Paul Scherrer Institut

Wir schaffen Wissen – heute für morgen

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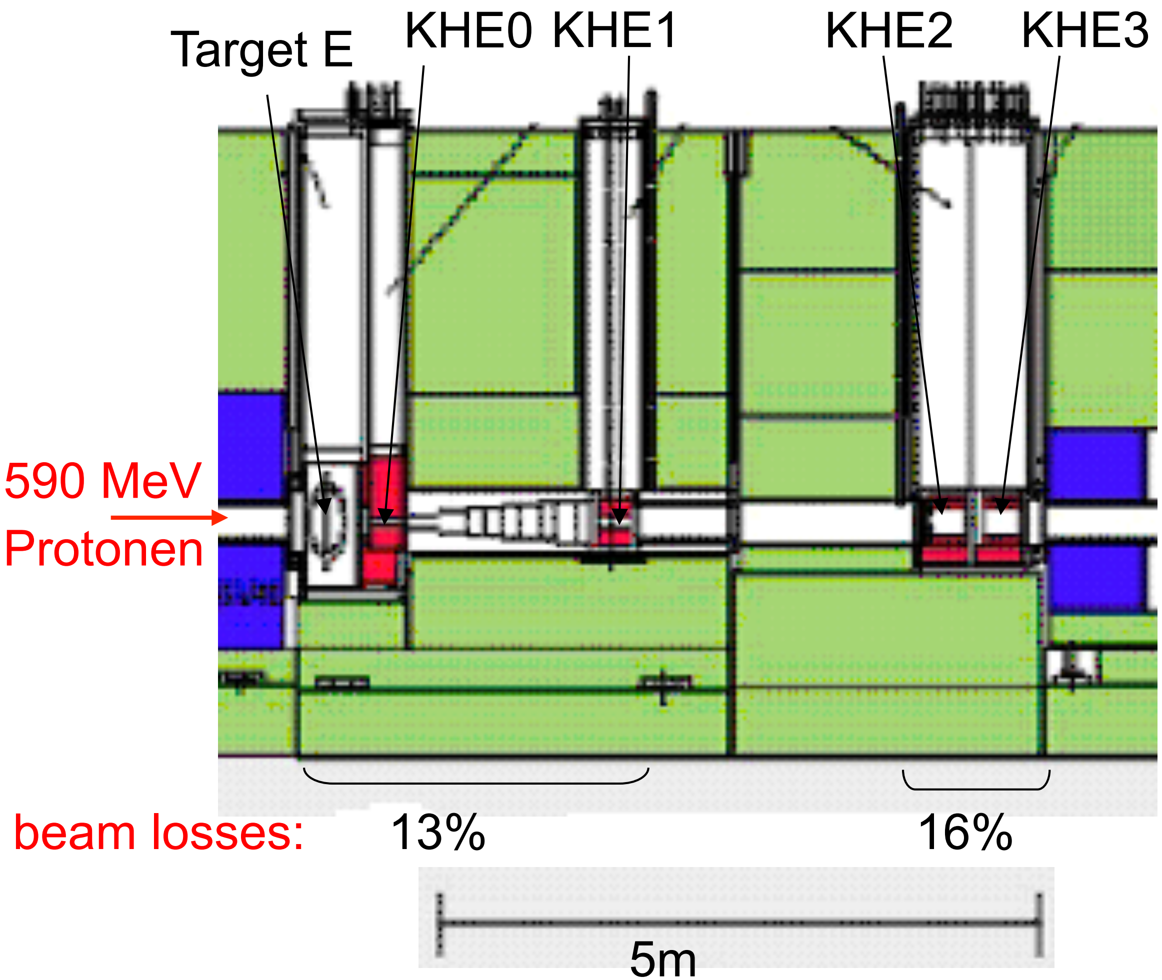
Examination of a copper collimator irradiated in the 590 MeV proton beam line at PSI

Contents

- Location, purpose and history of collimator KHE2
- DPA calculation with MCNPX, dcs (A. Konobeyev), MARS
- Inspection of KHE2
- Measured and calculated (residual) dose rate
- Photos from the inspection
- Calculation of the activation for 2 samples (comparison to measurement)
- Conclusion and outlook

Proton beam line from Target E to KHE2&3



Target E:
purpose: meson production
- 4 cm graphite wheel
- rotating with 1 Hz
- additional beam spread: ~6 mrad

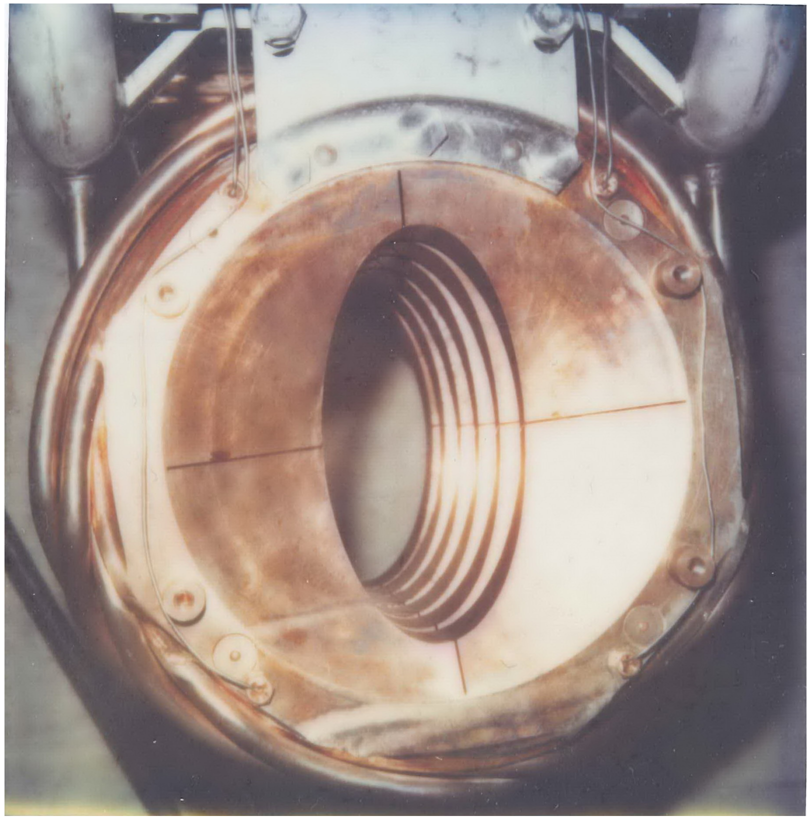
Collimator system: OFHC-Cu
- protection of the beam line
- reduction of beam losses (activation)

→large power deposition: 150 kW in KHE2

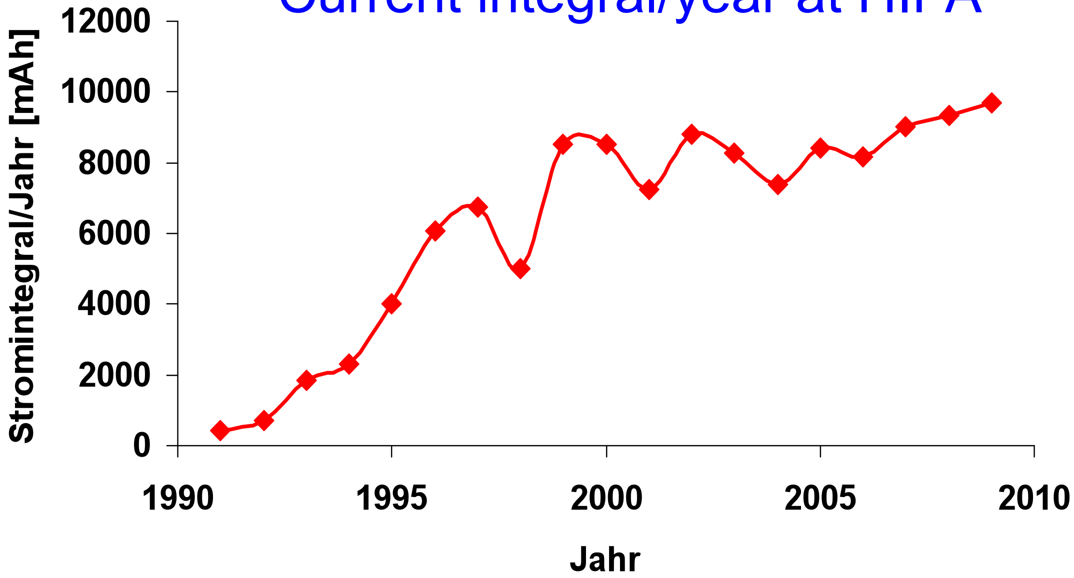
KHE2: Overview

Operation: from 1990 up to now
Current integral onto Target E:
1990-2009: 120.5 Ah
absorbed: ~ 12%

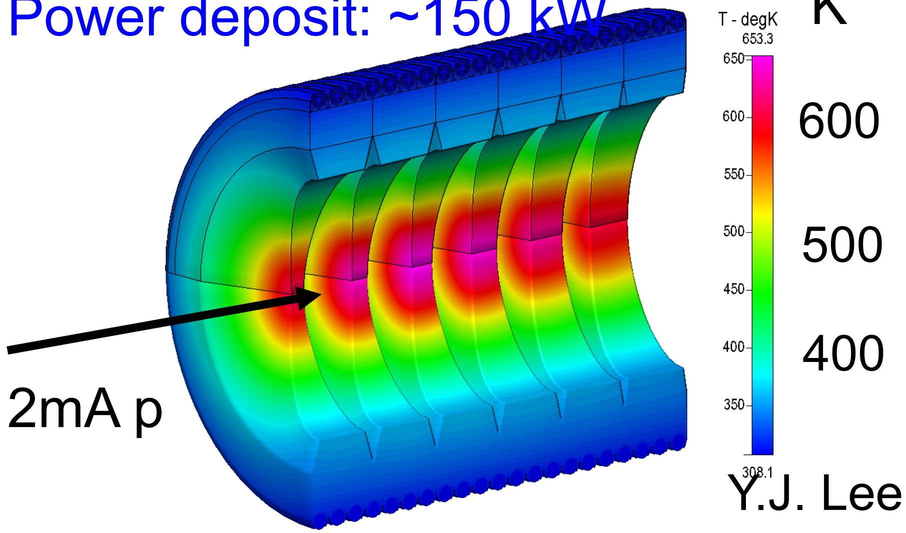
KHE2: 1990 before installation



Current integral/year at HIPA



Temperature distribution: max: 380 °C
Power deposit: ~150 kW



Displacement cross section (dcs)

$$\sigma_{dis}(E) = \int_{E_d}^{E\max} \frac{d\sigma_{dam}(E, E_R)}{dE_R} \nu(E_R)\, \mathrm{d}E_R$$

particle energy

damage cross section:

$$= \frac{w(E_R)}{xN_V}$$

damage function (no. of displaced atoms):

$$= \frac{\kappa T_{dam}}{2E_D}$$

modified Kinchin-Pease m.
= NRT model
(Norgett RobinsonTorrens)

$w(E_R)$: recoil spectrum
needs nuclear reaction models

x: thickness of the sample

N_V: atomic density ($atoms/cm^3$)

T_{dam} : damage energy

displacement efficiency κ = 0.8

some remarks on uncertainties:

- E_D in Cu: 18 – 43 eV, choice: 30 eV (for MCNPX, dcs)
- κ = 0.8: for hard sphere model (Rutherford formula) compensates for the forward scattering

DPA calculation

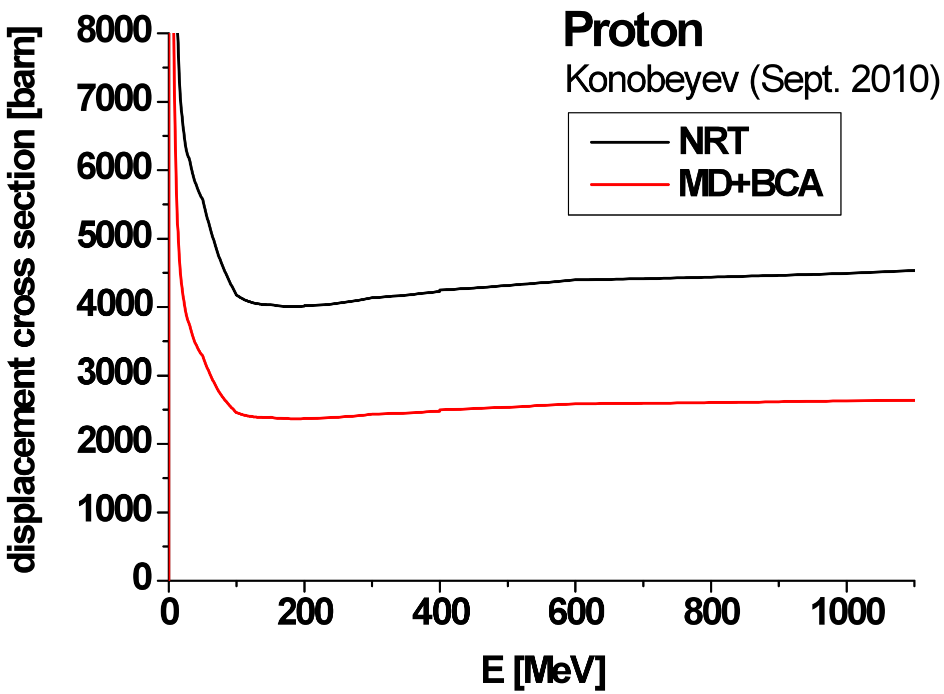
$$DPA = \eta \int \sigma_{disp}(E) \frac{d\phi(E)}{dE} \, dE$$

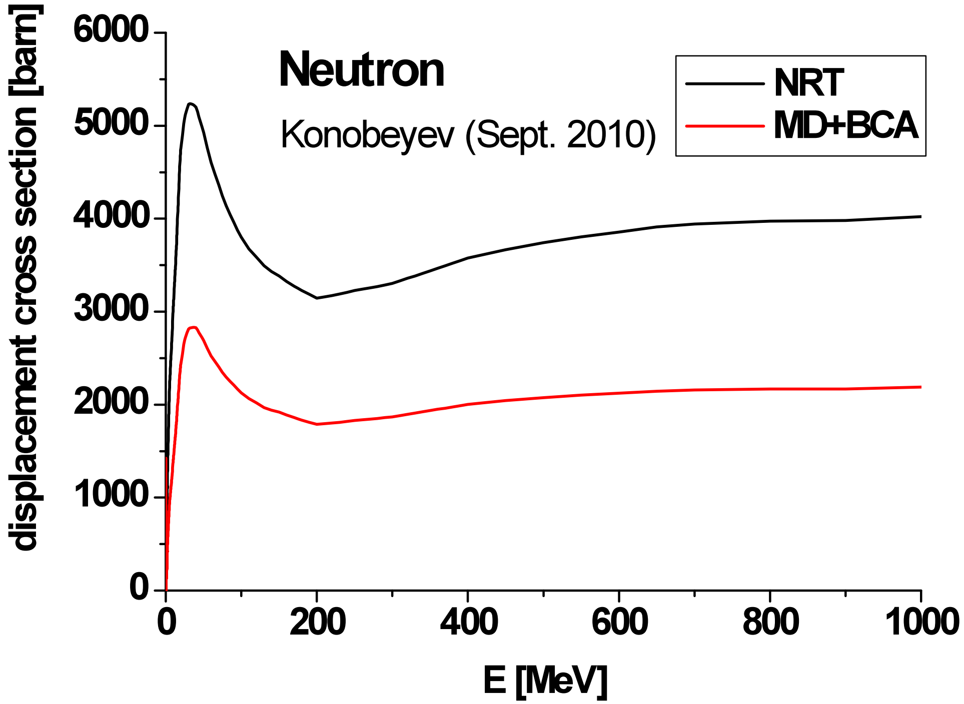
$\phi(E)$: fluence (particles/cm^2)
σ_{disp}: displacement cross section

Methods and codes:

- Displacement cross section (dcs) from A. Konobeyev (Sept. 2010) evaluated from several reaction c.s. codes, accounting for defect efficiency η, η=1 for NRT
- MCNPX2.5.0: CEM model and ENDF/B-VI (for n, < 20MeV)
  for protons:
  - displacement cross section for E = 590 MeV only
  → o.k. for 1. section of KHE2 (energy loss in 5 cm Cu: ~120 MeV)
  for neutrons:
  built-in damage cross sections (Monroe Wechsler and Marvin Barnett) as flux multipliers
- MARS15 (2010): see N. Mokhov talk
  - energy dependent displacement efficiency: $\kappa(E_R)$, in NRT: κ = 0.8
    κ(0.1keV) = 1.4 to κ(100keV) = 0.3
  - Coulomb interaction, formfactors, photons, muons, electrons
  - nice feature of 2-dim. plots showing distributions of DPA (+other quantities)

Displacement cross sections (dcs)





A. Konobeyev:

- E > 150 MeV: average of Bertini, Isabel, INCL4
- 20 < E < 150 MeV: CEM, DISCA code
- E < 20 MeV: ENDF/B-VII (neutrons)

elastic c.s.: optical model + screened Coulomb potential (protons)

see U. Fischer's talk for details

E < 28 keV: Molecular Dynamics (MD)

E > 28 keV: Binary Collision Approximation (BCA)

→ number of stable defects obtained with the IOTA code (ion-ion collisions)

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Checks on the MCNPX calculation

1. Comparison of the dcs for 590 MeV p

   MCNPX2.5.0 + CEM, 6227 barn

   A. Konobeyev: 4764 barn

   → fair agreement: 30 % deviation

2. Comparison of DPA:

   - (Old) Experiment at Pirex (PSI): 590 MeV protons on 0.3 mm Cu
     1 DPA = 1.5 10^{20} protons/cm^2 (LAHET calculation)
     (Singh,Horsewell, ASTM STP 1175, (1993), 1003)

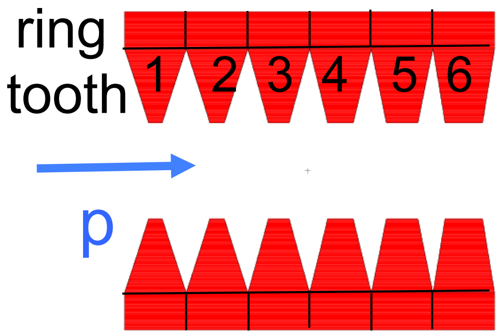
   - Calculation: MCNPX2.5.0 + CEM model
     0.93 DPA due to protons
     0.02 DPA due to neutrons

     → very good agreement!

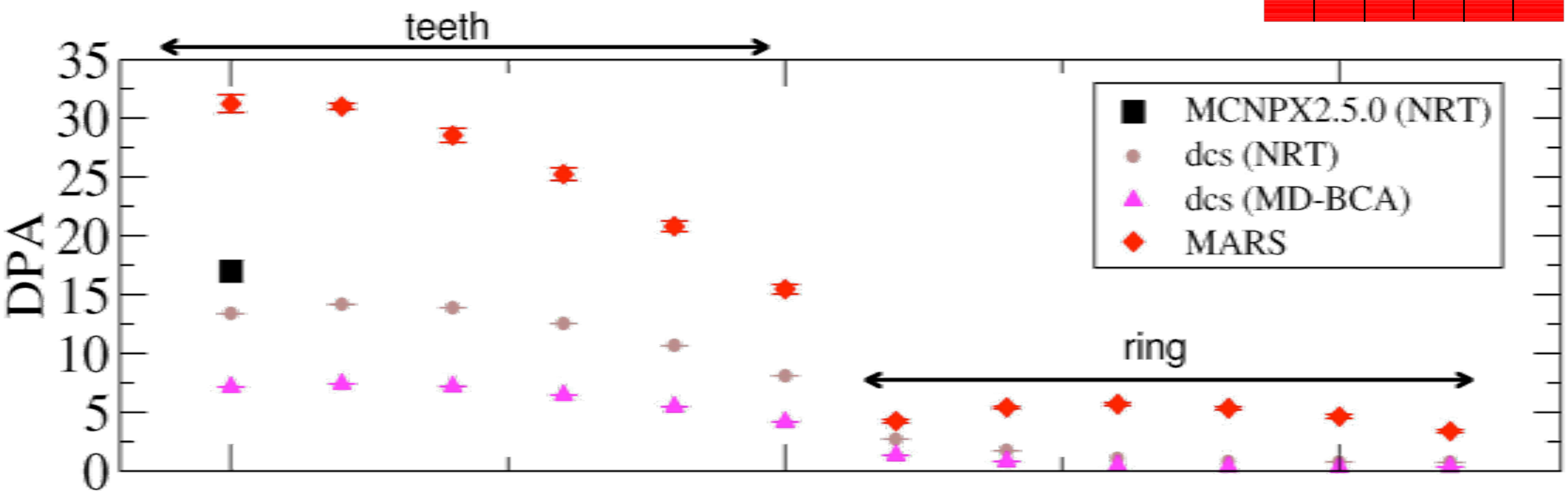
Comparison of results from MCNPX, dcs, MARS

DPA for 1. tooth: Comparison

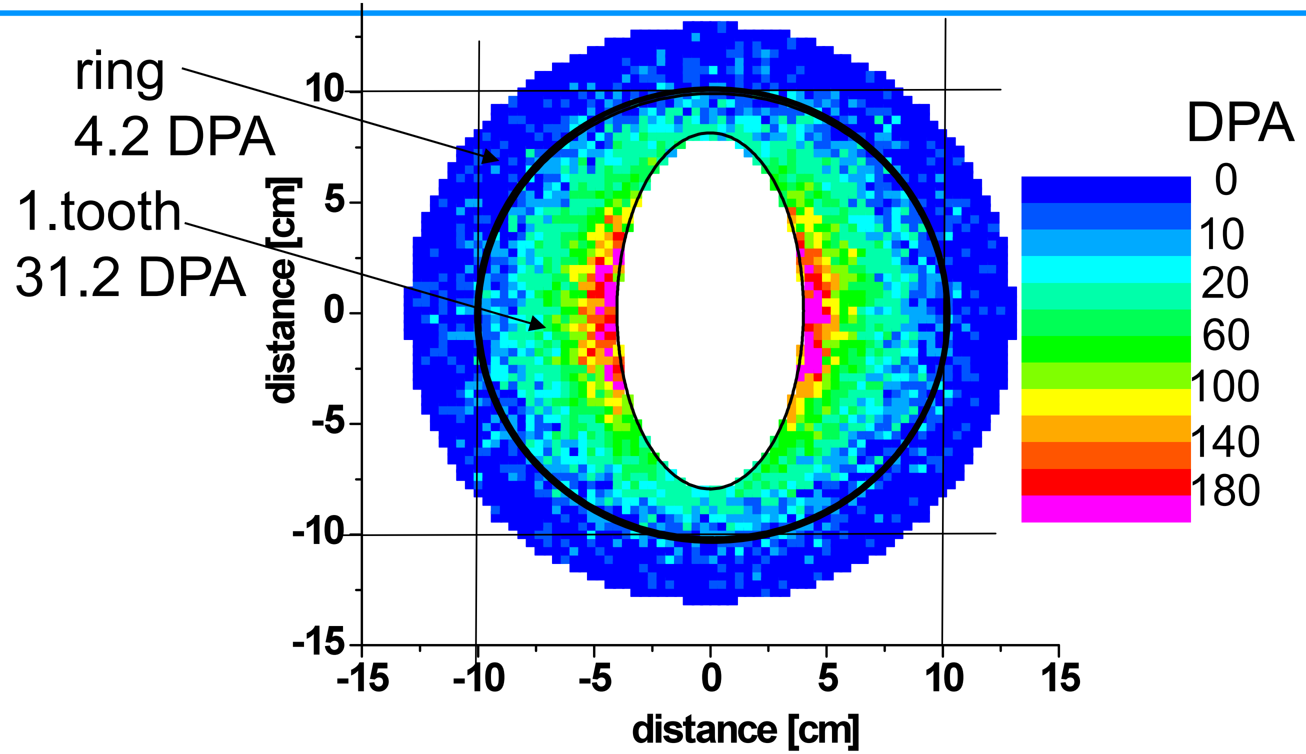
	NRT(MCNPX)	NRT(dcs)	MD(dcs)	MARS
protons:	11.6	8.2	4.8	
neutrons:	5.4	5.2	2.3	
Total:	17.0	13.2	7.1	31.2

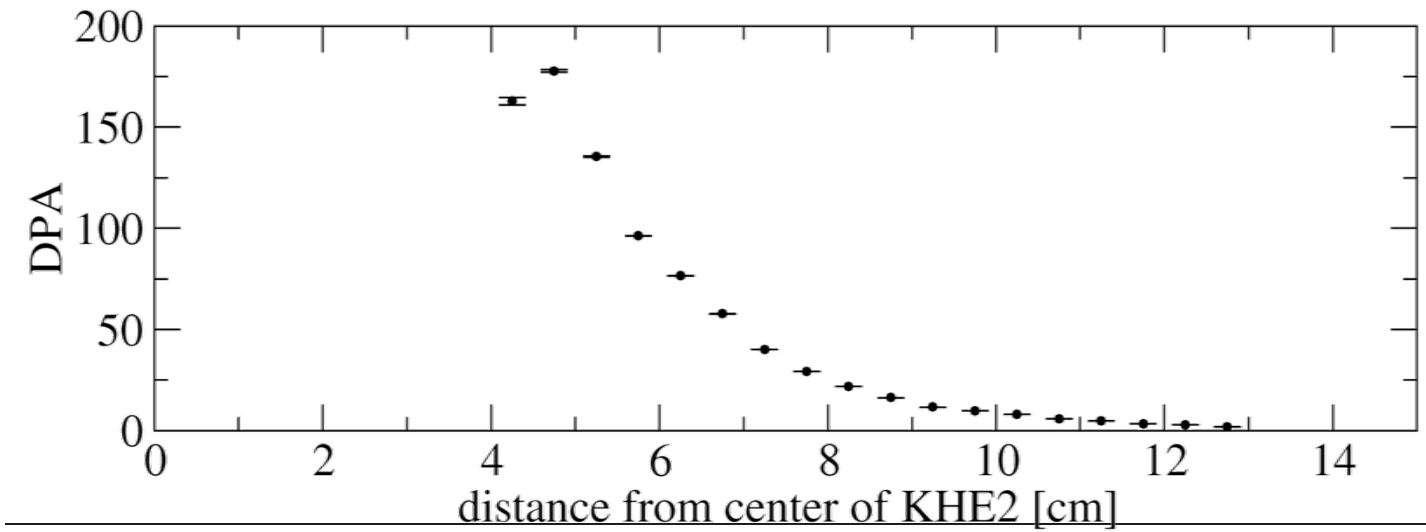


irradiation from 1991 – 2009



DPA distribution on the 1. tooth of KHE2 (MARS results)

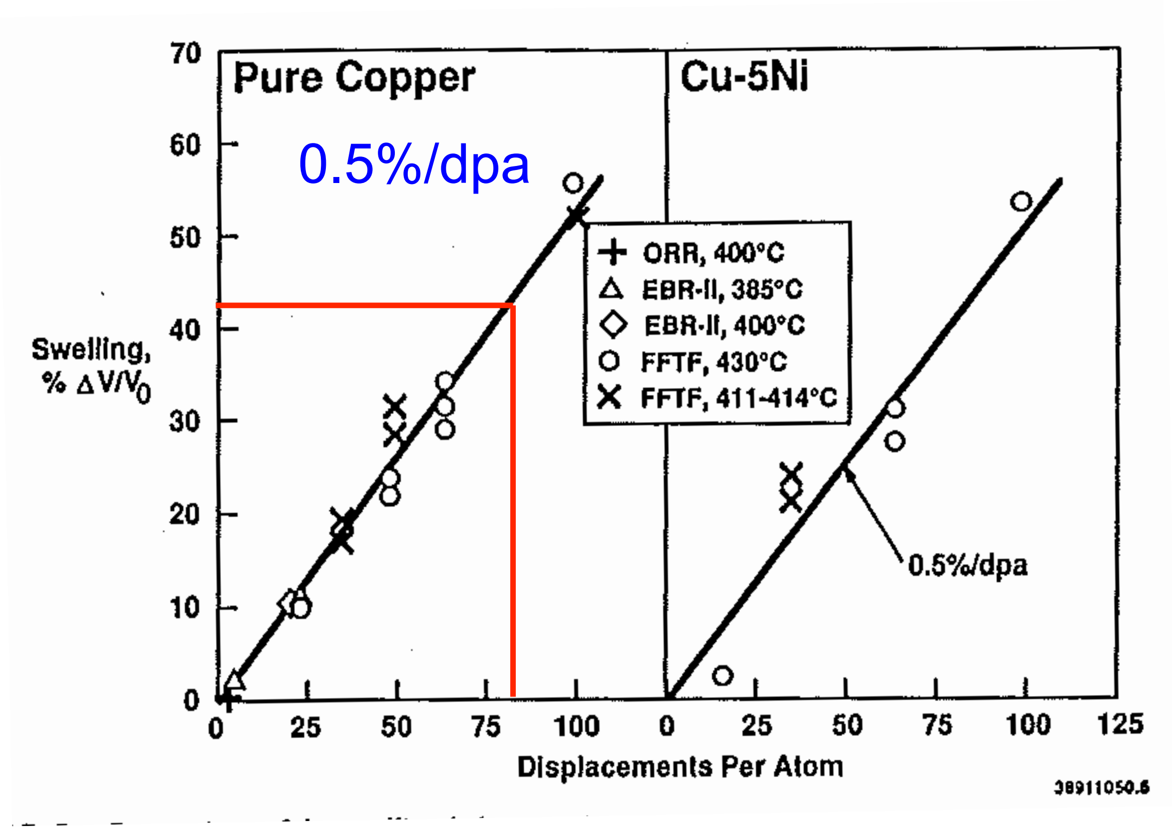




Radial dependence of DPA on 1. tooth

very high DPA at the inner side

Swelling after irradiation with neutrons



80 DPA → ~40 % swelling

S. Zinkle, Effects of Radiation on Material, 15th Symposium 1992, p. 813-834

- no saturation up to 100 dpa
- data are for neutrons only (thermal and fast reactors)

→ Not much is known for high energetic protons

Reasons for the inspection of KHE2

1) Operation reliability:

- no replacement at hand: would take ~3/4 year
- after 20 years of operation: end of life time? radiation damage?

- for reactor neutrons (therm. and fast)
  visible swelling would be expected inside (40 % for 80 DPA)

- change of mechanical properties: cracks, embrittlement
  and physical properties: therm. conductivity → important

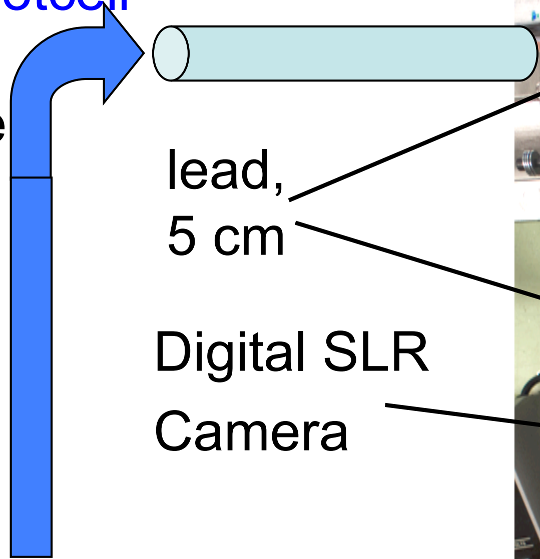
- high therm. load: ~150 kW at 2 mA, up to 380 °C
  → assumed that the therm. conductivity did not changed

2) New collimator of similar design planned for 3 mA operation:
KHE2 is limited to 2.5 mA ←→ ½ melting temperature (405 °C)
question: OFHC-Cu or Glidcop?

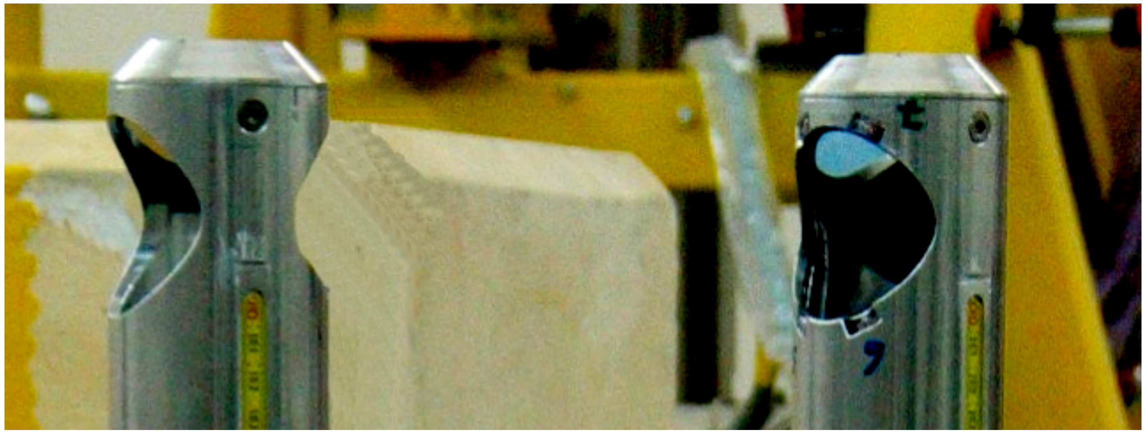
There is a remaining risk of failure after removal and reinstallation
→ good preparation, precautions and safety procedures necessary

Examination with the inspection tool

- constraint: contact-free!
- fully remotely controlled in the hotcell
- options:
  - photos from inside and outside via camera and mirror tube1
  - opening of the aperture with 2 laser distance meters
  - surface roughness with a tiltable laser beam

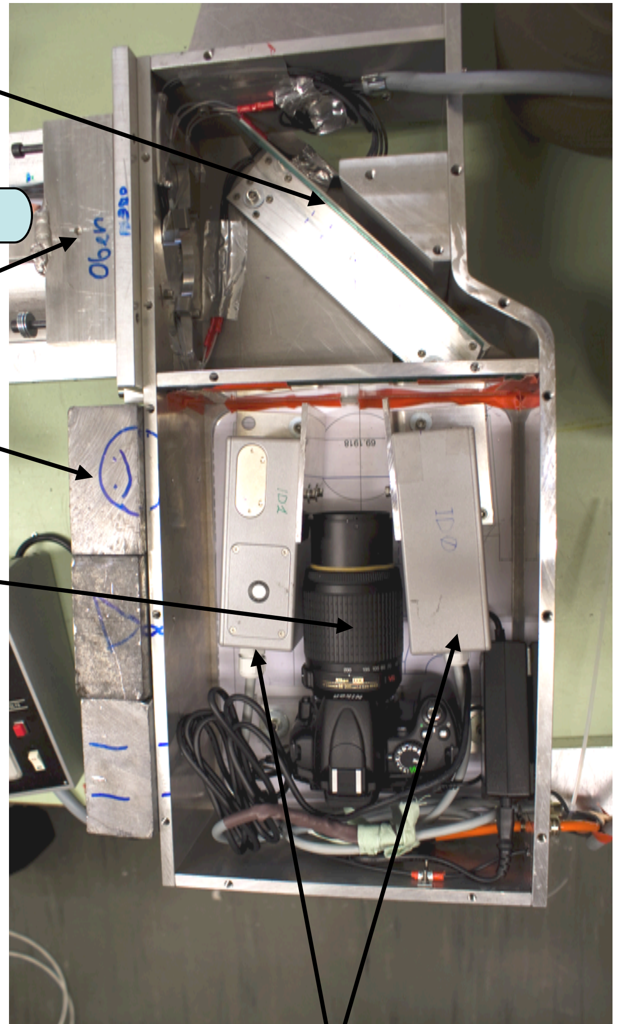


top part:



Tube2 with 2 mirror

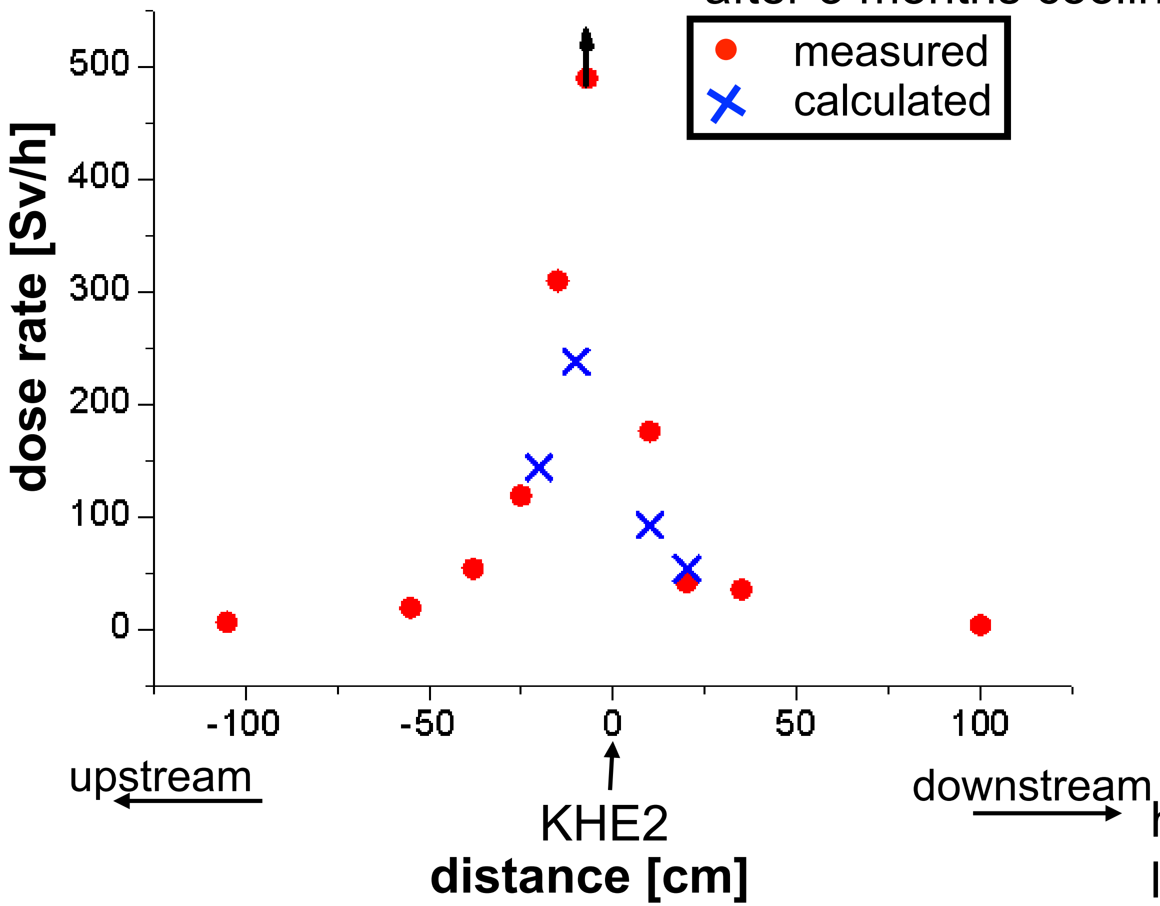
Tube1 with 1 mirror

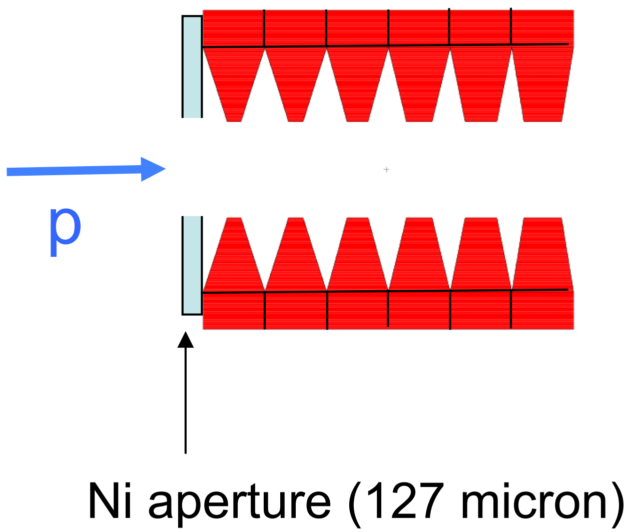


Calculation and measurement of the dose rates

- purpose of the calculation:
- planning of the shielding needed for camera in inspection tool
- shielding during transport sufficient
- calculated with MCNPX + Cinder'90, later measured in the hotcell (ATEC)

after 3 months cooling

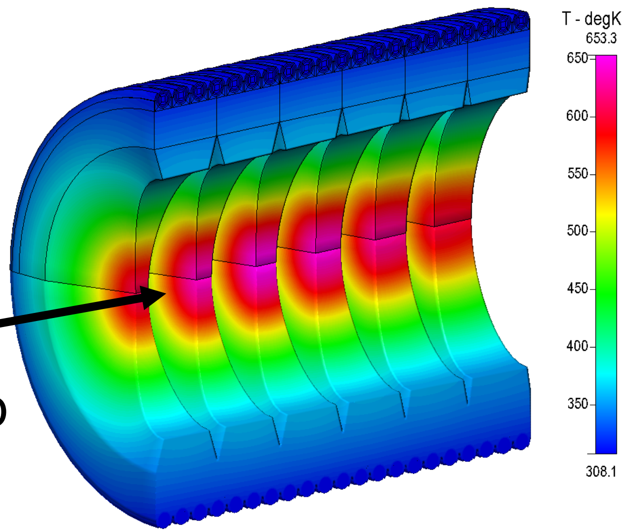


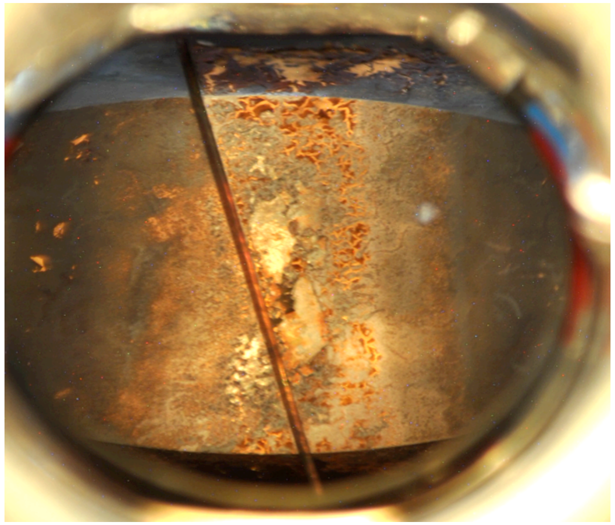


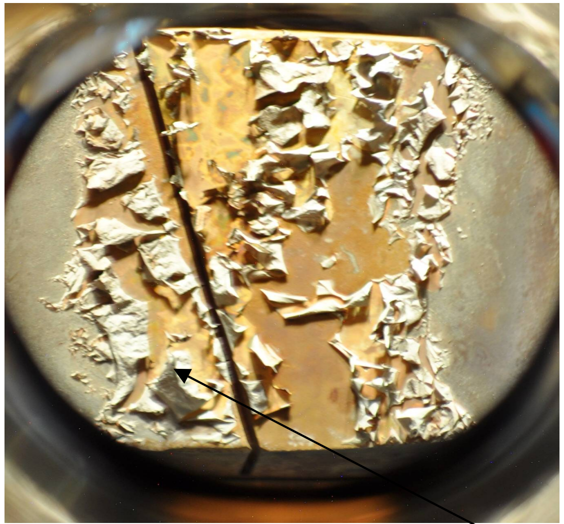
highest dose ever measured at PSI, limit of the dose meter: 500 Sv/h

Results: colli2 inside

- vertical: 80 - 100 °C (2mA)
  main damage at exit
  → low energetic particles produce more damage
- some pieces (1-2 mm height) seems to peel off
- grey surface
  → guess: errosion + dirt




entry

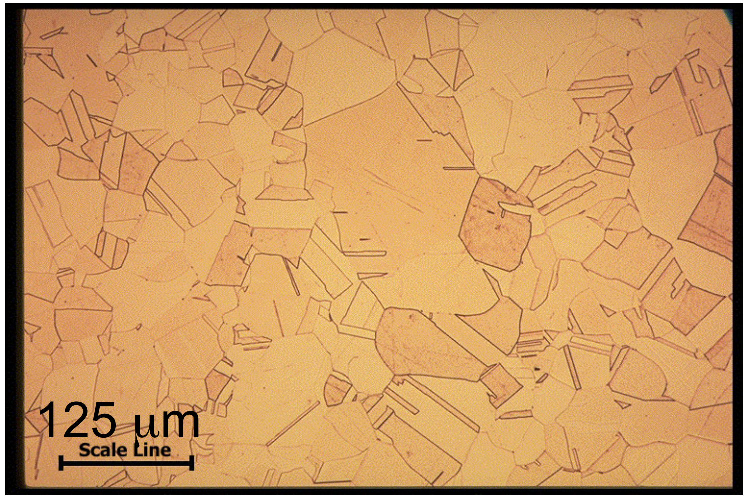

exit

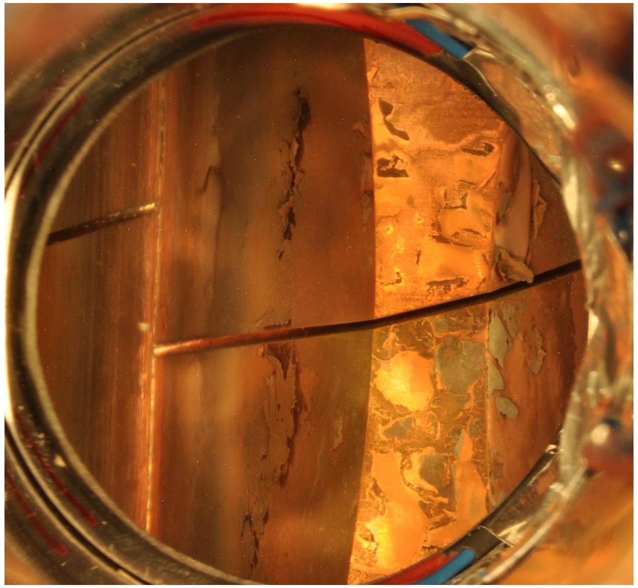
sample No 1

Results: colli2 inside

- horizontal: 350 - 400 °C (2 mA)
  main damage at entry
  → higher temperature
  - large grey pieces peeling off → dirt?
  - seems to reveal grain boundaries
  → might be grown due to temperature and irradiation
  → no swelling or deformation at slits

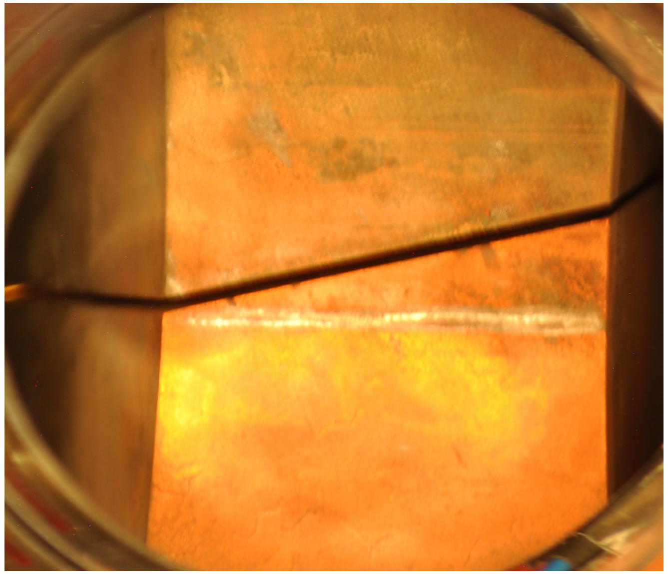
OFHC Cu





entry

slits completely intact !



exit

Results: colli2 inside

Most astonishing:
no damage of the surface
between vertical & horizontal,

Possible explanation:
thermal expansion/movement close
to the slits, highest stress

Measurement of the horizontal opening
via 2 laser distance meters:
result: very close to original values
accuracy: 0.5 mm
→ no swelling observed

example: $\Delta V/V=0.5\%/DPA$
$V=10x10x10mm^3$, 80 DPA
→ Δl = 2 x 1.2 mm

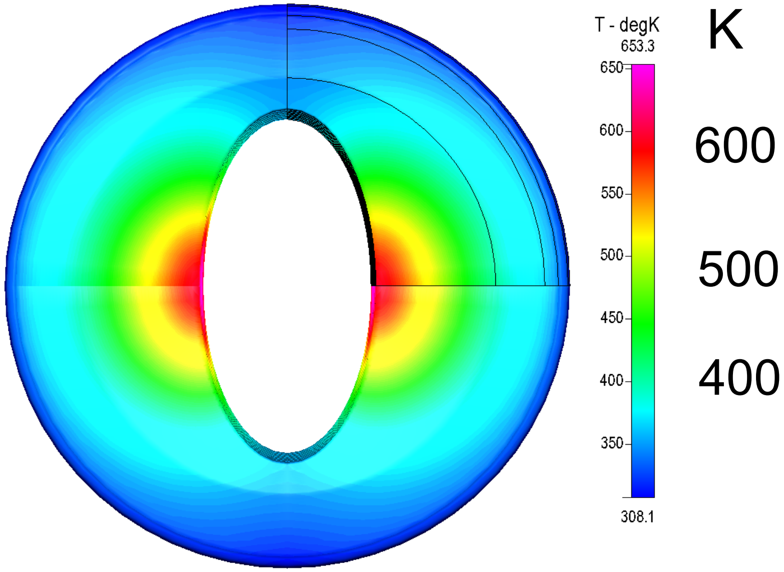
Results: colli2 outside

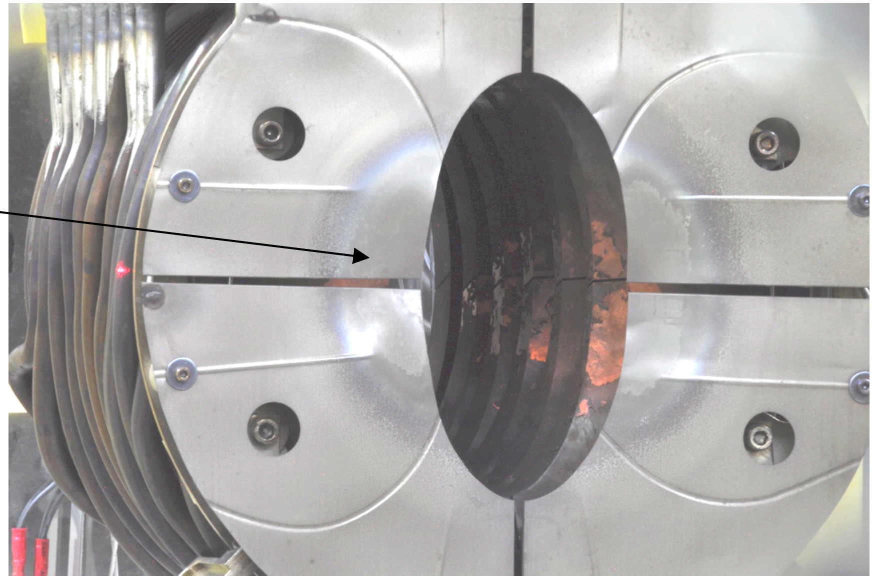
front:

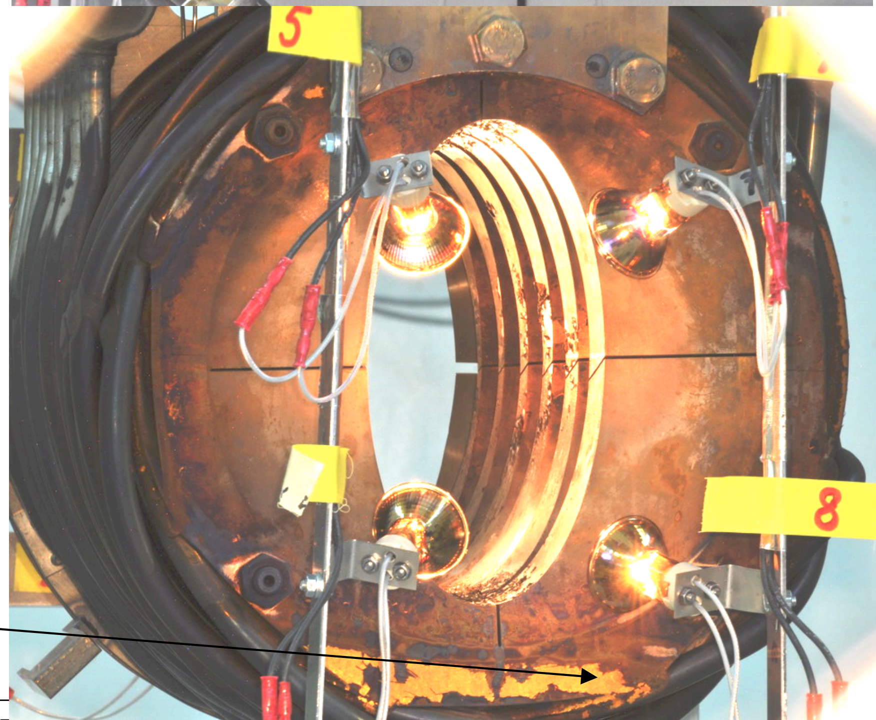
- aperture in very good shape
- one can see beam profile

back:

more damage at top & bottom





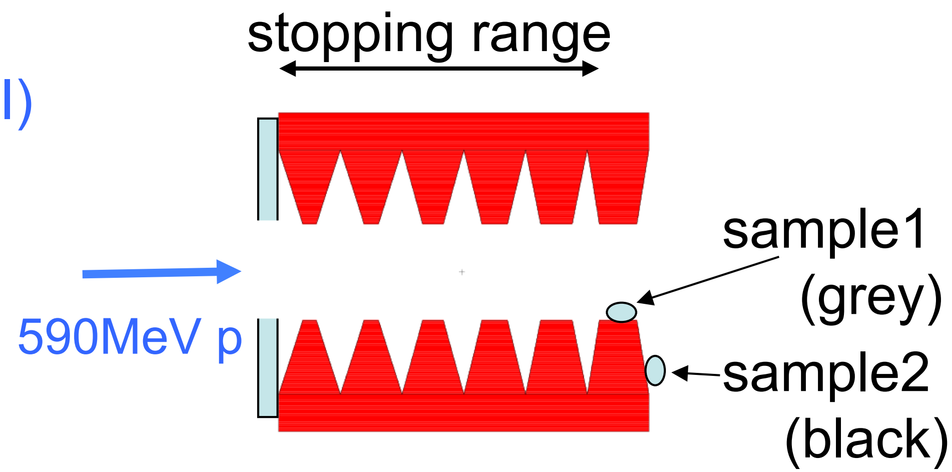


some black pieces peel off

→ „golden“ surface below

sample No 2

Nuclide inventory of the samples



Measurement: (RadWaste group at PSI)

γ-spectroscopy via HPG-detector:

Be-7 Na-22 Sc-46 Mn-54 Co-56 Co-57

Co-58 Fe-59 Co-60 Zn-65 Ag-110m

Calculation:

- MCNPX2.5.0 using Bertini-Dresner-RAL
- decay + buildup prg: Cinder'90
- irradiation time: 1990-2009
- cooling time: 6 months

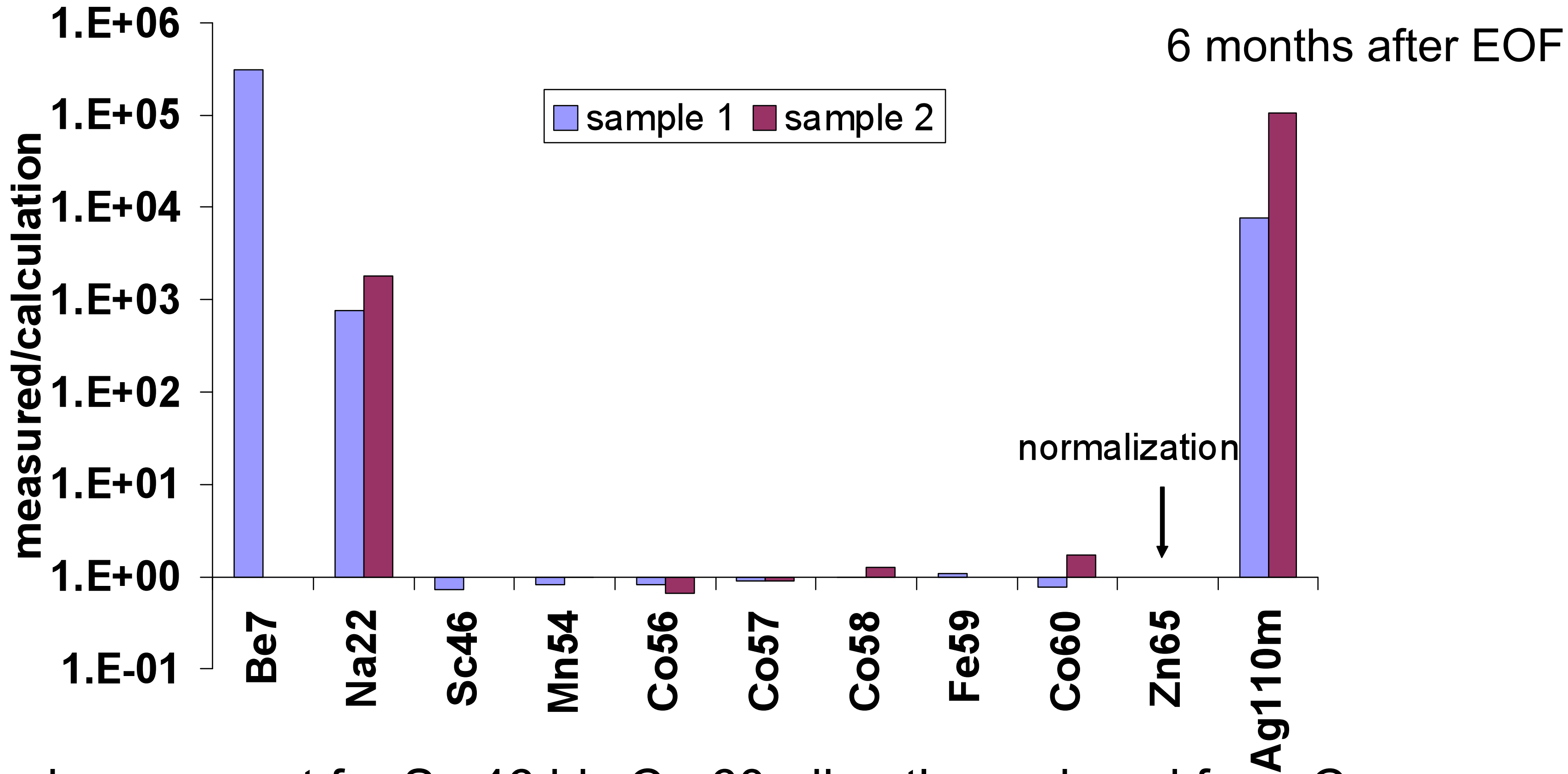
Assumption: pure copper (+17 ppm Ag, 3 ppm O_2)

Comparison:

Problem: weight of sample not known (very small, fragile)

→ normalization on the Zn-65 activity

Ratio of measured and calculated activity



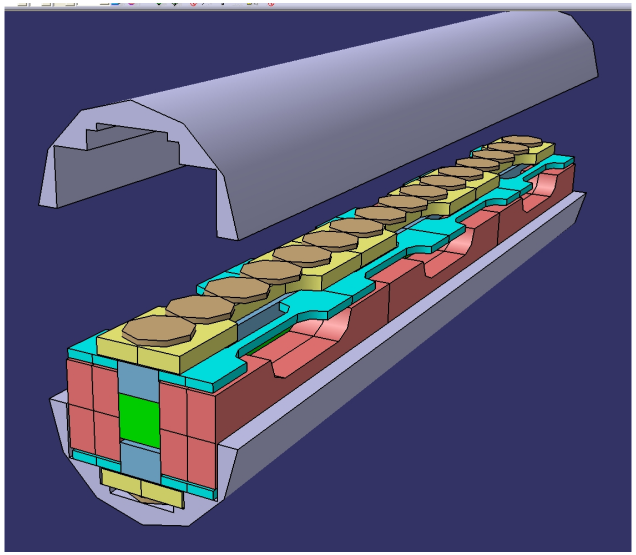
- good agreement for Sc-46 bis Co-60: directly produced from Cu
- large deviation for
  - Ag110m: → silver brazing solder: 68 % Ag, 27 % Cu, 5 % Pd
  - Be-7: only for sample 1 (inside), probably from Target E (graphite)
    → grey layer inside
  - Na-22: from surroundings?

Summary and Outlook

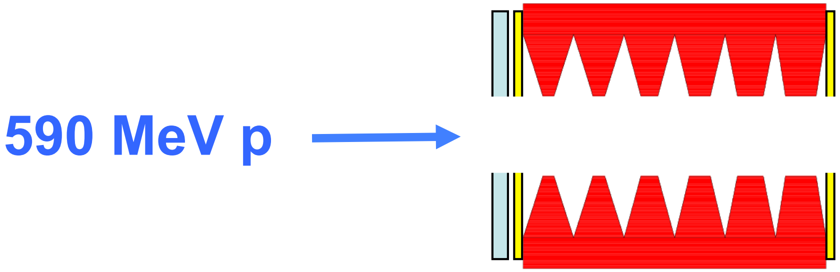
• Successfull inspection and reinstallation
→ surprisingly, no visible serious damage
• DPA high inside: 80 (MCNPX, dsc) –170 (MARS)

not yet known :
mechanical stability and therm. conductivity
planned in SD 2012:
-sample taking at colli2 for electr. resistivity,
therm. conductivity and tensile measurement
- almost identically is under construction
new: sample sheets (shown in yellow)

CAD Illustration



Sample in SINQ-Target (STIPVI): 2011-2012
filled with Cu und Glidcop
+ 1 thermocouple



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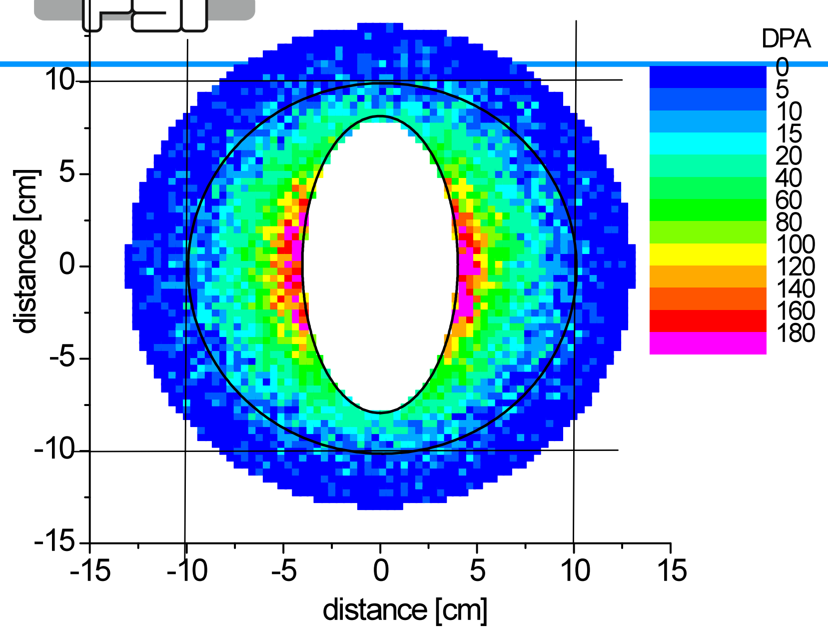
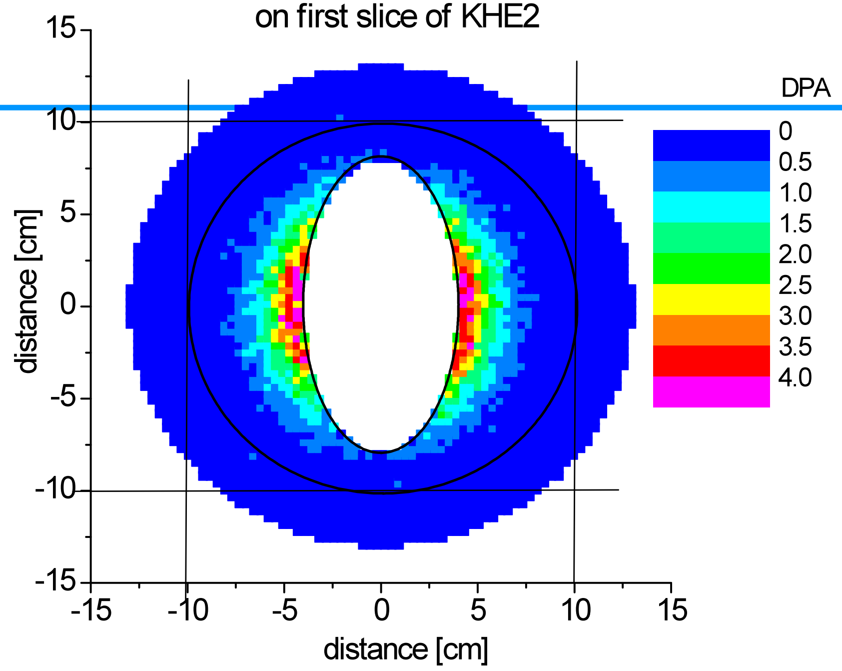
Acknowledgement

- staff of the hot cell ATEC:
  A. Hagel, H.Orlick, K. Mühlberg
- P. Dupperrex for tests with the movable laser beam
- radioprotection group and hall service
- mechanical workshop West
- Radwaste group of D. Schumann
- Mike Seidel for the support

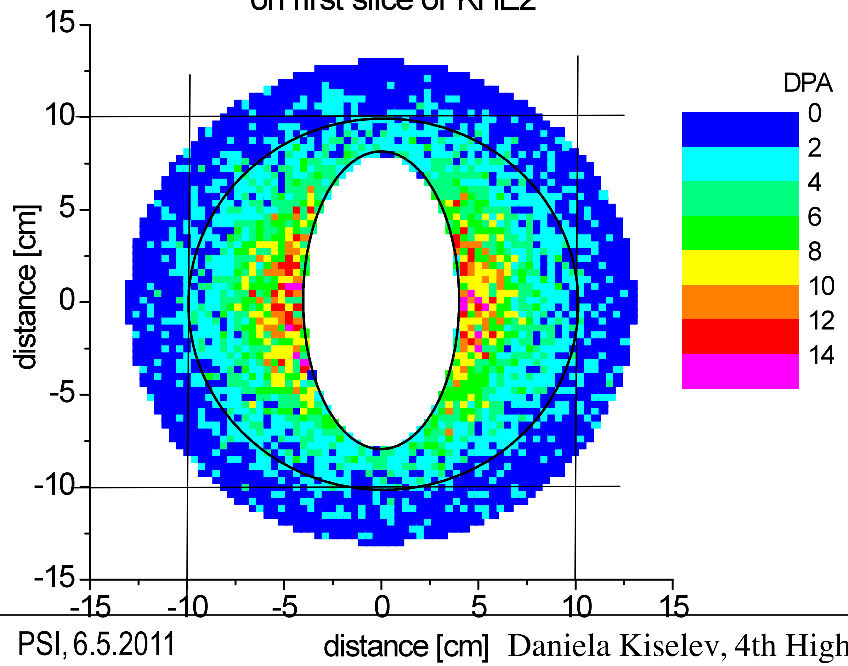
Total DPA
on first slice of KHE2

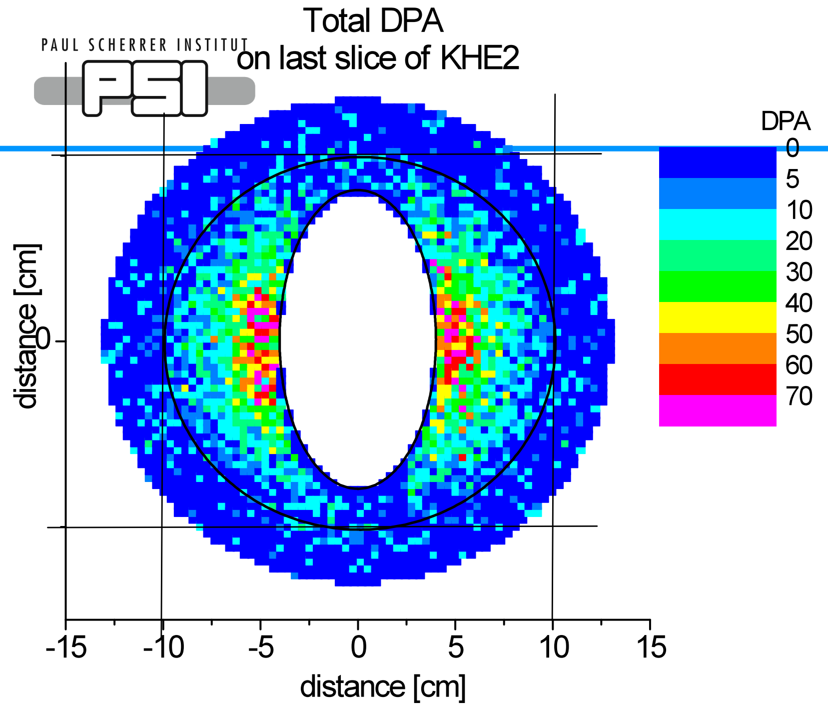


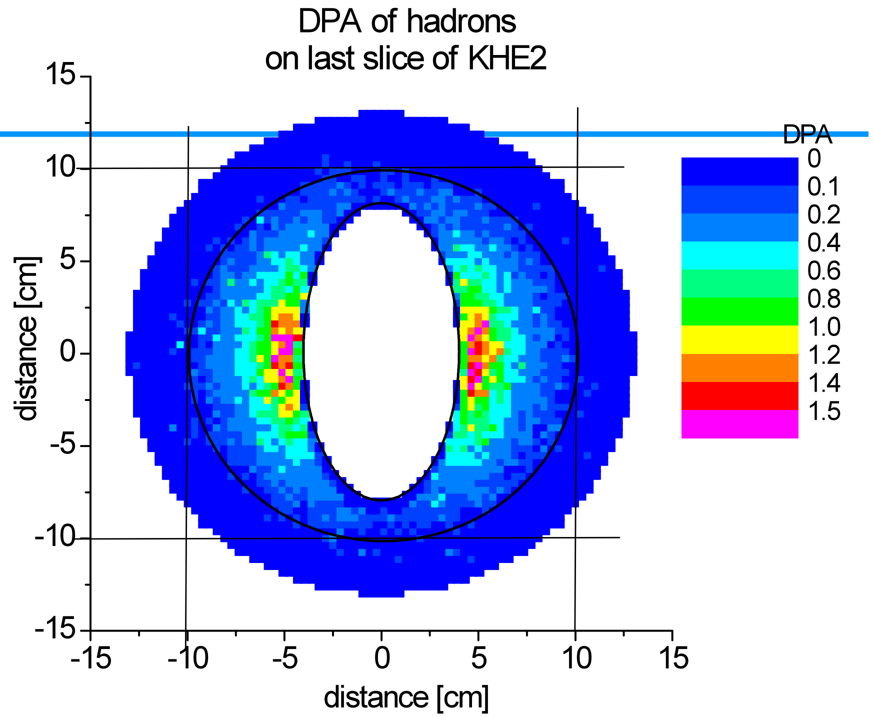
DPA from hadrons
on first slice of KHE2

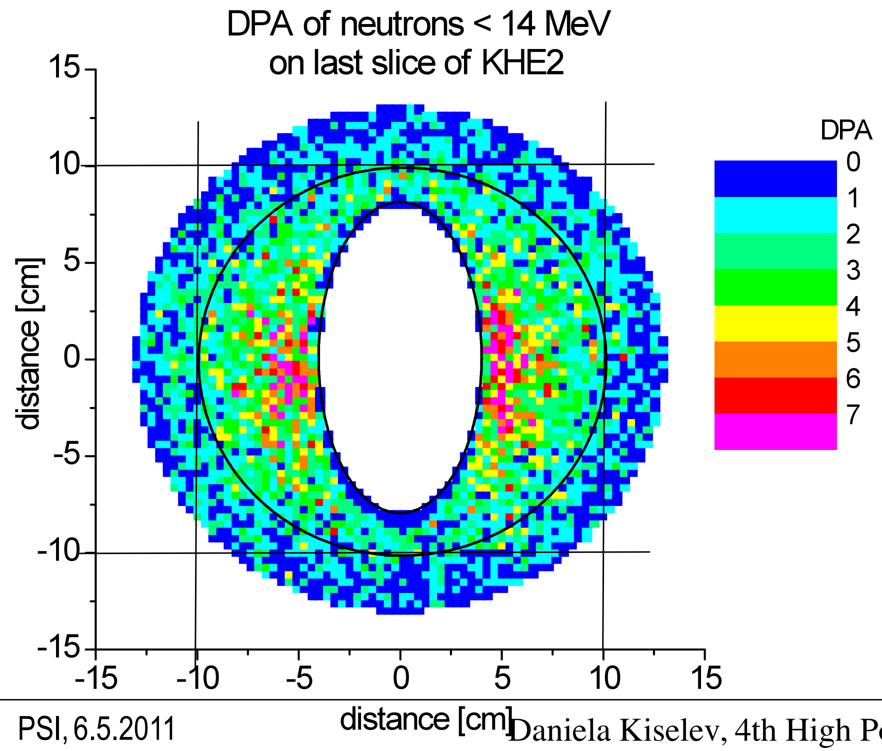


DPA from neutrons < 14 MeV
on first slice of KHE2

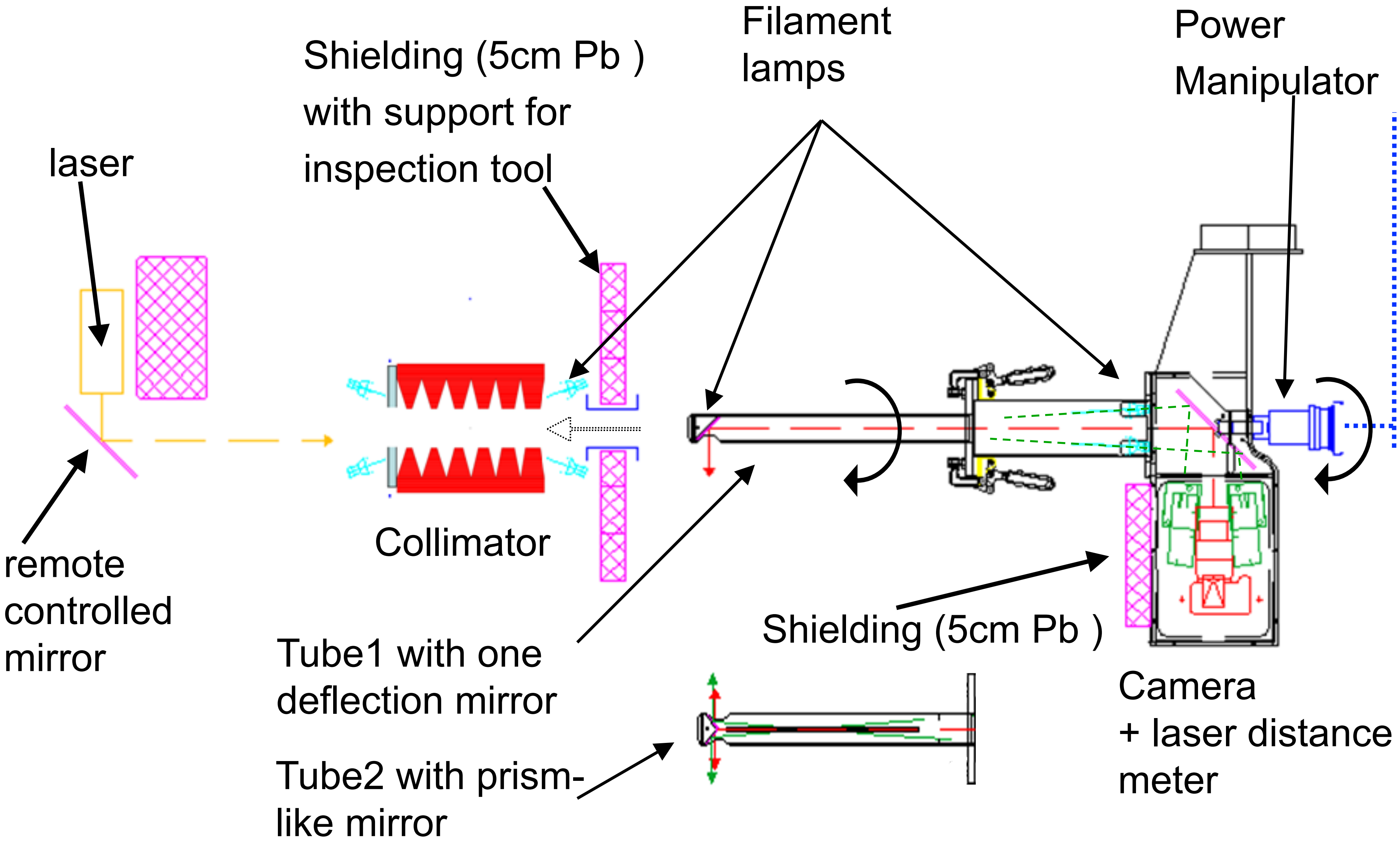



Total DPA
on last slice of KHE2
distance [cm]
distance [cm]
DPA
0
5
10
20
30
40
50
60
70


DPA of hadrons
on last slice of KHE2
distance [cm]
distance [cm]
DPA
0
0.1
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.5


DPA of neutrons < 14 MeV
on last slice of KHE2
distance [cm]
distance [cm]
DPA
0
1
2
3
4
5
6
7

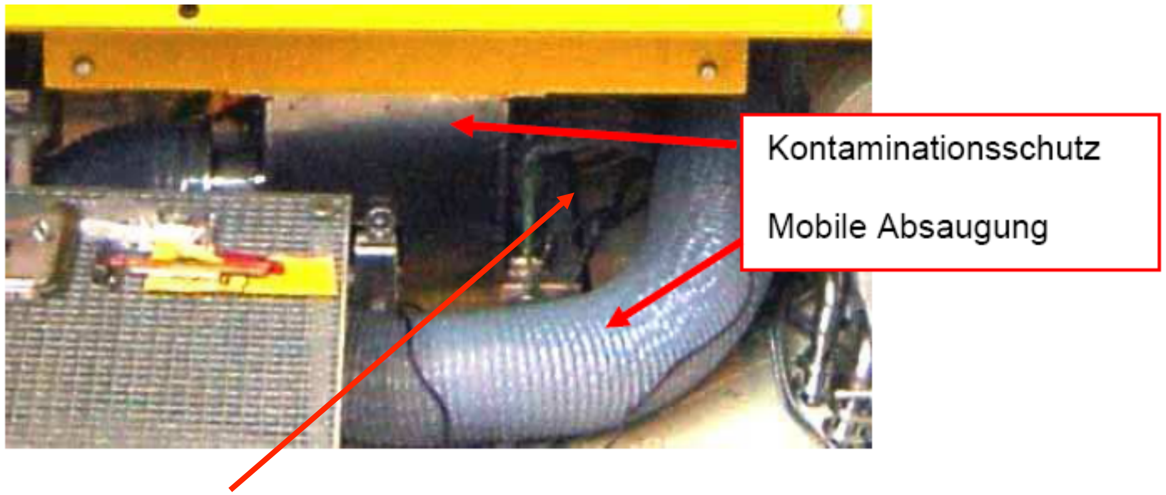
Inspection tool in the hot cell (fully remote controlled)



Radiological safety measured during the removal

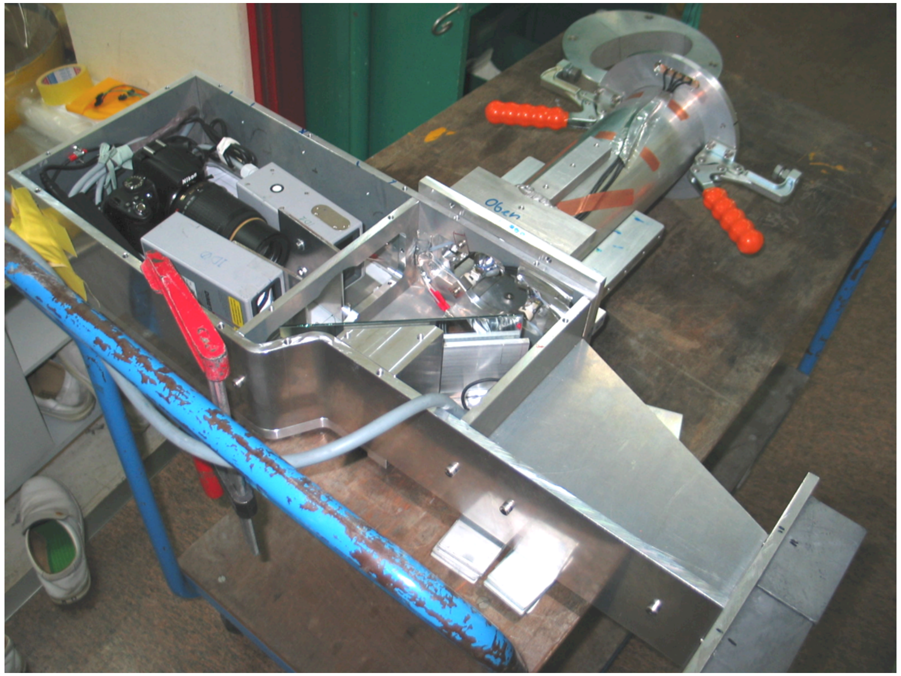
Radiological control:

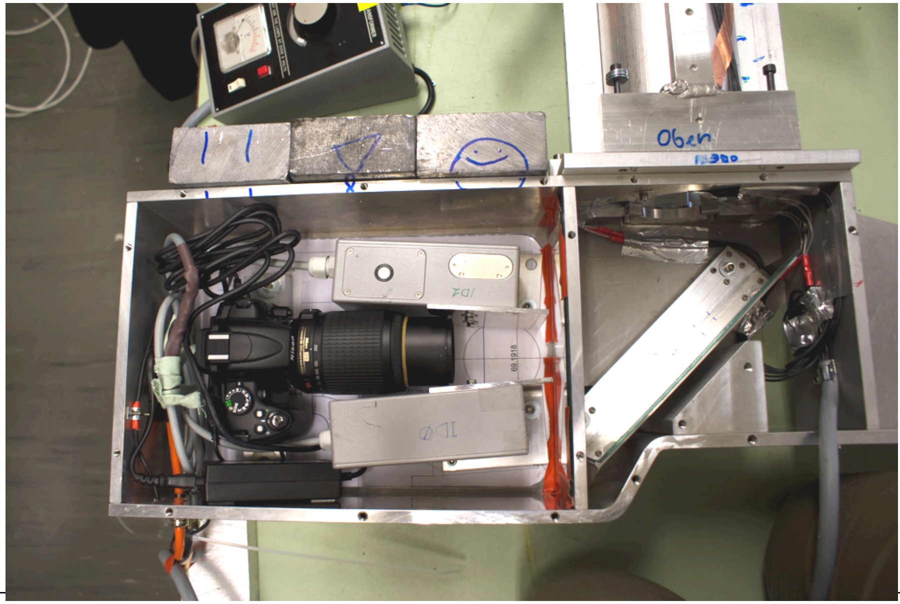
- dose measured at several locations
- Tritium monitor
- Contamination protection,
  air is sucked in
- dose rate at surface of the exchange flask:
  max. 1 mSv/h



dosimeter: up to 45 Sv/h measured

Preparation at the hotcell ATEC and tests

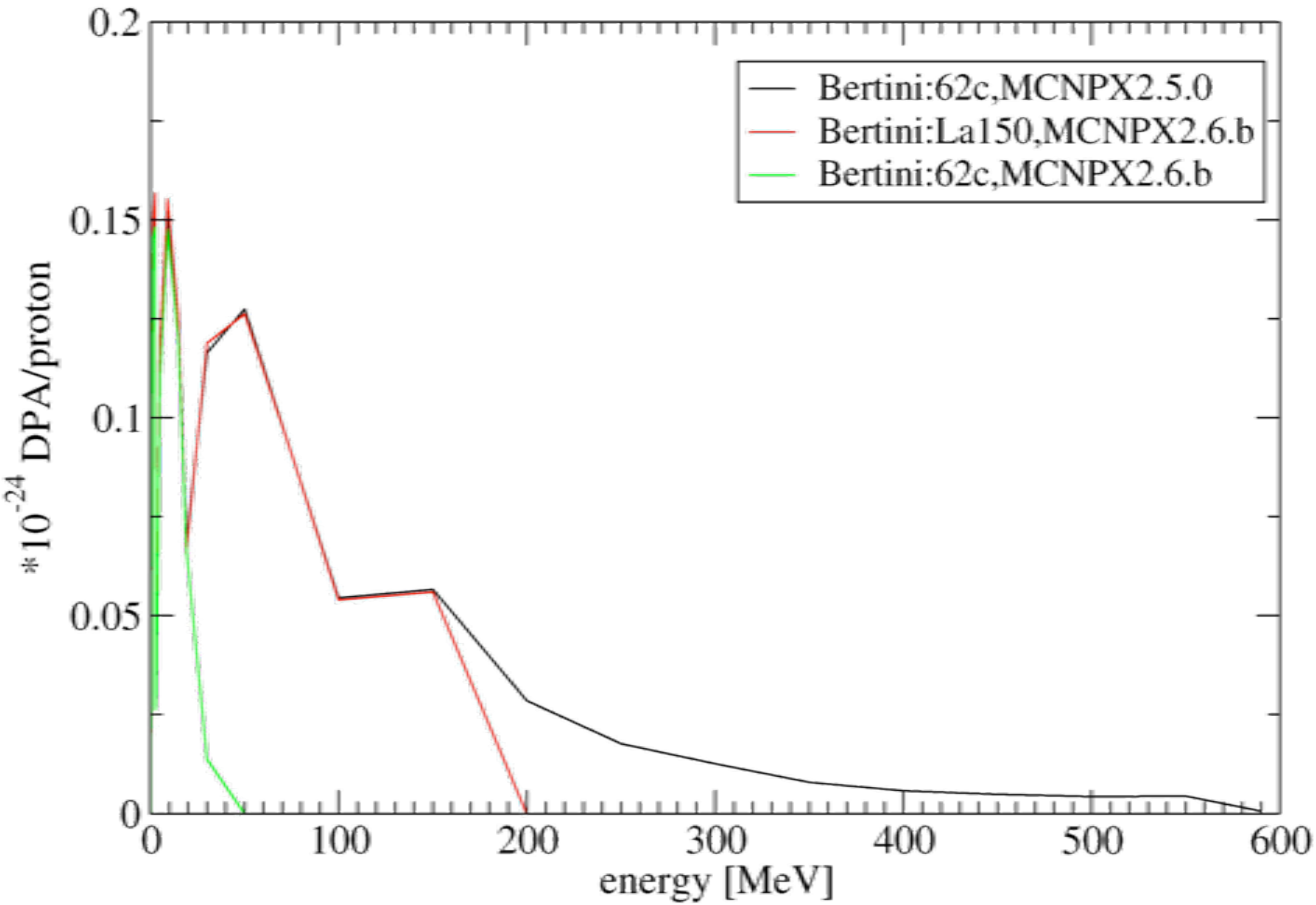




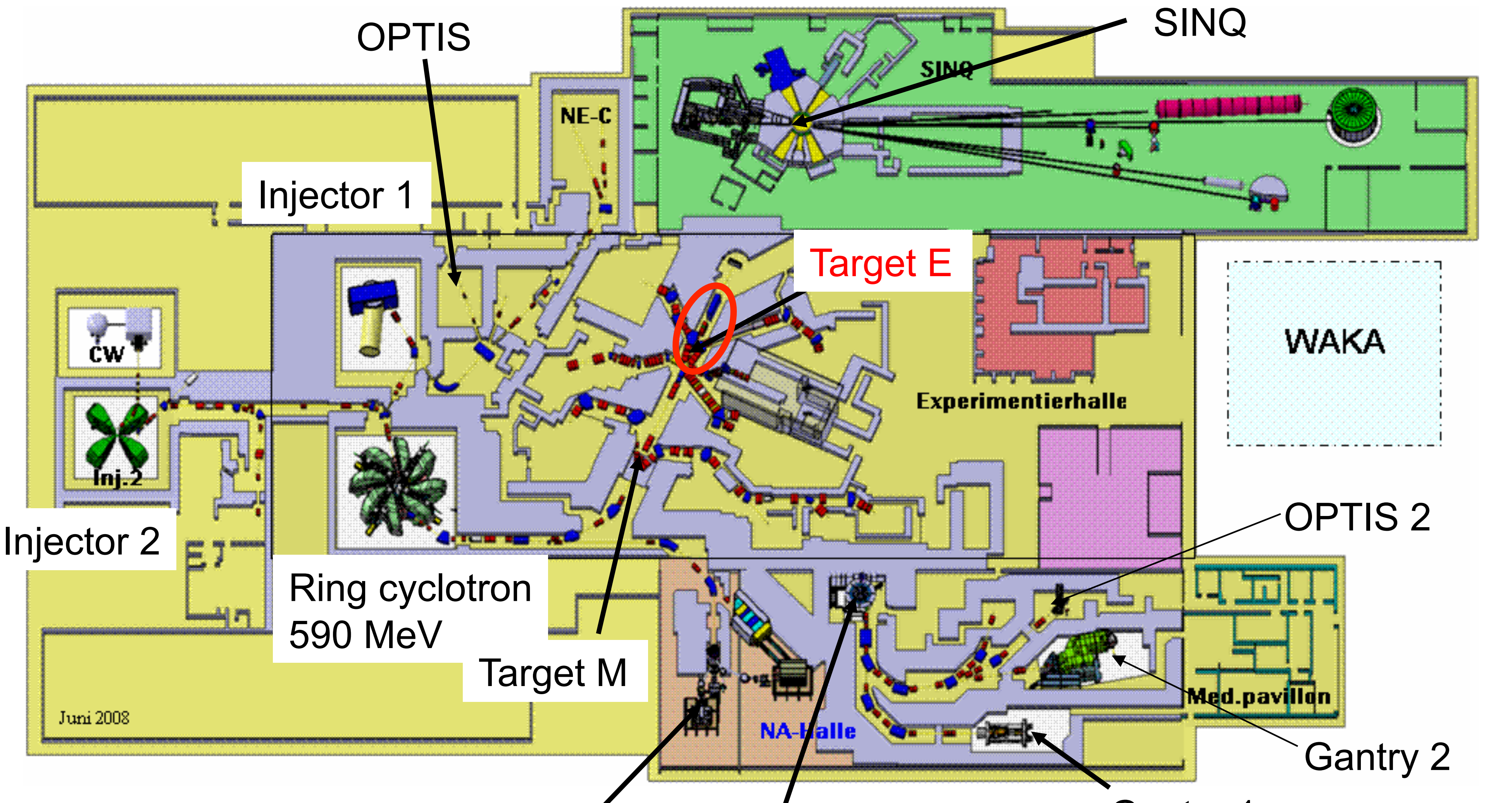
Against contamination:
all wrapped into plastic foil:
closed box with camera and
laser meters,
signal- and control cable in

Against damage:
guiding tube in front of collimator

f4:n tally weigthed with 444



PSI Proton Accelerator Facilities



nominal current: 2.2 mA