PSI experience with
High Power Target Design and operational considerations for muon production

[with slides from Th.Prokscha, G.Heidenreich]

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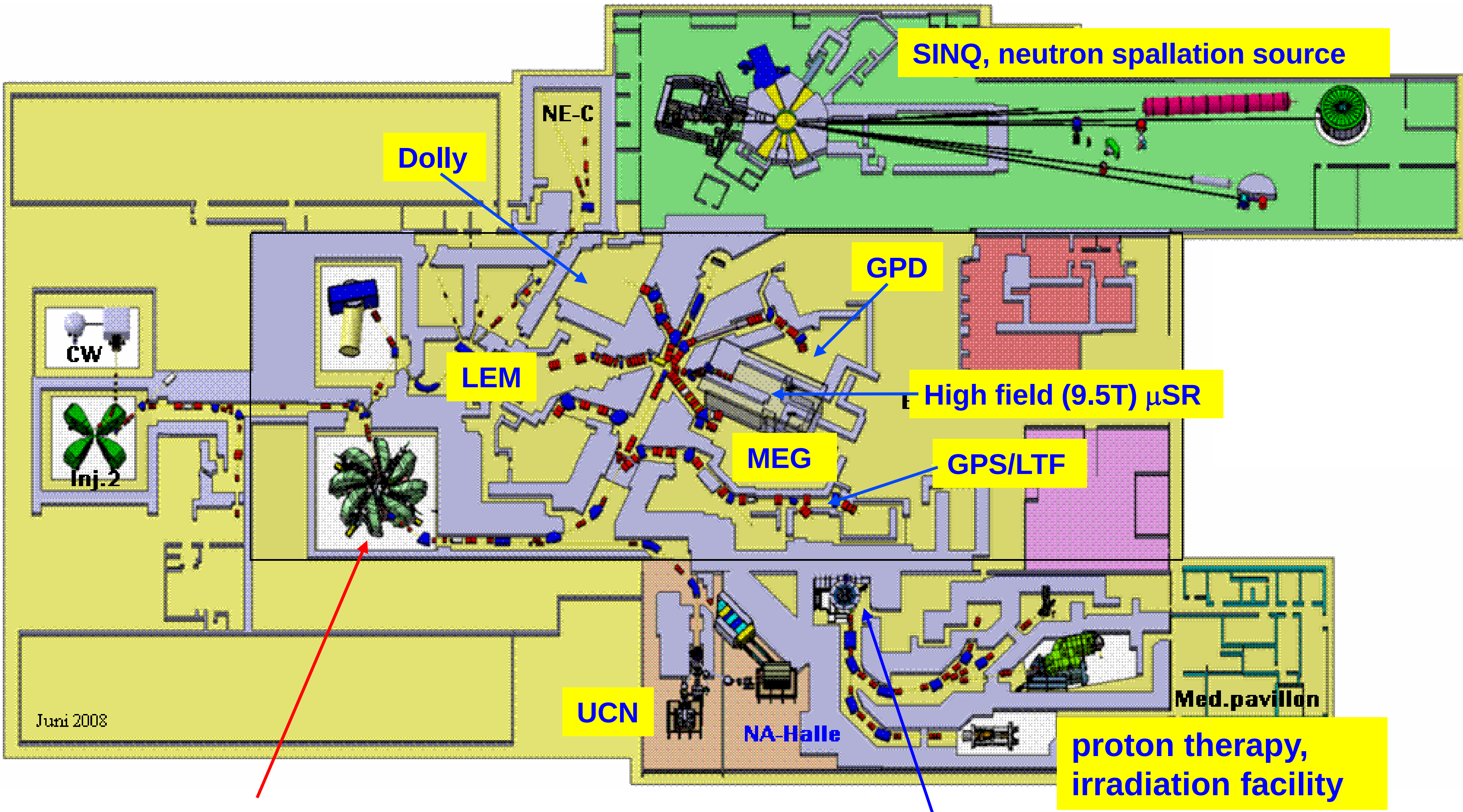
Outline

- overview PSI targets and parameters
- thermomechanical target aspects, mechanics and supporting infrastructure
- example for μ-beam capture and transport
- discussion

PSI proton accelerator complex



50 MHz proton cyclotron, 2.2 mA, 590 MeV, 1.3 MW beam power (2.4 mA, 1.4 MW test operation)

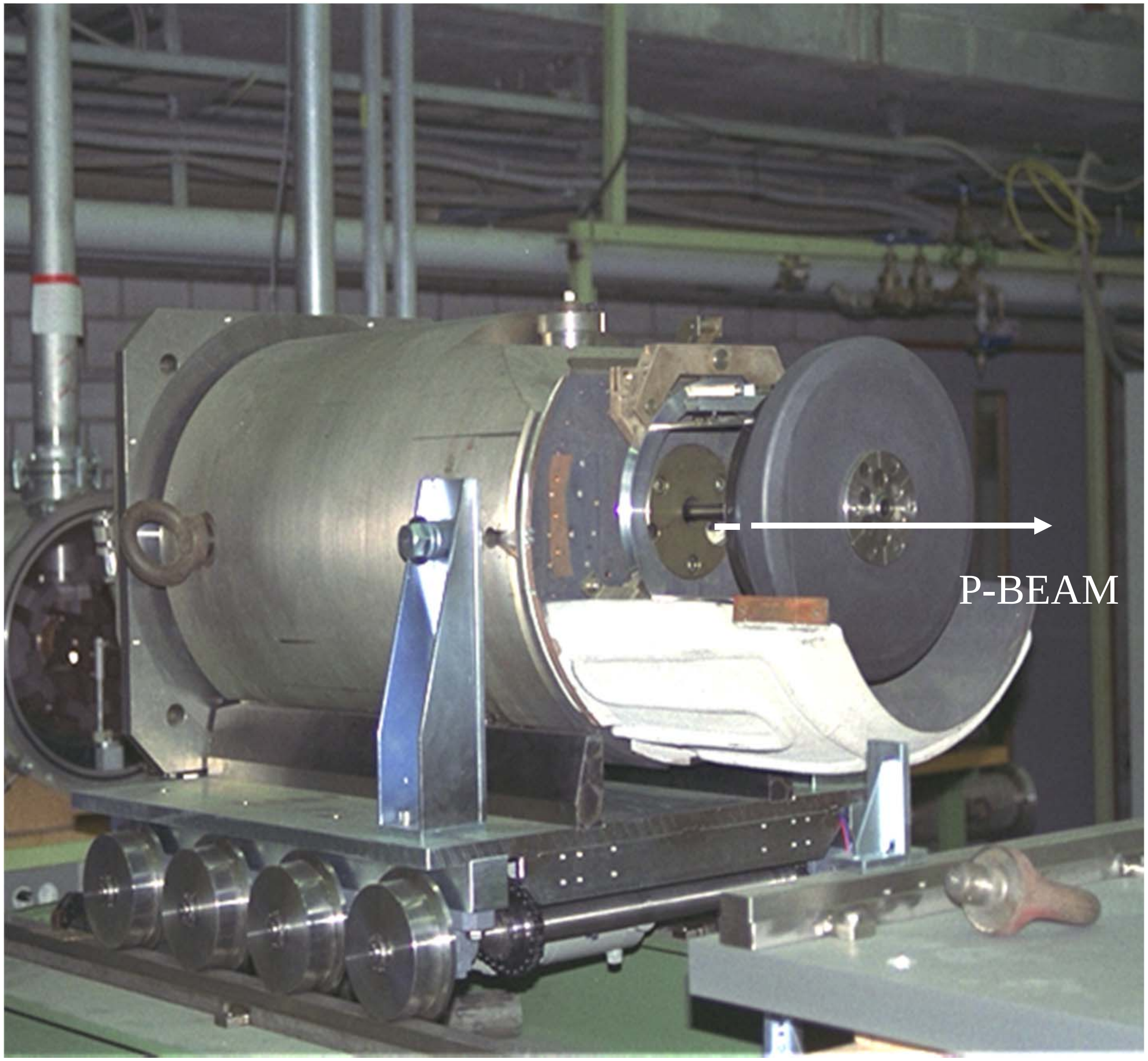
Comet cyclotron (superconducting), 250 MeV, 500 nA, 72.8 MHz

Meson production targets used at PSI

		Target M	Target E
1974-80	< 100 μA	**Be, Graphite *)** ∅ 190 mm 0.9 g/cm^2	**Be, Graphite *)** ∅ 190 mm 22 g/cm^2 **Pyrolitic graphite**)** 22 g/cm^2
1980-89	250 μA	**Graphite *)** ∅ 320 mm 0.9 g/cm^2	**Graphite *)** ∅ 280 mm 18 g/cm^2
since 1990	0.5 - 2 mA	**Graphite *)** ∅ 320 mm 0.9 g/cm^2	**Graphite *)** ∅ 450 mm 10 g/cm^2 (60 mm) or 7 g/cm^2 (40 mm)

*) rotating wheel target **) static target

Target-M design



Target M:

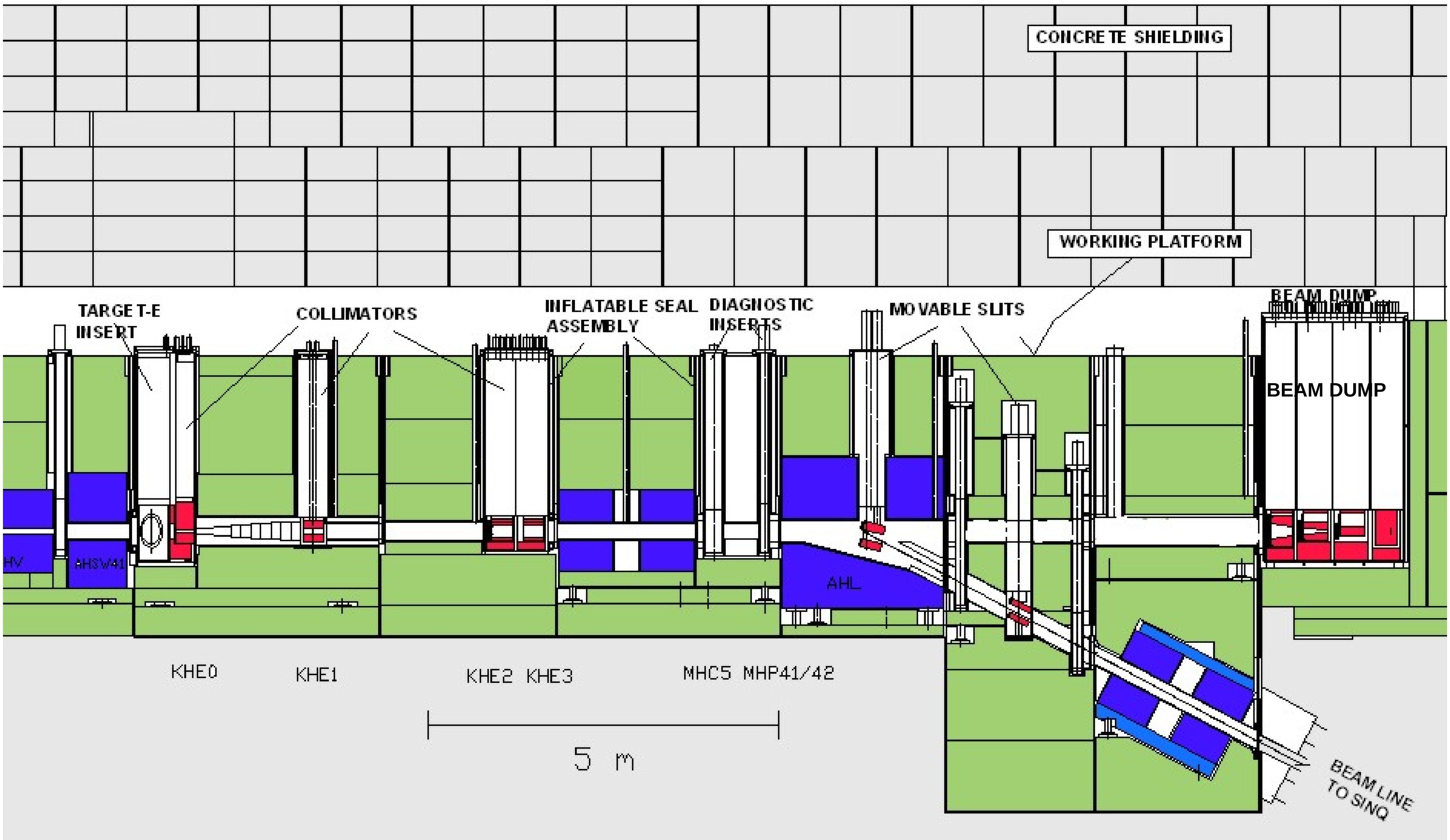
Mean diameter:	320 mm
Target thickness:	5.2 mm
Target width:	20 mm
Graphite density:	1.8 g/cm^3
Beam loss:	1.6 %
Power deposition:	2.4 kW/mA
Operating Temperature:	1100 K
Irradiation damage rate:	0.12 dpa/Ah
Rotational Speed:	1 Turn/s

Exchange of Target-M

Operation of the remotely controlled shielded flask

Dose rate ~10 mSv/h

Design of the proton channel between target-E and the beam dump

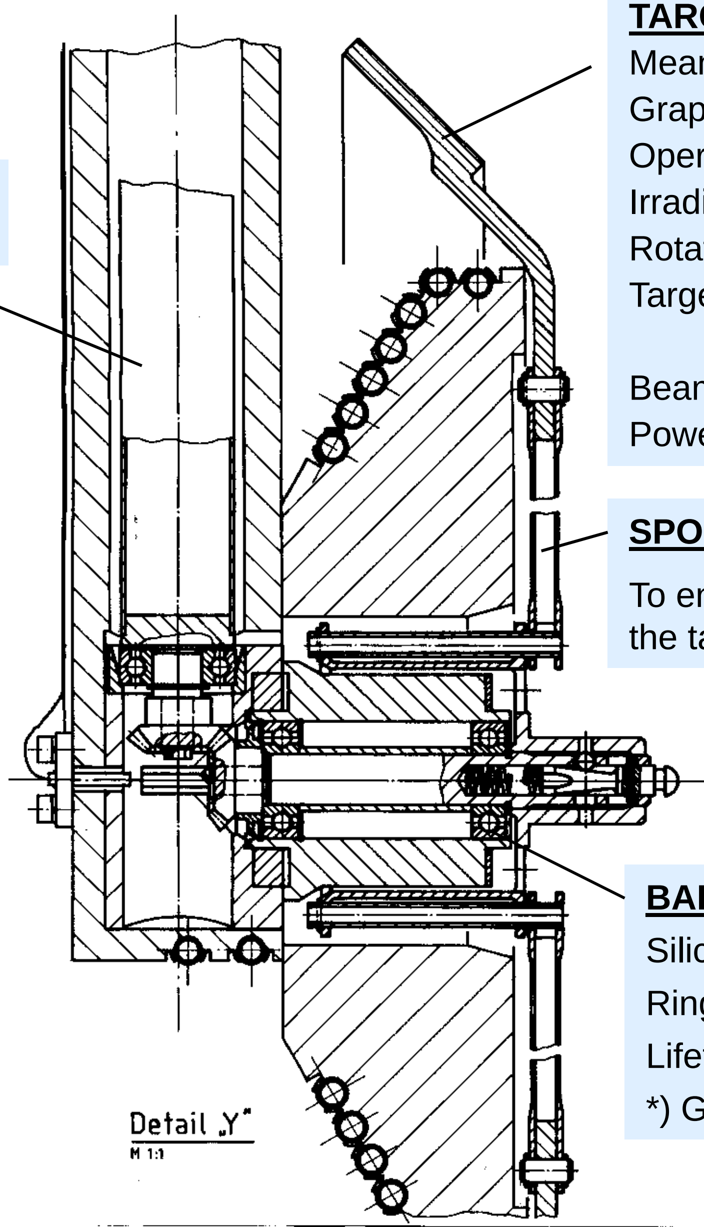


Working platform / Operation of the remotely controlled shielded flask

Design of Target station E

Target-E design

Drive shaft



TARGET CONE

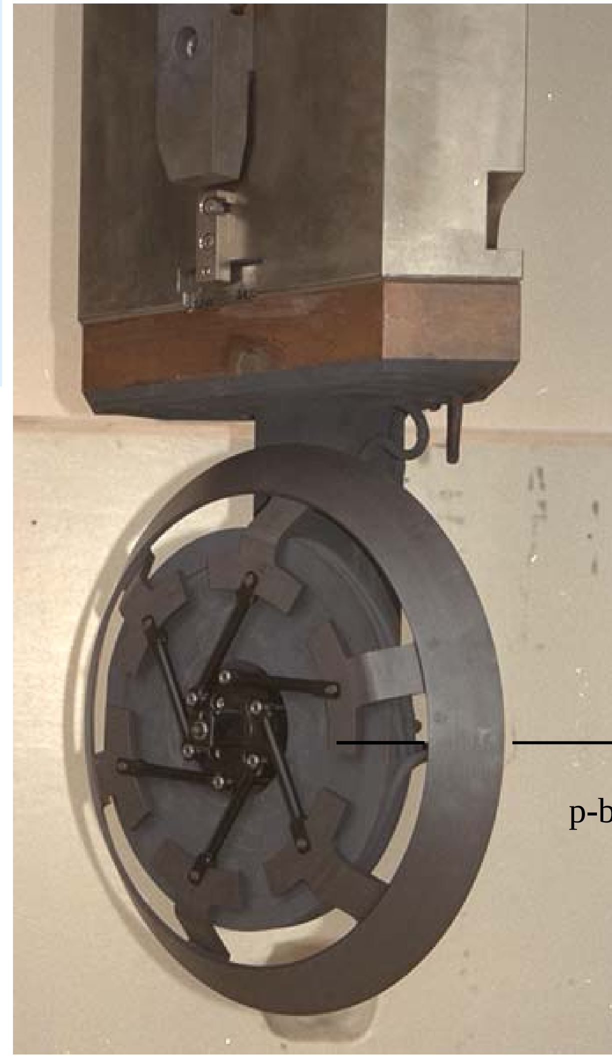
Mean diameter: 450 mm
Graphite density: 1.8 g/cm^3
Operating Temperature: 1700 K
Irradiation damage rate: 0.1 dpa/Ah
Rotational Speed: 1 Turn/s
Target thickness: 60 / 40 mm
10 / 7 g/cm^2
Beam loss: 18 / 12 %
Power deposition: 30 / 20 kW/mA

SPOKES

To enable the thermal expansion of the target cone

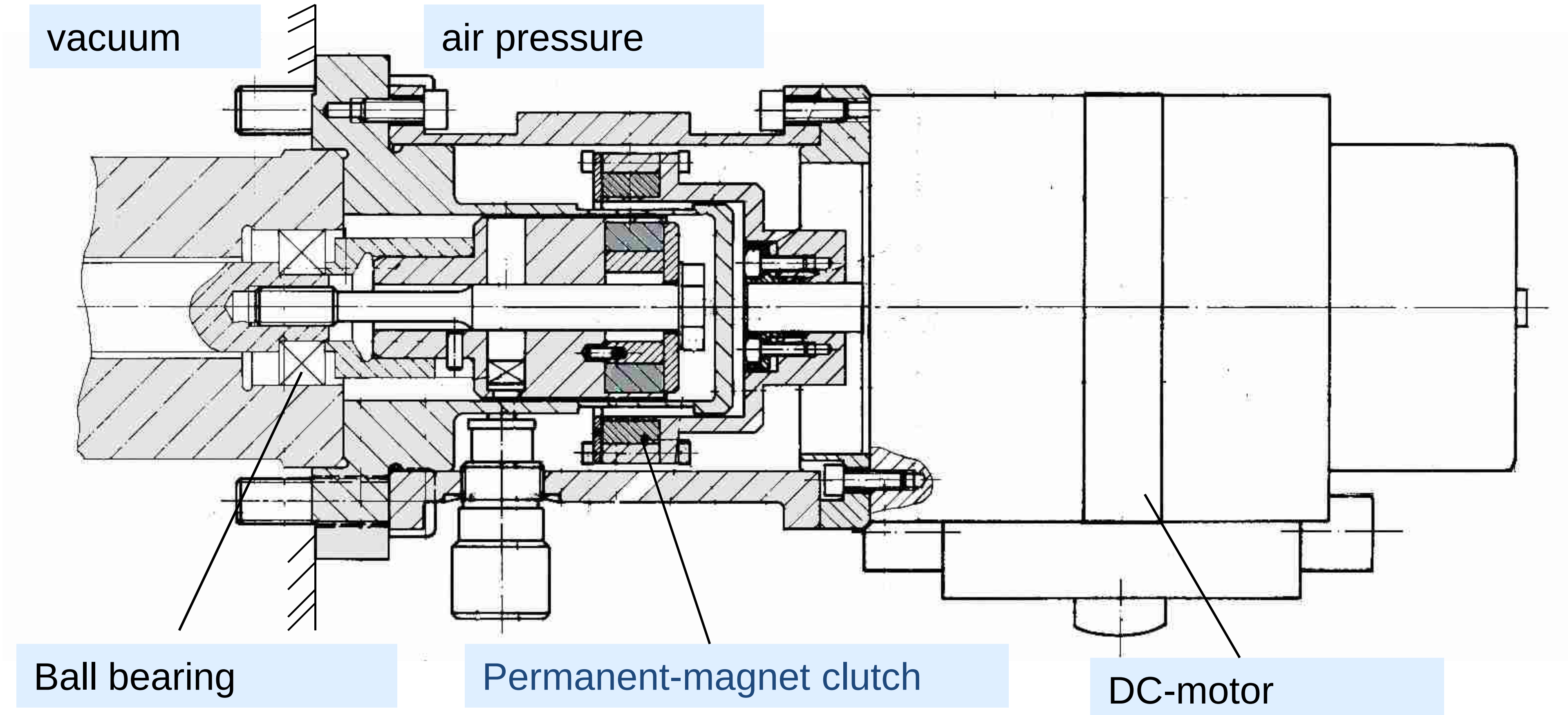
BALL BEARINGS *)

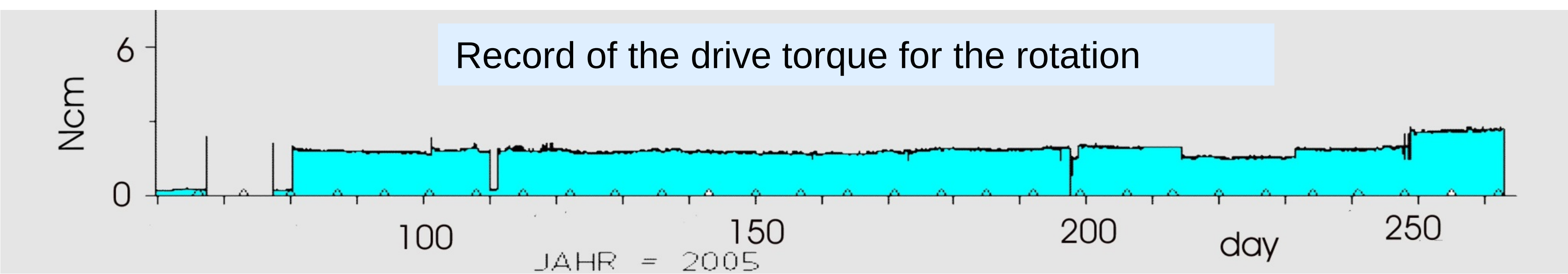
Silicon nitride balls
Rings and cage silver coated
Lifetime 2 y
*) GMN, Nürnberg, Germany



p-beam

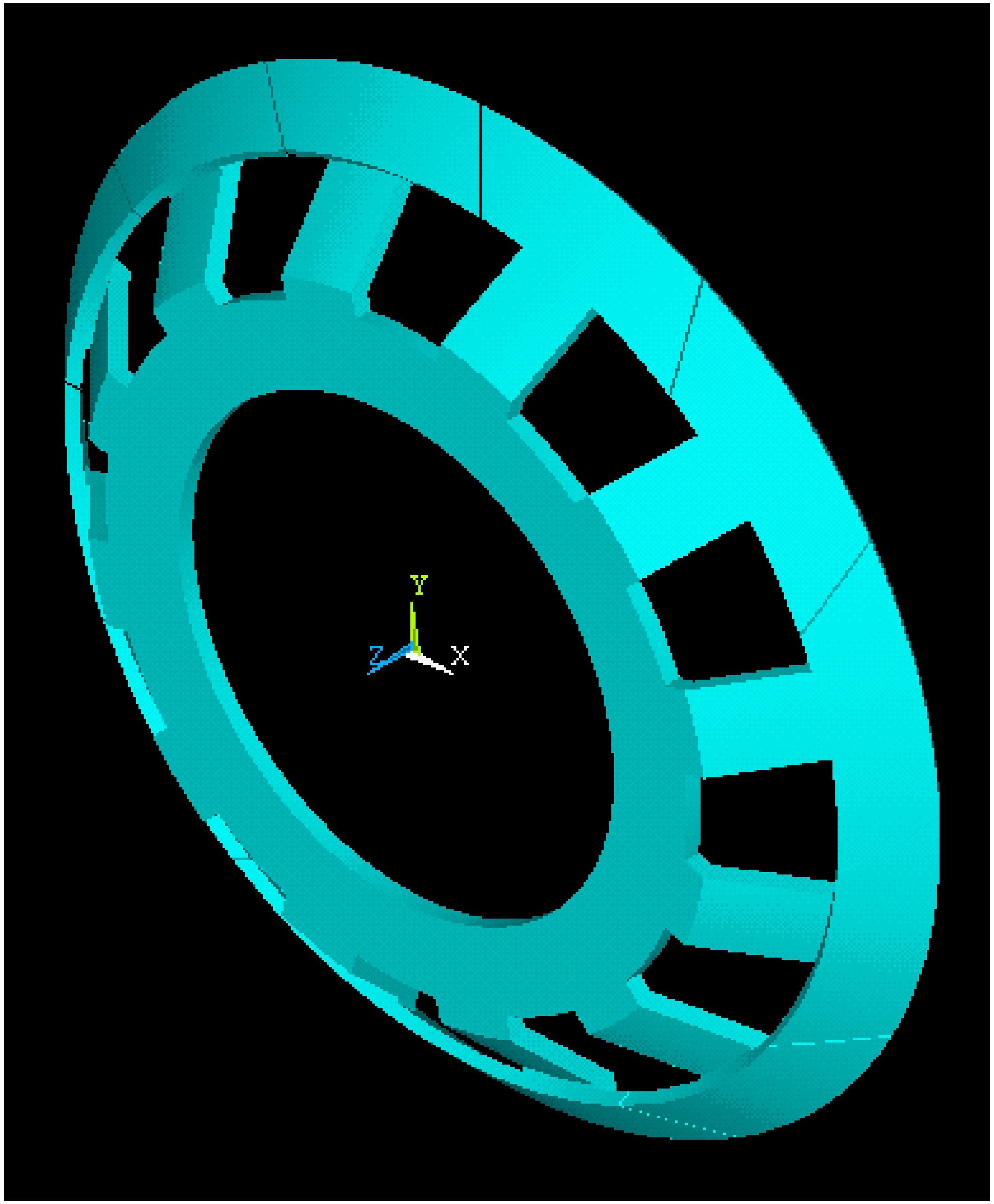
Drive motor & permanent-magnet clutch

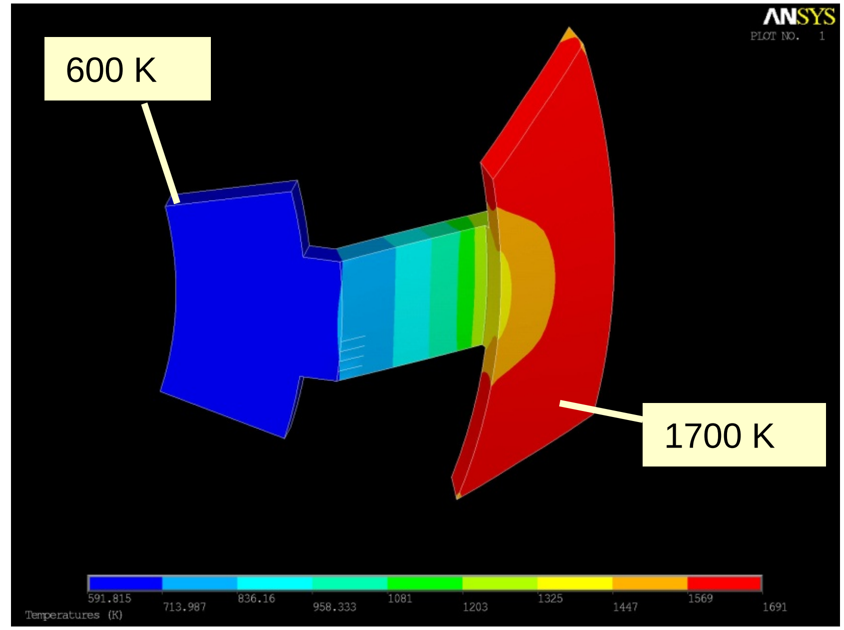


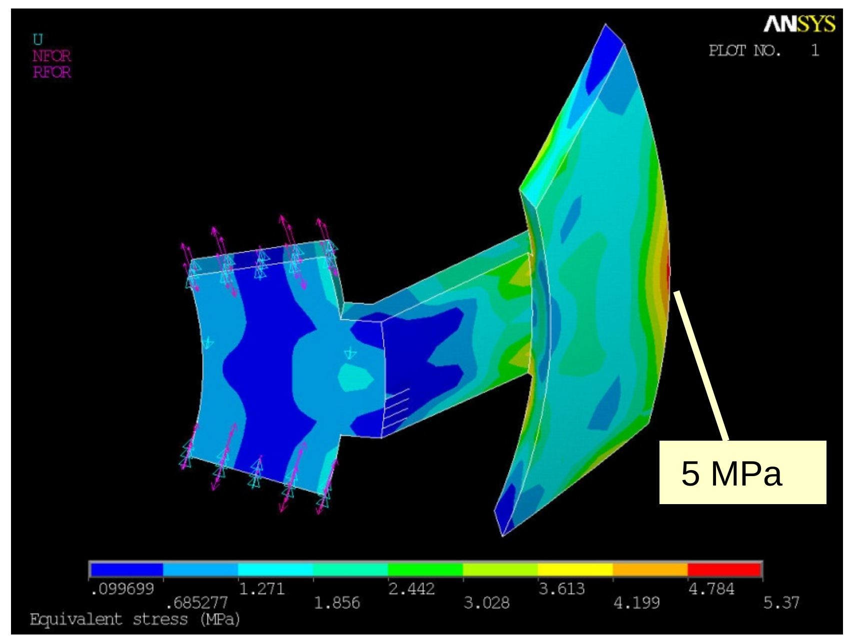


design of graphite wheel

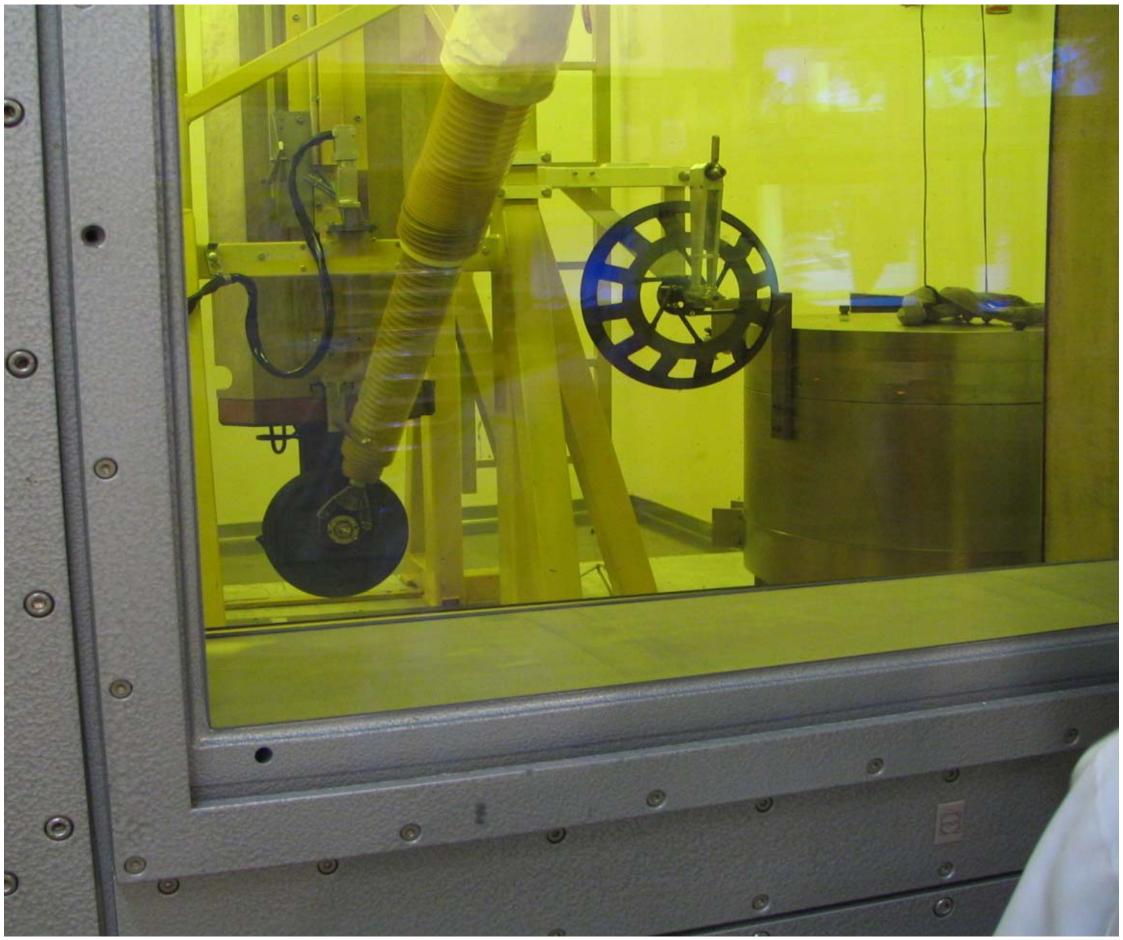
Temperature & stress distribution (2mA, 40 kW)



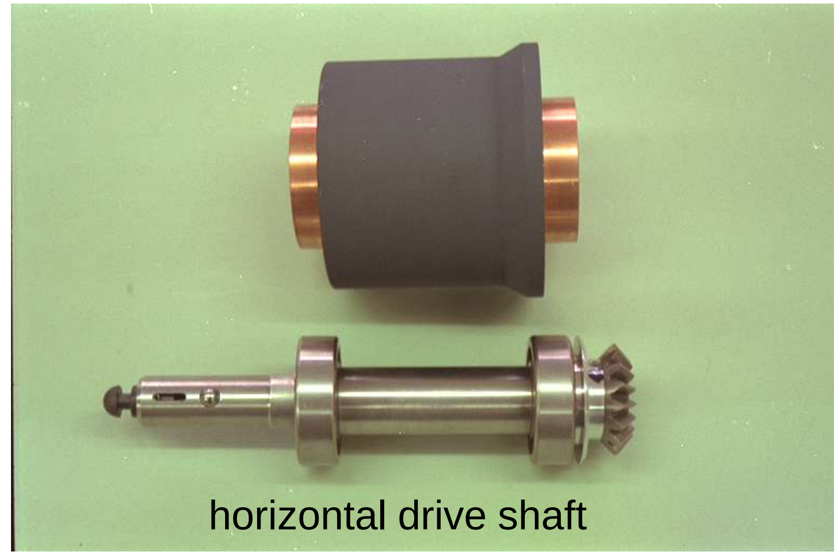




Maintenance of the target-insert in the hot-cell

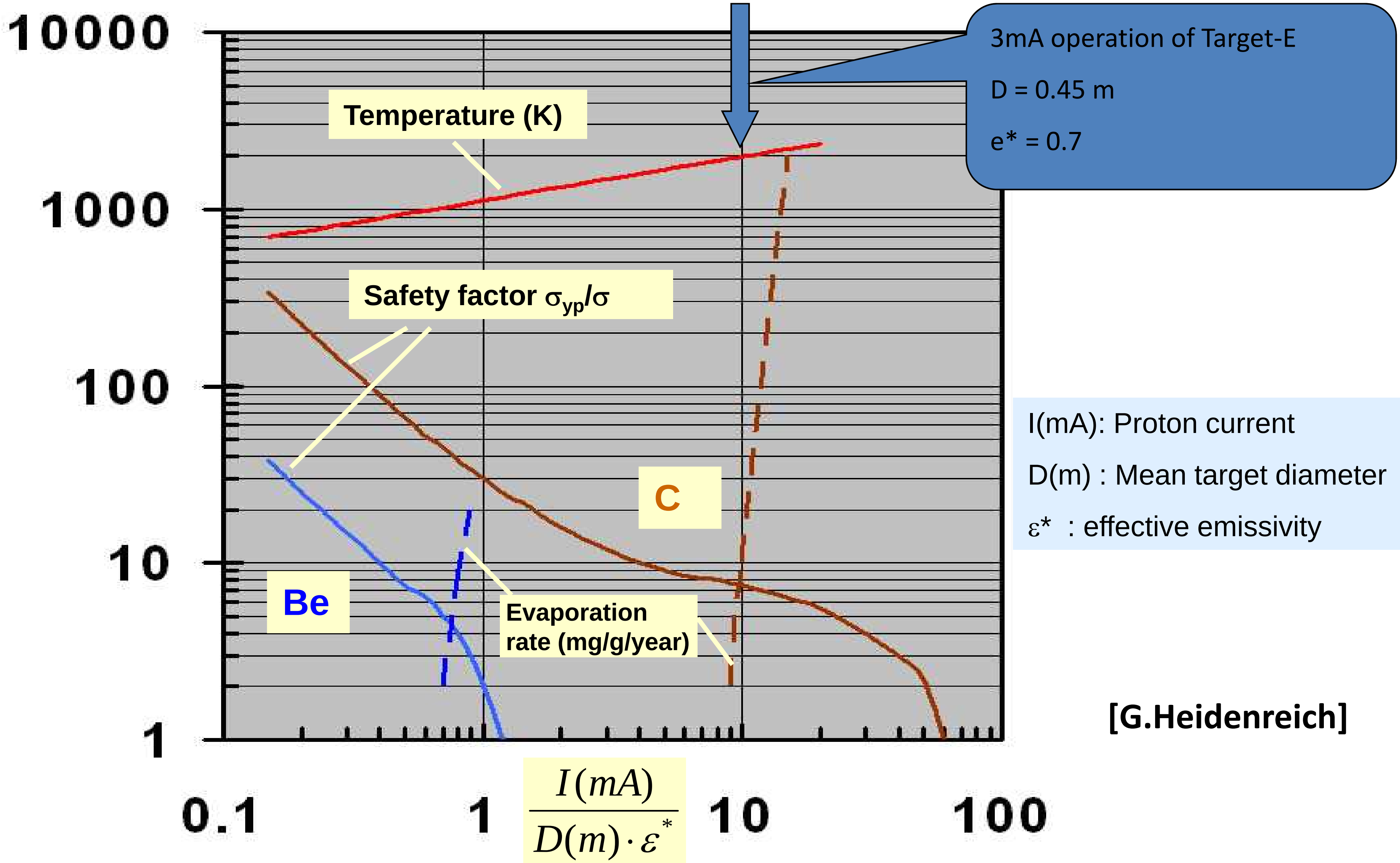


Exchange parts:



horizontal drive shaft

Operational limits of the rotating graphite & beryllium cones for target-E



I(mA): Proton current

D(m) : Mean target diameter

ε* : effective emissivity

[G.Heidenreich]

Lifetime of the pyrolitic graphite targets due to irradiation-induced dimensional changes

<u>Operational parameters:</u>

Proton current: 100 μA

Peak current density: 1000 $\mu A/cm^2$

Peak temperature: 1800 K

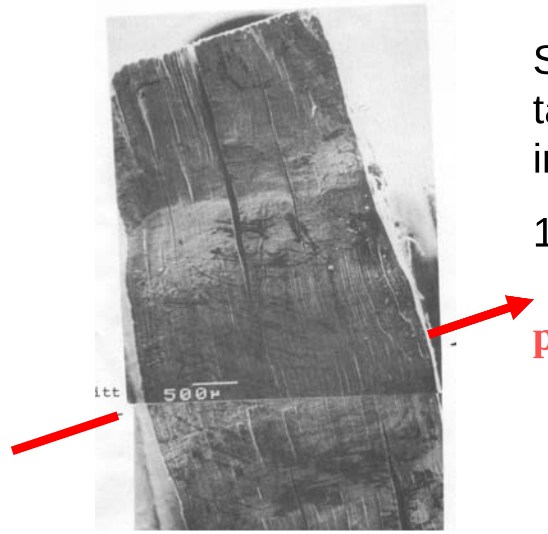
<u>Lifetime limits:</u>

Proton fluence: 10^{22} p/cm^2

Integrated beam current: 50 mAh

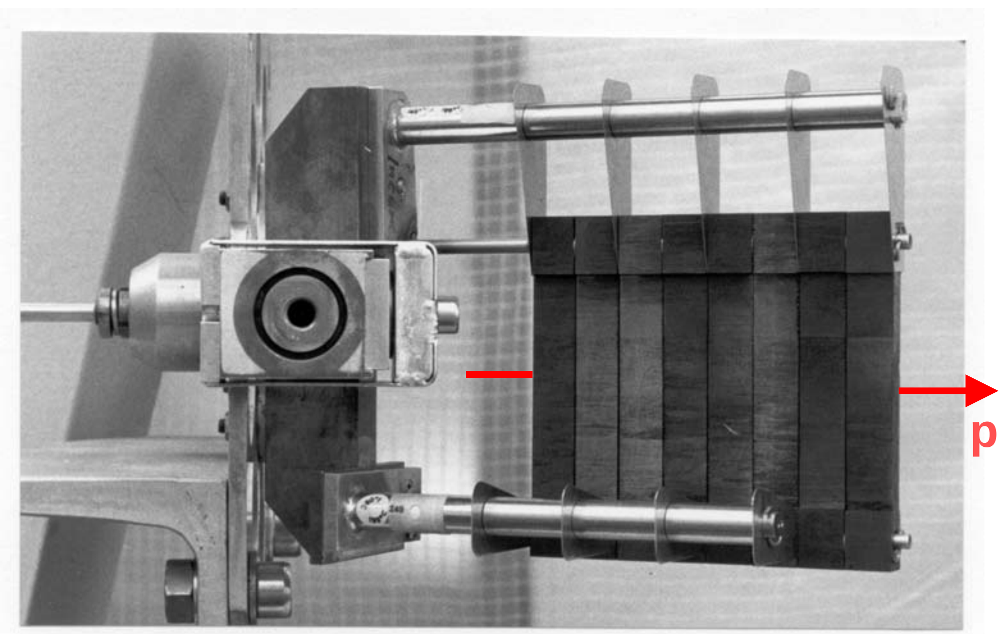
Irradiation-induced swelling: ~ 10 %

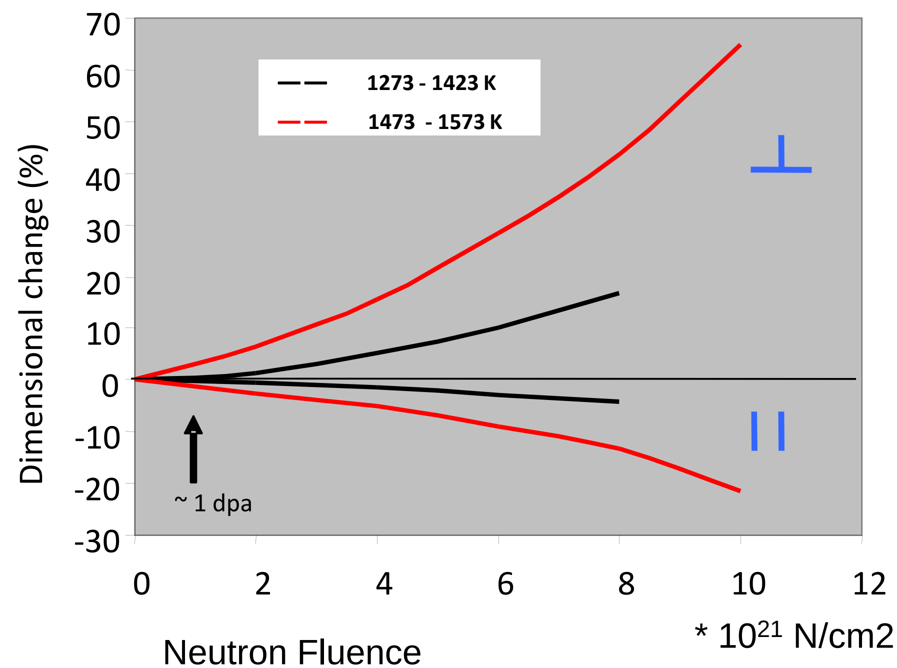
Irradiation damage rate: ~ 1 dpa



Swelling of the target after irradiation

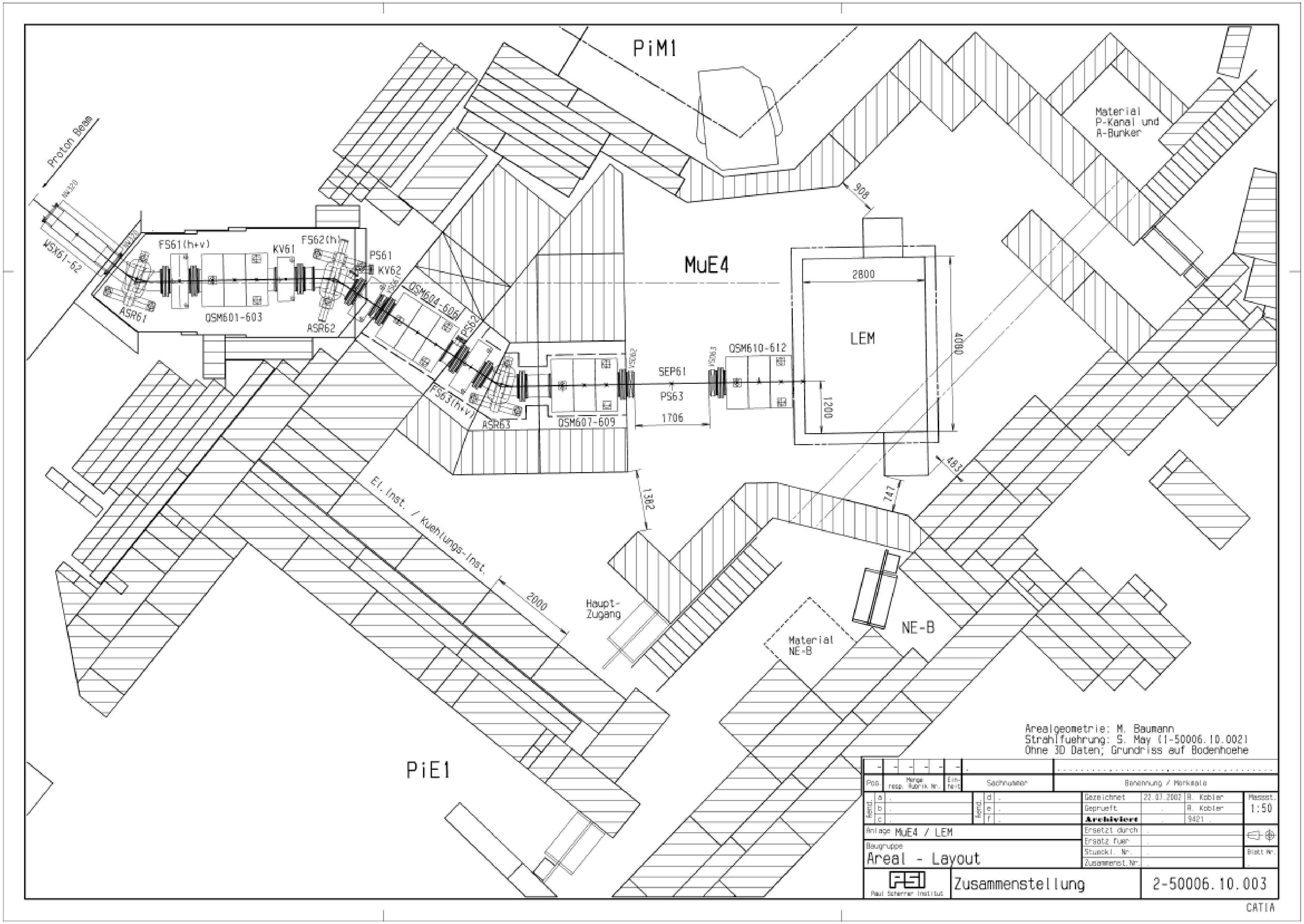
10^{22} p/cm2





J. Bokros et. al, Carbon 1971,Vol. 9,p. 349

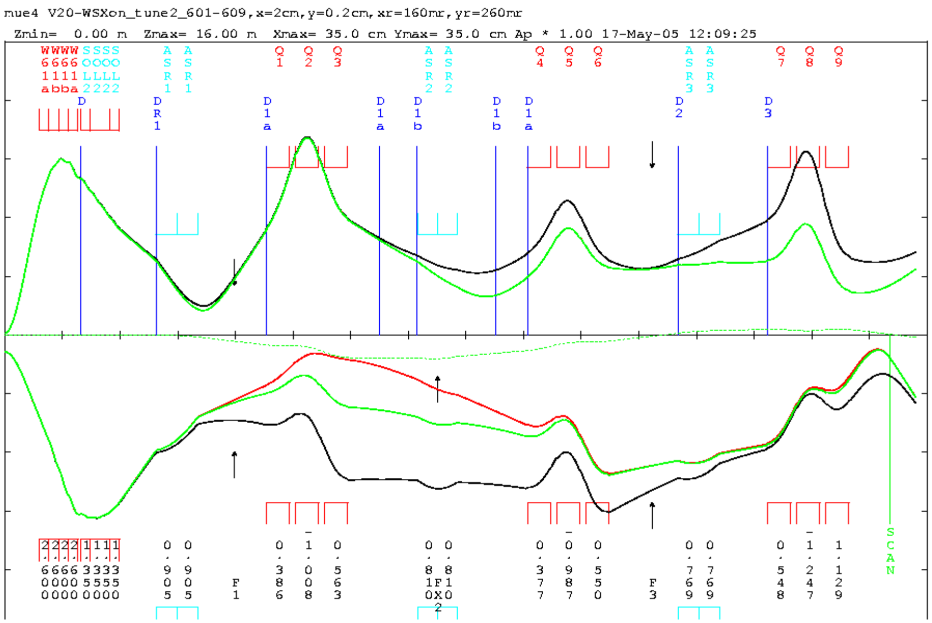
Muon- capture:
Layout of the μE4 high-intensity μ beam [Th:Prokscha]



Transport and TRACK calculations

y

x



TRANSPORT: ***PSI Graphic Transport framework*** **by U. Rohrer, based on a CERN-SLAC-FermiLab version by K.L. Brown et al.**

0% $\Delta p/p$ 1st

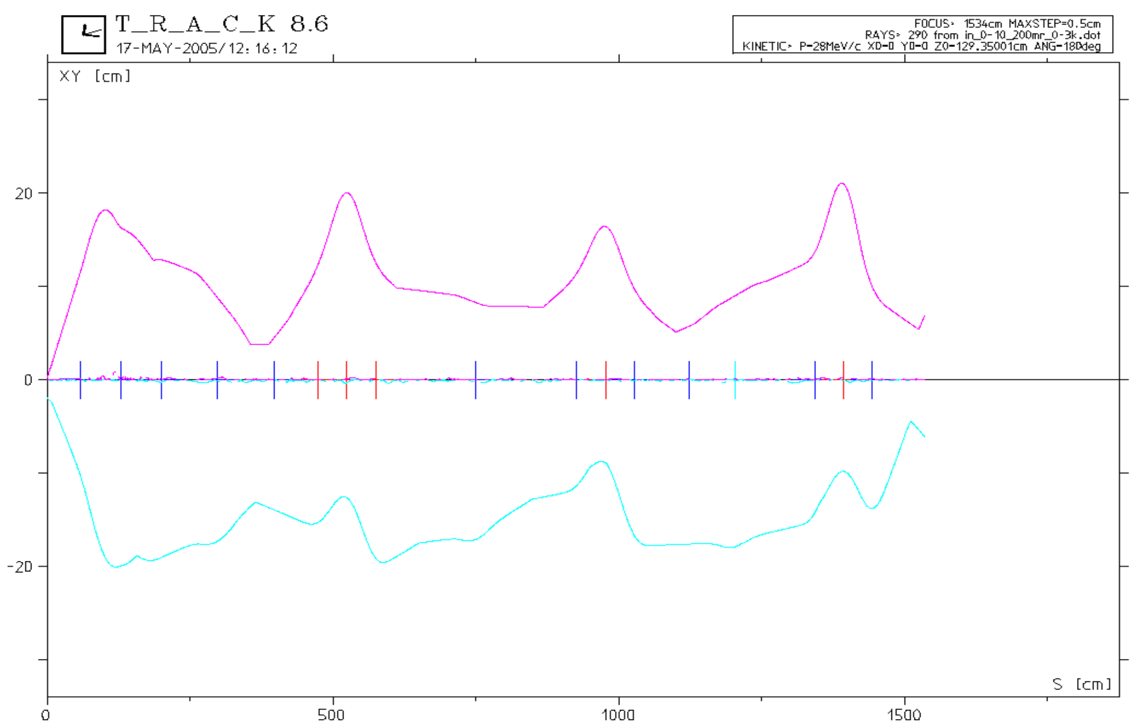
3% $\Delta p/p$ 1st

3% $\Delta p/p$ 2nd

$\Delta p/p$ (FWHM): 5% - 9.5%

y

x



TRACK: ***Three-dimensional Ray Tracing Analysis Computational Kit*****, developed by PSI magnet section (V. Vrankovic, D. George)**

Solenoid versus quadrupole

First order transfer matrix for static magnetic system with midplane symmetry:

$$\mathbf{R} = \begin{pmatrix} R_{11} & R_{12} & 0 & 0 & \dots & R_{16} \\ R_{21} & R_{22} & 0 & 0 & \dots & R_{26} \\ 0 & 0 & R_{33} & R_{34} & \dots & \dots \\ 0 & 0 & R_{43} & R_{44} & \dots & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots & \end{pmatrix}$$

➡

$$x_1 = R_{11}x_0 + R_{12}x_0' + R_{16}\frac{\Delta p}{p}$$
$$x_1' = R_{21}x_0 + R_{22}x_0' + R_{26}\frac{\Delta p}{p}$$
$$\vdots$$

First order transfer matrix for a solenoid, mixing of horizontal and vertical phase space:

$$\mathbf{R} = \begin{pmatrix} R_{11} & R_{12} & R_{13} & R_{14} & \dots & R_{16} \\ R_{21} & R_{22} & R_{23} & R_{24} & \dots & R_{26} \\ R_{31} & R_{32} & R_{33} & R_{34} & \dots & \dots \\ R_{41} & R_{42} & R_{43} & R_{44} & \dots & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \end{pmatrix}$$

➡

$$x_1 = R_{11}x_0 + R_{12}x_0' + R_{13}y_0 + R_{14}y_0' + R_{16}\frac{\Delta p}{p}$$
$$x_1' = R_{21}x_0 + R_{22}x_0' + R_{23}y_0 + R_{24}y_0' + R_{26}\frac{\Delta p}{p}$$
$$\vdots$$

Mixing of phase space might lead to an increase of beam spot size

Rotation Θ of phase space: $\Theta = \frac{B \cdot l_{eff}}{2(B\rho)}$ $\tan(\Theta) = -\frac{R_{31}}{R_{11}} = \frac{R_{13}}{R_{33}}$

$\Theta = 90^{\circ}$: x-y PS exchanged

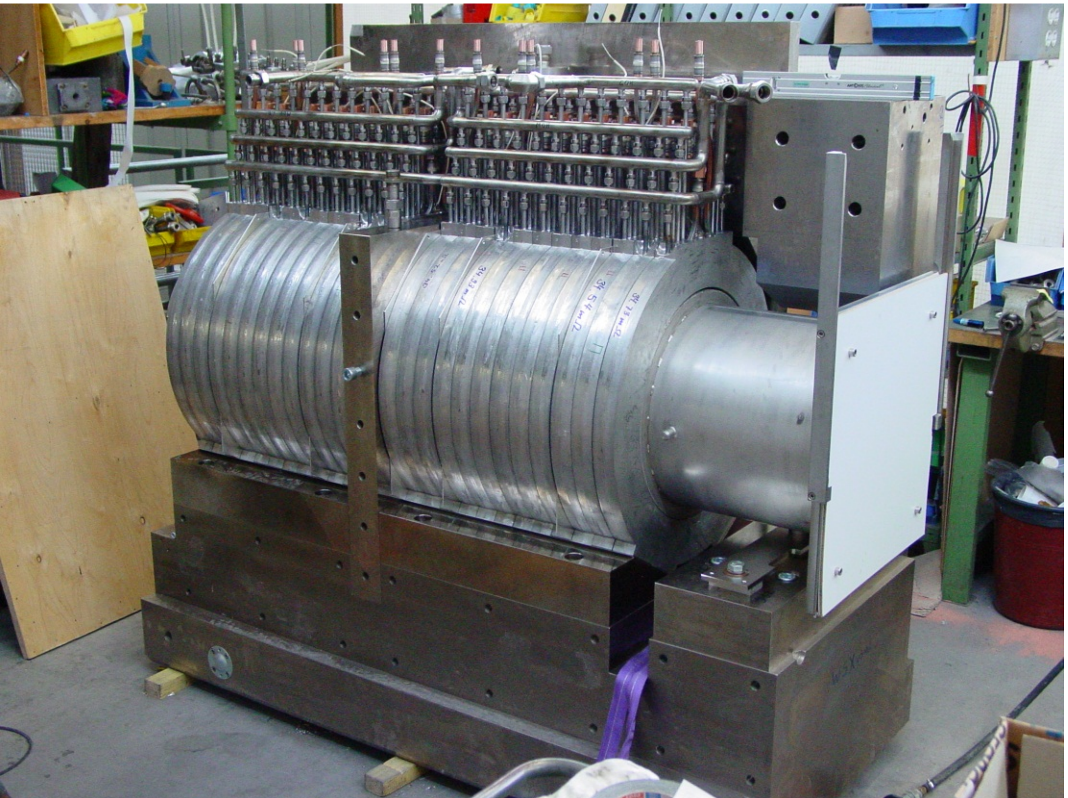
$$\mathbf{R} = \begin{pmatrix} 0 & 0 & R_{13} & R_{14} & \dots & R_{16} \\ 0 & 0 & R_{23} & R_{24} & \dots & R_{26} \\ R_{31} & R_{32} & 0 & 0 & \dots & \dots \\ R_{41} & R_{42} & 0 & 0 & \dots & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \end{pmatrix}$$

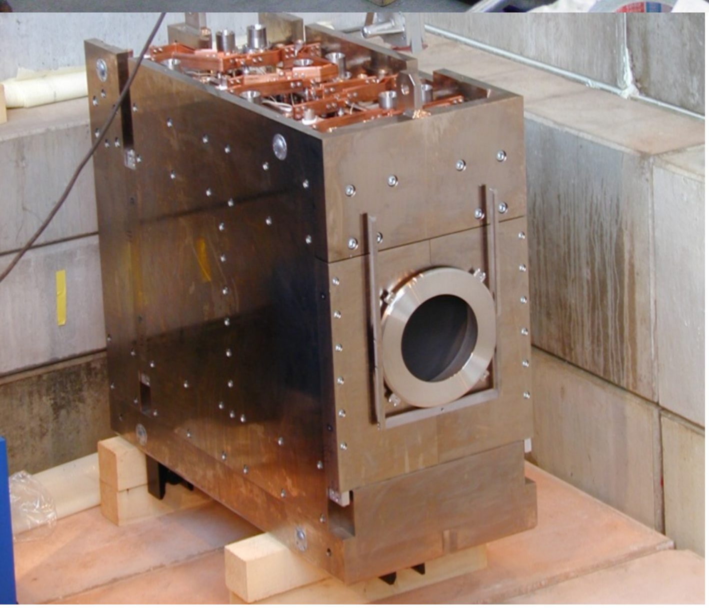
Azimuthal symmetry of solenoids leads to larger acceptance

Focusing powers $P_{S,T}$ of solenoid and triplet at same power dissipation in device:

$$1/f = P$$
$$P_T = P_S \cdot [l_{eff}^2/(2a^2)]$$
$$P_T > P_S \quad \text{if} \quad l_{eff} > \sqrt{2}a$$

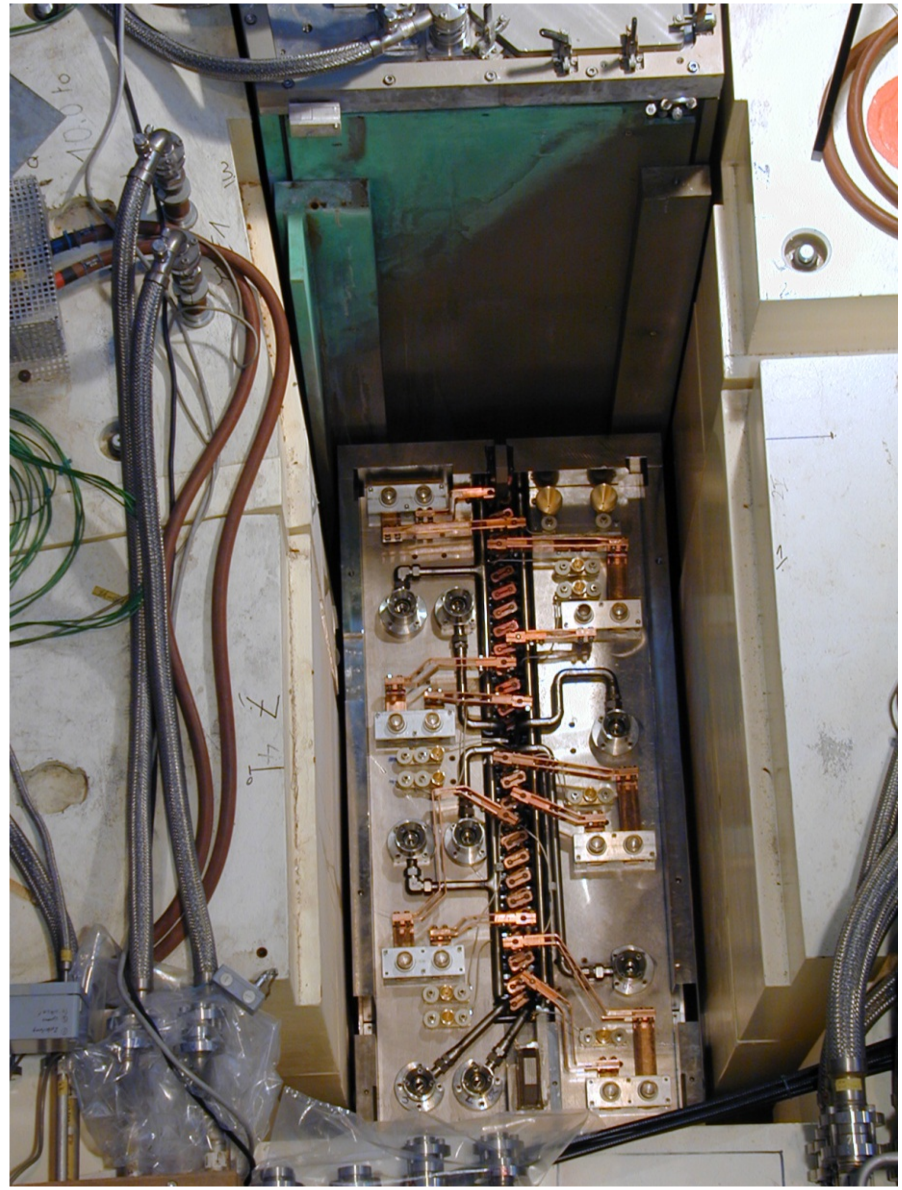
Double-solenoid WSX61/62



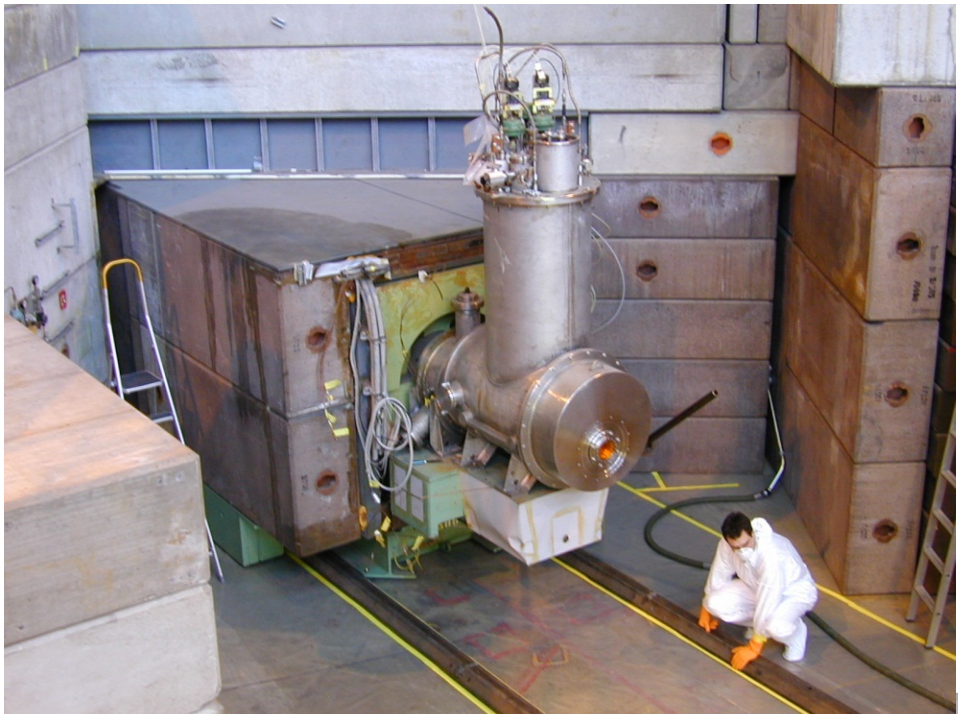


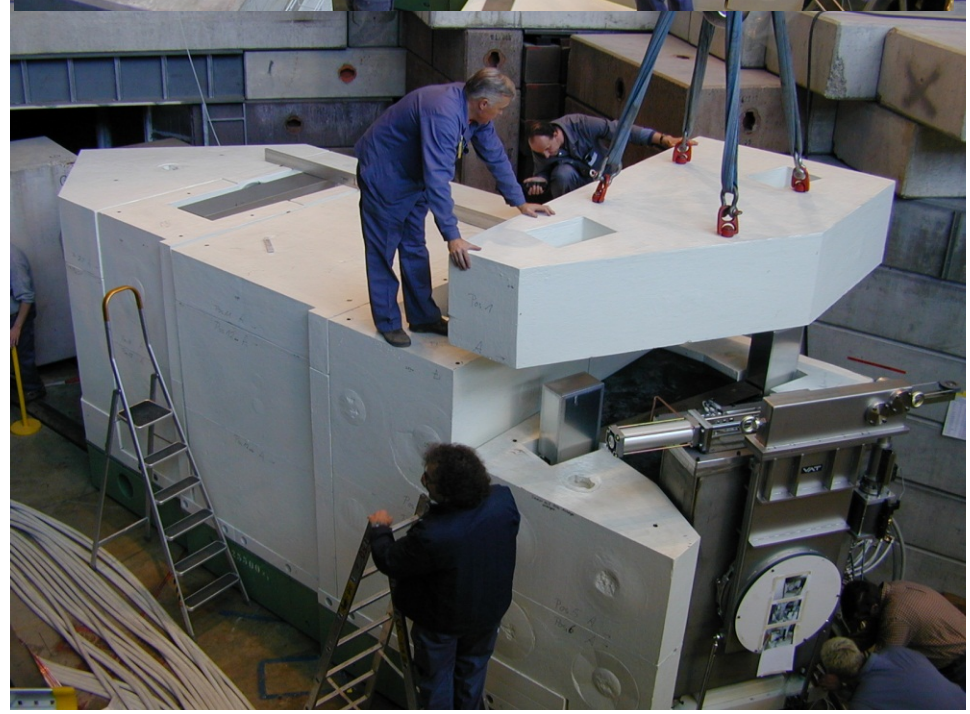
$B_{max} = 3.5$ kG

$Ø_i = 500$ mm



Installation of a section of μE4 in 2004





Discussion

- PSI concept is optimized for dual use of beam (Meson and Neutron Production); C = low-z material; strong focus at target: minimize emittance growth
- beam loss at 40mm C-target:
  10% inelastic nuclear interactions; 20% collimation of spent beam
- rotating graphite target concept with radiation cooling was optimized over many years; lifetime limited by anisotropy of graphite and resulting wobbling from radiation damage; pyrolithic graphite not suited!
- service and exchange systems, Hotcell are VERY IMPORTANT for practical operation
- Muon figures: $\approx 5 \cdot 10^8$ μ^+/s possible @p=28MeV/c; $\Delta p/p = 9.5\%_{FWHM}$; $\varepsilon_{x/y} = 5/10 \cdot 10^{-3}$m·rad
  T. Prokscha, et al., Nucl. Instr. and Meth. A (2008), doi:10.1016 /j.nima.2008.07.081
- activation after one year: order of 1…5 Sv/h; thanks to Graphite this is low compared to heavy target materials!
- issues: Tritium production in porous material; oxidation of graphite with poor vacuum of 10^{-4}mbar; carbon sublimation at higher temperatures; wobbling of wheel caused by inhomogeneous radiation damage