OPERATIONAL EXPERIENCE WITH THE SOLEIL POWER SUPPLIES

1rst POCPA Workshop – 19-21 May 2008 – ELETTRA

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Overview

- Some words about SOLEIL
- Description of the magnet power supplies installed at SOLEIL
- Main problems encountered since the beginning of the synchrotron commissioning in July 2005
- Conclusion

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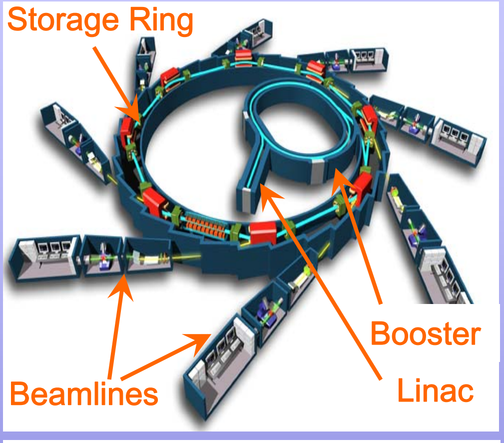
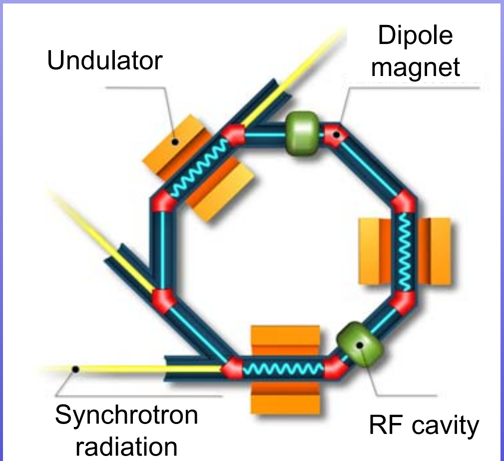
What is SOLEIL ?

SOLEIL is a particle (electron) accelerator that produces the synchrotron radiation, an extremely powerful source of light that permits exploration of inert or living matter.

How does SOLEIL work ?

SOLEIL machine is made up of 2 accelerators (a 100 MeV linear accelerator, the LINAC, and a 2.75 GeV circular one, the BOOSTER) and of a Storage Ring accommodating the magnetic elements (dipoles and undulators) which bend the electrons trajectory. With each curve, the relativistic electrons lose energy, which produces synchrotron light.





Main Accelerator Electromagnets

The main accelerator magnets are, dipole magnet for electron bending and synchrotron radiation, quadrupole magnet for electron focusing, sextupole magnet for controlling the electron beam stability, and corrector magnets for small angle corrections.

The specifications on the stability and reproducibility of their magnetic fields - hence on the currents delivered by the power supplies - are of course very demanding.

DIPOLE

SEXTUPOLE

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Booster power supply characteristics

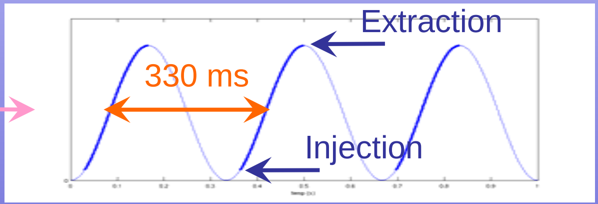
Characteristics of the Booster AC Power Supplies					
Fed magnet *	Max. Current [A]	Max. Voltage [V]	Output Frequency [Hz]	Current accuracy [ppm of nominal]	Nb.
D	± 580	± 1000	3	50	2
Q	± 250	± 450	3	50	2
S	± 30	± 30	3	50	2
C	± 1.5	± 2.5	DC	100	44

* D: Dipole magnets
S: Sextupole magnets
Q: Quadrupole magnet
C: Corrector magnet

The Booster PS have been manufactured by BRUKER except the Sextupole PS → built in house

Booster PS → In operation since Sept. 2005

Raise of the beam energy in the Booster from 100 MeV (energy at the output of the LINAC) to 2.75 GeV (beam energy in the Storage Ring)



Tracking requirement between the Booster power supplies

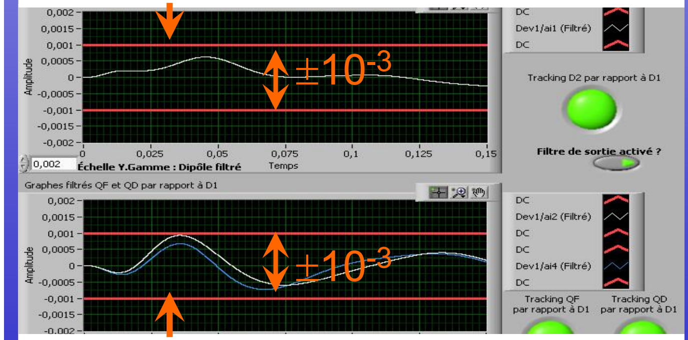
$$\left|\frac{I_{D1} - I_{D2}}{I_{D1}}\right| \leq 10^{-3}$$

$$\left|\frac{I_{D1} - k \cdot I_{Q1,2}}{I_{D1}}\right| \leq 10^{-3}$$

$I_{D1,2}$: Currents of the 2 dipole PS
$I_{Q1,2}$: Currents of the 2 quadrupole PS
k being such that :
$k \times I_{Q1,2}\,peak = I_{D1,2}\,peak$

This tracking is required from 4% of the current excursion (this current level corresponds to the beam injection into the Booster) to 100% (which corresponds to the beam extraction from the Booster)

Tracking error between both dipole currents on one 3Hz cycle → Specif. are met



Tracking error between dipole and quadrupole currents on one 3Hz cycle

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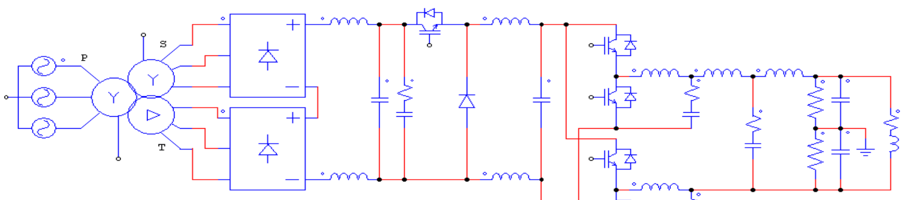
Control part description

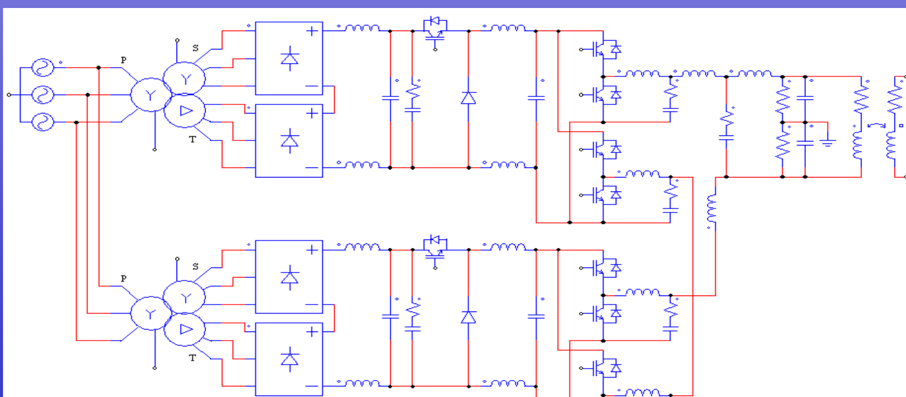
Same digital control as SLS (Swiss Light Source)

- DSP/FPGA-based control board
- Use of 16-bit 200kS/s ADCs
- High resolution PWM implemented inside the FPGA

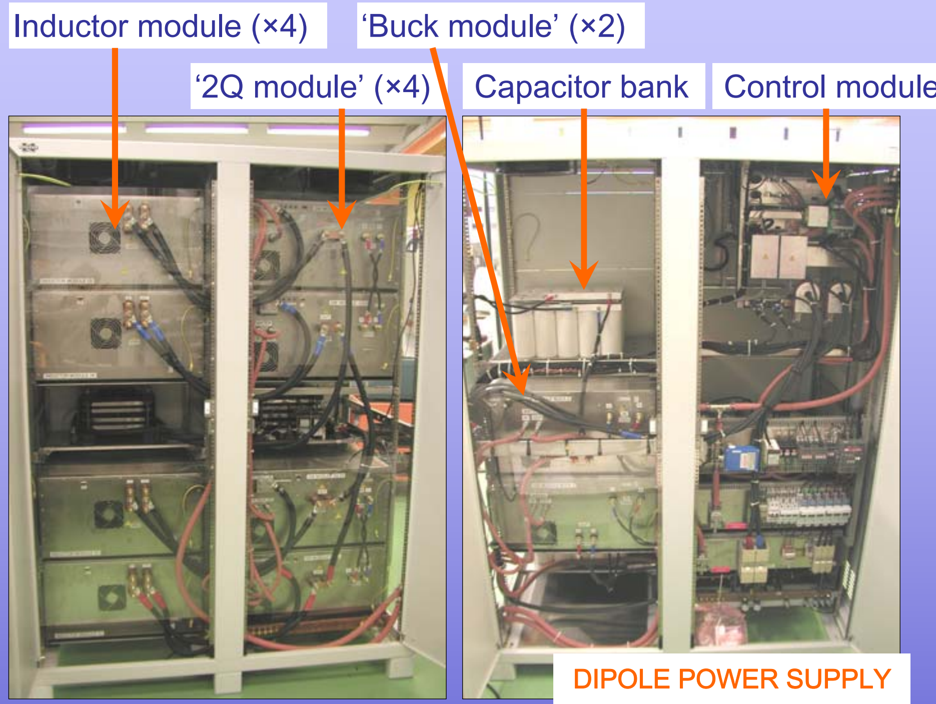
PS Topology



QUADRUPOLE POWER SUPPLY



DIPOLE POWER SUPPLY



- **Dodecaphase rectifying unit**
- **Intermediate stage: Buck with capacitor bank**

  → Enables to reduce low frequency (3Hz) fluctuations on the mains voltage
- **H-bridge output stage**

  IGBT switching frequency: 10kHz

  Interleaved operation → The effective frequency at the output is 20kHz
- **Efficiency: 87%**

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SOLEIL SYNCHROTRON

Transfer Lines power supply characteristics

Transfer Line 1 (Linac → Booster)					
Fed magnet	Max. Current [A]	Max. Voltage [V]	Current Resolution [ppm of nominal]	Current stability 24hours [ppm of nominal]	Nb.
D	250	20	60	100	1
Q	10	9	60	100	7
C	1.5	2.5	100	500	12
Transfer Line 2 (Booster → Storage Ring)					
Fed magnet	Max. Current [A]	Max. Voltage [V]	Current Resolution [ppm of nominal]	Current stability 24hours [ppm of nominal]	Nb.
D	580	80	50	50	7
Q	275	10	20	50	7
C	10	9	60	100	12

Transfer Line LT1 → PS in operation since early 2005

→ Manufactured by BRUKER

Transfer Line LT2 → PS in operation since March 2006

D & Q PS → HAZEMEYER
C PS → BRUKER

Storage Ring power supply characteristics

Characteristics of the Storage Ring DC Power Supplies					
Fed magnet	Max. Current [A]	Max. Voltage [V]	Current Resolution [ppm of nominal]	Current stability 24hours [ppm of nominal]	Nb.
D	580	610	10	10	1
S	350	140	50	50	5
S	350	75	50	50	5
Q	250	22	5	20	32
Q	250	14	5	20	128
C	+/-14	+/-10	2	20	60
C	+/-11	+/-14	2	20	60
C	+/-7	+/-3.5	30	50	34

Storage Ring PS

→ All manufactured by HAZEMEYER
Except for the correctors → BRUKER

In operation since March 2006

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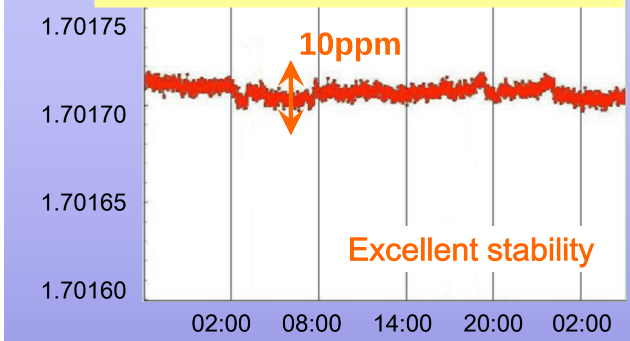
Storage Ring power supply characteristics

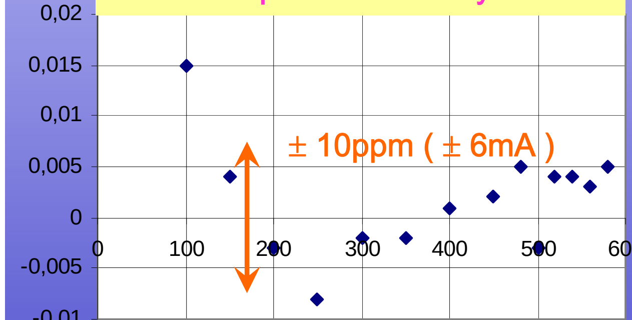
Main solutions permitting to fulfill the resolution and stability requirements

- **Ad hoc attenuation of the power filters** (for the short-term stability)
- **Precise current measurements** → Use of precision shunts in the corrector PS and DC Current transformers (DCCT) in the other PS
- **Digital Control** → Low dependency to temperature drifts
- **High control bandwidths** → High rejection of the 300Hz and 600Hz freq.
- **High resolution Analog to Digital conversion**
  - 18-bit 500kS/s ADCs with stable voltage ref. (15ppm/°C max. drift)
  - Over-sampling → Increase by 2 bits of the current resolution
- **High resolution PWM** → Dipole + Sextupole + Qpole PS: 150ps resolution using a programmable delay line
- **Very stable ambient temperature** → regulated at 21°C ±1°C

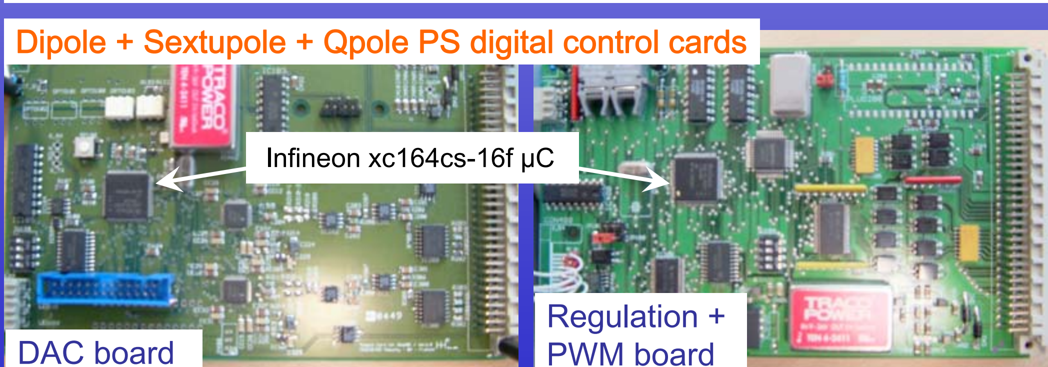
Dipole magnetic field stability (24 hours)



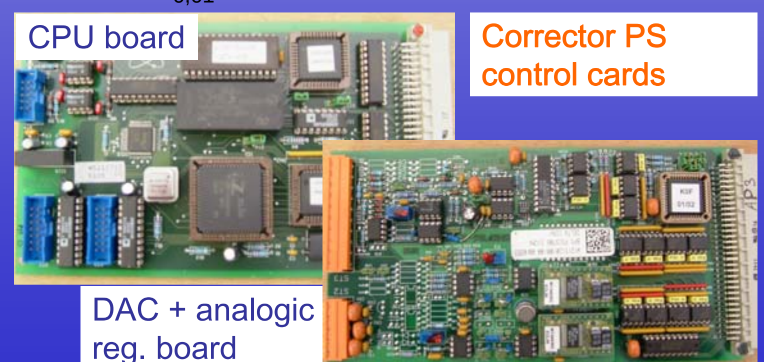
Dipole PS linearity



Dipole + Sextupole + Qpole PS digital control cards



Corrector PS control cards



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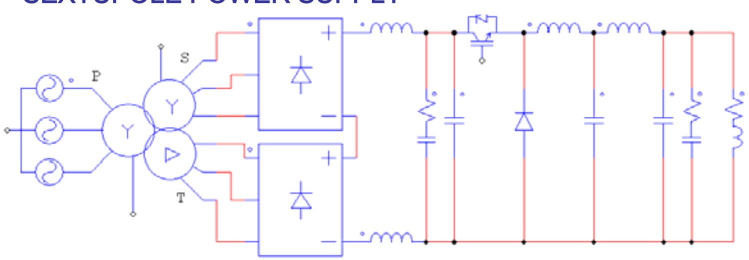
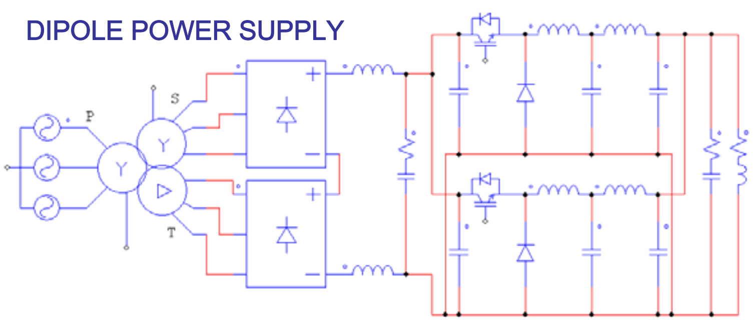
Storage Ring PS Topology

SEXTUPOLE POWER SUPPLY

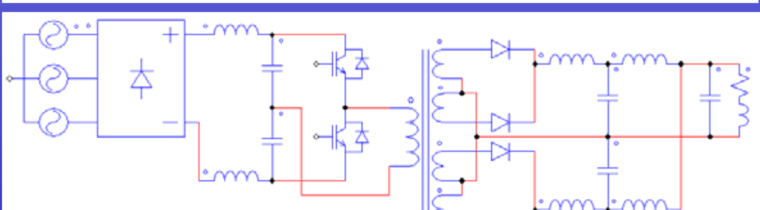


DIPOLE POWER SUPPLY



Quadrupole PS :

- Half bridge converter topology
- Efficiency: 90% (Switching freq. 20kHz)



QUADRUPOLE PS

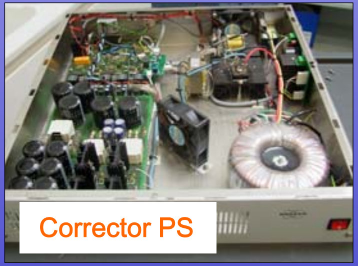
Dipole and Sextupole PS:

- AC/DC stage
  - 12-pulse rectifier → THDI @ Pn: 11% ; PF = 0.97
  - Rectifier output filter: Cut-off frequency 35Hz
- DC/DC stage
  - Buck converter (same power module for both types of Spole PS and also the LT2 Dipole PS)

    Switching frequency → S PS : 20kHz ; → D PS : 10kHz

    IGBT modules are water-cooled
  - Output filters: 80dB attenuation at the switching freq. → Output current ripple < 10% of the current resolution & long-term stability specif.

Efficiency @ nominal power: S PS: 90% ; D PS: 94%



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Insertion devices power supply characteristics

HU640 (DESIRS) ➔ in operation since August 2006

3 main PS: ±115V/±600A ; ±125V/±440A ; ±200V/±360A
4 corrector PS ±18V/±5A
Manufacturer: DANFYSIK

HU256 (CASSIOPEE & PLEIADES & ANTARES) ➔ in operation since Oct. 2006

1 set =
3 main PS: ±75V/±200A ; 95V/275A ; 40V/275A
+ 8 corrector PS ±12V/±10A
Manufacturer: DANFYSIK

HU80 (TEMPO & PLEIADES & CASSIOPEE) ➔ in operation since October 2006

12 corrector PS ±10V/±10A
Manufacturer: BRUKER

U20 (PROXIMA & SWING & CRISTAL) ➔ in operation since September 2006

12 corrector PS ±10V/±10A
Manufacturer: BRUKER

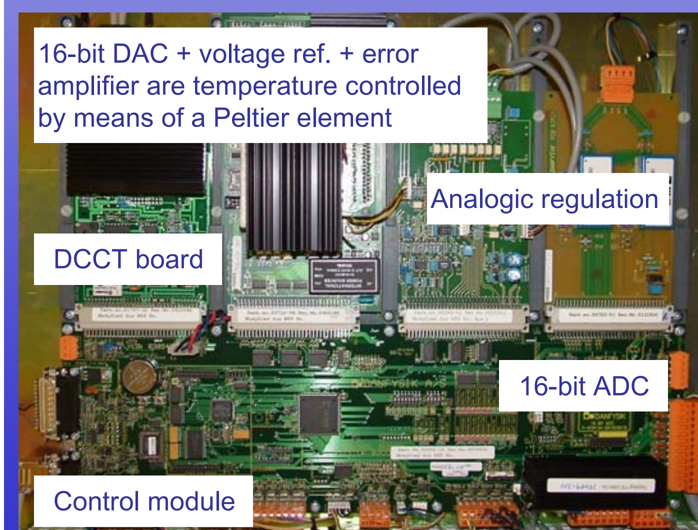
HU52 (DEIMOS) ➔ in operation since 2008

4 corrector PS ±10V/±10A
Manufacturer: BRUKER

HU80 corrector PS cabinet

HU640 main PS

Danfysik PS control boards



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Power supply control system

SOLEIL distributed PS control system uses Profibus-DP

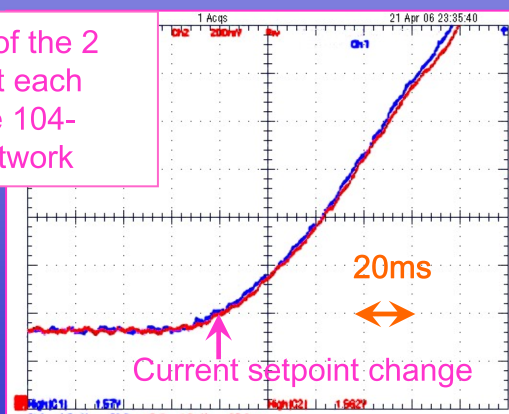
- Profibus is a robust, highly reliable fieldbus
- Flow up to 12Mb/s for a maximum of 126 devices per network (using repeaters)
- « sync » operating mode enables to reach the 1ms synchronization requirement of the quadrupole PS

Control of the 160 quadrupole PS

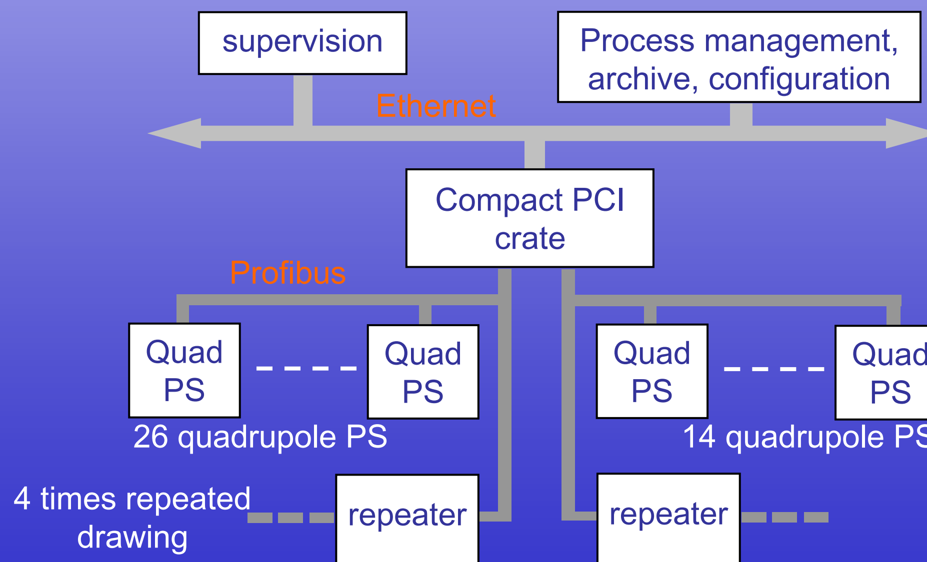
Specifications in terms of synchronization between the Quadrupole PS:
Ability to set the 160 Storage Ring quadrupole power supplies to a given current in a synchronous way
→ **1ms synchronization requirement.**

Quadrupole PS synchronization

Currents of the 2 devices at each end of the 104-device network



Specification is met



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SOLEIL SYNCHROTRON

Main problems encountered

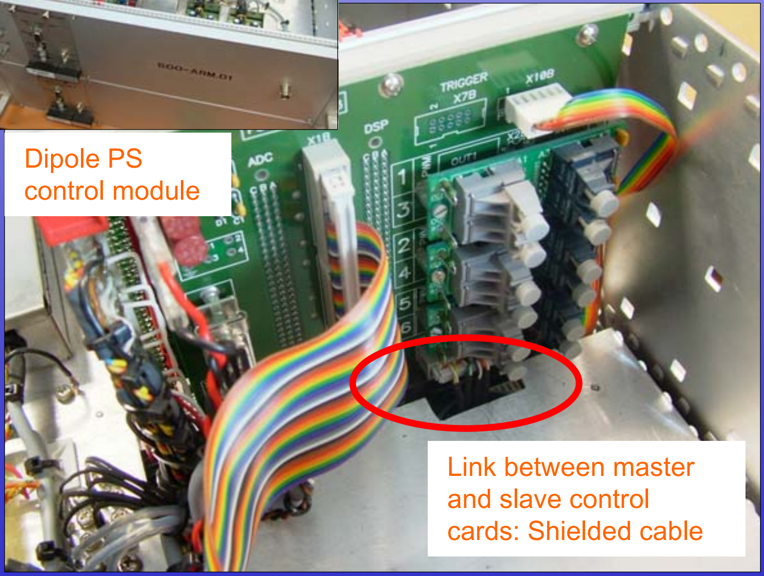
BOOSTER POWER SUPPLIES

• **IGBT short circuit protection:** False interlocks were generated
→ Modification of the IGBT driver boards (Vce threshold, tempo)

• **Serious problems on the Booster PS since June 2007:** Communication errors between the 2 PSI DSP/FPGA boards controlling the PS, causing one or both DSPs to crash → 4 explosions
→ Many interventions of BRUKER:

- Improvement of the EMI
- Modification of the distribution of the auxiliary power supplies feeding the low-level electronics
- Change of the IGBT snubbers
- Upgrade of the Tandem-PS firmware (by PSI):
  - 1/ Spare communication slots in the internal communication are eliminated → Less data are transmitted
  - 2/ Additional checksum test of communication slots
- Suppression of the optic fiber feedthroughs mounted on the back of the power modules (responsible for an attenuation causing a bad transmission of the PWM signals)

Dipole PS control module



Link between master and slave control cards: Shielded cable

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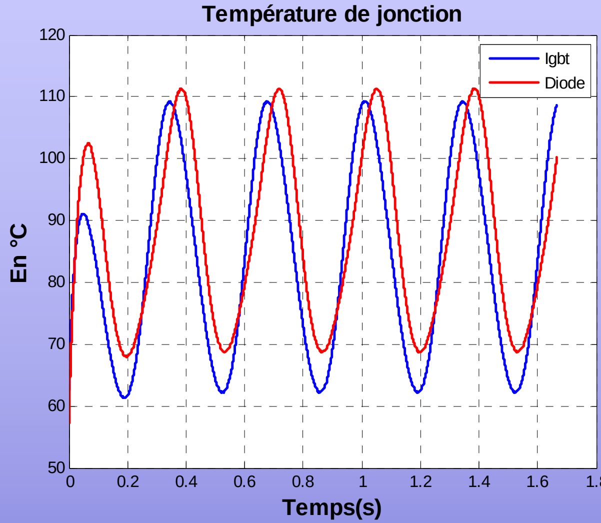
Main problems encountered

BOOSTER POWER SUPPLIES

- **Hydraulic circuit:**
  - Abnormal temperature rise on the 2Q modules IGBT heatsinks of one of the dipole PS due to an insufficient water flow
  - Two water leaks
- Other problems (inside the PS but also side magnet): Failures due to not enough tightened power connections

- **Conclusion:**
  - Excellent tracking performances
  - Some conception errors and reliability problems, which have been solved → any problem in 2008 !

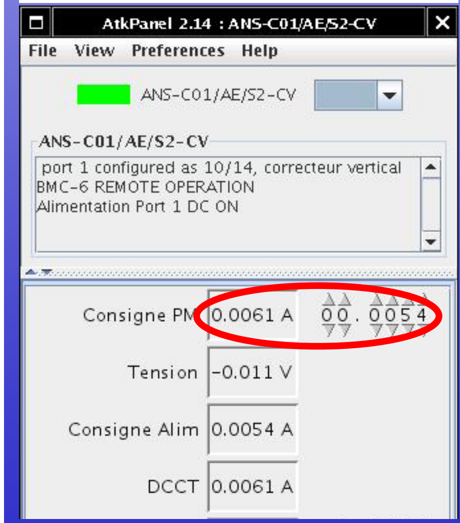


Dipole PS theoretical IGBT junction temp.

STORAGE RING POWER SUPPLIES

- **Corrector PS:**
  - No current soft-start had been specified → Design of a new board to correct this: ~150 boards have been installed
  - Current setting is not correctly taken into account → Software problem: Has been corrected in early 2008
  - PS internal reading frequency of the Profibus current setting is too low (max. 1Hz while 10Hz is needed by the physicists) → Software modification
  - **Remaining problem:** 2 16-bit DACs are used to convert the current setting. During the crossing from one DAC to the other one, 200mA current transients occur, responsible for beam orbit transients.
  → Should be corrected in 2008

Corrector PS regulation error
→ Pb. solved



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Main problems encountered

STORAGE RING POWER SUPPLIES

• Problem on the 21°C water circuit: Grains of resin were accidentally poured in the circuit

→ Filters have been put in the Quadrupole PS cabinets
→ Until mid-2007, the filters had to be regularly cleaned out

• Numerous failures of the +/-15V auxiliary power supplies in the HAZEMEYER PS

→ About 350 boards have been modified (change of non-correctly dimensioned bipolar transistors)

• Major breakdowns on 2 Sextupole PS:

→ DC bus capacitor explosion (Infant mortality problem)
→ IGBT + driver board failure

• 1 breakdown on the Dipole PS: Driver board failure

• Adding of an interlock to the Dipole PS to protect it against a possible unbalance between the output currents of the 2 Buck converters constituting the PS

• DC bus electrolytic capacitors of the Dipole PS were not correctly dimensioned → Abnormal rise of the capacitor case temperatures: Up to 70°C ! → 4-year lifetime
→ Installation by Hazemeyer of a forced convection cooling system designed by SOLEIL: Diminution of the temperatures by 20°C !

• 10% of the Qpole PS fans (used for the cooling of the regulation boards) have failed since 2006

STORAGE RING POWER SUPPLIES

• Conclusion:

- Excellent reproducibility and stability performances
- Some infant mortality problems in 2006 (electrolytic capacitors, IGBT drivers)
- Since then, good reliability (only 2 failures in 2008: 1 Quadrupole PS + 1 corrector PS)
- Some conception errors, which have been solved
- New functionalities had to be added (which were not in the original specifications).

OPERATIONAL EXPERIENCE WITH THE SOLEIL POWER SUPPLIES

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Main problems encountered

HU256 UNDULATOR POWER SUPPLIES

• **3 major breakdowns on the 95V/275A and 40V/275A PS (883 systems)**

→ 2 of them: Short-circuit between input and output of the 3-phase rectifier

→ The third one has been caused by a short-circuit between a winding of the high frequency transformer and the positive DC bus voltage

Other pb: These power supplies are very compact.

→ **Improvement of the PS reliability:** Electric insulation reinforcement, better mechanical mounting. **Any problem since mid-2007.**

HU640 UNDULATOR POWER SUPPLIES

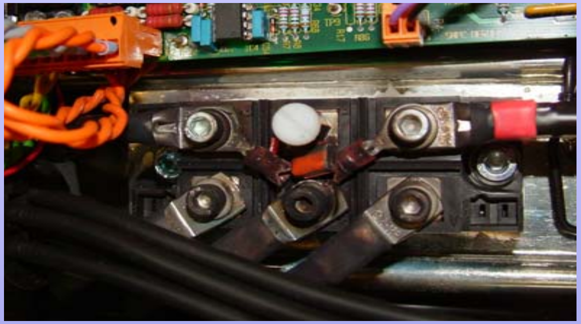
• **Water leak problem:**

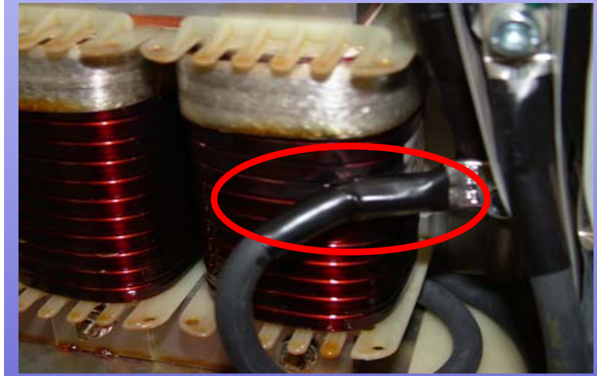
One of the hoses inside one PS (859 system) got disconnected (probably because the hose clip was not tightened properly)

→ Several IGBT driver boards + driver interface boards + a LEM transducer have been damaged

• **Communication problem:**

Still not solved → When such problem occurs, the control of one of the HU640 power supplies is lost either in remote mode or in both control modes (local & remote): Pb. on the serial links between Profibus gateway (+ Front panel board) and the PS CPU board.





Apart from major breakdowns, Danfysik is slow to react !

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Main problems encountered

ON ALL THE INSERTION DEVICES POWER SUPPLIES

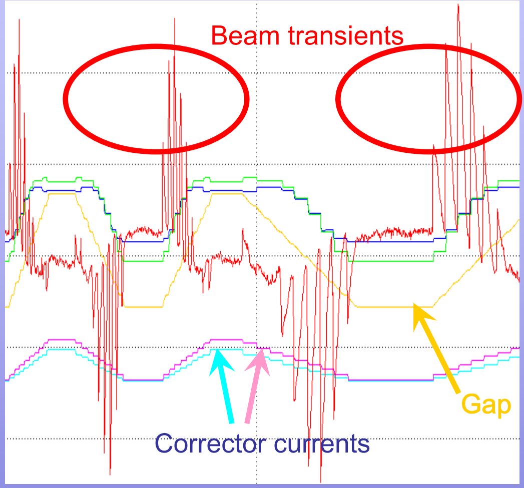
Work to improve the e- beam stability:
To perfectly correct the effect on the beam of the undulator main magnetic field variations, the corrector PS should arrive at their final value at the same instant the magnetic field reaches its new setting. This demands among others:

- Sufficient synchronization between the corrector currents and the undulator main magnetic field(s):
  - → The current settings should be written synchronously inside the PS → OK at SOLEIL thanks to Profibus (1ms synchronization guaranteed)
  - → The delay between the instant when the new current setting is written inside the PS and the instant when the PS output current begins to vary should be as small as possible.

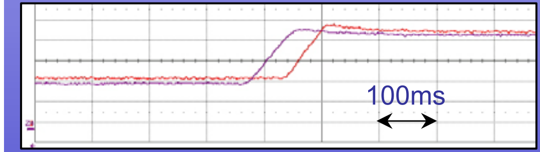
  At SOLEIL nothing had been specified in this sense: The Profibus interfaces of the corrector PS are too slow and lead to time responses which are not adapted to beam feedforward correction.

- Ability to change the corrector PS current settings at frequencies going from 30 Hz (for the slow-varying motorized insertions U20) up to 2 kHz for the fastest switching electromagnetic undulators (EMPHU, HU640). Again, because of the Profibus interfaces of the corrector PS, such performances cannot be reached, which all the more degrades the beam stability during changes of undulator configuration.

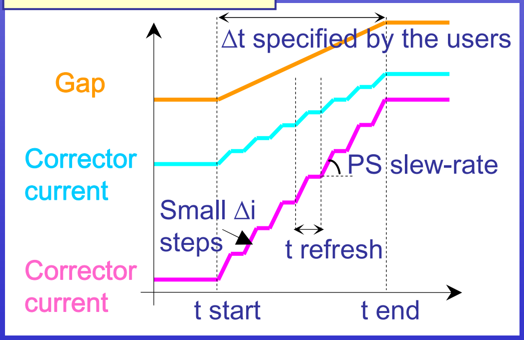
Gap variation of a U20 undulator



Synchronization errors (up to 100ms on the HU256 & HU640 PS)



Desired waveforms



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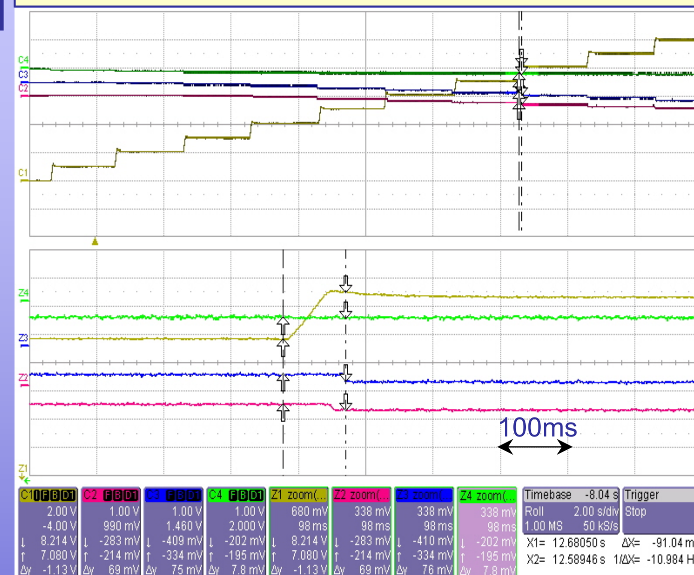
Main problems encountered

Solutions:

• Software modification to increase the speed of the corrector PS Profibus interface → The corrector currents of the motorized undulators (U20, HU80) can now be changed @ 30Hz (instead of 1Hz originally). The delay between the writing via Profibus of a new current setting inside the PS and the beginning of the output current variation is now less than 10ms.

• For the fast-varying undulators (like HU640), an external analog current setting is sent to each PS directly at the input of its analog current regulation loop. The analog references are generated by fast 16-bit DAC boards inserted in CPCI crates. This enables to vary the PS output current @ more than 1 kHz with a perfect synchronism.

Variation of the HU640 PS with Profibus control

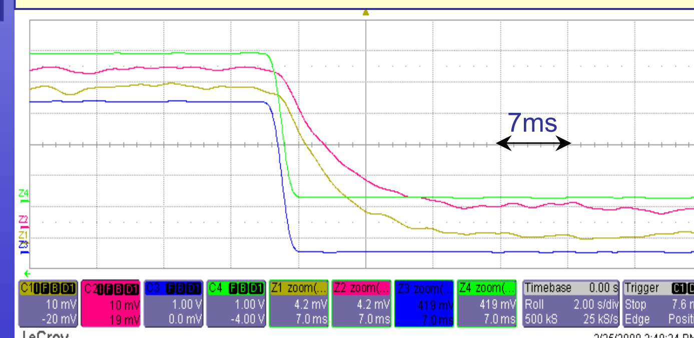


Booster parasitic magnetic field compensation

During beam injection in the Storage Ring, the Booster Qpole and Spole currents are responsible for perturbations of the stored beam, degrading thereby its stability. Up to now, to reduce these perturbations the Booster PS currents are set to a very low value apart from the injections.

A the end of the year, with the first Top-Up injection mode tests, a new power supply will be used to compensate the average effect of the various Booster magnets currents, by generating a compensation current inside a cable going round the Booster.

Synchronism between HU640 main PS and corrector PS using analog external ref.



Conclusion

Since the beginning of the synchrotron commissioning in July 2005, the main tasks of the power supply group cover

- **Intensive tests to check that our power supplies meet the specifications**

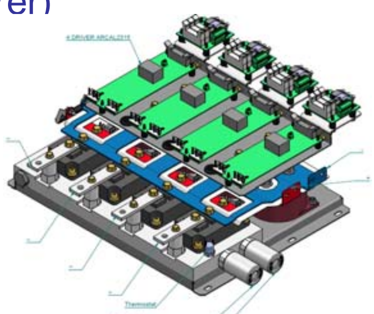
- **Improvement of the power supply performances:**
  - Better reliability
  - Optimization of the regulation parameters (lower current overshoots, better reference tracking, improved stability)
  - Modification of the corrector PS control interfaces (→ Faster time responses) to improve the e- beam stability
  - Adding of new functionalities (soft-start, complementary interlocks,…)

- **Correction of the conception errors** (Hardware + Software)
The only software we do not master is the Bruker corrector PS software (unreadable assembly code)

- **Maintenance of the power supplies** (of different conception following the manufacturer)

- **Repair of the power supplies that have failed**
Management of the spare parts

- **Conception of new power supplies:**
  - Main PS + corrector PS of the future electromagnetic fast-switching undulator EMPHU
  - PS for the compensation of the Booster parasitic magnetic field responsible for perturbation of the stored beam.



Semi-conductor assembly for the main PS of the future EMPHU undulator

Thank you for your attention