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New horizontal facility for Neutron Transmutation Doping of Silicon.

by

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1. Introduction.

DR 3 is a 10 MW heavy water cooled and moderated research reactor of a design similar to the British "PLUTO" type. DR 3 has been operating since 1960 and in 1988 the conversion to LEU (U_3Si_2/Al) started. Since December 1990 DR 3 has run on a full LEU core.

DR 3 is originally built as a Materials Testing Reactor, but today it is used as a Multipurpose Research Reactor. With a cold neutron source, six three-axis spectrometers and a small angle neutron scatter instrument DR 3 is appointed as a Large European Beam Facility and these neutron beam instruments are intensively used by researchers from Risø and from the other EEC-countries.

The main production activities are Neutron Transmutation Doping of Silicon (NTD), isotope production and activation analysis. At the moment DR 3 has seven facilities for NTD, which are specified in table 1:

Position in DR 3	Year of installation	Size	Coolant	Orientation	Control	Average flux (n/cm²/s)
4VGR3	1977/1978	3"	Air	Vertical	Manual	3.0 E+12
4VGR5	1977/1978	3"	Air	Vertical	Manual	2.5 E+12
7V1	1986	5"	H_2O	Vertical	Manual	25 E+12
7V3	1981	4"	D_2O	Vertical	Manual	20 E+12
7V4	1983	4"	D_2O	Vertical	Manual	30 E+12
7T2	1997	5"	H_2O	Horizontal	Computer	17 E+12
7T4	1990	5"	H_2O	Horizontal	Computer	17 E+12

Table 1. Overview of Silicon irradiation facilities at DR 3.

Figure 1 below shows a horizontal cross section of the reactor with the through-going experimental tubes as well as the vertical experimental positions. The shaded tube is where the newest facility for Silicon irradiation is installed.

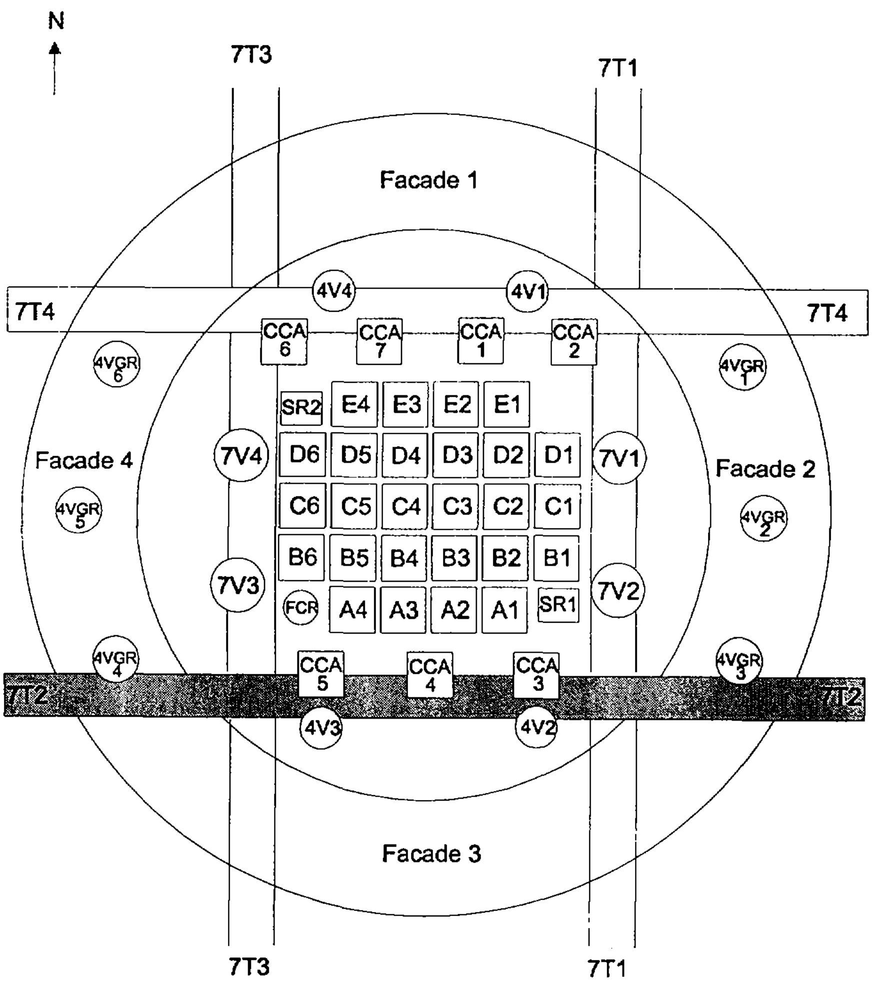

Figure 1: Horizontal cross section of DR 3.

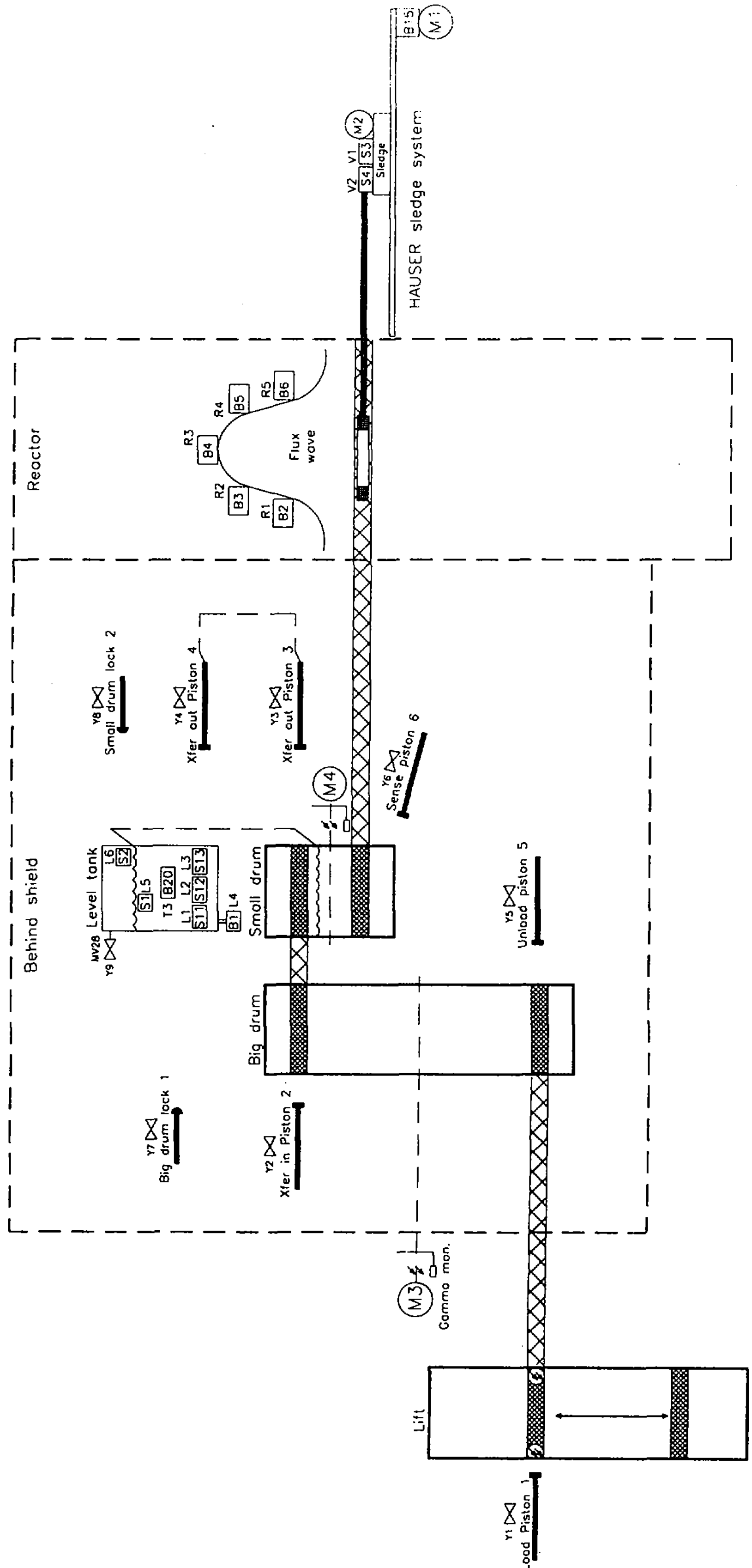

Figure 2: The new horizontal Silicon irradiation facility in 7T2.

2. Mechanical description of the new horizontal facility in 7T2

This facility is installed in one of the 7" through-going experimental tubes and consists of the following components:

- A lift - to load and unload Aluminium cans with Silicon crystals inside
- A large drum - containing the loading storage with 12 positions in the inner circle and the unloading storage with 24 positions in the outer circle.
- A small drum - inside a water tank, which is the irradiation storage.
- An irradiation tube - with a guide rod.

A schematic drawing of the facility is shown in figure 2.

The in-pile part

The in-pile part of the facility consists of an irradiation tube filled with water. Between this tube and the reactor liner is a 13 mm gab filled with CO_2. In this gab five β-emitters to control the irradiation process are placed. Inside the irradiation tube is a guide rod, which provides rotation during irradiation and the longitudinal movement through the reactor.

The water circuit

The water circuit consists of a hold-up tank placed in a loop below the reactor, pumps, heat exchanger, ion exchanger and a tank containing the small storage drum. There are two independent water systems:

1. The primary system functions as hydraulic transport for the cans during irradiation. The flow pushes the can against the end of the guide rod. It is possible to reverse the direction of the flow.

2. The secondary system provides flow through a nozzle situated close to a catch at the end of the guide rod. Increase of the pressure indicates engagement with the guide rod.

The water also functions as coolant for the irradiation tube as well as for the cans.

Automatic storage

The storage facilities consist of two corresponding drums and are shown in figure 3:

1. The irradiation storage is placed inside a water tank which is shielded with Lead. The drum has 12 positions in which the irradiated cans are stored for two days before transfer to the large drum. In two different positions the irradiation storage connects to the irradiation tube and to the large drum respectively. The upper positions are above the water level.

2. The large drum contains two storage: The loading storage with 12 positions in the inner circle and the unloading storage with 24 positions placed along the outer circle. This drum is dry and the irradiated cans are stored here for the next four days.

The transfer between the small and the large drum is done automatically in between irradiation. Exchange of cans is done by means of air cylinders: Locking tabs lock the drums during exchange and the small drum is locked as well during irradiation To load and unload the cans a lift corresponding with the large drum is used.

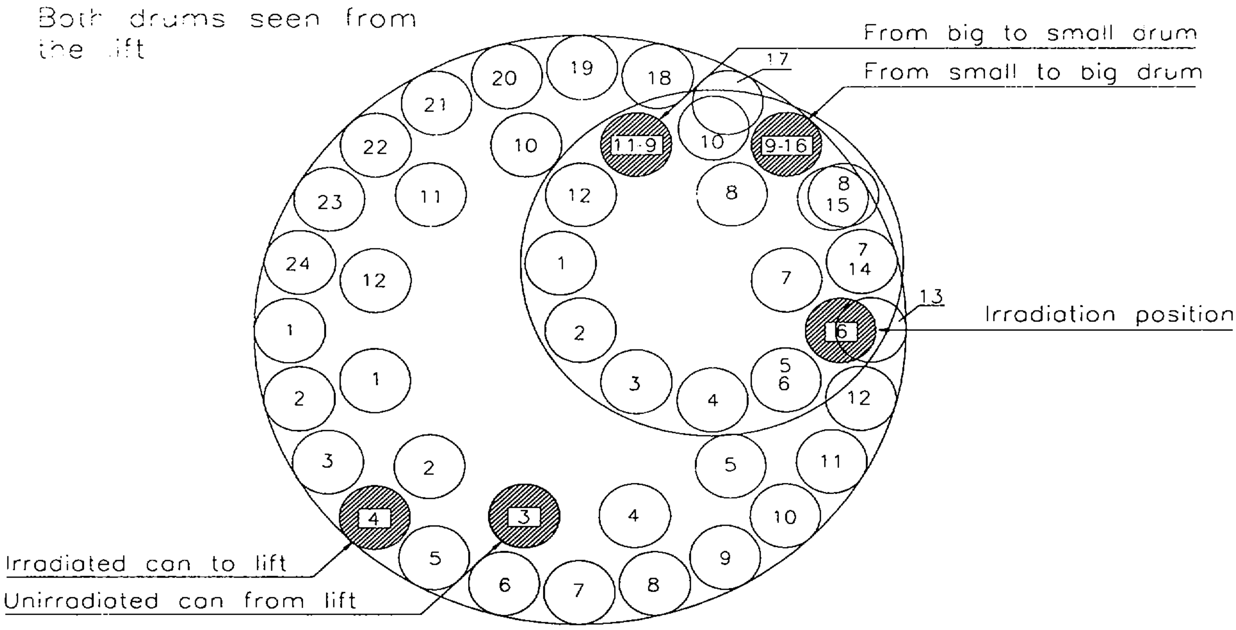

Figure 3: The corresponding drums.

Irradiation cans

The diameter of the Silicon crystals is 5" (12.7 cm) and the maximum length is 500 mm. The Aluminium cans are 600 mm long with a diameter of 132 mm. In each end of the can a 50 mm thick Graphite disc is placed to avoid flux depression at the ends of the Silicon crystal. Outside the can in both ends bearings of Graphite are placed for rotation of the can. Inside the can small Cobalt wires are placed as monitors to enable checking the dose received.

3. The instrumentation

The irradiation process is computer controlled and can be carried out automatically by the instrumentation based on preinstalled data. During the irradiation the instrumentation collects characteristic data for documentation.

The instrumentation consists of equipment for surveillance of the security regarding reactor operation and person- and system security. The system contains sensors for pressure, flow, temperature, conductivity, position, rotation etc. Furthermore it contains equipment for signal processing, security surveillance, control of the facility and circuits for reactor trip.

The position of the guide rod is registered in the computer in two ways: By a signal from a VME micro processor, which controls the guide rod and by an absolute encoder on the gear shaft of the motor ("HAUSER"). The positions of the drums are controlled by a resolver and the exact position relative to the irradiation tube and transfer tube is done by an indication disc with holes, which are scanned by a light sensor.

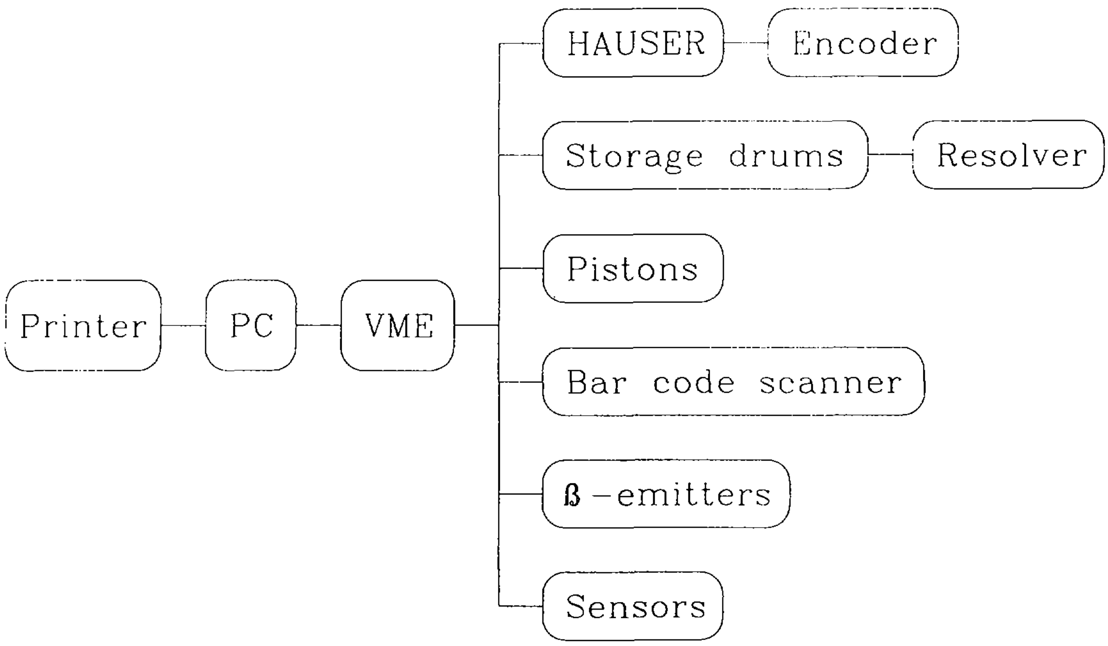

Figure 4: Overview of the controlling components.

The VME micro processor

To link the PC to the mechanical components the VME micro processor – VME – is used. The function of the VME is to control the hardware such as pistons, drums, the position of the guide rod etc. according to the instructions loaded into the PC. The VME is programmable and can be read by the PC. It also takes care of the storage statistics.

Software

The computer program provides the interface with the operator. There are two modes in this program:

1. **Operation mode** in which it is possible to start loading and unloading of cans and start an irradiation cycle.

2. **Service mode** from where the system can be operated manually between irradiation or in case of errors. To enter service mode a key is required.

The most important parameters are shown continuously on the screen as well as all the activities carried out. Alarms are listed as well. An overview of the three storage is also available.

4. The irradiation process

Loading

A reactor operator loads a can into the lift. He inserts a diskette containing the irradiation data for up to four cans. In the computer program he chooses the loading sequence and types the number of the can. The lift goes up and passes a bar code scanner which checks that the number on the can corresponds with the number typed by the operator. At the top of the lift a piston pushes the can into a hole in the inner circle of the large drum.

Start

After loading all the cans in a batch the irradiation process is ready to start. This is done from the computer by typing the number of the first can. The large drum turns until the can is in the position where it can be transferred to the small drum by a piston. Then the small drum turns until the can is in the position connecting to the irradiation tube. During this operation the direction of the flow is towards the drums. The guide rod is in the cooling position (shown in figure 5). When a micro switch indicates that the can is in the right position, the guide rod starts to rotate. The direction of the flow is reversed and the can is pushed into the tube until it reaches the guide rod and raises the indication pressure.

Irradiation

The guide rod and the can start moving towards the opposite end of the reactor with a maximum speed of 4.5 mm/s. After reaching the extreme position the guide rod changes direction of movement and the actual irradiation starts. The speed of the guide rod is computer controlled on basis of measurements of the neutron flux collected just before irradiation start. The speed of the guide rod is corrected continuously by the signals from the β-emitters. After passing the irradiation zone (shown in figure 5) the speed is increased to 4.5 mm/s until the can has reached the cooling position. The can stays in this position for 30 minutes whereupon it is transferred back to the small drum by reversal of the flow.

Unloading

When the activity of the can has decayed for a total of six days the operator is able to unload the can by choosing the unloading procedure in the computer program and typing the number. The required can is pushed out into the lift after a γ-monitor inside the large drum has measured the radiation level. A health assistant checks the radiation level before the can is lowered, and the operator removes the can.

5. Flux calculations

Before irradiation

The unperturbed neutron flux inside the tube filled with water is determined on the basis of the measurements from the β-emitters combined with a precalculated flux distribution. This determination of the flux serves to calculate how fast a certain crystal needs to move through the tube to achieve the specified irradiation dose.

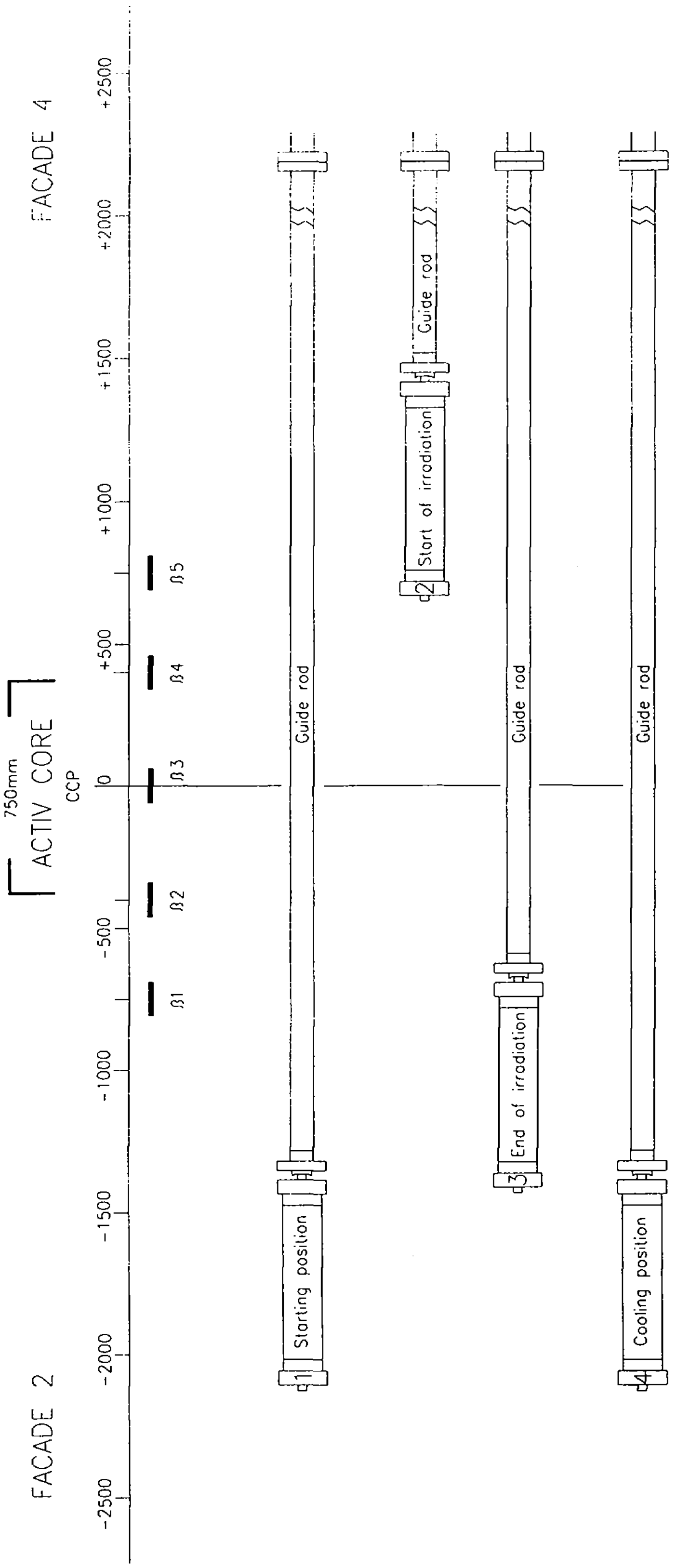

Figure 5: The positions of the can.

Calculation of the average neutron flux

Calculations of the unperturbed neutron flux in the irradiation tube filled with H_2O form a basis of performing the irradiation process. By the computer code, DR3_SIM, which is especially developed for this reactor, the flux profile through the tube is calculated. These results are then used to determine the data for the upper- and lower reflector using another computer code based on diffusion theory.

The values obtained from the five β-emitters are used as input to a spline interpolation for the actual flux, which is integrated to gain the average flux. These calculations are implemented in the computer control program.

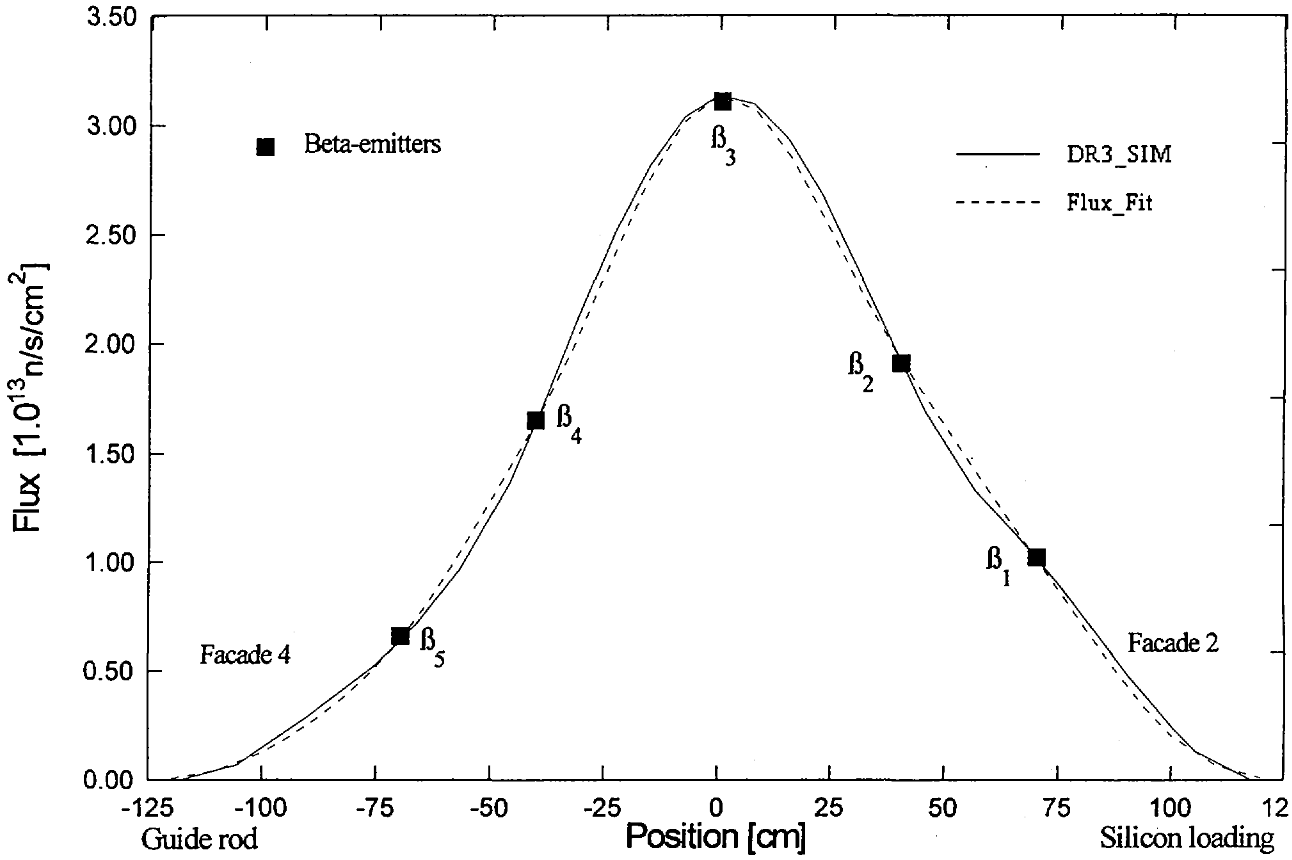

Figure 6: The neutron flux in the tube filled with H_2O.

Flux scan

To measure the neutron flux in the irradiation tube five β-emitters are placed in five different positions along the tube. The signals from these five β-emitters are used to determine the average flux as well as the required speed of the can before the start of an irradiation process. During irradiation these signals are used to correct the speed in case the neutron flux changes.

Before the facility was fully installed some flux measurements were carried out. A thin tube (6 mm diameter) was installed inside the irradiation tube. A polythene tube with short pieces of Cobalt wire embedded was inserted into this special flux scan tube. During flux scan it is not possible to perform irradiation. Corresponding values of the signals from the β-emitters were read. With reactor physical data valid for the time of the flux scan a run of the computer code DR3_SIM was done.

The results from the flux scan, readings of signals from the β-emitters and the computer calculations are shown in figure 7:

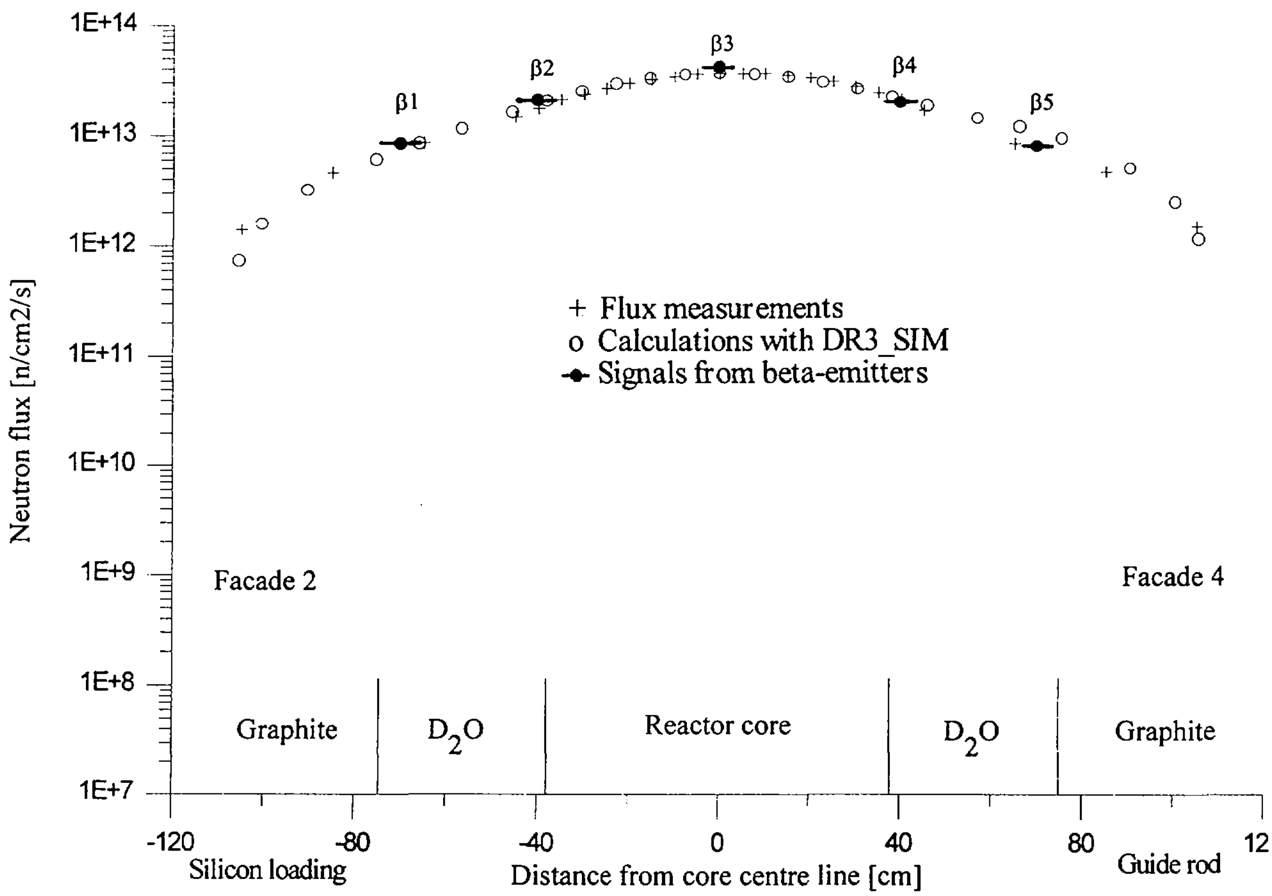

Figure 7: Thermal flux in 7T2.

6. Influence

7V3: Vertical Silicon irradiation facility

Calculations with the computer code DR3_SIM has not shown any significant influence from changes in the vertical Silicon facility 7V3. Readings of signals from the β-emitters when a Silicon crystal is lowered or redrawn from the rig have not shown any influence either.

Fine Control Rod (FCR)

Movement of the FCR do affect the neutron flux as illustrated in figure 8. A preferred interval for the position of the FCR has been chosen: 25-35 cm to compensate for this effect.

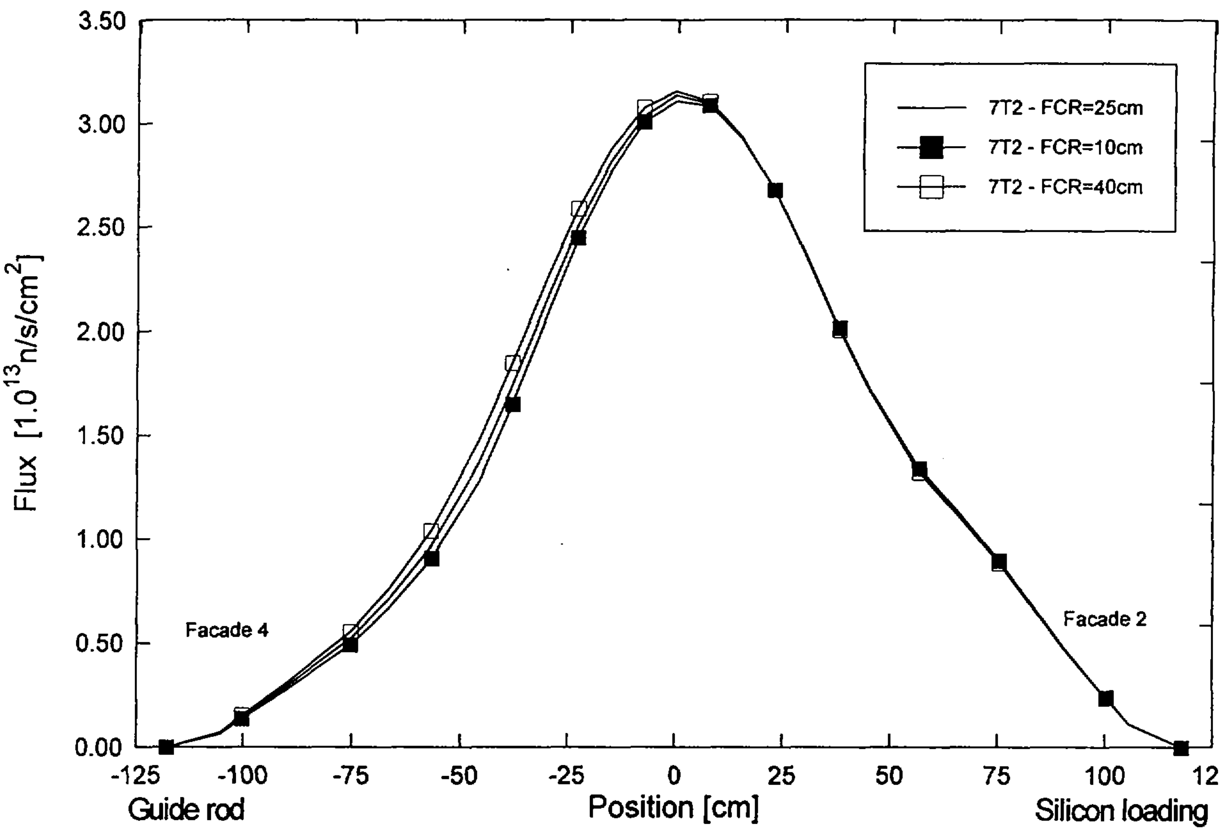

Figure 8: The influence of the FCR on the neutron flux in 7T2.

Absorber rigs

To maintain an almost constant angle of the coarse control arms (CCA) a moveable absorber rig is placed inside every fuel element. During the reactor cycle they are withdrawn one by one. Readings of the signals from the β-emitters when the absorber rigs in the A-row nearest 7T2 have shown no detectable change of the flux distribution.

Reactor trip

In case of a reactor trip during irradiation the system is able to compensate for the lack of flux. The speed of the guide rod is lowered according to the flux level.

7. Safety aspects

Reactivity changes

An Aluminium can filled with Silicon and Graphite placed right in front of the core results in a reactivity change of 0.053 % dk/k. If a can is inserted while the guide rod is in the opposite extreme position, the can will be transported into the irradiation area with the speed of the water which is 10.8 cm/s. This results in a maximum contribution of reactivity of 0.0094 dk/k pr. sec. Due to slip between the water flow and the can during transport the actual speed of the can will be lower. Therefore these calculations are conservative. The conditions for operating the reactor permit a maximum change in reactivity of 0.5 % dk/k pr. sec. for experiments with adjustable reactivity value.

Loss of water

A leak in the system will drain the irradiation tube and there will be no cooling of the can as well as of the tube itself. γ-heat will accumulate in the Aluminium tube and cause a temperature increase of 0.3 °C pr. sec. if the reactor is not shut down. Three level indicators placed in the water tank will cause a reactor trip in a "two out of three" system, if the water level falls below a specified level. There will be a preliminary warning before the trip.

Flow stop

In case of low, or no flow at all, the cooling of the can and of the irradiation tube is reduced. Three pressure transducers cause a reactor trip in case of low flow. The conditions are the same as mentioned above: A "two out of three" system with a preliminary warning before the trip. To allow operators to reverse the flow a 3 minute delay between warning and trip has been installed.

Health physic

The radiation level of the can is monitored automatically by a γ-monitor before transfer from the large drum to the lift. In case of a higher radiation level than acceptable, the removal sequence in the program can not be activated and the can remains inside the drum. Additionally a health assistant checks the level when the can is at the upper position in the lift.

8. Improvements

From the experience gained from the old horizontal facility some improvements of the new have been made. The two most significant improvements are listed below:

- **Five β-emitters** placed in five different positions has resulted in a better determination of the flux distribution.

- **The software** has been upgraded to a windows-based program which is much more user-friendly for the operators. Furthermore a lot more information regarding the irradiation is available on the screen.

- **The improved flux calculations** have made it possible to dope the Silicon crystals more accurately. The accuracy of the doping has been improved to ± 5 %.

9. References

1. K. Hansen and J. S. Olsen: Ny vandret Si-facilitet i 7T2 forsøgsrøret i DR 3. May 1995.

2. E. Nonbøl: Beregning af neutrònfluxen i den vandrette forsøgsrig 7T2 i DR 3. February 1997.