Injection systems for 3rd generation light sources

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In fact, this presentation will be mainly a description of the injection and extraction systems of the Synchrotron SOLEIL accelerators

The Synchrotron SOLEIL pulsed magnet systems
Main requirements and Choices

SOLEIL is a **3rd generation light source**, based on a **2.75 GeV Storage Ring** of 354 m circumference.
The electron beam generated in a low energy **LINAC** (110 MeV) is injected in the **Booster** Synchrotron which reach the beam energy from 100 MeV to 2.75 GeV in ~150 ms, and then injected in the **Storage Ring**.
Electron beam current will reach **500 mA in multibunch**, or **80 mA in 8 bunches**.
The scope is done on the **small dimension and small emittance** of the electron beam and the **excellent stability** of its position: ≤ ***10% of its horizontal and vertical dimension***.

SOLEIL has been designed to work in the **Top Up injection mode**, in order to give to the scientists photon beams of very constant intensity, with constant thermal load on the optics.

It induces strong requirements on the pulsed magnets systems:
- **Manage the thermal effect of the mirror current,**
- **Low jitter in field amplitude and timing,**
- **Excellent reproducibility, from the 1st pulse,**
- **Very low stray field seen by the stored beam near the septum magnet,**
- **The best matching between the 4 kickers involved in the Storage Ring injection.**

In addition they have to meet general requirements:
- Vacuum chambers **easy to bake up**,
- No EMC perturbation on the environment
- **Excellent reliability, no drift**
- **Easy** to service, tune and **improve**

So our technical choices were:
➔ Out vacuum magnets **easy to open**, air cooling,
➔ Accurate choice of **coating thickness** (alumina chambers)
➔ EMC shielding on all magnets and good grounding arrays
➔ **All solid-state switches**, with good voltage/current margin
➔ All **pulsed power supplies out of the vault**

The Synchrotron SOLEIL pulsed magnet systems

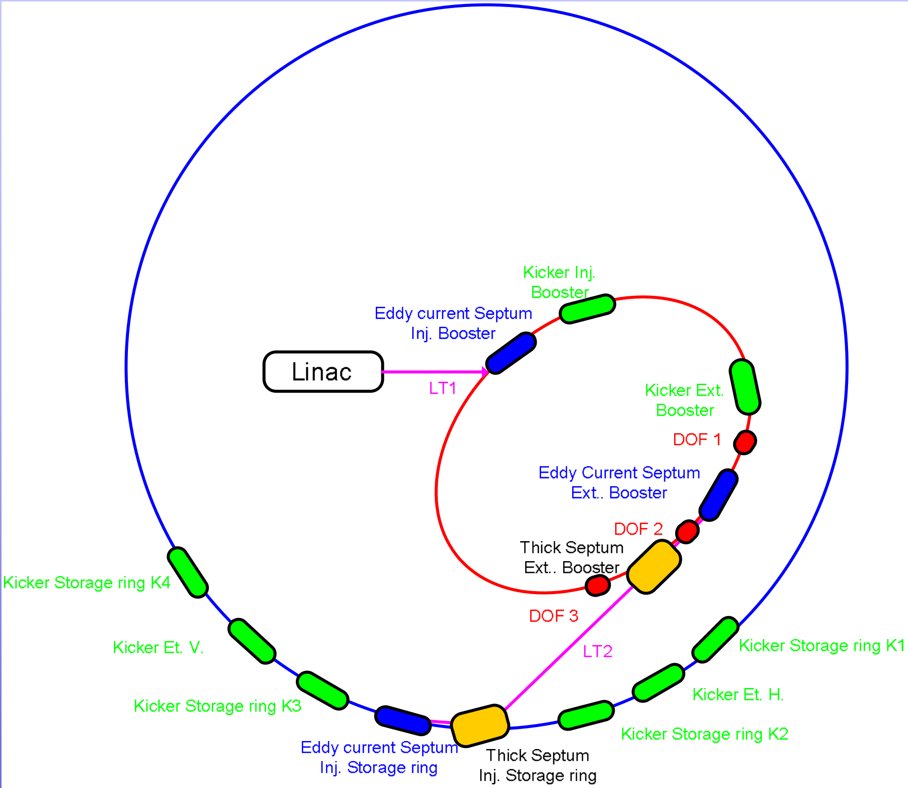
Different type of pulsed magnets
have been designed for each function :

Injection from Linac to Booster @ **110 MeV**:
1 thin septum magnet (eddy current, in vacuum)
1 fast kicker magnet
Located in one straight section

Extraction from Booster to SR @ **2.75 GeV**:
3 dipole bumpers ➔ close orbit bump
1 fast kicker magnet
1 thin septum magnet (eddy current, in vacuum)
1 thick septum magnet (direct drive, out vacuum)
Distributed in two straight sections

Injection in the SR (storage ring) @ **2.75 GeV**:
1 thick septum magnet (direct drive, out vacuum)
1 thin septum magnet (eddy current, in vacuum)
4 identical medium-fast kicker magnets
*All of them **located in one long straight section***

And two fast kickers dedicated to **SR Machine studies**
1 Vertical fast kicker
1 Horizontal fast kicker
In the same injection straight section



All these pulsed magnetic systems were designed by the SOLEIL groups:
-All technical specifications, choice of components,
-Control of the manufacturing,
-In house realisation of the more delicate pulsed power supplies (HV)
-All electrical and magnetic measurements

The Synchrotron SOLEIL pulsed magnet systems
Specifications and Design

Physics requirements

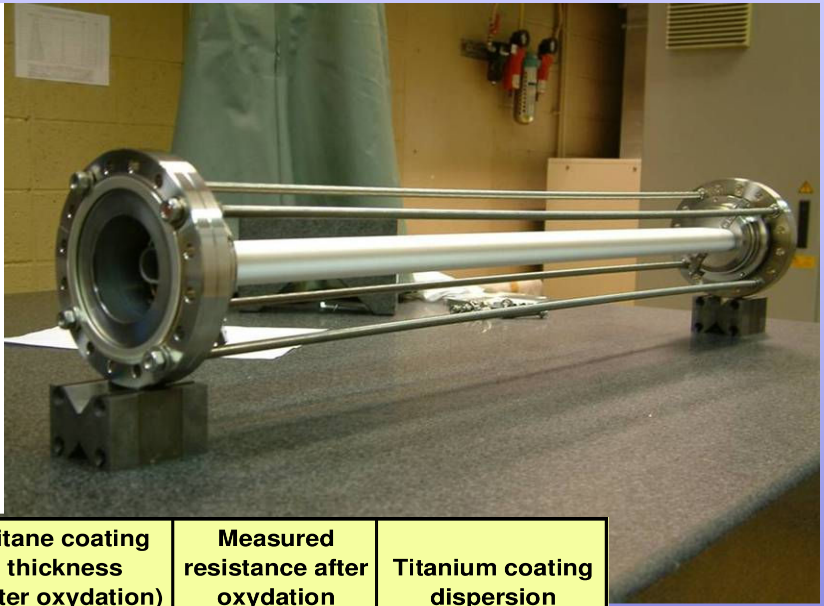
Function	Magnet	Deviation angle	Available length	Beam stay clear HxV	
		mrad	m	mm	
Booster	Fast Kicker	**12,95** nom	< 1 m	40*16	tfall <200 ns
Injection		*20 max*			
@ 110 MeV	Thin Septum	**131**	< 1 m	18*15	septum 3 mm
Booster	Fast Kicker	**1,5**	< 1 m	40*16	trise <200 ns
Extraction	Thin Septum	**9,3**	< 1 m	18*15	septum 3 mm
@ 2,75 GeV	Thick Septum	**110**	1,20 m	21,2*15	
	3 Slow Bumpers	**2,5 max**	< 1 m	60*16	
SR Injection	**4 Kickers identical**	**7,6**	0,850 m	80*25	duration 6* Trev max
@ 2,75 GeV	Thin Septum	23,7 nom	~1,20 m	18*15	septum 3 mm
		27,5 max			
	Thick septum	**110**	1,20 m	21,2*15	

Design parameters of Pulsed systems

B	Active length	Coil turns	Peak Current	Charging Voltage	Pulse shape	
mT	mm		A	V		
7,91 nom	600	1	252	**6500**	trapezoid	tfall <200 ns
12,22 max			*389*	*10500*		
161	300	1	1922	210	half-sine	duration 60 µs
23	600	1	**730**	**18500**	trapezoid	trise <200 ns
284	300	1	2924	291	half-sine	duration 70 µs
2x55	2x500	2	**7080**	111	half-sine	duration 3,3 ms
46 max	500	14	151 max	13	half-sine	duration 12 ms
116	600	1	**5220**	**7800**	half-sine	duration 6,5 µs
362 nom	600	1	4322	471,5	full sine	duration 130 µs
420 max			***5015***	*547*		
2x55	2x500	2	**7080**	111	half-sine	duration 3,3 ms

Alumina vacuum chambers for the Kicker magnets

- Technical specification for the alumina chambers
    - Al_2O_3 Thickness : **6** mm Booster, **7** mm SRing
    - ***Straightness and shape tolerance < 1 mm***
- Brazing probes => choice of alumina and brazing medium
- Manufacturing follow-up :
    - Dimensions control => reject if necessary
    - Tightness control
- Titanium internal coating :
    - Thickness calculated:
      Compromise pulse rapidity / current heating
    - Accurate tracking of the coating resistance

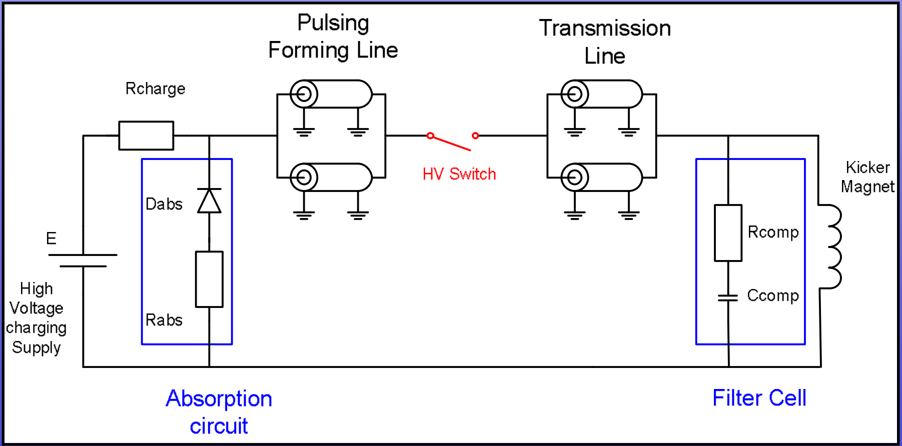


Vacuum chamber type for :	Number	Alumina internal dimensions (LxHxV) (mm)	Titane coating thickness (after oxydation)	Measured resistance after oxydation mean value	Titanium coating dispersion
Injection/Extraction Booster Kickers	2 Vac Ch installed + 2 spare	728x40x16	0,2 µm	35 Ω	± 12,5%
	2 brazed alumina tubes	728x40x16			
	1 alumina tube rejected				
Storage Ring Injection Kickers	4 Vac Ch installed + 2 spare	728x80x25	2 µm	0,956 Ω	+/-7%
	2 brazed alumina tubes	728x80x25	2 µm		
	1 alumina tube rejected	728x80x25			
Horizontal machine study Kicker	1 Vac Ch installed	728x80x25	0,5 µm	4,377 Ω	
Vertical machine	1 Vac Ch installed + 1 spare	428x80x25	0,5 µm	2,80 Ω	1%
Storage Ring tunes shaker	1 Vac Ch installed + 1 spare	428x80x25	1 µm	1,280 Ω	18%
	1 alumina tube rejected	428x80x25			

The fast kickers for the Booster injection and extraction
Magnet and circuit

Main choices:

- Kicker **magnet out of vacuum**, around the alumina vacuum chamber
- Window-frame geometry with symetrical C ferrite core, tightly adjusted to the alumina chamber (thanks to the ceramic straightness)
  ➔Magnet inductance is 1.8 µH (calculated)
- EMC shielding closing the kicker magnet
- Characteristic impedances (PFL and transmission) = **25 Ω** (50/2), suitable for **Tfall and Trise < 200 ns** (100% to 5%).
- **A non-matched circuit**, which avoid doubling the high voltage: **≤ 20 kV**
The reflection is back transmitted and absorbed at the PFL input.
- The pulsers are located on the Booster tunnel roof just above the magnet : coaxial transmission cables are only 7 meters long.



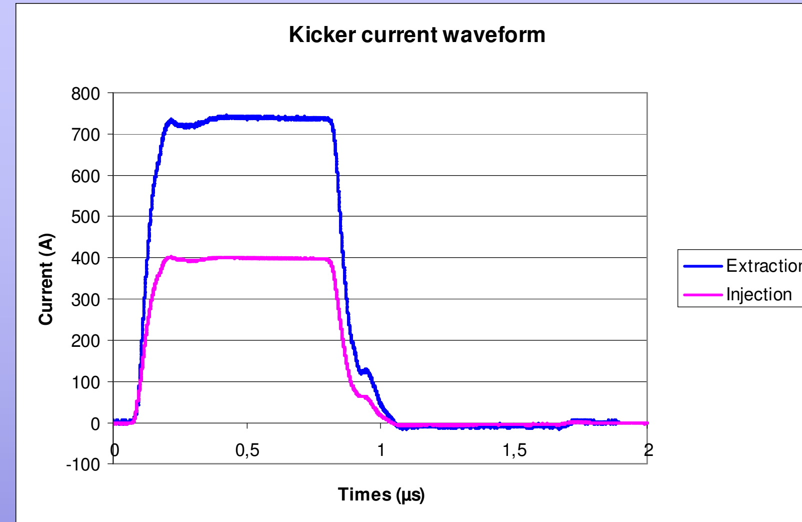
PFL circuit with an inductive load (mismatched) with compensation cell R-C: $\mathbf{I_{peak} = U_{charging} / Z_c}$

Magnetic measurements results:

	Injection	Extraction
@ voltage (kV)	9,4	17,7
peak current (A)	389	730
B mean in flat top (mT)	11,5	22,05
$\int Bdl$ (mT.m)	8,15	14,42
H transverse field homogeneity	< ± 0,35%	< ± 0,35%
Magnetic length (mm)	654	653,87

The fast kickers for the Booster injection and extraction
Pulser and HV switches

The 25 Ω PFL : rather compact (2 coax cable // type RG 220)



The pulser of each kicker was tuned to get a satisfactory pulse shape according to its requirements:
Flat Top : 350 ns with ±1 % flatness
Injection : Tfall = 200 ns @ I = 400 A, U = 10.5 kV
Extraction : Trise = 180 ns @ I = 730 A, U = 18.5 kV

Switching behaviour results:
- Time jitter = 1ns (full sample with 3000 shots)
- Amplitude jitter on flat top < 0.1%
- **No failure in 4.5 years operation**

Switch 25 kV – 1000 A, build with 5 HV cards (5kV-1000A) in series, based on fast MOS transistors in series/parallel array [supplier ➔

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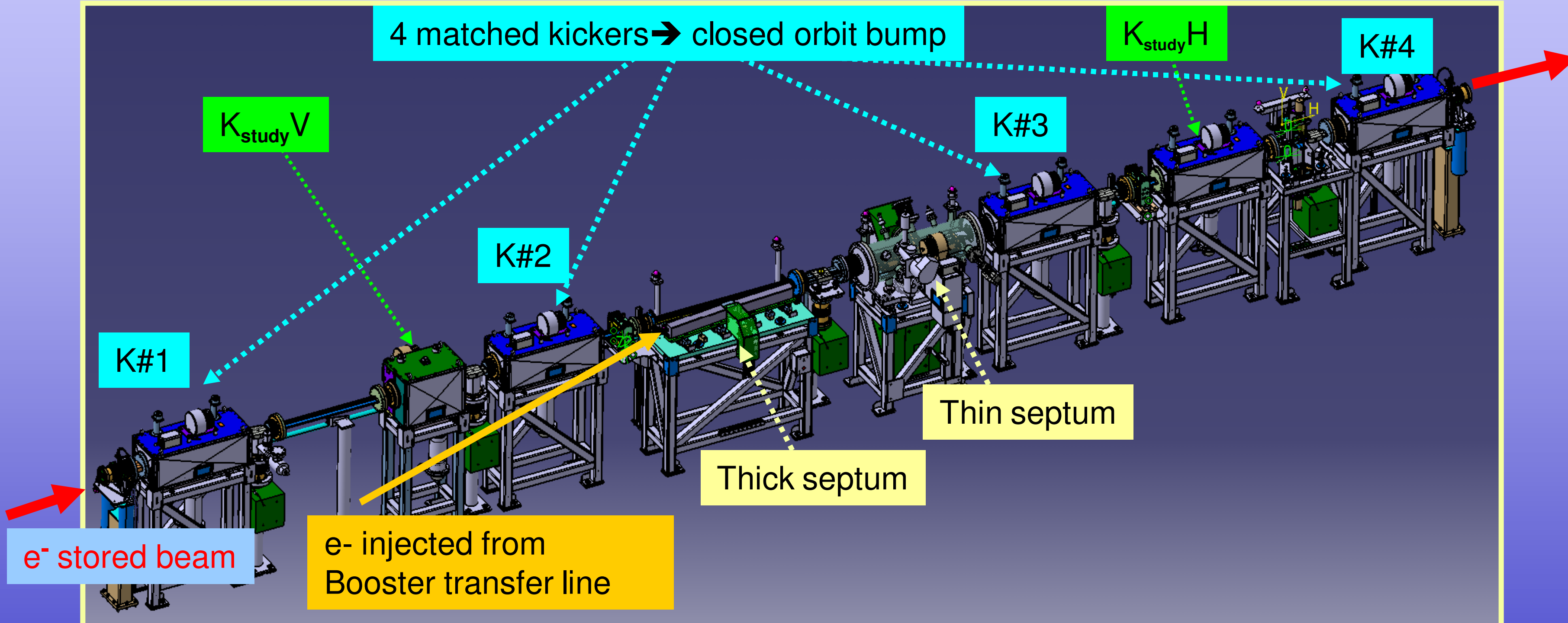
The Storage Ring injection section

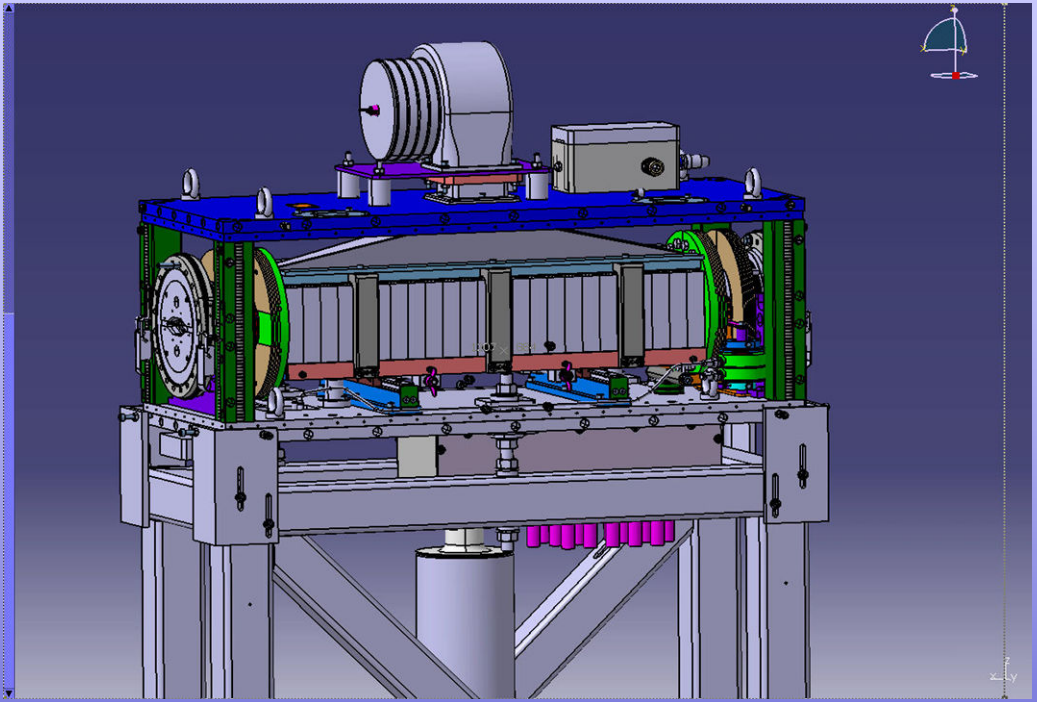
At SOLEIL we benefit of a long straight section of 12m, where all pulsed magnets for the Storage Ring injection are located.
Also the two Study Machine kickers are located there.



Particular requirements for the injection Storage Ring linked to **Top Up injection mode**:
Stability of the beam < 10% of the beam size in H and V, even when re-injecting

- **Good matching of the 4 kickers field pulse shapes**
- **Very little stray-fields** generated by the septum magnets
- **Small jitter in time and amplitude**

The four matched Kickers for the Storage Ring injection - 1



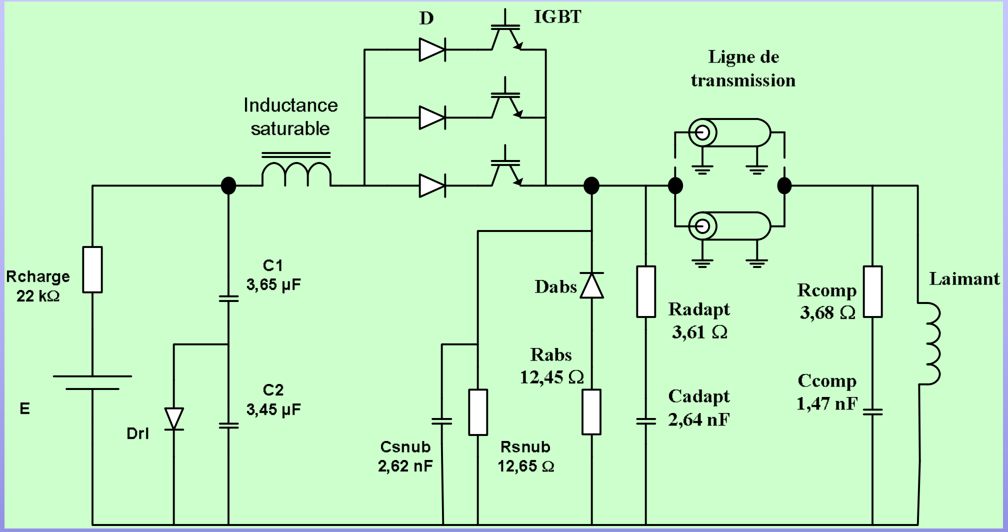
Mechanics tolerances tightly controlled:
- 2 half yokes coplaneity < 0.2 mm
- Relative position of the 2 half-coils ≤ 0.1 mm mounted (including parts stacking, and use of plastic dielectric part)

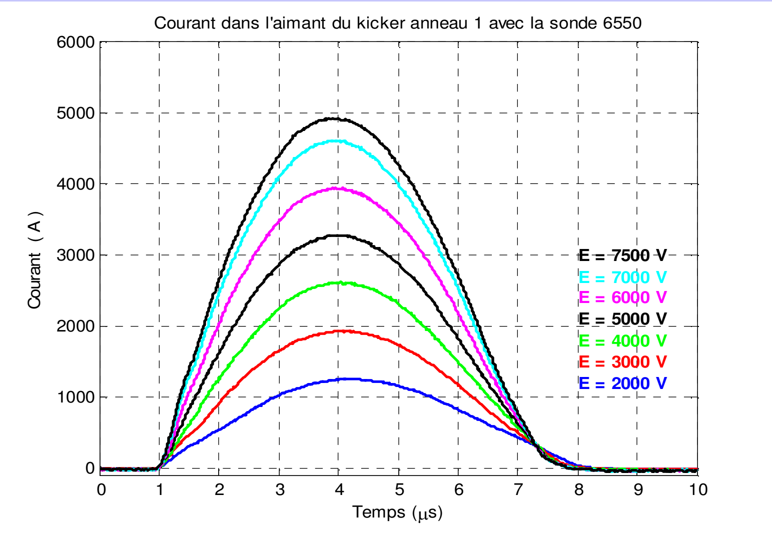
Forced air cooling distributed along the ceramic chamber
And redundant thermal measurements on alumina

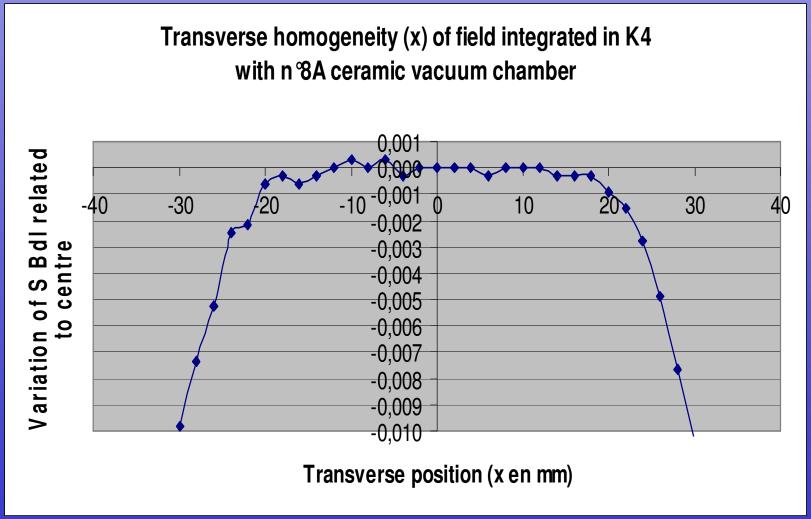
Pulser 8 kV 5500 A :
- HV Switch HT based on **3 IGBT in //** each module :12 kV, 2400 A peak
- Insulation constraints
- Identity between 4 kickers impose :
  Tight tolerances on components,
  Precise mechanical parts

Supplier of HV switches and **diodes:**
BEHLKE GmbH

The four matched Kickers for the Storage Ring injection - 2





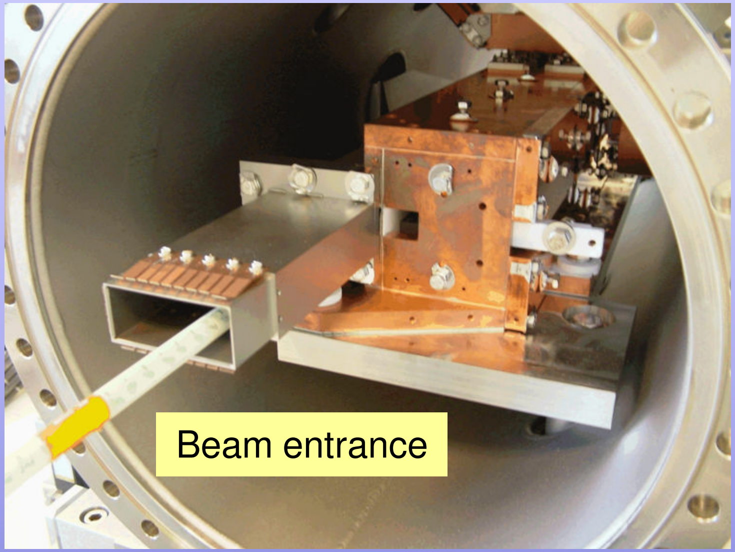


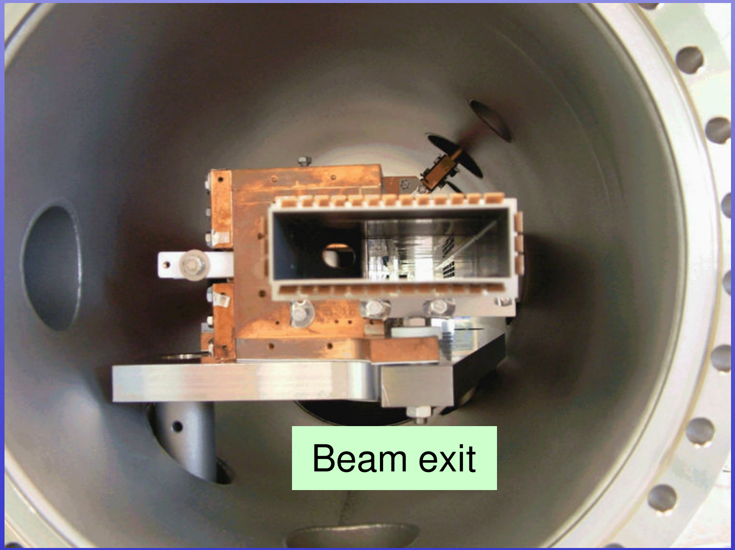
Electric results :
- Time Jitter < 1 ns; drift = non measurable
- Current and Voltage margins ≥ 30 %

Magnetic results :
- Very good transverse homogeneity < 0.1%
- Excellent linearity Voltage/Current/Field

Results seen by the beam :
After tuning of voltage, delays, pulse widths,
and pulse smoothing with saturating inductances:
4 kickers identity ~ **1.7 10^{-3}** of the peak field

Thin septum magnets (eddy current) - 1





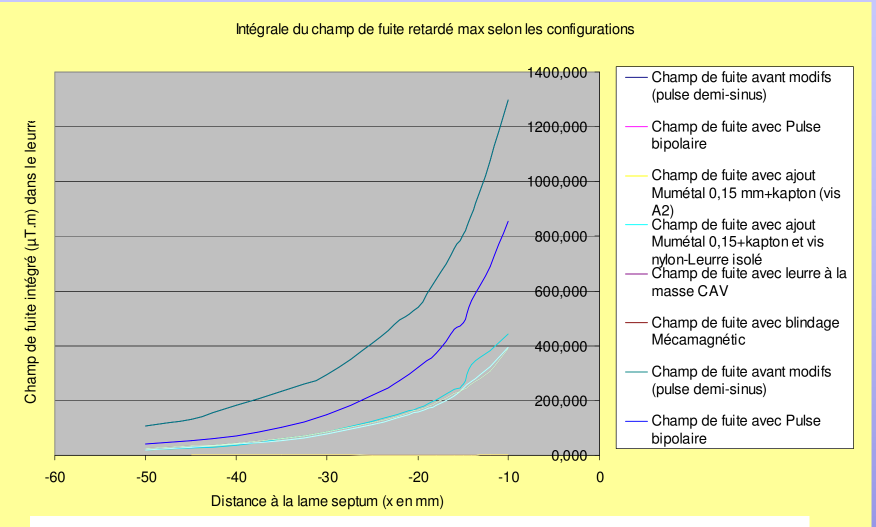
The coil is located deep in the C yoke, and is closed behind the yoke (passive drive)
The yoke is enclosed in **a copper box which drain the eddy currents**:
In the beam plane, **eddy currents flow in the thin septum = 3 mm** and so significantly reduce the stray field in the stored beam path

In vacuum magnets:
- UHV materials OFHC copper, 316 LN stainless steel
- UHV alumina feed-through for current and thermal drain connexions
- Mechanical assembly of the yoke iron sheets: *no glue!*
- Dielectric insulation by shooped alumina deposit
- No window to separate the vacuum levels: only differential pumping between transfer line and ring

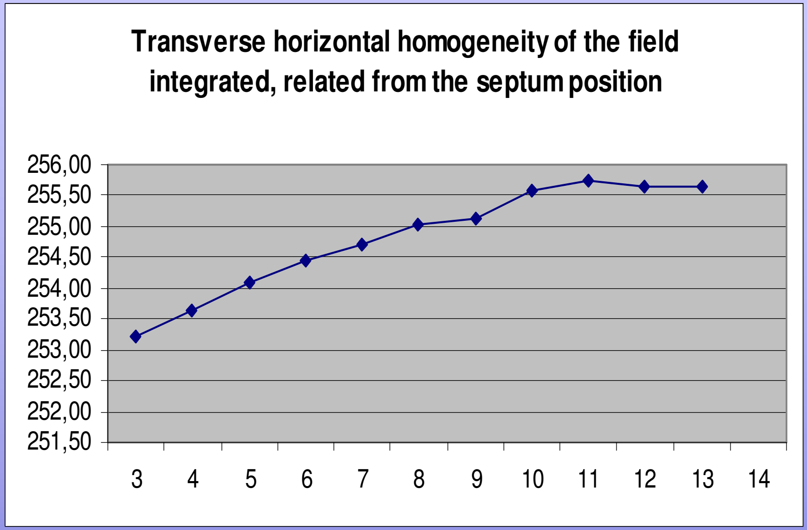
In the case of the SR injection thin septum:
- Addition of a **Mumetal 0.5 mm shielding <u>all around</u> the inner vacuum chamber where flows the stored beam**

➔ Finally the total septum thickness is 3.5 mm

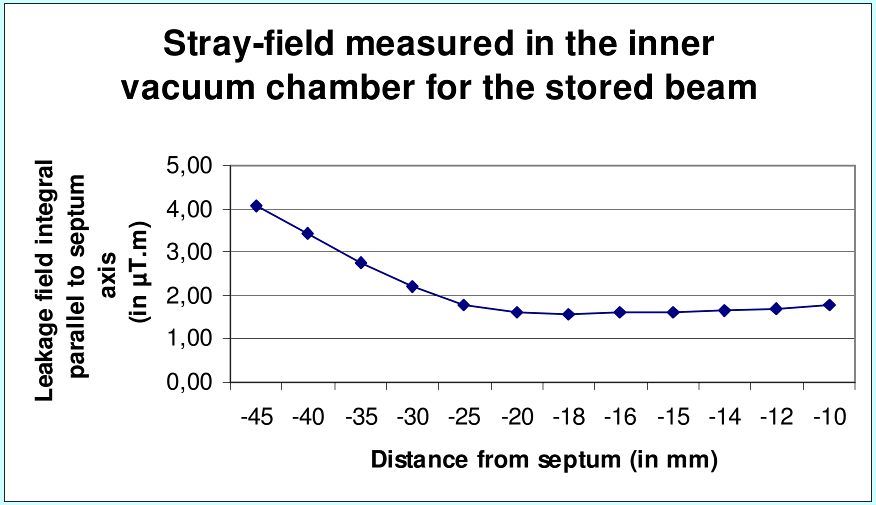
Thin septum magnets (eddy current) - 2



Stray-field: Initial situation and improvements



In the gap :
Field integrated homogeneity = +/- 5 10^{-3}



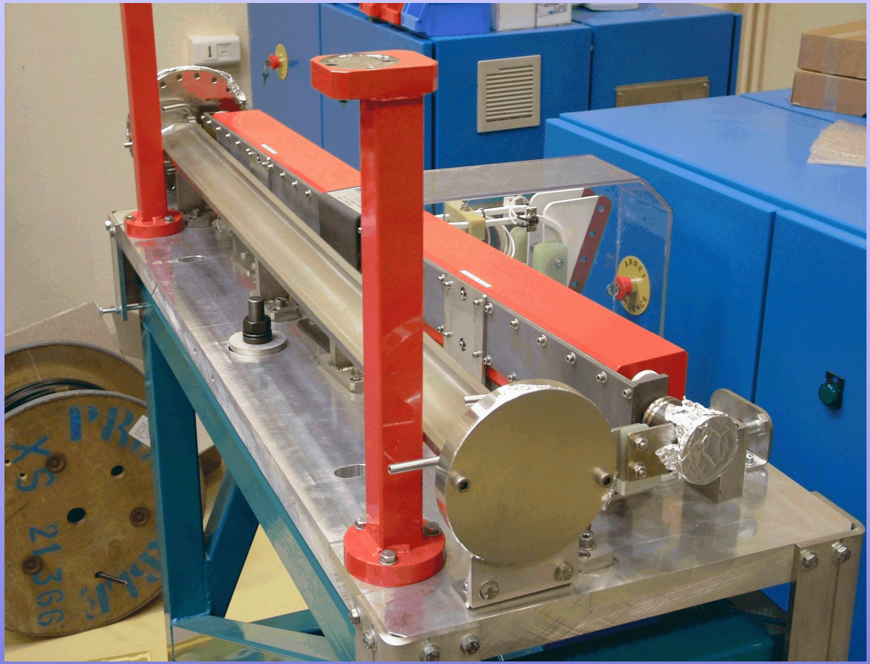
Final result of the measured stray-field

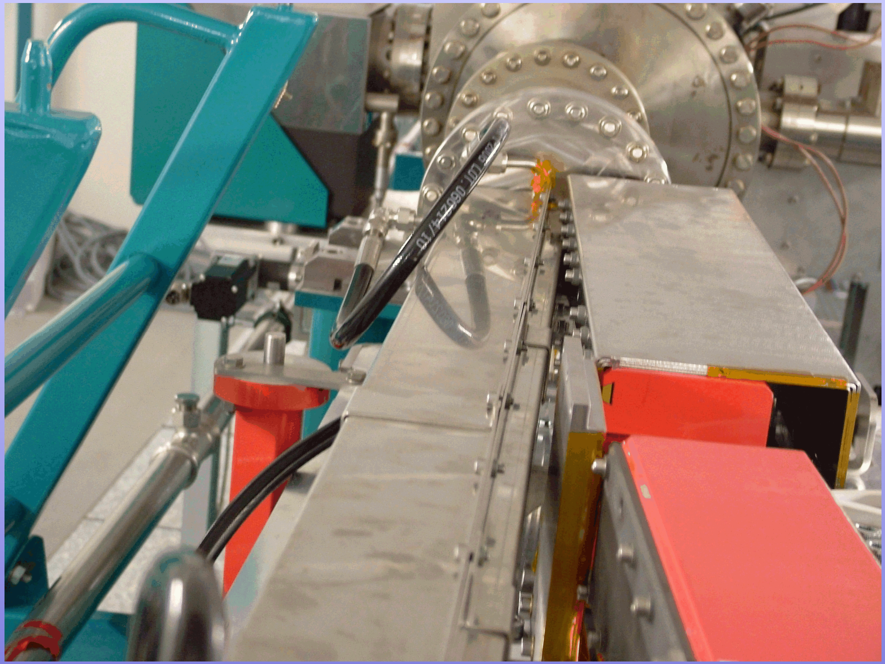
Out of the gap, in the space dedicated to stored beam:
A **very low stray-field is required**
Specifically for the **SR injection** = 12 µT.m max

Specific work for a **strong reducing of stray-field** :
- Excitation by bipolar pulses
- Design and install of surrounding Mumetal shielding

Results : < 4 µT.m in all the chamber
~10^{-5} of the main field

The thick septum magnet "direct-driven": acting as pre- or post-septum





Thick septum magnets realize the most part of deviation angle:
-110 mrad between transfer lines and circulating beam ➔ 1 Tesla in each yoke
=> 2 straight yokes in series, 2 turns coil
even then **high peak current 7080 A** (nominal)
- effective septum thickness can be important

Out of the gap, in the chamber where the stored beam circulates, a **low stray-field is required**
Specifically for **the SRing injection** = 12 µT.m max

Specific work for reducing the stray-field:
- Mumetal shielding surrounding the SR beam chamber
- Supra36 alloy shielding around the yokes
- **Grounding of the injected beam pipe**, to avoid longitudinal extension of **the eddy currents**, which generate leakage fields ➔Reduced from 200A to 4A

Fast kickers H and V for Machine Studies -1

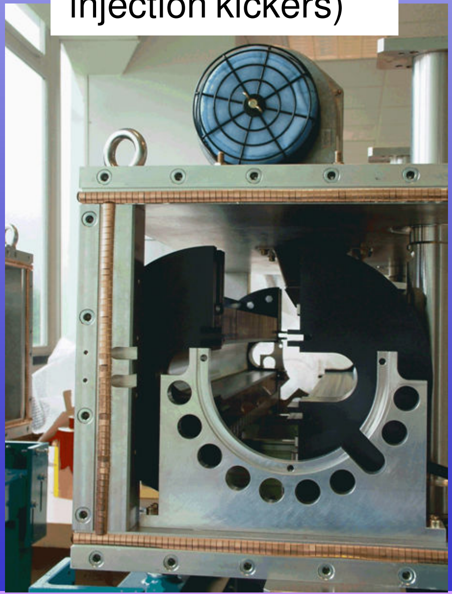
Characterization of the Storage Ring (acceptance, resonances) needs to be able to kick the beam in both planes (H and V), acting on only one 300ns macrobunch (1/4 of the ring filling).
Physical lengths available is 850m for the H kicker, but shorter for the V kicker: 550mm.

	Long magn	Angle	∫B dl	B nom
	mm	mrad	mT.m	mT
Kicker H	600	**2**	18,34	30,56
Kicker V	300	**0,6**	5,50	18,33

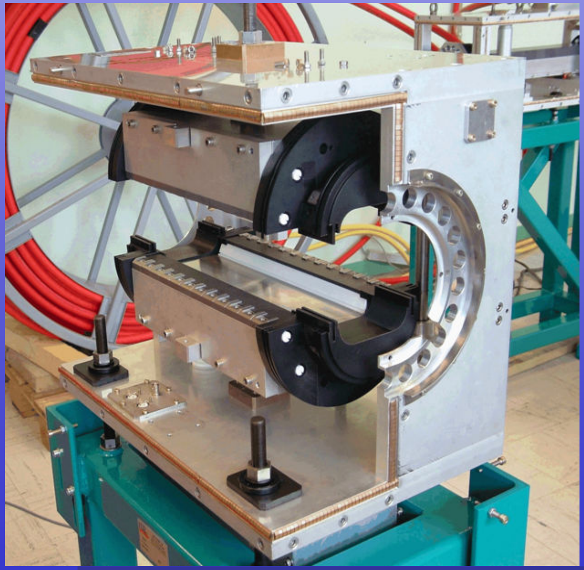
Nbr tour	Inductance aimant	Courant crête	Tension charge	Impédance PFL
	µH	A	kV	
1	2,0 µH	**1374 A**	**19 kV**	4 coax 50 Ω //
1	0,670 µH	**1488 A**	**15 kV**	6 coax 50Ω //

Paramètres temporels		
Plat	t_{rise}	t_{fall}
< 300 ns	~450 ns	~450 ns
à ± 5 %		

H Kicker magnet (similar to SR injection kickers)



V Kicker magnet (specific design)



Vacuum ceramic chambers

Fast pulses in the Storage Ring ➔ specific calculation and thermal modelisation: define good compromise **Rise Time/Heating** due to mirror current

➔Titanium coating = only **0.5 µm**

And an **efficient forced air cooling is mandatory** ➔ **Θ° < 40 °C**

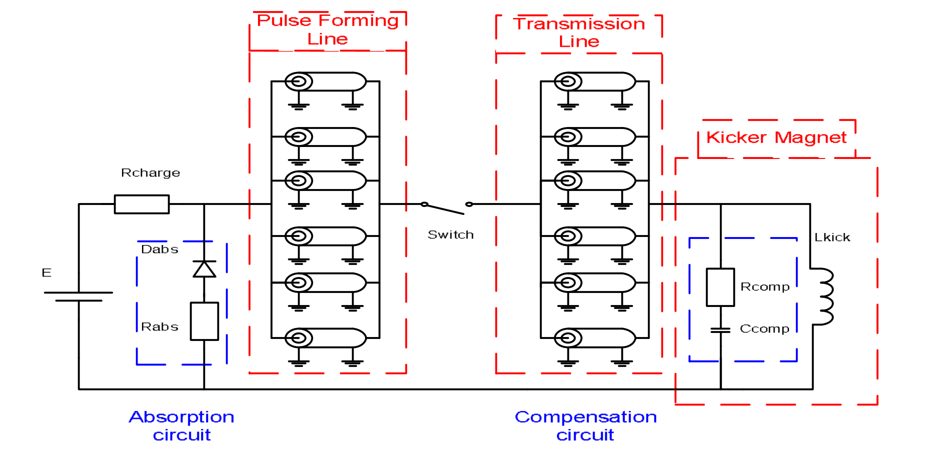
Fast kickers H and V for Machine Studies - 2

Same pulse forming circuit, as Booster kickers:
PFL on non-matched load, with compensation cell, **to minimize High Voltage**

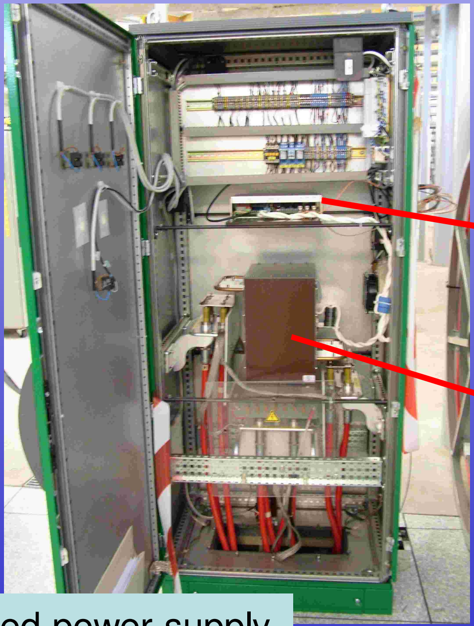
$$I_{peak} = U_{charge} / Z_c$$

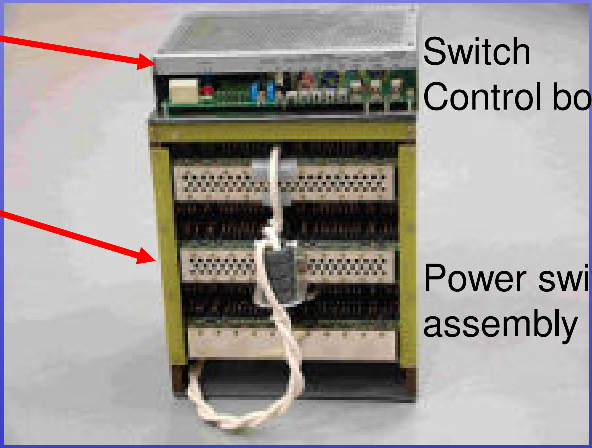
with suited impedances to each case:

But with much more current:
$K_{study}V$: **1500 A / 15 kV**, $Z_c = 50/6\ \Omega$
$K_{study}H$: **1400 A / 19 kV**, $Z_c = 50/4\ \Omega$



Switch 25 kV – 2700 A
Based on fast MOS transistors in series-parallel (13x10)





PFL and cabinet of a pulsed power supply

The Booster and Storage Ring injection performances
Amplitude and Time jitter

Amplitude reproducibility issues
Requirements: 0.1 % pulse to pulse, from the **1st pulse**

Concept: A classical feedback regulation from pulse to pulse is **not convenient**
The pulse amplitude has to be precisely defined by the charging power supply
Selection of the power supplies:
We fixed the **requirement at 1.10^{-4} of reproducibility** in pulsing mode for all PS
We selected the charging power supplies after measurements in our labs.
(measurement with Digital scope + Differential amplifier to extend the range)
➔ SEFELEC **HV** power supplies (based on Glassman PS): **results ~1.10^{-4}** (limit measurement accuracy)
➔ MICRONICS **LV** Power supplies: results ~ **5.10^{-4}**

Time jitter issues
Requirements (pulse to pulse) < 1ns for SR injection kickers (matching requirement)
< 2ns for Booster kickers and Machine Study kickers
relaxed to 10-100ns for the Septa and slow bumpers

Selection of the Switches:
- **SR injection kickers:** selection of **BEHLKE** HV **IGBT modules** (given for 500 ps jitter) and work in lab to determine their best control conditions ➔ ±0.7 ps full jitter estimated on pulses (difficult to measure)
- **Fast kickers**: selection of **ENERGYes** HV **MOSFET assemblies** (given <2 ns jitter)➔ ~ 1ns measured
-**Thin septa**: selection of the fast thyristor able to support the **high di/dt**: EUPEC T1052S
-**Thick septa**: slection of a **high current** thyristor: EUPEC T828N

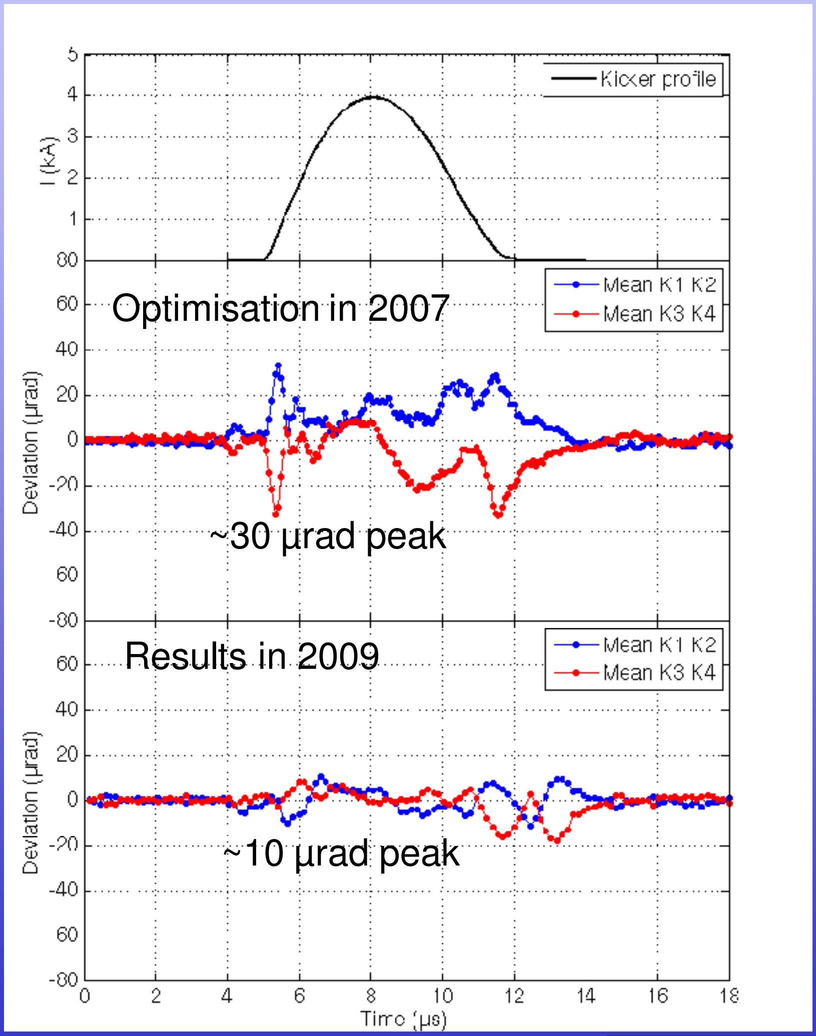
Low jitter Trigger signals:
- Very little jitter source and circuits, including Optical transmitters.

The Storage Ring injection performances – 1
Reduction of the residual bump at Storage Ring injection

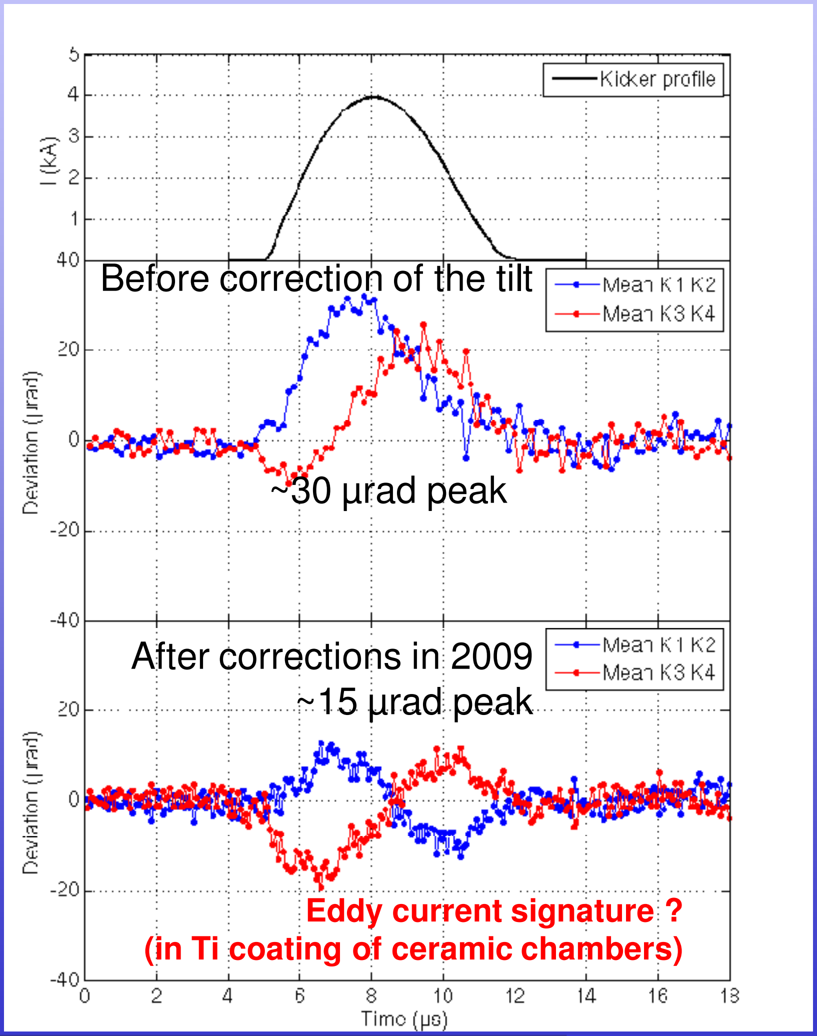
SOLEIL SYNCHROTRON

Reduction of the residual bump induced by mismatching between the 4 kickers

Horizontal plane



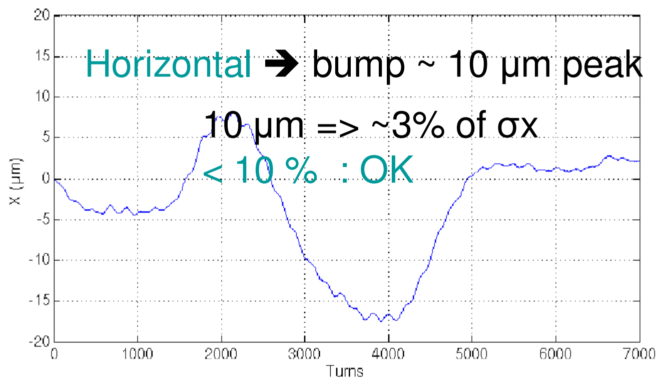
Vertical plane

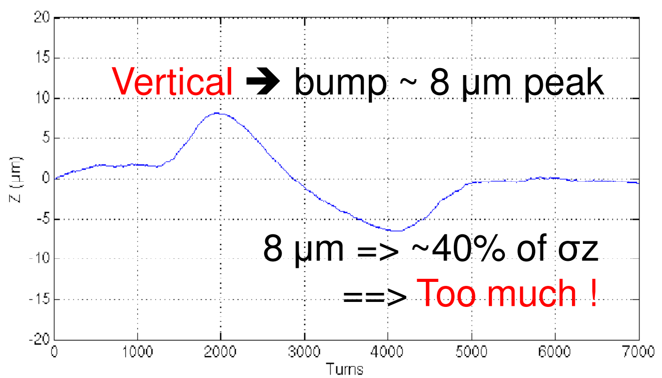


The Storage Ring injection performances – 2

Reduction of the residual bump at Storage Ring injection

Reduction of bump due to Thick Septum





Last results obtained in 2009

Present results on Storage Ring injection

The purpose is to obtain a bump ≤ 10% beam size

In the plane	H	V
10% ➔Target	*~ 30 μm*	*~ 2 μm rms*
Thin eddy current septum	~ 0	~0
Thick septum	10 μm (3%)	**8 μm (40%)**
4 kickers	70 μm (20%)	**40 μm (200%)**

*See more details in: **Alex Loulergue**, "Top Up Workshop" Melbourne, October 2009*

These results seems to be the best results obtained without active correction.
***Spring-8** did better with active correction.*

Improvements foreseen at SOLEIL

Kickers in H plane:

- Improvement of pulse smoothing

In vertical plane (kickers and thick septum) :

- Introduce an **active correction**

Some conclusions - 1

- **About HV switches:**
  - **Solid state switches can replace switching tubes**, easily up to 25 kV, and more, **with many advantages**:
    - **reliability** : no failure in 3.5 years, even in Top Up injection = very demanding
    - no drift
    - good reproducibility pulse to pulse
    - low time jitter
  - **Different types of HV switches exist: MOS, IGBT, …**
    - necessary to select the good Solid State switch for each need: more current or voltage
    - necessary to experiment and adjust the trigger signals and electronics around
    - But the auxiliary supplies and environment are very reduced compared to switching tubes
  - **Different suppliers of HV switches packages** exist: ENERGYES, BEHLKE, FID, …
    - And sure it is useful to make in-house developments
  - **Characteristics of solid-state switches are rapidly evoluting**
    - From 10 years, we could see significant opening of BEHLKE 'catalogue'
    - ENERGYES also is looking on new SiC MOS transistor for faster rise time, higher switching frequency (100 kHz), higher voltage (≥ 100 kV), …

- **About HV pulse forming circuit:**
  - **There is many different circuit available**:
    - matched PFL or PFN circuit, Blumlein, non-matched PFL, resonant circuit, and others…
  - It useful to select the circuit adequate for each need
  - And **if possible the circuit which minimize the voltage**

Some conclusions - 2

- About injection scheme:

Injection ‘on the axis’, or parallel and very close to the circulating beam axis has strong advantage:

reducing the injected betatron oscillation,

reducing the stored beam perturbation (for storage ring in Top Up)

The **in-vacuum thin septum magnet** is well adapted to parallel injection **very close** to beam axis

- About septum magnet and low stray field:

The **eddy current in-vacuum septum magnet is a good choice** in order to obtain a **very little stray field**

if the septum thickness is adequate

excited by a bipolar current pulse

and with a good magnetic shielding surrounding completely the circulating beam path

The direct drive septum magnet is also interesting (and thin septum are possible), but **taking care of the generated eddy current** in an inside chamber = strong source of stray field:

either the septum in vacuum, or with dielectric insulation at the metallic chamber flanges

- About closed orbit deviation by kickers:

It is possible to get a rather low level of mismatch between the kickers

Taking account that the work we made at SOLEIL was possible because the pulser are out of the ring tunnel

But probably the perfect matching of the kicker field shapes is out of reach, due to coated ceramic

- Injection really on axis by a pulsed multipole magnet is very attractive !