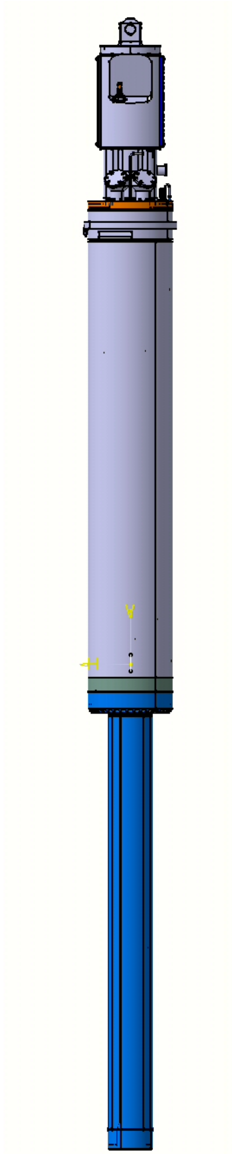


Workshop on
High-Power Targetry for Future Accelerators
Ronkonkoma, 8.-12.9.2003

MEGAPIE -
A liquid Pb-Bi target at SINQ

F. Groeschel
Paul Scherrer Institut
Villigen, Switzerland

on behalf of the
MEGAPIE Team

MEGAPIE-TEST

5th Framework Program

Projects on ADvanced Options for Partitioning and Transmutation (ADOPT)

PARTITIONING *(5 MEuro)*
PYROREP
PARTNEW
CALIXPART

TRANSMUTATION *(3.9 MEuro)*
Fuels:
CONFIRM
THORIUM CYCLE
FUTURE

TRANSMUTATION *(6 MEuro)*
Preliminary Design Studies for an Experimental ADS:
PDS-XADS

TRANSMUTATION *(6.5 MEuro)*
Basic Studies:
MUSE
HINDAS
N-TOF_ND_ADS

TRANSMUTATION *(7.2 MEuro)*
Technological Support:
SPIRE
TECLA
MEGAPIE - TEST

MEGAPIE Objectives

An experiment to be carried out in the SINQ target location to demonstrate the safe operation of a liquid metal spallation target of about 1 MW beam power

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

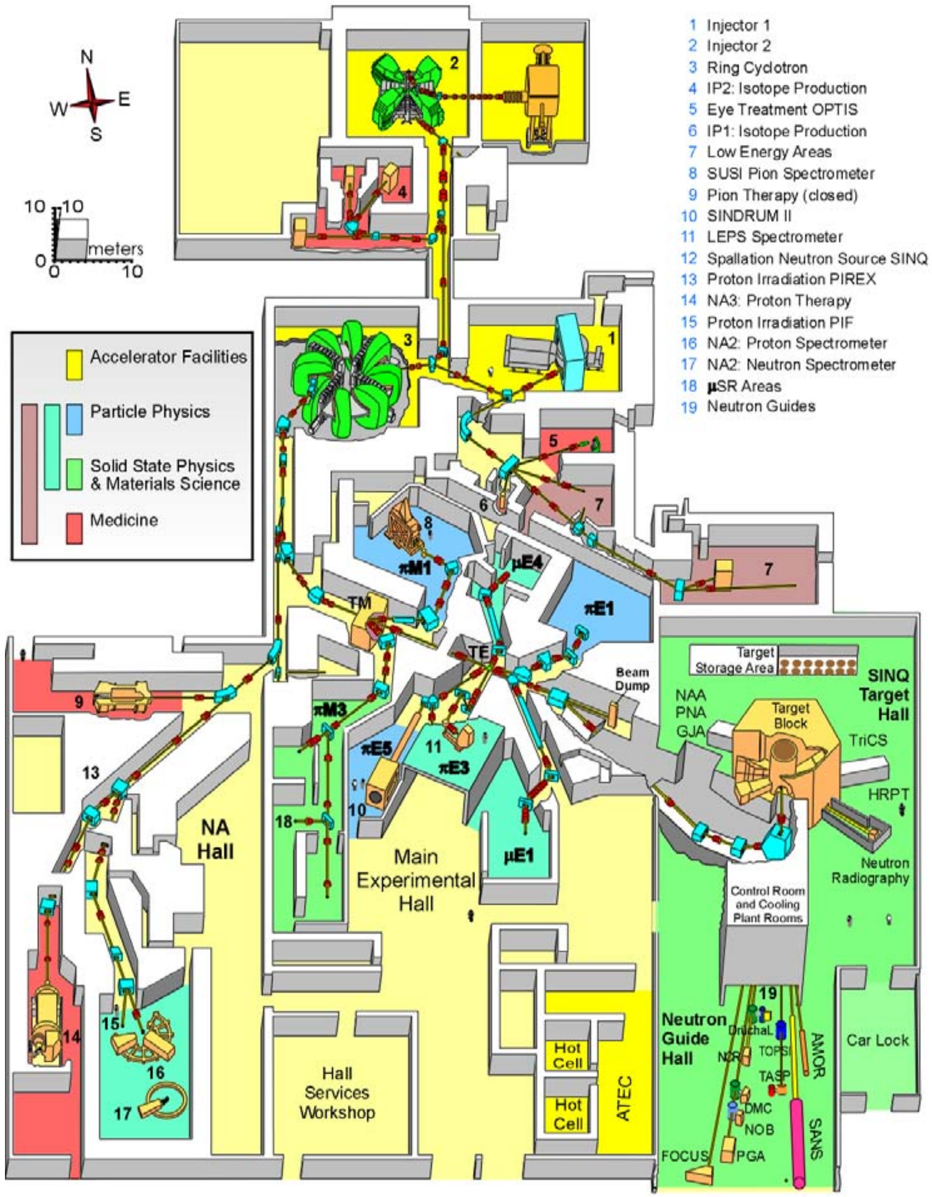
→Demonstration of feasibility for future ADS development

→Increase neutron flux for SINQ

Contents

- Objectives
- SINQ
- MEGAPIE Target
- Nuclear Assessment
- Thermal hydraulics
- Radiation Damage
- Heat Removal
- Handling of Radiactive Products
- Safety
- Status and Conclusions

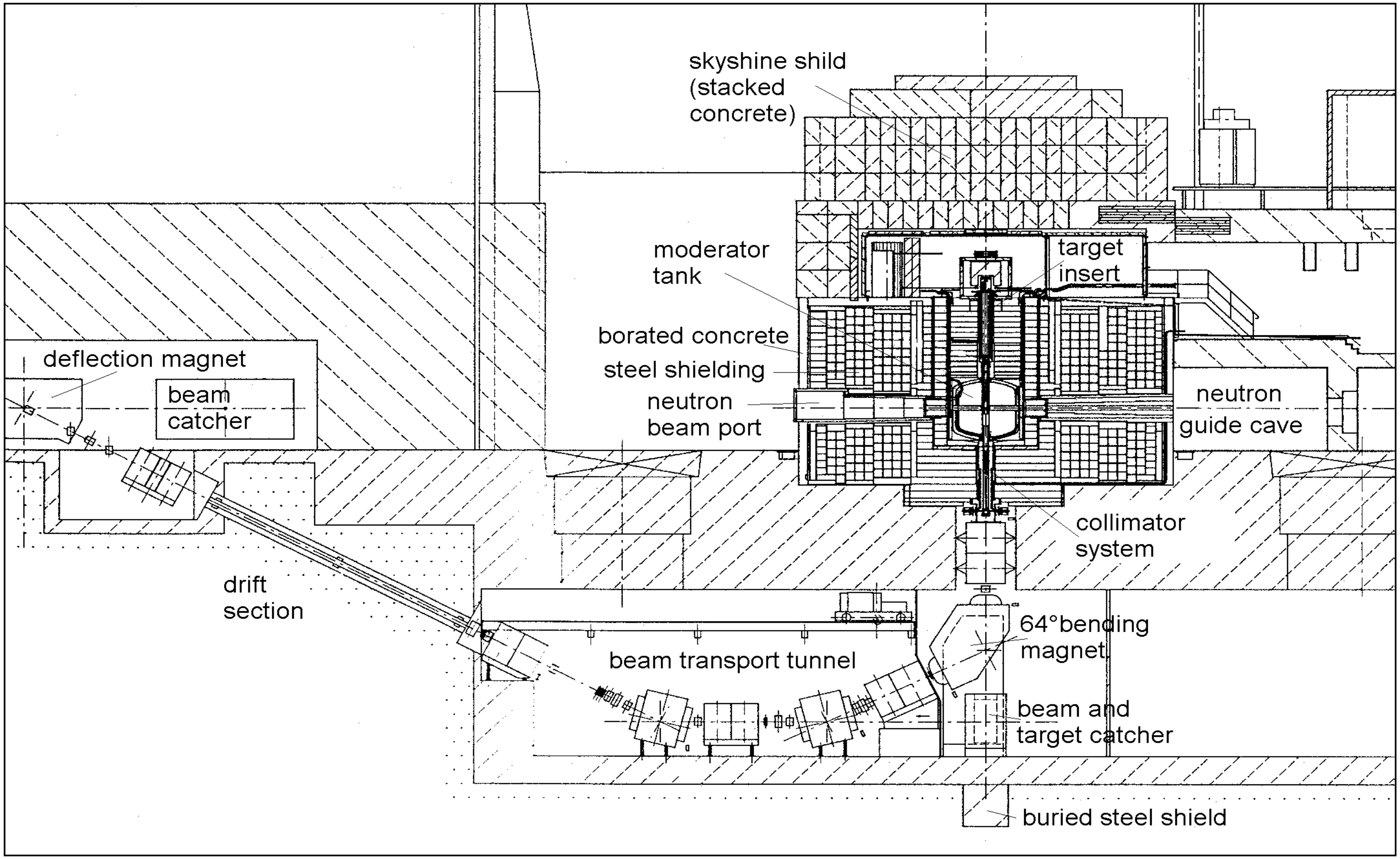
Accelerator Facilities of the Paul Scherrer Institut



590 MeV, 1.8 mA CW proton accelerator

575 MeV, 1.25 mA spallation neutron source

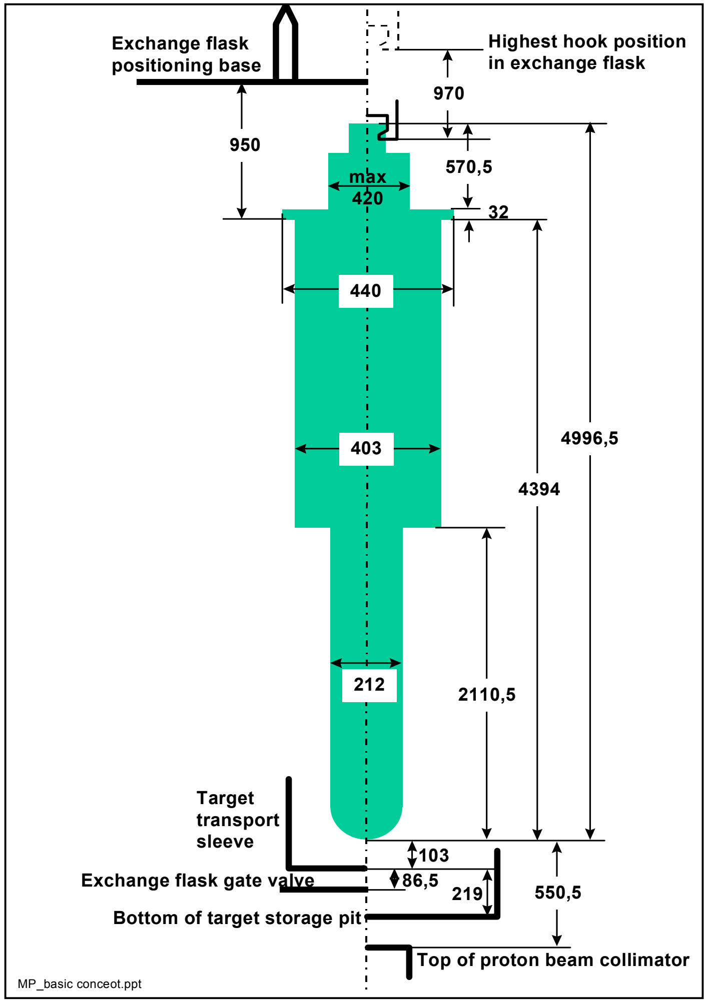
SINQ Spallation Neutron Source



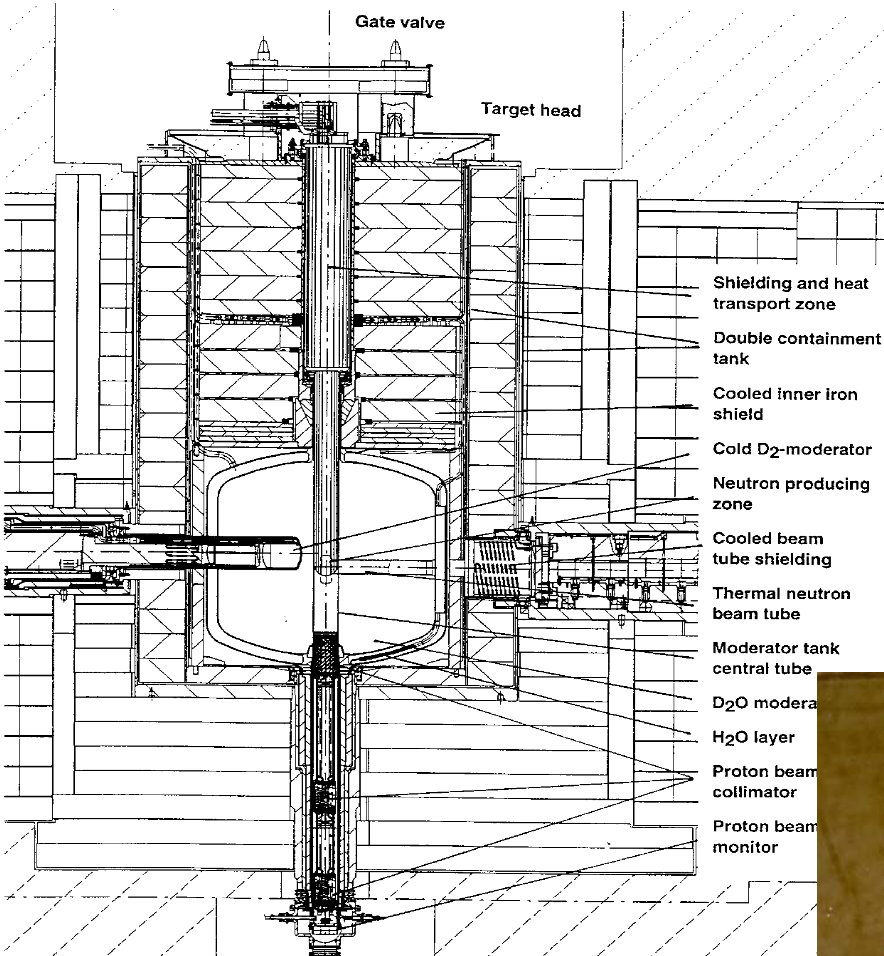
SINQ Target Mark II/III

- 150 rods (Ø 10.7 mm, 170 mm long)
- 316L stainless steel tubes filled with Lead
- about 20 rods for STIP program filled with miniature specimens of different materials (F/M steels, austenitic, W, Ta, SiC/SiC, Hg or LBDE capsules)
- Temperature range up to 250C (STIP-1), up to 350C (STIP2), 450C (STIP-3), → 650C (STIP-4)
- Irradiation period is 2 years (peak fluence of 20 dpa)

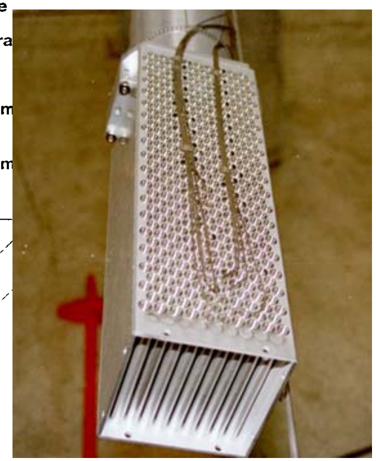
SINQ Target

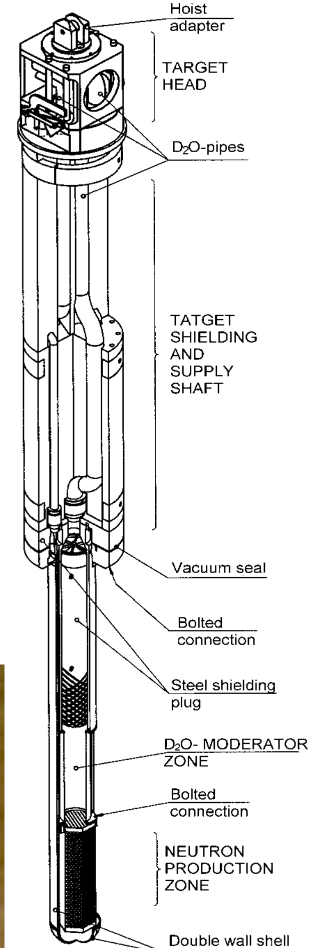

Exchange flask
positioning base
Highest hook position
in exchange flask
970
950
570,5
max
420
32
440
403
4996,5
4394
212
2110,5
Target
transport
sleeve
103
Exchange flask gate valve
86,5
219
550,5
Bottom of target storage pit
Top of proton beam collimator
MP_basic conceot.ppt

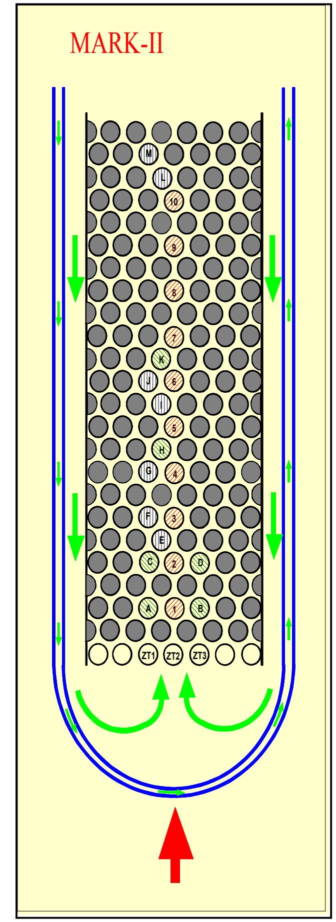
SINQ and Target



SINQ Target Block



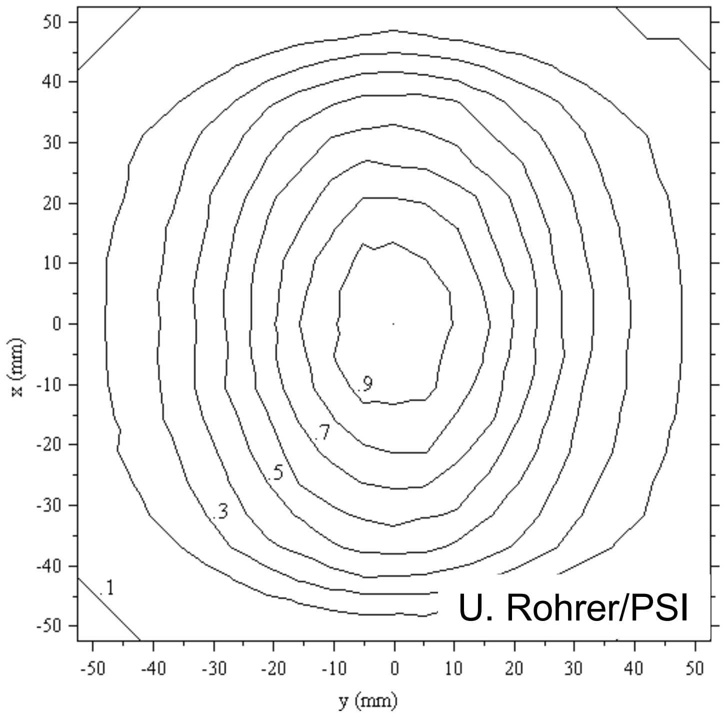




Solid Target

Proton Beam Profile

Normal Operation, Target E 4 cm



I_{max} 20.7 μA/cm² per 1 mA

σ_x = 2.1 cm, σ_y = 3.78 cm

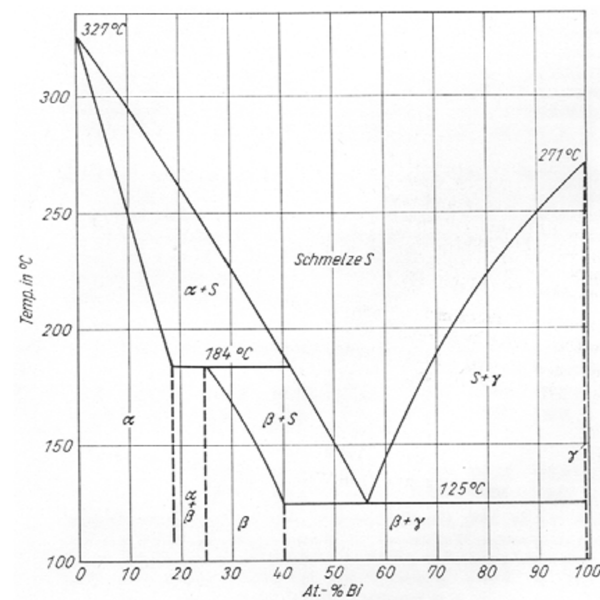
Accelerator Proton Beam in 2005:	**2.0 mA**
Beam on SINQ:	**1.4 mA at 575 MeV**

Reasons for LBE

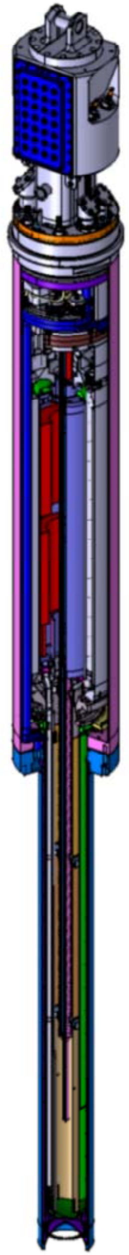
- No Radiation Damage
- Good Heat Removal
- Low Melting Point
- Low thermal neutron cross section
- Low activation of cooling water

- Corrosion
- Po production (α)
- Complex Handling
- Limitation Beam Window

Properties		Hg	Pb	Bi	LBE
Atomic Number		80	82	83	„82.5“
Mass	g/mol	200.6	207.2	209	208.2
Density (20°C)	g/cm^3	-	11.35	9.75	10.73
liquid		13.55	10.7	10.07	10.57
Lin. Thermal Expansion	$10^{-5}K^{-1}$	6.1	2.91	1.75	
Solidification Shrinkage ΔV	%	-	3.32	-3.35	-1.48
Meltimg Point	°C	-38.9	337.5	271.3	125
Boiling Point	°C	356.6	1740	1560	1670
Specific Heat	J/gK	0.12	0.14	0.15	0.15
Termal Neutron Cross Section	barn	389	0.17	0.034	0.11



MEGAPIE Target

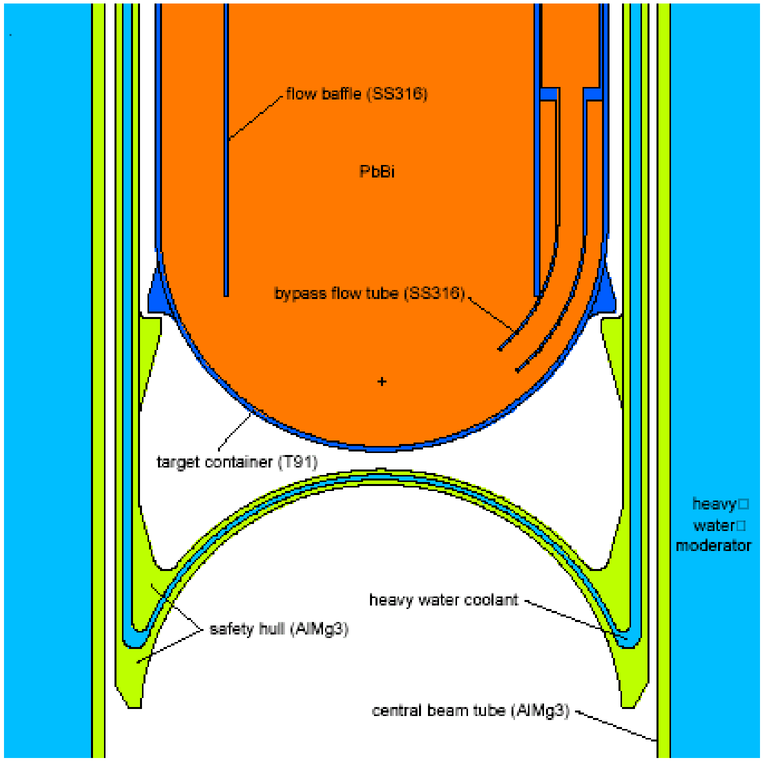


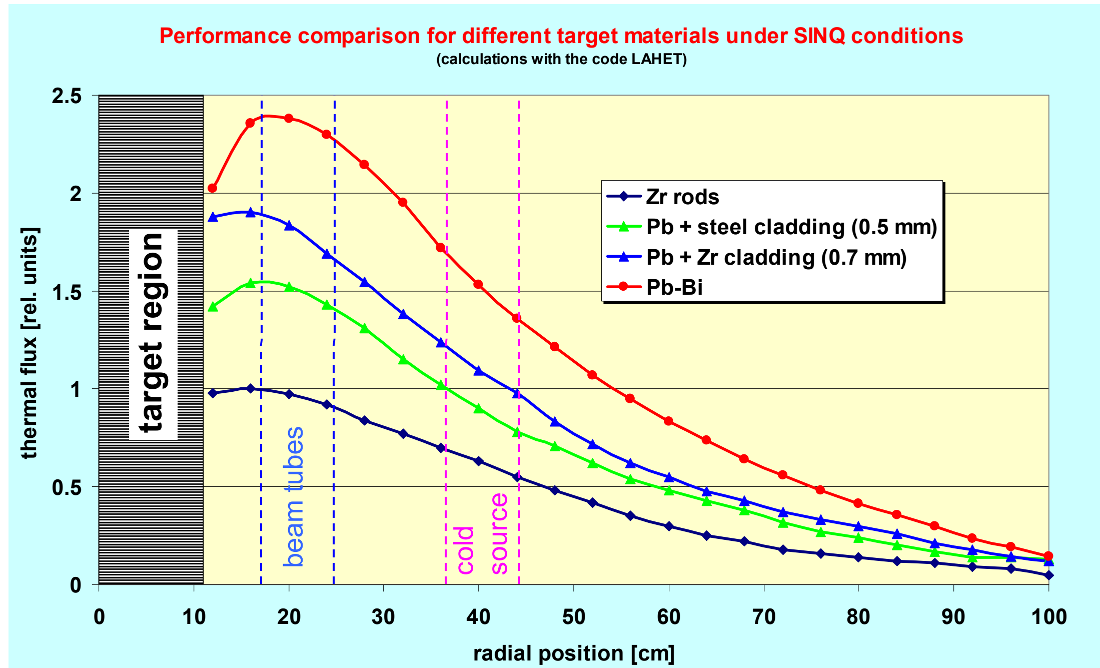
Beam energy:	575 MeV
Beam current:	1.74 mA (design)
Target material:	Lead-bismuth eutectic
LBE volume:	85 l
Wetted surface:	8 m^2
Deposited Heat:	650-700 kW
LBE T range:	230-380°C
Max. flow velocity:	~1.2 m/s
Beam window:	T91 martensitic steel
Window Temperature:	330-380°C
Radiation Damage:	20 dpa
Other components:	316L

Nuclear Assessment

- Code comparison calculations
- MCNPX and FLUKA
- Validation experiments (CERN, PSI, HINDAS) on gas and spallation products production
- Instrumentation of target with microfission chambers and activation foils
- Neutron flux measurement at beam ports

MEGAPIE Neutron Flux



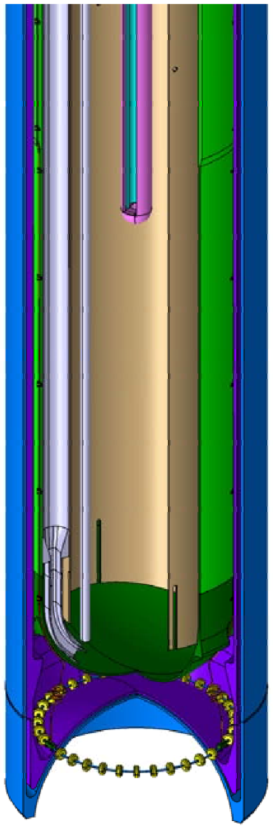


LAHET calculations A. Dementjev, E. Lehmann

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

Increase of >40% compared to current solid lead target

Neutron Yield

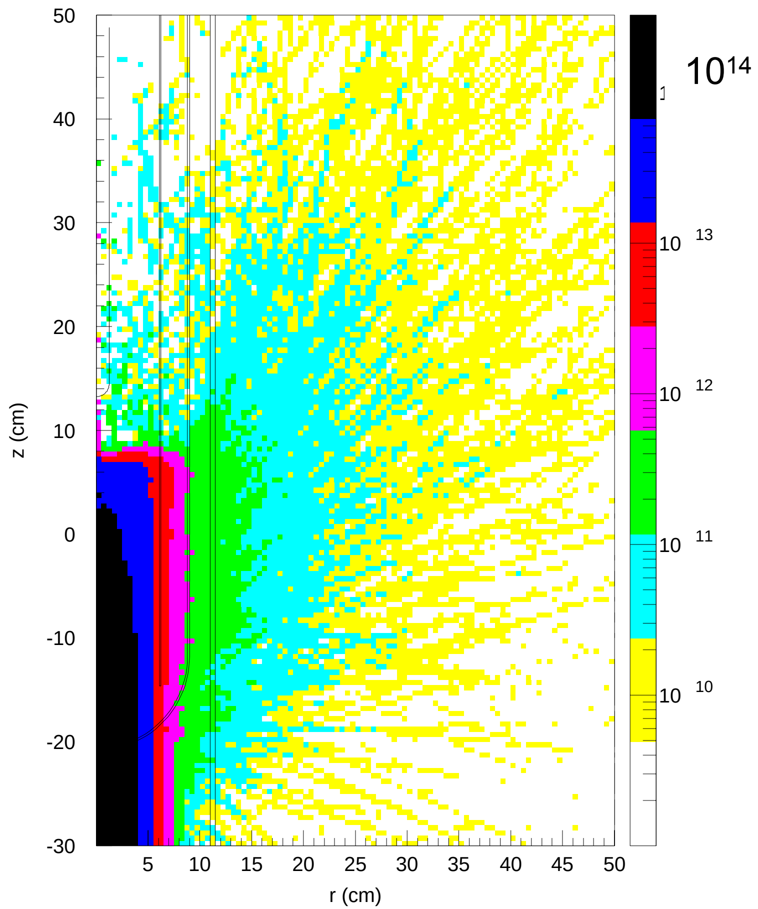


Neutrons per Proton

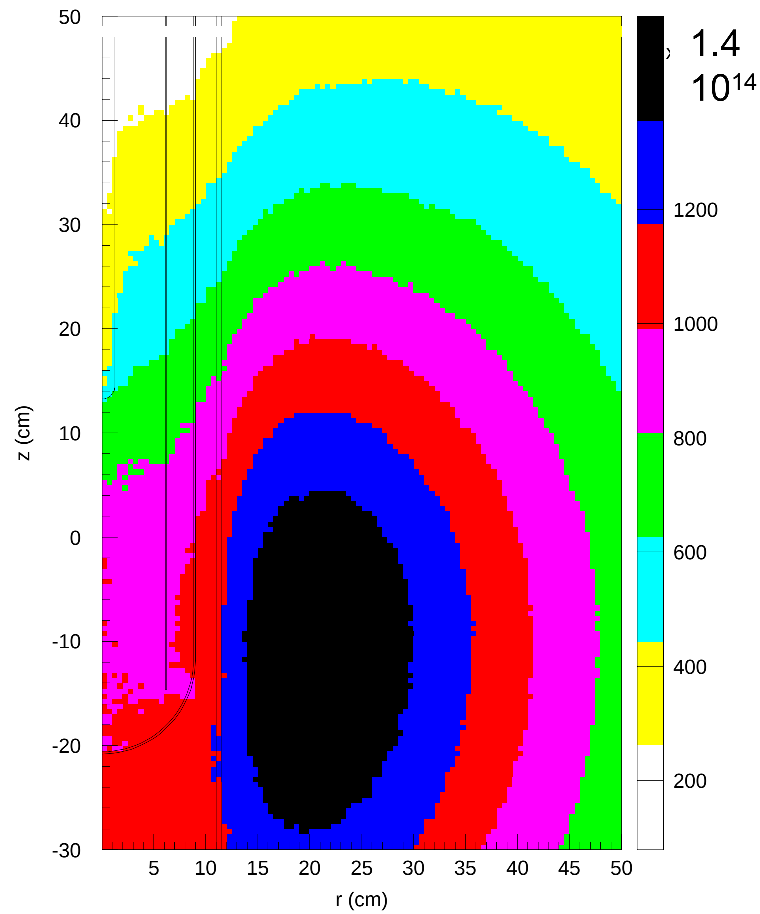
	Pb/steel	LBE
Total	**7.62**	**10.99**
Target Int.	**- 0.113**	**- 0.232**
Cladding	**- 1.01**	**- 0.635**
D2O	**- 0.044**	**- 0.401**
Container	**-0.248**	**- 1.23**
Net	**6.17**	**8.49**

E. Pitcher et al.: Icans-XVI, 2003

Nuclear Assessment



Proton Flux, 1.74 mA



Thermal Neutron Flux

E<0.625 eV

E. Pitcher, 2002

Beam Window: T91 martensitic 9Cr-1MoVNb steel

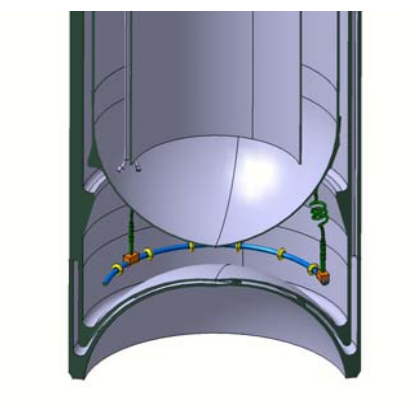
- Removal of Heat (5kW): cold LBE jet across window
  - CFD modelling
  - Experimental verification (KILOPIE, TECLA)
- Static and Fatigue Loads (ABAQUS, ANSYS, RCC-MR)
- Corrosion and LME (TECLA)
- Radiation Damage (SPIRE, STIP)

Lower Liquid Metal Container

LBE Container

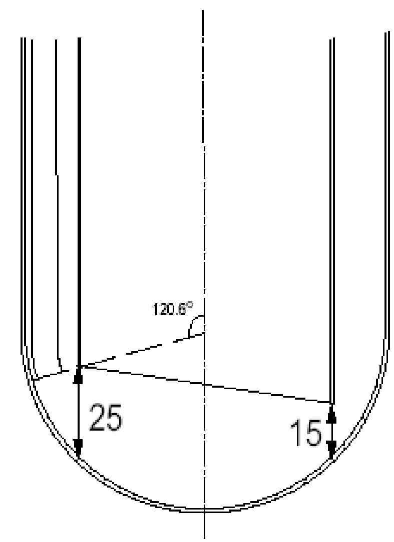
Beam Entrance Window

Carry LBE Leak Detector



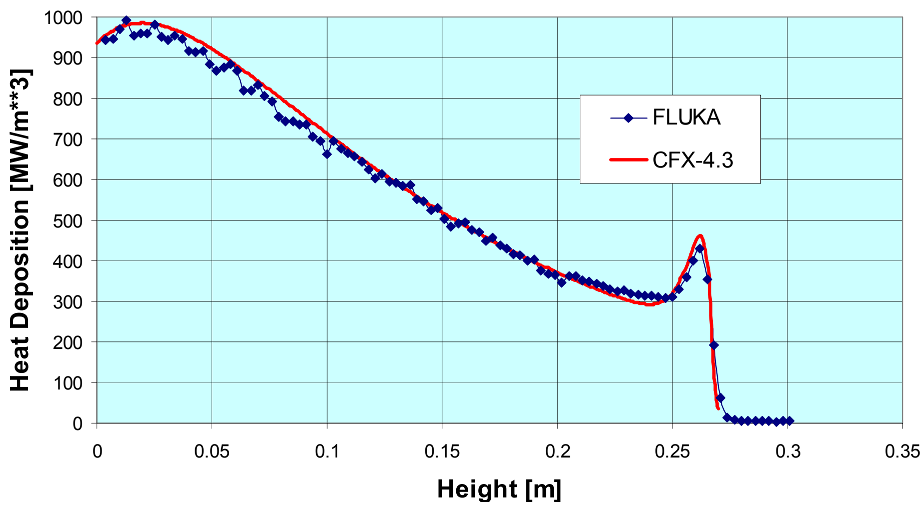
T91

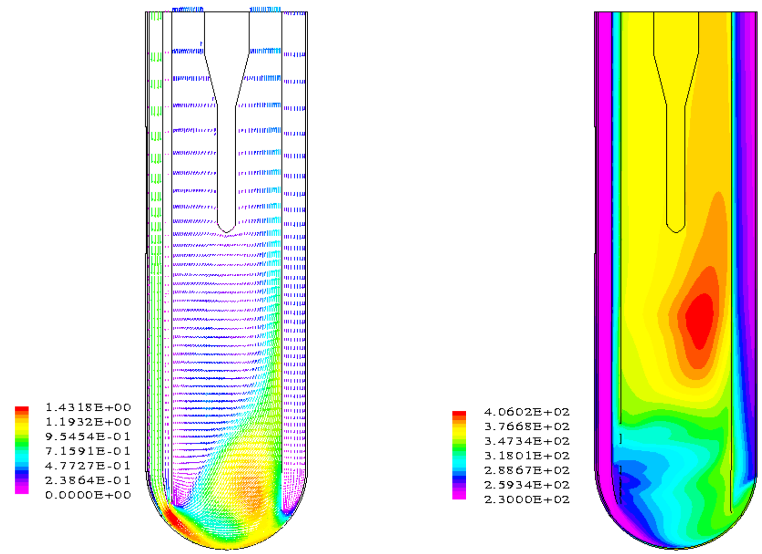
4 mm outside
2 mm in spallation zone
1.5 - 2 mm in window



Reference Design

Thermalhydraulics – CFD simulations





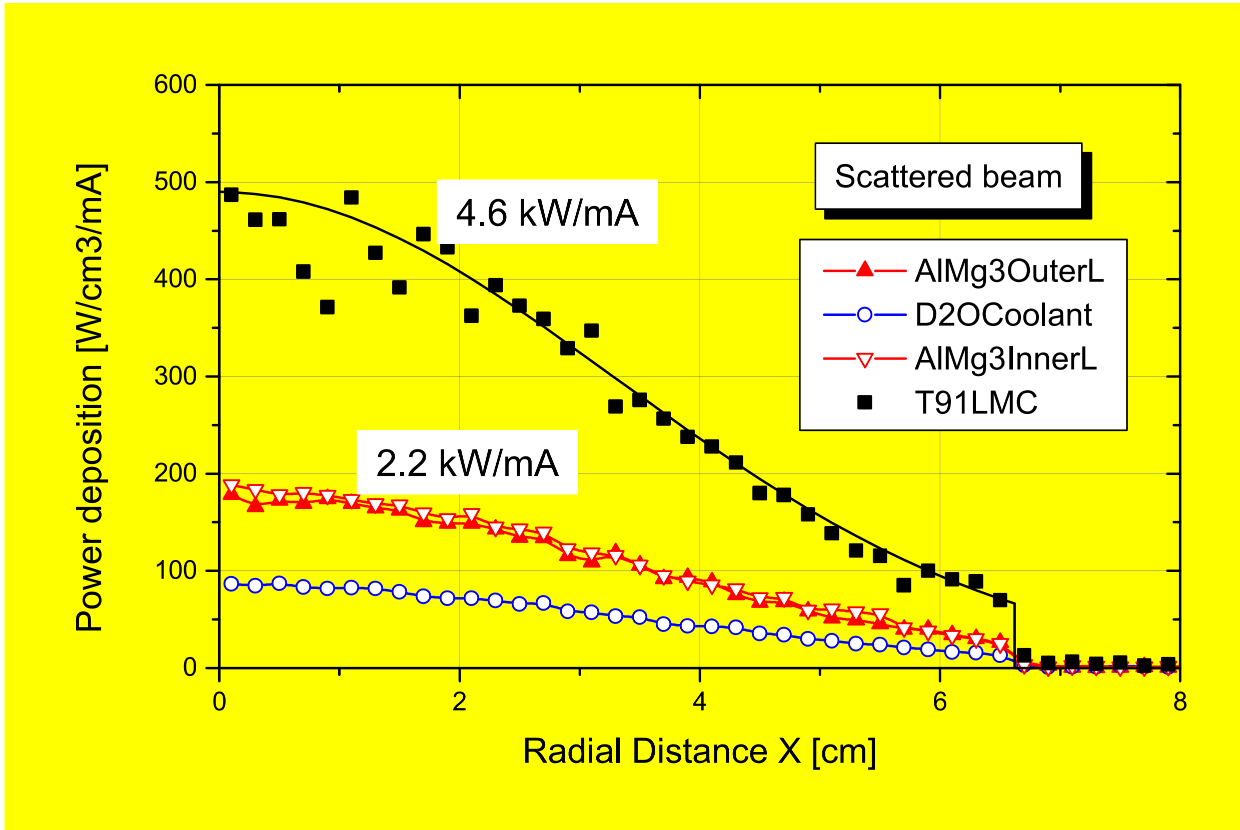
Material	FLUKA [kW]	CFX-4.3 [kW]
LBE	705.8	709.9
Window	5.56	5.28
T91 Hull	2.68	1.21
Guide tube	5.55	6.03
Total	719.6	722.4

1.74 mA

		T_{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

T. Dury, PSI, 2003

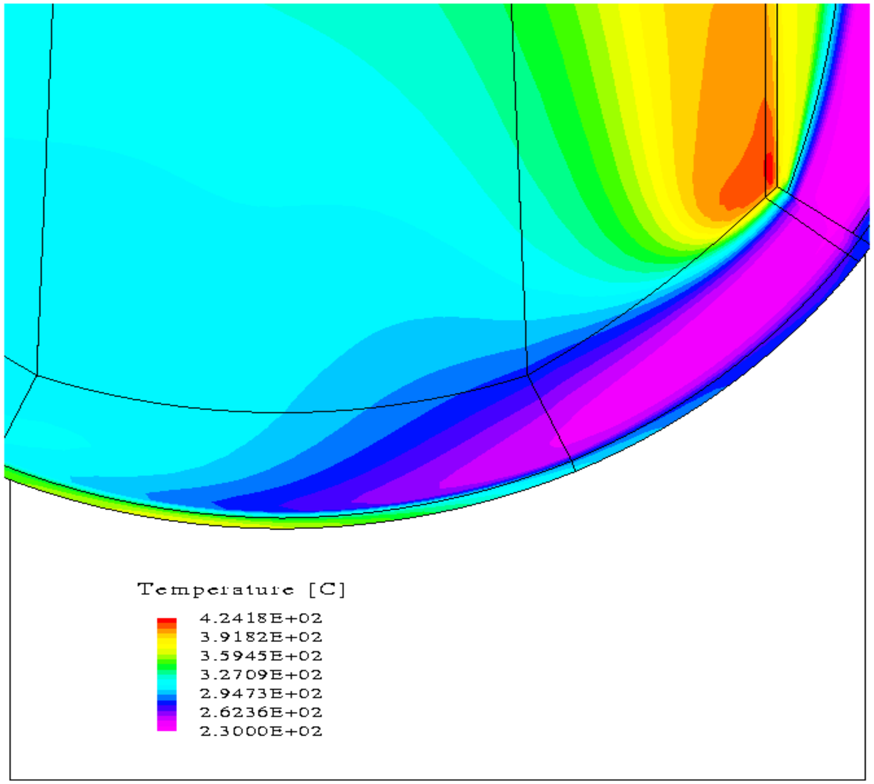
Power Deposition in Beam Windows



Y. Foucher, PSI Report 2002

Normal Operation Target E 4 cm
Baseline Profile

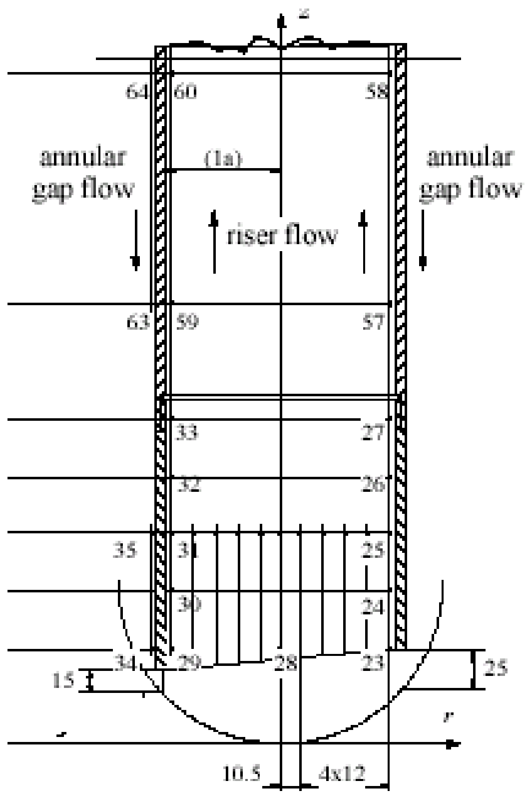
Beam Window Cooling



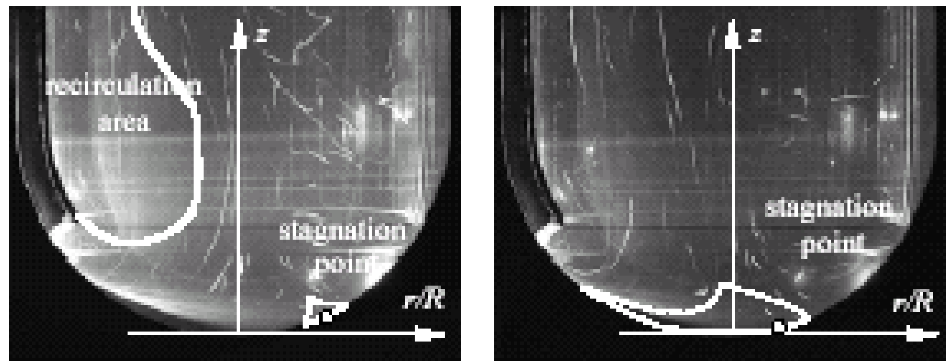
Baseline Beam Profile, 1.74 mA
Bypass Jet Flow: 0.25 l/s
Annular Down Flow: 3.75 l/s

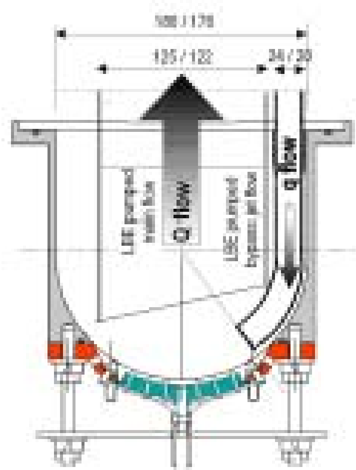
Y. Dury: PSI Report 2002, Annex

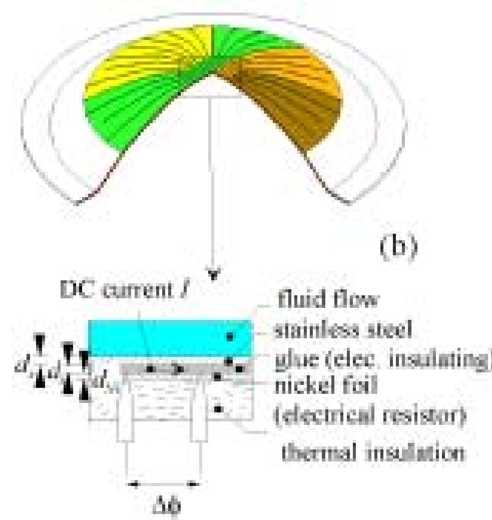
Experimental Validation



15 Q_{main}/Q_{bypass} 10







HYTAS Water Experiment, FZK

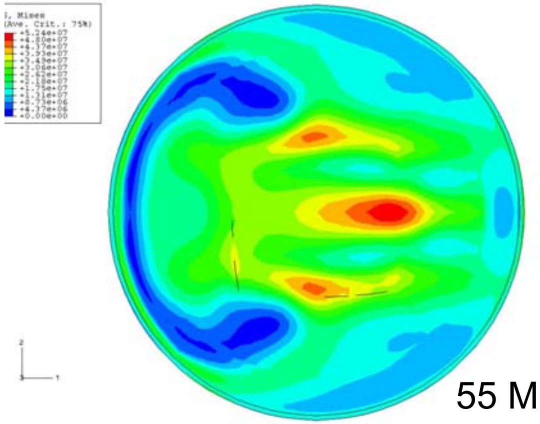
LBE Heated Jet Experiment, FZK

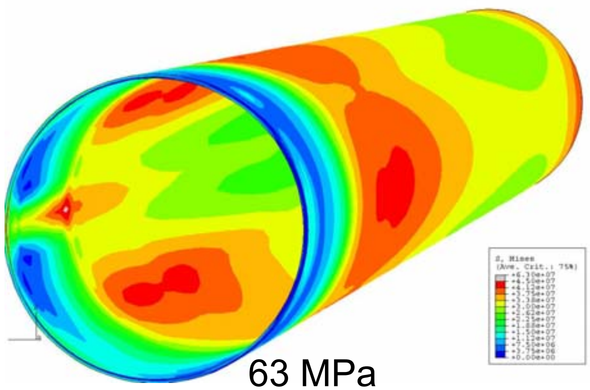
LBE KILOPIE Experiment, PSI-FZK

Stress Analysis

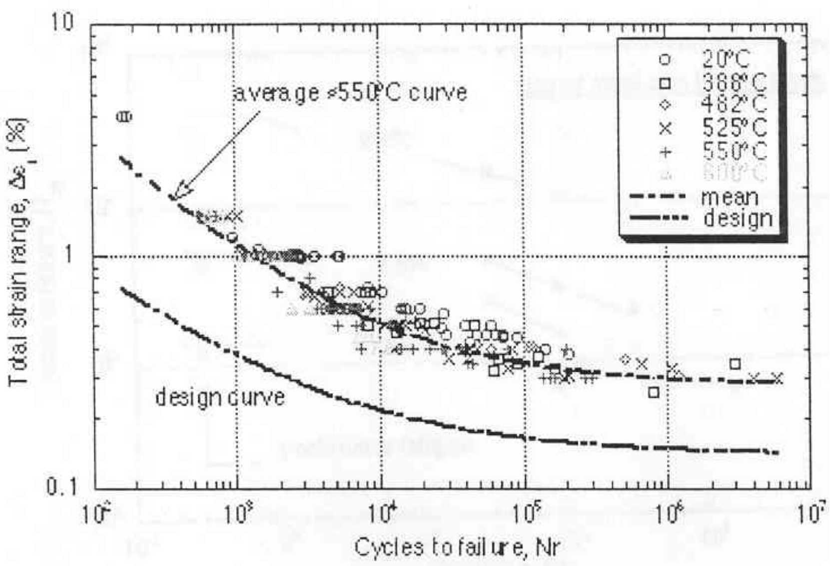
Guide Tube	Beam			LBE Weight	Max. Temperature (°C)		Max. Mises Stress (MPa)	
	Profile	Power (mA)	Orientation		Guide tube	Window	Guide tube	Window
Flat	old	2.5	0°	no	411	367	**201**	**44**
Flat	old	2.5	90°	no	359	380	**44**	**45**
Slanted	old	2.5	0°	no	364	368	**107**	**42**
Slanted	old	2.5	0°	yes	364	368	**105**	**57**
Slanted	old	2.5	90°	no	360	371	**44**	**42**
Slanted	old	2.5	90°	yes	360	371	**45**	**58**
Slanted	new	2.5	0°	no	367	370	**66**	**41**
Slanted	new	2.5	0°	yes	367	370	**63**	**55**
Slanted	new	2.5	90°	no	362	359	**46**	**43**
Slanted	new	2.5	90°	yes	362	359	**46**	**58**
Flat	new	2.0	0°	yes	337	353	**49**	**51**
Slanted	new	2.0	0°	yes	338	342	**49**	**46**

A. Zucchini, ENEA

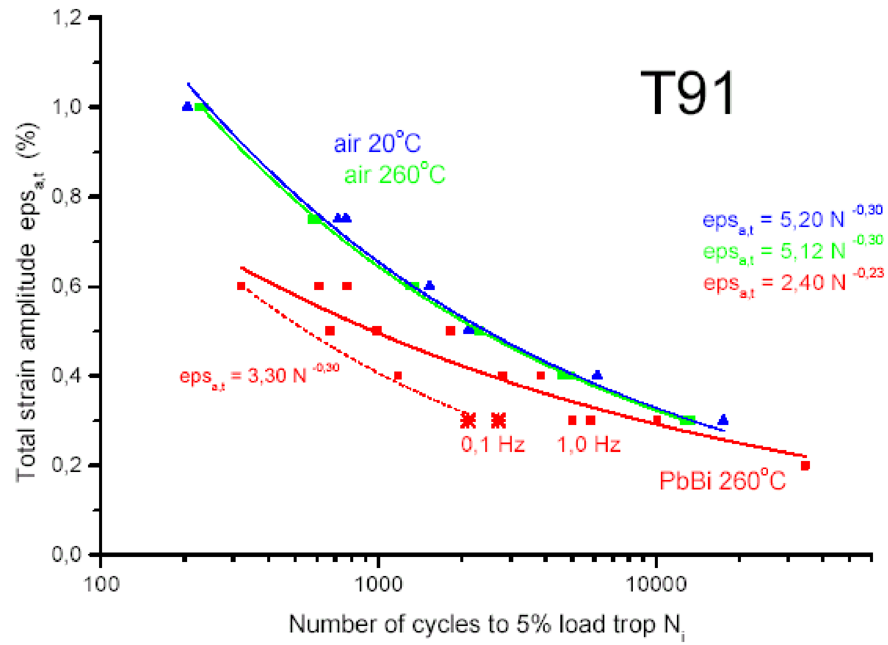




Fatigue Resistance of T91 – Influence of LBE

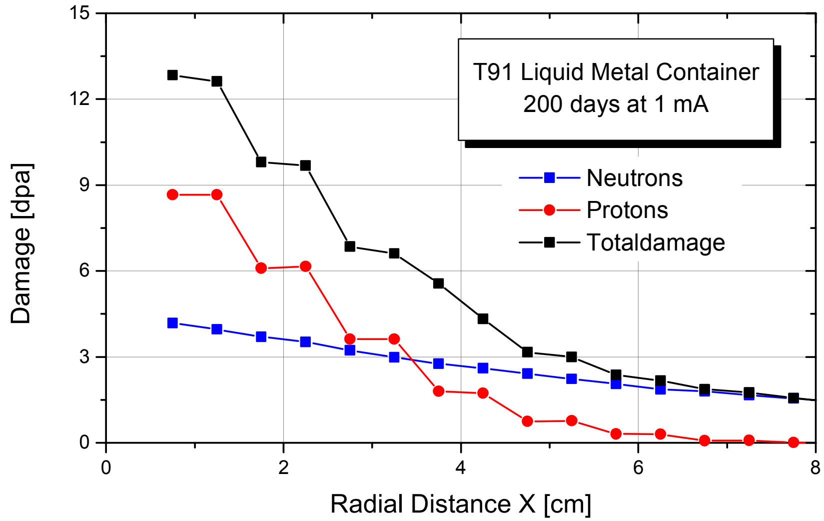


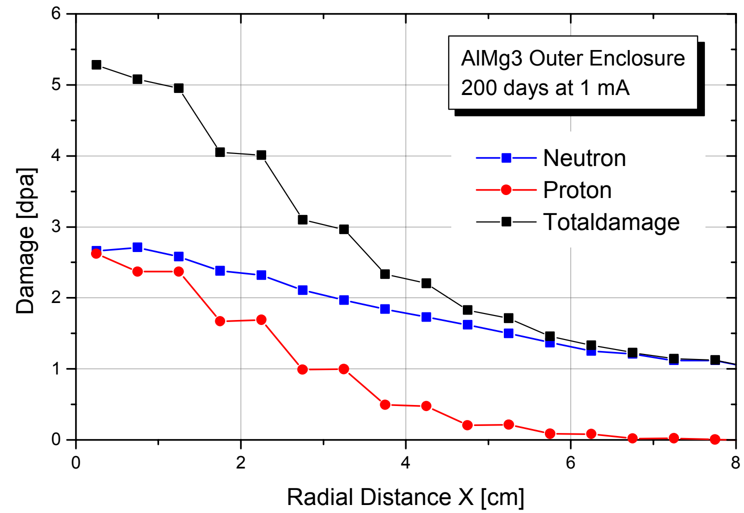
Design curve acc. RCC-MR

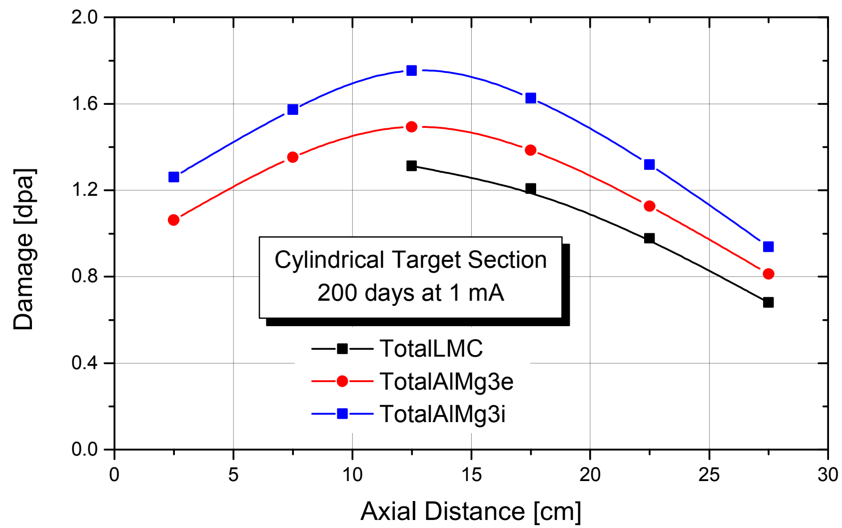


Kalkhof, Grosse: IWSTM-5, 2002

Radiation Damage

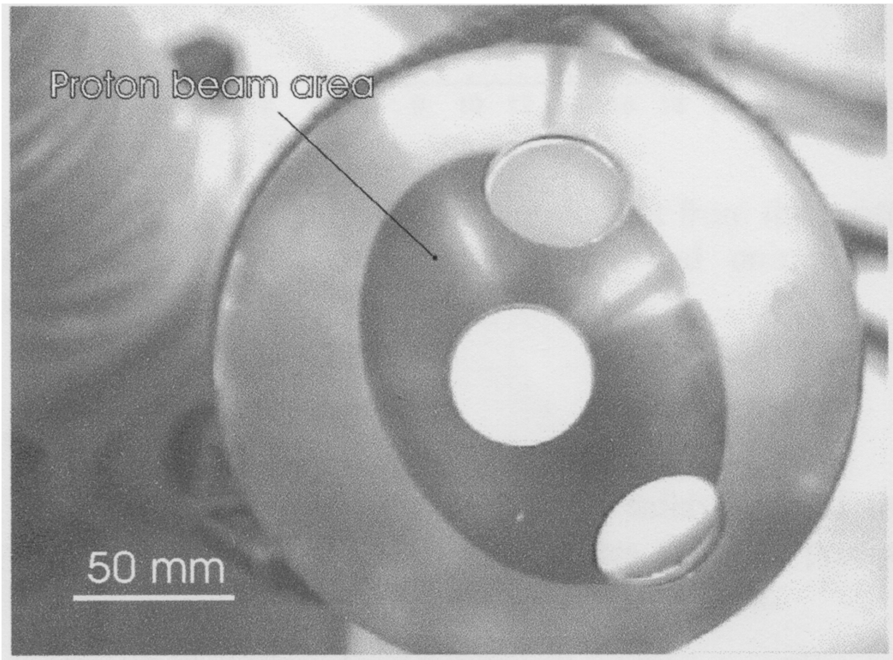


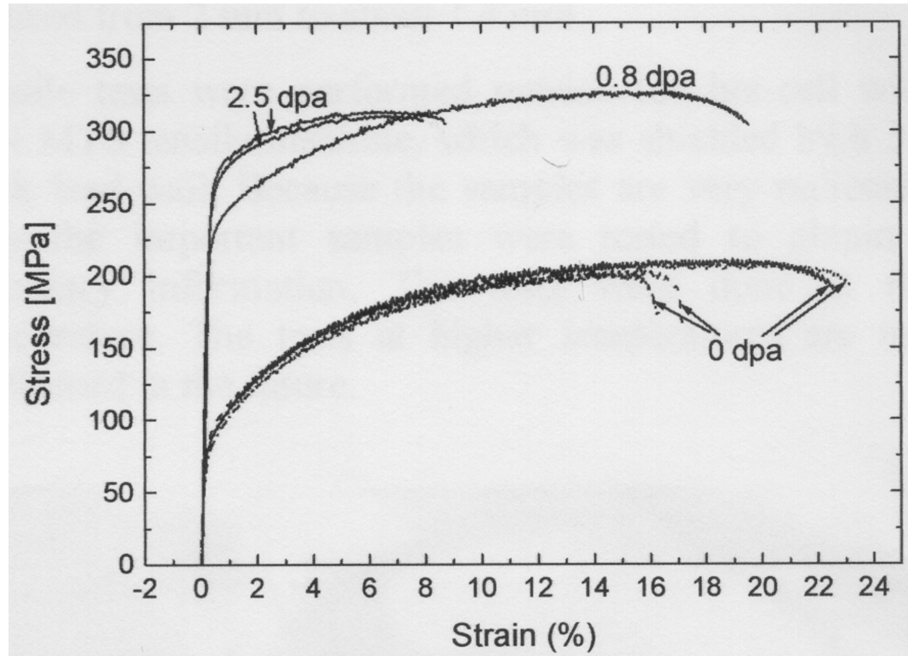




Y. Foucher, 2002

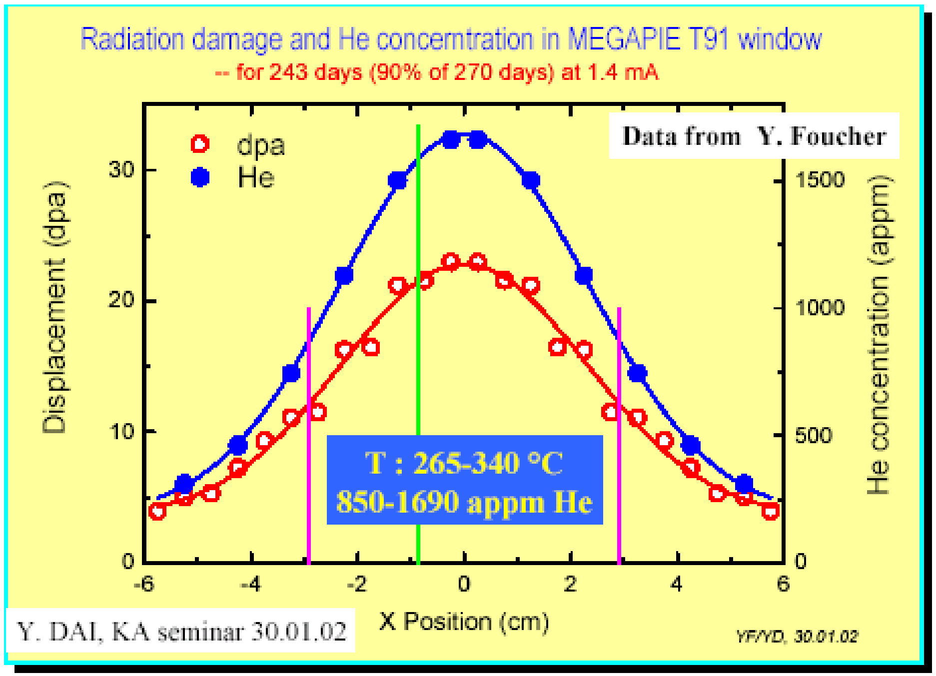
Radiation Damage



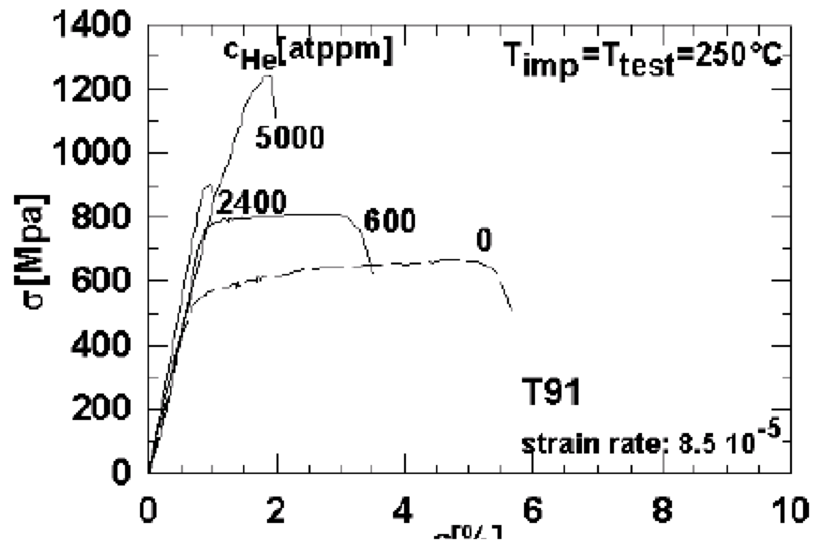


Dai et al.: PSI Annual Report 2001

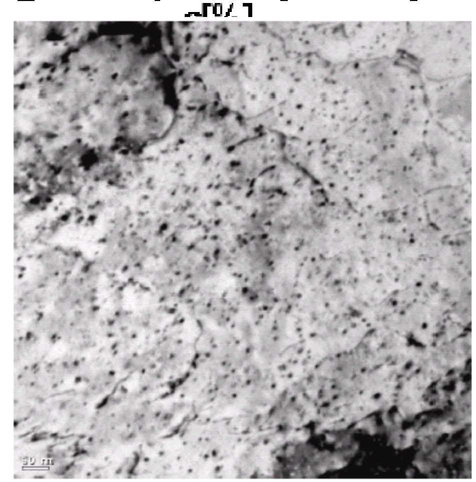
Radiation Damage and He Production



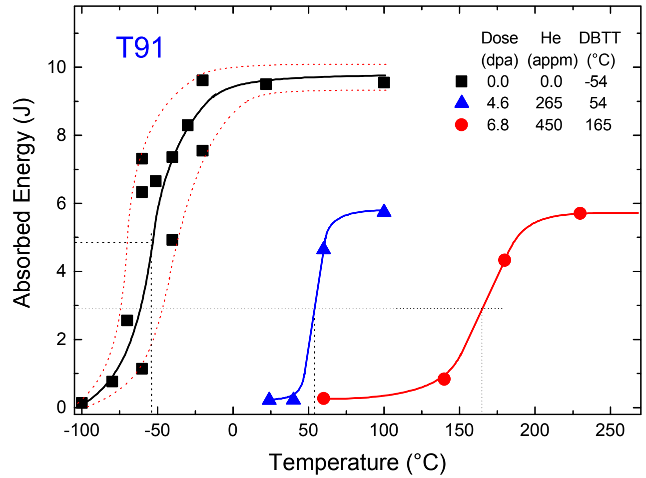
T91 implanted at 250 °C

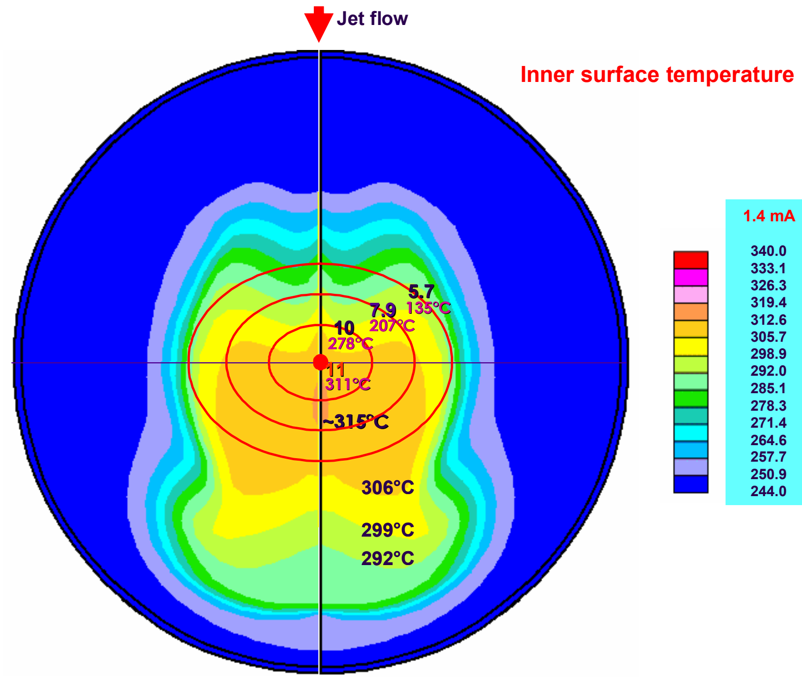


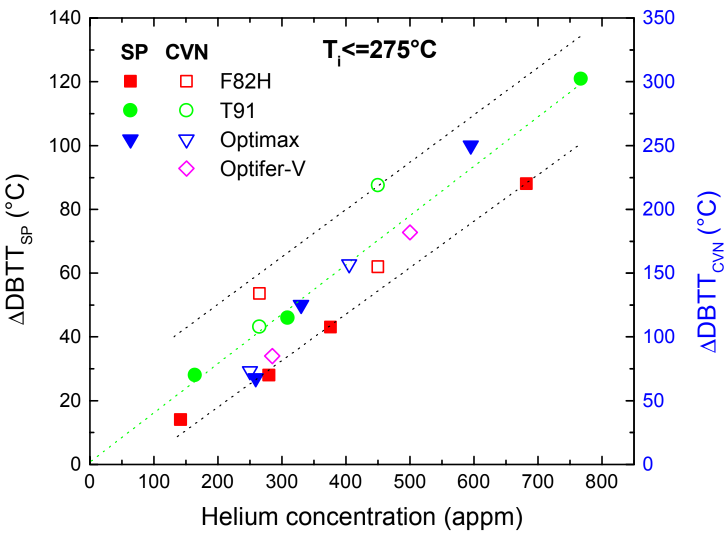
Henry, Jung: IWSTM-5, 2002

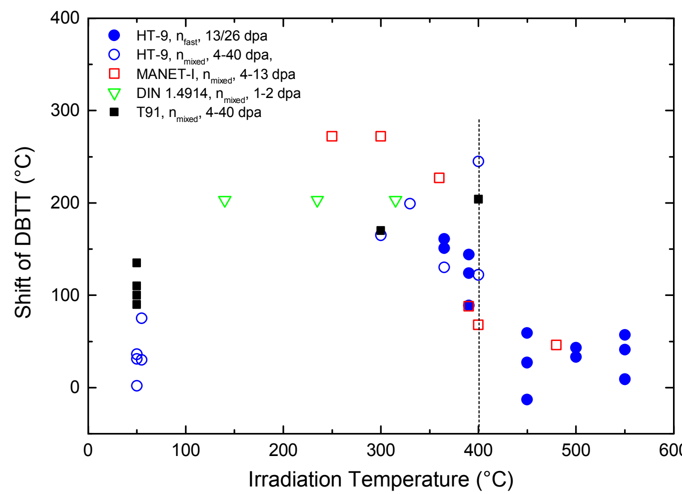


Radiation Effect on Impact Toughness

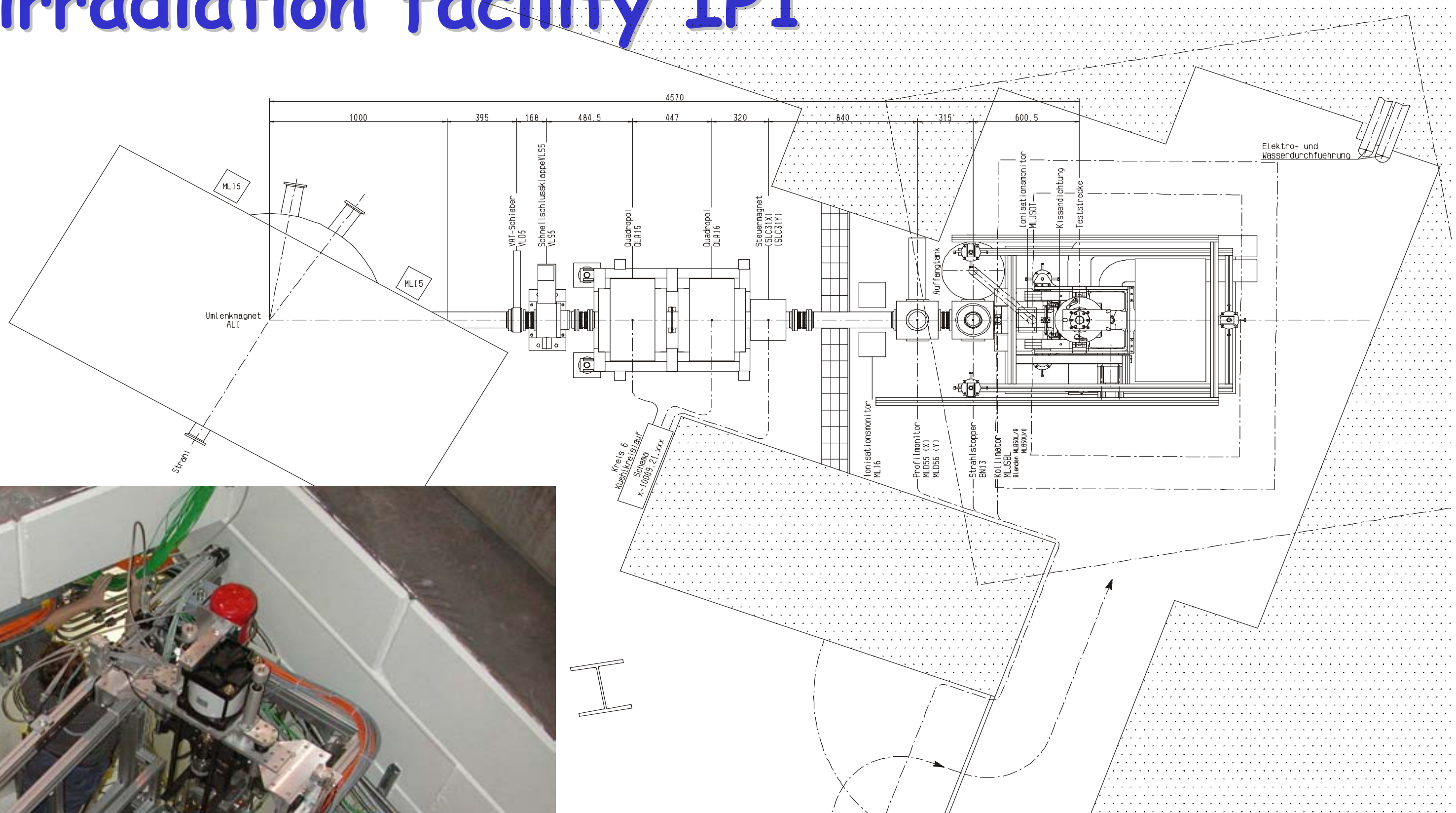


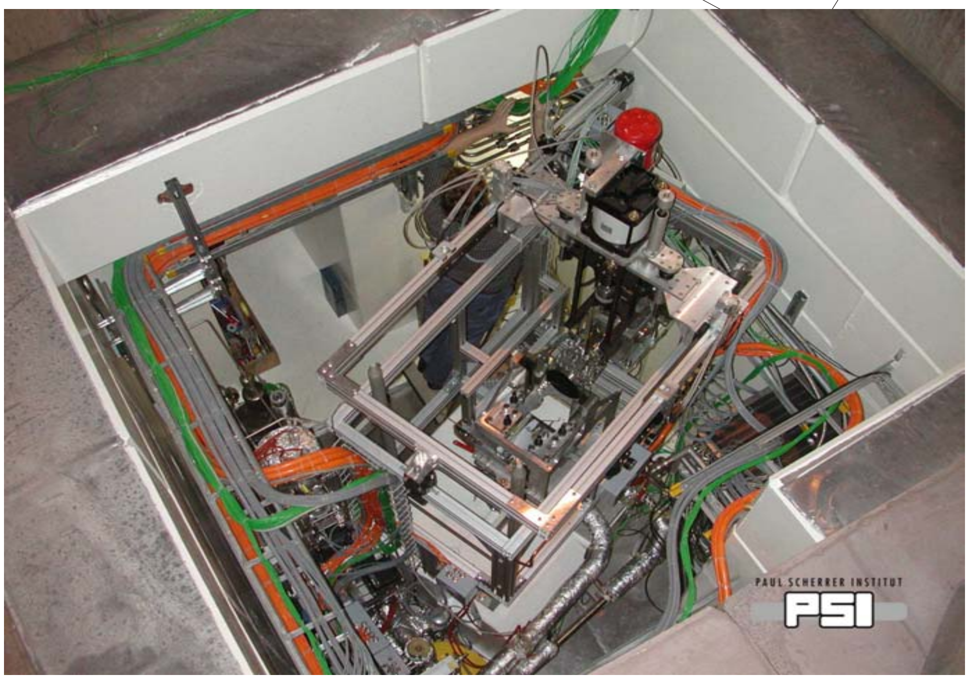






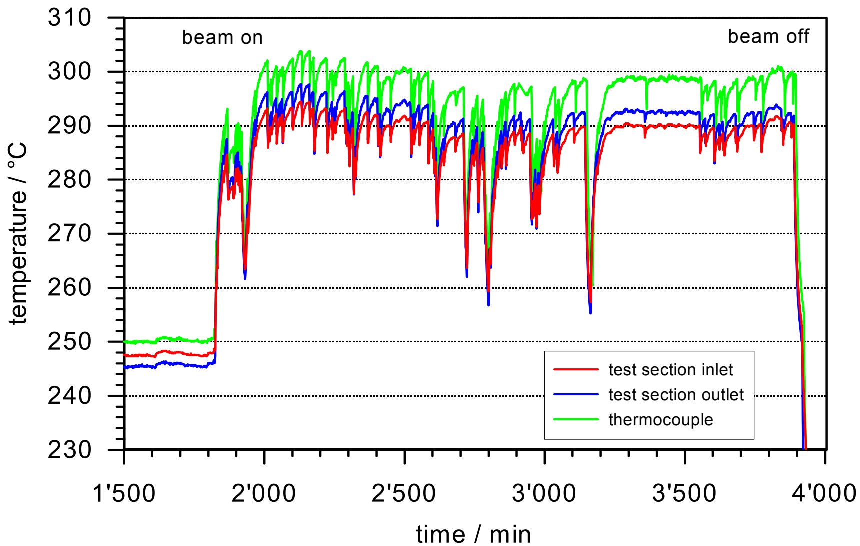
LiSoR in irradiation facility IP1

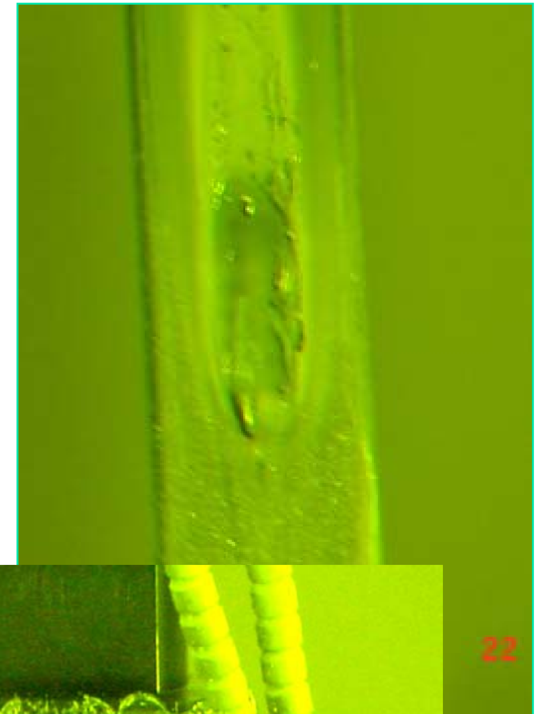


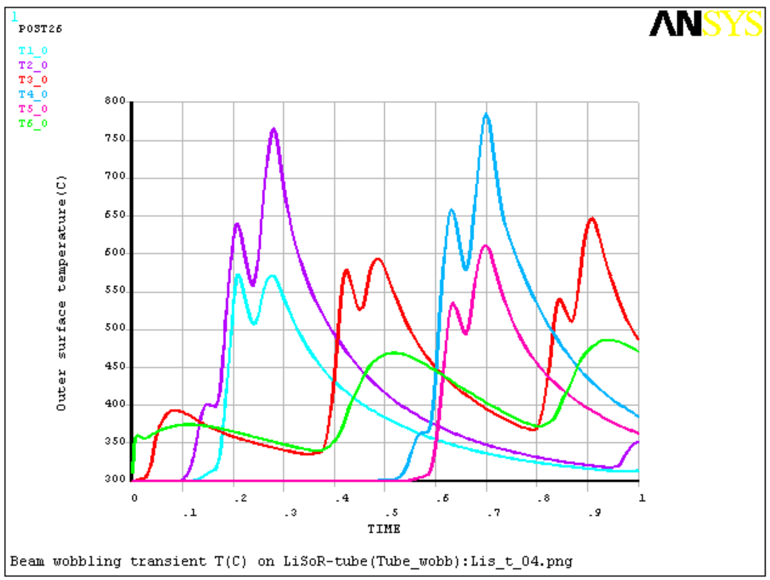


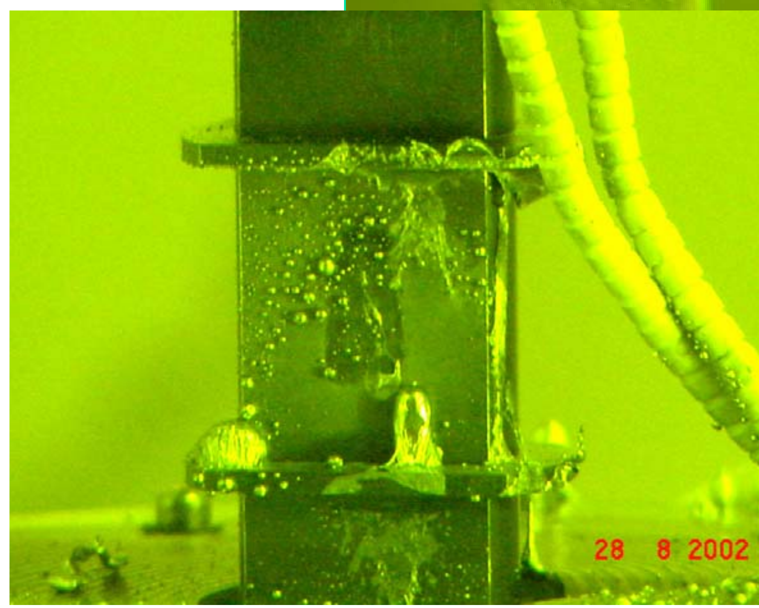
Beam energy-72MeV
Max current-30 μA
Max proton flux- $2x10^{14}$ p/cm^2/s
Beam time per test up to 10days
Radiation damage- ~ 0.25

LISOR – 1st Experiment





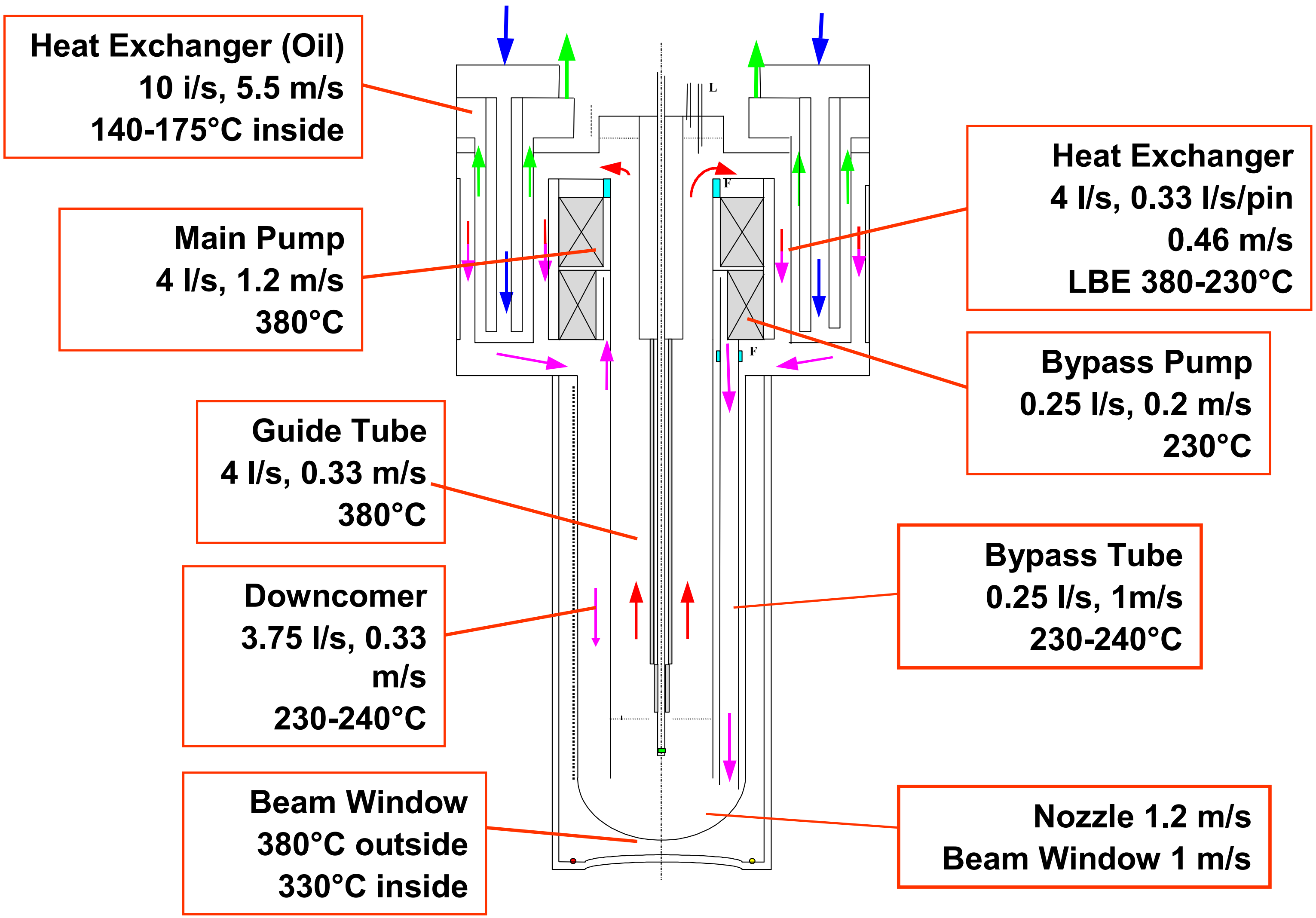




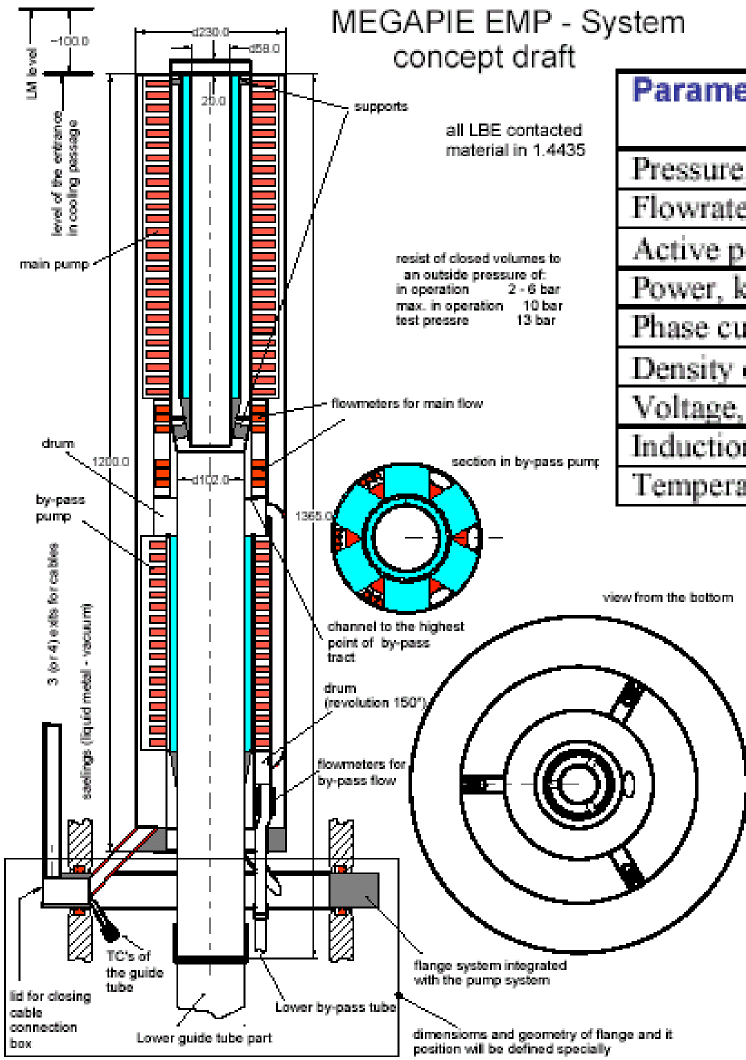
Heat Removal

- Forced flow by in-line electromagnetic pump (4 l/s)
- Bypass-flow by in-line EMP (0.25-0.35 l/s)
- 12 pin heat exchanger
- Diphyl THT intermediate cooling loop
  3-way valve and HEX bypass to control LBE THX outlet temperature
- Intermediate water cooling loop

LBE Flow Rates and Temperatures



EM Pump - System

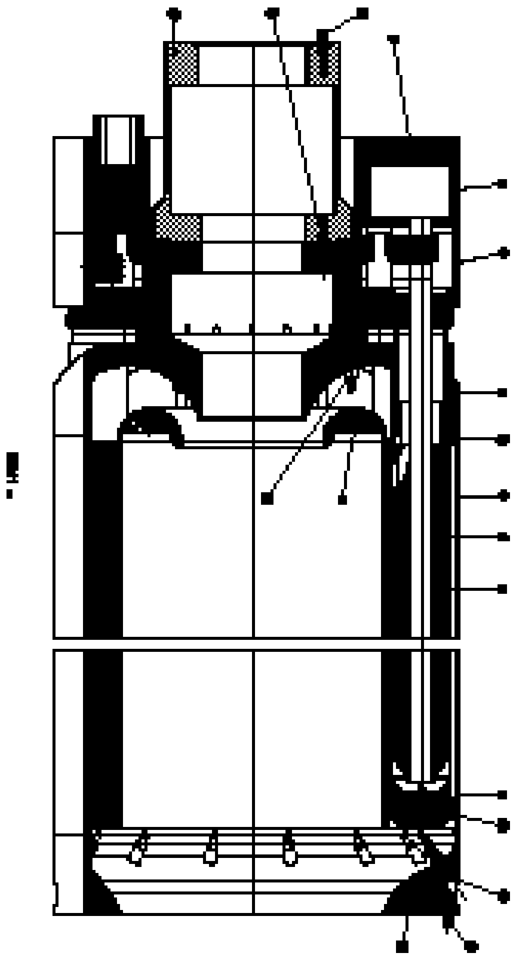


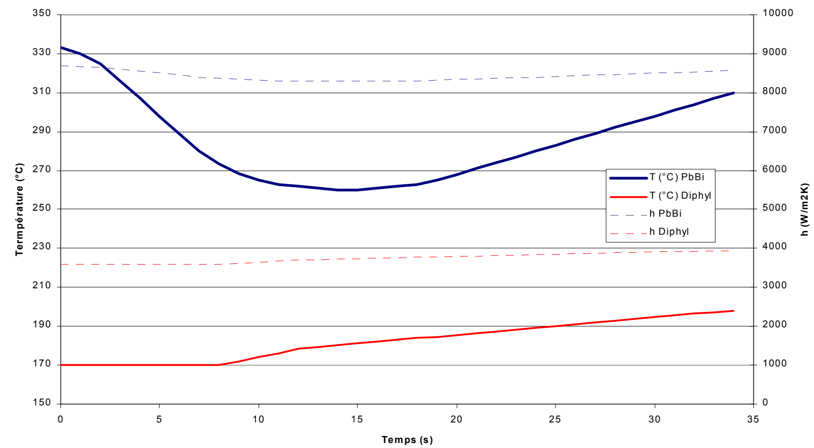
Parameters	Main pump	Bypass pump
Pressure, atm	0.2	0.5
Flowrate, L/s	5.0	0.35
Active power, kW	8.2	6.8
Power, kVA	9.8	8.14
Phase current, A	30.3	30.1
Density of current, A/mm^2	6.0	6.0
Voltage, V	108	90
Induction in passive magnetic core, T	1.2	1.14
Temperature, ^{0}C	480	320

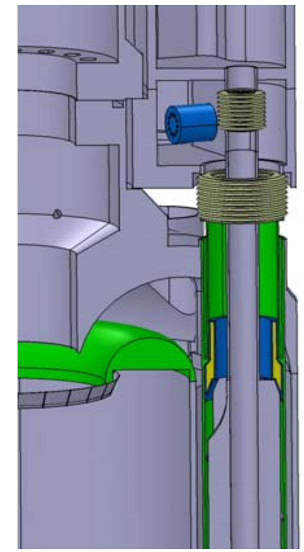
IPUL: Design Report, 2002

Target Heat Exchanger

- ❖ Heat Removal
- ❖ Thermal Transients

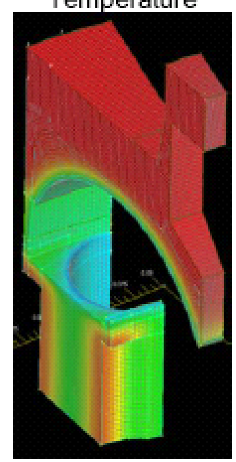






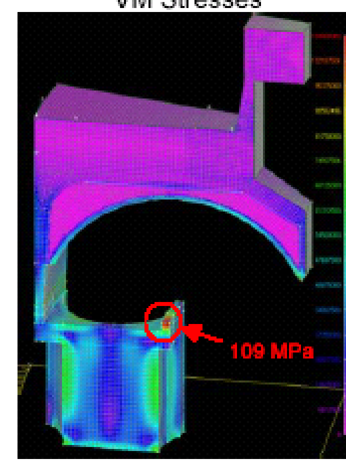
Stresses remain below 110 MPa limit according to RCC-MR

Temperature

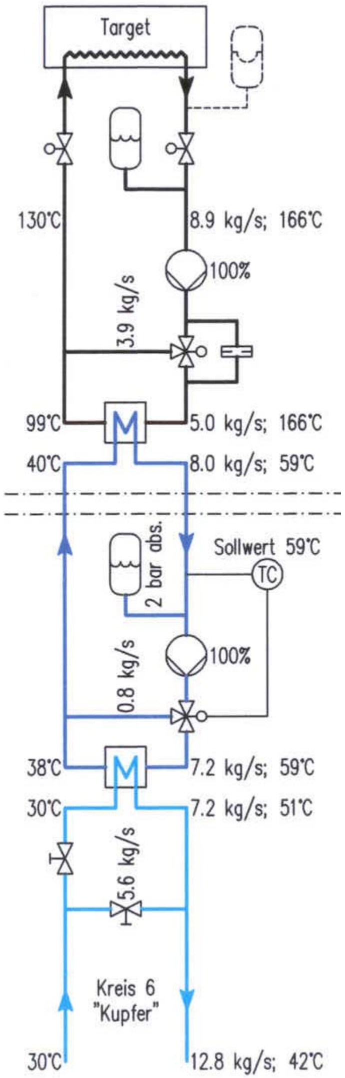


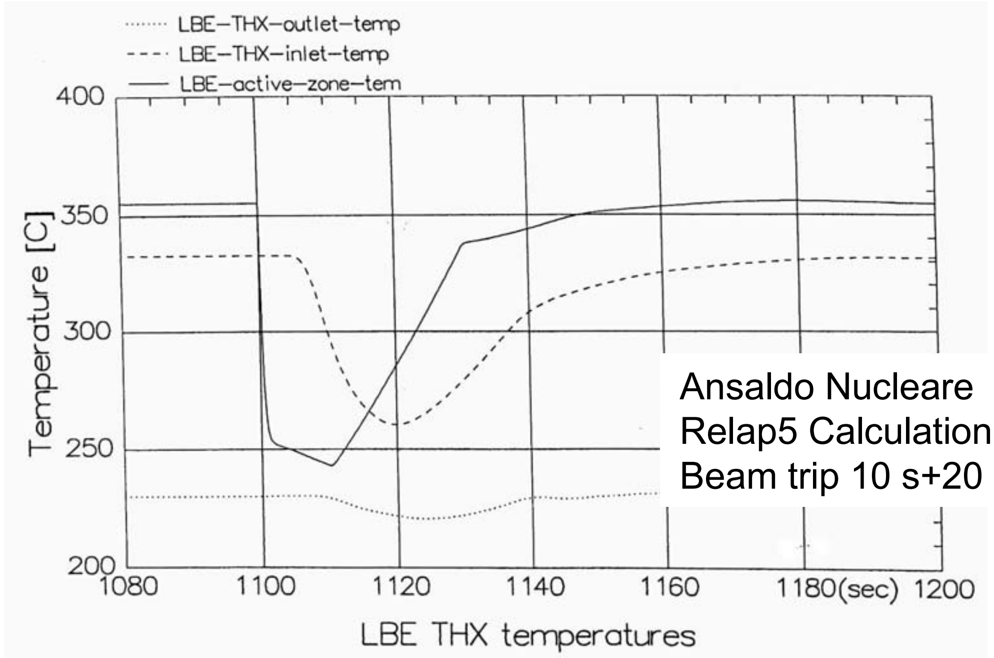
10 s

VM Stresses



Heat Removal System





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

	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

Handling of Spallation Products

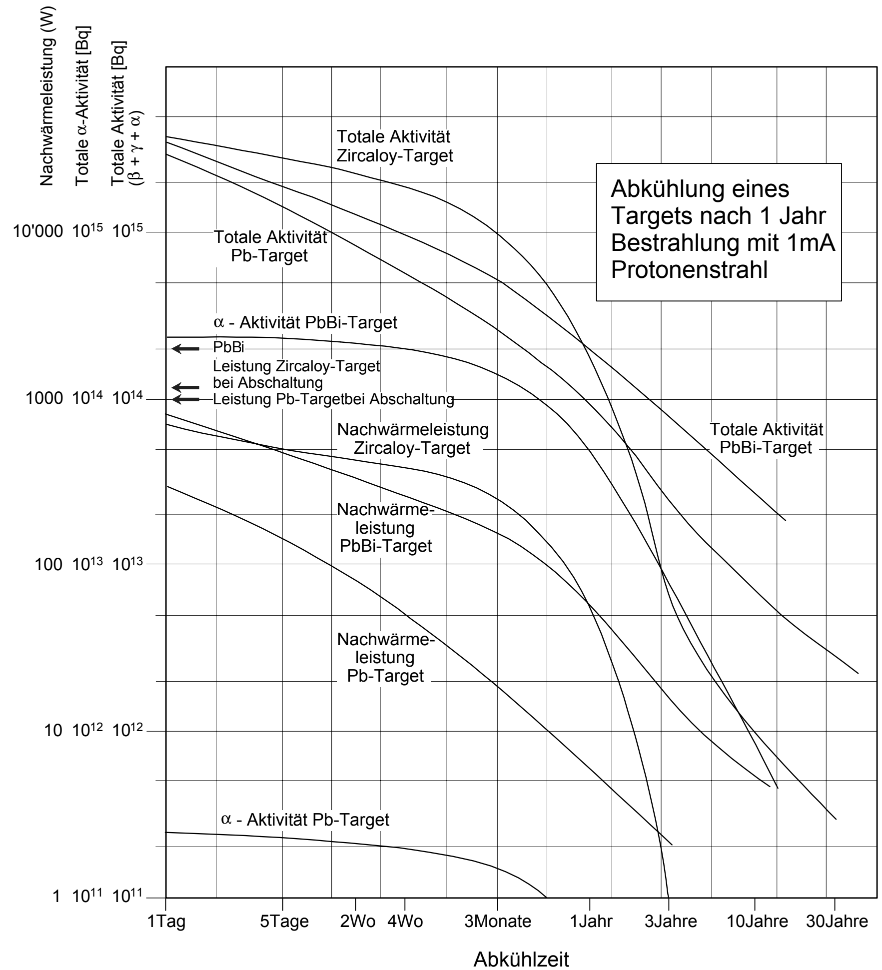
- Safe enclosure
- Drain or freeze ?
- Behaviour of Po
- Release of Volatiles

Spallation Products

F. Atchison, SINQ/816/AFN-702

Po	1.17	Cs	0.027	H	0.548
Tl	4.59	J	0.048	He	0.479
Hg	11.78	Te	0.137	Ar	0.001
Au	2.53	Sn	0.274	Kr	0.205
Pt	3.50	Cd	0.274	Xe	0.137
Ir	1.03	Zn	0.055		
Os	3.08				

Production (g) in a LBE target after 1 yea, 6000 mAh



Handling of Gases

- Safe enclosure
- Periodic venting in decay tank (shielding)
- Filters for volatiles (active carbon + HEPA particle filters)
- Gas sampling

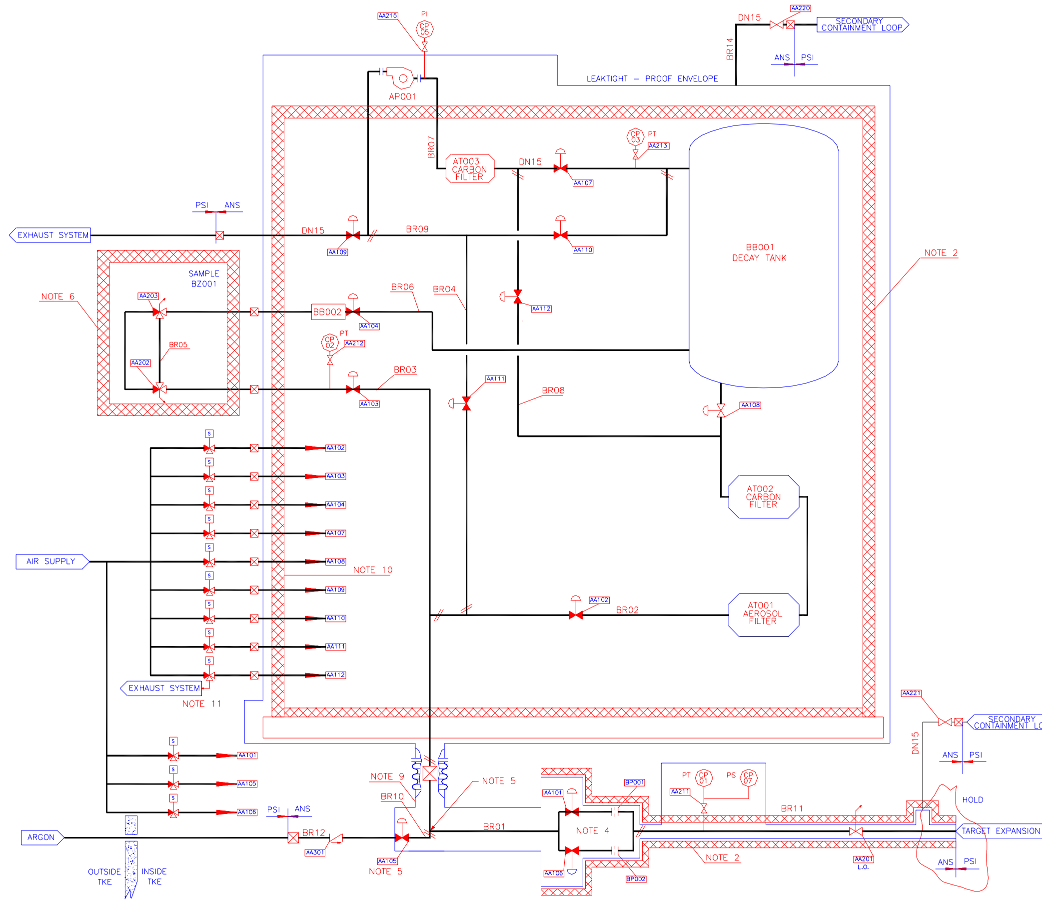
Gas Production and Handling

Production (Liter NTP)

After 1 year and 6000 mAh

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

Enderle: Neutronic Benchmark



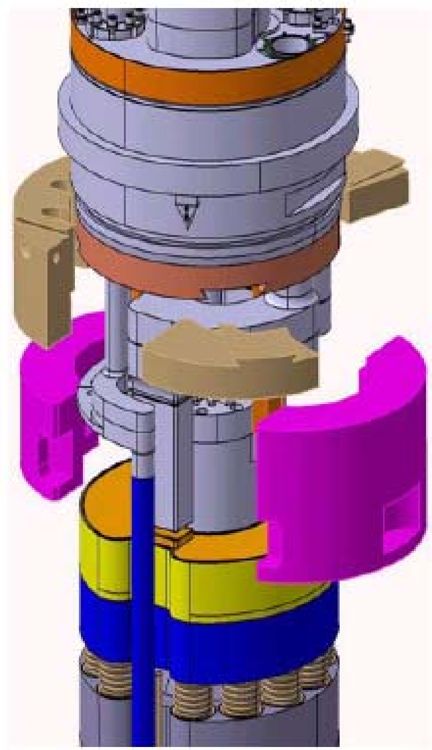
AnsaldoReference Design

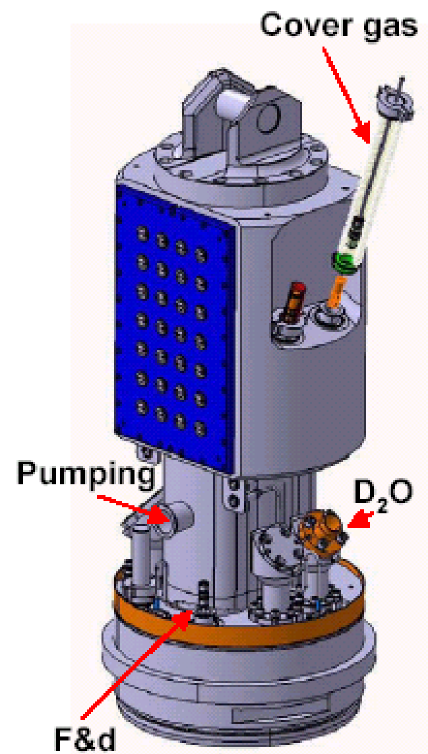
Target Head and Top Shielding

Target Support

Feedthrough for Supplies and Instrumentation

Shielding





Barrier Concept - Containment of Radioactivity

Internal effects

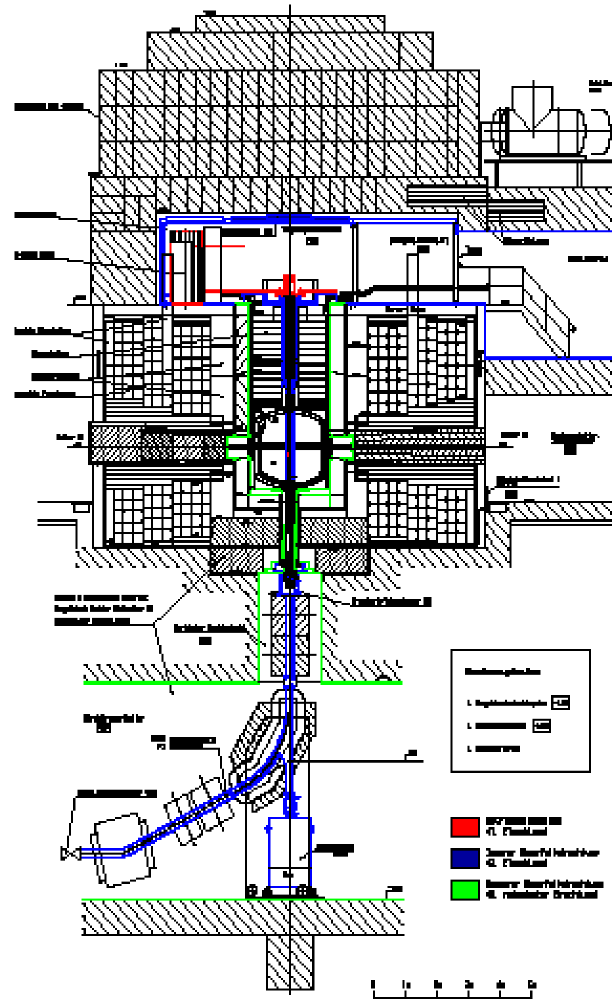
- Leak/Break of Liquid Metal Container
  - → Guillotine break of LMC
  - → Leak or Jet of LBE
  - → Water/Oil Leak
- Leak in Gas System

3 barriers for gas systems

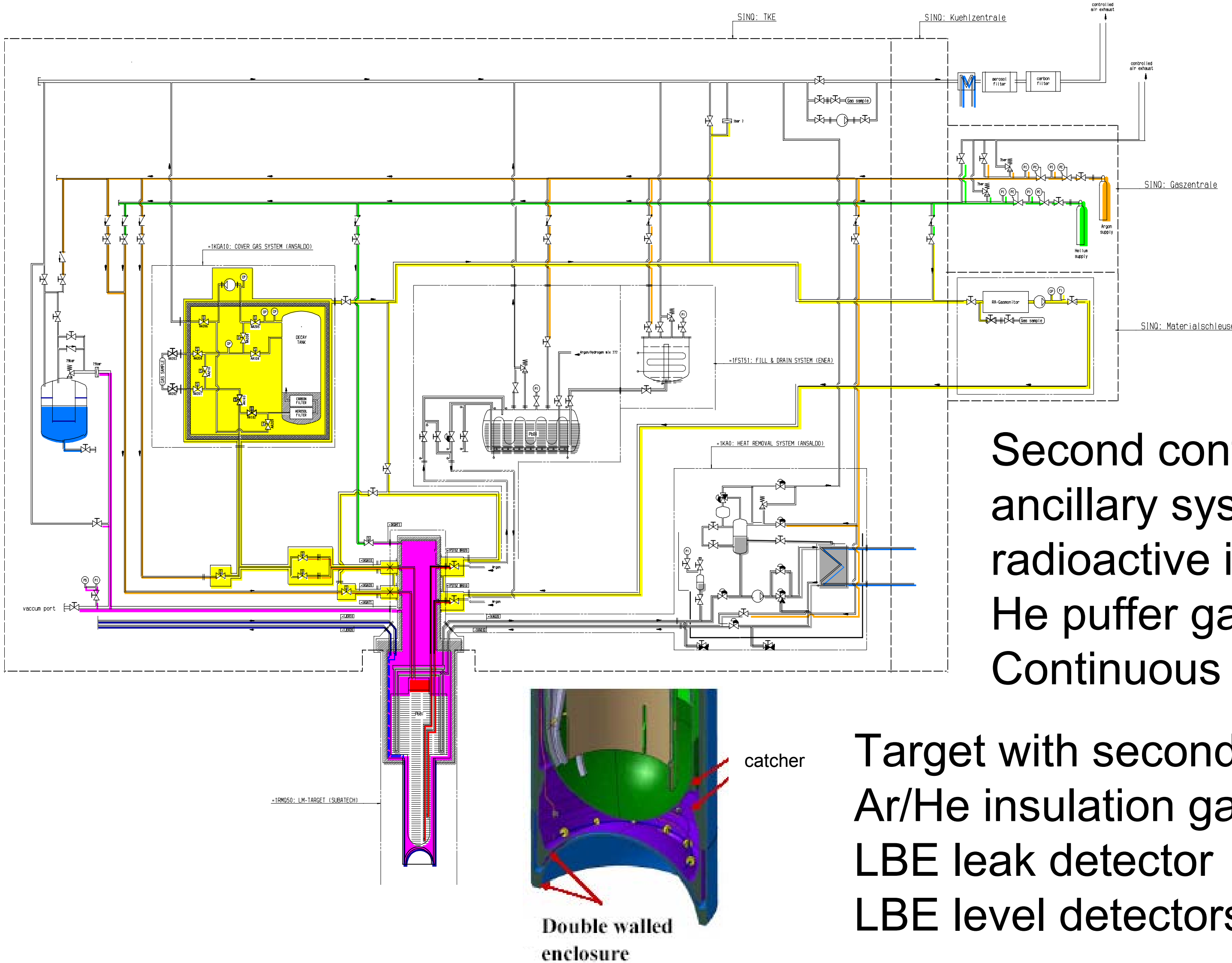
External effects

- Focused Beam
- Earthquake
- Airplane Crash
- Fire

4 barriers for liquid metal



Failure of 1st Containment



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

Target with second enclosure
Ar/He insulation gas <0.5 bar
LBE leak detector
LBE level detectors

Summary and Conclusions

- Design of main components completed
- Optimisation and validation ongoing
- Licensing Process ongoing
- Target manufacturing started
- Input from Design Support on
  → Thermohydraulics/Thermomechanics of transients
  → LM - Speciation and volatility of spallation products
  → Materials – Corrosion, LME and radiation damage
  → Reliability assessment
- Target on the Critical Path
  Delivery in June 2004
  Intensive testing in 2004
  → Irradiation in 2005