Experience with High Power Operation at PSI

M.Seidel, PSI

HB2008, Nashville

PSI High Power - Outline

- overview of the facility
- comments on CW acceleration with cyclotrons

[CW vs. pulsed operation, resonators, electrostatic elements, interruption and recovery statistics]

- high power related aspects

[beam loss, activation, instrumentation, interlock systems]

- practical operational experience – examples

[power density on target too high, leaking heavy water from moderator tank, inspection of highly activated collimator]

- upgrade plans

[space charge in cyclotrons, new resonators for Ring and Injector cyclotron, 10’th harmonic buncher]

- conclusion and outlook

Overview PSI Facility

Injector II Cyclotron 72 MeV

isotope production
(I_b <100μA)

Ring Cyclotron 590 MeV

2 mA /1.2 MW

target M (d=5mm)

target E (d = 4cm)

proton therapie center
[250MeV sc. cyclotron]

Cockcroft Walton

870 keV transfer channel

72 MeV transfer channel

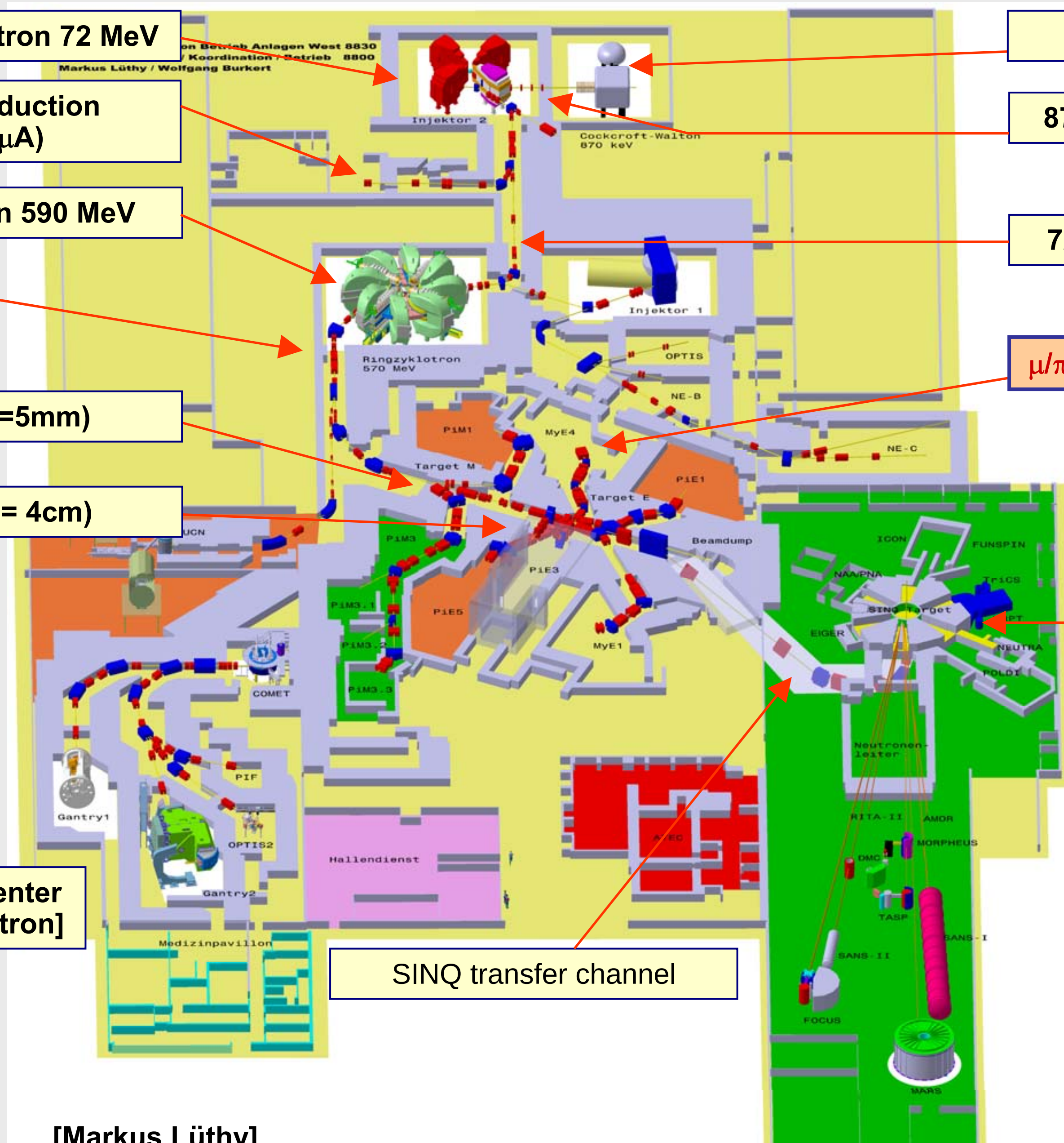
μ/π secondary beamlines

1.4 mA /0.8 MW
CW operation

SINQ
spallation source

SINQ
experiments

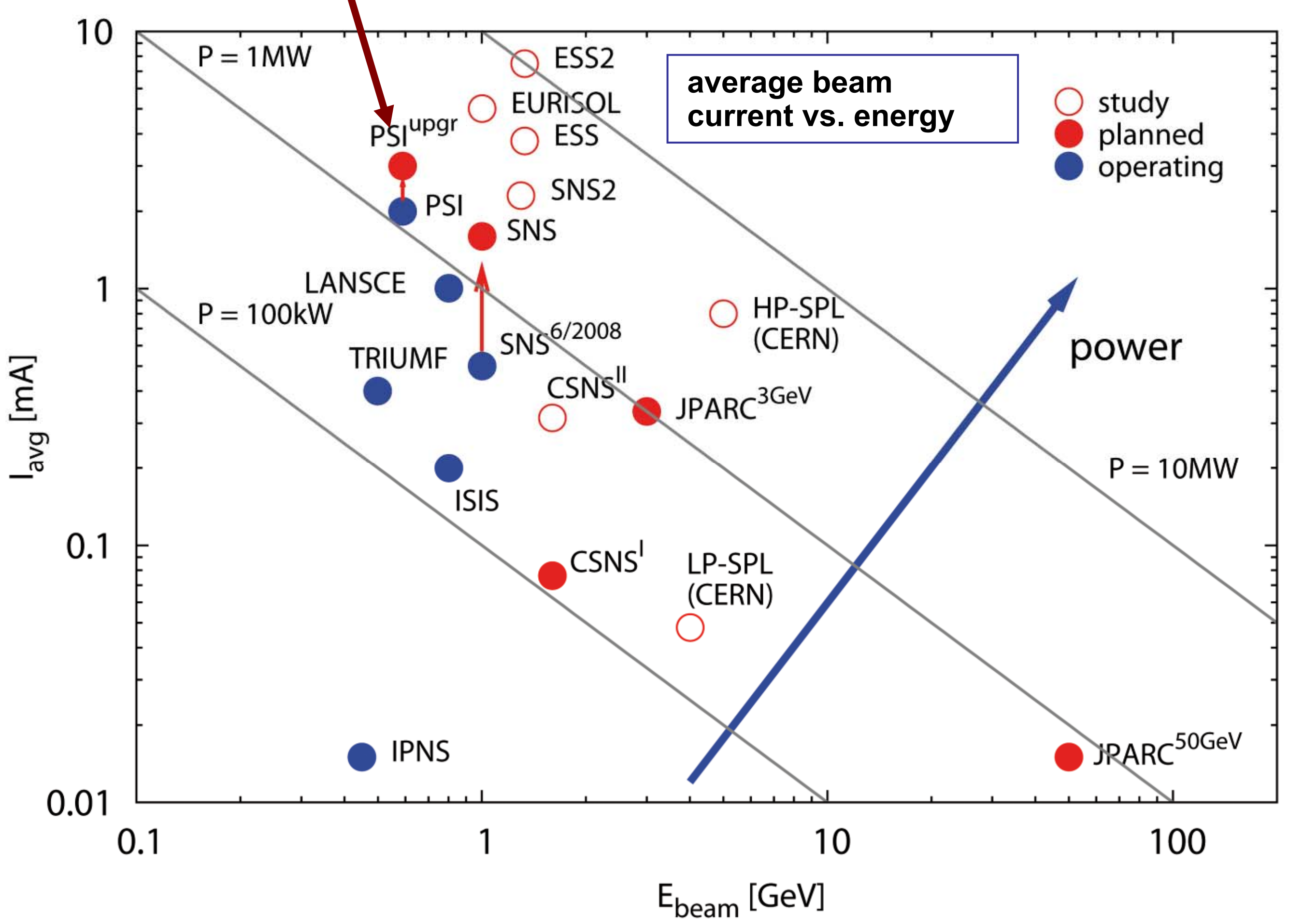
SINQ transfer channel



[Markus Lüthy]

High Power Proton Accelerators

PSI Upgrade Plan



PSI Parameters: [2mA, 1.2MW] → [3mA, 1.8MW]

plot: selected accelerators

current vs. energy

power ∝ current × energy

note: neutron output is proportional to beam power, only weakly dependent on energy

the PSI cyclotron based facility is still at the forefront with respect to the **average beampower**

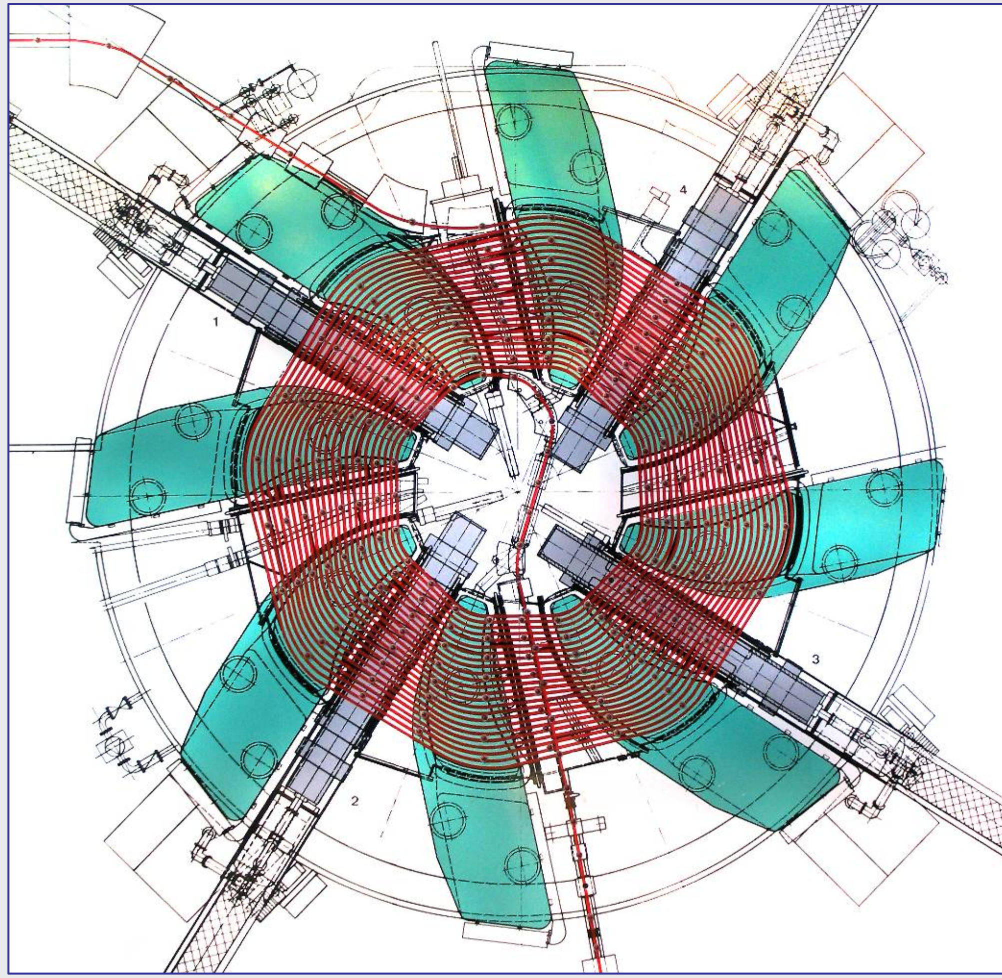
(this is CW operation!)

CW Acceleration using a Sector Cyclotron

590 MeV Ring Cyclotron

(magnets) in operation for 30+ years

- 8 Sector Magnets	1 T
- Magnet weight	~250 tons
- 4 Accelerator Cavities	850kV (1.2MV)
- Accelerator frequency:	50.63 MHz
- harmonic number:	6
- beam energy:	72 $\rightarrow$ 590MeV
- beam current (now):	2.0 mA
- extraction orbit radius:	4.5m
- relative Losses @ 2mA:	~1..2$\cdot 10^{-4}$



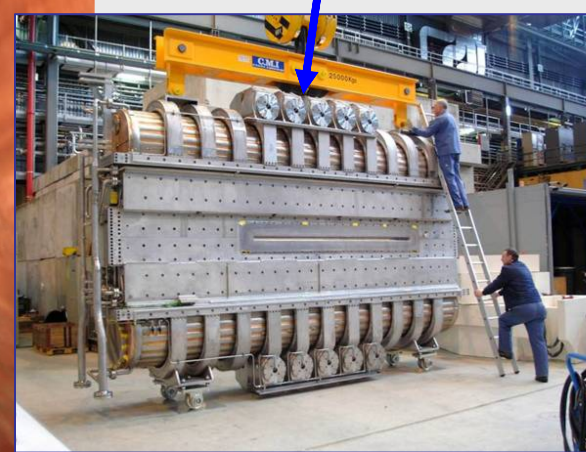
Pro:	Con:
- CW operation is inherently stable	- inj./extr. difficult, interruptions, losses!
- efficient power transfer with only 4 resonators	- large and heavy magnets (therm. equiliblium!)
- cost effective	- energy limited ~1GeV
[- no pulsed stress in target]	[- no pulsed structure for neutrons]

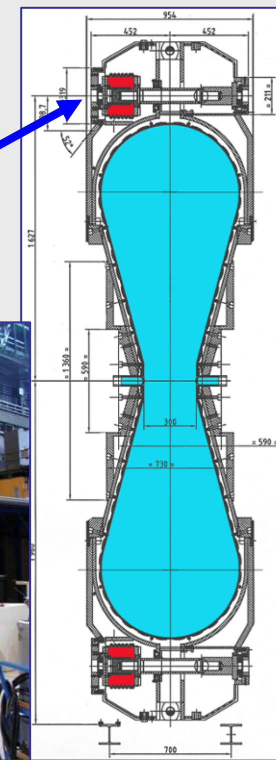
major component: RF Resonators for Ring Cyclotron

- **the shown Cu Resonators have replaced the original Al resonators** [less wall losses, higher gap voltage possible, better cooling distribution, better vacuum seals]
- **$f = 50.6$MHz**; **$Q_0 = 4\cdot10^4$**; **U_{max}=1.2MV** (presently 0.85MV→186 turns in cyclotron, goal for 3mA: 165 turns)
- transfer of up to **400kW power to the beam** per cavity
- deformation from air pressure ~20mm; **hydraulic tuning devices** in feedback loop → regulation precision ~10μm

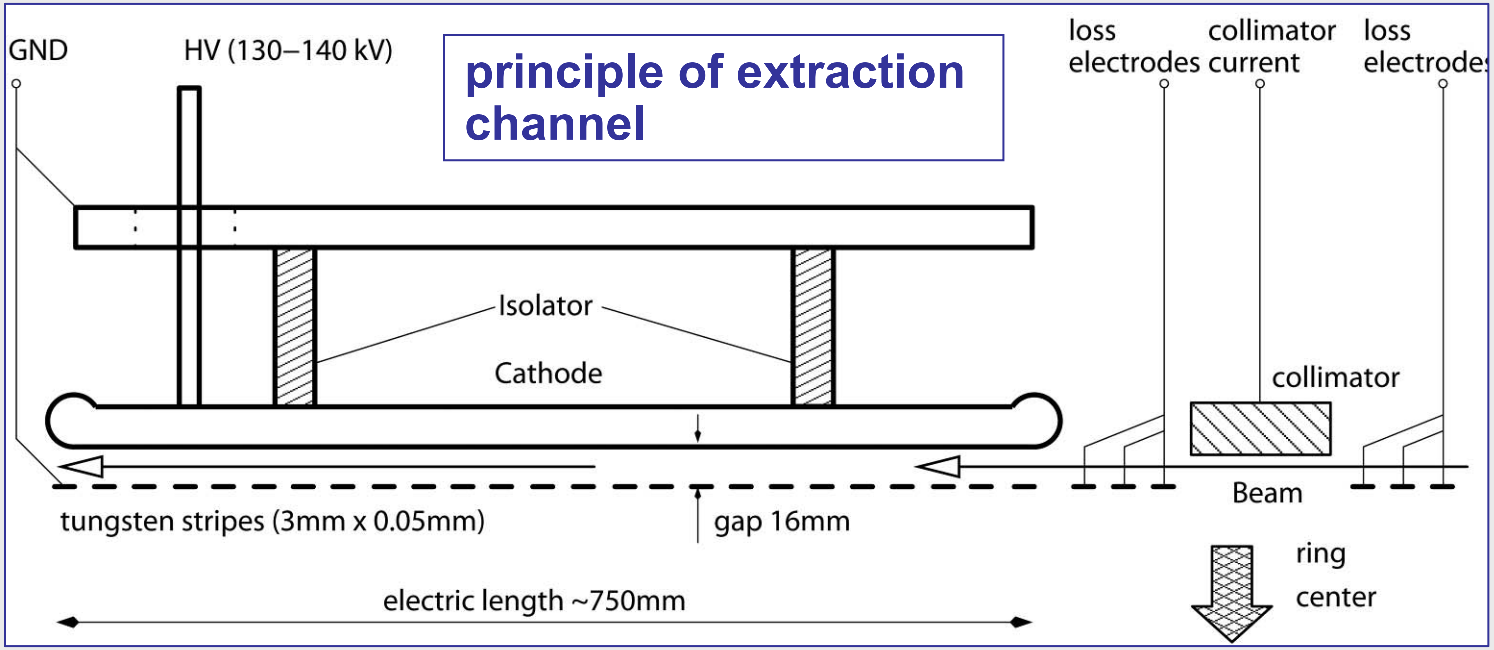
resonator inside

hydraulic tuning devices (5x)





critical: electrostatic elements



parameters extraction channel:

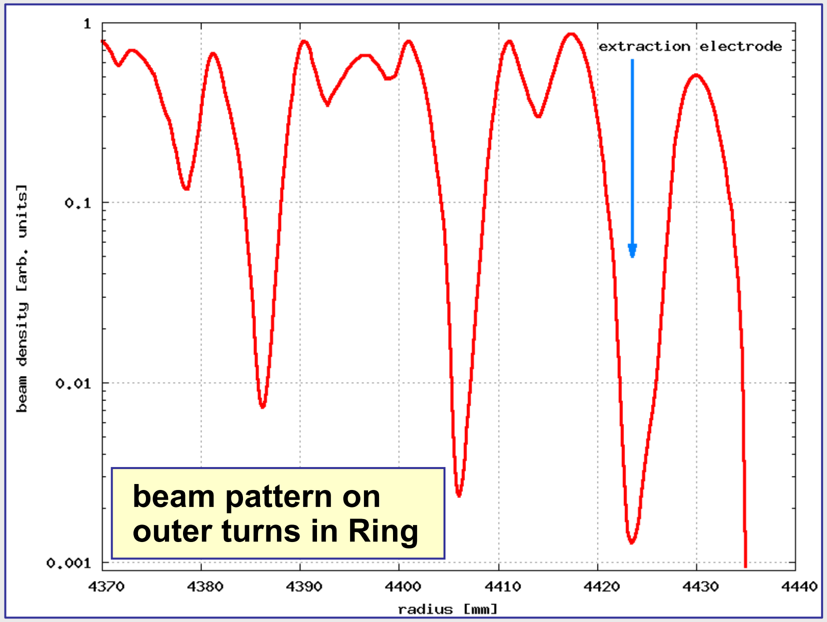
E_k = 590MeV

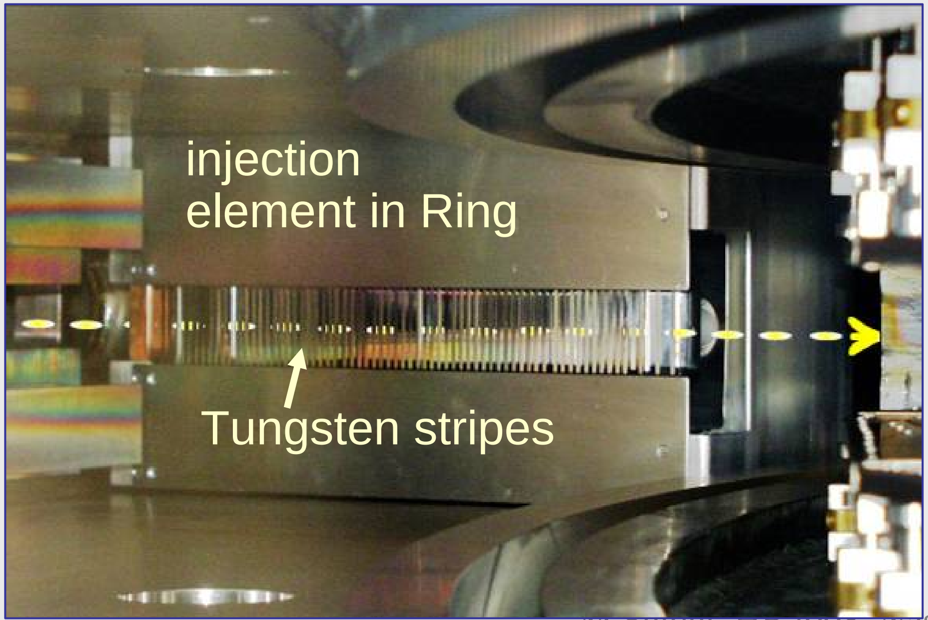
E = 8.8 MV/m

θ = 6.8 mrad

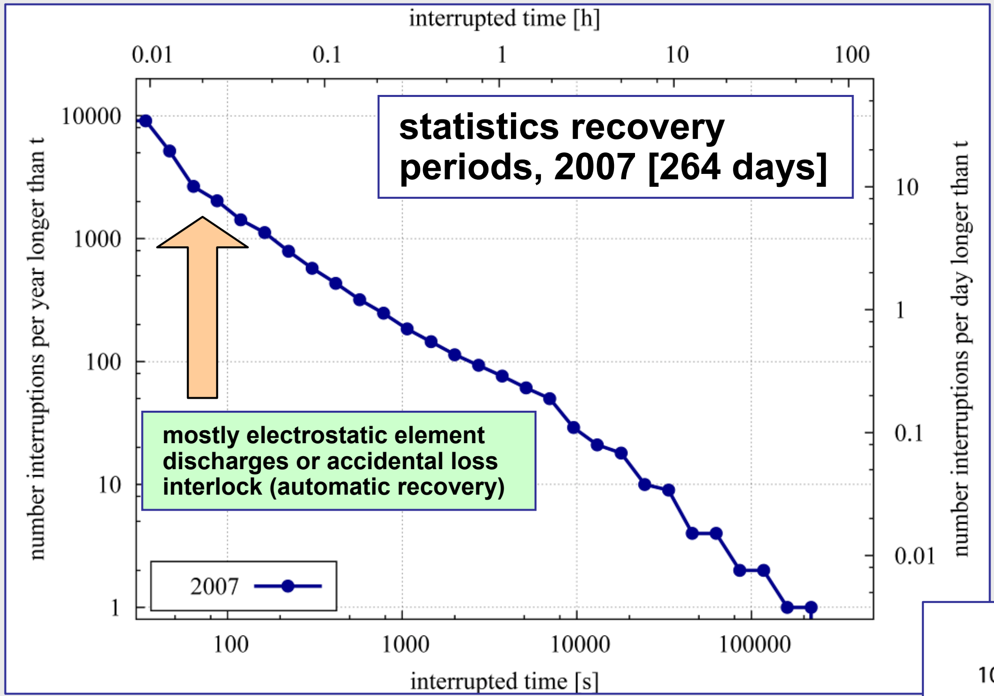
ρ = 110 m

U = 141 kV





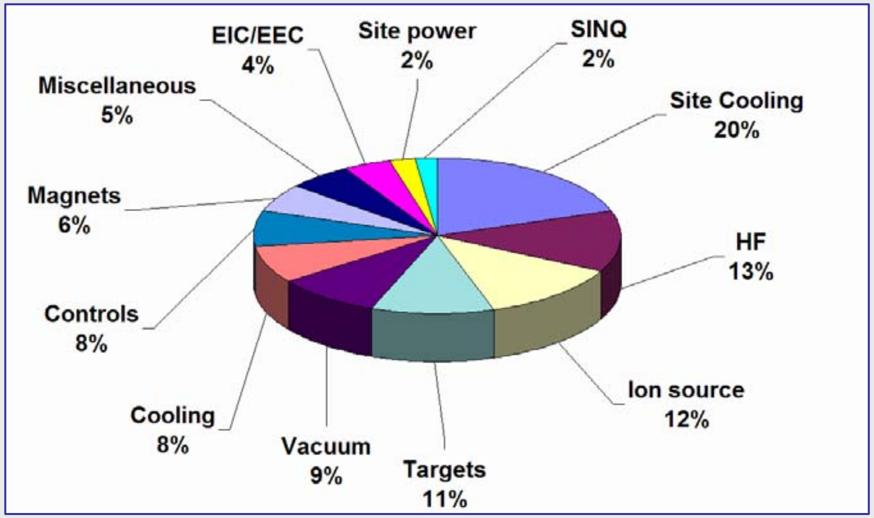
Statistics of run and recovery periods



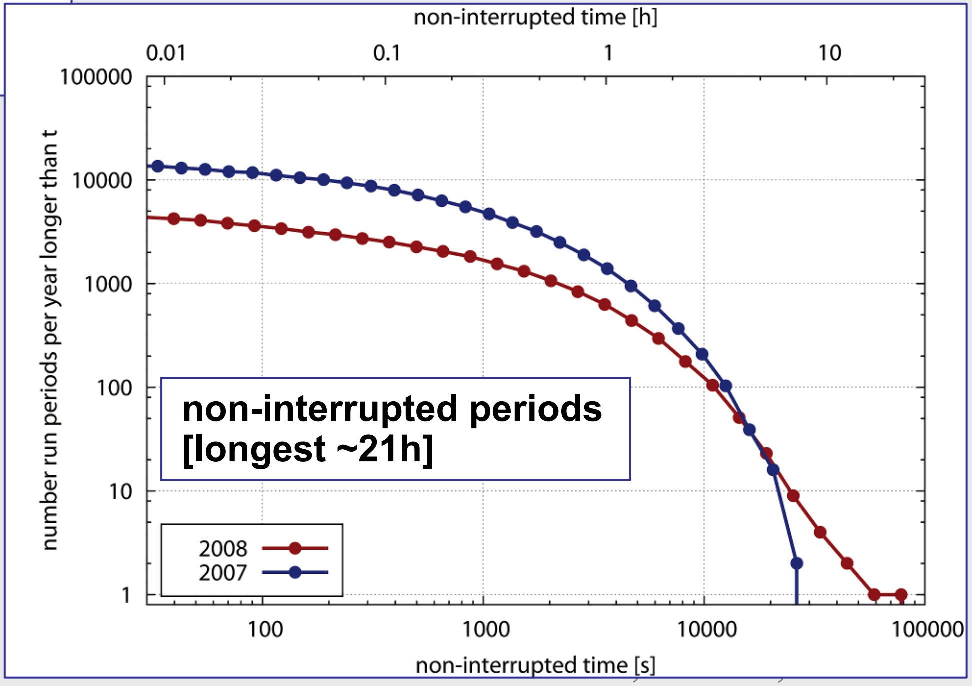
integrated histograms of all run periods and breaks/recovery periods in **2007, 2008 [47% of '07]**

note: **double logarithmic scale**

for example read: *there are 5 run periods longer than 8 hours in 2008*

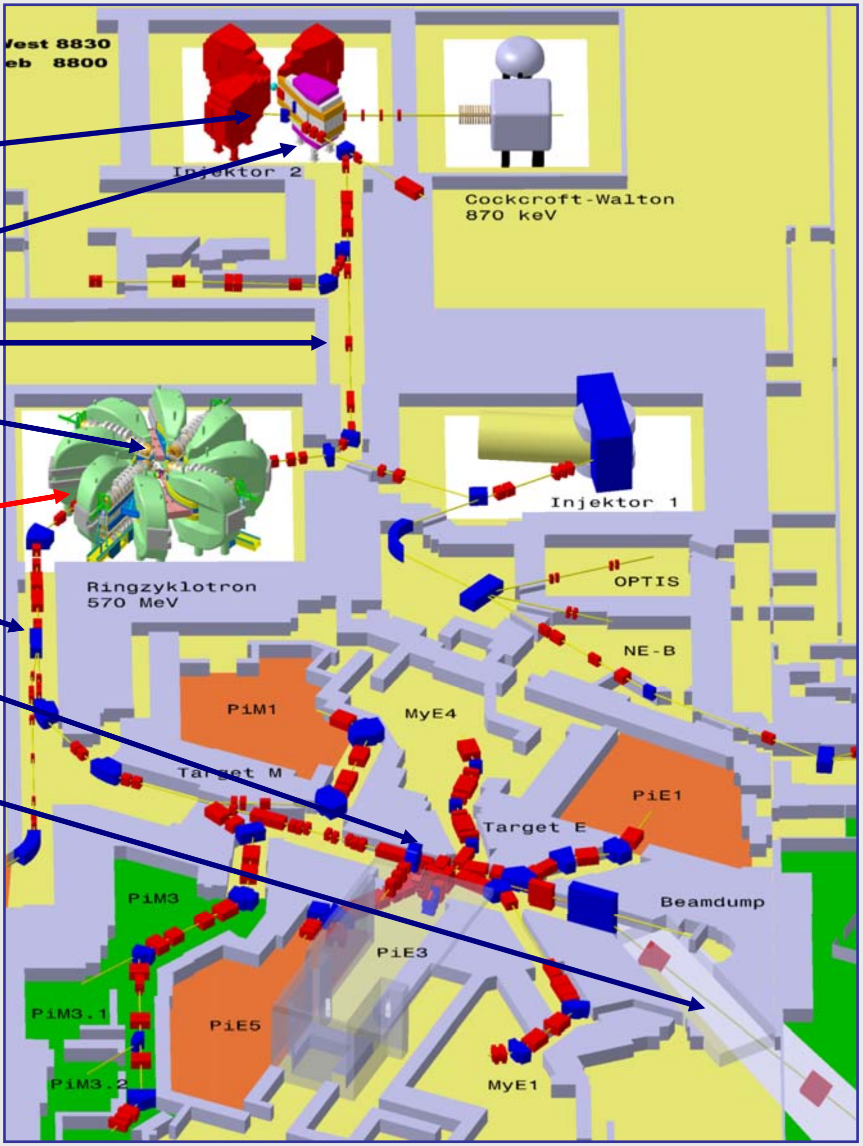


serious interruptions >10min (A.Mezger, report 2007)



Particle losses along the accelerator

Accelerator Section	kin. energy [MeV]	max.loss [μA]	typ. loss [μA]
Injector II, extraction	72	5	0.3
collimator FX5 (shielded)	72	10	5
transport channel II (35m)	72	0.1	
Ring Cyc., Injection	72	2	0.3
Ring Cyc., Extraction	590	**2**	**~0.4**
transport channel III	590	0.1	0.02 (est)
target E+M (shielded)	590	30%	30%
transport channel IV	575	0.1	
SINQ target (shielded)	575	70%	70%



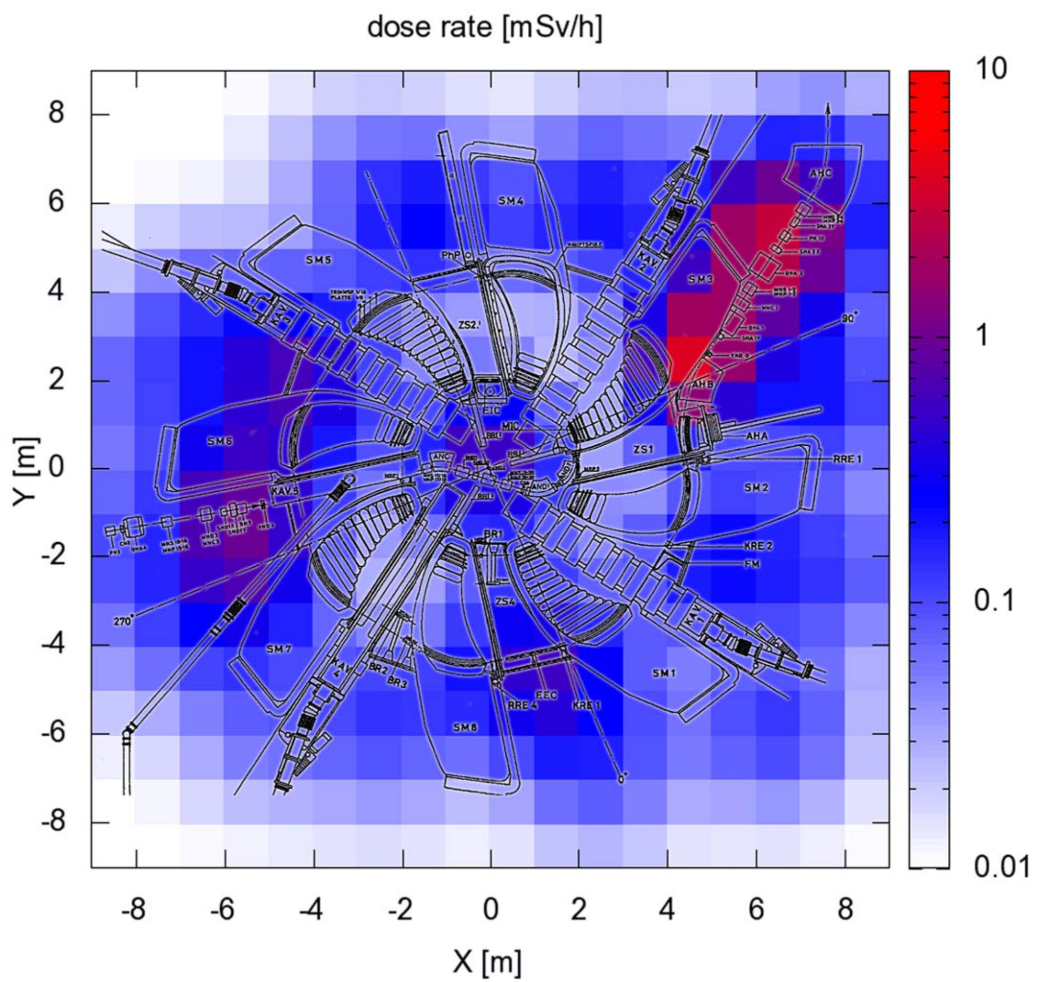
acceptable for service:

~ $2 \cdot 10^{-4}$ relative losses per location

component activation – Ring Cyclotron

activation allows necessary service/repair work

- personnel dose for typical repair mission 50-300μSv
- optimization by adapted local shielding measures; shielded service boxes for exchange of activated components
- detailed planning of shutdown work



activation map of Ring Cyclotron

(EEC = electrostatic ejection channel)

personal dose for 3 month shutdown:

57mSv, 188 persons
max: 2.6mSv

cool down times for service:

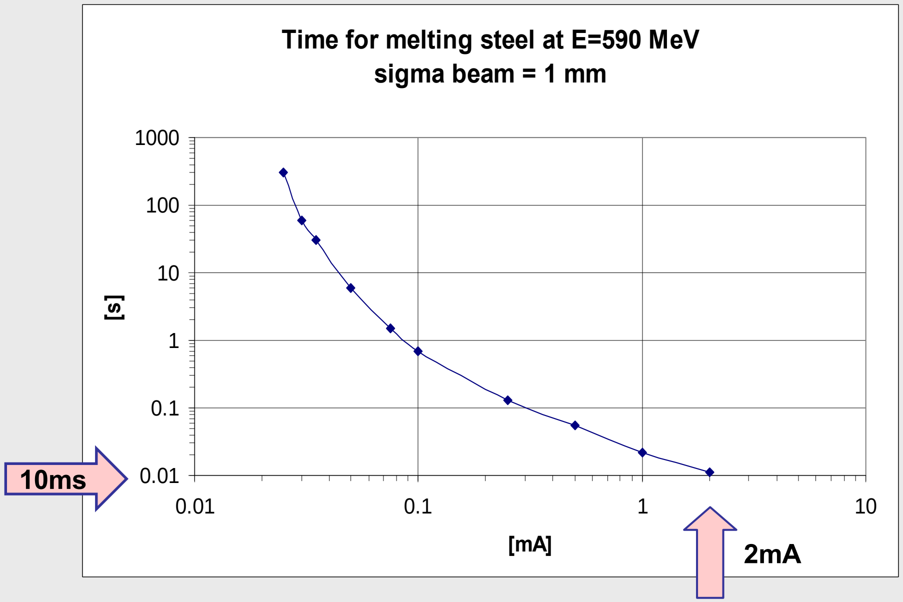
2000 → 1700 μA for 2h

0 μA for 2h

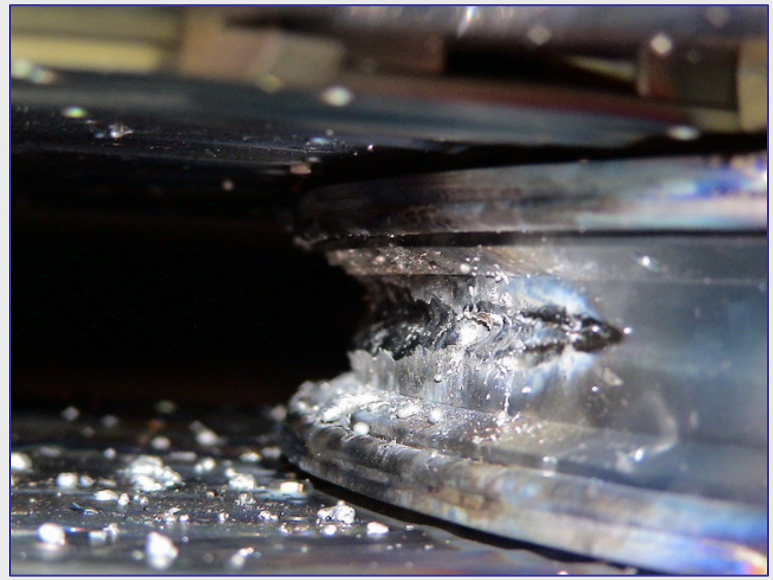
map interpolated from ~30 measured locations

Machine protection

if the **beam hits the vacuum chamber** this may cause a shutdown of up to one year duration, depending on damaged component → careful safety measures and **interlock systems** required to protect the accelerator



courtesy of G.Heidenreich (PSI)


Cyclotron damage at injection (2004) to be avoided

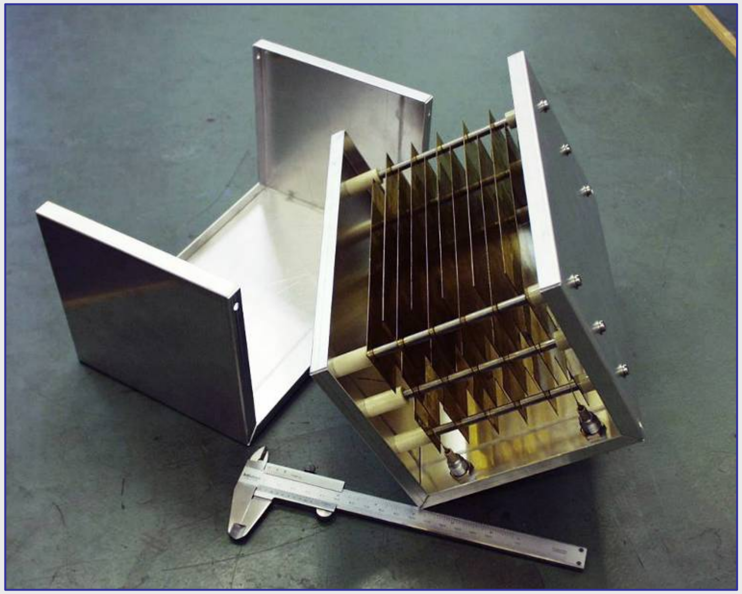
1. **Machine protection system** that will switch off the beam in less than 5 ms in order to avoid thermal damage.
2. Monitor and limit losses in order to minimize **activation** of components.

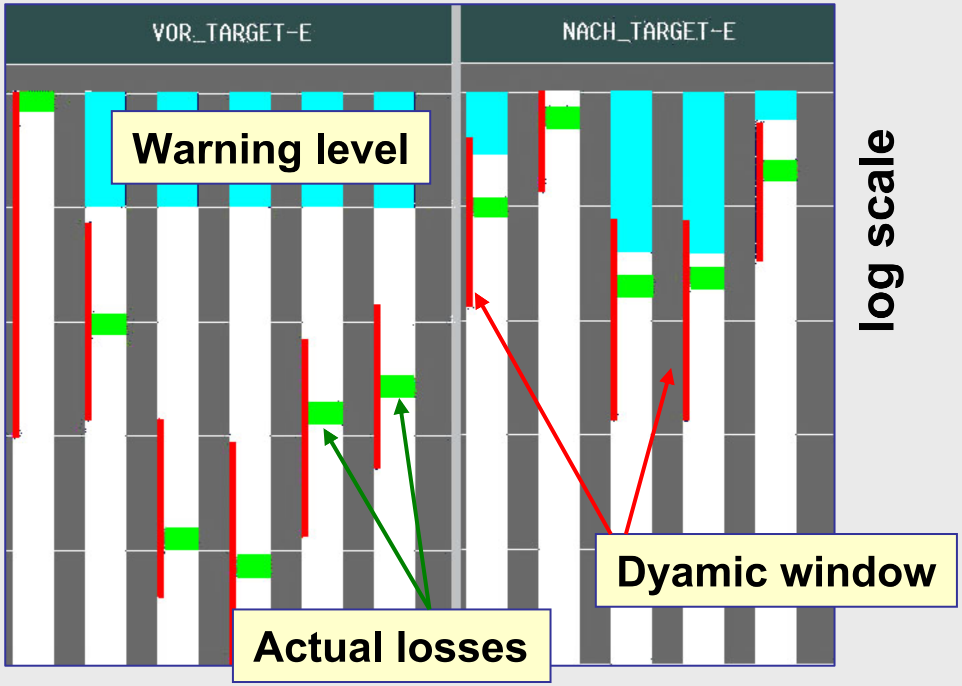
Diagnostics for Tuning/Protection

System based on ca. 150 interconnected very fast (<100μs) hardware **CAMAC** and VME modules treating about 1500 signals provided by the equipment:

1. Ionisation chambers as beam loss monitors with fixed warning and interlock limits; critical ones also with limits as function of the beam current.

Simple and reliable device



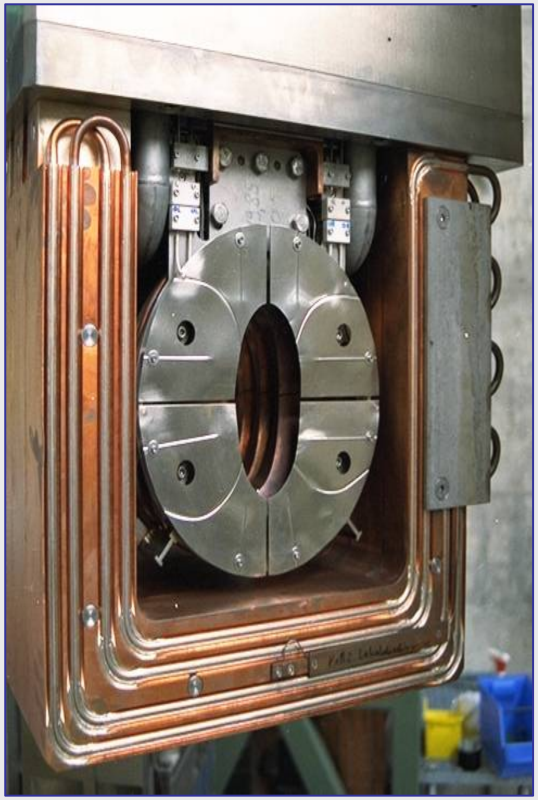


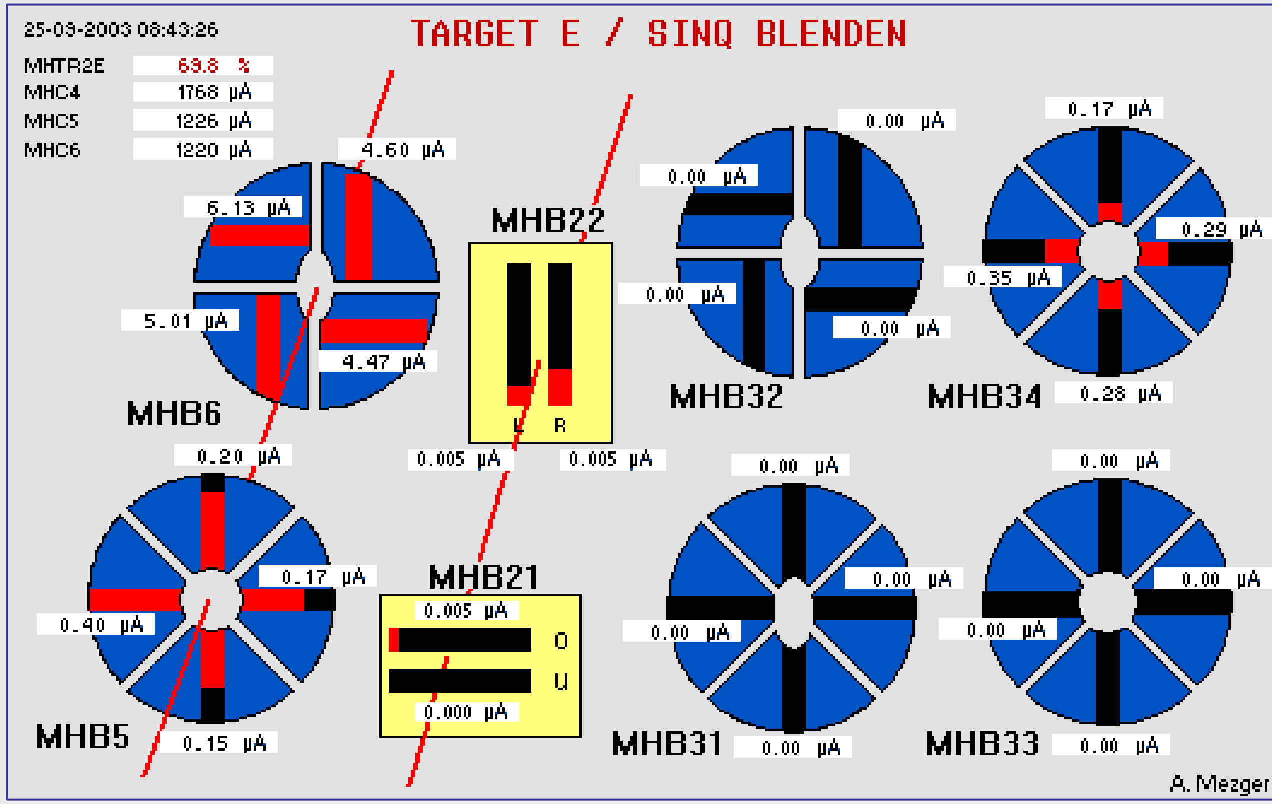
Permanent display of losses

→ **losses outside margins are interlocked (including low values)**

Diagnostics (cont.)

2. Segmented Collimators measuring the balance of right and left, up and down scraped beam currents





→ interlock is generated in case currents or asymmetry of currents exceeds margin

Diagnostics (cont.)

3. Beam current transmission monitors compare the beam current at different spots for detecting loss of beam, normally 100% of transmission except at the targets and when beams are splitted.

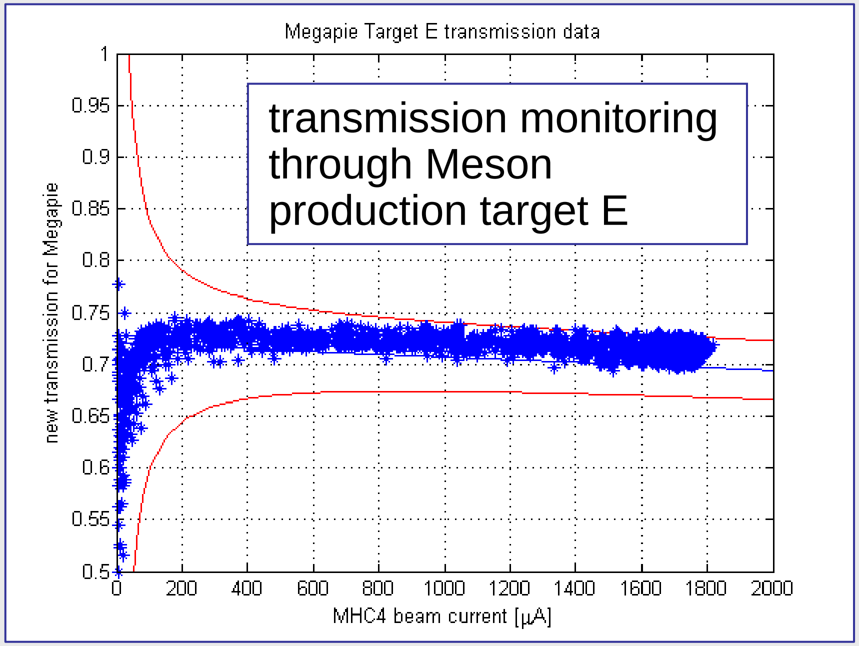
100 % transmission in main cyclotron

100 % transmission in beampipes, except for splitted beams

97 % transmission of thin target M

70 % transmission of thick target E

Integration time:
110 ms at 0 µA down to 10 ms above 1.5 mA
Window:
± 5 µA at 0 µA and ± 90 µA at 2 mA

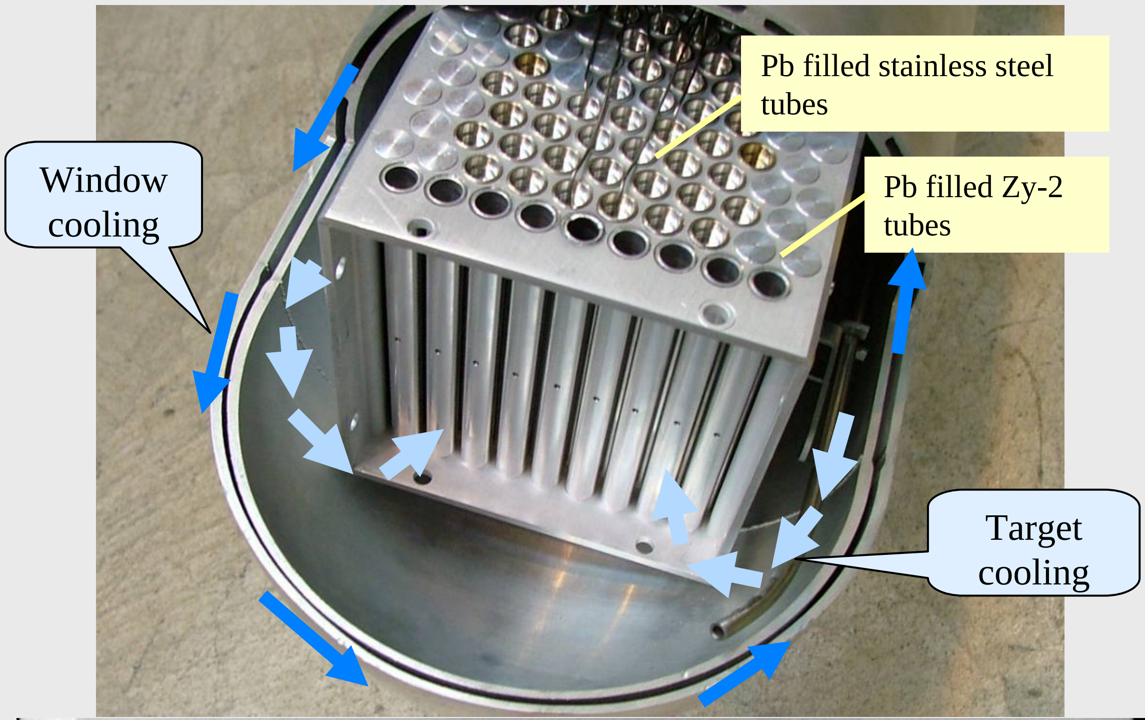


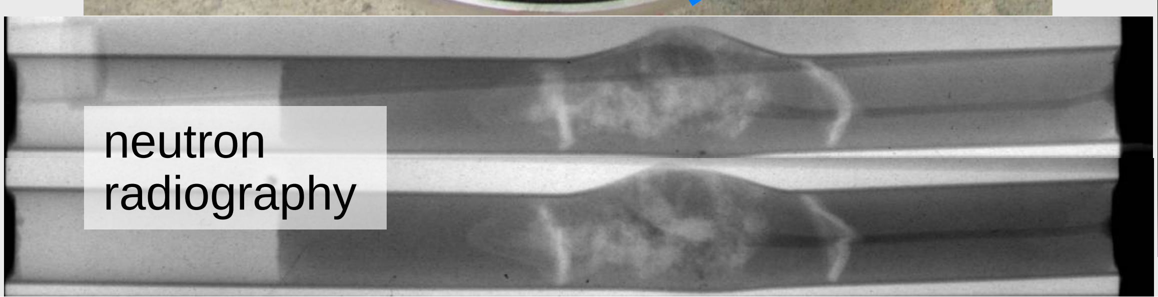
4. Many other signals: validity window on magnet settings, cavity voltages, …

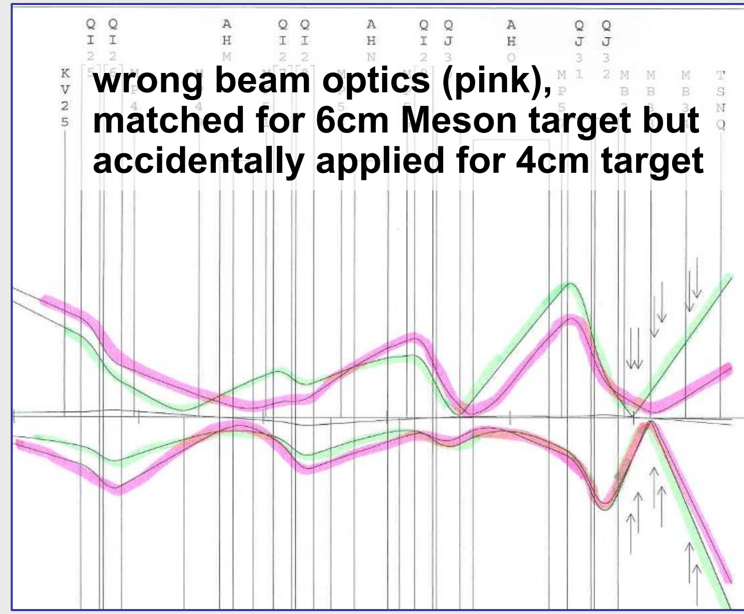
practical experience: overheating of Lead filled steel tubes in spallation target

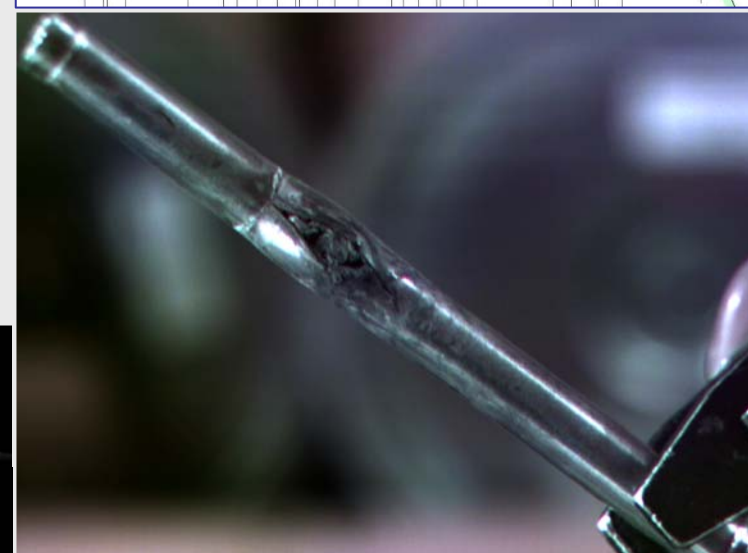
➔ **cause: wrong beam optics installed, caused narrow beam width → power density too high**

➔ **usual current density <=40μA/cm², in this case: 70μA/cm²**



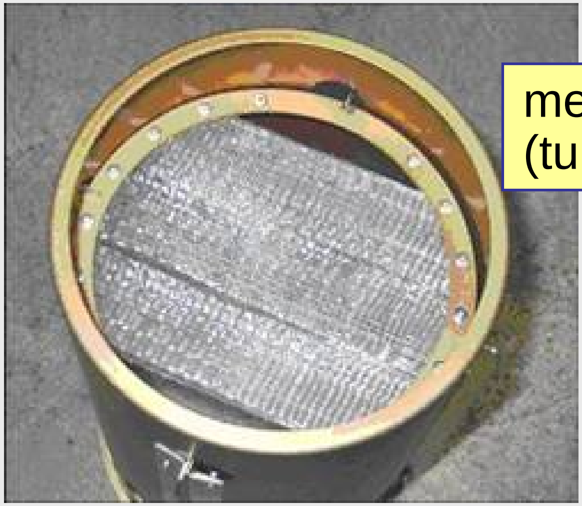




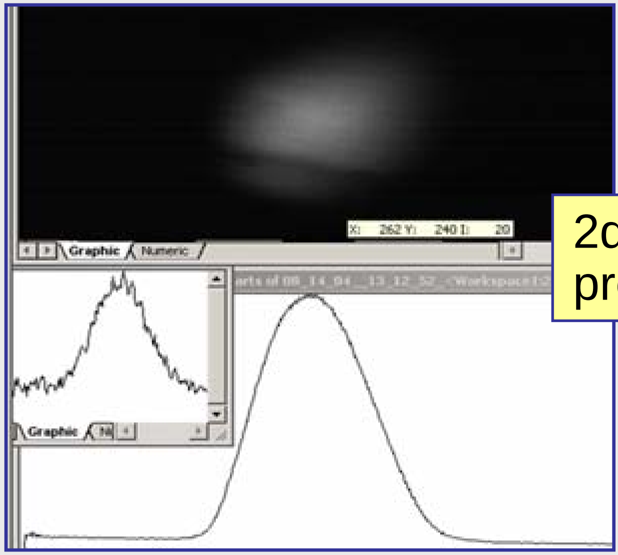


improved interlock system: direct current density monitoring

beam projection on a **glowing mesh** observed with an **optical camera**; problem: lifetime of camera; new version: **glass-fiber optics** to shielded camera position

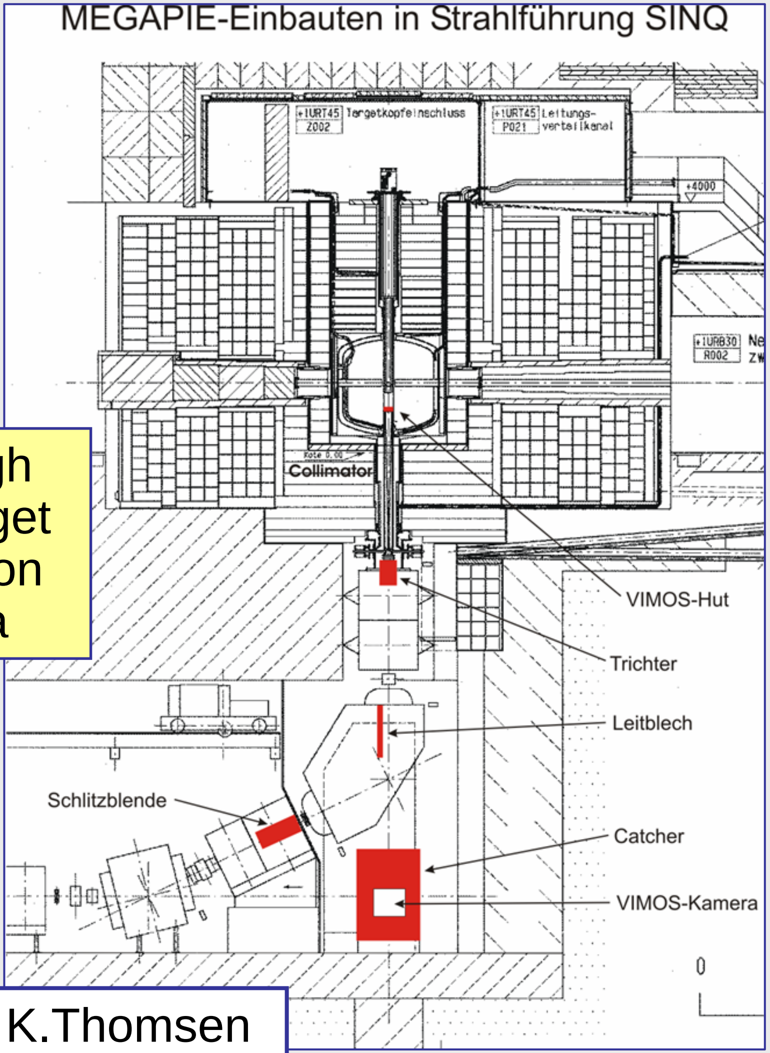


metallic mesh (tungsten)



2d display and projection

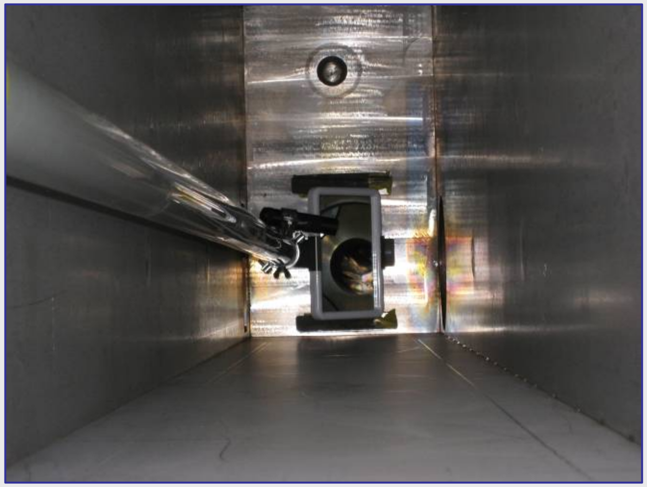
vertical cut through beamline and target showing installation of VIMOS camera

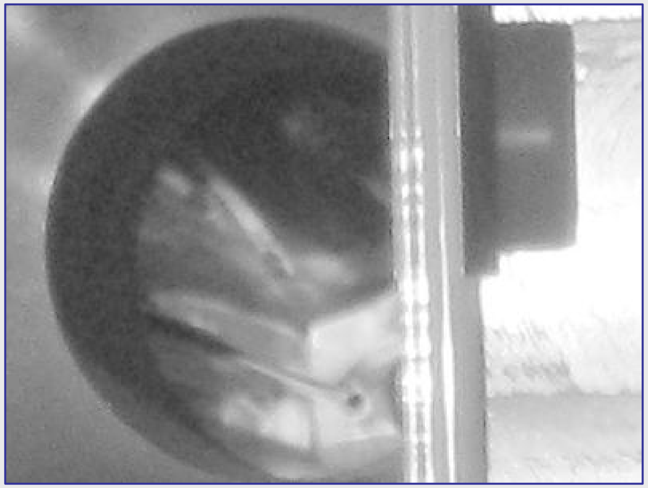


VIMOS, K.Thomsen

practical experience: inspecting a highly activated collimator

- **cause**: Meson target region is vented during target exchange (less ^3H for personnel)
- **observation**: highly activated dust particles transported by air flow
- **fear**: dust comes from damaged iron collimator??
- **measures**: - install **separated** venting system with **filters** for this purpose
  - chemical/radiological **analysis in hot cell** → Fe_2O_3
  - **Monte Carlo Simulation** → must have been direct beam hit! [talk D.Kiselev WG-D]
  - **activation measurement** using rate meter: >10Sv/h; using dosimeters → ~ 2Sv/h, compatible with halo losses
  - **optical inspection** using mirror → collimator mechanically intact
- conclusion: problem not understood, but seems no hazard; **example shows the need for special tools, instruments, skills…**





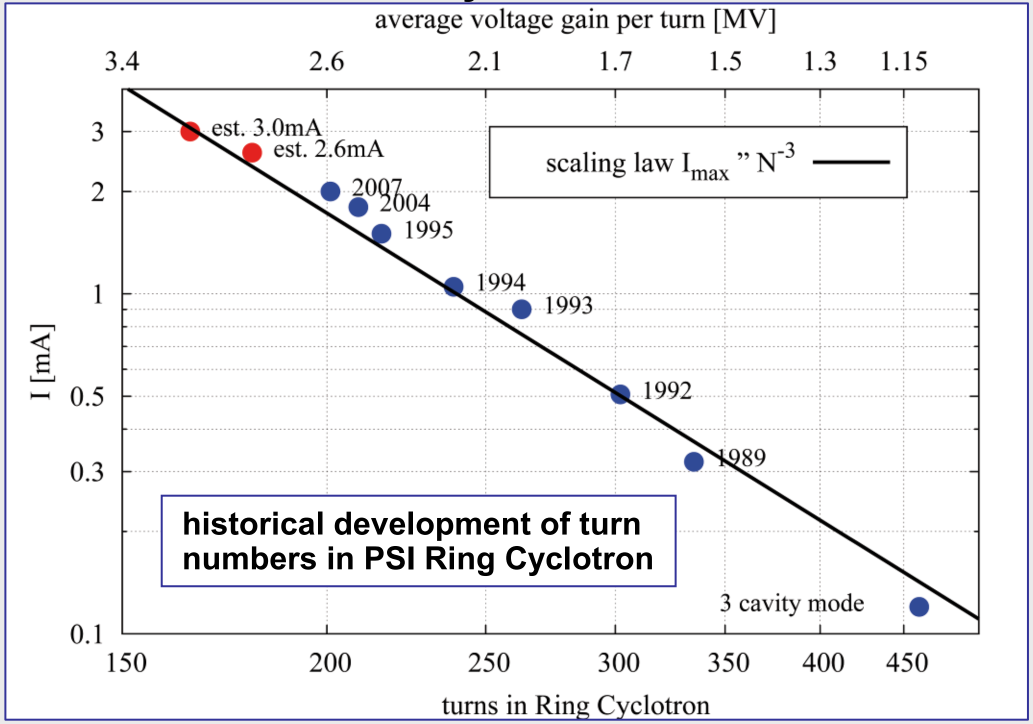
inspection of suspect steel collimator using mirror; shows intact surfaces [endoscope camera died from radiation]

Cyclotron Facility Upgrade Path – short bunches, fast acceleration!

- keep **absolute losses constant**; increase acceleration voltage and beam quality, better turn separation at extraction
- losses ∝ [**turns**]^3 ∝
  [**charge density (sector model)**] × [**accel. time**] / [**turn separation**] (W.Joho)
- new components: **resonators** - 4 in Ring, 2 in Injector; **harmonic bunchers**: 3'rd harmonic for Injector; 10'th harmonic for Ring

planned turn numbers and voltages

	turns Ring	turns Injector
now (2.0mA)	202→186 (U_{peak}≈3.6MV)	81 (U_{peak}≈1.12MV)
inter. step (2.6mA)	~180 (U_{peak}≈3.7MV)	~73 (U_{peak}≈1.25MV)
upgrade (3.0mA)	~165 (U_{peak}≈4.0MV)	~65 (U_{peak}≈1.40MV)



avoid tail generation with short bunches

study of beam dynamics in Ring Cyclotron

→ behavior of short bunches, generated by 10'th harmonic buncher

→ optimum parameters of flat-top cavity at these conditions

-multiparticle simulations

-10^5 macroparticles

- precise field-map

- bunch dimensions:

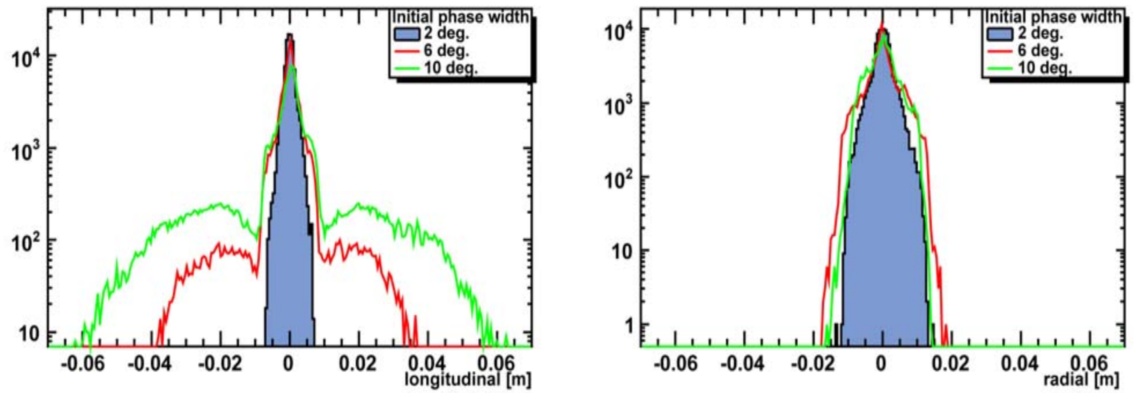
σ_z ~ 2, 6, 10 mm;

σ_{xy} ~ 10 mm

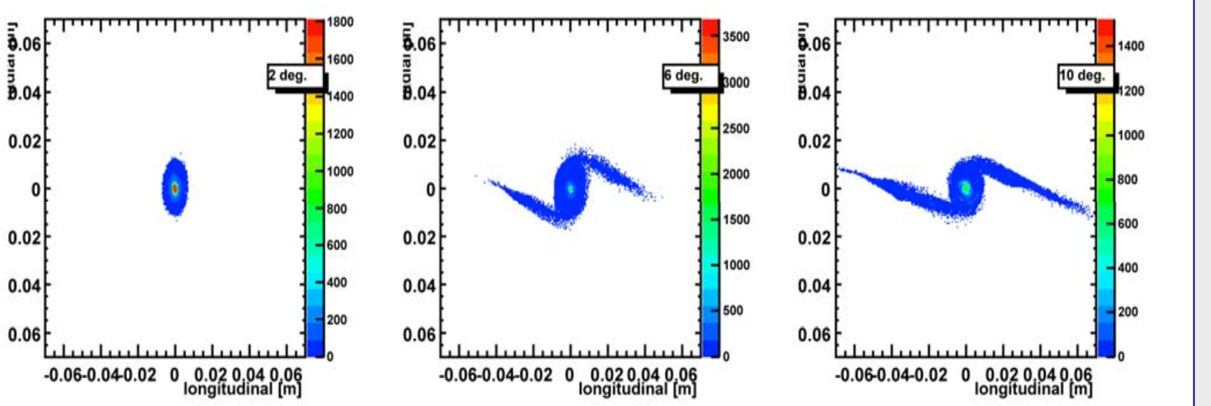
→ operation with short bunches and reduced flattop voltage seems possible

see talk by J.Yang this workshop!

after 100 turns!

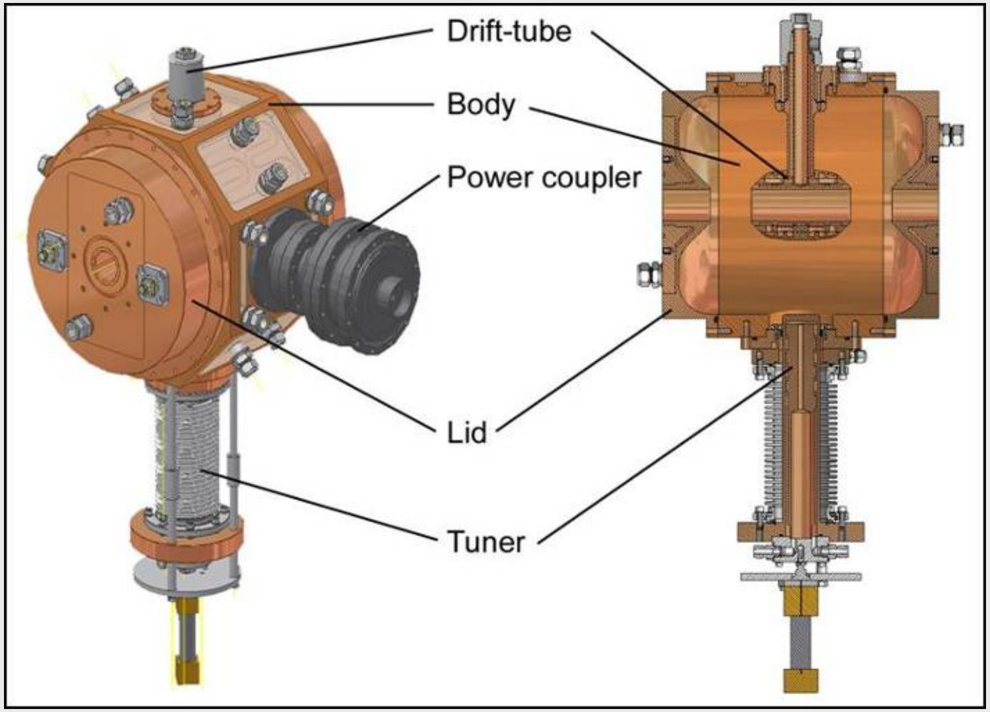


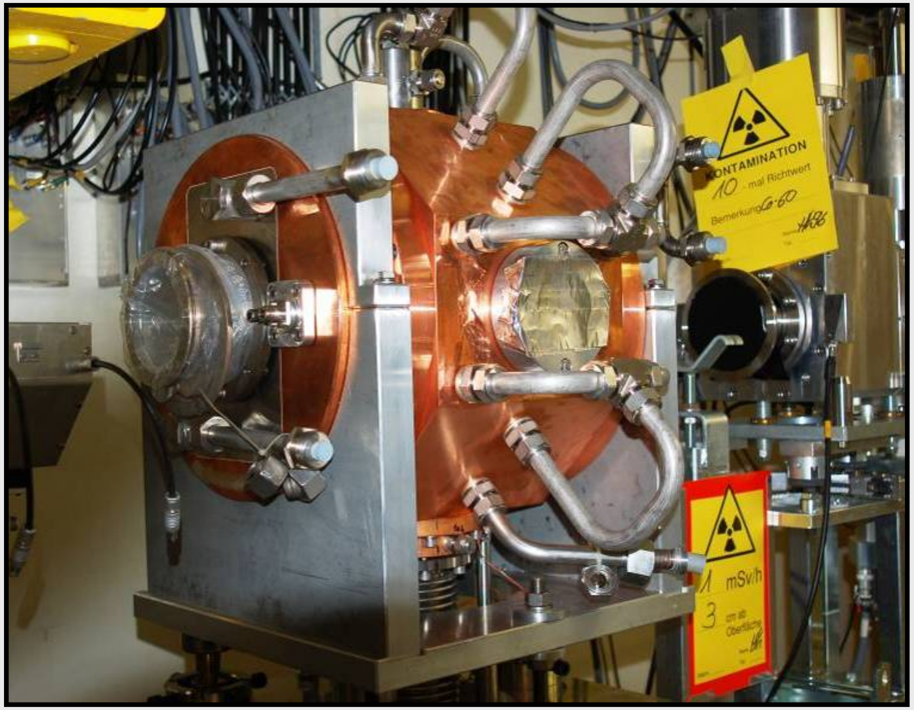
radial/long. bunch distribution, varying initial bunch length



to achieve the desired short bunch length: 10’th harmonic Buncher between Injector and Ring

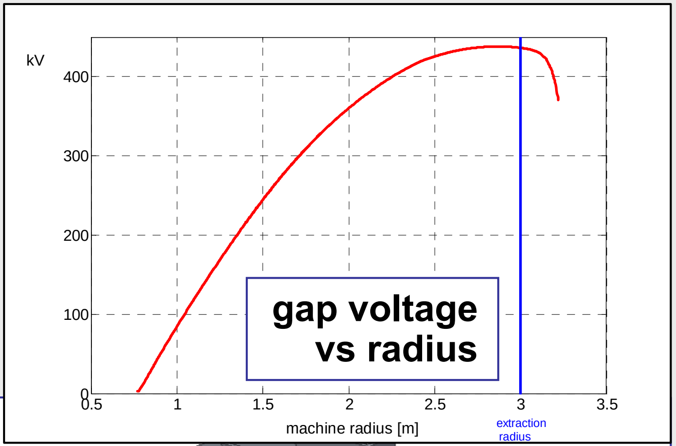
- operating frequency 506 MHz; U_{gap} = 220kV; P ~ 25kW
- compress bunch length at injection in Ring-Cyclotron
- installation planned (desired) within 2008

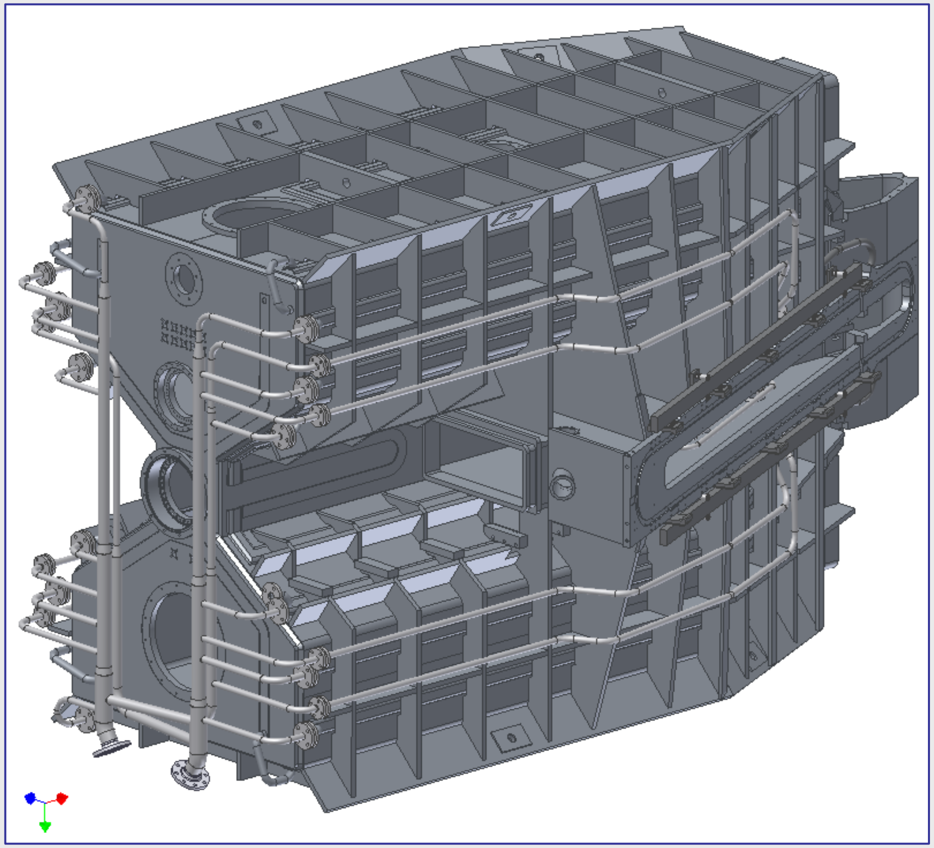


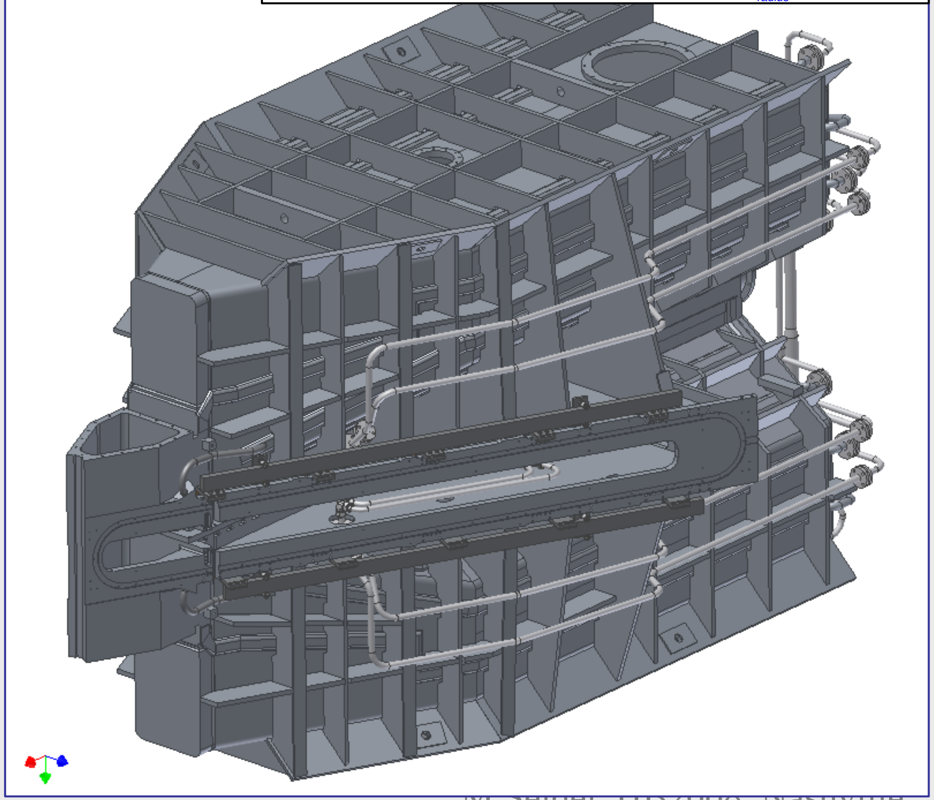


Components: Additional Cavities for the Injector II Cyclotron

- two new cavities planned for f **= 50.6MHz, U_{max} = 500kV**; **Q_0 = 28k**, Material: **Aluminum**; sector shape: tight mechanical tolerances on the position of sealing surfaces
- **replace two 150 MHz flat-top cavities**
- resonators on order from industry, delivery anticipated for 2009/2010; **operation in 2011**



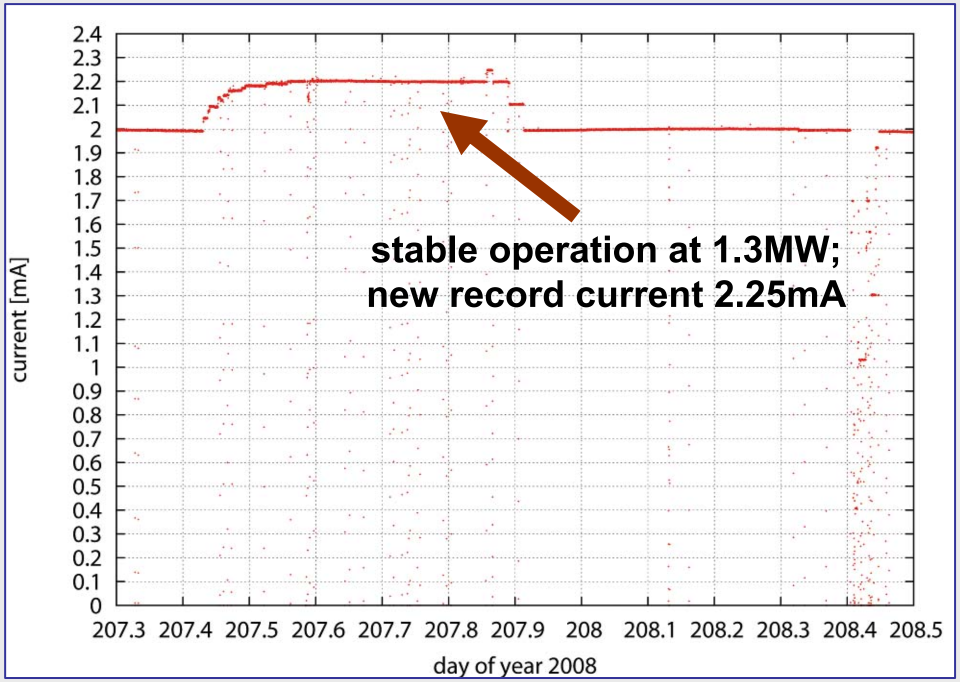




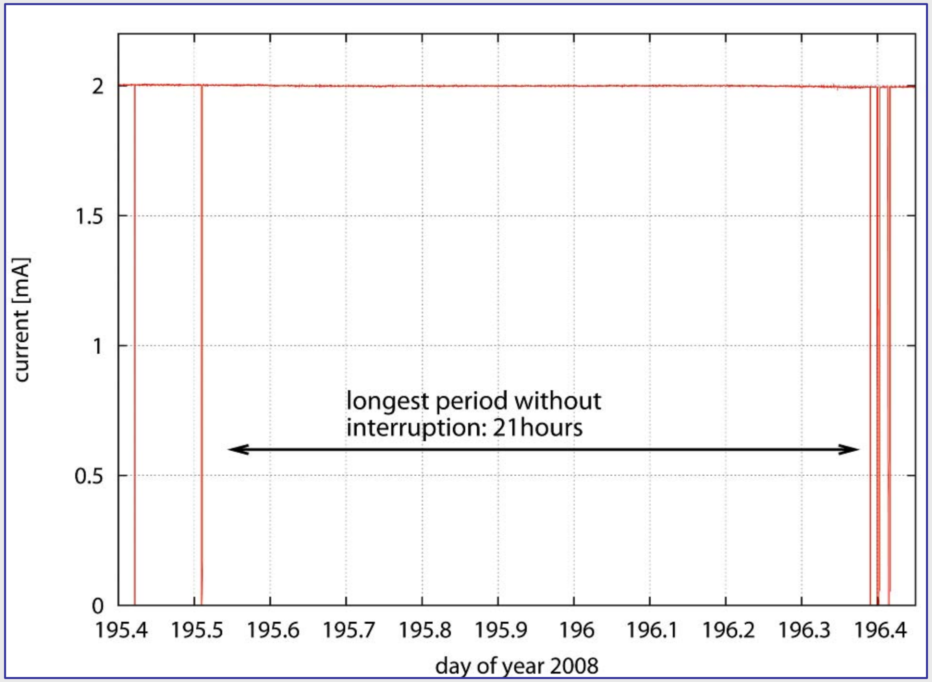
recent achievements in 2008

new resonators in Ring: enhanced gap voltage possible →
reduced turns 202-186 → reduced losses →
less short interrupts, higher current and power!

2200μA demonstrated without problems (legal permission to exceed 2mA for 2 shifts per 2 weeks)

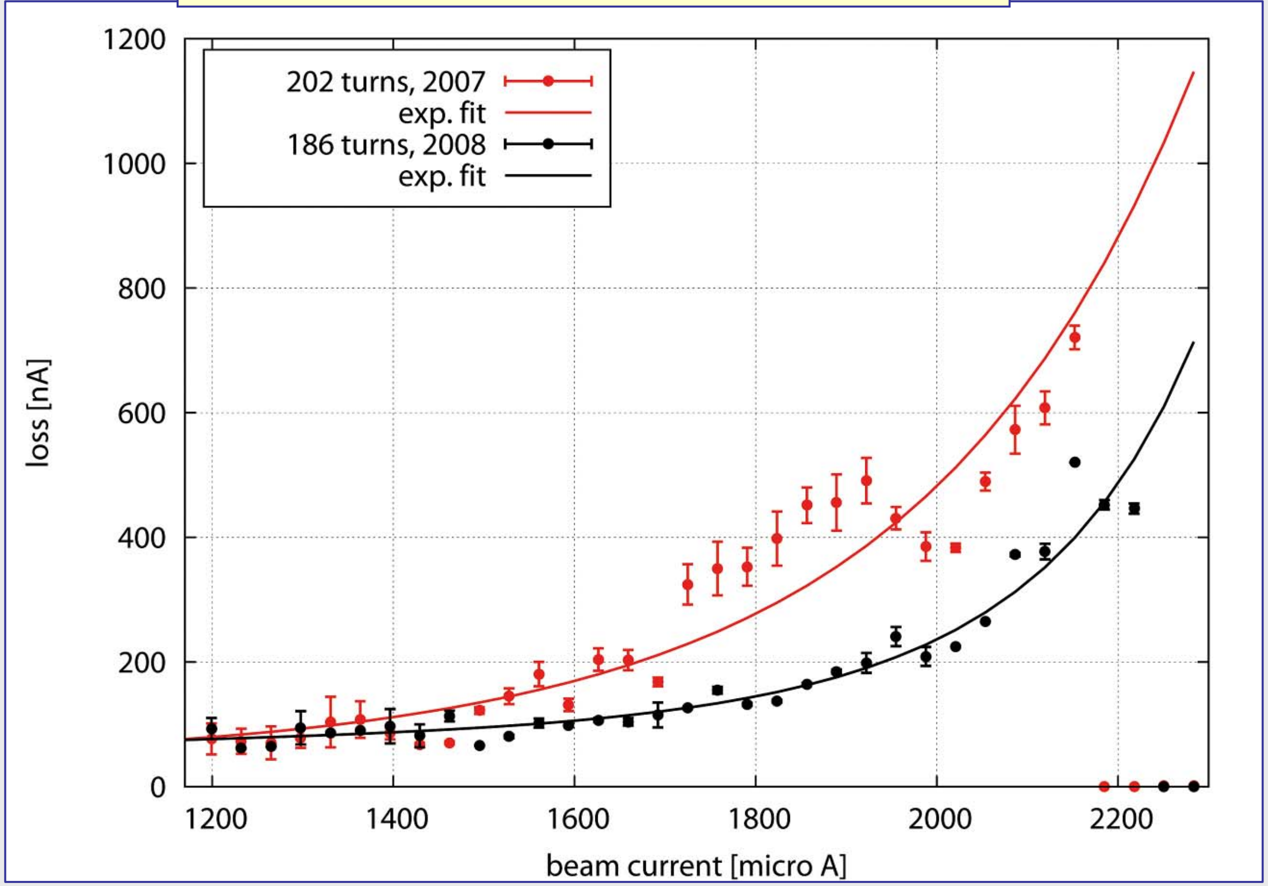


operation is more stable!



losses reduced by turn number reduction

absolute loss (nA) in Ring Cyclotron
as a function of current



recently achieved:

gap voltage increase:
780kV → 850kV

turn number reduction:
202 → 186

figure shows absolute losses for optimized machine setup

Summary / Outlook

- specialized instrumentation and fast loss control at the level of 10^{-4} per location are essential for high power operation; to deal with activation and possible unusual situations the lab needs special infrastructure
- in cyclotrons losses depend strongly on the number of turns required (i.e. high gap voltages desirable)
- the PSI cyclotron facility has significant further potential $\rightarrow$ an upgrade of the beam power **from 1.2 to 1.8 MW** is in progress, achieved with new resonators and additional harmonic bunchers; operation at 1.8MW is planned for **2012**
- for high power CW beam production **cyclotrons present a very valid and cost efficient option!**

Thank you for your attention!