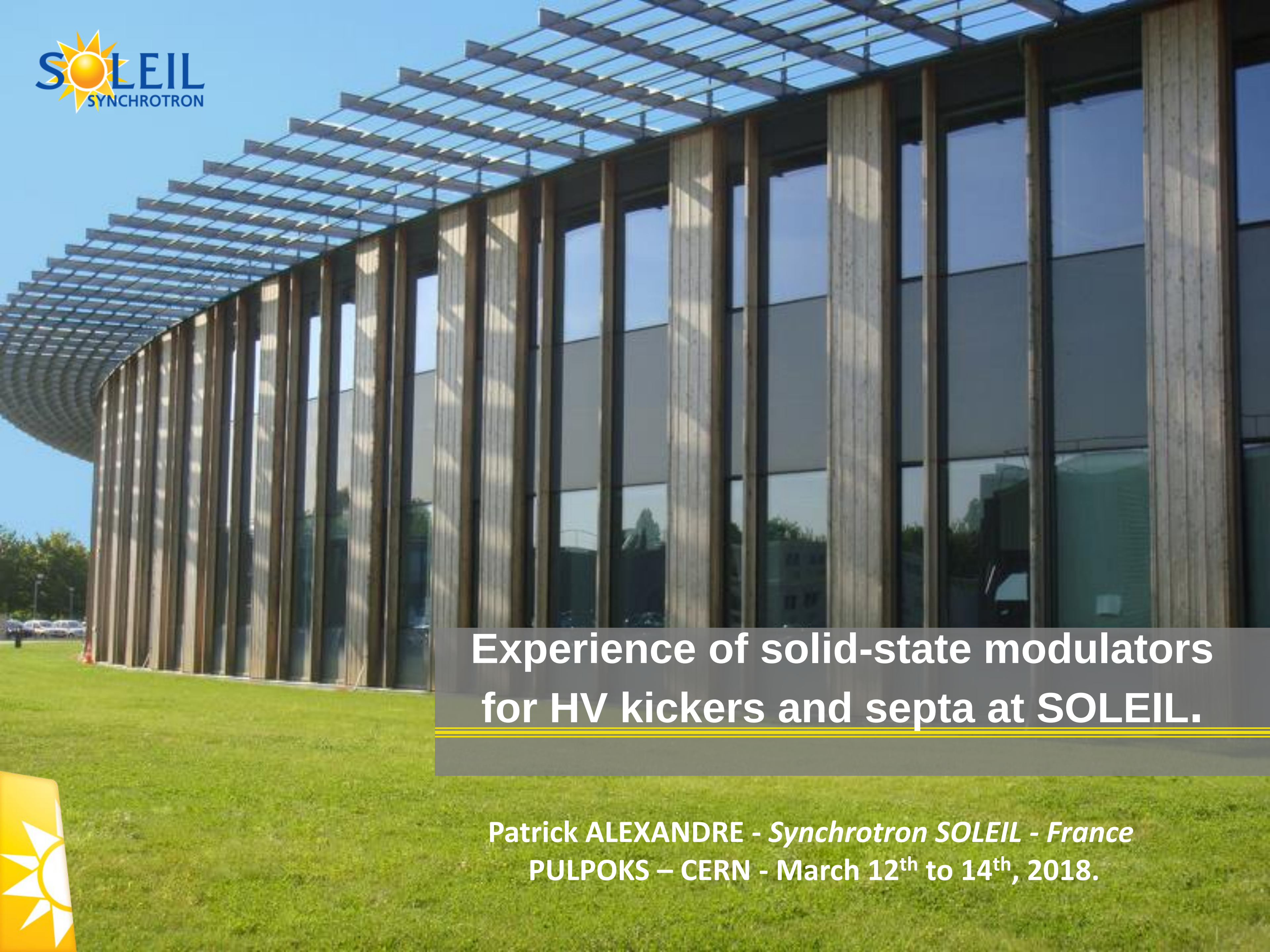


Experience of solid-state modulators for HV kickers and septa at SOLEIL.

Patrick ALEXANDRE - ***Synchrotron SOLEIL - France***

PULPOKS – CERN - March 12th to 14th, 2018.

Synchrotron SOLEIL

- 3rd generation synchrotron light source with currently 29 beam lines.
- Synchrotron radiation spectrum from far infrared to hard X-rays from either bending magnets or insertion devices.
- Operating at 2.75 GeV with various storage ring fillings :
  - 500 mA multi-bunch (416 bunches).
  - 450 mA hybrid (445mA ¾ ring + 5 mA single bunch).
  - 100 mA - 8 bunches.
  - 18 mA - single bunch.
  - Low-alpha & slicing modes.
- All modes available in **Top-Up** (stored beam regulated at 0,1%).

Beam injection/extraction requirements

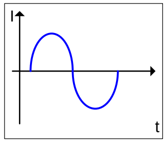
- Top-Up injection in the storage ring is performed with **traditional 4 kicker bump & septa magnets.**
- Maximum perturbation on stored beam smaller than 10% of beam size.

  30 µm rms (Hor.) & 2 µm rms (Ver.)*
- Repetition rate of all pulsed systems: **3 Hz.**
- Good mechanical tolerances & alignment of magnets & vacuum chamber coating.
- Good precision of pulser (current pulse peak value & shape) & <u>good HV power supplies.</u>
- Good precision of timing.
- Reliable:
  - ~ 5500/6000 yearly hours of operation of SOLEIL.
  - Maximum 1 % of failure time for the <u>whole</u> machine.
- **During the accelerator design, there were several iterations to get required the beam deflections while using <u>semi-conductor switches,</u> <u>reasonable voltages</u> & <u>pulsers outside of tunnels.</u>**

Pulsed Magnets

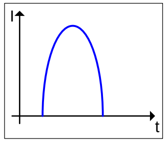
Septa

Eddy current septa
Inj / Ext Booster
Inj Storage Ring



U = 557 V
I = 5515 A
t = 140 µs

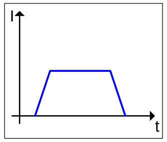
Direct Drive septa
Ext. Booster
Inj. Storage ring



U = 100 V
I = 7180 A
t = 3,3 ms

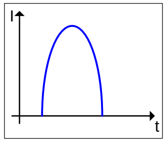
Kickers

PFL kickers
Inj / Ext Booster



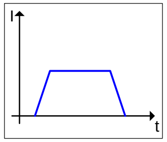
U = 18 kV
I = 730 A
tr = 170 ns
tt= 450 ns
tf = 170 ns

Storage ring kickers
Inj. Storage ring



U =5,5 kV
I = 3,6 kA
t = 6,5 µs

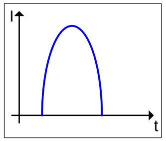
Storage ring study kickers (PFL) (pingers)



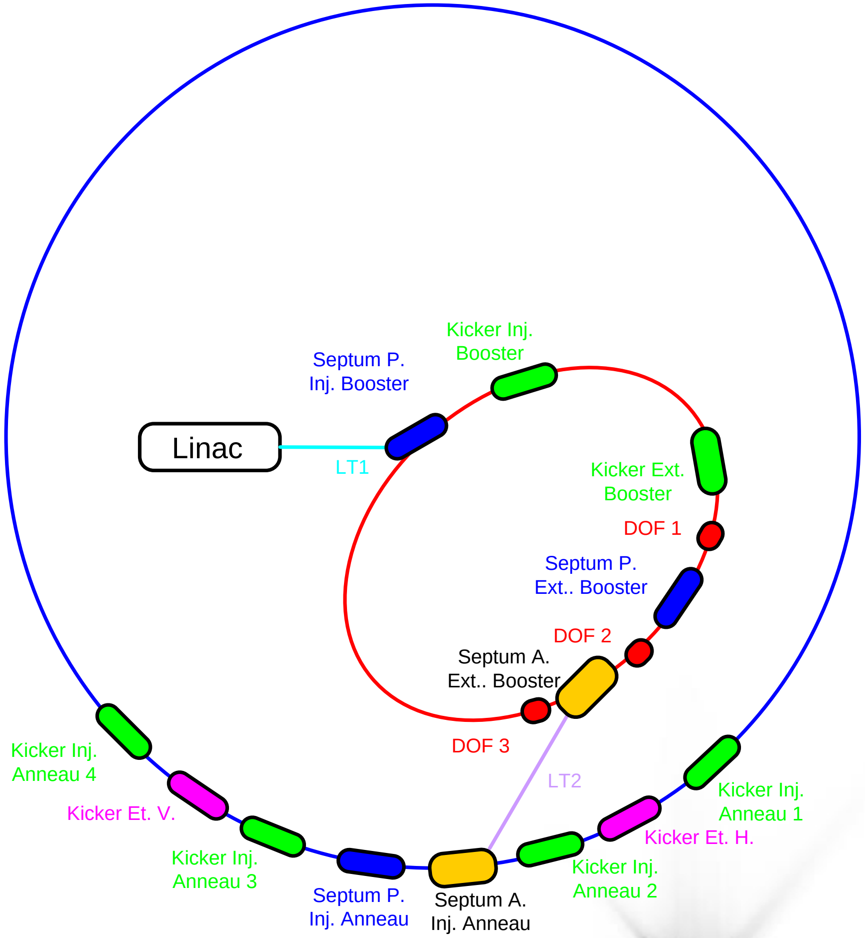
U = 19 kV
I = 1500 A
tr = 450 ns
tt = 300 ns
tf = 430 ns

DOF (Bumpers)

Bumpers
Ext. Booster

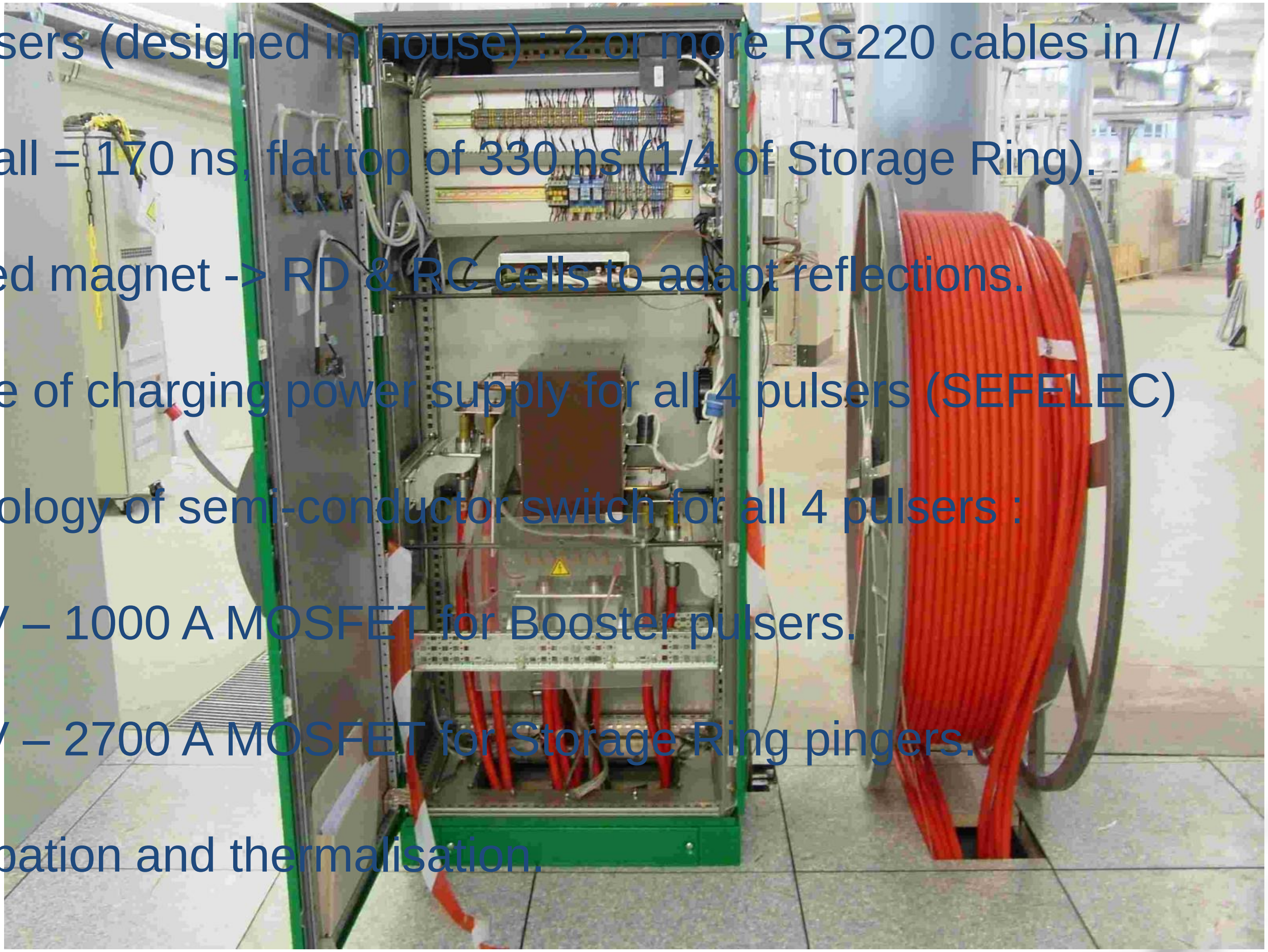


U =5,23 V
I = 65,03 A
t = 12 ms



Focus on pulser & semi-conductor performances

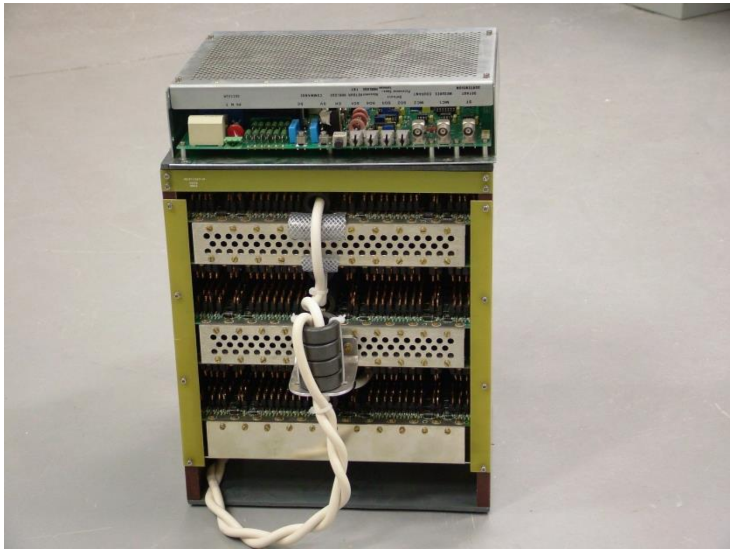
PFL kickers (Inj/Ext Boo & SR pingers)

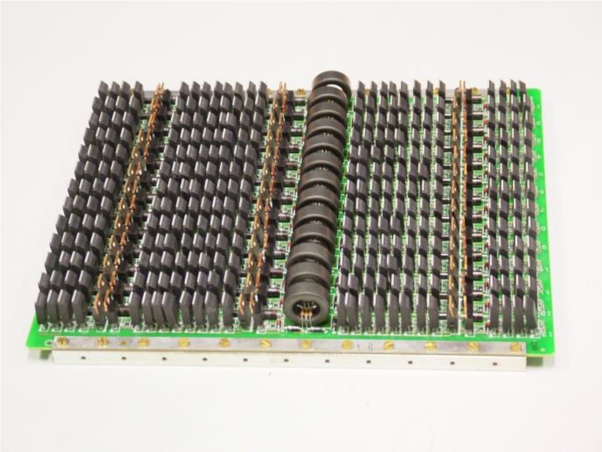


- 4 PFL pulsers (designed in house) : 2 or more RG220 cables in //
- Trise = Tfall = 170 ns, flat top of 330 ns (1/4 of Storage Ring).
- Unmatched magnet -> RD & RC cells to adapt reflections.
- Same type of charging power supply for all 4 pulsers (SEFELEC)
- Same topology of semi-conductor switch for all 4 pulsers :
  - 25 kV – 1000 A MOSFET for Booster pulsers.
  - 25 kV – 2700 A MOSFET for Storage Ring pingers.
- Air dissipation and thermalisation.

Soprano by COMECA HV switches

- Based on series – parallel of individual MOSFET transistors (IRF840).
- Five 5kV boards in series (25kV total).
- All stages are triggered via magnetic switching. ON & OFF capability.
- Tolerant to failure of an individual MOSFET.
- Injection Booster : 6.8 kV / 272 A.
- Extraction Booster : 18 kV / 719 A.
- <u>Current pulse reproducibility *(worse case measurement*)*</u> : **$3.5_{*}10^{-3}$**
- Jitter for a 5 card stack : 1,6 ns.





Eddy current septa pulsers.

- **Capacitive resonant discharge into magnet inductance.**
  - 240 µF charged at 550 V to deliver full sine 140 µs 5,5 kA pulse.

- All 3 pulsers are identical (*charging voltage is adjusted according to deflection required*). Micronics charging power supply (2x300V-2A).

- Switches are EUPEC T1052 S thyristors :
  - V_{RRM} = 1 kV
  - I_{surge} = 22.5 kA
  - I^2t = 2530 kA^2s
  - dI/dt_{max} = 400 A/µs
  - Antiparallel diode : SEMIKRON

- Mounted on press-pack configuration with ventilation.

- Current pulse reproducibility (*worse case measurement**) : **$1.6_{*}10^{-3}$**

Direct drive (thick) septa pulsers.

- **Capacitive resonant discharge into magnet inductance.**
  - 106 mF charged at 101 V to deliver half-sine 3.3 ms & 7.2 kA pulse.

- Both pulsers are identical (*charging voltage is adjusted according to deflection required*). Micronics charging power supply (150V-200A).

- Switches are EUPEC T828N thyristors :
  - V_{RRM} = 400 V
  - I_{surge} = 13.5 kA
  - I^2t = 910 kA^2s
  - dI/dt_{max} = 300 A/µs

- Mounted on water cold plates (heat dissipation and thermalization).

- Current pulse reproducibility (*worse case measurement**) : **$3.7_* 10^{-3}$**

- *Charge and discharge cycles of capacitor is decoupled by a simple MOSFET (thyristor holding current).*

Storage ring kicker pulsers.

- **Capacitive resonant discharge into magnet inductance.**
  - 1,6 µF charged at 5500 V to deliver half-sine 6,5 µs & 3,8 kA pulse.
  - RC & RD cells to tune shape of pulse.

- Switches are **Behlke IGBT HTS 121-240-SI**
  - V = 12 kV
  - I_{peak} = 2400 A / module

- Completed with **series diodes Behlke FDA 16kV 1500A.**

- 3 modules mounted in parallel (to get required current) with same length of connection stripline.

- Individual charging voltage (SEFELEC HVPS in continuous charge) & triggering signal for each pulser.

- Current pulse reproducibility (*worse case measurement**) :
  - **$3.6{*}10^{-3}$ / $3.7{*}10^{-3}$ / $4.0{*}10^{-3}$ / $4.6{*}10^{-3}$**
  - **Jitter for all 4 pulser is in the nanosecond (not measured on current pulse).**

Storage ring kicker pulsers.

Overall pulser performance.

- Major breakdown or beam loss due to pulsed magnets since 2006:

none that we can remember or trace…

- Why ?
  - Design and operationnal margins !
    - Working voltages & current, capacitor & PFL voltage withstand, semi-conductor switch voltage and current capability, magnet voltage withstand, etc…
  - Fault detection : Behlke switches & continuous charging voltage monitoring.
  - Actual Top-Up rate : 1 shot every 2 – 3 minutes.
  - Maintenance and performance check (5 shutdowns a year).
  - How to determine when a pulsed system is going to fail ?

Performance on stored beam.

- **Eddy current septum :** no effect on stored beam after improved shielding on stored beam pipe.
- **Thick septum** : 10 µm (Hor.) & 8 µm (Ver.) *peak** after extra shielding & installing electrically insulated vacuum chamber for injected beam.
- **4 kickers :** 70 µm (Hor.) & 40 µm (Ver.) *rms** after :
  - Installation of additionnal energy storage capacitors, saturating inductances, tuning RC & RD cells, working on timing/jitter reduction and charging voltage to adjust shape of all 4 pulses. Realignment…
  - A lot of night machine shifts to adjust storage ring injection!
- **Still not on target (*30 µm rms (Hor.) & 2 µm rms (Ver.)*), but beamlines *don't complain* (only 2 use gating).**
- *Working on a feedforward pair of vertical kickers to cancel vertical perturbation & improving shielding on thick septum.*

Conclusions

- Excellent reliability and very good beam performance of semi-conductor based pulsers at SOLEIL.
  - Physics design allowed the use of semi-conductors switches, reasonable voltages and have the pulsers outside the tunnel.
  - Operationnal margin, tuning and maintenance help a lot !
- Future work to reduce perturbation in Top-Up operation.
- New developments in semi-conductors : SiC & GaN -> where can they bring us in terms of « massive » pulsers. **<u>What needs for the 4th generation (DLSR) ?</u>**
- When possible, use semi-conductor ! *SOLEIL 352 MHz RF system is based on semi-conductor individual amplifiers and never failed as well*.

Thank you for your attention !

Back up 1

- Measurements of reproducibility :
  - Complete system : HV power supply, capacitors/PFL, switches, coaxial transmission, magnet, vacuum chamber titanium coating,RD-RC cells, current transformers & oscilloscope.
  - Done during shutdown : cooling air and water not stable.
  - Done over 15000 shots without warm-up time.
  - All shots taken into account (no gaussian profile considered).
  - Actual Top-Up measurements : better (in the few 10^{-4} range on the current).
  - 4 kickers magnetic identity **: 1.7 10^{-3} of the magnetic field (measured with beam & whole shape).**
  - **Perturbation measured : bumps measured at BPM with β_x = 14 m and β_z = 12 m**

Back up 2 : nominal design

Devices	Beam Energy	Nominal Deviation	Bnom	Magnetic Length	Time parameters	Nbr turns	Magnet Inductance	I peak (A)	V supply (V)	Energy storage Capacitance
Fast kicker for Booster injection	110 MeV	20 mrad	12,22 mT	0,60 m	flat top300ns;tfall 200ns	1	1,8 µH	389 A	12 kV	2 coax 50 W //
Fast kicker for Booster extraction	2,75 GeV	1,5 mrad	23 mT	0,60 m	flat top300ns;trise 200ns	1	1,8 µH	730 A	22,5 kV	2 coax 50 W //
4 Kickers for Storage Ring injection	2,75 GeV	7,6 mrad	116 mT	0,60 m	tfall < 3,54µs;T/2~6,5µs	1	2,0 µH	5220 A	9,2 kV	2* 3,1µFseries
Horizontal Kicker for Storage Ring study	2,75 GeV	2 mrad	30,56 mT	0,60 m	flat top280ns;total 1180ns	1	2,0 µH	1374 A	19 kV	4 coax 50 W //
Vertical Kicker for Storage Ring study (short)	2,75 GeV	0,6 mrad	18,33 mT	0,30 m	flat top280ns;total 1180ns	1	0,670 µH	1488 A	15 kV	6 coax 50W //
Thin Septum (passive) for Booster injection	110 MeV	131 mrad	0,161 T	0,3 m	T/2 60µs	1	0,950 µH	1922 A	142	326 µF
Thin Septum (passive) for Booster extraction	2,75 GeV	9,3 mrad	0,284 T	0,3 m	T/2 80µs	1	0,950 µH	3390 A	~280	326 µF
Thin Septum (passive) for SR injection nom	2,75 GeV	23,7 mrad	0,362 T	0,6 m	T/2 60µs	1	1,4 µH	4325 A	318	240 µF
Thin Septum (passive) for SR injection 20mm	2,75 GeV	25,7 mrad	0,393 T	0,6 m	T/2 60µs	1	1,4 µH	4700 A	438	240 µF
Thin Septum (passive) for SR injection max	2,75 GeV	27,5 max	0,420 T	0,6 m	T/2 60µs	1	1,4 µH	5015 A	467	240 µF
Thick Septum (active) for Booster extraction	2,75 GeV	110 mrad	1,01 T	2 x 0,5 m	T/2 3,3ms min	2	7,750 µH*	7080 A	120	106 mF
Thick Septum (active) for Storage Ring injection	2,75 GeV	110 mrad	1,01 T	2 x 0,5 m	T/2 3,3ms min	2	7,750 µH*	7080 A	120	106 mF
DOF1 Bumper for Booster extraction	2,75 GeV	2,5 mrad	0,046 T	0,5 m	T/2 12 ms	12	225 µH	145 A	14 V	
DOF2 Bumper for Booster extraction	2,75 GeV	0,3 mrad	0,00552 T	0,5 m	T/2 12 ms	13	225 µH	17,4 A	1,8 V	
DOF3 Bumper for Booster extraction	2,75 GeV	1,8 mrad	0,03312 T	0,5 m	T/2 12 ms	14	225 µH	104,4 A	10 V	