High Intensity Operation and Control of Beam Losses in a Cyclotron based Accelerator

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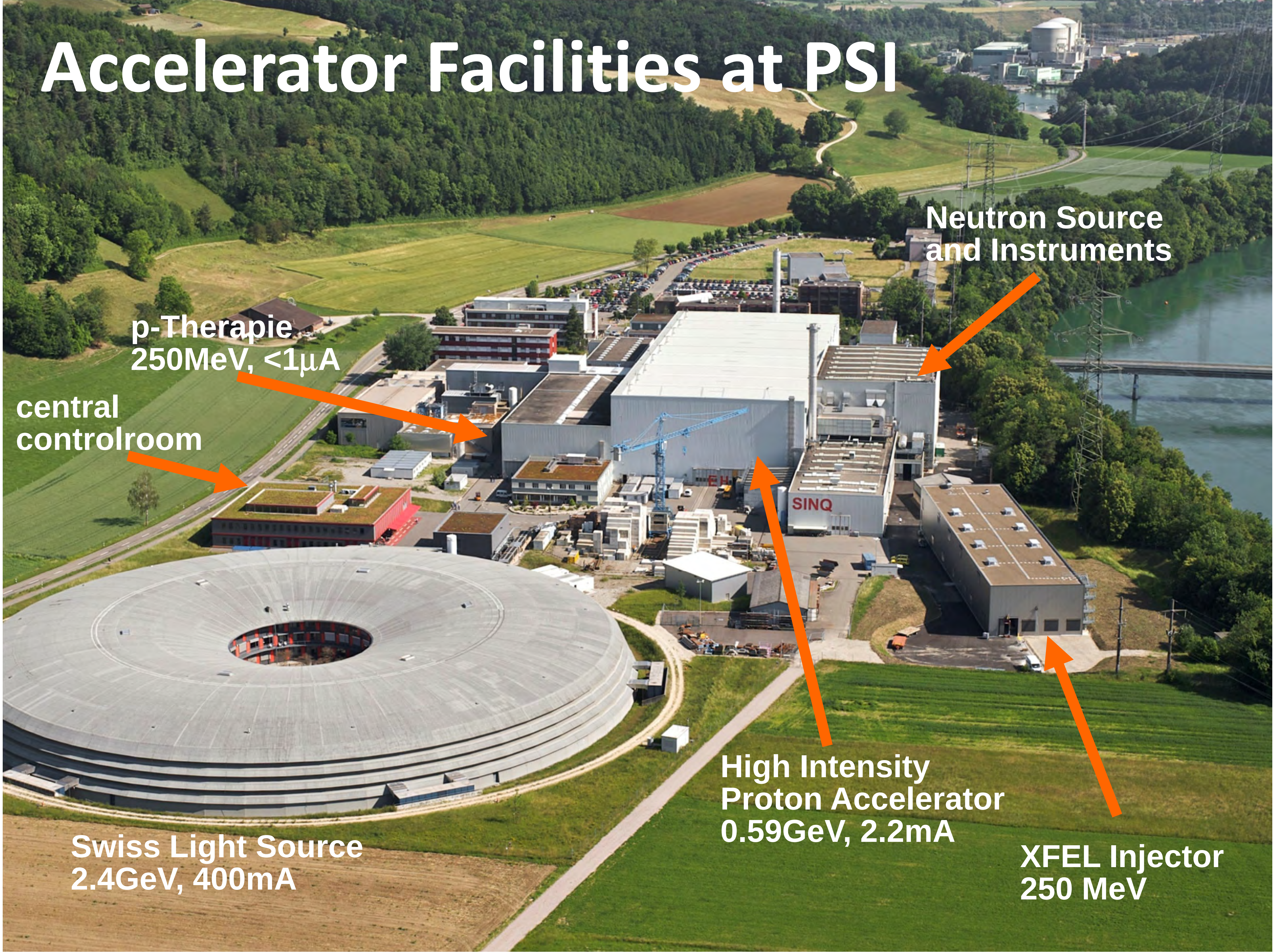
for the PSI Accelerator Team


Accelerator Facilities at PSI
Neutron Source and Instruments
p-Therapie 250MeV, <1μA
central controlroom
SINQ
High Intensity Proton Accelerator 0.59GeV, 2.2mA
XFEL Injector 250 MeV
Swiss Light Source 2.4GeV, 400mA

Outline

- overview on accelerator and it’s performance

  [facility, achieved intensity]

- cyclotrons for high intensity beams

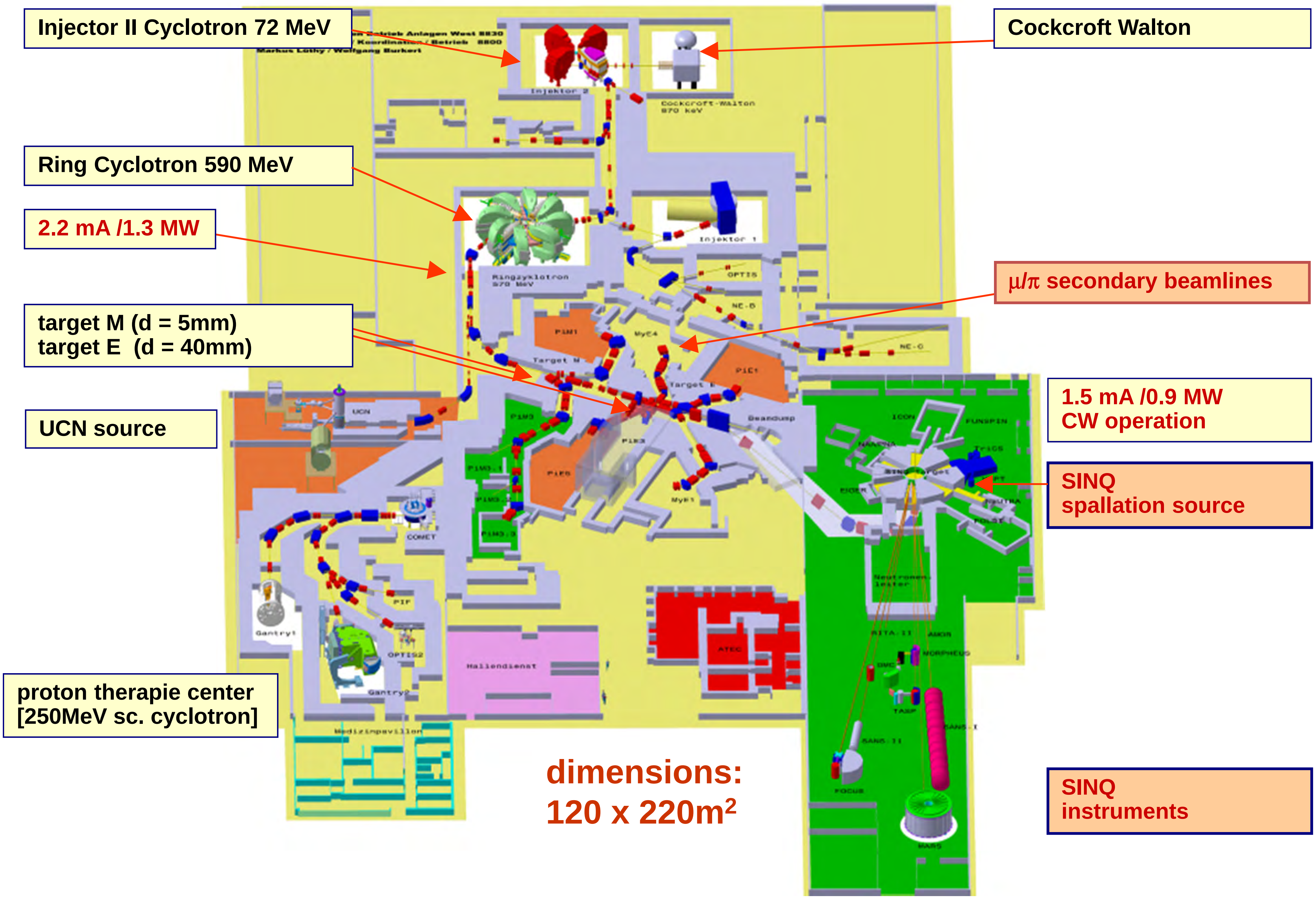
  [separation scaling with turn number, off-center injection, space charge scaling]

- losses and resulting activation

  [measured loss statistics, activated components, service personnel dose]

- summary

Overview PSI Facility



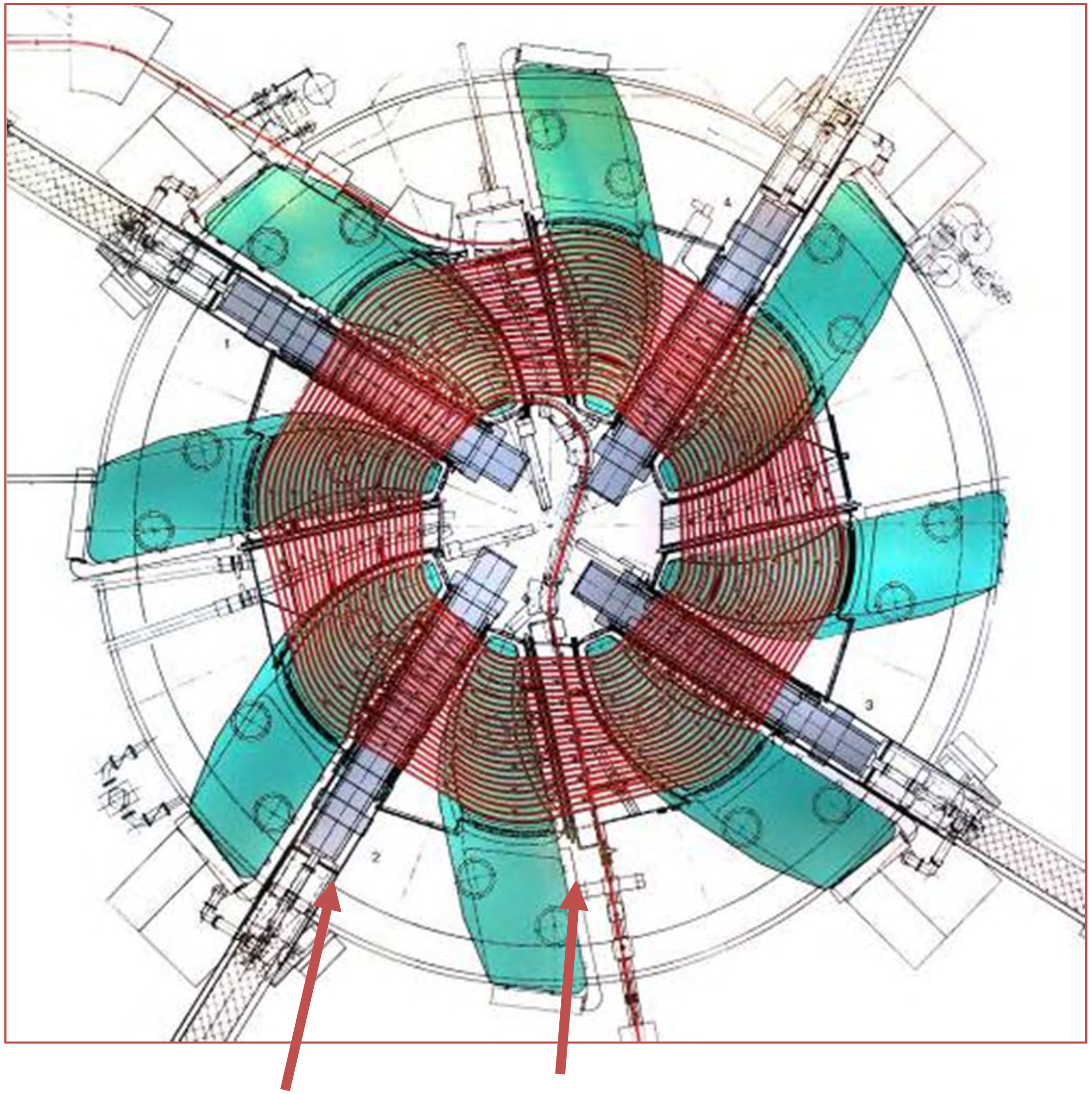
PSI Ring - a sector cyclotron

- **edge+sector focusing**, i.e. spiral magnet boundaries (angle ξ), azimuthally varying B-field (flutter F)

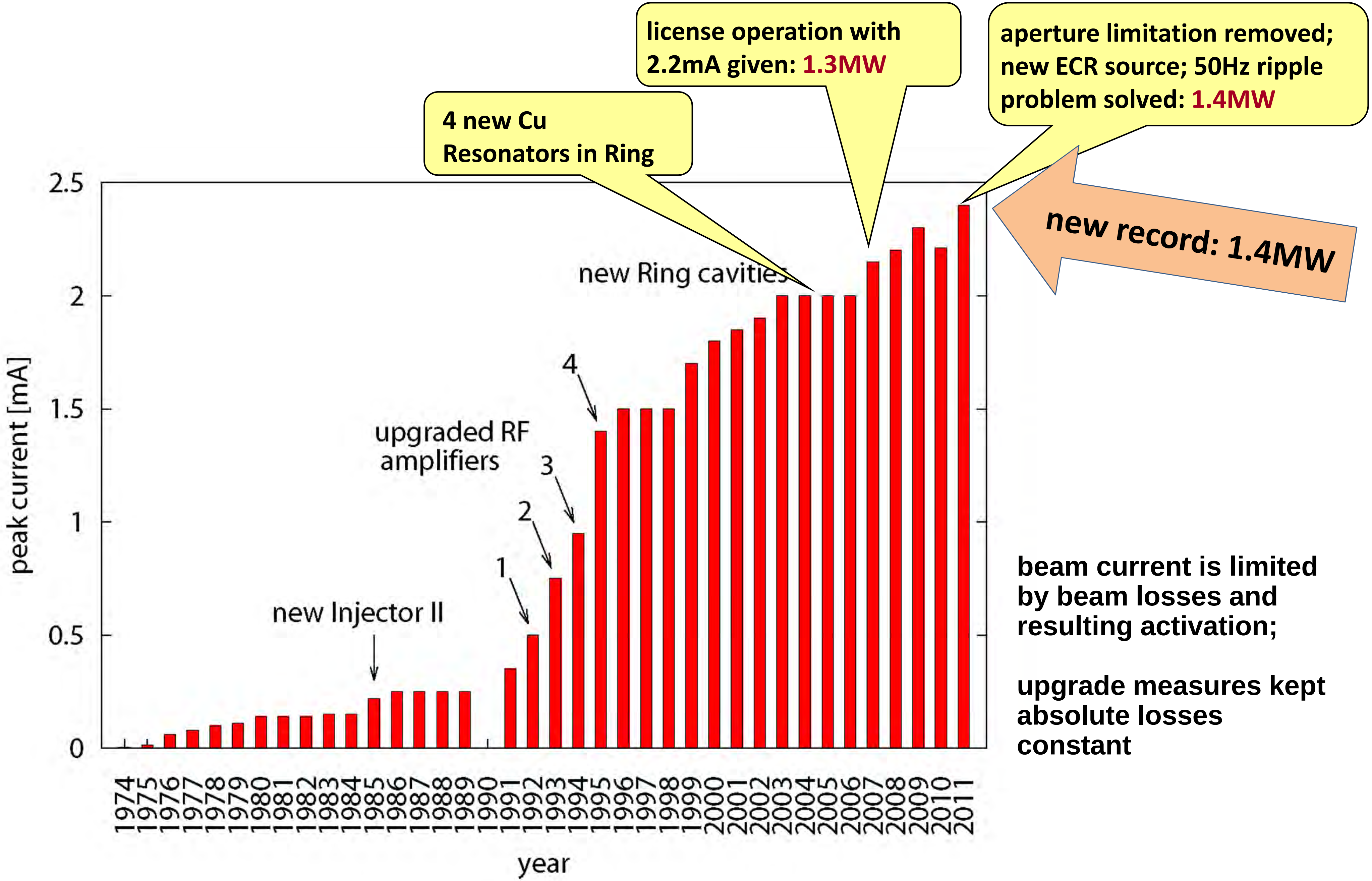
$Q_y^2 \approx - R/B\ dB/dR + F\ (1+2\cdot\tan^2(\xi))$

- **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



history of max. current in the PSI accelerator



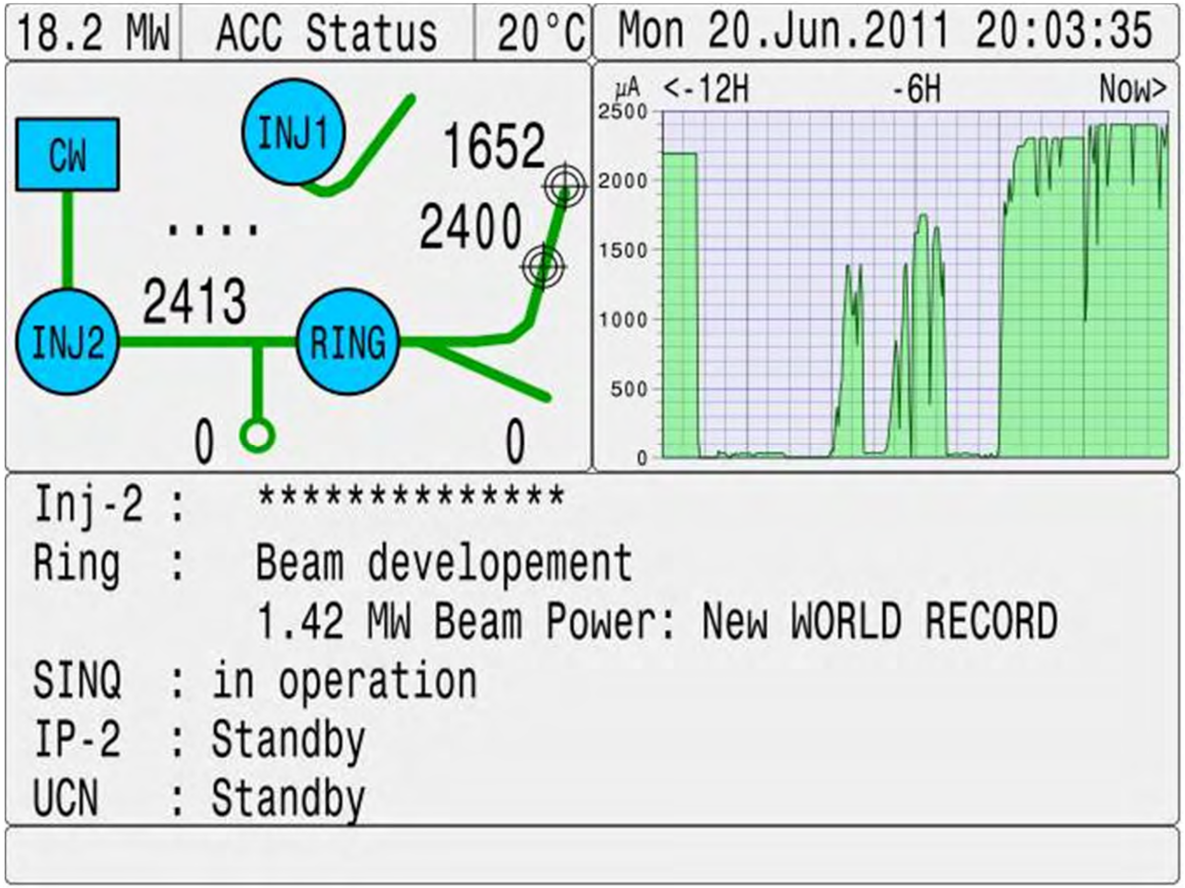
beam current is limited by beam losses and resulting activation;

upgrade measures kept absolute losses constant

new beam intensity record at PSI-HIPA

- **low beam losses are key issue**
- **recent improvements**:
  - new ECR source (emittance)
  - reduced 50Hz residual beam jitter
  - aperture restrictions in Ring removed

→ **higher current at same loss rate possible**



- cyclotrons for high intensity beams

  [separation scaling with turn number, off-center injection, space charge scaling]

classification of circular accelerators

	bending radius	bending field vs. time	bending field vs. radius	RF frequency vs. time	operation mode (pulsed/CW)	comment
betatron	→	↗	↘		pulsed	induction
microtron	↗	→	→	→	CW	varying *h*
classical cyclotron	↗	→	→ / ↘ (dashed)	→	CW	simple, but limited E_k
isochronous cyclotron	↗	→	↗	→	CW	suited for high power!
synchro-cyclotron	↗	→	→ / ↘ (dashed)	↘	pulsed	higher E_k, but low P
FFAG	→ / ↗ (dashed)	→	↗	↗	pulsed	strong focusing!
a.g. synchrotron	→	↗		→ / ↗ (dashed)	pulsed	high E_k

critical for cyclotrons: **extraction, tuning, space charge**

turn separation and interpretation

for clean extraction a large stepwidth (**turn separation**) is of utmost importance; in the PSI Ring all efforts were directed towards maximizing the turn separation

general scaling:

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

- limited energy (< 1GeV)
- large radius *R*
- high energy gain U_t

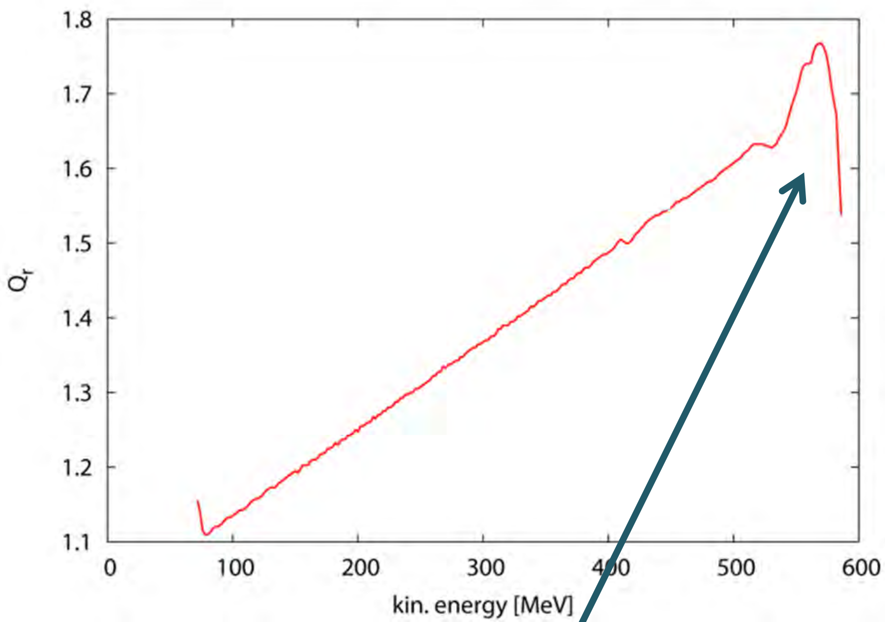
violating isochronicity:
(more general expression, possible on outer turns)

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

- reduce field slope, i.e. decrease field index *k*

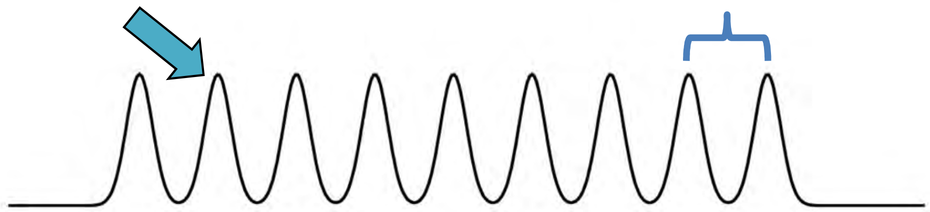
extraction with off-center orbits

betatron oscillations around the “closed orbit” can be used to increase the radial stepwidth by a factor 3 !

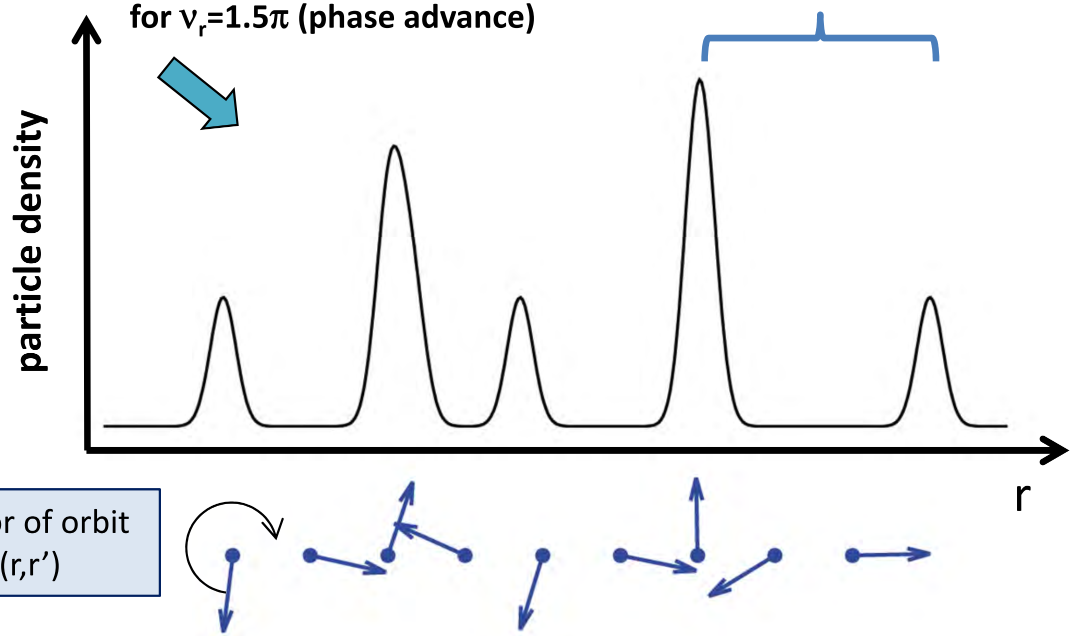


radial tune vs. energy
typically $\nu_r \approx \gamma$ during acceleration;
but decrease in outer fringe field

without orbit oscillations: stepwidth from E_k-gain (PSI: 6mm)

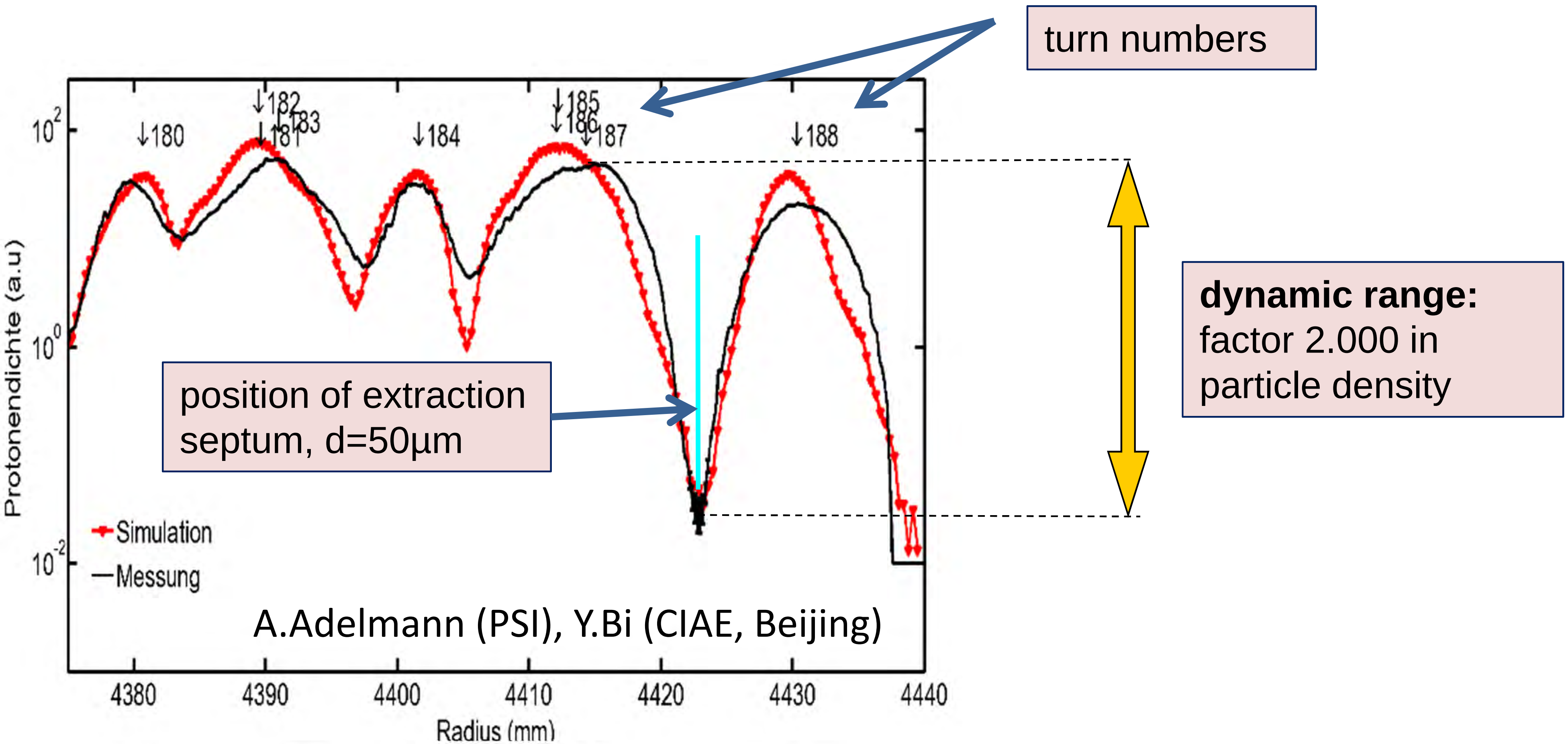


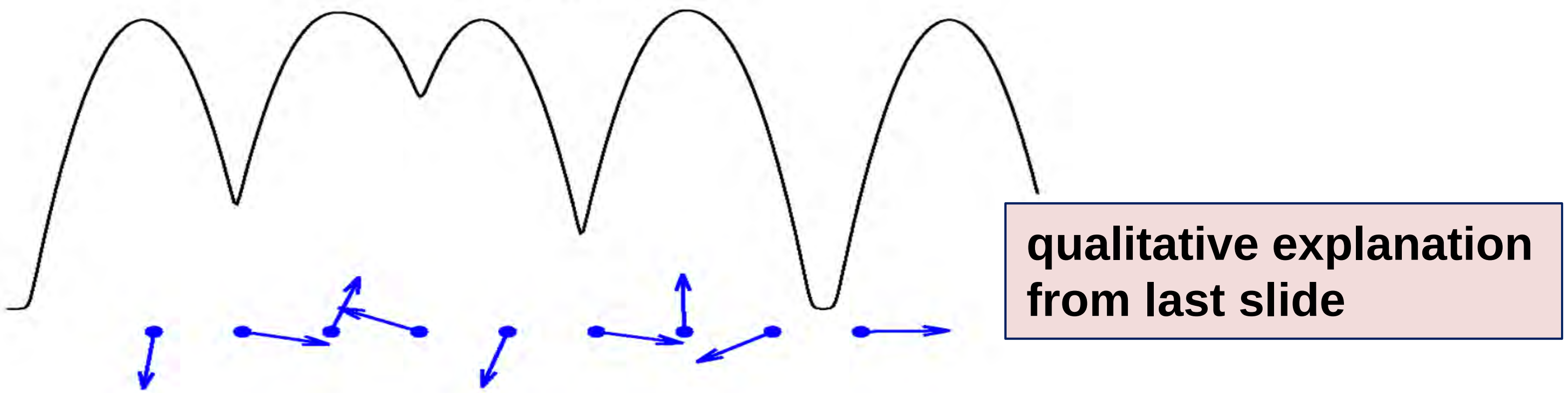
with orbit oscillations: extraction gap; up to 3 x stepwidth possible for ν_r=1.5π (phase advance)



phase vector of orbit oscillations (r,r')

extraction profile measured at PSI Ring Cyclotron





tail generation: longitudinal space charge

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

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

- ▶ loss at extraction element [1/turn separation] $\rightarrow \propto$ (# turns)^1

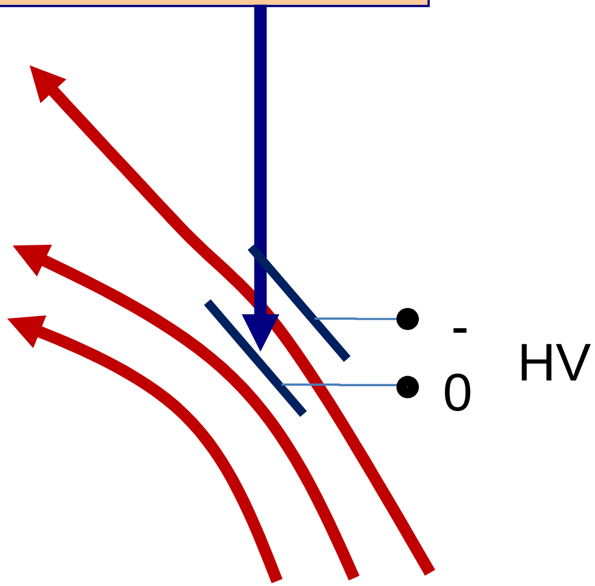
In summary:

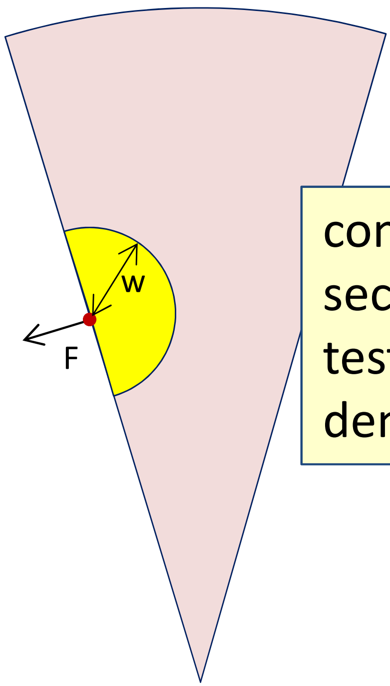
- scaling of losses **~ (# turns)^3 → high gap voltage advantageous!**

  is confirmed clearly by observation at PSI

[Joho 1981; T.Planche Tuesday]

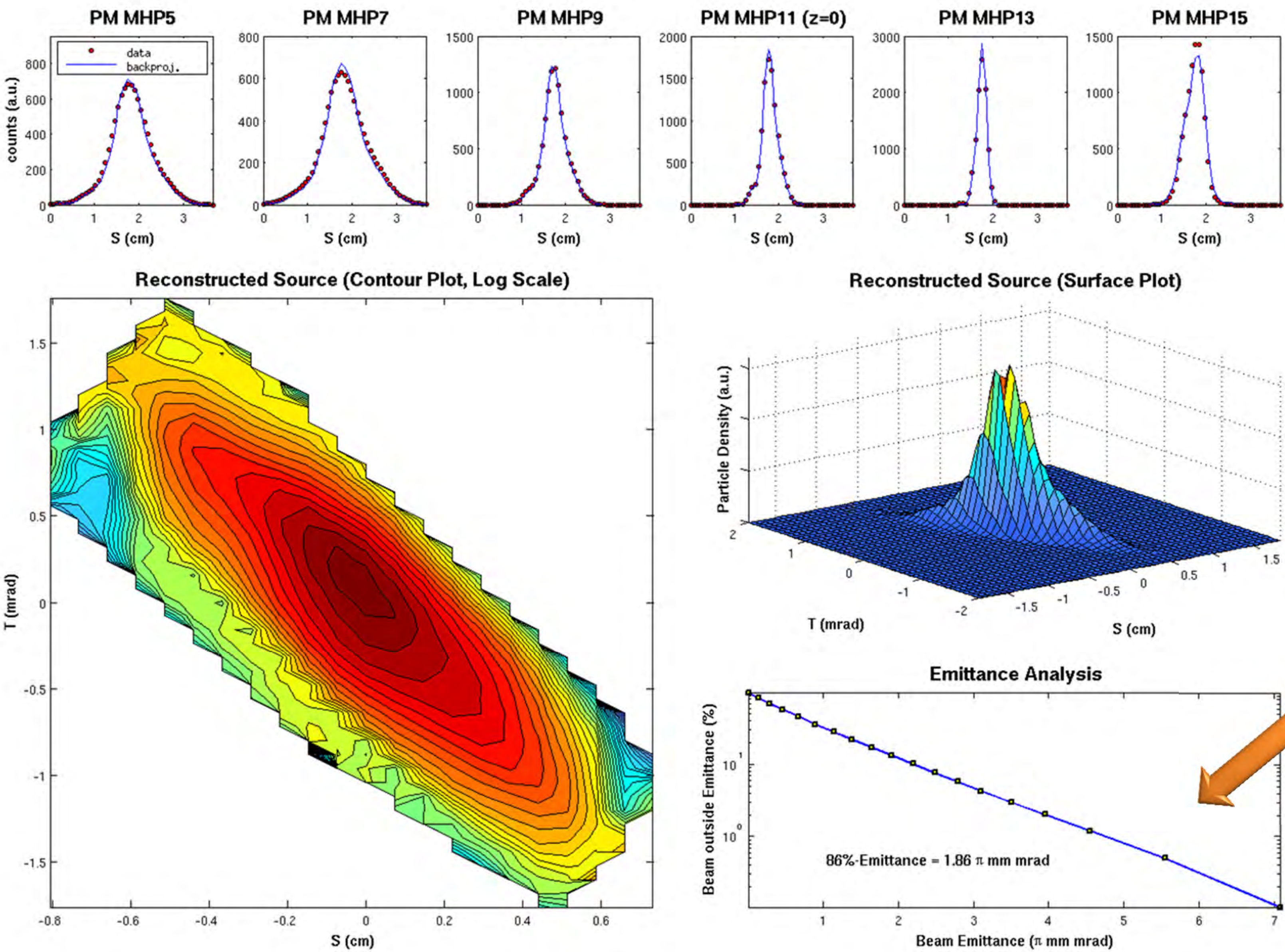
Extraction electrode
Placed between turns
[D.Reggiani, Wednesday]





consider rotating sectors of charge
test particle sees charge density within a circle

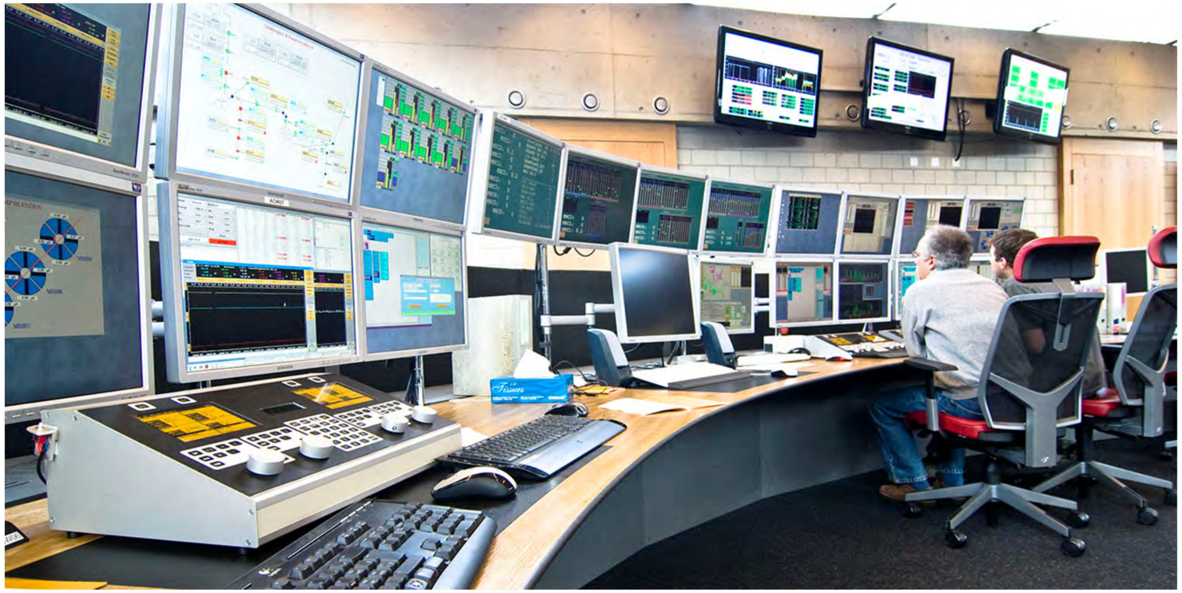
tomographic phase space reconstruction – no tails visible (within resolution)



action distribution, straight line = Gaussian [exp-J/ε]

590MeV after Ring D.Reggiani

comment on tuning



- **systematic strategy for general setup**; e.g. using intermediate beam dumps to divide the machine into sections; using measurements of beam properties to identify problems

  [radial probes, radial probes with tilted wires, phase probes, loss monitors, masks with current measurement, collimators, wire scanners, inductive BPM’s, ionization chambers]

- beam **loss fine tuning** (last 20%..50% of full current) is done **completely empirically**; subtle effects lead to population of beam tails; all machine sections starting from the ion source can contribute to the tails

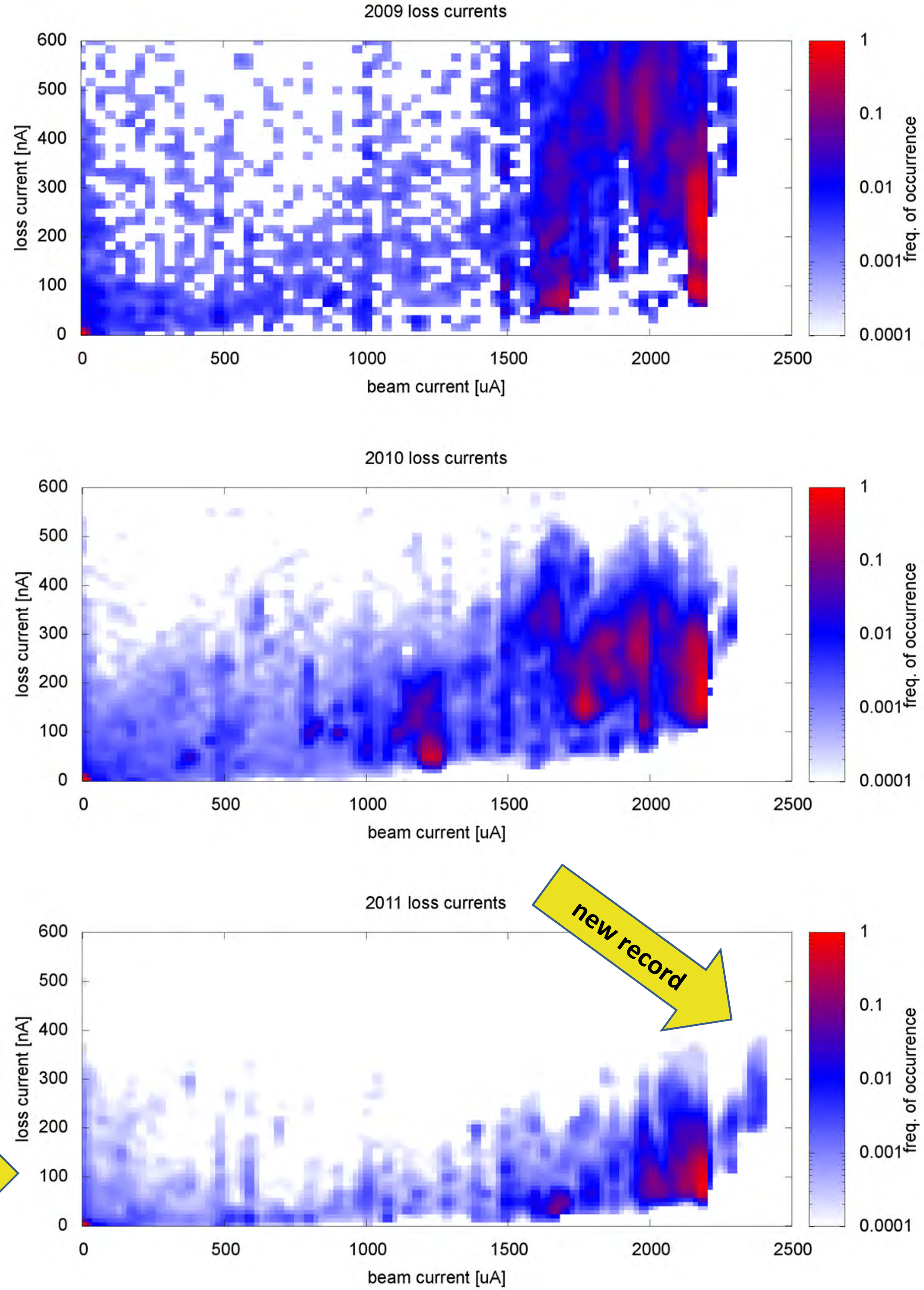
- losses and resulting activation

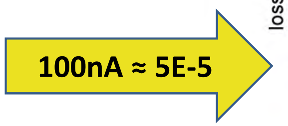
[measured loss statistics, activated components, service personnel dose]

loss development at PSI-HIPA

plots:

- **loss current [nA] vs. beam current [μA]**
- color code = frequency of operation at particular working point
- limit at 2200μA for standard operation;
  beyond that: test operation

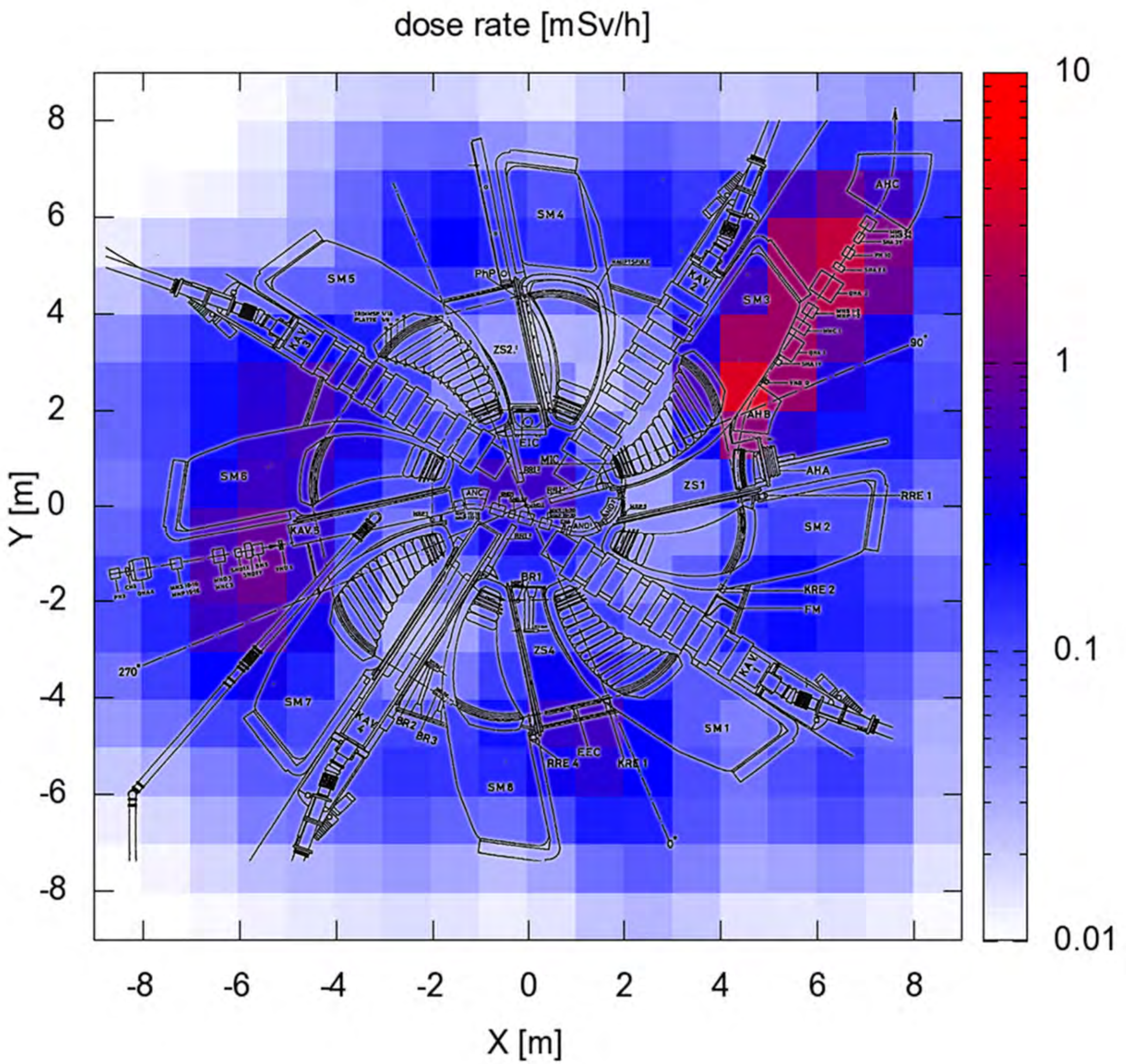




component activation – Ring Cyclotron

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 (2012):

41mSv, 149 persons
max per person: 3.2mSv

cool down times for service:

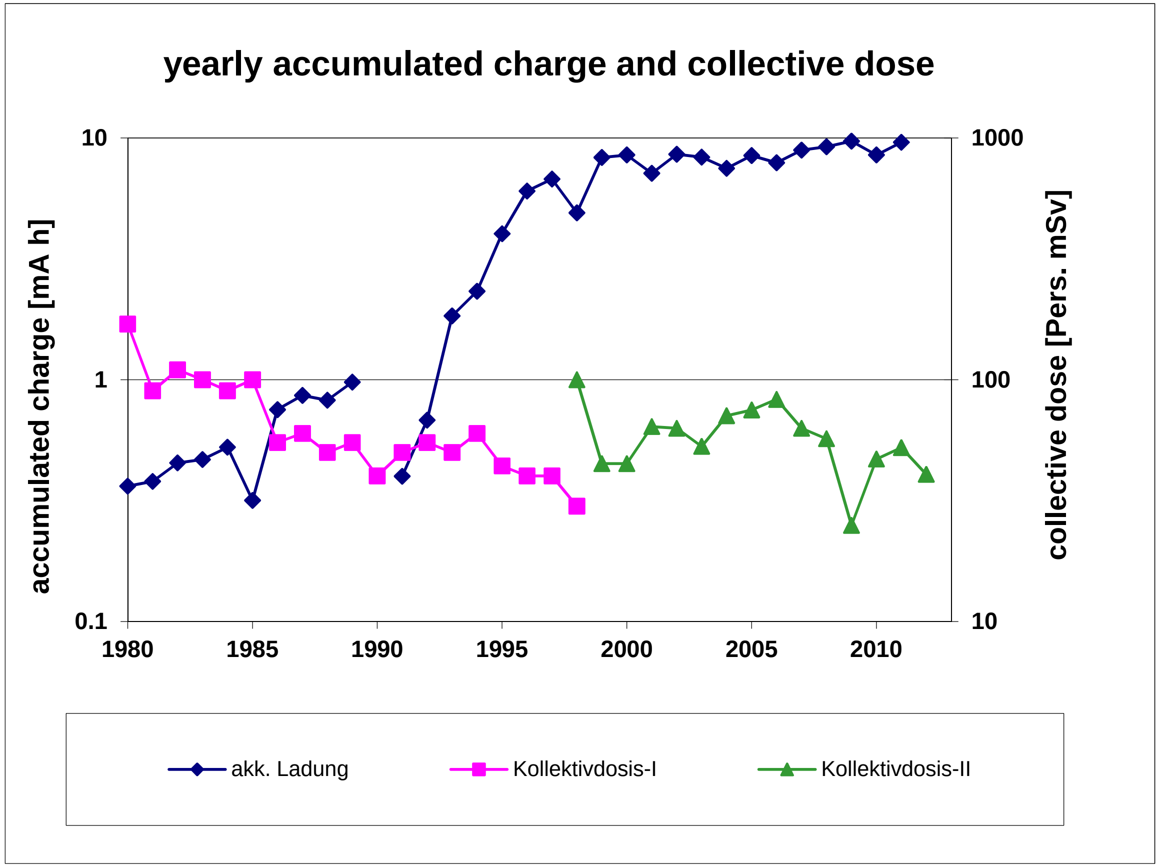
2200 → 1700 μA for 2h

0 μA for 2h

map interpolated from ~30 measured locations

comments on radiation safety at PSI

- only small fraction (~150-190) of monitored personnel really involved
- group of 10 colleagues responsible for radiation safety of accelerator facility
- monitoring of radiation in facilities by TLD/CR39 dosimeters (~100) + grid of remotely readable dosimeters (12+4); some (~5) dosimeters outside PSI area
- 10 hand and foot monitors at exits of experimental hall
- access to hot-cell and specific radioanalytics

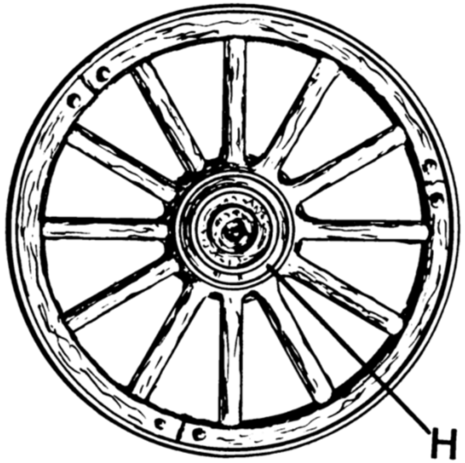


history of accumulated charge and collective dose
[note: step in number of considered persons]

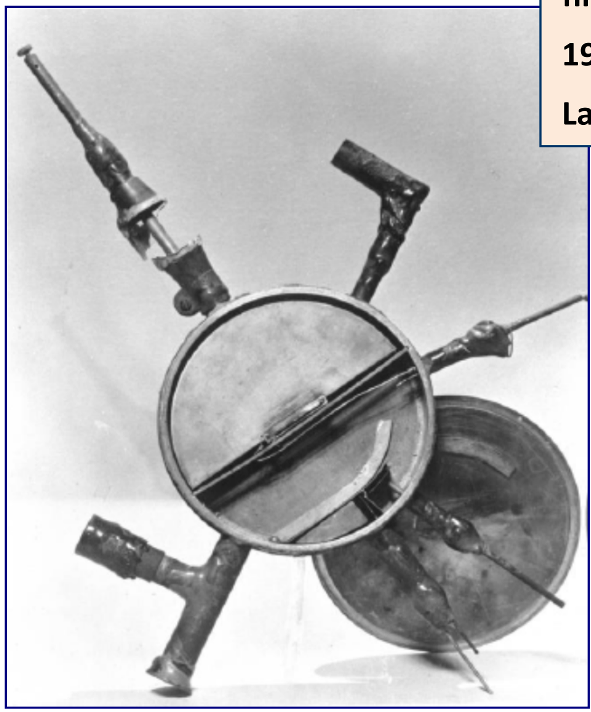
Summary

- excellent progress at PSI in recent years; **1.3MW** CW beam power is standard (record 1.4MW) ; the relative loss level is of the order **$1..2 \cdot 10^{-4}$, i.e. < 300Watts**; average availability is **90%**; **25-50 trips** per day
- all stages of the accelerator contribute to halo generation; **empirical tuning** is most successful $\rightarrow$ depends on **experience of operator**
- very **high power operation** of accelerators requires special expertise in certain areas such as
  - loss monitoring/instrumentation, interlock and permit systems
  - thermo-mechanical and cooling problems
  - handling/characterization/disposal of activated components
  - licensing

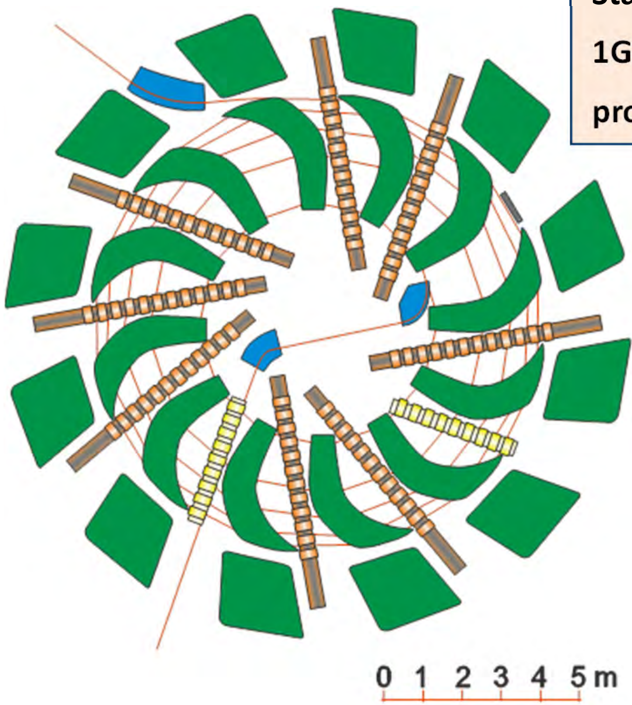
message: good concepts are sustainable!



first cyclotron:
1931, Berkeley
Lawrence



Stammbach et al
1GeV/10MW
proposal (1997)



HB2012, Beijing
Thank you for your attention !

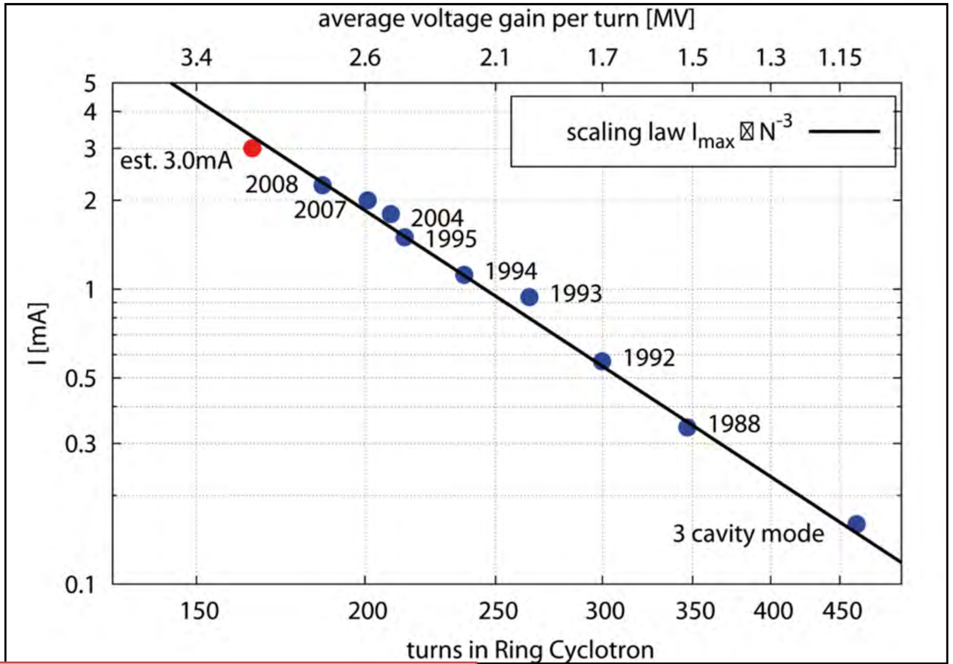
spare transparencies

longitudinal space charge; evidence for third power law

- at PSI the maximum attainable current indeed scales with the third power of the turn number
- maximum energy gain per turn is of utmost importance in this type of high intensity cyclotron

→ thus with constant losses at the extraction electrode the maximum attainable current scales as:

$$I_{\max} \propto n_t^{-3}$$



historical development of current and turn numbers in PSI Ring Cyclotron

Losses – required vacuum quality

- losses are caused by inelastic scattering at residual gas molecules
- use inelastic reaction cross section to estimate losses
- convert to mean free path
- compute pressure for 10^{-5} relative loss

common gases :
(norm.cond.)

$$\begin{aligned} \lambda_{\text{inel}}(\text{air}) &= 747\text{m} \\ \lambda_{\text{inel}}(\text{CO}) &= 753\text{m} \\ \lambda_{\text{inel}}(\text{H}_2) &= 6110\text{m} \\ \lambda_{\text{inel}}(\text{Ar}) &= 704\text{m} \end{aligned}$$

mean free path:

$$\lambda_{\text{inel}} = \frac{A}{\rho N_A} \frac{1}{\sigma_{\text{inel}}}$$

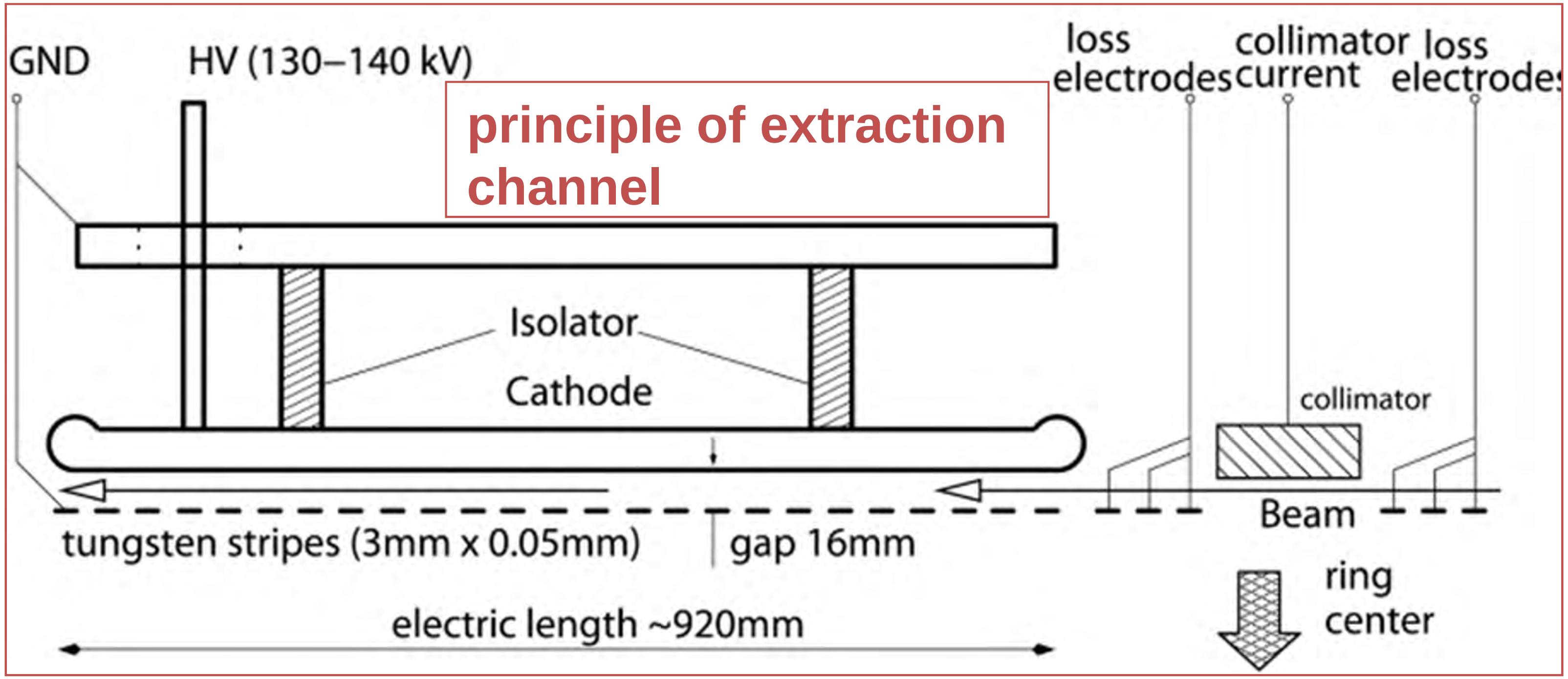
$$\lambda_{\text{eff}} = \left(\frac{1}{P_0} \sum \frac{P_i}{\lambda_{\text{inel}}^i} \right)^{-1}$$

beam loss:

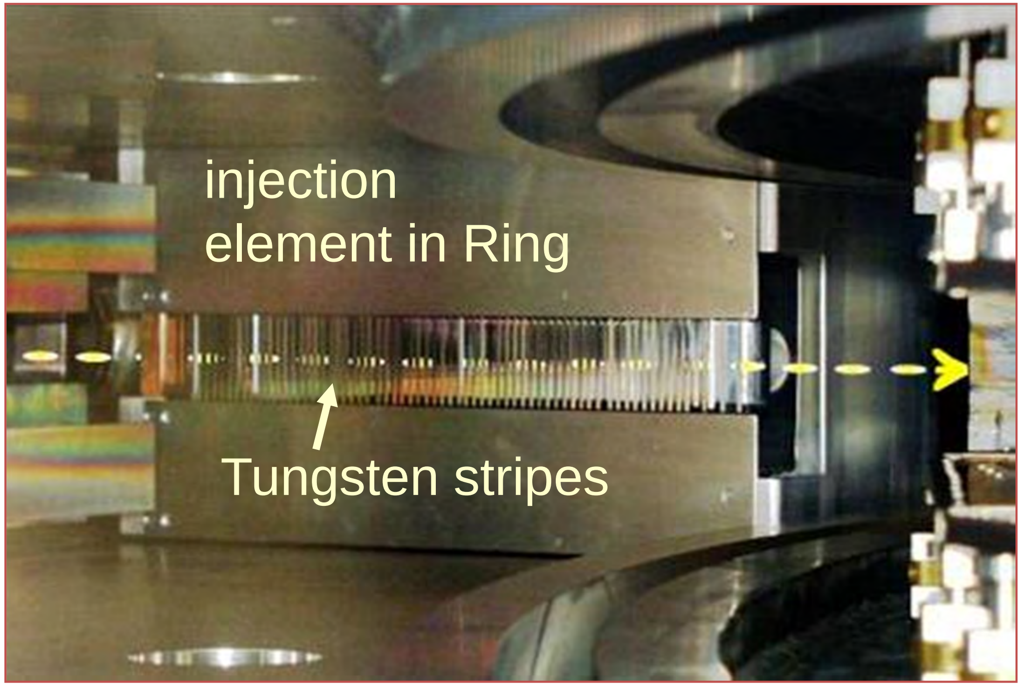
$$\frac{N_0 - N(l)}{N_0} = 1 - \exp(-l/\lambda_{\text{eff}}) \approx l/\lambda_{\text{eff}}$$

pressure for loss < 10^{-5}: P_i(air) > 0.01 mbar $\rightarrow$ **easily achievable, vacuum no problem!**

electrostatic elements for inj./extr.



major loss mechanism is scattering in 50µm electrode!



parameters extraction channel:

E_k= 590 MeV

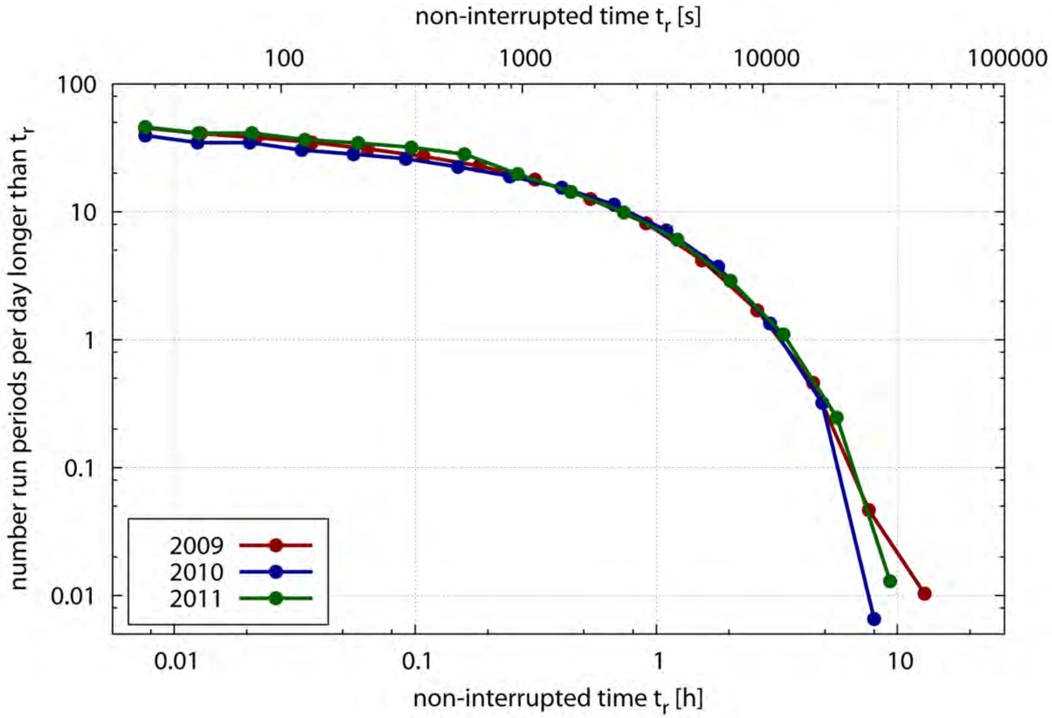
E = 8.8 MV/m

θ = 8.2 mrad

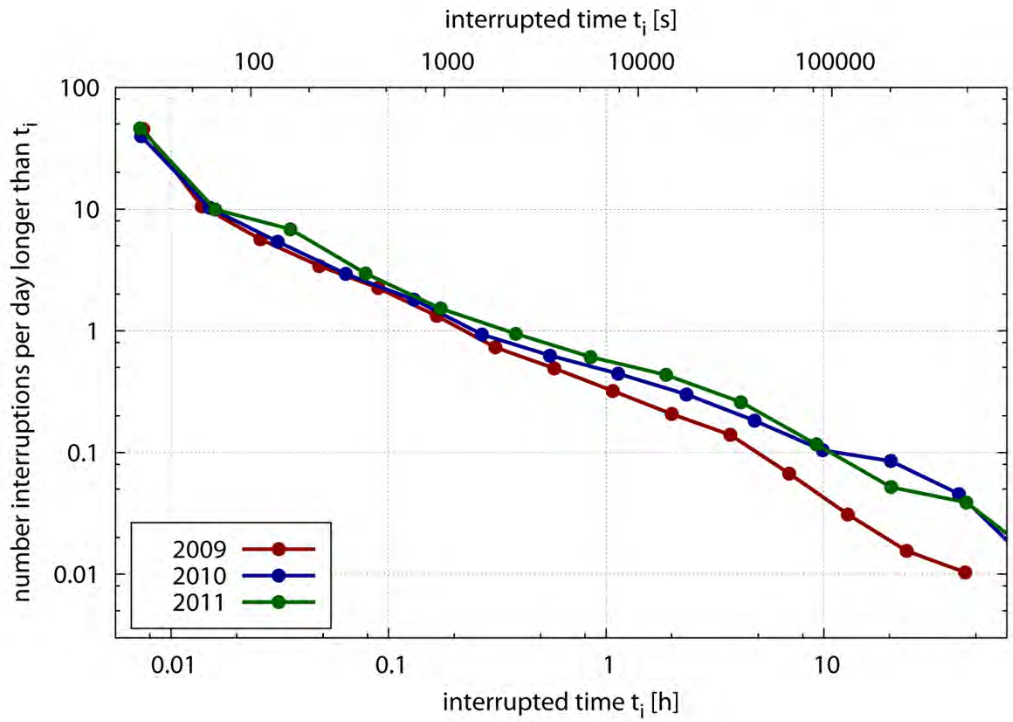
ρ = 115 m

U = 144 kV

HIPA beam trip statistics: non-interrupted run durations

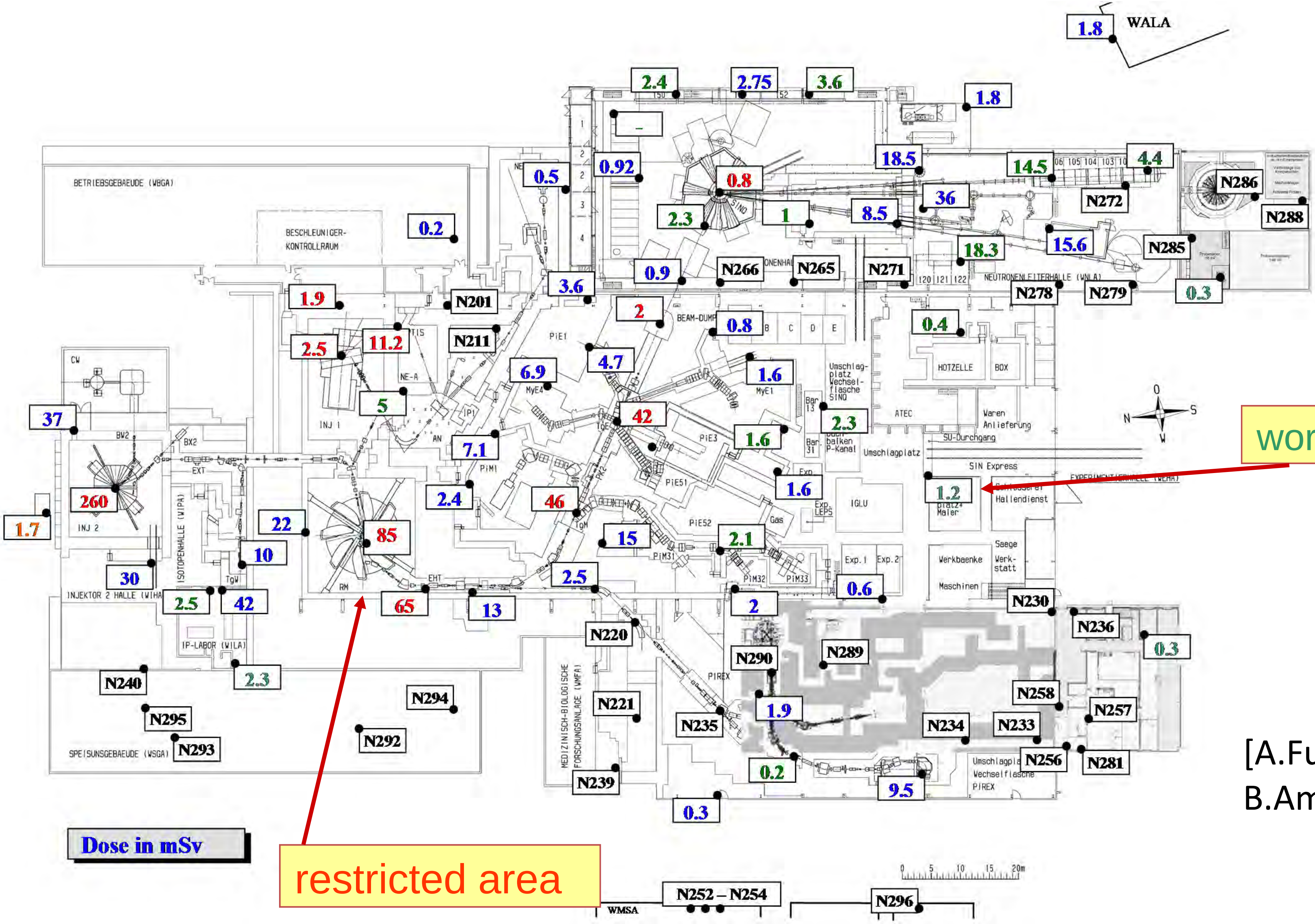


HIPA beam trip statistics: duration of interruptions



these are integrated histograms
at a certain time you read **how many events with such duration or longer occur per day**

radiation monitoring: dosimeter network in experimental hall



work area

restricted area

[A.Fuchs, B.Amrein]