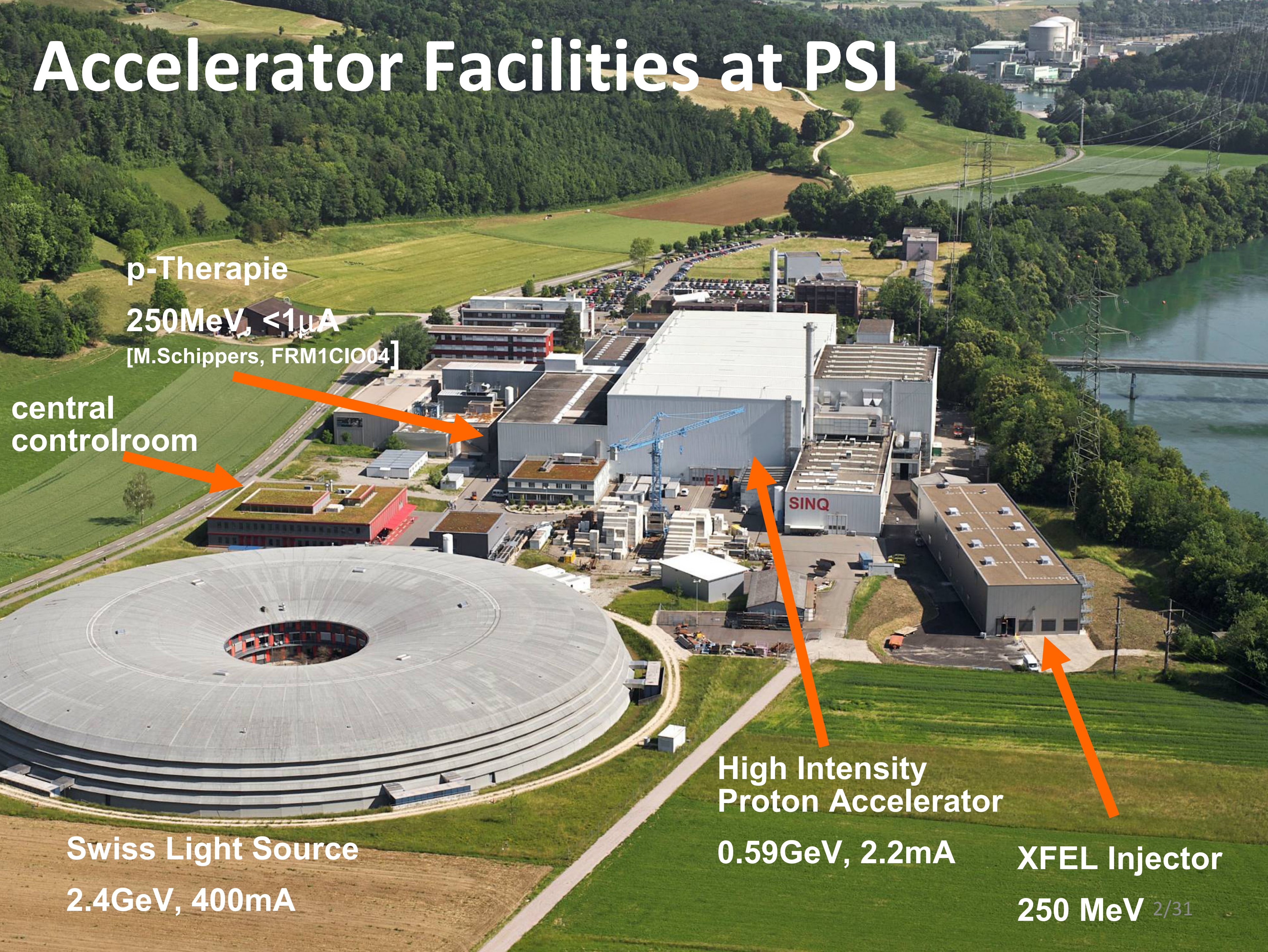
TOWARDS THE 2 MW CYCLOTRON AND LATEST DEVELOPMENTS AT PSI

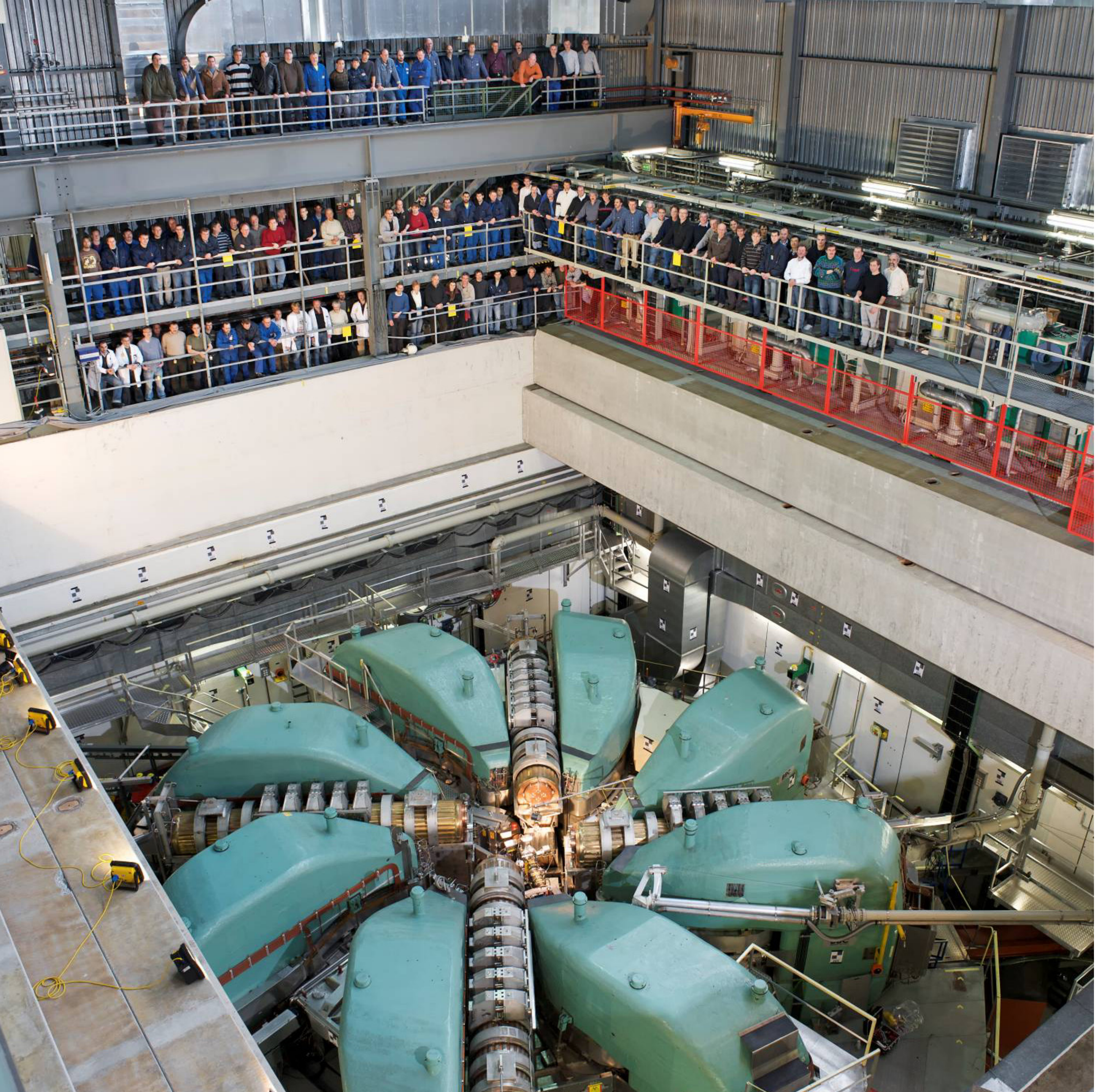
Mike Seidel, Ch. Baumgarten, M. Bopp, J. Grillenberger, Y. Lee, D. Kiselev, A. Mezger, H. Müller, M. Schneider, A. Strinning

and others of the PSI Accelerator Team

Cyclotrons 2010, Lanzhou, China

Accelerator Facilities at PSI





PSI Ring Cyclotron with team [2010]

Outline

- Facility Overview

  [accelerator chain, performance]
- Recent Performance Improvements and Developments

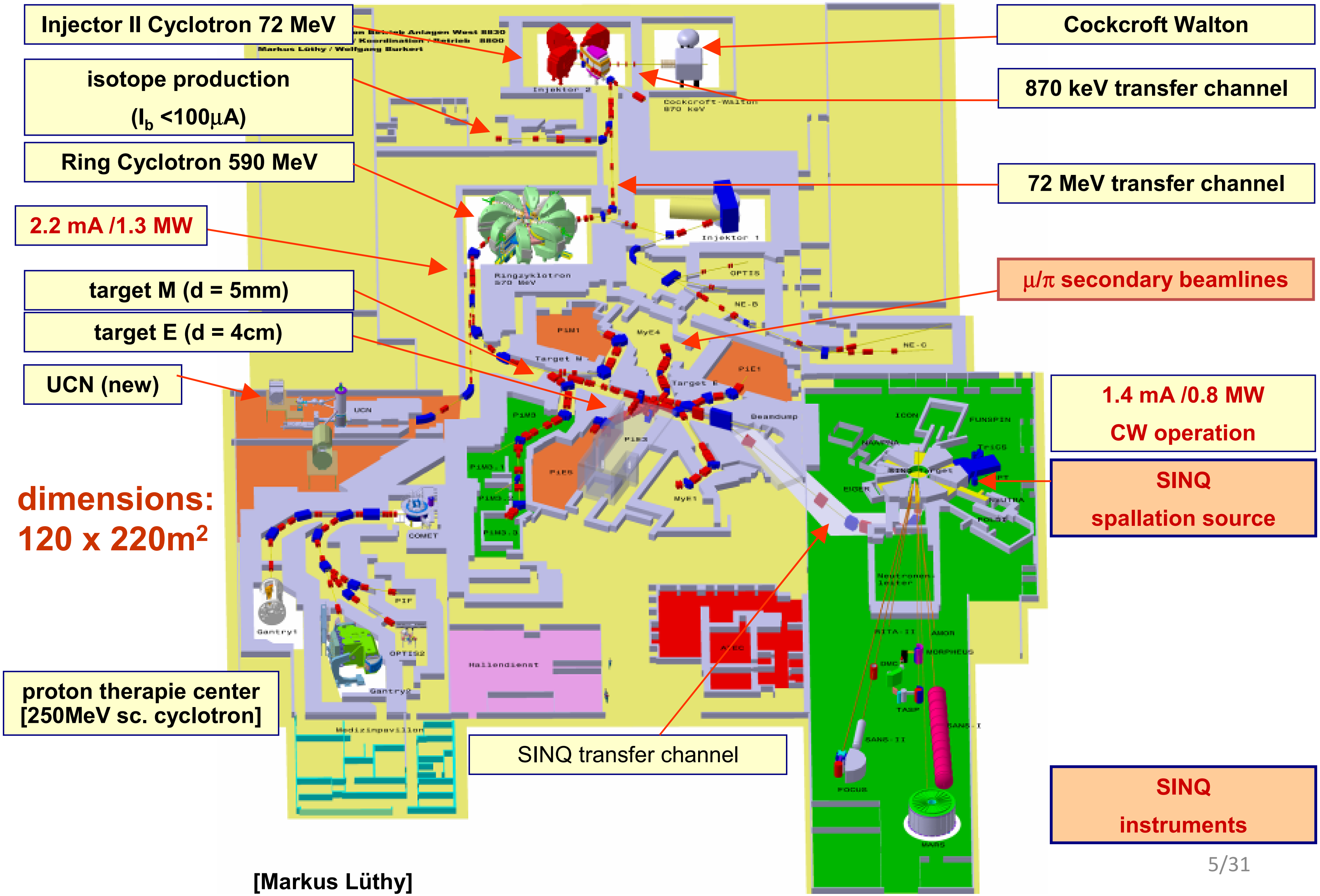
  [Ring resonators, ECR proton source, 10th harmonic buncher, first beam on UCN source]
- Operational Experience

  [beam currents and losses in ’09/’10, problems with 50Hz jitter]
- Planned Upgrade Measures

  [resonators for injector II, new high power absorbers]
- Summary and Outlook

  [the case for high power cyclotrons]

Overview PSI Facility

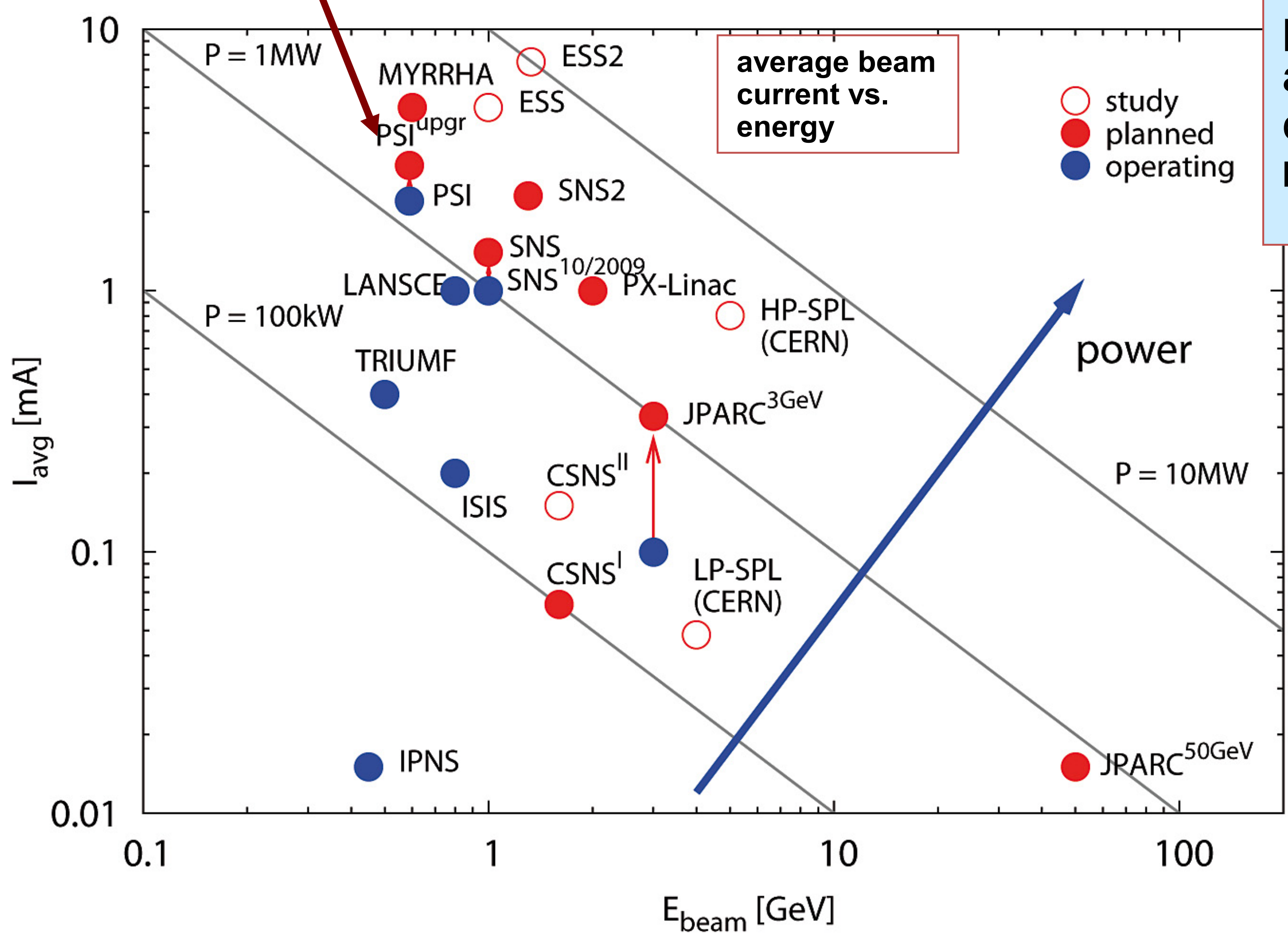


dimensions:
120 x 220m²

[Markus Lüthy]

High Power Proton Accelerators

PSI Upgrade Plan



average beam current vs. energy

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

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

Next:

- Recent Performance Improvements and Developments

  [Ring resonators, double seals, ECR proton source, circular beam / 10th harmonic buncher, first beam on UCN source]

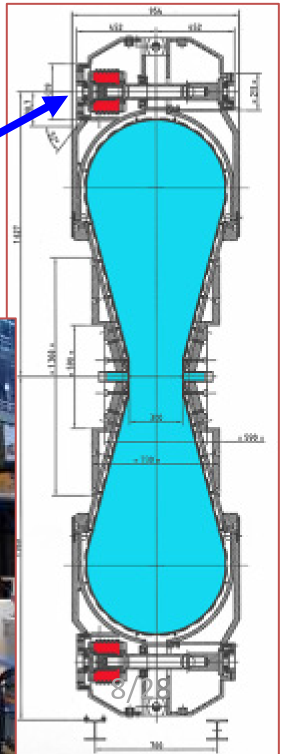
major component: RF resonators for Ring cyclotron

- **the shown Cu Resonators have replaced the original Al resonators (from 2008)** [less wall losses, higher gap voltage possible, better cooling distribution, better vacuum sealing surfaces]
- **f = 50.6MHz**; **Q_0 = 4·10^4**; **U_{max}=1.2MV** (presently 0.85MV→187 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)



new inflatable double-seals

Motivation:

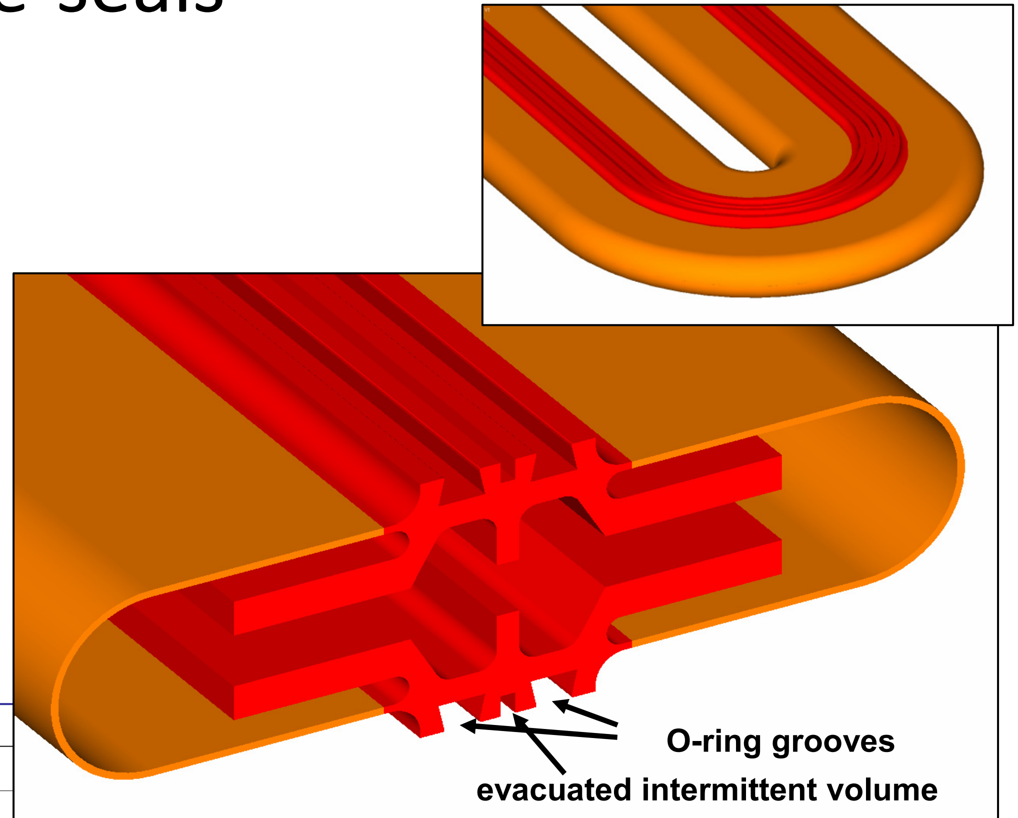
➔ frequent leaks with old seals

Issue:

➔ mechanically difficult design with length of ~3.5m

Experience:

➔very good experience so far; practically no leaks occurred; early detection of problems via intermittent vacuum

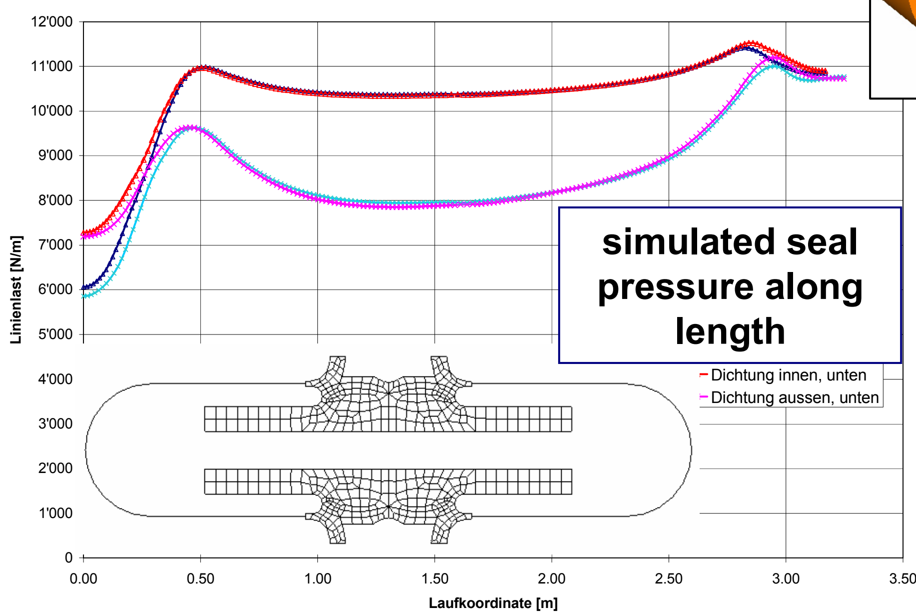


Idea: U.Heidelberger (PSI)

design: company InnoRat

production: company Wartmann

FE computation: company Ingenis

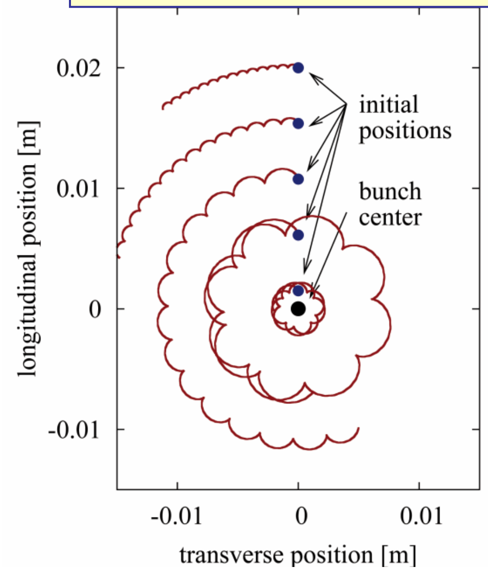


simulated seal pressure along length

circular beam in cyclotron with short bunches – motivation for "superbuncher"

simplified model:

test charge in bunch field with vertically oriented bending field



in theory

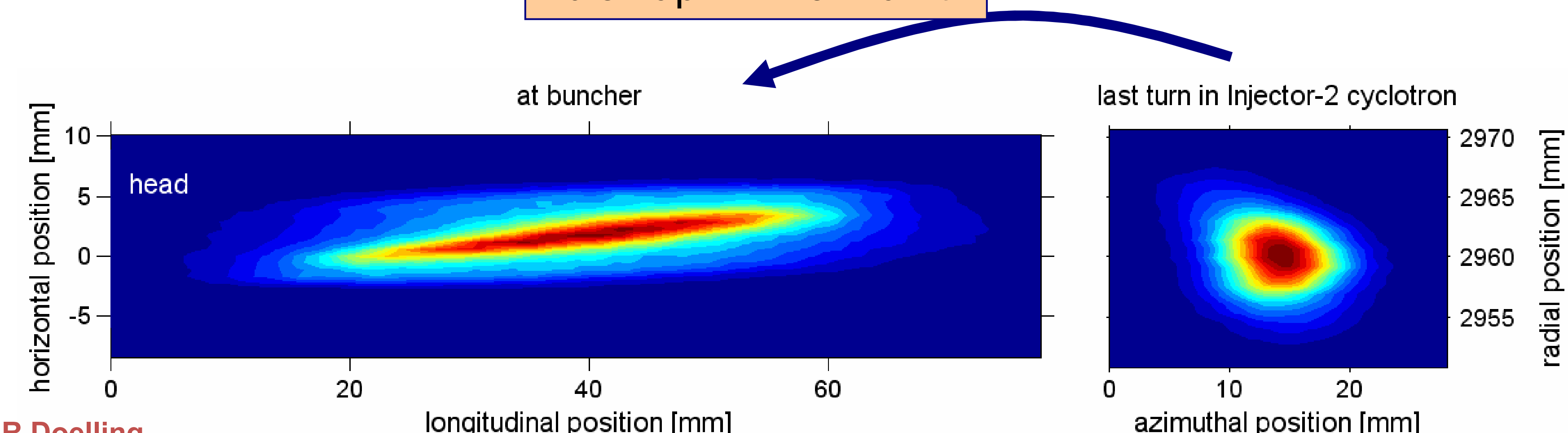
strong space charge within a bending field leads to rapid cycloidal motion around bunch center [Chasman & Baltz (1984)]

→ bound motion; circular equilibrium beam destribution

in practice

time structure measurement in **injector II cyclotron** → circular bunch shape observed

blowup in ~20m drift



[court. R.Doelling see WEM2CIO04]

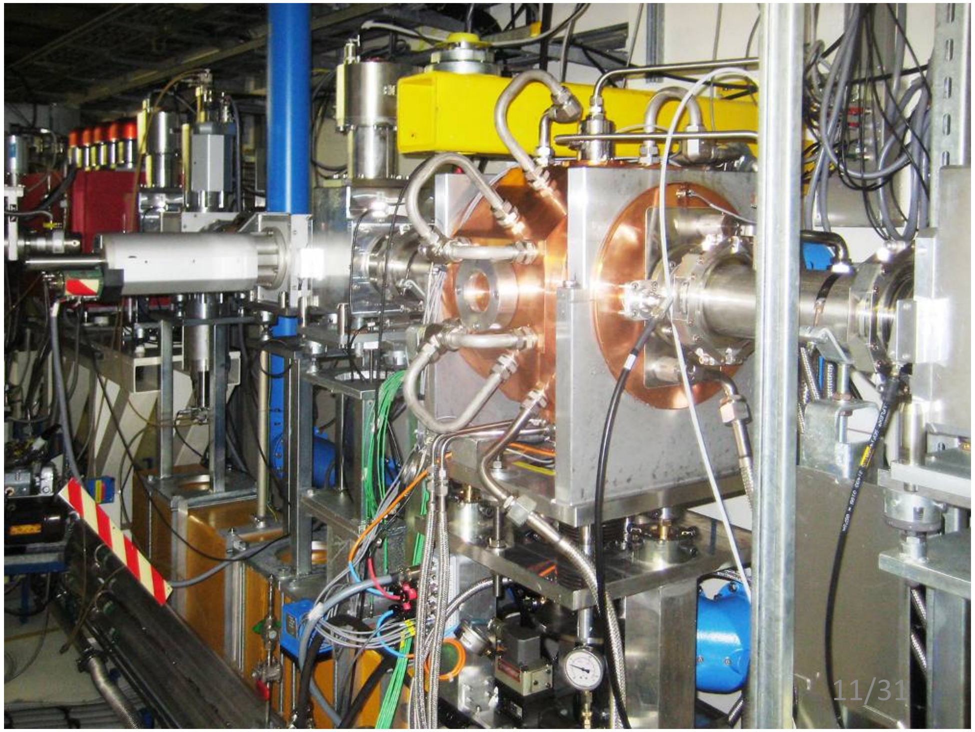
500MHz (10th harmonic) Buncher

status tests **[M.Humbel 2009]**:

► positive effect on Ring extraction losses observed with small currents (200uA)

► at larger currents losses increase; no further studies in 2010 because of technical problems in other areas

► better phase control needed; necessity for adjusting transverse optics suspected



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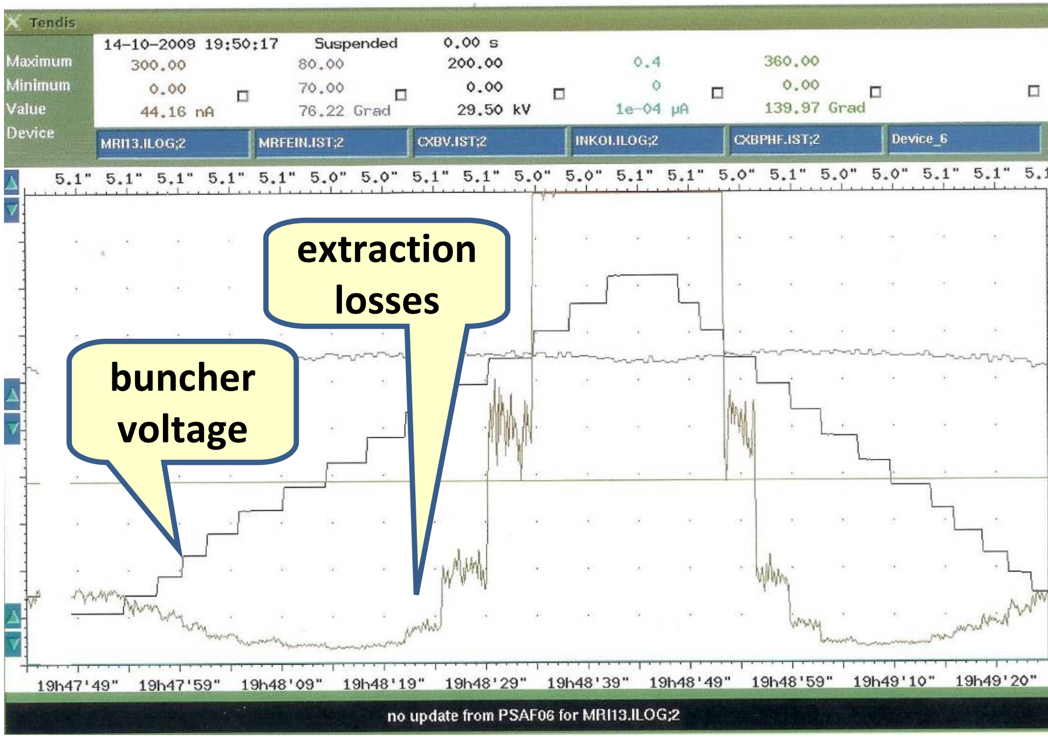
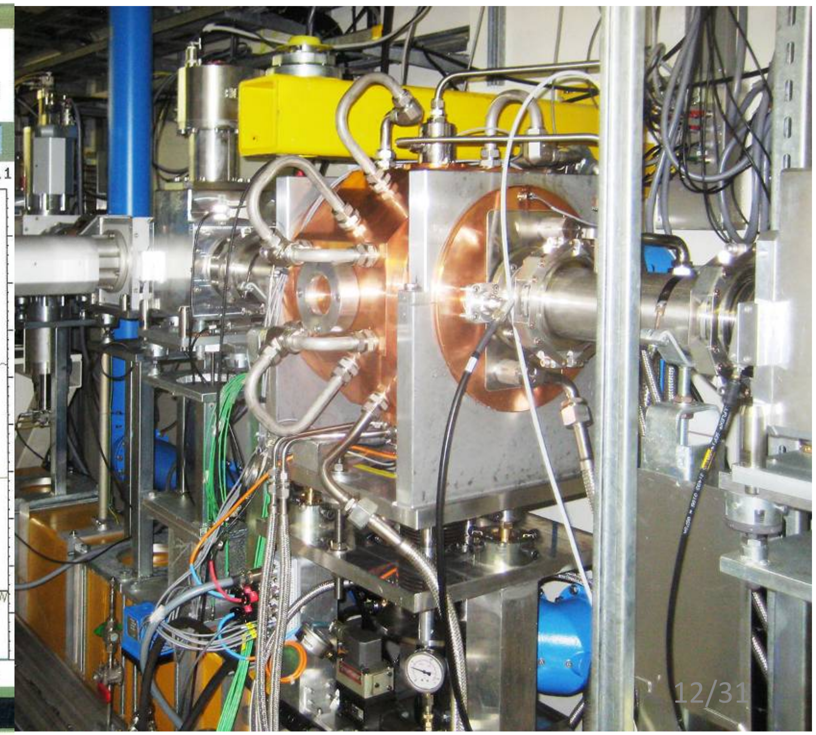
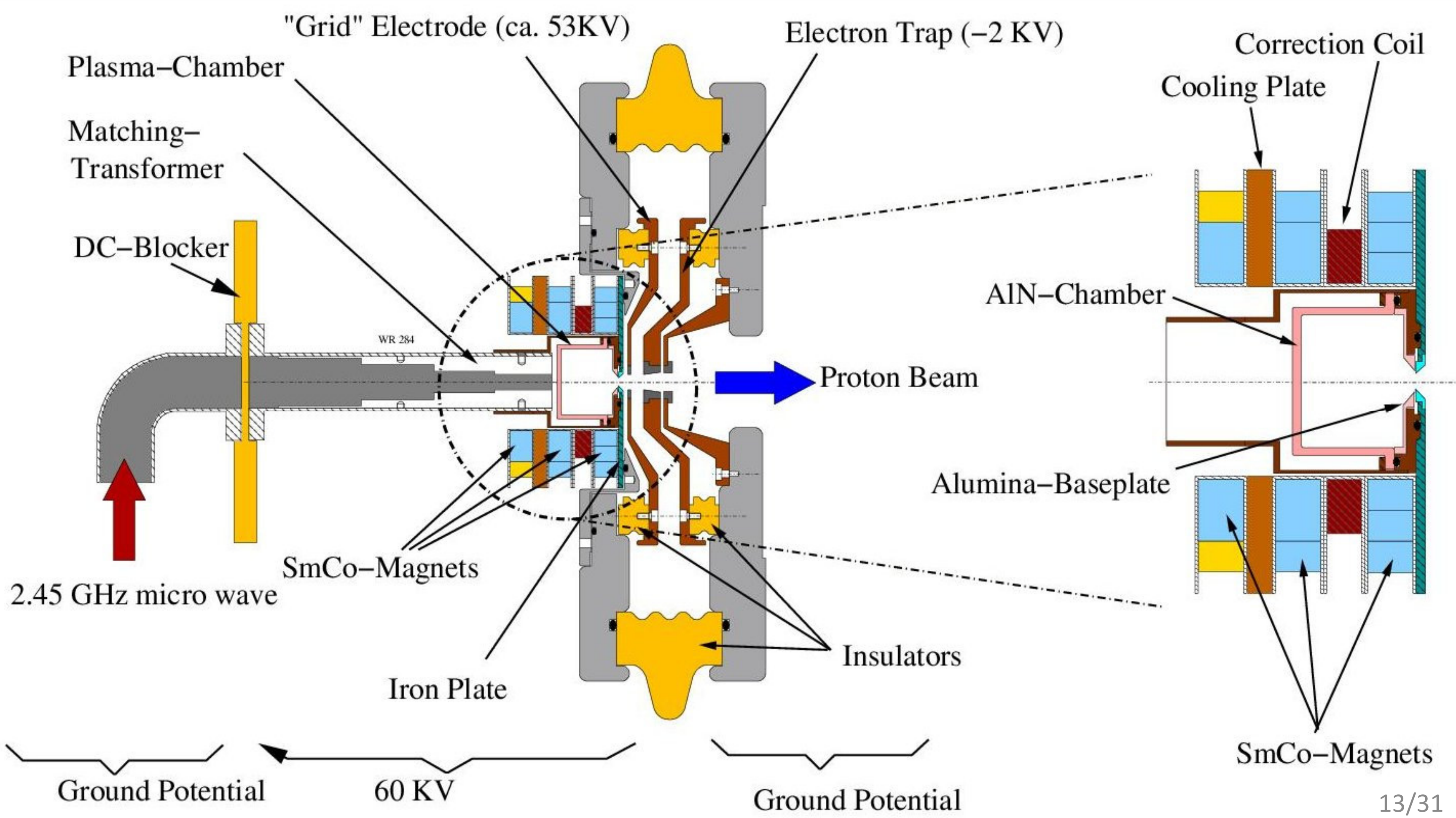




New ECR-Source + Extraction System

- ► **better reliability**
- ► **smaller emittance**

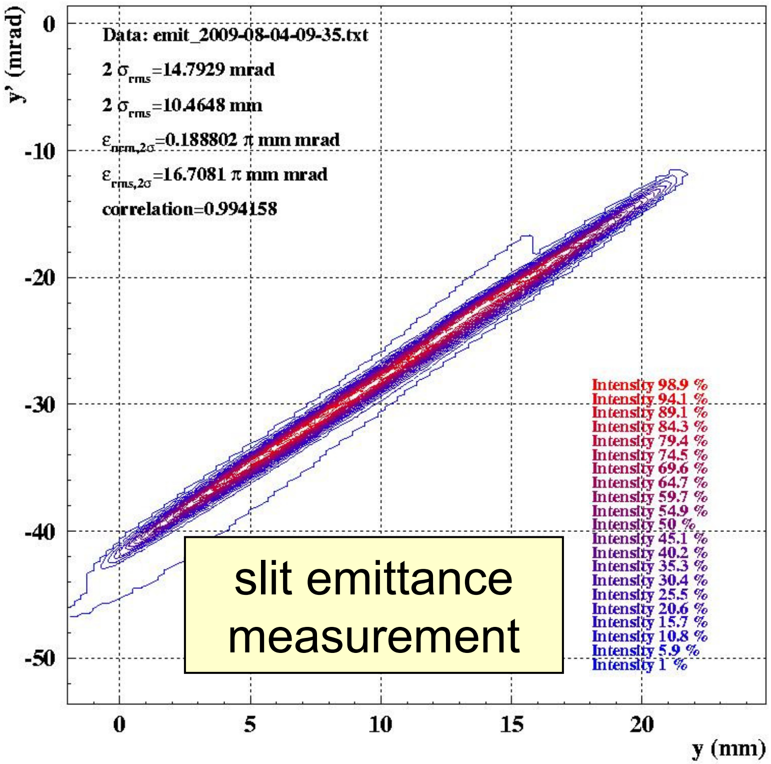
[Ch.Baumgarten]



ECR Source Performance Summary

- output 12 mA...18mA for P_{RF}=390...600 W
- trip rate about 1/day
- beam current noise < 1% at optimal settings
- 8 weeks of 24-h operation verified (more possible)
- beam emittance $\beta\gamma\varepsilon_{rms}$= 0.046 π mm mrad
- plasma chamber tested with more than 700 Watts

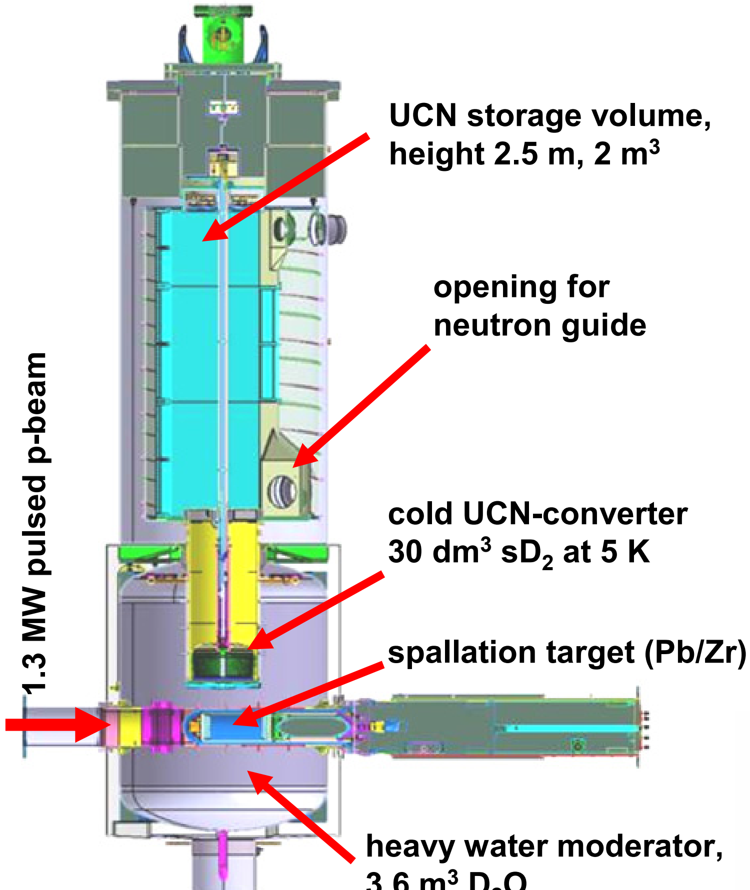
ECR source in place



slit emittance measurement

[Ch.Baumgarten]

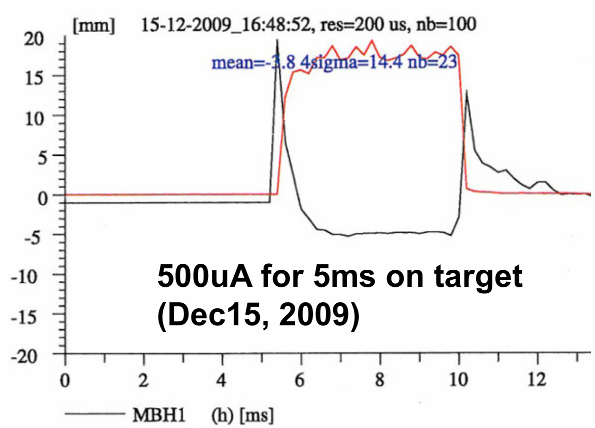
New customer: source for Ultra Cold Neutrons



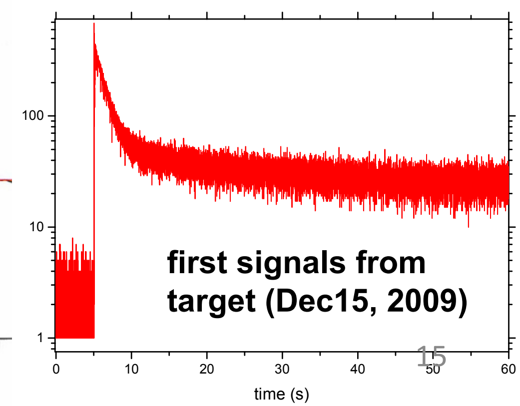
UCN Tank:

height = 6.5 m
diameter = 1.7 m
mass = 3.3 to

- **pulsed operation**: 8sec beam on / 900sec beam off (beam is switched between SINQ and UCN target)
- ultra cold neutrons: **~ 200neV**
- UCN converter using **solid D_2** at 5K
- expect. density in storage vol.: **$1000 cm^{-3}$ UCN** (~$10 cm^{-3}$ UCN today at ILL PF2)
- **application**: precision measurement of electric dipole moment **(nEDM)**; precision n-lifetime measurement (under discussion)



500uA for 5ms on target (Dec15, 2009)



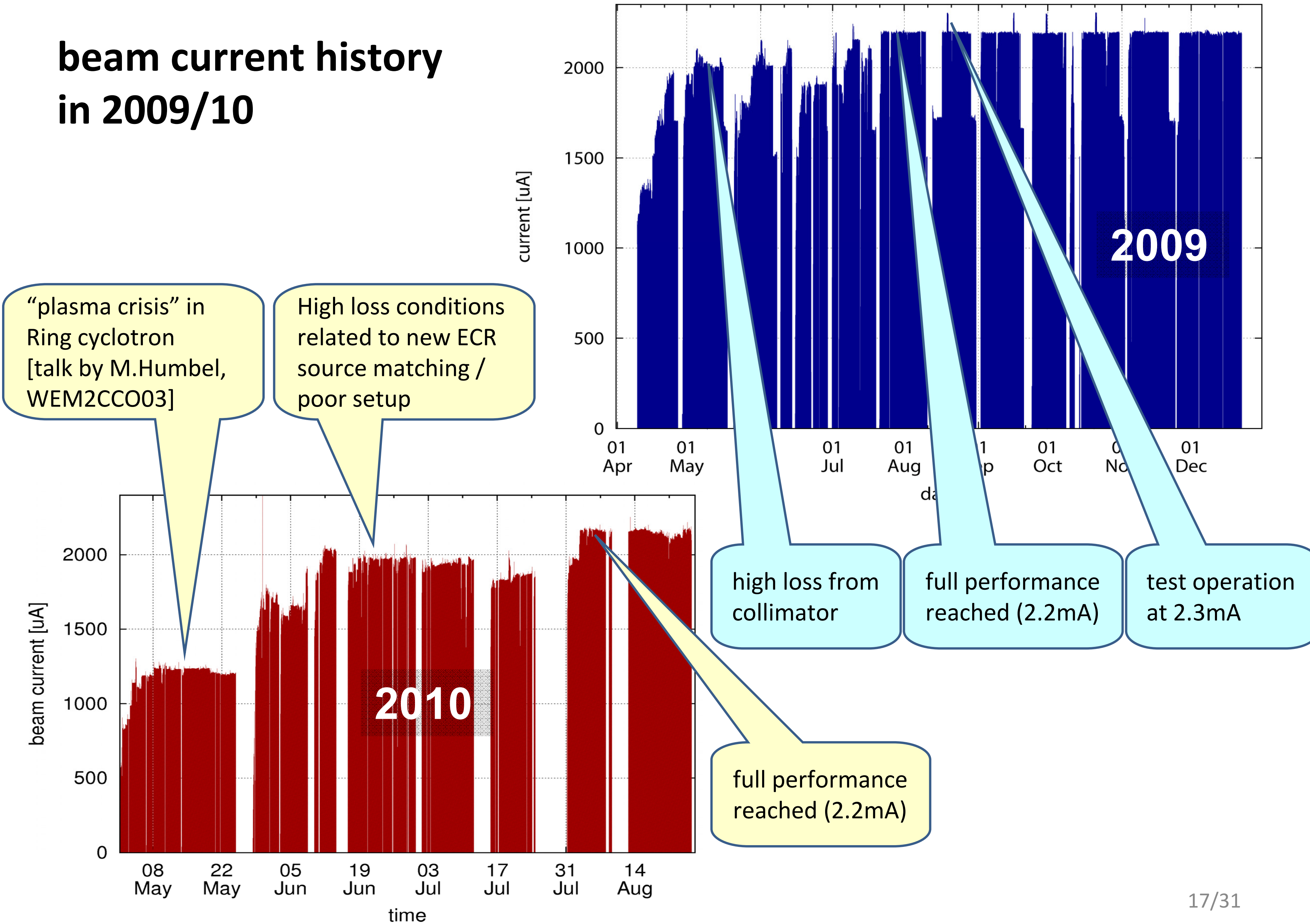
first signals from target (Dec15, 2009)

Next:

- Operational Experience

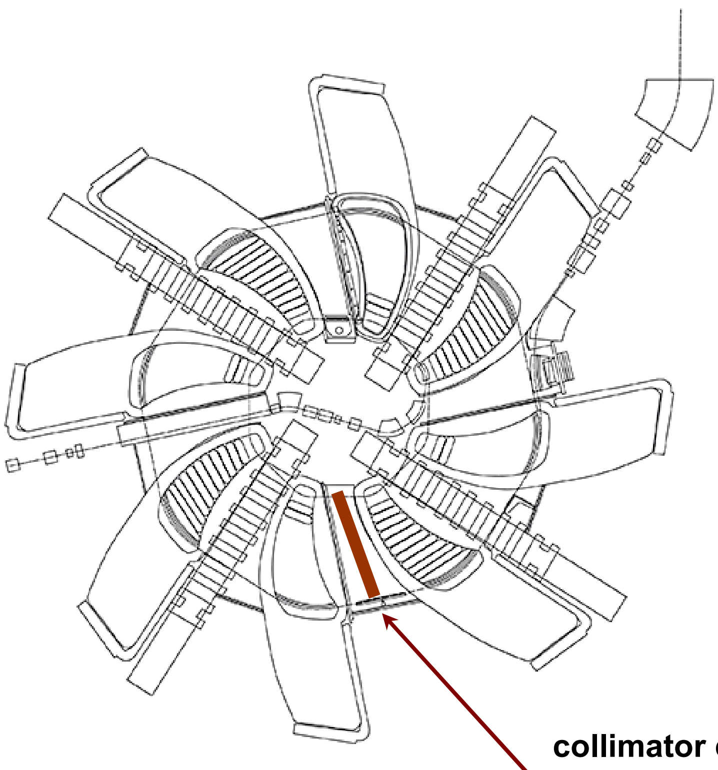
  [beam currents and losses in ’09/’10, problems with 50Hz jitter, enhanced losses]

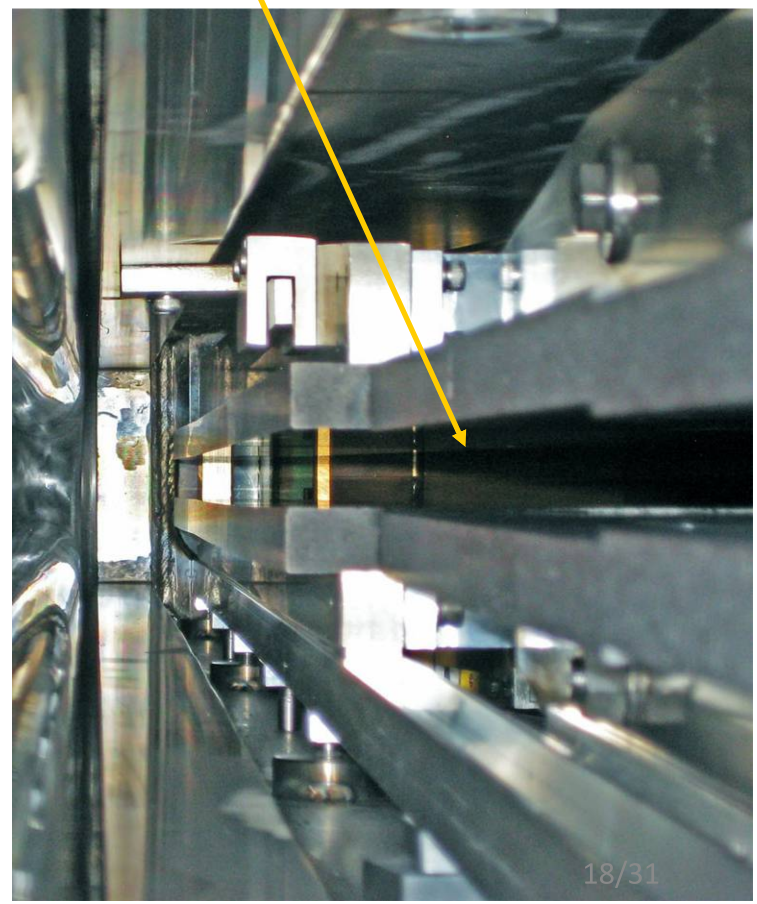
beam current history in 2009/10



Observation of higher losses in early 2009

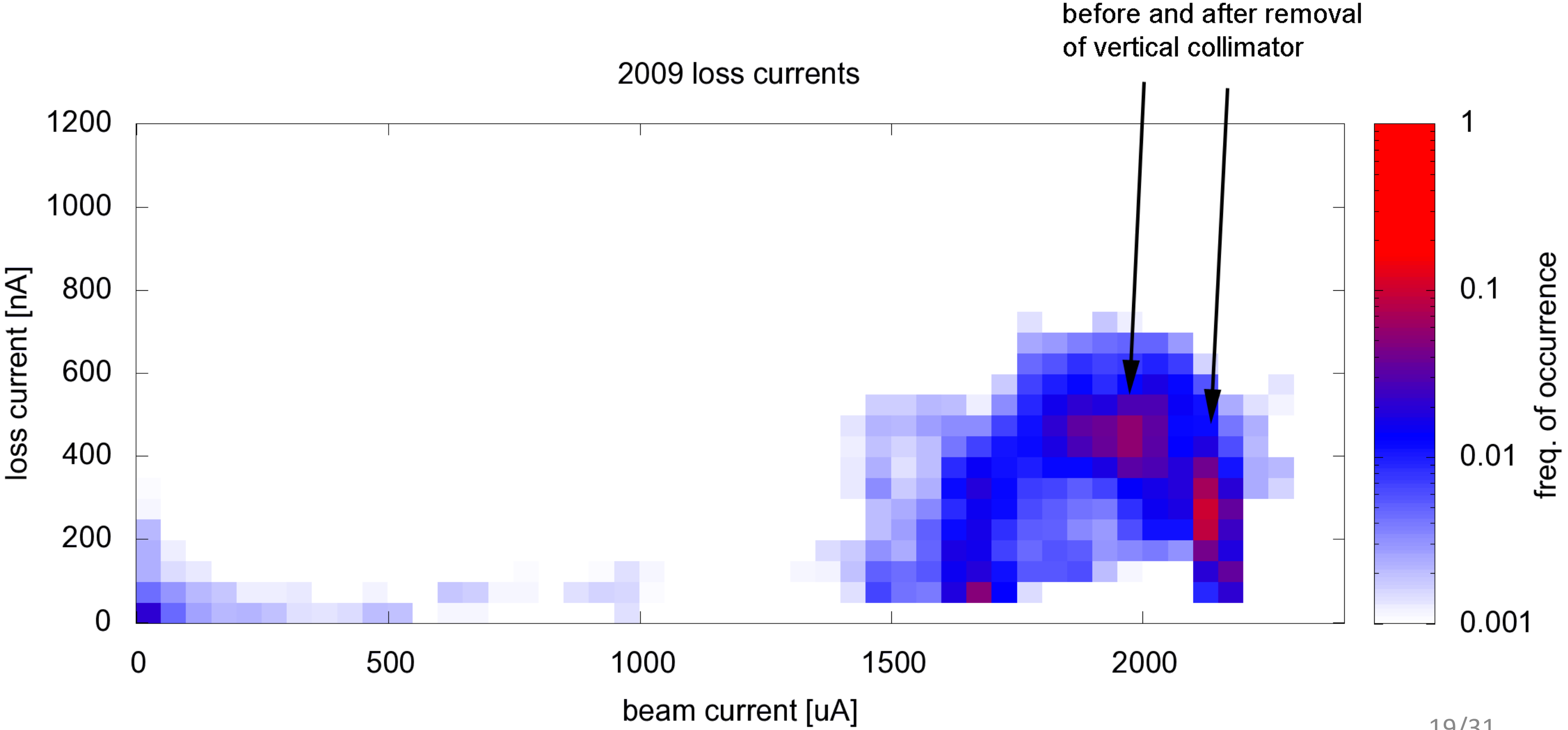
- graphite collimator (chamber protection) probably deformed or misaligned by RF heating → reduced vertical aperture
- decision: complete removal; rely now on (much improved) interlock system





beam loss statistics w/o collimator

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



enhanced losses in 2010 - attempt to detect beam tails (poor 2010 vs. good 2009 conditions)

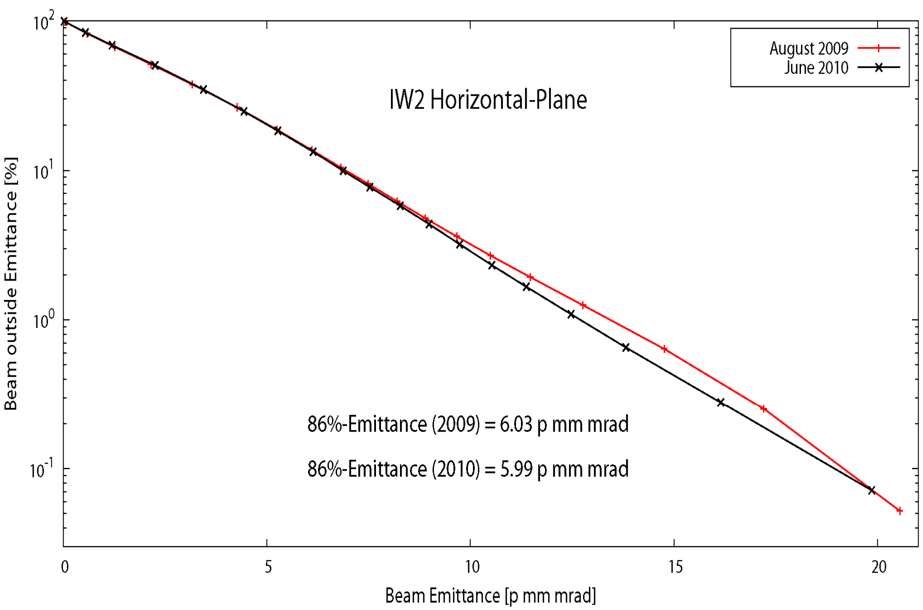
Method: measure integrated distribution of particle action @72MeV

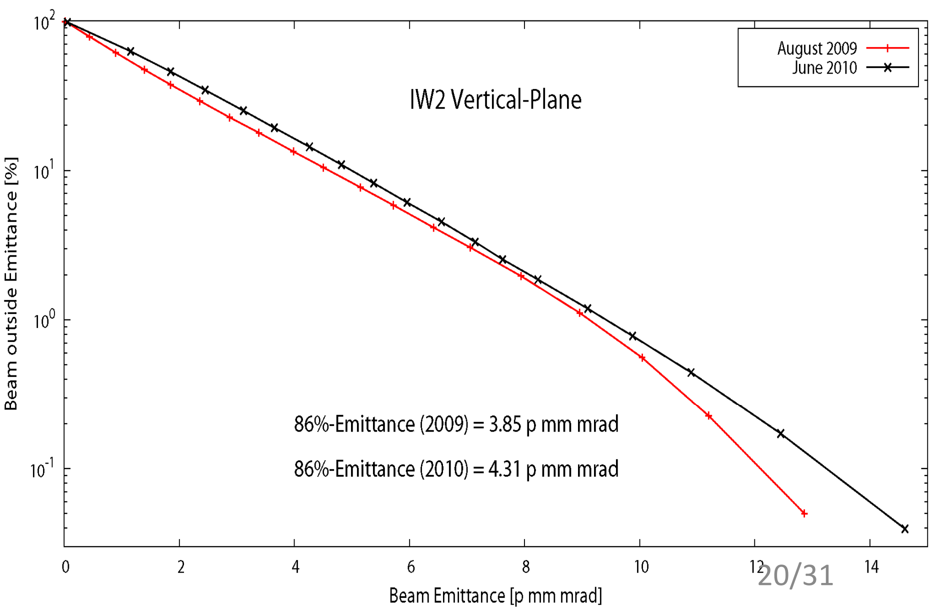
for Gaussian distribution the integrated distribution of particle action
"**percentage outside certain emittance**" is **purely exponential**;

$\rightarrow$ no beam tails visible down to 10^{-3}

$$\rho(I_x) = \frac{1}{\varepsilon_x}\exp\left(-\frac{I_x}{\varepsilon_x}\right), \langle I_x \rangle = \varepsilon_x$$

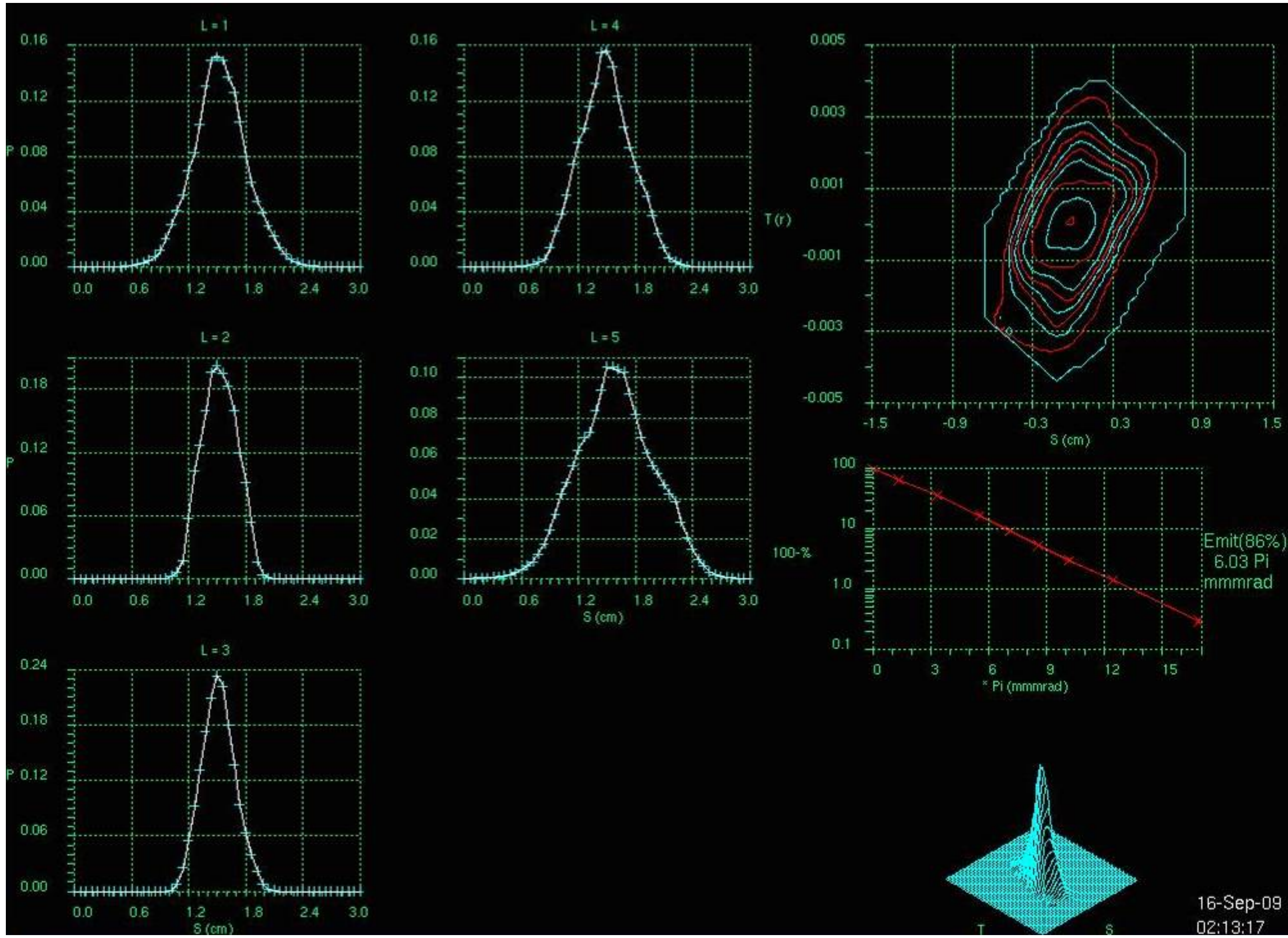
$$\eta(I_x) = \int_{s=I_x}^{\infty} p(s)\,ds = \exp\left(-\frac{I_x}{\varepsilon_x}\right)$$





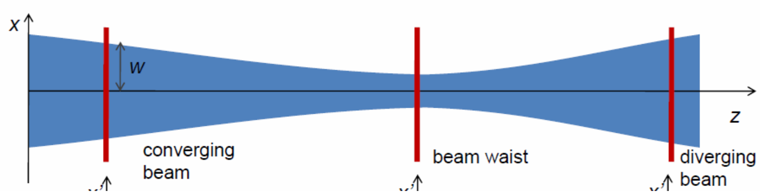
tomographic phase space reconstruction using five wire scanners

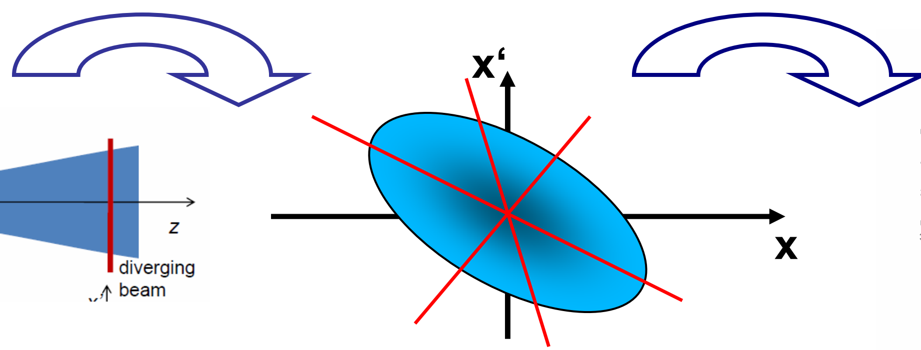
[D.Reggiani]

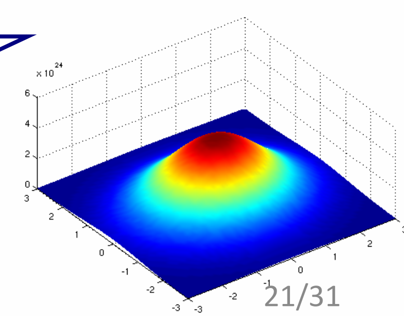


72 MeV:
ε_x **= 6 mm mrad**

method:
maximum entropy

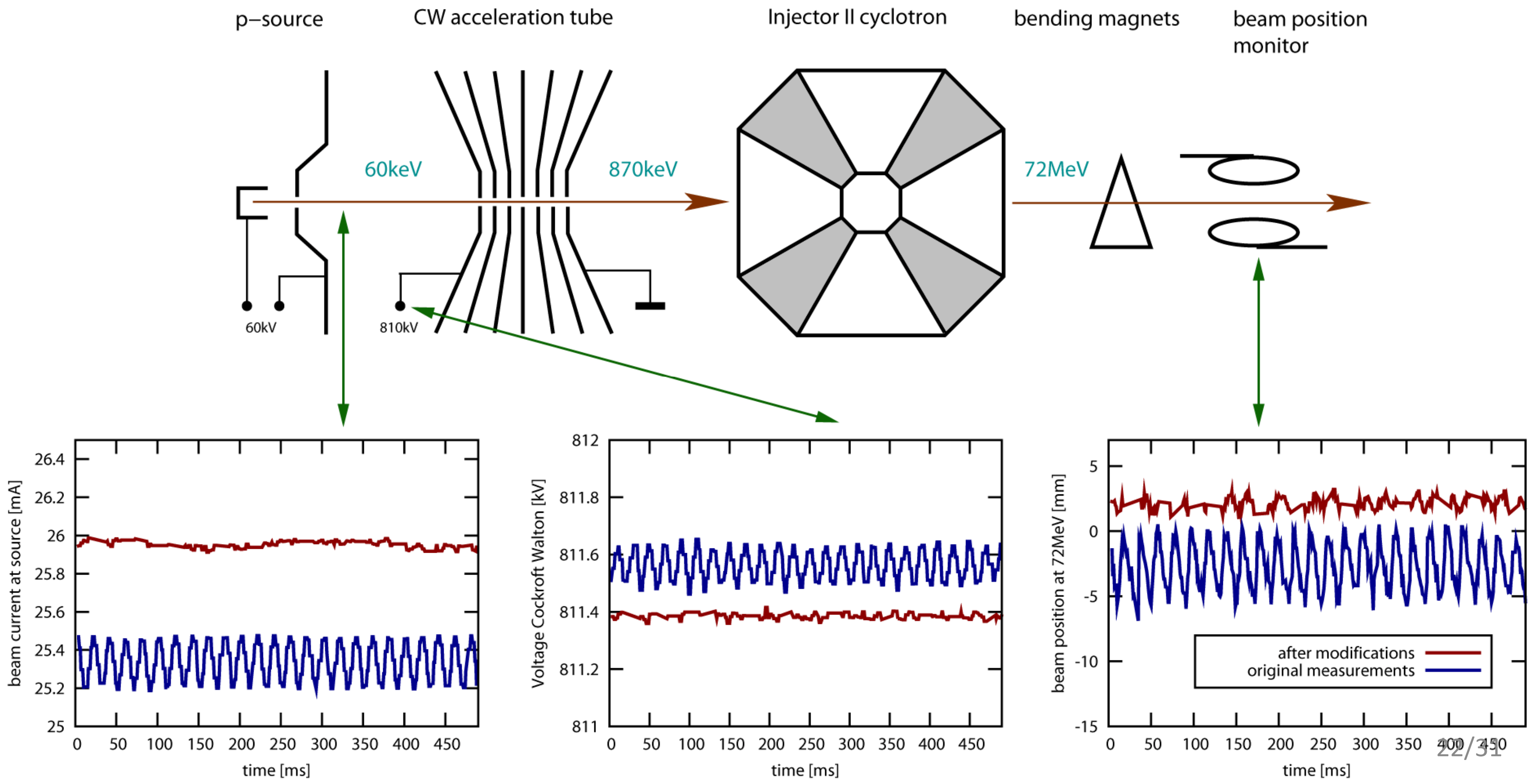


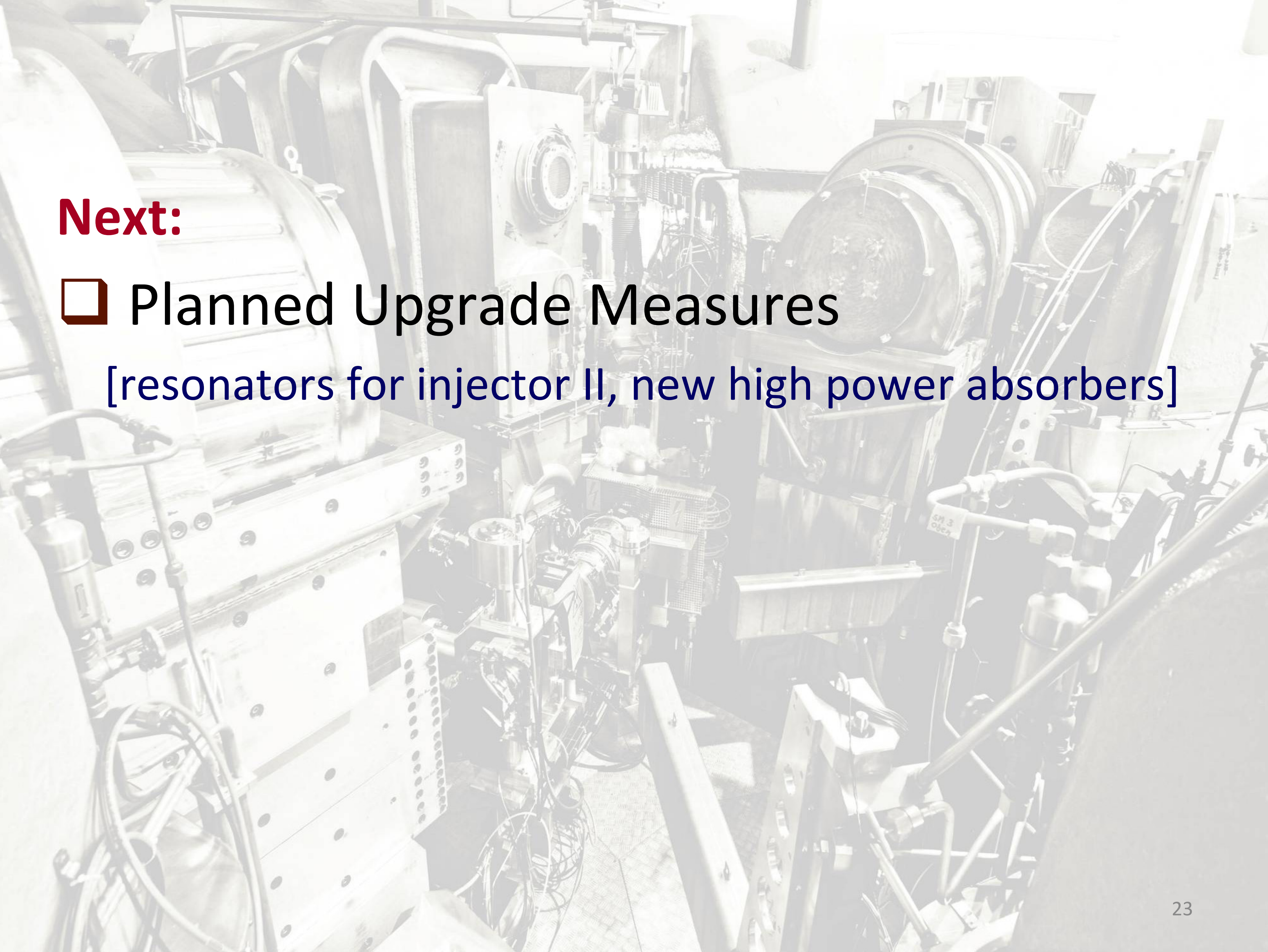




50 Hz ripple modulates the beam

- 50 Hz ripple was always present in HIPA, but was strongly enhanced after installation of the new ECR source
- **position modulation of ≈1rms beam width** (!) was observed
- it could be traced to a modulation of the RF power in the source, caused by an AC modulation of the filament heating of the magnetron





Next:

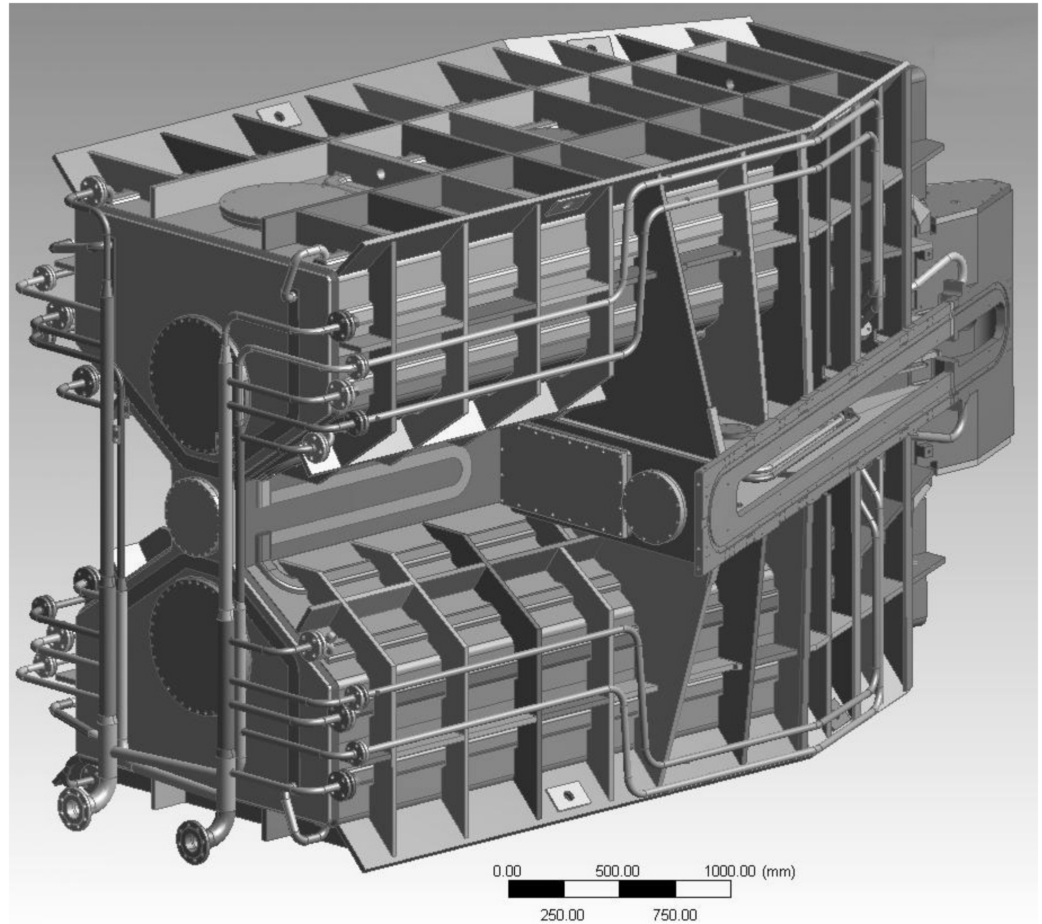
- Planned Upgrade Measures

  [resonators for injector II, new high power absorbers]

under production: new 50 MHz Resonator 2&4, Injector 2

Specification

Resonance frequency:	**50.6328 MHz**
Accelerating voltage:	**400 kV**
Dissipated power:	**45 kW@400kV**
Tuning range:	**200kHz**
Cavity RF-wall:	**EN AW 1050**
Structure:	**EN AW 5083**
Vacuum pressure:	**10^{-6} mbar**
Cooling water flow:	**15 m3/h**
Dimension:	**5.6x3.3x3.0 m**
Weight:	**7000kg**



status: first resonator delivered; tested at 100kW !

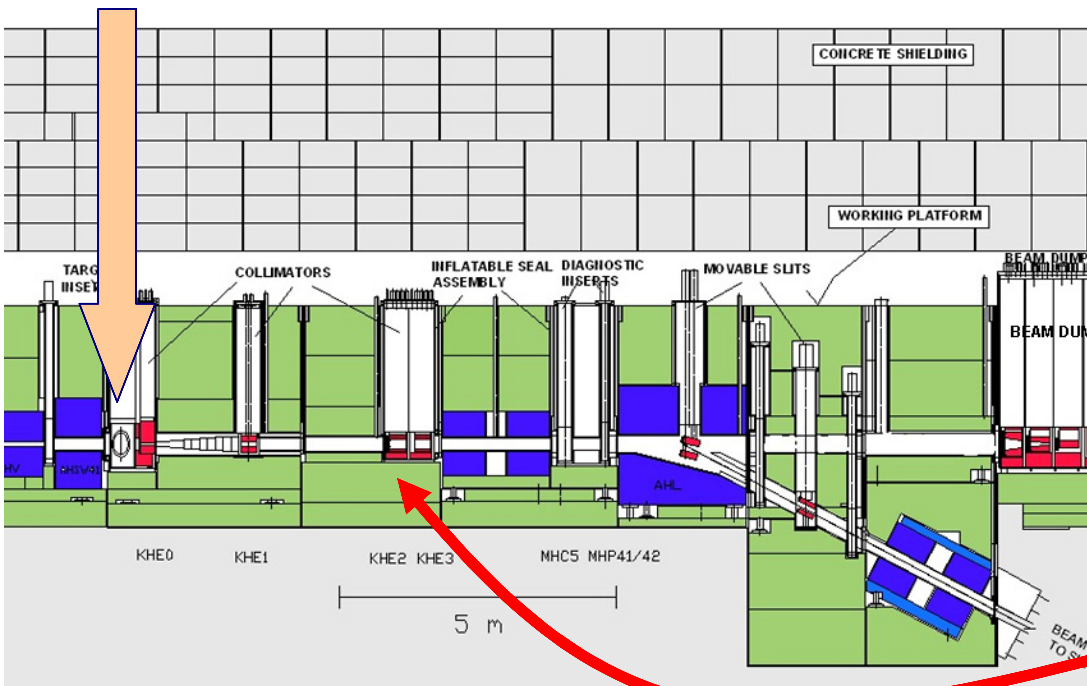
[design: PSI, company: SDMS/France]

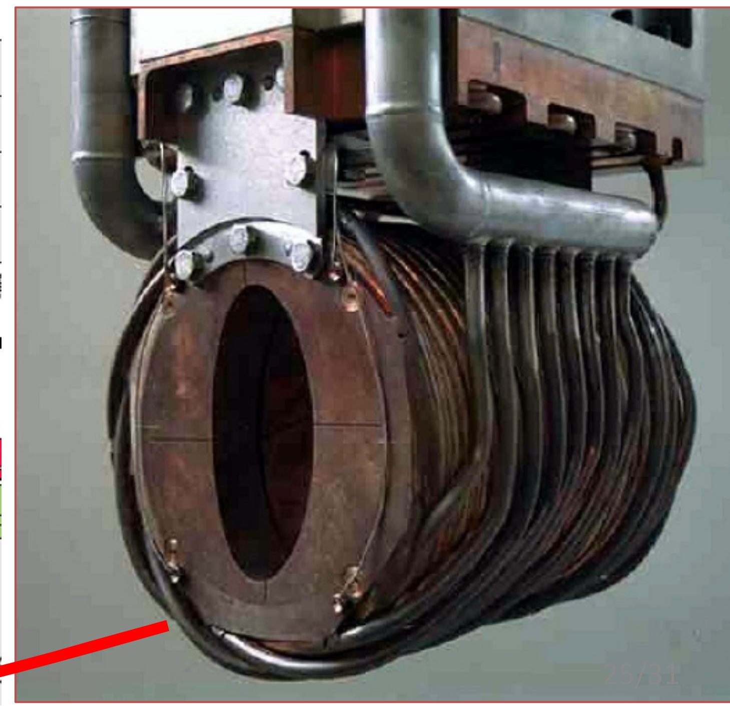
[see talk by Lukas Stingelin, WEM2CIO01]

high power collimators behind Meson production target

- power: **~85kW/2mA per absorber**, ~130kW for upgrade
- new collimator required with improved cooling / more even power distribution
- material **GlidCop** under discussion
- inspection of presently installed collimator: estimated dose **12..35dpa(!)**
- estimated activation **~150Sv/h(!)** @ 20cm distance **[D.Kiselev, J.Y.Lee]**

target E (d = 4cm)

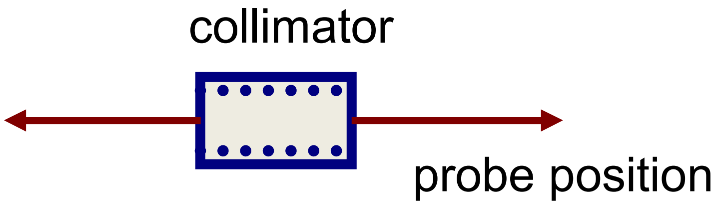




inspection of highly activated collimator in hot cell

observed:
thin flitter of Cu;
bulk copper intact;
no swelling

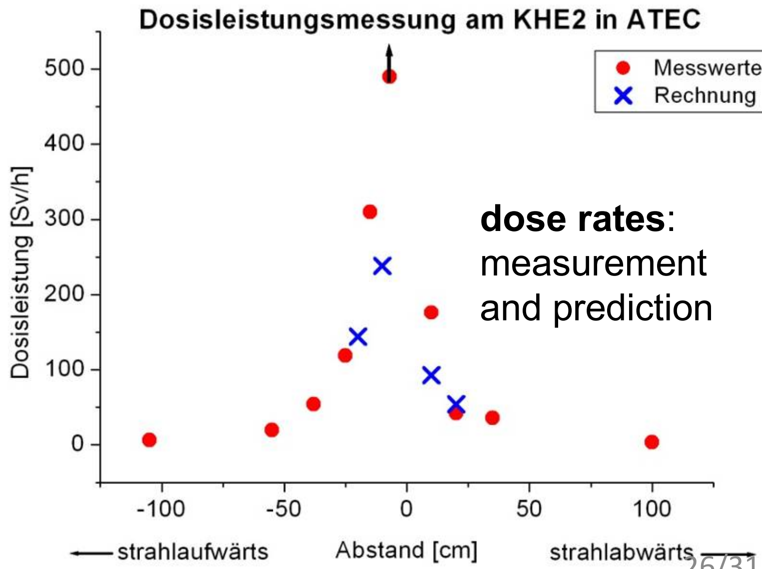
prediction of dose rates near activated components:
beam depostion → rad.nuclide distribution in space → prediction of dose rate at probe position



[D.Kiselev]

codes:
Cinder´90

MCNPX



dose rates:
measurement
and prediction

Next:

- Discussion and Summary

  [cyclotrons for high intensities, cyclotrons vs. linacs]

Discussion: high intensity beam in cyclotrons

critical: extraction loss

- beam tails, blowup by long. space charge (overlapping turns)
  [sector charge density] × [time in cyc.] → ∝ (# turns)^2
- loss at extraction element [1/turn separation] → ∝ (# turns)^1

large orbit radius *R* advantageous

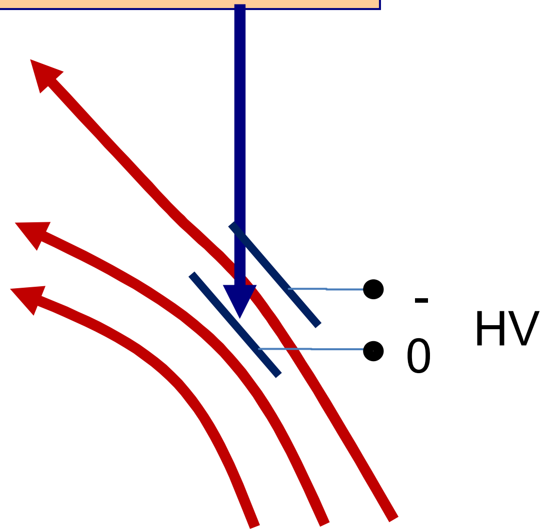
energy gain per turn ∝ 1/# turns

horizontal tune

$$\frac{dR}{dn_t} = \frac{R}{\gamma(\gamma^2-1)}\frac{U_t}{m_0c^2} \approx \frac{\gamma}{1+\gamma}\cdot\frac{R}{\nu_r^2}\cdot\frac{U_t}{E_k}$$

increasingly difficult with higher energy (limit ~ 1GeV)

Extraction electrode Placed between turns



In summary:

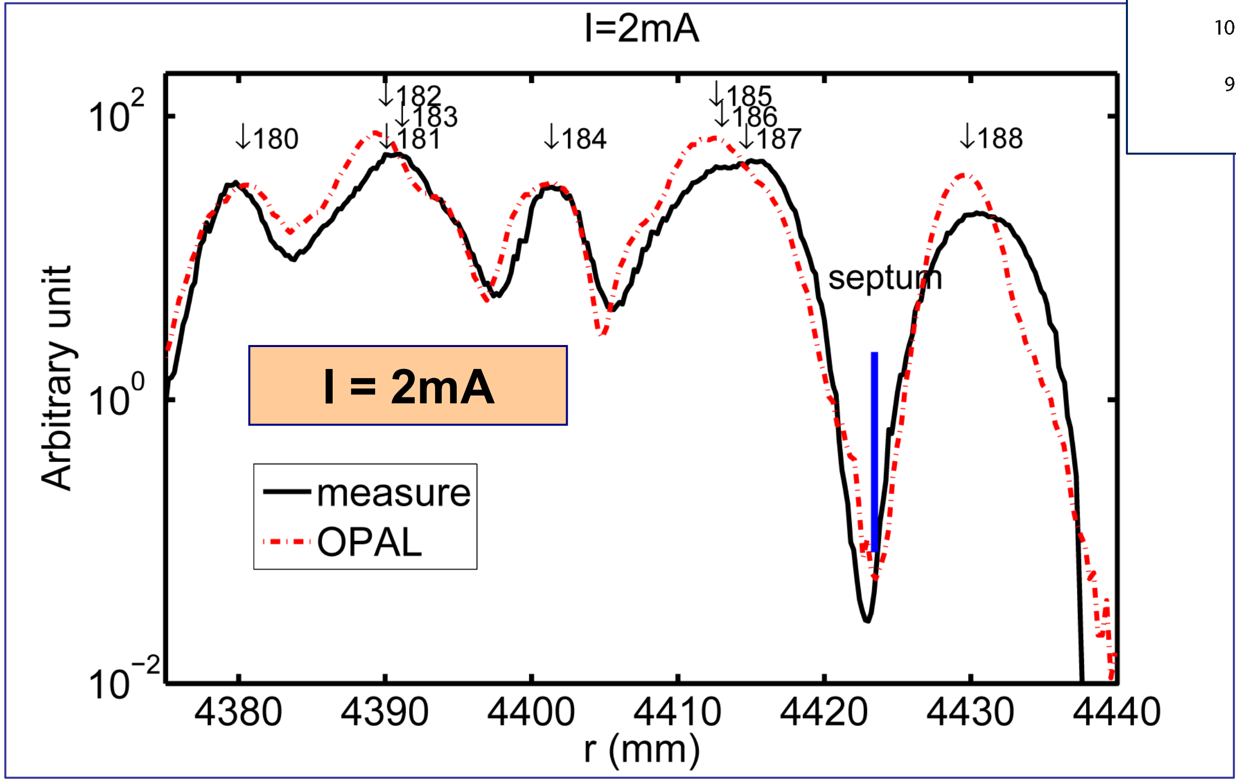
- scaling of losses ~ (# turns)^3 [Joho, 1981]

→ high gap voltage!

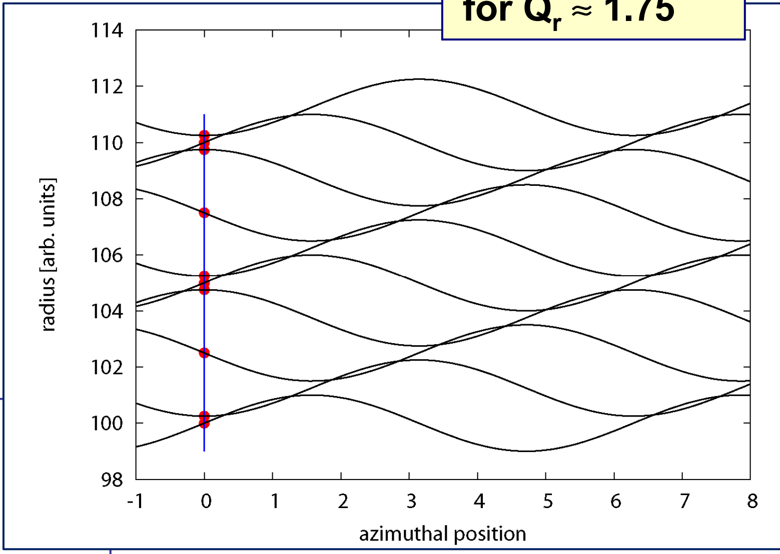
- large radius (non-compact cyclotron!)
- E_k < 1GeV

PSI Ring cyclotron – turn separation at extraction

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



turn pattern for $Q_r \approx 1.75$



Simulation work

[Y.J.Bi CIAE Beijing,

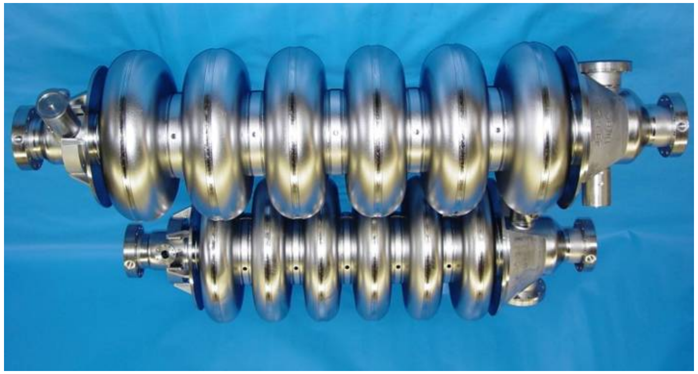
Poster: MOPCP045

A. Adelmann, PSI,

talk: THM2CIO01]

Discussion

PSI: 50MHz Resonator

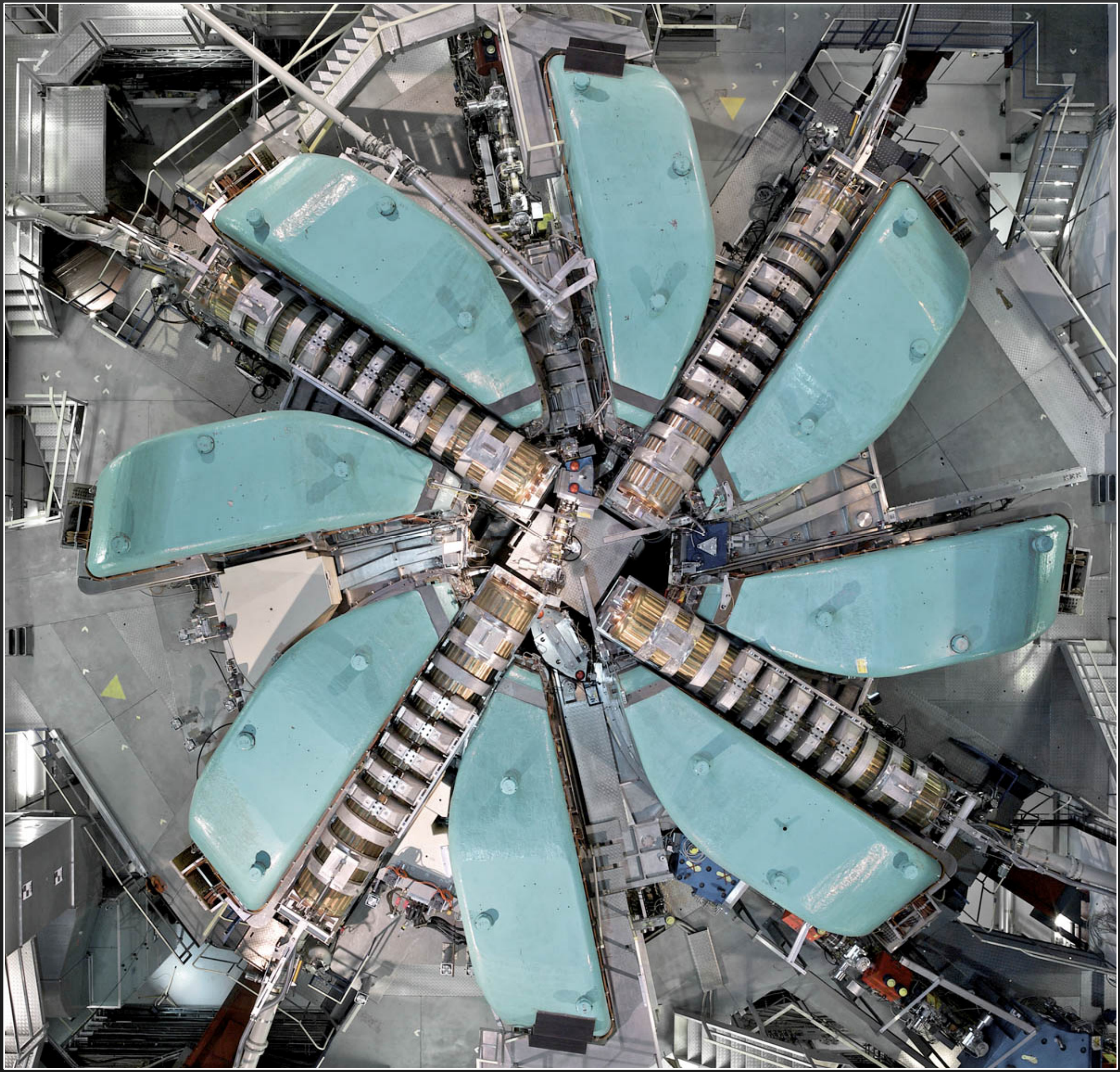


SNS supercond. Resonators (RI Instruments)

	Cyclotron		Superconduct. Linac
Pro	**compact in-expensive design**, efficient power transfer, only few resonators needed, relatively simple	Pro	**large beam aperture**, no bending fields, tuning straightforward, high energy possible
Con	**injection/extraction critical**, complicated bending field, **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

- excellent progress at PSI in recent years; the PSI accelerator delivers **1.3MW** beam power in CW mode; average reliability is **90%**; **25-50 trips** per day
- upgrade to 1.8MW is under way; next steps involve new resonators/amplifiers in injector II; new high power collimators behind target E
- the cyclotron concept presents an effective alternative **to generate a high power beam e.g. for ADS**; **1GeV/10MW cyclotron** seems feasible in next step; in comparison to LINACS beam dynamics and tuning of cyclotrons are difficult, though.



Thank you for your attention !