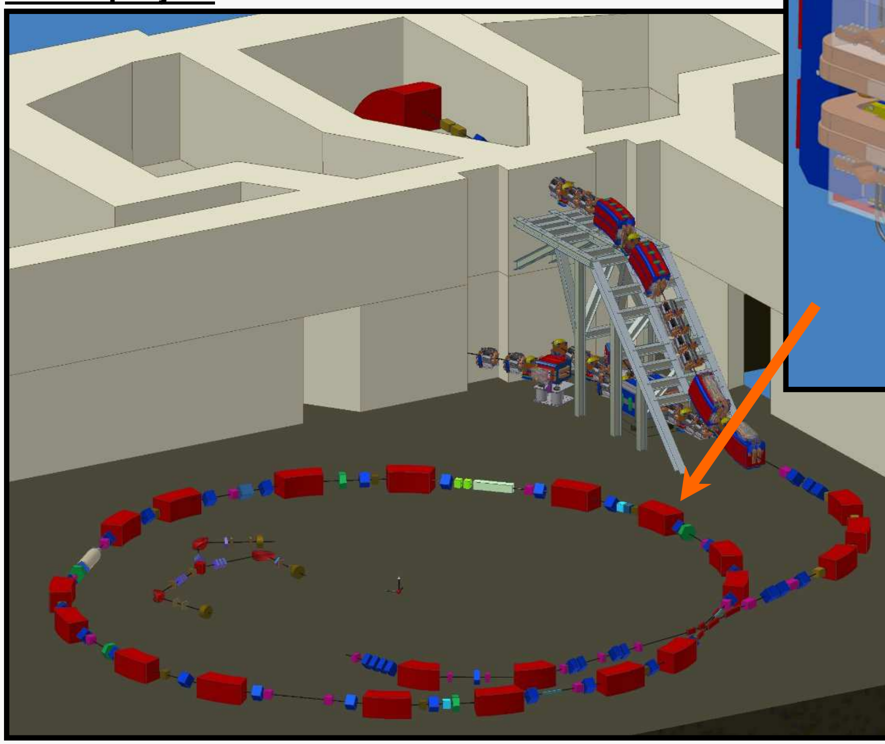
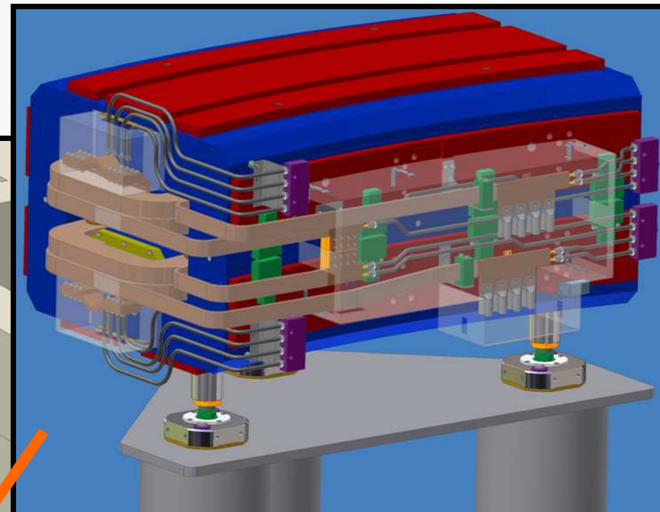
Curved fluxmeter for static and dynamic characterization of pulsed CNAO magnets

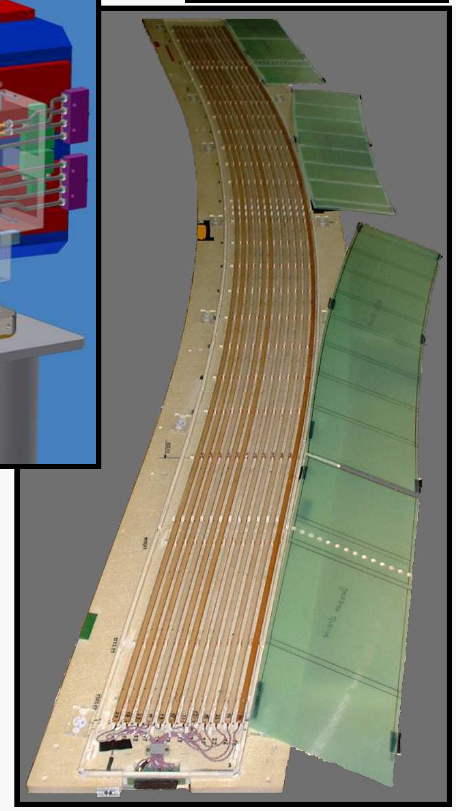
CNAO project





CNAO curved dipole

Curved fluxmeter



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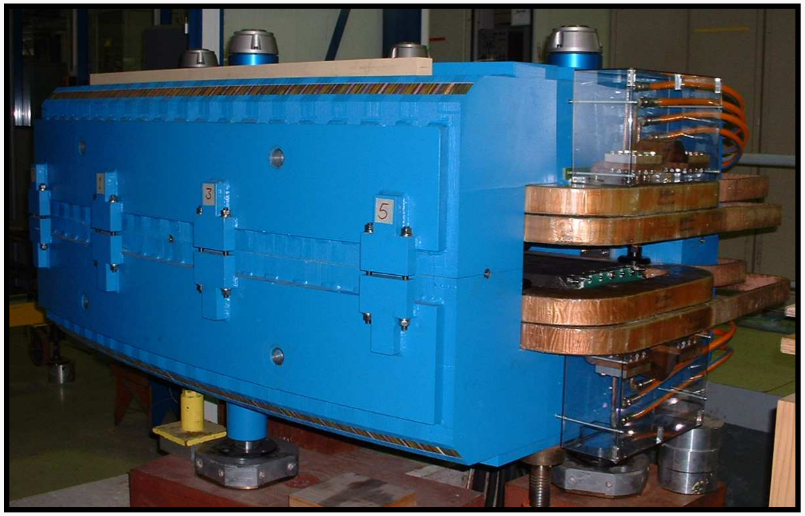
CNAO measurements: 26 curved dipoles



Nominal maximum field [T]	1.4992
Bending radius [m]	4.231
Bending angle [deg]	22.5
Magnet gap height [mm]	72
Magnetic length (@ max.) [m]	1.6772
Overall length [m]	1.9046
Good field region [mm]	± 60 (hor); ± 28 (vert)
Field Quality [ΔB/Bnom]	$\pm 2 \cdot 10^{-4}$
Nominal Current [A]	2800
Maximum Current [A]	3000
I nominal / I injection ratio	17
Field stabilization time	500 ms

- Curved fluxmetre choice :

⇒ designed to measure integrated field and its uniformity along the bent beam path.

⇒ allows small difference between the measured integrated field and the integrated field on the real trajectories of the beam.

⇒ method based on bucked signals appears to be the most appropriate for the high homogeneity of the field requested.

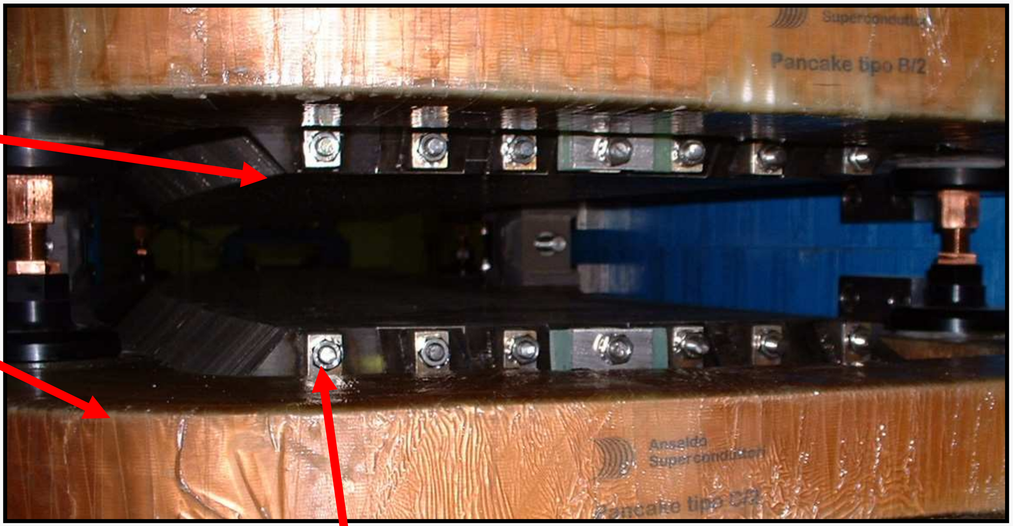
Magnet specificity: optimal homogeneity

- **Optimal homogeneity for injection current (168A) and nominal current (2800A) in the 2D design.**

Due to:

Minimun pole profil compensation to optimize homogeneity at low current.

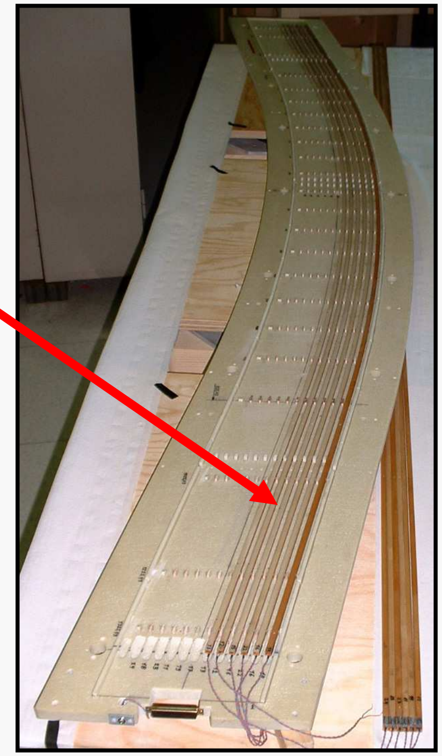
Coils positioned close to the poles to compensate the saturation of the poles at nominal current.



Disadvantage:

Limited accessibility for the shimming due to the coil positioning.

Fluxmeter making



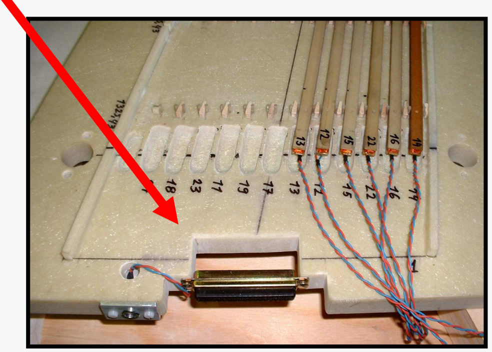
Fluxmeter

- 11 curved coils (+ 1 spare) - Coils size = 6 x 8 x 2755 mm.
Mounted on a rigid support, and maintained by glass fiber pins (15 mm spacing).

- A cover protect the coils ⇒ the reference coil can slide on it without creating any vibration on the fluxmeter's coils.

- 14 Delrin wheels ⇒ to roll the fluxmeter longitudinally.

- Connections of the coils with twisted pair cables to a CANNON connector.

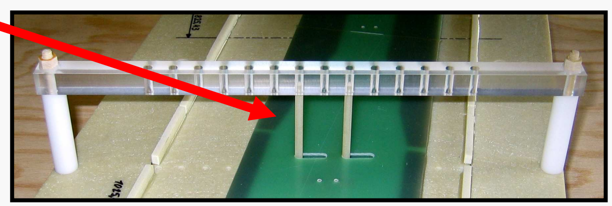


Reference coil

- Reference coil curved in the same way as the fluxmeter's coil.

- Stability guaranteed by its glass fibre support (116 mm width, 10 mm height).

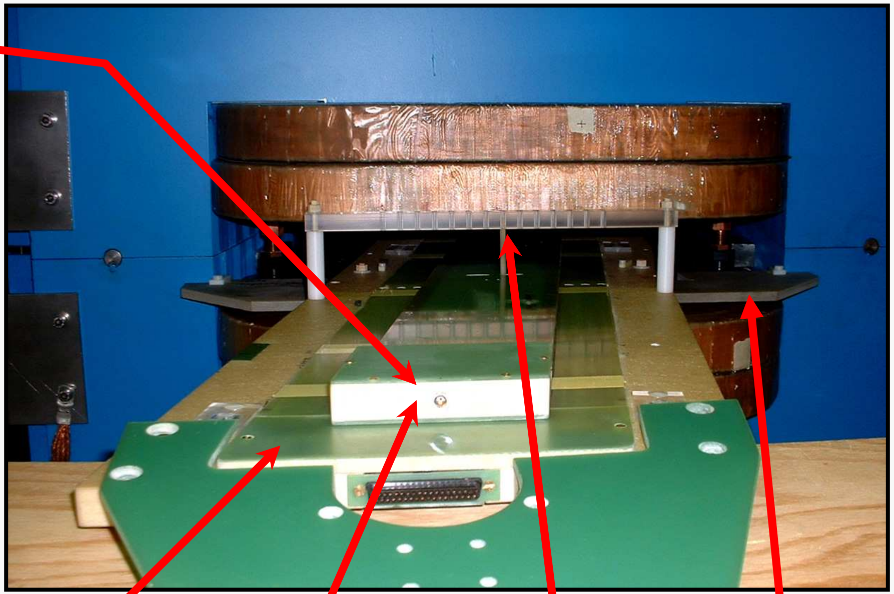
- Precise positioning of the reference coil on each coil of the fluxmeter with a system based on vertical rods .



Calibration method

The fluxmeter is cross-calibrated with respect to the additional curved reference coil.

(For CNAO application we don't need absolute field values, but a relative comparison between the 26 dipoles and the reference magnet.)



ABSOLUTE VALUES

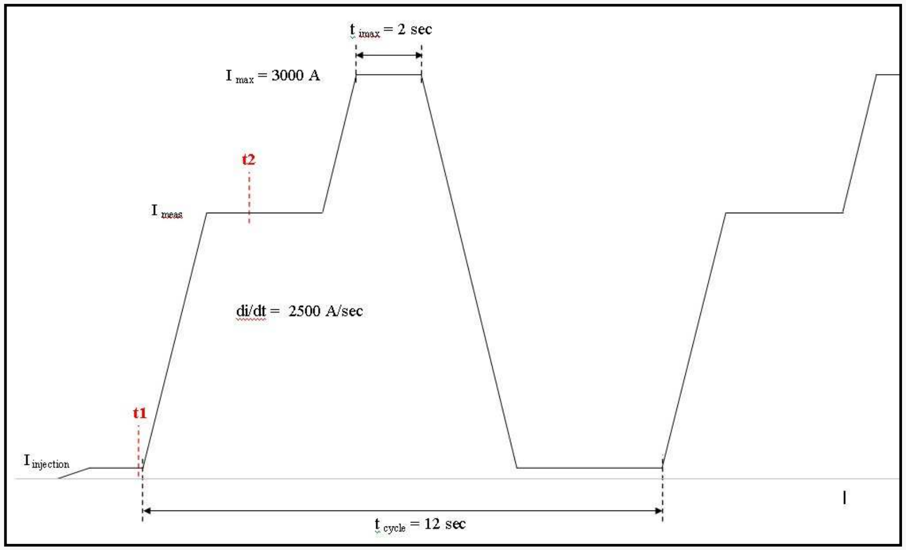
Long curved coils cannot be calibrated a CERN (calibration magnet with aperture large enough not available) so absolute accuracy is limited to few 10^{-3}.

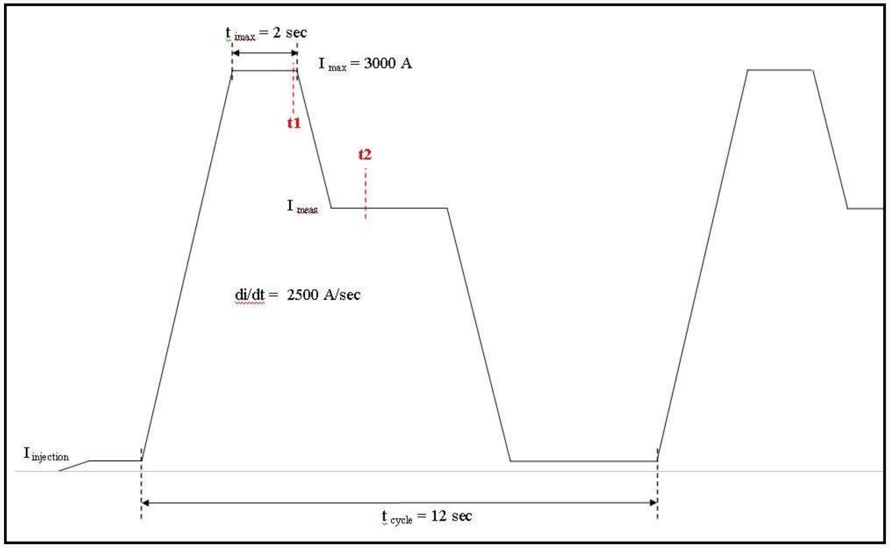
Their areas taken into account are their surfaces before being bent.

RELATIVE VALUE

By comparison with a reference coil, which can be placed next to any other, the relative accuracy of all coils is better than 10^{-4}.

Current measurement cycles used





- Field measurement done between t1 and t2 to study dynamic effects for ramp up and ramp down current.
- For every measurement the current is ramped up to the maximum current I_{max} during the cycle $\Rightarrow$ the same hysteresis cycle followed for any measurements.
- Timing precision = 1 ms (Timings handled with a VME crate).

Shimming

- Different shimming configurations tested:

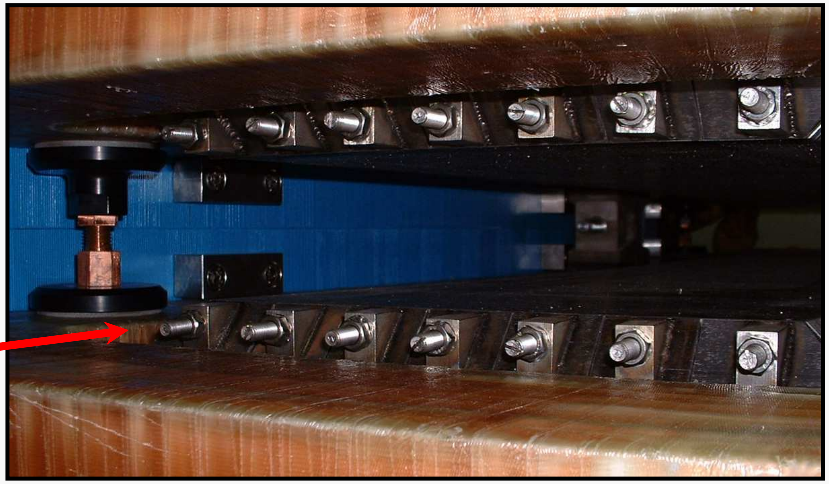
⇒ shims with **straight edge**
⇒ shims with **45° chamfers**

- With **45° chamfers** ⇒ improvement for field homogeneity over straight edge. They reduce peak fields near the end plates ⇒ but not as good as expected.

- Original shimming bolts (**magnetic**) did perturb low field close to the poles (Due to the bolt head volume).

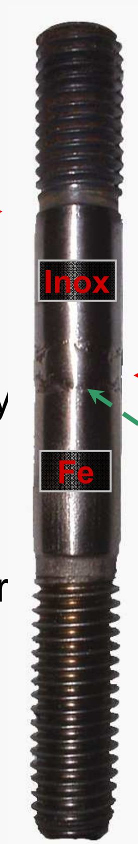
- Non magnetic (**stainless steel**) bolts did not allow to obtain an homogeneity within the specifications close to the poles (Lack of magnetic volume in the holes).

- **Bi-metal bolts** (**Fe-Inox**) did allow to fulfill the homogeneity in the total good field region.

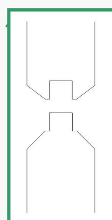


Bi-metal bolts effect on shimming

Bi-metal bolts:



Welding

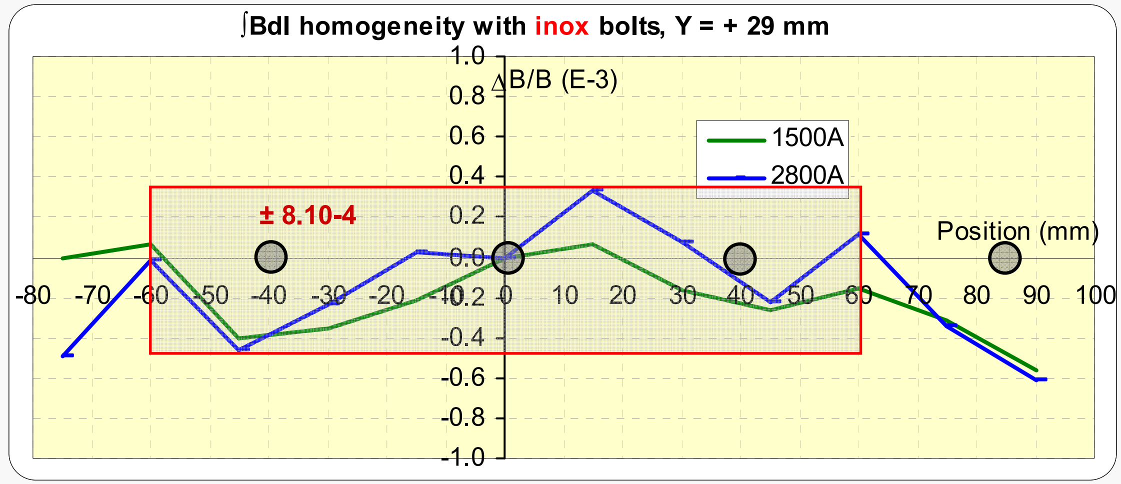


⇒ allow ± 10^{-4} field homogeneity adjustment (We couldn't obtain it only with shimming plates).

⇒ allow the magnet to fulfill the specifications for both I injection and I nominal.

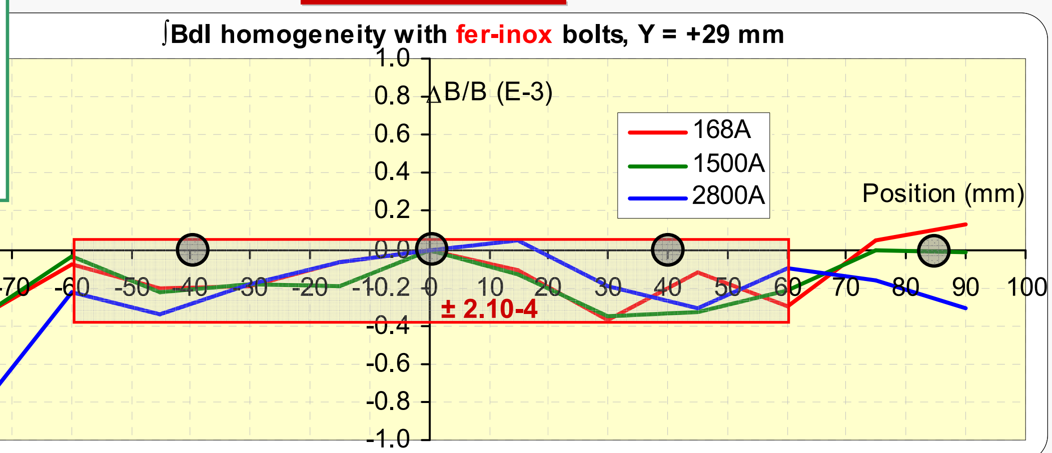
⇒ widen the good field area on the Y axis.

Inox bolts



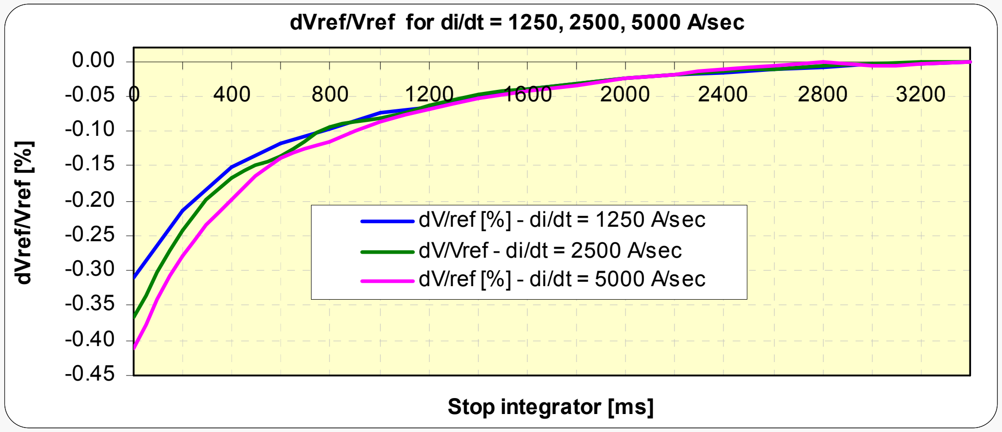
= Bolts position

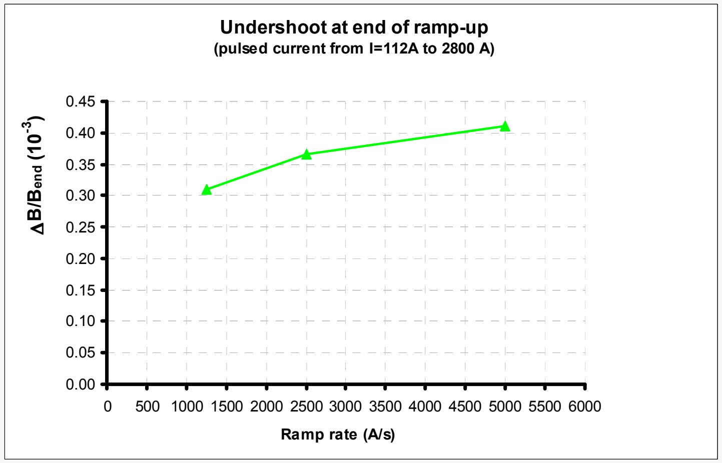
Fe-Inox bolts



Magnet dynamic behavior

- Strong Eddy current effects, field stabilized more than 2 seconds after the current flat-top start, with growing current.
- Even with phosphated metal sheets. (2nd prototype)
- Eddy current not proportional to di/dt (curves below) ⇒ CNAO magnet behaves like a short magnet.
- Needs at least 30 cycles to stabilize the remanent field ⇒ Problem due to the only hot-rolled yoke metal sheets ?
  (CNAO magnets are built using only hot-rolled metal sheets, without a following cold-rolled process as on other former magnets).

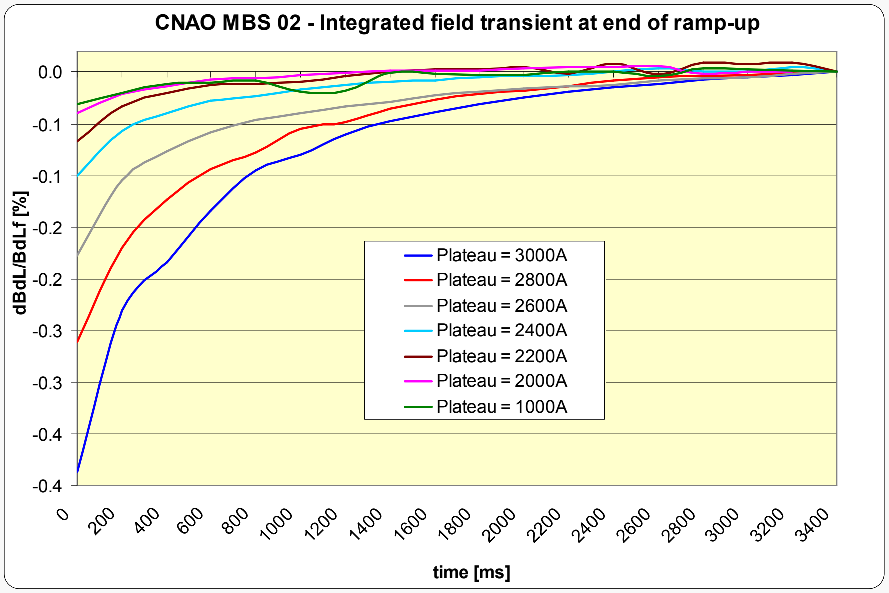


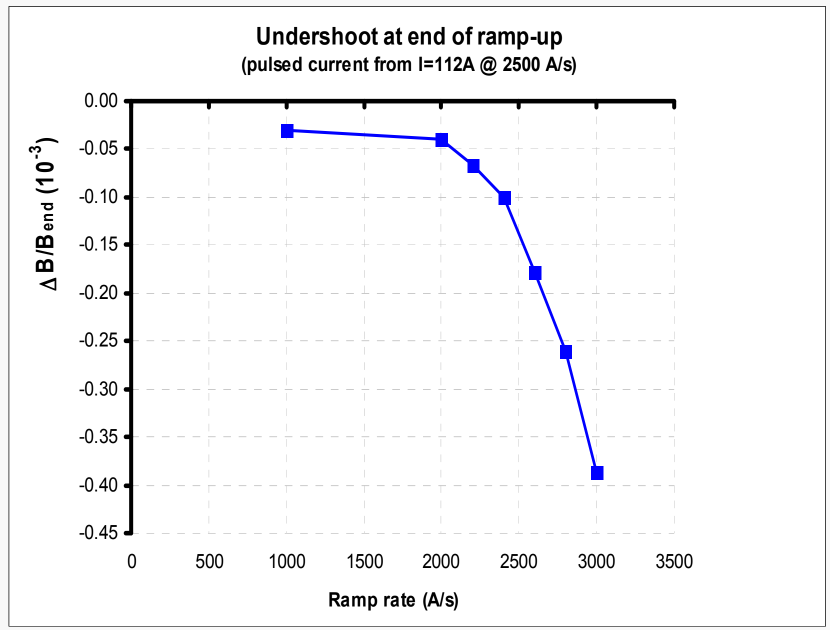


Magnet dynamic behavior

- Amplitude of the transient at the end of ramp-up (undershoot) vs. flat-top level

→ The time constant does not depend on either ramp rate or flat-top level





Eddy current with growing and decreasing current

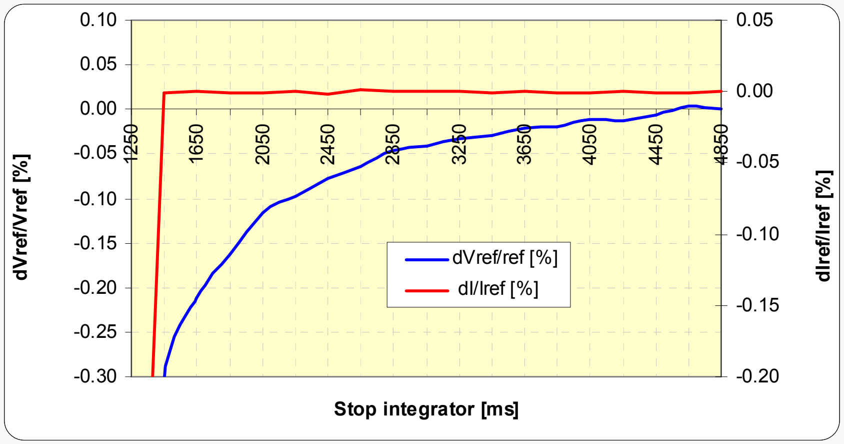
- With decreasing pulsed current, Eddy current effects are much less important. It takes 4 times less to be within 2.10^{-4} of the stabilized field.

- Due to the steel permeability curve:

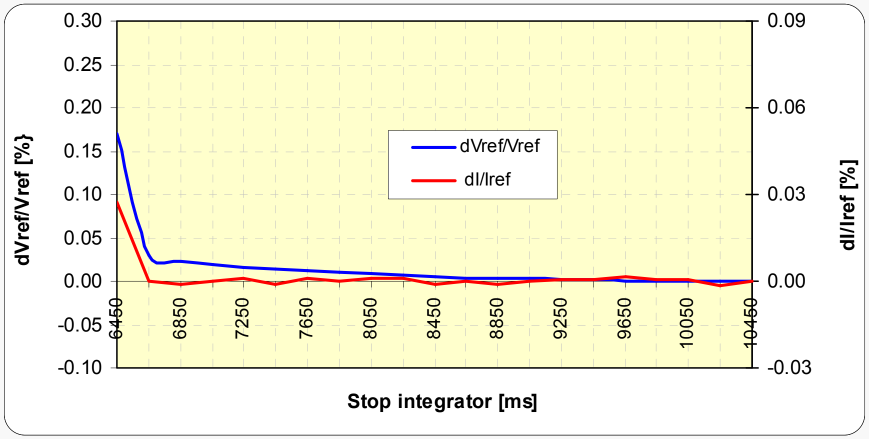
3000 A $\Rightarrow$ low permeability $\Rightarrow$ long Eddy current effects

168 A $\Rightarrow$ higher permeability $\Rightarrow$ short Eddy current effects

Eddy current with growing current from 168 to 3000 A (∫Bdl)

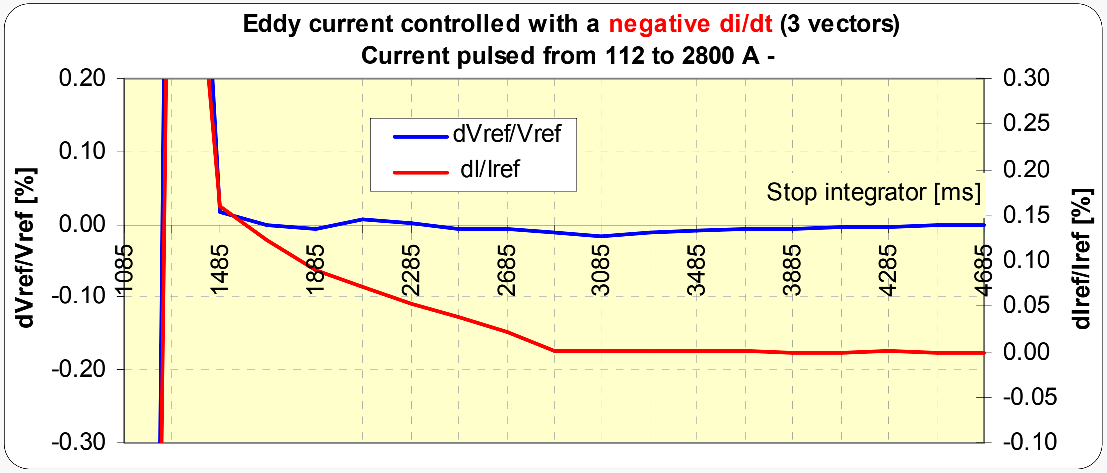


Eddy current with decreasing current from 3000 to 168 A (∫Bdl)



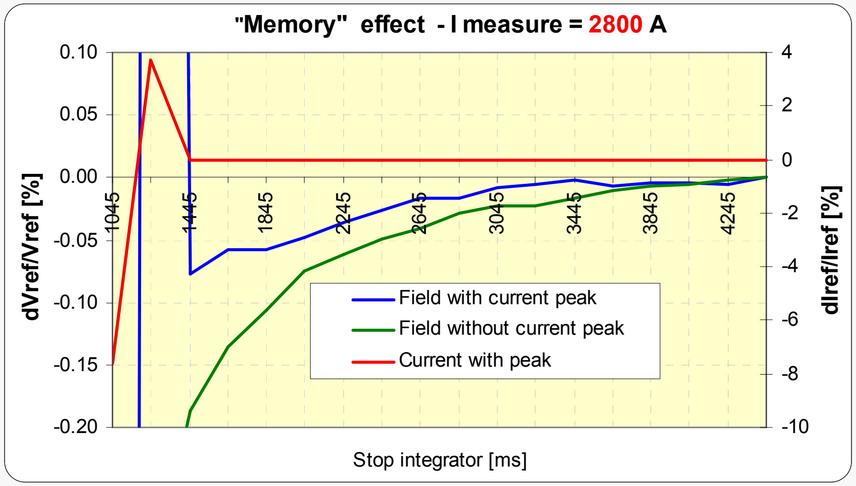
Eddy current effects controlled with a negative di/dt

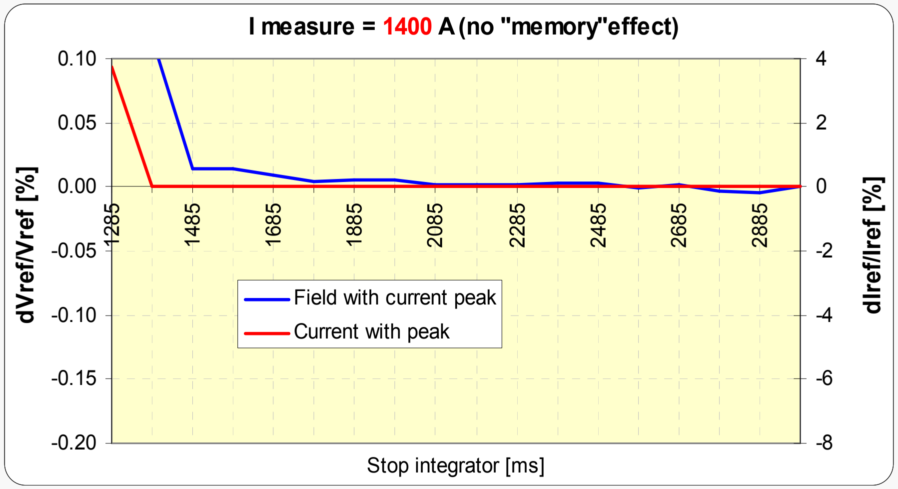
- Eddy current effects can be limited with an "over current peak" and a controlled negative di/dt (curves below).
- Limitation ⇒ each current flat-top needs its own peak et negative di/dt curve for an efficient Eddy current control.
- Finally not applicable to CNAO project because of the variety of pulsed current.



"Memory" effect

- Left curve below: magnet pulsed form 168 to 3000 A (di/dt 5000 A/sec), immediately followed with a negative ramp (di/dt - 5000 A/sec) from 3000 to 2800 A.
- After this current peak, the field curve general shape is the same than for a measure without any peak current.
- The magnet did act as if there was a "memory" effect of the Eddy currents.
- In non saturated state (1400 A curve) we can partly compensate the ramp up Eddy currents by a similar ramp down, but in a saturated state (2800 A curve) there is a "memory" of the highest Eddy currents.





Conclusion

The B-train solution for Eddy current control

- Real-time field measurement fed back to machine control system (closed loop).
- Real-time field adjustment $\Rightarrow$ allows to always obtain the wanted field, independently of the last current cycle used.
- Automatic compensation of short term as well as long term drifts and better reproducibility.
- Eddy current control for faster operation.
- More safety for patients

Efficiency of bi-metal bolts for high quality homogeneity adjustment