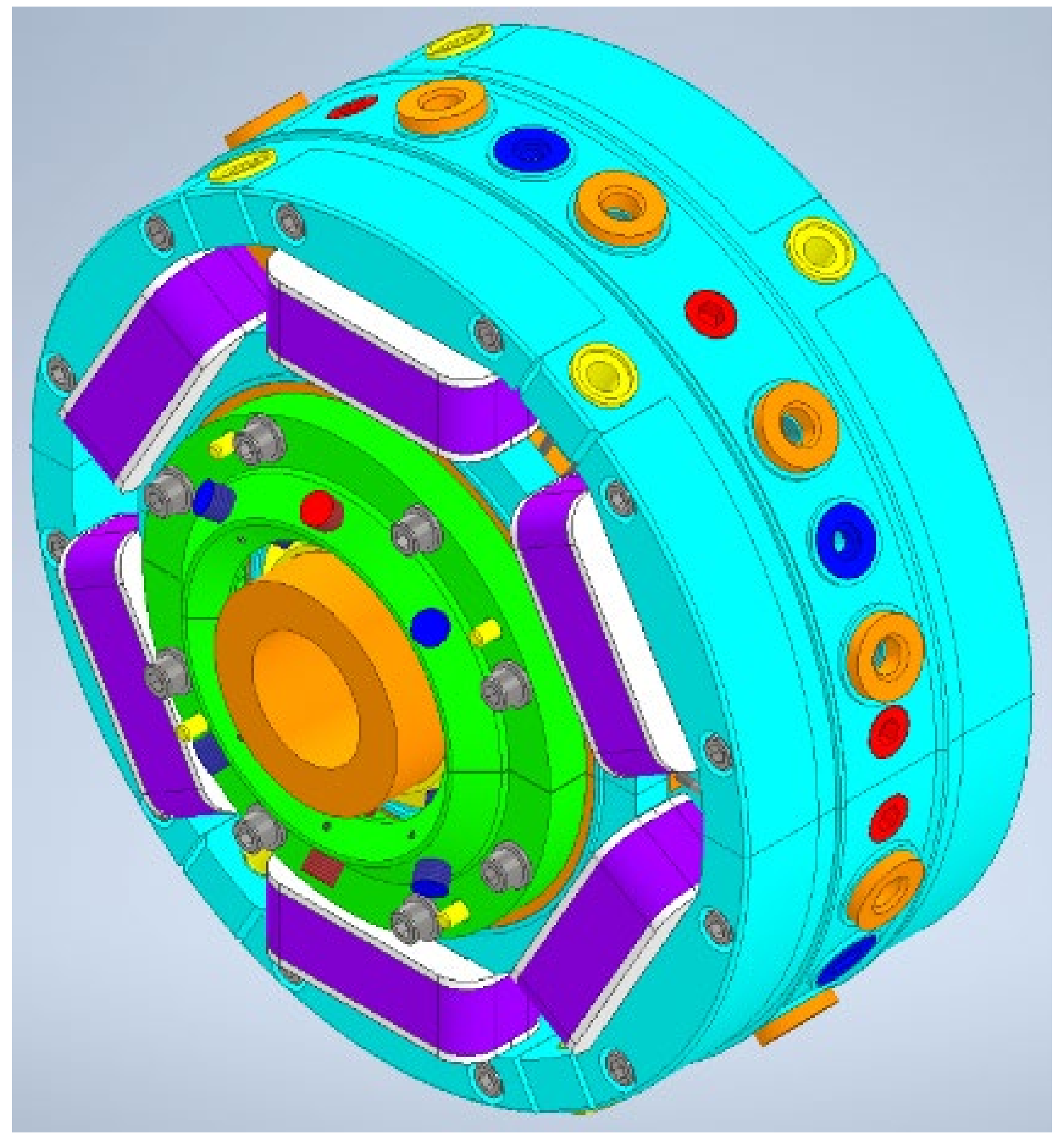
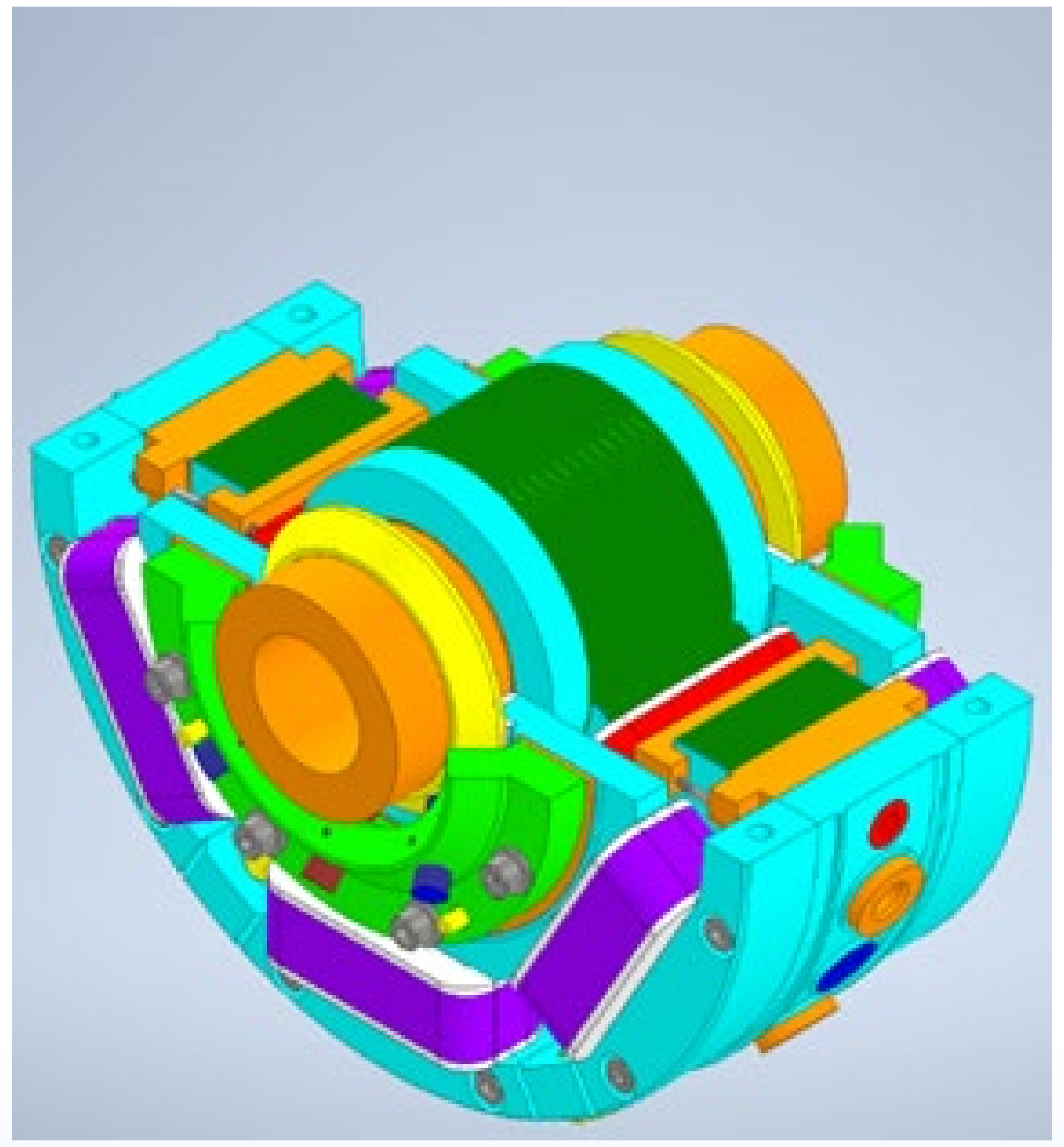
Design of a Permanent Magnet Biased Homopolar Magnetic Bearing for sCO$_2$ Turbine Applications

The 8th International Supercritical CO$_2$
Power Cycles Symposium
February 27-29, 2024, San Antonio, TX
Paper #107

Robert Lipham[1,*], Heeju Choi[2], Marshall Bielefeld[3,*], Dongil Shin[4,*], Erwin Thomas[5], Alan Palazzolo[5], Randall Tucker[6,*]

1: Southwest Research Institute, San Antonio, TX
2: Electron Energy Corporation, Lancaster, PA
3: Axon Enterprise, Scottsdale, AZ
4: GE Vernova, Niskayuna, NY
5: Texas A&M University, College Station, TX
6: OTBOG Energy, Somerville, TX
*: Work performed while at Texas A&M

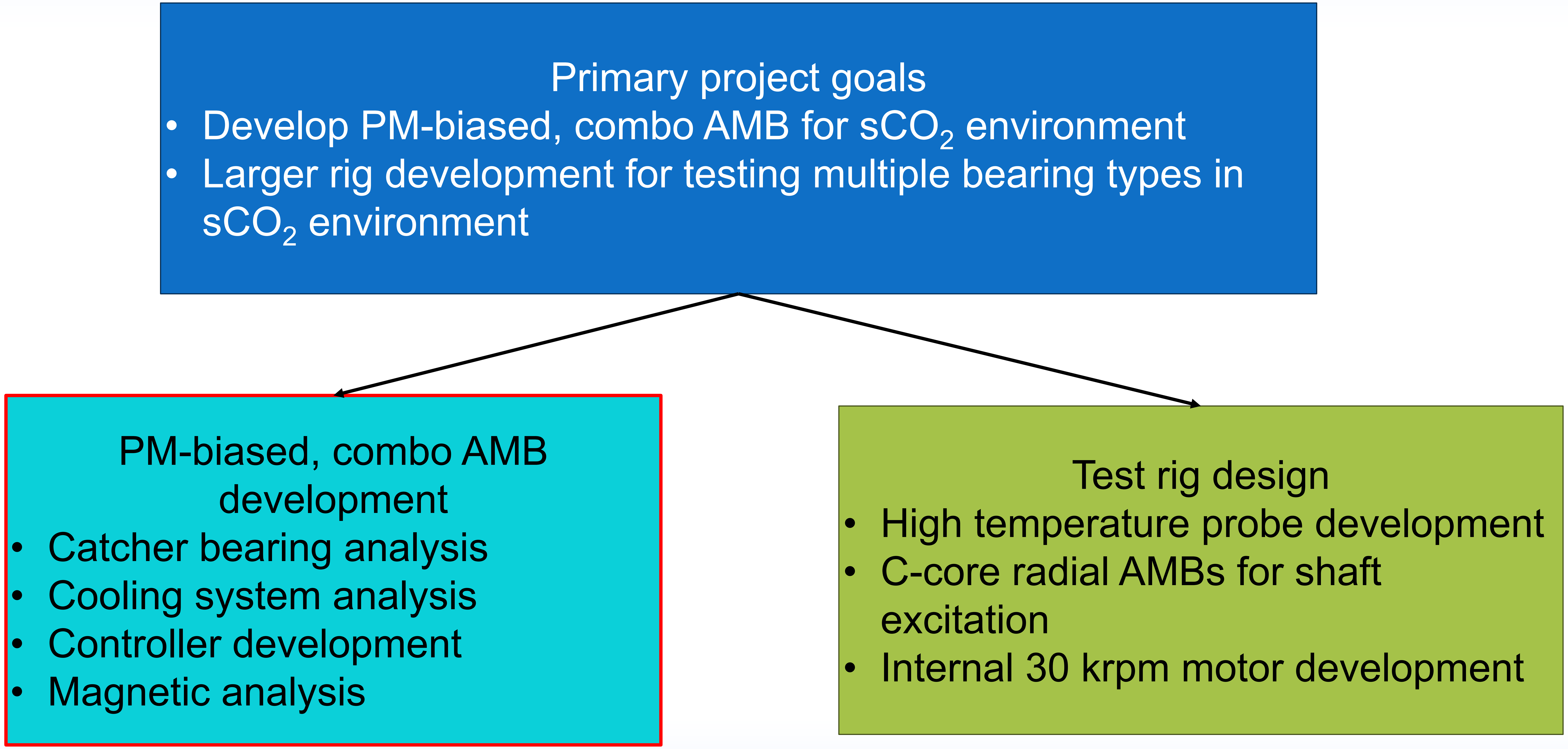




Acknowledgement

This work is based upon work supported by the U.S. Department of Energy, Office of Nuclear Energy, under Award Number SC0018813. This financial assistance from Department of Energy is gratefully acknowledged.

This presentation will focus on AMB design development



Primary project goals

- Develop PM-biased, combo AMB for sCO_2 environment
- Larger rig development for testing multiple bearing types in sCO_2 environment

PM-biased, combo AMB development

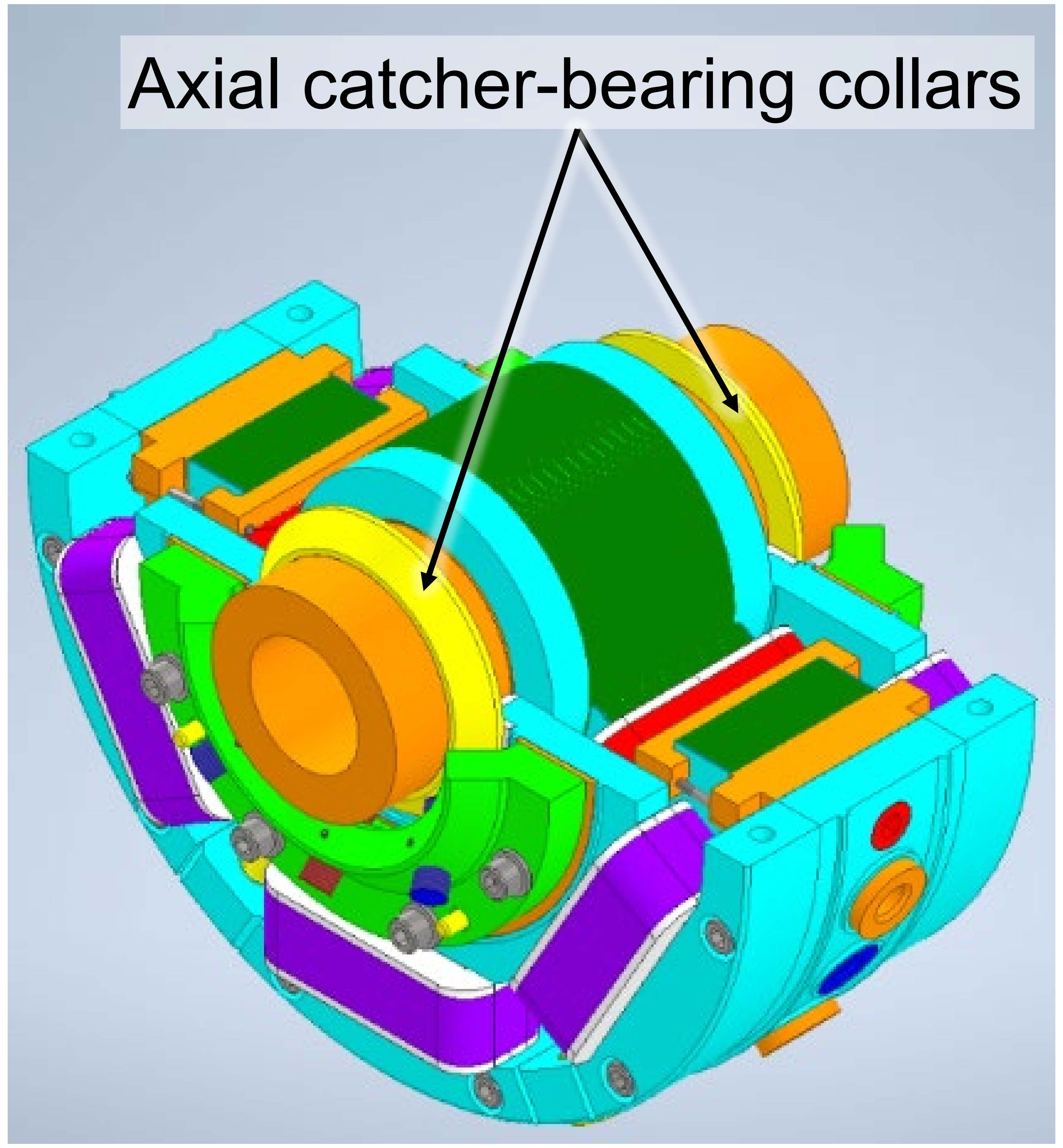
- Catcher bearing analysis
- Cooling system analysis
- Controller development
- Magnetic analysis

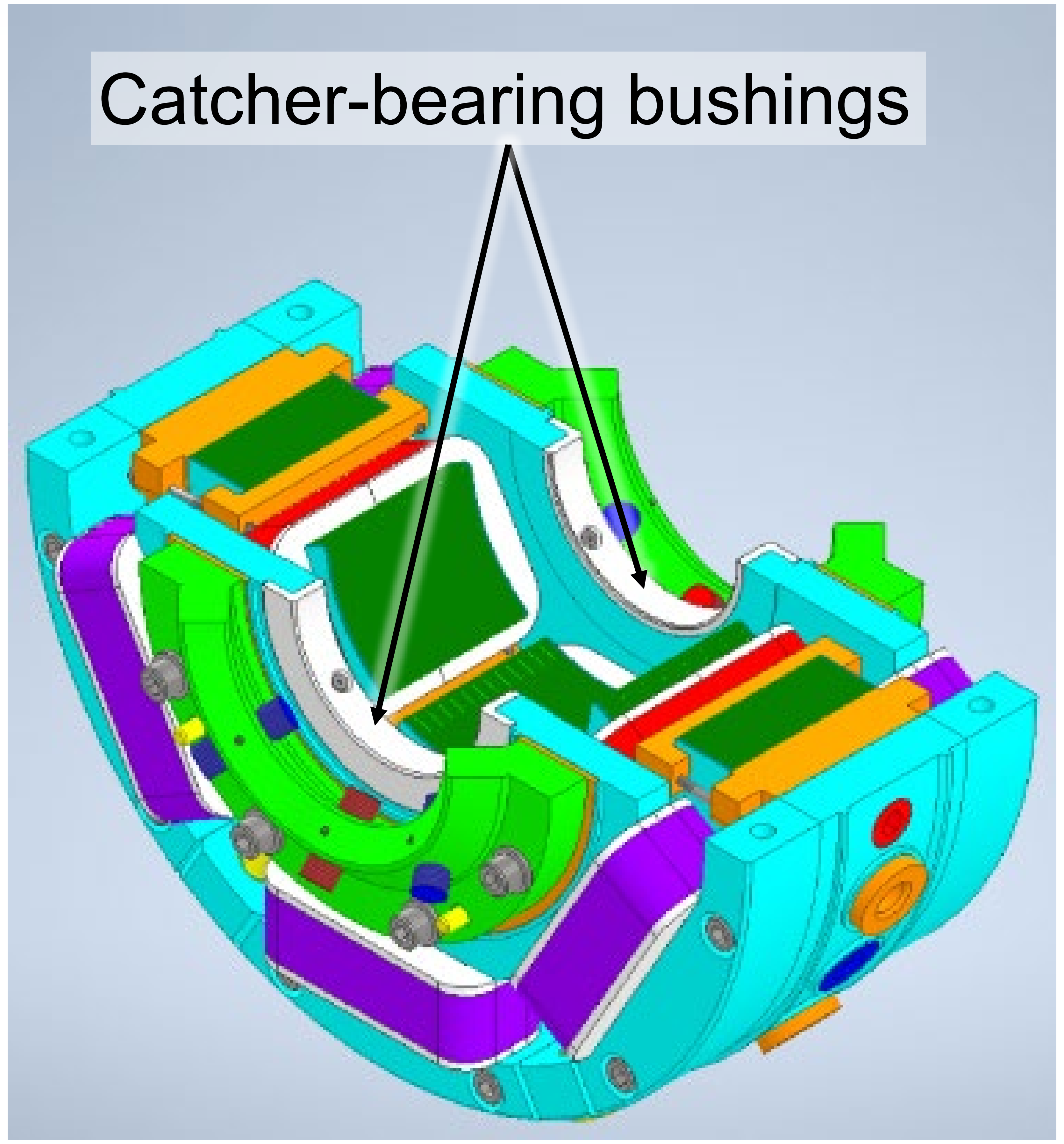
Test rig design

- High temperature probe development
- C-core radial AMBs for shaft excitation
- Internal 30 krpm motor development

Combo AMB design features

Catcher-bearings are included to protect the system during power loss

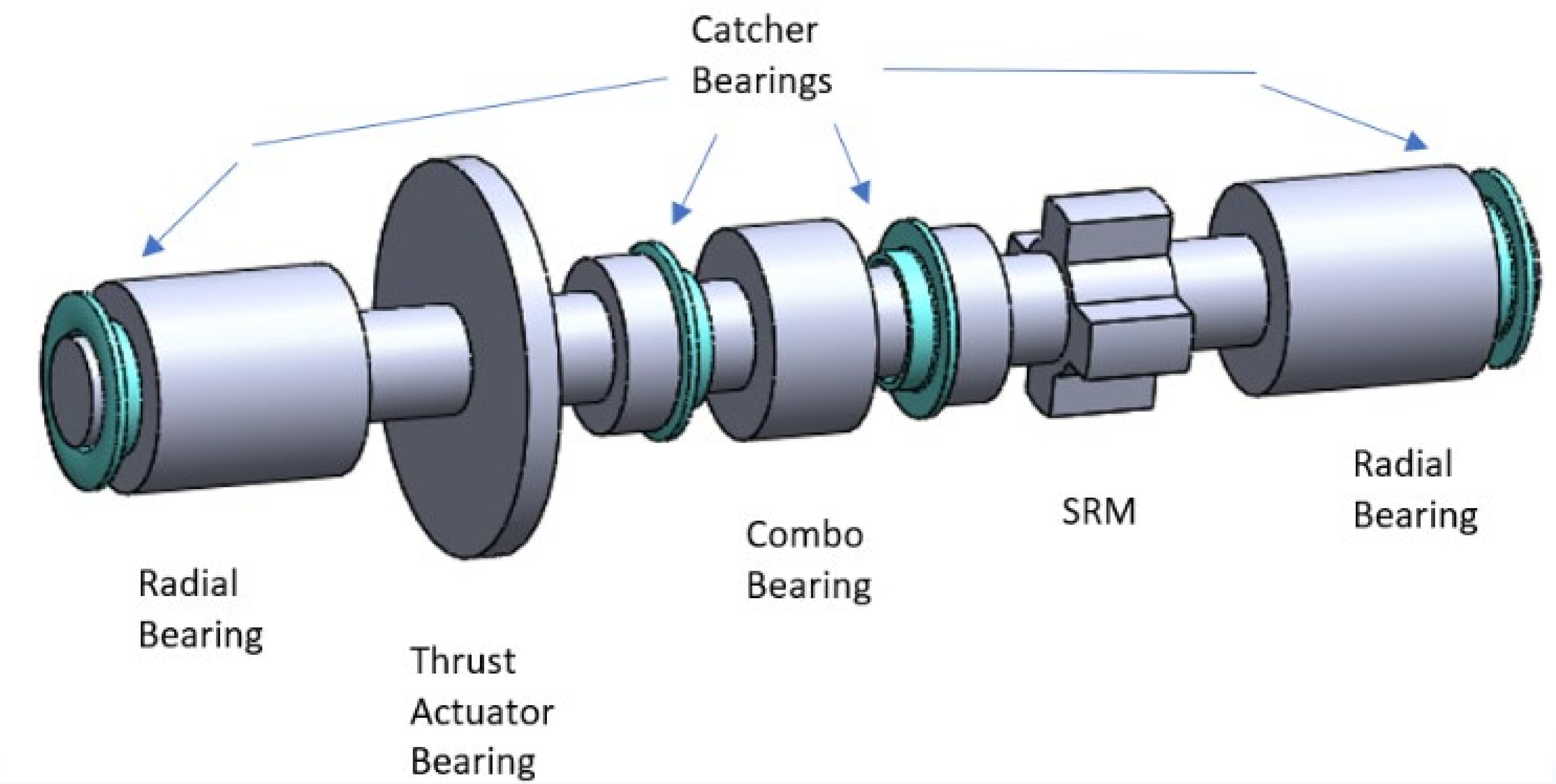


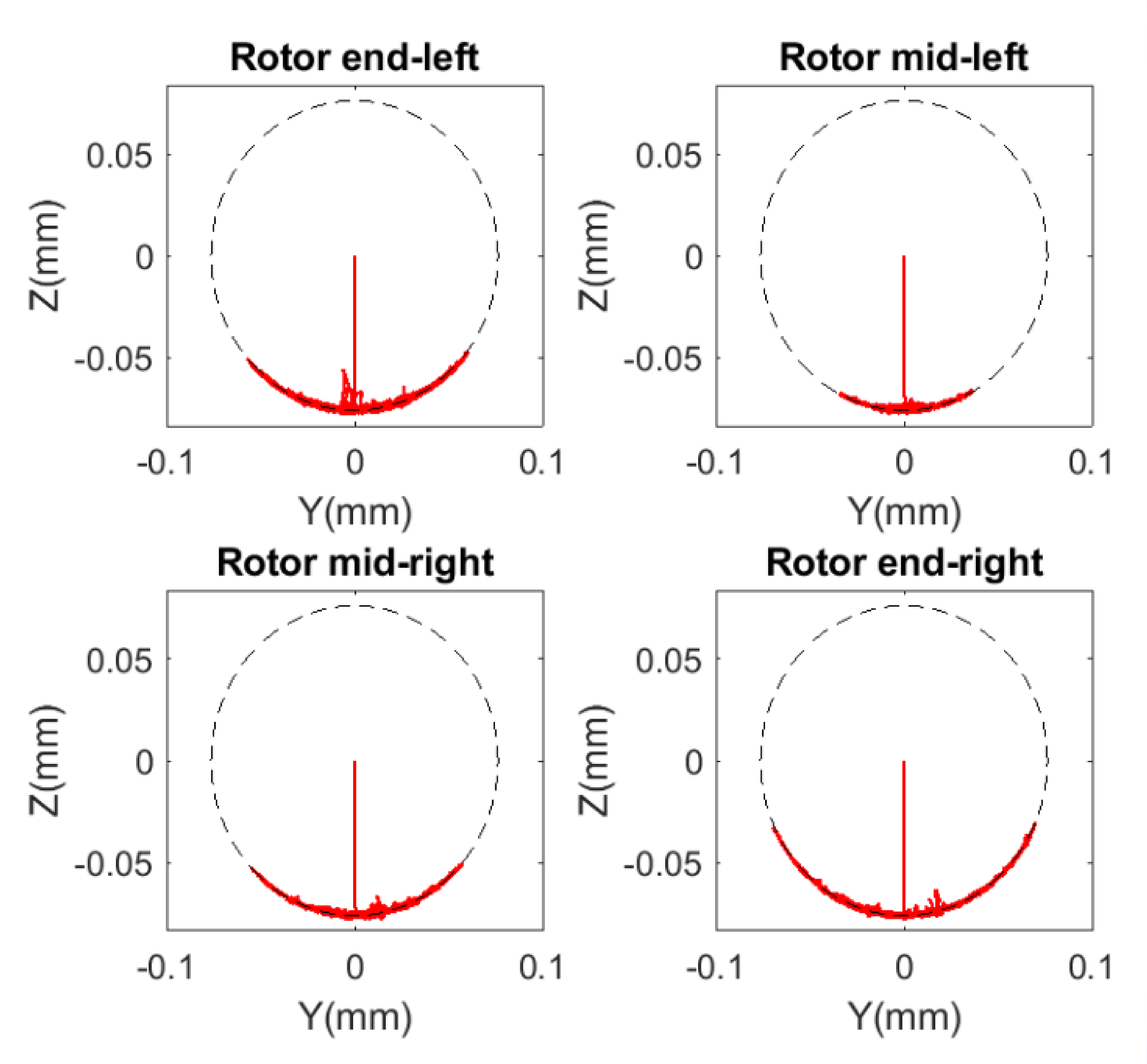


Graphalloy® selected for catcher bearing surface coating

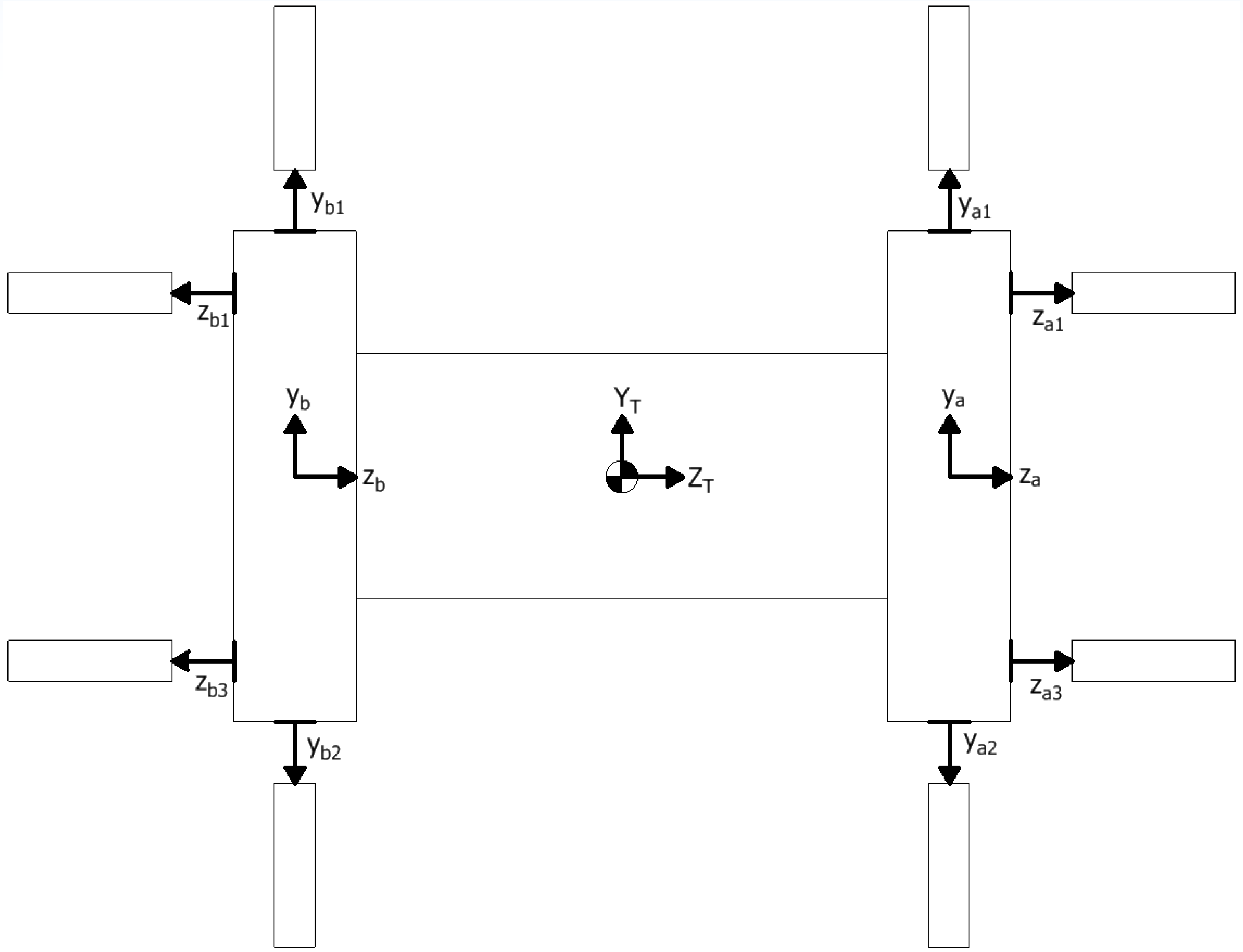
- Carbon-based surface coating
- Can withstand up to 800 °C

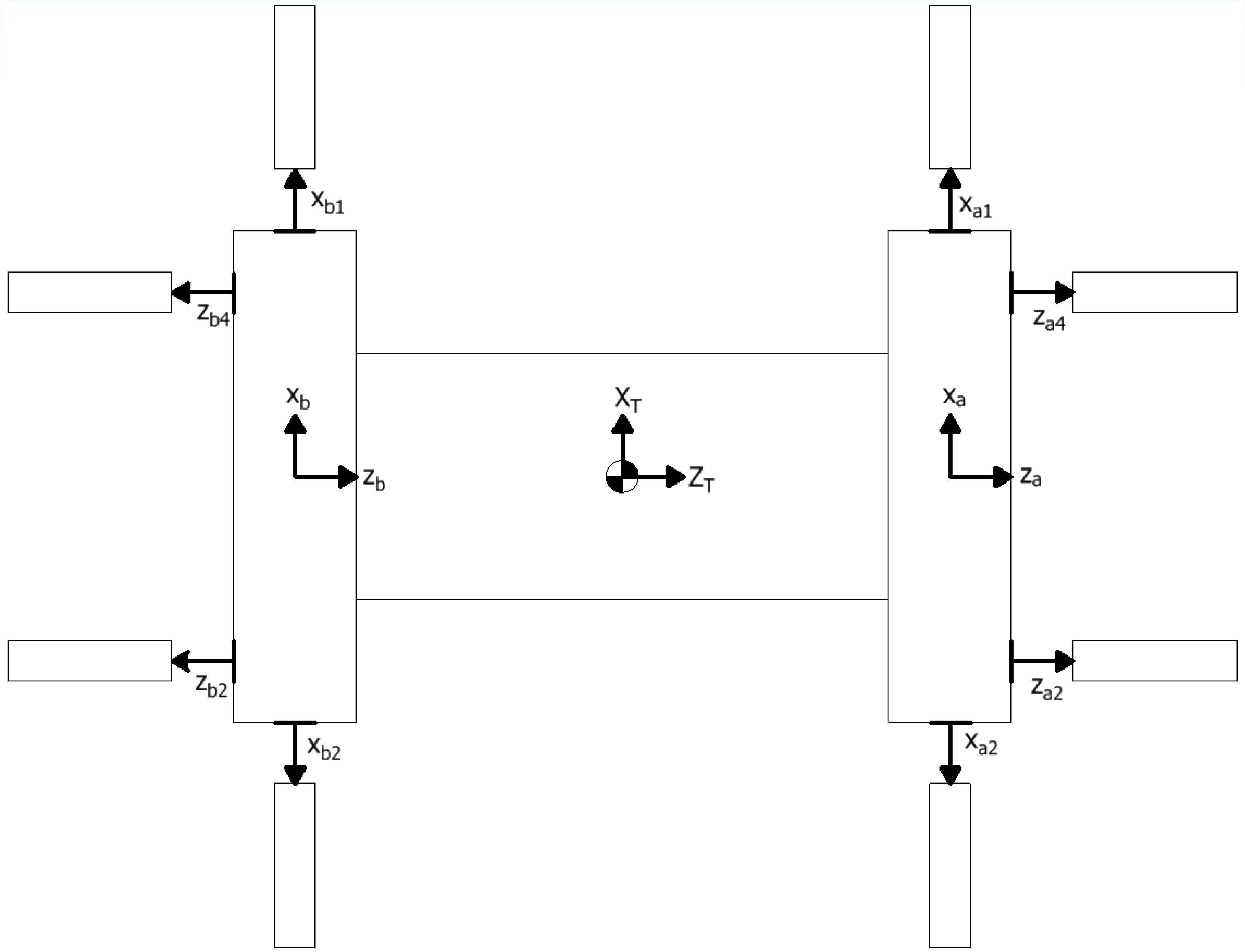
Drop simulations show safe catcher-bearing operation





The standard combo AMB probe arrangement requires high probe count and adds axial length

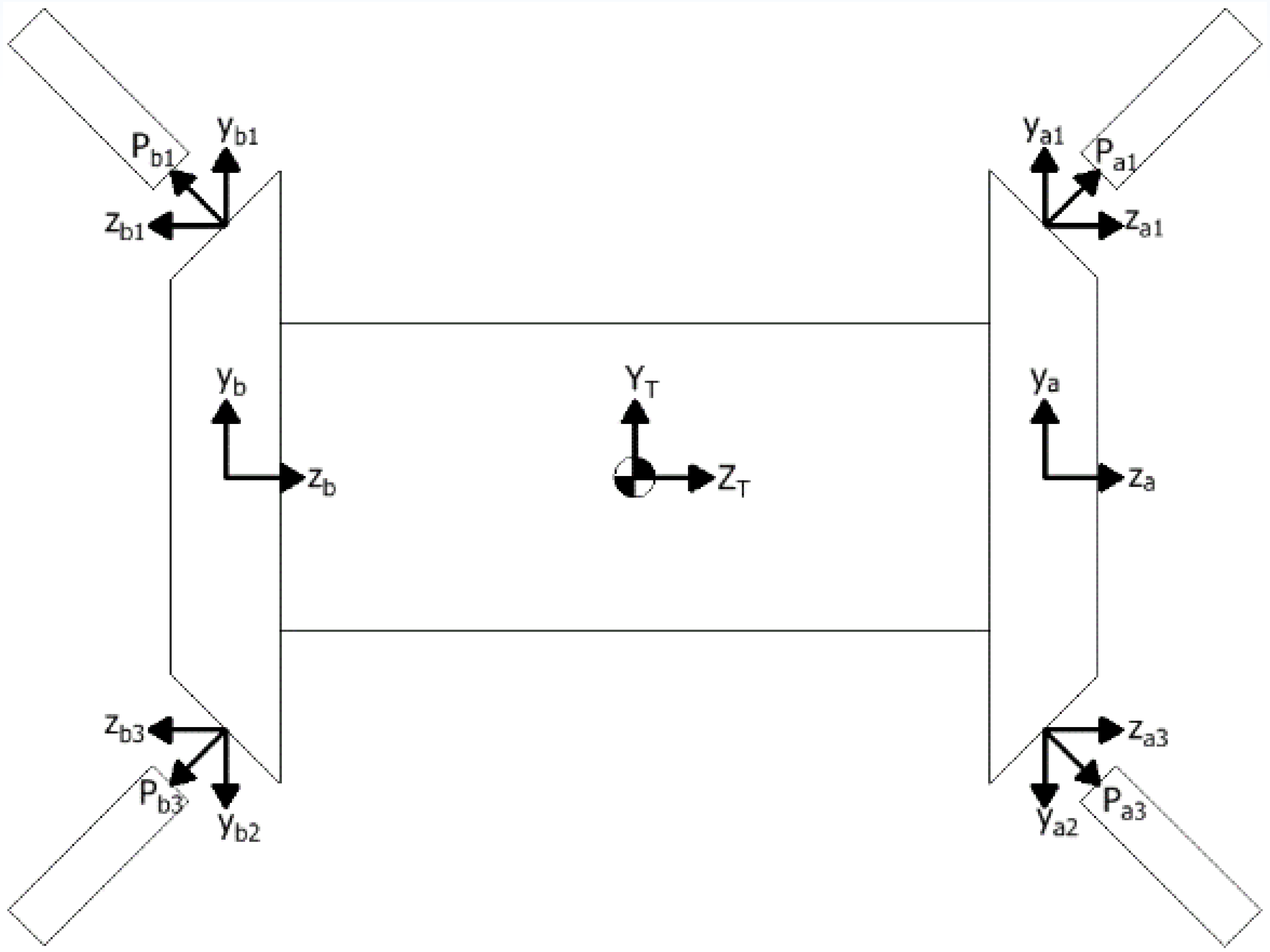


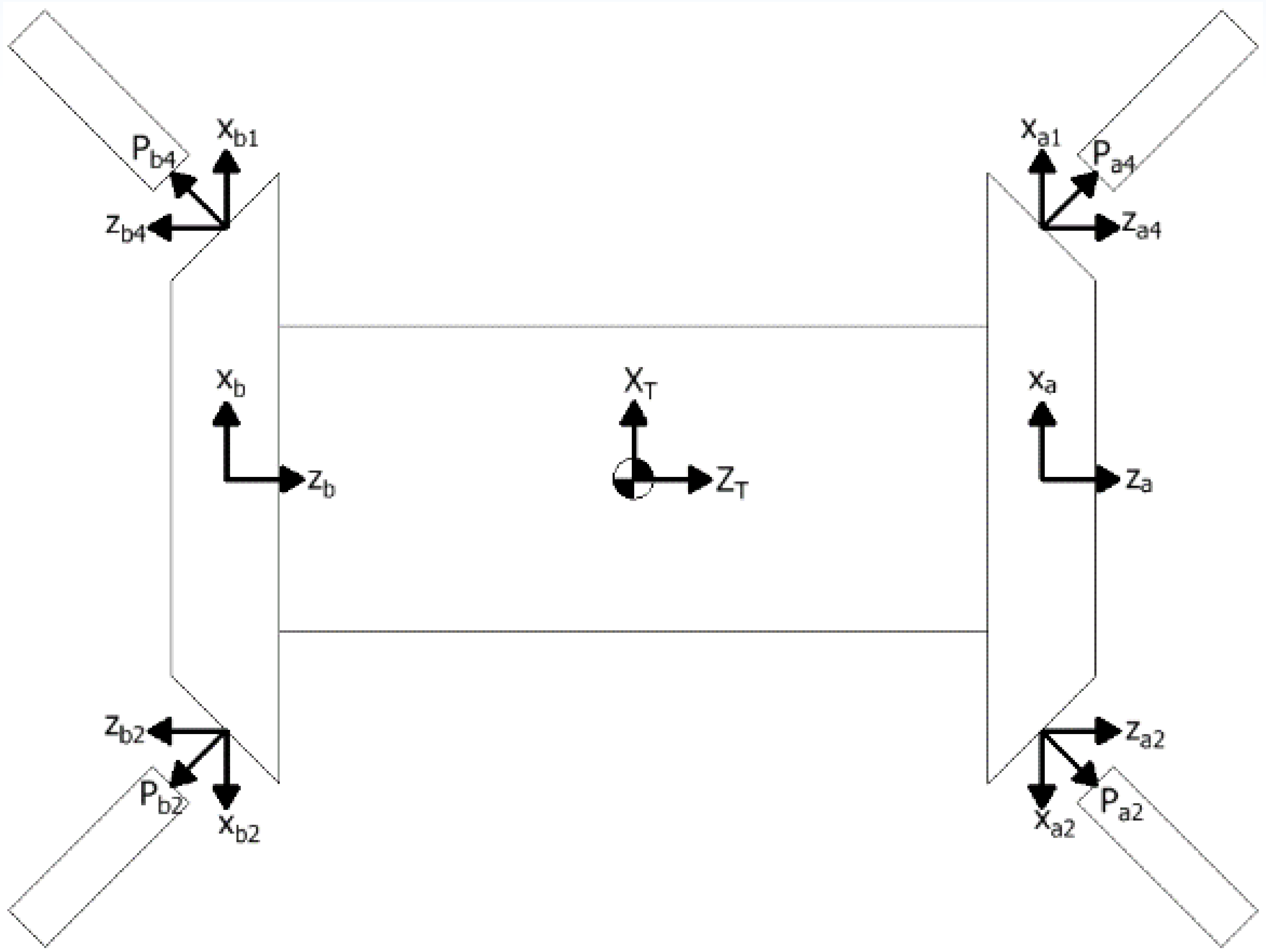


$$X_T = \frac{1}{4}\left(G_{xa1}\left(V_{xa10} - V_{xa1}\right) - G_{xa2}\left(V_{xa20} - V_{xa2}\right) + G_{xb1}\left(V_{xb10} - V_{xb1}\right) - G_{xb2}\left(V_{xb20} - V_{xb2}\right)\right)$$

$$Z_T = \frac{1}{8}\sum_{n=1}^{4}\left(G_{zan}\left(V_{zan0} - V_{zan}\right) - G_{zbn}\left(V_{zbn0} - V_{zbn}\right)\right)$$

A coupled combo AMB probe arrangement can reduce both probe count and axial length

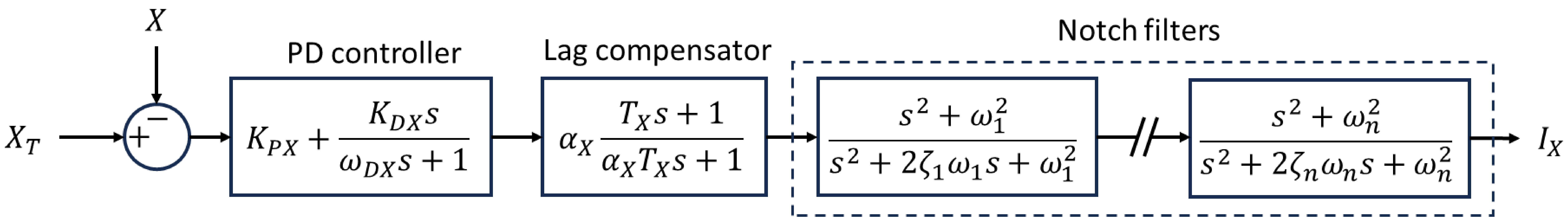




$$X_T = \frac{\sqrt{2}}{2} \cdot \frac{1}{4} \left(G_{a4}(V_{a40} - V_{a4}) - G_{a2}(V_{a20} - V_{a2}) + G_{b4}(V_{b40} - V_{b4}) - G_{b2}(V_{b20} - V_{b2}) \right)$$

$$Z_T = \frac{\sqrt{2}}{2} \cdot \frac{1}{8} \sum_{n=1}^{4} \left(G_{an}(V_{an0} - V_{an}) - G_{bn}(V_{bn0} - V_{bn}) \right)$$

SISO feedback controller selected for combo AMB



X

X_T + −

PD controller

$$K_{PX} + \frac{K_{DX} s}{\omega_{DX} s + 1}$$

Lag compensator

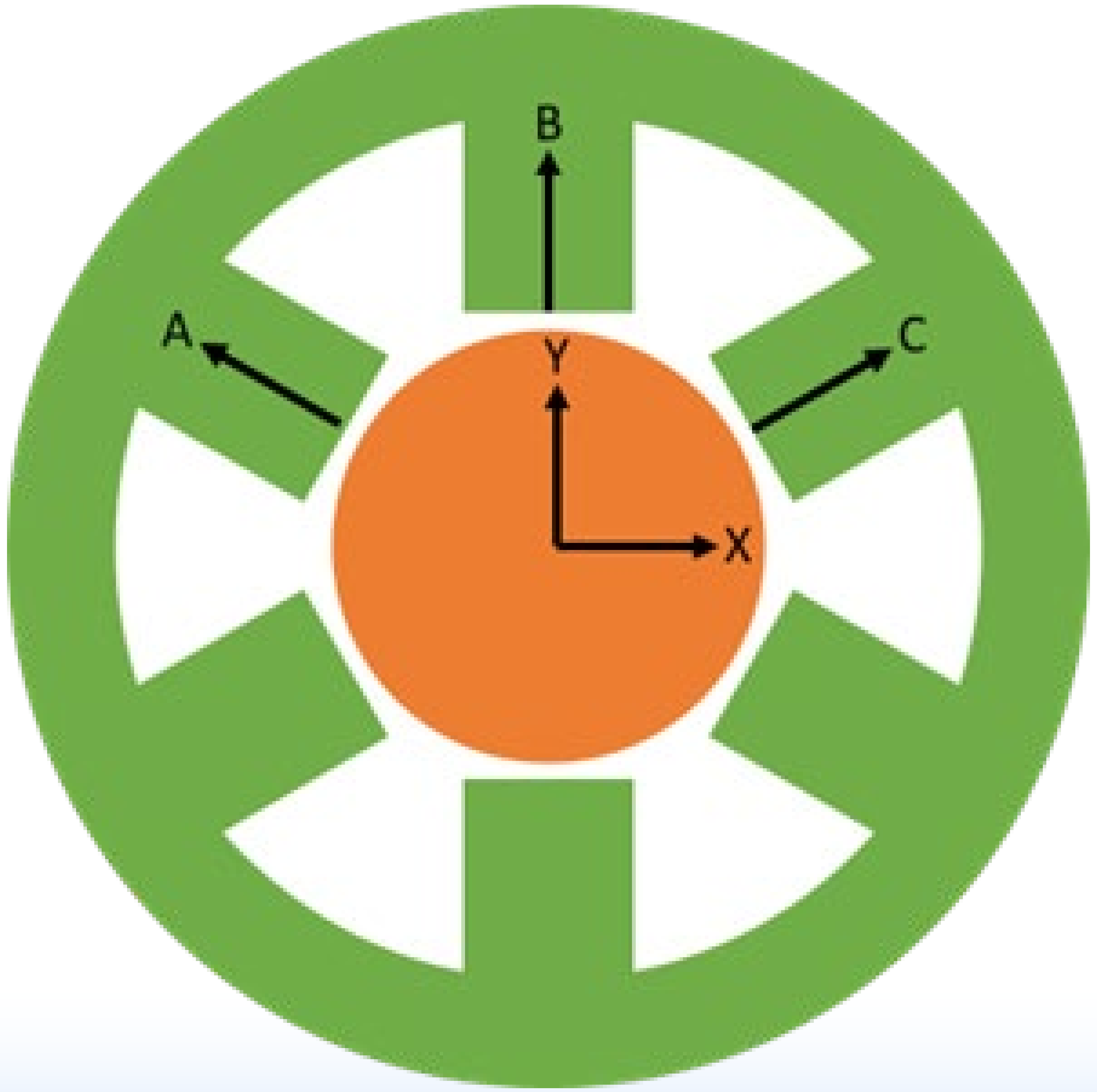
$$\alpha_X \frac{T_X s + 1}{\alpha_X T_X s + 1}$$

Notch filters

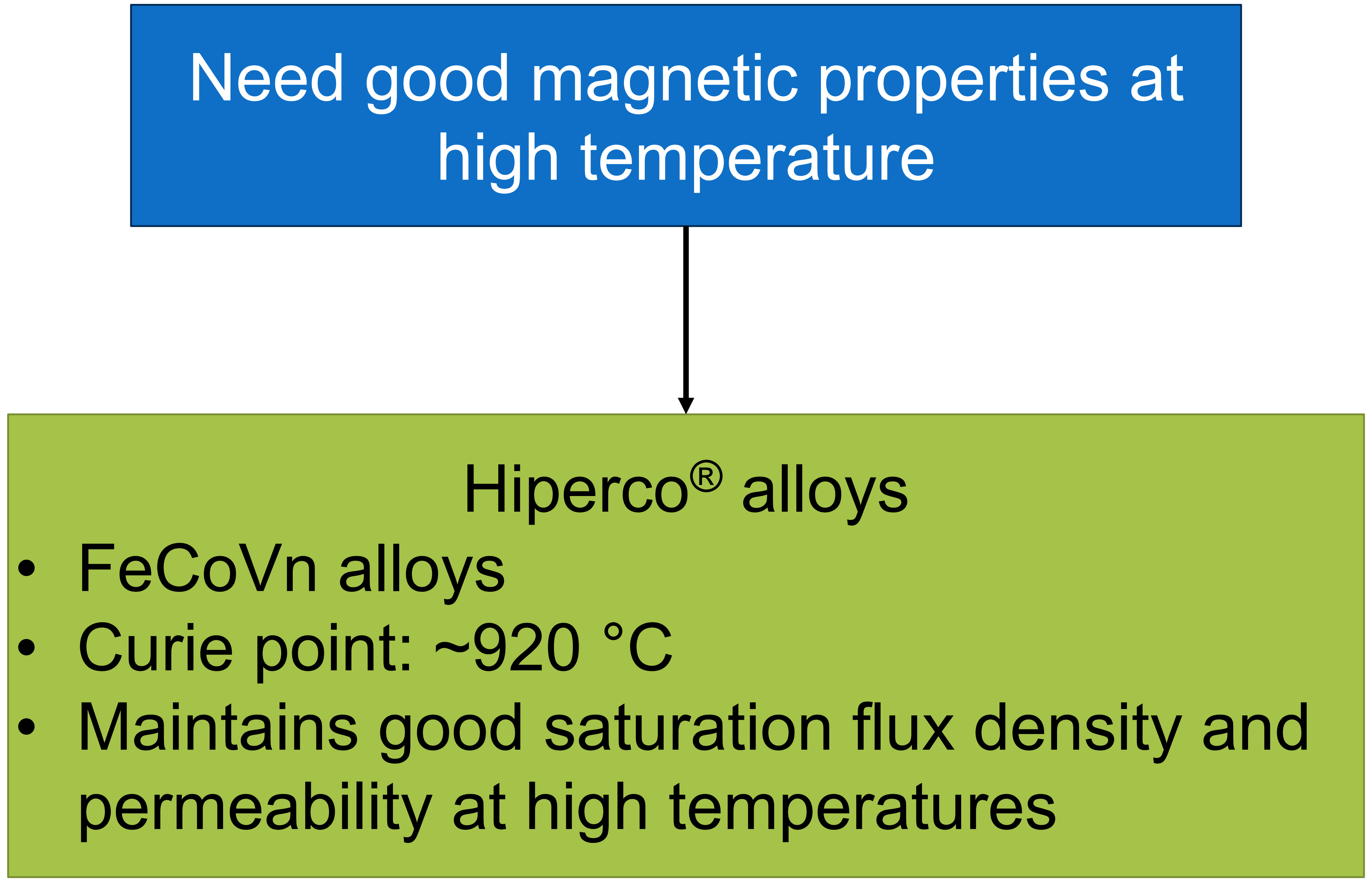
$$\frac{s^2 + \omega_1^2}{s^2 + 2\zeta_1 \omega_1 s + \omega_1^2} \quad // \quad \frac{s^2 + \omega_n^2}{s^2 + 2\zeta_n \omega_n s + \omega_n^2}$$

I_X

$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \frac{1}{2} \begin{bmatrix} -\sqrt{3} & 1 \\ 0 & 2 \\ \sqrt{3} & 1 \end{bmatrix} \begin{bmatrix} I_X \\ I_Y \end{bmatrix}$$



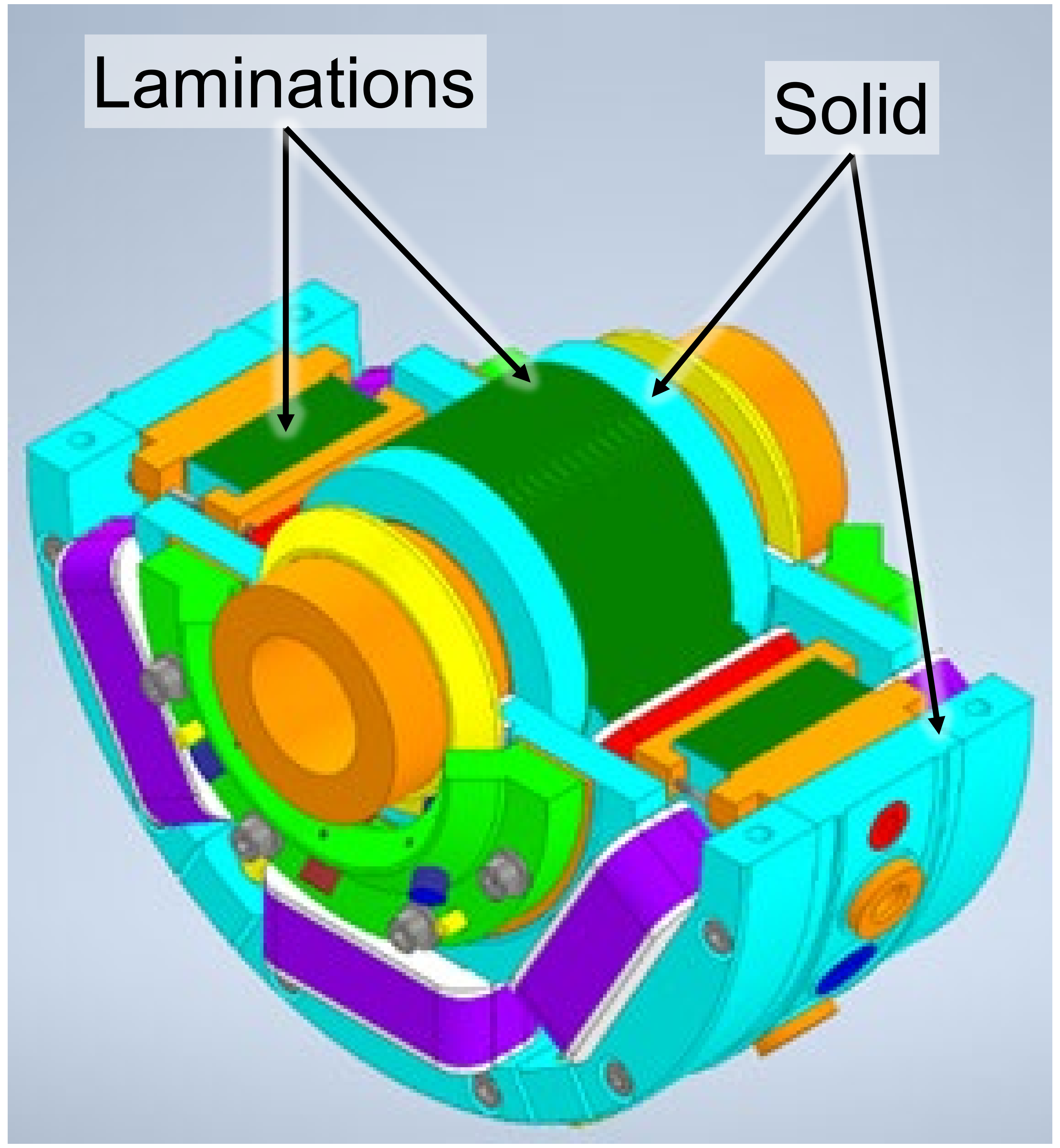
Hiperco® alloys selected for laminations and solid components



Need good magnetic properties at high temperature

Hiperco® alloys

- FeCoVn alloys
- Curie point: ~920 °C
- Maintains good saturation flux density and permeability at high temperatures



SmCo selected for PM material

Need good magnetic properties at high temperature

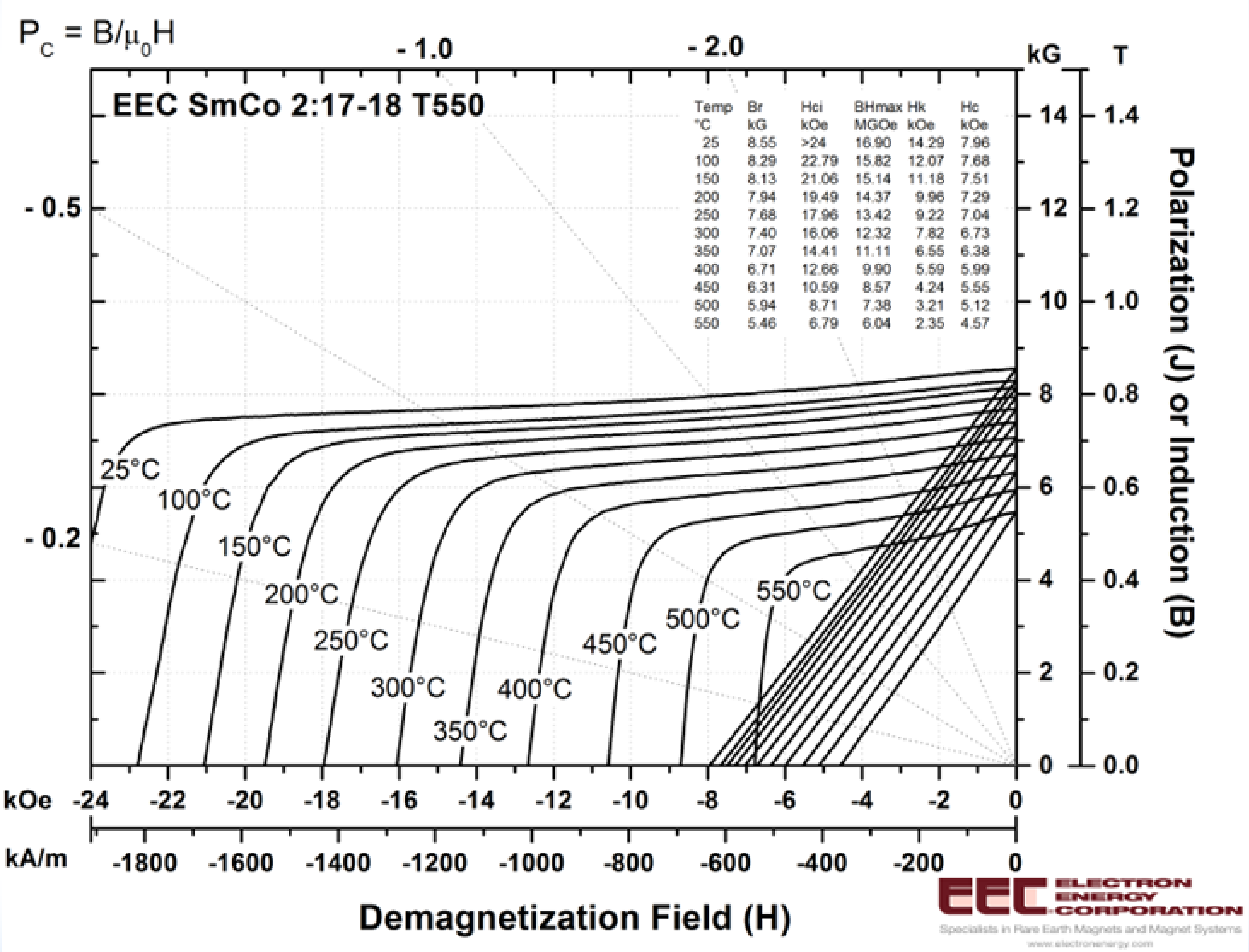
SmCo 2:17-18 T550 (EEC)

- High residual flux density
- High-temperature operation
- No demagnetization concern up to 550C
- Strong sCO2 corrosion resistance

Limitations

- Strong drop in residual flux density with temperature increase (reversable)

Need to keep PMs cool for better force density



Temp °C	Br kG	Hci kOe	BHmax MGOe	Hk kOe	Hc kOe
25	8.55	>24	16.90	14.29	7.96
100	8.29	22.79	15.82	12.07	7.68
150	8.13	21.06	15.14	11.18	7.51
200	7.94	19.49	14.37	9.96	7.29
250	7.68	17.96	13.42	9.22	7.04
300	7.40	16.06	12.32	7.82	6.73
350	7.07	14.41	11.11	6.55	6.38
400	6.71	12.66	9.90	5.59	5.99
450	6.31	10.59	8.57	4.24	5.55
500	5.94	8.71	7.38	3.21	5.12
550	5.46	6.79	6.04	2.35	4.57

High pressure N_2 and sCO_2 selected as potential cooling mediums for thermal modeling efforts

Goal: Keep PM temperatures below 200 °C for better AMB performance

Several cooling mediums examined in initial modeling

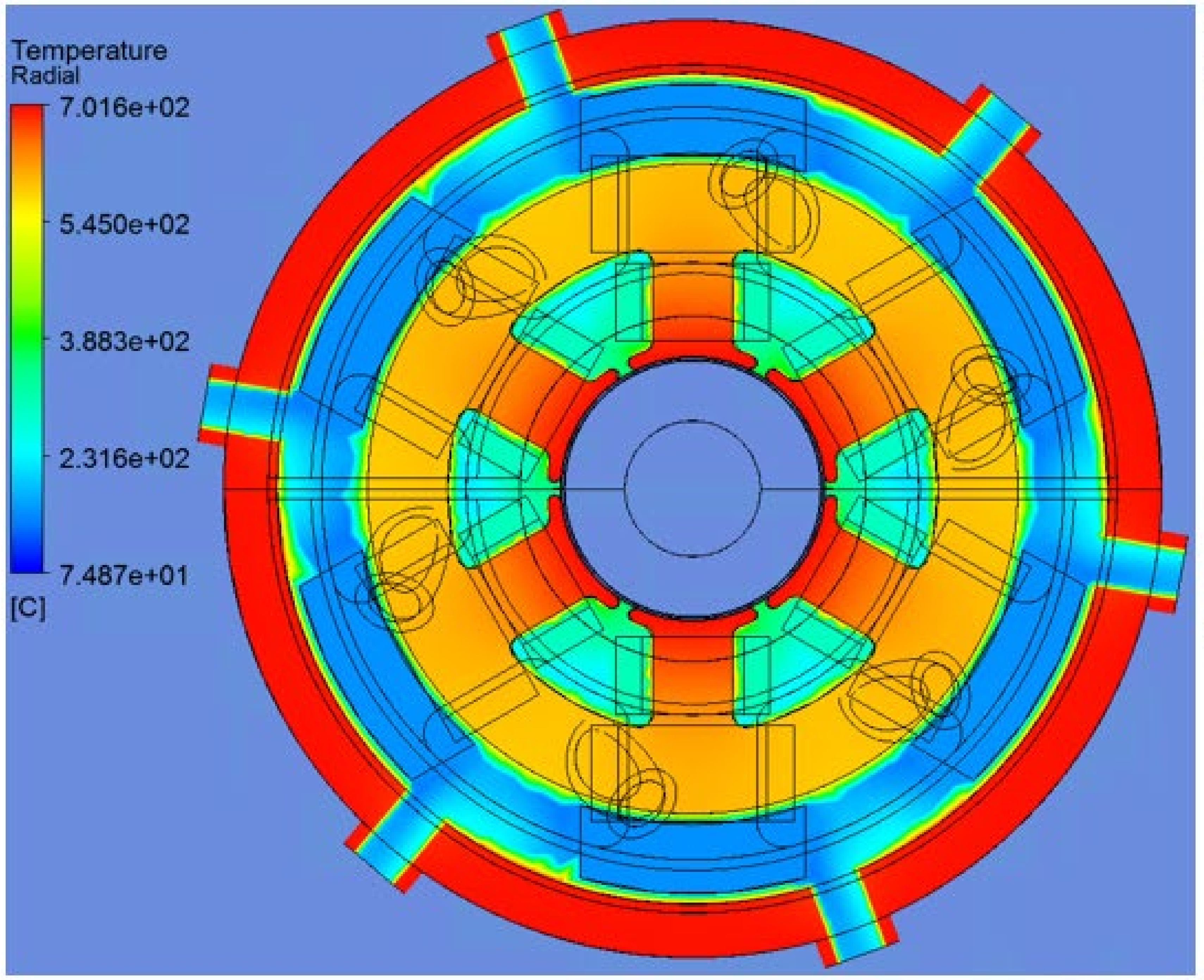
Selected for further modeling

~~Atmospheric air~~
- ~~**Excessive pressure differential**~~
- ~~**Flow rate requirement too high**~~
- ~~**PM temperature target could not be reached**~~

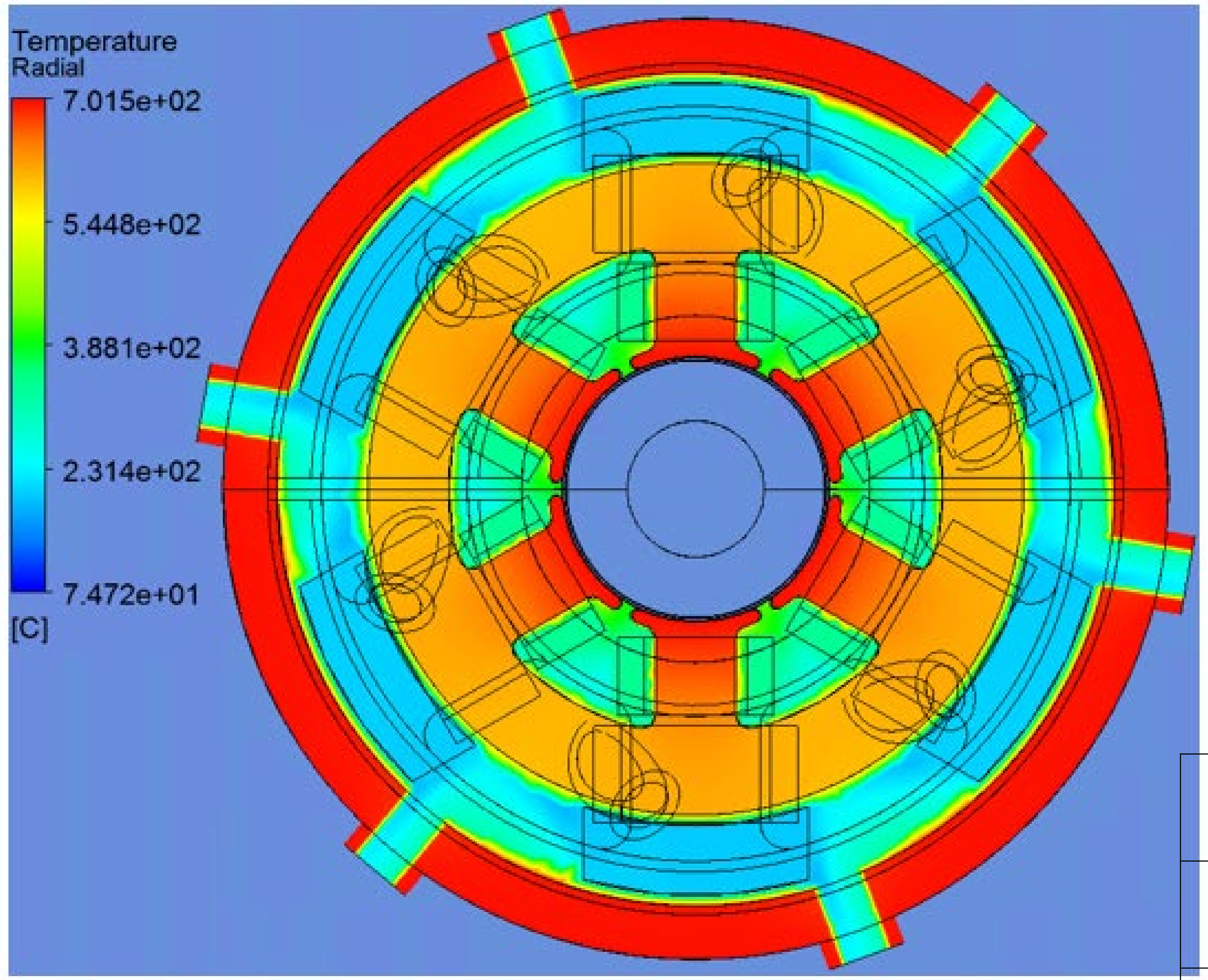
High-pressure N_2
+ Minimal pressure differential
+ Good thermal properties at high pressure
– sCO_2 contamination with leaking N_2

High pressure sCO_2
+ Minimal pressure differential
+ Good thermal properties at high pressure
+ No contamination of sCO_2 in machine

sCO_2 outperforms N_2 cooling for 4000 psi & 75 °C inlet and 700 °C AMB external temperature



SCO2 @75°C



N2 @75°C

Parameter	**sCO_2**	**N_2**
Mass flow rate	0.025 lbm/s	
Inlet volumetric flow rate	**0.035 cfm**	0.103 cfm
Inlet pressure	4000 psi	
Inlet temperature	75 °C	
Avg. PM temperature	**156 °C**	200 °C
Avg. lamination temperature	626 °C	**632°C**

Further improvements to system cooling

Thin film flow around magnets

Fluid outlet at shaft-stator gap

Insulating material applied to AMB exterior

More concentrated cooling flow around magnets

Better cooling flow across laminations

Much lower thermal boundary condition at AMB exterior

Average magnet and lamination temperatures close to 100 °C

AMB performance simulations

Simulation conditions

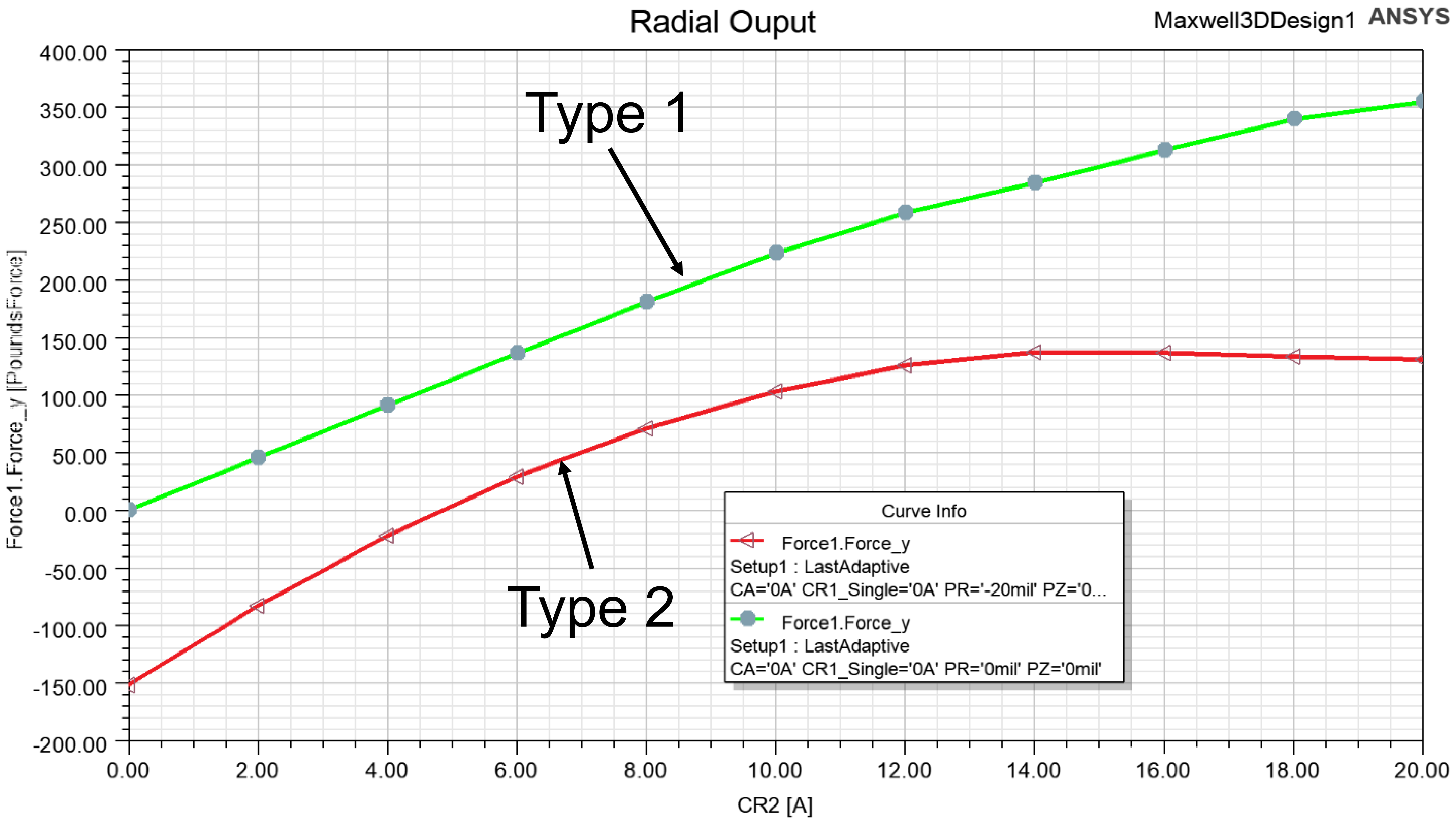
- Magnetostatic
- Material properties at 100 °C average temperature

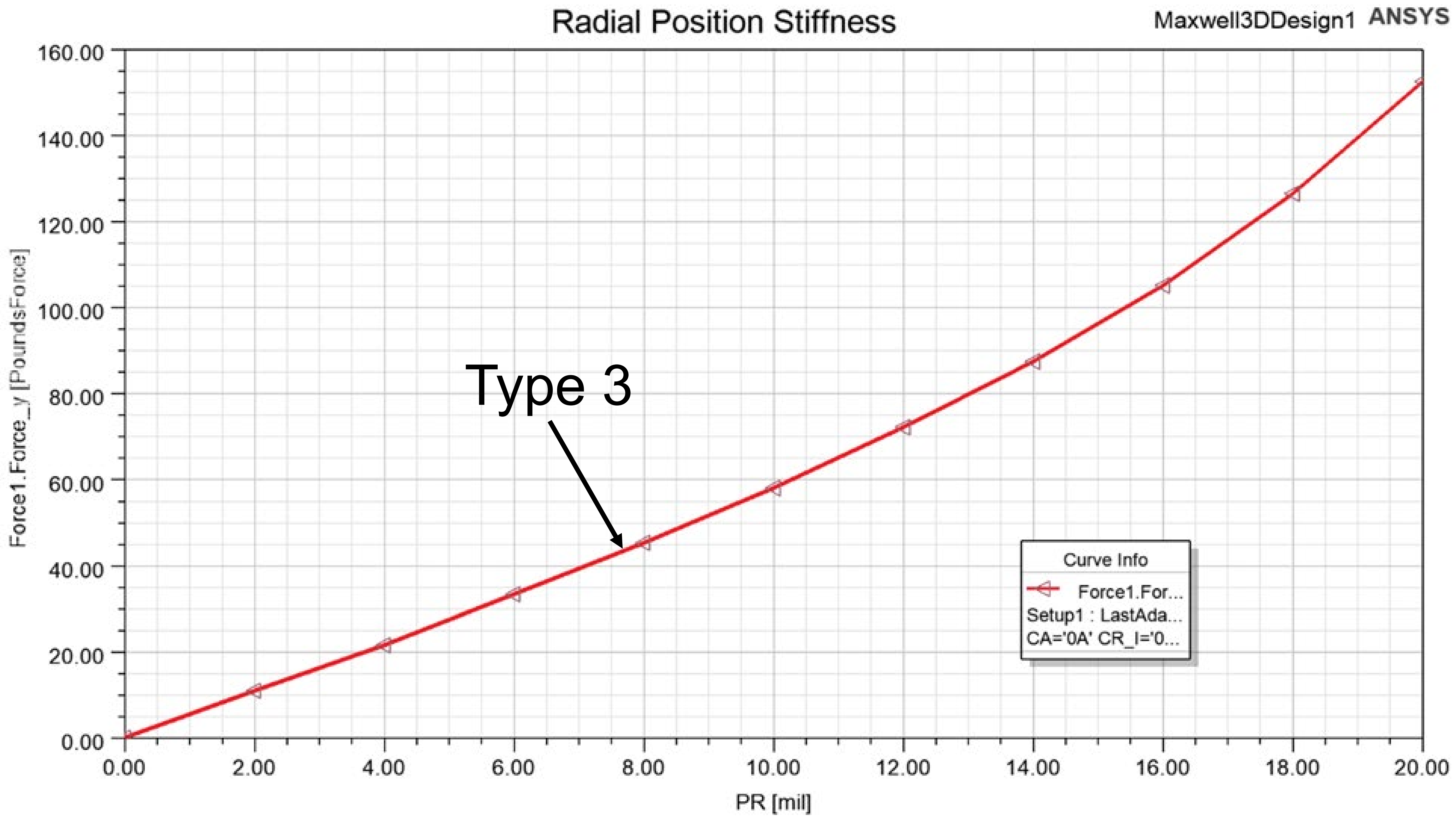
6 total studies

Study type	Parameters	Goals
1	• Shaft at center • Current sweep	• Estimate load capacity • Estimate current stiffness
2	• Shaft at -20 mils • Current sweep	• Estimate liftoff force
3	• Zero current • Shaft position sweep	• Estimate negative position stiffness

Axis study	Parameters	Constants
Radial	• Y-axis current sweep • Y-axis position sweep	• Z-axis current zero • Z-axis position centered
Axial	• Z-axis current sweep • Z-axis position sweep	• Y-axis current zero • Y-axis position centered

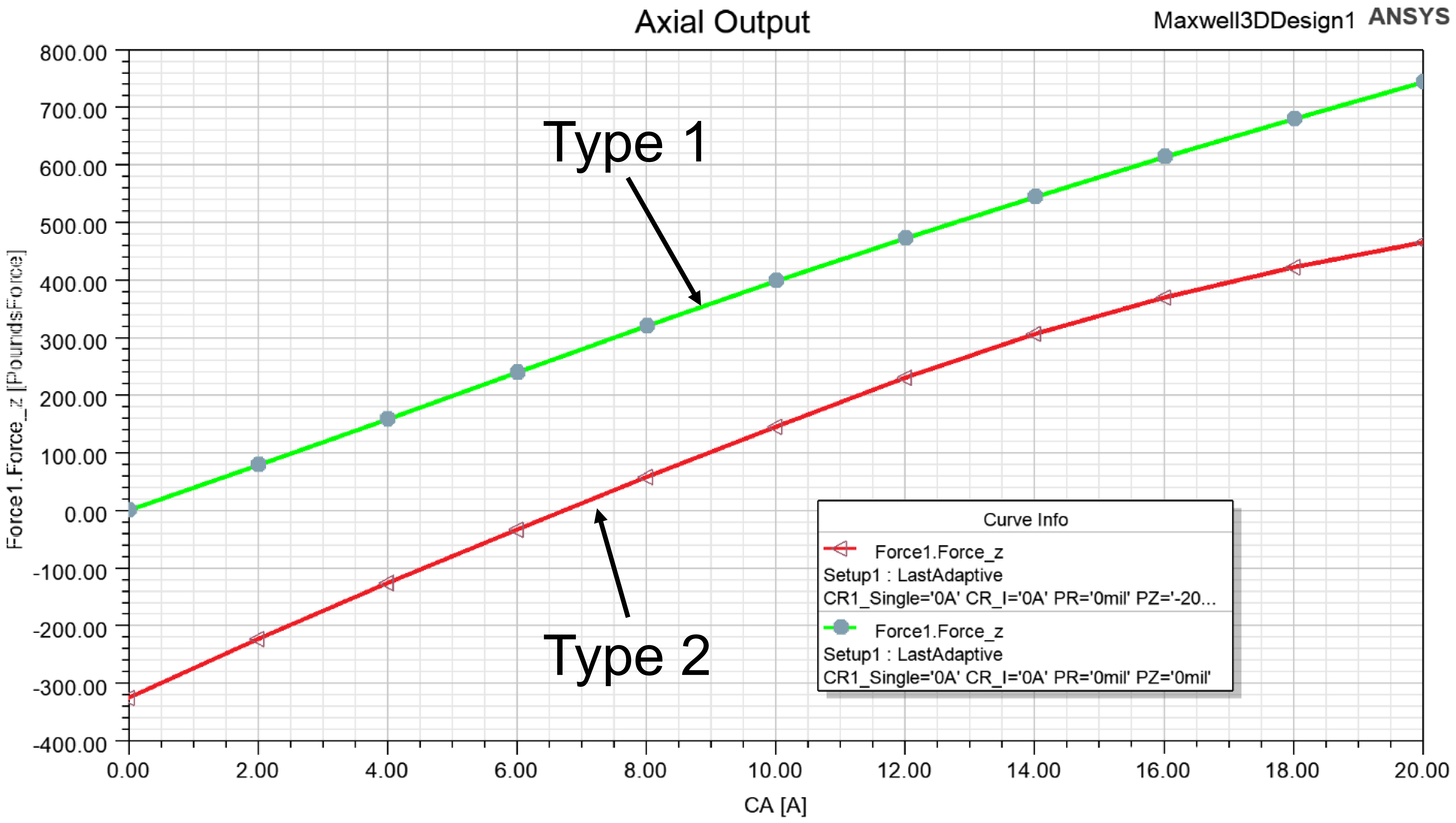
Simulation results: Radial performance

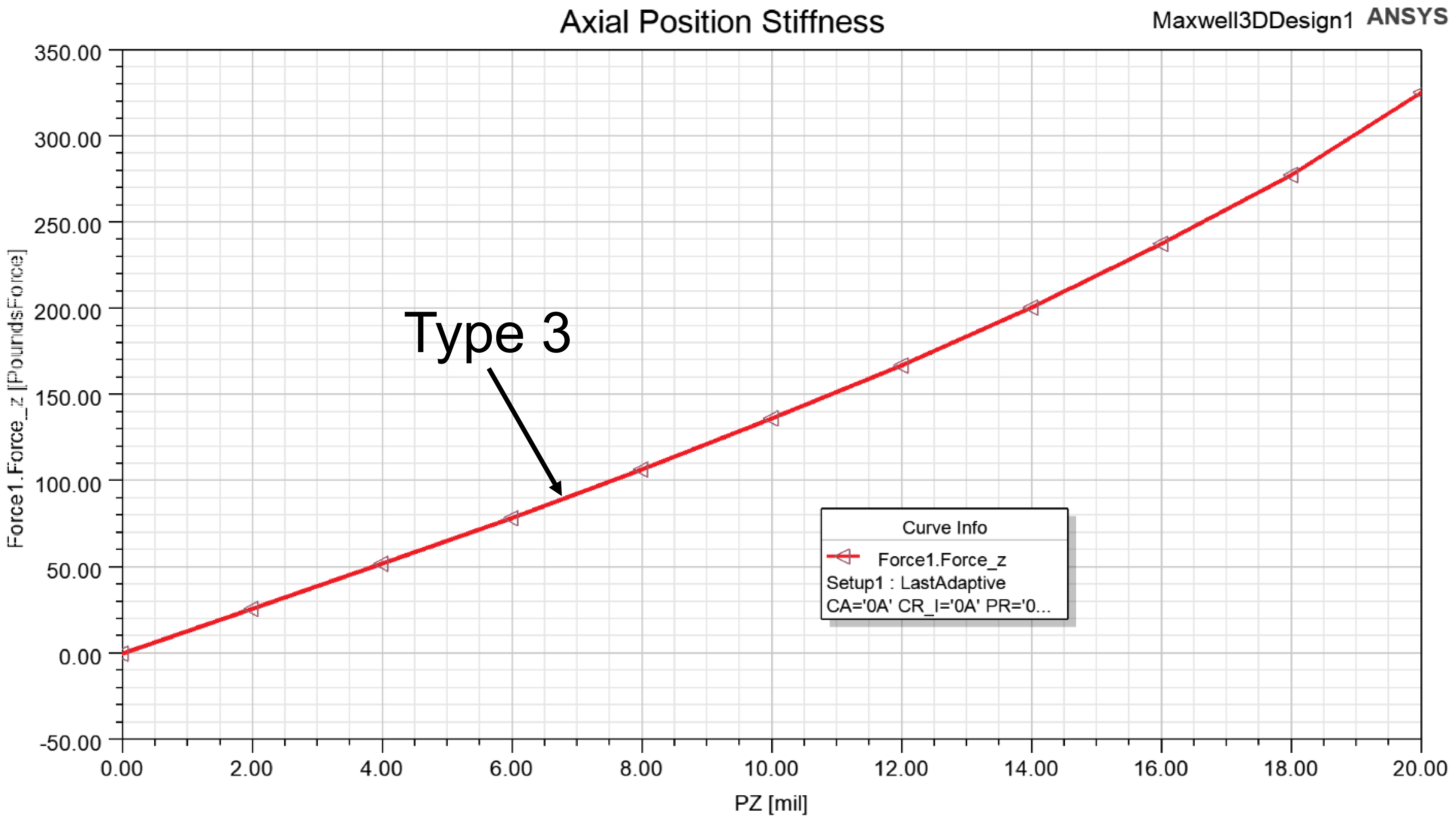




Output	Current stiffness	Position stiffness	Liftoff force from -20 mils at 10 A	Load capacity at 20 A
Radial	22.5 lbf/A	5,830 lbf/in	100 lbf	350 lbf

Simulation results: Axial performance





Output	Current stiffness	Position stiffness	Liftoff force from -20 mils at 10 A	Load capacity at 20 A
Axial	40 lbf/A	13,300 lbf/in	150 lbf	740 lbf

Conclusions

Catcher bearings selected and analyzed for drop stability

Cooling system analyzed

Simulations show stable drop behavior

sCO_2 cooling system developed for 100 °C internal temperature

Control loop structure and current transform selected

Load capacity and dynamic coefficients estimated

Control system developed

Magnetic FEA completed for design