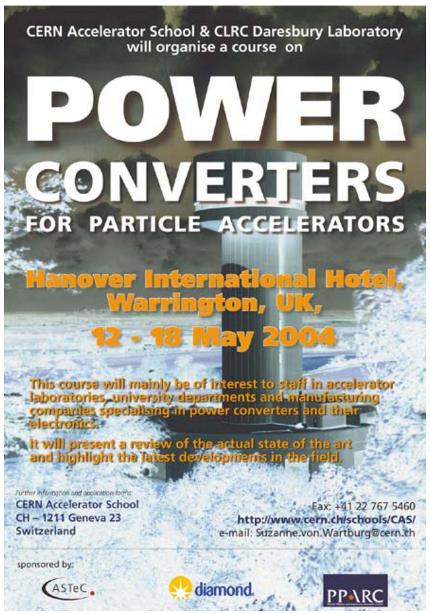
Regulation: recalls and digital loops

12-18th May 2004
Power Converters
for particle accelerators
Warrington, UK

Frédérick BORDRY
CERN



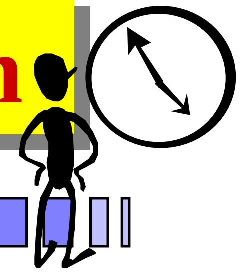
Basic recalls
(continuous and discrete domains)

Digital control system: RST algorithm

Example :LHC power converter regulation

MIMO to SISO

Continuous - time Models : Time Domain



Time Domain :

$dX/dt = F[X(t),U(t)]$; $X(to) = X(0)$

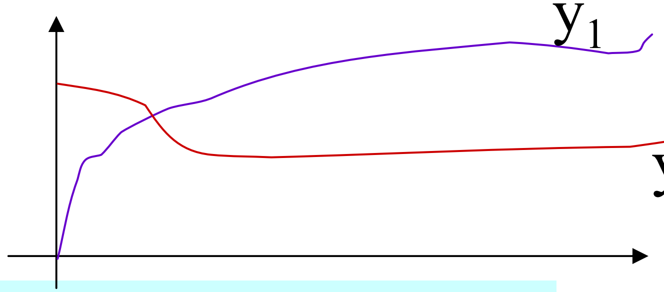
$Y(t) = G[X(t),U(t)]$

Linear system

$dX/dt = A(t).X(t) + B(t).U(t)$

$Y(t) = C(t).X(t) + D(t).U(t)$

$U(t)$ → $X(t) = [x_1, x_2, \ldots .x_n]^T$ n : system order → $Y(t)$

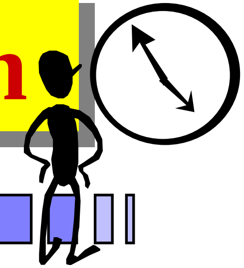


Examples : mono-input mono-output

1st order : $dy/dt = - y(t)/T + G/T\ u(t)$

2nd order : $d^2y(t)/dt^2 + 2.z.\omega_o.dy(t)/dt + \omega_o^2.\ Y(t) = \omega_o^2.\ u(t)$

Continuous - time Models : Time Domain



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Linear system

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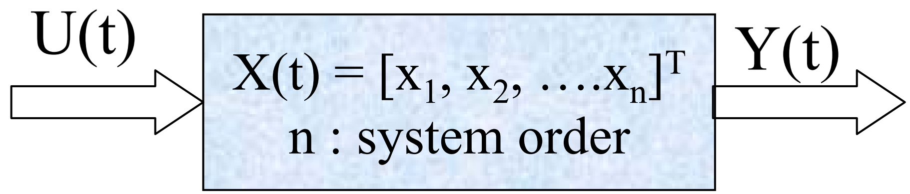
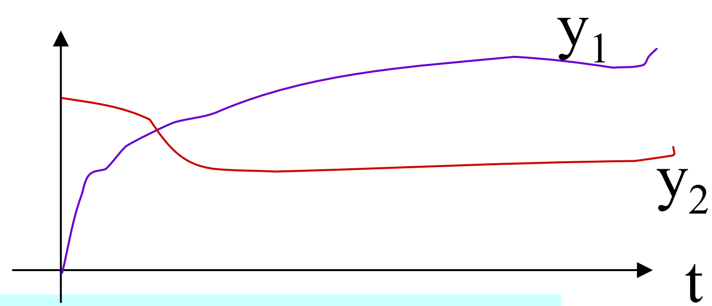
$$Y(t) \;\; = \;\; C.X(t) + D.U(t)$$





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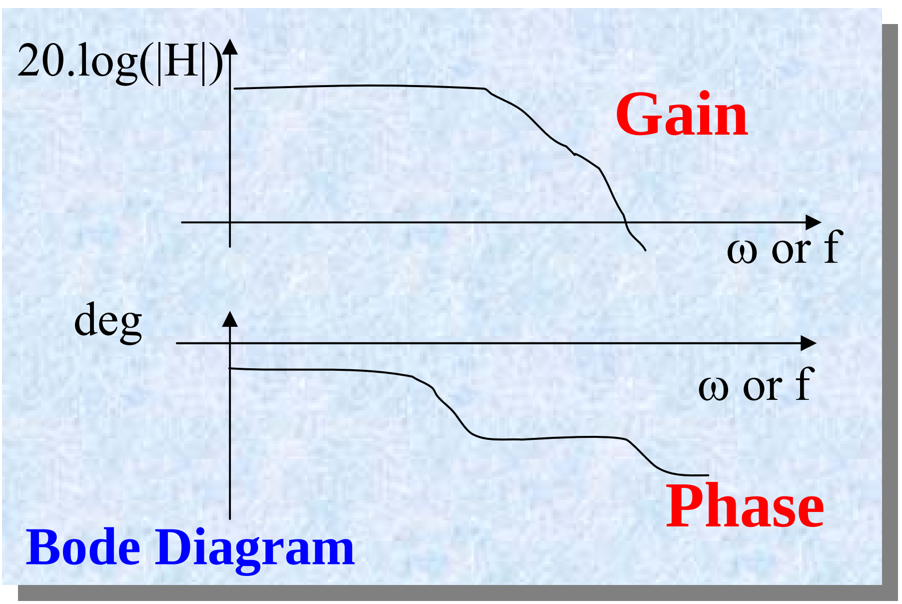
Continuous - time Models : Frequency Domain

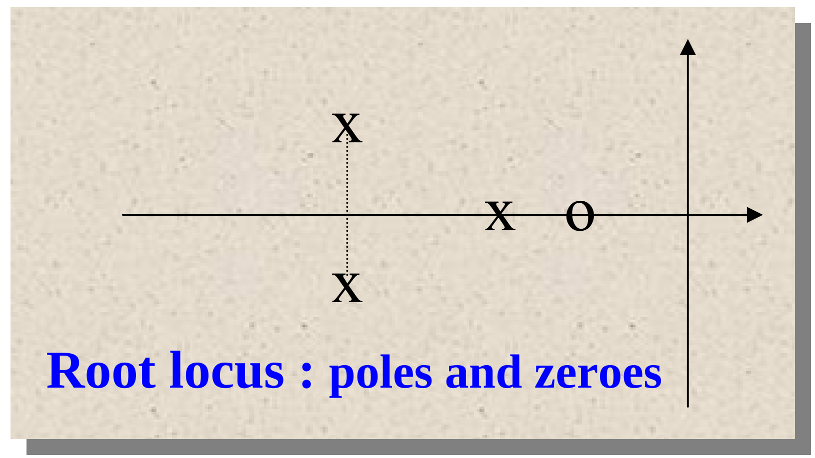
Linear system **H(s) : transfer function**

$u(t) = e^{j\omega t}$ → **System** → $y(t) = H(j\omega) \cdot e^{j\omega t}$

$u(t) = e^{st}$ → **System** → $y(t) = H(s) \cdot e^{st}$

Note:
State Equation
Differential Eq.
Transfer function
Observability,
Controllability



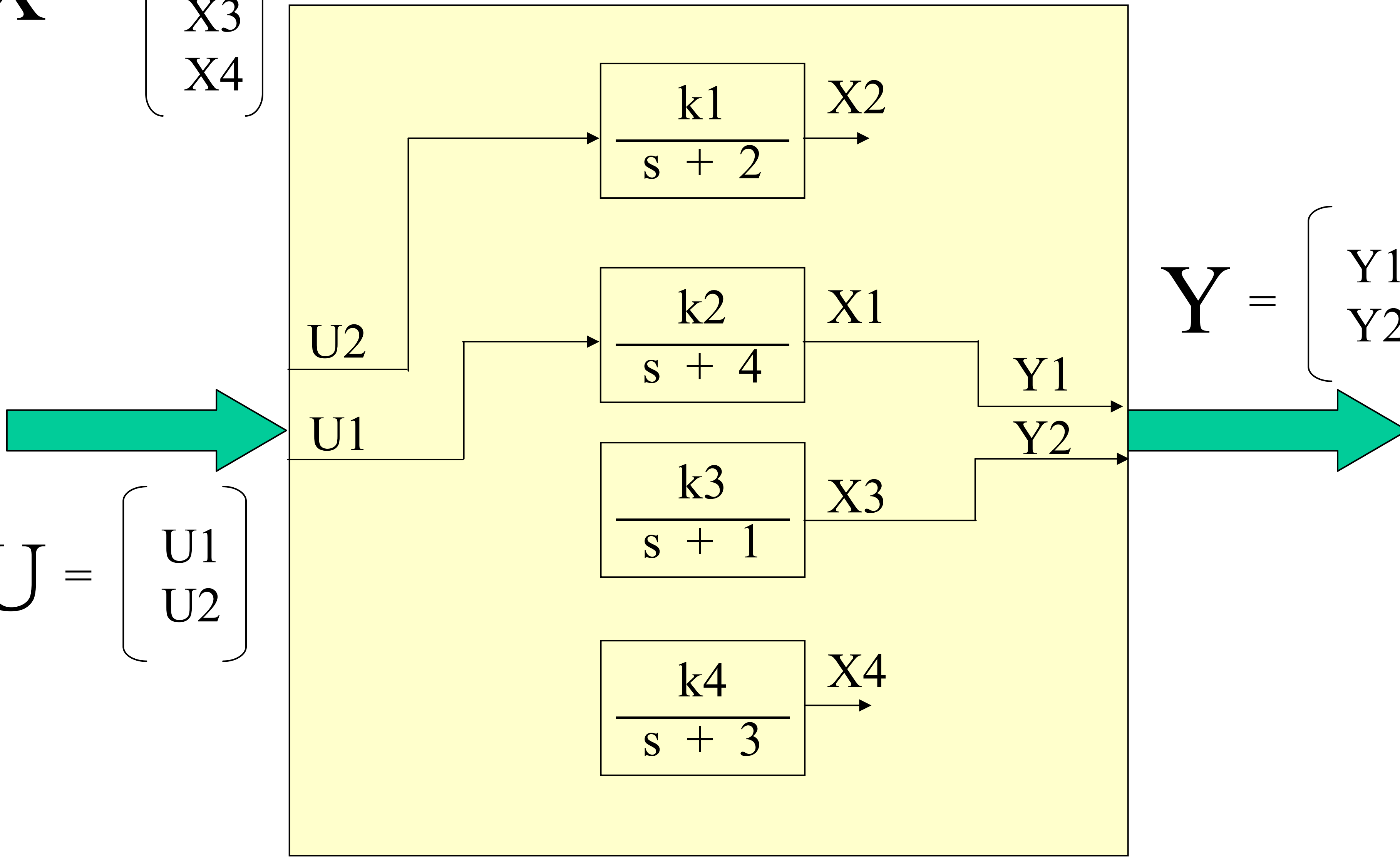


Nyquist, Nichols,...

Observability

Controllability

$$X = \begin{pmatrix} X1 \\ X2 \\ X3 \\ X4 \end{pmatrix}$$

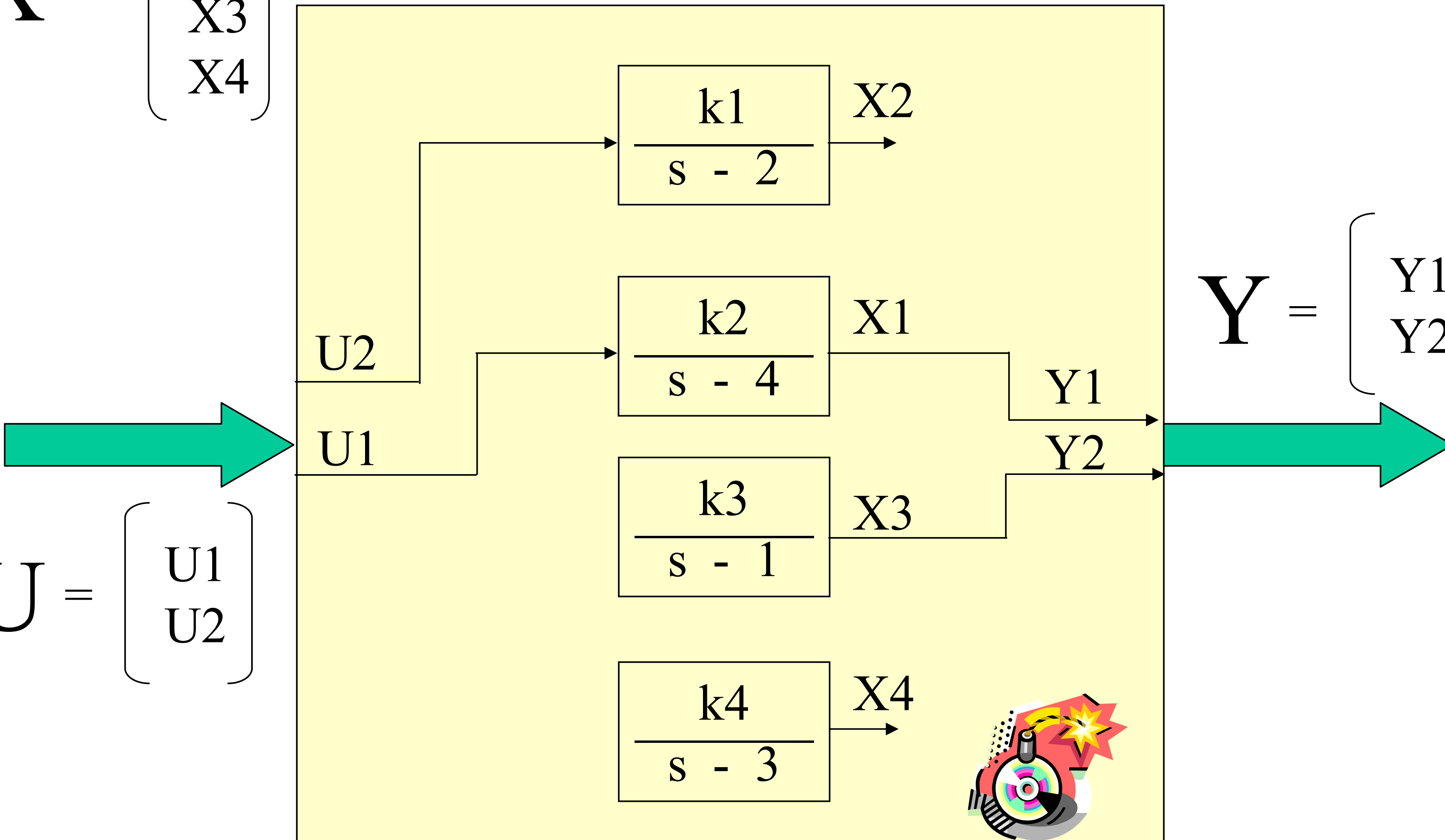


$$Y = \begin{pmatrix} Y1 \\ Y2 \end{pmatrix}$$

$$U = \begin{pmatrix} U1 \\ U2 \end{pmatrix}$$

Observability
Controlablity

$$X = \begin{pmatrix} X1 \\ X2 \\ X3 \\ X4 \end{pmatrix}$$



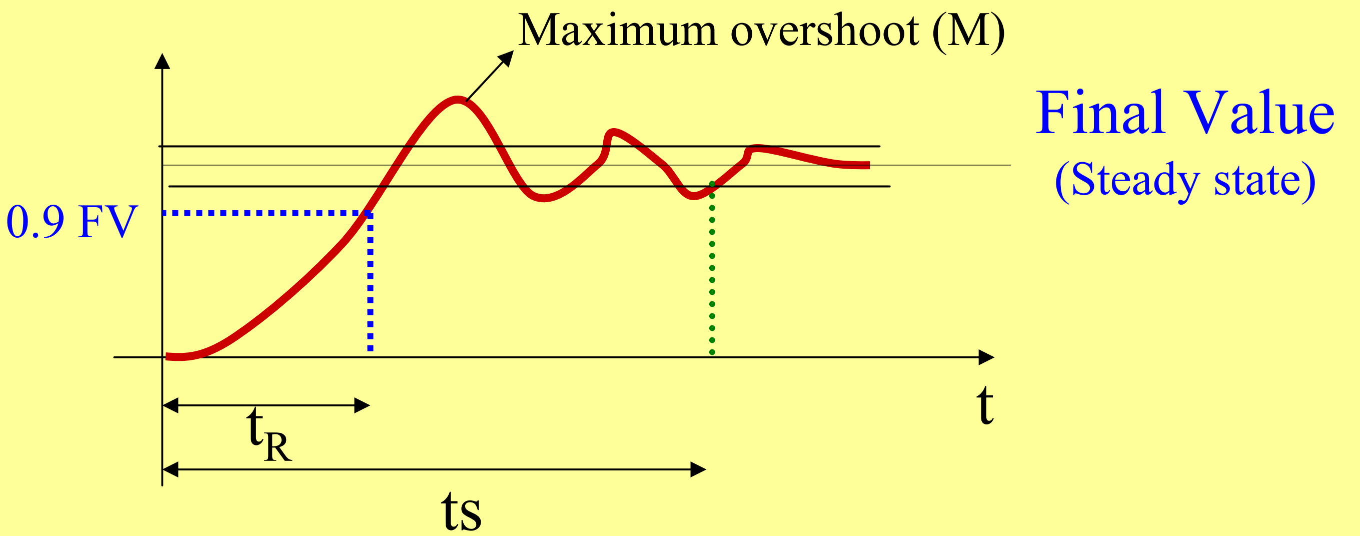
$$U = \begin{pmatrix} U1 \\ U2 \end{pmatrix}$$

$$Y = \begin{pmatrix} Y1 \\ Y2 \end{pmatrix}$$

Must modify the system structure : addition of transducers and/or actuators

Continuous - time Models : Time responses

Response of a dynamic system for a step input



Example : 1st Order
H(s) = G/(1+sT)
FV = G
t_R = 2.2 T
t_S = 2.2 T (for 10% FV)
t_S = 3 T (for 5% FV)
M = 0

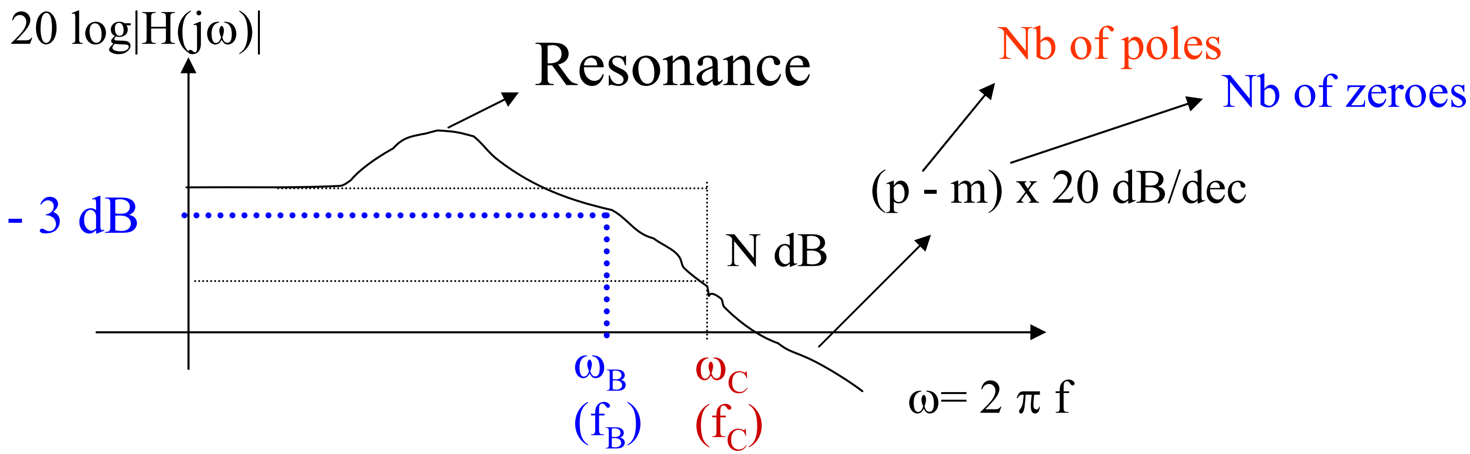
t_R : Rise Time ; define as the time needed to attain 90% of the final value ; or as the time needed for the output to pass from 10 to 90% of the final value

t_S : Settling Time ; define as the time needed for the output to reach and remain within a tolerance zone around the final value (±10%, ± 5%, ±1%,…)

FV : Final Value ; a fixed output value obtained for $t \rightarrow \infty$

M : Maximum Overshoot ; expressed as a percentage of the final value

Continuous - time Models : Frequency responses



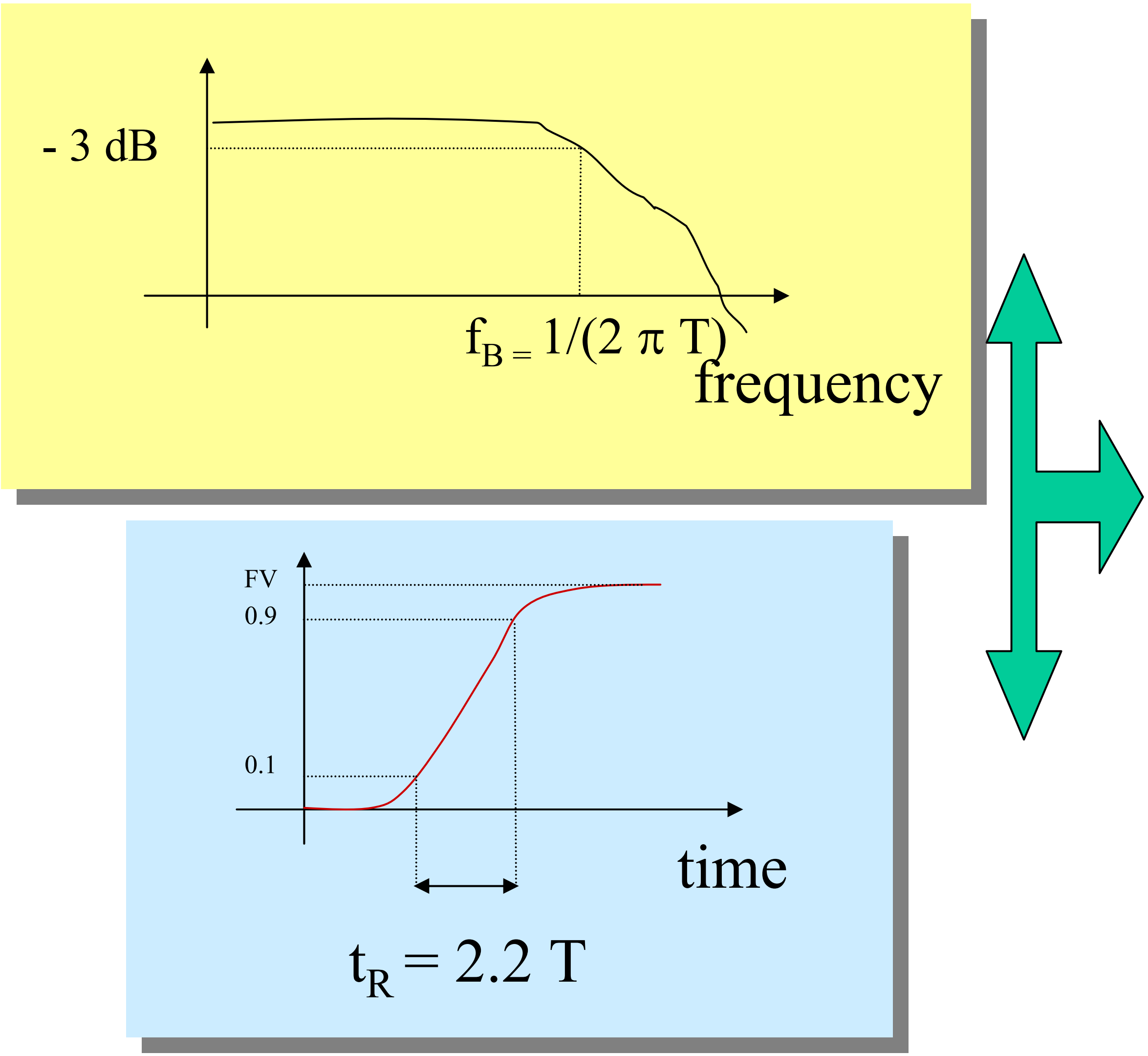
f_B : Bandwidth ; the frequency from which the zero-frequency (steady state) gain G(0) is attenuated by more than 3 dB ; $G(\omega_B) = G(0) - 3dB$ or $G(\omega_B) = 0.707 \cdot G(0)$

f_C : Cut-off frequency ; the frequency from which the attenuation is more than N dB ;

$$G(\omega_C) = G(0) - NdB$$

Q : Resonance factor ; the ratio between the gain corresponding to the maximum of the frequency response curve and the value G(0)

Reciprocity : Time / Frequency



$$f_B \cong 0.35 / t_R$$

System with delay τ

$u(t) \Rightarrow u(t - \tau)$

Reflects the fact that the input will act with a time delay of τ

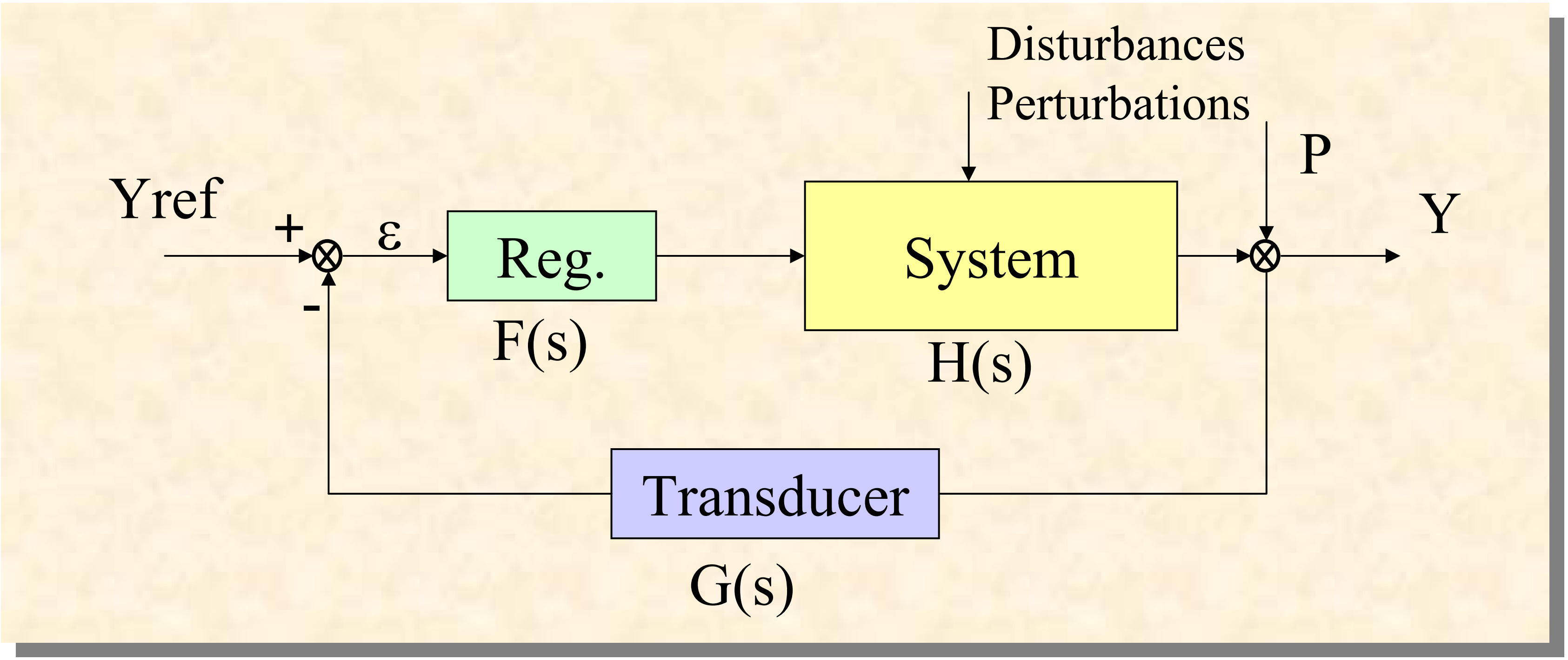
Transfer function

$H(s) \Rightarrow H(s)\, e^{-s\tau}$

$H_{delay}(j\,\omega) = e^{-j\,\omega\,\tau} = |1|\, e^{-j\,\omega\,\tau}$

No change on the gain but a phase proportional to the frequency

Closed Loop



Open loop : system H(s) ; system with controller F(s).H(s)

Closed loop : $H_{CL}(s) = F(s).H(s) / [\ 1 + F(s).\ H(s)\ G(s)\ ]$

Steady state error : F(s).H(s) must contains the internal model of the reference (the transfer function that generates Yref(t) from the Dirac impulse ;
e.g. step = (1/s) * Dirac ; ramp = $(1/s^2)$ * Dirac, sine wave = $\omega_0/(p^2+\omega_o{}^2)$*Dirac …)

Closed Loop : Perturbation rejection

Perturbation-output sensitivity function :

$S_{yp}(s) = Y(s) / P(s) = 1 / [1 + F(s).H(s).G(s)]$

Perturbation rejection :

$S_{yp}(0) = 0$ to get a perfect rejection of the perturbation in steady state (controller must contain the classes of perturbation)

and

$|S_{yp}(\omega)| < G \; ; \forall \, \omega$

[Typical value : $|S_{yp}(\omega)| < 2$ (6dB) ; $\forall \, \omega$]

If the energy of the perturbation is concentrated in a given frequency band, the $|S_{yp}(\omega)|$ should be limited in this band.

System dynamics

U → $\boxed{\dfrac{dX}{dt} = A.X + B.U}$ → Y

$$X(t) = \underbrace{e^{A(t-t_0)}.X(t_0)}_{\text{Free state response}} + \underbrace{\int_{t_0}^{t} e^{A(t-\tau)}.B.U(\tau)\,d\tau}_{\text{Forced state response}}$$

Stability of the system:

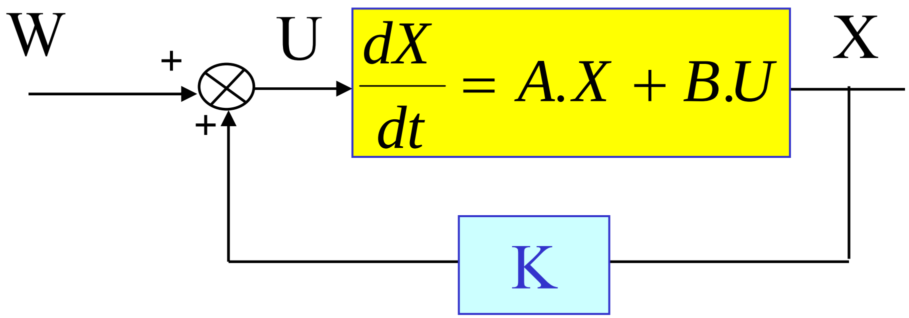
$$\lim_{t\to\infty} e^{A(t-t_0)}.X(t_0) = 0$$

Sign of the real part of A eigenvalues must be negative.
Eigenvalues determine the dynamics of the system

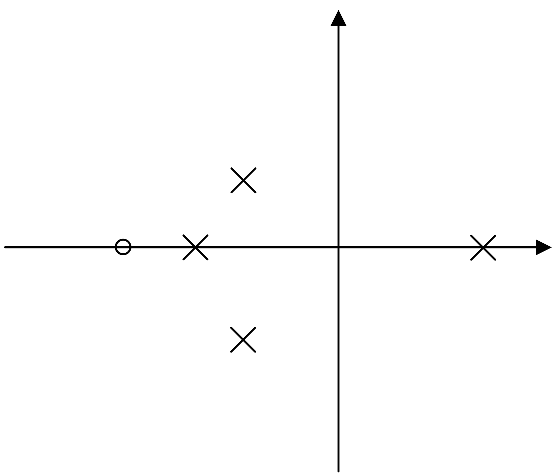
State feedback : change of system dynamics
(controllable and observable modes)

$$\frac{dX}{dt} = A.X + B.U$$

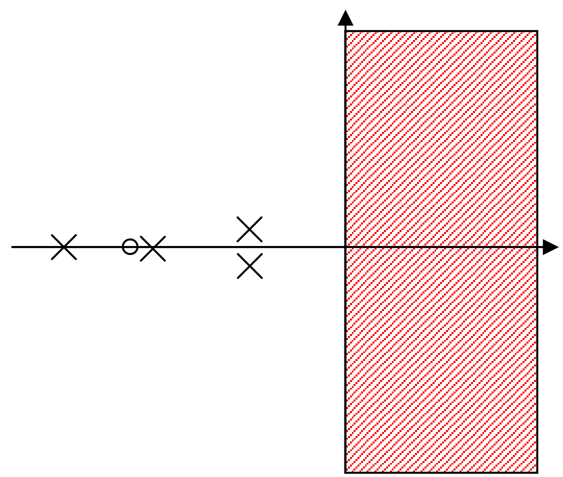
$$U = W + K.X$$



$$\frac{dX}{dt} = \underbrace{(A + B.K)}_{A_K}.X + \underbrace{B}_{B}.W$$



A



$A + B.K$

The system is (completely) controllable at any time t_o if for any state $X(t_o)$ in the state space Σ and any state X in the state space Σ , there exist a finite time $t_1 > t_o$ and an input $U[t_o,t_1]$ that will transfer the state $X(t_o)$ to the state X at time t_1.

ENERGY ?

Physical limitations ?

Closed Loop : Stability % Margins

Modulus Margin :

$\Delta M = |1 + H(j\omega)|_{min} = |S^{-1}{}_{yp}(j\omega)|_{min}$

Measure of perturbation rejection and robustness of non linearity and time variable parameters

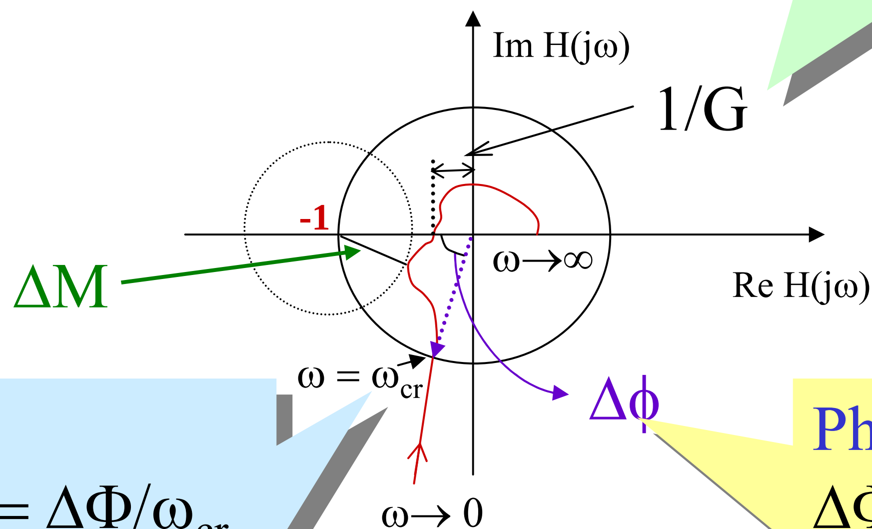
Typical : $\Delta M > 0.5$ (-6dB) [min: 0.4 (-8dB)]

Gain Margin :

$\Delta G = 1 / |H(j\omega_{180})|$

for $\Phi(\omega_{180}) = -180°$

Typical : $G > 2$ (6dB) [min: 1.6 (4dB)]



Delay Margin :

$\Delta\Phi = \omega_0.\tau$; $\Delta\tau = \Delta\Phi/\omega_{cr}$

additional delay that could be tolerate by the open loop system without instability for the closed loop system

Phase Margin :

$\Delta\Phi = 180° - \Phi(\omega_{cr})$

ω_{cr} : crossing pulsation

for $|H(j\omega_{cr})| = 1$

Typical : $30° < \Delta\Phi < 60°$

Modulus Margin :

$$\Delta M = |1 + H(j\omega)|_{min} = |S^{-1}_{yp}(j\omega)|_{min}$$

Measure of perturbation rejection and robustness of non linearity and time variable parameters

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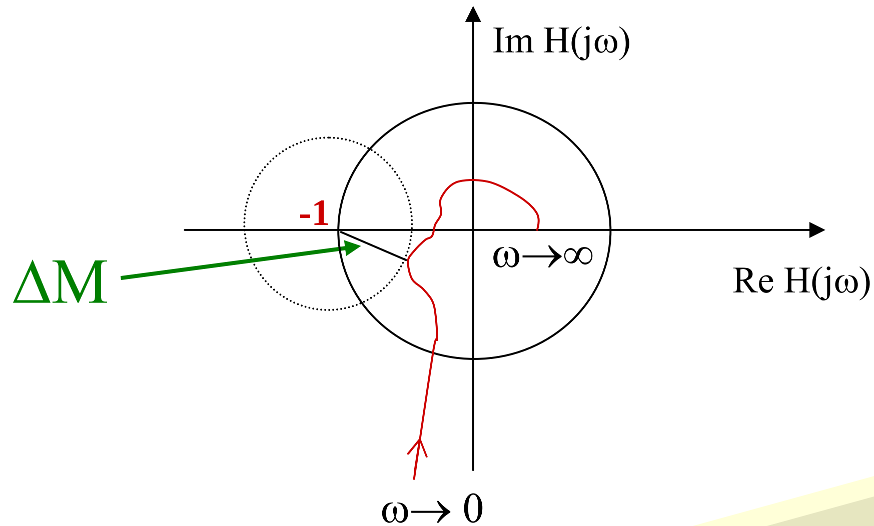
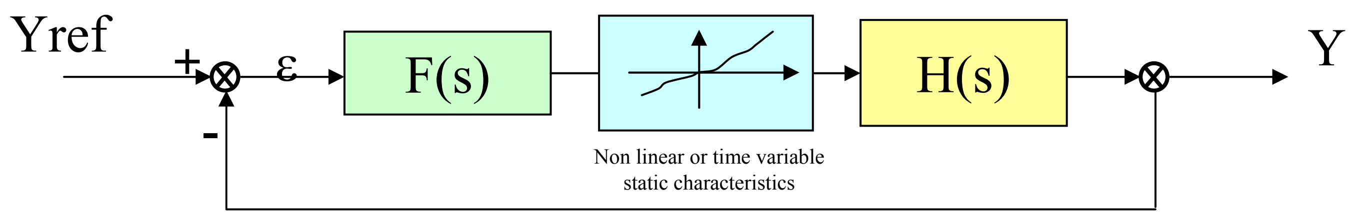


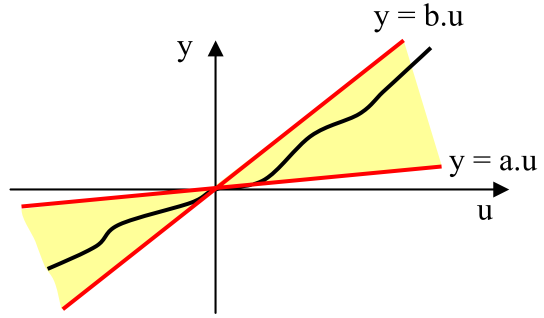
Modulus margin:

$\Delta M > 0.5$ implies a gain margin $\Delta G > 2$ and a phase margin $\Delta\Phi > 30^0$.

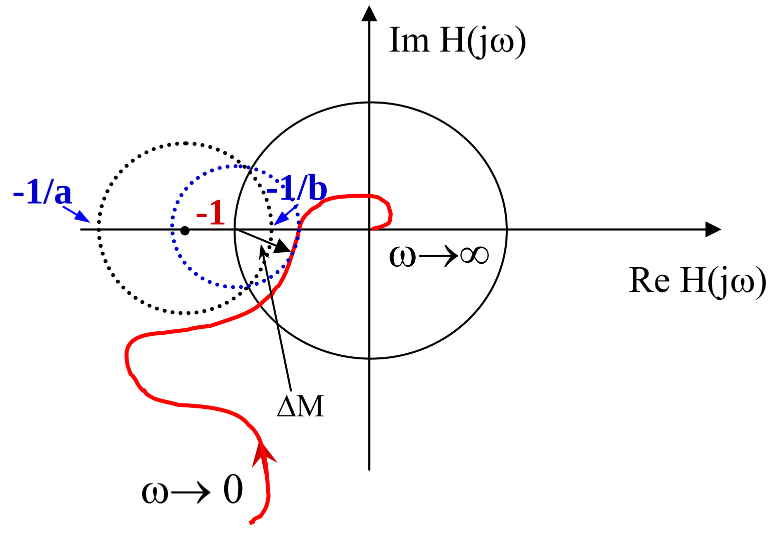
More generally, a good modulus margin guarantees good values for gain and phase margins. The converse is not true.

Robustness of non linearity and time-variable parameters % Modulus Margin





For a given modulus margin ΔM, the system will tolerate non-linear or/and time variable characteristics if these characteristics are located inside the sector defined par a minimum linear gain 1/(1+ΔM) and a maximum linear gain 1/(1-ΔM)



If the non-linear and/or time variable characteristics belongs to an angular sector [a,b] (b>a>0), the closed-loop system is stable if the Nyquist plot leaves on the left (for ω ↗) the "critical" circle with center on the real axis and passing through the points (-1/b,0) and (-1/a,0) (without crossing the circle)

Controller Design

In order to design and tune a controller :

1) To specify the desired closed control loop performance

Regulation and tracking : rise time and max overshoot

or bandwidth and resonance

2) To choose a suitable controller design method

3) To know the dynamic model of the plant to be controlled

=> control model

Control model :

- Non parametric models : e.g. frequency response, step response,…
- Parametric models : e.g. state equation, differential equation, transfer function,,

To get the model :

-knowledge type model (based on the physic laws) ;

Converters : State space average models;

Equivalent average circuit models

- identification models (from experimental data)

Choice of the desired performance

The choice of desired performance in terms of the response time (bandwidth) is linked to the dynamics of the open-loop system and to the power availability of the actuator during the transient : acceleration of the natural response requires control peaks that are greater than the steady-state values

Umax/Ustatic $\cong$ desired speed/natural speed

$\cong$ desired bandwidth / natural bandwidth

$\cong f^{CL}_{B} / f^{OL}_{B}$

Or, the actuators will have to be chosen as a function of the desired performance and the open-loop response of the system

Choice of the desired performance (cont'd)

The robustness of the closed-loop system is linked to the ratio f^{CL}_{B} / f^{OL}_{B}

(sensitivity to the uncertainty or variation of the model parameters)

If the ratio is too high => bad robustness and need to have a good knowledge of the process model (high frequency identification) or use of adaptive control

LHC orbit corrector

[±60A,±8V] (arc corrector)

Magnet : L=7 H ; R = 30 mΩ (60m of 35 mm^2)

T = L/R = 300 s => $f^{OL}_B \cong 0.5$ mHz

U_{static} = R.I = 1.8V

Large signal : $u_{max}/u_{static} \cong 4$ => $f^{CL}_B \cong 2$ mHz => $t_R = 175$ s

(dI/dtmax ≅ 1A/s)

Small signal : $f^{CL}_B \cong 1$ Hz => $u_{max}/u_{stat} \cong 1/\ 0.5\ 10^{-3} = 2000$!

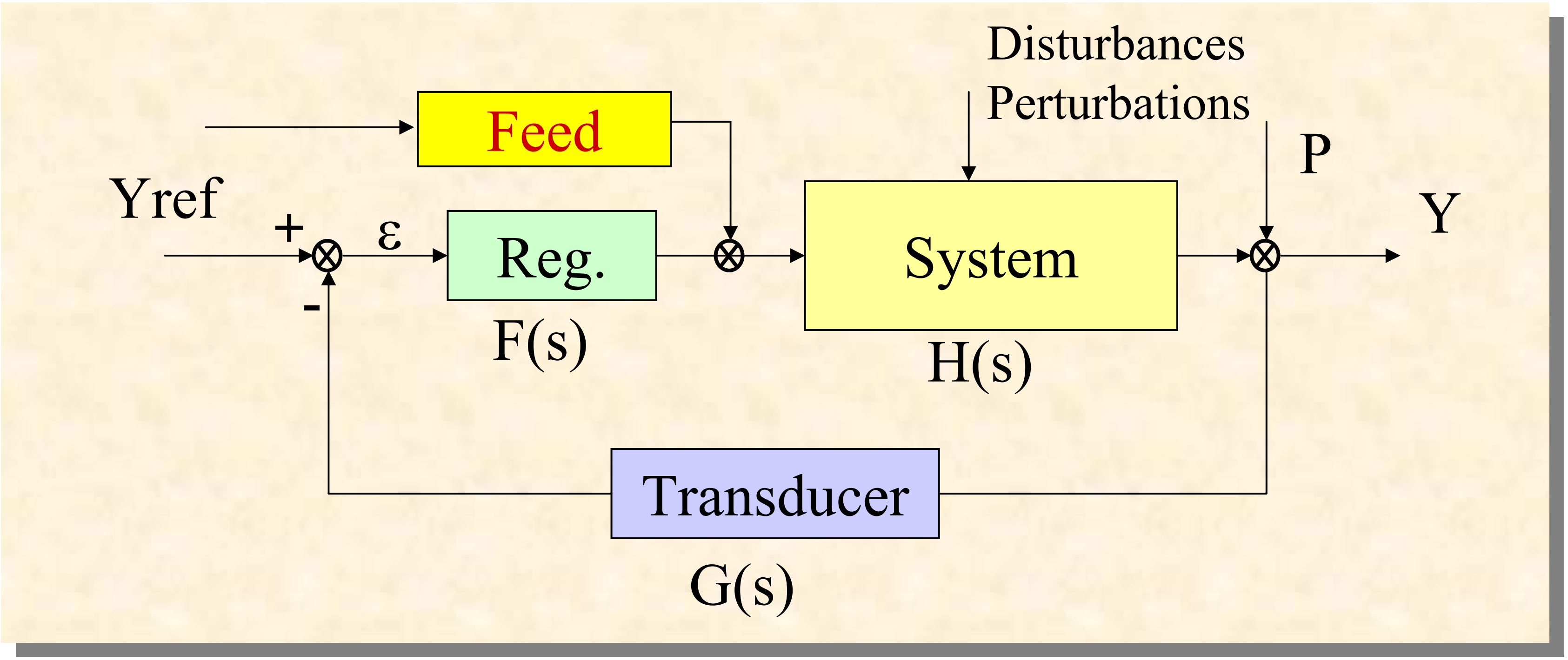
Then u_{static} = 6 / 2000 = 3mV => ΔI = 3mV/30 mΩ = 0.1 A = 0.15 % Imax

"The power converters involved in feedback of the local orbit may need to deal with correction rates between 10 and 500 Hz";

fs (rate ?) = 500 Hz => $f^{CL}_B \cong$ 50Hz (ΔI = 1% : Umax = 2400 V ?????...)

(U_{max}= 8V => ΔI = 30 ppm Imax)

Analogue Control Systems

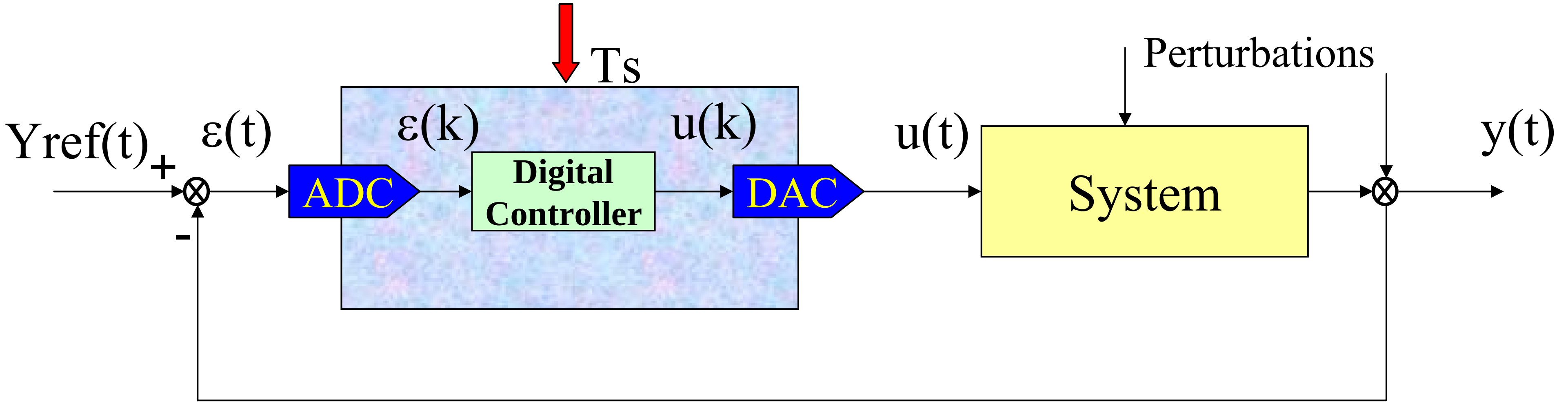


Open loop : system H(s) ; system with controller F(s).H(s)

Closed loop : $H_{CL}(s) = F(s).H(s) / [\ 1 + F(s).\ H(s)\ G(s)\ ]$

Digital control systems

Digital realisation of an "analogue type" controller

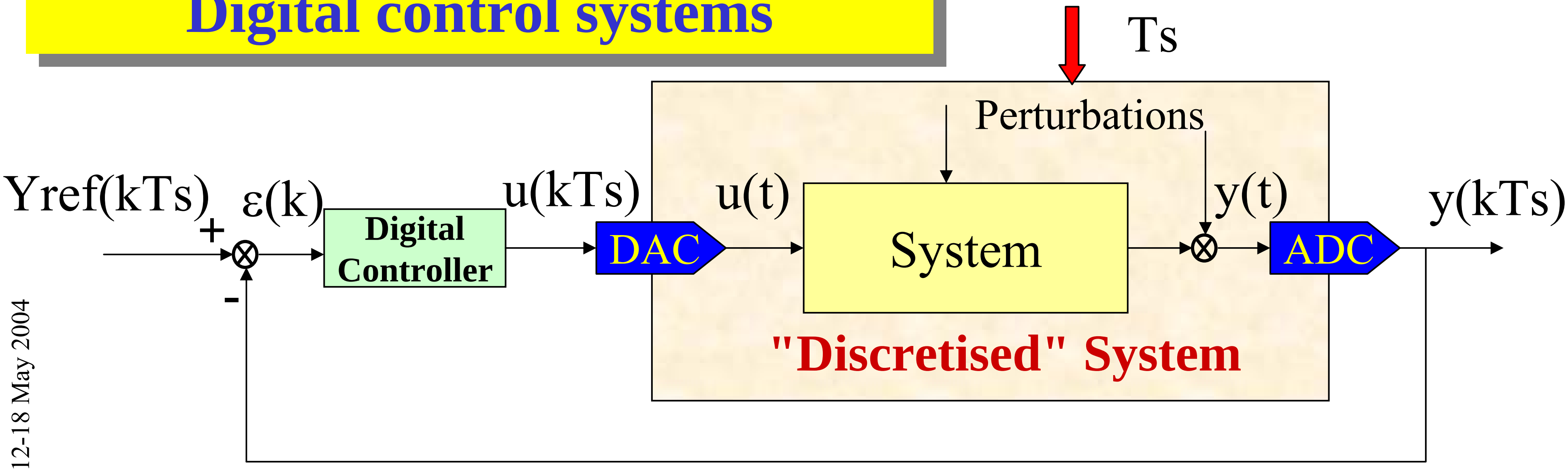


ADC- Digital controller - DAC should behave the same as an analogue controller (e.g. PID type), which implies **the use of a high sampling frequency** (the algorithm implemented is very simple)

Bad use of the potentialities of the digital controller

"It's not enough to put a tiger in your tank,
you've got to add BRAIN"

Digital control systems



The sampling frequency is chosen in accordance with the bandwidth desired for the closed-loop system

Intelligent use of the "computer" : high sampling period and then implementation of complex algorithms requiring greater computation time.

Not only a copy of analogue control : BRAINWARE

Discrete-time system models
and
digital control algorithms

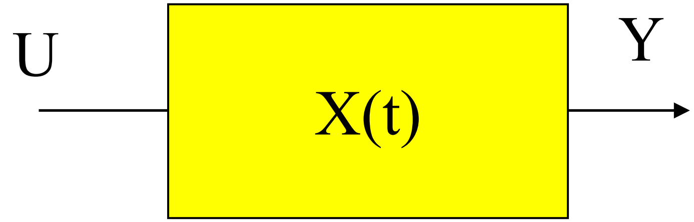
$$y(k) = f[y(k-i), u(k-j)]$$

or

$$H(z^{-1}) = z^{-d} \; B(z^{-1})/A(z^{-1})$$

$$\frac{dX}{dt}(t) = A.X(t) + B.U(t)$$

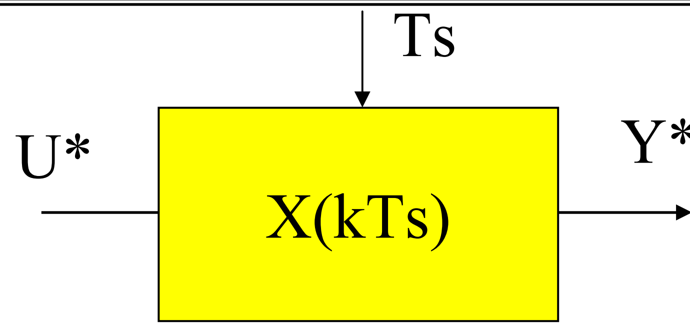
$$Y(t) = C.X(t) + D.U(t)$$



Ts : sampling period

$$X[(k+1)Ts] = F.X(kTs) + G.U(kTs)$$

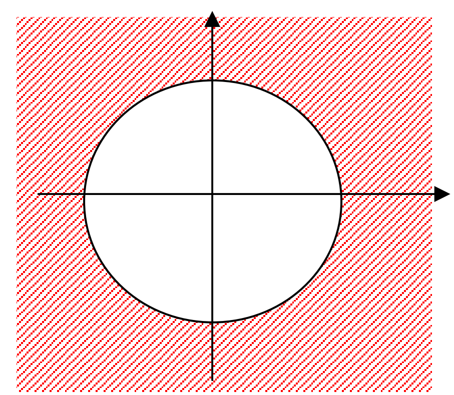
$$Y(kTs) = C.X(kTs) + D.U(kTs)$$



$$F = e^{A.Ts}$$

$$G = A^{-1}.\left(e^{A.Ts} - I\right).B$$

$$X[(k_0+n)Ts] = \underbrace{F^n.X(k_0Ts)}_{\text{Free state response}} + \sum_{j=1}^{n} \underbrace{F^{n-j}G.U[(k_0+j-1)Ts]}_{\text{Forced state response}}$$



Stability of the system:

$$\lim_{n\to\infty} F^n.X(k_0Ts) = 0$$

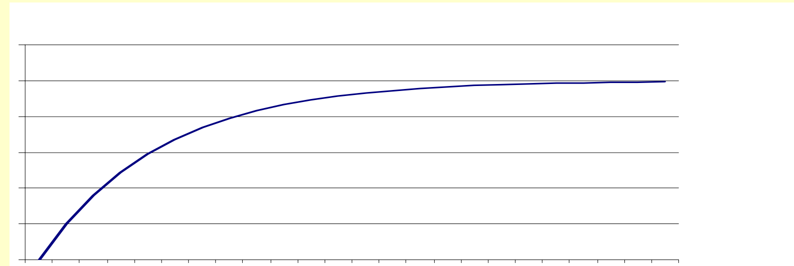
F eigenvalues modulus must be lower than 1

First order system

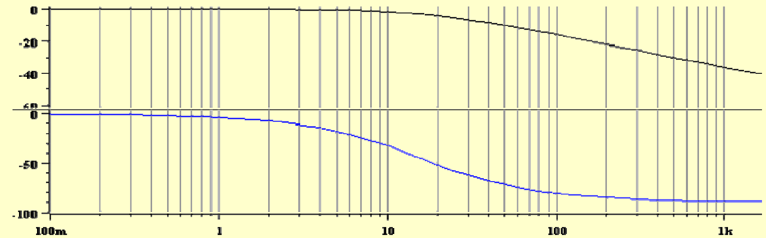
Analogue world

$$\frac{dy}{dt}(t) = -\frac{1}{T}.y(t) + \frac{G}{T}.u(t)$$

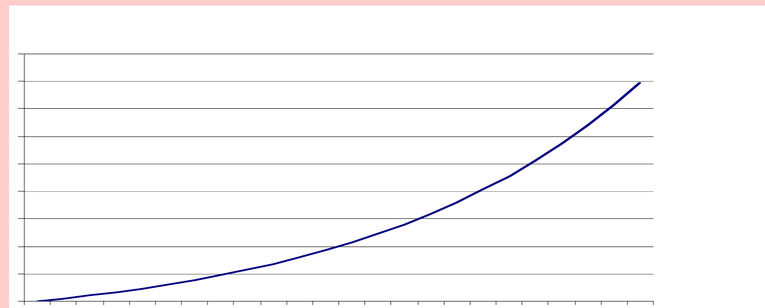
$$H(s) = \frac{G}{1+sT}$$



$T > 0$



$T < 0$



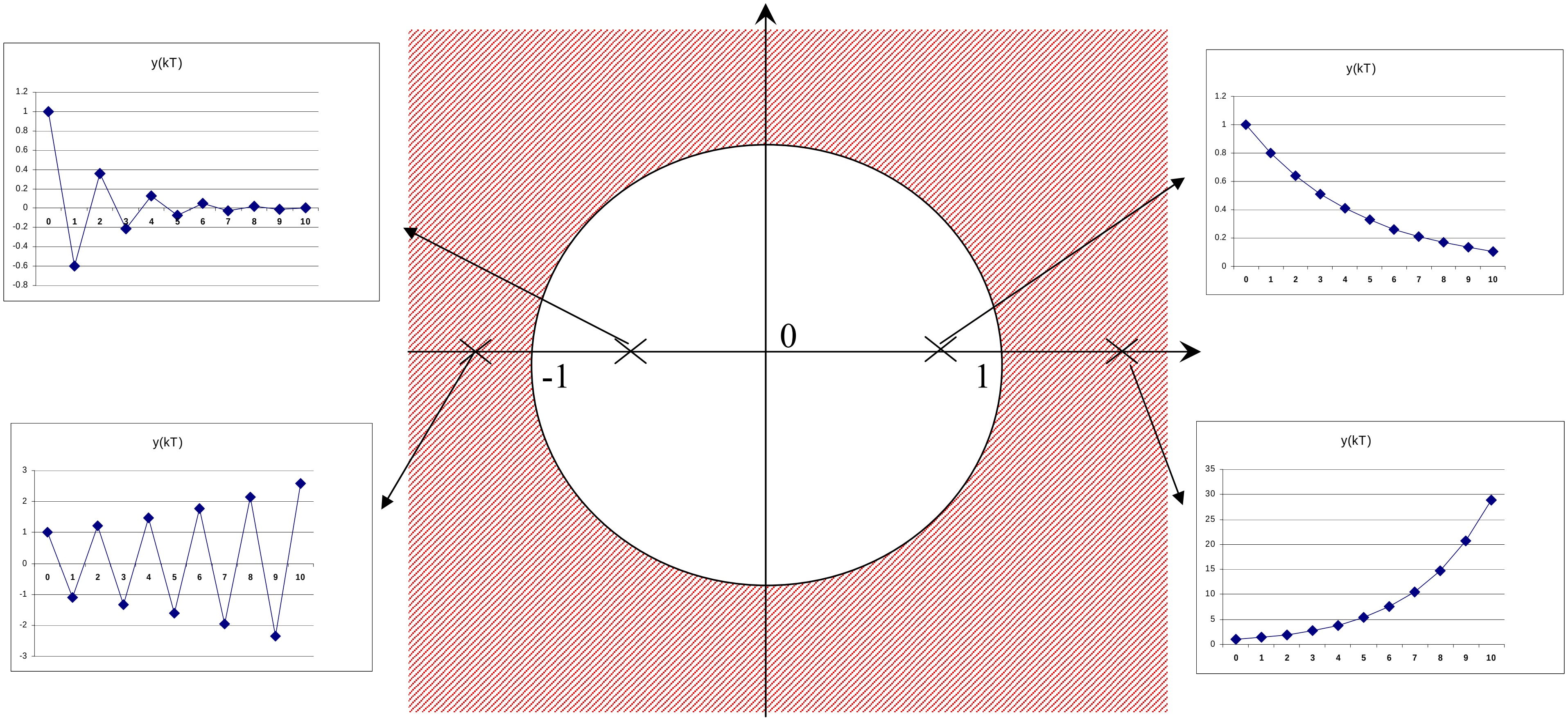
Discrete world

$$y(kTs) = -a_1.y[(k-1)Ts] + b1.U[(k-1)Ts]$$

$$H(z) = \frac{b_1}{z+a_1} = \frac{b_1 z^{-1}}{1+a_1 z^{-1}}$$

Digital first order system

$$H(z)=\frac{b_1}{z+a_1}=\frac{b_1 z^{-1}}{1+a_1 z^{-1}}$$



Free state response

Choice of sampling frequency

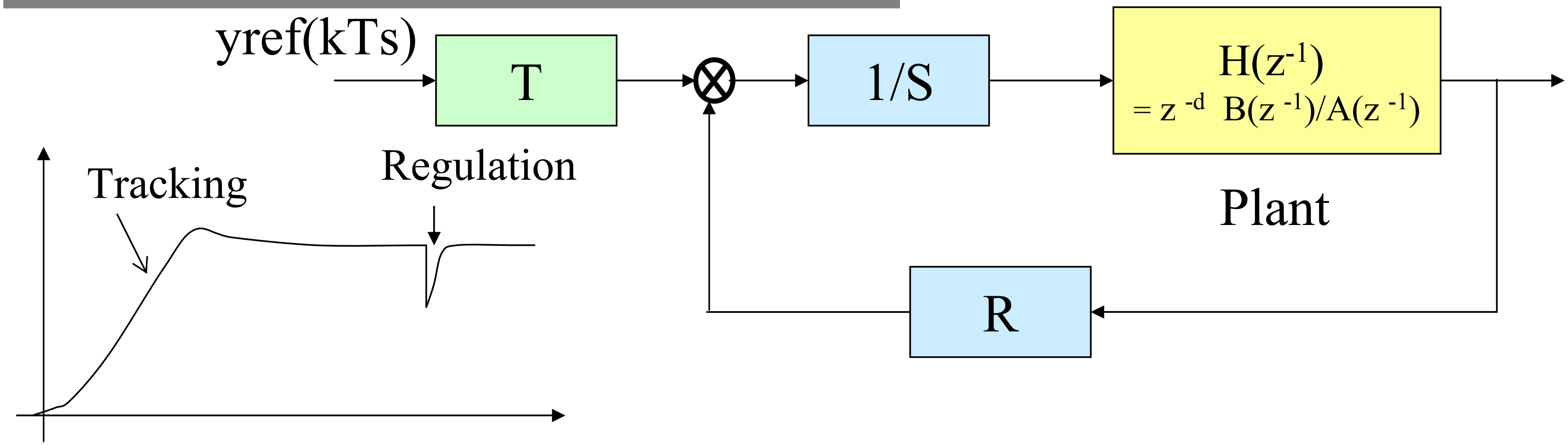
$$fs = 1/Ts = (6 \text{ to } 25) * f^{CL}_{B}$$

fs : sampling frequency

f^{CL}_{B} : bandwidth of the closed-loop system

If fs is fixed => limit for f^{CL}_{B} ($< fs/15$)

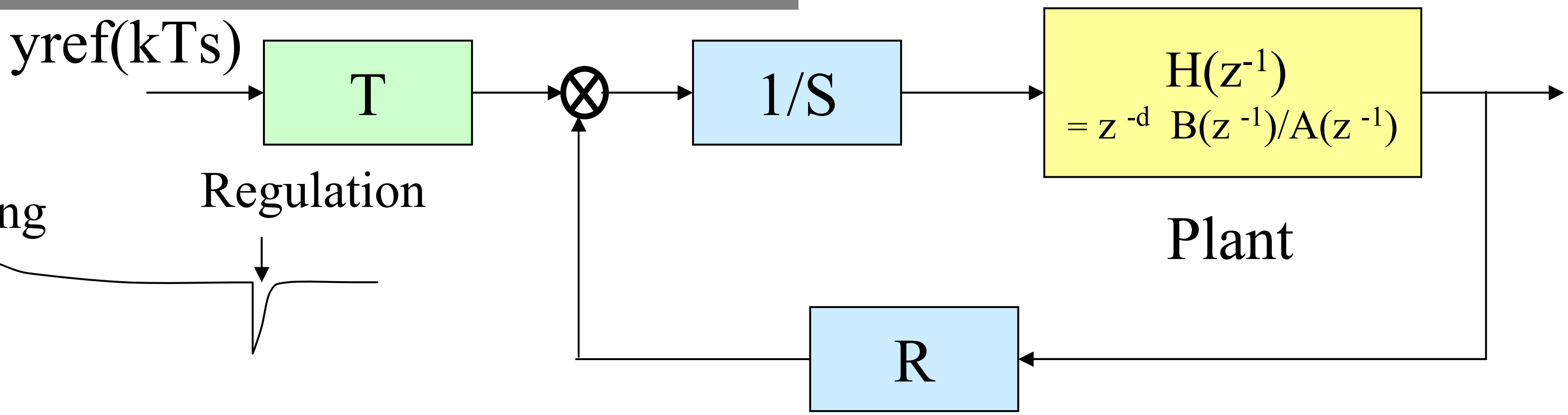
R.S.T control : generic control

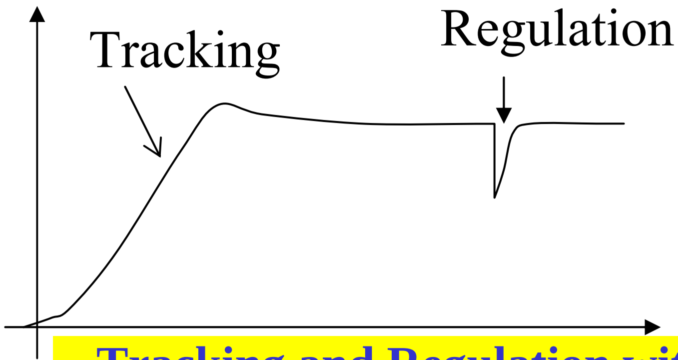


RST :

- minimum variance tracking and regulation
- tracking and regulation with weighed input
- tracking and regulation with independent objectives,…

R.S.T control : generic control





Tracking and Regulation with independent objectives

This control strategy permits a R.S.T digital controller to be designed for both stable and unstable systems:

- without restriction on the degrees of the polynomials $A(z^{-1})$ and $B(z^{-1})$ of the plant transfer function

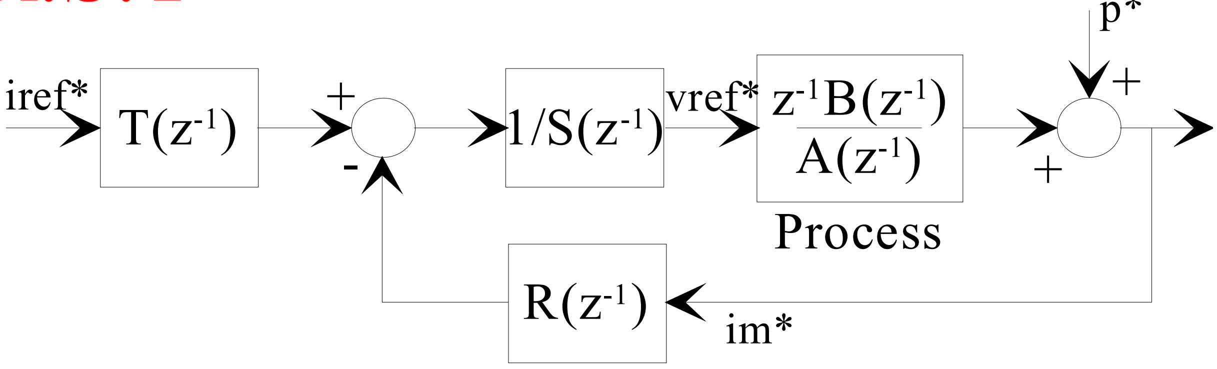
- without restriction on the sampled time delay of the system (d)

This strategy can only be applied to discrete-time models with stable zeroes (minimum phase systems):

- high sampling period => unstable zeroes

- fractional time delay > 0.5 x Ts

R.S.T



Tracking:

$$\frac{im^*}{iref^*} = \frac{z^{-1}.B.T}{A.S + R.B.z^{-1}}$$

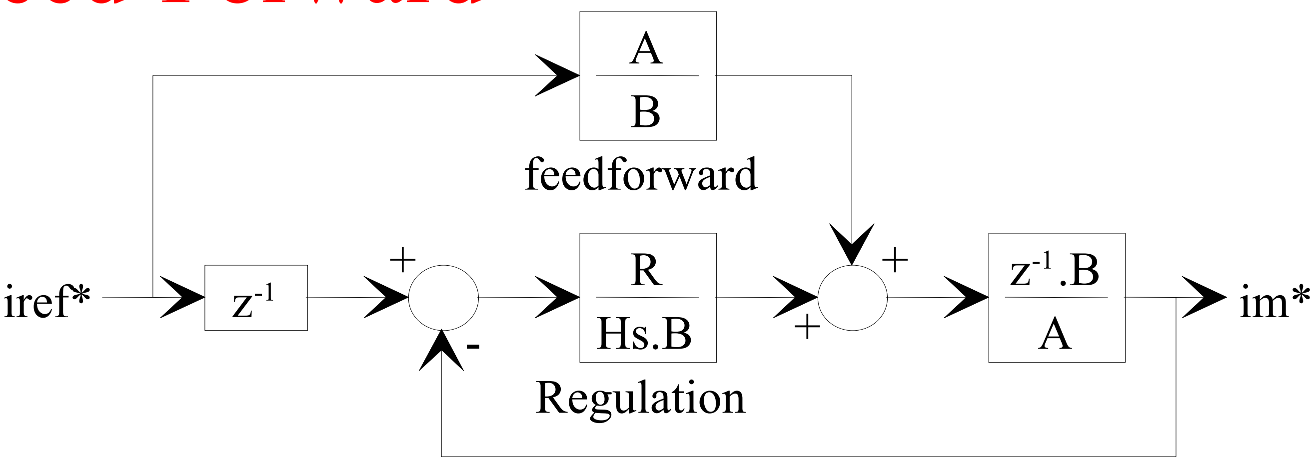
Regulation:

$$\frac{im^*}{p^*} = \frac{A.S}{A.S + R.B.z^{-1}}$$

Tracking and Regulation
With Independent Objectives

$$S = B \,.\, Hs$$
$$T = A \,.\, Hs + z^{-1} \,.\, R$$

Feed-Forward



$$\frac{Im^*}{Iref^*} = z^{-1}$$

$$\frac{Im^*}{p^*} = \frac{A.Hs}{A.Hs + R.z^{-1}}$$

Time delay : 1st order system example

$H(s) = G \;/\; (1 + T.s) \quad \Rightarrow H(z^{-1}) = b_1\, z^{-1} \;/\; (\, 1 + a_1\, z^{-1}\,)$

with $a_1 = -e^{-Ts/T}$; $b_1 = G.(1-e^{-Ts/T})$

$H(s) = G\, e^{-s\tau} \;/\; (1 + T.s)$ τ : time delay

Ts : sampling period

$\tau = d.\, Ts + L$; $0 < L < Ts$ fractional time delay

$$H(z^{-1}) = z^{-d}\,(b_1\, z^{-1} + b_2\, z^{-2}\,) \;/\; (\, 1 + a_1\, z^{-1}\,)$$
$$= z^{-d-1}\,(b_1 + b_2\, z^{-1}\,) \;/\; (\, 1 + a_1\, z^{-1}\,)$$

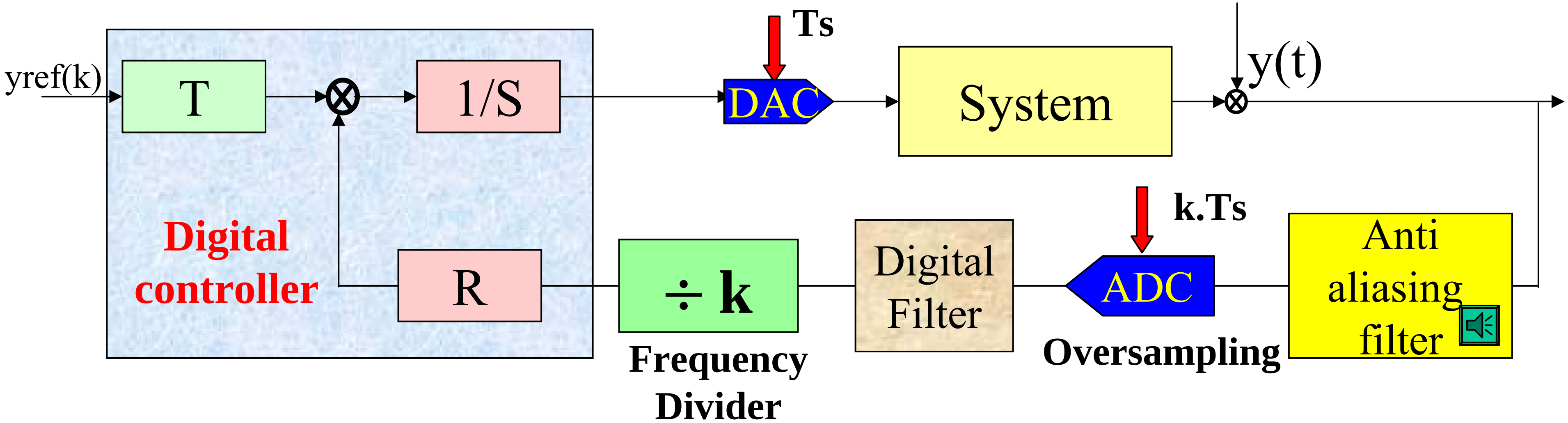
with $a_1 = -e^{-Ts/T}$; $b_1 = G(1-e^{(L-Ts)/T})$; $b_2 = G\, e^{-Ts/T}\,(e^{L/T}-1)$

fractional time delay => introduction of a zero in the discrete transfer function (if $L = 0 \Rightarrow b2 = 0$)

If $L > 0.5$: $|b_2| > |b_1|$ => unstable zeroes

No problem on the system stability but limitation on the possible method to compute the regulator

Summary



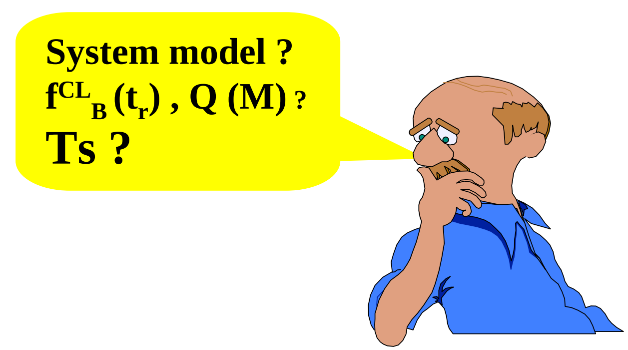
Based on f^{OL}_{B} and power of the actuator : choice of the closed-loop performance [f^{CL}_{B} (t_r) and Q (M)]

Robustness $\propto$ f^{CL}_{B} / f^{OL}_{B} (Internal saturation : controlability)

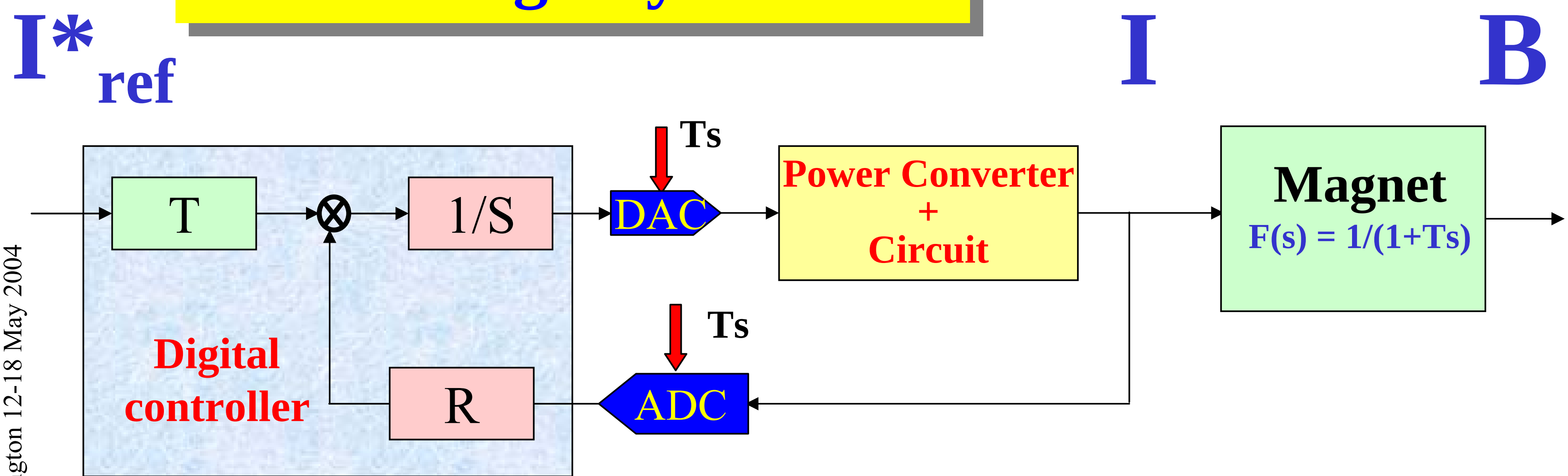
fs (sampling frequency) : choice based on the f^{CL}_{B}

$$fs = 1/Ts = (6 \text{ to } 25) * f^{CL}_{B}$$

Discrete model $H(z^{-1})$ at Ts



Tracking : dynamics



Dynamics :

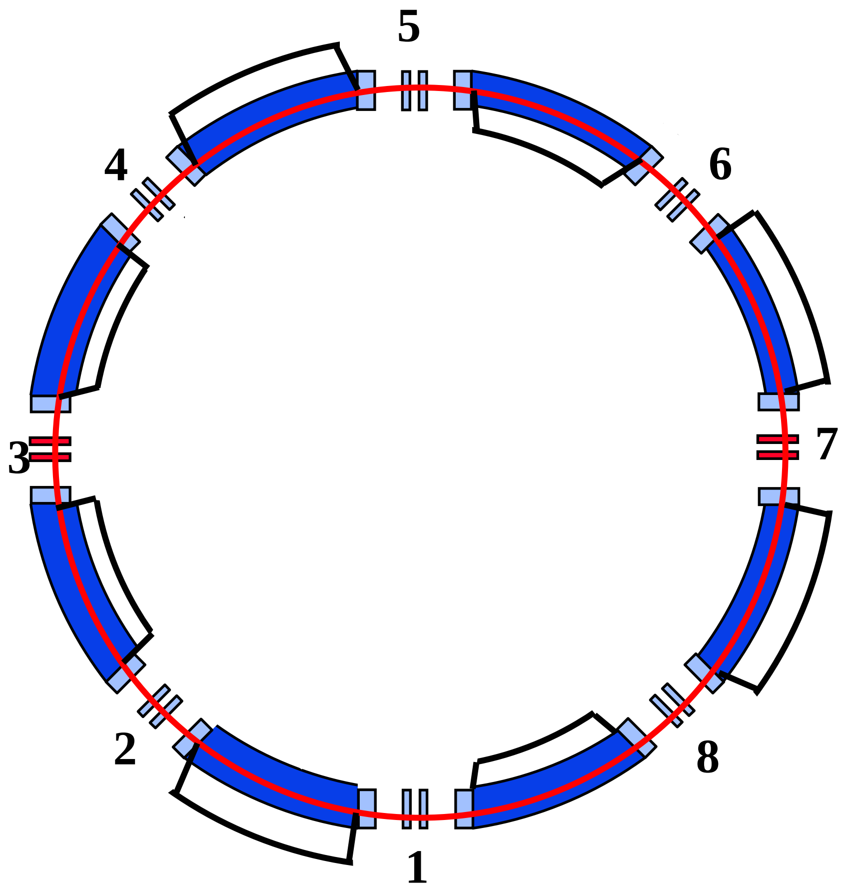
- Measurement and command must be synchronised : timing system

- Lagging error :

 # Iref => I : regulation loop could be designed with no lagging error independent of the load time constant

 # I => B : time constant (T : vacuum chamber, beam screen…) must be known : Measurement campaign in collaboration with magnet specialists

Tracking between the 8 main dipole converters



20 ppm Accuracy

$\Delta B/B_{nom} = \Delta I/I_{nom} = 20\text{ppm}$

$\Delta B = 9 * 20\ 10^{-6} = 1.8\ 10^{-4}\ T$

$\Delta B/B_o = 3.3\ 10^{-4}$

Orbit excursion :

$\delta X = D_x\ .\ \Delta B/B_o = \sim 0.7\ mm$

Could be corrected with a pilot run and new cycle => reproducibility

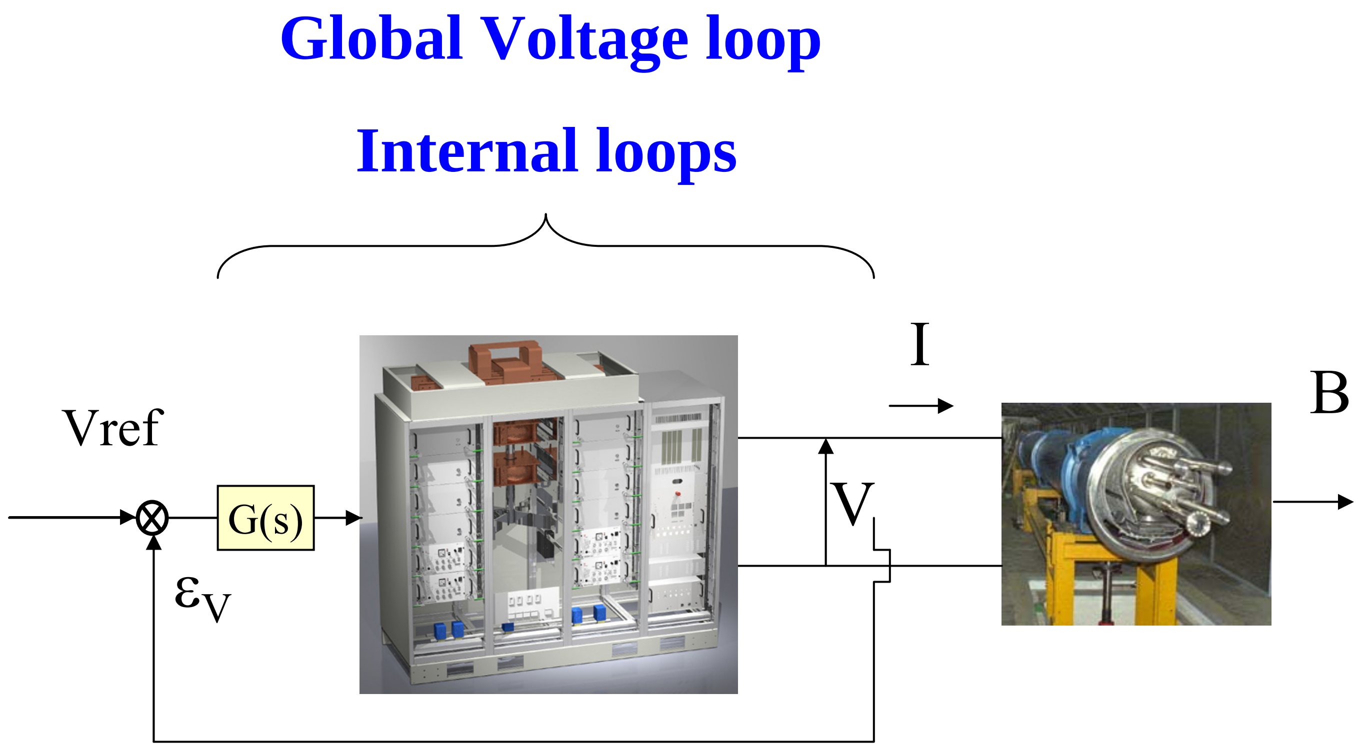
10 ppm reproducibility

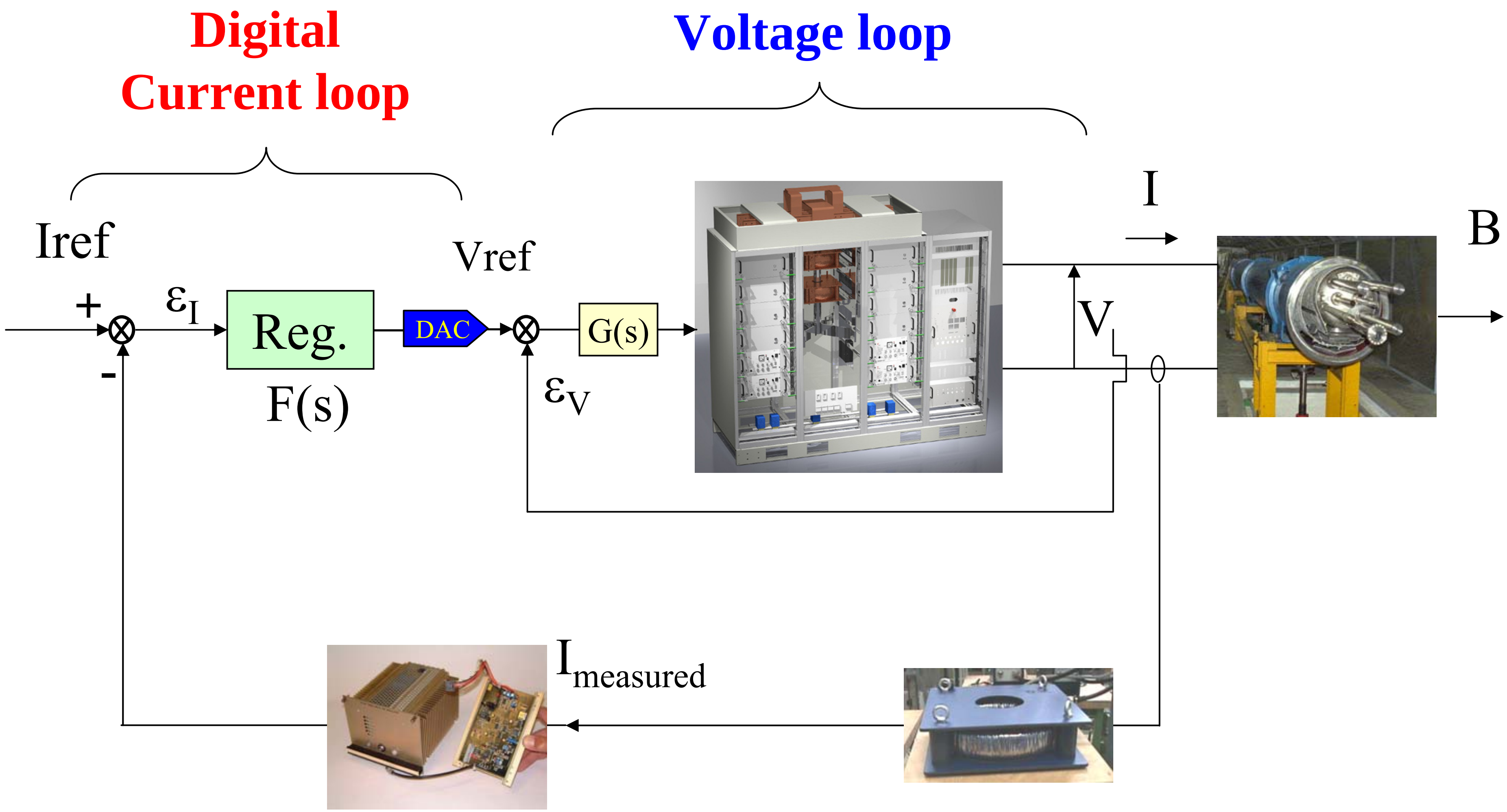
Orbit excursion :

$\delta X = D_x\ .\ \Delta B/B_o = \sim 0.35\ mm$ **!!!**

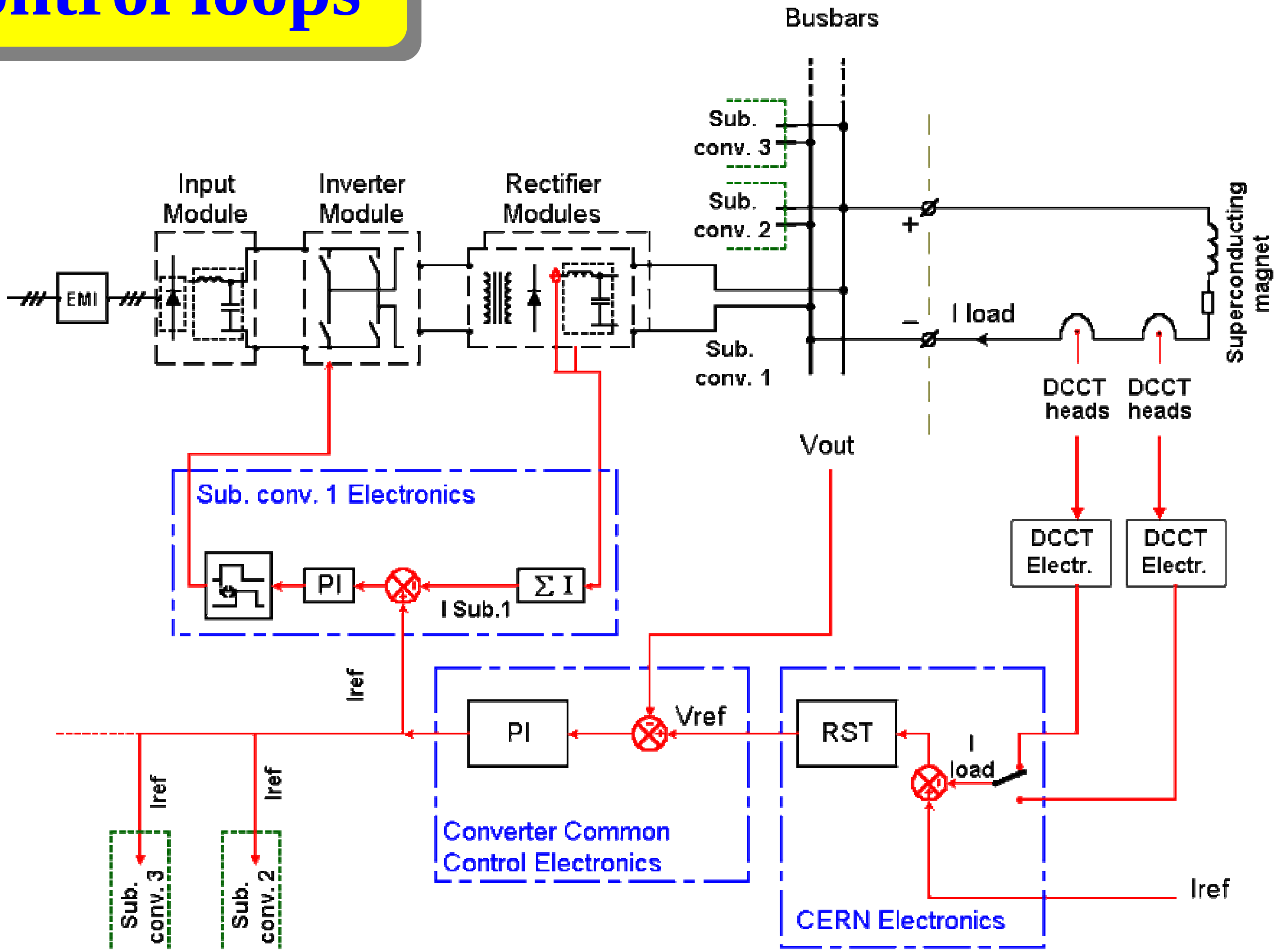
"It would be better with 5 ppm"

Example :LHC power converter control




Digital
Current loop
Voltage loop
Iref
+
-
εI
Reg.
F(s)
DAC
Vref
εV
G(s)
I
V
B
Imeasured

Control loops



1- Fast internal current source F^{CL}_{B} ~ 8 kHz

2- Global voltage loop F^{CL}_{B} ~ 700 Hz

3- High precision current loop (DCCT) F^{CL}_{B} ~ 0.1 - 1 Hz

Digital controller

Connection rack

High precision 13kA DCCT

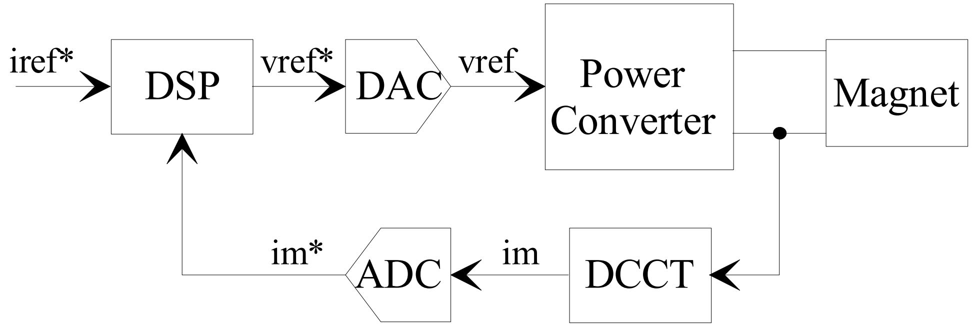
- **Very high performance is needed for the 24 main circuits: 8 main dipole and 16 main quadrupole (F and D) circuits.**

  - ✓ **Short term stability (30 mins) : ± 3 ppm**
  - ✓ **Reproducibility (24 hours) : ± 5 ppm**
  - ✓ **Accuracy (1 year) : ± 20 ppm**

    1 ppm = 1 part per million = 0.0001%
    For main circuits 1 ppm = 13 mA

  - ✓ **no overshoot**
  - ✓ **no lagging error**

Power Converter Digital Loop



SYSTEM MODEL

The power converter (PC) with the voltage loop can be modelled by a second order system with two complex poles and a natural frequency equal to ωpc=6,28krad/s. The magnet model is a first order system with a high time-constant (τm=Lm/Rm=23ks for the main dipole circuits and τm=450s for the quadrupole circuits). If **the sampling period** of the digital loop is **high in comparison with the time-constant of the power converter** (Ts>10/ωpc), the converter model can be reduced to a simple gain G_{PC}. Then the discrete model of the system is:

$$\frac{im^*}{vref^*} = \frac{Gpc.1/rm.\left(1-e^{-Ts/\tau m}\right).z^{-1}}{1-e^{-Ts/\tau m}.z^{-1}} \quad \mathbf{(1)}$$

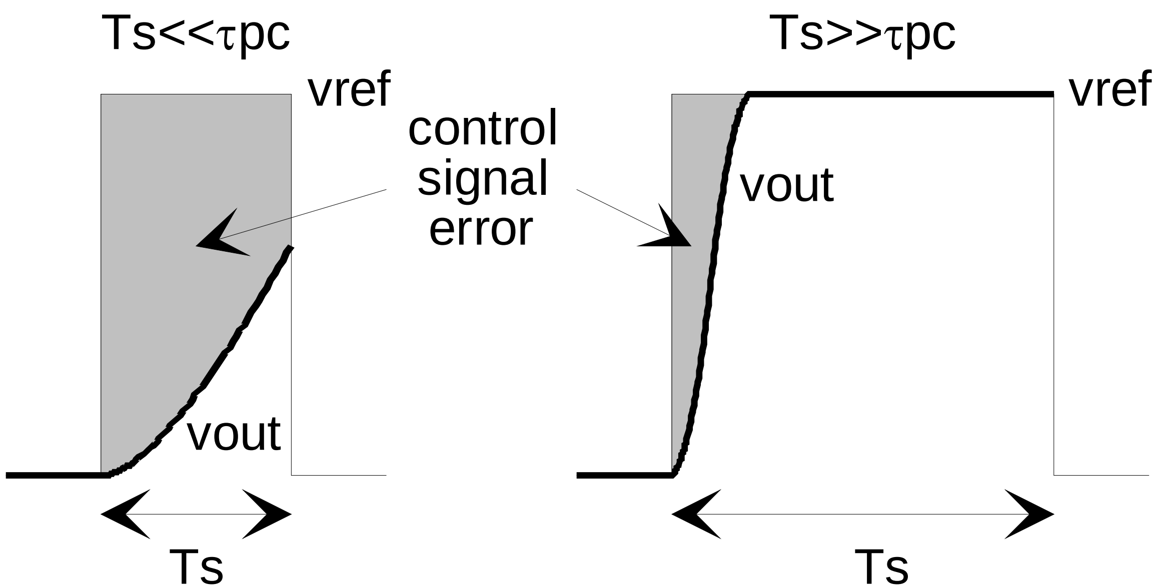
Furthermore, in the case of a high time-constant of the magnet in relation with the sampling period the equation **(1)** becomes:

$$\frac{im^*}{vref^*} \approx \frac{Gpc.Ts/Lm.z^{-1}}{1-z^{-1}} \qquad \mathbf{(2)}$$

With the preceding assumptions, the system (power converter and magnet) can be considered, by the digital control, as a pure integrator.

$F^{cl}_B \approx 1Hz \Rightarrow Fs \approx 10Hz$

The sampling period (Ts) must be high in comparison with the converter time-constant: $Ts >> \tau pc = 1/\omega pc$.

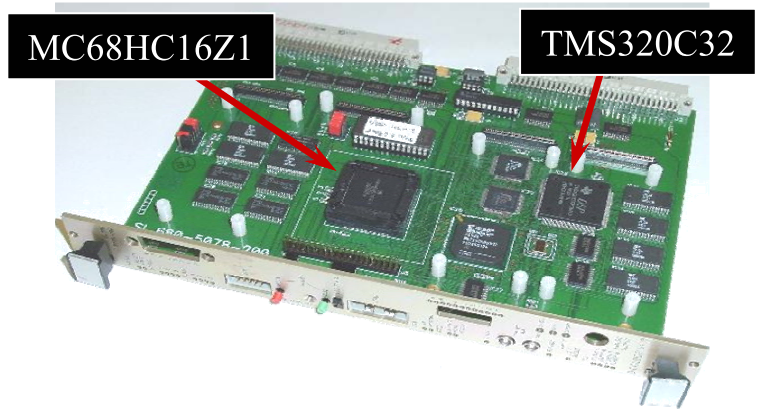


$Fpc \approx 1kHz$;

(if $Fs \rightarrow 1kHz$ need to include the digital model of the voltage source)

Once again : not to chose Ts too small !!!!.... no copy of analogue world

RST CONTROLLER DESIGN



Tracking:

To get a good tracking of the reference (no lagging error, no overshoot), the transfer function that the controller must achieve between the reference iref* and the output im* is:

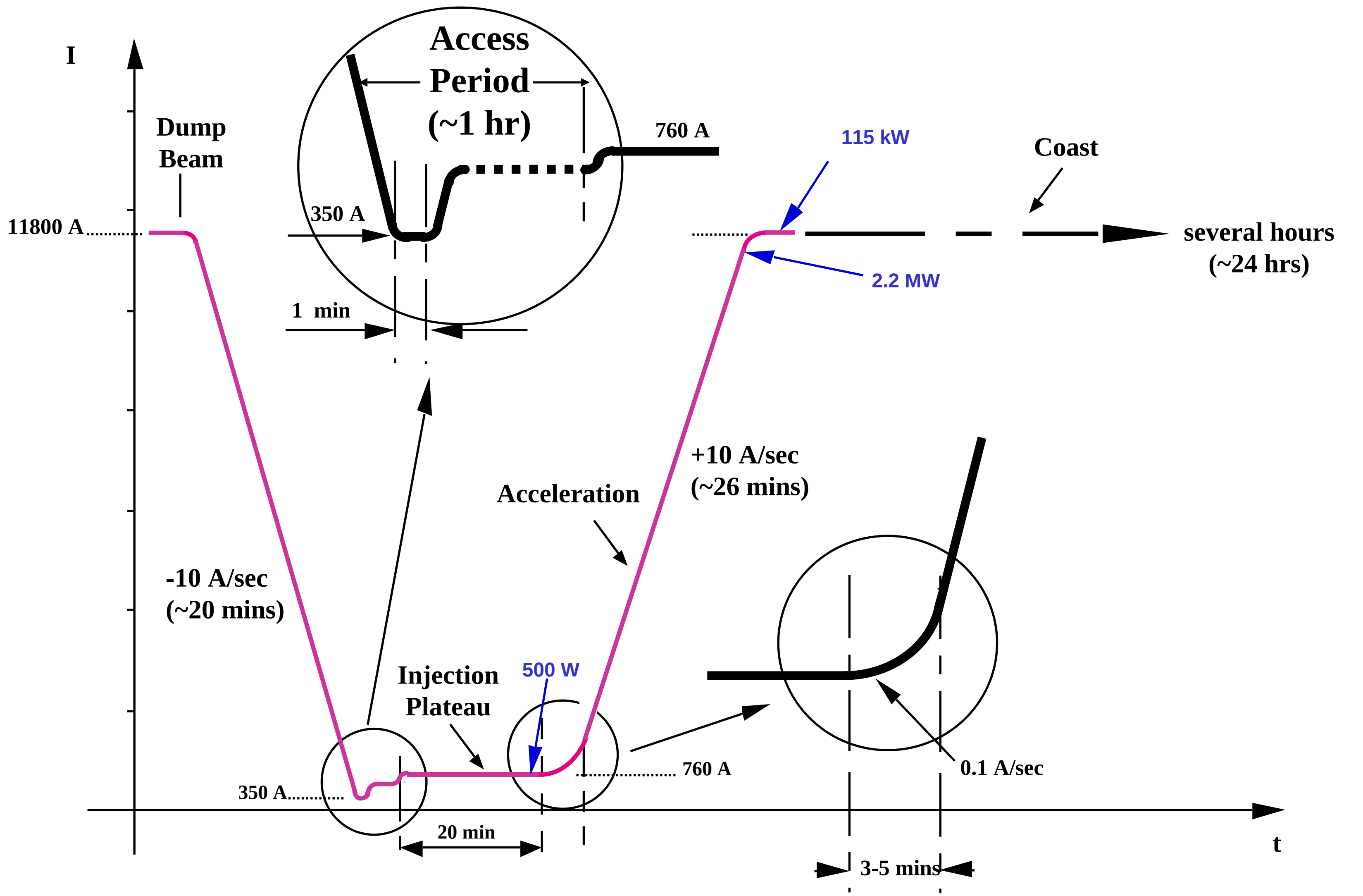
$$\frac{im^*}{iref^*} = z^{-1}$$

Regulation:

According to the LHC cycle, the bandwidth for the closed-loop system is chosen $f_B^{CL} \in [0.1\text{Hz}, 1\text{Hz}]$. The regulation is defined by the pole placement with a natural frequency wcl $\in [0.628\text{rad/s}, 6.28\text{rad/s}]$ and with a damping factor greater than 1. To ensure a zero steady-state error when the reference is constant, the transfer function $1/S(z^{-1})$ must contain two integrators .

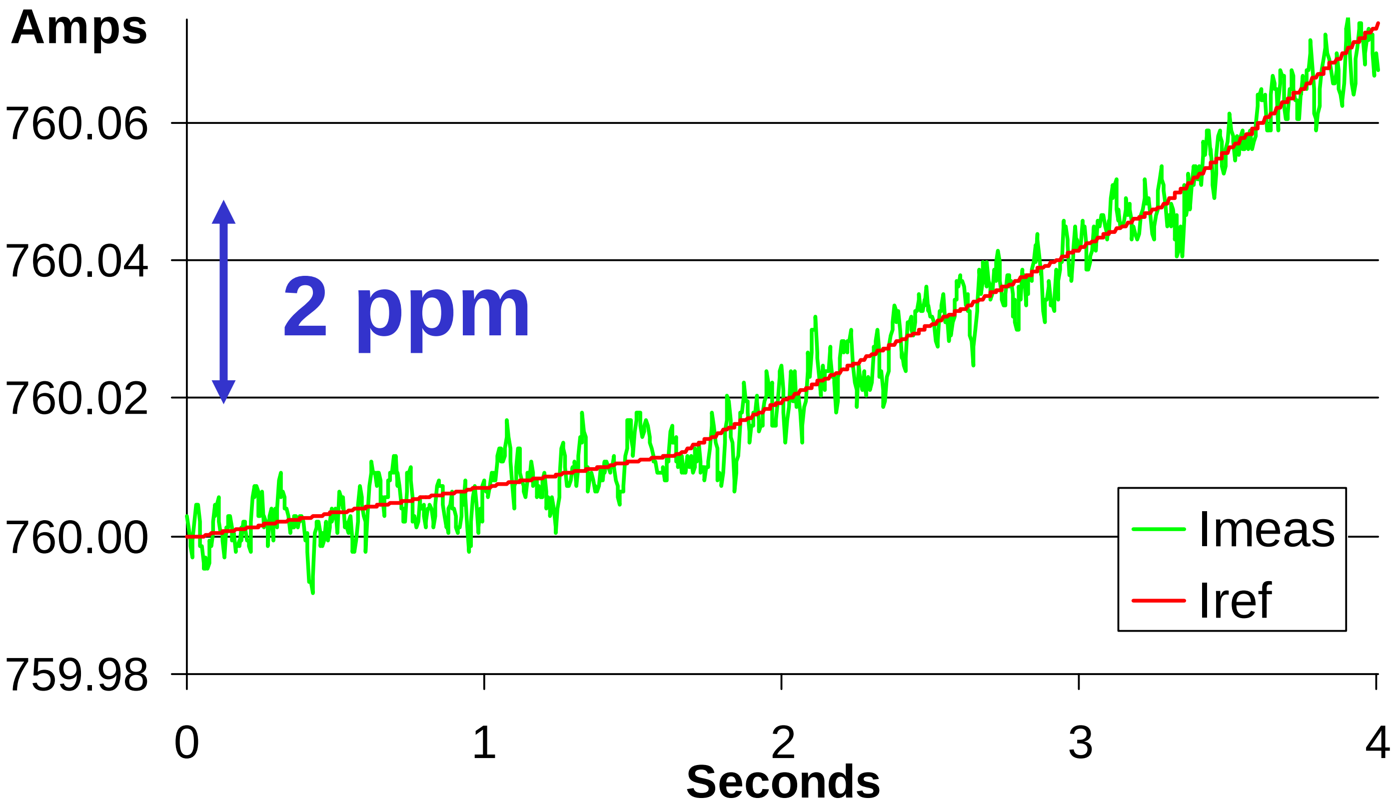
$$\left(1 - z^{-1}\right)^2$$

Main Dipole Current Cycle

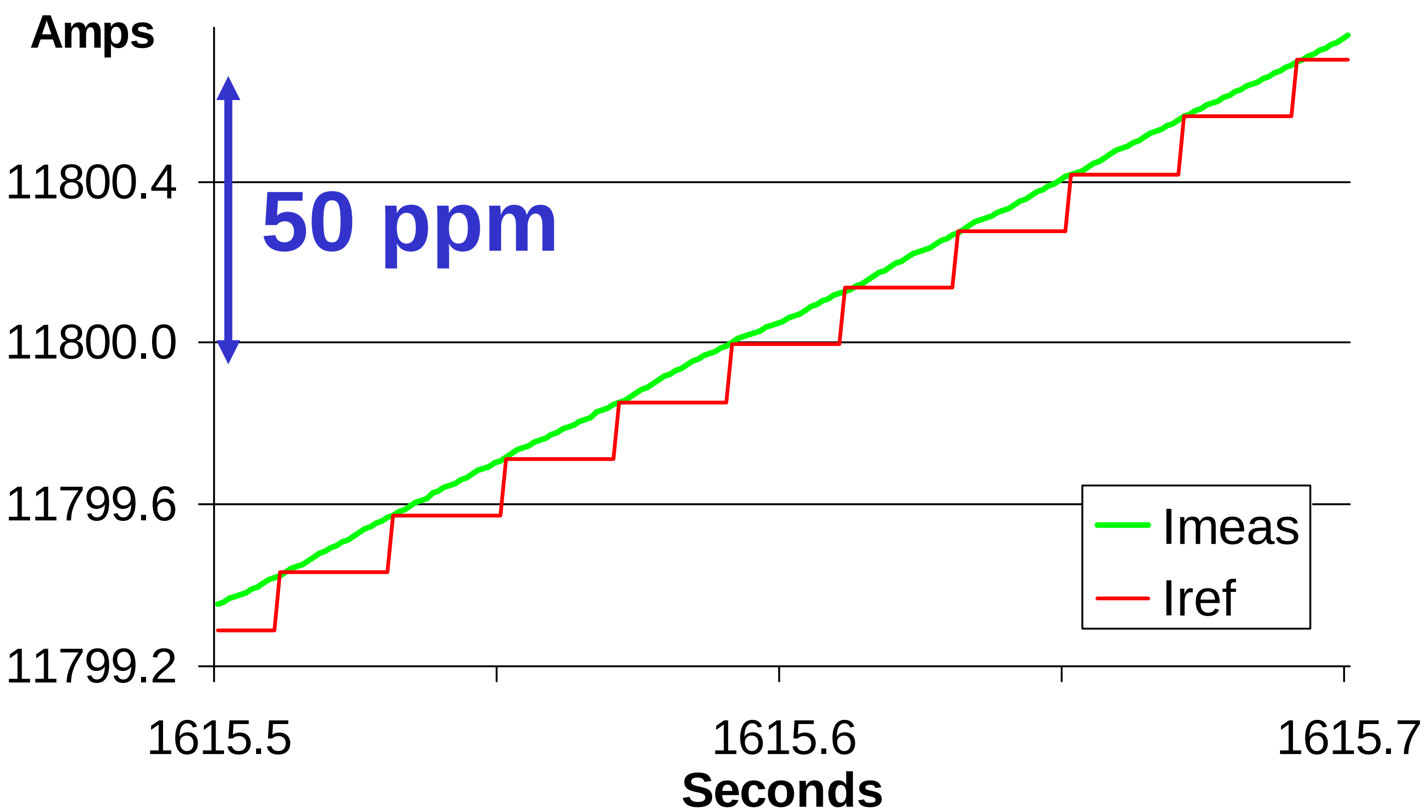


Start of the ramp (from 200 A to 225 A)

String 2 dipole circuit ramp (0-4s)

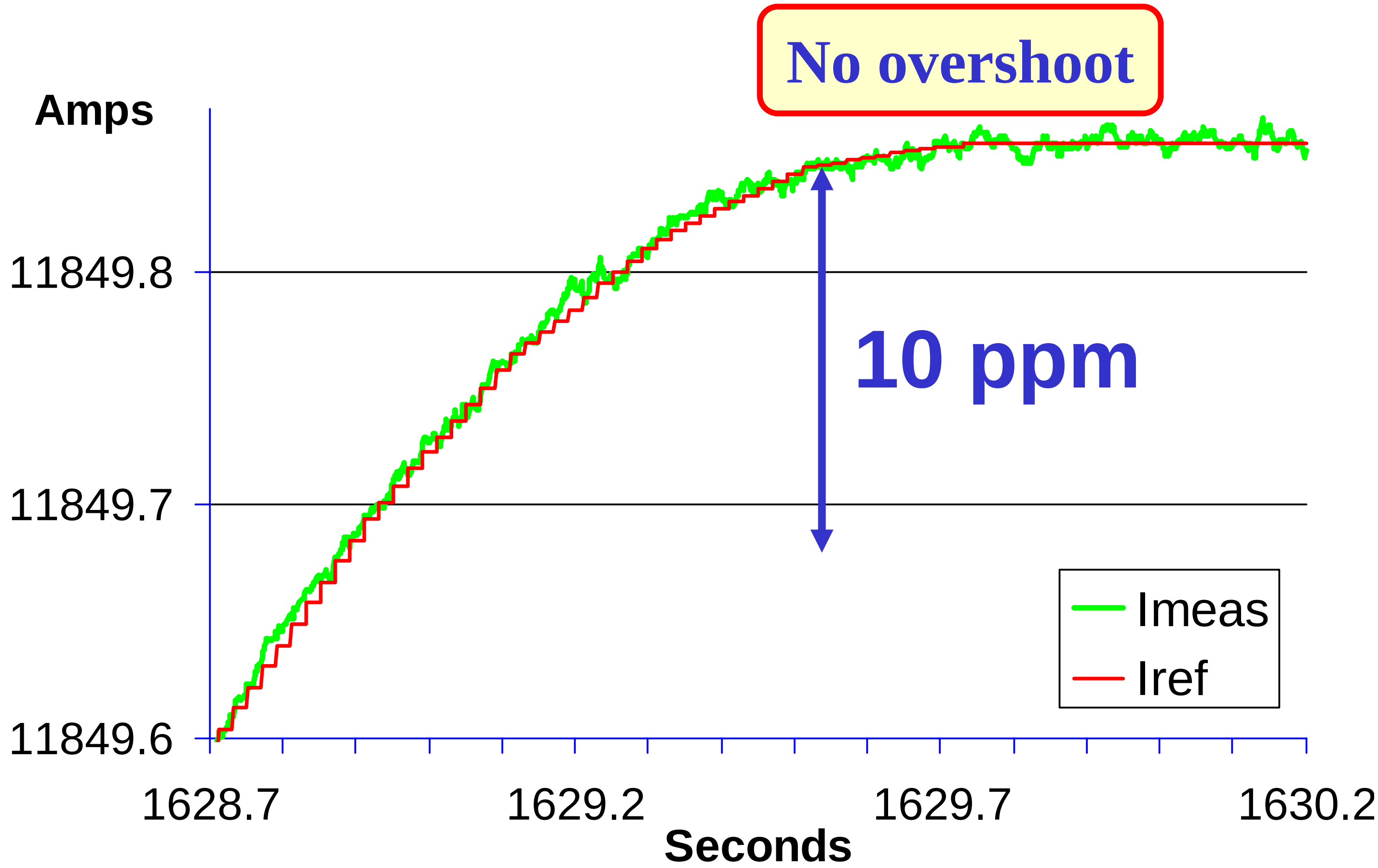


String 2 dipole circuit ramp (200ms)



Fk. Bordry AB/PO

String 2 dipole circuit ramp (last 1s)



Multi Input and Multi Output Systems (MIMO)

Example : LHC Inner triplet powering

MIMO system => SISO system

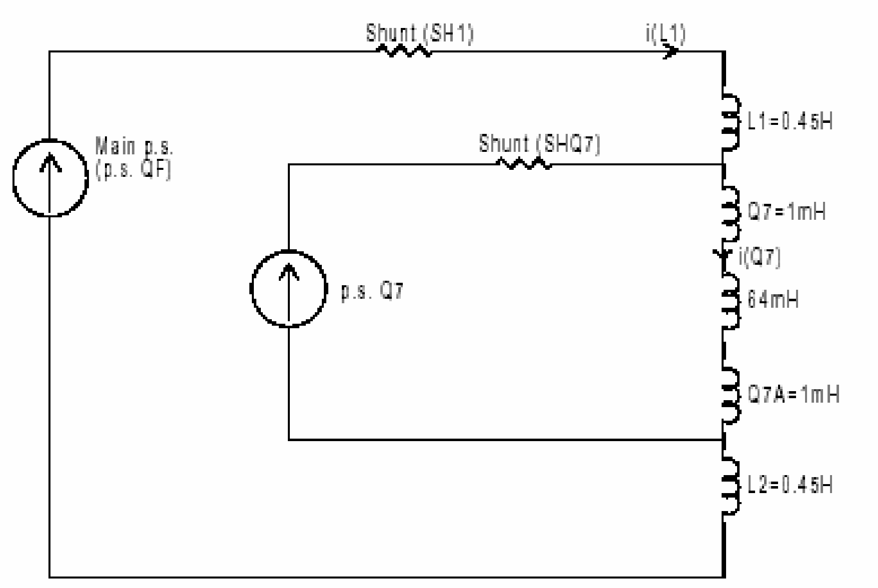


Figure: 1 Single Shunt P.S. Model

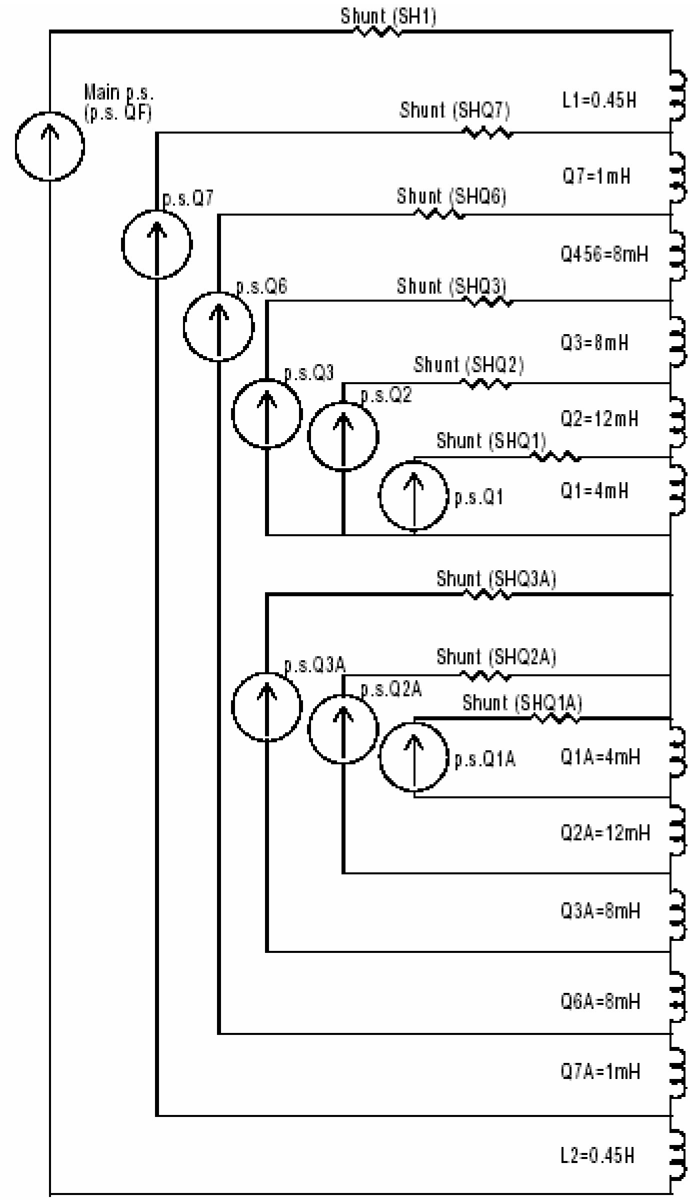
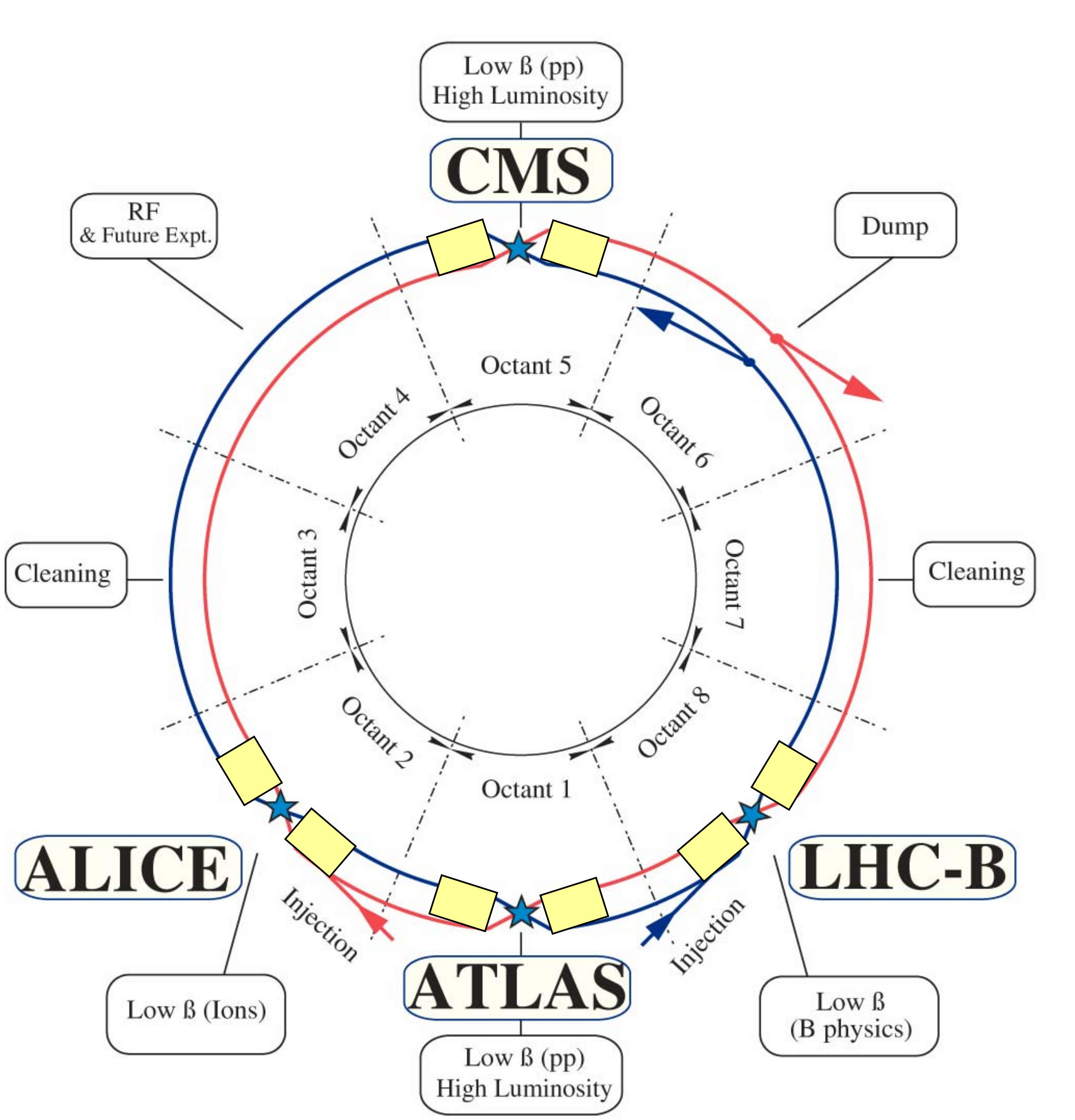


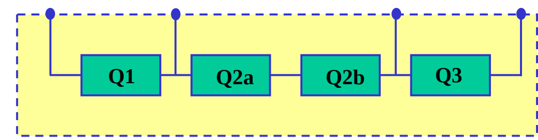
Figure: 3 Single Sextant PS Model

RHIC INSERTION REGION SHUNT POWER SUPPLY

(D. Bruno's paper at PAC'99)

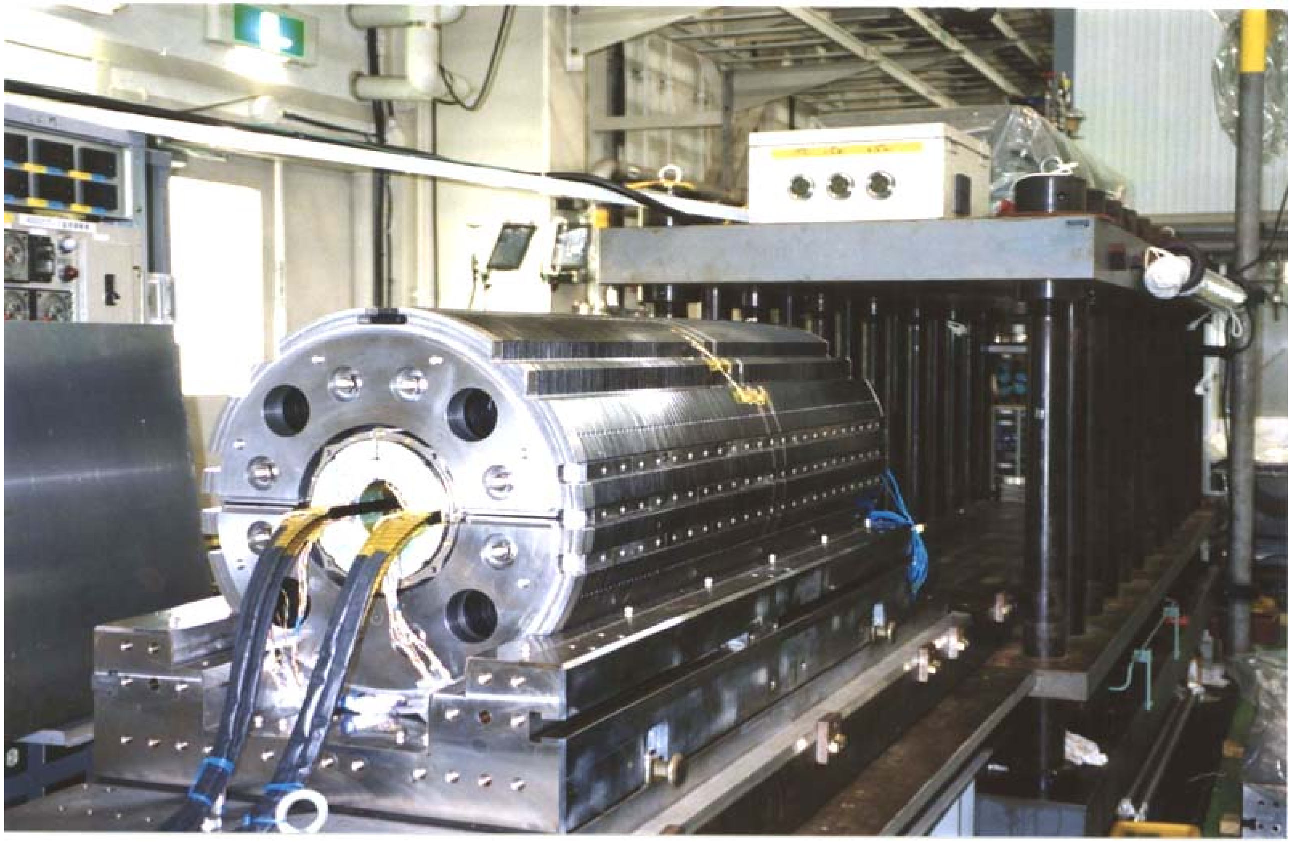
But also SPS transfer line (bypass converters), …



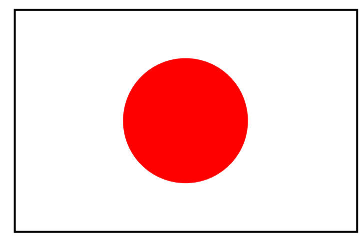


Inner triplet

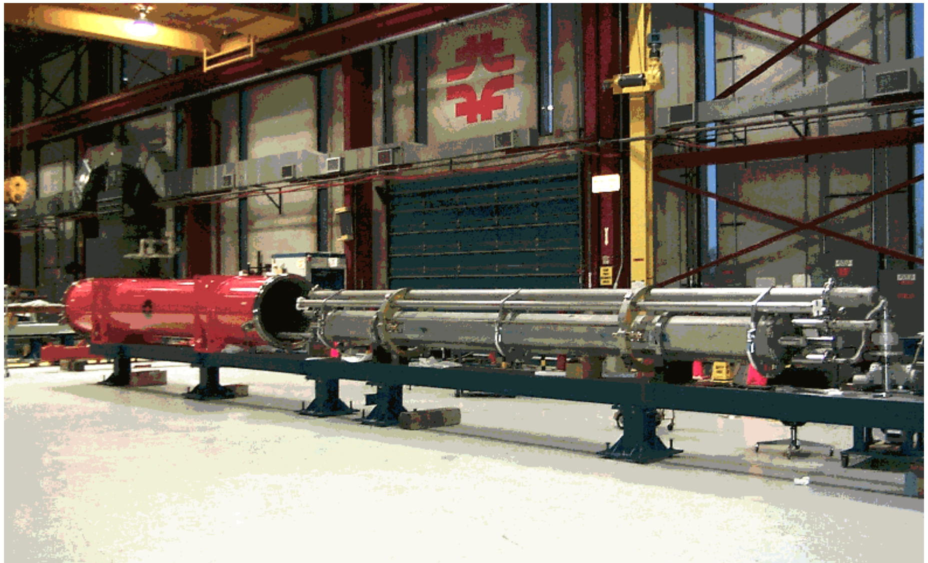
Prototype low-β quadrupole

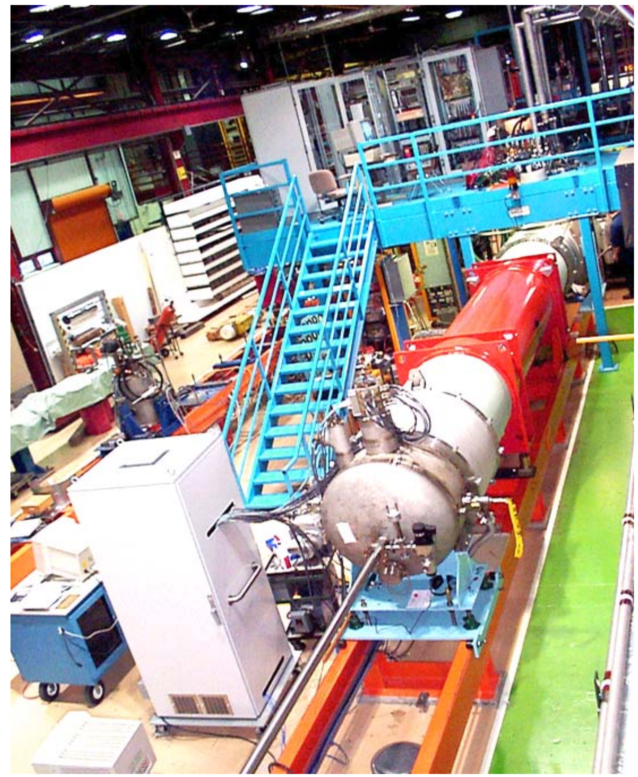


MQXA (KEK)
205 T/m
I = 6450 A
Iultimate = 7 kA
L1= 91 mH



Prototype MQXB being readied for cryostat insertion



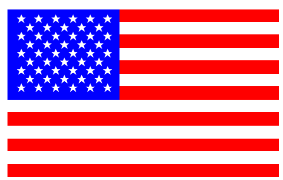


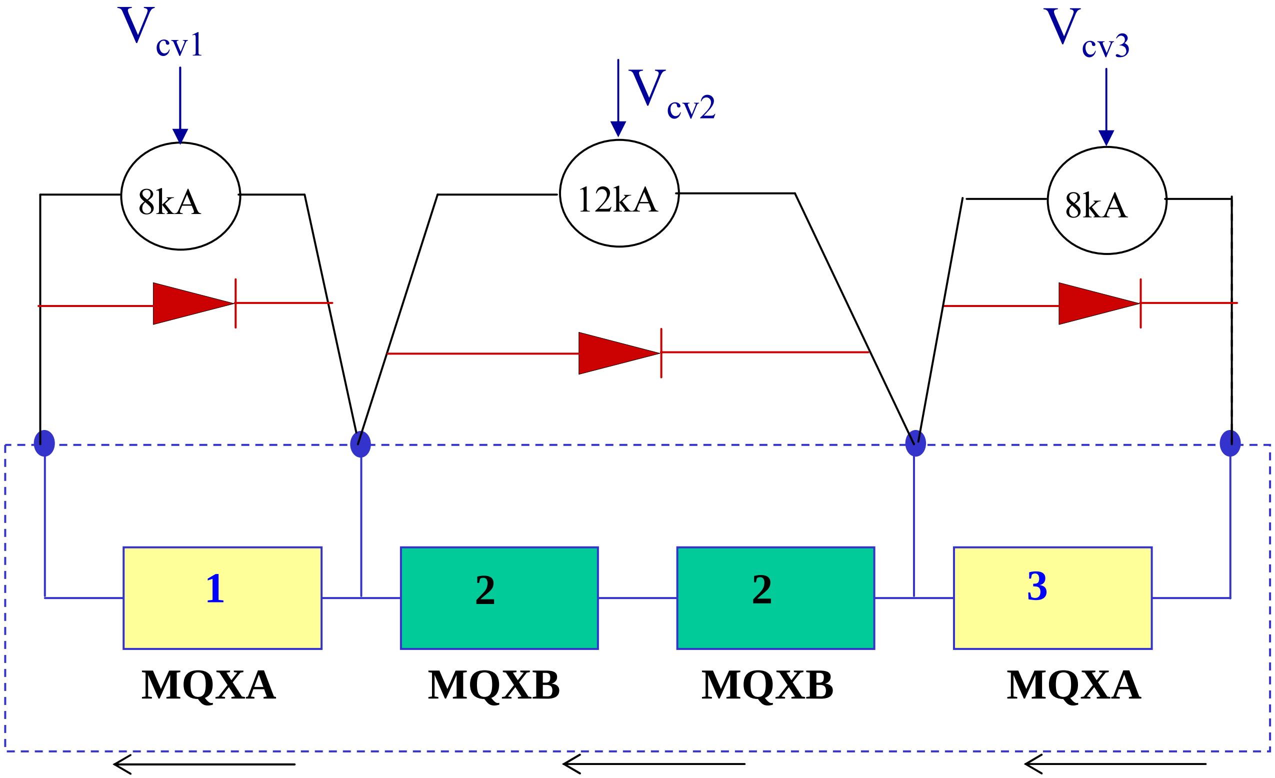
MQXB (Fermilab)

205 T/m

I = 11390 A (Iultimate = 12290A)

L2= 18.5 mH

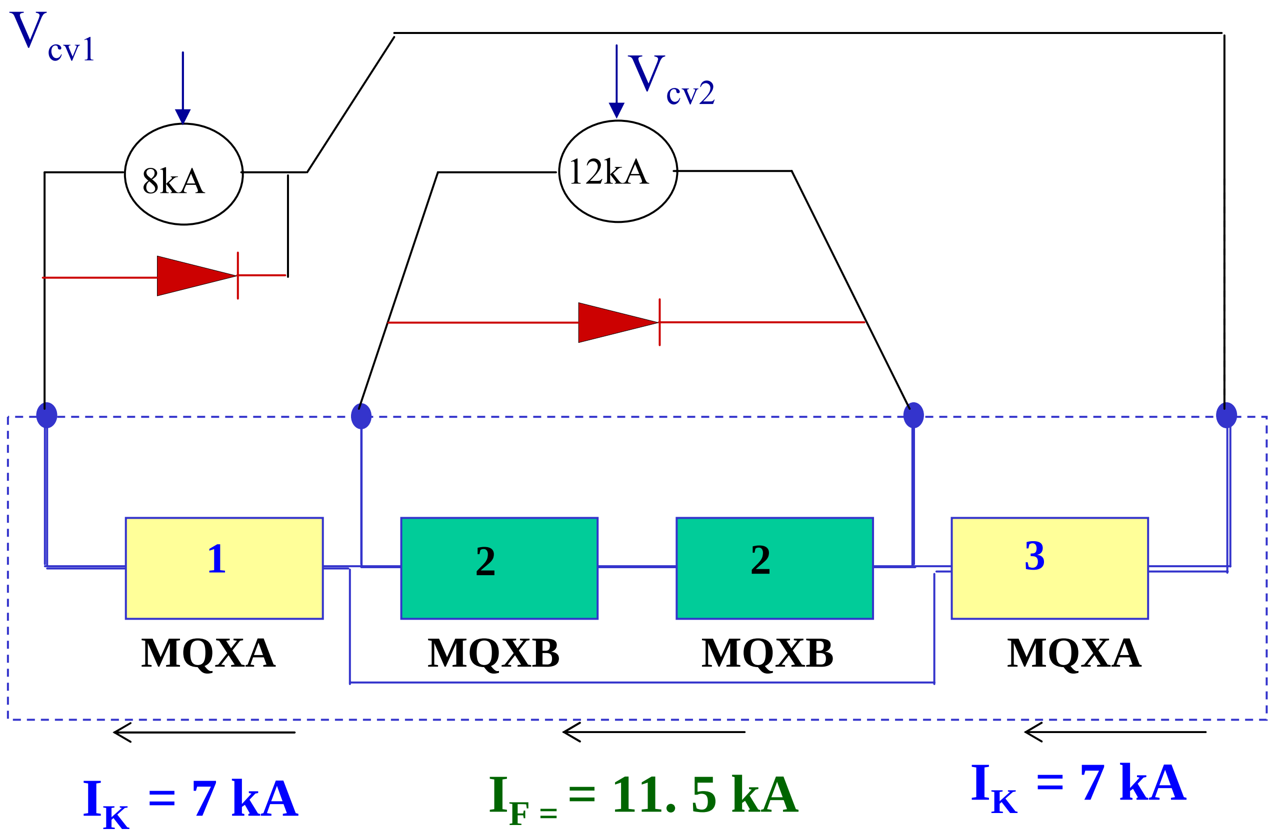




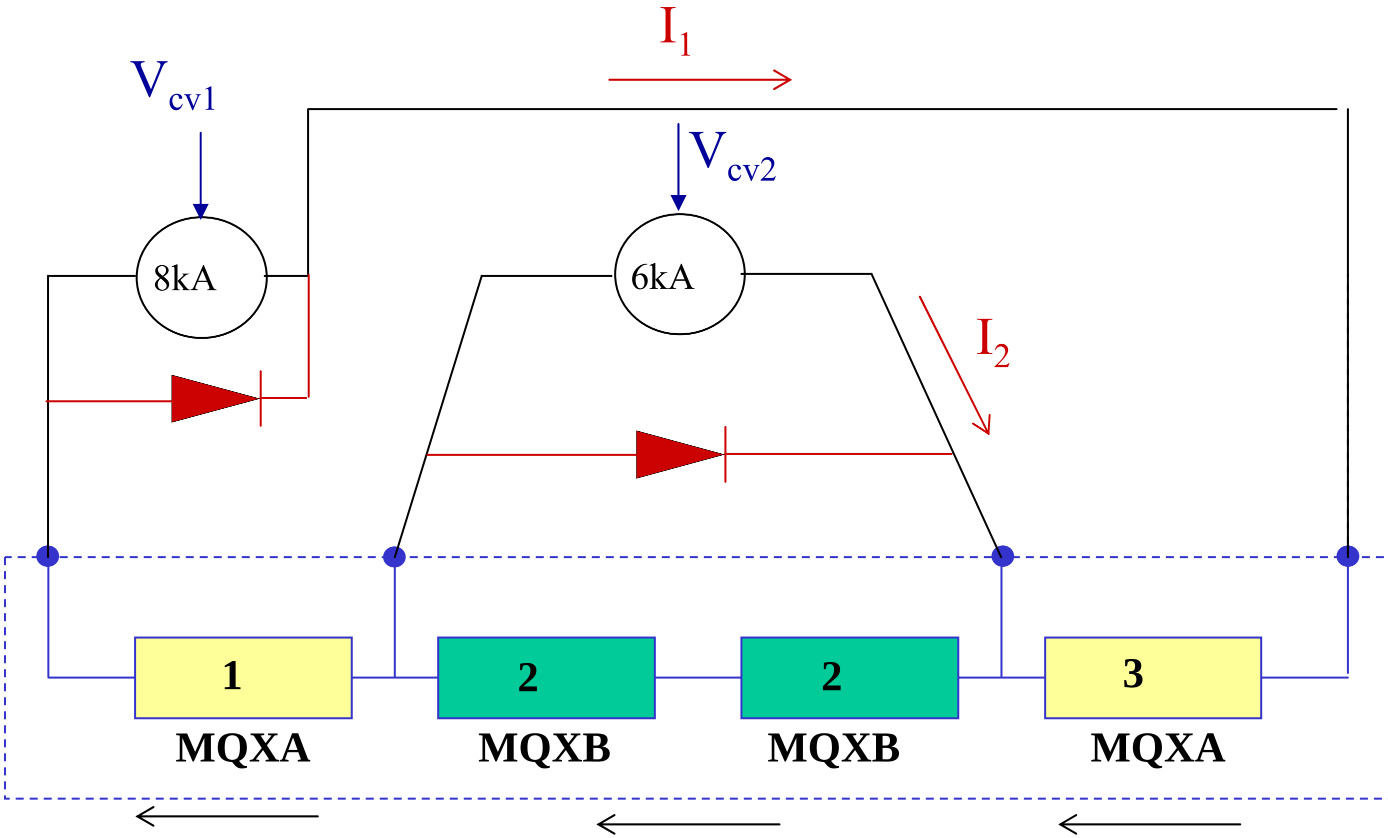
I_K = 7 kA

$I_{F=}$ = 11. 5 kA

I_K = 7 kA



V_{cv1}
8kA
12kA
V_{cv2}
1
2
2
3
MQXA
MQXB
MQXB
MQXA
I_K = 7 kA
I_{F} = = 11. 5 kA
I_K = 7 kA

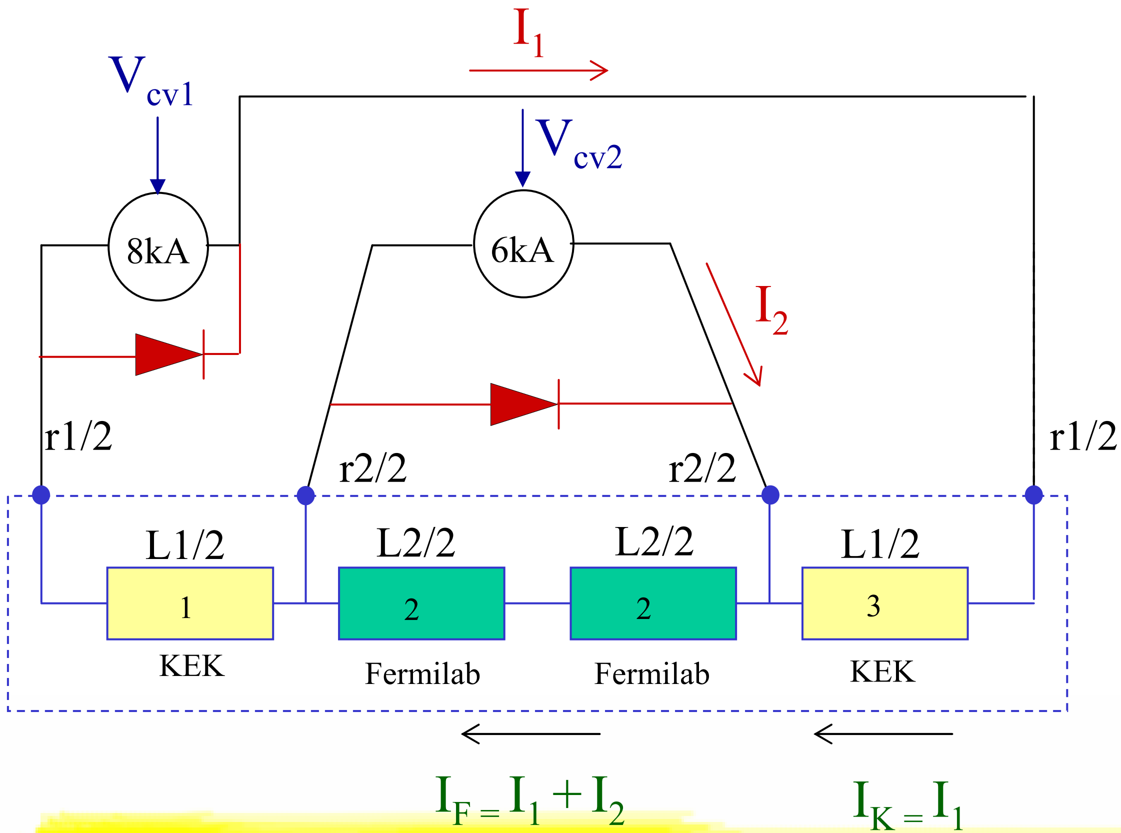


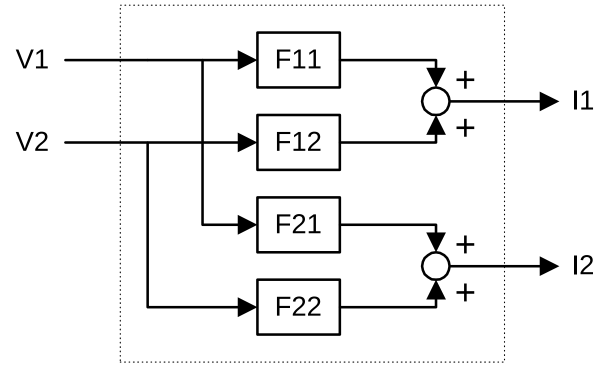
$I_K = I_1 = 7$ kA

$I_F = I_1 + I_2 = 11.5$ kA

$I_K = I_1 = 7$ kA

Inner Triplet : nested power converters

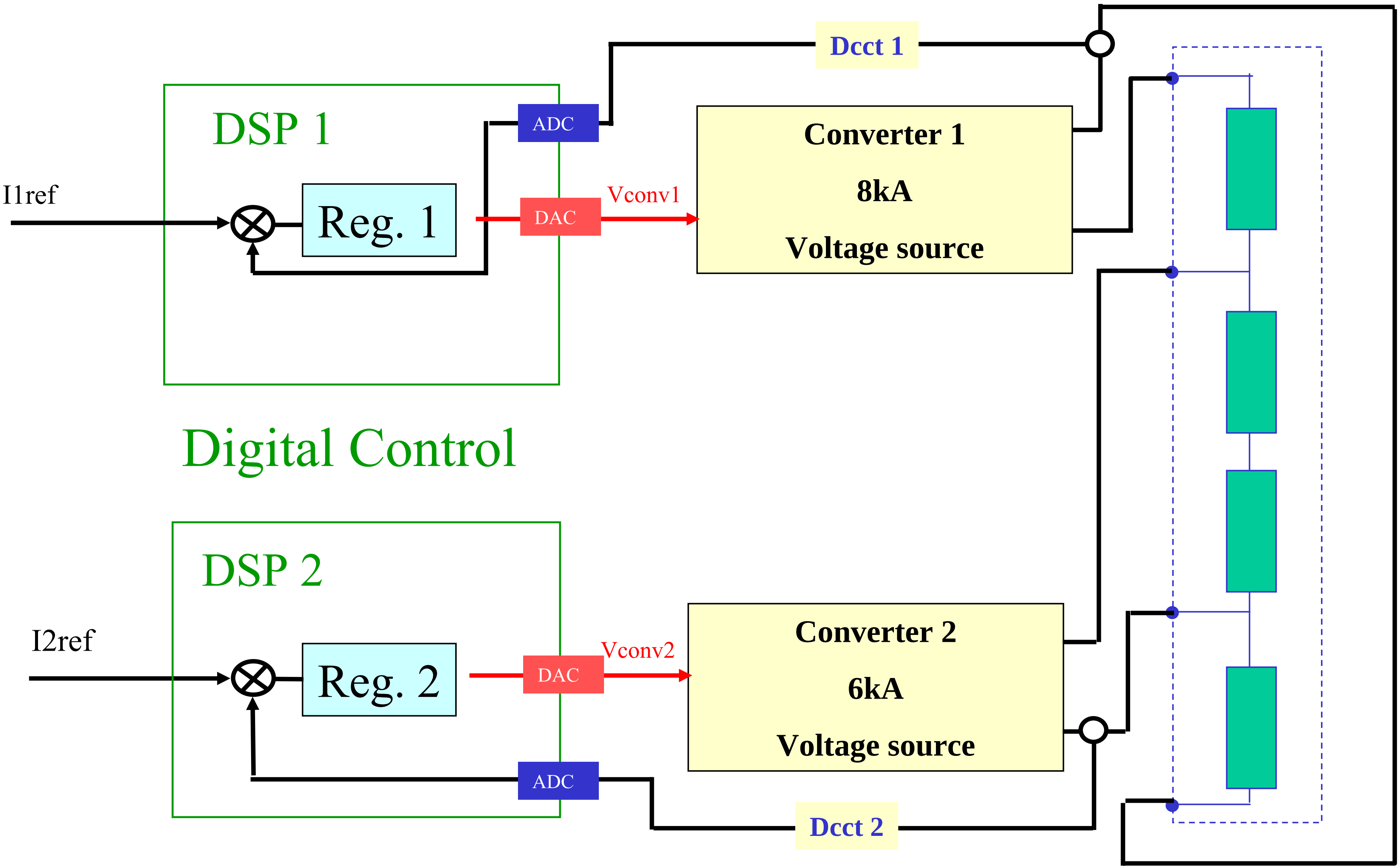




Inductive coupling

$$\frac{d}{dt}\begin{bmatrix} i1 \\ i2 \end{bmatrix} = \begin{bmatrix} -\frac{r1}{L1} & -\frac{r2}{L1} \\ \frac{r1}{L1} & -r2.\left(\frac{1}{L1}+\frac{1}{L2}\right) \end{bmatrix} \cdot \begin{bmatrix} i1 \\ i2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L1} & -\frac{1}{L1} \\ -\frac{1}{L1} & \frac{1}{L1}+\frac{1}{L2} \end{bmatrix} \cdot \begin{bmatrix} Vcv1 \\ Vc2 \end{bmatrix}$$

Digital Control



Current loops

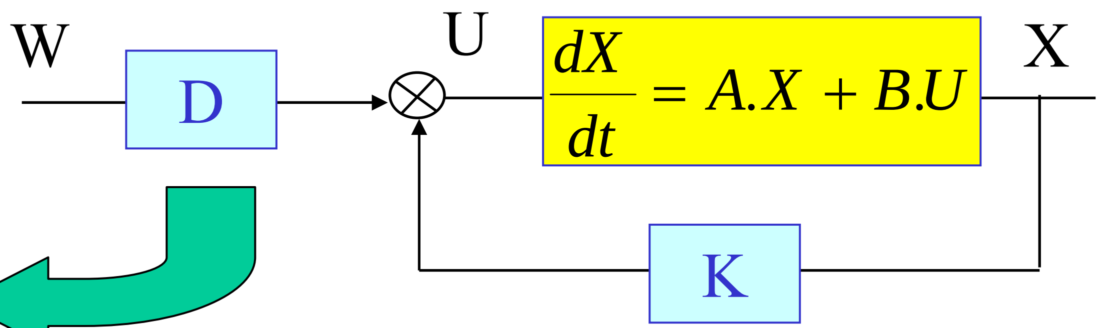
Conclusion

In theory, it is possible to use 2 independent controllers without decoupling but…

- the precision decreases with the order of the system
- the current loops are less robust: - to non linearities
- to parameter changes
- a ratio of at least 10 is needed between the current loop bandwidths and the frequency of the reference currents
- slow down the ramp rate

Decoupling Principle :

$$\frac{dX}{dt} = A.X + B.U$$



$$\frac{dX}{dt} = \underbrace{(A + B.K)}_{Ad}.X + \underbrace{B.D}_{Bd}.W$$

Ad and Bd : diagonal matrices

Choice :

$$Ad = \begin{bmatrix} -\frac{r1}{L1+L2} & 0 \\ 0 & -\frac{r2}{L2} \end{bmatrix}$$

$$Bd = \begin{bmatrix} \frac{1}{L1+L2} & 0 \\ 0 & \frac{1}{L2} \end{bmatrix}$$

Decoupling matrices :

$K = B^{-1} . (Ad - A)$

$D = B^{-1} . B$

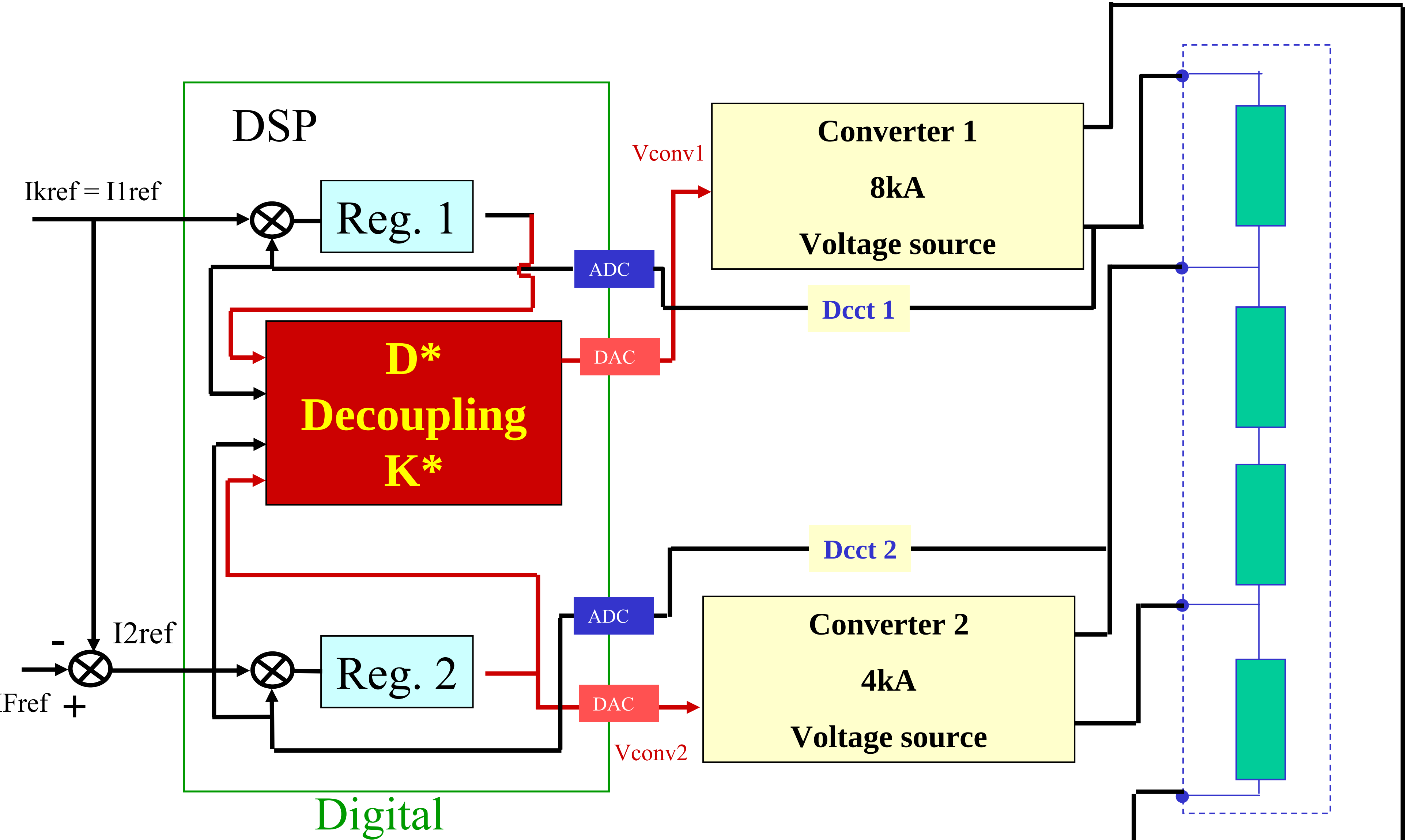
Digital :

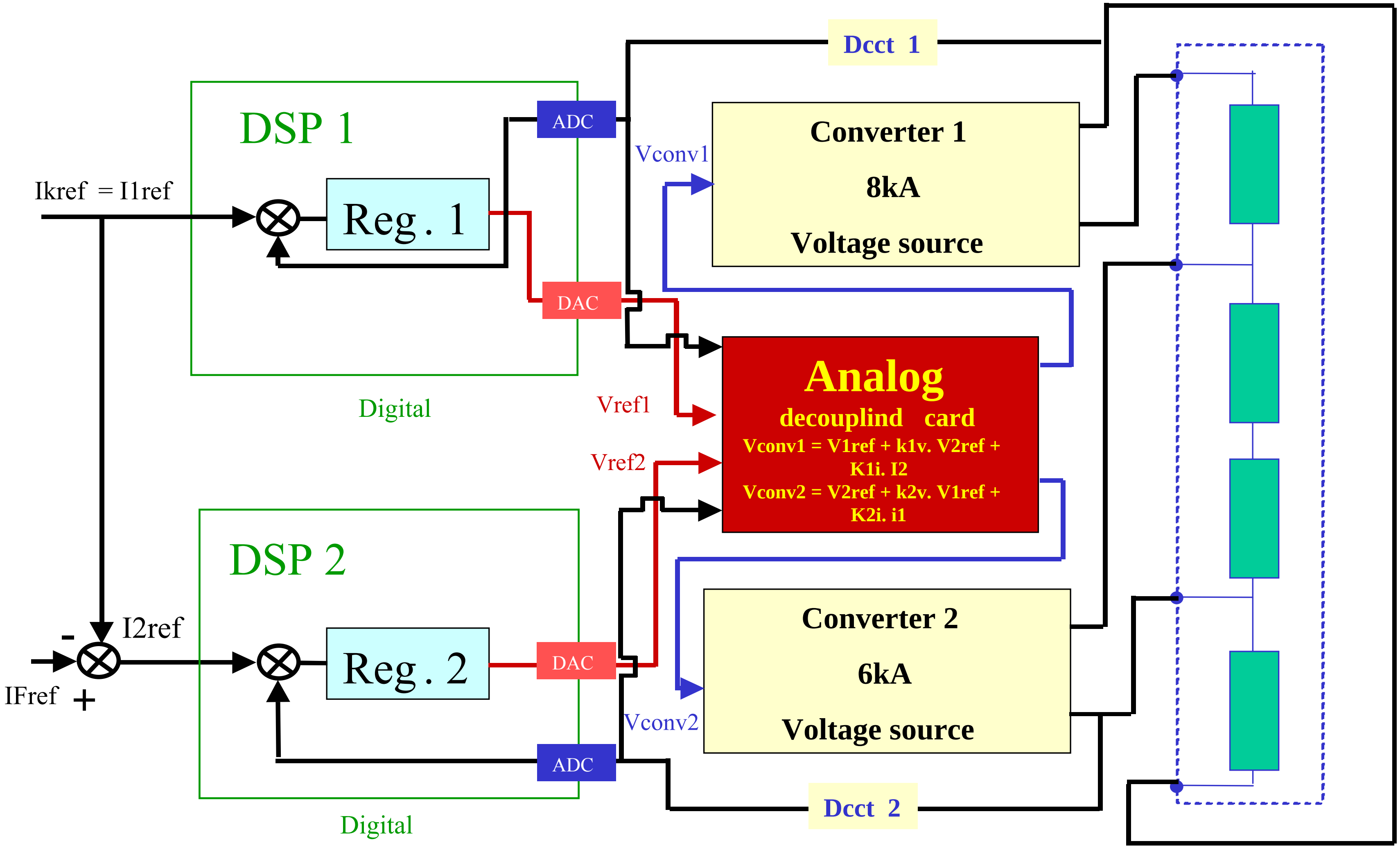
$X^*(k+1) = F^*.X^*(k) + H^*.U^*(k)$

with $F^* = e^{A.\,ts}$; $H^* = A^{-1}.(e^{A.\,ts} - I).B$

ts : sampling period

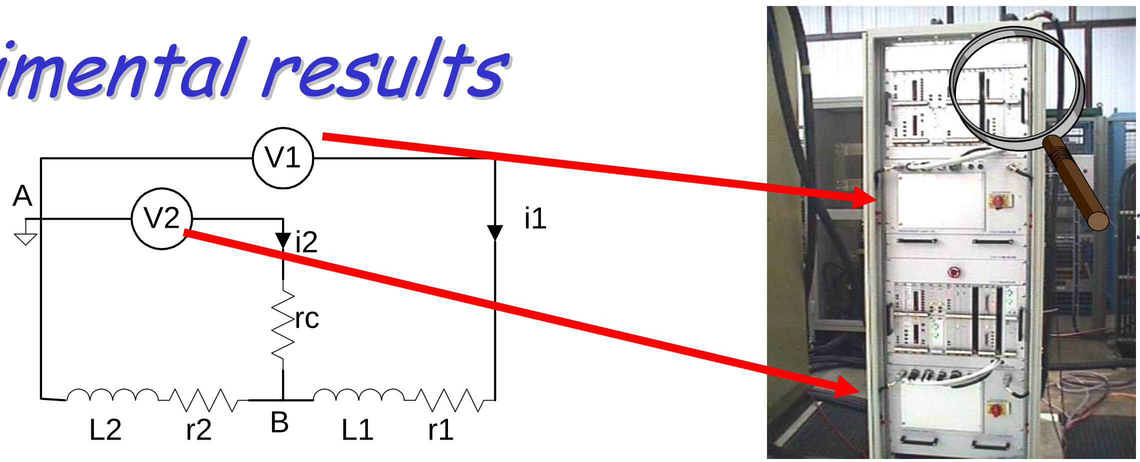
$X^*(k+1) = Fd^*.X^*(k) + Hd^*.W^*(k)$

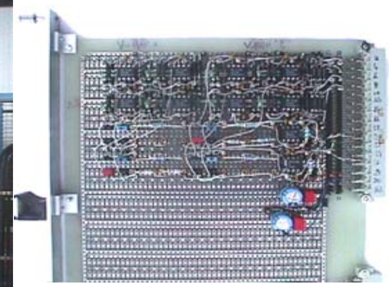

DSP
Ikref = I1ref
Reg. 1
ADC
D*
Decoupling
K*
DAC
Vconv1
Converter 1
8kA
Voltage source
Dcct 1
Dcct 2
ADC
Converter 2
4kA
Voltage source
I2ref
-
IFref
+
Reg. 2
DAC
Vconv2
Digital



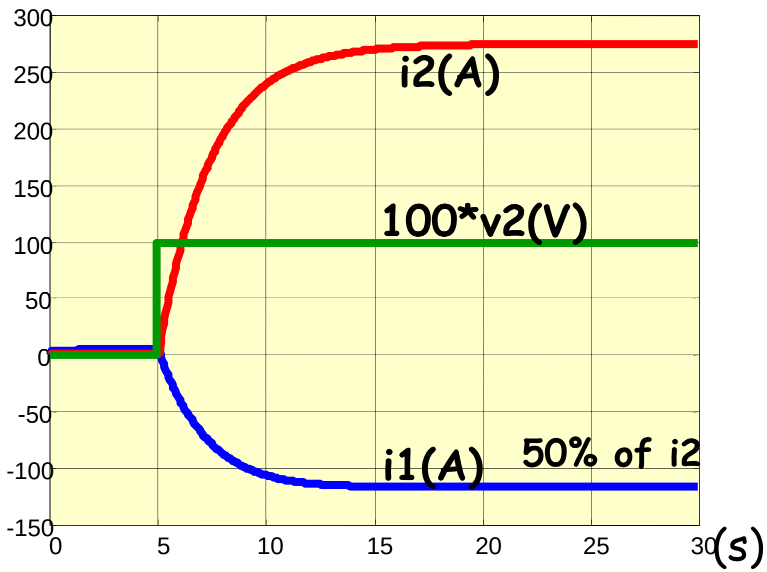
DSP 1
Reg. 1
ADC
DAC
Ikref = I1ref
Digital
Dcct 1
Vconv1
Converter 1
8kA
Voltage source
Analog
decouplind card
Vconv1 = V1ref + k1v. V2ref + K1i. I2
Vconv2 = V2ref + k2v. V1ref + K2i. i1
Vref1
Vref2
DSP 2
Reg. 2
DAC
ADC
I2ref
IFref
-
+
Digital
Converter 2
6kA
Voltage source
Vconv2
Dcct 2

Experimental results

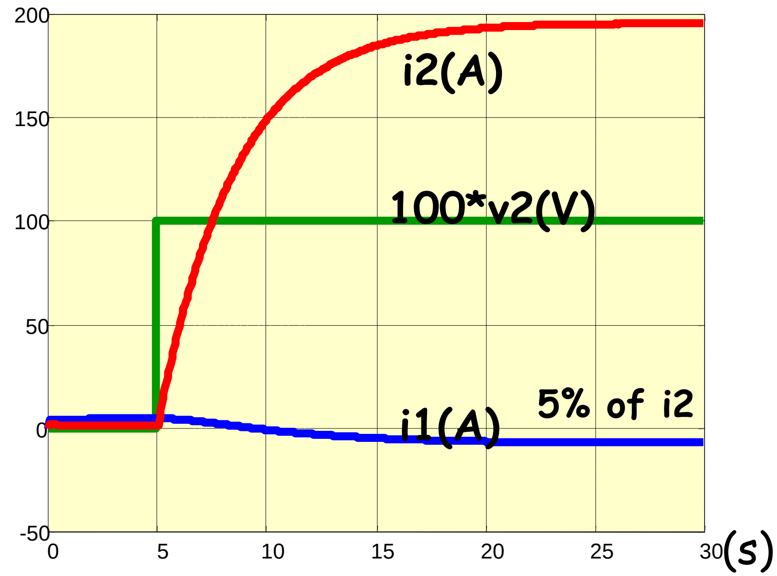




2 * [600A,10V]



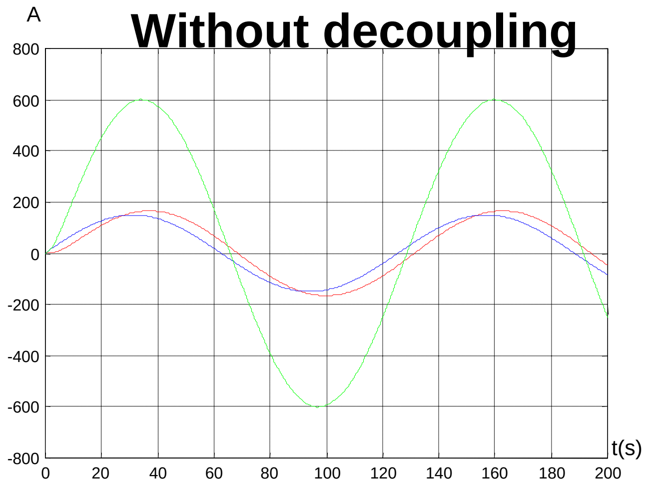
Without decoupling



With decoupling
(10% parameter error)

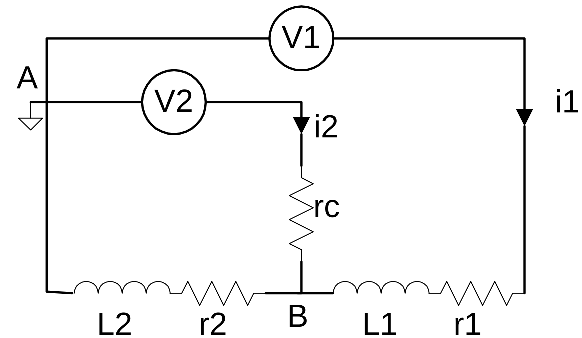
Decoupling solution

Without decoupling

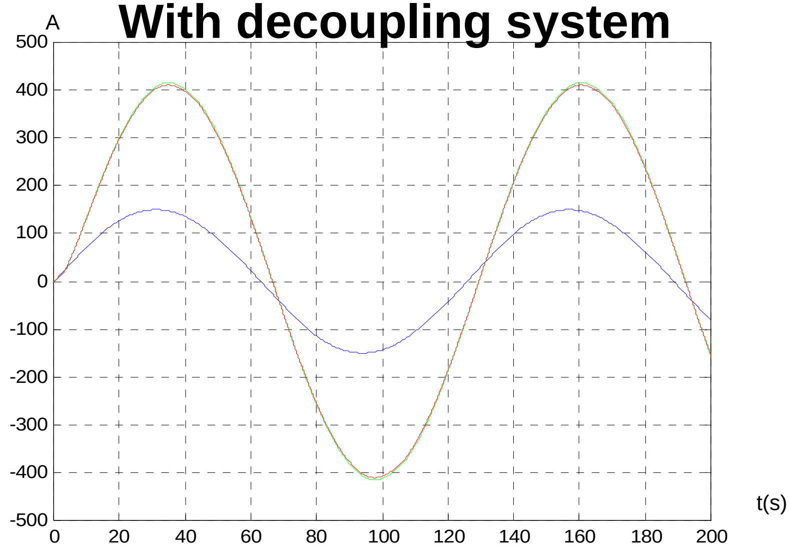


Blue:50*V(references)

Green:I1 with V1=V and V2=0
red: I1 with V1=V and V2=V



With decoupling system



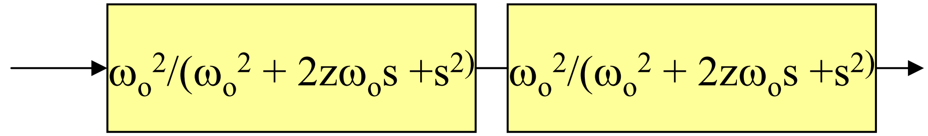
Blue:50*V(references)

Green:I1 with V1=V and V2=0
red: I1 with V1=V and V2=V

The end

Thank for your attention

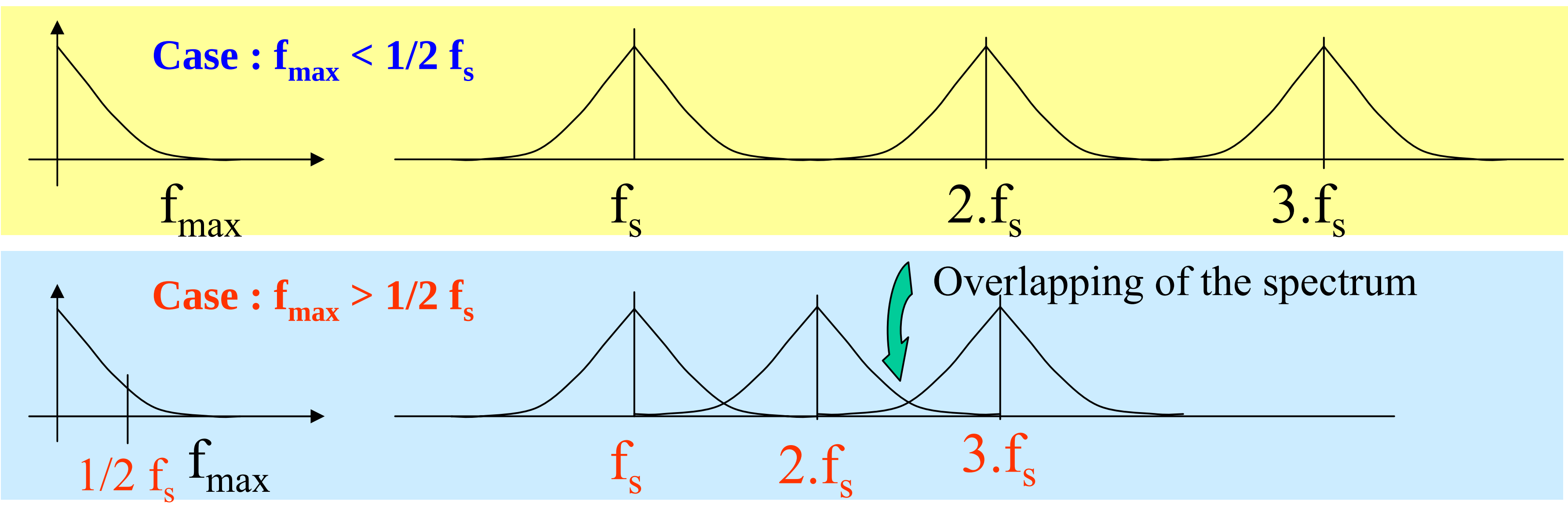
Anti-aliasing



Since the sampling frequency is fixed, in order to avoid the folding (overlapping, aliasing,…) of the spectrum (=> distorsions), the analogue signals must be filtered prior to sampling to ensure that

$$f_{max} < 1/2\ f_s \quad \textbf{(Nyquist or Shannon criteria)}$$

In the case of low frequency sampling, a sampling at a higher frequency could be carried out (integer multiple of the desired sampling frequency), using an appropriate anti-aliasing filter. Then the sampled signal is passed through a digital anti-aliasing filter followed by a frequency divider => giving a sampled signal with the required frequency (fs)



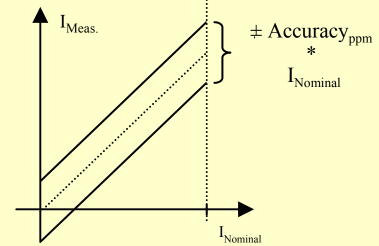
Glossary

Precision

– **Accuracy**

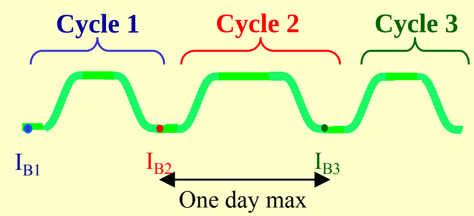
Long term setting or measuring uncertainty taking into consideration the full range of permissible changes* of operating and environmental conditions.

*** requires definition**



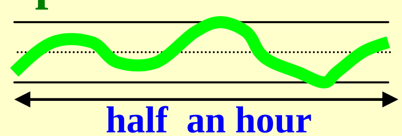
– **Reproducibility**

Uncertainty in returning to a set of previous working values from cycle to cycle of the machine.



– **Stability**

Maximum deviation over a period with no changes in operating conditions.



Accuracy, reproducibility and stability are defined for a given period

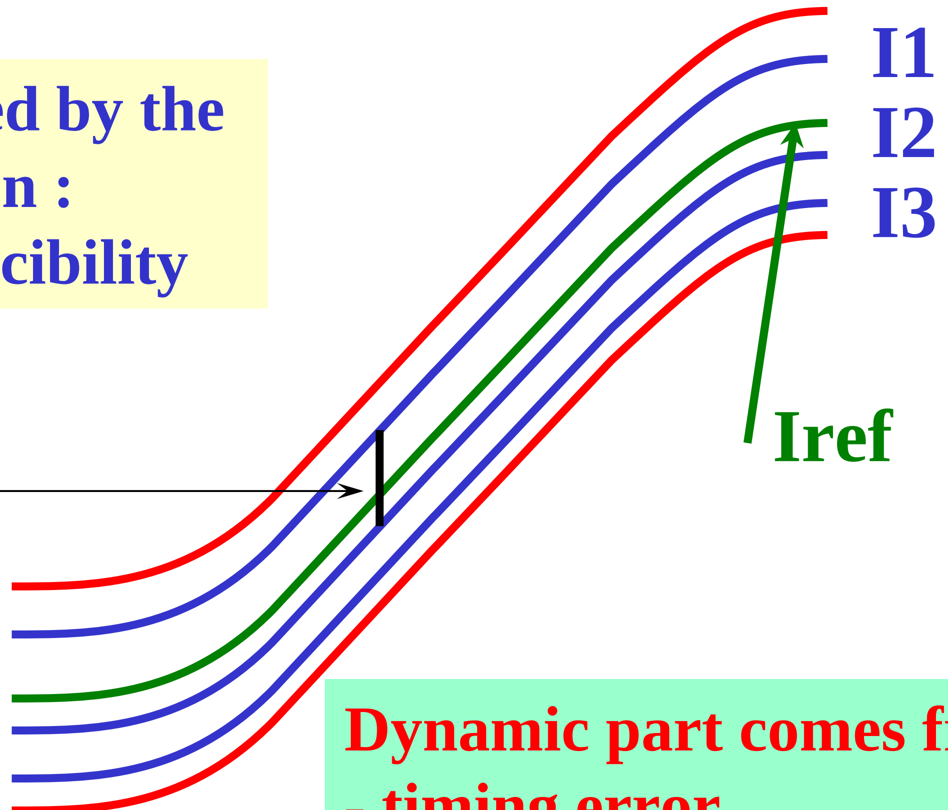
Precision is qualitative . Accuracy is quantitative.

Tracking

Ability of the converterS to follow the reference function (static, dynamics)

Static part is covered by the static definition : accuracy, reproducibility

Tracking error between I1 and I2



Dynamic part comes from :

- **timing error**
- **lagging error in the regulation**

System Identification

1) Input/Output data acquisition under an experimental protocol

2) Choice of model structure (complexity : system order)

Parametric or non-parametric, continuous-time or discrete time

3) Estimation of the model parameters

4) Validation of the identified model

Structure and parameter values