Operation of the accelerator driving the VENUS-F core for the low power ADS experiments GUINEVERE/FREYA at SCK-CEN

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on behalf of

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CNRS/IN2P3, France **SCK-CEN, Belgium**

2nd International workshop on Technology and Components of Accelerator-driven Systems, Nantes, May 21-23, 2013

Presentation overview

- GUINEVERE, FREYA
  - Presentation
  - Facility
- Accelerator
  - Specifications
  - Design
  - Ion source
  - Magnet
  - Target
  - Neutron source monitoring
  - Accelerator commissionning in stand-alone mode
- Coupled operation
  - First coupling
  - Accelerator commissionning in coupled mode
  - Accelerator operation, feedback
  - Operational issues
  - Accelerator and reactor groups interactions
- Conclusions and outlook

Genesis and goals of GUINEVERE

- Since 2006, within FP6 EUROTRANS, ECATS domain (DM2) :
  Experiments dedicated to Coupling an Accelerator, a Target and a Subcritical blanket
  ➔ driving and monitoring a subcritical reactor

- Provide a system representing an ADS demonstrator, continuing the MUSE-4 experimental program (FP5) run at CEA-Cadarache

- Investigation of
  - ❖ on-line reactivity monitoring
  - ❖ sub-criticality determination
  - ❖ operational procedures in an ADS (core loading, system startups and shutdowns)

- Collaboration CNRS/IN2P3 (France), SCK-CEN (Belgium) & CEA (France)

SCK•CEN cnrs IN2P3 Les deux infinis SIXTH FRAMEWORK PROGRAMME PACEN cea

GUINEVERE

- Generator of Uninterrupted Intense NEutrons at the lead VEnus Reactor

- Low(zero)- power coupling of
  - a fast lead core reactor, VENUS-F
  - a versatile neutron source, GENEPI-3C

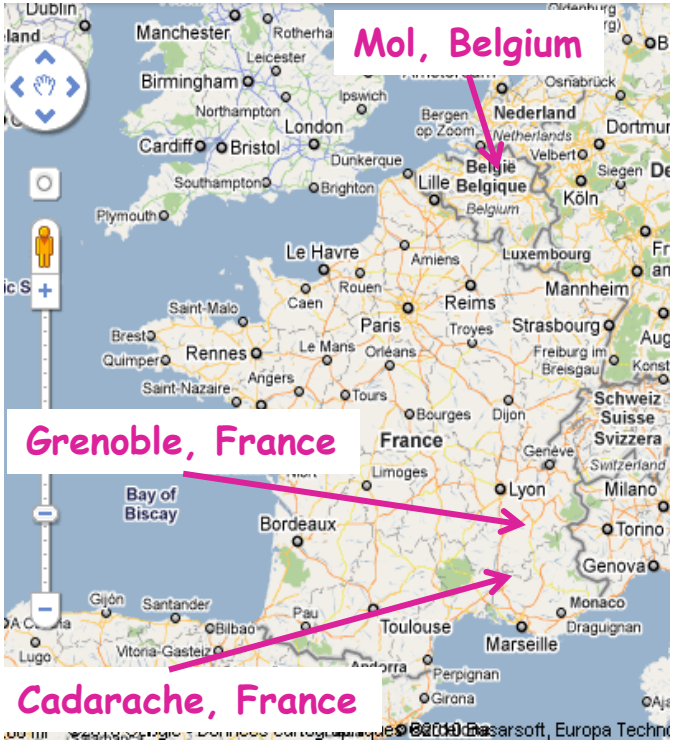
- Project consists of

  ❖ modification of the existing VENUS reactor into a fast reactor with a lead moderator

  ➔ VENUS-F by SCK-CEN (Mol, Belgium)

  ❖ construction of a new accelerator to provide pulsed & continuous neutron source

  ➔ GENEPI-3C by CNRS/IN2P3 (France)



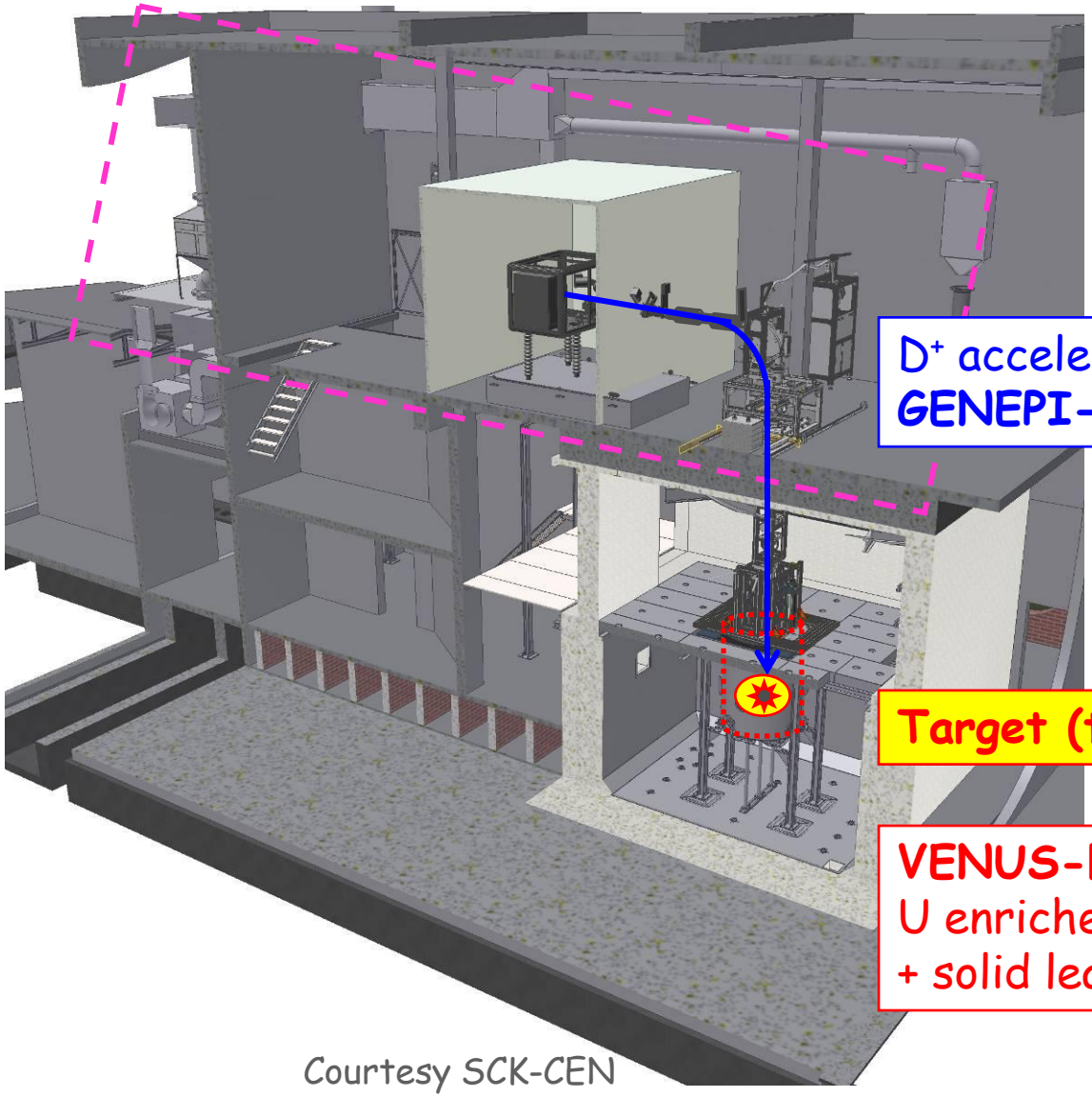
❖ experimental program on the monitoring of a subcritical reactor

➔ European collaboration : IN2P3, CEA, SCK-CEN and EC

started with FP6 GUINEVERE and continued with FP7 FREYA (*talk by A. Kochetkov)*

The experimental ADS facility

New floor built for the coupling



Courtesy SCK-CEN

The GENEPI-3C accelerator specifications

- GEnerator of NEutrons Pulsed & Intense
  - Electrostatic Deuteron accelerator (240 keV)
  - Neutron (14 MeV) production via $T(d,n)^4He$

- Accelerator capable of producing alternatively
  - ❖ Intense pulsed mode
    - 40 mA peak current
    - FWHM < 1 µs
    - repetition rate : 10-5000 Hz
  - ❖ Continuous mode (DC)
    - DC beam up to 1 mA
  - ❖ DC interrupted
    - DC + programmable beam trips with fast transition time

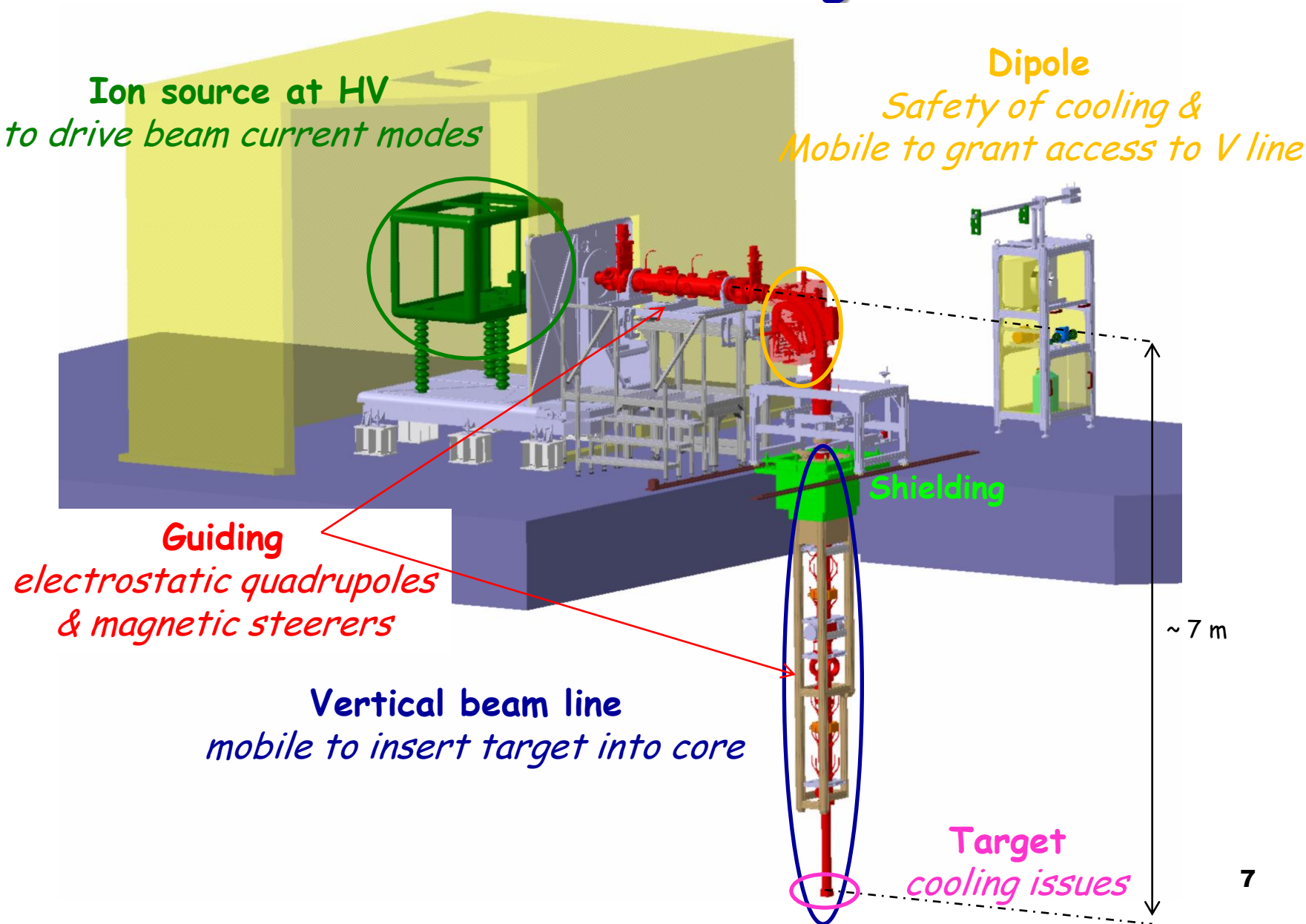
DC interrupted mode

Mean current	160 µA to 1 mA
Beam trip rate	0.1 to 100 Hz
Beam trip duration	~ 50 µs to 10 ms
Transition edge	~ 1 µs

- Designed & built by CNRS/IN2P3 (France) collaboration (2007-2009)
  - LPSC Grenoble, LPC Caen, IPHC/DRS Strasbourg & IPN Orsay

- Largely based on technology of the previous machines
  - GENEPI-1 at Cadarache for MUSE-4
  - GENEPI-2 at LPSC for nuclear cross section measurements

Accelerator design

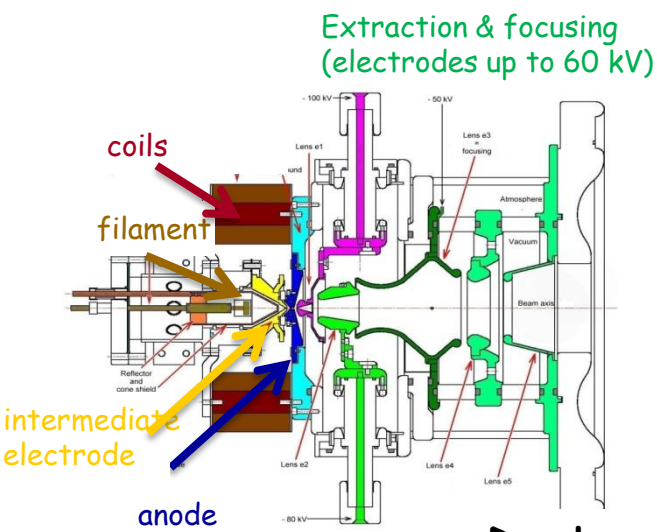


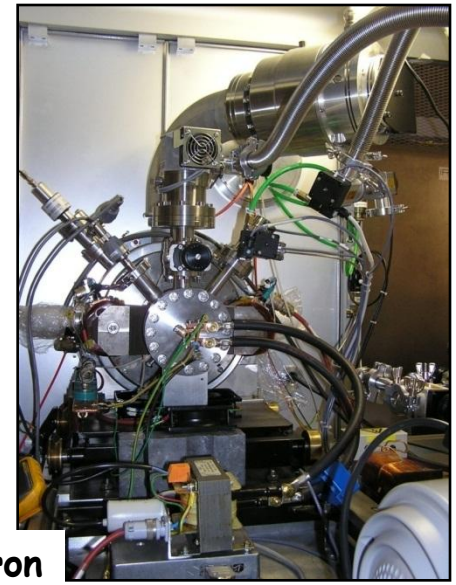
Ion source

- Duoplasmatron : production of Deuterons for the 3 beam modes (intensity, time structure)
  - well adapted to pulsed mode, experience with GENEPI-1/2
  - R&D for DC modes on test bench

- DC modes specifications mostly reached
  - 1 mA D^+
  - Programmable interruptions on some parameters range
  - ON/OFF transitions ~ µs

- DC operation : ionization efficiency D^+ ~ 40%
  - 60% beam lost by magnetic separation
    - ➔ **~ 400 W of beam power dumped at the bend magnet**

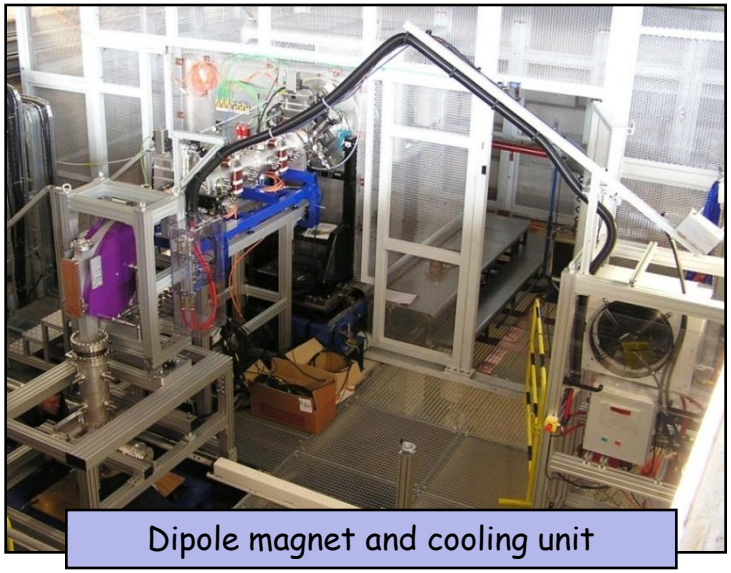




Duoplasmatron

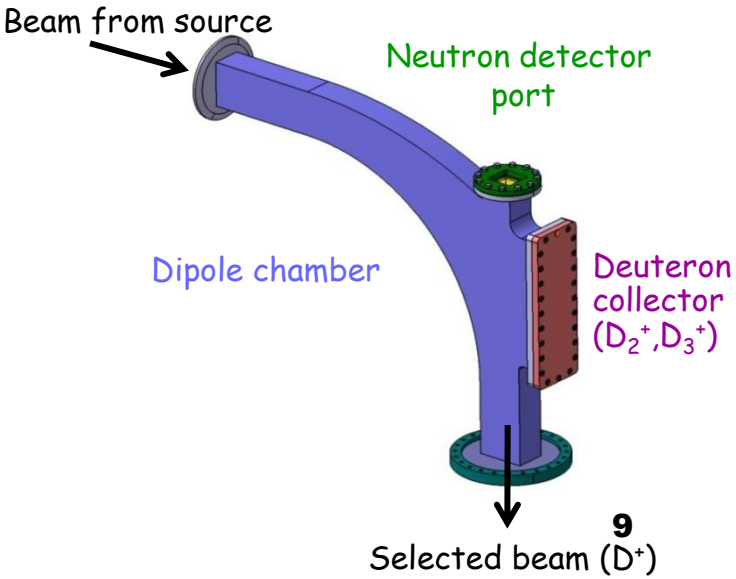
Dipole magnet

- Deflect the beam down towards core & perform magnetic separation
- Magnet features : C design, 0.5 m radius, 0.2 T, 30° faces
- Water cooled with stringent precautions against leaks
  - waterproof protection for coil, double layer piping, watertight casing for connections with leak detection, deported cooling unit with watertight casing
- Deuteron collector to dump species other than D^+ cooled by air : **~ 400 W to dissipate**
  + shielding against neutron production from implanted D : Borated PE casing
- Mobility of dipole (cart) and connections (counterweighted pipes) to access the vertical line



Dipole magnet and cooling unit

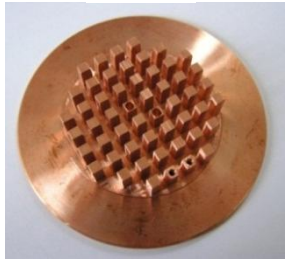
Borated PE casing



Tritium target

- Target holder : copper disk with Thin layer of TiT (12 Ci)
  - Titane deposit: 1100 μg/cm2
  - Tritium loading (impregnation)
  - Titanium hydride ρ=4.2 g/cm2
  - T/Ti ~ > 1.5

Back



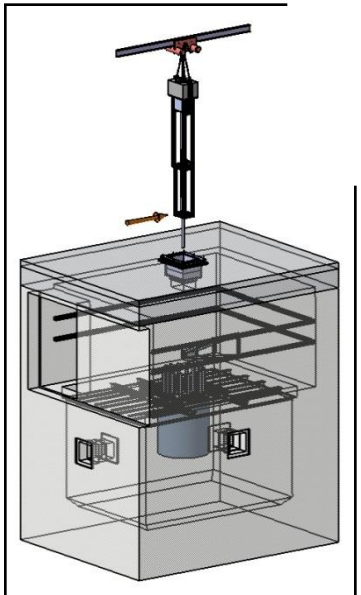
Pin fins (cooling)
+ current meas.
+ temperature meas.

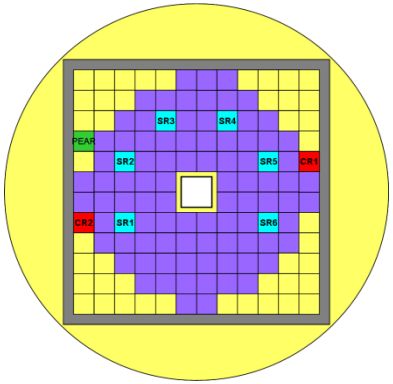
Φ = 60 mm

- Mounted on beamline termination (thimble)

- Cooling with compressed air to dissipate the beam power of 250 W
  - No Hydrogen within core & limited room (less than 2x2 FA)
  - Cooler & drier system (6 bars), diffuser with 4 inlets
  - To limit Tritium desorption T < 60 ° C

- Target inserted in the core by V line craning
  - Dipole magnet translated away
  - V line & shielding embedded in support structure
  - Guided at upper & lower level



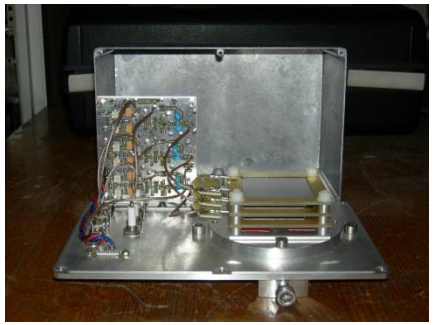


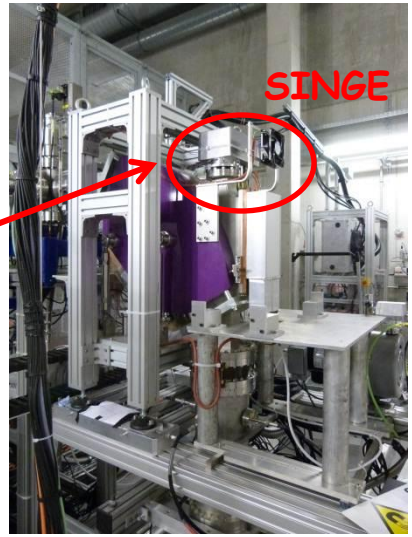
Talks by N. Marie & S. Chabod

Neutron source monitoring

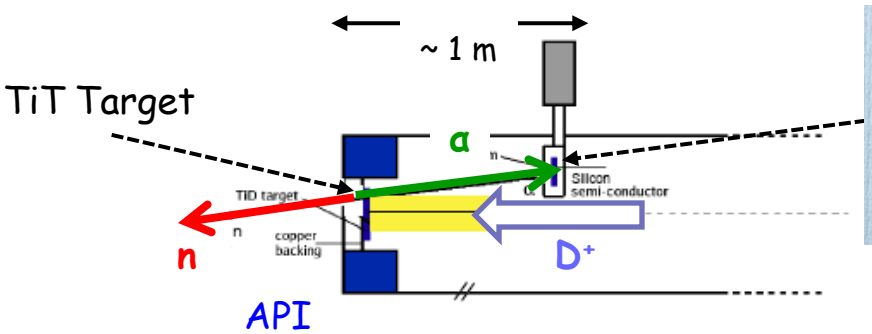
- Recoil neutron telescope facing the target : direct monitoring of 14 MeV neutrons (SINGE)
  - conversion into proton via (n,p) reactions in an H material window
  - 3 Silicon detectors ➔ high energy protons stop in 3rd detector
  - located on top of the magnet, ~ 7 m from target
  - triple coincidence to discriminate reactor fission neutrons

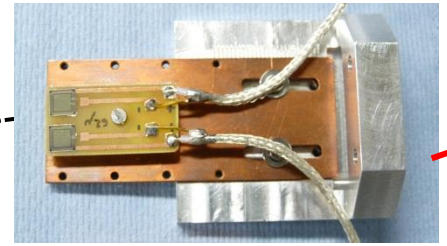
SINGE
recoil n monitor

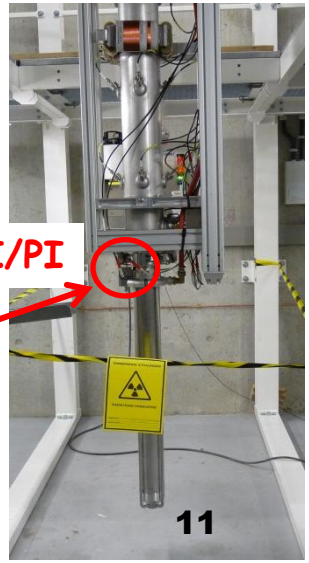




- Particle detector facing the target : absolute monitoring of rate (API/PI)
  - Silicon semiconductor detector under direct solid angle
  - Detection of the alpha or protons emitted at backward angles from $T(d,n)^4He$
  - Absolute rate monitoring determined using solid angle (geometrical efficiency)







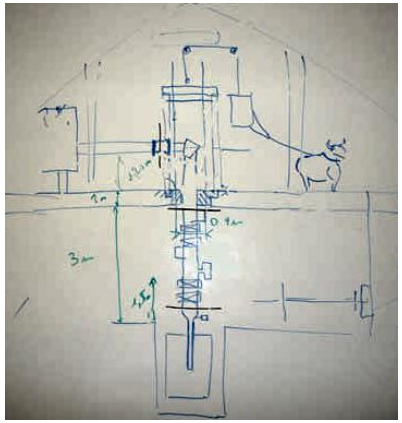
Project timeline

- European financing : official project launch — Dec 2006
- Machine design — 2007-mid 2008
- Construction and assembly at LPSC — 2008-2009
- Machine commissioning at LPSC (3 stages) — Sep 08-August 09
- Disassembly, transfer to SCK-CEN and re-assembly — Sep 09-March 10
- Machine commissioning in stand-alone mode at SCK-CEN — March-Sep 2010

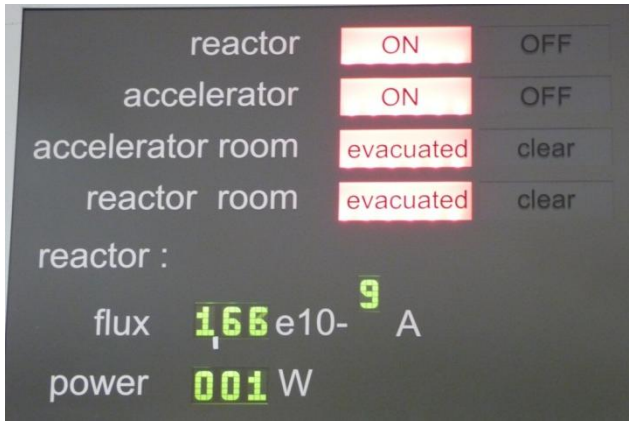
  ➔ multiple reports for the safety authorities to proceed

  & wait for final authorization

  + commissioning of the reactor in the critical phase
- Authorization for the coupling of GENEPI-3C to the reactor — Sep 2011
- First coupling — Oct 2011



2006



2011

Accelerator assembly at SCK-CEN

- 2009:
  - Sep: re-assembly of GENEPI-3C at Mol started
- 2010:
  - Feb : Assembly of accelerator completed

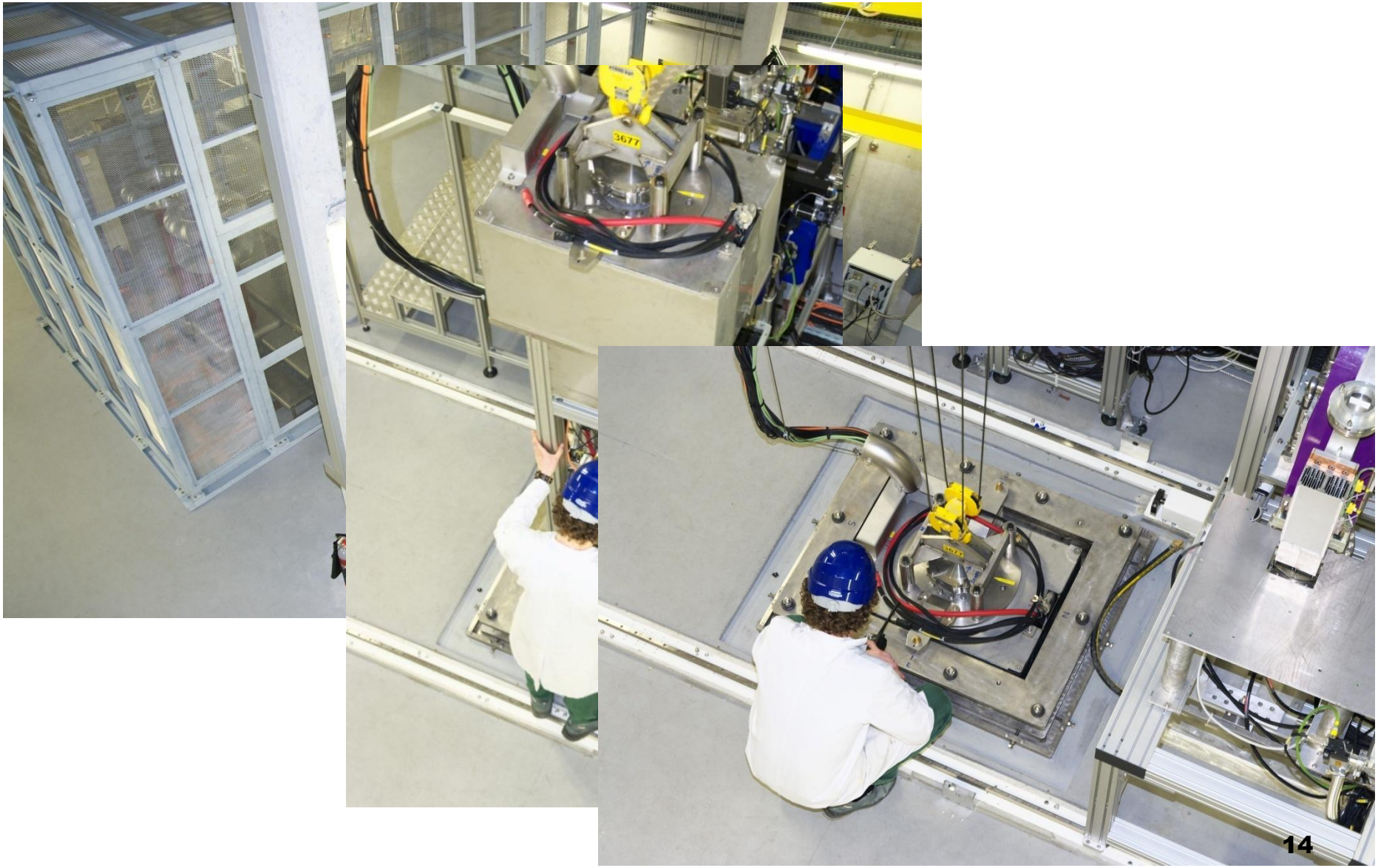

Alignment


Faraday cage

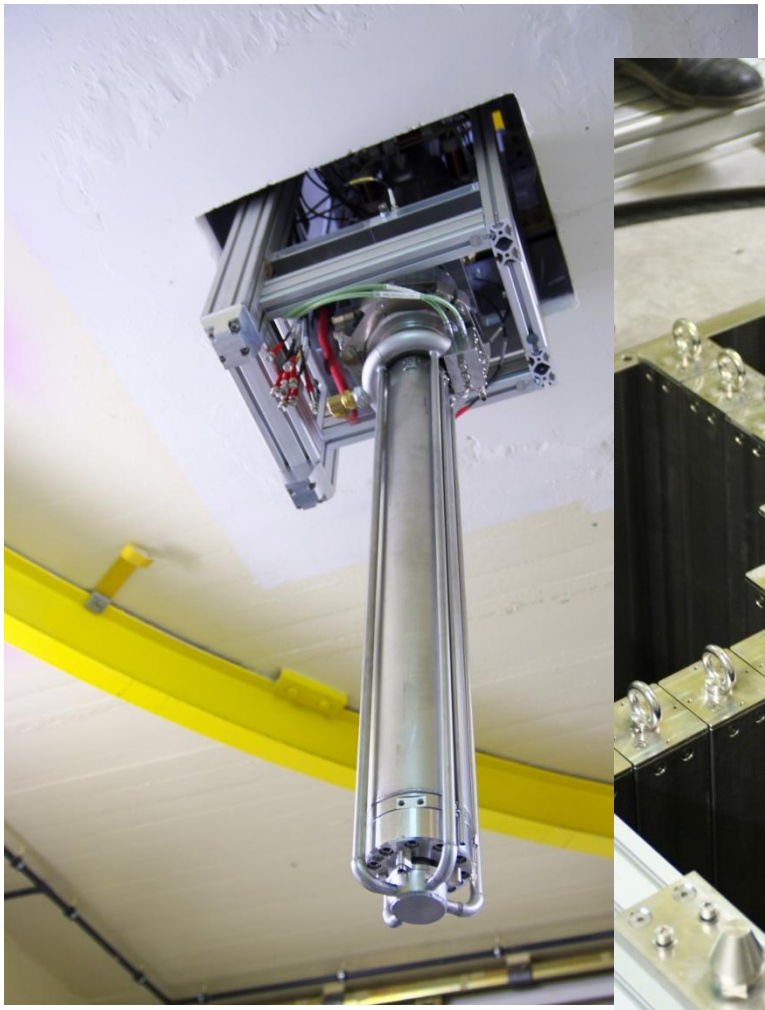

High voltage head

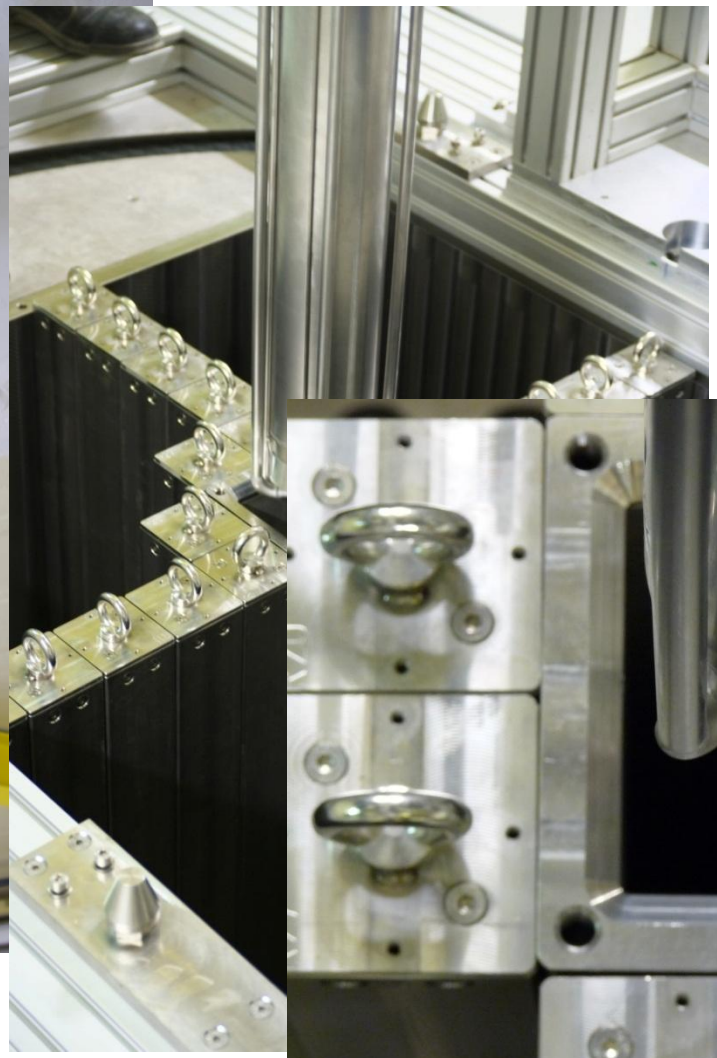

Vertical beam line

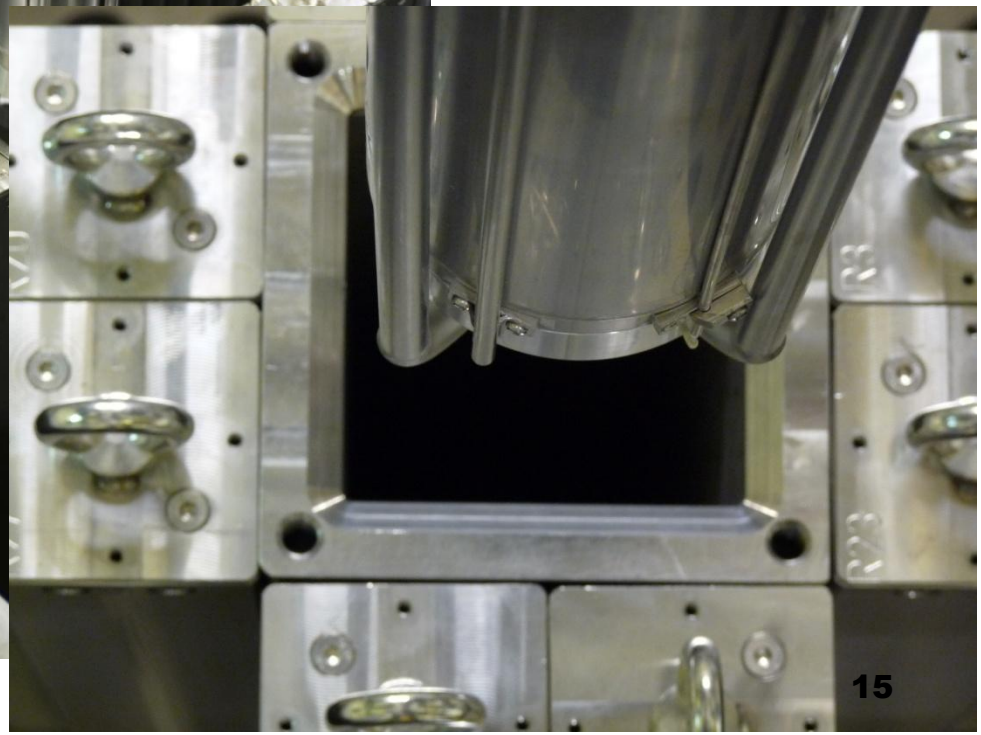
Beam line insertion into the core (upper level)



Beam line insertion into the core (lower level)

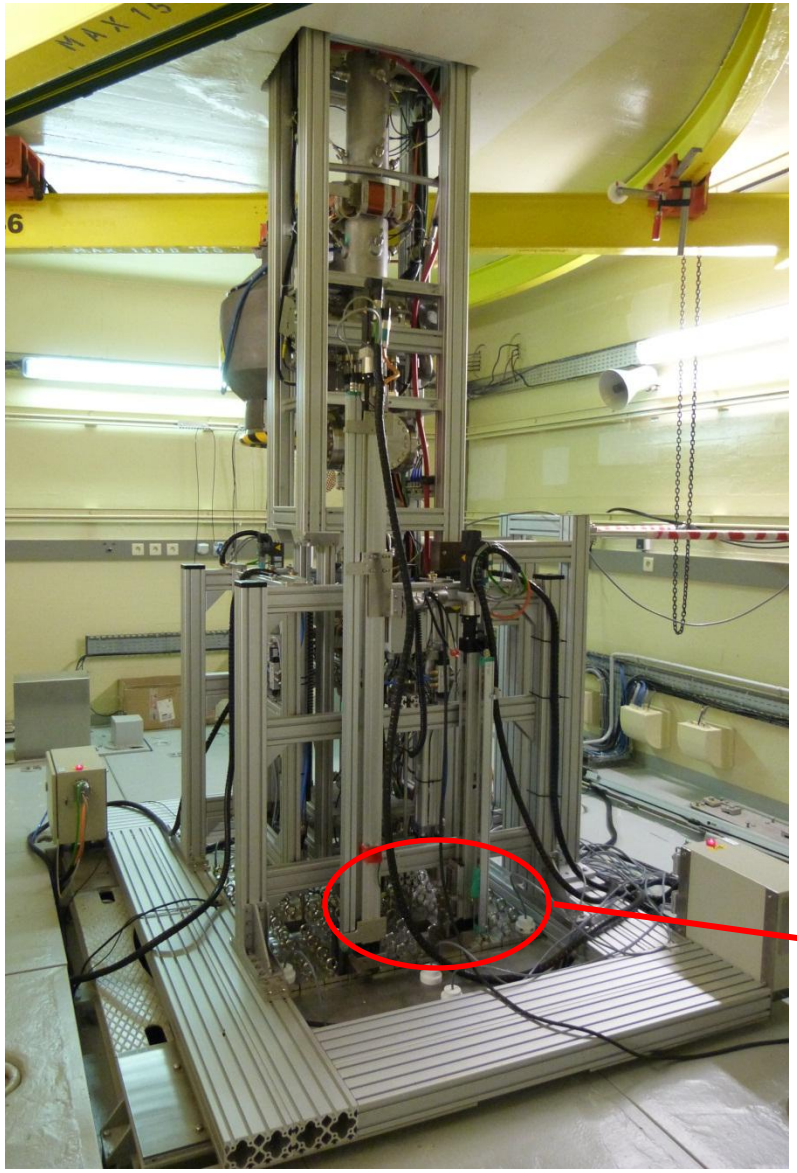


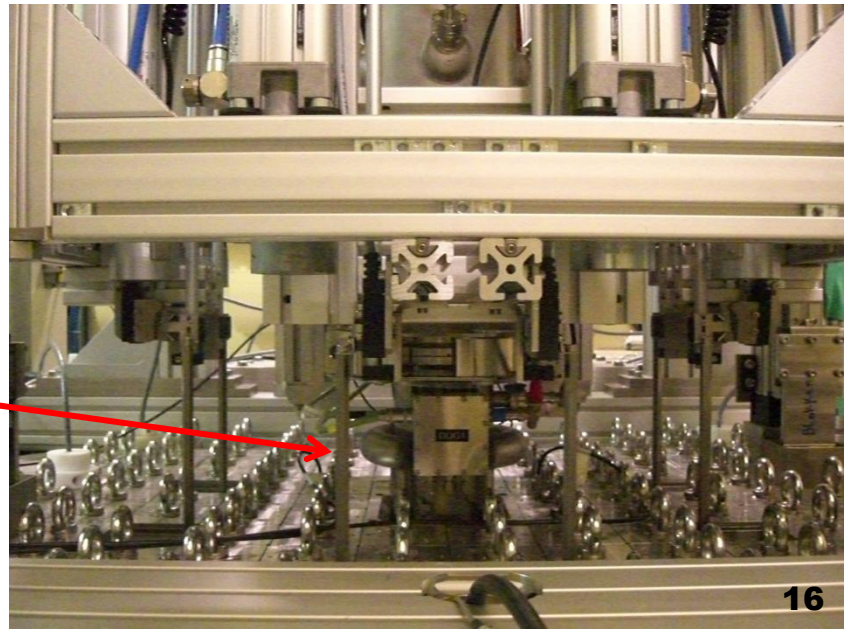




During test phase, before core loading

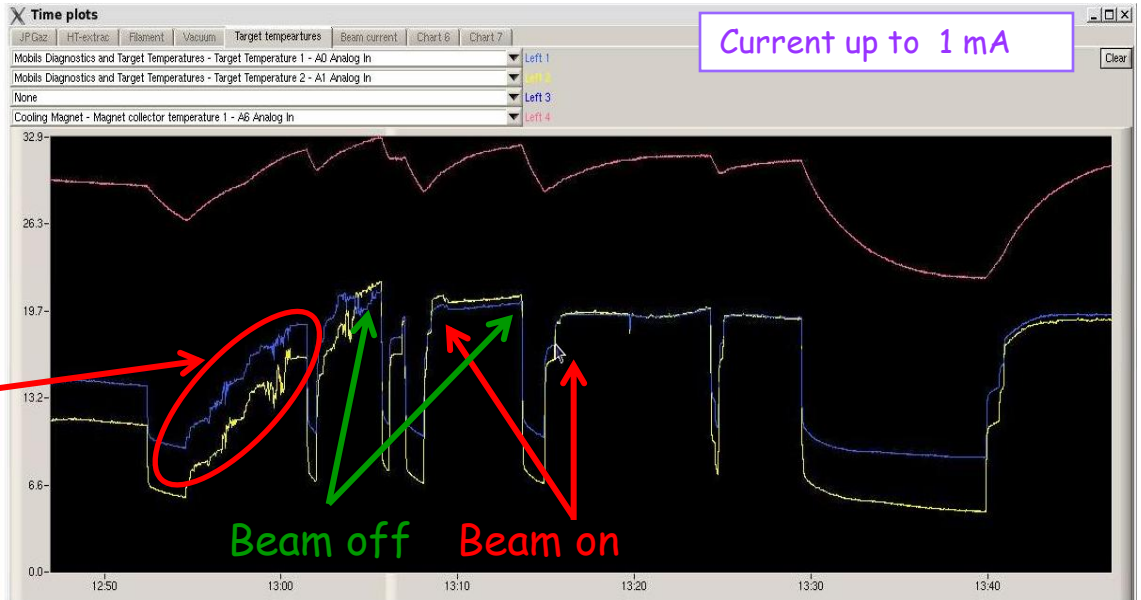
Beam line inserted in the loaded core





Accelerator commissioning in stand-alone mode
March-September 2010

- Commissionning with dummy target and unloaded core along with permits from nuclear safety authorities
  - Some debug : incorrect connections, fix breakages
  - June : Beam on target
  - Beam transported with mostly LPSC settings (pulsed and DC modes)
  - Maximum beam current in pulsed mode too low
  - Target cooling validation
  - Some instability on long high current runs (discharges)
  - Authorization for Tritium target handling & use



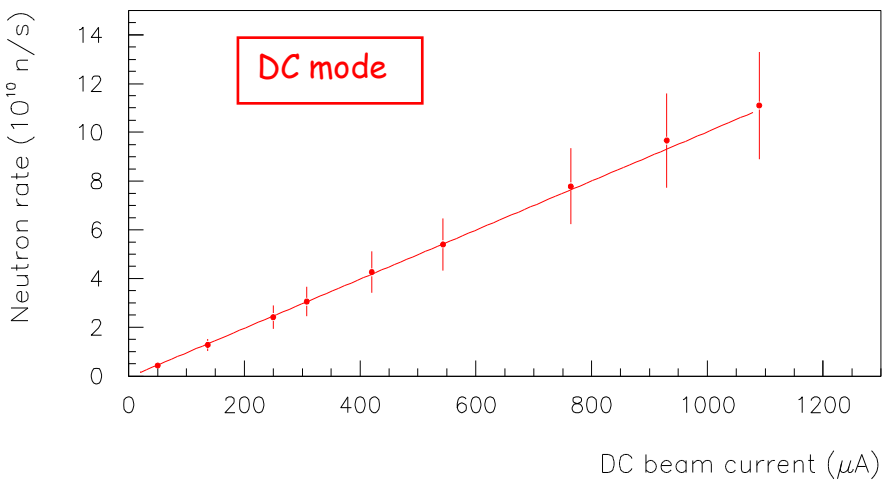
Intensity ramp

Deuteron collimator (magnet)

Target (2 redundant meas.)

Neutron production

- Tritium target installed ➔ 14 MeV neutron production via $T(d,n)^4He$
- Commissioning of the 2 neutron detectors
- Measured production rates from new target (API)
  - ❖ pulsed mode ~ 1.15×10^6 n per pulse for f=10-5000 Hz
  - ❖ DC mode ~ 10^8 n.s-1.μA-1 for I = 0.1 - 1 mA



~ 10^{11} n.s^{-1} for I = 1 mA

Excellent agreement with neutron production expectations w/ new target!

Autumn 2010 – autumn 2011

- Overall commissioning report for safety authorities: performed by end of Sep 2010
  - Request for reactor core loading authorization from BEL-V
  - Machine shutdown

- February - June 2011: Critical phase carried out, after authorization received (January)

- Problem: HTO Tritium release higher than expected
  - request for accelerator-reactor coupling and increase of annual limit for HTO release

- May – July 2011: some machine upgrades (hardware & software)
  - while expecting authorizations from nuclear safety authorities

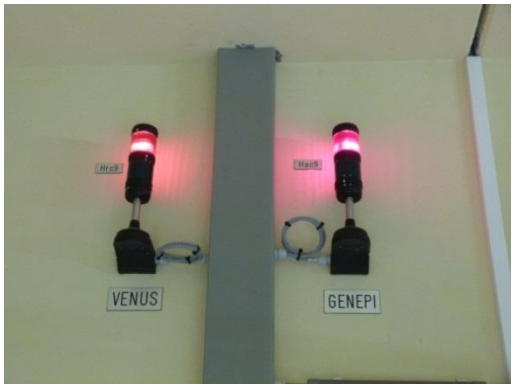
- **26 September 2011: Authorization of the coupling of the GENEPI3C accelerator and the subcritical VENUS-F reactor**

- October 3-11, 2011: machine restart, preparation for coupling

1st Coupling : October 12, 2011

- 14:00 : Machine and reactor ready
- 15:02 : Beam on target at 40 Hz, then ramp up to 200 Hz
- 15:10 : initiate reactor bars lifting sequence
  - Safety rods up one by one (from 1 to 6) : 25 min
  - Control rods (x2) up simultaneously to desired level : 5 min

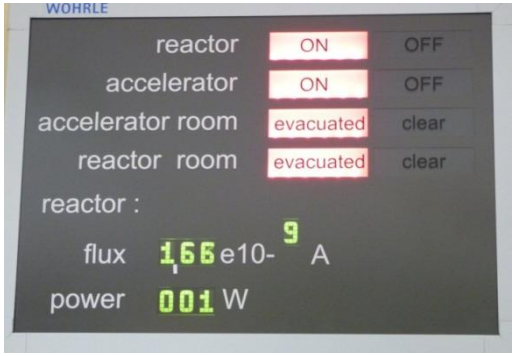
- **15:35 : 1st coupling of GENEPI3C & VENUS-F**



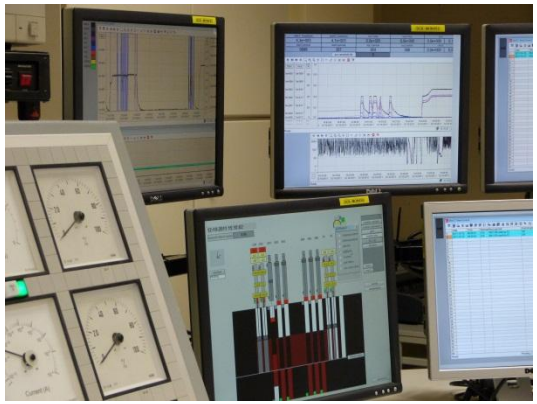
Reactor & accelerator state indicator

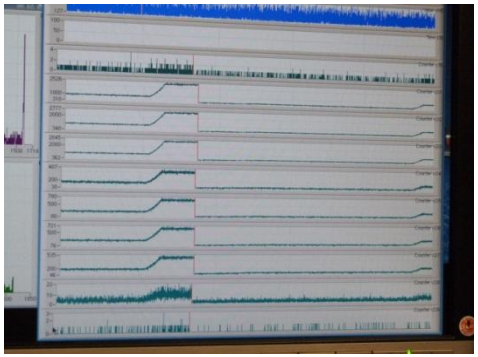
- then, beam frequency increase to 400, 500 and 1000 Hz (15 min)

  ➔ **Measured core power driven by accelerator intensity**



- DAQ adjustments, data taken by physics for test





Neutron production during safety bars lift up

Commissioning of coupled machine operation
October 2011-March 2012

- October 12- November 10: coupling with pulsed beam

  I_{beam} ~ 20 mA peak, $\tau < 1\ \mu s$ width, repetition rate ~ 1 kHz

- November 16 -22: coupling in DC mode

  reduced current due to fission chambers pile-up issue ➔ I_{beam} ~ 15-100 μA

- November 23 - December: coupling in DC interrupted mode

  I_{beam} ~ 75 μA, typical settings : T_{off} = 400 μs, trip rate = 500 Hz

  ➔ beam off 20% of time, but trip tuning difficult at so low current

- December – February : hardware failures & repairs (pump, source)

- March 1 – 15 : coupling in pulsed beam, with some software issues

On a « good » day of DC beam, the integrated charge on target was ~ 700 mC

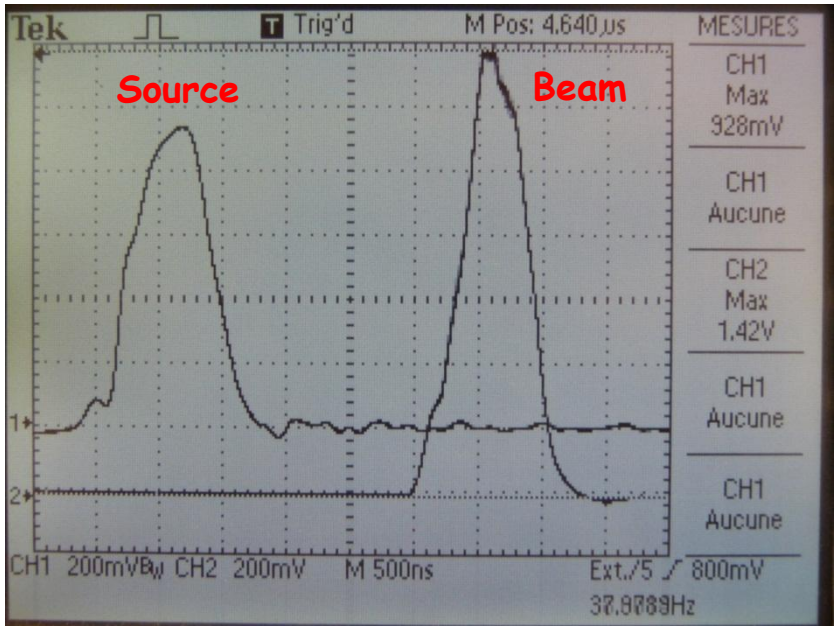
➔ Significant progress to be made

Coupled machine operation
April 2012

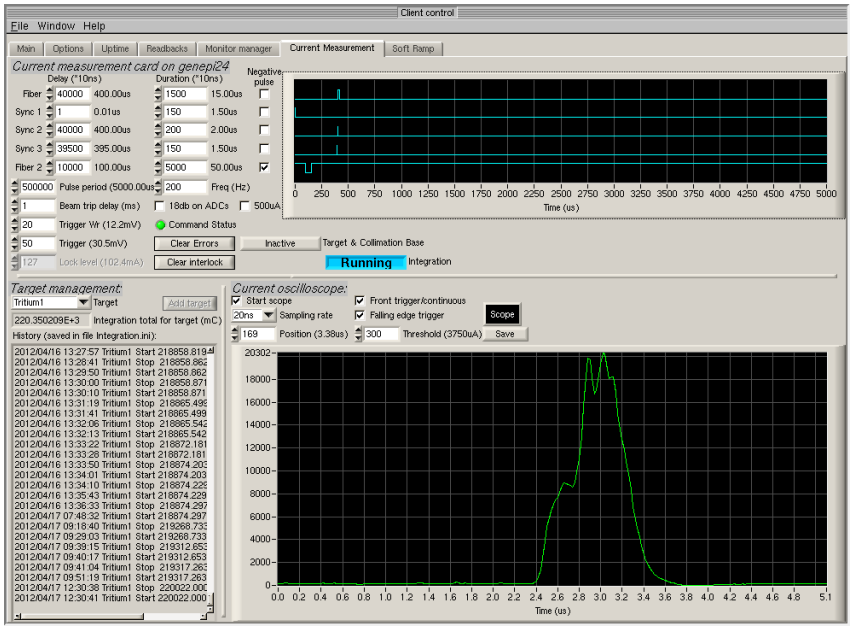
- Coupling in pulsed beam

  typical settings: I_{target} = 20 mA peak, rate = 200 Hz

- Straightforward operation: stable machine, nearly no discharges or beam trips



Analog o'scope



Command-control : digital o'scope

Pulsed beam parameters

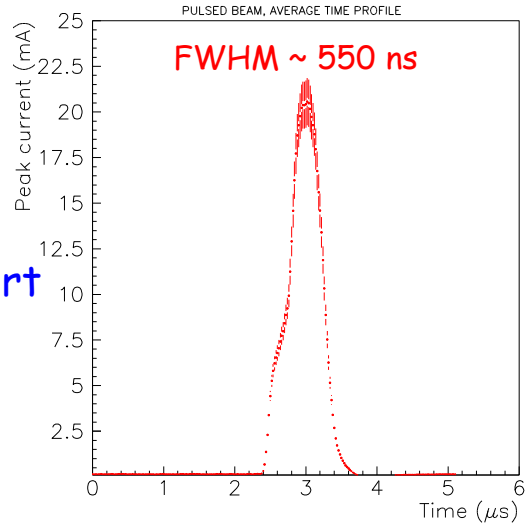
- Premilinary analysis on a few daily runs

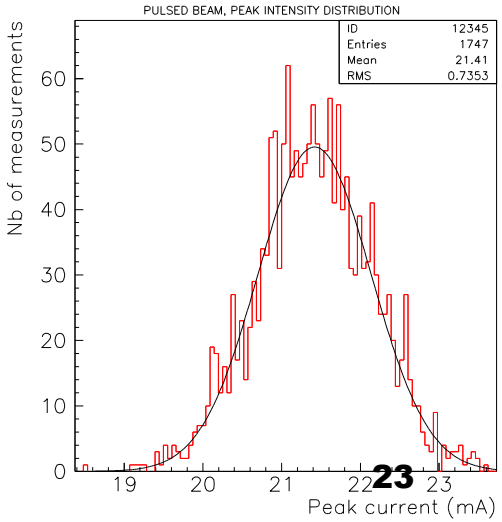
- Peak current
  - I peak ~ 20-25 mA
  - instead for 40 mA required
  - because of anode hole reduction to optimize DC beam transport
  - not an issue for the physics program

- Pulse width
  - T_{pulse} ~ 550 ns (FWHM)
  - $\sigma(T_{pulse})/ T_{pulse} < 1\%$

- Pulse frequency
  - $\sigma(f)/f < 10^{-5}$

- Pulse shape to be investigated to understand the fine structure



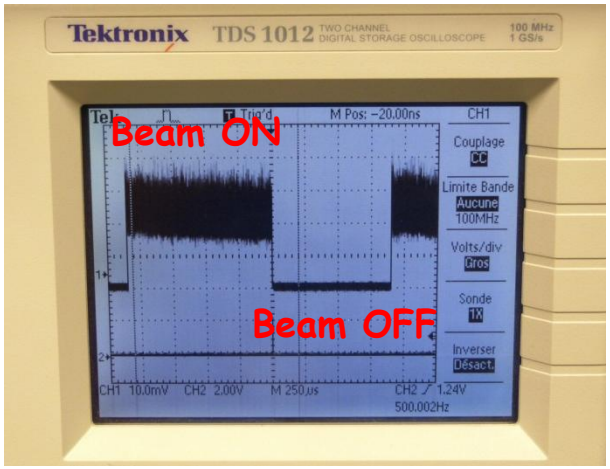


Machine specifications seem mostly met

Coupled machine operation : DC modes

- The current limitation on target was removed (fission chambers reshuffling)
  - ➔ standard operating conditions for the accelerator (hundreds of μA)
  - ➔ reliability of DC modes operation greatly improved

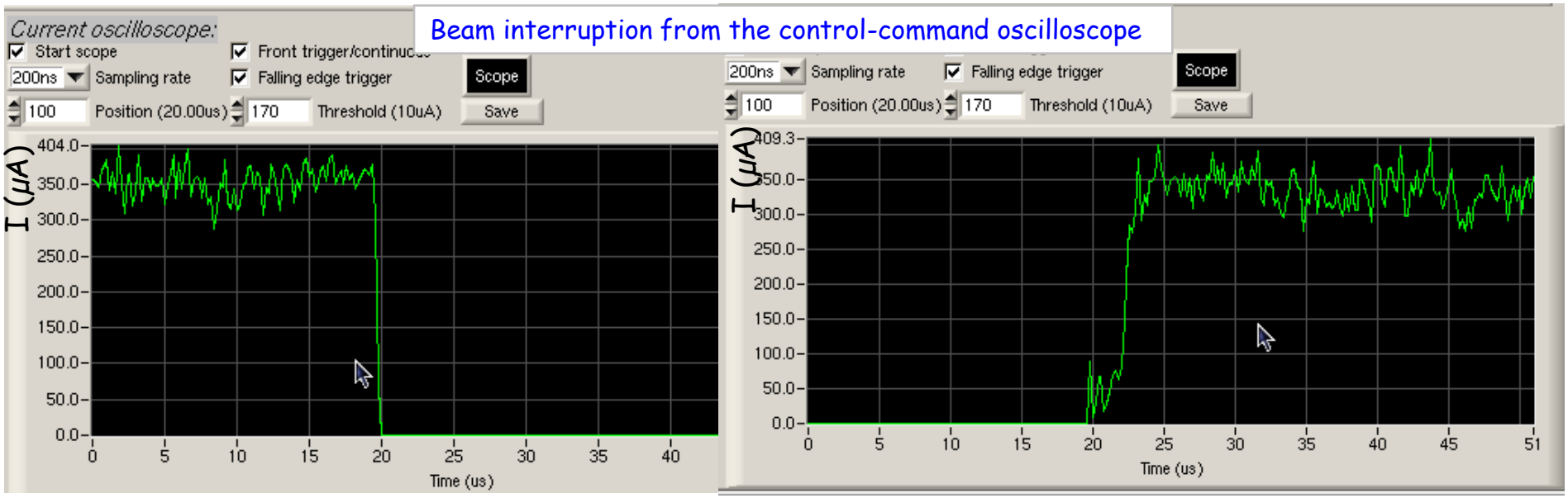
- But steady operation of DC interrupted remains tricky
  - DC interrupted was commissioned for the first time at SCK-CEN
  - Fine tuning of the source parameters required
  - Electric discharges remain fairly numerous
  - ➔ operating issues were discovered on the field and during the data taking



Analog o'scope

DC interrupted beam parameters

- Typical settings for physics :
  - I_{target} = 200-400 μA
  - duration = 300 μs and rate = 200 Hz ➔ T_{OFF}/T_{ON} ratio = 6%



Machine specifications : $T_{ON/OFF}$ ~ 1 μs

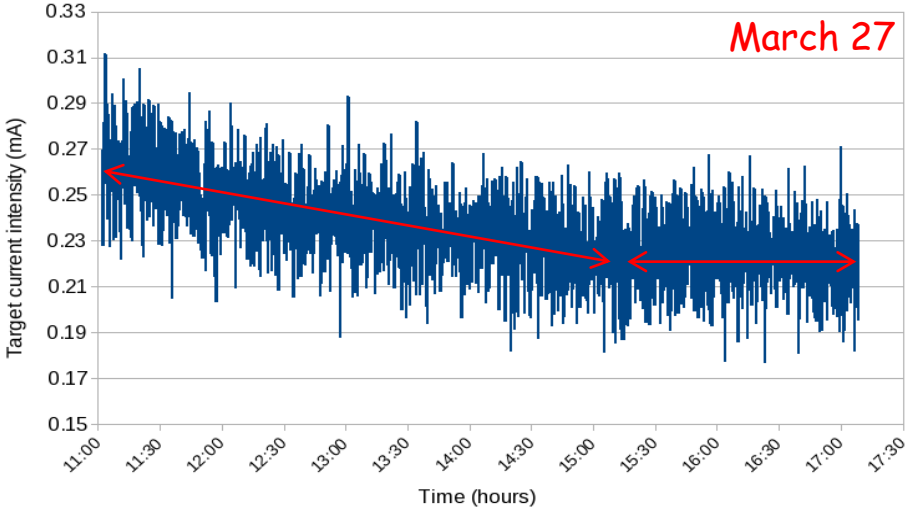
- Some tunability of rates, but not all of the specified range
  - hundreds of μA : stable rate for T_{OFF}/T_{ON} ratio between 90% and 6%
  - unstable at lower current

A good day of running can generate a charge as high as ~ 5 C, corresponding to ~7.5 hours of beam

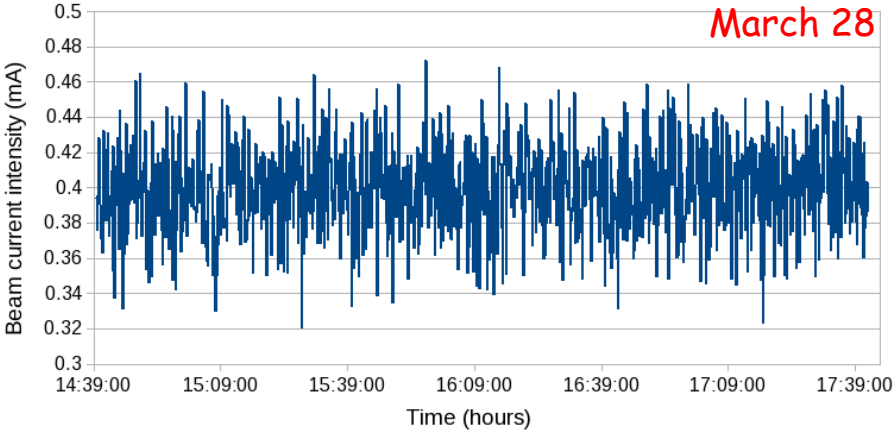
Beam current stability

- Beam current drops on a daily basis
  - decrease independant of beam mode
  - similar behavior seen on GENEPI-2 at LPSC (pulsed mode only)
  - thermal effect?

- No feedback applied on the beam current
  - could be implemented if necessary



Whole day run

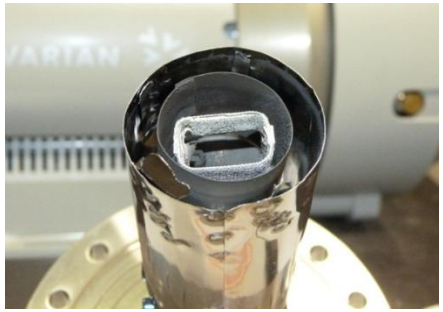


Stable afternoon run

➔ Under investigation

Major operational issues

- Fast aging of ion source : filament depletion and/or shield destruction



  - 1 week to recover from filament depletion
  - longer downtime if shield destroyed
  - preventive exchanges of filament chamber ~every long shutdown

  ➔ heat treatment of shield material under investigation

- Electric arcs created at high voltage

  - most arcs within vacuum, some external discharges
  - most arcs without incidence on beam delivery
  - but some arcs can yield total beam loss

    upon beam restart, neutron rate exceeds safety threshold imposed by doubling time

    ➔ Reactor SCRAM (nearly all of the time)

  ➔ improved CEM within the HV head

    + harden ion source electronics

  But no treatment to air ventilation system in accelerator room

  ➔ up to 70% humidity, 28° C measured during data taking

  ➔ may cause some discharges

Feedback on the coupled operation - 1

- **Pulsed beam:** the operation of the coupled system is stable and robust

  - Starting or restoring the beam is performed with a soft current (frequency) ramp (the ramping time was determined according to the reactor doubling time)
  - Very few electric discharges

  ➔ **Nearly no reactor SCRAM**

- **DC or DC interrupted beam**: the operation of the coupled system is more tricky

  - Source instabilities in beam interrupted mode

    Plasma does not ignite at every period ➔ no reactor SCRAM

  - Most discharges are not harmful but some important external arcs SCRAM the reactor

    ➔ All rods drop

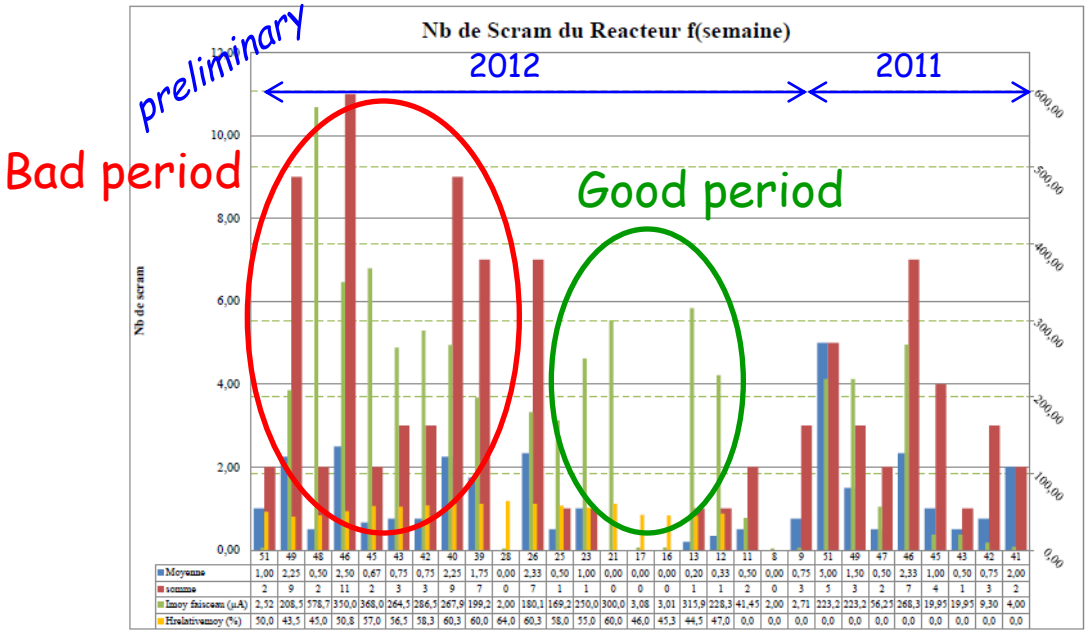
    ➔ Coupling procedure must be restarted from scratch

    ➔ Half an hour required to restore the reactor (over 8 hours of daily running)

  ➔ **Some reactor SCRAMs**

Feedback on the coupled operation - 2

- Records are being analyzed over ~ a year of operation, preliminary trends:
  - Good periods with no reactor SCRAM per week
  - Bad periods average to 6 SCRAMS per week, mostly with high beam power & humidity



	51	49	48	46	45	43	42	40	39	28	26	25	23	21	17	16	13	12	11	8	9	51	49	47	46	45	43	42	41
Moyenne	1,00	2,25	0,50	2,50	0,67	0,75	0,75	2,25	1,75	0,00	2,33	0,50	1,00	0,00	0,00	0,00	0,20	0,33	0,50	0,00	0,75	5,00	1,50	0,50	2,33	1,00	0,50	0,75	2,00
somme	2	9	2	11	2	3	3	9	7	0	7	1	1	0	0	0	1	1	2	0	3	5	3	2	7	4	1	3	2
Imoy faisceau (µA)	2,52	208,5	578,7	350,0	368,0	264,5	286,5	267,9	199,2	2,00	180,1	169,2	250,0	300,0	3,08	3,01	315,9	228,3	41,45	2,00	2,71	223,2	223,2	56,25	268,3	19,95	19,95	9,30	4,00
Hrelativemoy (%)	50,0	43,5	45,0	50,8	57,0	56,5	58,3	60,3	60,0	64,0	60,3	58,0	55,0	60,0	46,0	45,3	44,5	47,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

➔ *Analysis underway*

- Given machine improvements, we expect reduced SCRAM rates during the coming run

- But remaining bad air conditions in accelerator room for many months per year:
  - Typically, humidity > 55% (may-october)

Accelerator and reactor groups interactions

- For an effective operation of the coupled facility, an excellent communication level is required between the accelerator and the reactor teams for:
  - Long term planning to optimize the facility downtimes (maintenance, upgrades) and running periods
  - Weekly/daily planning for preparation of running conditions, problem solving, optimum scheduling of reactor and accelerator safety checks, site access ...

- Maintenance work such as ion source exchange or vacuum equipment replacement is now conducted jointly by CNRS and SCK-CEN teams

- At the VENUS facility, the accelerator and reactor control rooms were constructed on top of each other to foster exchanges

- So far the accelerator was driven in the accelerator room from a PC, but the machine command-control system is fully functional from another PC installed in the reactor room

- Reactor pilots are being trained to drive the accelerator
  - Eventually, reactor pilots can drive the whole facility

Summary

- Low power ADS facility in operation since 1.5 year

- The experimental program is progressing and yields first physics results
  - 3 talks given at this meeting: A. Kochetkov, N. Marie and S. Chabod

- While some improvements remain to be done on the beam specifications (current stability and intensity), the machine specifications are largely met

- Goals:
  - Improve reliability and beam specifications
  - Analyze data of coupled operation to provide specific machine reliability parameters
    - MTBF (Mean Time Between Failures)
    - MTTR (Mean Time to Repair)

- The main operational constraint is the facility downtime generated by reactor SCRAMS caused by severe electric discharges
  - Several improvements implemented : we expect reduced SCRAM rates in the future
  - Problem specific to structure of GENEPI-3C
    versatile source, electrostatic machine ≠ MYRRHA

- In spite of the discrepancies of accelerator structures between such a mock-up machine and a high power proton driver for an ADS demonstrator facility, valuable feedback from the coupled operation can be provided to ADS projects, such as MYRRHA

Special thanks to a great team (CNRS, SCK-CEN)

Oct 2011 : 1st coupling

And thank you for attention!

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