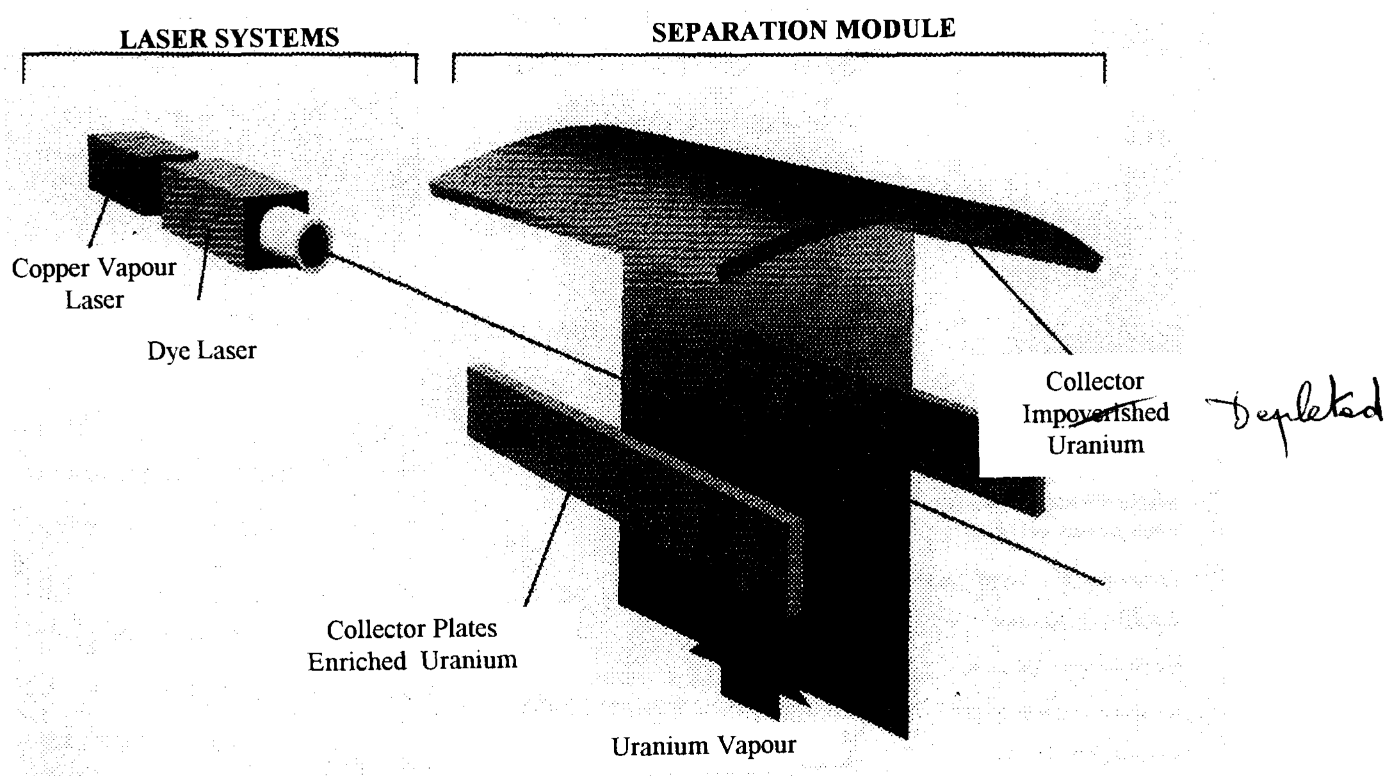
HIGH VOLTAGE FAST SWITCHES FOR NUCLEAR APPLICATIONS

D. CHATROUX, Y. LAUSENAZ, J.F. VILLARD
Commissariat à l' Energie Atomique
DCC/DTE/SLC/LETC
BP 111 26702 Pierrelatte Cedex (France)
Tel : (33) 4 75 50 75 63
Fax : (33) 4 75 50 49 62
e-mail : Daniel.Chatroux@CEA.FR

D. LAFORE
CEGEMA-ESIM
Technopôle de Château-Gombert
13 451 Marseille Cedex 20 (France)
Tel : (33) 4 91 05 45 23
Fax : (33) 4 91 05 45 65
e-mail : Lafore@ESIM.IMT-MRS.FR

1. SILVA :

The Commissariat à l'Energie Atomique (C.E.A.) carries out French researches in nuclear field. One of its projects is the development of the Uranium Vapour Laser Isotopic Separation (SILVA).



SILVA Atomic Vapour Laser Isotope Separation

The aim of SILVA is to replace the current Gaseous Diffusion uranium enrichment process, which is used in the EURODIF plant in PIERRELATTE.
In order to increase the U_{235} isotope rate to 3 or 4 per cent in uranium, the present Gaseous Diffusion process needs an electrical power of **3000MW**.
This consumption could be reduced to **300MW** with **SILVA** process.
SILVA consists in a selective ionization of the 235 uranium isotope, using laser beams generated by dye lasers pumped by Copper Vapour Laser (C.V.L.).
A SILVA enrichment module includes a laser system, whose photons, after an appropriate optical conditionning, irradiate a metallic vapour obtained by intense focalized heating generated by an electron beam.
In order to reach optimal conditions, both luminuous intensities of laser irradiations and vapour density of uranium atoms have to be adjusted. For example a few 10^{13} atoms per cubic centimeter and several kilowatts of light per square centimeter are required, hence the need for **pulsed lasers working at high repetition rate.**
Copper Vapour Laser (C.V.L.) is presently considered as one of the best tools for optical pumping of dye lasers working in the ranges needed for ionization scheme.
Laser systems involving combinations of CVLs and dye lasers set in chains makes possible the repetition rates which are needed in order to totally irradiate uranium atoms moving at speeds closing on 1000 meters/second.
$^{235}U+$ photoions obtained by laser irradiation must be collected among a preponderant population of ^{238}U atoms. This is carried out by an electric field. Photoions are oriented towards polarized plates and then collected.

at present

2. POWER REQUIREMENTS :

Power electronic is involved in SILVA for three power supplies :

- **Copper Vapour Laser** power supply
- **Extraction** power supply to generate the electric field in the vapour
- **Electron beam** power supply for vapour generation

Copper Vapour Laser	**Extraction**	**Electron Beam**	
Pulses	Continuous	Continuous	
1600 A or 5000 A	6 A	6 A	
25 kV or 60 kV	6 kV	50 kV	**High voltage**
200 ns pulse width			
5 kHz / 200 μs			
α = 0.1 %			Very small α
10 kW or 50 kW	36 kW	300 kW	**High power**
Jitter < 2ns			
200ns pulses width	short circuit	short circuit	**Very fast**

Common points of the three power supplies are :
- high power,
- high voltage
- very fast (because of the pulse width or because of frequent short circuit)

3. THYRATRON FOR HIGH POWER COPPER VAPOUR LASER

Typical requirements for a 100W Copper Vapour Laser power supply are :

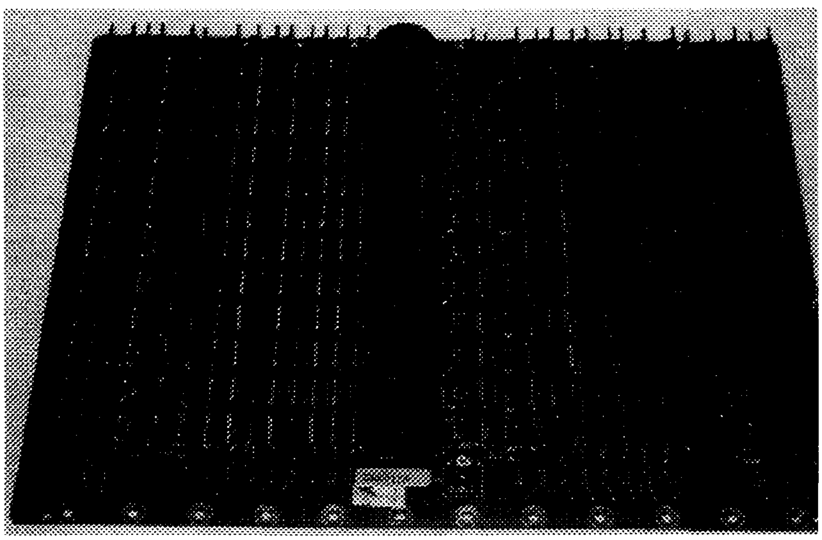
– output peak voltage	=	25kV
– output peak current	=	1600A
– pulse width	=	200ns
– repetition rate	=	5kHz.

First, the power supply was made with two thyratrons in parallel but the cost of this solution was too high considering individual cost and low lifetime of thyratrons (1000h). In close collaboration with universities and particularly with the Ecole Supérieure d'Ingénieurs de Marseille (**E.S.I.M.**) [1], solid-state power supplies have been developed by the laboratory to replace thyratrons in high voltage pulsed power applications. The main principle is serial [2],[3] or matrix connection of solid-state switch components.

Theorical and practical results have also led us to a conception of high voltage switching supplies using serial or matrix connected fast components such as MOSFET transistors and Insulated Gate Bipolar Transistors (IGBT), made of :

- galvanic insulation by transformers between control signals and power,
- synchronous drive circuits by serial connection of the primaries of the transformers,
- standard components without individual test,
- individual voltages enclosed in safety margins by active or intrinsic avalanche clamping [4],
- modular design of 3 or 5kV cards linked in series and industrially produced,
- distributed cooling either by forced ventilation or by oil.

4. FIVE KILOVOLTS 800 AMPERES MOSFET MATRIX

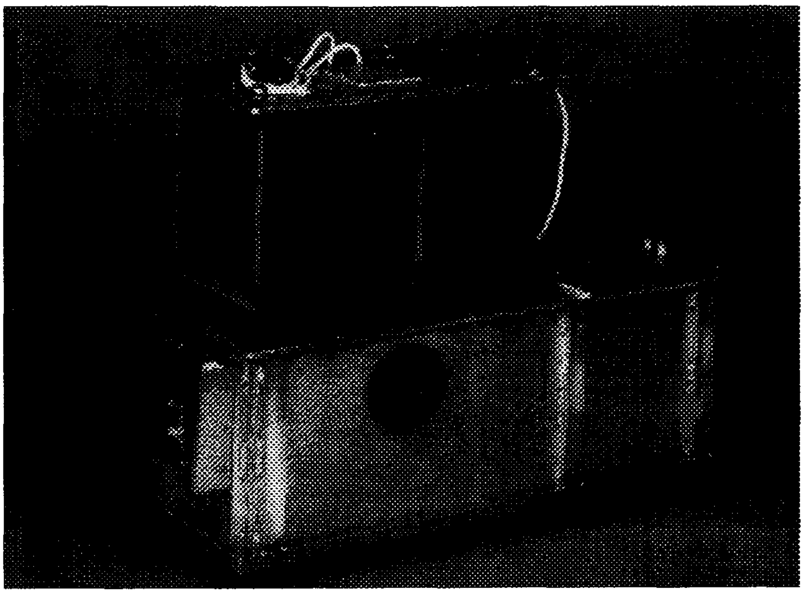


350 MOSFETs board switching 5kV 700A CENTRALP

Development studies of the **industrial products** are realised by **CENTRALP** under contract. This company has excellent experience in electrical power products. The main result of this collaboration is an industrial MOSFETs module switching 25kV 1600A.

There is a very good collaboration between CENTRALP and the laboratory. The goal of the laboratory is to do research for SILVA or CEA needs. Results are pattented and CENTRALP has a licence. CENTRALP realises the products for CEA and other customers. CENTRALP has an industrial computer division with a CMS high level of quality production, and also a power supply division that exchanges informations with CEA and realizes new products under licence.

5. 25 KILOVOLTS 1600 AMPERES MODULE



25kV 1400A switch for laser CENTRALP

6. RELIABILITY

One of the main goal of the solid-state power supplies developed for SILVA is a **very good reliability.**

A prototype of a pulsed power supply including **3500 MOSFETs** has already been running 20 000 hours without any failure.

About twenty power supplies containing MOSFETs matrix have been realised and used in copper vapour lasers. They have already run during a cumulative time of more than **50 000 hours without any failure**.

The MTBF (Mean Time Before Failure) is longer for this 3500 MOSFETs realisation than calculated. The result of the calculation was 20 000 hours.

In fact, with this design, we have failure tolerance. We observe that the failure of one or some components is not a problem and the global switch has keep the same behavior. For this design, with a sufficient safety margin, **the reliability of the module is very high because it is tolerant towards some components failures**.

One of the subjects of the laboratory is a basis study of reliability of components linked in series and in matrix. [5].

7. OTHER SWITCHES

MOSFET switches are industrial switches with a demonstrated high reliability. More than 200 boards have been produced.
Other switches are in development [6] or are already used in some prototypes :

- IGBTs boards;
- DIODES matrix switches linked in series with the MOSFETs boards
- THYRISTORS matrix switches including small standard thyristors, involving very low costs and high dI/dt
- NANOSECOND solid-state switch,

Switches are serial/parallel associations of low-cost small standard semiconductors components on a printed circuit board providing very fast switching time high voltage high current commutation with high reliability.
All switches are based on parallel and serial association of semiconductors. These semiconductors are well known low cost standard power electronic components (MOSFET, IGBT, THYRISTOR, DIODE) in TO 220 package.
Hundreds of components are associated on a printed circuit board to make a high voltage, high current, low cost swich board. It's a low cost high performance solution because, in power electronic, it's cheaper to have a part of PCB than a specific mecanical part. It's cheaper to have some standard components in parallel or in series than to have a specific one.
The laboratory carries out the selection of the most standard references in the market, chooses the best suppliers for these components, and designs the switch.
In fact, it is possible to have a lot of differences between two components for the same reference but from differents suppliers. For example, for the same MOSFET reference of two different suppliers, it's possible to have 15 ns voltage fall time or a 50 ns voltage fall time.
One part of know-how of the laboratory concerns the design and drivers of the switches.
Complete switch is designed as a module of some switch boards in series or some high voltage modules in parallel.
MOSFET swich board is a fast 800 A 5000 V switch. For a copper vapour laser power supply, a 1600 A 25 kV switch is a two modules in parallel, each containing five boards in series, design.

MOSFET SWITCH

MOSFET switch is made up of about 350 MOSFETs IRF 840. The matrix is designed about 27 in parallel and 13 in serie. Suppliers of the MOSFETs are selected. There is no individual selection of components. Maximum current is more than 1000 A limited by MOSFETs. We specify a nominal current of 800 A.
Voltage specification for the board is 5 kV. Voltage drop is 20 ns typically. Jitter is less than one nanosecond and is dependant on the driver.
MOSFET switch is designed for replacing a THYRATRON for high reliability applications. For high repetition rate applications the switch provides reliability for the same cost.

In a 100 Watts Copper Vapour Laser, the power supply of 10 kW provides 25 kV 1600 A pulses with a 5kHz repetition rate. The initial power supply used two thyratrons in parallel. MOSFET swich has the same cost for 20 times higher reliability.
MOSFET switch is turned on by a current pulse in a high voltage silicon cable. This cable passes through ferrite magnetic toroidal cores to make high voltage transformers. Turn off is slow because the gate capacitance is discharged by resistors.
Other MOSFETs switches are turn on and turn off controled.
MOSFET switch is designed for 100 ns to 2 µs pulses. For longer pulses IGBT switch is more adapted.
Because of the intrinsic diode, the MOSFET switch is a good conductor for inverse current. To stop reverse current a diode switch in serie is necessary.

IGBT SWITCH

Using IGBT instead of MOSFET on the previous printed board provides a **3 kA** current commutation. IGBT switch is not well adapted for very short pulses because of the silicon modulation delay [7]. The switch is better adapted for 1µs to 10µs pulses.

THYRISTOR SWITCH

MOSFETS and IGBTs have a silicon surface including thousands of cells in parallel. Conduction of the component starts on all the surface. There is no dI/dt limitation as in a thyristor. On a thyristor surface, the gate is located on a small part. At turn on, conduction plasma is created near the gate and diffuses slowly on all the surface. There is a critical current rate specified by supplier in order not to burn the component by focalisation of current on a small part of the component surface. The dI/dt depends of gate distribution on the surface. For high dI/dt the gate has to be interdigitated.
Thyristor switch is designed with small thyristors in parallel. The dI/dt specified for a small thyristor has the same level as a high current one. Because of the parallel design, global dI/dt of thyristors in parallel is the sum of individual dI/dt. Furthermore this specified dI/dt is given for a low gate current.
With an initial high level of gate current it is possible to reach higher dI/dt. A small thyristor, 12 A nominal current, is 100 A/µs specified. In fact, with a 2 A initial gate current, we measure a dI/dt of 1000 A/µs. With 30 thyristors in parallel the dI/dt calculated with supplier specification is 3 kA/µs but the real limitation is higher than 30 kA/µs with high initial gate current.
With a switch of two boards in series with 150 thyristors each, we generate a **10 000 A** 20 000 volts pulse for a 100µs duration.
With thyristors, maximum current is dependant on pulse duration. For high power pulse, the temperature rise of the component is dependant on current and duration of the pulse. The temperature rise has to be limited to avoid cumulative thermal stress and failure.

Thyristor board switch specifications are :

- voltage :10 kV,
- current : 10 kA for 100μs duration
  or 1 kA for 1ms duration
- dI/dt : 10 kA/μs

DIODE SWITCH

Only some diodes are avalanche specified. The laboratory made a high current low duration avalanche tester for power electronic components. Some standard diodes have been selected. We selected the reference of one supplier and so the design of one type of diode. **There is no individual selection**.
With these selected diodes we designed diode printed boards without any auxiliary clamping component or resistor to balance the different voltages.
Each high voltage diode board is a 150 diodes matrix, 10 in parallel, 15 in series.

Diode board switch is specified :

- voltage :15 kV,
- current : **1 kA**
- reverse recovery time t_{rr} : 50 ns

NANOSECOND SWITCH

For nanosecond switching, the well known solution is a small bipolar transistor in avalanche mode. The transistor is polarised between collector and emitter with a voltage lower than collector-base maximum voltage but higher than collector emitter maximum voltage with base not connected. Base is connected to emitter with a short circuit or a low impedance resistor. An overvoltage or a small base current provides a nanosecond commutation of the bipolar transistor.
Bipolar in an avalanche mode is a good solution for low frequency repetition rate. In case of high frequency, the power losses dissipation in the small transitor is too high. Reliability of the nanosecond switch is not good.
For high reliability high frequency nanosecond switches, we designed two solutions :

- The nanosecond pulse is generated by a snapp-off diode selected for this application. The direct current is low (2 A), and the inverse current in the recovery period is high (60 A). The switch off of the diode generates a 500 V nanosecond or perhaps subnanosecond pulse. The amplitude of the pulse is difficult to adjust because it depends on the diode recovery behavior. Repetition rate we use is 20 kHz.
- The nanosecond pulse is generated by a **standard MOSFET** turned on with a particular driver. The amplitude is very easily ajustable through the voltage on MOSFET. Voltage drop has a 1 ns duration for a 500 V pulse in 50 ohms. With this technology of driver it's possible to have MOSFETs in series, in parallel and in matrix. Now a 2 kV 1 ns in 50 ohms switch is under development.

All switches may be produced by CENTRALP under licence for new applications, for industrial use or for research applications.

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