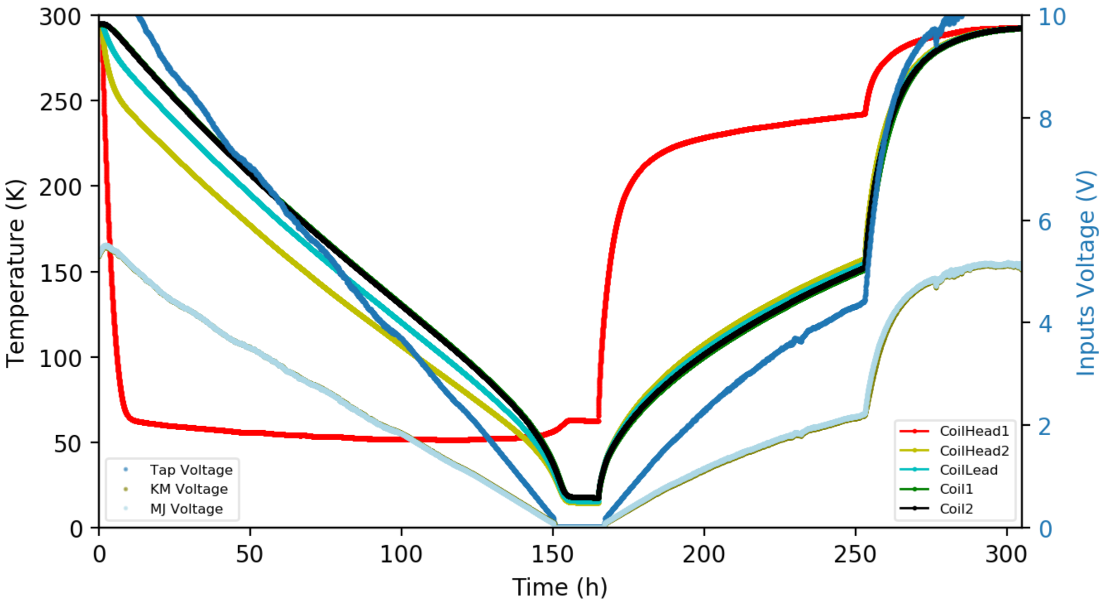

- Quench tests.
  - Self protected
- 10-hours excitation tests
- Power abort test
- Magnetic field measurements
  - Very good agreement

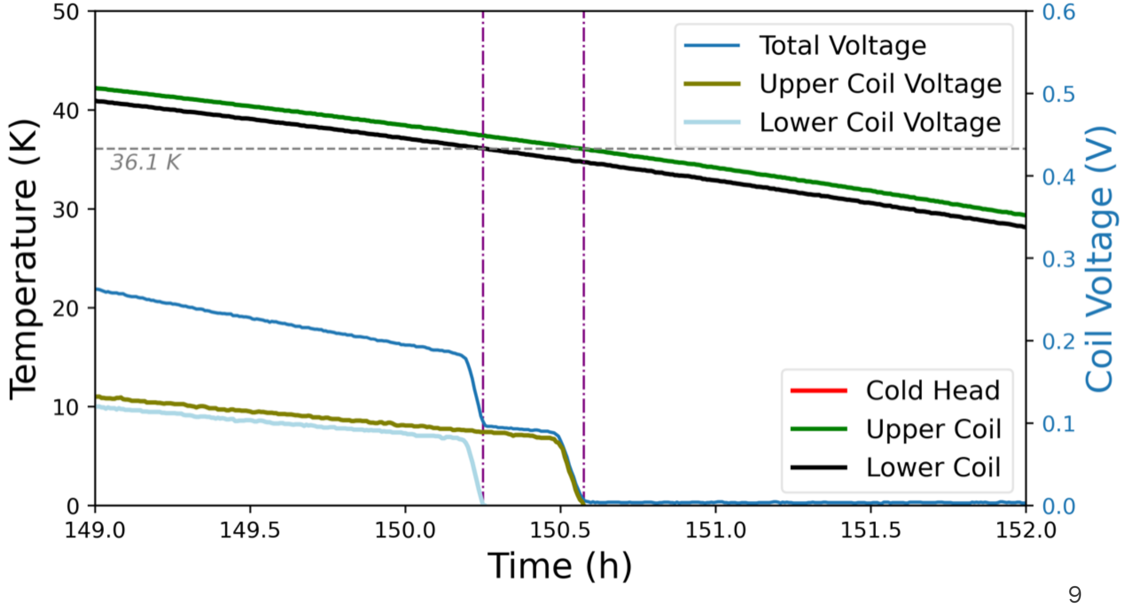
# FIRST TESTS AT HITACHI

H. WATANABE *ET AL.*, "DEVELOPMENT OF PROTOTYPE MGB2 SUPERCONDUCTING SOLENOID MAGNET FOR HIGH-EFFICIENCY KLYSTRON APPLICATIONS", *IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 30, NO. 4, PP. 1-6, JUN. 2020.*
DOI:10.1109/TASC.2020.297223

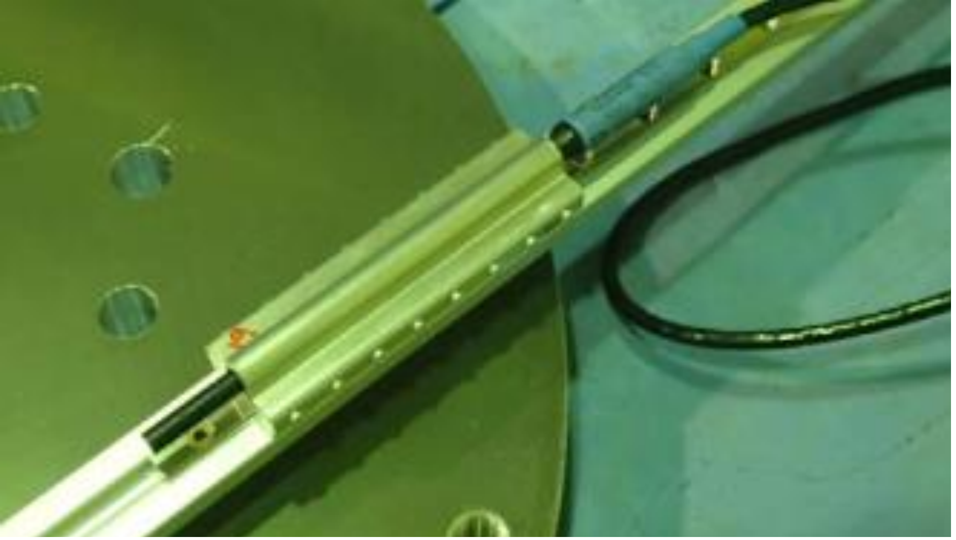
# COOL-DOWN

- Two twin coils cooled by conduction.
  - Insulation vacuum
  - Helium only on the cryocooler/cold head
  - Air cooled-compressor Cryocooler plus cold head

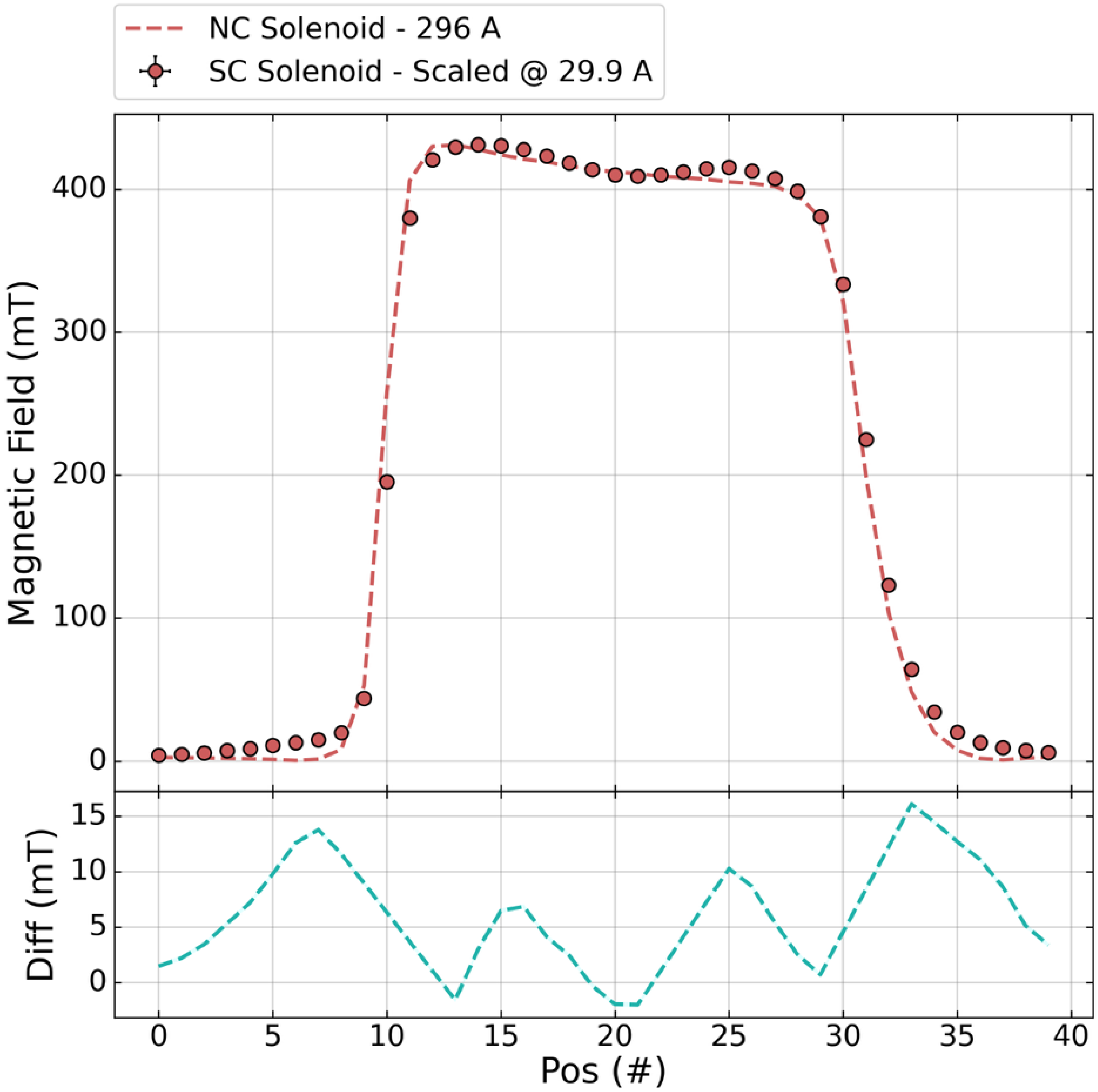



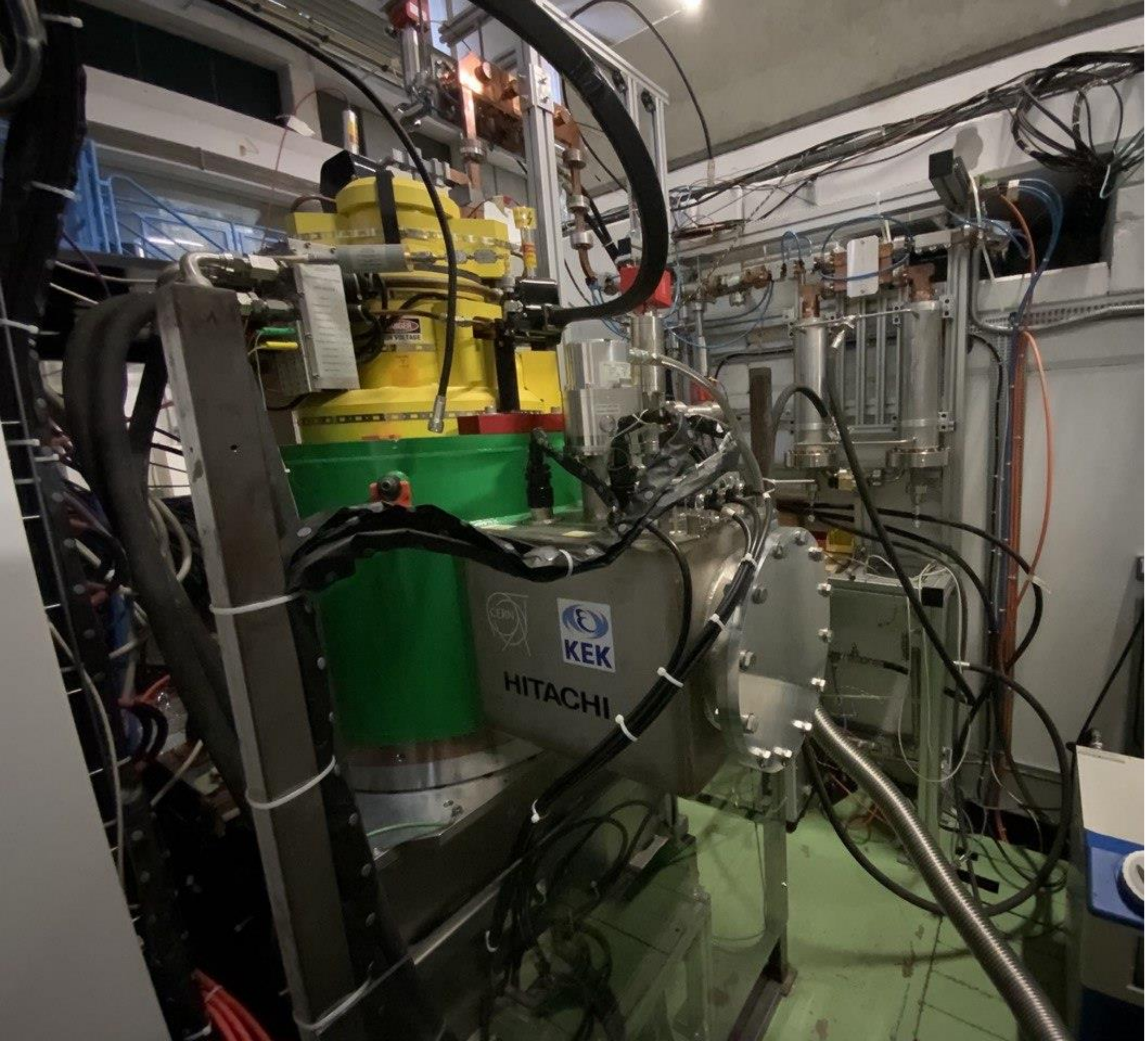

- Available instrumentation:
  - Temperature sensors. Thermo-couples and PtCo sensors
  - Voltage taps
  - Heaters (not used at CERN)



# MAGNETIC MEASUREMENTS

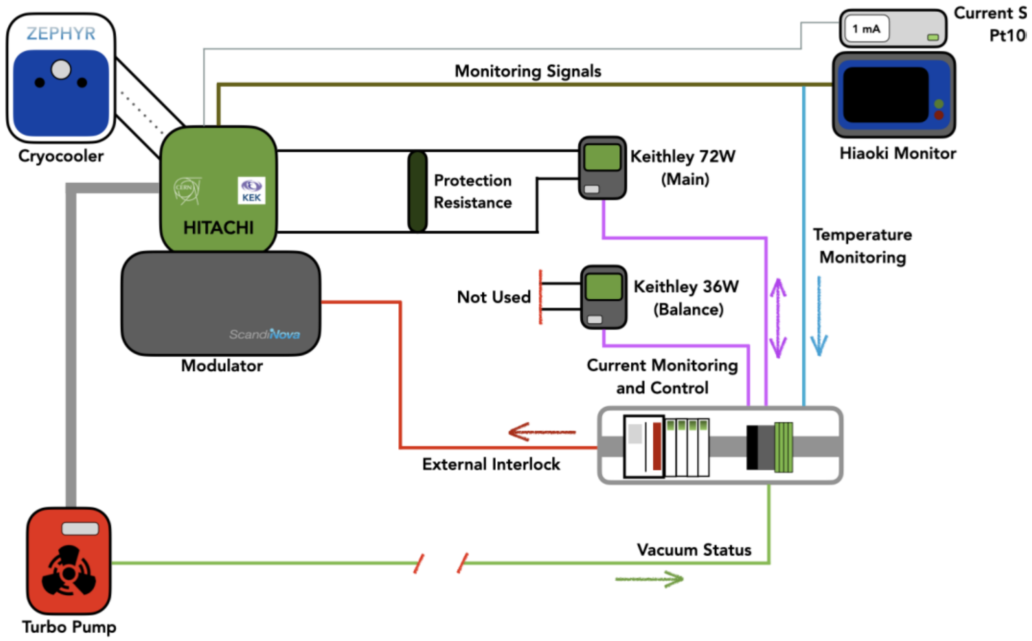
- Measurements done with a hall probe
- Homogeneity and reproducibility are very good!
- Small difference between magnets at the level of fringe fields
- Close to the cathode where beam rigidity is smaller. Probably important for performance

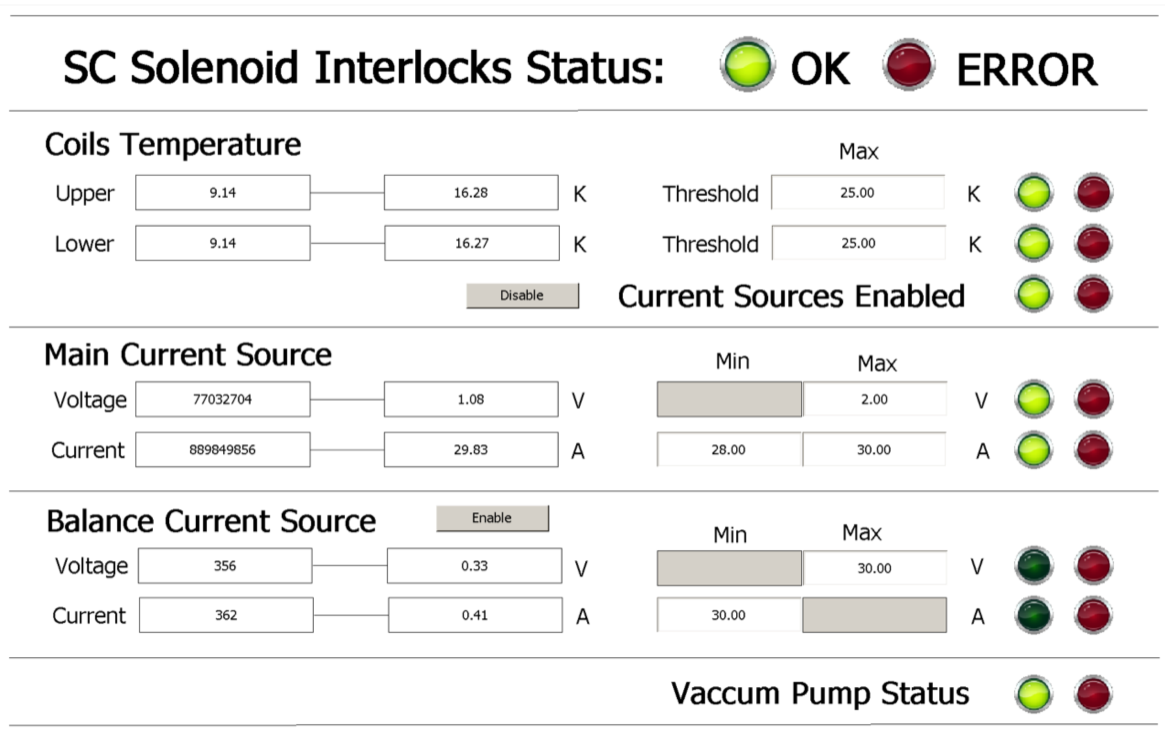





# INSTALLATION IN THE KLYSTRON

- Full compatibility with klystron and modulator interfaces
- Larger volume required on the side of modulator
- Special care needed  with handling as the load is asymmetric
- Vacuum pump permanently connected (insulation vacuum)



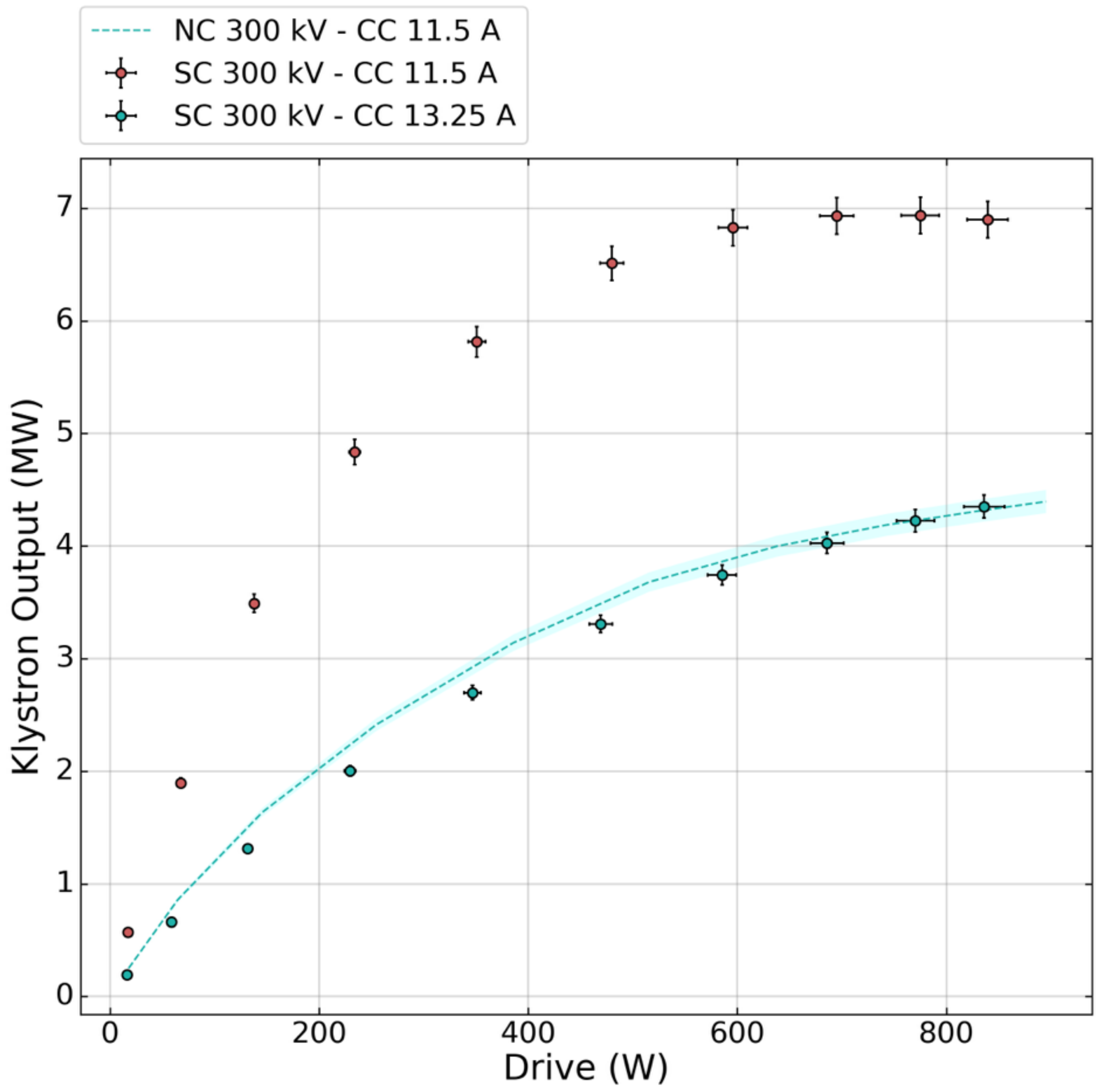




# INTERLOCKS AND SAFETY

- From two to three feeds (**current**, **cooling**, vacuum)
- Interlocks on vacuum and temperature to protect the solenoid
- Interlock on solenoid current to protect the klystron

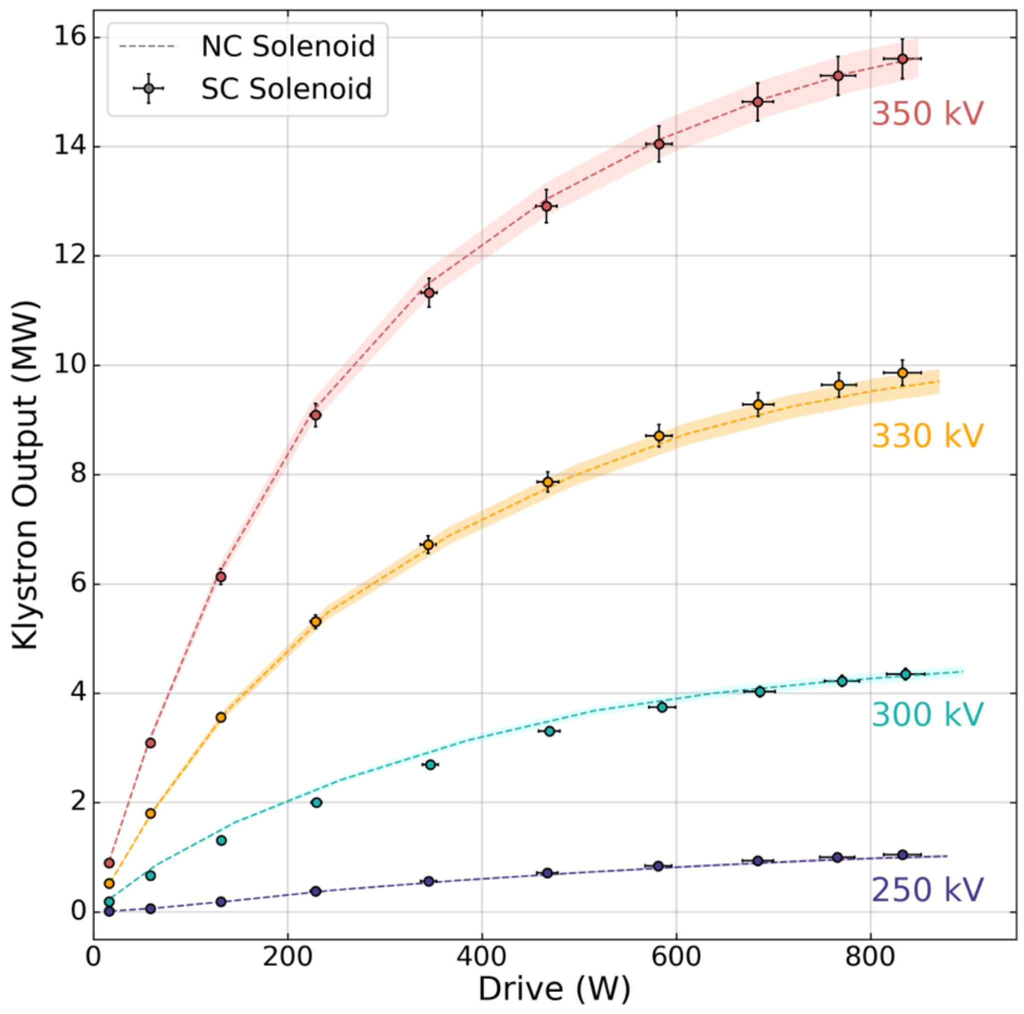
# FIRST MEASUREMENTS

- Measurements could not be done at nominal conditions as load not conditioned to full power
  - Max power ~20 MW
  - Originally optimized at CPI for nominal power @ 50 MW
- Current adjusted for central field.
- Nominal counter-coil settings for NC solenoid
- SC gain curve shows higher gain and faster saturation
- Counter-coil current adjusted for smaller beam to match original gain



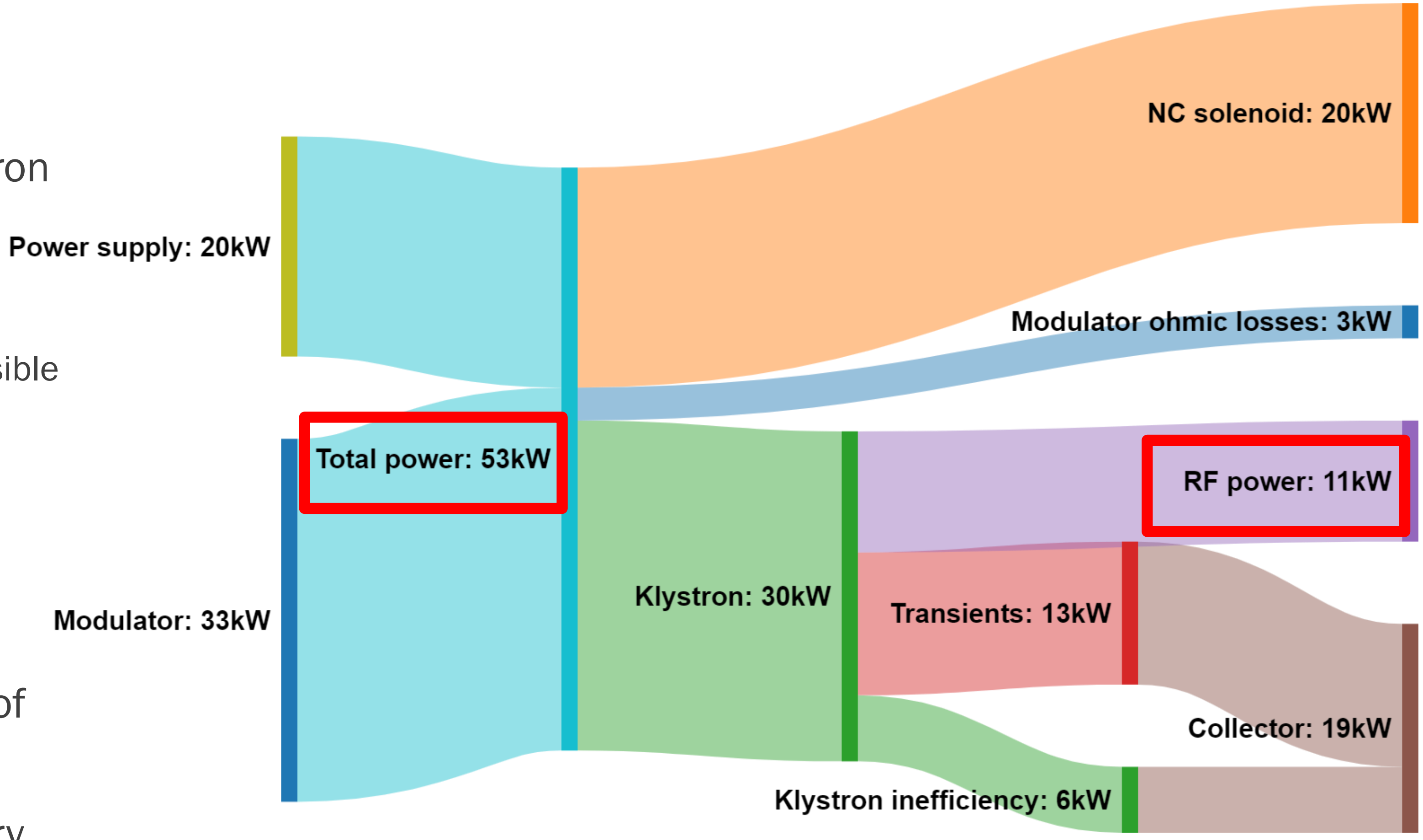
# RE-TUNING OF THE COUNTER- COIL

- Counter-coil re-tuned by an additional 20% in current to recover performance
- Same correction is valid for every klystron gain
- Counter-coil current settings are valid for all set-points



# CONCLUSIONS

- SC technology can be applied to klystron solenoid
- Energy consumption reduced by 90%
  - 20 -> <3 kW. Further reductions still possible
- Magnetic field very similar to the conventional magnet
- No interception
- Some adjustments needed to recover performance inside the tuning range of the power supply
- Large operational margin makes it very stable and robust against failures




AC power/RF efficiency = 21%

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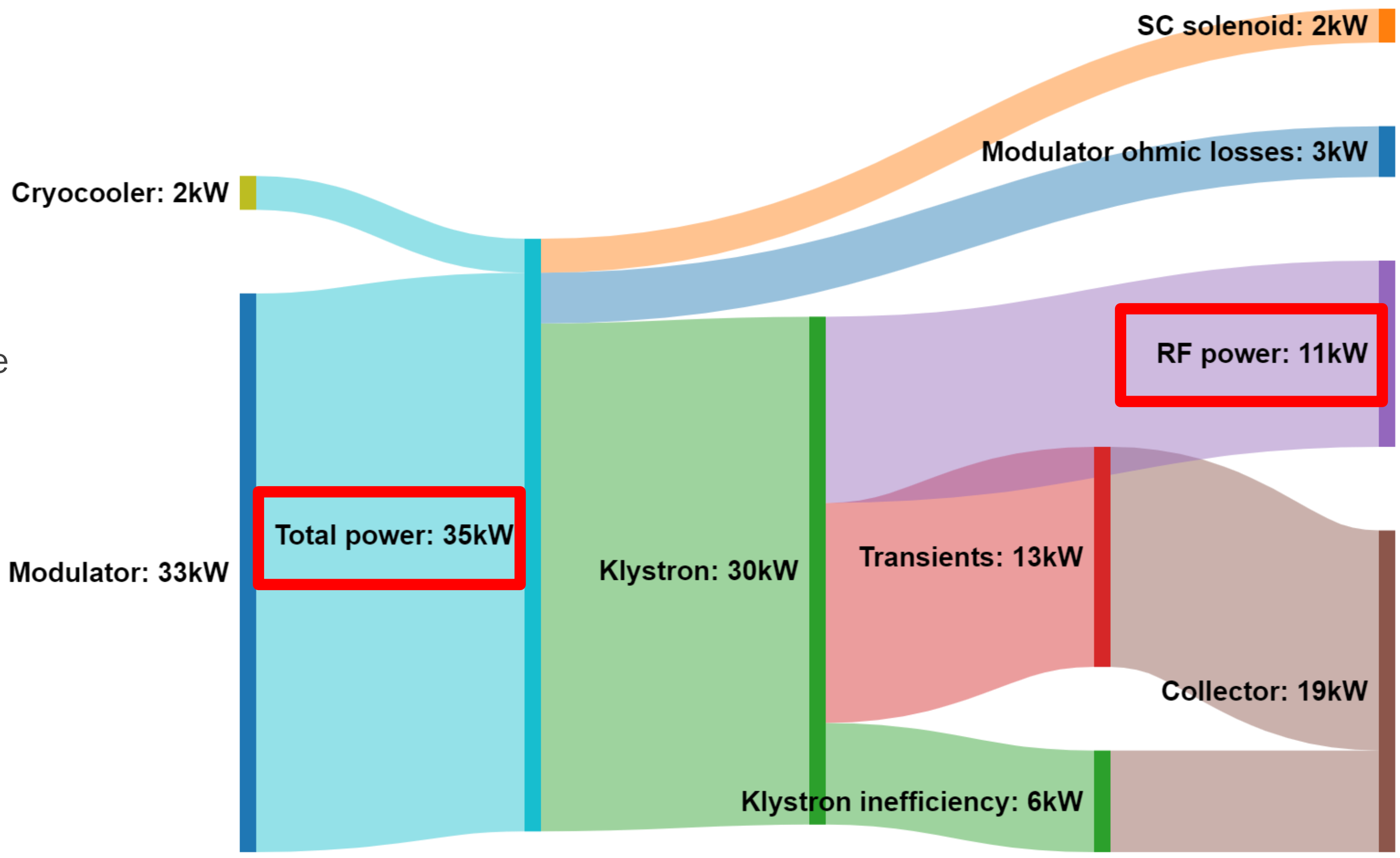
<u>With a high efficiency klystron , modulator AND a SC solenoid we will save >50% of the power for the same output RF power!</u>




AC power/RF efficiency = 31.7%

# THANKS