Cyclotron Based High Intensity Proton Accelerators

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Outline

- Cyclotron Basics

[classic cyclotron, isochronous sector cyclotron, resonators, extraction, space charge and loss scaling]

- PSI Experience

[facility overview, loss handling, power conversion efficiency, reliability and trip statistics, targets]

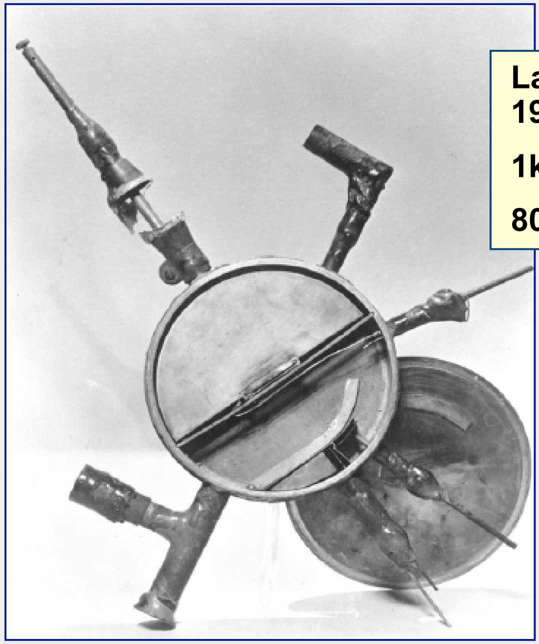
- Developments / Paper Studies

[PSI upgrade program, 10MW cyclotron]

- Discussion

[advantages and drawbacks of cyclotron accelerators]

Classical Cyclotron



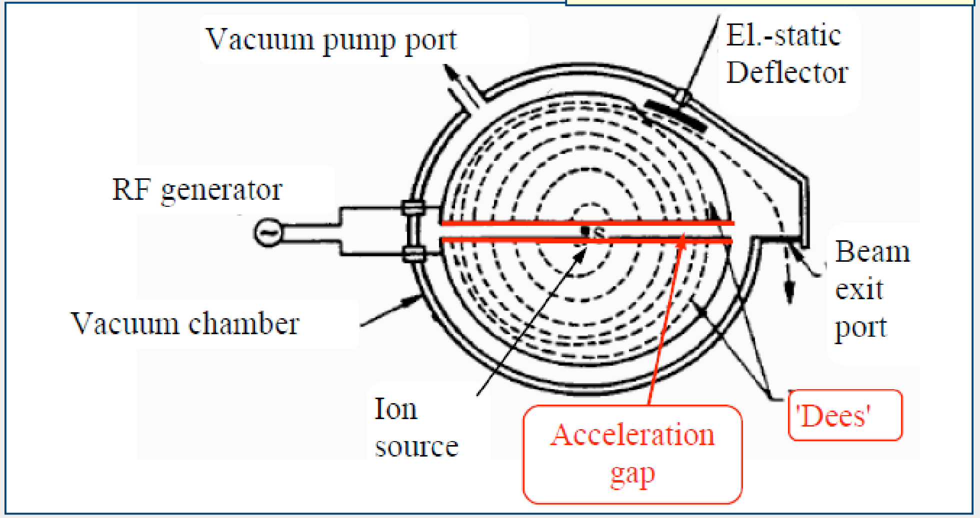
Lawrence / Livingston, 1931, Berkeley

1kV gap-voltage

80kV Protons

note spiral orbit:

$\boldsymbol{r \propto E_k^{1/2}}$



➔ two capacitive electrodes „Dees“, two gaps per turn

➔ internal ion source

➔ critical: vertical beam focusing by transverse variation of bending field

$$Q_y = \left(- \frac{r}{B} \frac{dB}{dr} \right)^{1/2}$$

but isochronous condition for relativistic ions requires positive slope…

advantage:

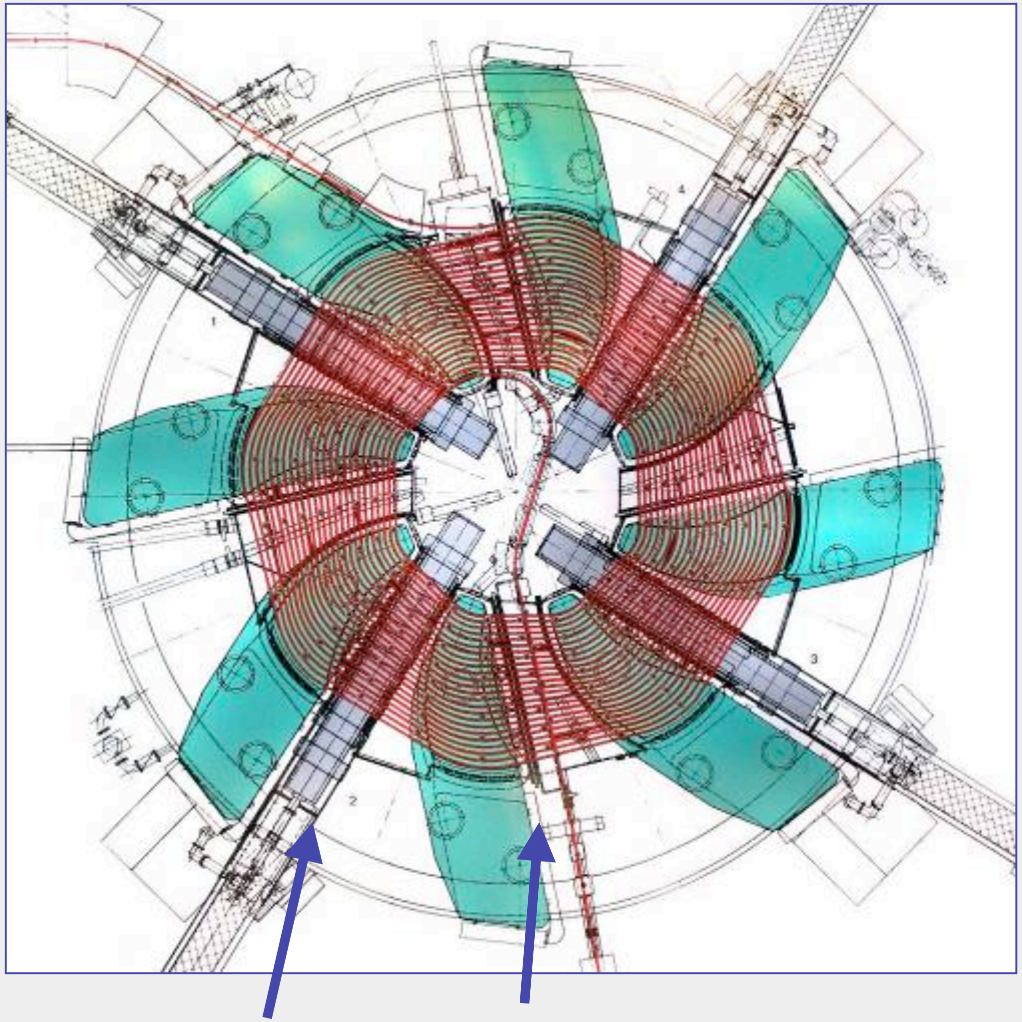
➔ CW operation

➔ periodic acceleration, i.e. multiple usage of accelerating voltage

today: Sector Cyclotrons

• **edge+sector focusing**, i.e. spiral magnet boundaries (angle ξ), azimuthally varying B-field (flutter F)
$Q_y^2 \approx n + F\,(1+2\cdot\tan^2(\xi))$
• **modular layout** (spiral shaped sector magnets, box resonators)
• **electrostatic elements** for extraction / external injection
• **radially wide vacuum chamber**; inflatable seals
• detailed **field shaping for focusing and isochronisity** required

• strength: **CW acceleration**; high **extraction efficiency** possible: 99.98% = $(1 - 2\cdot 10^{-4})$
• limitation: **kin.Energy ≤ 1GeV**, because of relativistic effects

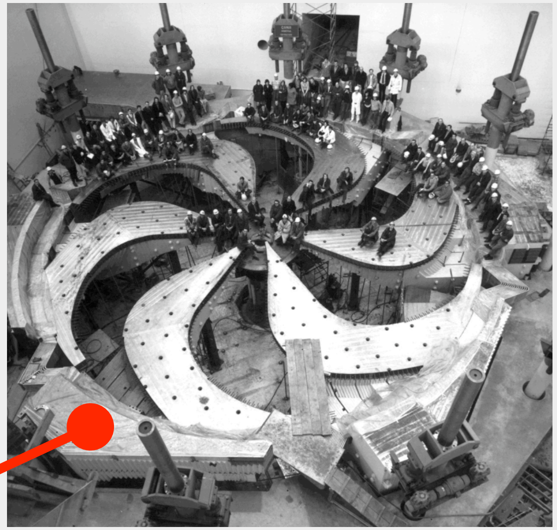


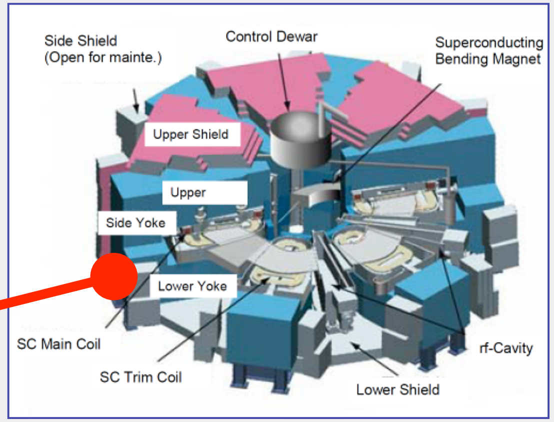
50MHz resonator

150MHz (3rd harm) resonator

Cyclotron Examples

Name / Lab	K [MeV]	P [kW]	
Cyclone 14 SEC (IBA)	14	70	protons for isotope production
TRIUMF Cyclotron	520	100	**18m diameter**
PSI Ring-Cyclotron	592	**1300**	optimized for power, 15m diameter
Superconducting Ring Cyclotron / RIKEN	**2600**	1 (86Kr)	6 sc. Magnets @ 3.8T, ions e.g. 86Kr, 238U



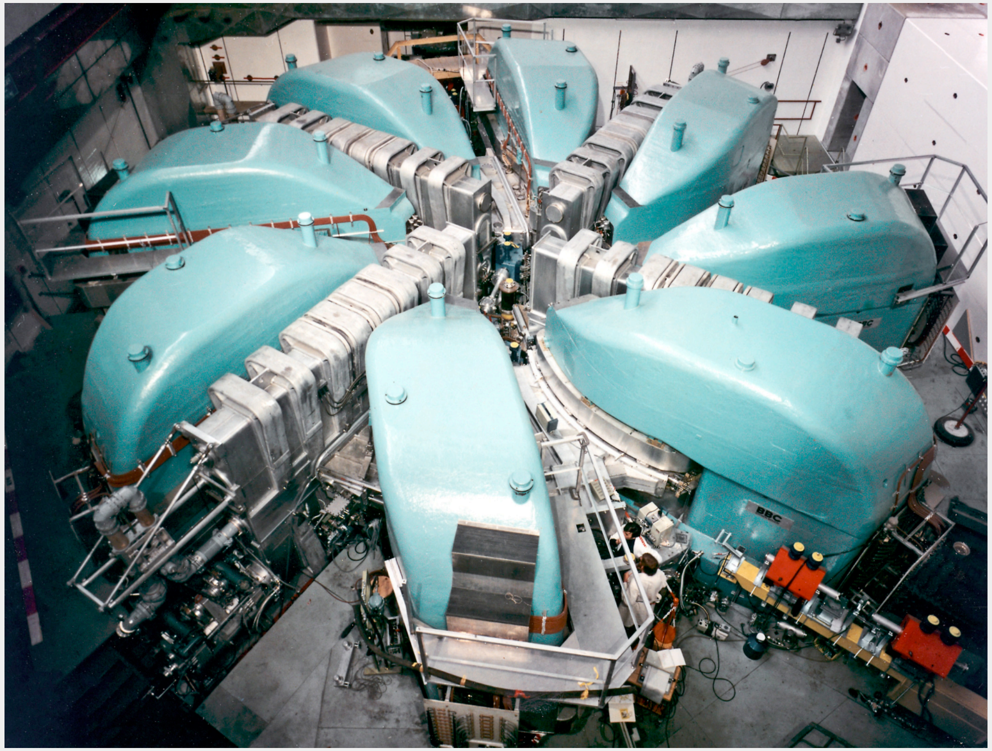


K-Value / bending limit: maximum kinetic energy [MeV] for protons in non-relativistic regime; typical names: *K300-Cyclotron*

$$(E_k/A) = K \cdot (Z/A)^2$$

PSI Ring Cyclotron

8 Sector Magnets:	1 T
Magnet weight:	~250 tons
4 Accelerator Cavities:	850 kV (1.2 MV)
1 Flat-Top Resonator	150 MHz
correction coil circuits:	15
Accelerator frequency:	50.63 MHz
harmonic number:	6
kinetic beam energy:	72 → 590 MeV
beam current max.:	2.2 mA
extraction orbit radius:	4.5 m
outer diameter:	15 m
relative Losses @ 2mA:	-~1..2·10^{-4}
transmitted power:	0.26-0.39 MW/Res.



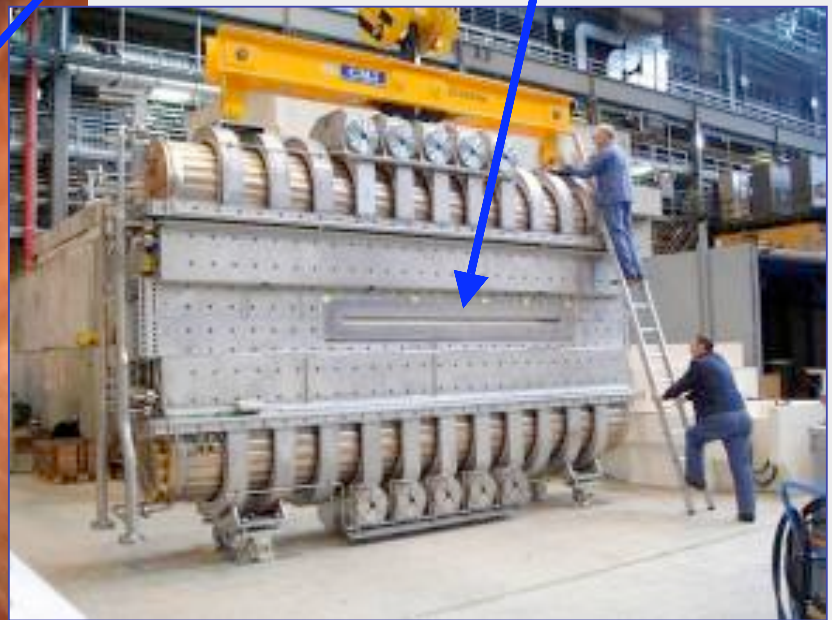
major component: RF Resonators for Ring Cyclotron

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

inside resonator

beam slit



Ring Cyclotron Resonators cont.

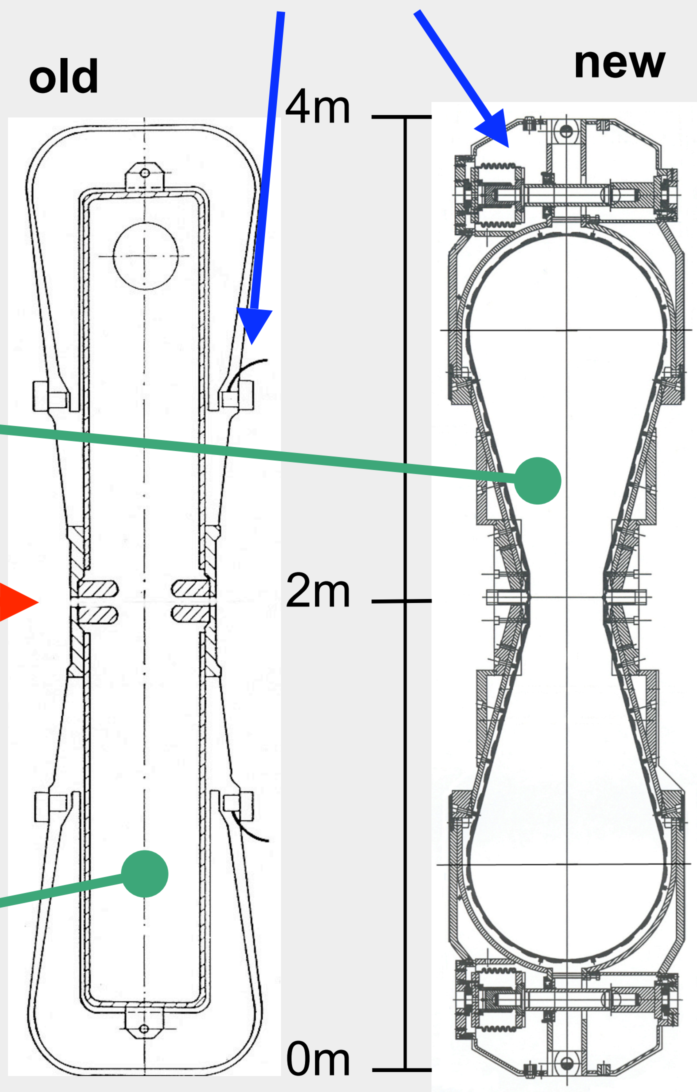
new Cu-Resonator

Oper. freq. = 51 MHz

Max. gap voltage > 1MkV

Power dissipation = 500 kW

Q0 ≈ 48'000



beam(s)

original Al-Resonator

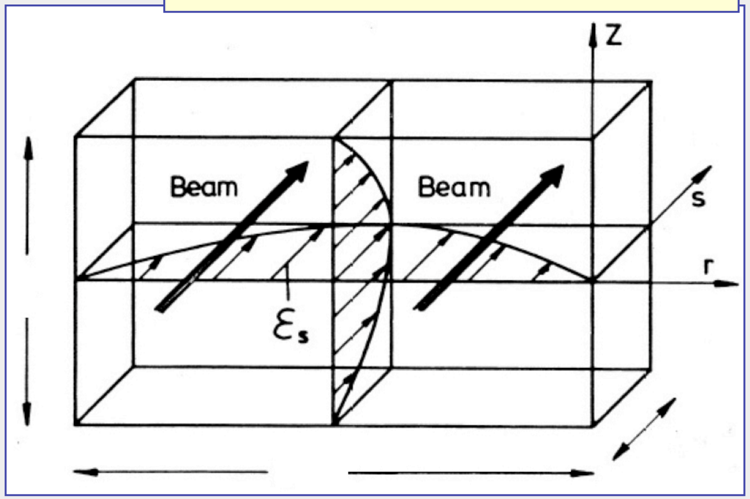
Oper. freq. = 51 MHz

Max. gap voltage = 760 kV

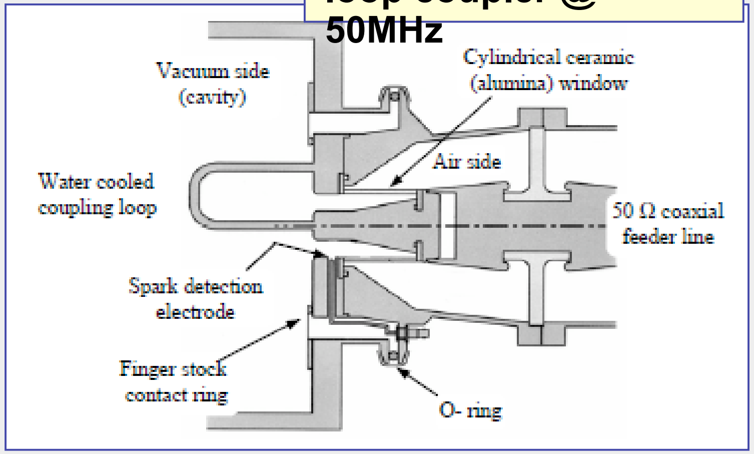
Power dissipation = 320 kW

Q0 = 32'000 (meas. value)

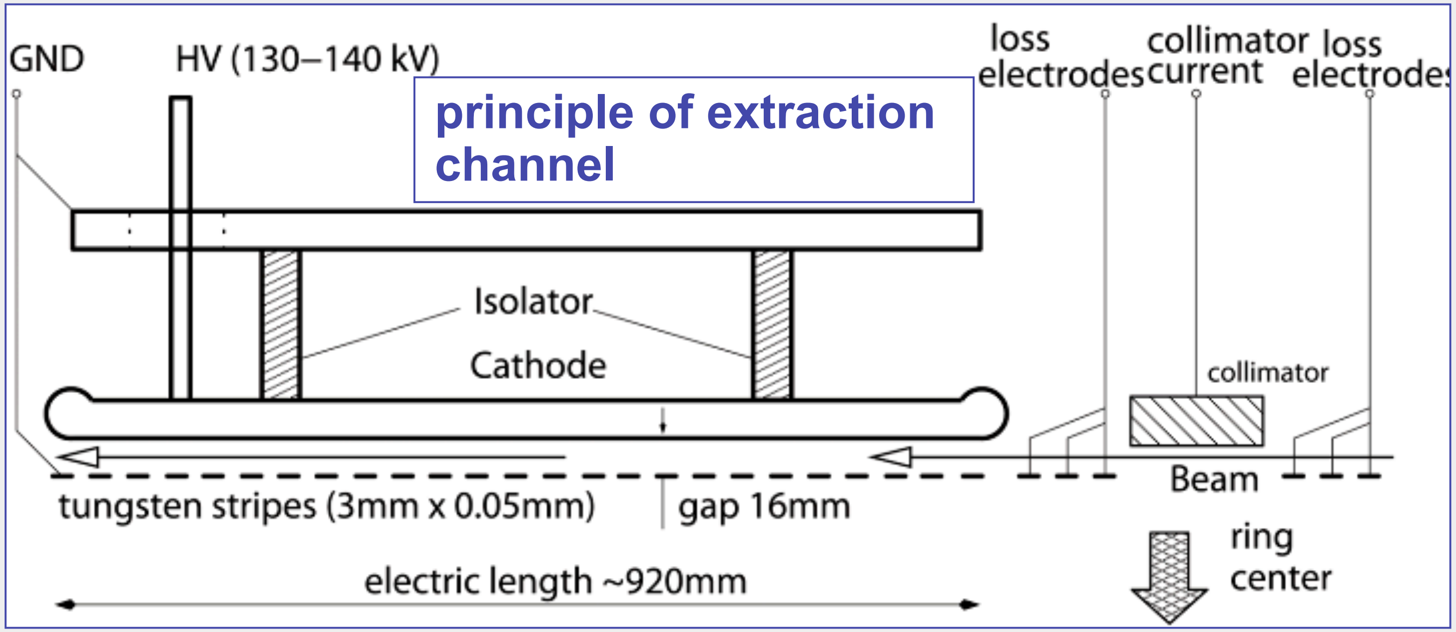
electric field in box resonator



loop coupler @ 50MHz

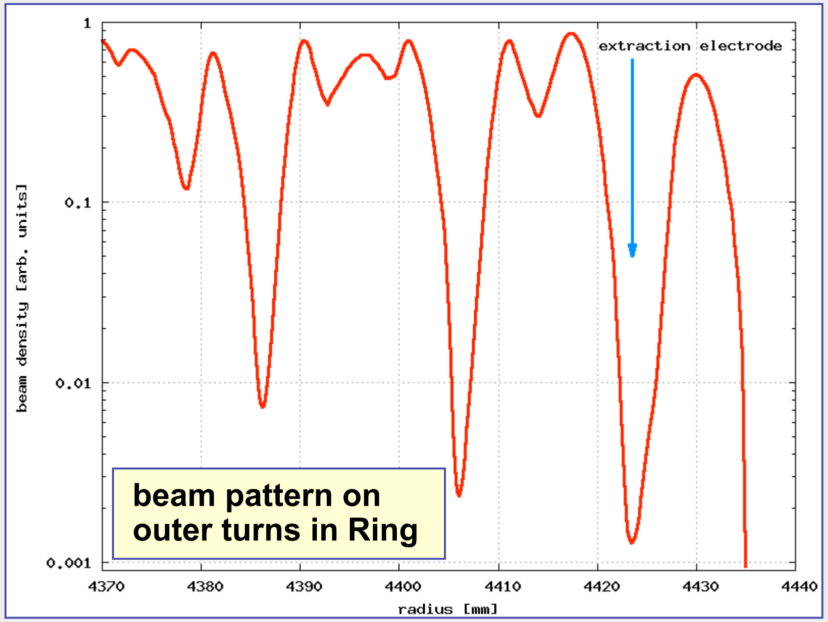


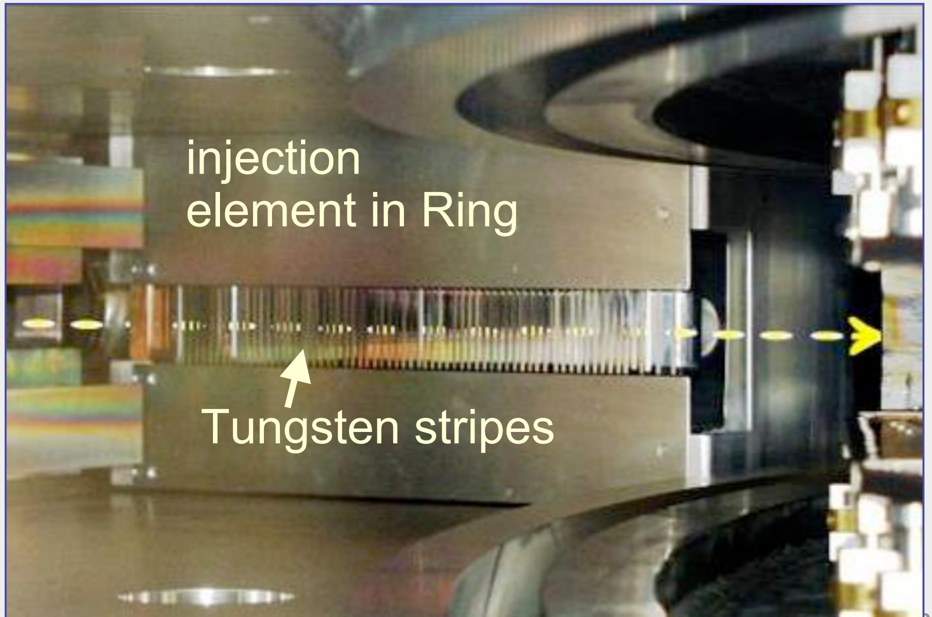
critical for losses/trips: electrostatic elements



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

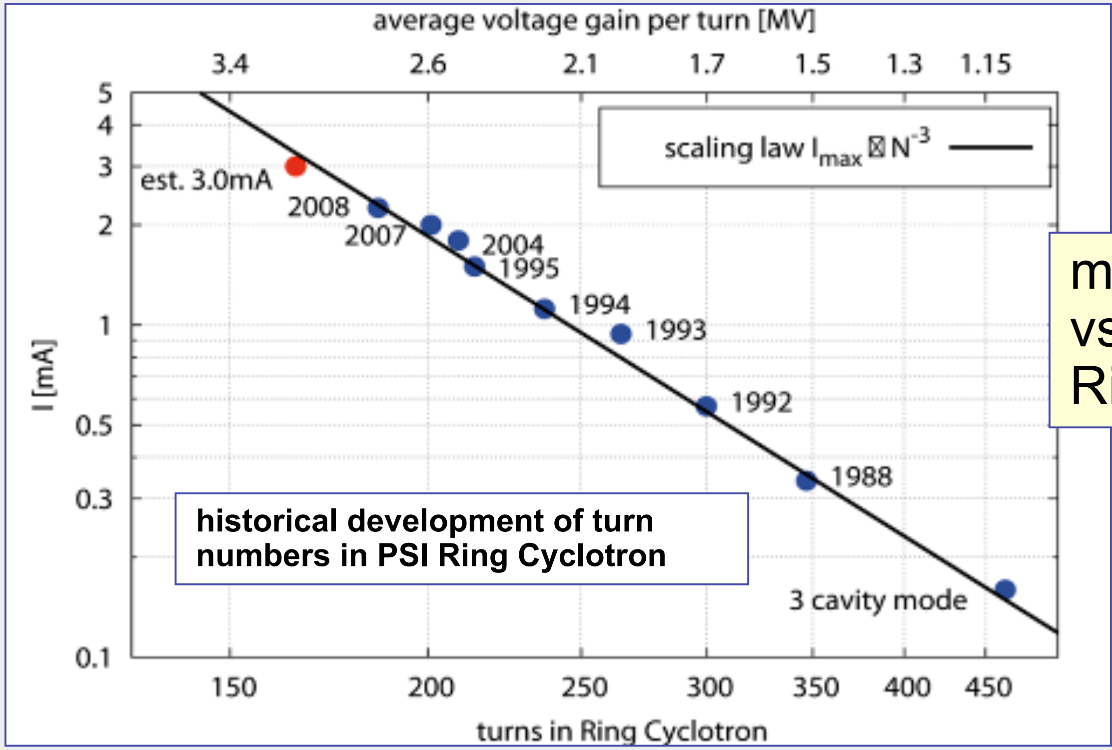
major loss mechanism is scattering in 50μm electrode!





space charge at high intensity

- intensity is limited by losses, caused by space charge beam blow-up
- 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



maximum current vs. turn number in Ring cyclotron

new regime: “round beam” with short bunches

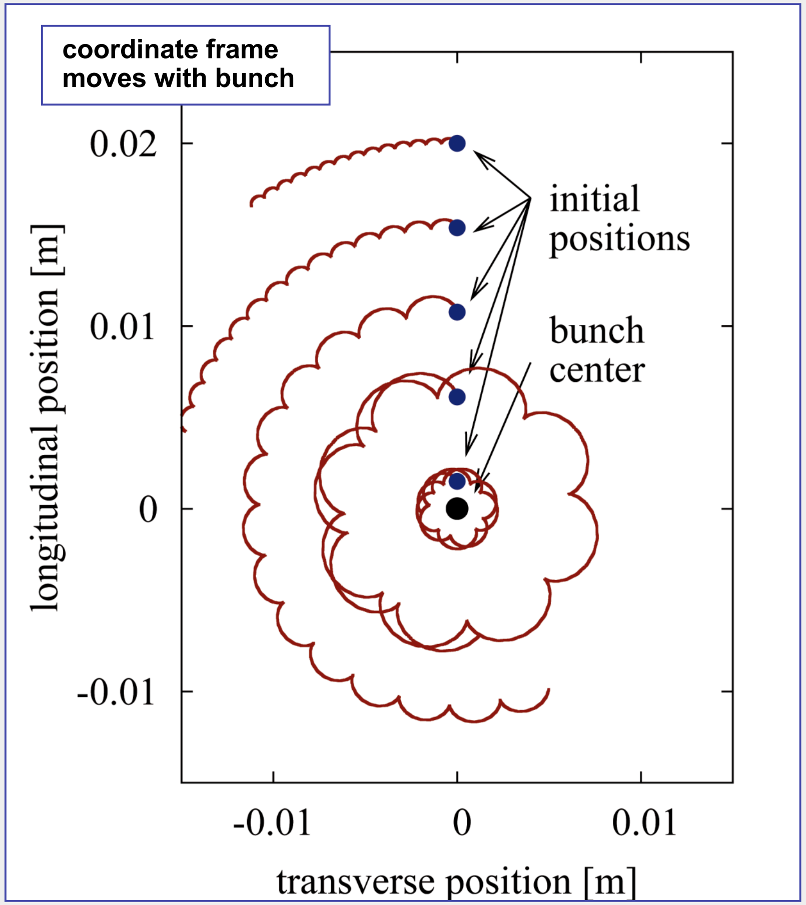
idealized model for illustration:

protons in the field of a round, short bunch + vertically oriented magnetic field (neglect relativistic effects and focusing)

[Chasman & Baltz (1984)]

though the force is repulsive a “*bound motion*” is established

→ for short bunches a round beam shape is formed



→ a round beam is observed in the Injector II cyclotron

round beam simulation

study of beam dynamics in PSI Ring Cyclotron

➔ goal: behavior of short bunches; effect of new 10'th harmonic (500MHz) buncher

Plot: distribution after 100 turns

varying initial bunch length

-multiparticle simulations

-10^5 macroparticles

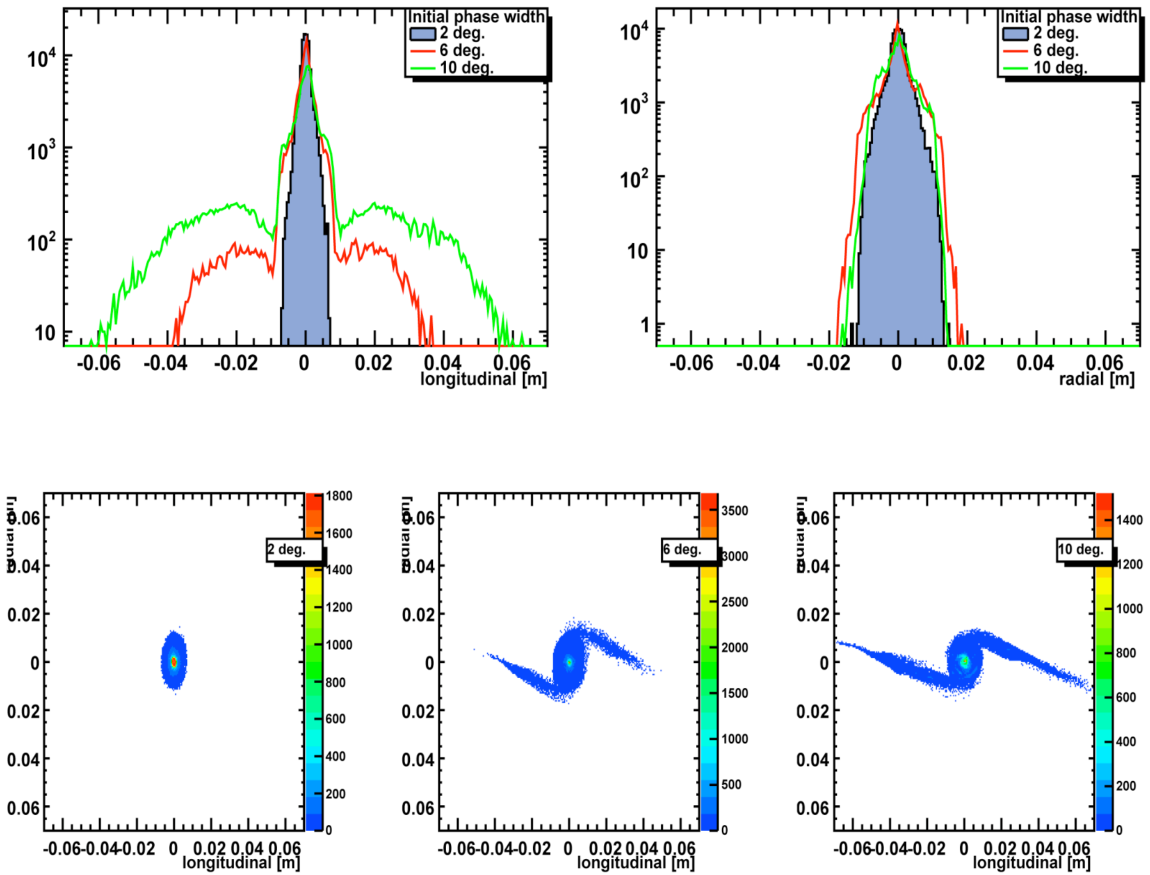
- precise field-map

- bunch dimensions:

σ_z ~ 2, 6, 10 mm;

σ_{xy} ~ 10 mm

→ **reduce bunchlength!**
500MHz buncher under commissioning; reduction of flat-top voltage seems possible



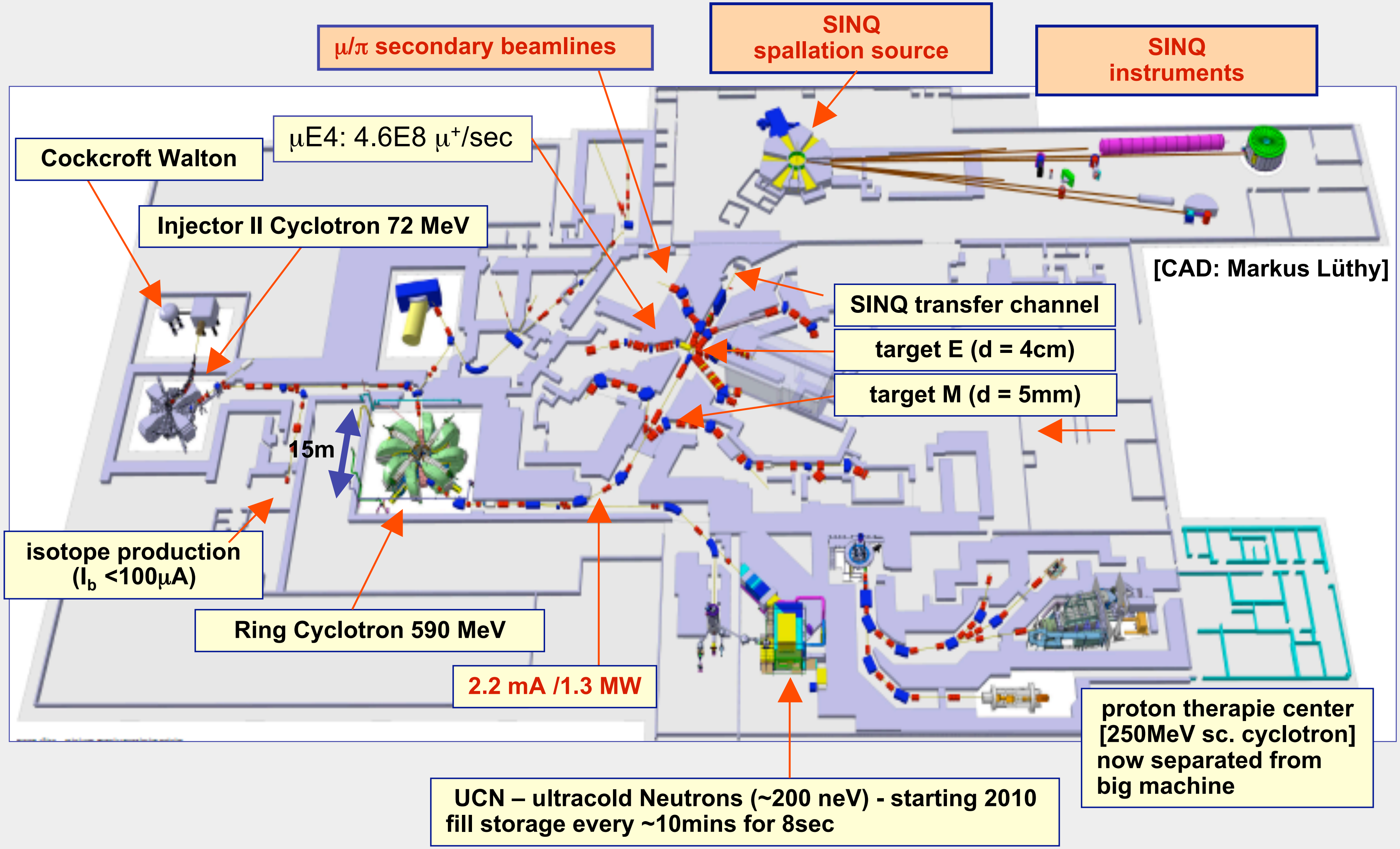
J.Yang, CAEA

Next:

- PSI Experience

[facility overview, loss handling, power conversion efficiency, reliability and trip statistics, targets]

Overview PSI Facility



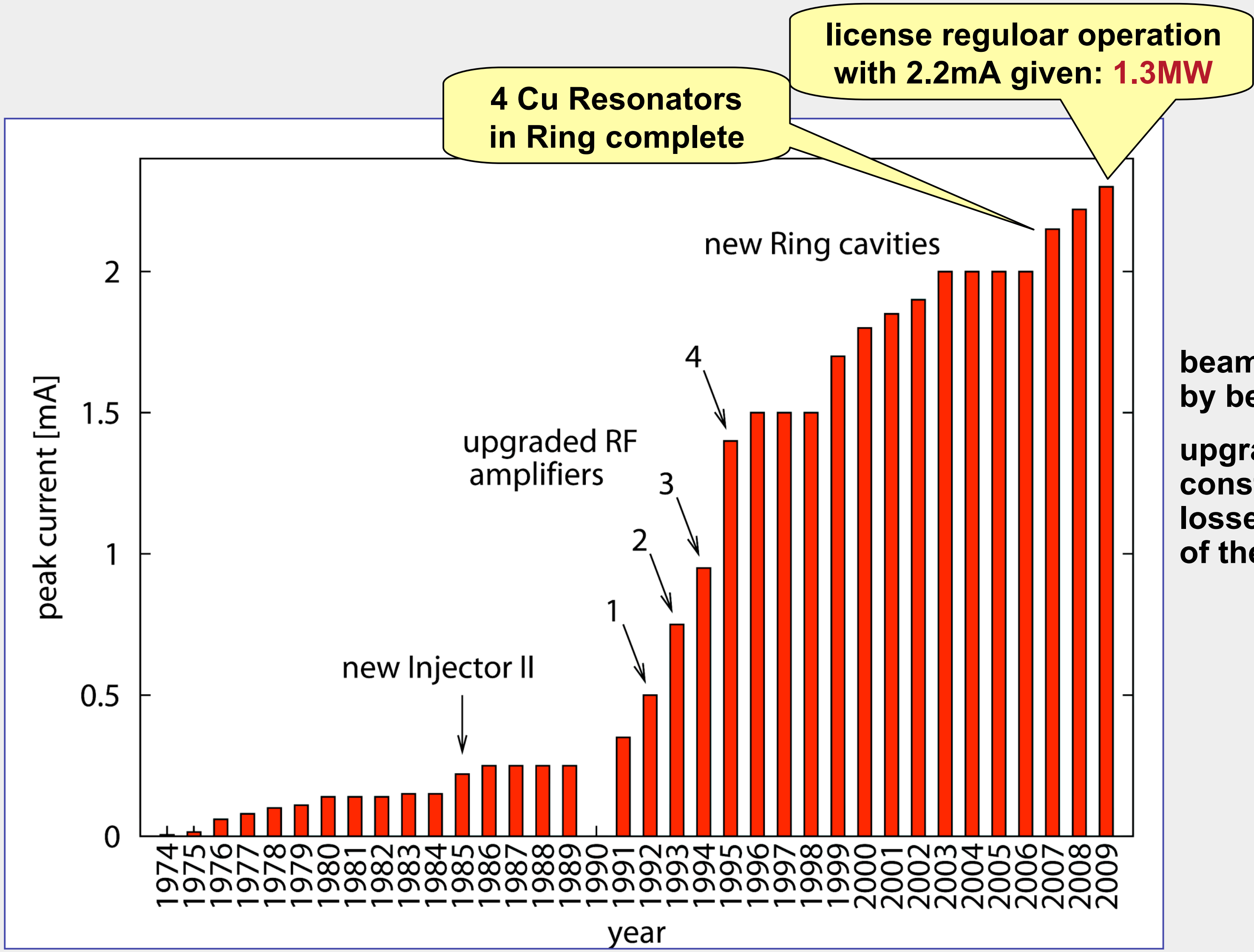
dimensions experimental hall: $130 \times 50 \times 20$ m^3

Ring Cyclotron: ø15m

crane: @15m height, 60tons

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

history max. current of the PSI accelerator

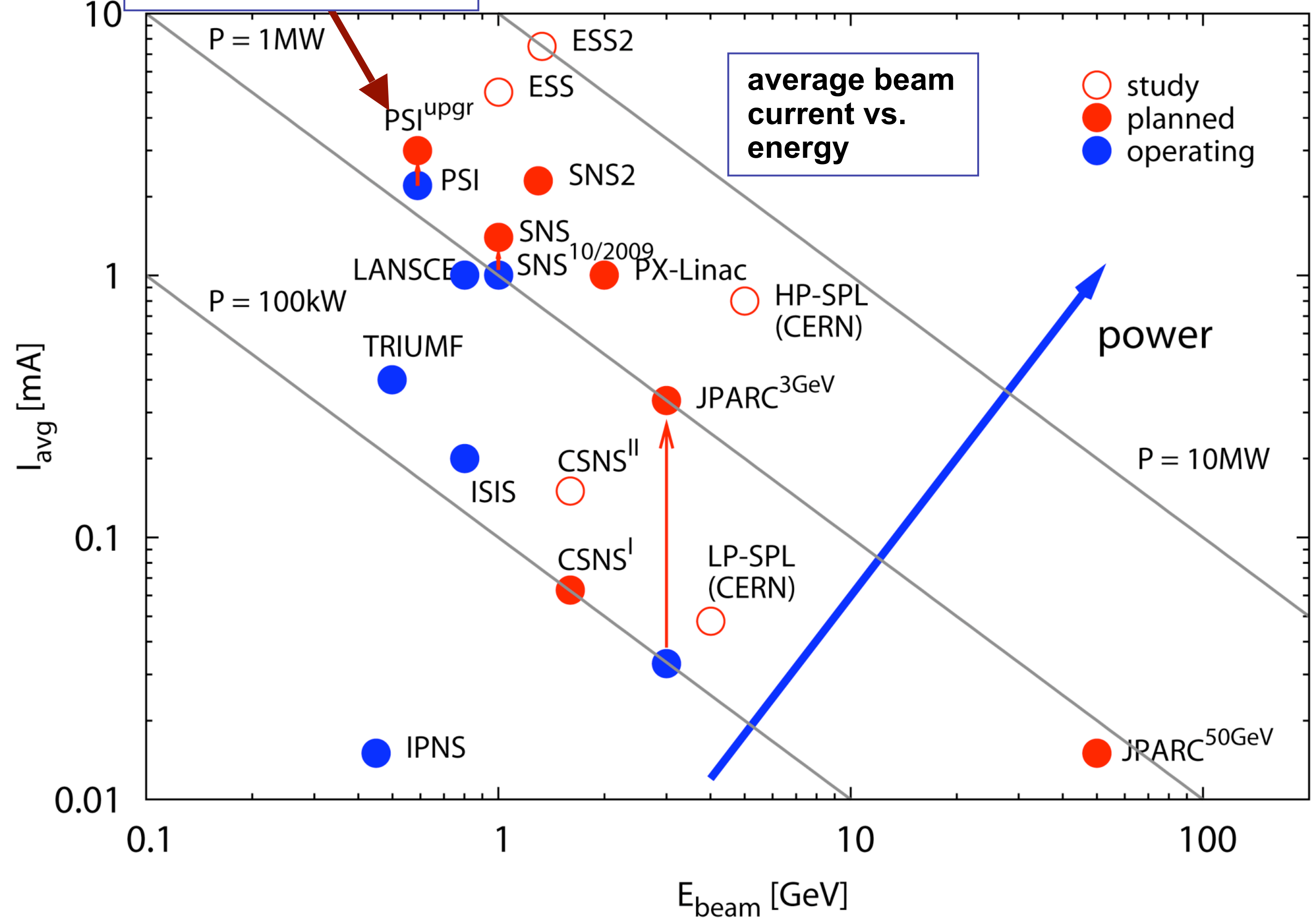


beam current is limited by beam losses;

upgrade path foresees constant absolute losses by improvements of the accelerator

High Power Proton Accelerators

PSI Upgrade Plan



plot: selected accelerators

current vs. energy

power ∝ current·energy

PSI Parameters: [2.2mA, 1.3MW] → [3mA, 1.8MW]

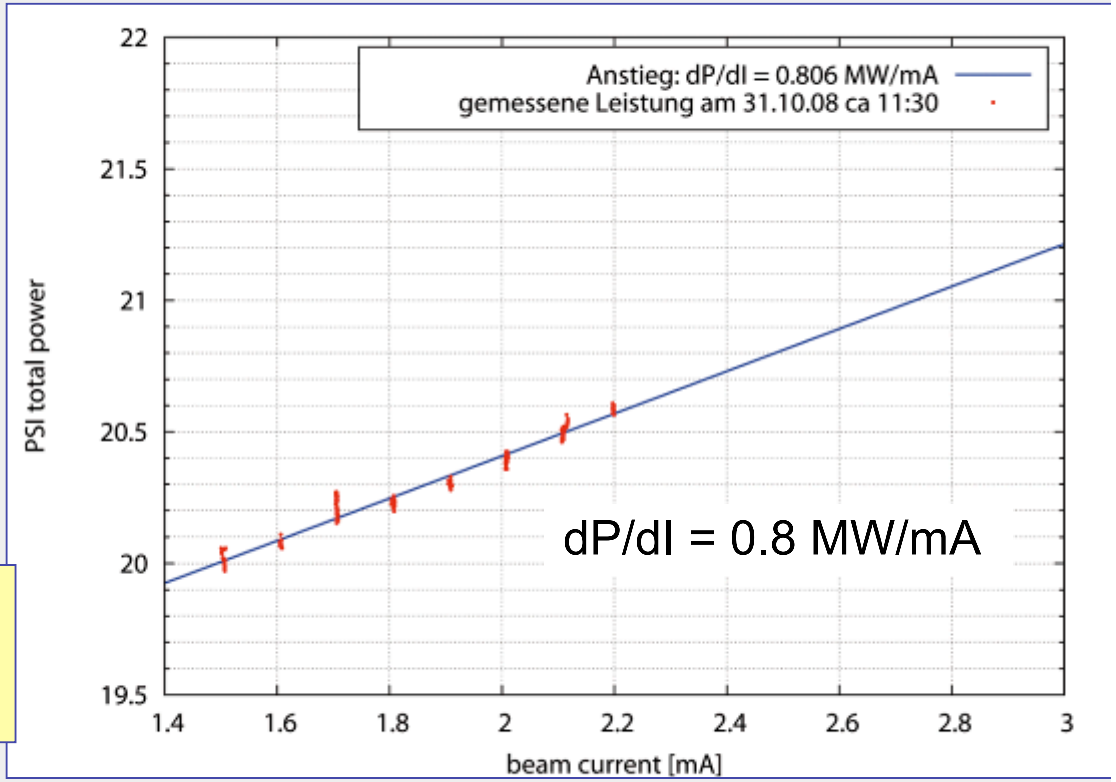
Grid to Beam Power Conversion Efficiency

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

PSI: ~10MW Grid → 1.3MW Beam

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

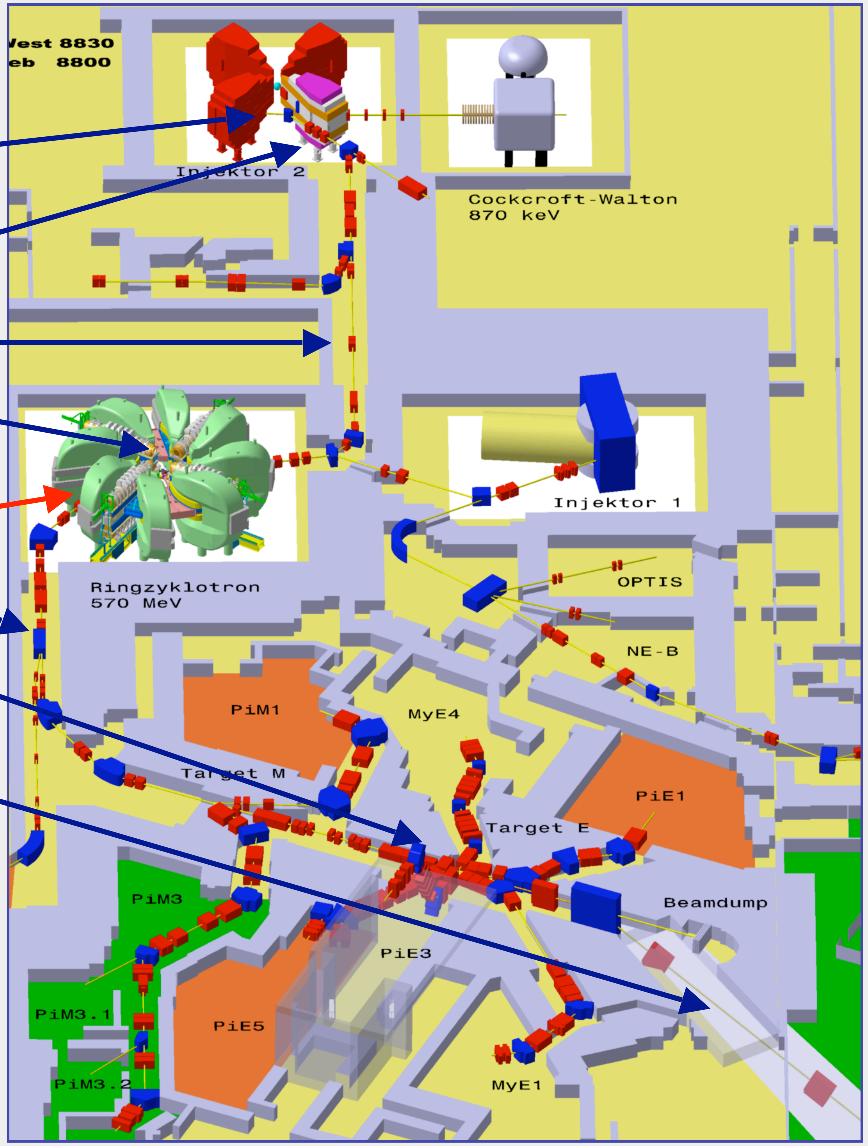
contains many loads not needed for ADS !



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

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%

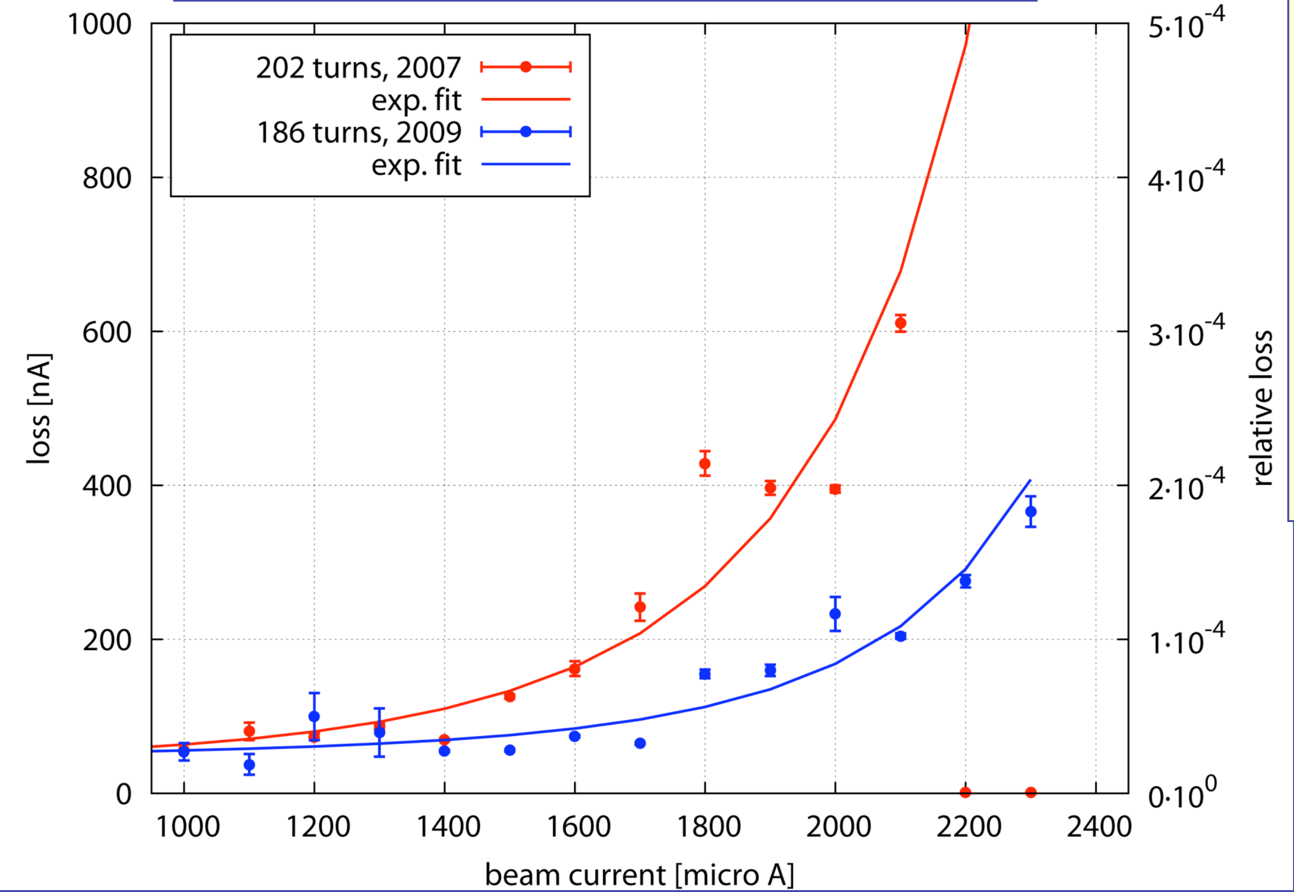


acceptable for service:

~ $2 \cdot 10^{-4}$ relative losses per location (@590MeV)

losses in Ringcyclotron reduced by turn number reduction

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



last improvements:

gap voltage increase: 780kV → 850kV

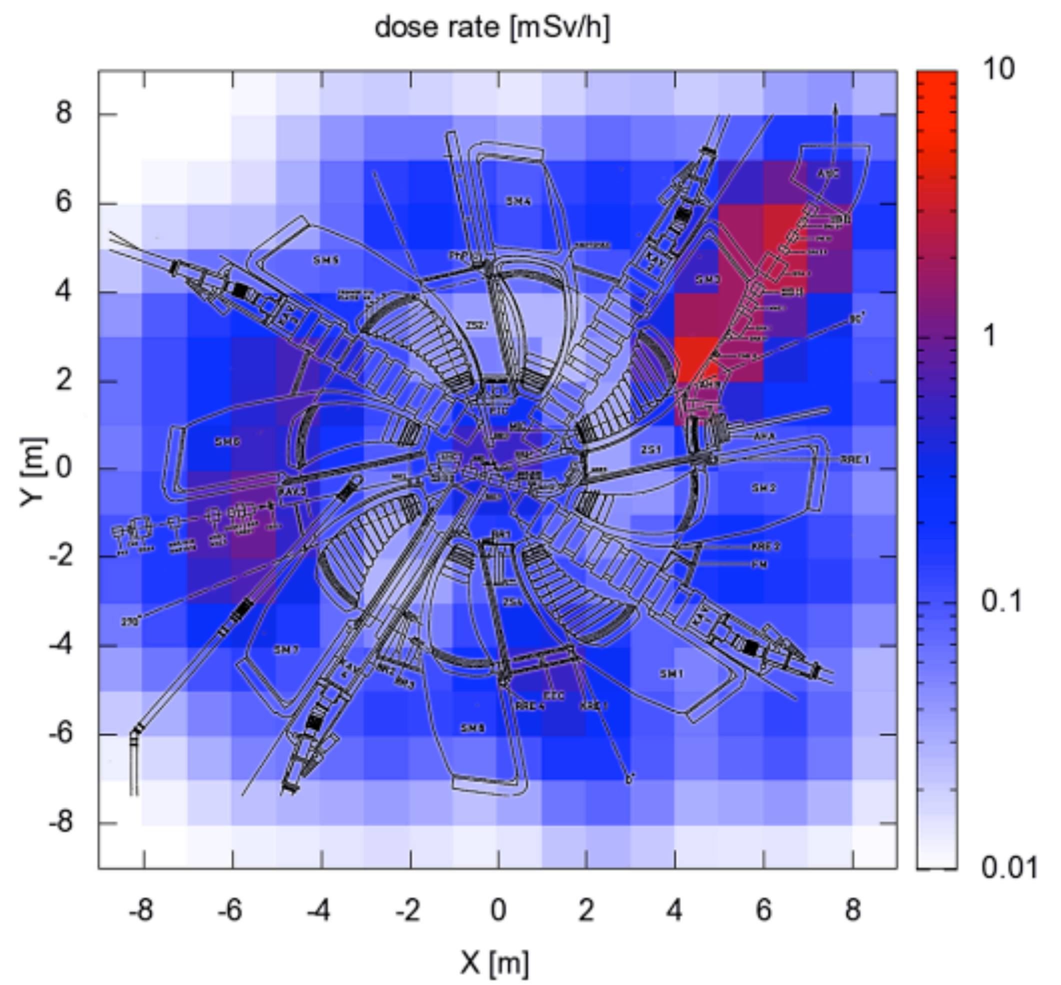
turn number reduction: 202 → 186

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:

2200 → 1700 μA for 2h

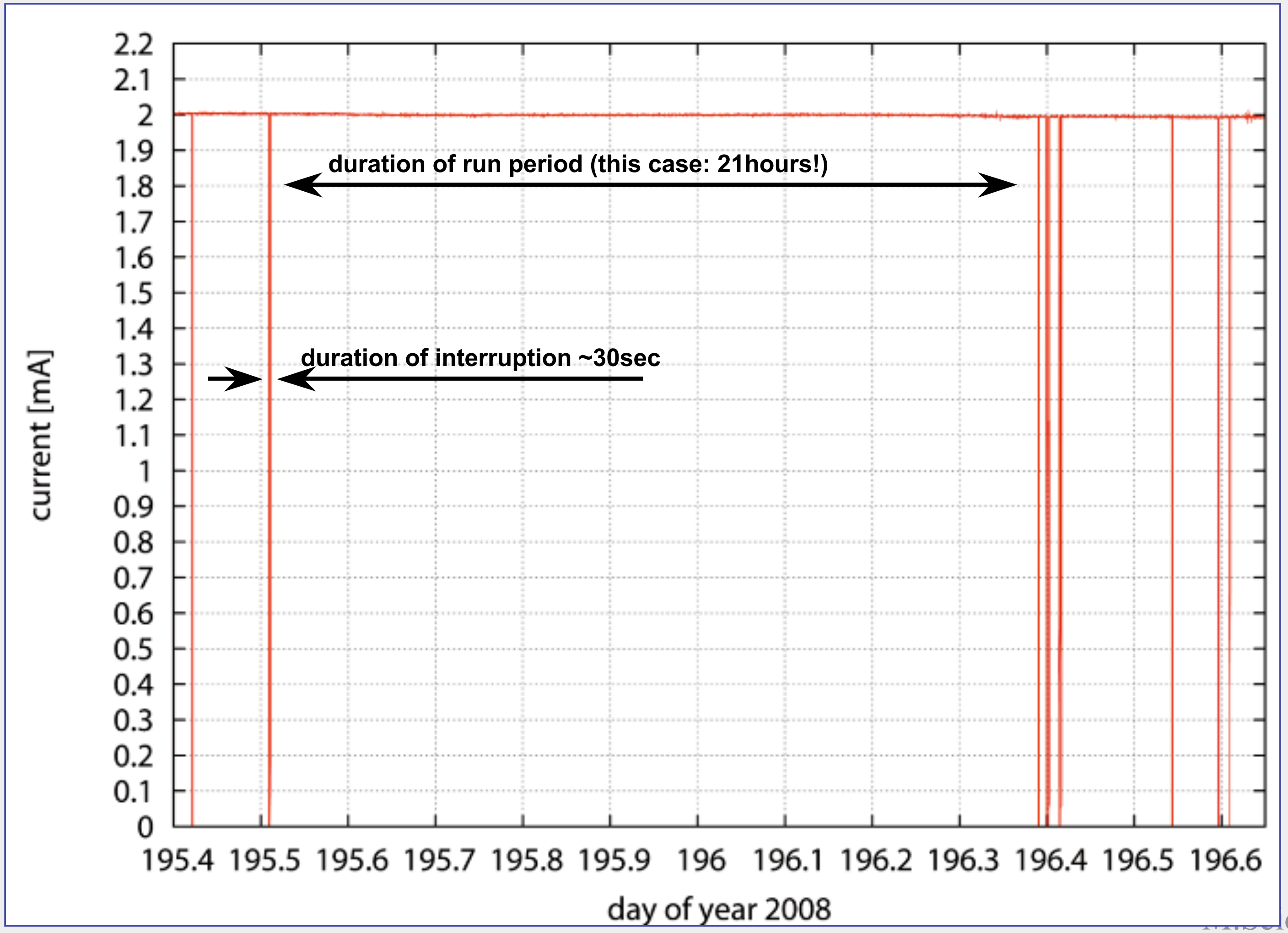
0 μA for 2h

map interpolated from ~30 measured locations

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 beam trips 07/08

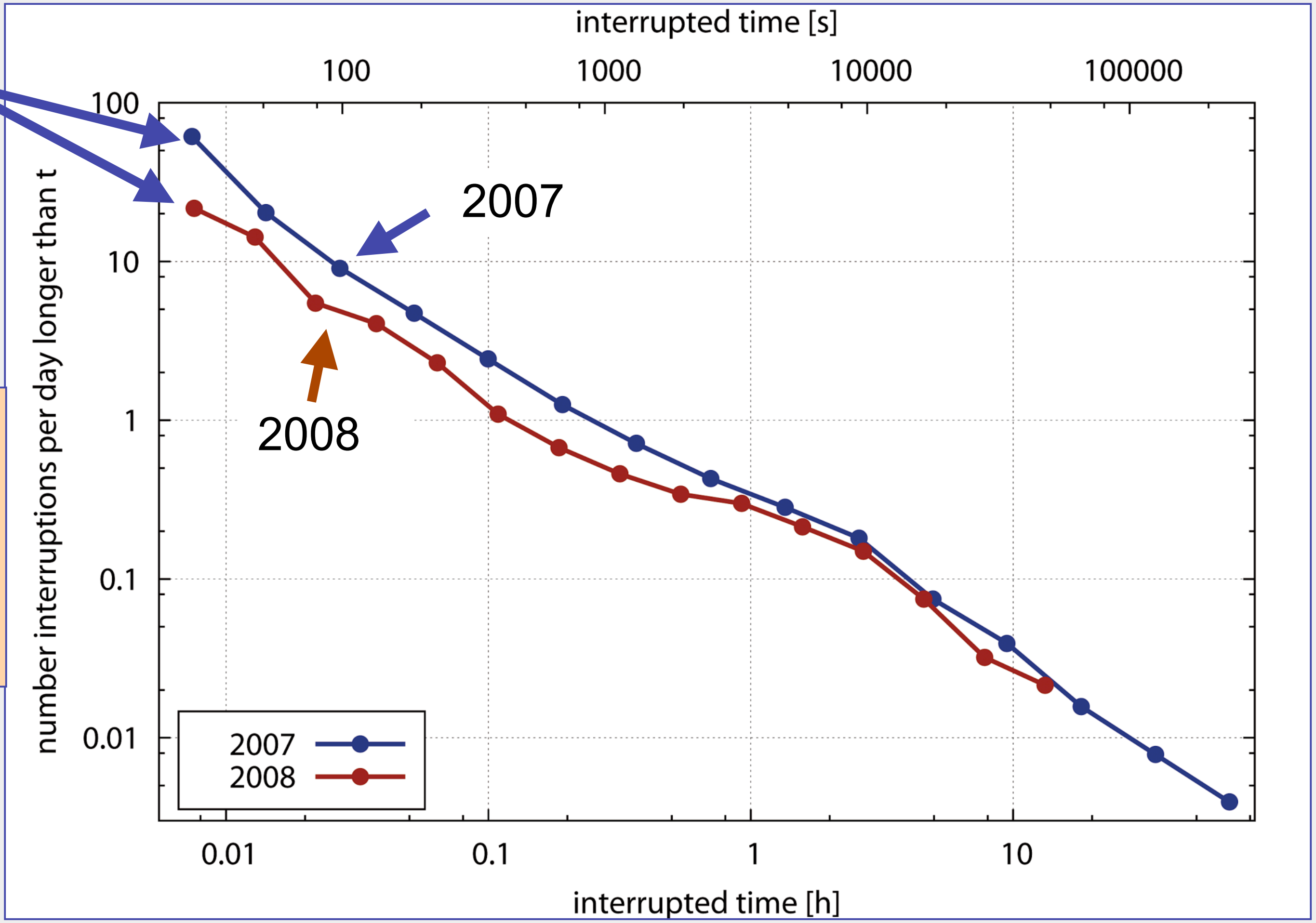
➔ histogram for occurrence of interruptions as function of duration, integrated from right; average number per day; comparison 2007/2008

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

total number of interrupts per day [integrated histogr.]

read this plot as follows:

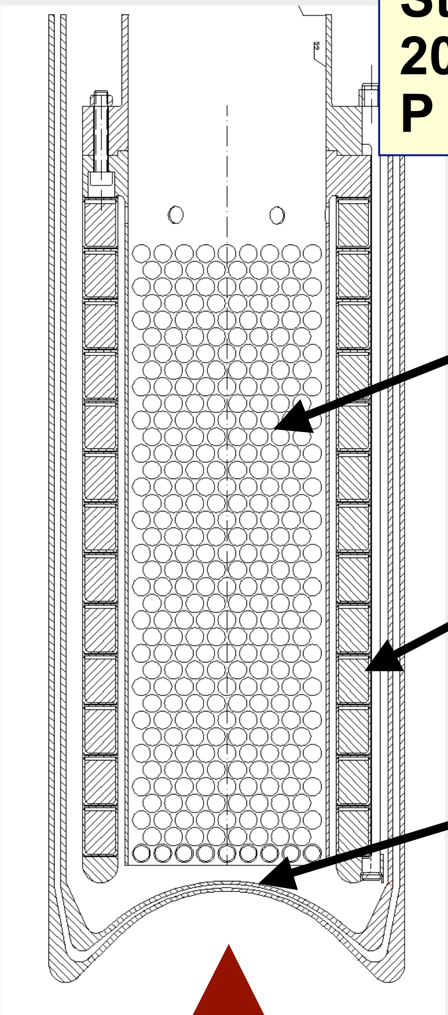
there are typically *n* trips per day that last longer than *t*

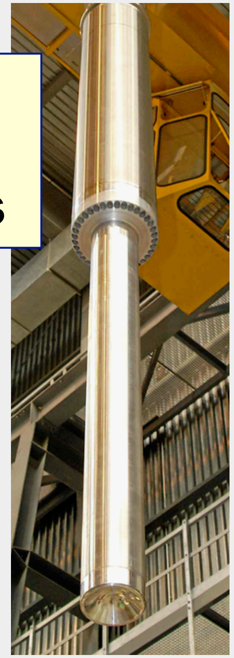


Spallation Target Expertise at PSI

Standard solid target 2009 in operation; P ~ 0.95 MW

Liquid metal testtarget (MEGAPIE) 2006 in operation for 3 months





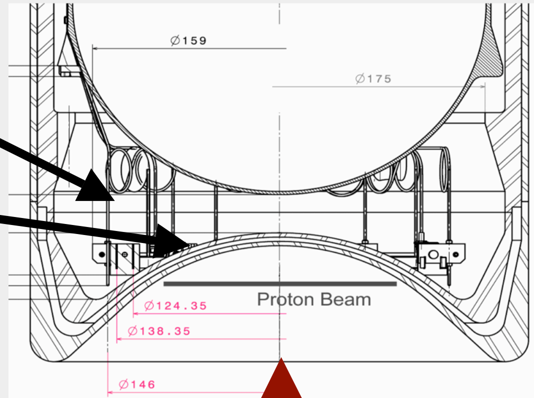
Zircaloy tubes, filled with lead, D_2O cooling

lead blankets
(reflector for th. neutrons)

beam window
(water cooled)

Lead-Bismuth
eutectic, ~230 °C

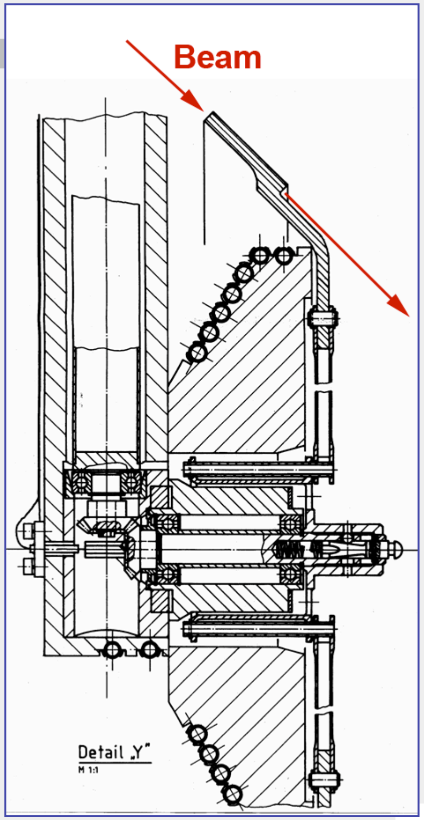
leak detectors



beam

beam

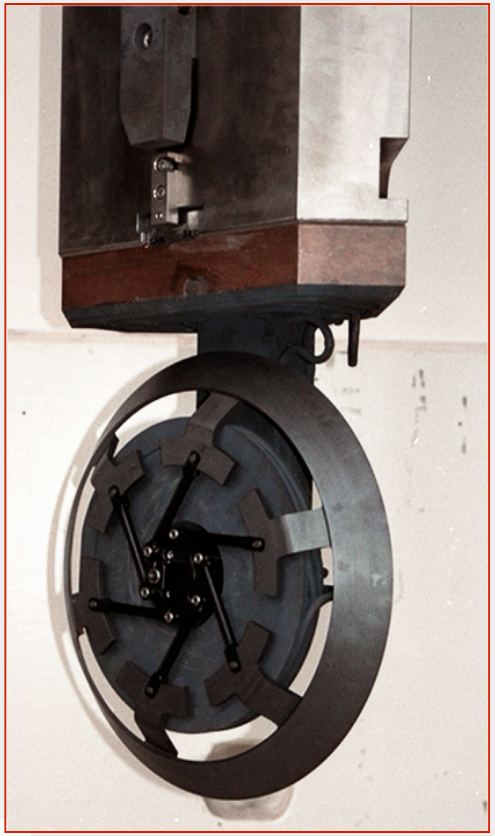
issues:
- ➔ beam material interaction
- ➔ neutronics
- ➔ static and dynamic stress
- ➔ fluid dynamics
- ➔ activation and disposal



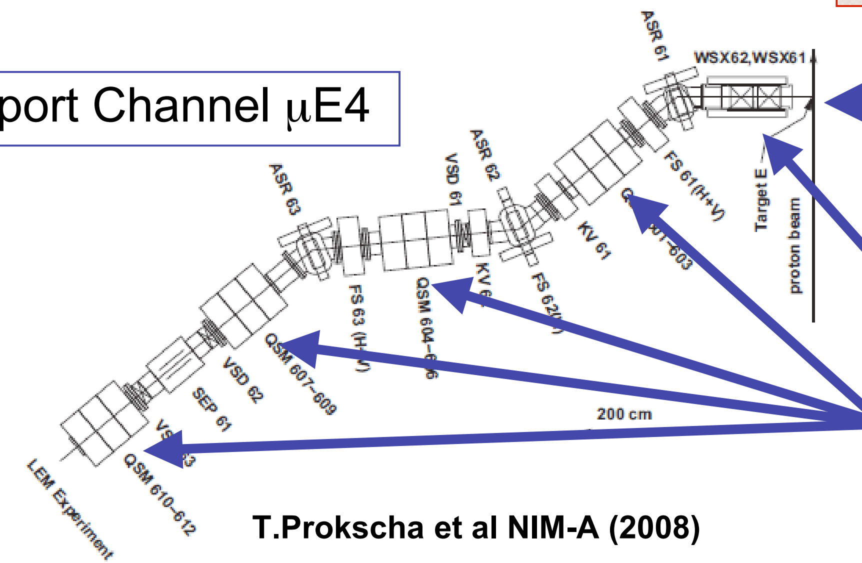
Meson Production Target

TARGET CONE

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:	**40 mm**
	7 g/cm^2
Beam loss:	12 %
Power deposit.:	20 kW/mA



Muon Transport Channel μE4



T.Prokscha et al NIM-A (2008)

target, d=40mm

solenoids

quadrupoles

Muon Rate:

4.6E8 μ^+/sec

@ p=29.8 MeV/c

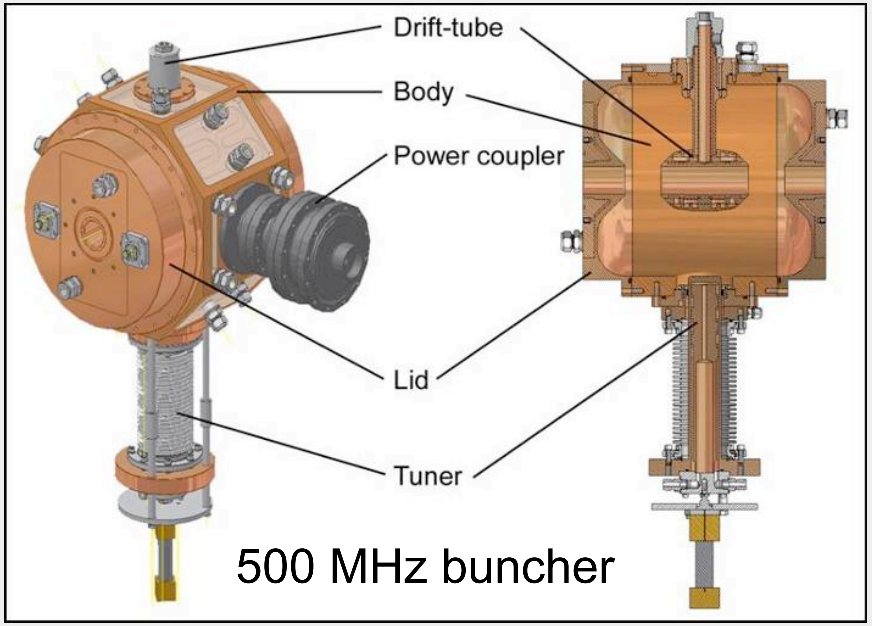
Next:

- Developments / Paper Studies

[PSI upgrade program, 10MW cyclotron]

Cyclotron Upgrade – fast acceleration, short bunches!

- goal: **2.2mA → 3mA [1.8MW]**
- philosophy: keep **absolute losses constant**
- higher gap voltages → faster acceleration → reduce space charge effects
- short bunches → less tail generation



500 MHz buncher

measures:

➔ new resonators in Ring Cyclotron [done!]

➔ 10'th harmonic buncher before Ring [under commissioning]

➔ new ECR ion source [expected for 2010]

➔ **<u>new resonators in Injector II (replace flattops)</u>** [expected for 2012]

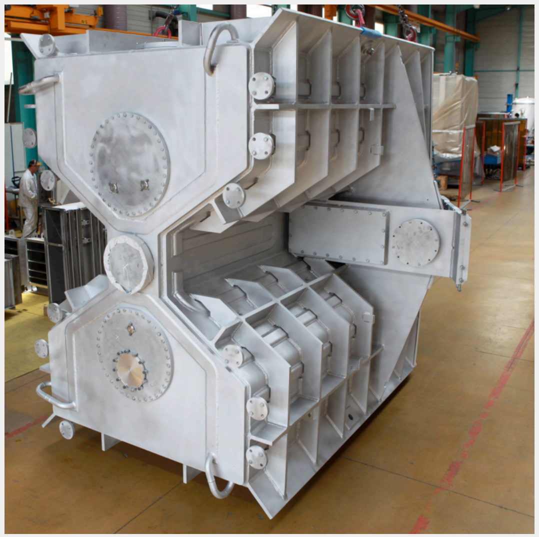
➔ new RF amplifiers for all four resonators in Injector II [expected for 2012]

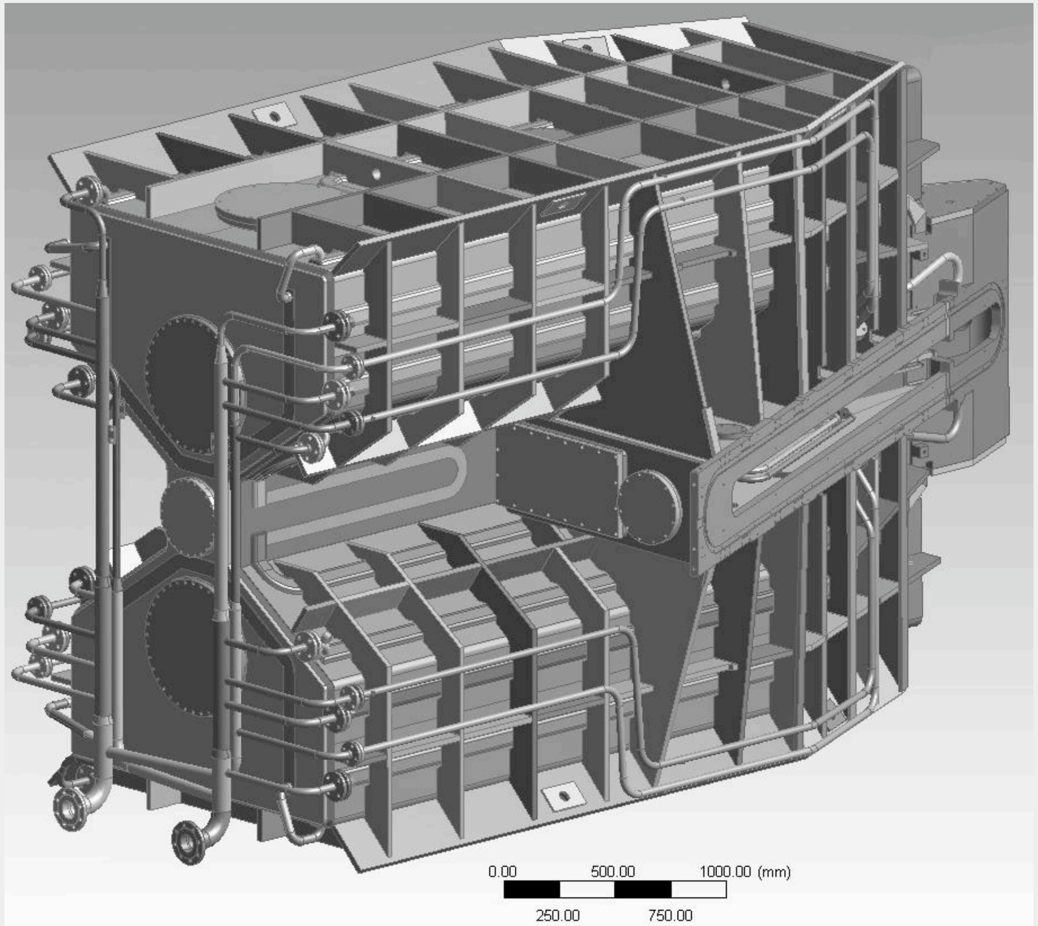
➔ replace absorbers behind 4cm Meson Prod. Target [expected for 2013]

New 50 MHz Resonator 2&4, Injector 2

Specification

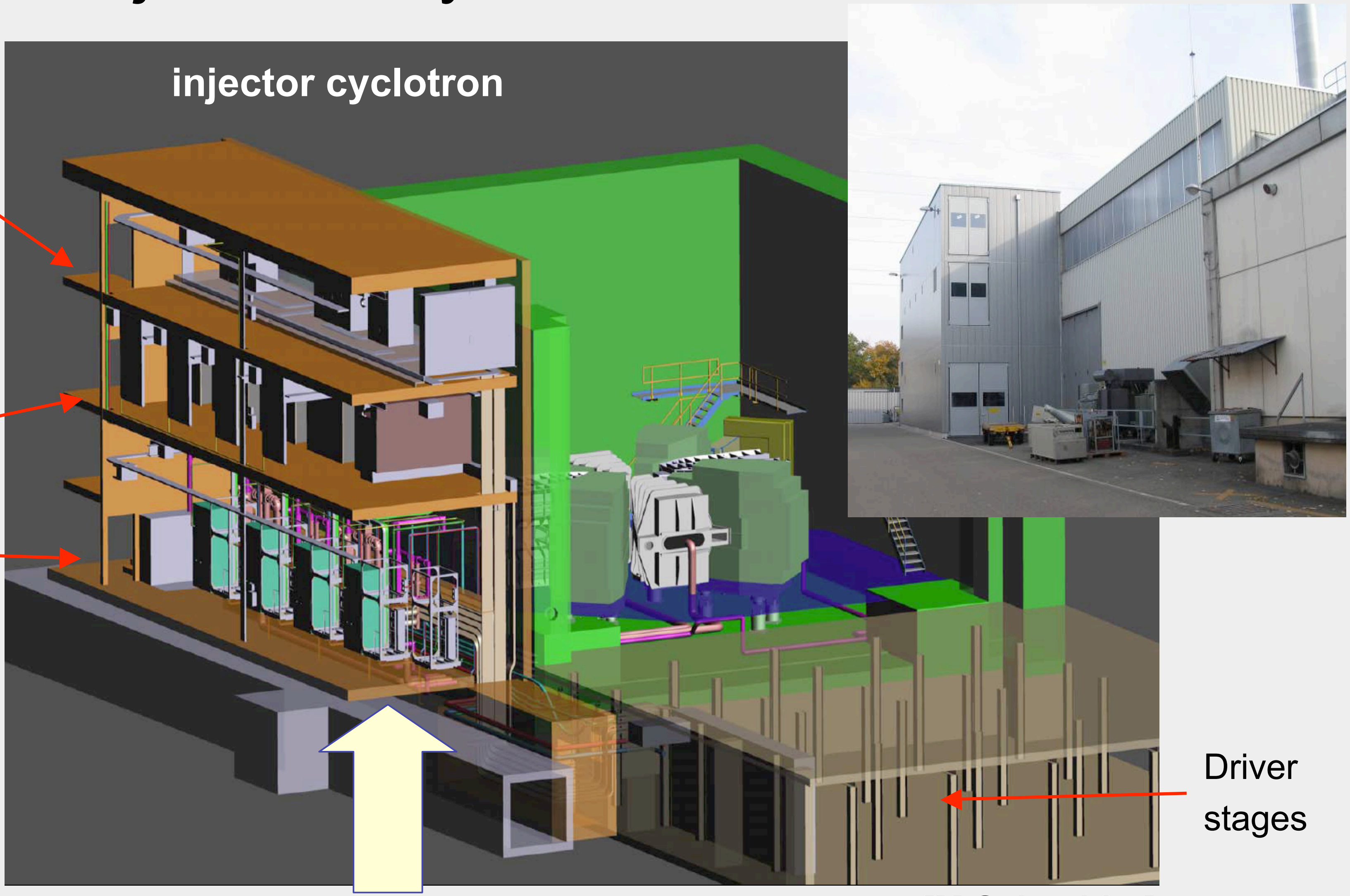
Resonance frequency:	50.6328 MHz
Accelerating voltage:	400 keV
Dissipated power:	45 kW@400kV
Tuning range:	200 kHz
Cavity RF-wall:	EN AW 1050
Structure:	EN AW 5083
Vacuum pressure:	1e-6 mbar
Cooling water flow:	15 m3/h
Dimension:	5.6x3.3x3.0 m
Weight:	7‘000 kg





M.Bopp, PSI; company: **SDMS**/France

amplifiers and resonators for the Injector II Cyclotron



power supplies

Plate power supplies

Amplifiers

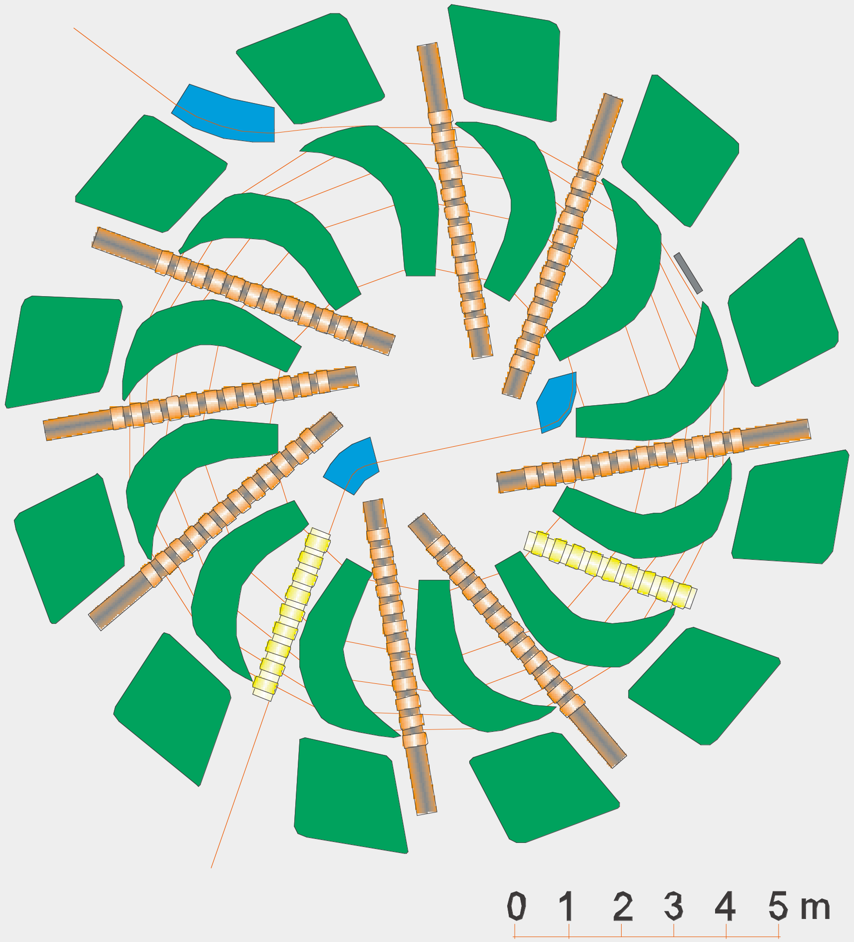
Driver stages

[M.Schneider]

new annex

Parameter Set for a 10 MW Cyclotron

[1997, Th.Stammbach et al]

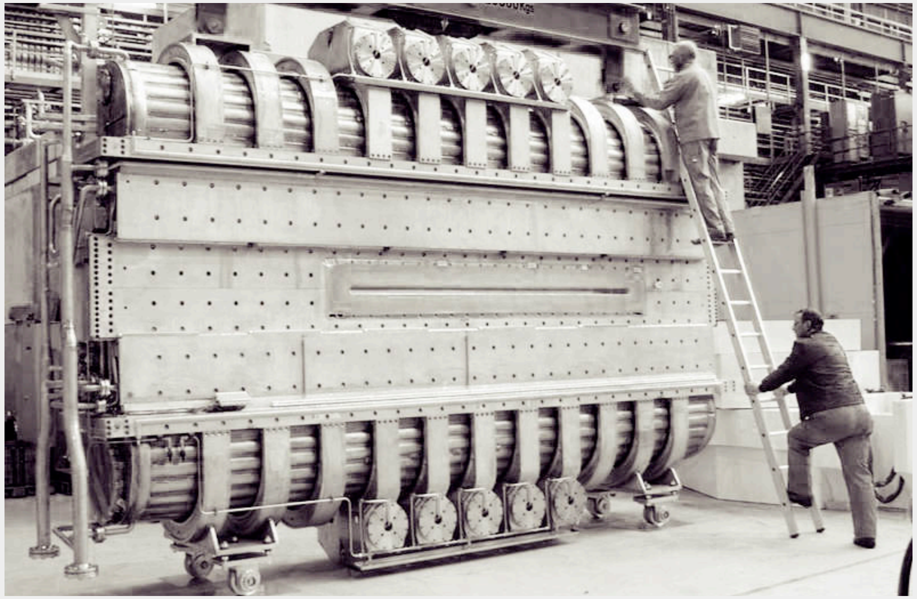


parameters	1 GeV Ring	PSI Ring
Energy	1000 MeV	590 MeV
Injection energy	120 MeV	72 MeV
Magnets	12 (B_{max} = 2.1 T)	8 (B_{max} = 1.1 T)
Cavities	8 (1000 kV)	4 (800 kV)
Frequency	44.2 MHz	50.63 MHz
Flat tops	2 (650 kV)	1 (460 kV)
Injection radius	2.9 m	2.1 m
Extraction radius	5700 mm	4462 mm
Number of 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

lastly:

- ❑ Discussion and Summary

[advantages and drawbacks of cyclotron accelerators]



Discussion

pro and contra cyclotron

pro:
- compact and simple design
- efficient power transfer
- only few resonators and amplifiers needed

con:
- injection/extraction critical
- energy limited to 1GeV
- complicated bending magnets
- elaborate tuning required

other:
- naturally CW operation

Summary

- the cyclotron concept presents an effective option **to generate a high power beam for example for ADS** applications; **1GeV/10MW cyclotron** seems feasible; fundamental limit at 1GeV energy
- the PSI accelerator delivers **1.3MW** beam power – upgrade to 1.8MW is under work; average reliability is **90-94%**; **~25 trips** per day (2008); grid-to-beam power conversion efficiency is ~15%; 30%-40% seems possible
- **not mentioned**: machine interlock system; infrastructure and auxiliary systems in context of activation; licensing of facility; thermomechanical and fluid-dynamics problems of targets, absorbers, dump

Thank you for your attention!

many thanks to the PSI cyclotron team:

S.Adam, A.Adelmann, B.Amrein, Ch.Baumgarten, M.Bopp, K.Deiters, R.Dölling, P.A.Duperrex, H.R.Fitze, A.Fuchs, J.Grillenberger, D.Götz, R.Kan, D.Kiselev, M.Humbel, A.Mezger, D.Reggiani, M.Schneider, S.Teichmann, M.Wohlmuther, J.Yang, H.Zhang + many others…