# Low level control for the HIE- ISOLDE High Resolution Separator magnet

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# Introduction

Scope: To upgrade the field control system for the High Resolution Separator (HRS) magnets in order to achieve better performances for HIE-ISOLDE.

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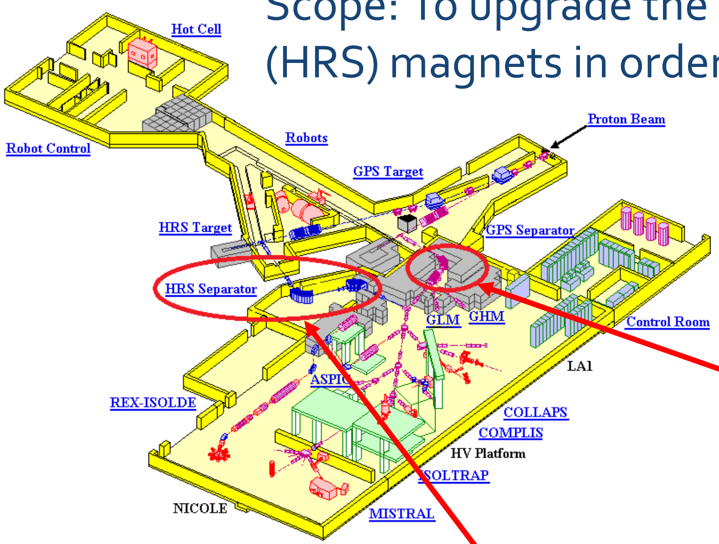


What is the HRS?

Two magnets forming one of ISOLDE's two mass separators

HRS= High Resolution Separator (90° and 60° magnet )

GPS= General Purpose Separator (70° magnet )

# Presentation Overview

1) Update pre-LS1 system to the CERN BE/CO standard

2) Study of a new control algorithm

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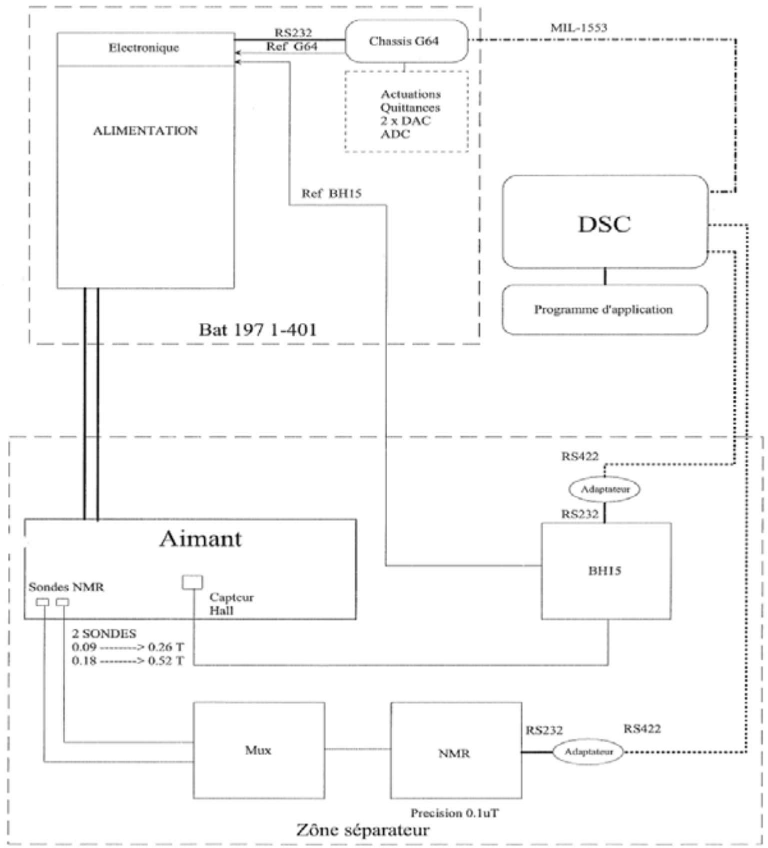
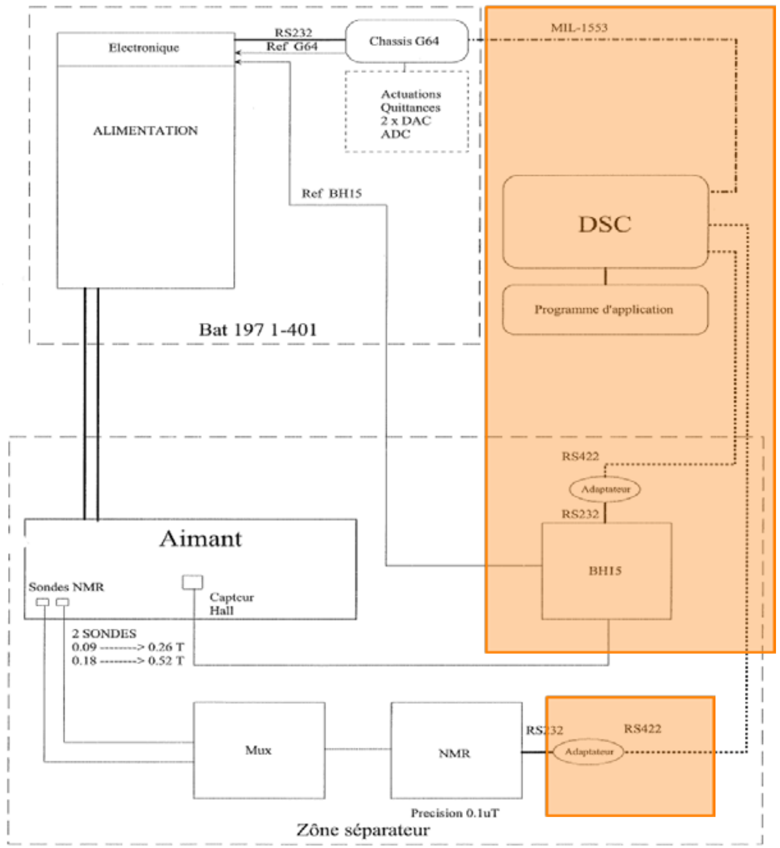
# Control system update plan




HRS Hardware scheme

# Control system update plan




HRS Hardware scheme

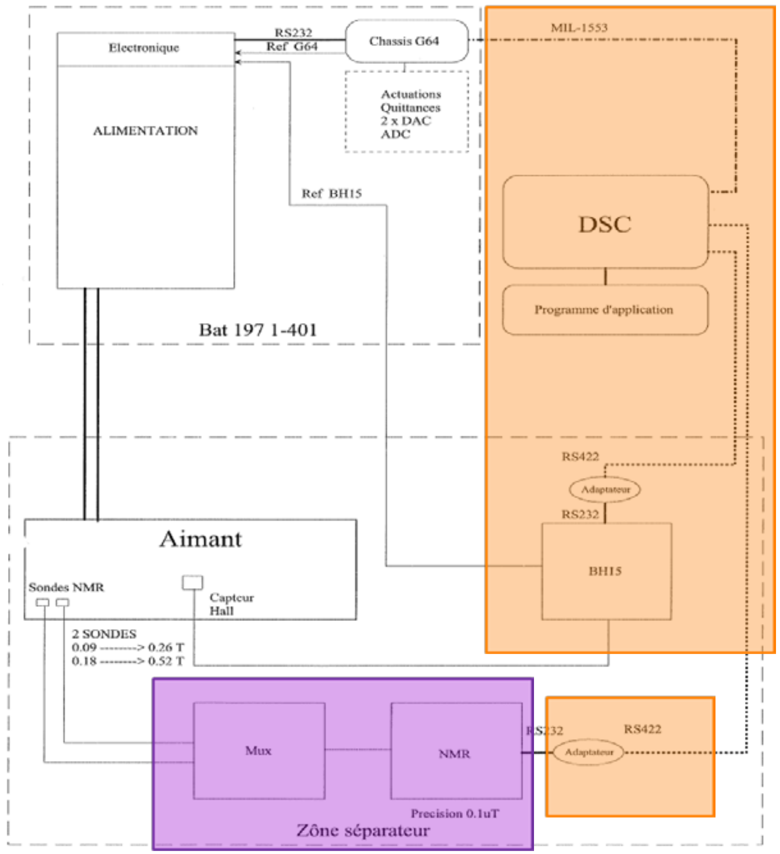
## During LS1

The obsolete $VME\ MIL - 1553$ bus master card replaced by new $PCI\ MIL -$ 1553 bus master card

Real time GM classes ($powvrt$ - $hrsmagrt$) replaced by FESA3 classes

NMR communication protocol ($RS232$) replaced by $GPIB$ protocol

# Control system update plan




HRS Hardware scheme

## When available

$PT2025$ replaced by $PT2026$ ($more\ precise\ \&\ faster$)

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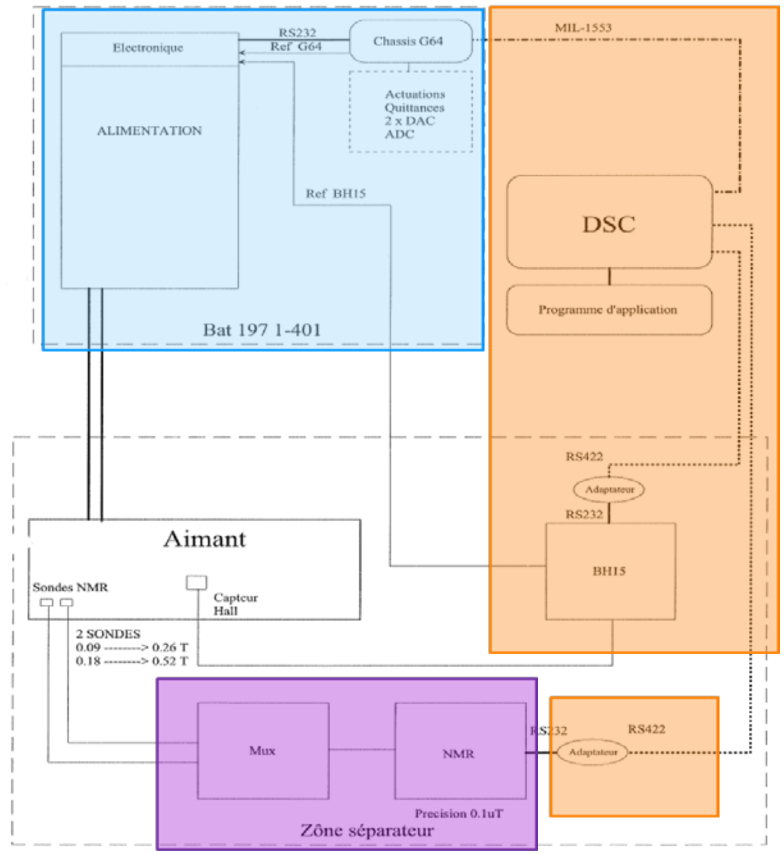
# Control system update plan

## Possibly in 2016

Power supply and $G64$ crate substituted by $FGC3$

## When available

$PT2025$ replaced by $PT2026$ ($more\ precise\ \&\ faster$)




HRS Hardware scheme

## During LS1

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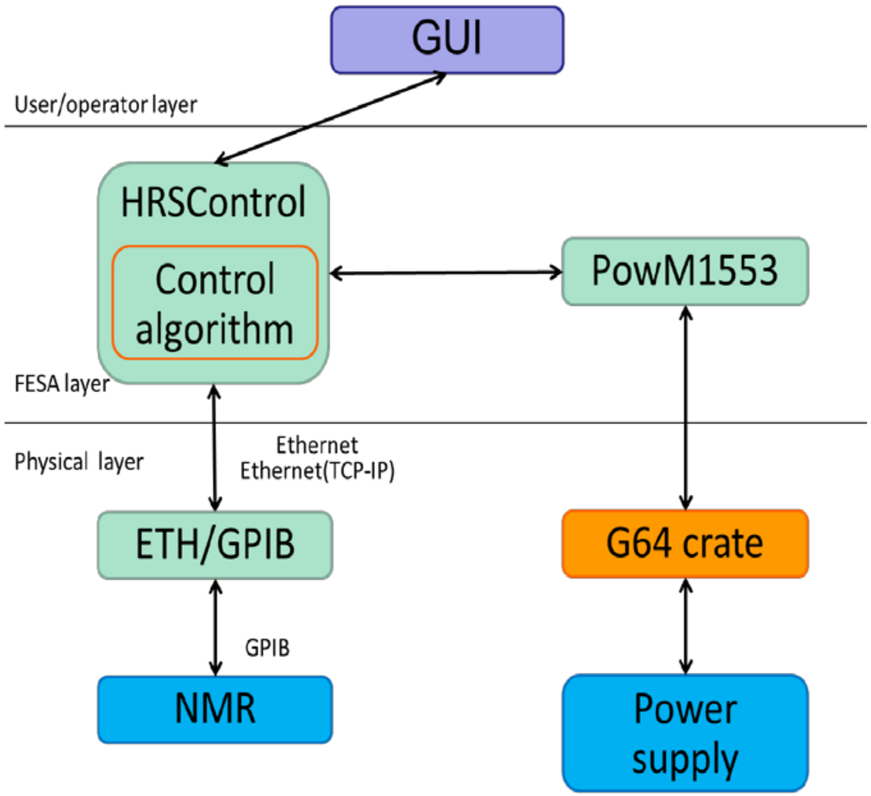
# Control system update details




Communication system overview

- FESA is a CERN-wide framework for equipment-specialists to develop real-time control software
- The HRSControl FESA3 class
  - uses the pre-LS1 field control algorithm.
  - interacts through BE/CO functions with:
    - GUI
    - $PowM1553$ $FESA3$ class
    - NMR $FESA3$ class
- The new Ethernet/GBIP driver allows faster communication with the teslameter.
- The FESA classes are instantiated on Kontron Front End Controller (FEC) industrial computers.

# Control system update: new FESA classes

- The new $FESA3$ classes (NMR and HRS) are developed and instantiated
- Old user attributes remain unchanged
- New functionalities added:
  - Possibility to check the NMR status words
  - Possibility to reset the NMR by software
  - Possibility to change the device connected (NMR, PowM1553 class) without stopping the class
  - A time stamp and measurement status have been added to the NMR value

**HRSControl**

**PROPERTIES**

*USER/EXPERT*
+ UserSettings
+ PowMAcquisition
+ FgcAcquisition
+ NmrAcquisition

*EXPERT ONLY*
+ ExpertSettings
+ ExpertManControlSetting
+ PowMExpertSetting
+ FgcExpertSetting
+ NmrExpertSettin

**METHODS**
+ Real_time_action RunControl
+ Real_time_action CheckRbacToken

**NMR**

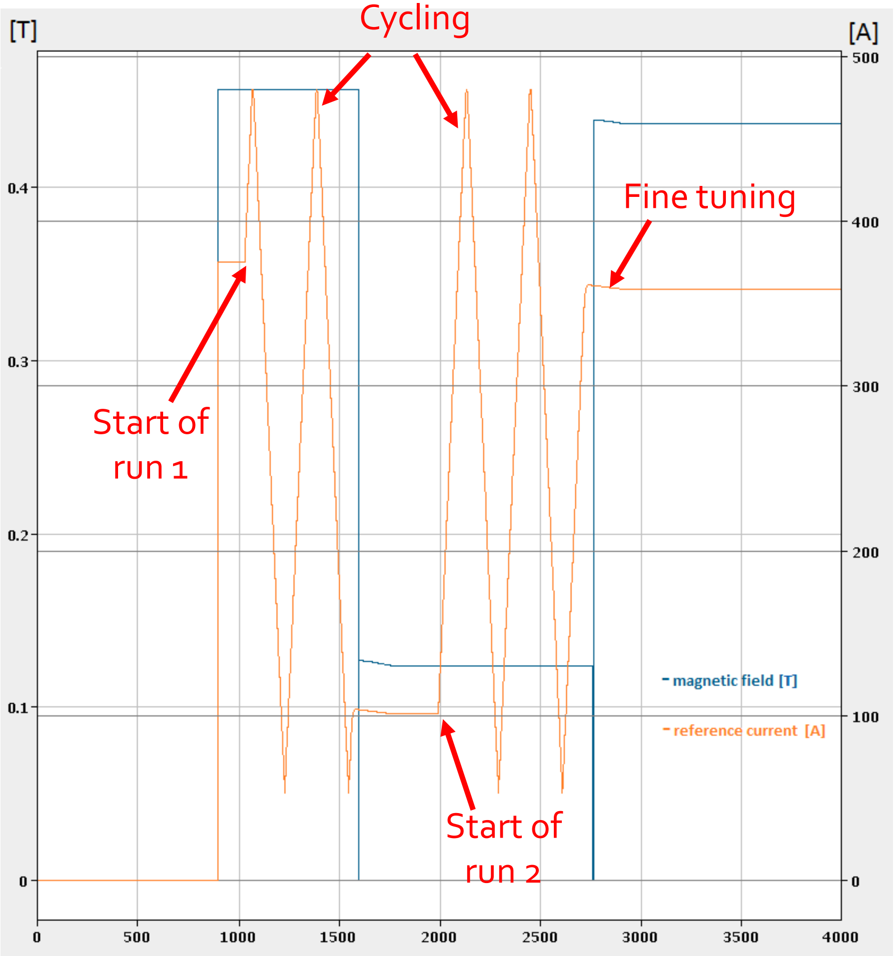
**PROPERTIES**

*USER/EXPERT*
+ fieldMeasure
+ fieldStatus
+ fieldTimestamp

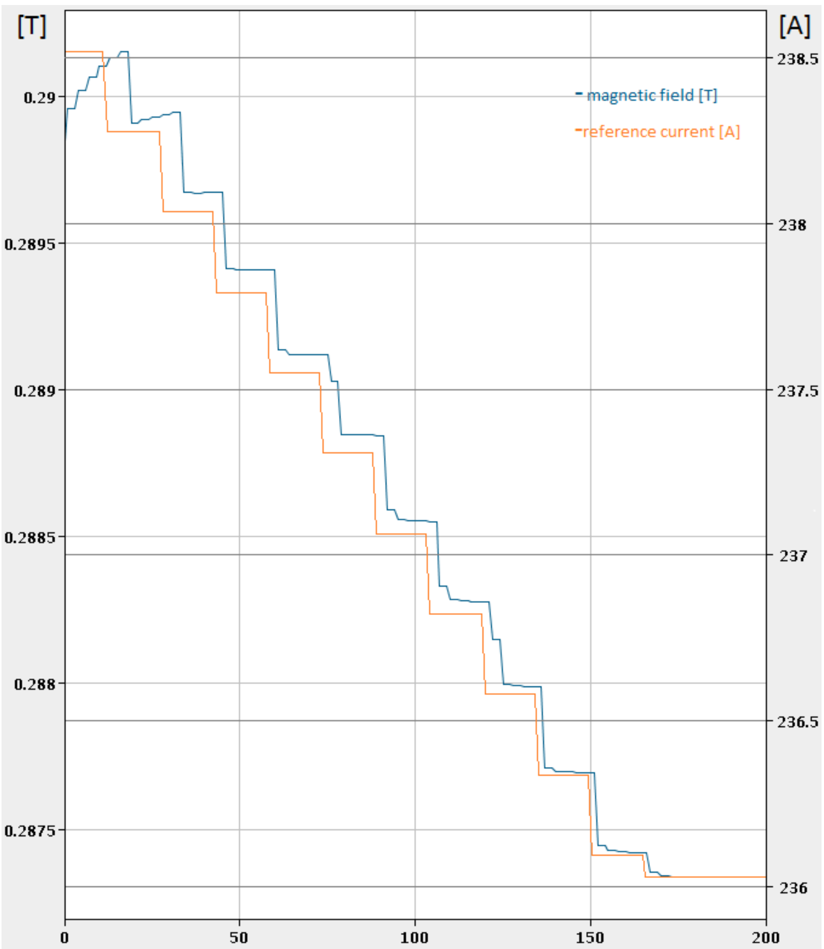
*EXPERT ONLY*
+ reset

**METHODS**
+ Real_time_action Read
+ Real_time_action Reset

# Control system update: operational results




HRS magnet 90 cycling example




HRS magnet 90 fine tuning example

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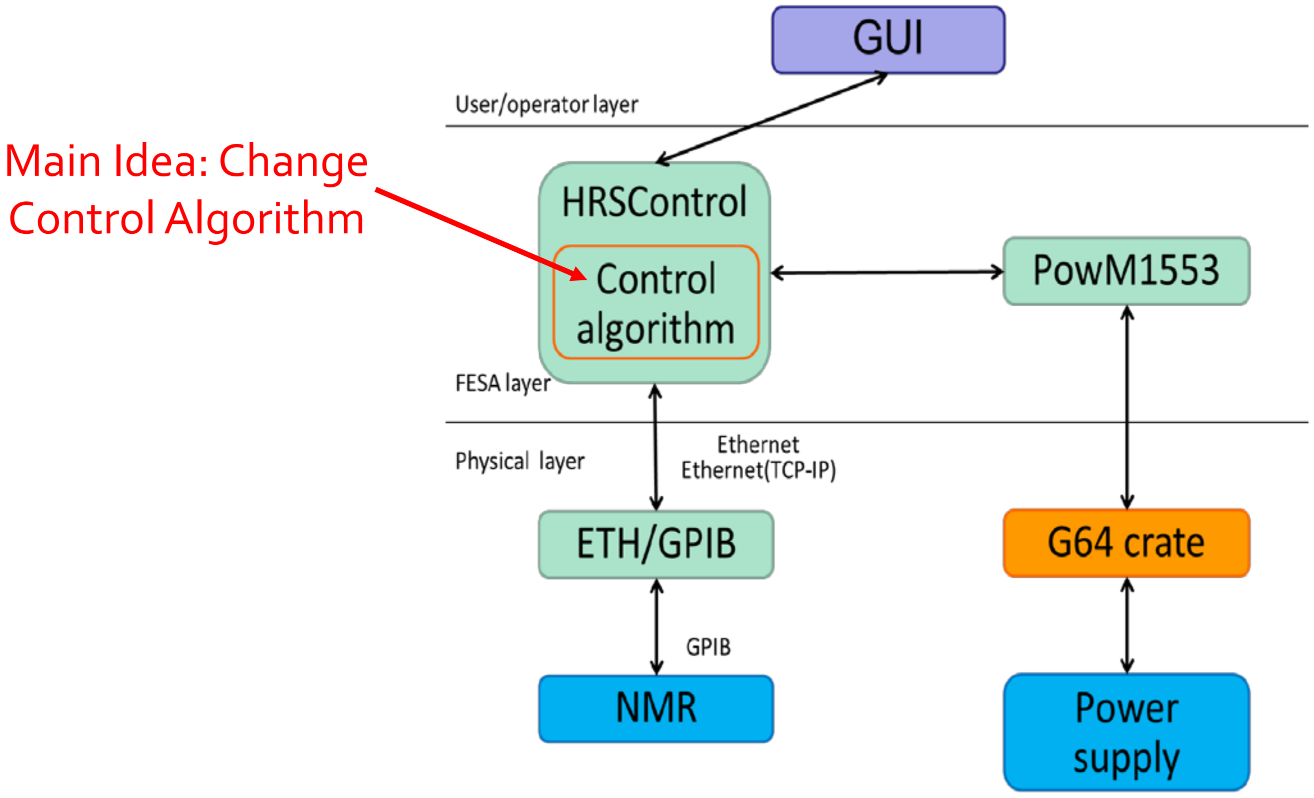
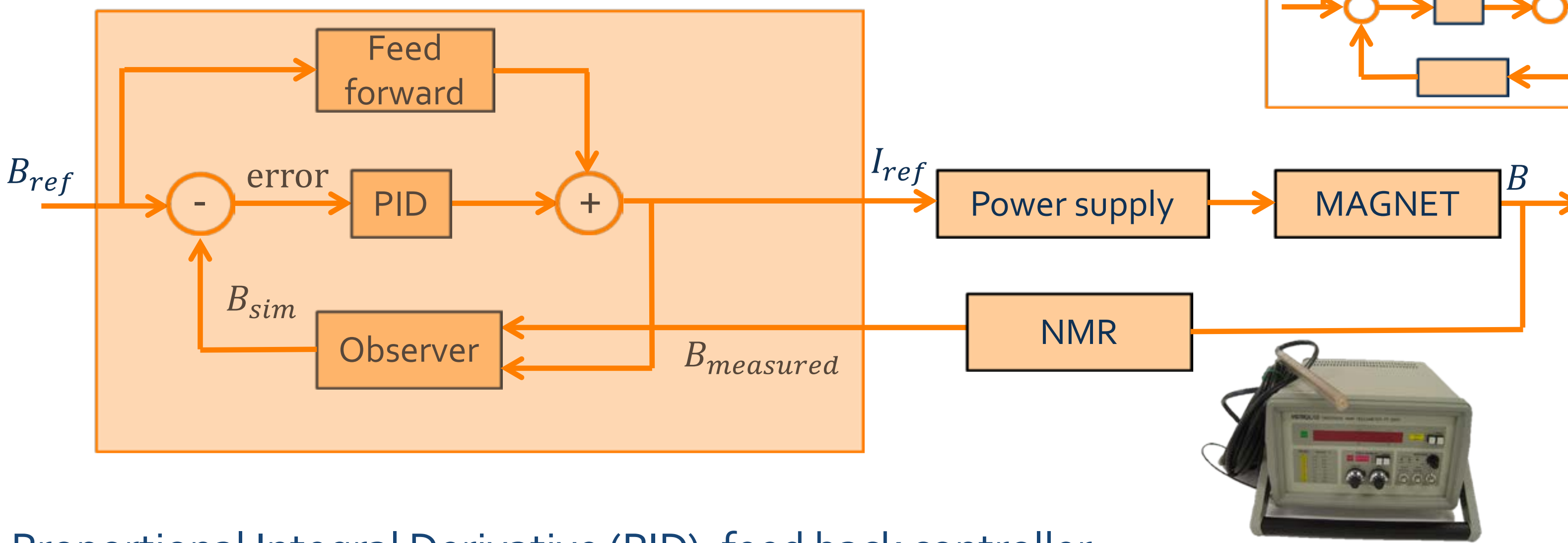
2) Study of a new control algorithm

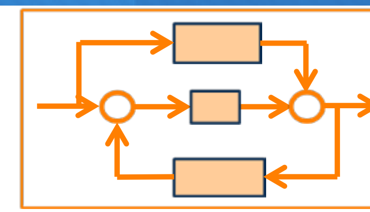
# New control system: Introduction



# New control system: Algorithm

Algorithm overview:

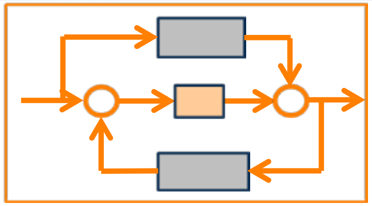


Teslameter PT2025

- Proportional Integral Derivative (PID): feed back controller
- Observer: combines measurements with model estimation
- Feed forward: consists of the a priori knowledge of the system (magnet model)
- Pre-cycle could no longer be used since the hysteresis model has no memory

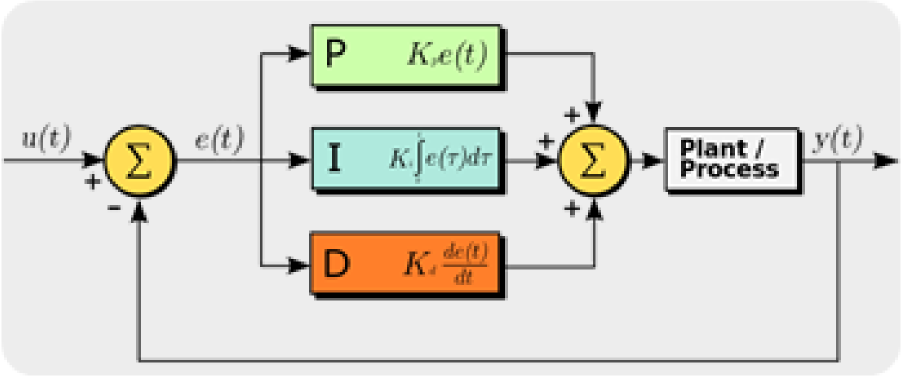
# New control system: PID controller



AIM: monitor and modify the system process variable to reduce the difference between the desired value u(t) and the system output y(t)

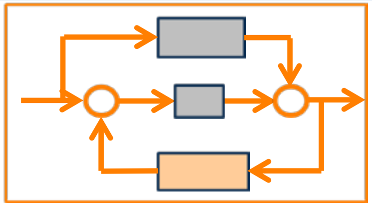
$$i(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt}$$

$K_p = proportional\ gain;$
$K_i = integral\ gain;$
$K_d = differential\ gain.$




$u(t) = B_{ref}\ and\ y(t) = B_{meas}\ by\ NMR$

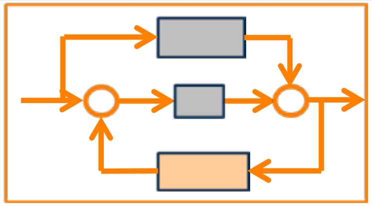
# New control system: observer



WHY: estimation of  the magnetic field value

- High frequency magnetic field evaluation
- Improve precision

# New control system: observer



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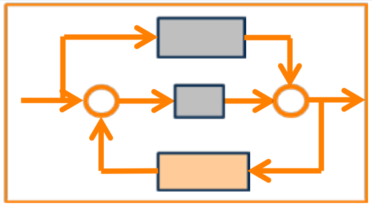
HOW:

- Use observer to combine:
  - available measurements
  - model field estimates

# New control system: observer



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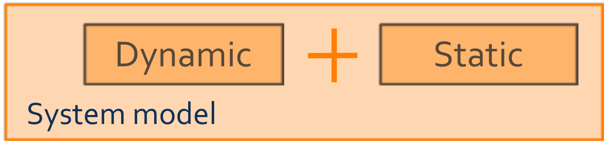


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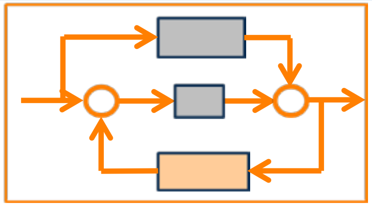
- Model comprises 2 subsystems:

# New control system: observer



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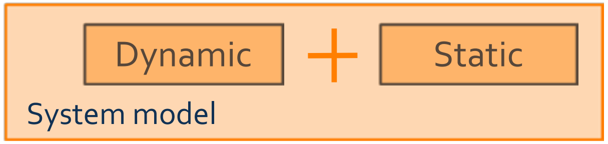
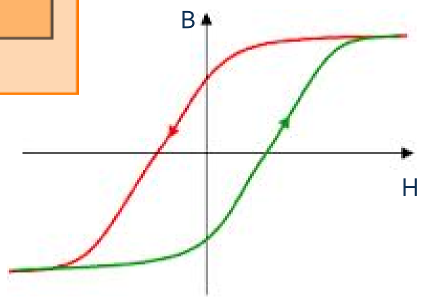
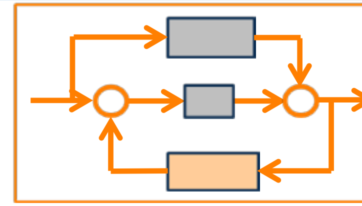



HOW:

- Use observer to combine:
  - available measurements
  - model field estimates
- Model comprises 2 subsystems:
  - Static: Coleman-Hodgdon hysteresis model (modified Duhem model)

# New control system: observer



WHY: estimation of the magnetic field value

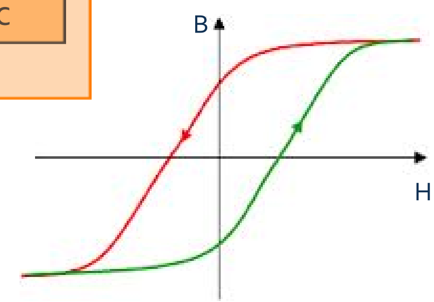
- High frequency magnetic field evaluation
- Improve precision

HOW:

Dynamic + Static

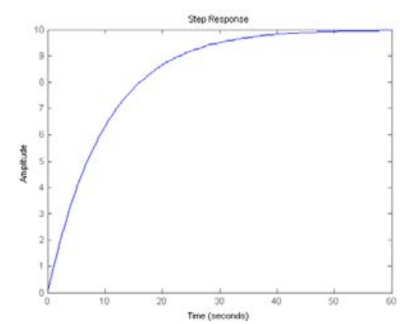
System model

- Use observer to combine:
  - available measurements
  - model field estimates
- Model comprises 2 subsystems:
  - Static: Coleman-Hodgdon hysteresis model (modified Duhem model)
  - Dynamic: First order model of the system delay: $G(s) = \frac{k}{1 + \tau s}$

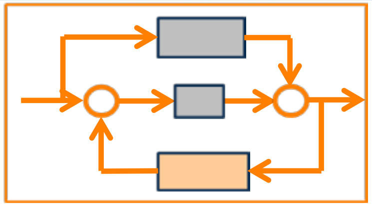



Where: $k$ = system gain

$\tau$ = system time constant



# New control system: observer model



## COLEMAN-HODGDON MODEL

$$\dot{B} = C_\alpha |\dot{H}| [f(H) - B] + \dot{H} g(H)$$

Where: B = magnetic flux f(H) = odd, monotone increasing, real valued function
H = magnetic field g(H) = even, real-valued function

- Ordinary differential equation hysteresis model
- Physical model
- Unidirectional
- Large variety of hysteresis shapes according to f(H) and g(H)
- Rate independent
- Counterclockwise

Soft ferromagnetic model

$$f(\mathrm{H}) = \begin{cases} Ca[H + H^*] - bH^* & for\ H < -H^* \\ bH & for\ H < -H^*\ and\ H > H^* \\ Ca[H - H^*] + bH^* & for\ H > H^* \end{cases}$$

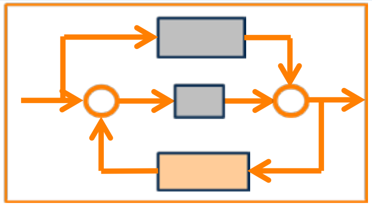
$$g(H) = \begin{cases} u & for\ -H^* \leq H \leq H^* \\ Ca & for\ H < -H^*\ and\ H > H^* \end{cases}$$

Model constraints:

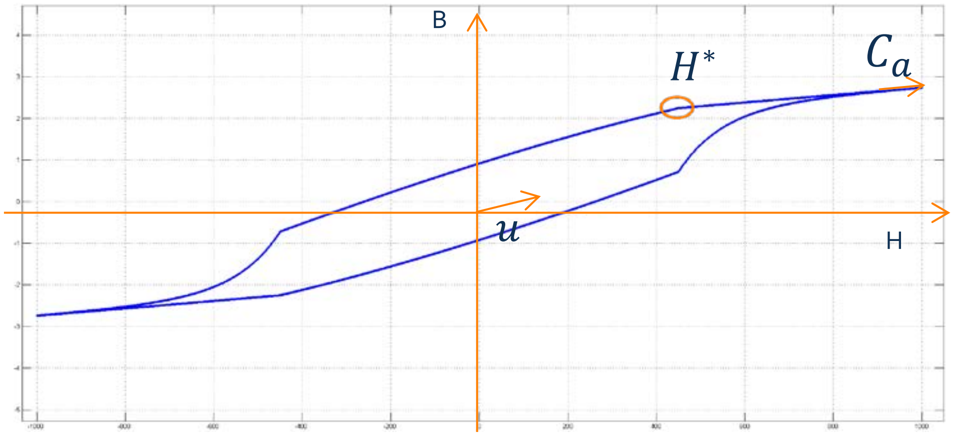
- $C_\propto, C_a, b, u, H^* > 0;$
- $b > u$
- $b - u < u[1 - e^{-2C_\propto H^*}]$
- $b - u < C_a[1 - e^{-2C_\propto H^*}]$

Observer update according to: $B = \hat{B}_{sim} + k * (B_{nmr} - \hat{B}_{sim})$

# New control system: model identification



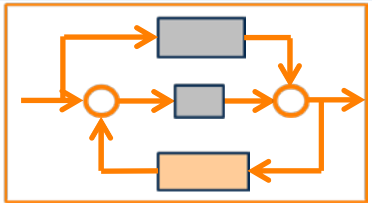
+ Off-line hysteresis parameter estimation:
  - low frequency signal input to avoid dynamics
  - detection of the parameters from main loop
  - non linear fitting (trust region to respect constraints)



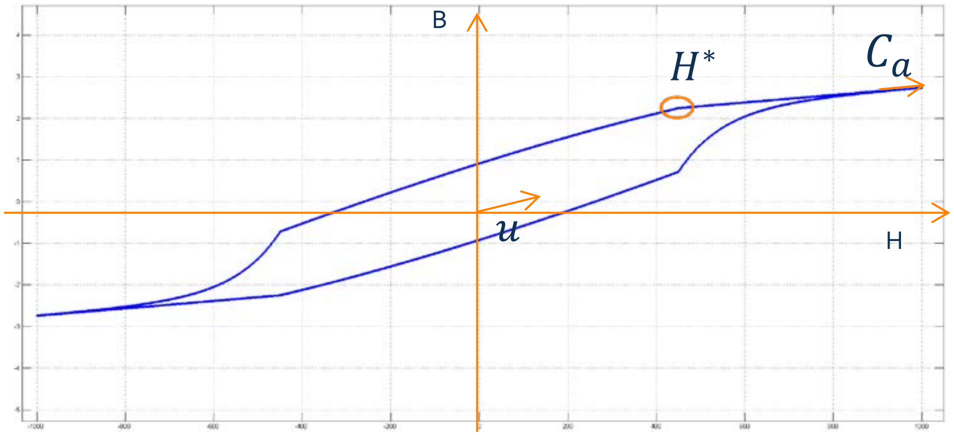

Simulated hysteresis

$H^*$ is the value of the saturation starting point
$u$ is the slope value of the hysteresis at $H = 0$
$C_a$ is the limiting slope for large H

# New control system: model identification



- Off-line hysteresis parameter estimation:
  - low frequency signal input to avoid dynamics
  - detection of the parameters from main loop
  - non linear fitting (trust region to respect constraints)
- Off-line dynamic parameter estimation
  - high frequency signals

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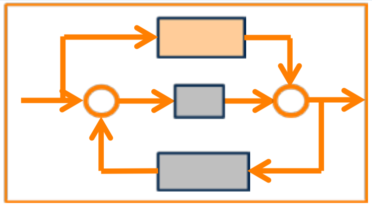

- WHY: to linearise the system by compensating nonlinearities (hysteresis)

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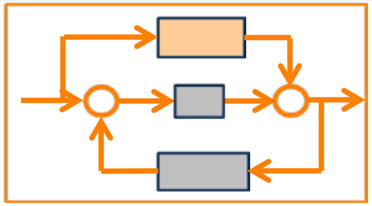
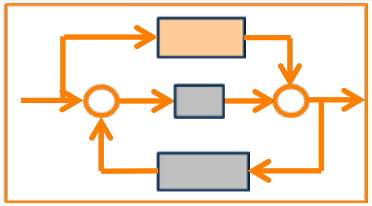


- WHY: to linearise the system by compensating nonlinearities (hysteresis)
- HOW
  - Theory: use model to predict the process input variable (current) to obtain the desired output (field)

# New control system: feed forward



- WHY: to linearise the system by compensating nonlinearities (hysteresis)
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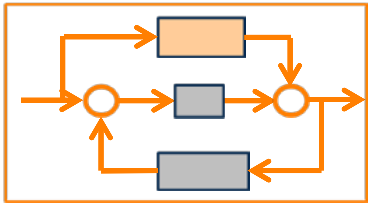
  - Practice: invert the magnet model

# New control system: feed forward



- WHY: to linearise the system by compensating nonlinearities (hysteresis)
- HOW
  - Theory: use model to predict the process input variable (current) to obtain the desired output (field)
  - Practice: invert the magnet model
    - Inversion of the Coleman-Hodgdon model using the lambert function (calculated by on-line numerical integration)

# New control system: stability

- The PID feedback loop with differential hysteresis is asymptotically stable:


Where: $d_1$ = input noise
$d_2$ = measurement noise
$r$ = reference signal

- Stability condition hypothesis
  1) If the input is continuous ⟶ output continuous
  2) The hysteresis is monotone ⟶ (ferromagnetic hysteresis)
  3) The hysteresis operator is Lipschitz
  4) The hysteresis is multi-bracket continuous
  5) The output is bounded (saturation)

The PI limiting condition ($k_d = 0$) ⟶ $0 < k_i < \frac{k_p k_i}{m_1} < \frac{k^2{}_1}{\lambda m_1}$

The PID limiting condition ⟶ $0 < k_i < \frac{k_p k_1}{m_1} < \frac{k_p k_1}{\lambda k_d}$ , $0 < k_p < \frac{m_1 k_i}{k_1} + \frac{k_1}{\lambda}$ , $0 < k_d < \frac{m_1(k_p k_1 - m_1 k_i)}{k_1^2}$

"H. Logemann B. Jayawardhana and E. P. Ryan. PID control of second order systems with hysteresis. International Journal of Control, 2008."

# New control system: Simulation

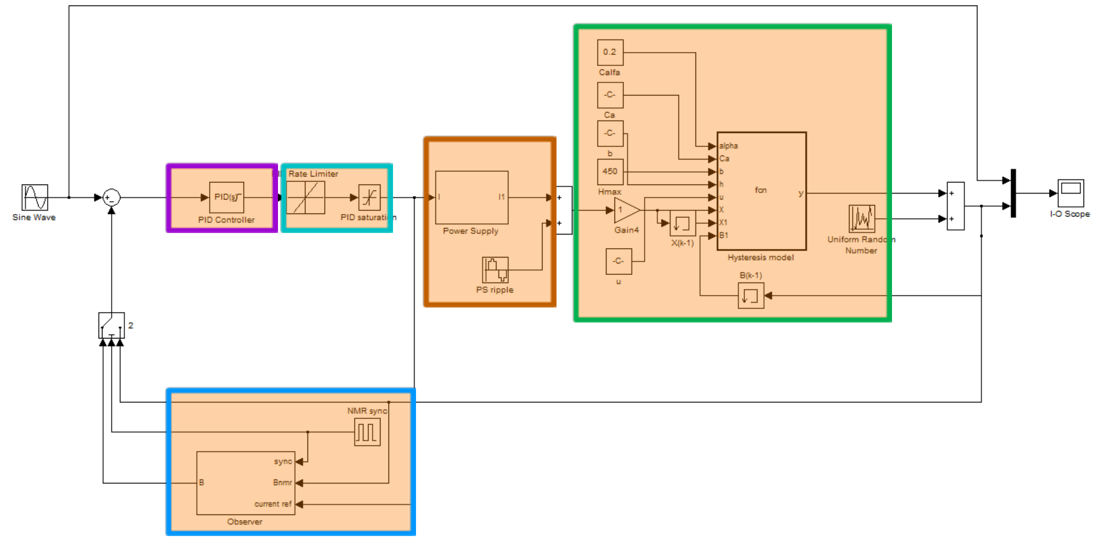
## Model simulation:

| C-H param | system | model |
|---|---|---|
| $u$ | 0.2 | 0.02 |
| $b$ | 0.0009 | 0.009 |
| $C_a$ | 0.0014 | 0.014 |
| $H^*$ | 450 | 410 |
| $C_\alpha$ | 0.0024 | 0.002 |

Hysteresis parameters table

| Dynamic param | system | model |
|---|---|---|
| $\tau$ | 30 | 40 |
| $k$ | 1 | 1 |

Dynamic parameters table




| PI constant | value |
|---|---|
| $k_p$ | 180 /500 |
| $k_i$ | 6 /30 |

PID parameters table

| saturation | value |
|---|---|
| Maximum | 500 |
| Minimum | 0 |
| slope | $5A/step$ |

Saturation parameters table

## Observer model error:

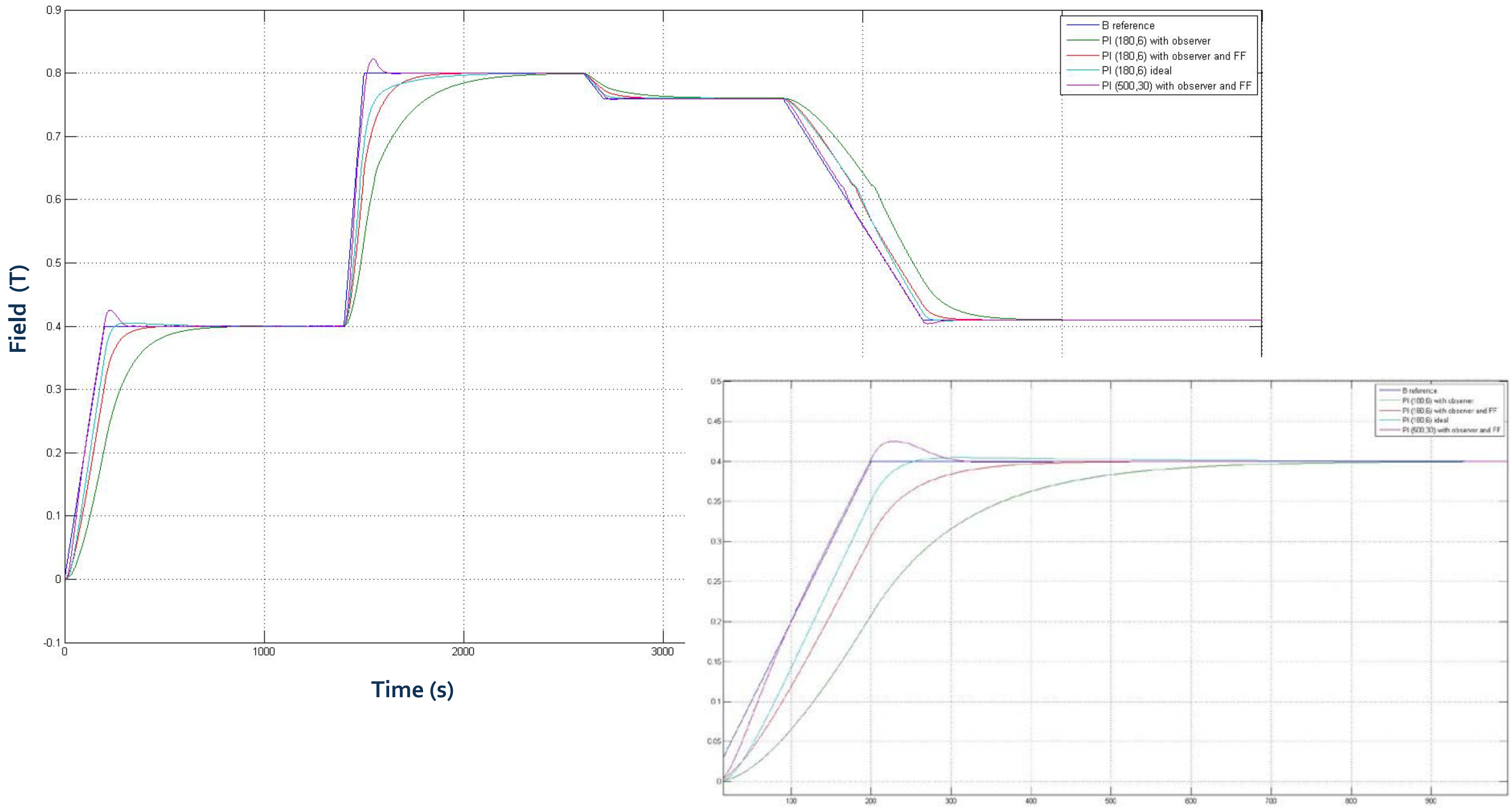
- maximum = 2.3%
- average = 0.1%

## Noise:

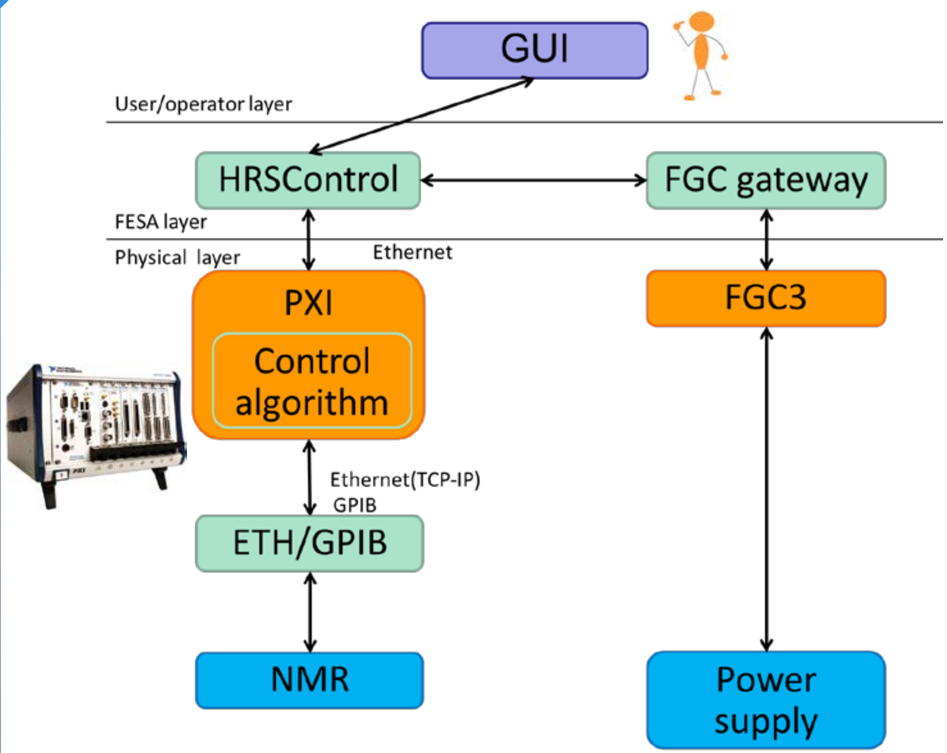
- PS: sinusoidal ripple + 3% offset error
- NMR: $WN(0,5e^{-6})$

# New control system: Simulation results

Improved control performance achievable with PID tuning



# New control system: implementation




Communication system overview

- New algorithm could be implemented in NI Labview Real Time on a PXI platform (*Fast development time*)
- The GUI would be the same as current control thanks to the FESA3 class standard interface layer.
- $FGC3$ could be used to achieve better current control

# Conclusions

- System update
  - the $FESA3$ classes have been developed
  - the $GPIB$ drivers for the NMR has been realised

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  - the $FESA3$ classes have been developed
  - the $GPIB$ drivers for the NMR has been realised

- New control algorithm study which could:
  - reduce setup time
  - be more precise

# Thank you for your attention