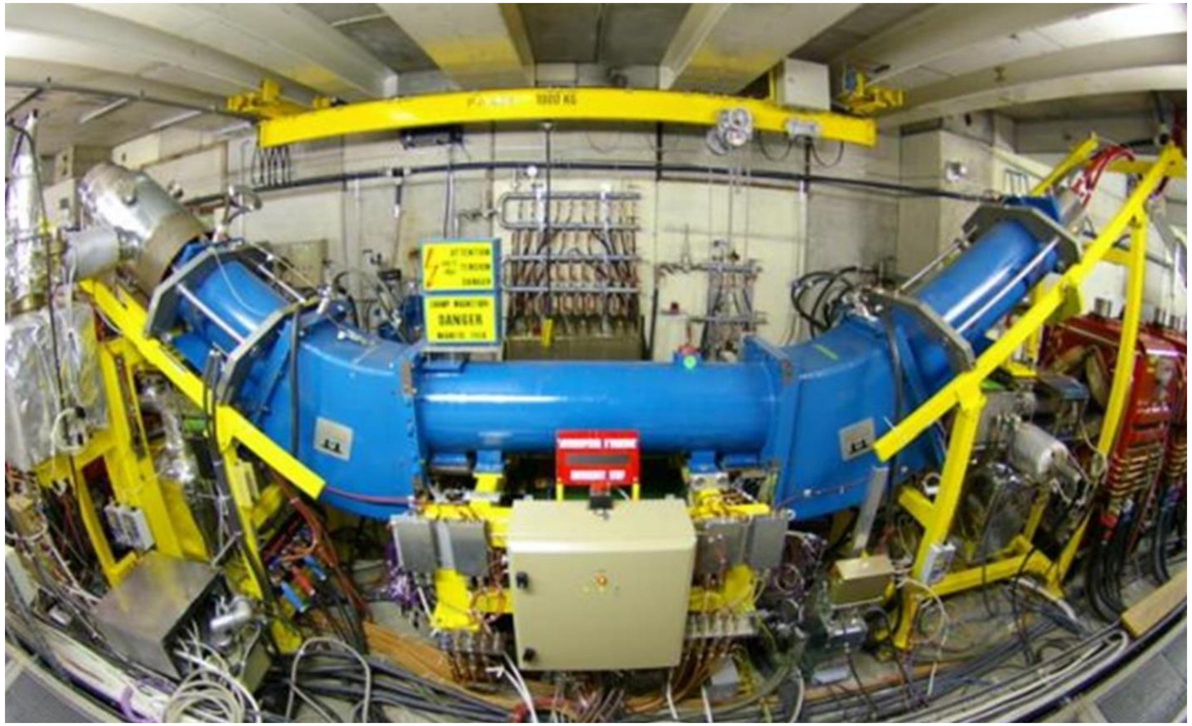
# Magnet system of the new AD electron cooler

**Luke von Freeden**

7 March 2025

# Introduction



## Overview of the AD cons project

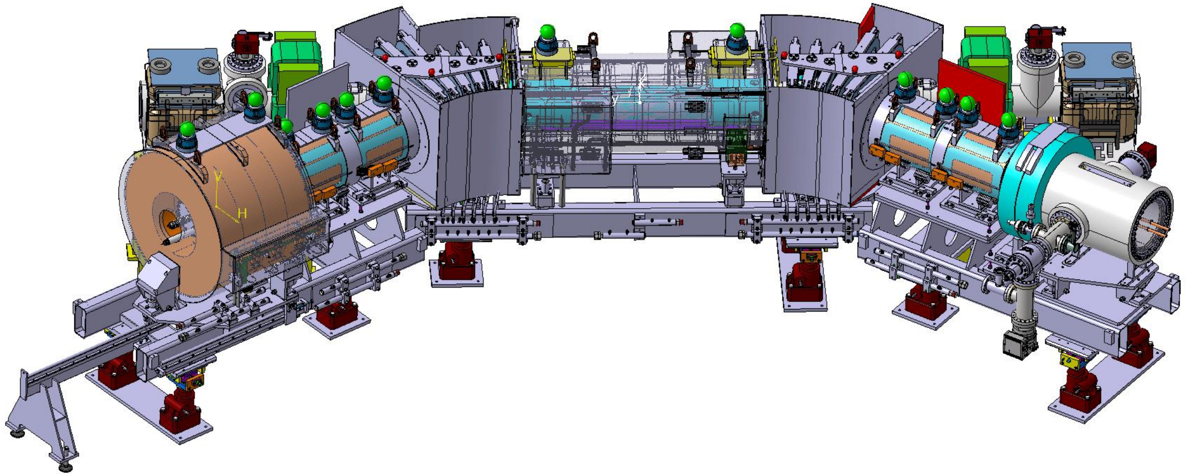
## Magnet system in electron cooling

## Functional specification of 2023

## Design of this electron cooler

## Magnetic measurement

## Project roadmap



# The AD cooler consolidation project

Present AD electron cooler magnet system built in 1978 used for in 3 experiments: ICE → LEAR → AD

Major breakdowns of collector in 2018 lead to consolidation review in 2019

No spares for a most of the magnets, limited design information, original manufacturer defunct since 2000.

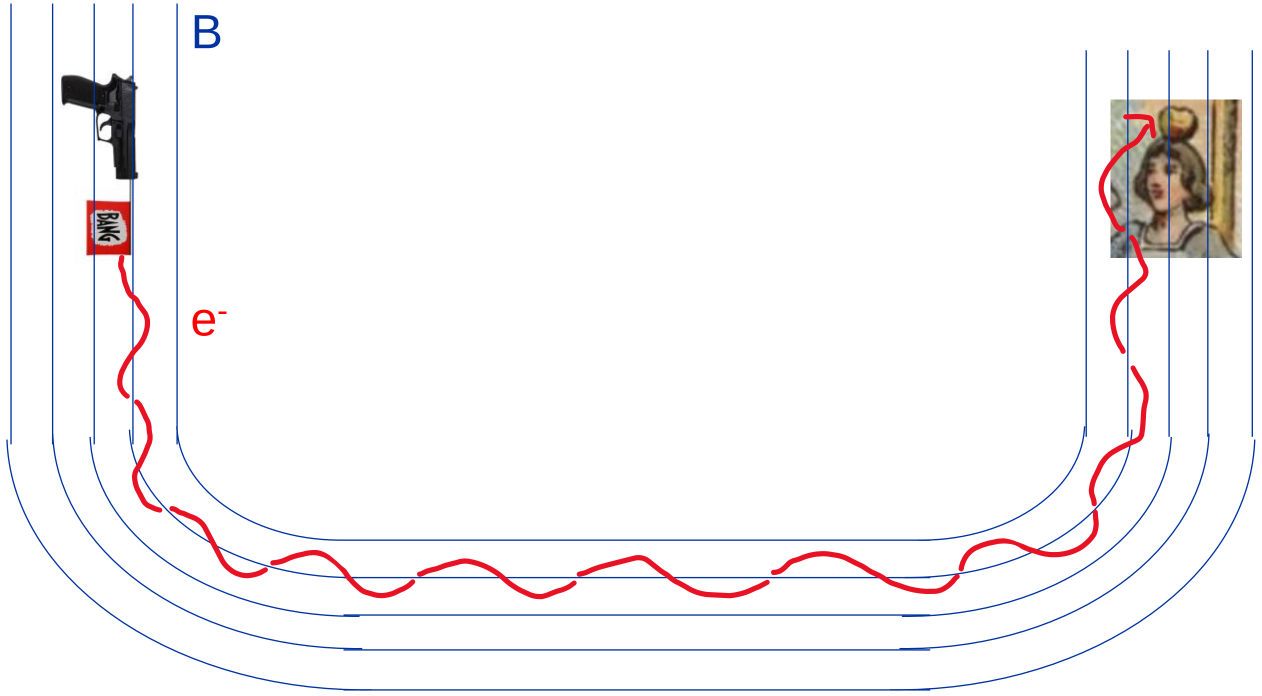
Review identified full-system replacement as best way to minimise down-time. Opportunity to upgrade the system to improve cooling performance.

# Magnet system of an electron cooler

**Electrons produced by gun are trapped onto field lines**

**Magnetic field guides the electrons from gun to collector**

**Any transverse momentum from gun → spiraling around field line**



# Field quality in the drift

**Electrons spiral around flux lines**

- → **apparent temperature to antiprotons combination of temp and B**
- → **B flux lines must be flat in drift.**

$$W_\perp = k_b T_c$$

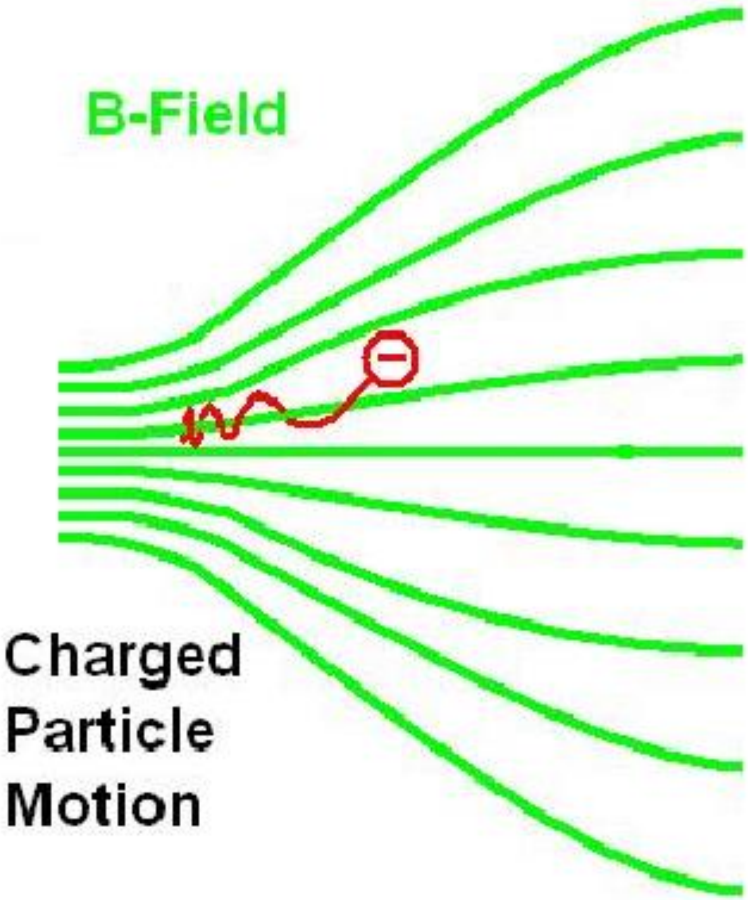



Image remixed from WikiHelper2134 under CC BY-SA 3.0

**Field quality in electron cooler**

$$q_f = \left| \frac{B_\perp}{B_{||}} \right|$$

$$\mathrm{rms}\, q_f = \sqrt{\frac{1}{V} \iiint_V \left( \frac{B_\perp}{B_{||}} \right)^2 dV}$$

# Adiabatic expansion

**For a charged particle in a magnetic field, magnetic moment is invariant:**

$$\mu = \frac{mv_\perp^2}{2B}$$

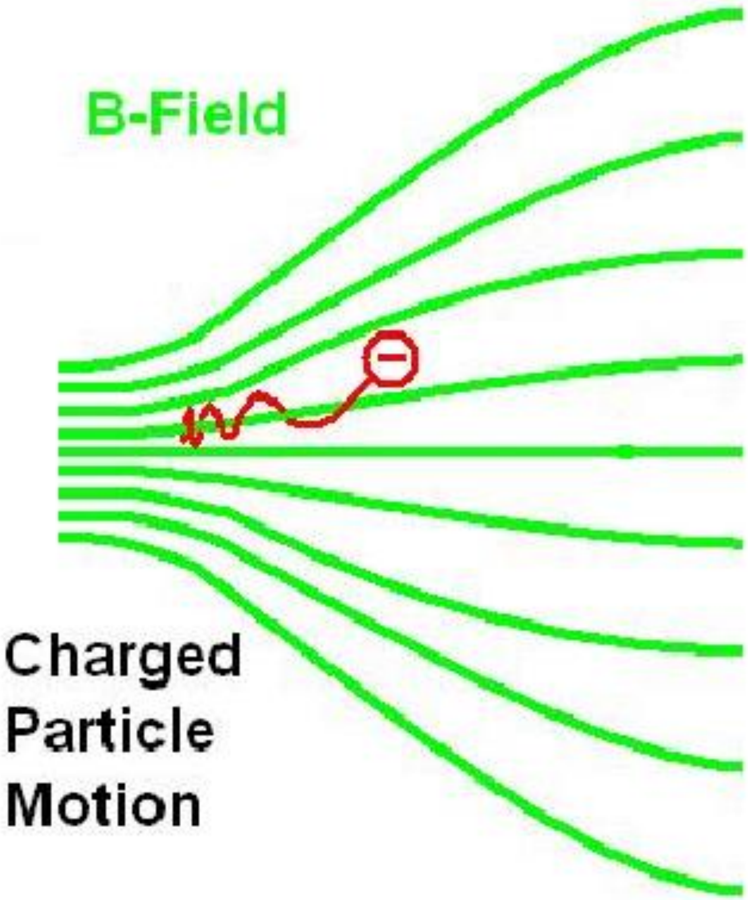
**Reducing B → reduction in transverse K.E. (moved to parallel)**

$$W_{\perp,2} = W_{\perp,1}\frac{B_1}{B_2}$$

**Adiabatic condition: the rate of change of B is small relative to the cyclotron wavelength.**

$$\chi = \frac{\lambda_c}{B}\left|\frac{\mathrm{d}B}{\mathrm{d}z}\right| \qquad \lambda_c = \frac{2\pi\sqrt{2m_e E_e}}{eB}$$

**Typically, $\chi < 0.5$ is acceptable.**



# Functional specification

| | Present | This Spec. |
|---|---|---|
| AD ring length [m] | 182.43 | 182.43 |
| Drift magnet length [m] | $\sim 1.5$ | $\sim 1.5$ |
| Drift magnet field [G] | 600 | $\sim 600^*$ |
| Cooling region length [m] | $\sim 1$ | $\geq 1$ |
| Cooling region radius = $r_{\text{e-beam}}$ [mm] | 25 | $\geq 25$ |
| Cooling region max$(B_\perp/B_\parallel)$ | $10^{-3}$ | $\sim 10^{-4}$ |
| Cooling region rms$(B_\perp/B_\parallel)$ | n.a. | $\sim 10^{-5}$ |
| Toroid field [G] | 600 | $\sim 600^*$ |
| Toroid angle $\phi_0$ [rad] | 0.6283 | n.a.$^\ddagger$ |
| Toroid radius $r_{tor}$ [m] | 1.133 | n.a.$^\ddagger$ |
| Toroid integrated transverse field [Gm] | $\sim 160$ | $\lesssim 160$ |
| Gun magnetic field [G] | 600 | n.a.$^\ddagger$ |
| Gun perveance [$\mu$P] | 0.58 | n.a.$^{\ddagger\dagger}$ |
| Cathode radius [mm] | 25 | n.a.$^\ddagger$ |
| Cooling region $e^-$ beam $k_B T_\perp$ [meV] | 100 | $\lesssim 100$ |
| Cooling region $e^-$ beam $k_B T_\parallel$ [meV] | — | $\lesssim 1$ |
| $e^-$ beam energy stability [$\Delta E/E_0$] | — | $\sim 10^{-5}$ |
| $e^-$ beam intensity $I_0$ [A] | up to 2.4 | up to 4.8 |
| $e^-$ beam intensity stability [$\Delta I/I_0$] | — | $\sim 10^{-4}$ |
| $e^-$ beam max relative losses [$\delta I/I_0$] | — | $\sim 10^{-5}$ |
| $e^-$ beam start/stop time [s] | — | $\ll 1$ |
| BPMs $e^-$/pbar relative accuracy [$\mu$m] | — | $\lesssim 100$ |
| Vacuum pressure in cooling section (torr) | $2 \times 10^{-11}$ | $\ll 10^{-11}$ |
| E-cooler availability during physics | — | 99% |

D. Gamba, C. Carli, L. Ponce, A. Rossi, G. Tranquille, L. Varming Joergensen *Functional specification of the new electron cooler,* Sept. 2022 EDMS 2772724

# Overview of the magnet system

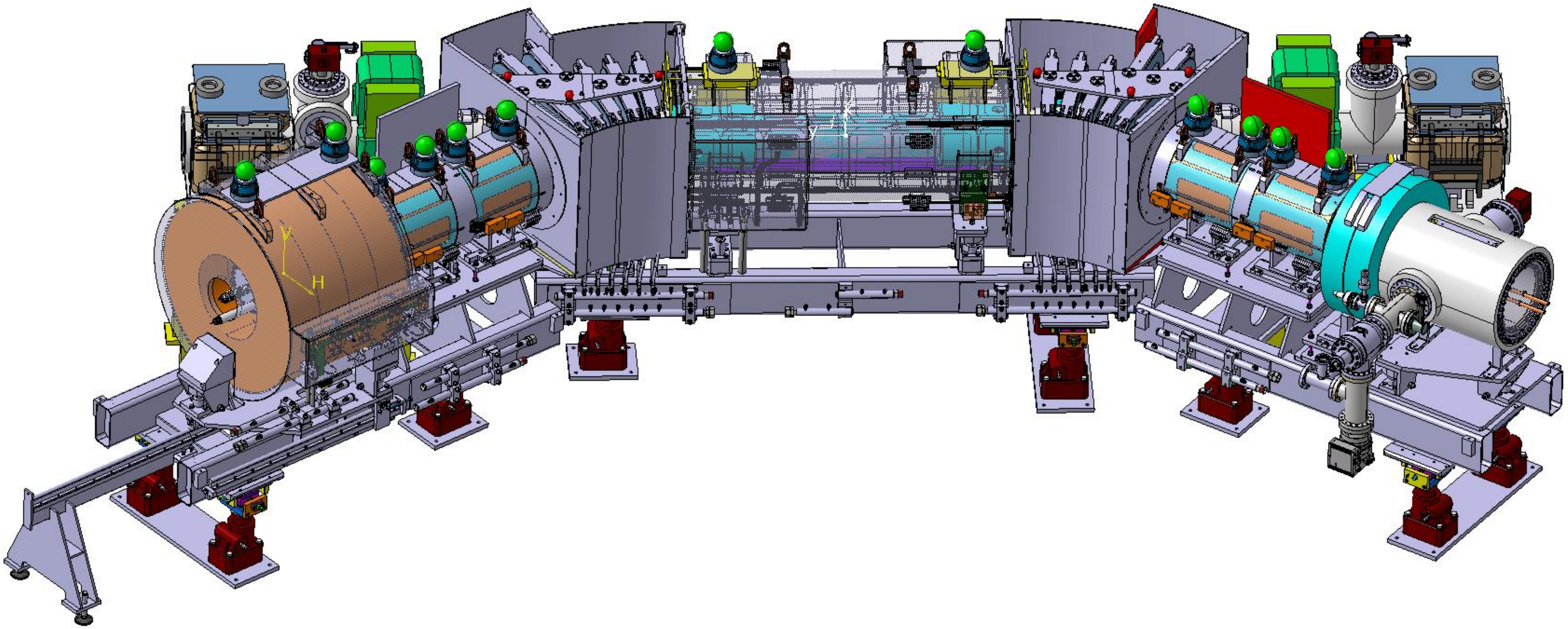


Image courtesy of V. Maire and N. Chritin EN-MME

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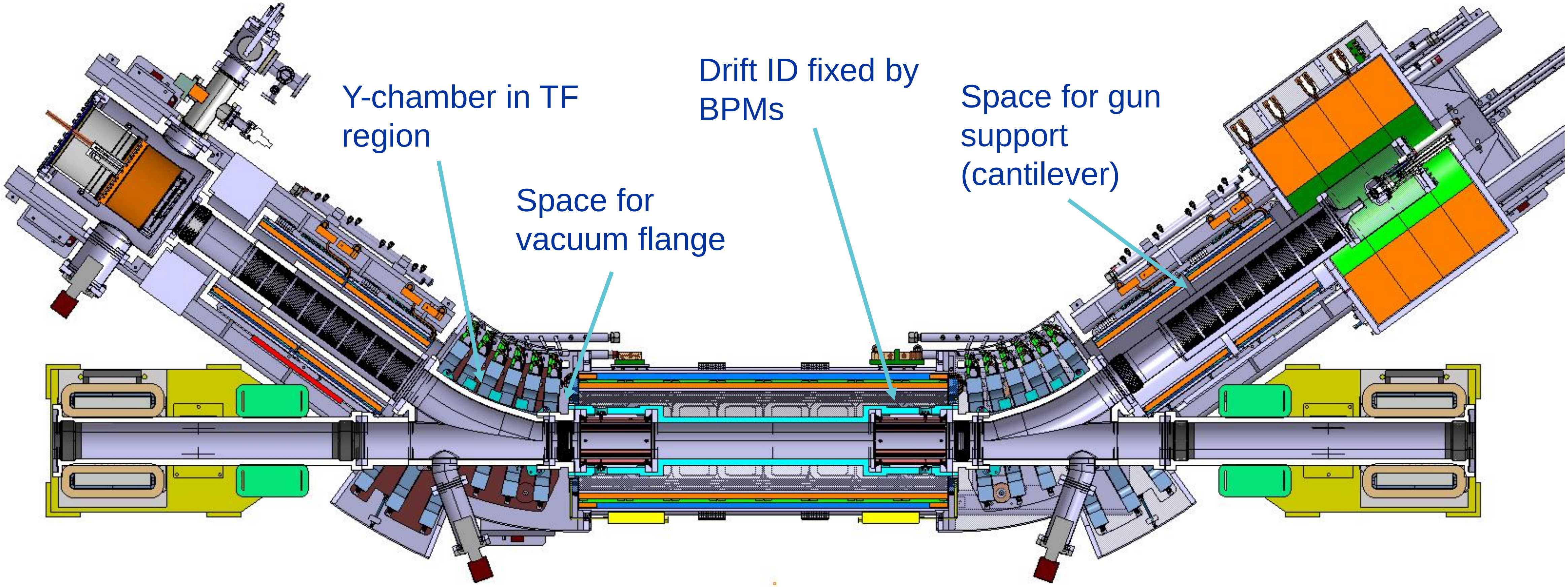

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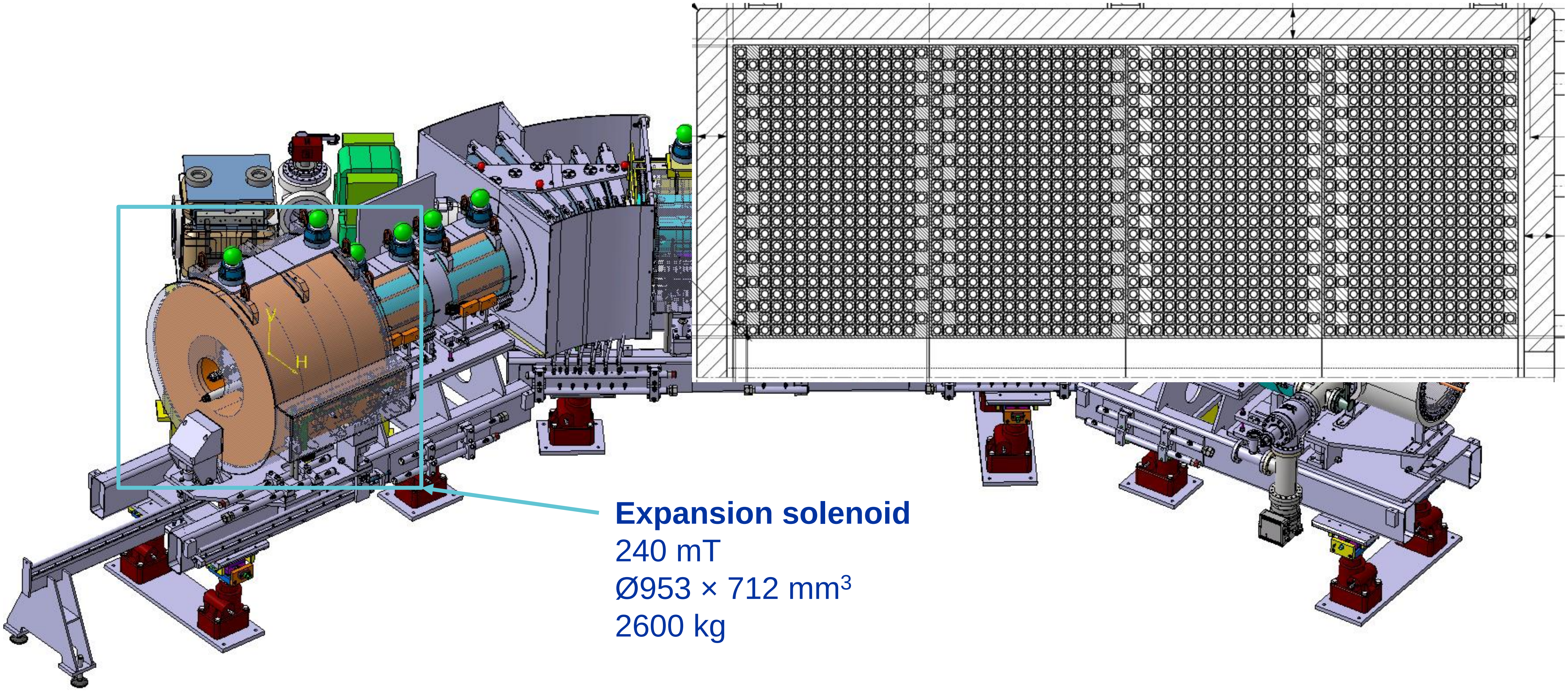
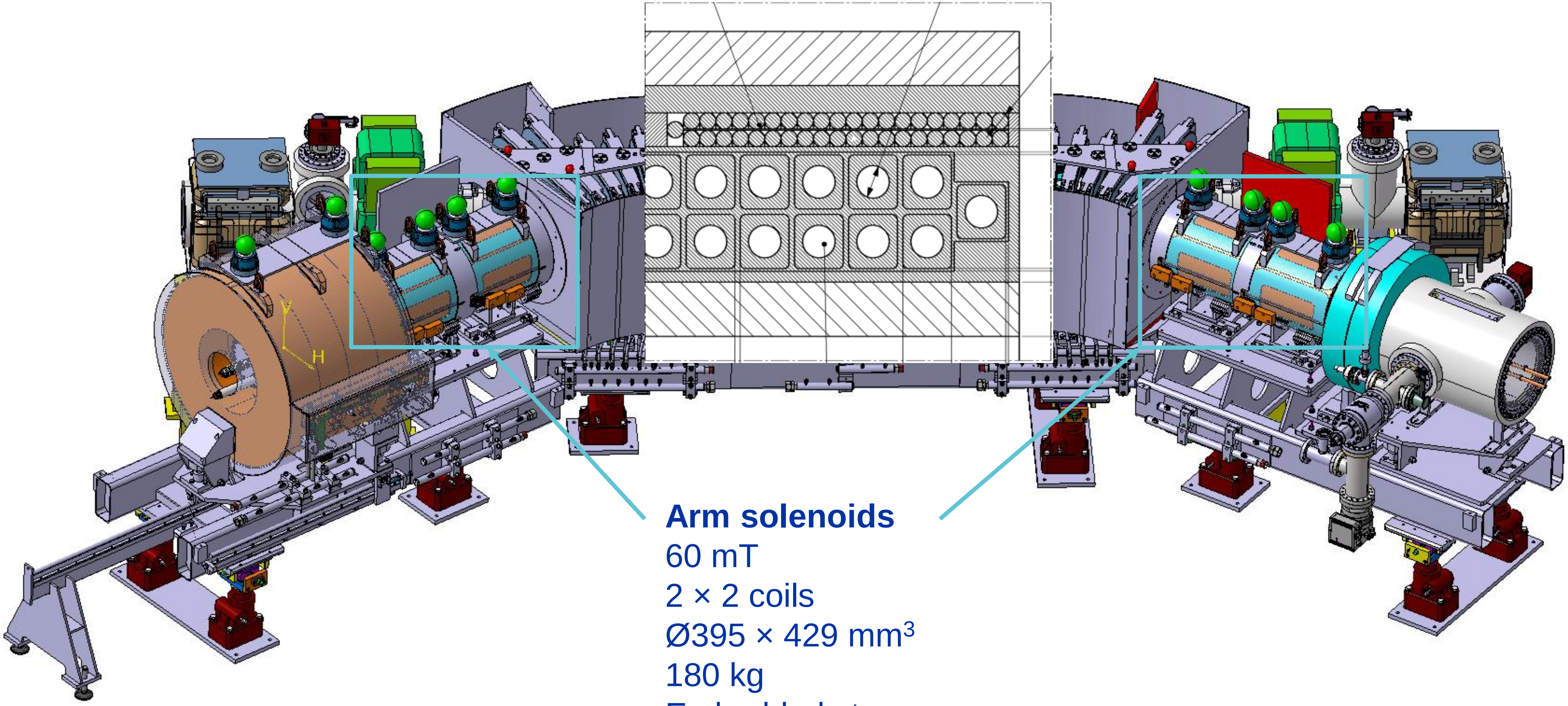


**Expansion solenoid**
240 mT
Ø953 × 712 $mm^3$
2600 kg

Image courtesy of V. Maire and N. Chritin EN-MME

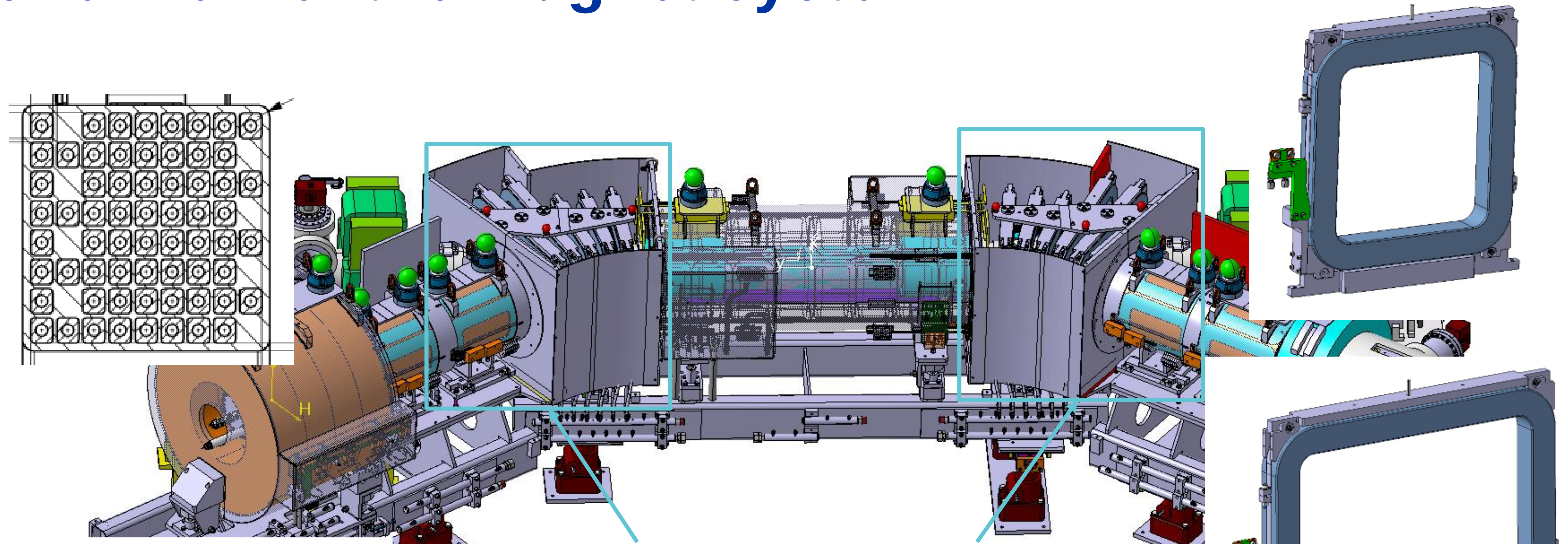
# Overview of the magnet system

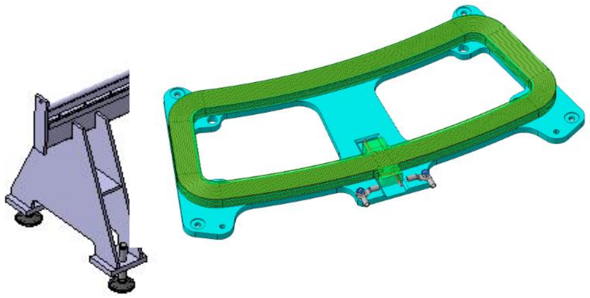


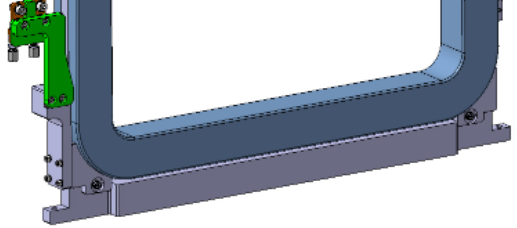

**Arm solenoids**
60 mT
2 × 2 coils
Ø395 × 429 $mm^3$
180 kg
Embedded steerer

Image courtesy of V. Maire and N. Chritin EN-MME

# Overview of the magnet system



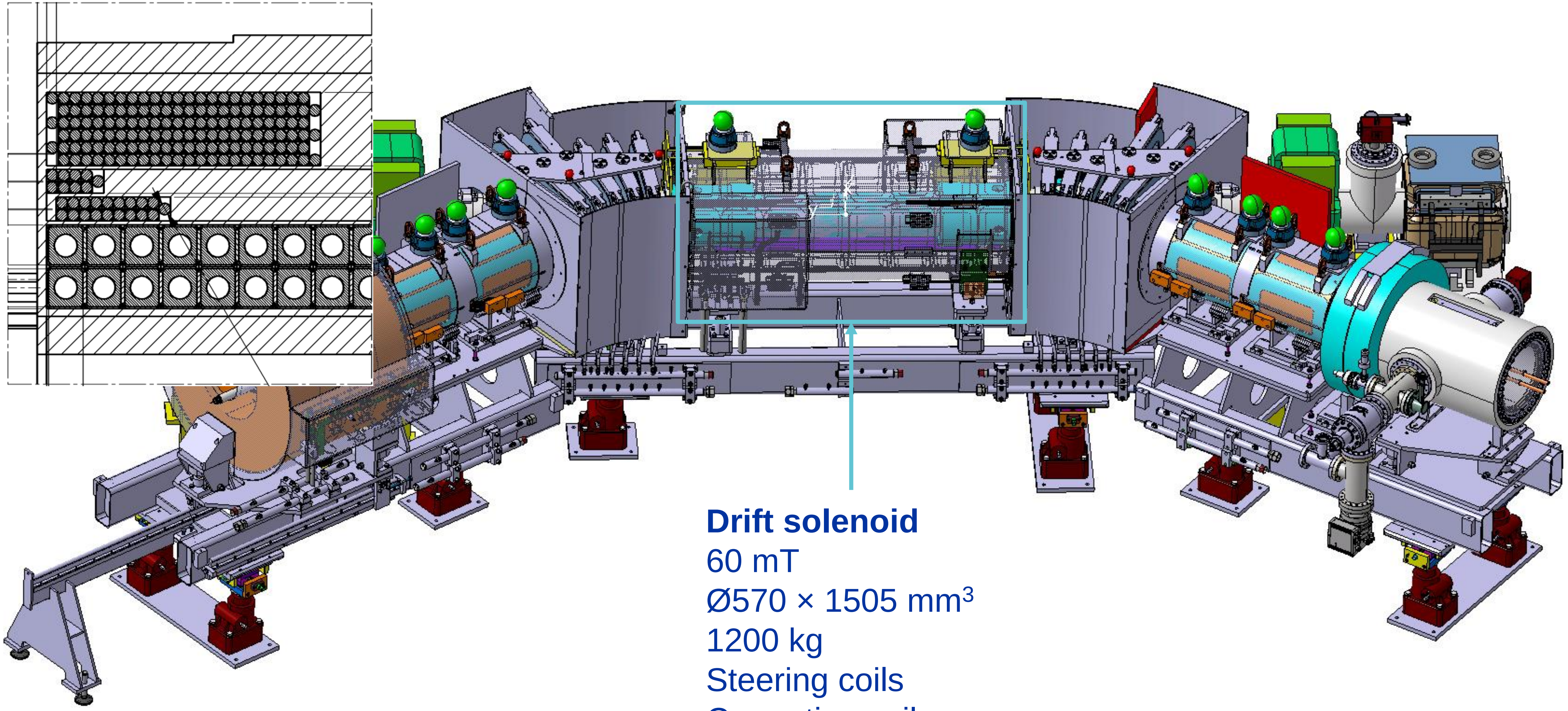




**Toroidal field regions**
60 mT
2 × 6 racetrack coils
$63 \times 525 \times (505 \ \& \ 725)\ \mathrm{mm}^3$
35 & 42 kg
Steering coil

Image courtesy of V. Maire and N. Chritin EN-MME

# Overview of the magnet system



**Drift solenoid**
60 mT
Ø570 × 1505 $mm^3$
1200 kg
Steering coils
Correction coils

Image courtesy of V. Maire and N. Chritin EN-MME

# Overview of the magnet system

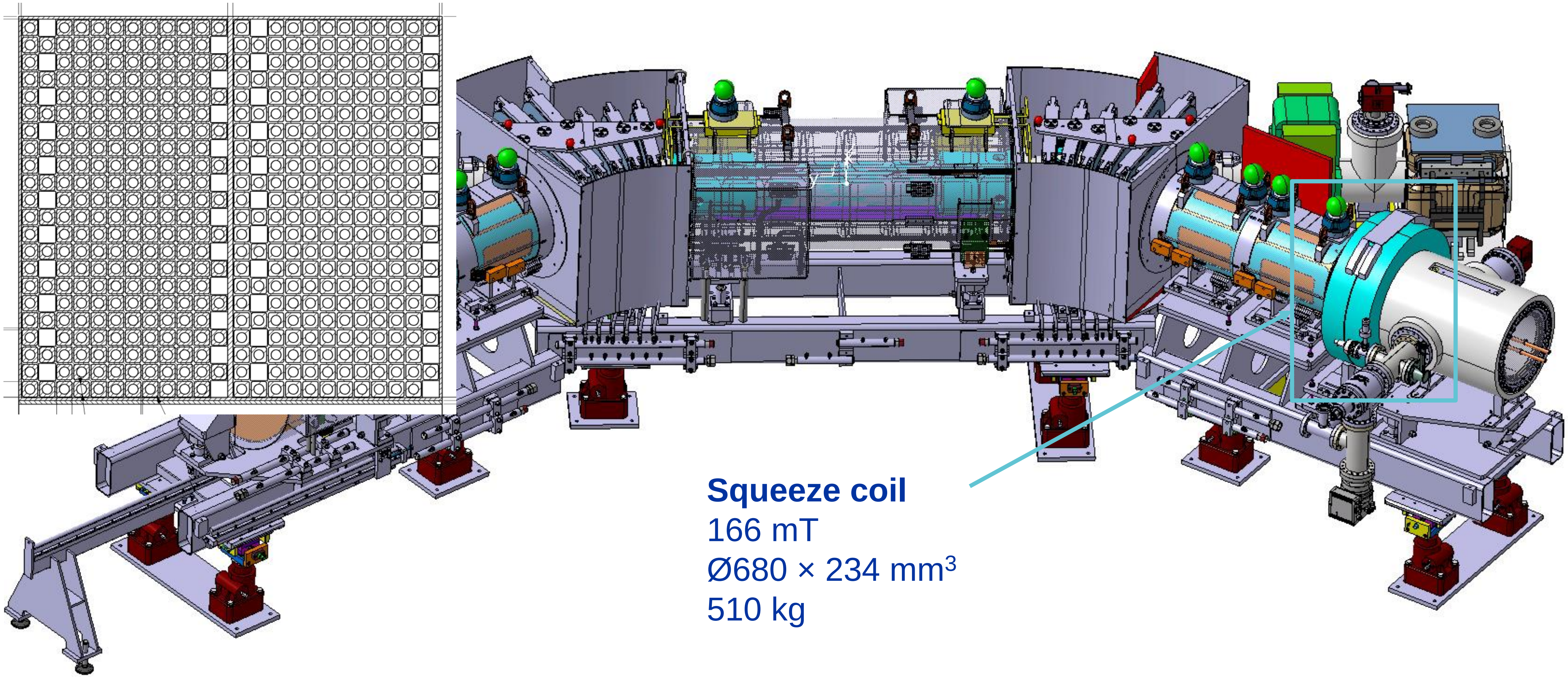
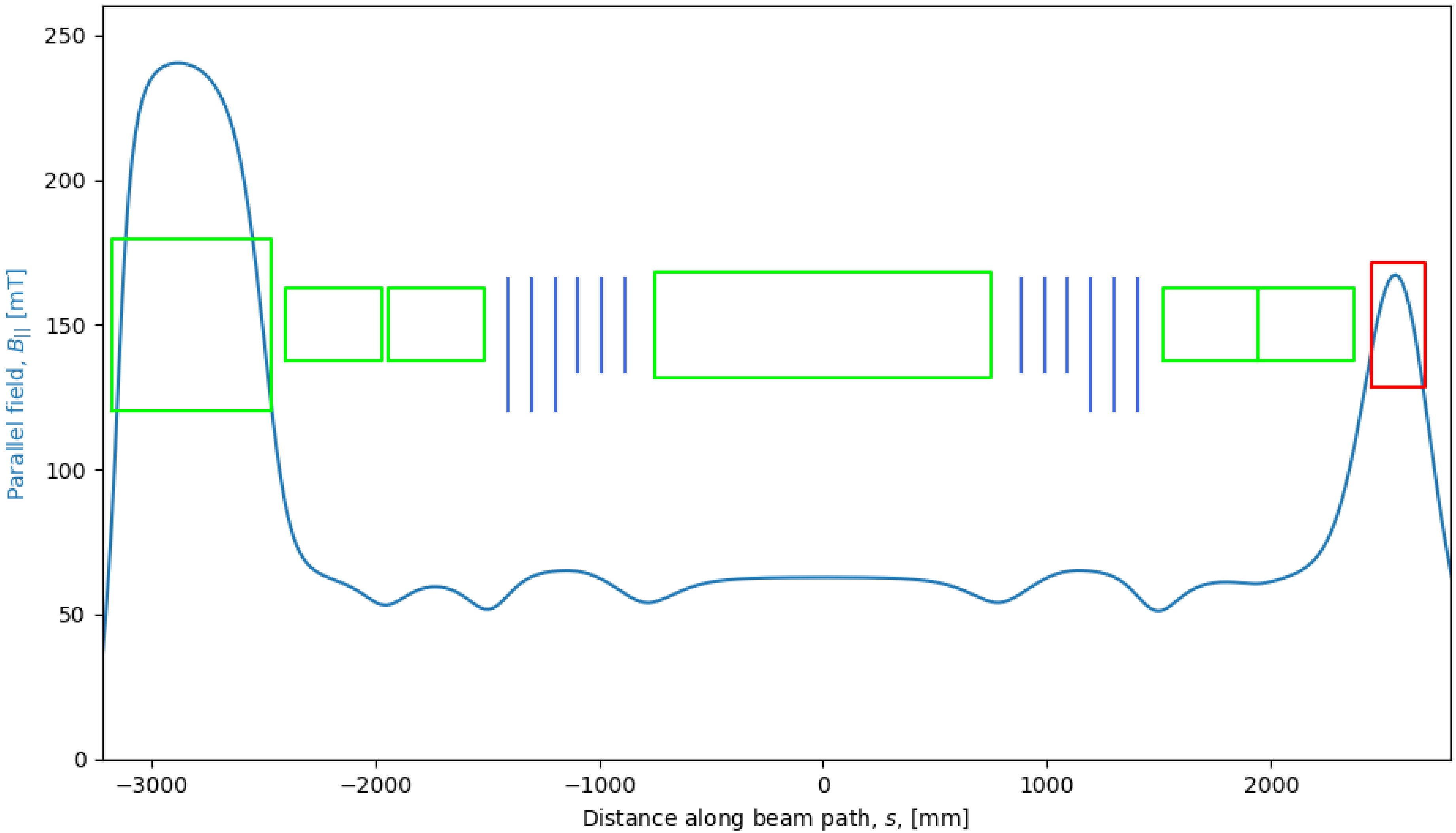
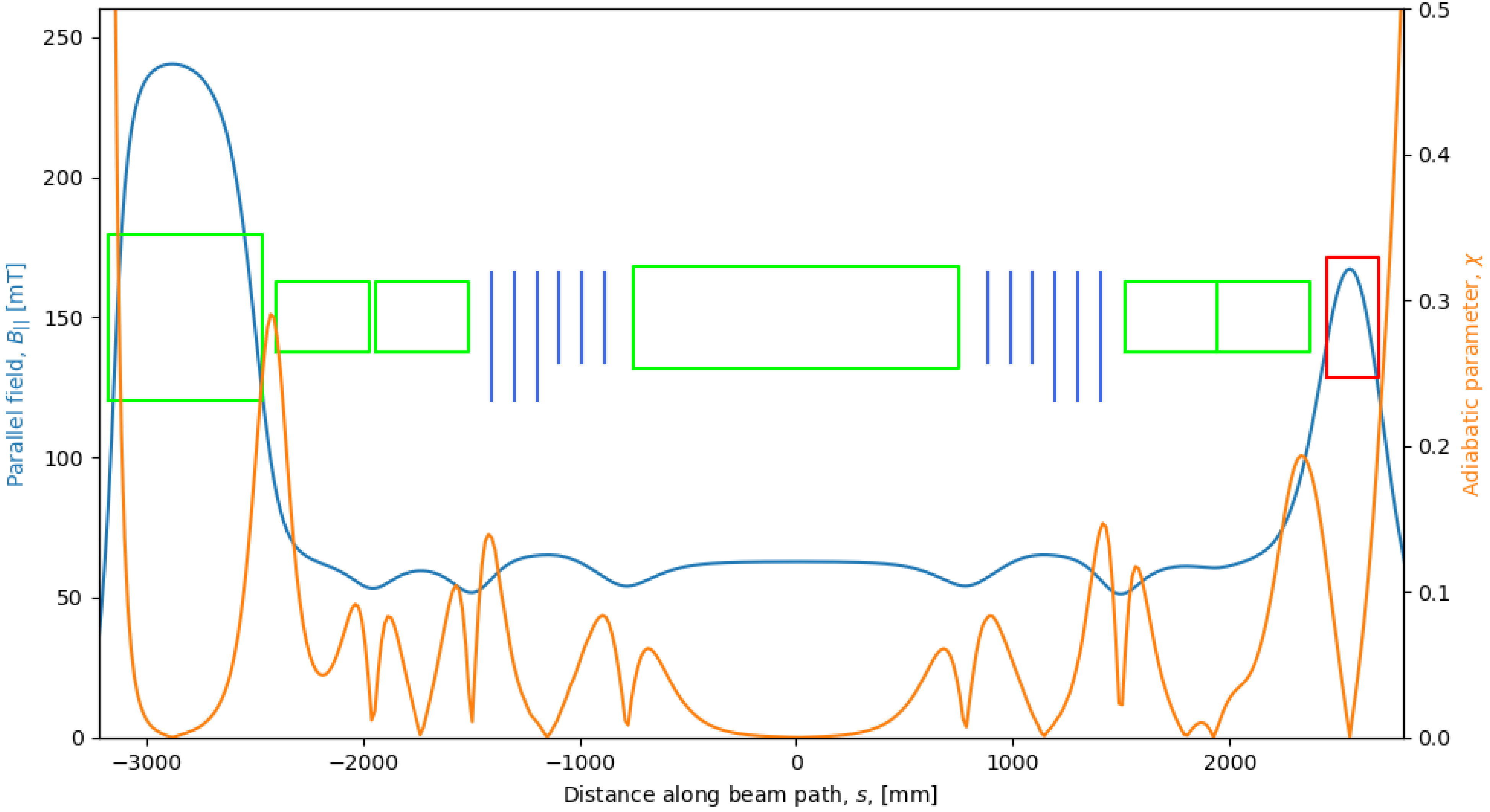



Image courtesy of V. Maire and N. Chritin EN-MME

# Main field along $e^-$ trajectory



# Main field along e⁻ trajectory



# Field errors in the drift

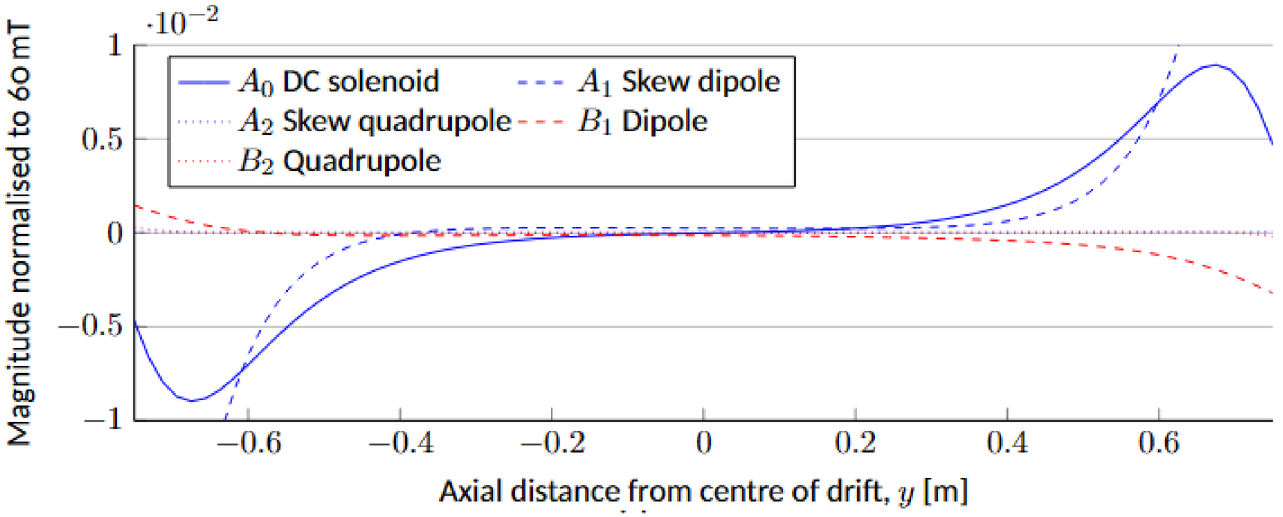
**Without correction, relative error > 5 × 10$^{-3}$ in GFR (Ø60 × 1000 mm$^3$)**

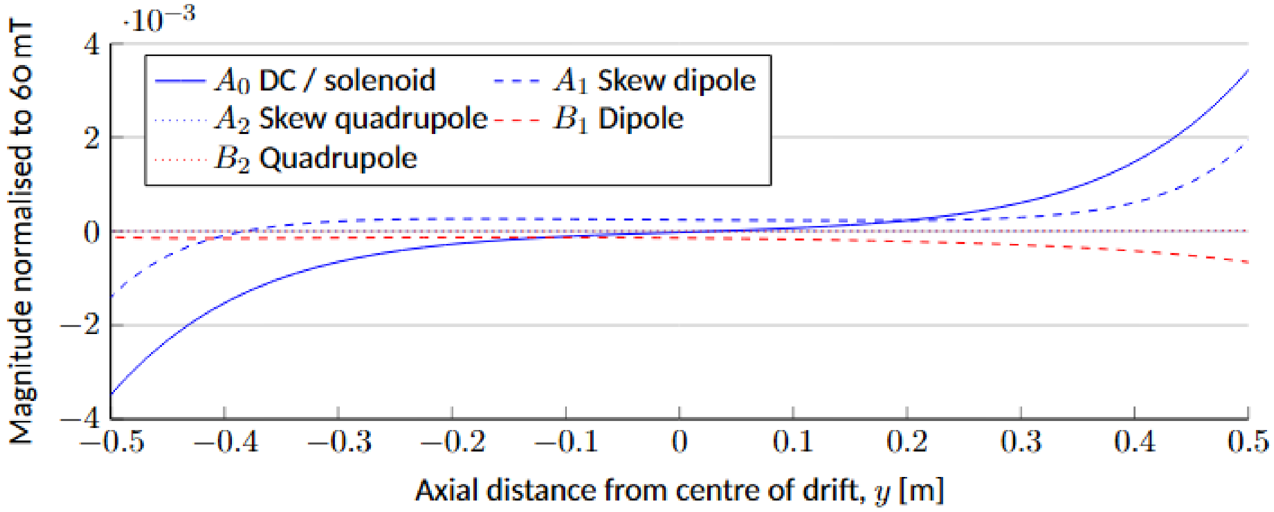
**Strong solenoid component due to drift to TF gap**

**Skew dipole component due to pollution from TF region**

**Normal dipole component due to slight up-down asymmetry in shield**

**Higher orders << 1 × 10$^{-4}$**



# Field correction scheme

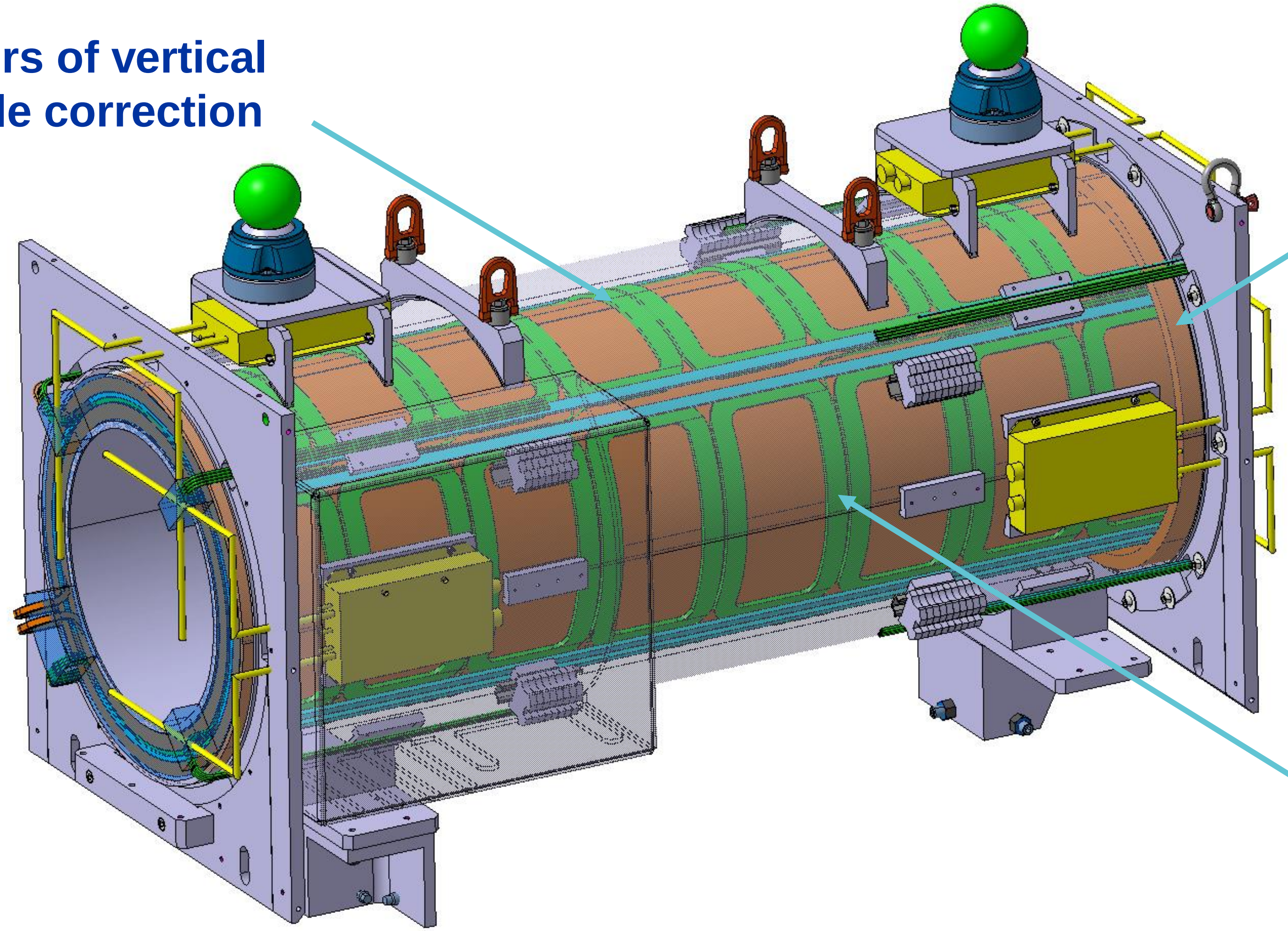
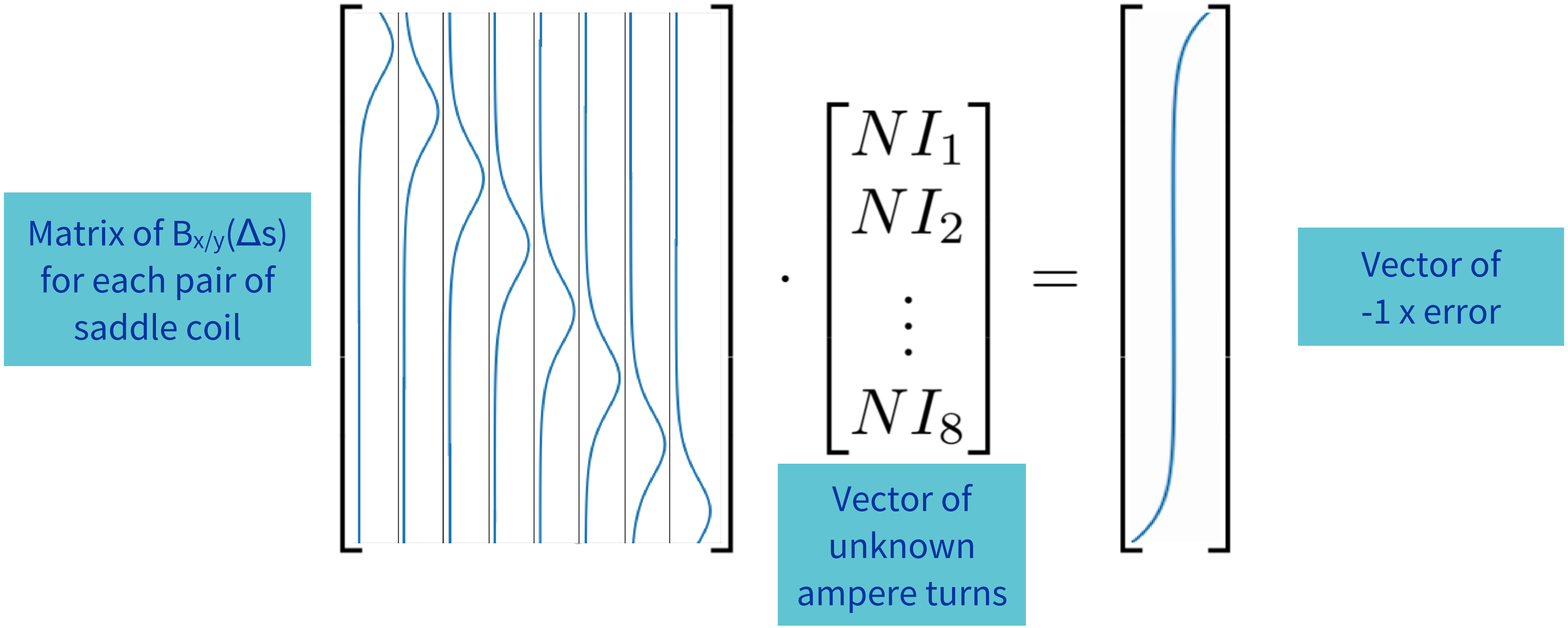
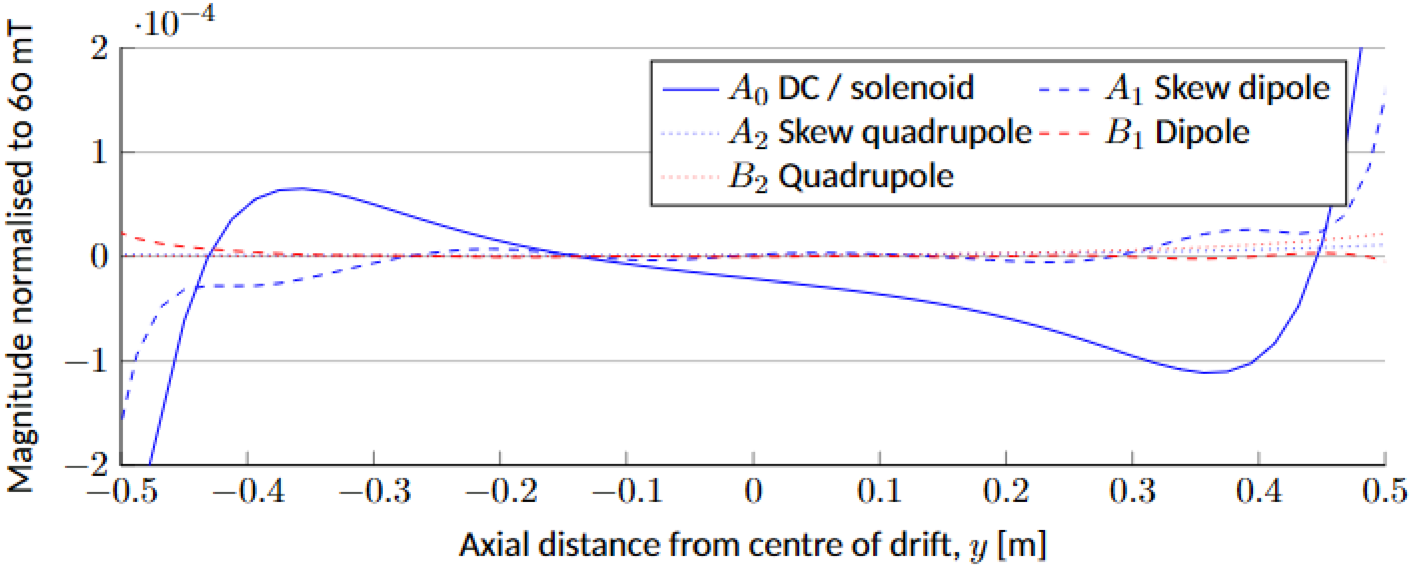



Image courtesy of V. Maire and N. Chritin EN-MME

# Setting the correction currents via least squares



# Results of the field correction



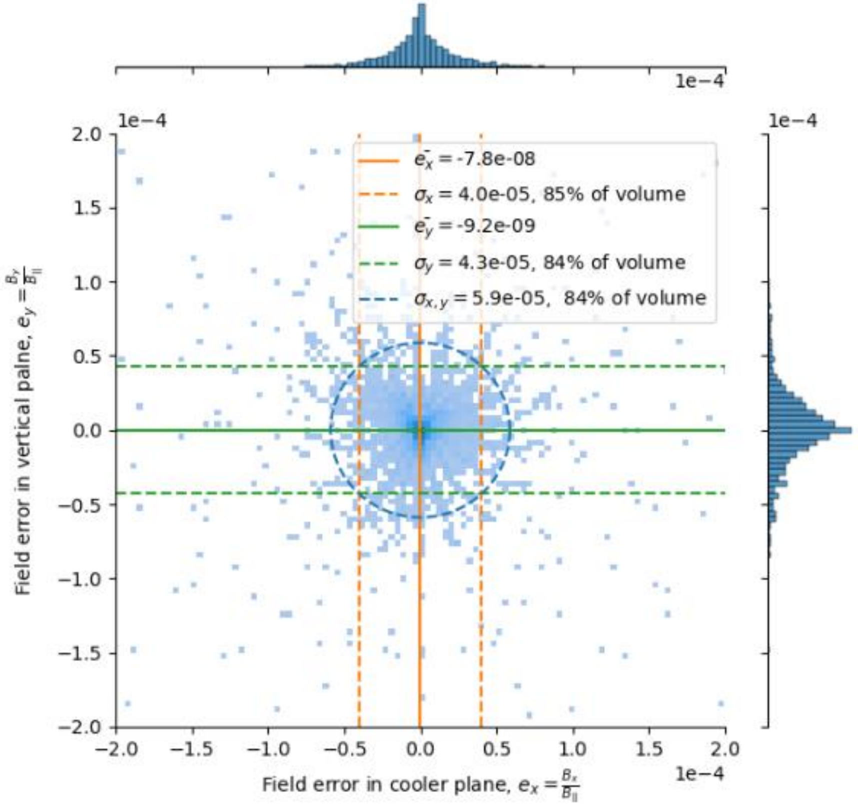
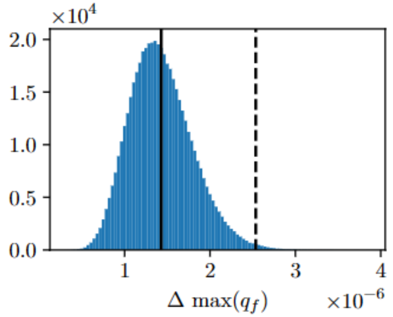




**Table 1: Final current in the design of the correction coils in Ampere.**

| Type | Field direction | Coil position | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Solenoid | Axial | 10.926 | | | | | | | 10.926 |
| Skew | Horizontal | 7.026 | -0.623 | -0.260 | -0.282 | -0.210 | -0.250 | 0.074 | -7.632 |
| Normal | Vertical | 0.025 | 0.208 | 0.134 | 0.124 | 0.154 | 0.246 | 0.416 | 1.408 |




< 2.5 × $10^{-6}$ (3σ) from supply precision and ripple

At least 24% (1.5 × $10^{-3}$) current margin in all coils

# What that means for the AD

## w/ thanks to D. Gamba

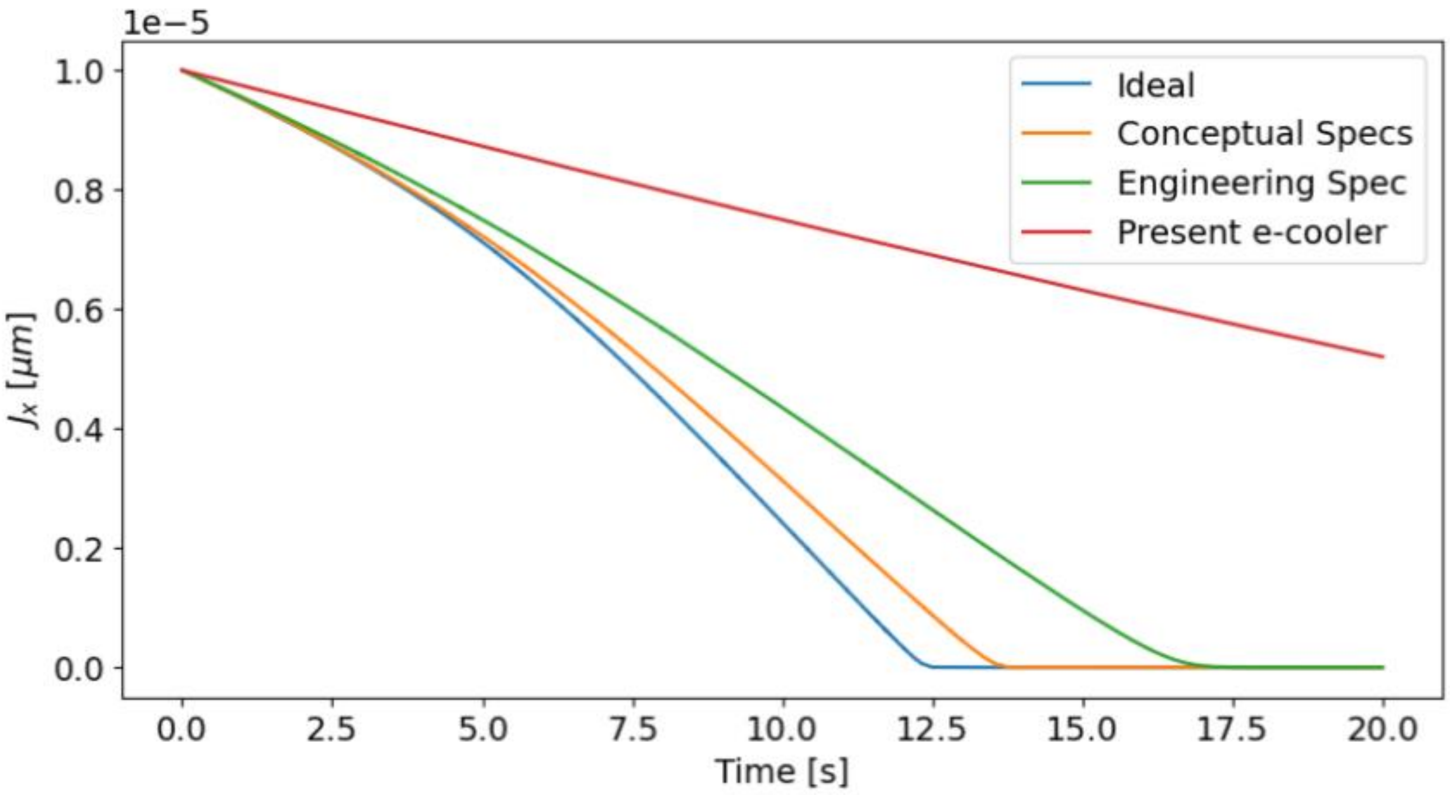



**Figure 10: Simulated transverse emittance as a function of time during cooling at 300 MeV/c with $I_{e^-}$ of 2.4 A for a reference particle and for different drift field quality: the ideal case, the functional/conceptual specification [2], this engineering specification, and the present electron cooler. Courtesy of D. Gamba.**

# Steering scheme

**Constant offset** due to central flux line not exactly following the reference trajectory

| | | Gun to drift centre | Drift centre to collector arm |
|---|---|---|---|
| Uncorrected difference V | [mm] | $-17.1\beta\gamma + 2.0$ | $-16.5\beta\gamma - 1.7$ |
| Uncorrected difference H | [mm] | 4.8 | -5.1 |
| Steering margin V @ 10 A (18 A) | [mm] | 13.5 (21.5) | 9.8 (17.8) |
| Steering margin H @ 10 A (18 A) | [mm] | 5.3 (13.3) | 4.6 (12.6) |

**Offset with accelerating voltage** cross drift from centripetal forces acting on the electrons in TF region

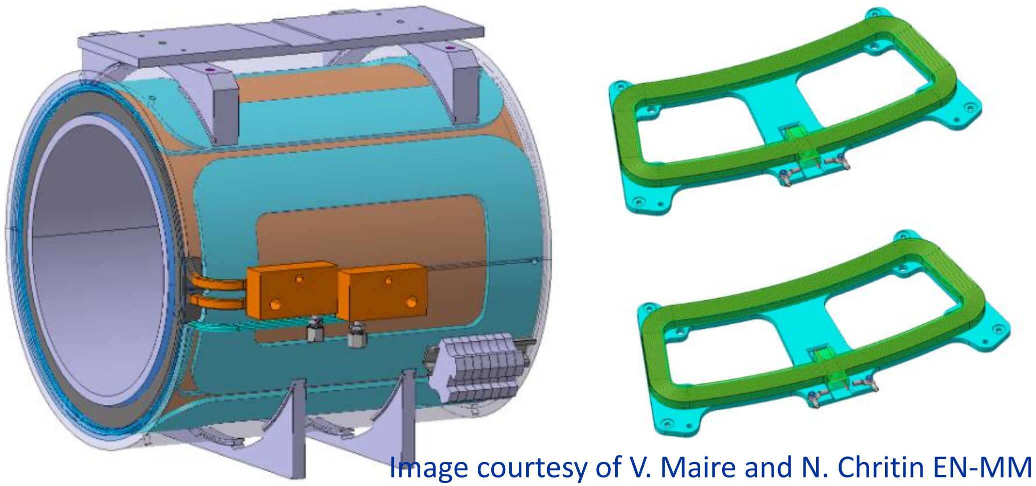
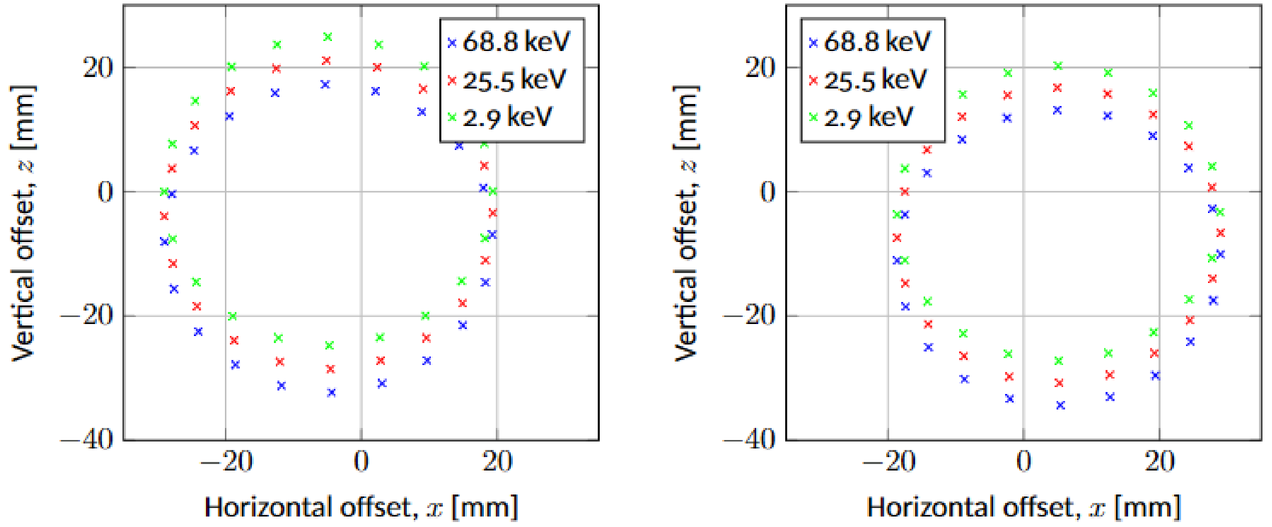


Image courtesy of V. Maire and N. Chritin EN-MME




(a) Centre expansion solenoid to drift centre. (b) Centre drift to centre last collector arm solenoid.

**Figure 11: Particle tracking without steering for different acceleration voltages corresponding to the cooling plateaus at 100 MeV $c_0^{-1}$, 300 MeV $c_0^{-1}$, and 500 MeV $c_0^{-1}$.**

# Measurement, alignment and correction

**Measurement and correction performed on surface**

**Tolerance of current and survey → field quality change between correction in B. 311 and installation in tunnel $< 3 \times 10^{-5}$**

**Fiducialisation of all magnetic axes allows direct spare substitution**

# Development of translating flux meter

## w/ thanks to M. Pentella, C. Petrone, and TE-MSC-MMM

### Translating flux meter proof of concept

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 32, NO. 6, SEPTEMBER 2022 9000605

**Induction-Coil Measurement System for Normal- and Superconducting Solenoids**

Carlo Petrone, Stefano Sorti, Eivind Dalane, Bertrand Mehl, and Stephan Russenschuck

### Flux meter applied to 60 mT solenoid correction

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 34, NO. 5, AUGUST 2024 9001404

**Alignment of a Solenoid System by Means of a Translating-Coil Magnetometer**

M. Pentella, V. Kjellqvist, C. Petrone, S. Russenschuck, and L. von Freeden

**Novel translating flux meter developed through research in TE-MSC-MMM**

**Two key outputs yielding very promising results:**

- PCB design optimised for field errors in 60 mT
- 3D cylindrical harmonic description

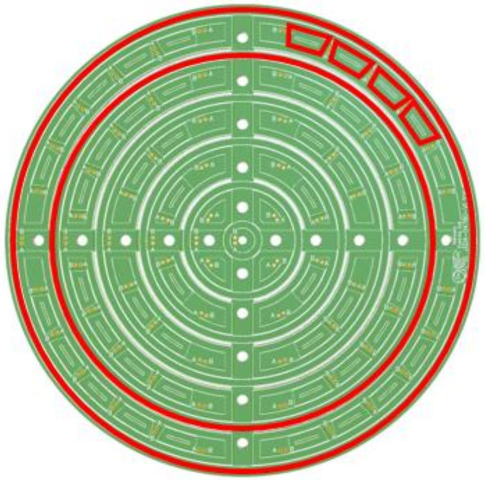
$$B_z(r,\varphi,z) = \sum_{n=0}^{\infty} I_0(\lambda_n r)\left[F_{0,n}\cos(\lambda_n z) - E_{0,n}\sin(\lambda_n z)\right]$$

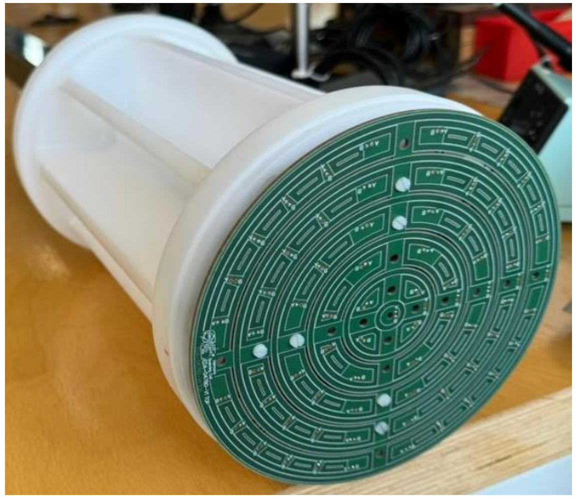
$$+ I_1(\lambda_n r)\left[A_{1,n}\cos(\varphi) + B_{1,,n}\sin(\varphi)\right]\left[F_{0,n}\cos(\lambda_n z) - E_{0,n}\sin(\lambda_n z)\right]$$

$$\Delta x = \frac{1}{\frac{\partial B_z}{\partial r}|_{m=0}}\left(\frac{1}{\pi}\int_0^{2\pi}\Delta B_z(r,\varphi,z)\cos(\varphi)\,\mathrm{d}\varphi\right)$$

$$\Delta y = \frac{1}{\frac{\partial B_z}{\partial r}|_{m=0}}\left(\frac{1}{\pi}\int_0^{2\pi}\Delta B_z(r,\varphi,z)\sin(\varphi)\,\mathrm{d}\varphi\right)$$

Magnetic axis coordinates estimated from the dipole term $\Delta B_z(r,\varphi,z)$ (feed-up of the harmonics).





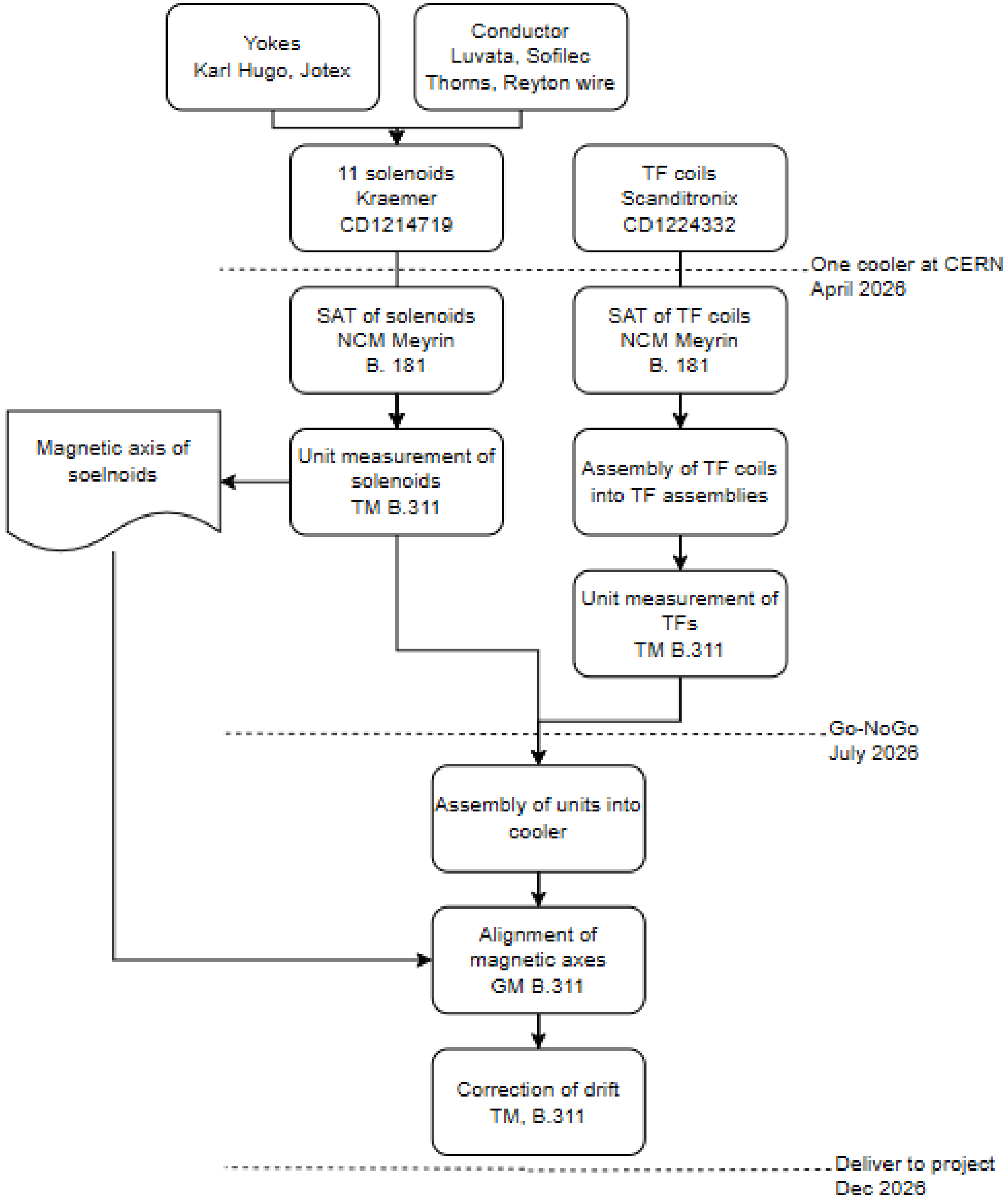
# Project roadmap

## Contract 1 – 11 solenoids

- 1+1 Drift, 4+1 Arm, 1+1 expansion, 1+1 squeeze
- Launched with Krämer Aug 24
- Batches to be delivered Nov 25 to Aug 26
- Free issued shields and conductor reduced total price

## Contract 2 – TF region coils

- 6+1 small racetracks, 6+1 large racetracks, 4+1 steerers
- Launched with Scanditronix Sept 24
- Manufacturing file accepted
- Batches to be delivered Aug 25 to Dec 25



# Conclusion

**A new AD electron cooler magnet system has been designed**

**The new design gives at least a factor 5 improvement in field quality**

**The procurement is ongoing, first coils mid this year with installation in LS3**

# Further reading

**Functional specification – EDMS 2772724**

**Engineering specification – EDMS 3014577**

**Design report and MT29 paper to follow**

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