Performance of the PSI High Power Proton Accelerator

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Outline

- motivation for this talk
- overview of the PSI facility

[accelerator chain, cyclotrons, applications , shielding/infrastructure]

- generation and transport of a high power beam

[cyclotrons, power conversion efficiency, losses / critical aspects, upgrade plans]

- reliability and trip statistics

[failure statistics, involved subsystems, short trip statistics, critical elements]

- cyclotrons for ADS applications

[comparison to LINACS, Pro’s and Con’s, Power and Energy Reach]

- conclusion

Motivation

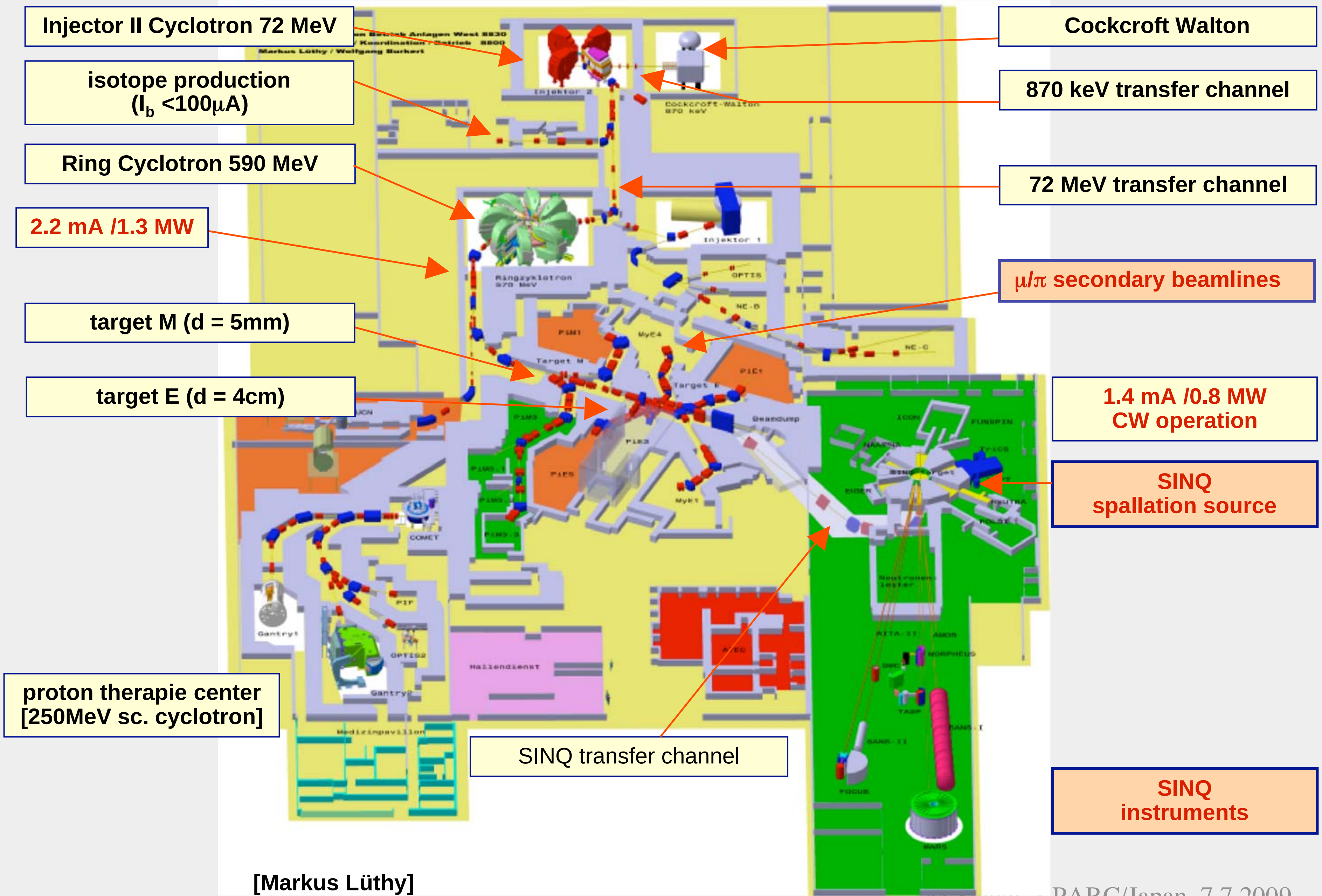
→ **overview of facility and demonstration of practical experience with high power beam operation**

- show good performance at PSI [1.3MW@0.59GeV, 94% reliability]
- significant advancements in past years

→ **advertisement for high power cyclotrons**

- high efficiency, compact facilities, comparably good reliability
- cyclotron concept not well known at major accelerator labs

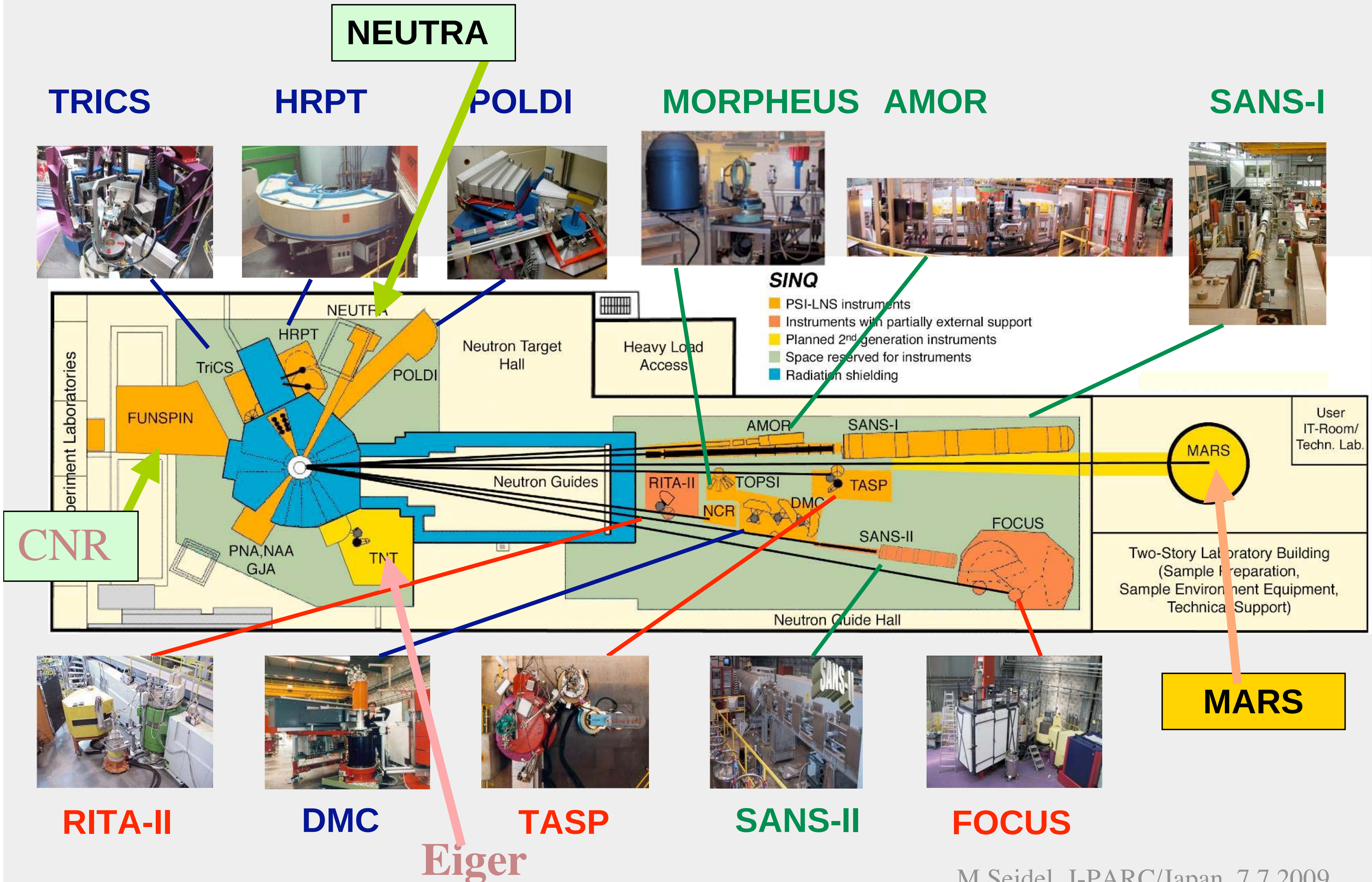
Overview PSI Facility



[Markus Lüthy]

Spallation Source Experimental Area – 13 Instruments

K. Clausen



dimensions experimental hall: 130×50×20 m³

Ring Cyclotron: ø15m

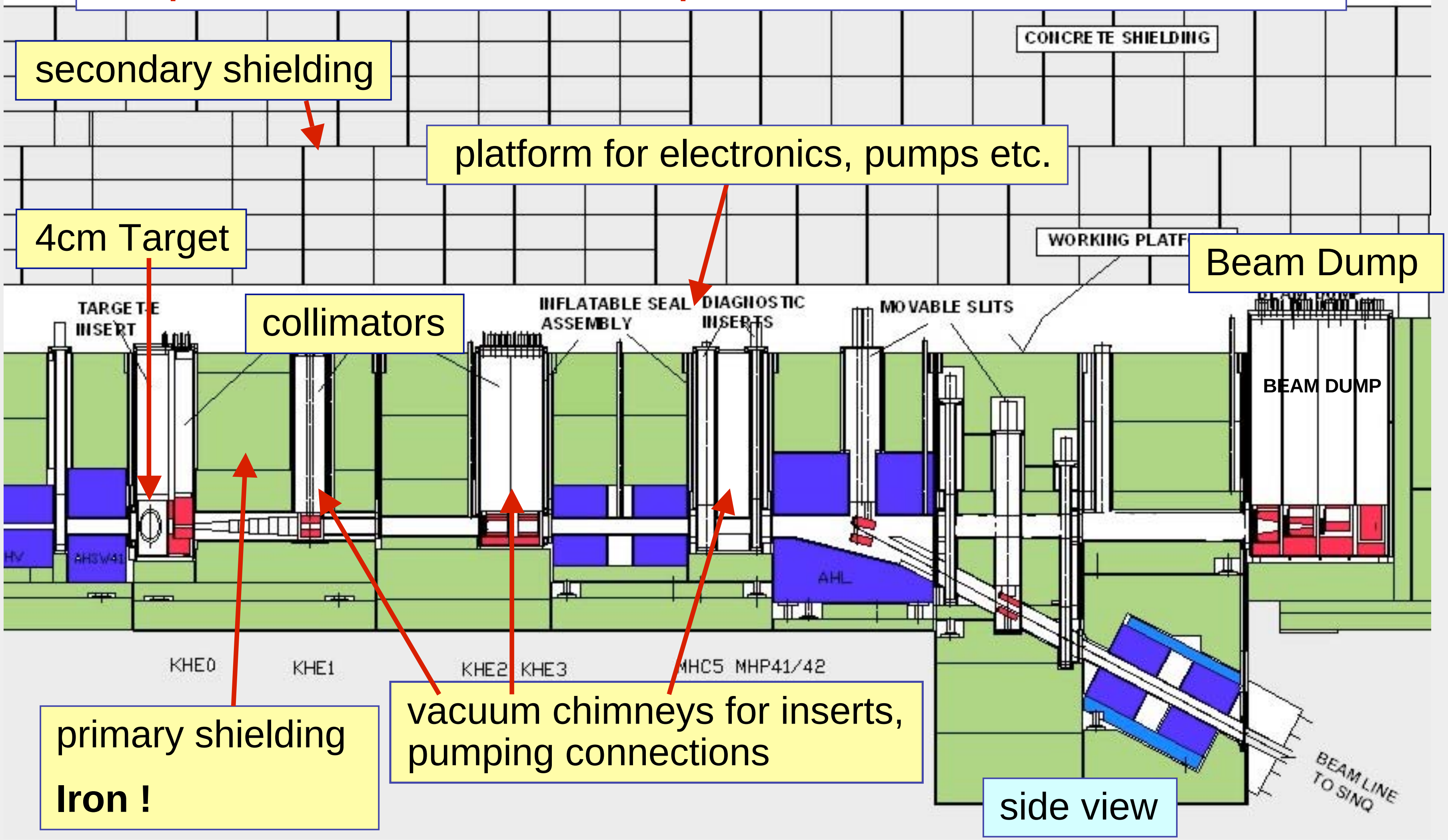
crane: @15m height, 60tons

10.000 shielding blocks in 14 shapes; heavy concrete and 30% steel; weight 32.000 tons

shielding – Meson production target / 590MeV transport channel

- ➔ elaborate shielding required
- ➔ reliability of activated components!; water cooling; few electrical connections

Component activation in beamline up to ~300Sv/h!



special infrastructure – mobile shielding / exchange flask

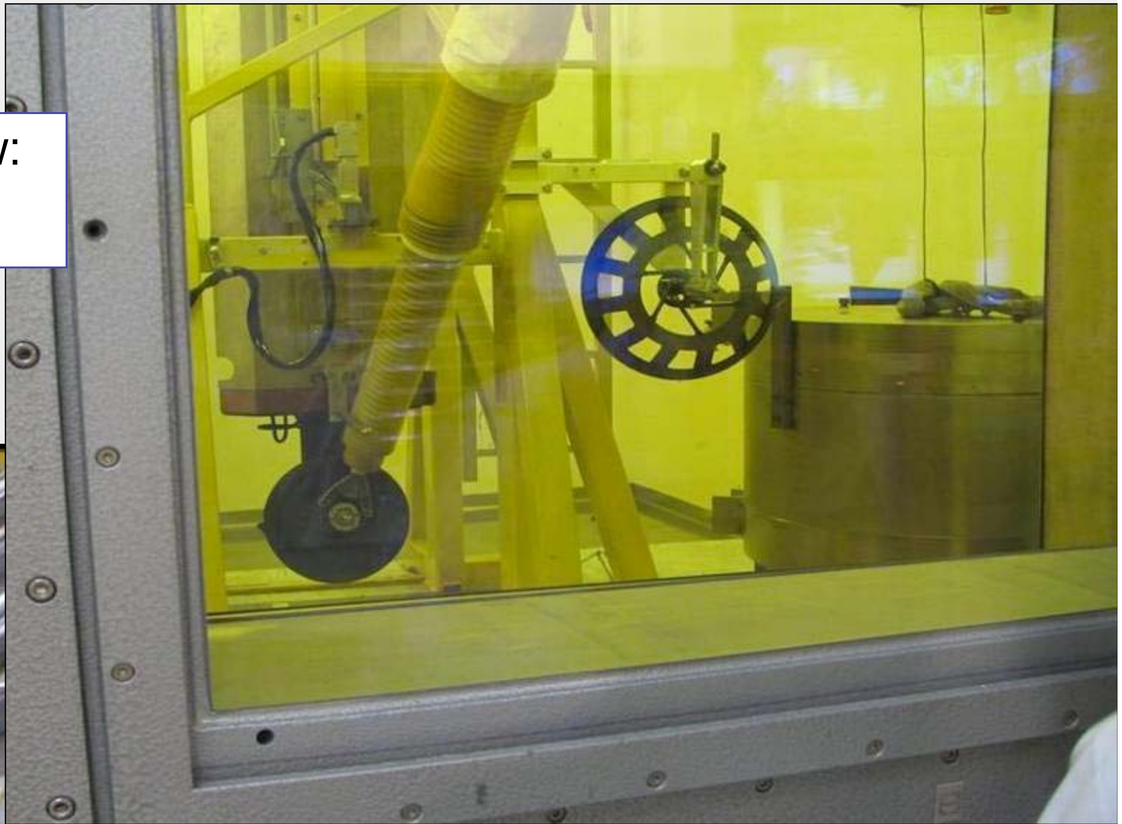
- mobile and specifically adapted shielding devices are used for targets and critical components as extraction elements or septum magnets
- target exchange flasks are complicated and expensive devices [heavy, motors, instrumentation, SPS controls]

picture: exchange flask for Meson production target E (4cm graphite wheel)

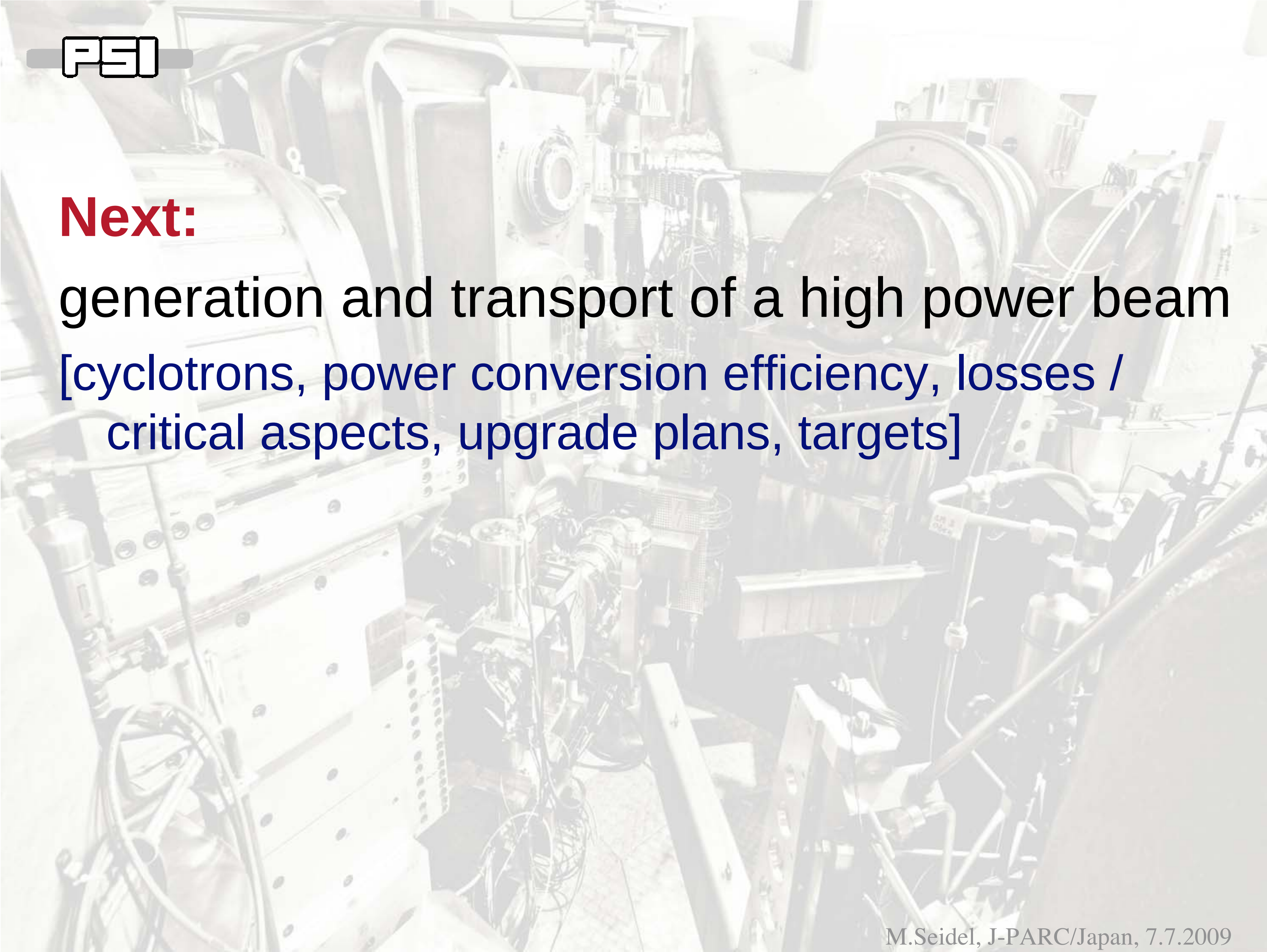
special infrastructure – hot cell facility

view through lead-glass window:

Meson production target wheel



irradiated SINQ spallation target,
taken out of the cover

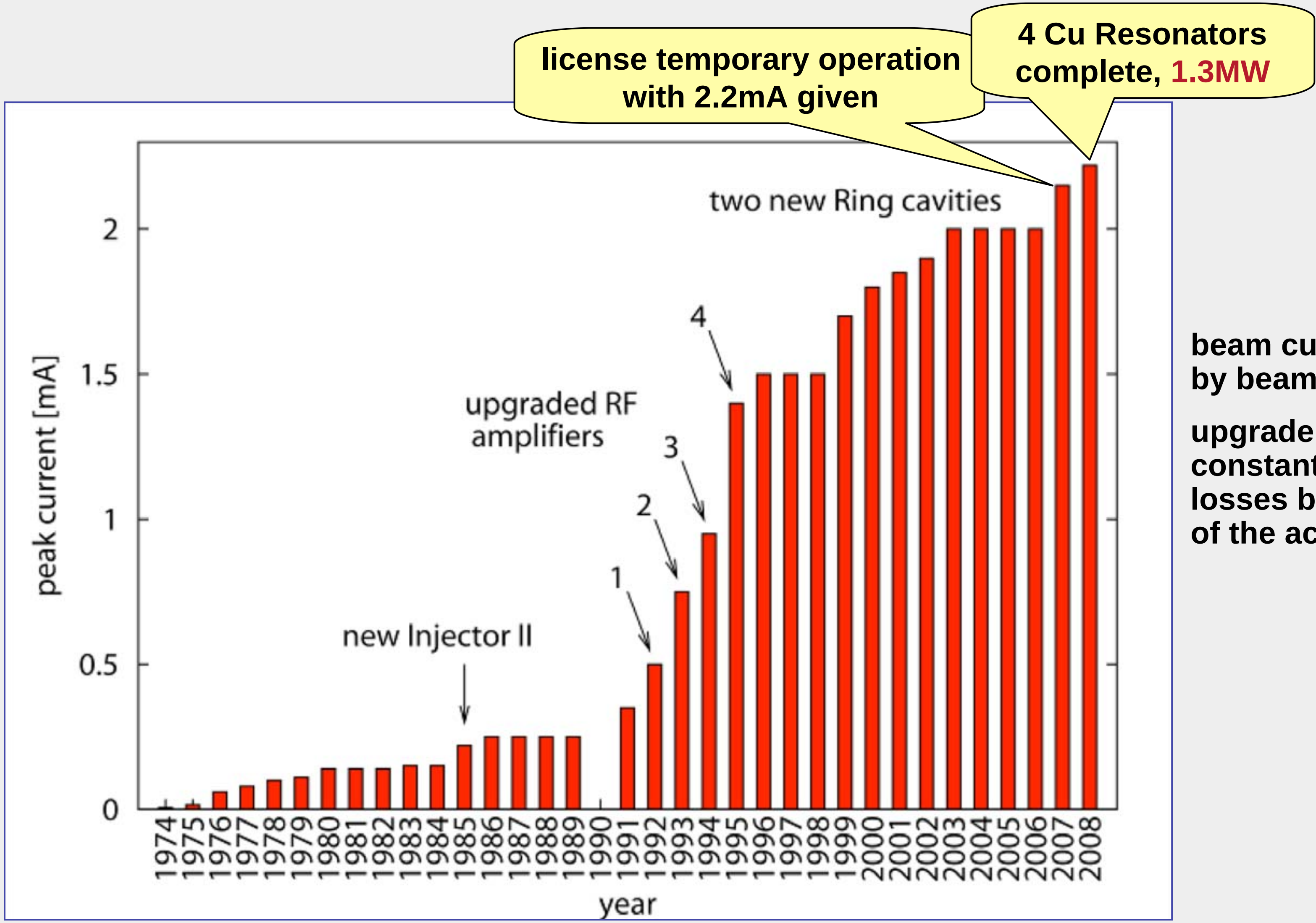


Next:

generation and transport of a high power beam

[cyclotrons, power conversion efficiency, losses / critical aspects, upgrade plans, targets]

history max. current of the PSI accelerator



beam current is limited by beam losses;

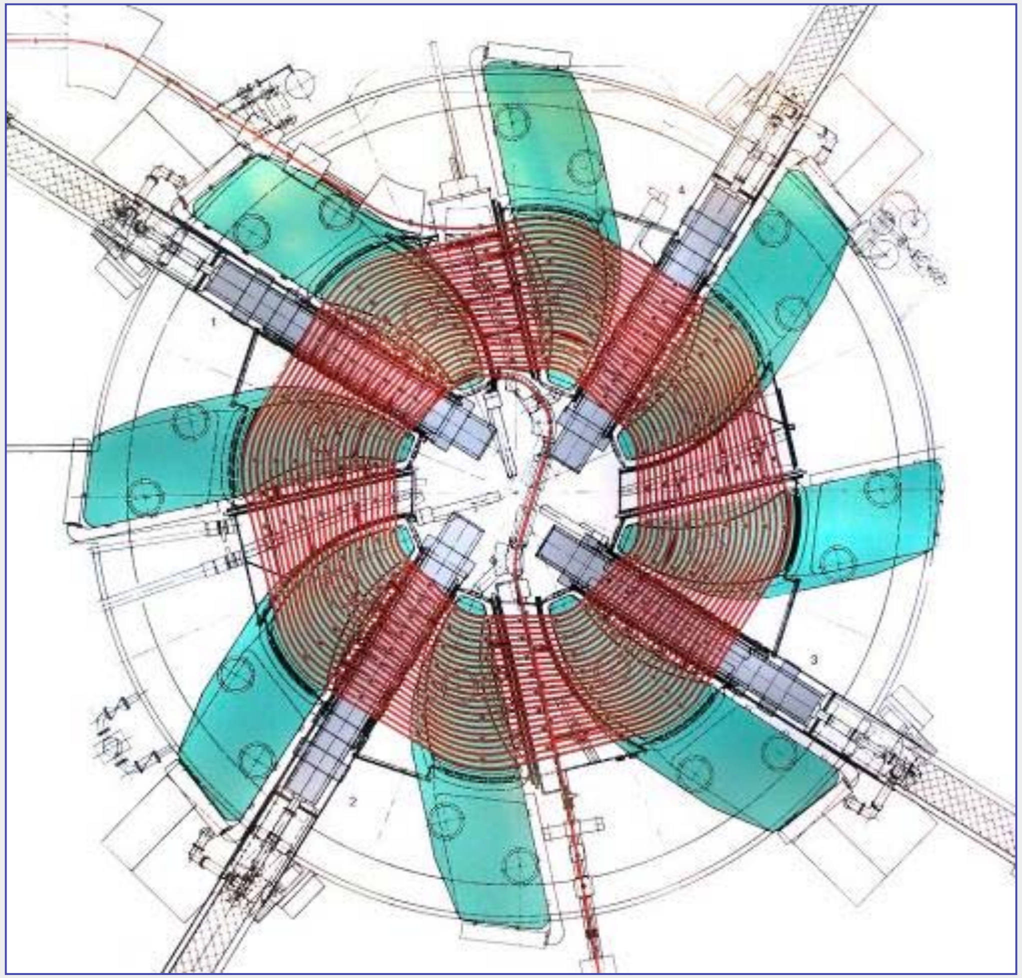
upgrade path foresees constant absolute losses by improvements of the accelerator

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 → 590MeV**
- **beam current max.:**	**2.2 mA**
- **extraction orbit radius:**	**4.5m**
- **relative Losses @ 2mA:**	**~1..2·10^{-4}**
- **transmitted power:**	**0.26-0.39 MW/Res.**



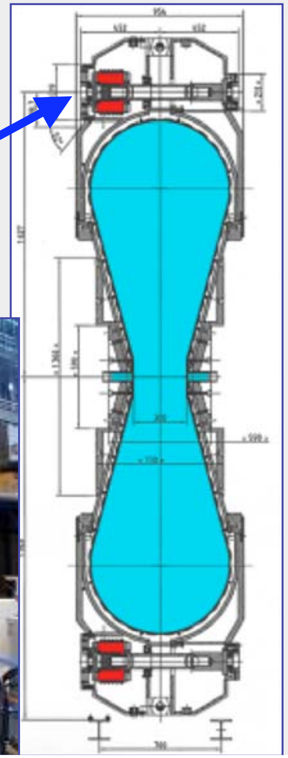
major component: RF Resonators for Ring Cyclotron

- **the shown Cu Resonators have replaced the original Al resonators** [less wall losses, higher gap voltage possible, better cooling distribution, better vacuum seals]
- **f = 50.6MHz**; **Q_0 = 4·10^4**; **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

→ very good experience so far

resonator inside

hydraulic tuning devices (5x)



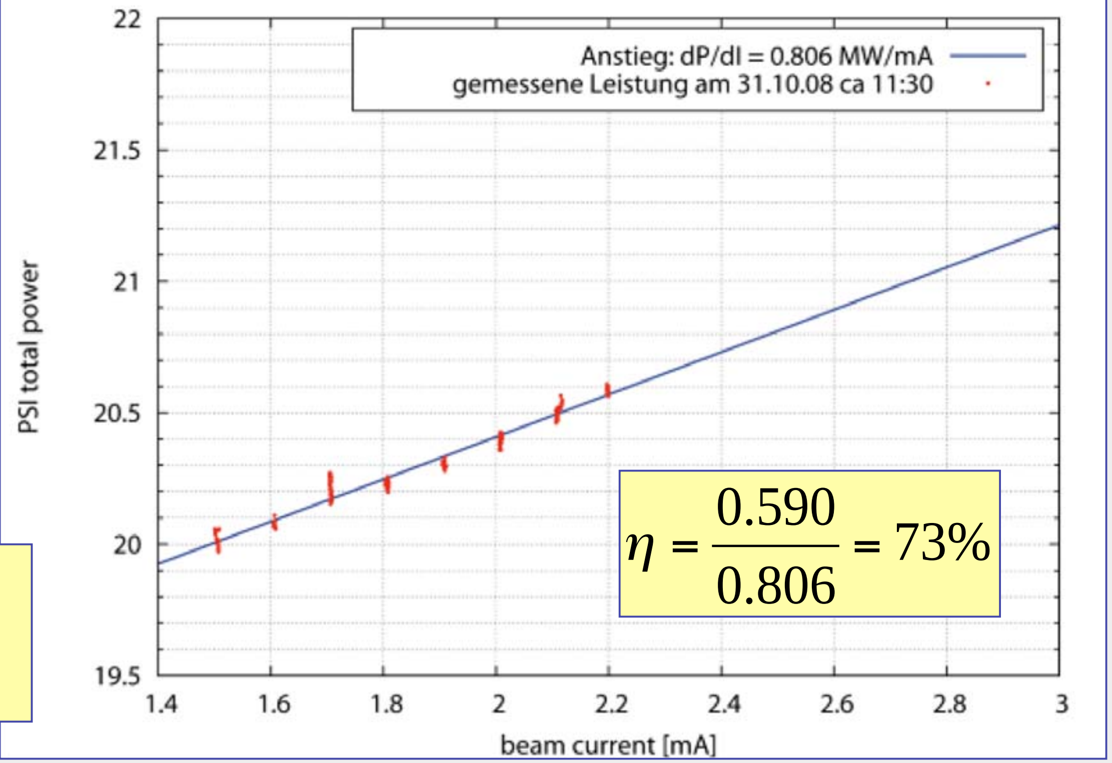
Grid to Beam Power Conversion Efficiency

for industrial application, transmutation etc., the aspect of **efficient usage of grid power** is very important

PSI: ~10MW Grid → 1.3MW Beam

$$P_{\text{grid}}(I) \approx (8.0 \pm 0.5)\text{MW} + 0.81\text{MW} \cdot I[\text{mA}]$$

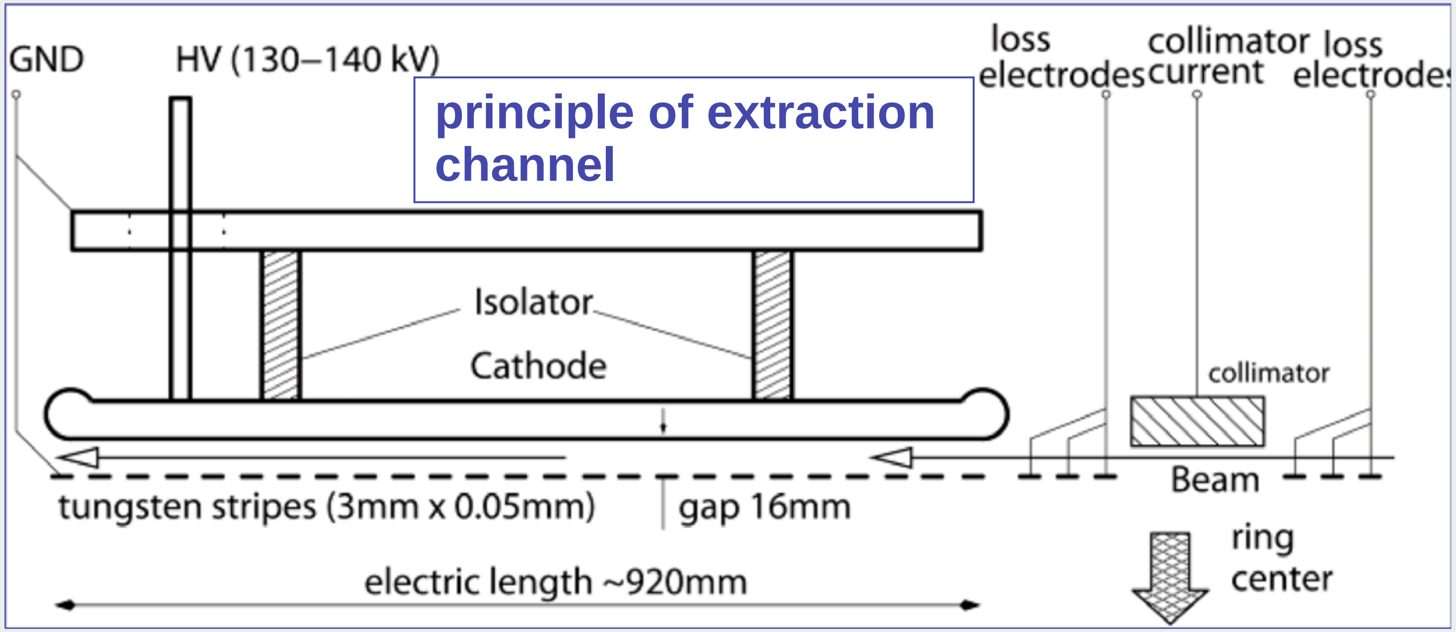
contains many loads not needed for optimized ADS facility!



$$\eta = \frac{0.590}{0.806} = 73\%$$

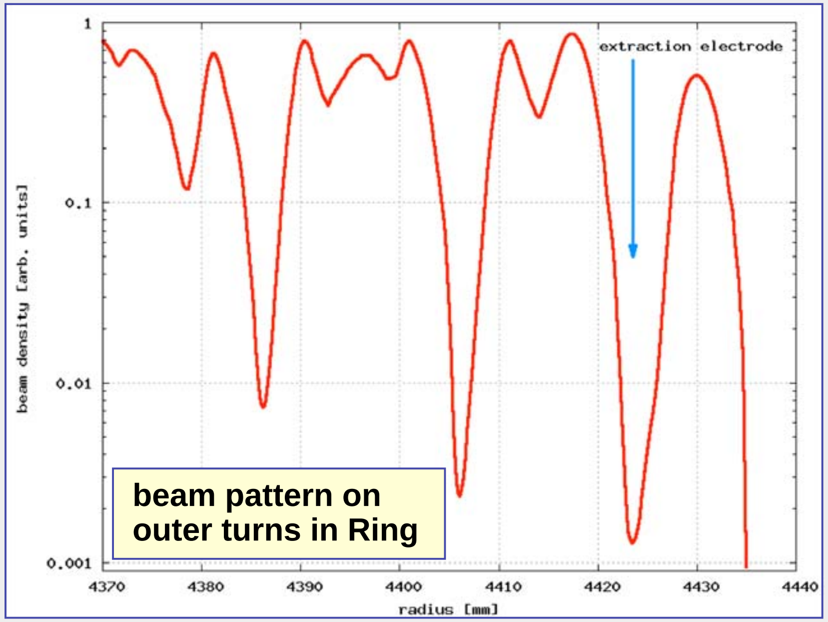
▶ **differential measurement of electrical power vs. beam power (total PSI power shown)**

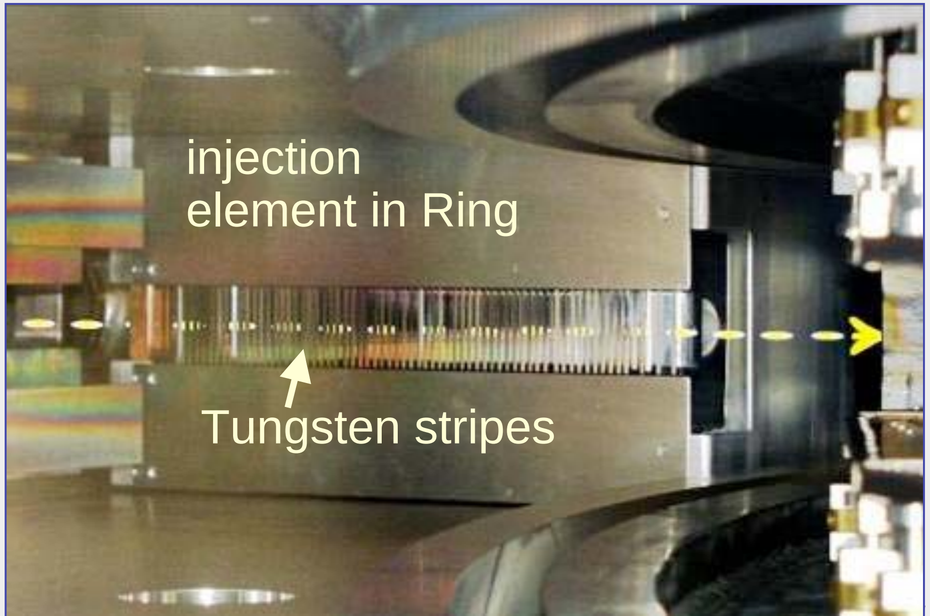
critical for losses/trips: electrostatic elements



parameters extraction chan.:
E_k = 590MeV
E = 8.8 MV/m
θ = 8.2 mrad
ρ = 115 m
U = 144 kV

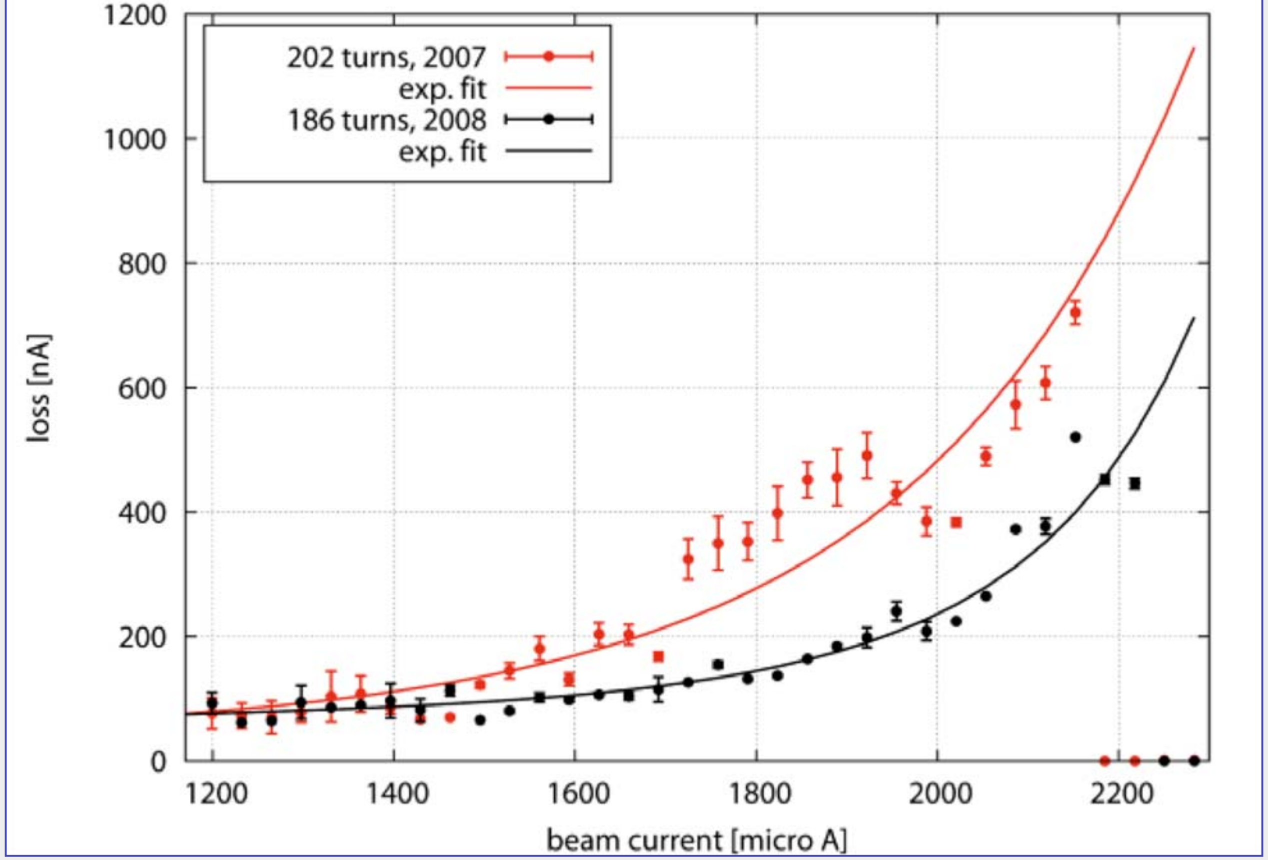
major loss mechanism is scattering in 50μm electrode!





losses reduced by turn number reduction

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



recently achieved:

gap voltage increase:
780kV → 850kV

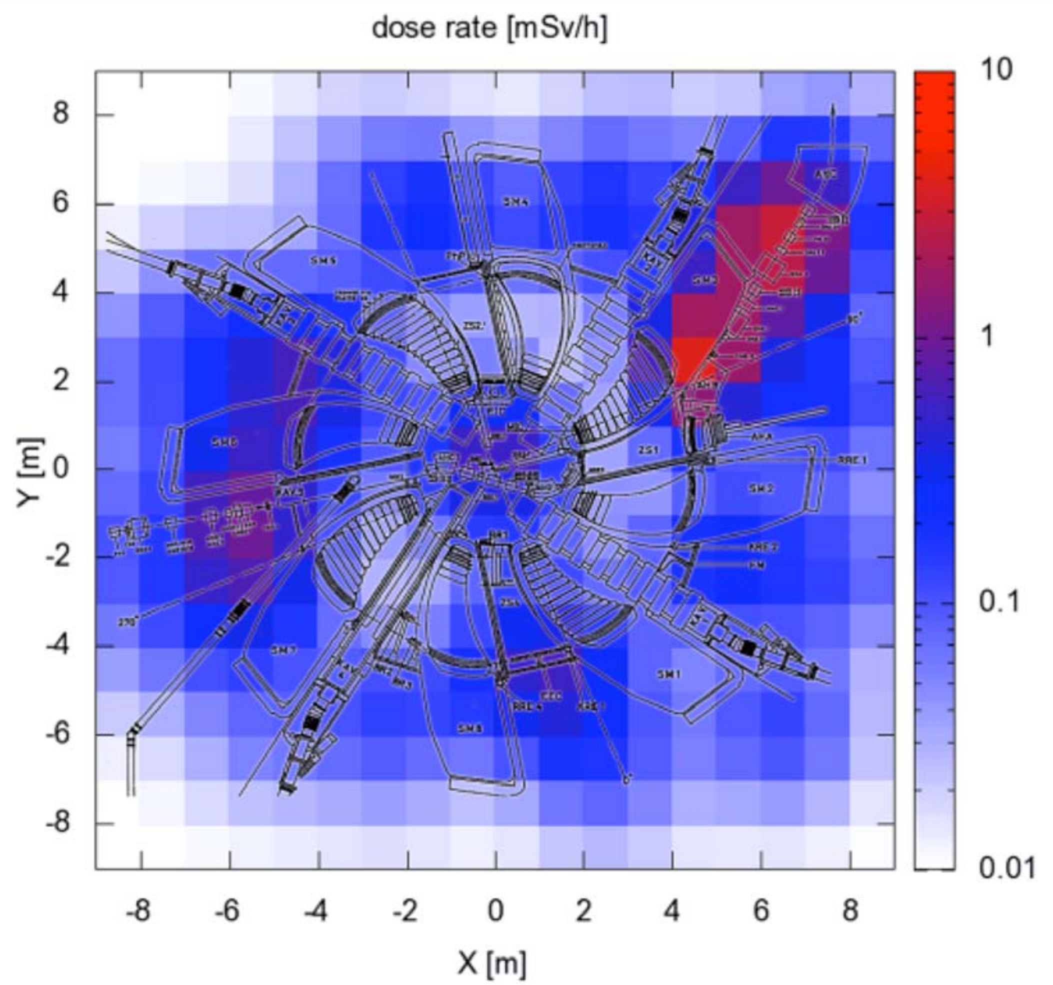
turn number reduction:
202 → 186

figure shows absolute losses for optimized machine setup

component activation – Ring Cyclotron

activation level allows for 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 (2008):

57mSv, 188 persons
max: 2.6mSv

cool down times for service:

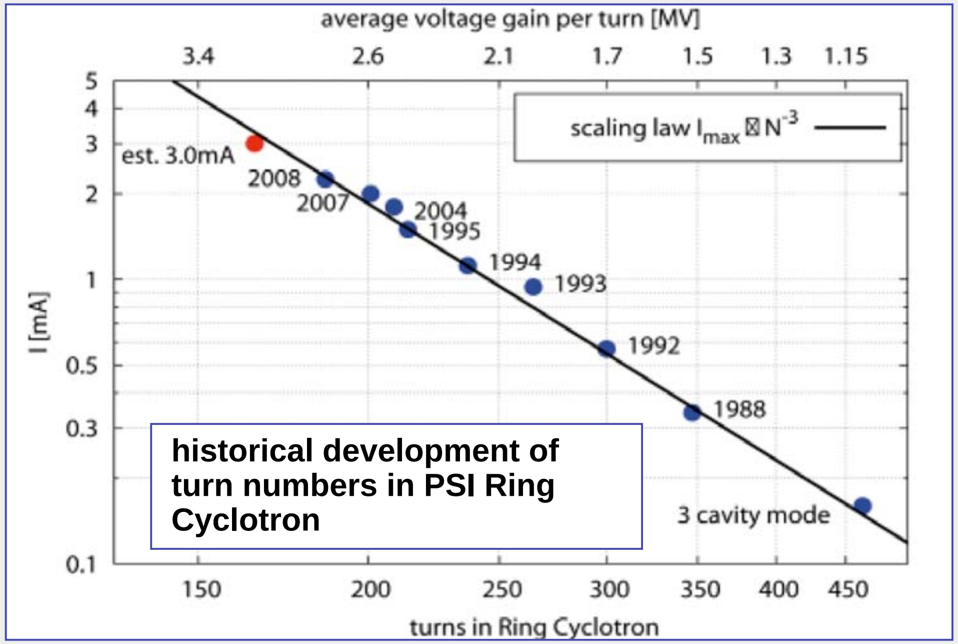
2000 → 1700 μA for 2h

0 μA for 2h

map interpolated from ~30 measured locations

Cyclotron Upgrade – fast acceleration, short bunches!

- goal: 3mA [1.8MW]
- philosophy: keep **absolute losses constant**
- losses ∝ [turns]^3 ∝ [charge density (sector model)] × [accel. time] / [turn separation] (W.Joho)



measures:

➔ new Resonators in Ring Cyclotron [done!]

➔ 10'th harmonic buncher before Ring [still under work, but close]; important: numerical modeling → neighboring bunches, interplay with flattop

➔ new ECR ion source

➔ replace flattops with new accel. resonators in Injector II [expected for 2011]

➔ new RF amplifiers for all four resonators in Injector II [expected for 2011]

➔ replace absorbers behind 4cm Meson Prod. Target [expected for 2012]

avoid tail generation with short bunches

numerical 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

-10^6 macroparticles

[on supercomputer simulation of all protons in bunch feasible!]

- precise field-map

- bunch dimensions:

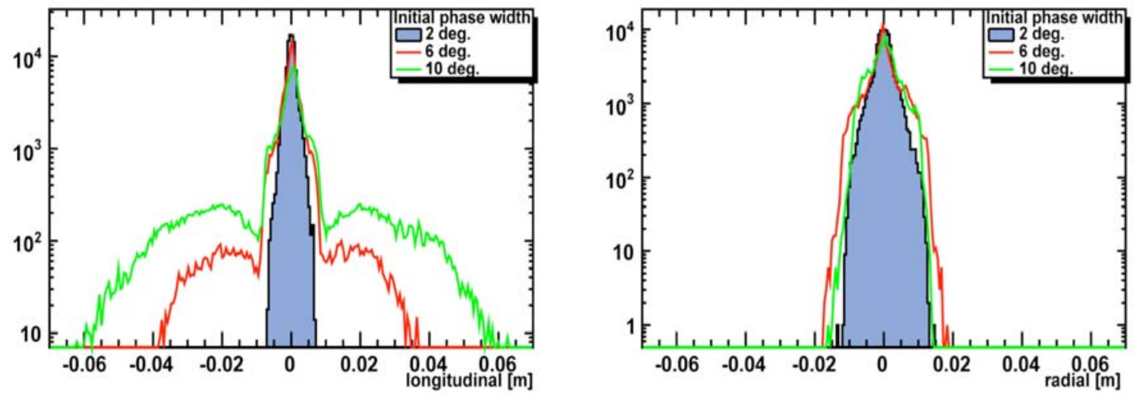
σ_z ~ 2, 6, 10 mm;

σ_{xy} ~ 10 mm

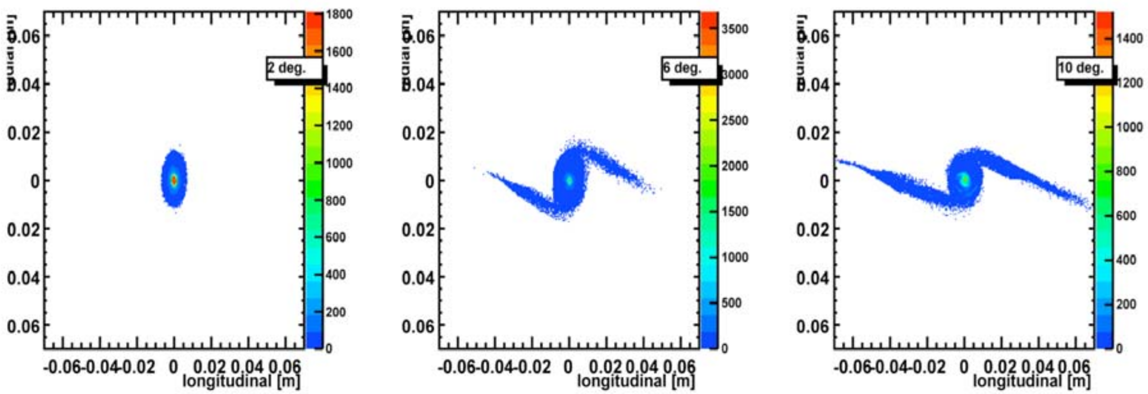
→ operation with short bunches and reduced flattop voltage seems

court.: J.Yang CAEA

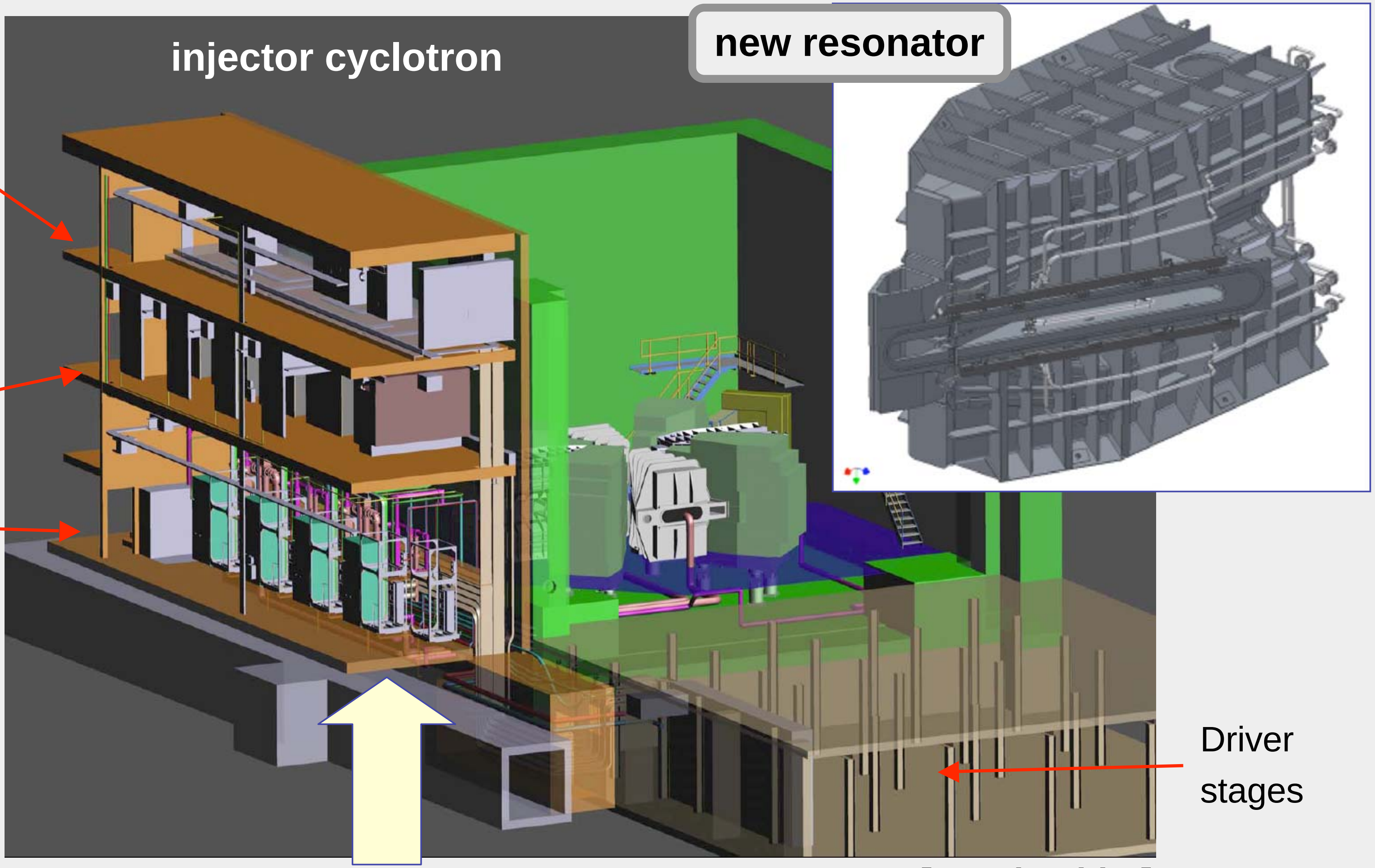
after 100 turns!



radial/long. bunch distribution, varying initial bunch length

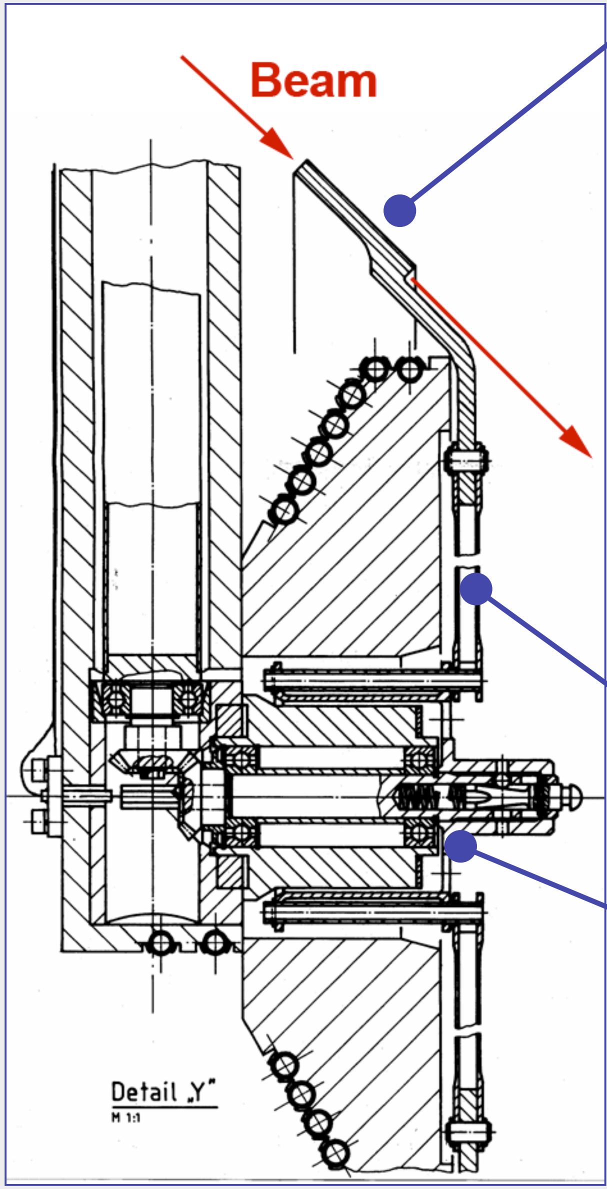


present PSI upgrade project: resonators Inj.II for 2.2 → 2.6 → 3.0mA



[M.Schneider]

High Power Meson Production Target



TARGET CONE

3.0mA o.k., limit: sublimation

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

SPOKES

To enable the thermal expansion of the target cone

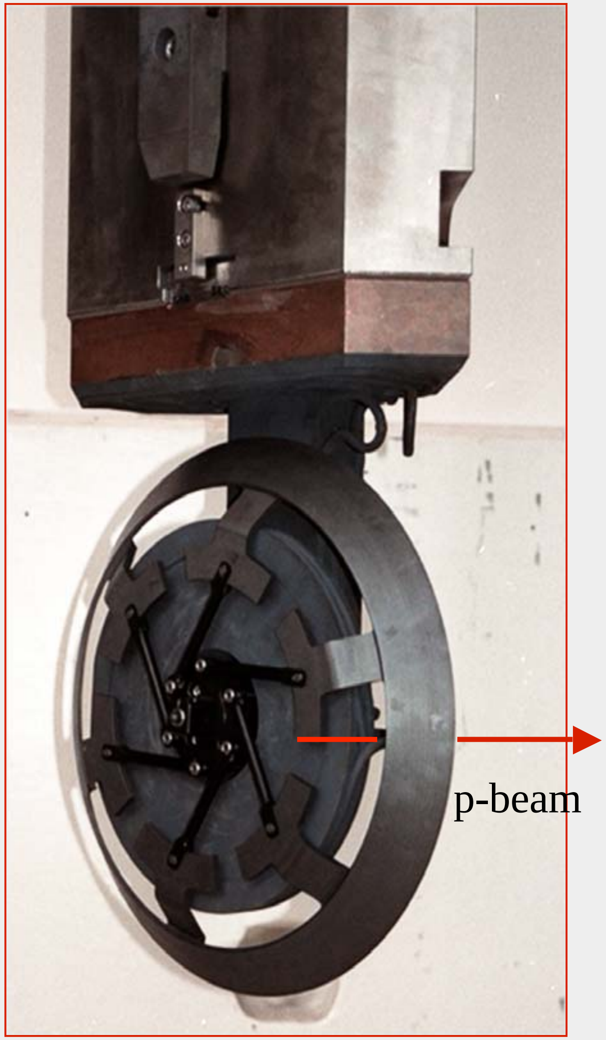
BALL BEARINGS *)

Silicon nitride balls

Rings and cage silver coated

Lifetime 2 y

*) GMN, Nürnberg, Germany



G.Heidenreich et. al.

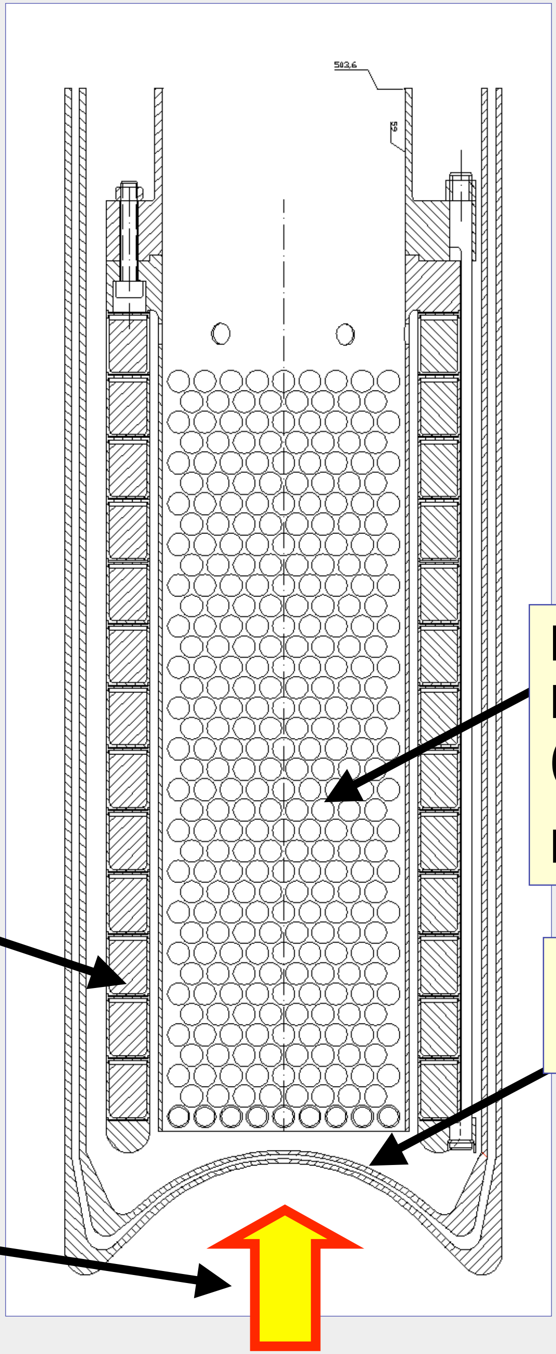
SINQ Spallation Target

recent improvement in neutron flux: ~35%

-more dense packaging

-entrance window inverted (less water in beam path)

-lead reflectors



lead filled Zircaloy tubes
D=1cm, gap: 1.2mm
(cannelloni target)

D_2O cooled

blanket / reflector made from lead

beam entrance window, water cooled

proton beam
4σ diameter: 10cm
40μA/cm²

Next:

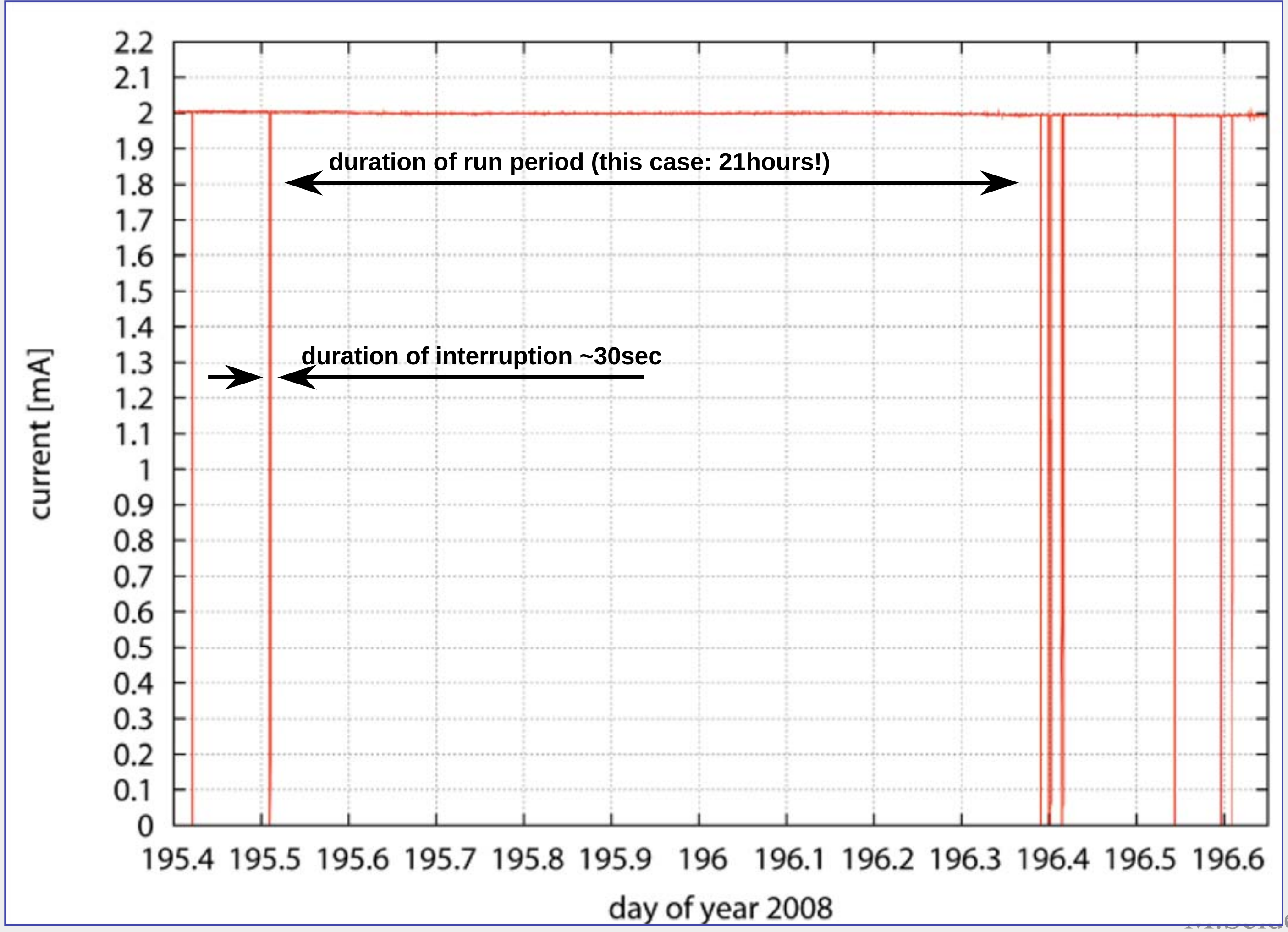
aspects important for potential ADS application [energy amplifier / transmutation]

- reliability and trip statistics
- cyclotrons for ADS applications?

reliability: statistics of run- and interruption periods

➔ cyclotron operation is typically distorted by short (30sec) interruptions from trips of electrostatic elements or beam-loss interlocks

➔ significant improvement with reduced turns (new Reson.) was observed in 2008



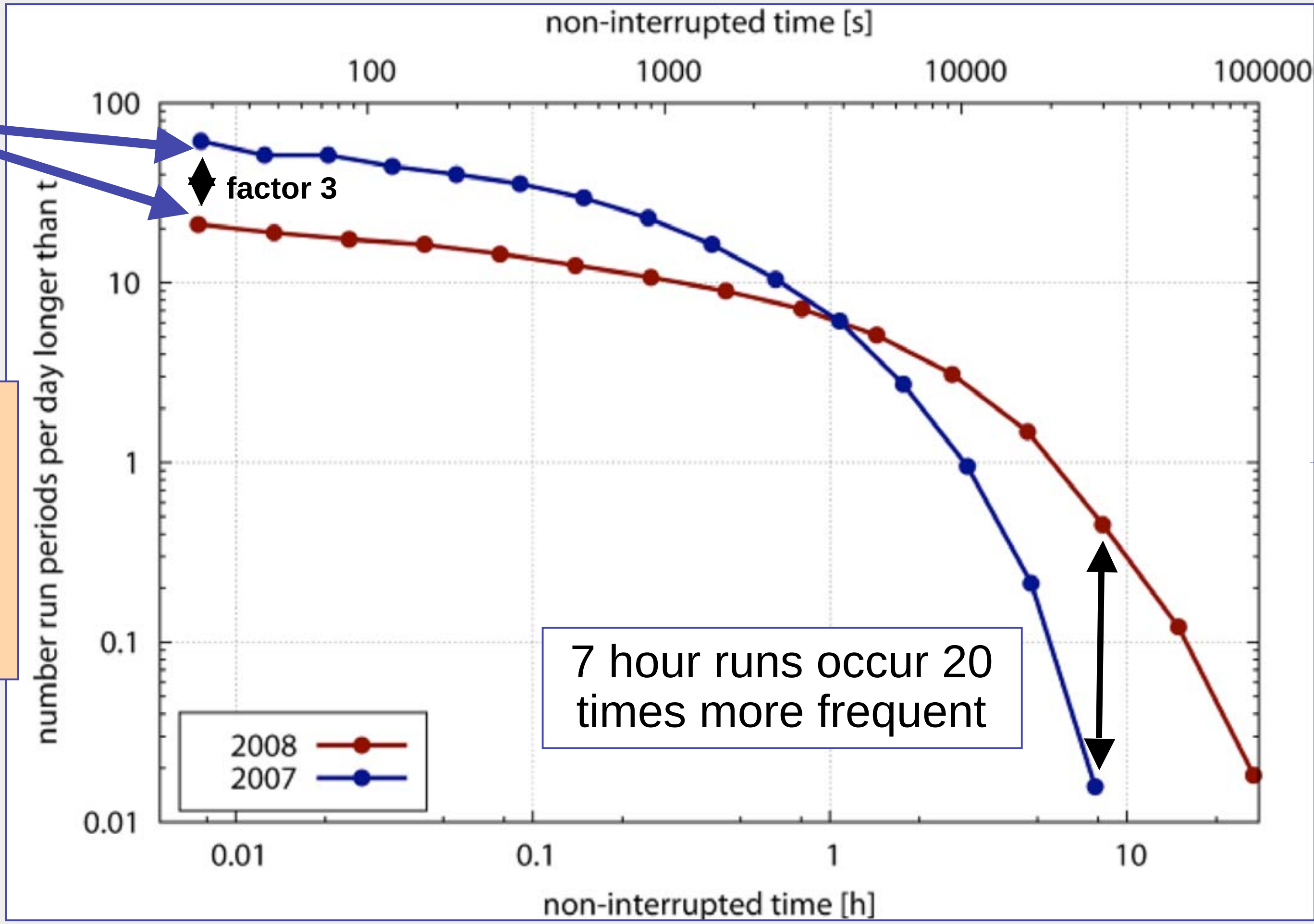
in the discussion on application of cyclotrons for **ADS systems** the frequency of interruptions is of major interest

statistics of run durations 07/08

➔ histogram for occurrence of **uninterrupted run periods** as function of duration, integrated from right; average number per day; comparison 2007/2008

➔ high reliability is important for our users and for other potential high power applications of cyclotrons

total number of runs/interrupts per day [integrated histogr.]

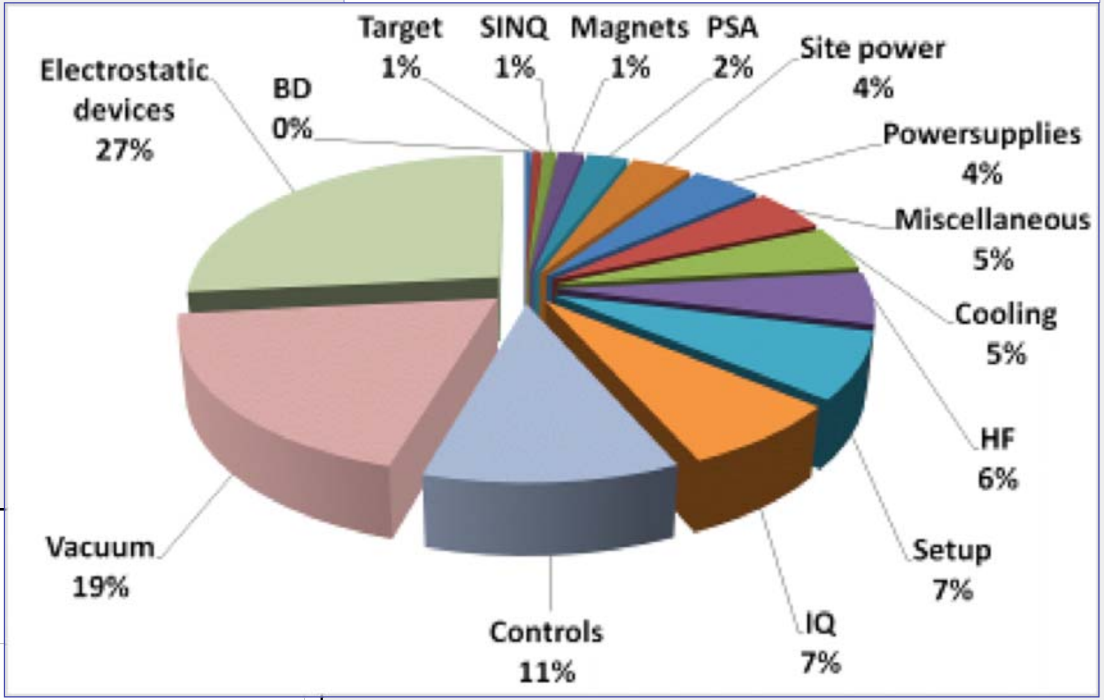


read this plot as follows:

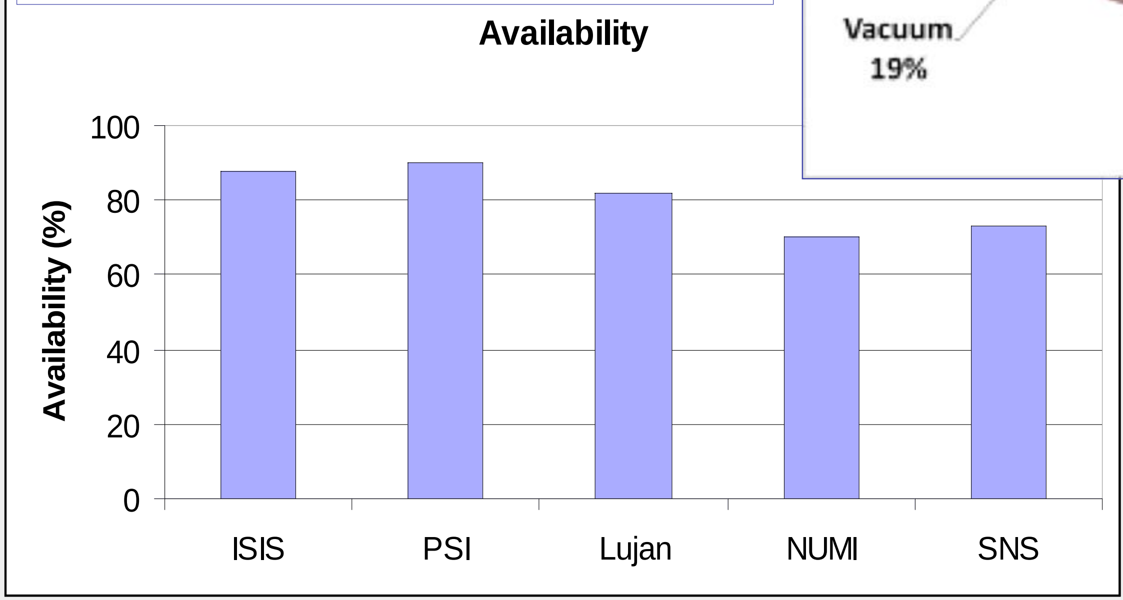
there are typically *n* run periods per day that last longer than *t*

overall availability in comparison

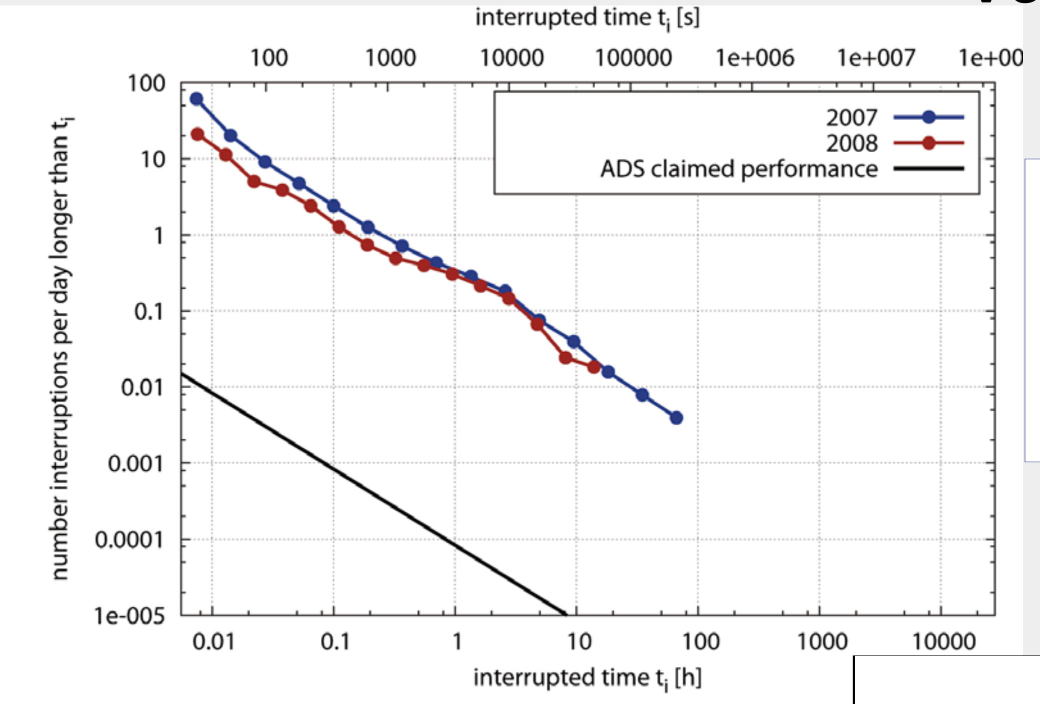
PSI: subsystems causing failures



availability of different high power accelerators (data compiled at HB2008, Nashville)



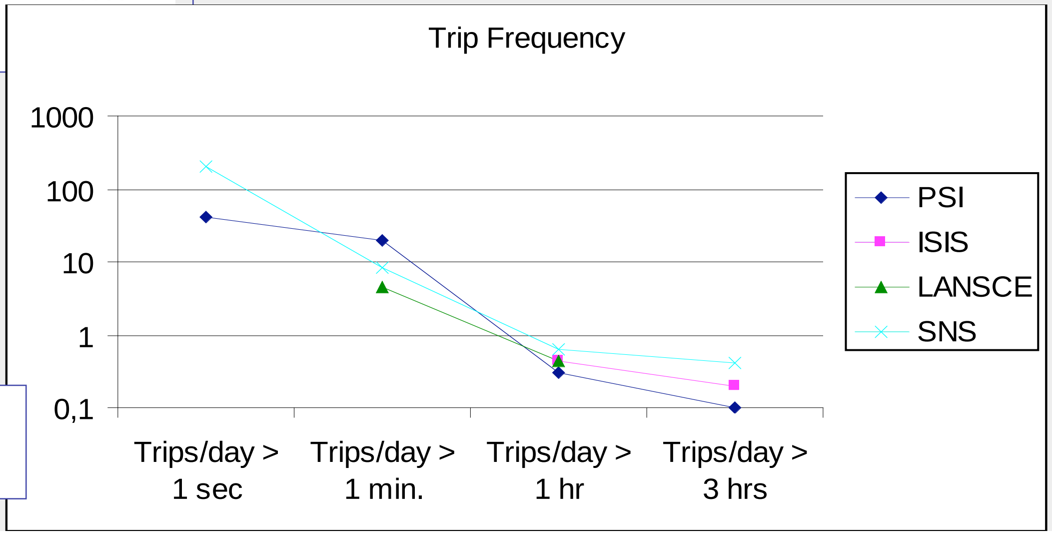
trip performance: 3.5 orders of magnitude worse than ADS-desired values



trip statistics PSI

for comparison:

hypothetical τ^{-1} distribution with one trip per 100d



for comparison: data compiled at HB2008 (Nashville)

possible measures to improve the reliability of cyclotron-accelerators

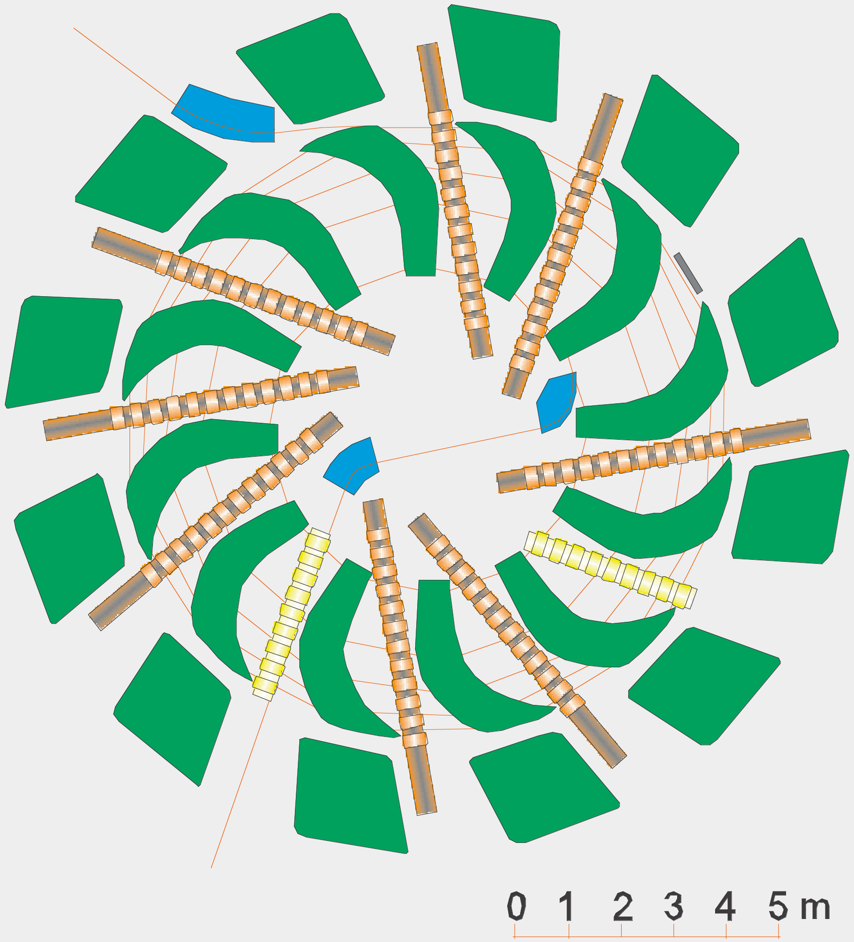
- trip rate of electrostatic elements: higher turn separation; possibly very quick charge up after trip to keep interruption short
- redundancy of resonators in cyclotron; quick pre-computed compensation of failed resonator with remaining ones
- possibly second injector (source + RFQ)

my personal opinion: developments are needed not only for accelerators, but also on the target/reactor side

→ better tolerance against beam trips?

Proposal for a 10 MW driver

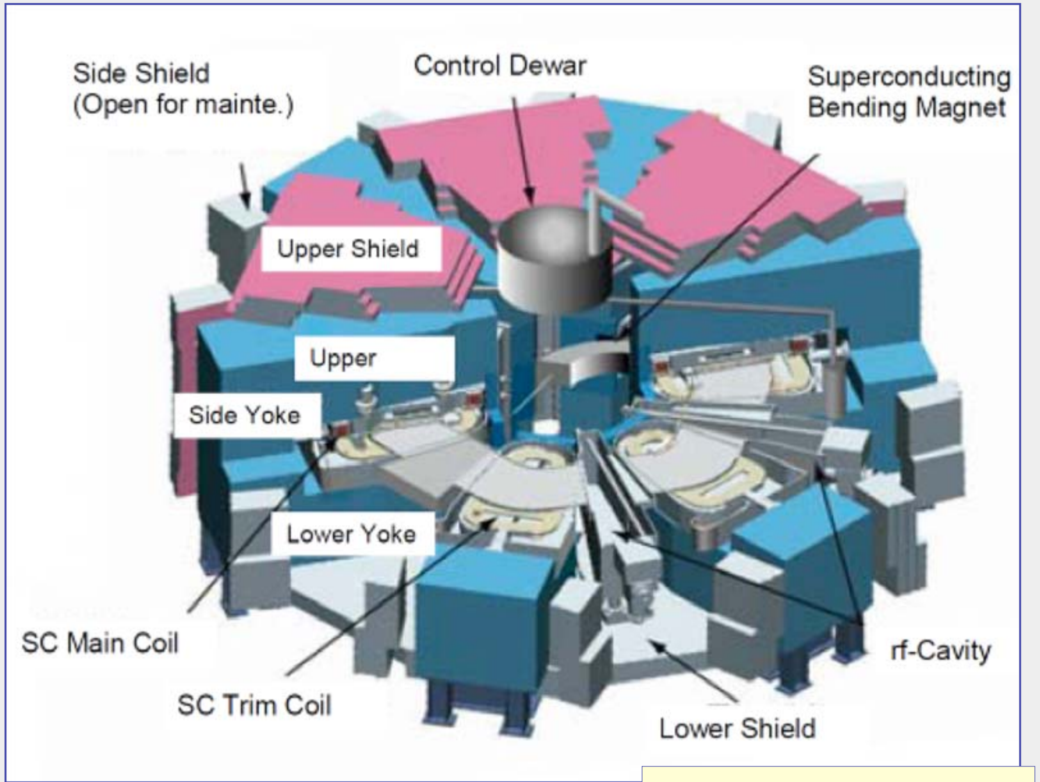
[1997, Th.Stammbach et al]



parameters	1 GeV Ring	PSI Ring
Energy	1000 MeV	590 MeV
Injection energy	120 MeV	72 MeV
Magnets	12 (B_{max} = 2.1 T)	8 (B_{max} = 1.1 T)
Cavities	8 (1000 kV)	4 (800 kV)
Frequency	44.2 MHz	50.63 MHz
Flat tops	2 (650 kV)	1 (460 kV)
Injection radius	2.9 m	2.1 m
Extraction radius	5700 mm	4462 mm
Number of turns	140	186
Energy gain at extraction	6.3 MeV	2.4 MeV
DR/dn	11 mm	5.7 mm
Turn separation	7 s	7 s
Space charge limit	10 mA	2.2 mA (3.0 @ 4 MV/turn)
Beam power	10 MW	1.3 MW

state of the art cyclotron technology at RIKEN/Japan

6 superconducting sector magnets, B ~ 4.5T



RIKEN cyclotron

high field bending magnets can be utilized also for high intensity cyclotrons

➔ gain space for more/optimized resonators

➔ introduction of sc. resonators could be envisaged

➔ note: turn separation ~ avg. orbit radius; so goal of stronger field is not to make cyclotron more compact!

Discussion

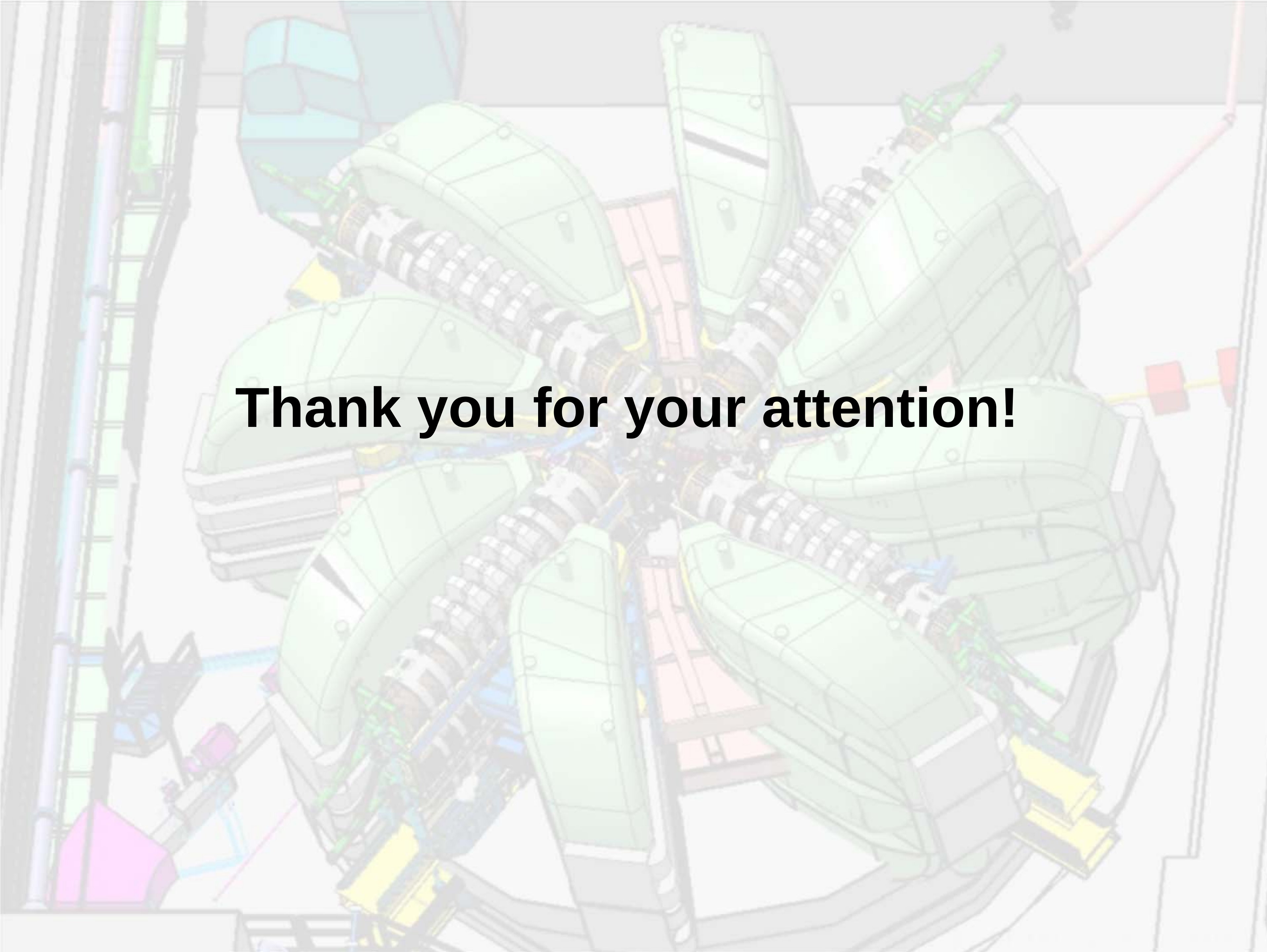
PSI: 50MHz Resonator

TESLA Collab.: 1.3GHz sc. Resonator

	Cyclotron		Superconduct. Linac
Pro	compact in-expensive design, efficient power transfer, only few resonators needed, relatively simple	Pro	large beam aperture, no complicated bending fields, tuning straightforward, high energy possible
Con	injection/extraction critical, complicated bending magnets, elaborate tuning required, energy limited 1GeV	Con	non-compact accelerator, power coupler critical, needs large cryogenic facility
Oth.	naturally CW operation	Oth.	pulsed operation possible

Summary

- the PSI accelerator delivers at max. **1.3MW** beam power in CW mode; average reliability is **90-94%**; **~25 trips** per day (2008)
- the cyclotron concept presents an effective alternative **to generate a high power beam for ADS** applications; **1GeV/10MW cyclotron** seems feasible in next step; fundamental limit at 1GeV energy – no obvious limit for power
- the reliability statistics at PSI is o.k. for today's standards but still **3 orders of magnitude below** the claimed requirements for ADS → development of **failure tolerant systems**, but also **improvements on the reactor side desirable!**



Thank you for your attention!