Production of a 1.3 Megawatt Proton Beam at PSI

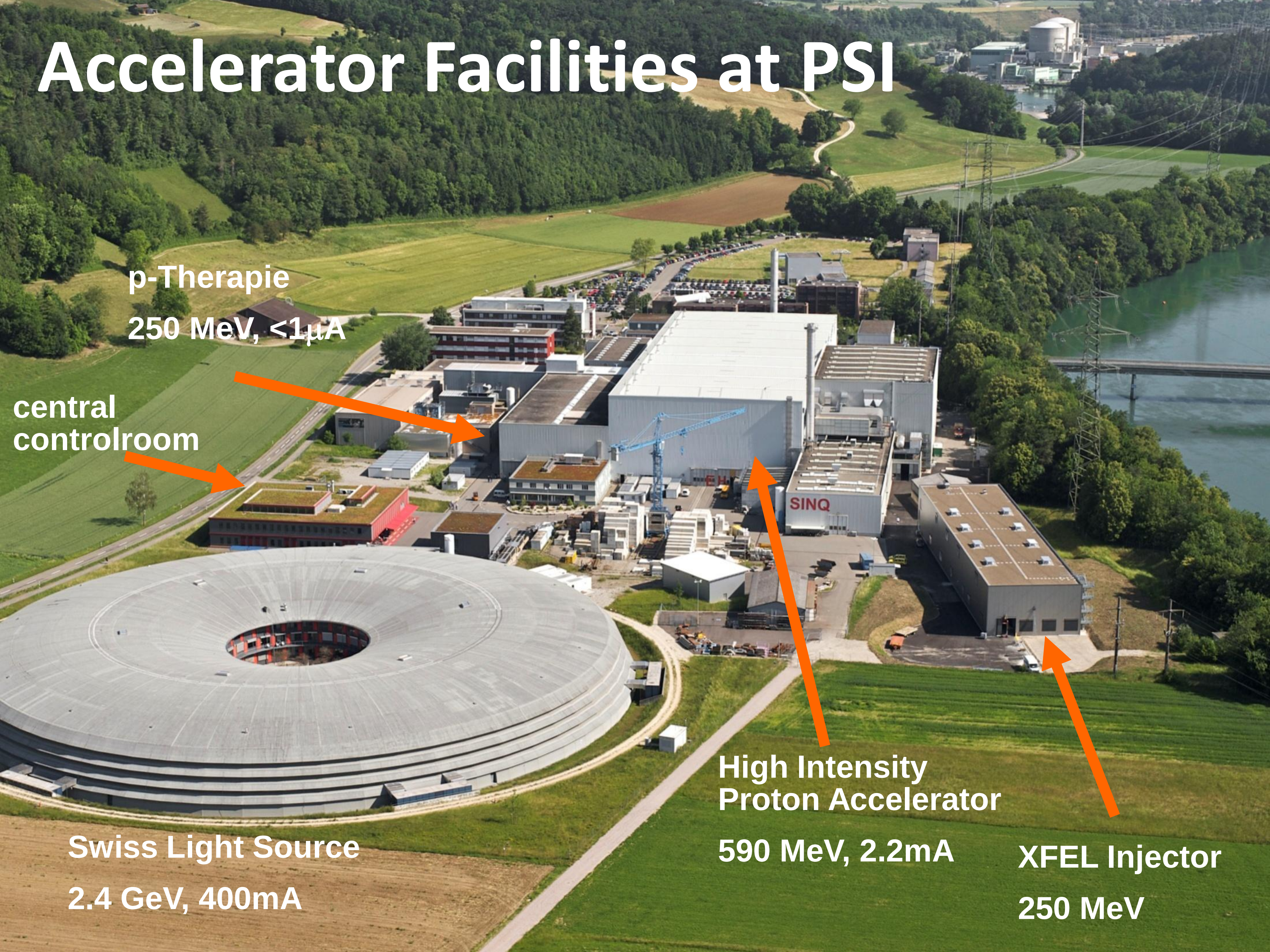
Mike Seidel

and S. Adam, A. Adelmann, Ch. Baumgarten, J. Bi[*], R. Doelling, H.R. Fitze, A. Fuchs, M. Humbel, J. Grillenberger, D. Kiselev, A. Mezger, D. Reggiani, M. Schneider, J. Yang[*], H. Zhang, T.J. Zhang[*]

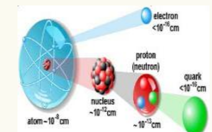
PSI, Villigen, Switzerland; [*]CIAE, Beijing, China

IPAC 2010, Kyoto, May 25

Accelerator Facilities at PSI



PSI user laboratory key numbers 2009



2009	SLS	SINQ	SμS	LTP	PSI total
Beamlines	15	13	6	5	39
Instrument Days	1778	2105	681	640	5204
Experiments	1053	488	188	5	1734
User Visits	3145	789	342	250	4526
Individual Users	1518	406	148	150	2168
New Proposals	724	323	178	-	1225
	photons	neutrons	muon spectroscopy	particle physics	

[S.Janssen]

Outline

- ► Facility Overview

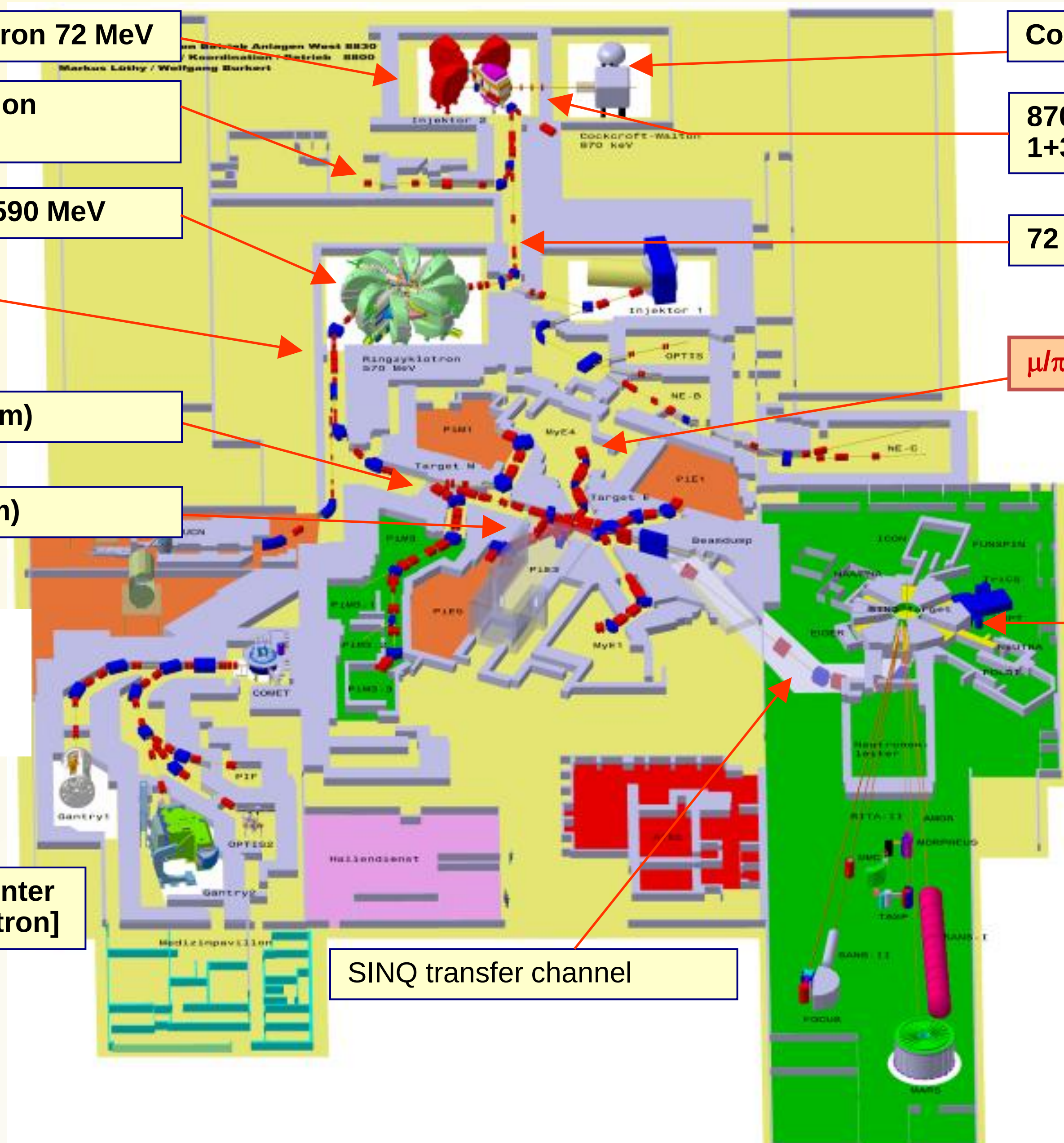
  [accelerator chain, performance]
- ► Sector Cyclotrons

  [cyclotron principle, basic beam dynamics, compact vs high intensity cyclotron]
- ► Subsystems with Relevance for High Intensity Operation

  [RF resonators, interlock systems, targets]
- ► Operational Experience

  [beam loss and activation, availability]
- ► Summary and Outlook

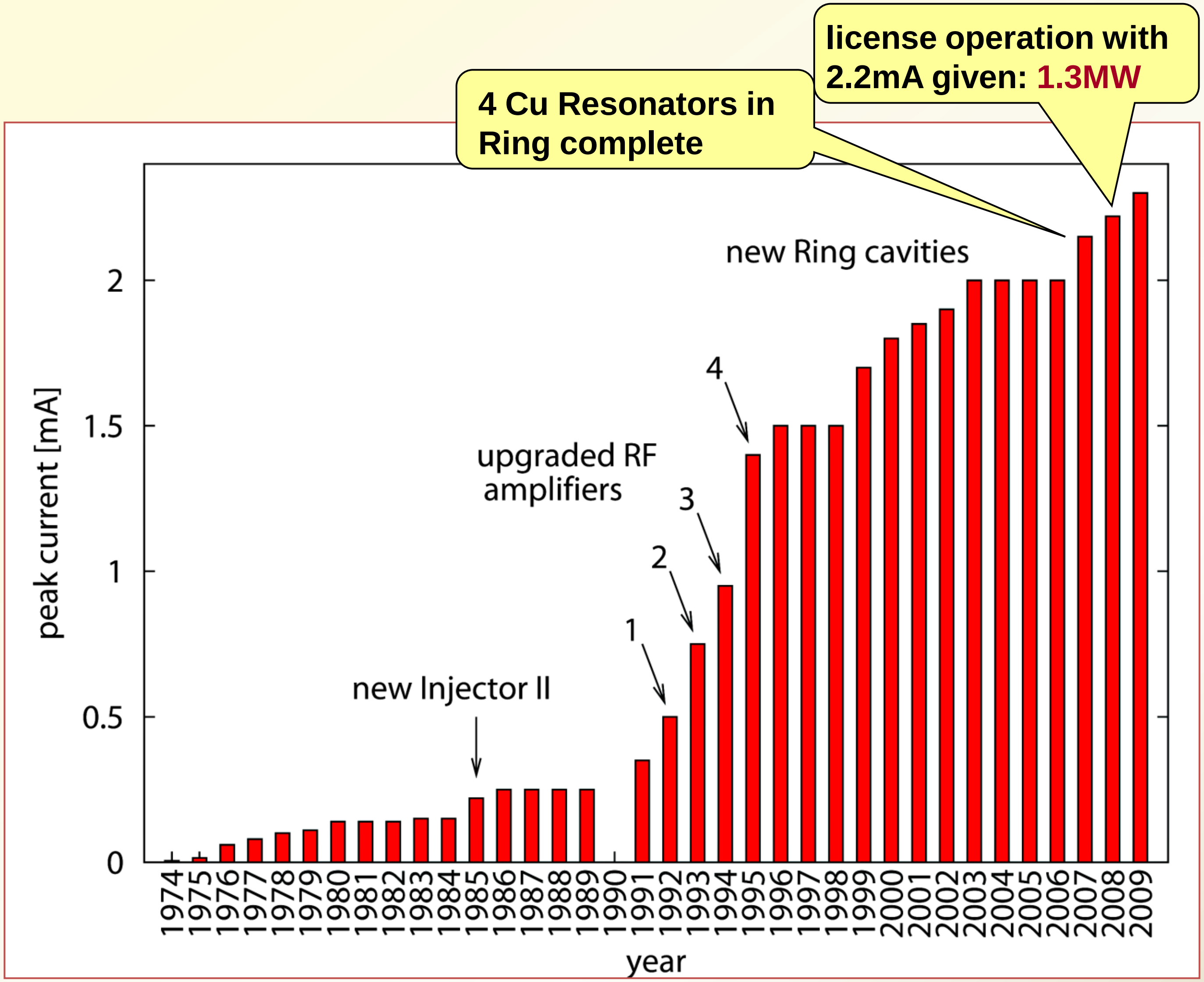
Overview PSI Facility



dimensions:

120 x 220m^2

history of max. current in the PSI accelerator

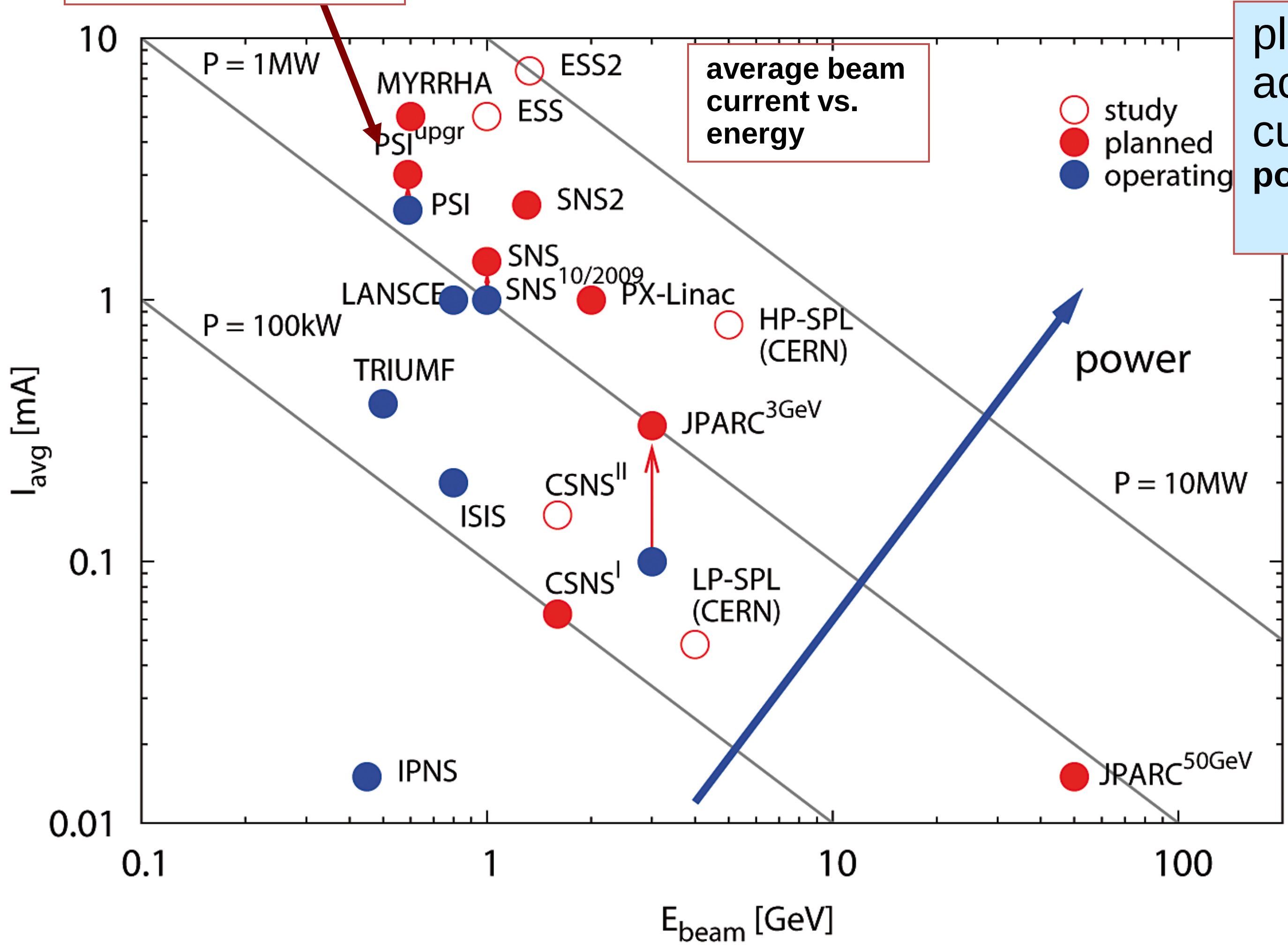


beam current is limited by beam losses and resulting activation;

upgrade measures kept absolute losses constant

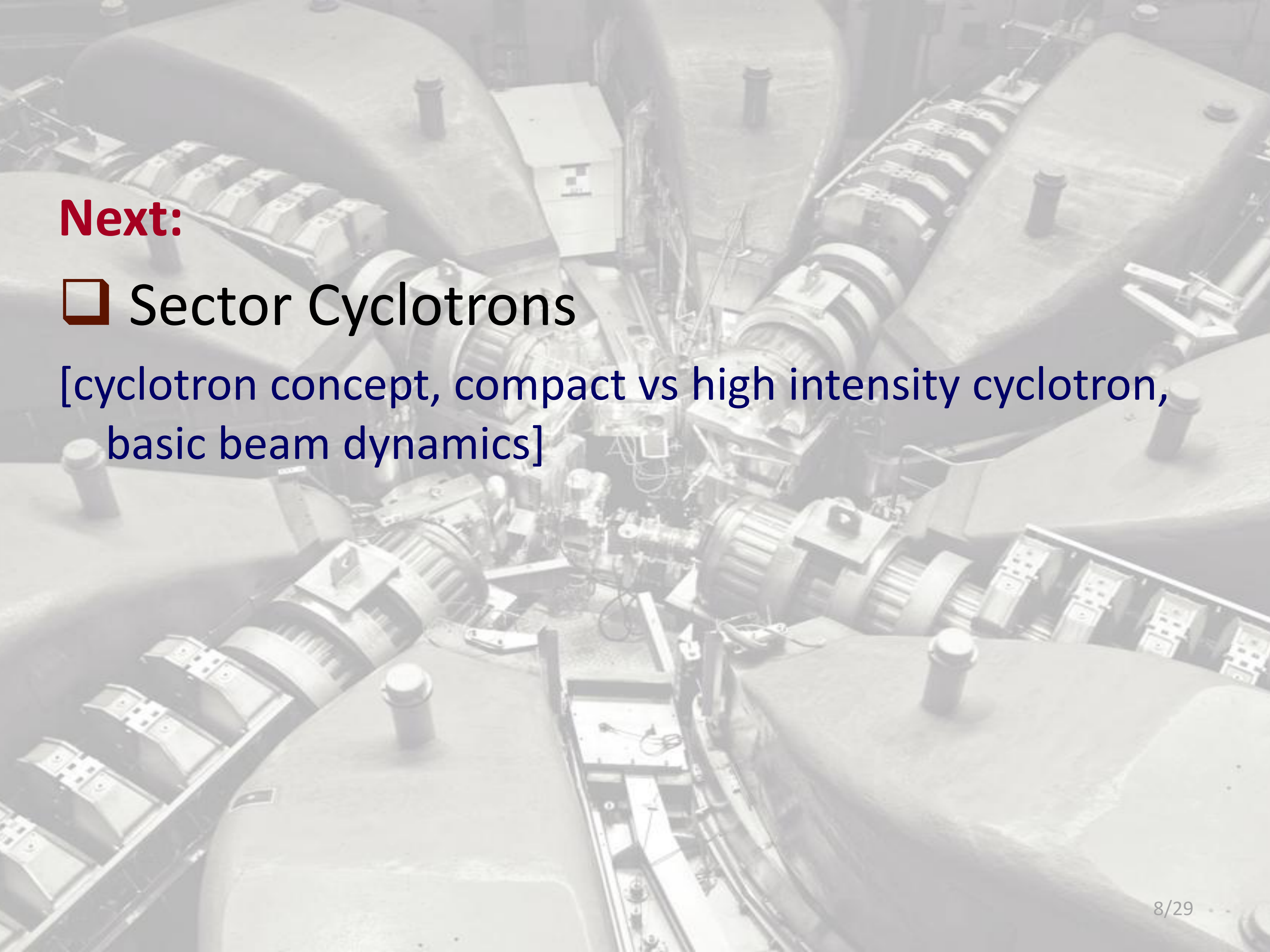
High Power Proton Accelerators

PSI Upgrade Plan



plot: selected accelerators current vs. energy
power ∝ current·energy

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

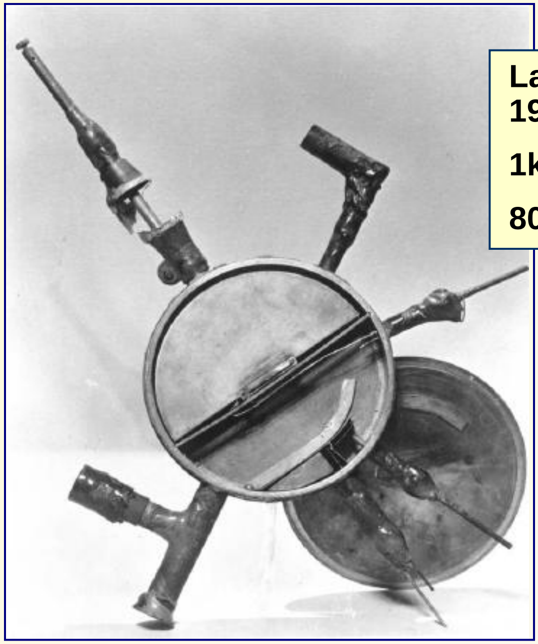


Next:

- ❑ Sector Cyclotrons

[cyclotron concept, compact vs high intensity cyclotron, basic beam dynamics]

classical cyclotron



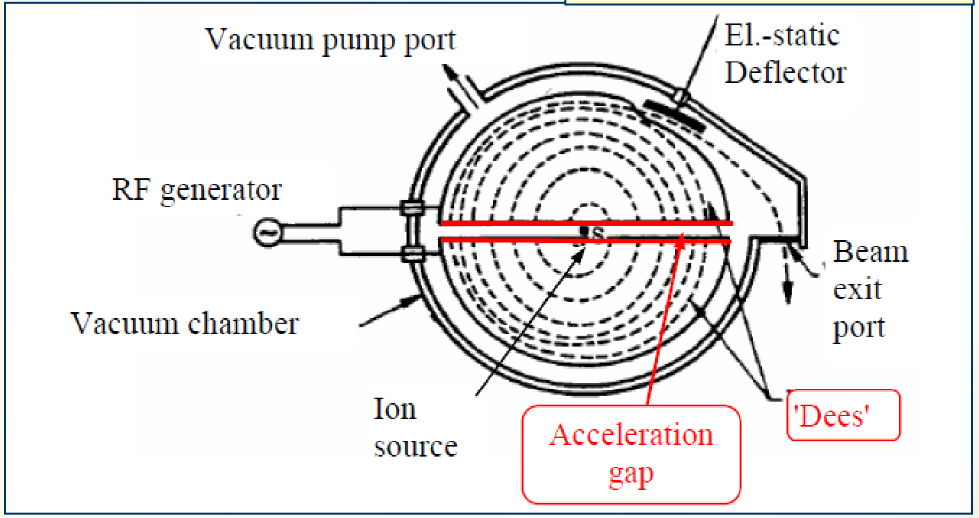
Lawrence / Livingston, 1931, Berkeley

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

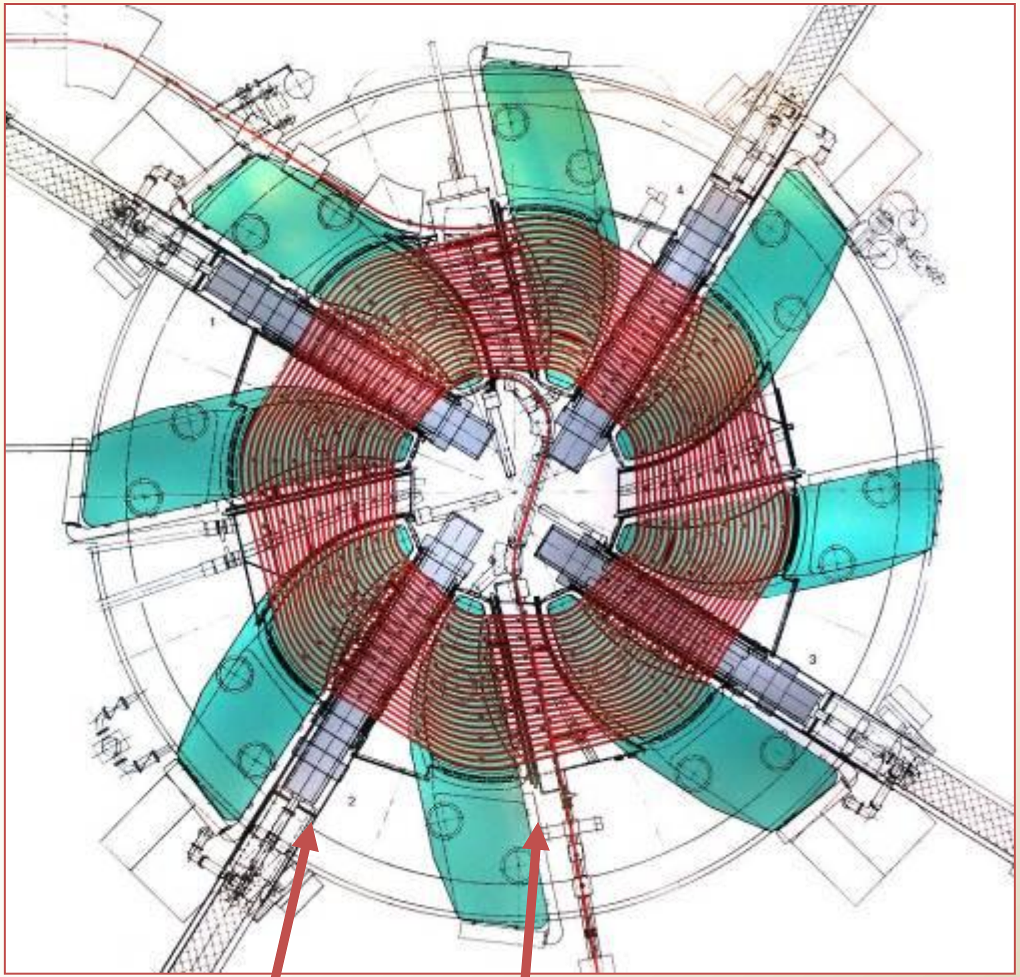
today: sector cyclotrons

• **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

• strength: **CW acceleration**; high **extraction efficiency** possible: 99.98% = 1 - $\mathbf{2\cdot10^{-4}}$
• limitation: **kin.Energy ≤ 1GeV**, because of relativistic effects



50MHz resonator

150MHz (3rd harm) resonator

high intensity beam in cyclotrons

critical: extraction loss

► beam tails, blowup by long. space charge (overlapping turns)

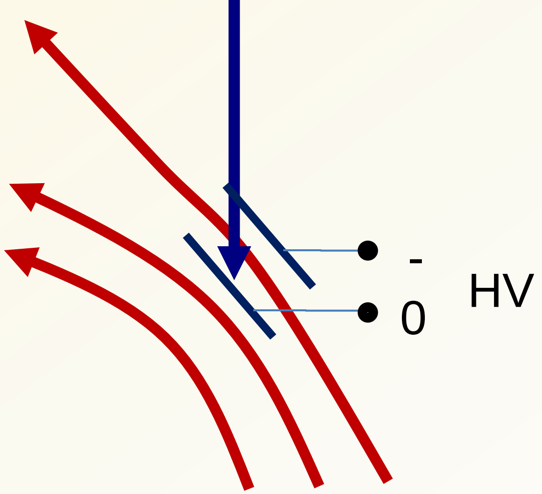
[sector charge density] × [time in cyc.] → $\propto$ (# turns)^2

► loss at extraction element [1/turn separation] → $\propto$ (# turns)^1

large orbit radius *R* advantageous

energy gain per turn $\propto$ 1/# turns

Extraction electrode Placed between turns



$$\frac{dR}{dn_t} = \frac{R}{\gamma(\gamma^2 - 1)} \frac{U_t}{m_0 c^2}$$

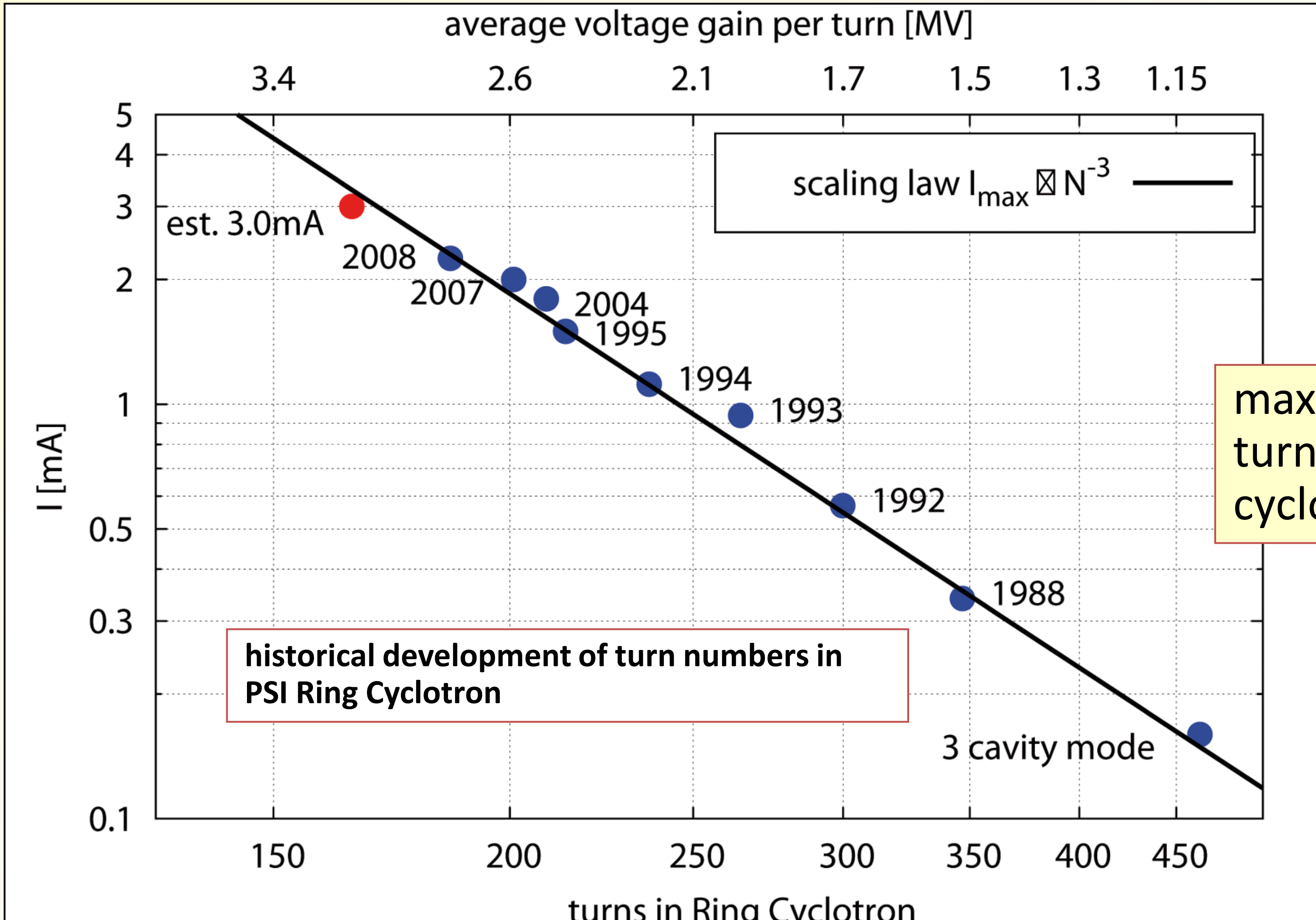
increasingly difficult with higher energy (limit ~ 1GeV)

In summary:

- scaling of losses ~ (# turns)^3 → high gap voltage!
- large radius
- E_k < 1GeV

3’rd power scaling law and turn number history in Ring cyclotron

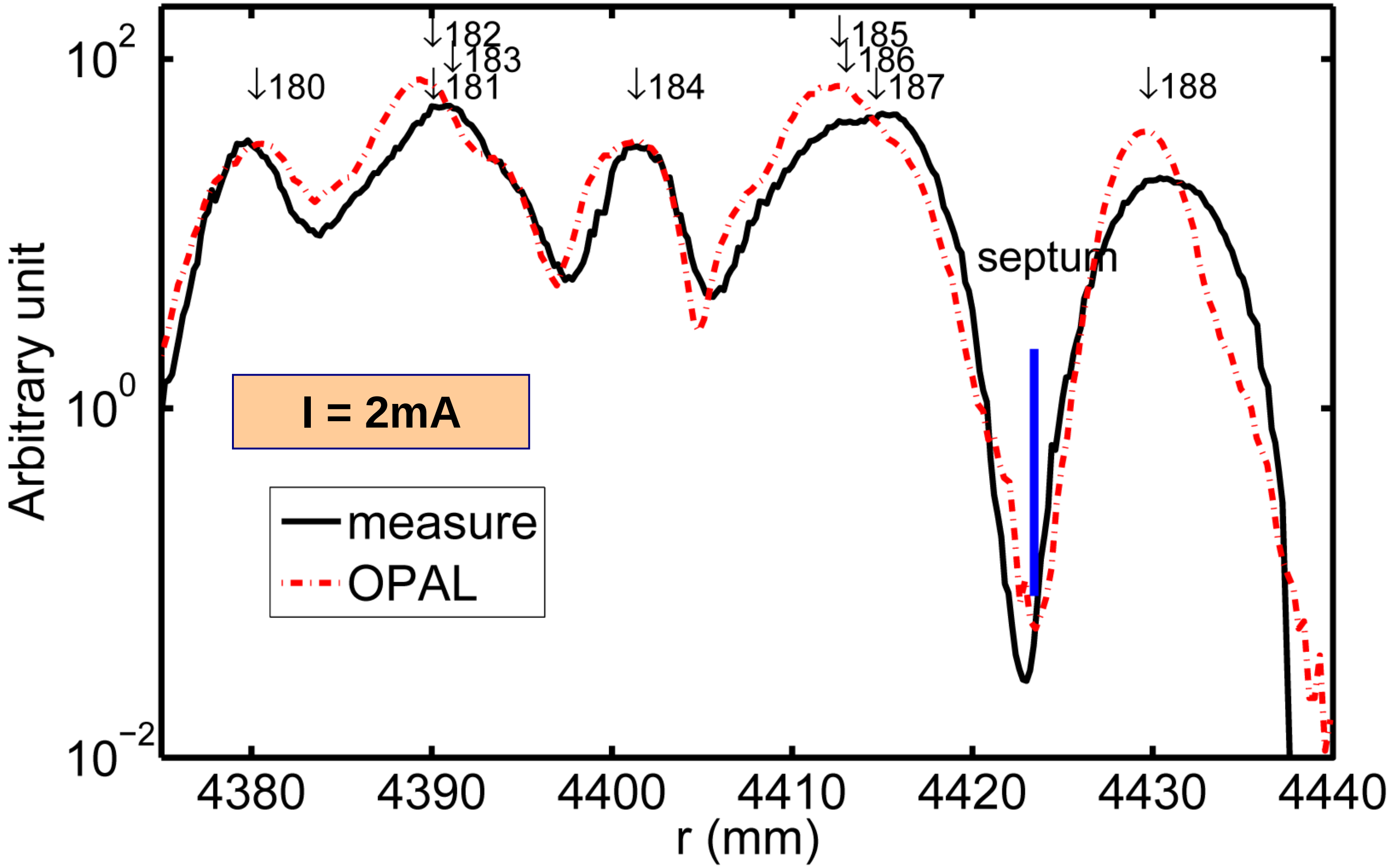
► upgrade through fast acceleration (higher voltage→ RF systems, resonators)



maximum current vs. turn number in Ring cyclotron

Ring cyclotron beam profile at extraction– simulation and measurement

beam profile scan of outer turns in Ring Cyclotron
comparison of simulation and data



[Y.J.Bi CIAE Beijing,
A. Adelmann]

high intensity vs. compact (medical) cyclotron

PSI Ring Cyclotron

optimized for high intensity
sector cyclotron (magnets/resonators)
E_k = 590MeV, I_{max} = 2.2mA (1.3MW)
B_{max} = 1.1T, R_{extr} = 4.5m, N_{turn} =186
extraction efficiency 99.98%
loss: < 200W

Comet Cyclotron (cancer therapy)

optimized for cost/compactness
superconducting magnet (integrated design)
E_k = 250MeV, I_{max} = 1000nA (250 W)
B_{max} = 3.8T, R_{extr} = 0.8m, N_{turn}~620
extraction efficiency ~80 %
loss: < 50W

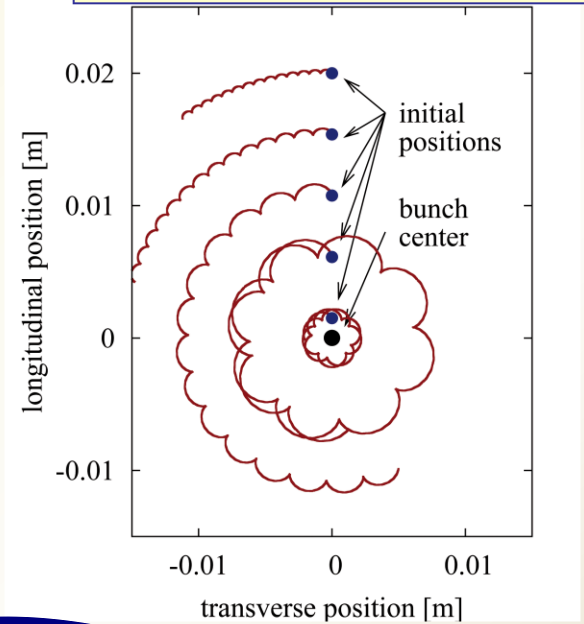
Comet during assembly

for high intensity beams in cyclotrons one needs:
- **fast acceleration, i.e. high gap voltage! (loss $\propto N_{turn}^3$)**
- **large extraction radius!**

space charge with short bunches – new regime, circular beam distribution

simplified model:

test charge in bunch field with vertically oriented bending field



in theory

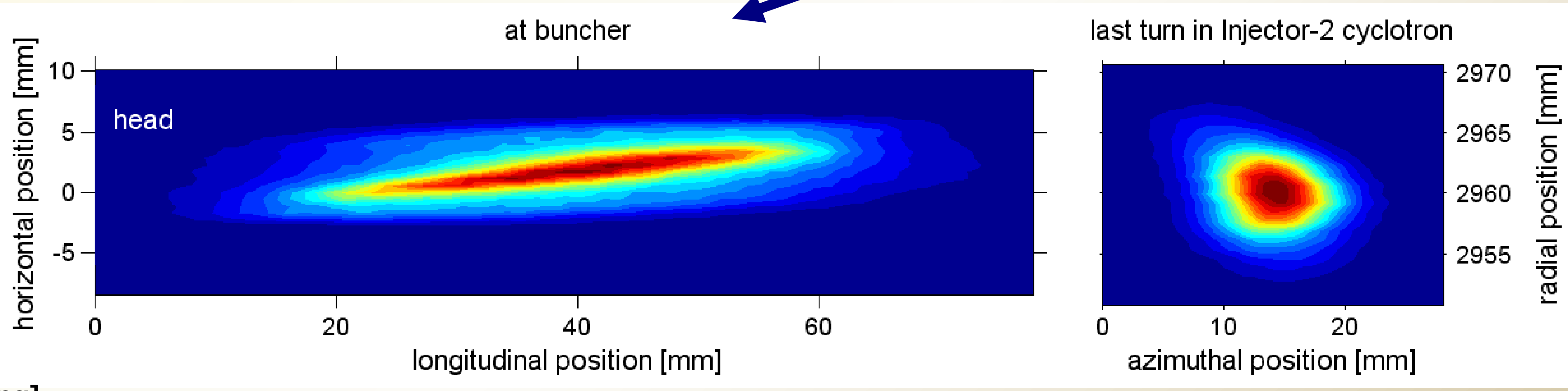
strong space charge within a bending field leads to rapid cycloidal motion around bunch center [Chasman & Baltz (1984)]

→ bound motion; circular equilibrium beam destribution

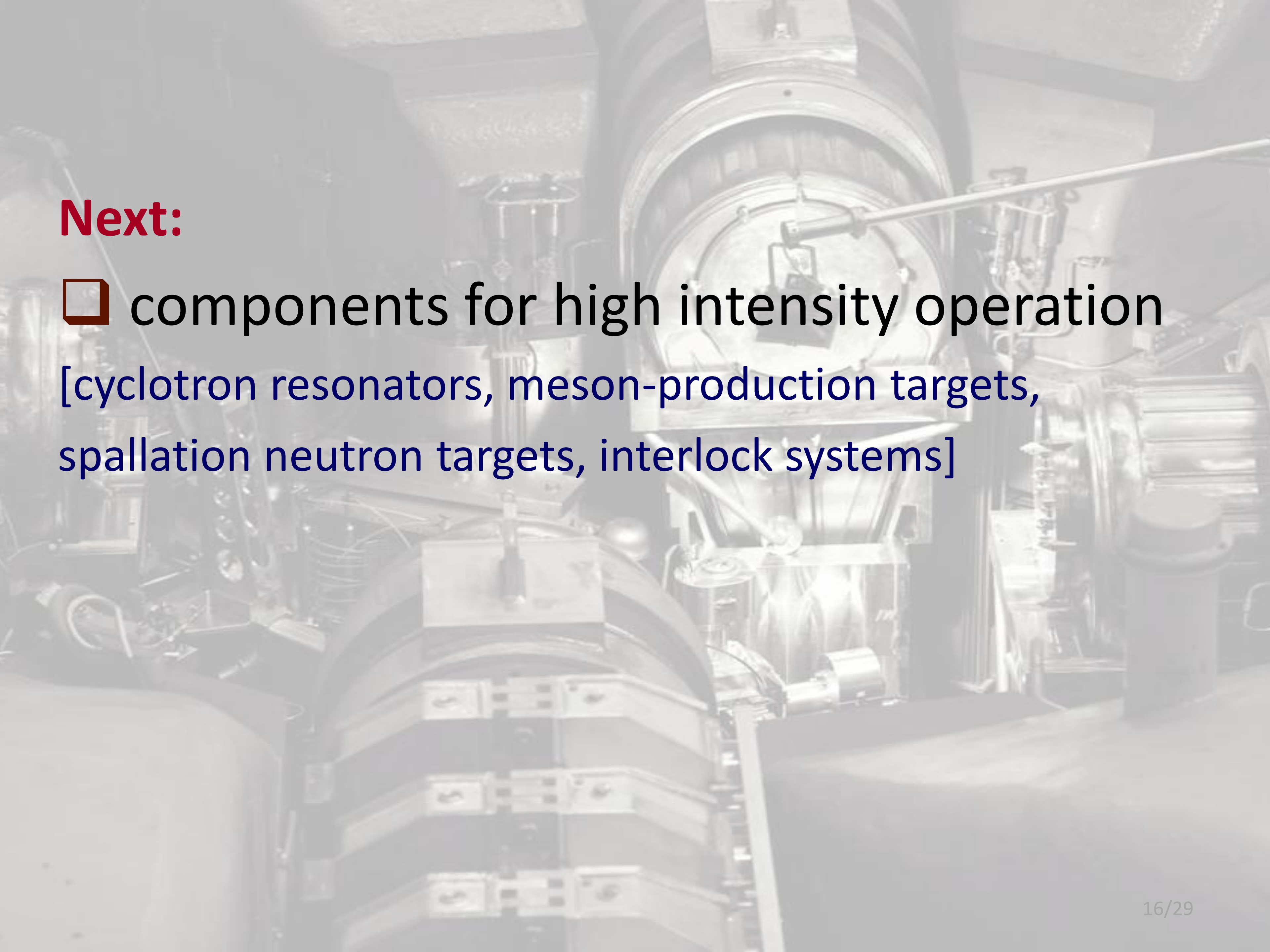
in practice

PSI's Injector II cyclotron → circular bunch shape observed; same regime desirable in Ring (10'th harmonic buncher)

blowup in ~20m drift



[court. R.Doelling]



Next:

- ❑ components for high intensity operation

[cyclotron resonators, meson-production targets, spallation neutron targets, interlock systems]

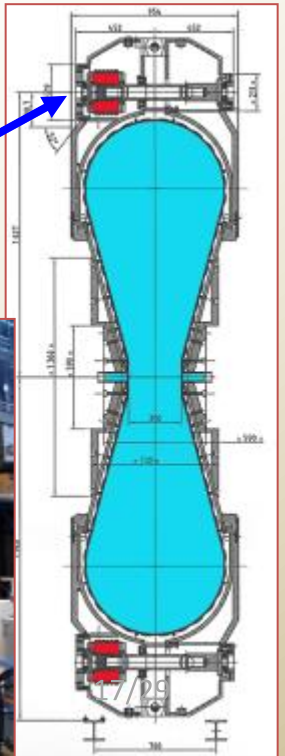
major component: RF resonators for Ring cyclotron

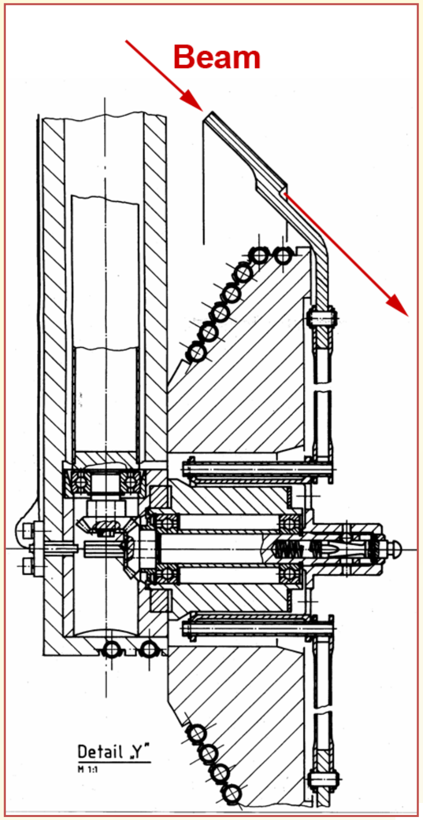
- **the shown Cu Resonators have replaced the original Al resonators** [less wall losses, higher gap voltage possible, better cooling distribution, better vacuum seals]
- **f = 50.6MHz**; **Q_0 = 4·10^4**; **U_{max}=1.2MV** (presently 0.85MV→188 turns in cyclotron, goal for 3mA: 165 turns)
- Wall Plug to Beam Efficiency (RF Systems): **32%**
  [AC/DC: 90%, DC/RF: 64%, RF/Beam: 55%]
- transfer of up to **400kW power to the beam** per cavity

→ **very good experience so far**

resonator inside

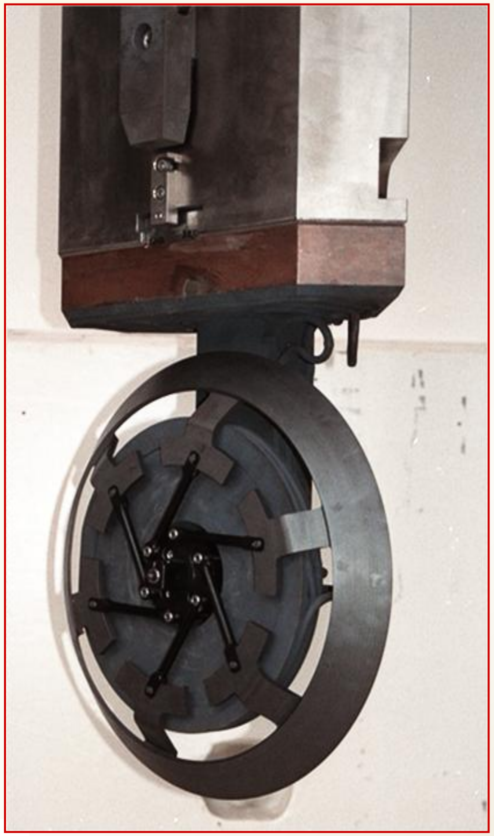
hydraulic tuning devices (5x)



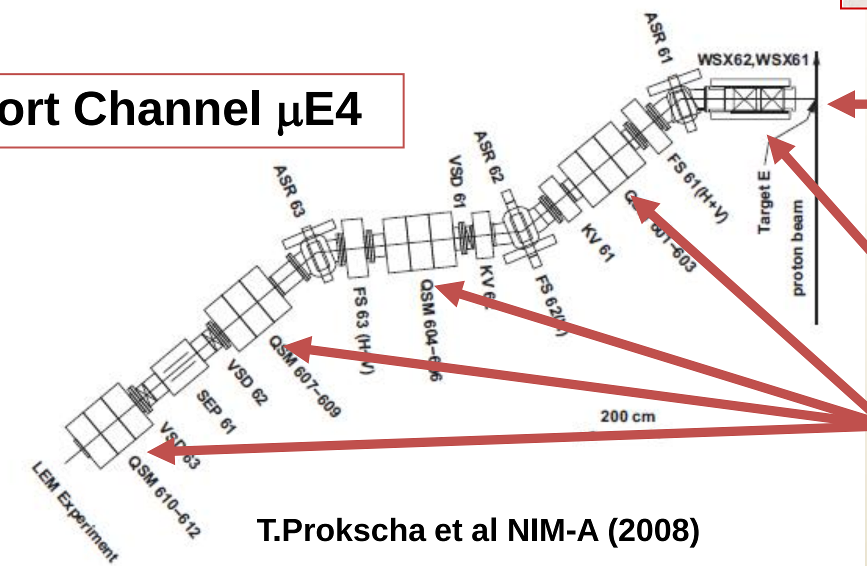


meson production target

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:

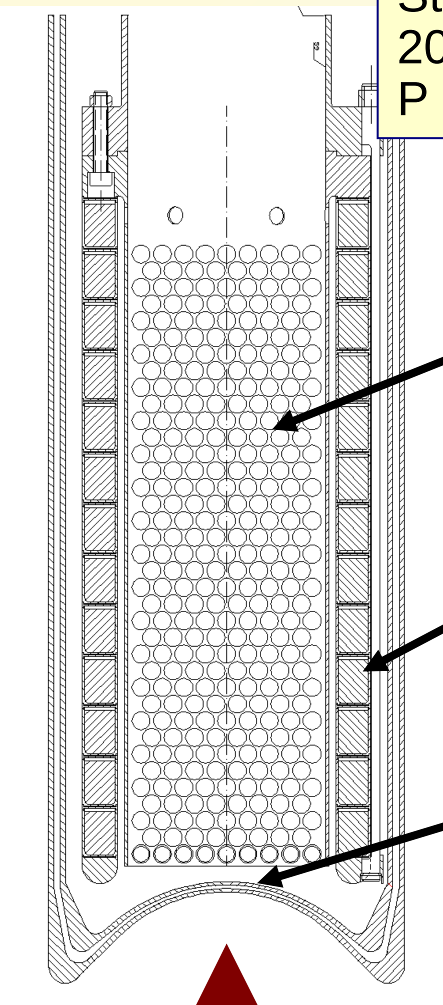
4.6E8 μ^+/sec

@ p=29.8 MeV/c

spallation target expertise at PSI

Standard solid target
2009 in operation;
P ~ 0.9 MW

Liquid metal test-target
(MEGAPIE) 2007 in
operation for 3 months



Zircaloy tubes, filled with lead, D_2O cooling

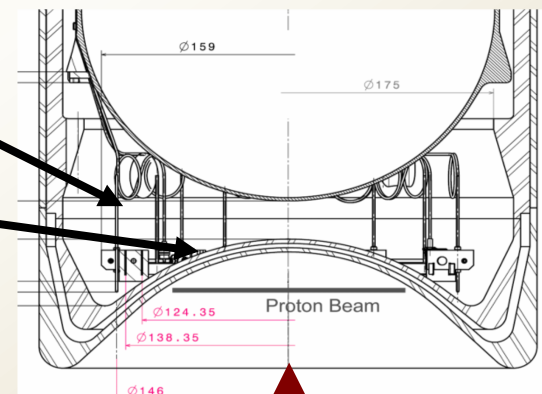
lead blankets
(reflector for th. neutrons)

beam window
(water cooled)

beam

Lead-Bismuth
eutectic, ~230 °C

leak detectors



beam

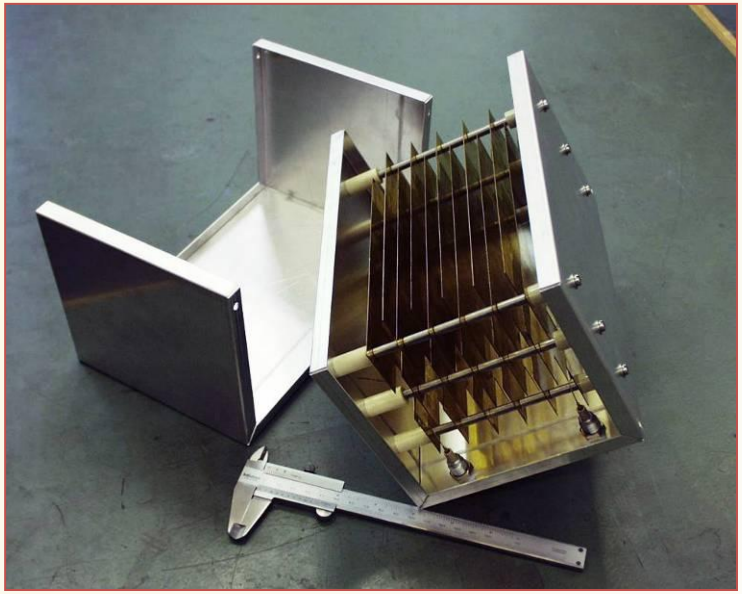
issues:
- ➔ beam material interaction
- ➔ neutronics
- ➔ static and dynamic stress
- ➔ fluid dynamics
- ➔ activation and disposal

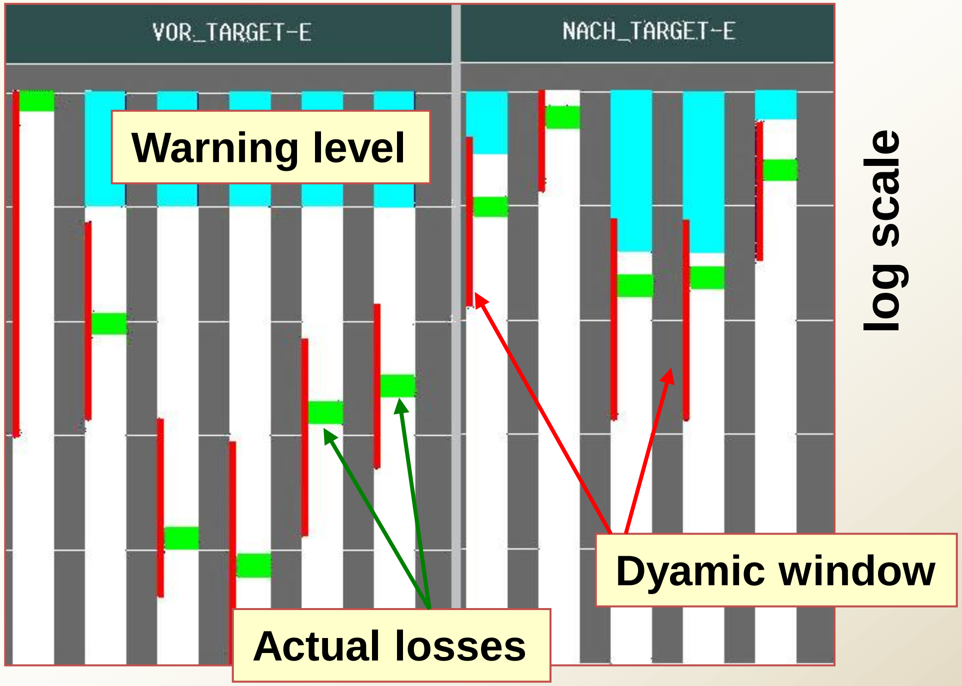
diagnostics/interlocks for machine protection

system based on ~150 interconnected fast (<100μs) **VME** and **CAMAC** m**odules** treating about 1500 signals (loss monitors, segmented collimators, transmission measurements, temperatures, set values of magnets, resonators)

example: 110 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)

Next:

- operational experience

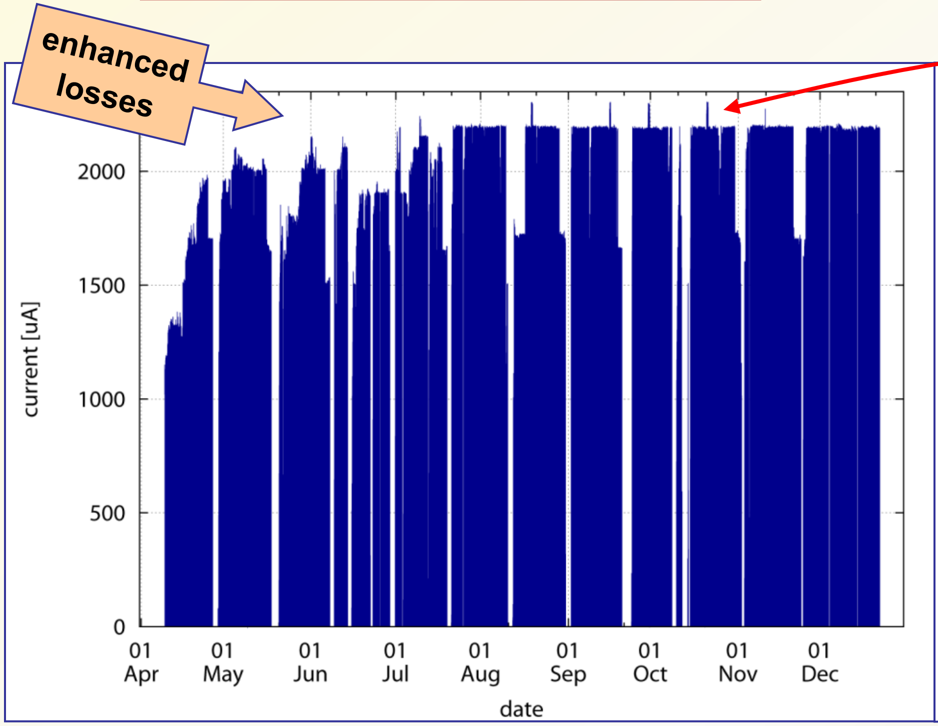
[new intensity record in 2009, beam loss experience, activation and service personnel dose]

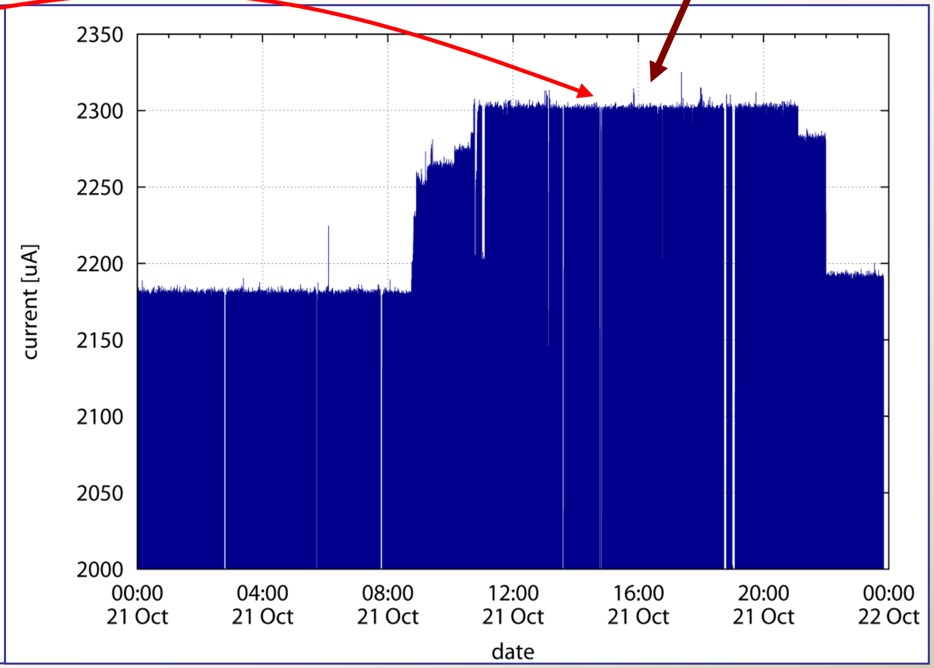
new beam intensity record in 2009

- since 2009 license for **standard operation 2.2mA** (before 2.0mA); **test operation at 2.4mA**
- new maximum current: 2.3 mA (1.36 MW)

beam operation in 2009 –
service 8 shifts every 3 weeks

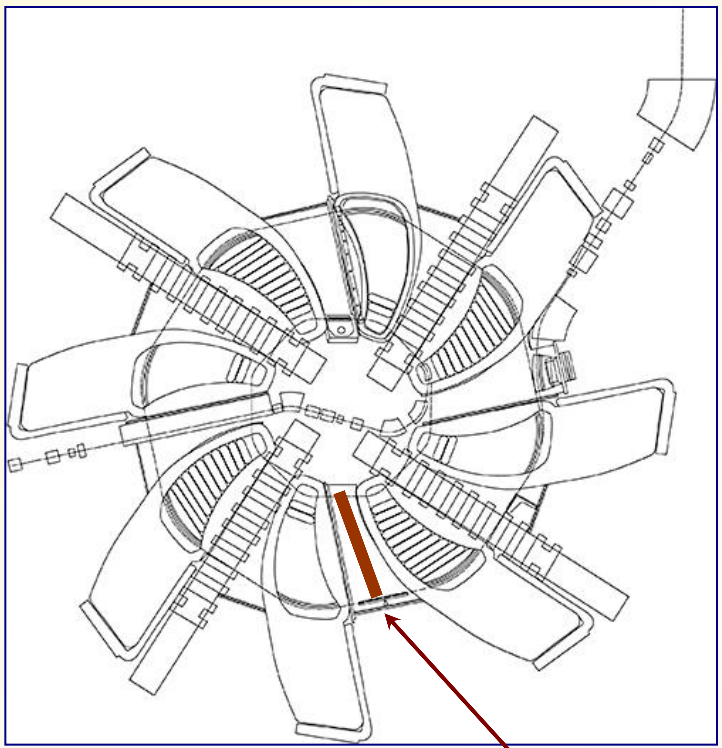
test run:
stable operation at 2.3mA





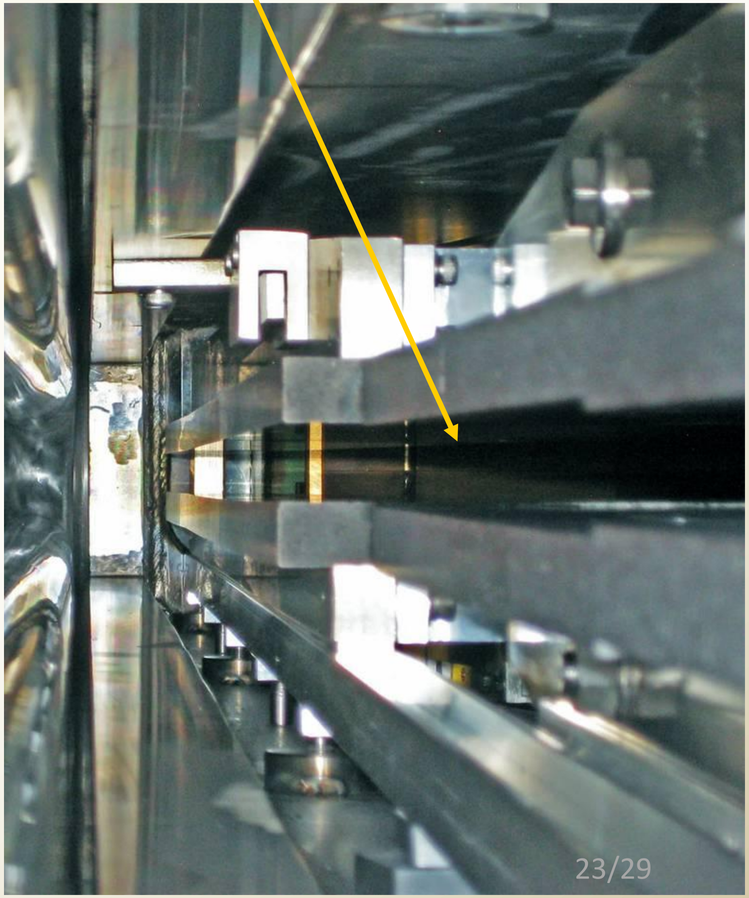
observation of higher losses in early 2009

• graphite collimator (chamber protection) probably deformed or misaligned by RF heating → **reduced vertical aperture**
• decision: **complete removal**; rely now on (much improved) interlock system



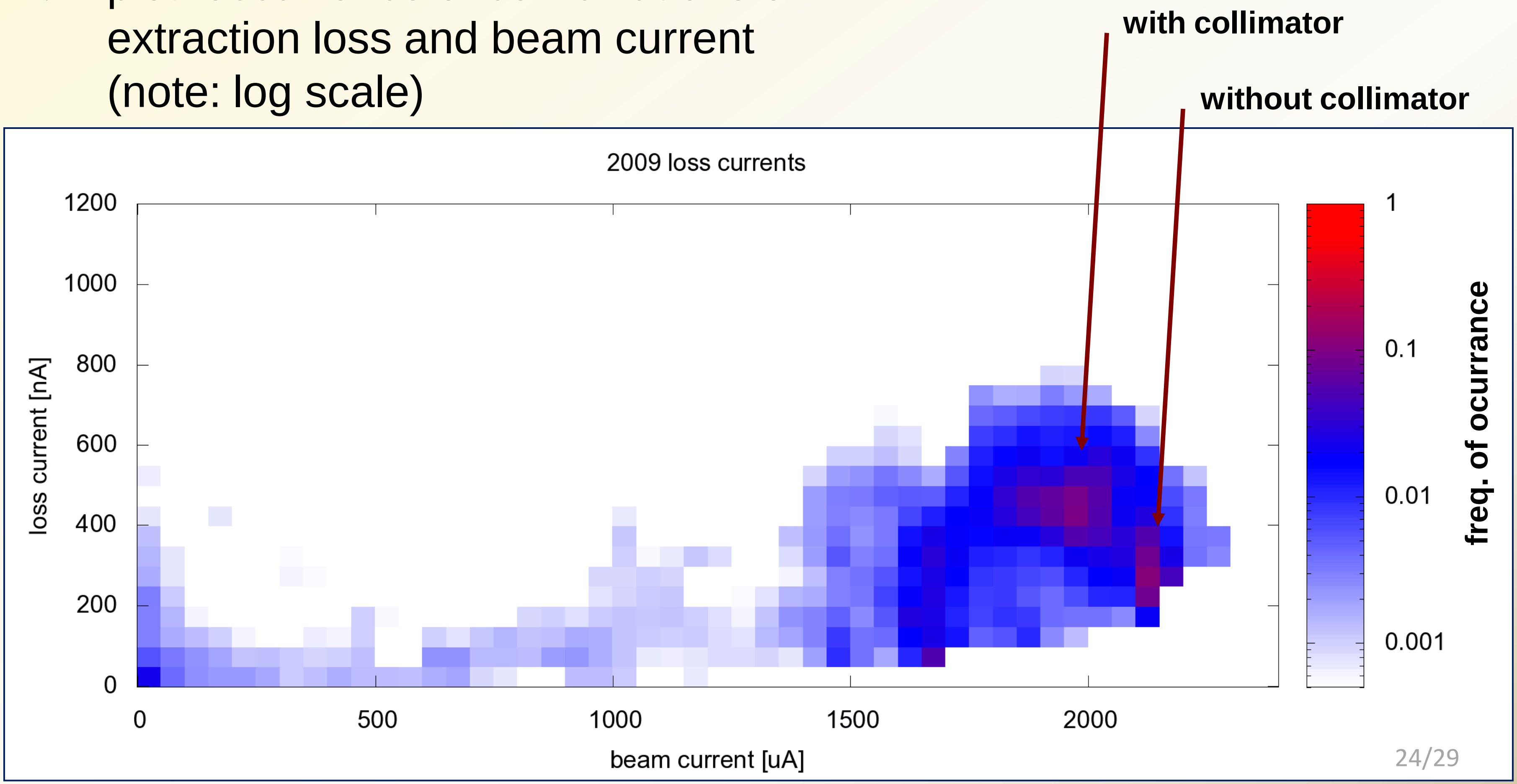
collimator covers complete radius

beam-gap



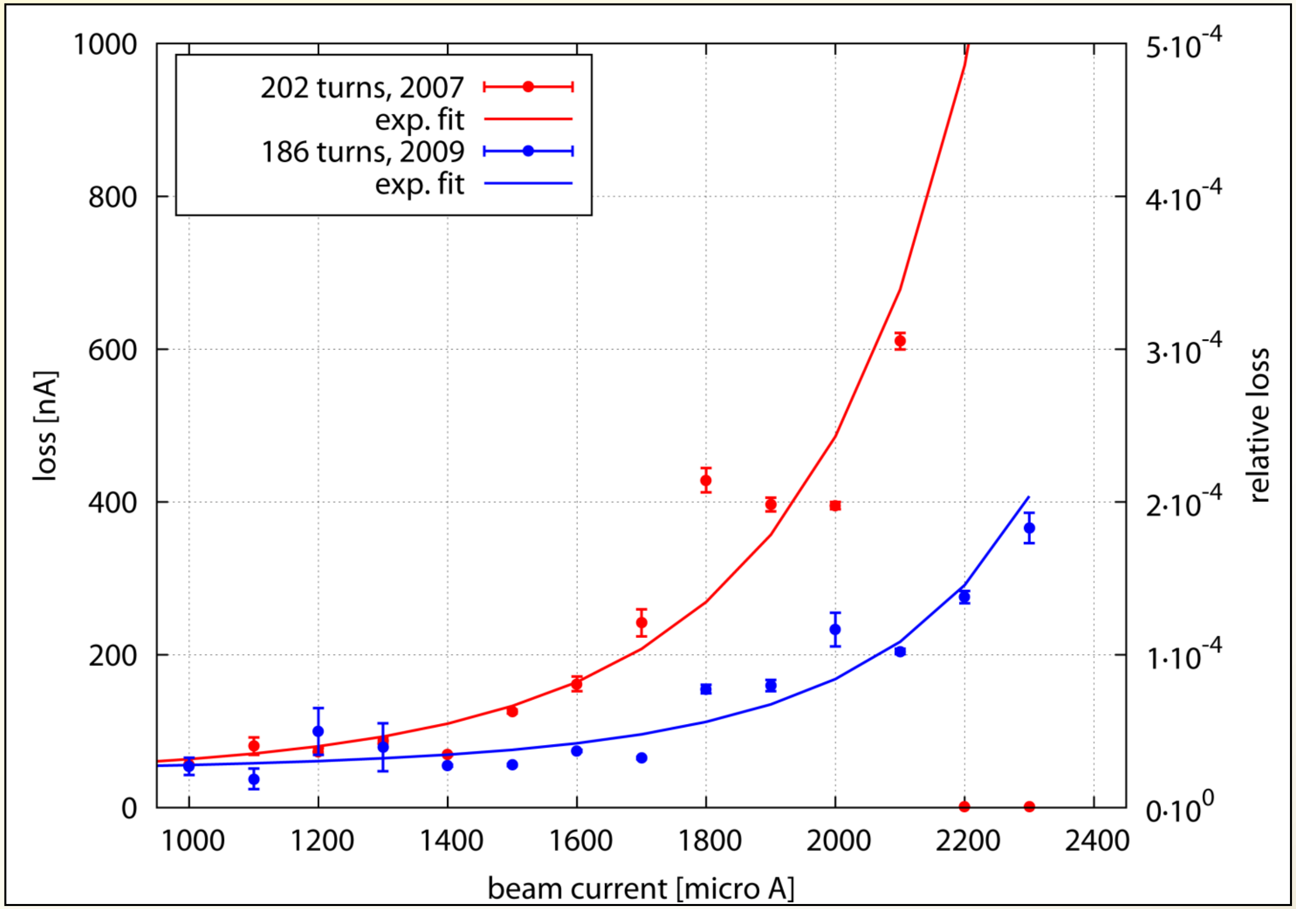
beam loss statistics with/without collimator

- after removal of collimator operation at 2.2mA without problems
- plot: occurrence of combinations of extraction loss and beam current (note: log scale)



loss scaling with current
[two setups / turn numbers]

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



gap voltage increase in 2008:

780kV → 850kV

turn number reduction:

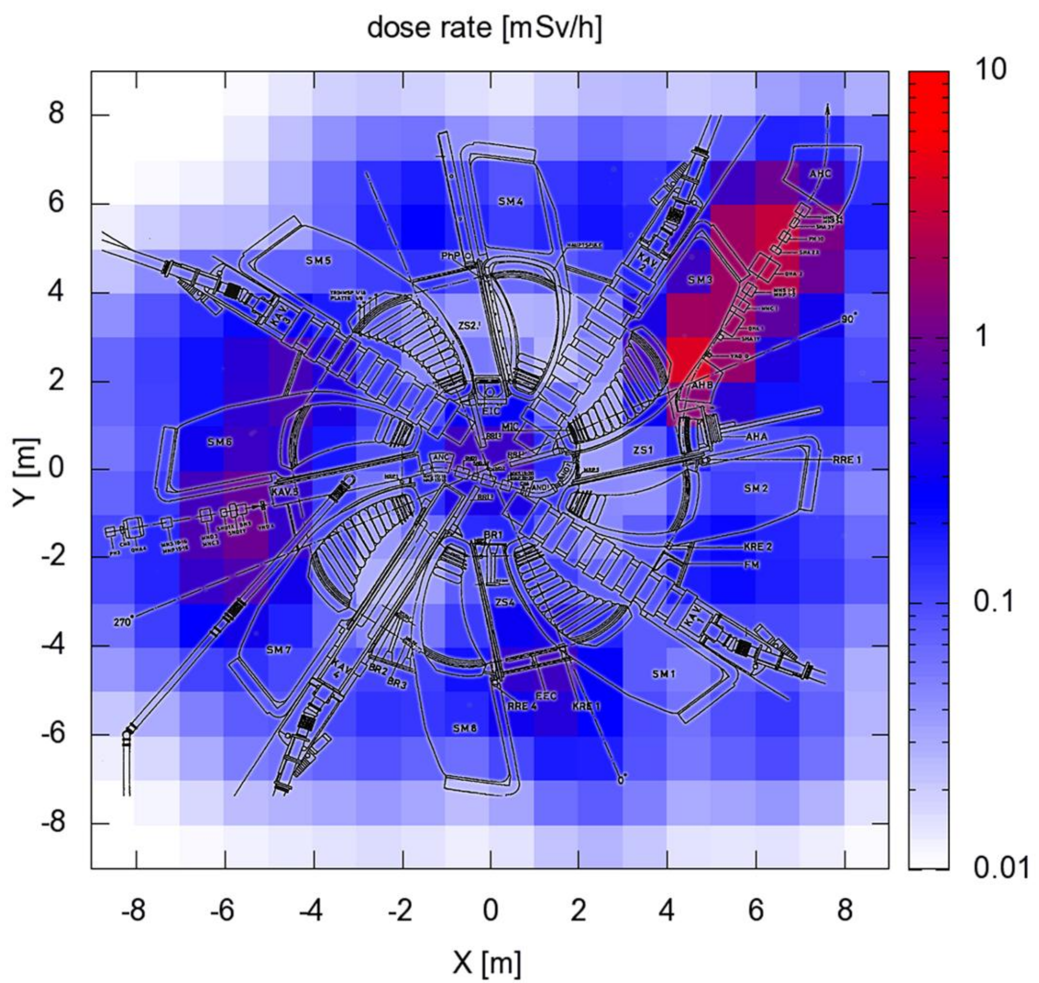
202 → 186

figure shows 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)

personnel dose for 3 month shutdown (2010):

47mSv, 186 persons
max per person: 2.9mSv

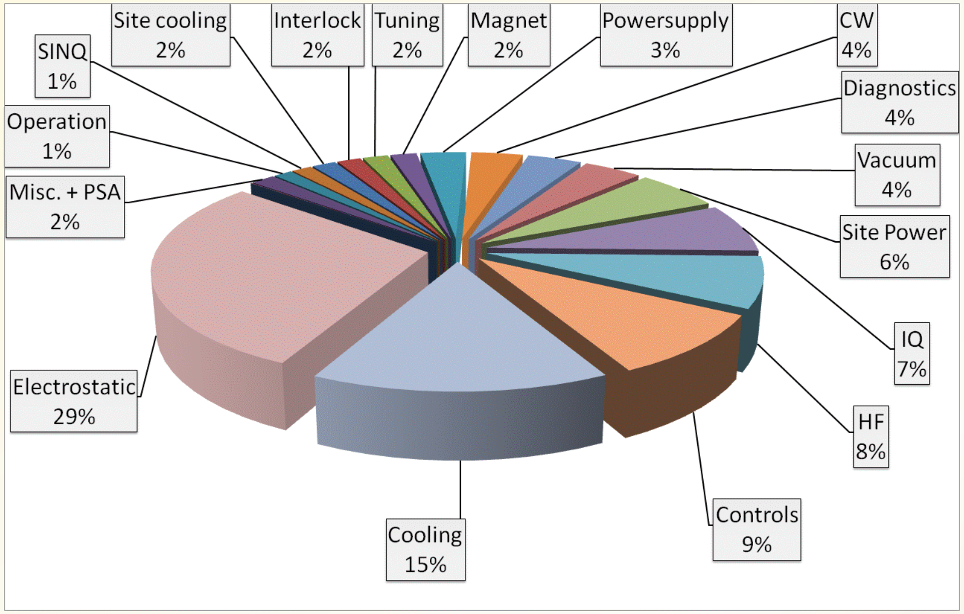
cool down times for service:

2200 → 1700 μA for 2h

0 μA for 2h

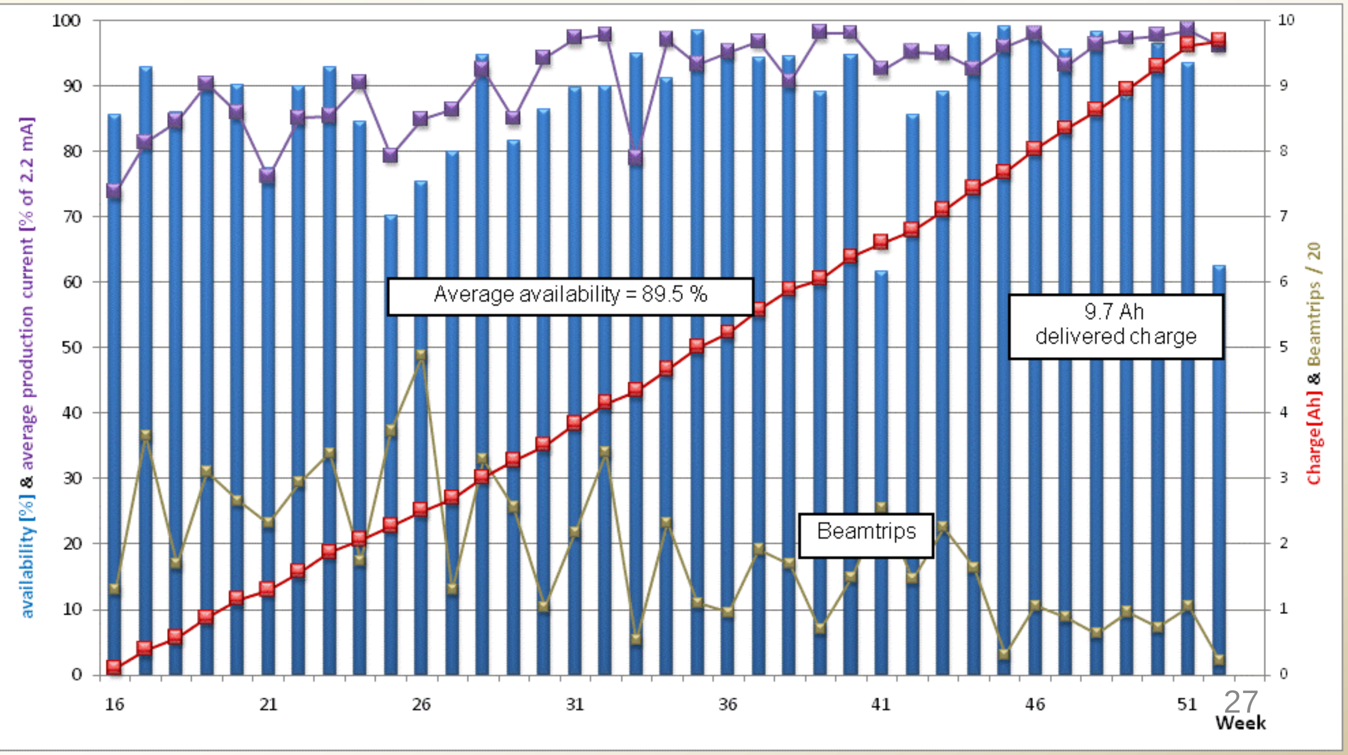
map interpolated from ~30 measured locations

PSI-HIPA operational data 2009



Downtime Causes
- electrostatic elements
- controls problems
- cooling/site power
- RF not prominent!

Performance 2009
Charge delivered: **9.7Ah**
Reliability: **89.5%**
Beam trips: **25..50 d^{-1}**



Reliability History:

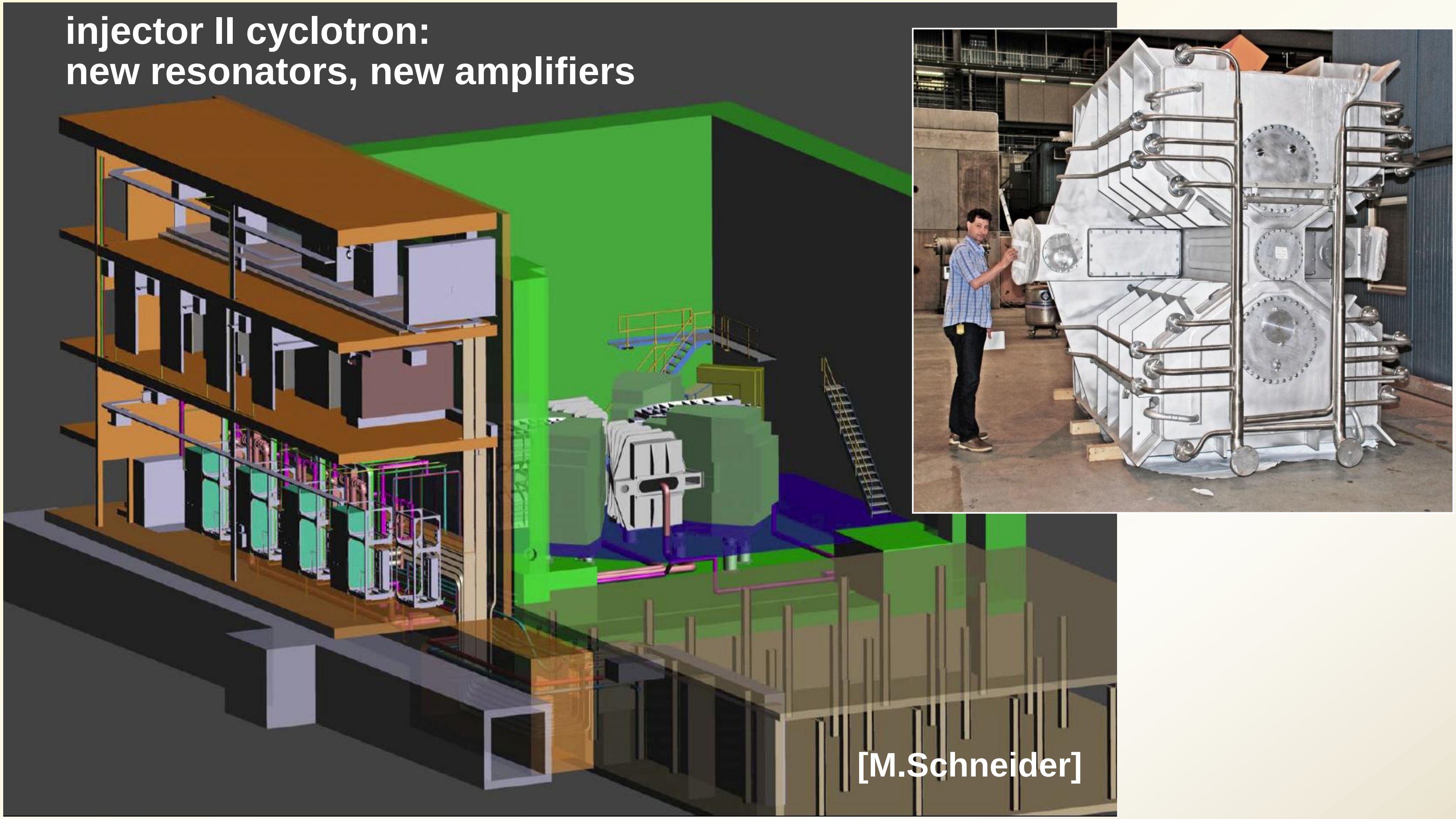
2009:	89.5%
2008:	90%
2007:	90%
2006:	86%
2005:	84%

Summary/Outlook

- ► the PSI accelerator delivers **1.3MW** beam power; loss: ~10^{-4}; average reliability is **90%**; **25-50 trips** per day; grid-to-beam power conversion efficiency is 32% considering RF systems only; ~ 15% including everything
- ► upgrade to 1.8MW is under work; new resonators Inj II; new 10'th harmonic buncher; completion planned for 2013
- ► cyclotron concept presents an effective option **to generate high power beams, for example for ADS** applications **[e.g. 1GeV/10MW]**

see also …

- MOPE065: **D.Reggiani** et al, *Transverse Phase-space Beam Tomography at PSI and SNS Proton Accelerators*
- THPEC088: **Y.Lee** et al, *Simulation based Optimization of a Collimator System for the Beam Current Upgrade at the PSI Proton Accelerator Facilities*
- MOPE063: **P.-A. Duperrex** et al, *New On-line Gain Drift Compensation for Resonant Current Monitor under Heavy Heat Load*
- MOPEC072: **Y. Lee** et al, *Simulation based Analysis of the Correlation between the Thermo-mechanical and the High Frequency Electromagnetic Characteristics of a Current Monitor at the PSI Proton Accelerator Facilities*



Thank you for your attention !