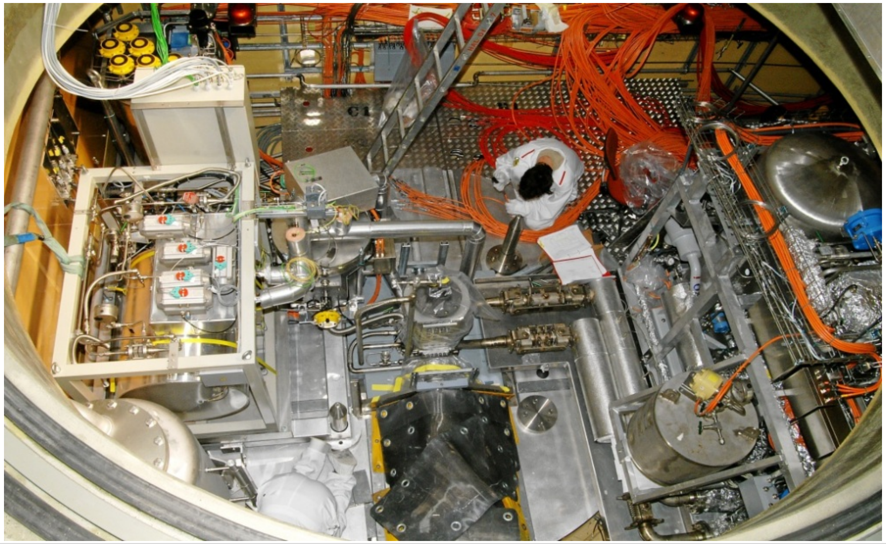
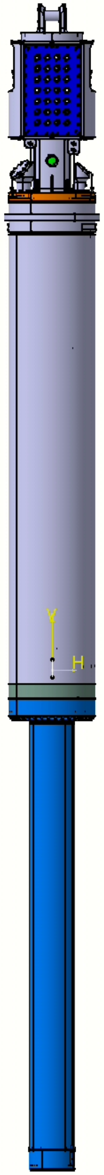
Karlsruhe Institute of Technology

MEGAPIE Project Overview

From kick-off till the end of irradiation

Friedrich Groeschel, IAM-AWP





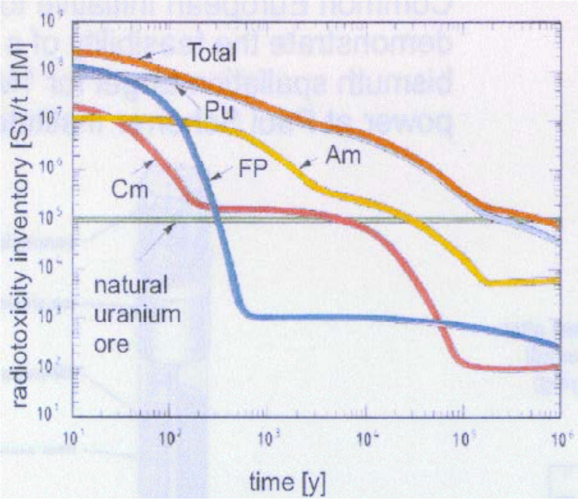
The MEGAPIE Initiative

- A collaboration to design, build, operate and explore a liquid lead-bismuth spallation target of 1 MW of beam power, taking advantage of the existing spallation neutron facility SINQ at the Paul Scherrer Institute

- The minimum design service life will be 1 year (6000 mAh).

→ Demonstration of feasibility for future ADS development

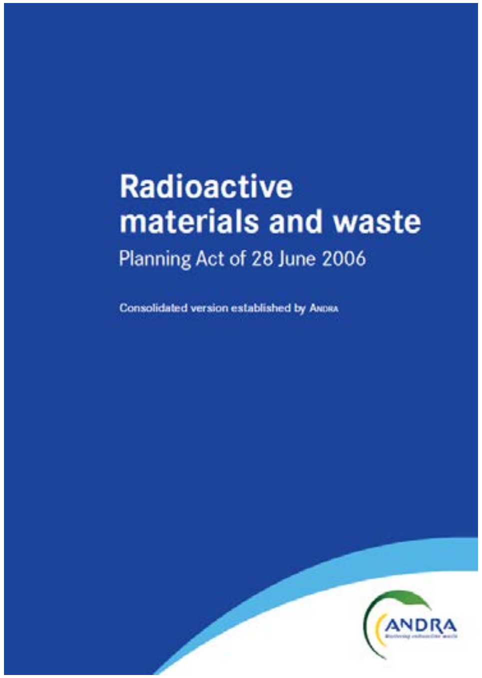
→ Increase neutron flux for SINQ



Incentives

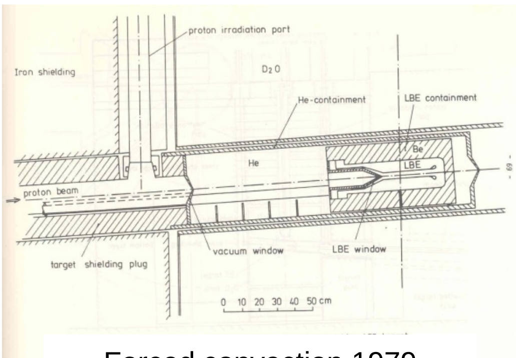
- National Programs on Partitioning and Transmutation of long-lived nuclear waste
- French Waste Management Research Act of 1991
- 15 years of research to develop sustainable nuclear waste management plan

□partitioning and transmutation of long-lived radioactive elements: the corresponding studies and investigations must be carried out in association with those conducted on the new generations of nuclear reactors and on the accelerator-driven reactors dedicated to the transmutation of waste, in order to provide an assessment of the industrial prospects of those systems by 2012 and to commission a pilot facility before 31 December 2020.

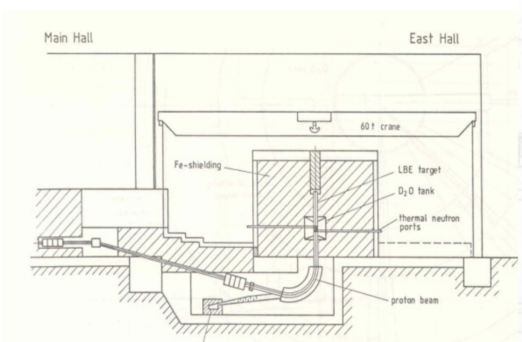


LM Spallation Target Concepts at PSI

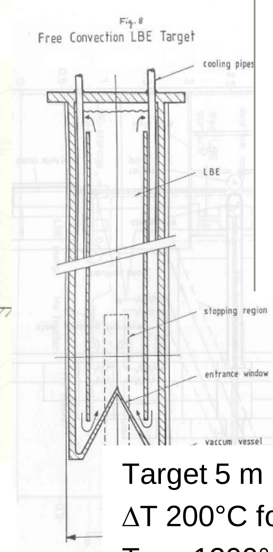
Tschalär 1979-1985



Forced convection 1979



Vertical beam concept



Free convection,1981

First inclined, then vertical

Target 5 m high

ΔT 200°C for 3.2 l/s

T_{max} 1200°C at beam start

28.5.1986

SIN — Schweizerisches Institut für Nuklearforschung CH-5234 Villigen

(Diese Unterlage darf nicht ohne Rücksprache mit dem Verfasser zitiert werden!)

Projekt SINQ

Klassifizierung: Basisdokument		Kurzzeichen:	PSP-Nr.: 8
Ersetz für:	Erstellungs-/Änderungsdatum: 28.5.1986	Doku-Nr.: SINQ/ 800/FIN/601	
Federf. Autor: Co-Autoren: Schweizerischer Bundesrat		Unterschrift Federf. Autor:	

Titel: Botschaft über Bauvorhaben der ETH und des SIN

Die SINQ besteht prinzipiell aus:
- einem Schwermetall-Target (Blei-Wismut-Gemisch),
- einem Moderator (schweres Wasser) und speziellen kalten Moderatoren (flüssiger Wasserstoff),
- einem massiven Abschirmungsring.

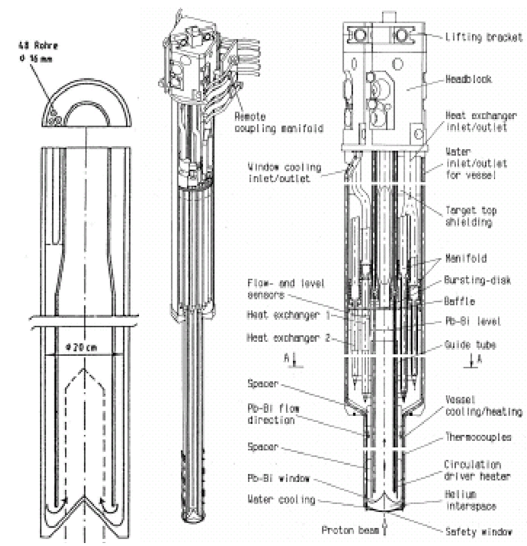
Zur Abfuhr der Wärme, die durch die Abbremsung des Protonenstrahls entsteht, wird die Naturkonvektion aus

Forschungsbetrieb

Verteiler: Projektleitung, Referatsverantwortliche, Leiter Funktionsbereich

Ersetz 86.

Datum: Visum FBV: Datum: Visum PL:



Natural convection with driver heater

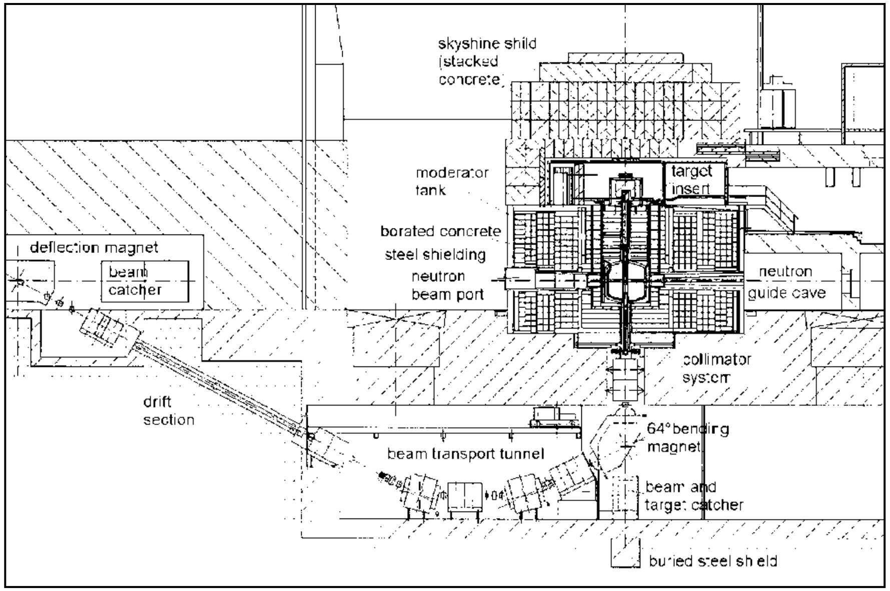
G. Bauer, 1990

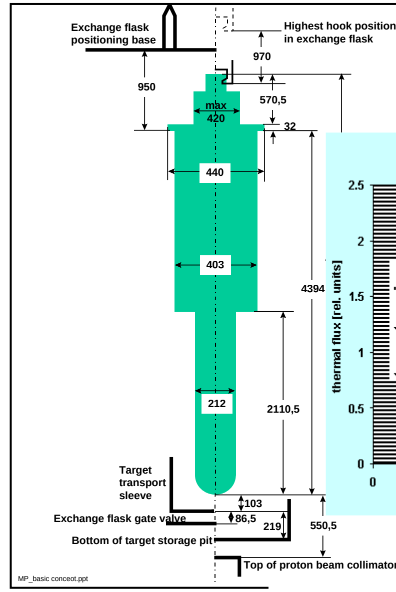
MEGAPIE Partnership

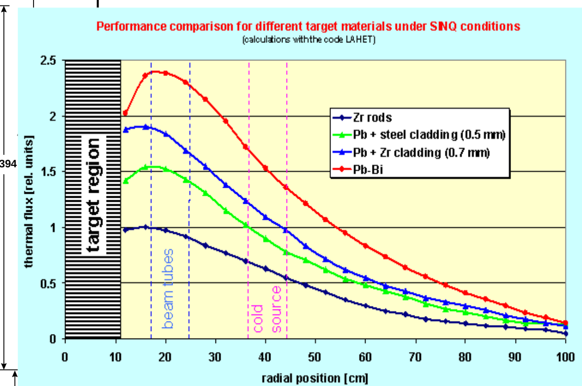
KAERI, JAERI and
DOE joined in 2002

Initiated by
G. Bauer/PSI
M. Salvatores/CEA
G. Heusener/KIT

Baseline phase (1999- early 2000)







Specify goals of the project
List boundary conditions
Define technical options
Identify R&D-needs
Outline operational procedures and
Define post irradiation examination
Identify requirements for final dispo

J. Nucl. Mat., Vol. 296 (2001) 17-33
IWSMT-4 (J. Nucl. Mat.)
and Proc. ICANS XV (JAERI-KEK report)

Beam power about 1 MW at 575MeV, 1.74 mA
Target is LBE (T_m=125C)
Design life of target about 1 year (6000 mAh)
Target dimensions have to comply with the
- Target Block in the SINQ
- Exchange Flask
- Target Storage Positions

Compatible with WCL
Re-implementation of solid target within 1 month
Incremental total project costs 10 MCH

MEGAPIE*, a 1 MW Pilot Experiment for a Liquid Metal Spallation Target

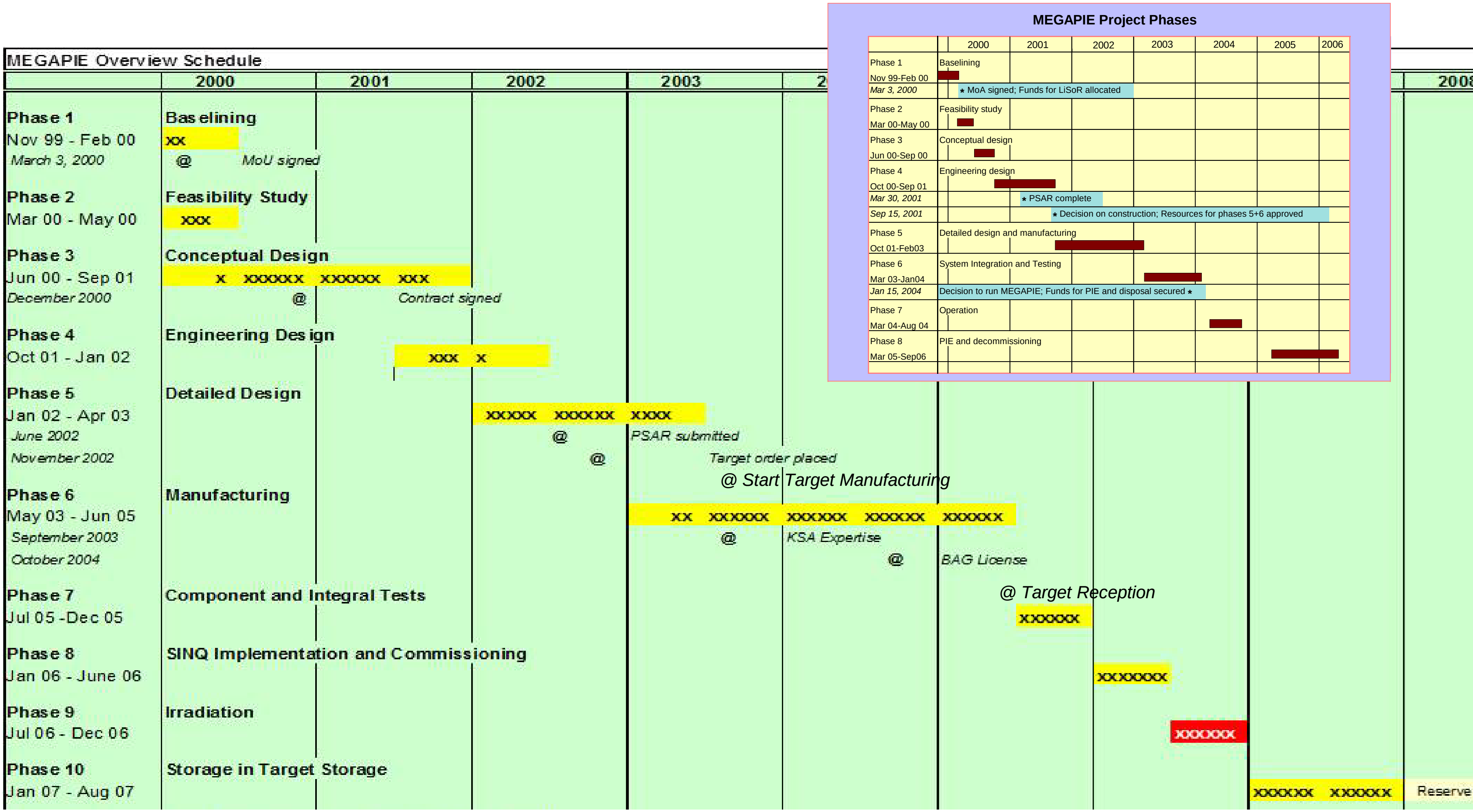
G.S. Bauer[1], M. Salvatores[2], and G. Heusener[3]

[1] Paul Scherrer Institut, Spallation Neutron Source Division, CH-5232 Villigen-PSI, Switzerland

[2] CEA Cadarache, Direction des Réacteurs Nucléaires, F-13108 Saint-Paul-lez-Durance Cedex France

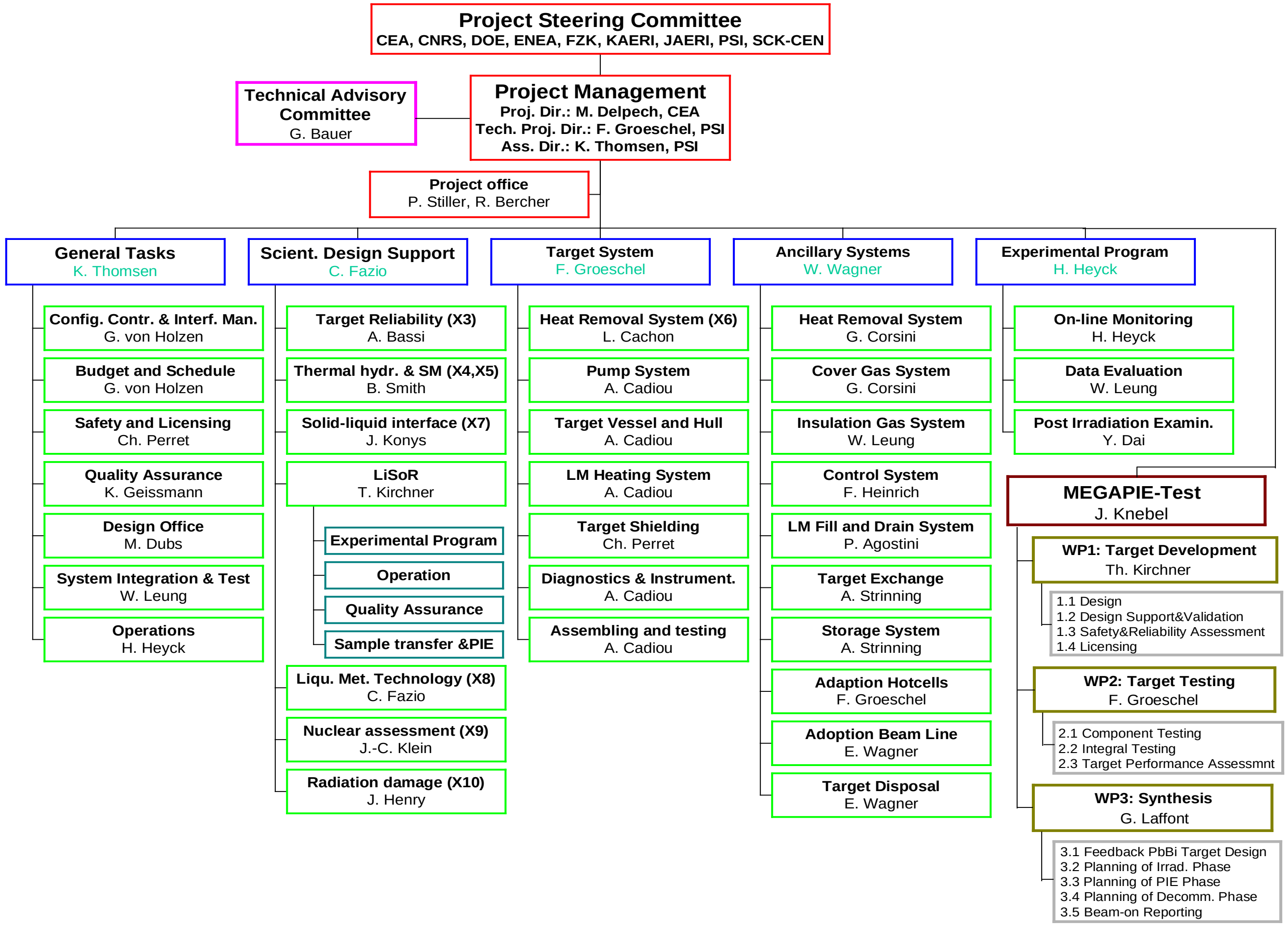
[3] Forschungszentrum Karlsruhe, Projekt Nukleare Sicherheitsforschung, D-76021 Karlsruhe Germany

MEGAPIE Project Phases (as of 2004)



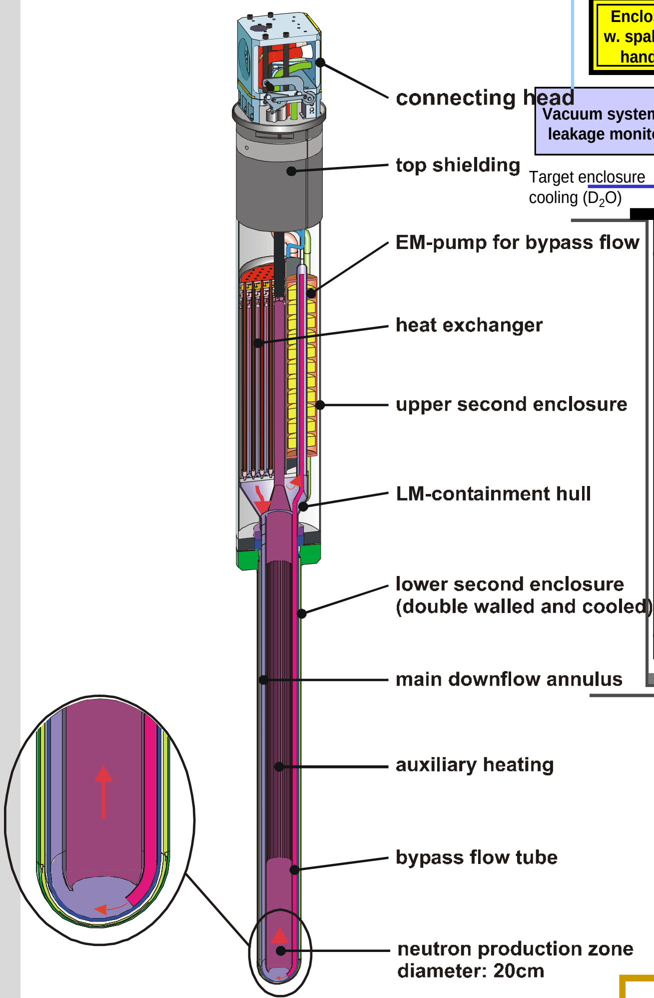
Consolidated Project Organisation

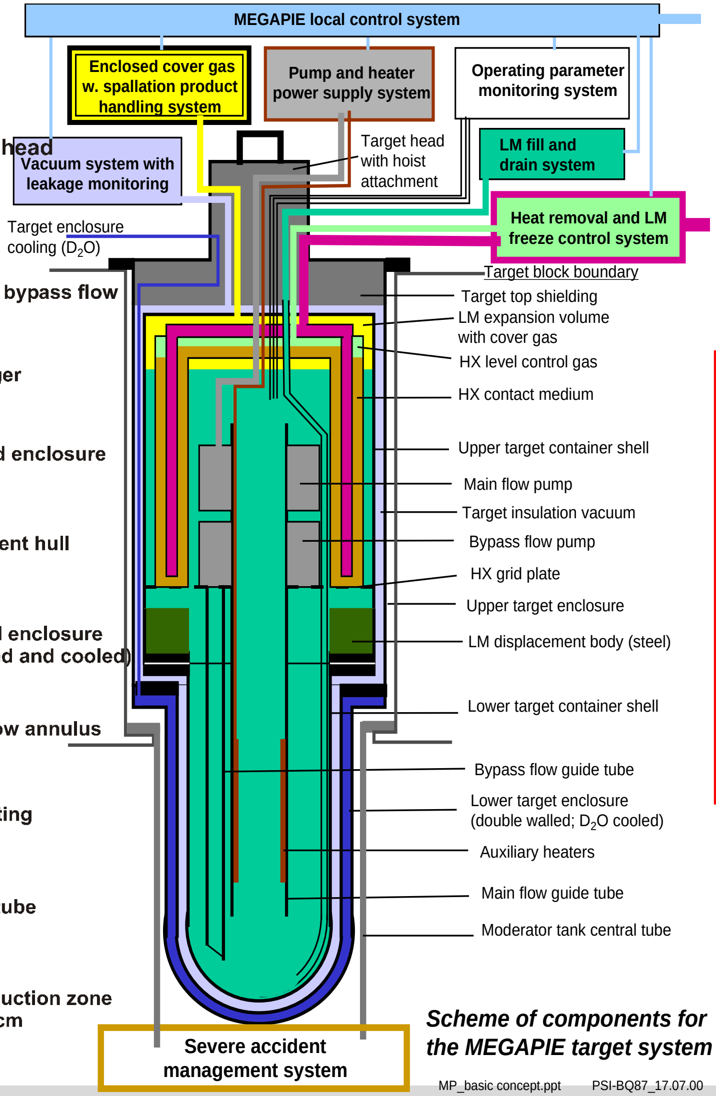
Design Phase



3/2002 updated in 2/2005 to focus on commissioning, testing and operation

Feasibility phase (- mid 2000)





Scheme of components for the MEGAPIE target system

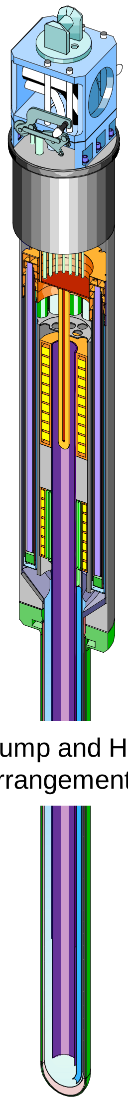
Refine technical options
Establish design data base
Analyse anticipated load levels
Identify problem areas
Perform scoping calculations
Verify cost and schedule plans
Identify requirements to ancillary systems

- Concept of main and bypass flow with two independent pumps favored with respect to mono-pump option
- EMP vs. mechanical pump
- LMC-Material: F/M vs. SS/Inconel 718
- LTE: AlMg3 vs. Zry

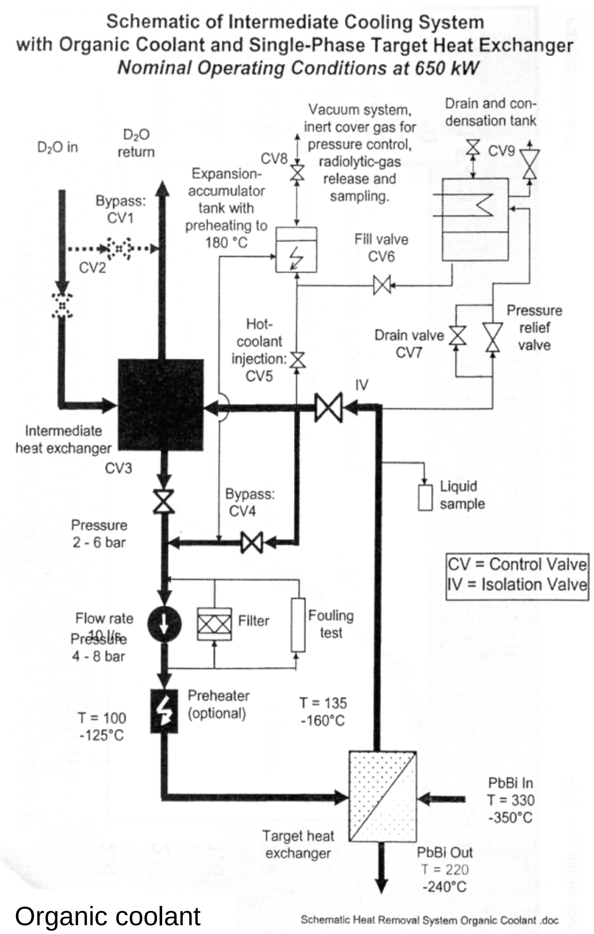
TRM in Cadarache (July 2000) completed the phase: The target is feasible

Conceptual Design phase (- Sep 2001)
Design Support

- Select reference technical design
- Select reference materials
- Define instrumentation and controls for operation
- Size individual components
- Verify compatibility of components' specifications
- Identify possible sources of failure
- Analyse consequences of individual components failure
- Outline design for ancillary systems

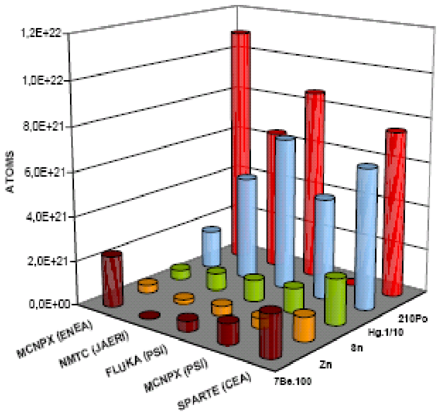


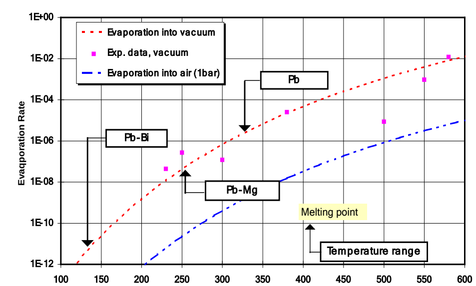
Pump and HEX arrangement



Organic coolant

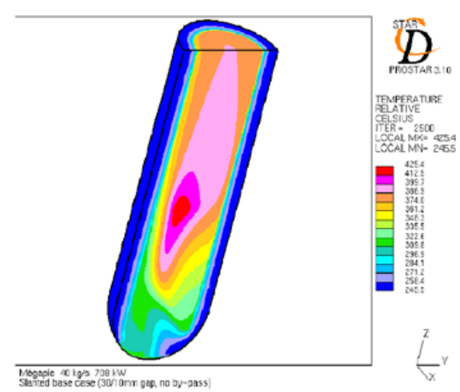
TRM at FZK in February 2001 launched
Design Support due to partnership established



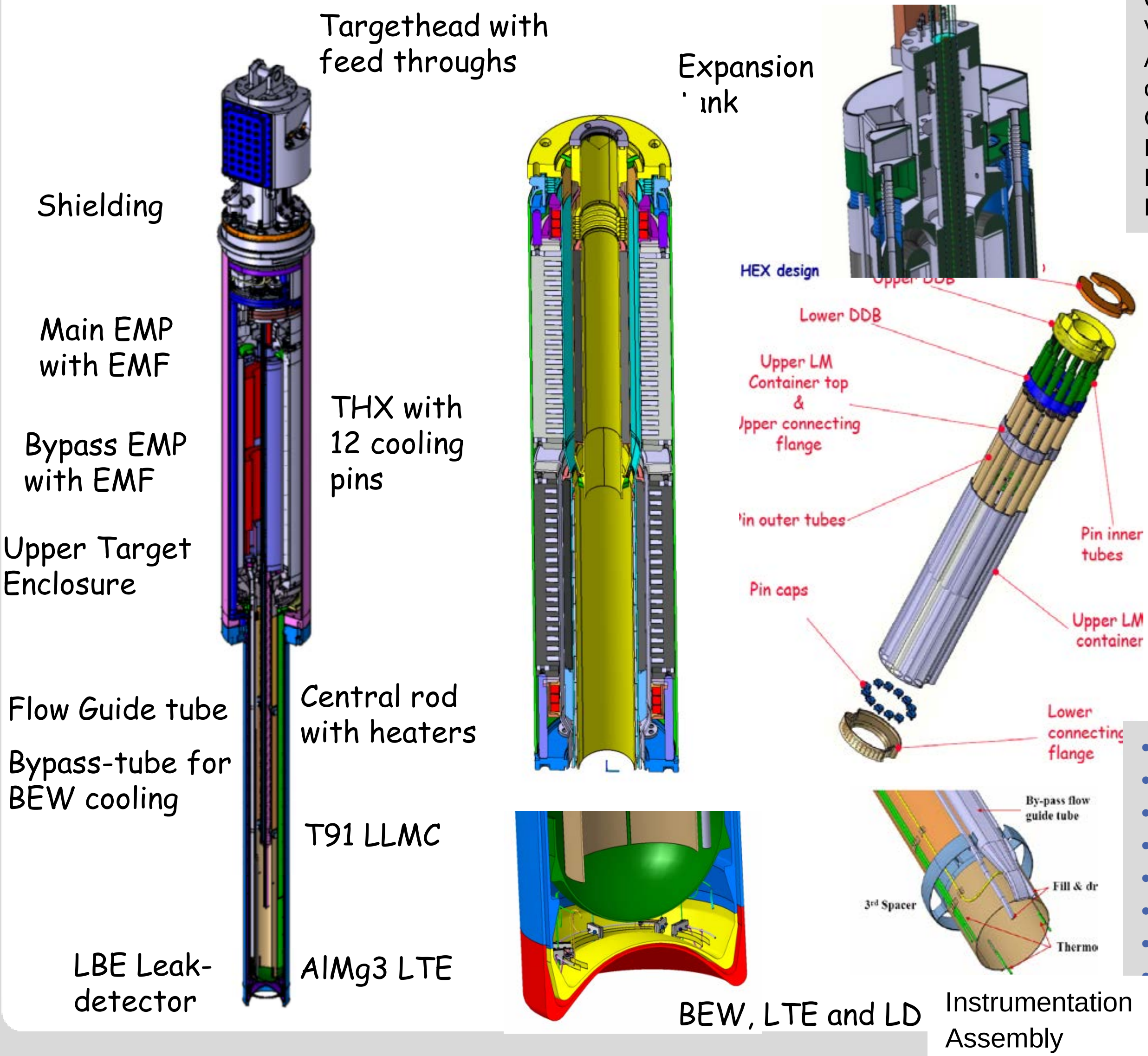


Spallation products and Po-release

CFD Benchmark experiments defined



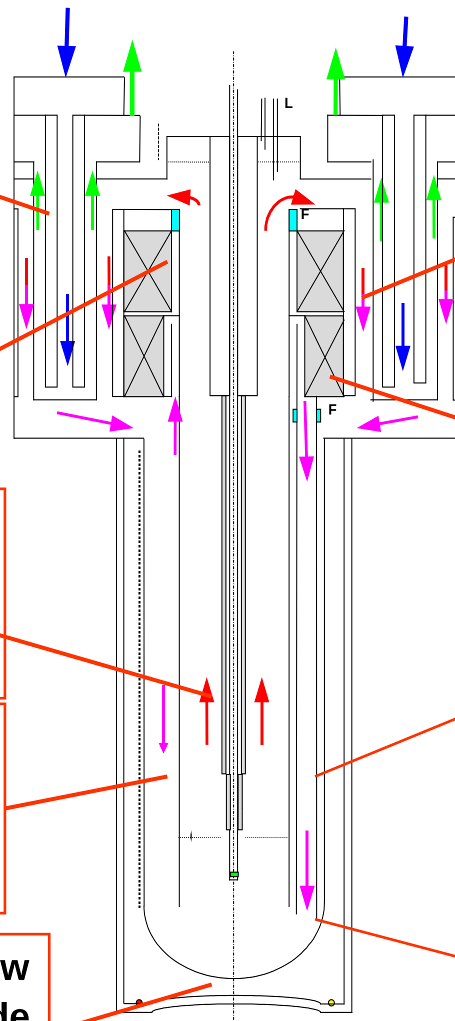
Engineering Design phase (-mid 2002)



Carry out detailed calculations to optimise system
Verify designs of all individual components
Analyse life expectancy and possible failure modes of components and system
Carry out overall safety and life time analysis
Design ancillary systems
Establish QA plan for manufacturing and testing
Produce final design report

- Double containment (LMC, LTE)
- LTE → AlMg3, concave sphere
- Central rod with neutron monitor (AISI 316)
- HEX → 12 AISI 316 single wall cooling pins
- EMP System → 2 Flowmeters
- Insulating Gas System (Ar → He))
- Cover Gas System (Absorbers, Overpressure)
- Instrumentation and Leak Detectors

Mass Flow and Temperatures



Heat Exchanger (Oil)
10 l/s, 5.5 m/s
140-175°C inside

Main Pump
4 l/s, 1.2 m/s
380°C

Guide Tube
4 l/s, 0.33 m/s
380°C

Downcomer
3.75 l/s, 0.33 m/s
230-240°C

Beam Window
380°C outside
330°C inside

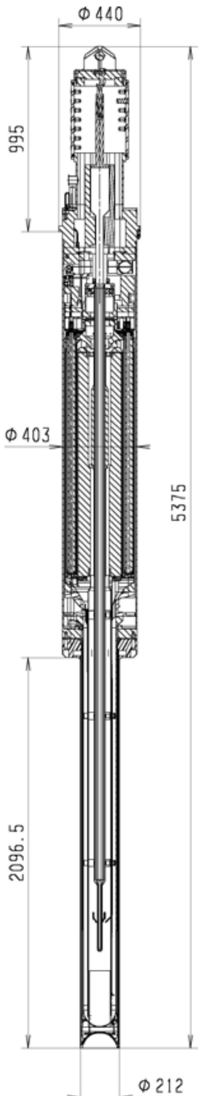
Heat Exchanger
4 l/s, 0.33 l/s/pin
0.46 m/s
LBE 380-230°C

Bypass Pump
0.25 l/s, 0.2 m/s
230°C

Bypass Tube
0.25 l/s, 1m/s
230-240°C

Nozzle 1.2 m/s
Beam Window 1 m/s

MEGAPIE Target Design



Dimensions

Length: 5.35.m Weight: 1.5 t
LBE volume: 82 l Gas Volume: 2 l
Wetted surface: 8 m^2
Design pressure: 16 bar Operating pressure:0-3.2 bar
Design Temperature: 400ºC Insulation Gas: <0.5 bar He

Materials

Lower Liquid Metal Container: T91
Upper Container: 316L
Lower Target Enclosure: AlMg3

Heat Removal and Beam Window Cooling

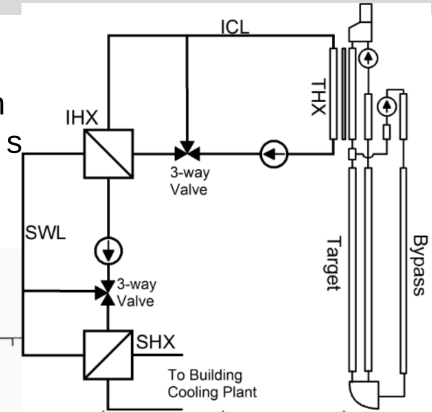
Deposited Heat: 650 kW
Forced convection assisted by buoyancy
Main pump: EM in-line pump (4l/sec)
Bypass pump: EM in-line pump (0.35l/sec)
LBE T range 240-380°C, max. flow rate ~1 m/s
Beam window T91 steel, T 330-380°C, 20-25 dpa

TRM Bologna, March 2002 marked nominal end of Engineering Design Phase for the Target to launch tendering

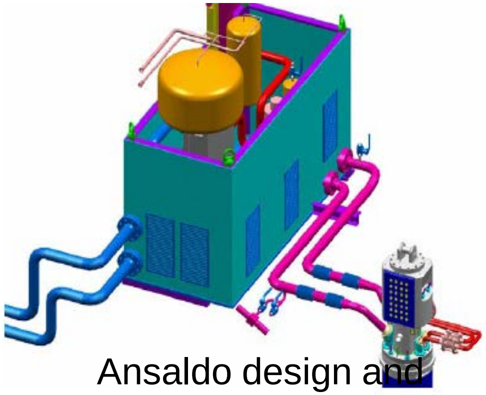
Order to ATEA in Nov 2002

Design of Heat Removal System

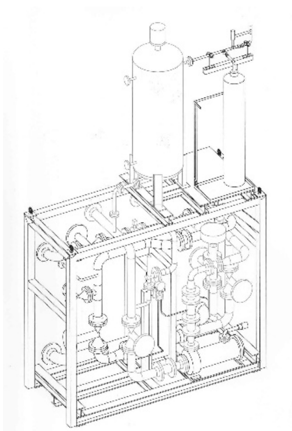
Ansaldo Nucleare
Relap5 Calculation
Beam trip 10 s+20 s
ramp



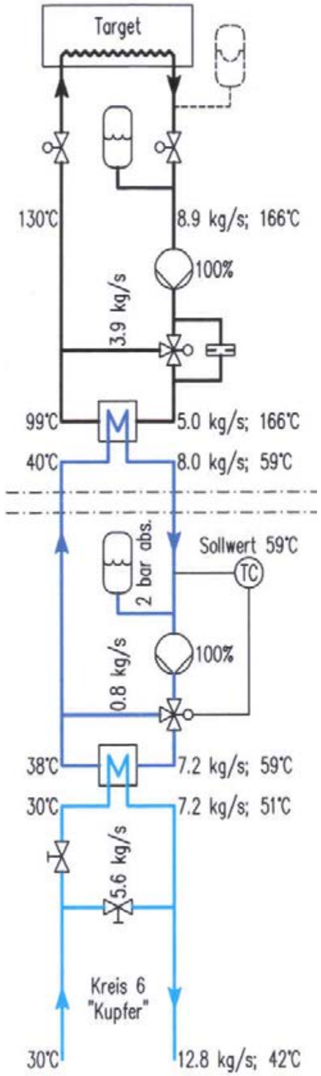
Diphyl THT
Contract to Ansaldo

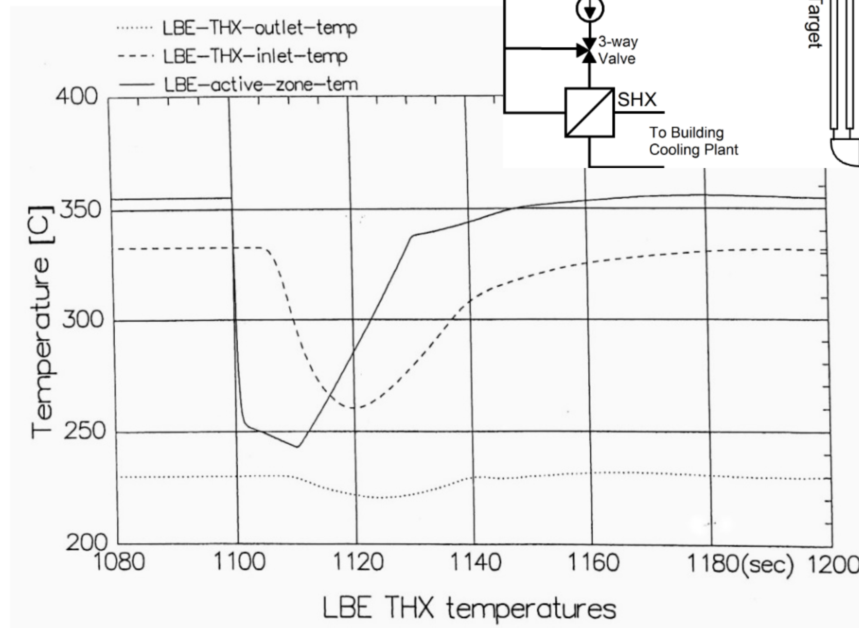


Ansaldo design and
Relap5 calculations



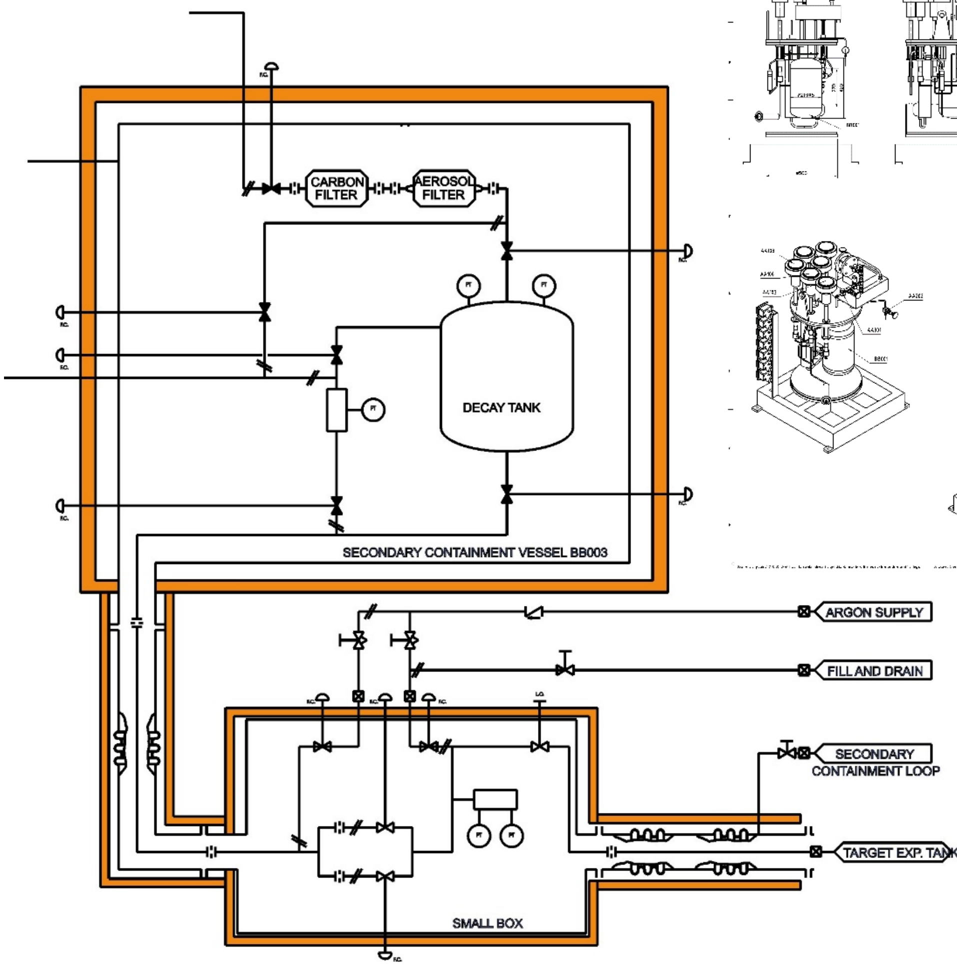
PSI design of
intermediate water loop

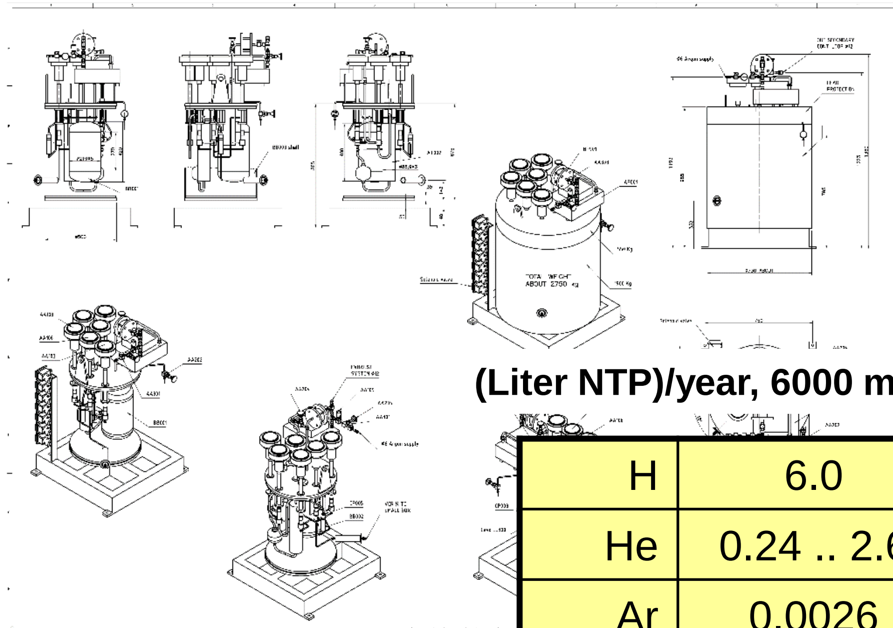




	LBE THX	THT IHX	H2O IHX
Inlet	330 C	165 C	40 C
Outlet	230 C	130 C	59 C
Flow Rate	9.28 kg/s	THT Velocity	3.5 m/s
Pump Head	12 m	THT P drop	626 kPa

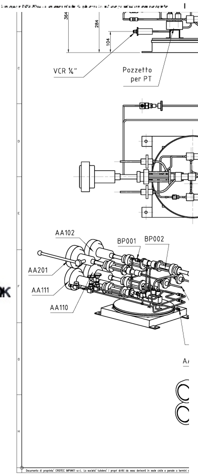
Design of the Cover Gas System

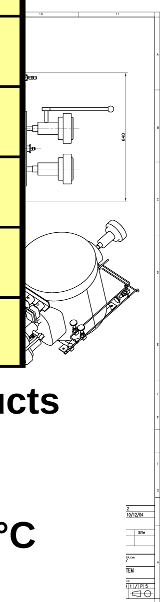




(Liter NTP)/year, 6000 mAh

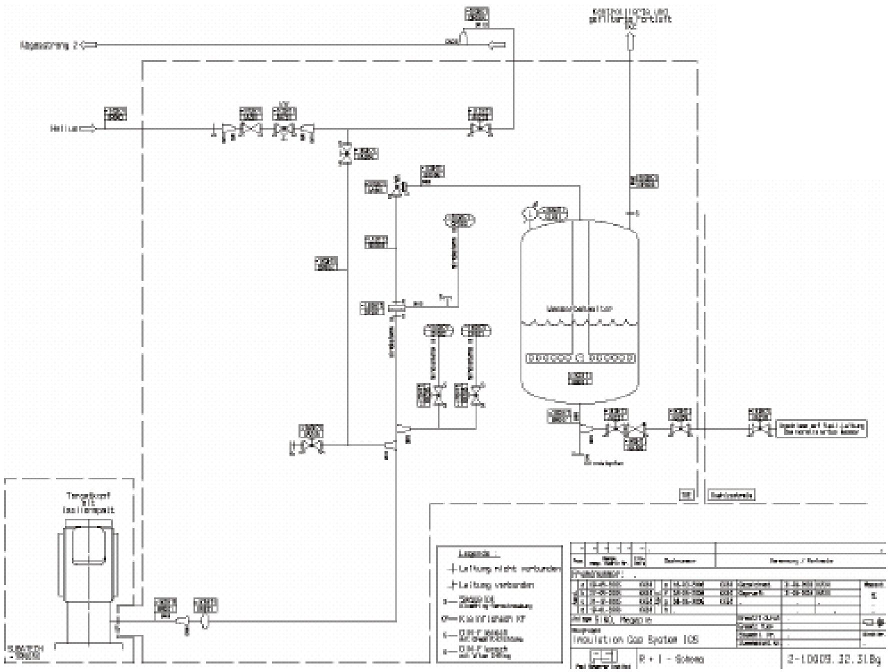
H	6.0
He	0.24 .. 2.6
Ar	0.0026
Kr	0.06
Xe	0.024
Total	6.3 ... 8.7



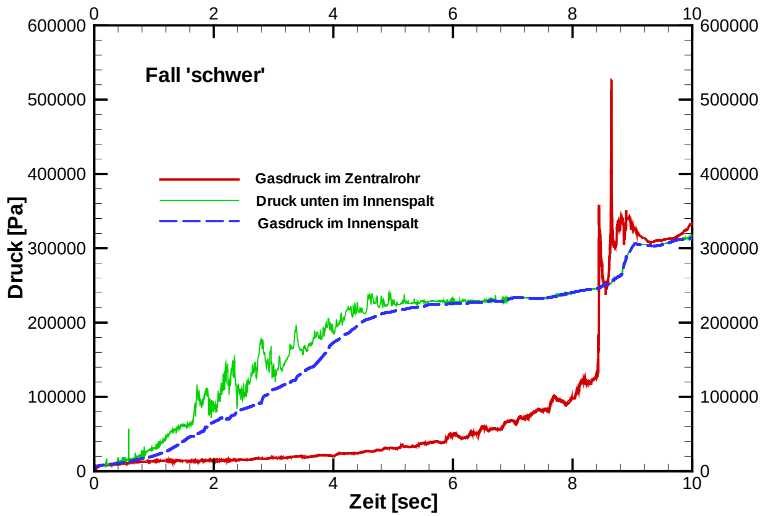


Absorption of volatile products
Pd/Ag + Hg → Pd/AgHg
$CuO + H_2 \rightarrow Cu + H_2O$
$CaO + H_2O \rightarrow Ca(OH)_2$ 140°C
was discarded in favour of venting

Design of the Insulation Gas System



21.3 l of D2O fill the Isolation Gas Space instantaneously and evaporate thereafter

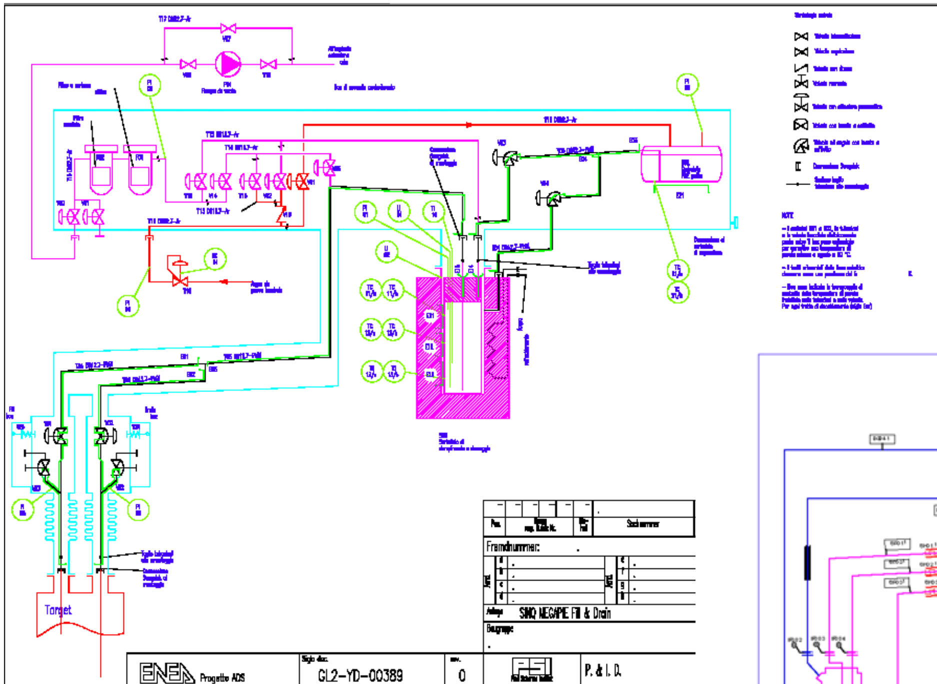


Design Base Accidents

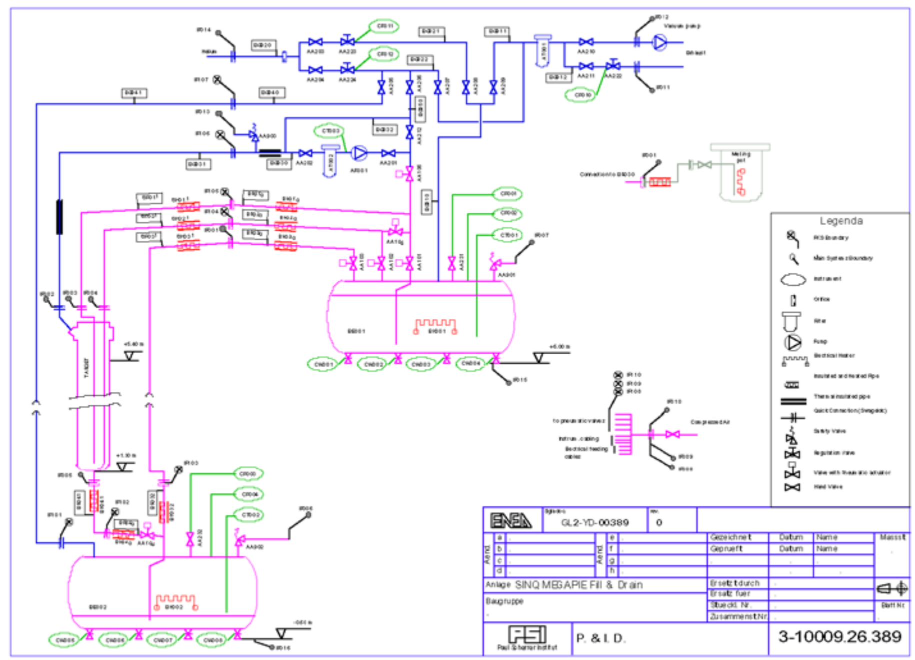
- Water ingress into insulation gap
- Rupture disc, steam condensor
- CFD/FEM, No failure of LMC due to thermal shock

Design of the Fill and Drain System

Karlsruhe Institute of Technology



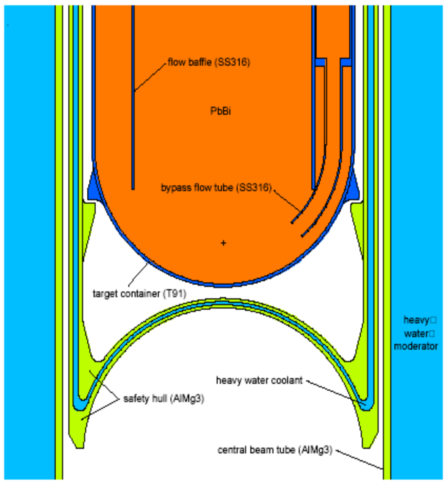
Baseline layout for active draining (ENEA):

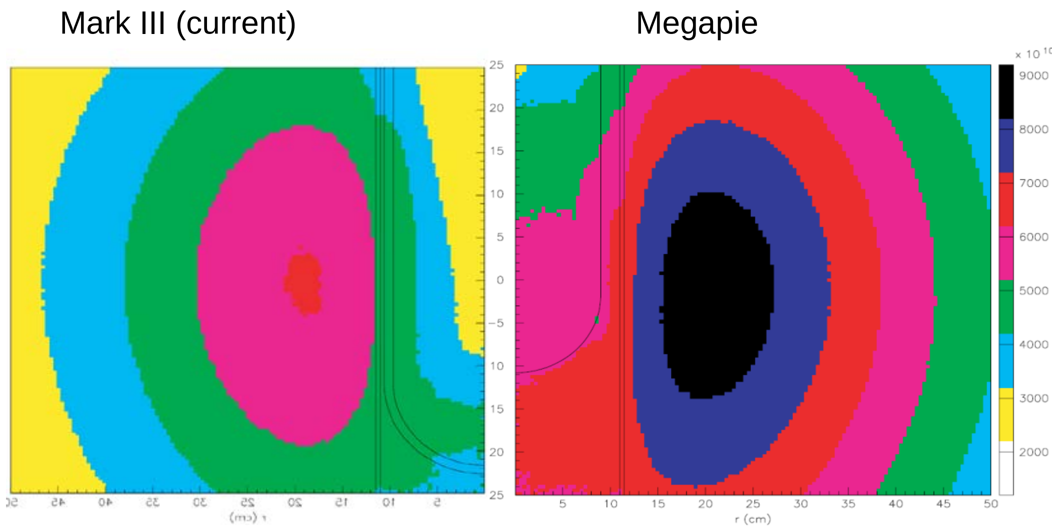


Simplified concept for only in-active draining

→ LBE Freezing challenge

Design Support - Neutronics
MEGAPIE Neutron Flux compared to solid targets





Thermal (E < 0.625 eV) neutron flux maps (neutrons/cm^2/s/mA)

Peak flux
1.8-2 E14 total neutrons
1.2-1.3E14 thermal neutrons
at 1.74 mA

	Pb/steel	LBE
Total	**7.62**	**10.99**
Target Int.	**- 0.113**	**- 0.232**
Cladding	**- 1.01**	**- 0.635**
D2O	**- 0.044**	**- 0.401**
Container	**-0.248**	**- 1.23**
Net	**6.17**	**8.49**

Increase of >40% compared to current solid lead target

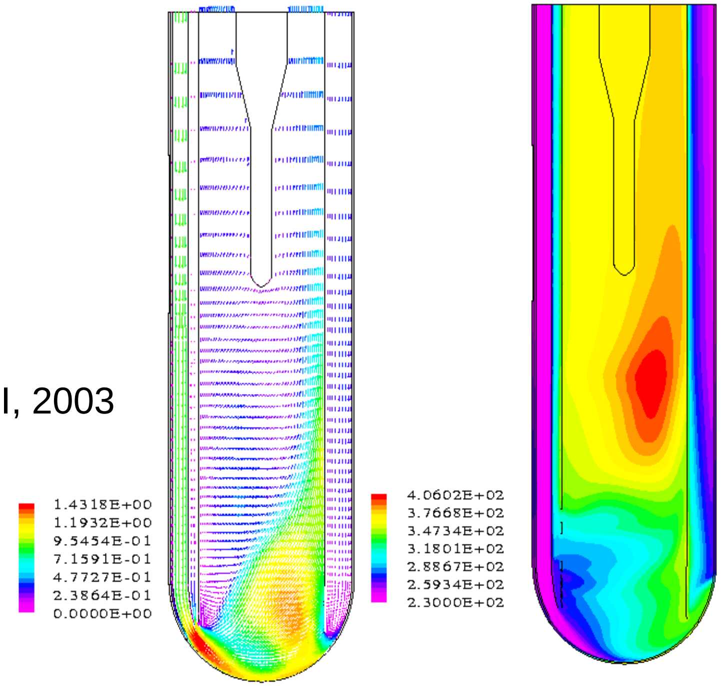
Design Support - Thermalhydraulics

Power deposition, Flow structure and Temperature

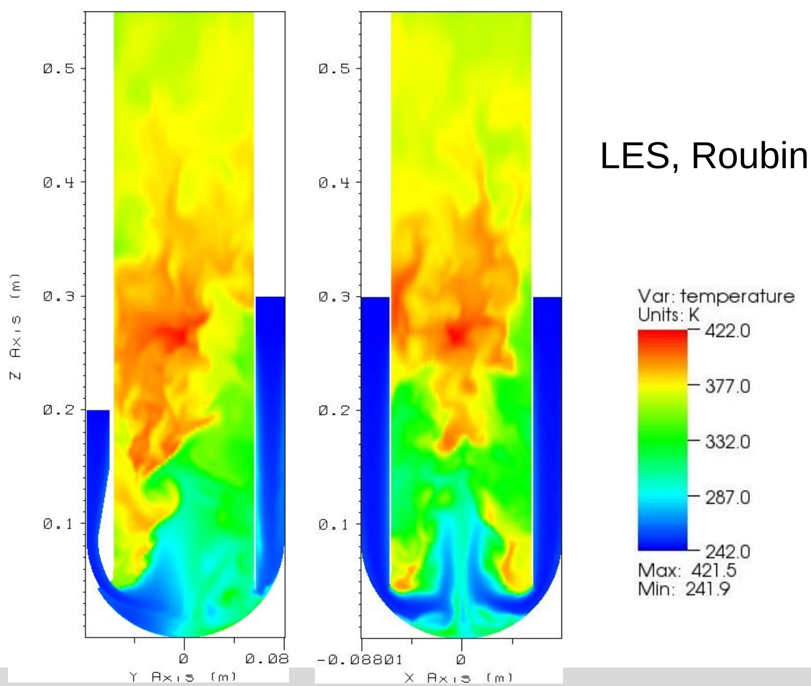
Material	FLUKA [kW]	CFX-4.3 [kW]
LBE	705.8	709.9
Window	5.56	5.28
T91 Hull	2.68	1.21
Guide tube	5.55	6.03
Total	719.6	722.4

1.74 mA

T. Dury, PSI, 2003

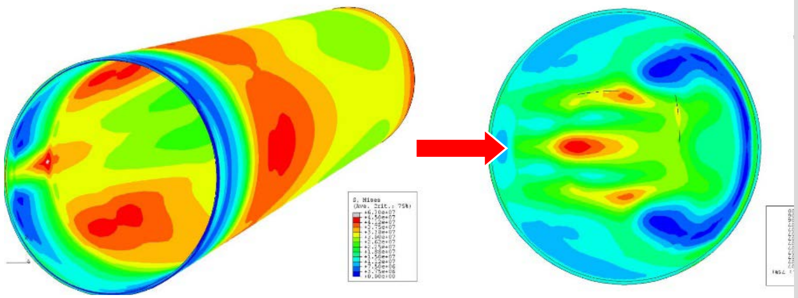


LES, Roubin, CEA



		T_{peak} [C]			
Beam	Maj. Axis	LBE	Guide T.	C. Rod	Window
1.74 mA	= Bypass	422.7	368.2	386.8	370.2
	⊥ Bypass	424.1	363.1	389.5	360.3
1.4 mA	= Bypass	384.4	339.4	355.7	342.5

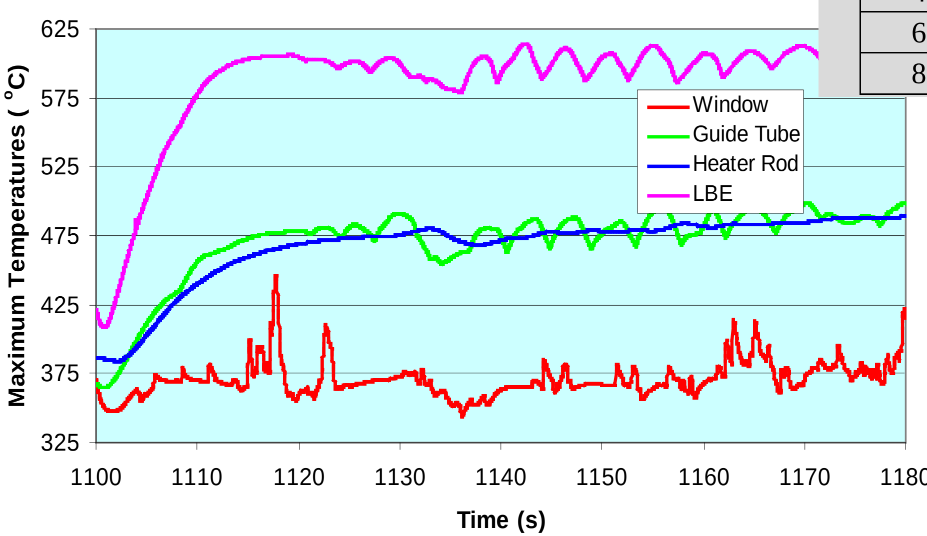
Design Support
Stress Analysis in Beam window and guide tube

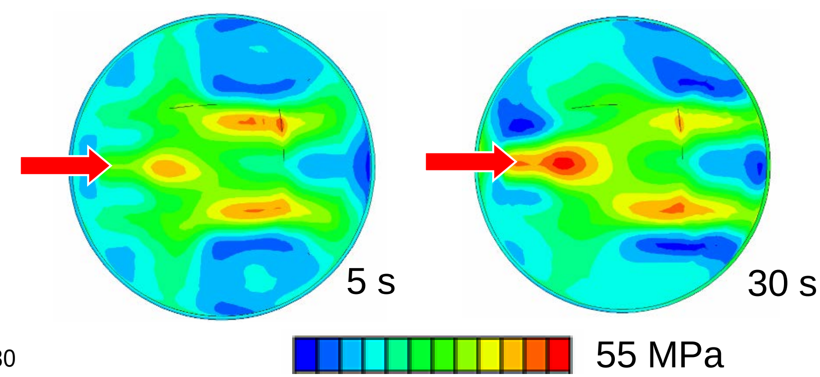


63 MPa **Steady State** 55 MPa

Time (s)	Max. Mises Stress (MPa)		
	Guide tube	Window	Target vessel
0	49.1	44.6	44.6
1	57.5	47.5	47.5
2	54.2	43.9	43.9
3	59.0	43.2	43.2
4	65.0	43.0	43.0
5	70.8	47.1	47.1
10	118.8	41.6	41.6
15	149.1	44.8	61.7
20	163.0	45.1	89.7
30	180.9	46.4	55.4
40	140.0	44.3	53.0
60	155.1	45.3	45.3
80	175.5	47.8	60.2

Main Flow Trip

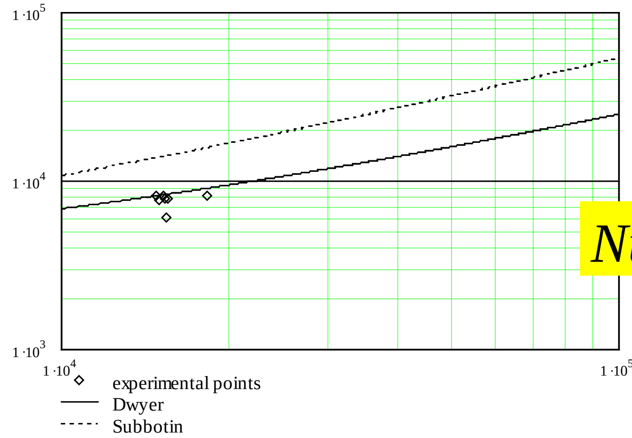




55 MPa

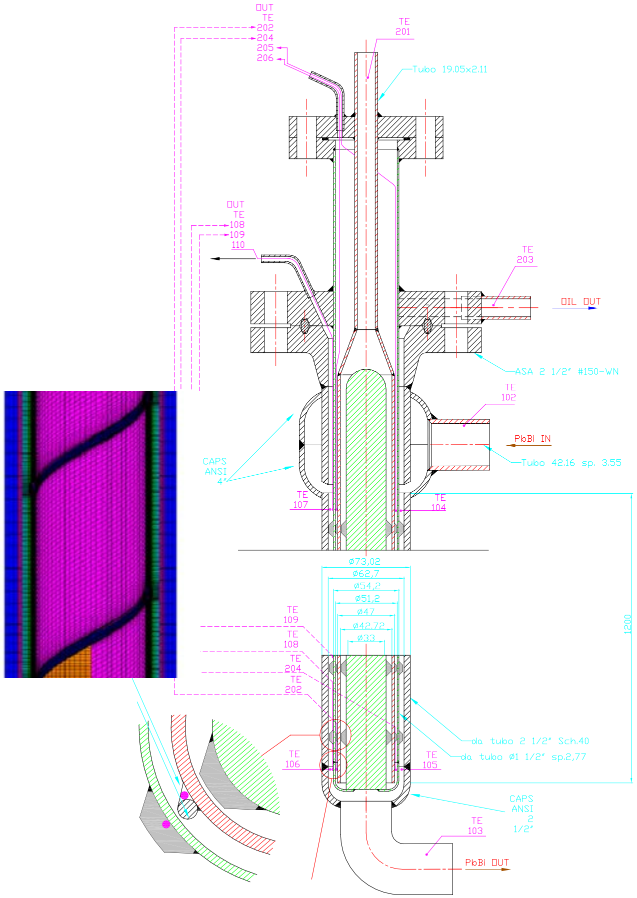
A. Zucchini, ENEA

Design Support – Experimental Validation
Single Pin Test



$$Nu = 5.59 + 0.0162 Pe^{0.76}$$

Dwyer LBE side



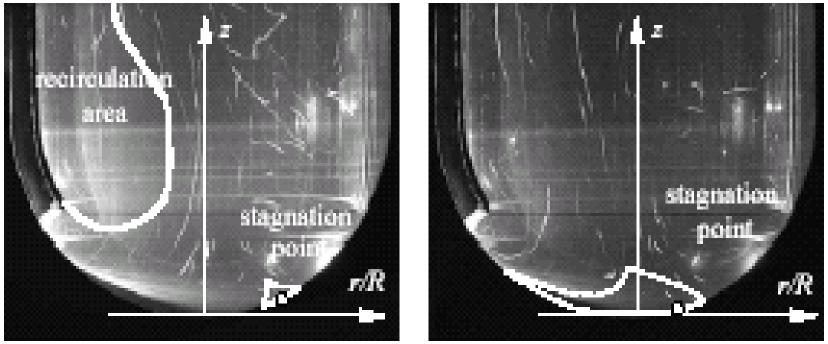
	E1			E2		
	experim.	unmodified Relap	modified Relap	experim.	unmodified Relap	modified Relap
Power [W]	27430			21590		
Oil inlet T [K]	410.15			409.35		
Oil outlet T [K]	436.65	436.90	436.90	430.25	430.79	430.8
LBE inlet T [K]	579.05	592.31	579.94	537.25	550.82	535.33
LBE outlet T [K]	455.95	473.19	461.38	445.85	462.64	447.71
H global W/(m²K)]	1790.04	1407.2	1596.68	1831.14	1368.57	1714.52
Percent error		21.4%	10.8%		25.3%	6.4%

- Spiralling increased oil side heat exchange by 80%
- Relap5 was modified

Design Support

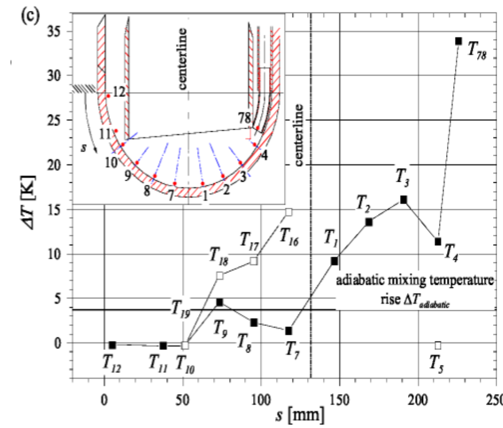
Experimental Validation of Window Cooling

15 Q_{main}/Q_{bypass} 10



HYTAS Water Experiment, FZK

LBE Heated Jet Experiment, FZK

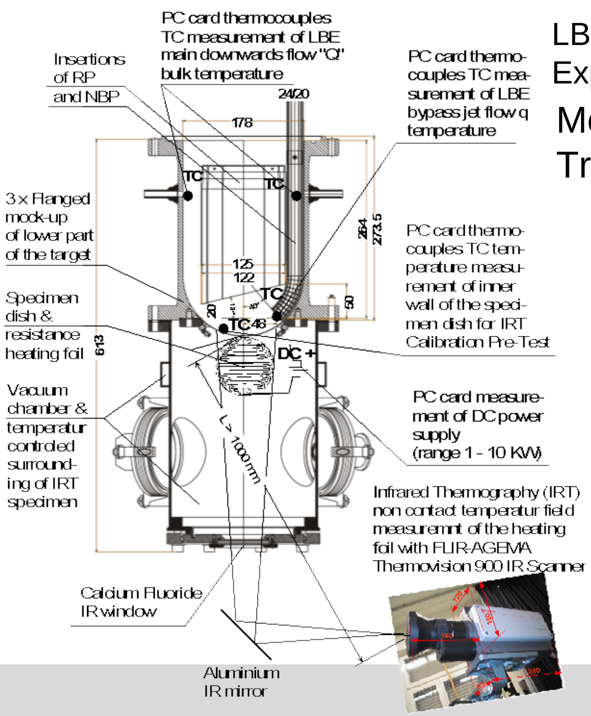


Recommendation to change flow rates to:

Q_{main} = 37.0 kg/s; Q_{bypass}= 3.0 kg/s

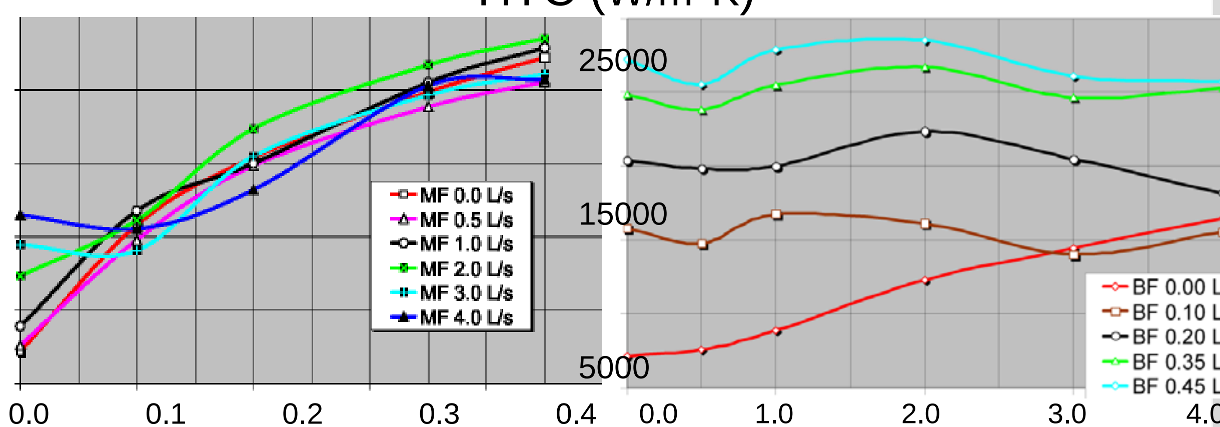
for which stable flow conditions were observed

LBE KILOPIE Experiment, PSI-FZK



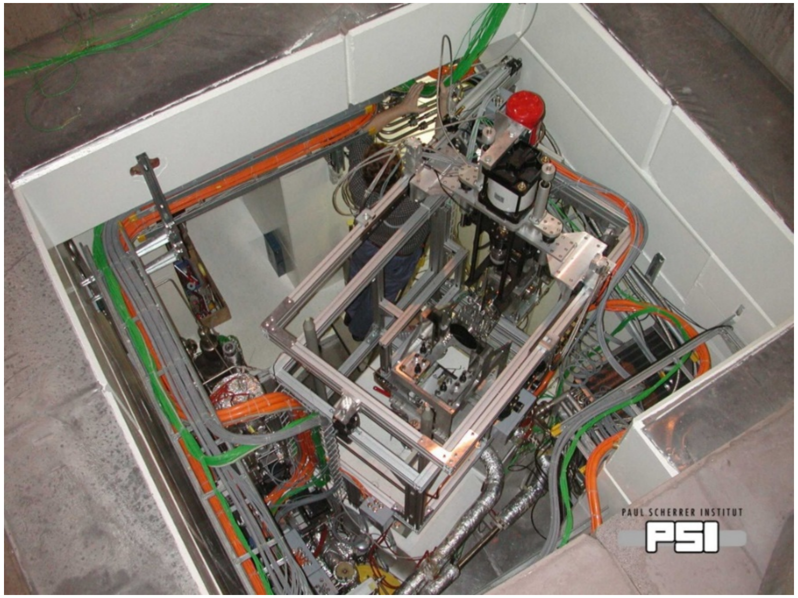
Measurement of the Heat Transfer Coefficients (HTC)

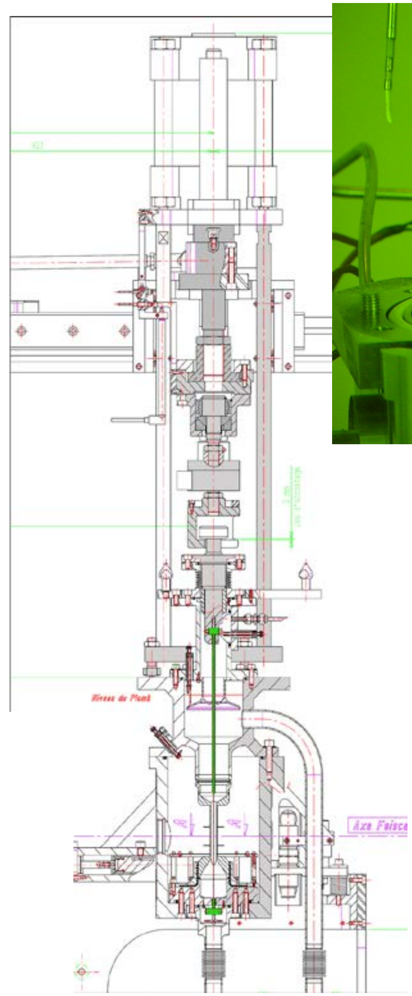
HTC (W/m^2K)

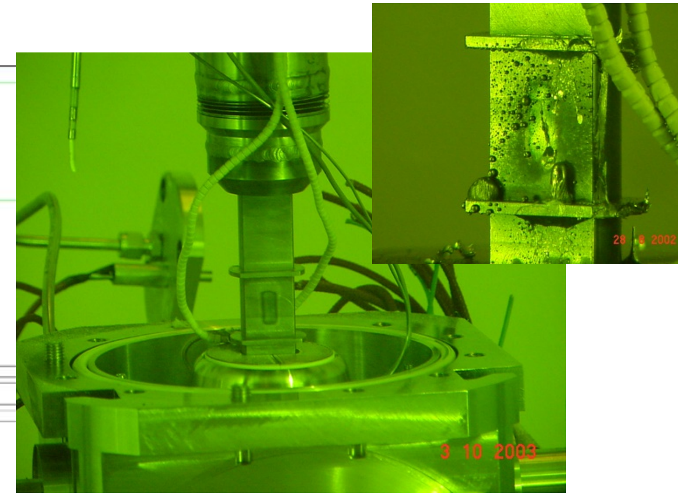


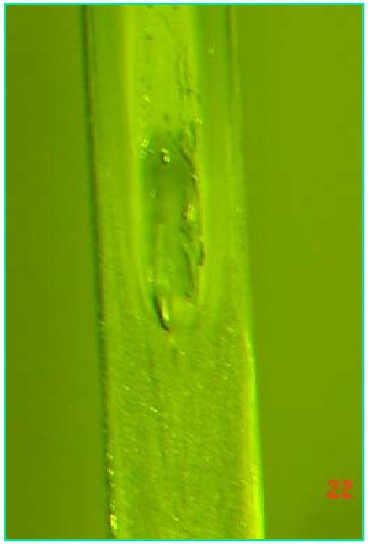
Design Support – LISOR Experiment

Material Behaviour under Irradiation



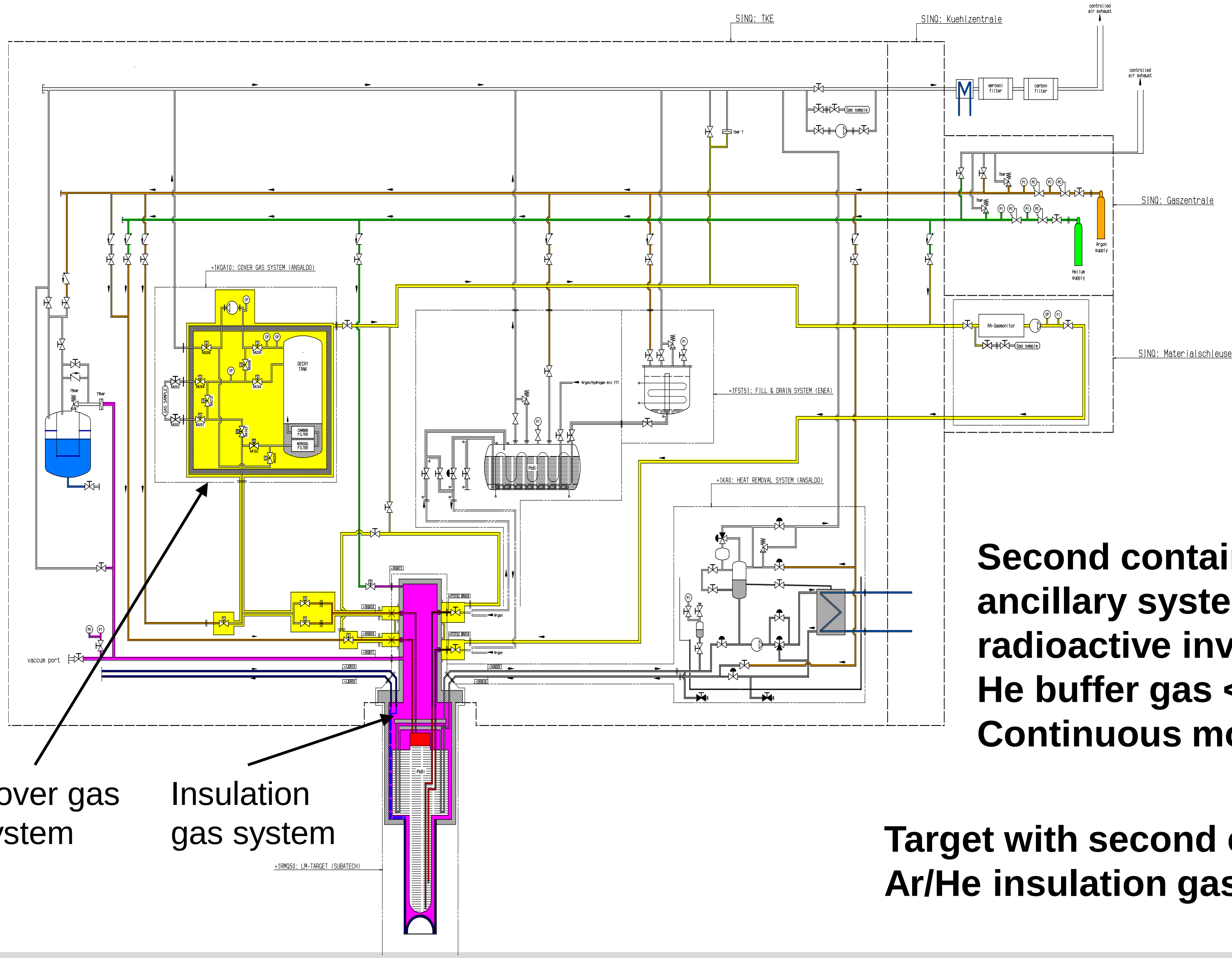






Beam energy-72MeV
Max current-50 μA
Max proton flux- $3.1x10^{14}$ $p/cm^2/s$
Beam time per test-10, 20, 40 days
Radiation damage- ~ 0.5, ~1, ~2 dpa

Integration of Ancillary System
Second Containment



Cover gas system

Insulation gas system

Second containment for ancillary systems with radioactive inventory.
He buffer gas < 0.9 bar
Continuous monitoring

Target with second enclosure
Ar/He insulation gas <0.5 bar

Safety

Reference Accident Case

MEGAPIE-TEST

CONTRACT N° FIKW-CT-2001-00159 MEGAPIE - TEST

DELIVERABLE D11

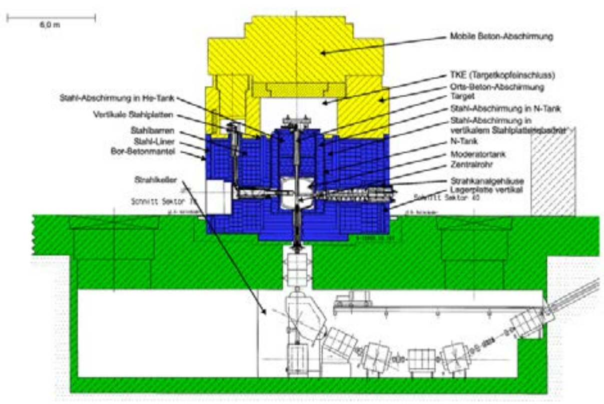
MEGAPIE

Preliminary Safety Assessment Report

Ch. Perret

Paul Scherrer Institut

April 2004

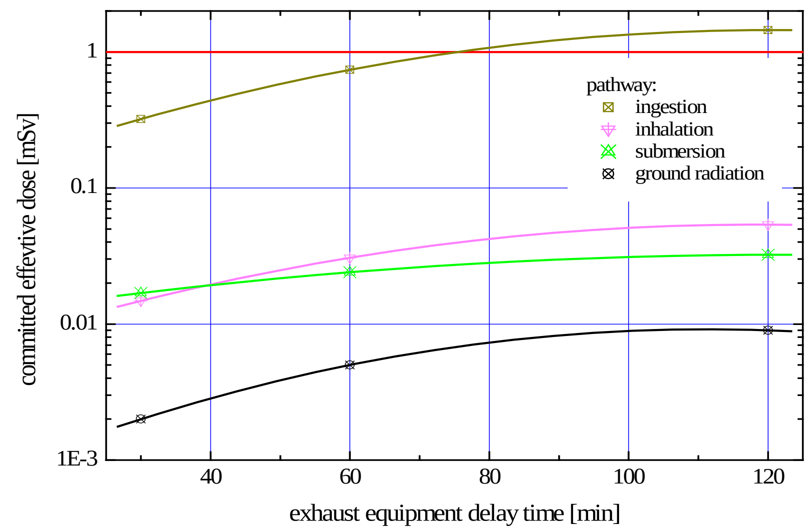


Examples of dose conversion factors [Sv/Bq]:

- ingestion of ^{210}Po: 3E-11
- inhalation of ^{209}Po: 6E-13
- submersion due ^{121}Xe: 4E-18
- ground radiation due ^{125}I: 2E-16

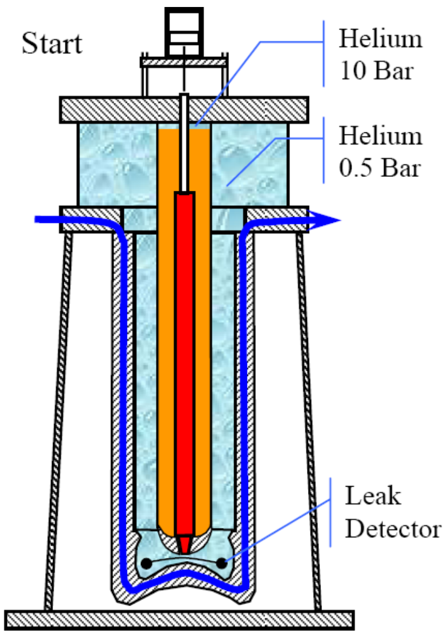
KSA expertise postulated all-embracing reference reference accident case - endorsed by BAG (60.M48)

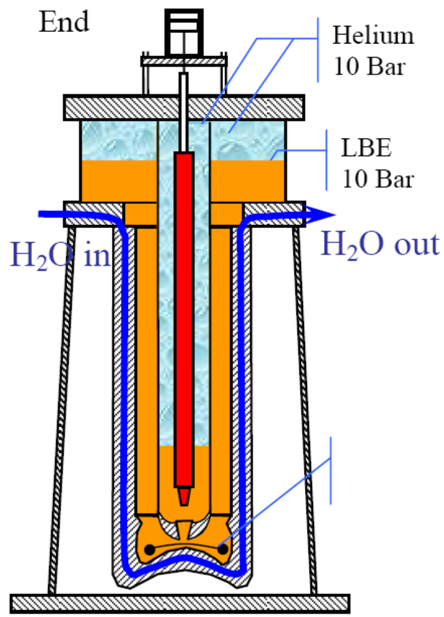
1. Beam window breaks
2. LBE causes breach of LTE
3. LBE-water interaction pressure built-up, destruction of central tube, leak of moderator tank (5m^3)
4. LBE and D_2O spill into STK
5. Damage of target head, spill of Diphyl THT oil, ignition in contact with hot LBE
6. Release path STK → TKE via damaged target

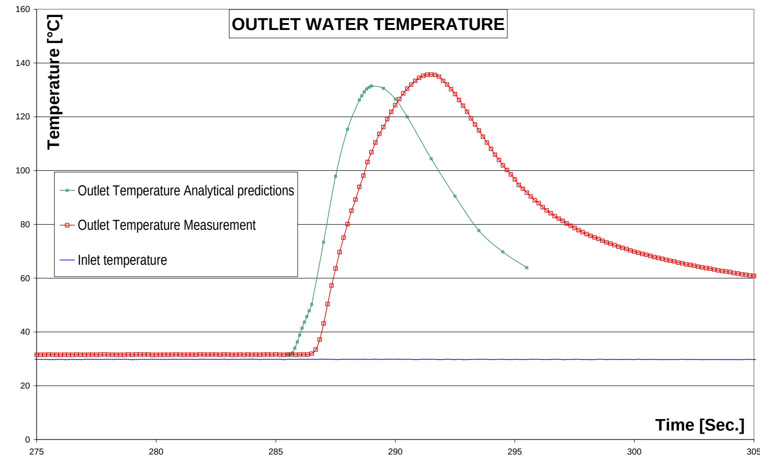


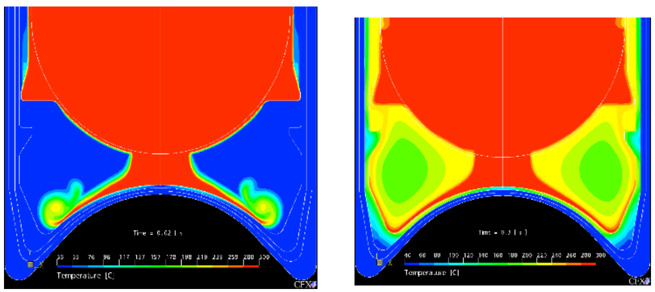
Safety

Full Scale LBE Leak Test







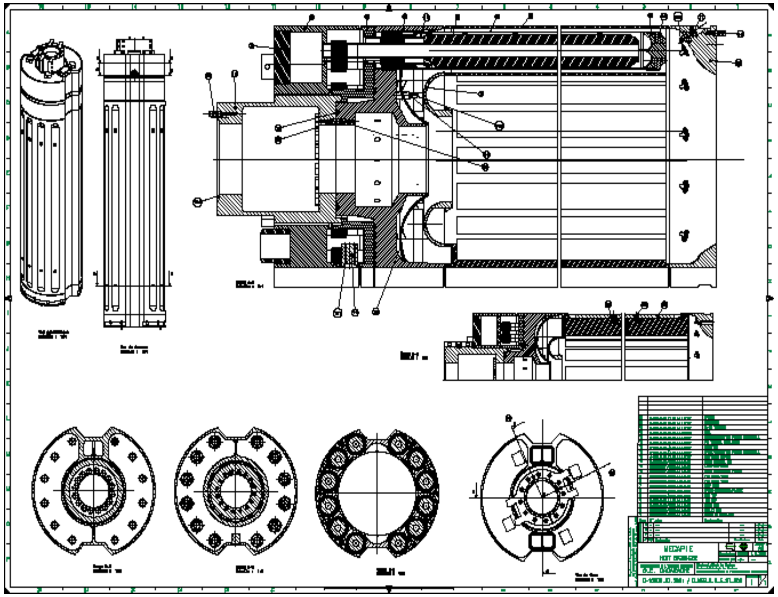


LBE: in target at 300°C
H_2O: 2.2ltr/s, 40°C, 6 bar
CG pressure 10 bar
He gap pressure 0.5 bar
Orifice diameter 30mm
LBE jet speed 12 m/s

LBE fills space between target and safety hulls
Press.-equalisation ~ 10s
Inlet H_2O temp. ~ 30°C
Peak H_2O temp. ~ 135°C
Time to peak ~ 5s

Conclusions for Megapie in SINQ:
ΔT (D_2O) ~ 105°C T_{max} ~ 145°C
T_{sat} ~ 160°C ε_{max} ~ 0.6%
Some plastic straining occurs…but test demonstrates that leak is contained, without boiling of safety-hull coolant, but the margin (15°C) is narrow

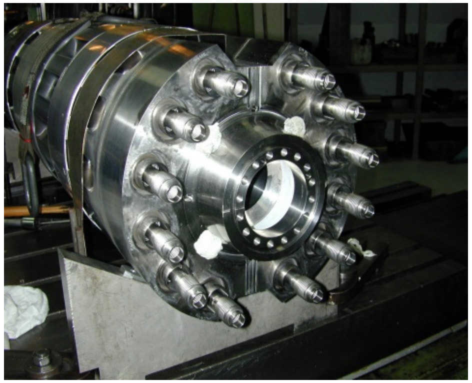
Detailed Design and Manufacturing

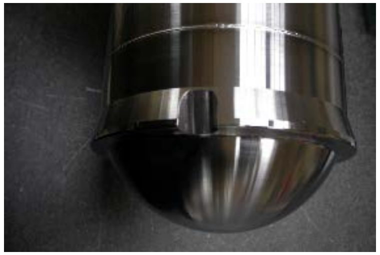


Produce drawings of individual parts for manufacturing
Procure and quality control individual parts of subsystems
Assemble and factory test subsystems
Provide test rigs and equipment

Quality assurance rules

- Nuclear standard :
  - Quality Assurance Program (QAP)
  - Quality Plans (QP)
  - Manuf & Inspec Plans (MIP)
  - COFREND Personal Qualification
  - Document Handling (Approval)
  - Design Changes Handling (DCR)
  - Non Conformances Handling (NCR)





Factory Assembly and Acceptance Tests

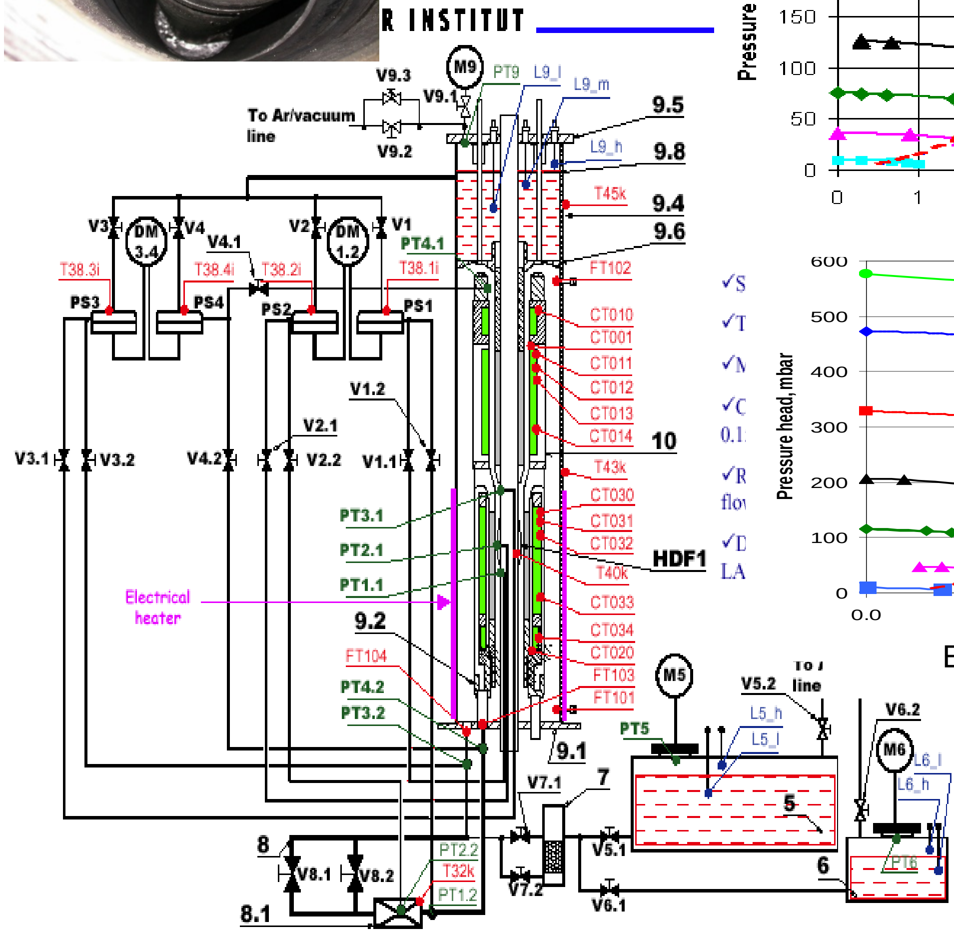
Delivery June 2005

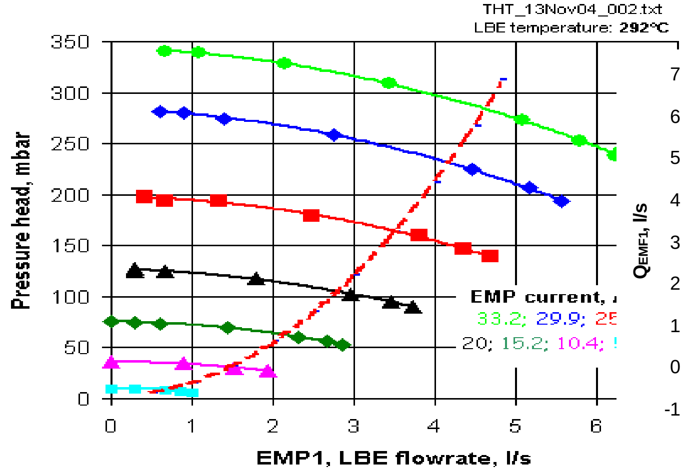
Synthesis reports and Documentation as build

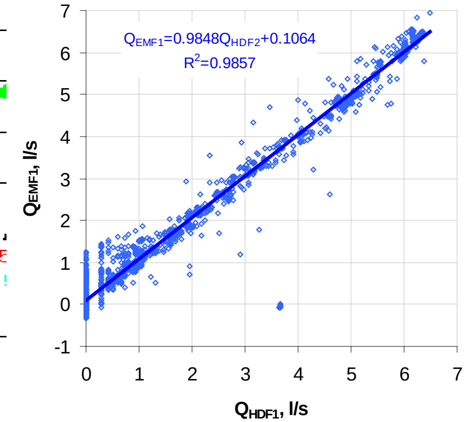
TRM Mol, June 2005
Ready for testing

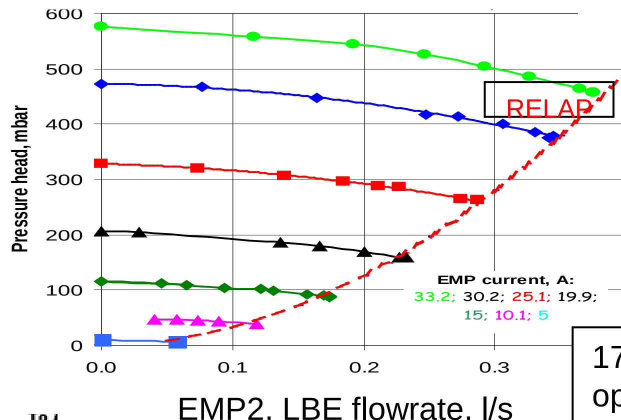
Component Testing

EMP test stand at IPUL





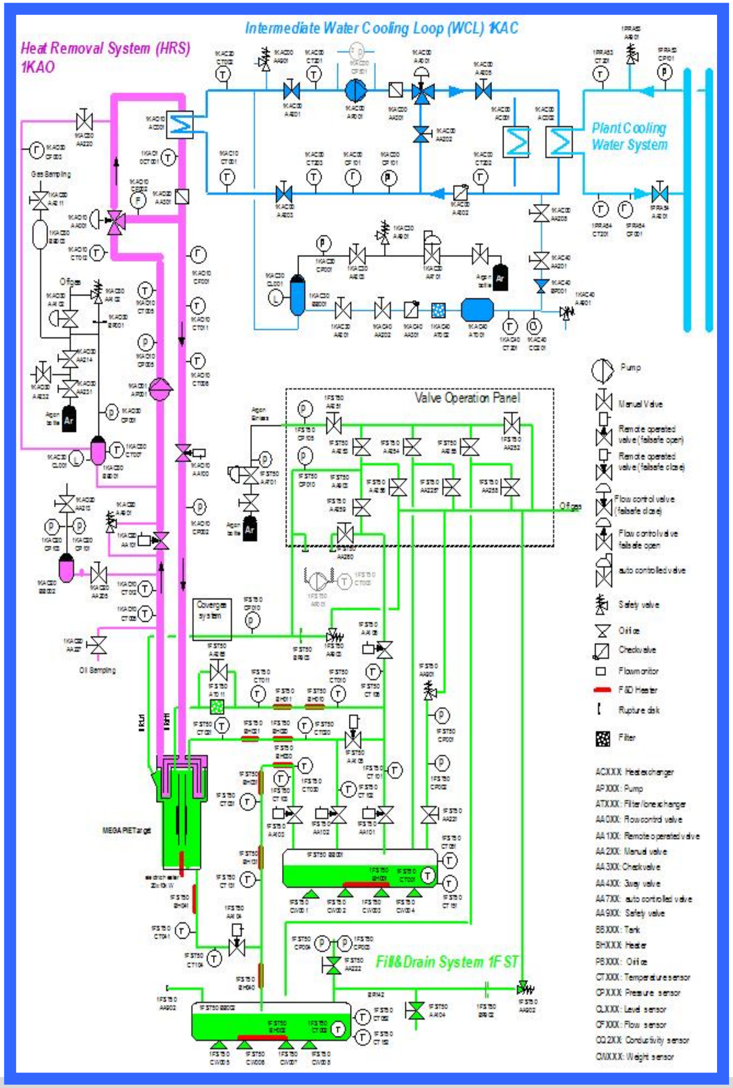




1700 hours of run-in operation

EMPS completed in September 04
Final Test in LBE test facility in 11-11/04
Delivered to ATEA for assembly 29.11.04
☑ Excellent pump performance
☹ Flowmeter Problems

MEGAPIE Integral Test

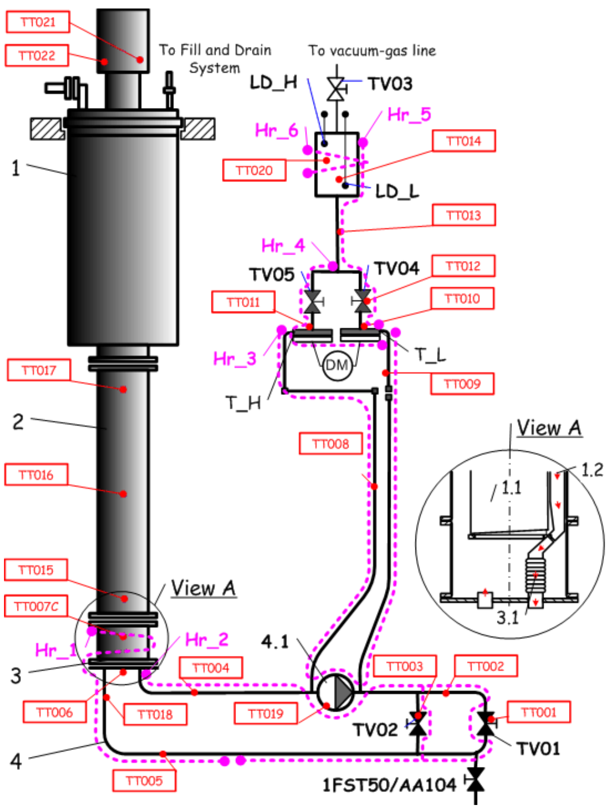


Assemble complete system from components
Carry out functional tests without beam
Demonstrate concepts for remote operations on irradiated target

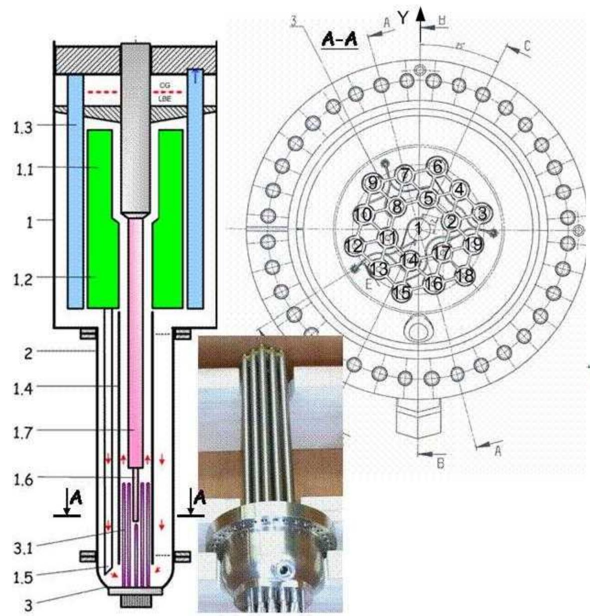
EMP/EMF performance
Thermal hydraulic test with 165 kW heater
Beam window coolig tests
September – Dezember 2005
133 hours of operation with LBE

MEGAPIE Integral Test

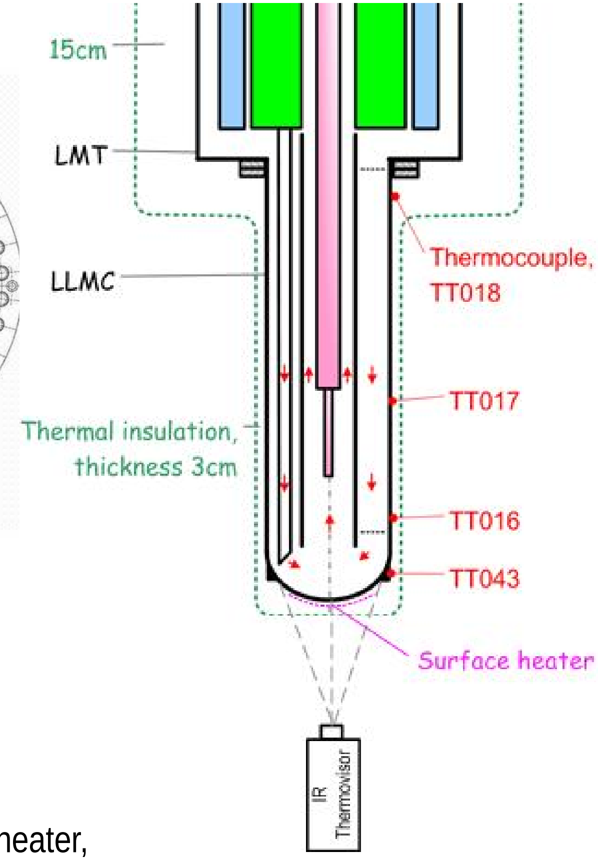
Test configurations



For by-pass EM pump and flowmeter check and recalibration: LLMC dummy; external loop with throttled valves and reference Venturi flowmeter

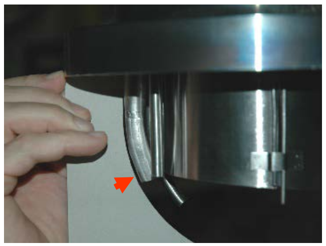


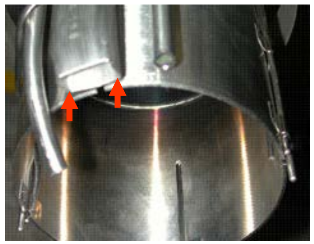
For thermohydraulic test: PbBi eutectic heater, 165kW; water cooling loop 700kW is replaced on 240kW; water, oil, PbBi flowrates and temperatures in accordance with preliminary calculated “scaled” conditions

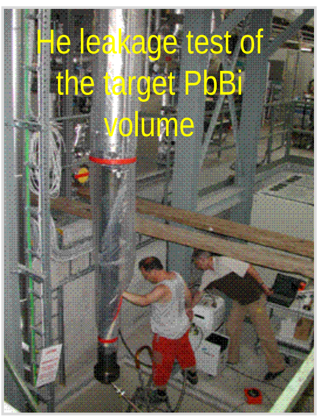


For the target window cooling experiments: IR scanner; surface heater

MEGAPIE Integral Test
Dry Check, End inspection

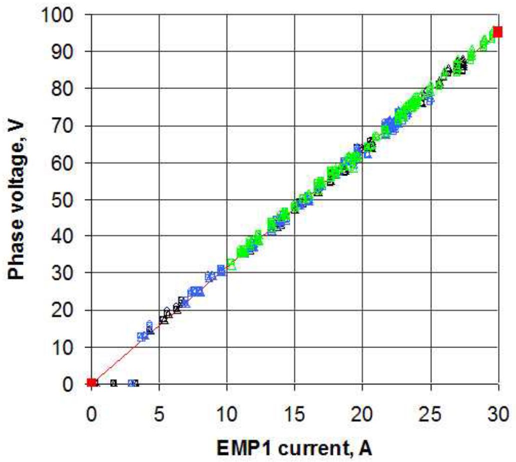


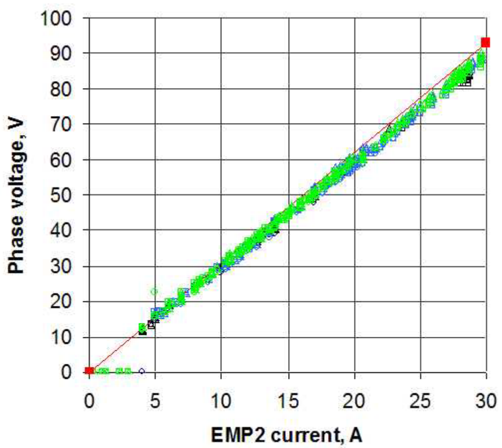




MEGAPIE Integral Test

Pump and Flowmeter Performance





- ☞ Volt – Ampere characteristic of the EMP1 meets IPUL predictions
- ☞ The main PbBi flowrate to all appearance meets the specification. Our evaluations from the target thermal balance give: 26A ↔ 41kg/s 22A ↔ 36kg/s
- ☞ EMP1 temperature, 22A: Temperature of PbBi + 15…20°C, ok.
- ☞ Accuracy of the main flowmeter does not meets the specification: relative error of the PbBi flowrate measurements calculated for fixed EMP1 current 23A is ±20% (instead 8% promised by IPUL).
- ☞ In the case of the by-pass flow termination the EMP2 temperature growths to app 350°C with rate app 5K/min. We use the pump temperature in the target safety system as indication of the by-pass channel obstruction with gas bubbles
- ✋ Performance of the by-pass flowmeter is not acceptable, relative error of the PbBi flowrate measurements caused by the pump leakage magnetic flux and PbBi temperature fluctuations reaches 70%.

MEGAPIE Integral Test

Thermalhydraulic Test

One preheats and fills the LMT with LBE

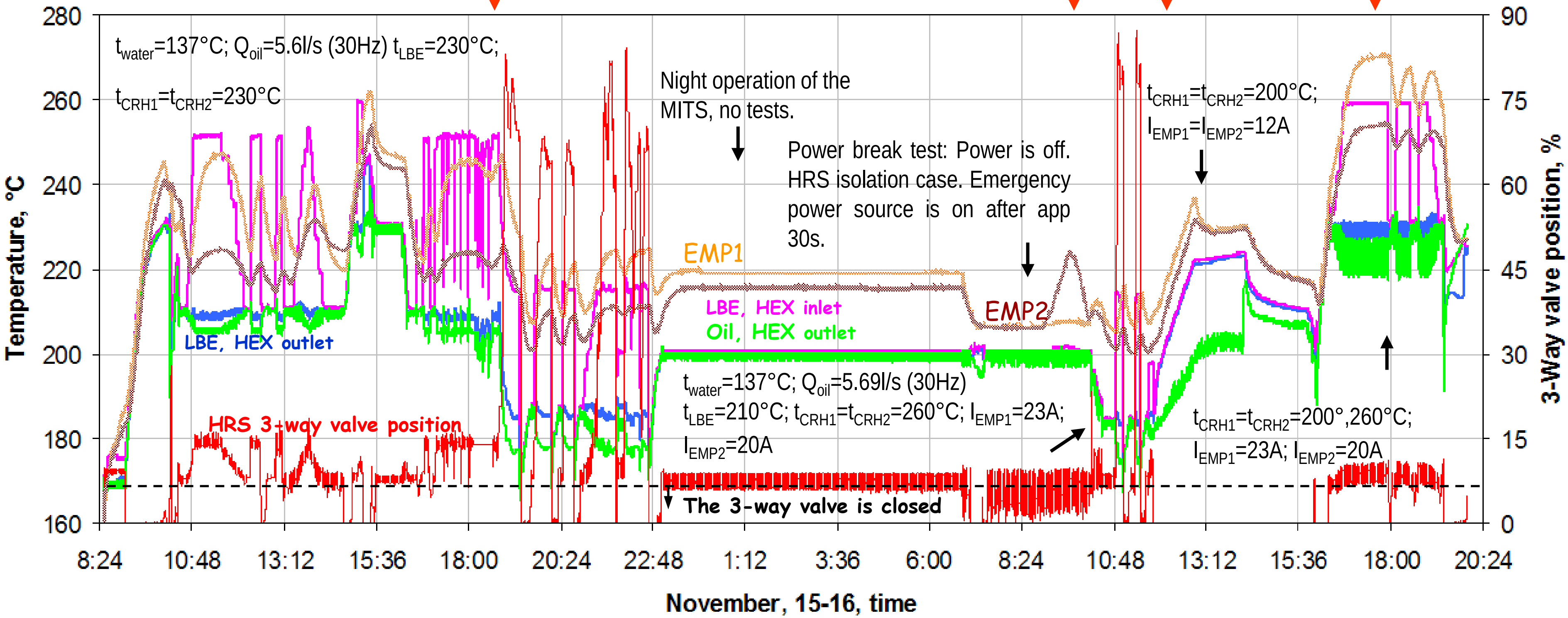
LMT operates in "Hot stand-by" (Leung scaled cond). One varies: EMP current (I_{EMP1}=0…26A; I_{EMP2}=0…30A); LMCH power (0…100%); LBE temperature control PID coefficients.

LMT operates in "Hot stand-by" (M.Dierckx scaled conditions). One varies LMCH power and PID coefficients in accordance with M.Dierckx procedure.

Measurements of EMP2 outlet – inlet temperatures differences verse the pump current.

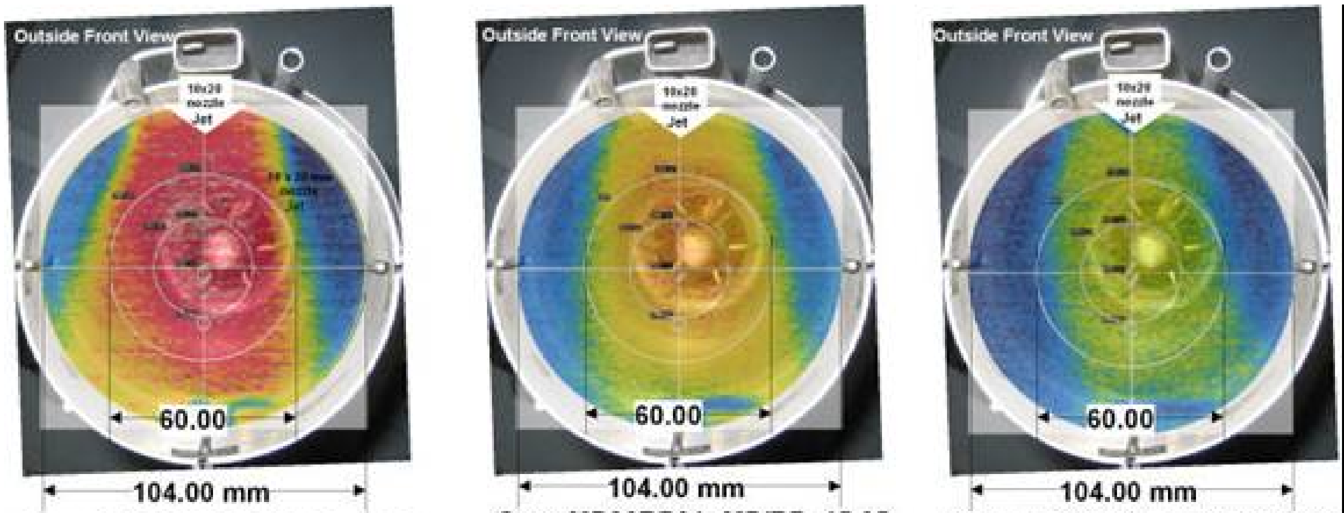
Replacement of "scaled" WCL (240kW) on standard one (700kW), A2→A3. LMT operates in HRS isolation case

LMT thermohydraulic test with standard WCL (t_{water}=30°C). LMCH power on/off, 0…100%



Conclusion: The target is able to evacuate 580kW of the thermal power from the beam window to the THX, inlet - outlet temperatures difference will not exceed 120°C in SINQ.

MEGAPIE Integral Test
Window Cooling Experiments



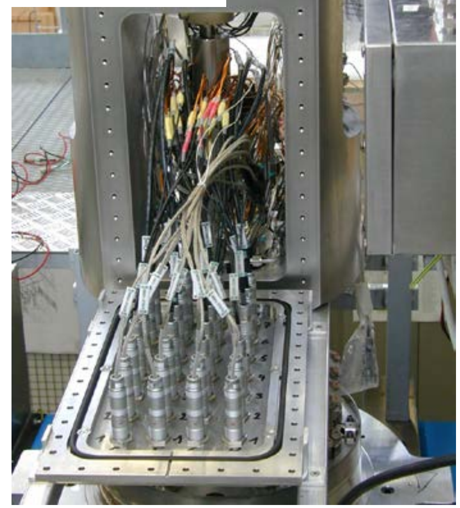
Case MP22BP30; MP/BP=11.09 | Case MP22BP21; MP/BP=15.85 | Case MP22BP15; MP/BP=22.18

Heat transfer coefficient, W/m^2 K:	19692	18062	16670

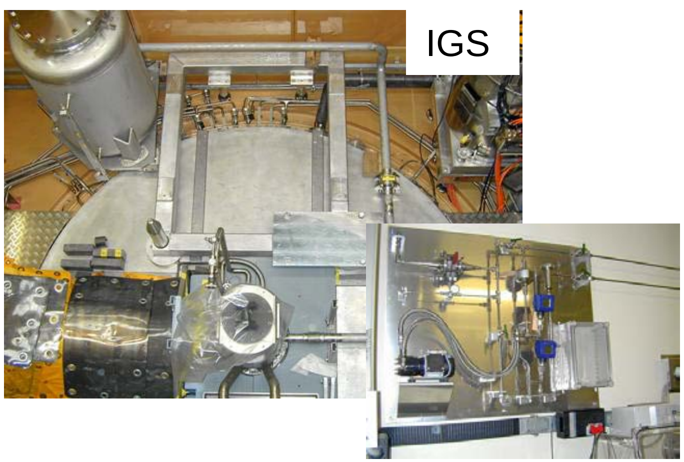
Conclusions: The by-pass jet is slightly deformed because of draining pipe. The cooling pattern is covering 32mm footprint area. The heat transfer coefficient for nominal EM pumps currents corresponds to prediction, approx. 18000W/m2 K.

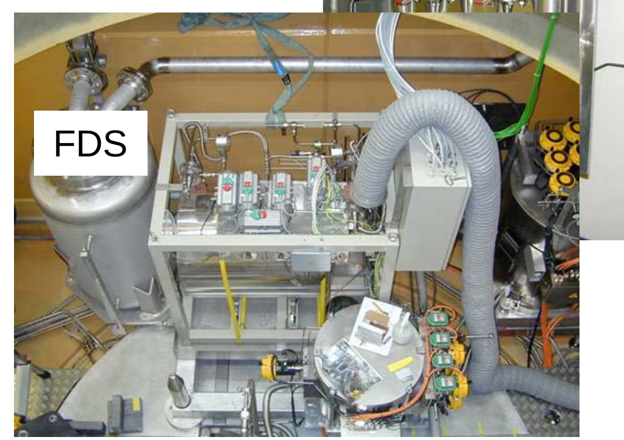
Final Target Assembly (Jan – Mar 2006)

Assemble complete system from components
Carry out functional tests without beam
Demonstrate concepts for remote operations on irradiated target, in particular draining of PbBi



Implementation in SINQ (Jan – Jun 2006)





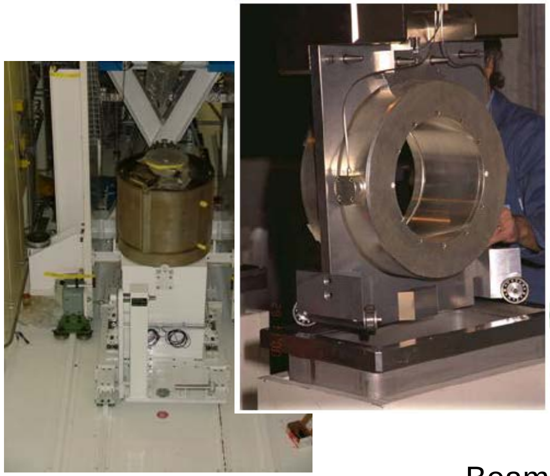
Implementation in SINQ (Jan – Jun 2006)

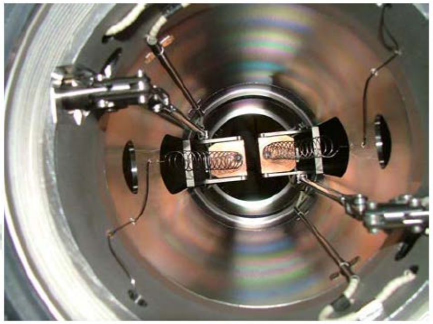
- Active carbon and HEPA filters
- Earthquake resistant ventilation dampers
- Autonomous filter unit
- Mobile filter unit

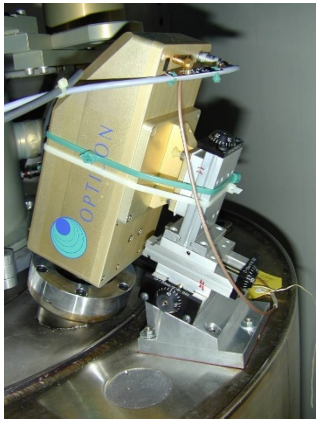
Ventilation Upgrade

N2-Inertisation

LowOx-Facility
- TKE 10 – 11 %
- STK 5 – 6%





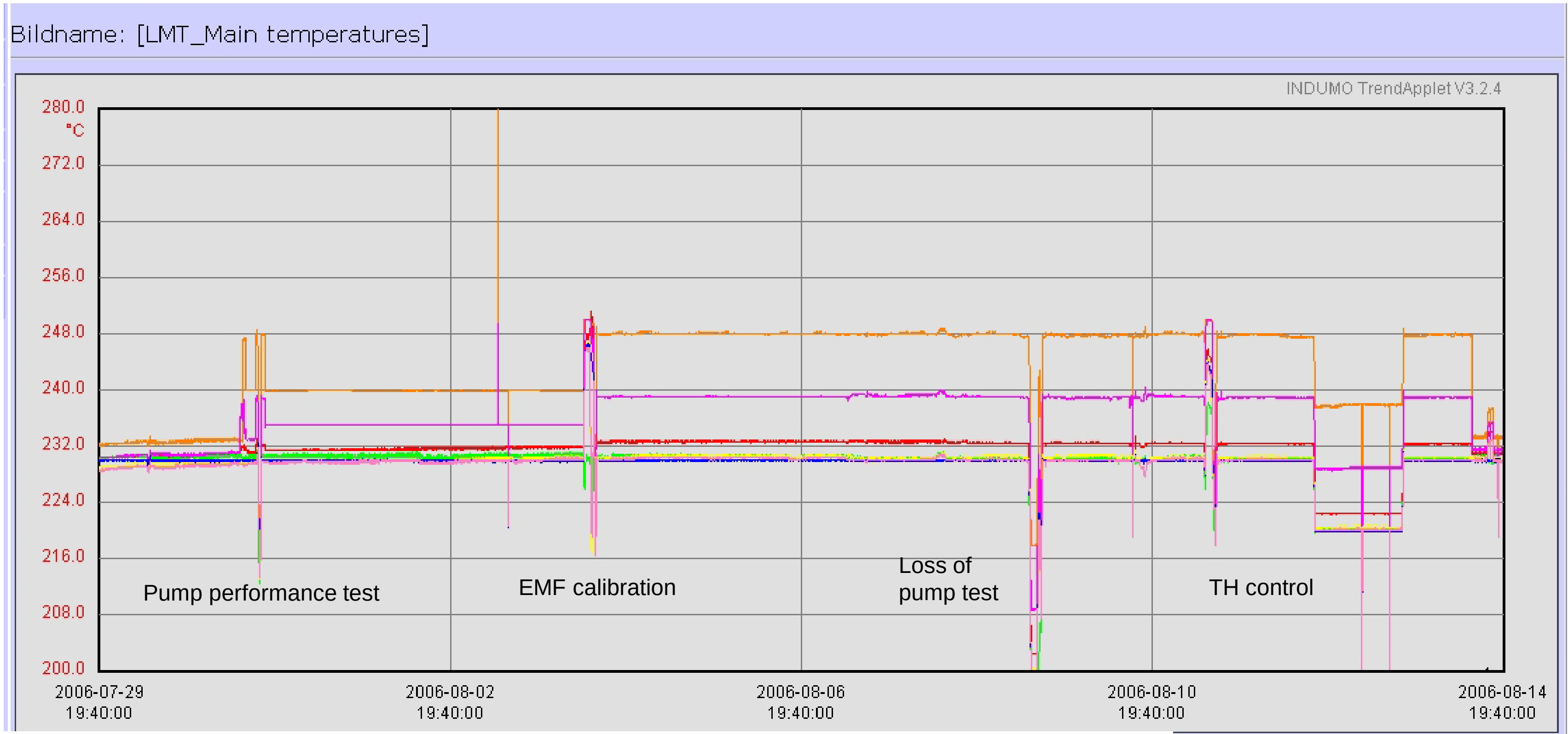


Beamline Upgrade

Control System

Commissioning

Off-beam operation over 17 days



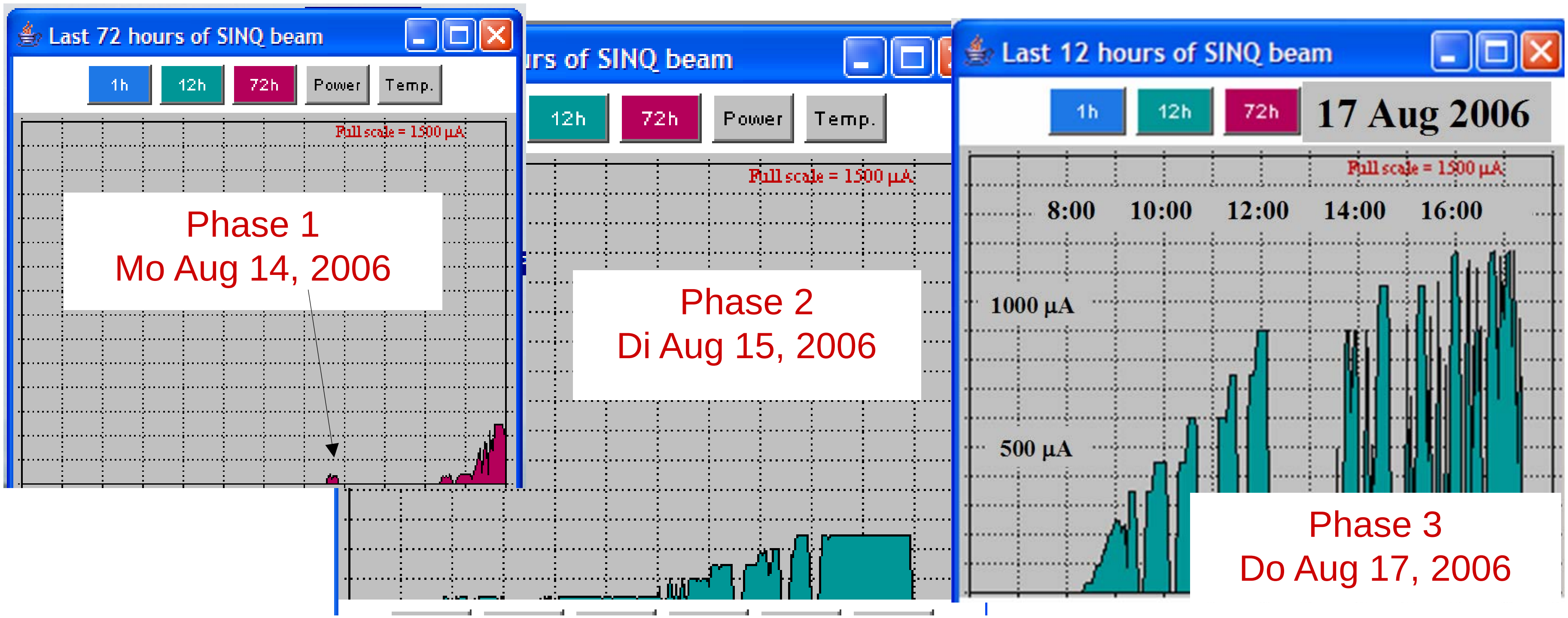
- All target temperatures > 140C, LBE and filling pipe temperatures 250C
- Cover Gas pressure 1.75 bar Ar, IG pressure < 1 mbar
- LTE cooling water flow reduced

Manned and unmanned operation

Operation

Start-up phase

Insert target in SINQ
Run target with beam
Continuously record relevant operation parameters
Make periodic checks according to monitoring plan
Remove target at end of irradiation period

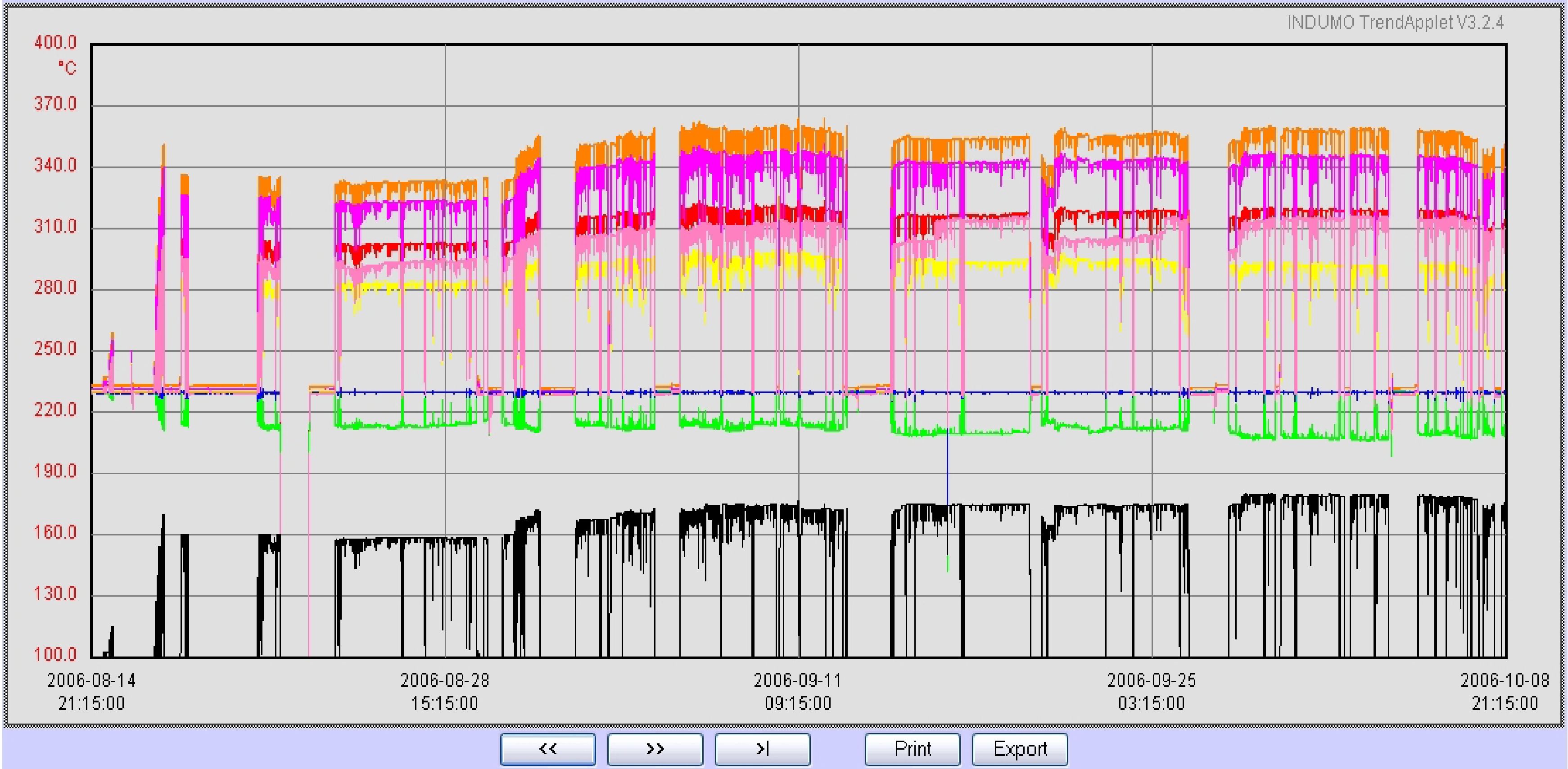


Failure of Heater

- Sparking in CRH power cable in IG during insulation gas exchange probably in connector → power loss
- Failure of 4 of 6 heater circuits in central rod
- Heater power 22 kW → 8.9 kW

Operation

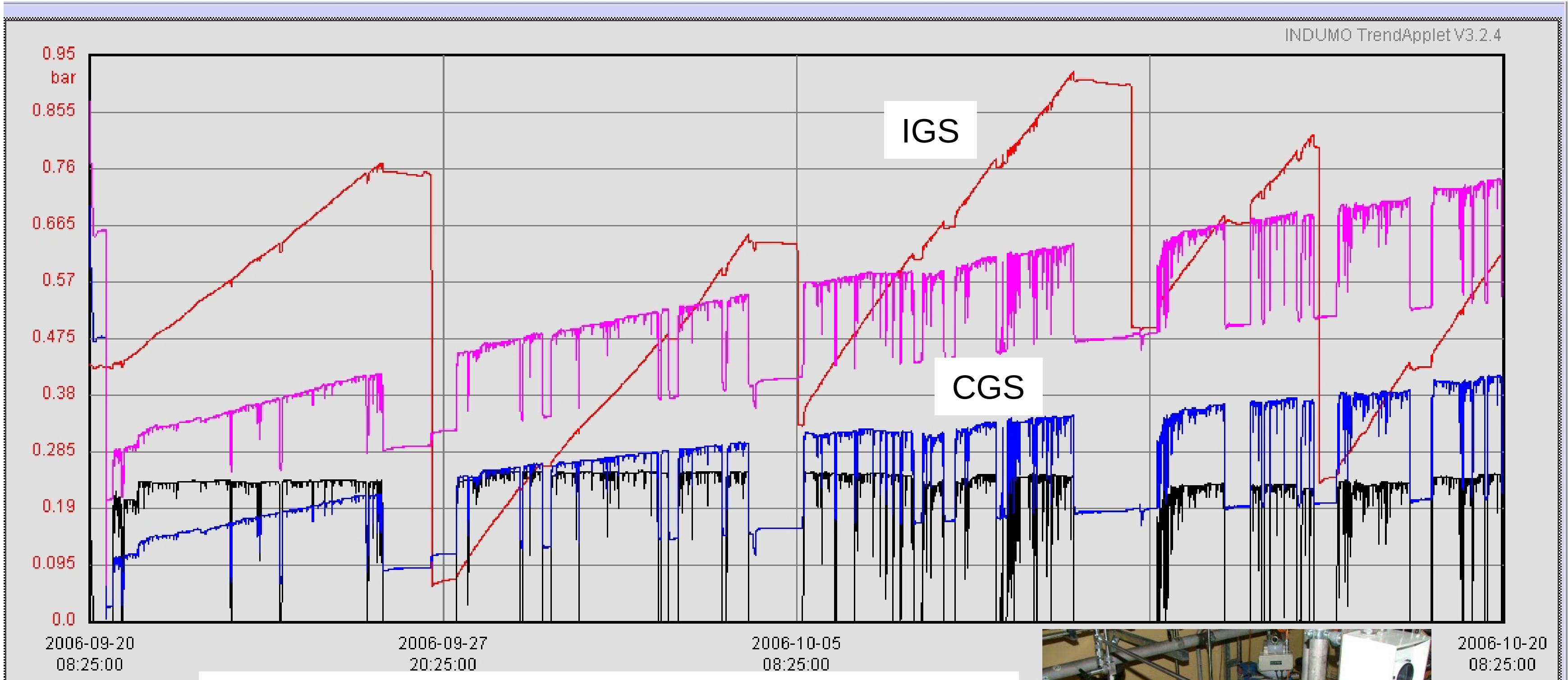
Target Temperatures



Farbe	Anzeige	Name der Trendlinie	Beschreibung	Skala Min	Skala Max	Cursorwert	Einheit	Min	Max
	☑	MP_1RNQ51_FT003_Z400_AVG	Temperatur Mittelwert	-270	1372	0	°C	100	400
	☑	MP_1RNQ52_CT005_Z400_AVG	THX Oil Outlet Temperatur	-270	1372	0	°C	100	400
	☑	MP_1RNQ51_FT004_Z400_AVG	Temperatur Mittelwert	-270	1372	0	°C	100	400
	☑	MP_1RNQ51_FT005_Z400_AVG	Temperatur Mittelwert	-270	1372	0	°C	100	400
	☑	MP_1RNQ51_CT074_Z400_AVG	LBE Temperatur MFGT bottom outside	-270	1372	0	°C	100	400

Operation

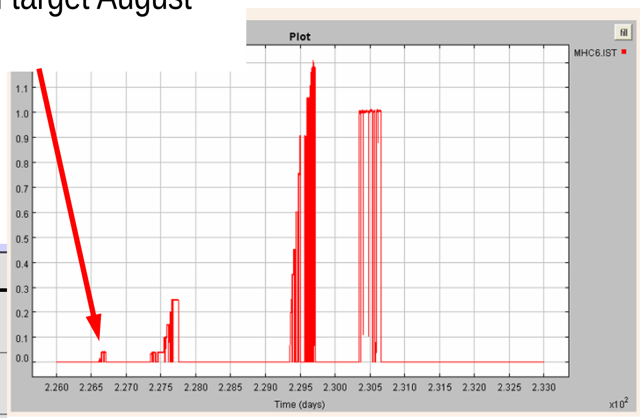
Cover Gas and Isolation gas



- installation of 180 l decay vessel in cooling plant, regular (weekly) venting into the exaust system
- Drift and failure of one CGS pressure sensor
- Leak in decay vessel

Operation
Beam History

First protons on target August 14, 2006



Beam: August 14 – December 21, 2006

- Accumulated charge: 2.8 Ah
- Peak Current: 1400 mA
- Beam trips (< 1 min): 5500
- Interrupts (< 8 h): 570