PAUL SCHERRER INSTITUT

Wir schaffen Wissen – heute für morgen

Paul Scherrer Institut

D. Reggiani, A. Parfenova

HIPA Status, Dynamics and Diagnostics

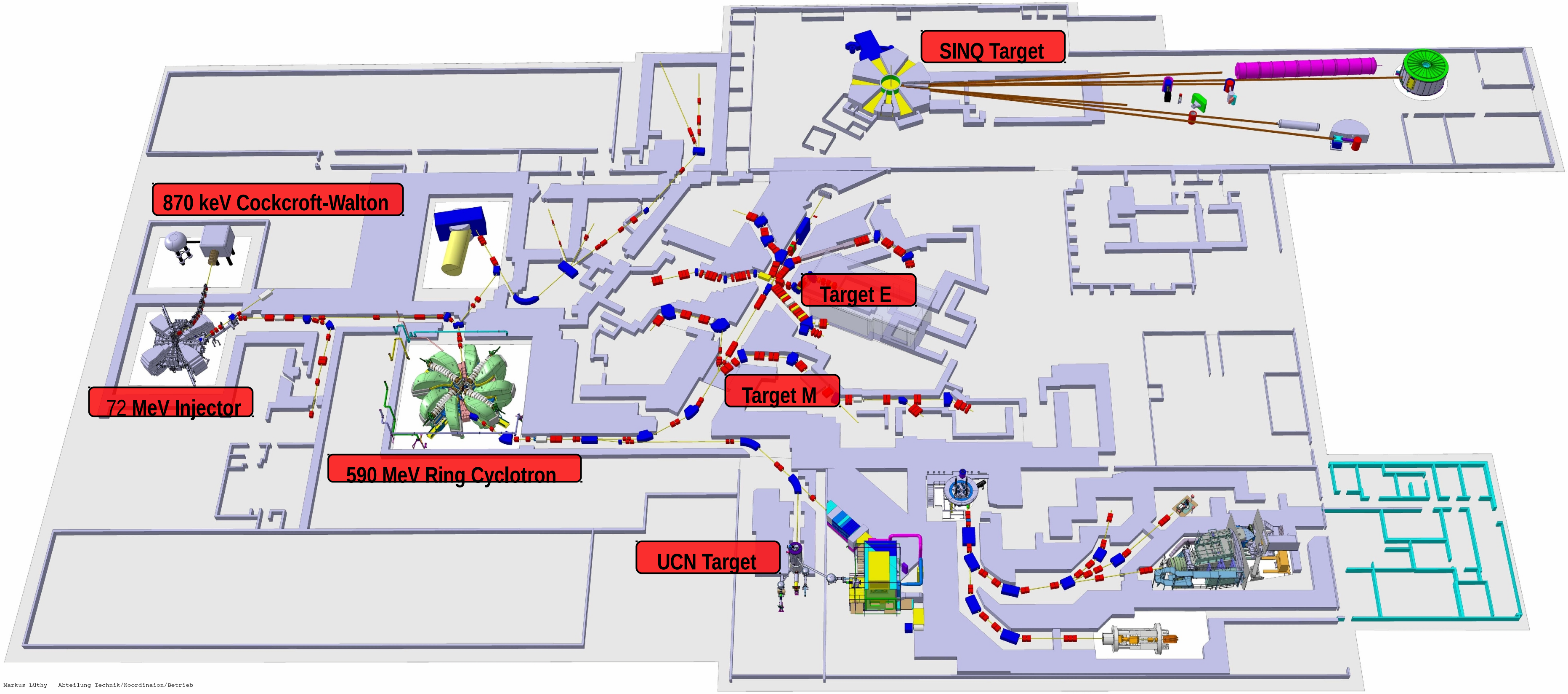
Beam Dynamics meets Diagnostics Workshop, 05.11.2015, Florence, Italy

Outline

- Introduction to the PSI High Intensity Proton Accelerator (HIPA)
- HIPA status and beam delivery statistics
- Ring Cyclotron:
  - Beam Dynamics and Extraction
  - Beam diagnostics: phase measurement
  - Flat-Top cavity Issues
- Beam transfer to the meson production targets M/E and SINQ
- Beam switchover to the UCN source
- Beam diagnostics for setup & optimization
- Conclusion & Outlook

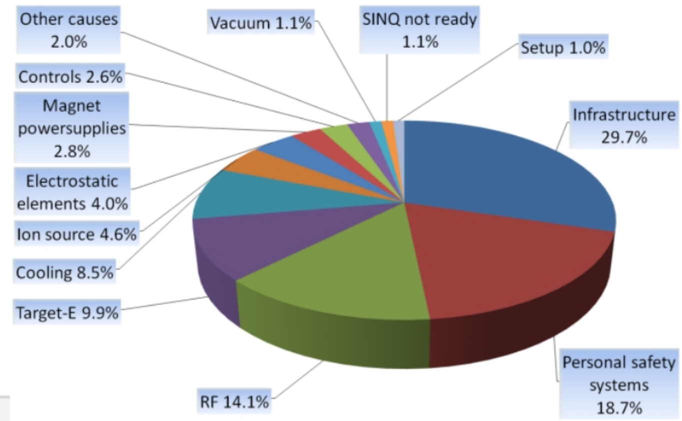
The PSI Proton Accelerator Facility

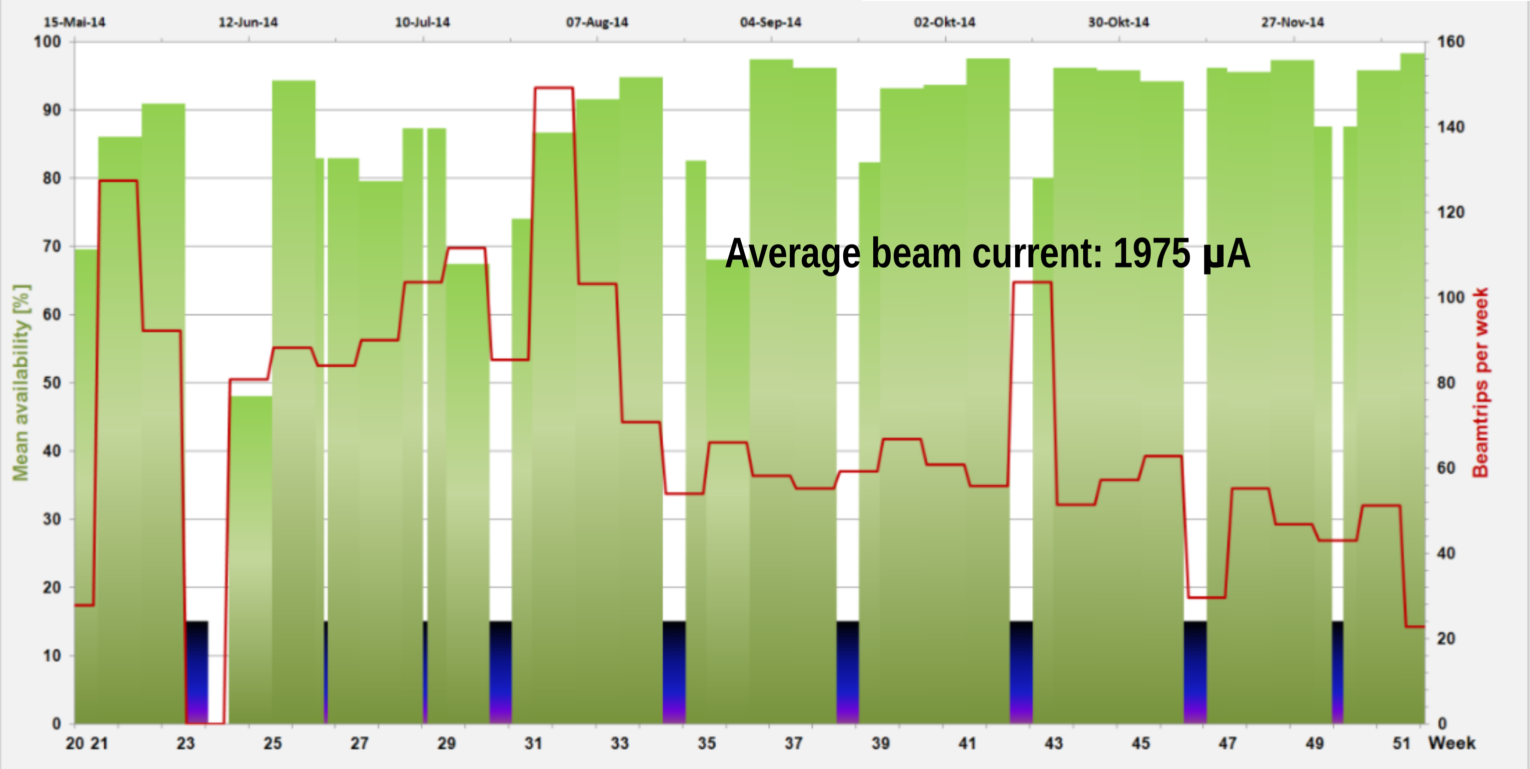
- CW, 590 MeV, up to 2.4 mA (1.4 MW) to meson production targets M and E (7 beam lines)
- CW, 575 MeV, up to 1.7 mA (0.95 MW) to neutron spallation target SINQ (18 beam lines)
- Macro-Pulsed, 1% duty-cycle, 590 MeV, 2.2 mA (1.3 MW) to UCN target (3 beam lines)
- Upgrade program towards 3.0 mA (1.8 MW) ongoing!



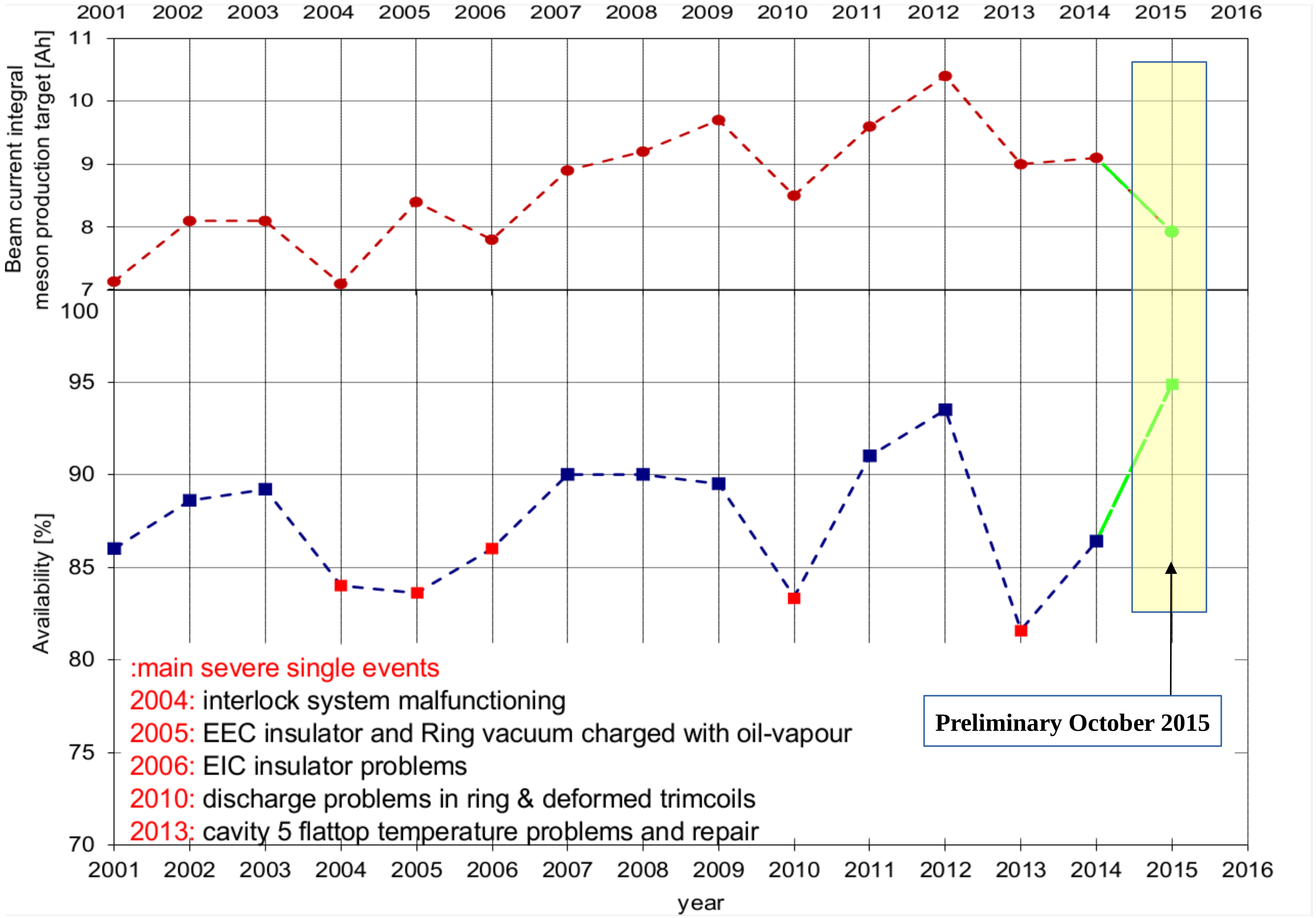
HIPA 2014 Operation Statistics

Beam-time statistics for HIPA	2014
Total scheduled user beam time	**4608 h**
Compensated outage time	**+84 h**
Beam current integral	
To meson production targets	9.1 Ah
To SINQ	6.0 Ah
To UCN	0.02 Ah
To isotope production targets	0.08 Ah
Outages	
Total outages (current < 1 mA, time > 5s) minutes)	520 h
Availability (with compensated outage time)	86.4%

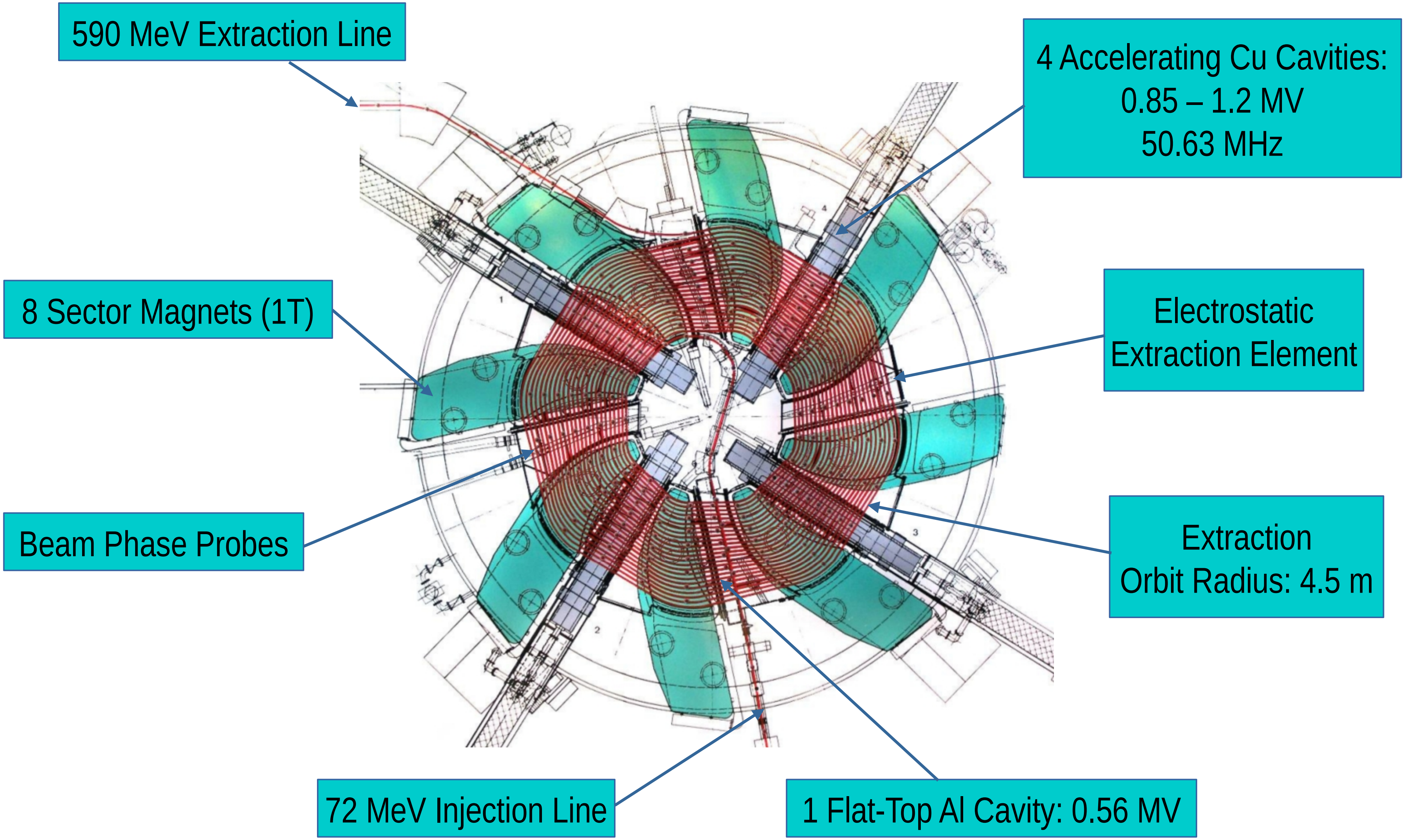




HIPA Performance 2001 - 2015

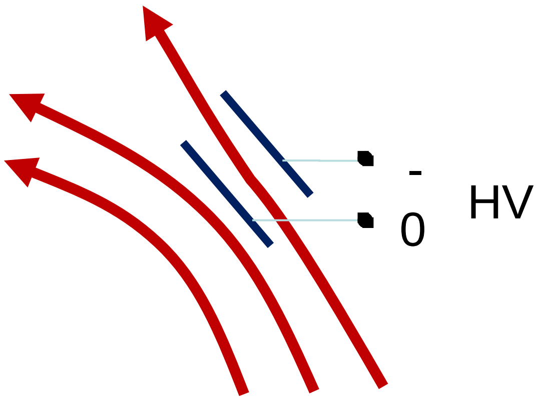


The 590 MeV Ring Cyclotron



Extraction from Ring Cyclotron

Extraction electrode placed between last two turns



Extraction losses: limiting factor of any high power cyclotron!

Losses minimization through:

- «Thin» extraction device
- Large turn separation

Turn separation

- Radius increment per turn

Orbit Radius: Large Machine!

Large energy gain per turn: Powerful RF System!

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

Higher Energy disadvantageous Limit: E < 1 GeV

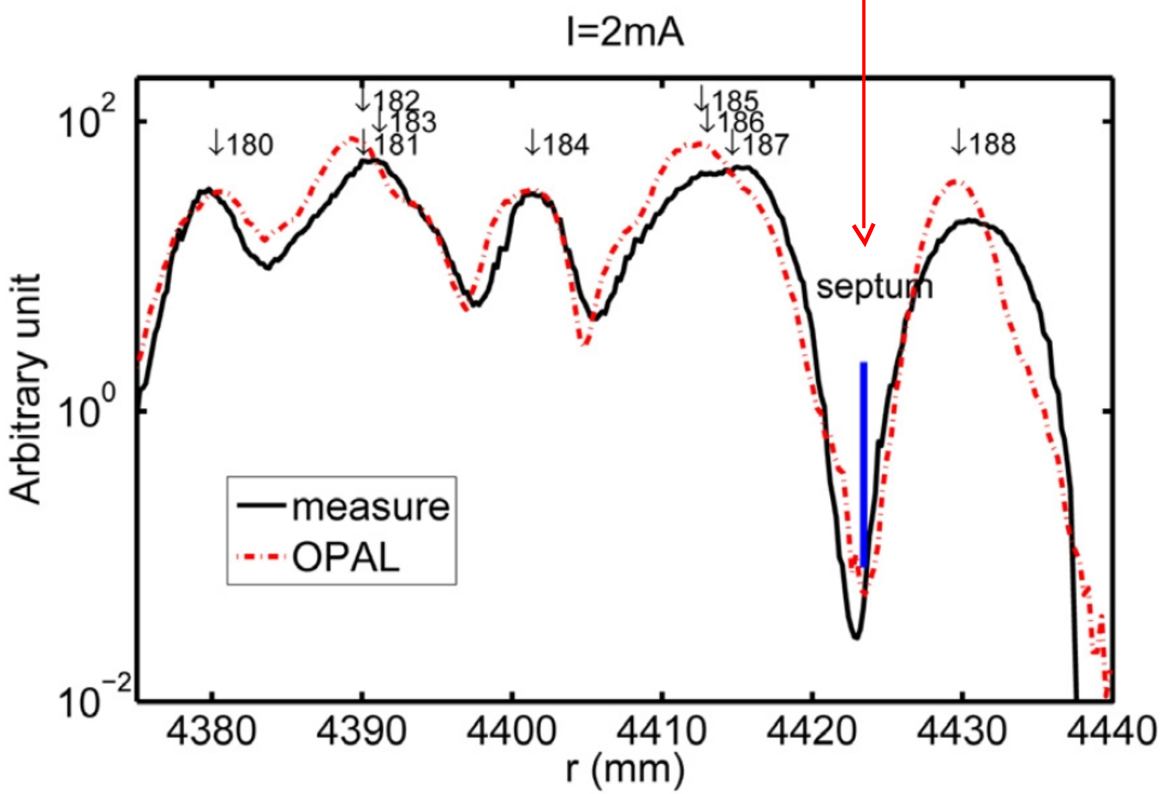
- Off-center orbit Extraction:

Exploit betatron oscillation to increase turn separation by a factor of 3!

Turn Separation at PSI Ring

- Acceleration term: $$\frac{dR}{dn_t} = \frac{R}{\gamma(\gamma^2 - 1)} \frac{U_t}{m_0 c^2} \xrightarrow[R\,=\,4460\text{ mm},\ U_t=\,3\text{MeV},\ \gamma\,=\,1.63]{\text{at exctraction}} \approx 6\text{ mm}$$

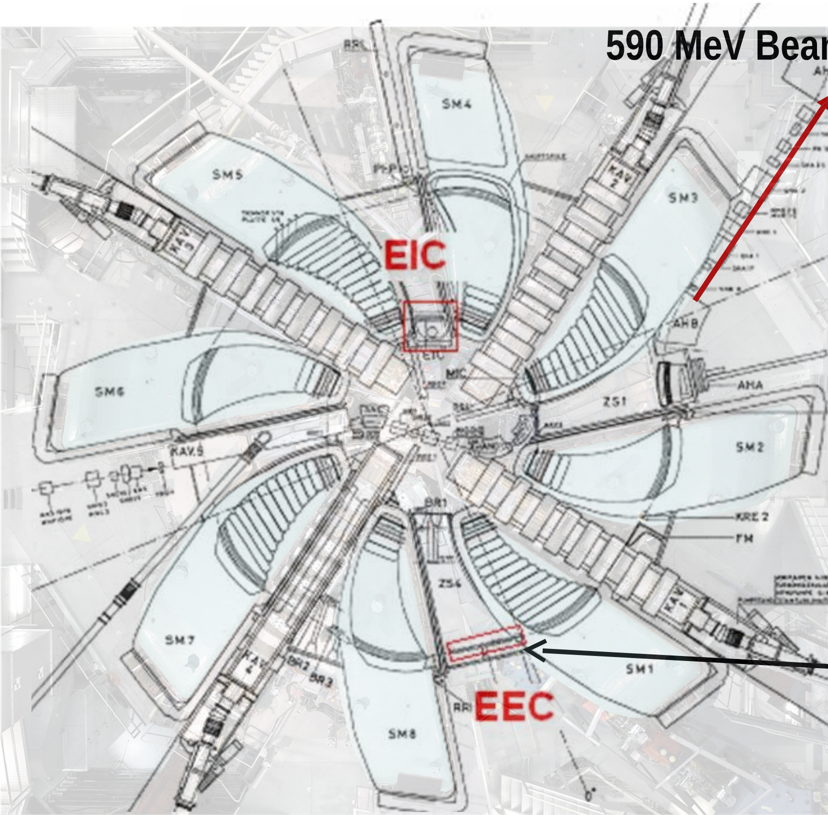
- Including off center orbit extraction: ***ΔR = 18 mm***

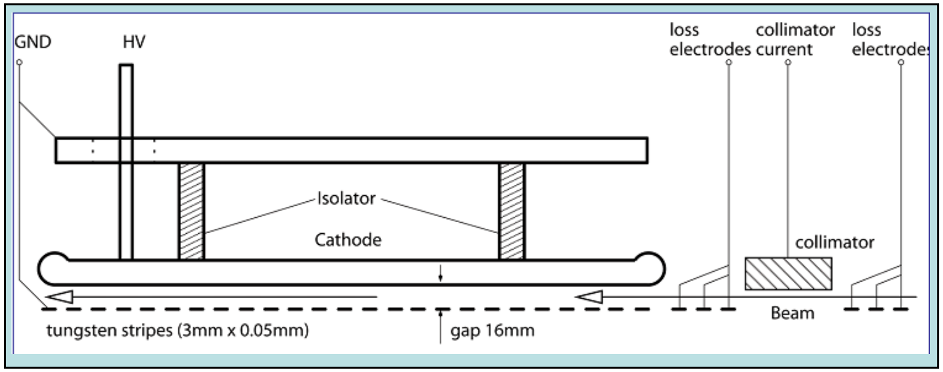


Y.J. Bi et al., Proceedings HB2010

Principle of Extraction Channel

590 MeV Beam Exctraction Line





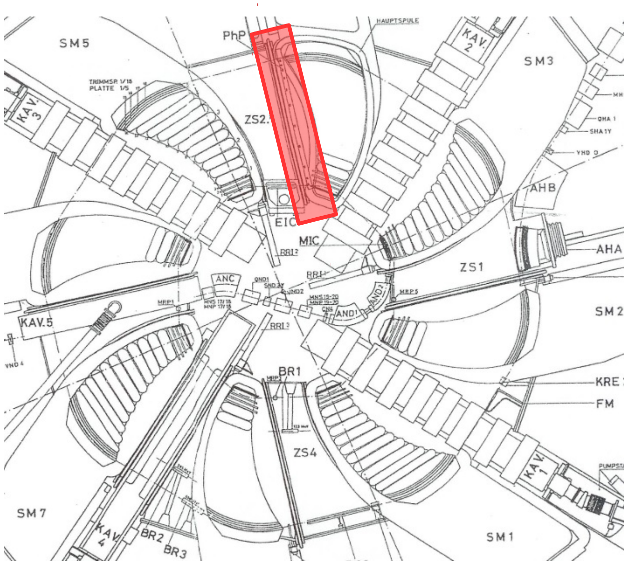
EEC: Electrostatic Extraction Channel

Gap = 16 mm θbeam = 8.2 mrad

Extraction Efficency: 99.98 %

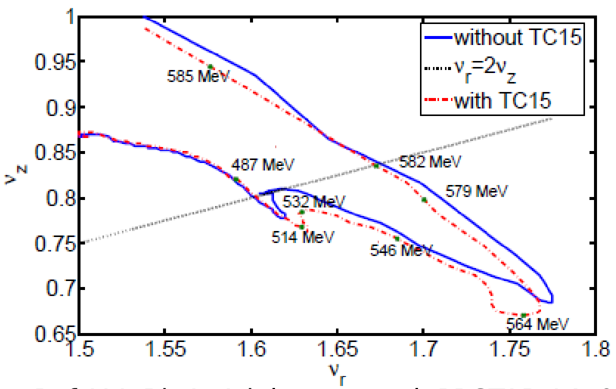
Ring Phase Probes and Trim Coils

11 Phase probes measure **the beam phase at different radial positions in the ring.**

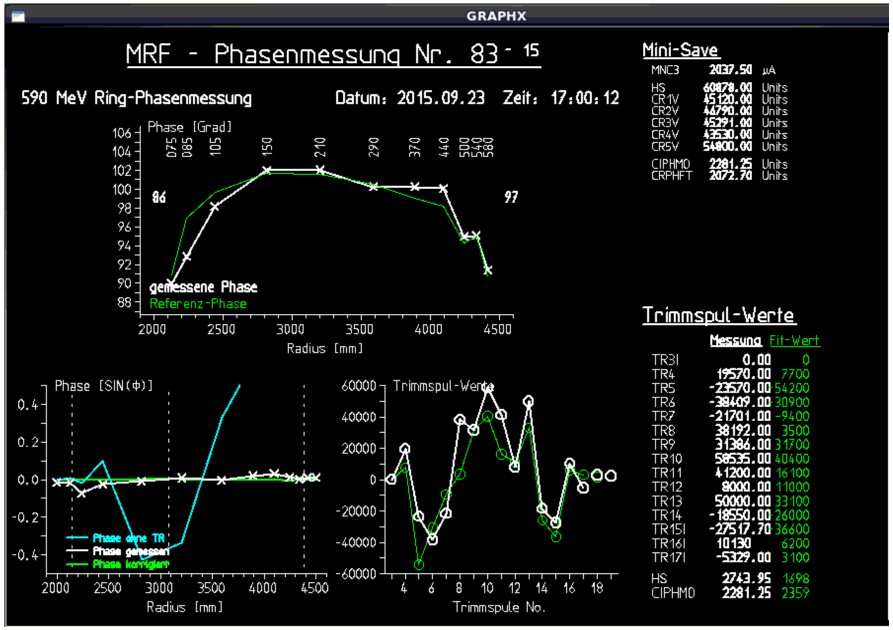


- Goal: detect the phase of the beam wrt the accelerating RF field in the cavities and find best trim coils setting
- 17 trim coils adjust the main magnetic field to keep the phase of the beam as close as possible to the reference (RF) phase
  $\longrightarrow$ maintain isochronism
- Trim coil 15 requires strong excitation to avoid losses via multiple crossing of $\nu_r = 2\nu_z$ coupling resonance
- Program (by M. Humbel) fits optimal setting for trim coils using phase measurement through iterative procedure

Tune diagram PSI ring 590 MeV Ring-Cyclotron

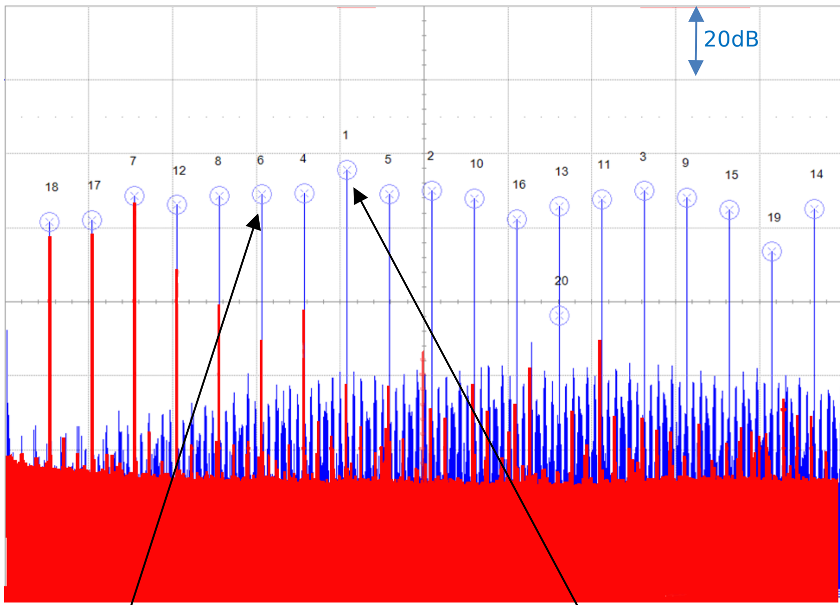


Ref. Y. J. Bi, A. Adelmann et al, PRSTAB 14, 054402 (2011)



Ring Cyclotron Phase Measurement

RF Pickup with 2.2mA (Blue) / without (Red)



Peaks	Frequency	Amplitude
1	405.0627 MHz	-24.2 dBm
2	506.3284 MHz	-29.8 dBm
3	759.4927 MHz	-30.0 dBm
4	354.4299 MHz	-30.5 dBm
5	455.6956 MHz	-30.7 dBm
6	303.7970 MHz	-30.9 dBm
7	151.8985 MHz	-31.2 dBm
8	253.1642 MHz	-31.3 dBm
9	810.1254 MHz	-31.8 dBm
10	556.9612 MHz	-32.0 dBm
11	708.8597 MHz	-32.1 dBm
12	202.5314 MHz	-33.7 dBm
13	658.2269 MHz	-34.1 dBm
14	962.0240 MHz	-34.8 dBm
15	860.7583 MHz	-35.1 dBm
16	607.5935 MHz	-37.6 dBm
17	101.2657 MHz	-37.9 dBm
18	50.6328 MHz	-38.2 dBm
19	911.3903 MHz	-46.4 dBm
20	658.1950 MHz	-63.6 dBm

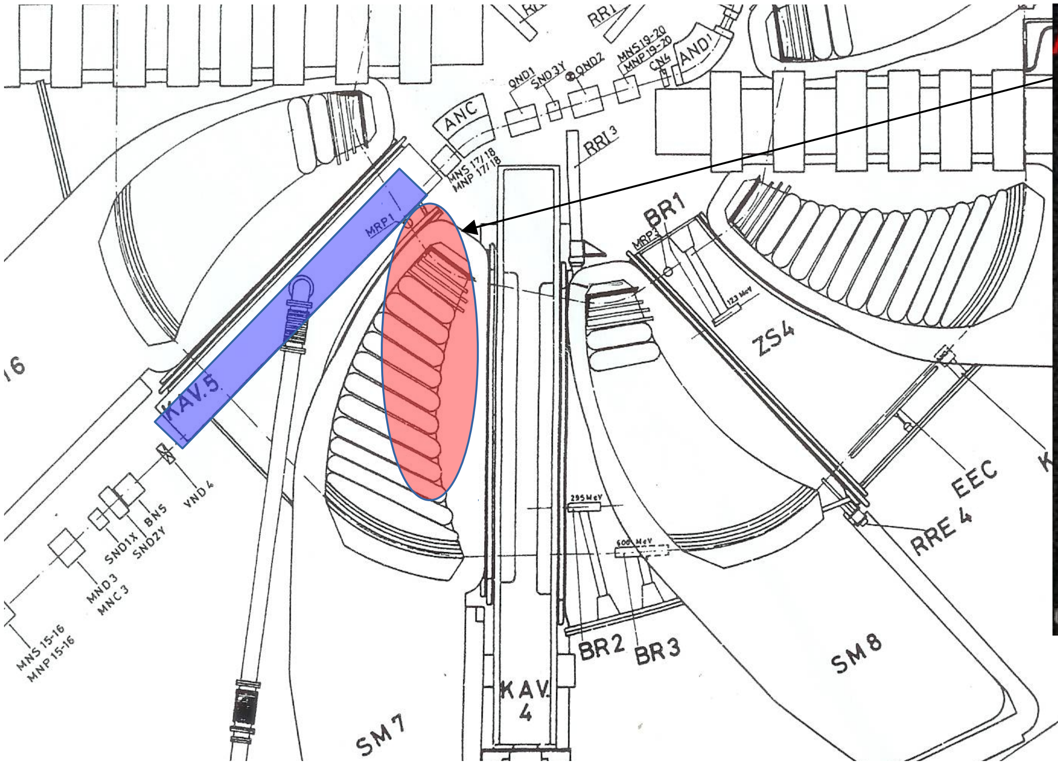
SNR = 40 dB at 6th Harmonic

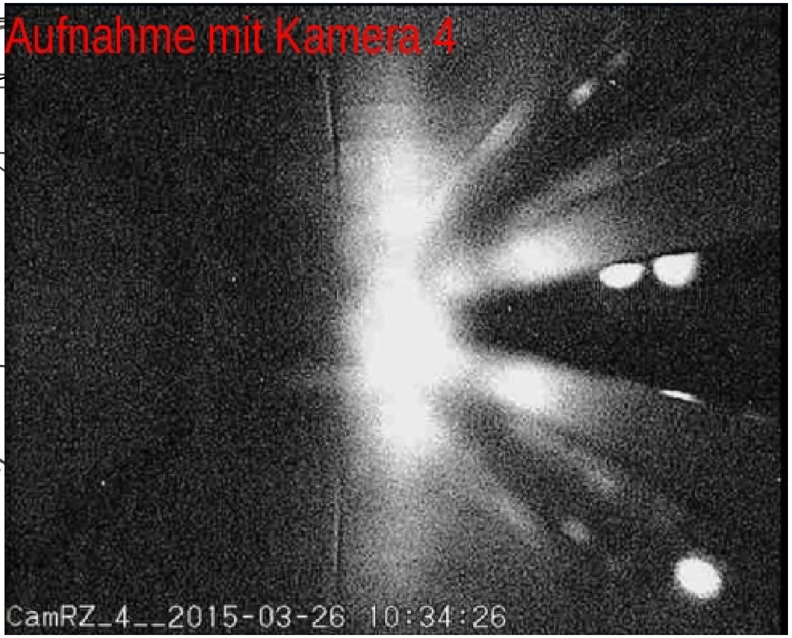
SNR = 60 dB at 8th Harmonic

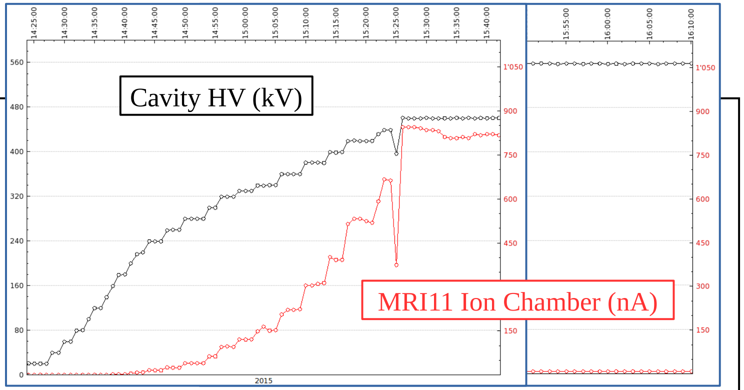
- Since 2008 new copper cavities run at higher voltage (850 kV) and larger RF power.
- Increased RF power interferes with old phase probes measurements at the 2nd harmonic (bad signal to noise ratio)
- At 6th harmonics RF field interference is much weaker
- New strategy: **measure the 6th harmonics of the beam signal at 303.79 MHz** and compare it with the reference phase delivered by the RF system
- **RF field noise measured with beam off** and subtracted from signal at normal operation
- Resulting signal defines the beam phase

Courtesy of P.-A. Duperrex, E. Johansen, U. Mueller

Flat Top Cavity Issues







30.03.2015 14.04.2015

3rd Harmonic 560kV Flat Top Cavity - reduces beam energy spread
- allows beam intensity > 1.0 mA

FT-Cavity Known Issues (affecting acc. perf. In 2010, '13, '14):

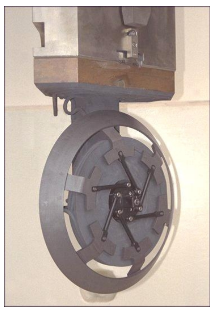
- **Multipacting** in Flat Top Cavity
- RF-induced **glowing** effects in SM7
- **High reflected RF-Power** and wall deformation

Significantly improvement after painting the FT cavity inner wall with **Aquadag** colloidal graphite coating (April 2015)

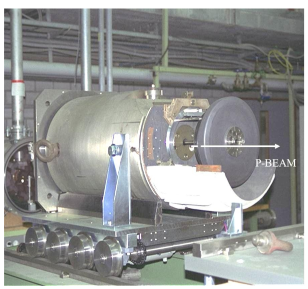
The 590 MeV Proton Channel

Cu-Collimator

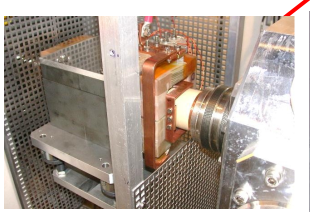
Target E
40 mm thick

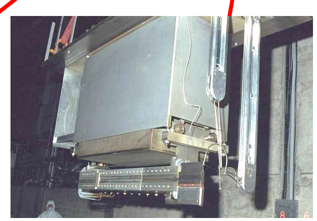


Target M
5 mm thick

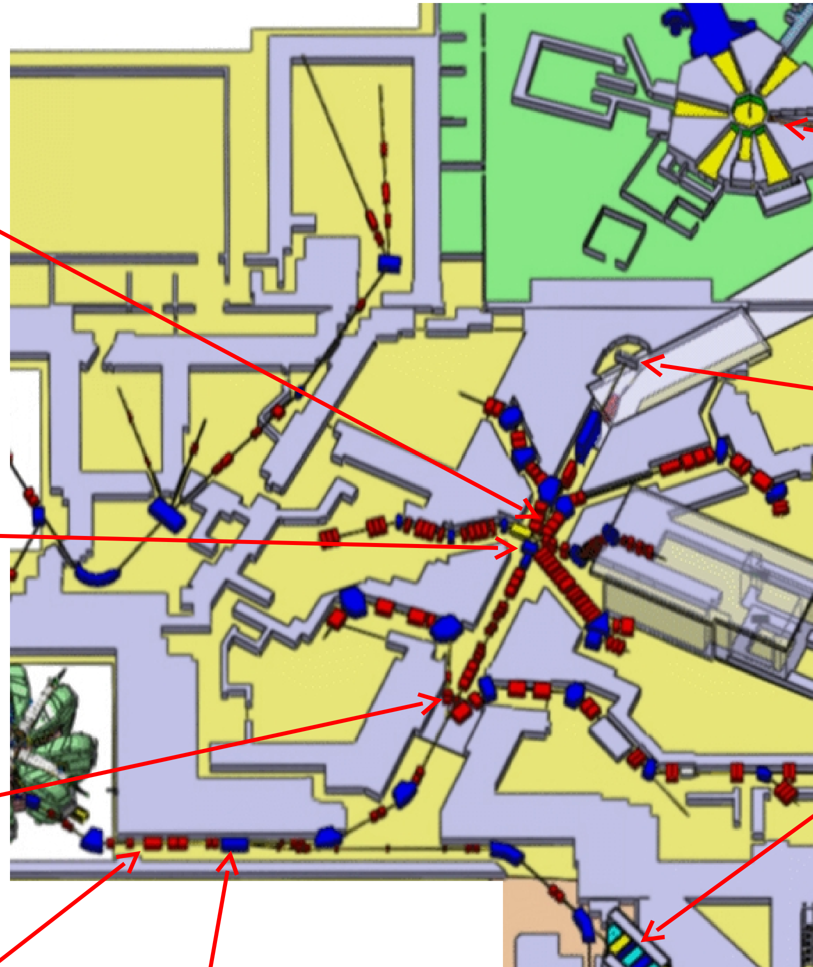


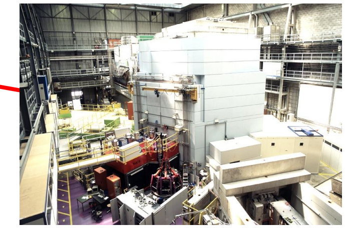
UCN
Kicker



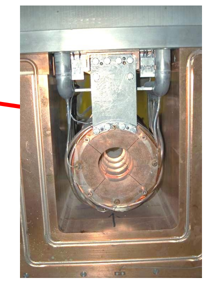


Septum

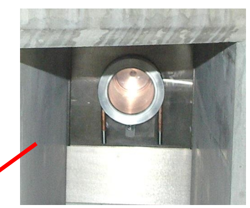




SINQ
Spallation
Source



SINQ
Beam-Dump

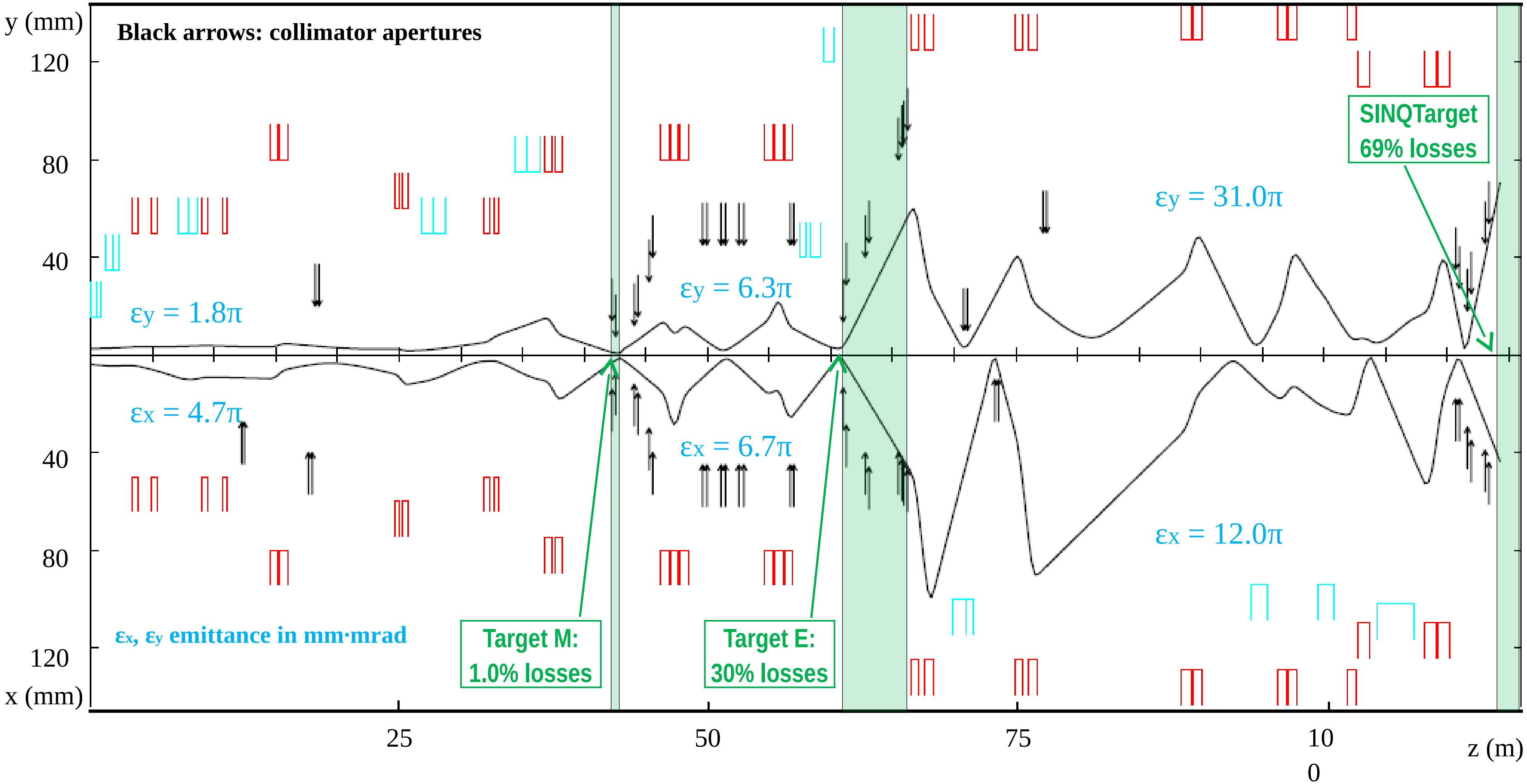


UCN
Beam-Dump

UCN
Spallation
Source

1.4 MW Beam Transport

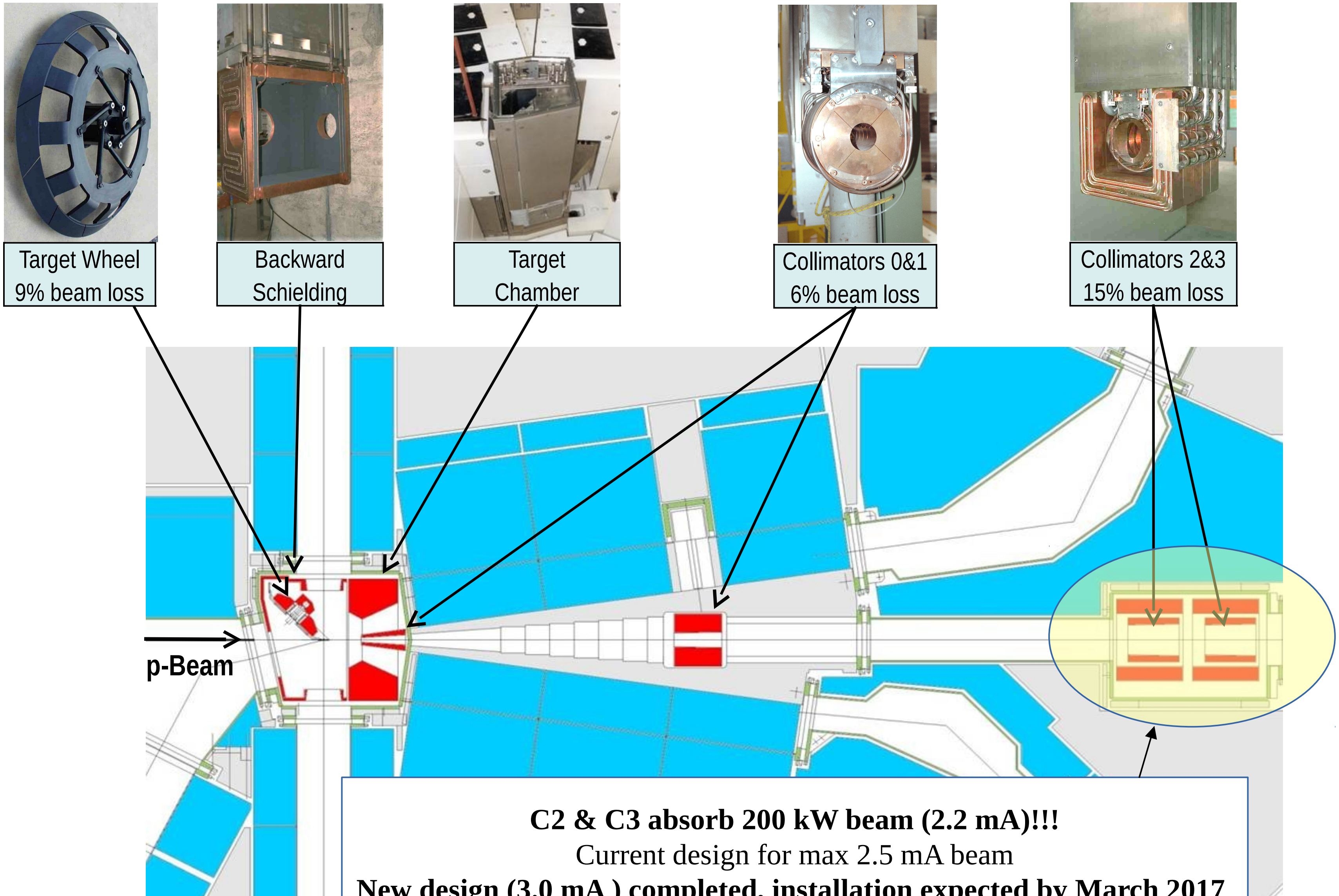
1.4 MW Beam Envelopes from Cyclotron Extraction to SINQ Target (with Magnet and Collimator Apertures)



Peak beam current density on target M and E: 200 kW/mm²

Average losses away from targets: 0.6 W/m

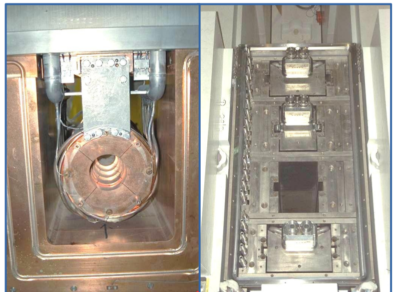
Target E Region



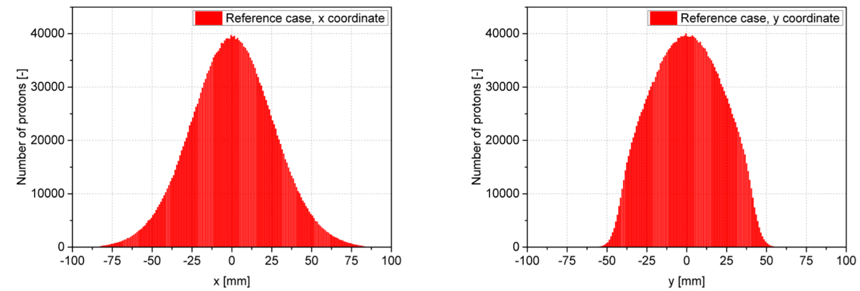
C2 & C3 absorb 200 kW beam (2.2 mA)!!!
Current design for max 2.5 mA beam
New design (3.0 mA) completed, installation expected by March 2017

Beam Transport to SINQ

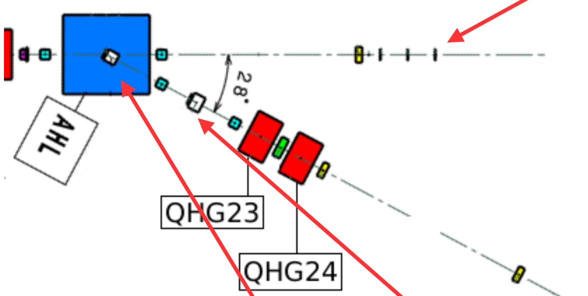
700 kW beam dump
(1 MW beam on target E)

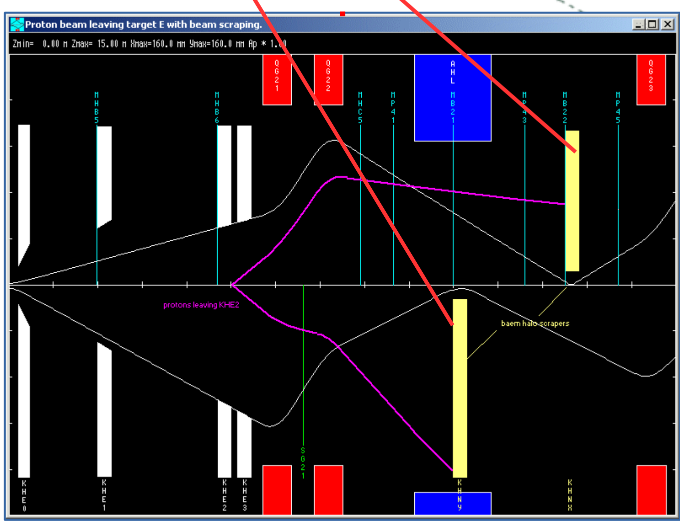


Beam distribution at SINQ target



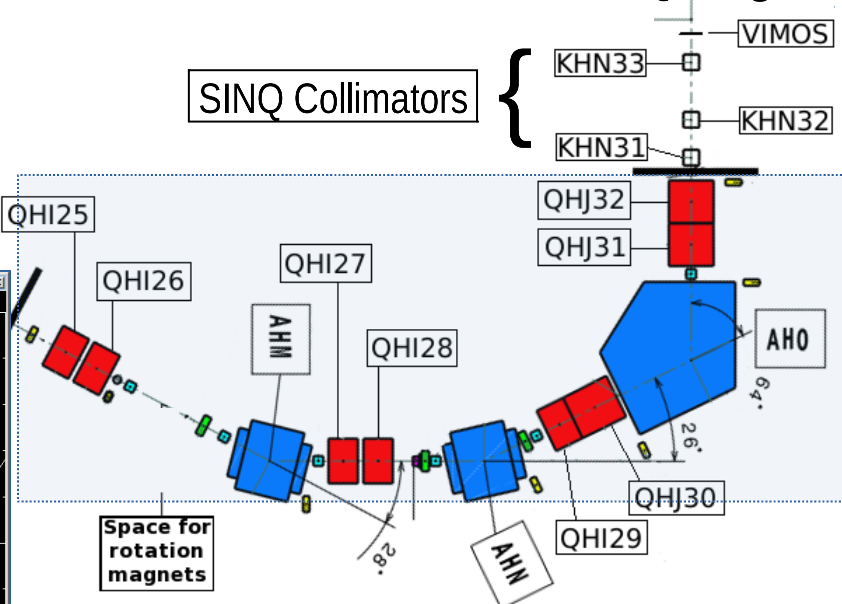
Vertical bending plane

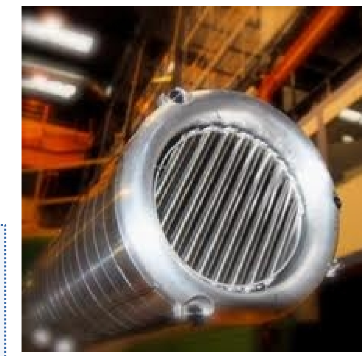




SINQ Target

SINQ Collimators





H and V movable slits
(halo scrapers)

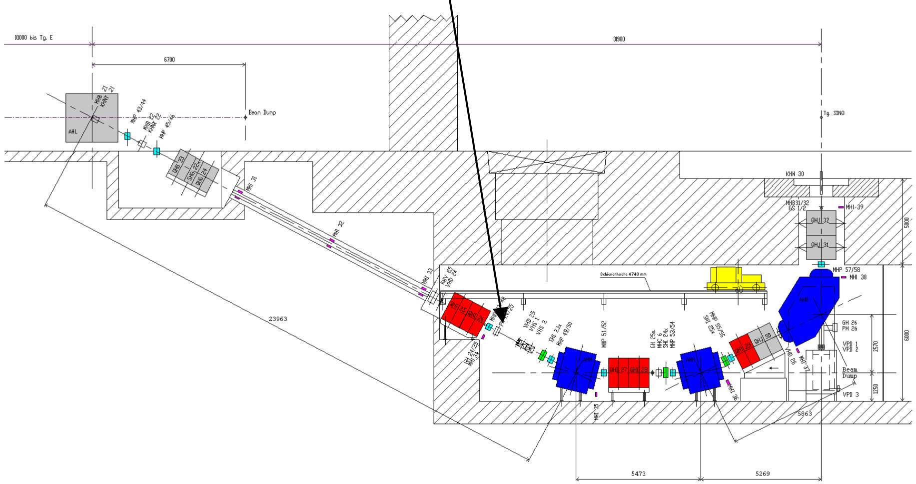
Feasibility Study: SINQ Beam Rotation System

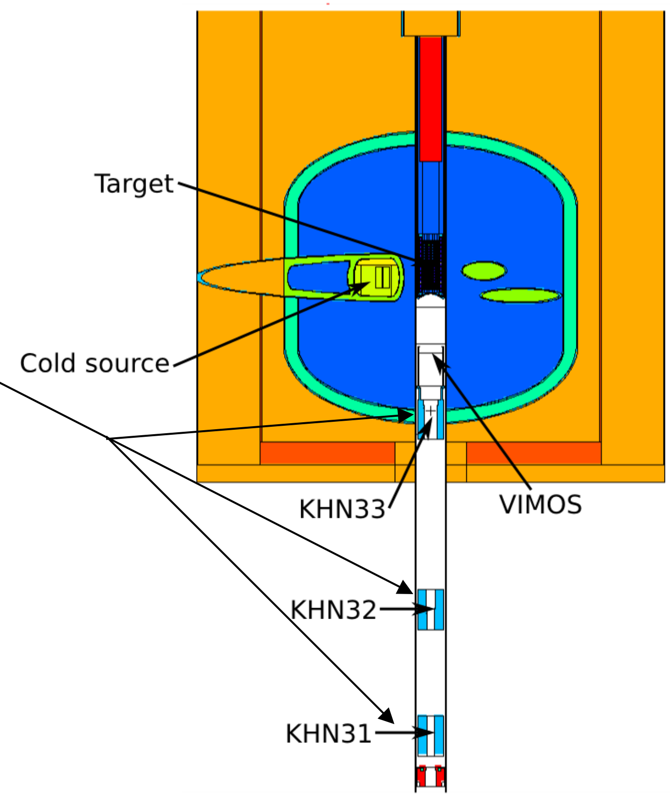
Peak current density on the SINQ target could become an issue in view of an intensity upgrade
→ Consider a beam flattening system:

- Non linear elements (i.e. octupoles): distort beam footprint and can present edge peaks
- Fast beam rotation system: seems a good option

Simulation strategy

- Losses from rotating beam not significantly larger than standard case (critical region: SINQ collimators)
- BRS-Location: ~25 m upstream of SINQ target (only accessibe free spot)

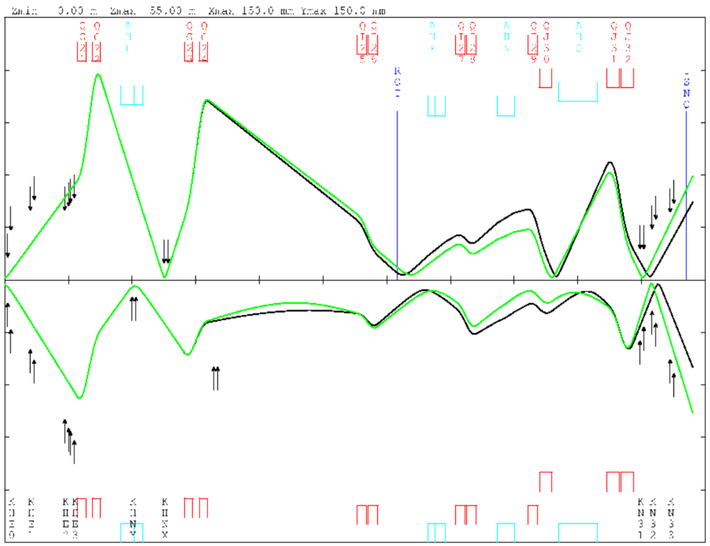




Tibor Reiss, Davide Reggiani, Mike Seidel, Vadim Talanov, and Michael Wohlmuther, Phys. Rev. ST Accel. Beams 18, 044701 – Published 2 April 2015

SINQ Beam Rotation: Transport-Turtle Simulations

Transport simulation: beam envelope

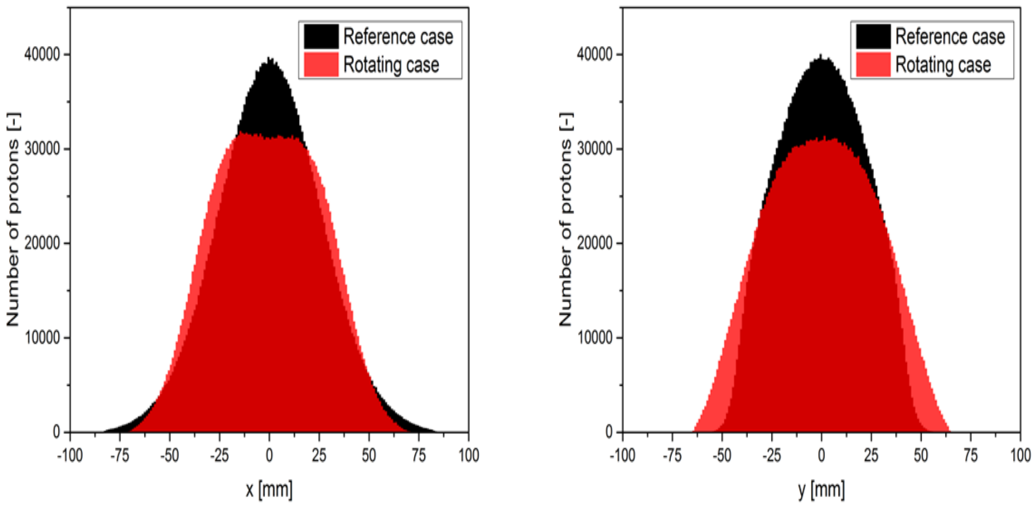


Without rotation

with rotation
(~25% smaller envelope)

Turtle simulation: beam distribution on SINQ

with rotation: ~ 50% less beam current density
in the central cm²

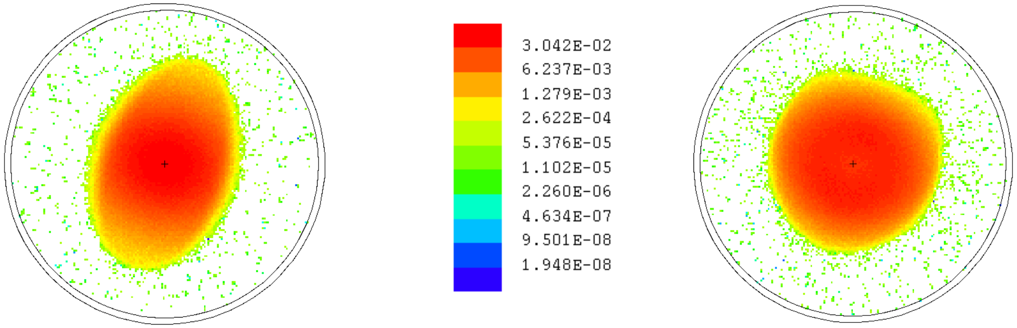


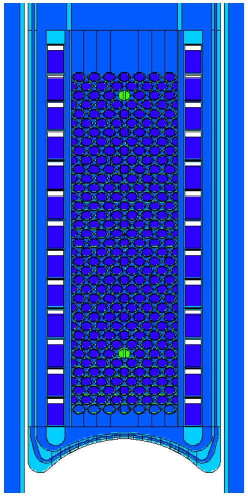
Sizable but still acceptable increase of beam losses on SINQ collimators

SINQ Beam Rotation: MCNPX Simulations

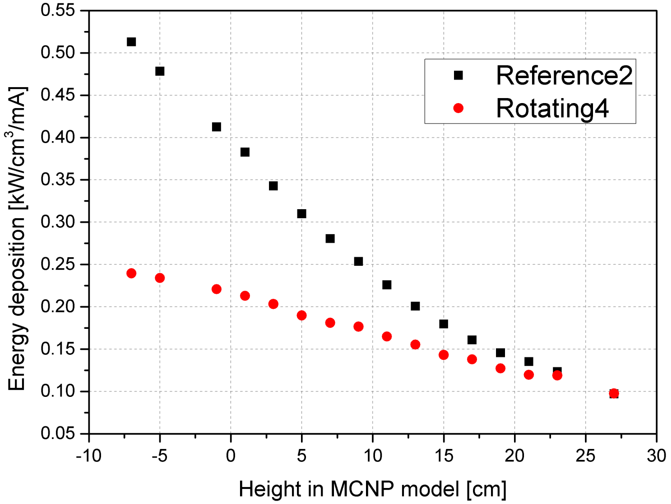
MCNPX simulation of the beam distribution on the SINQ target entrance window

No rotation (current situation) **Rotating Beam**

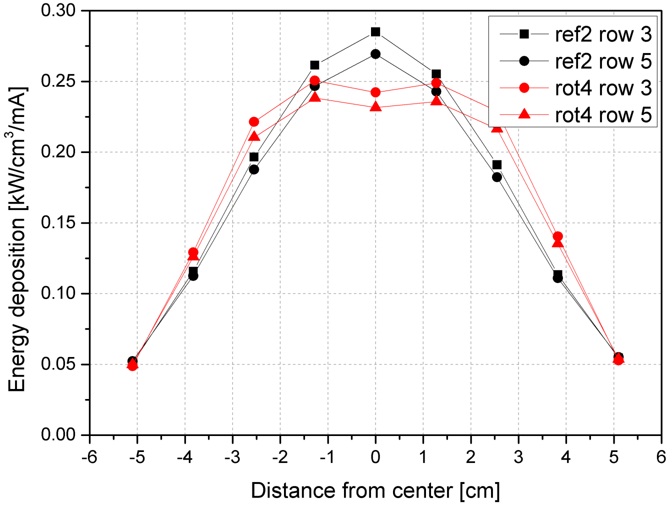




Energy deposition in the central rods along the target (longitudinal)



Energy deposition along selected rods (transverse)

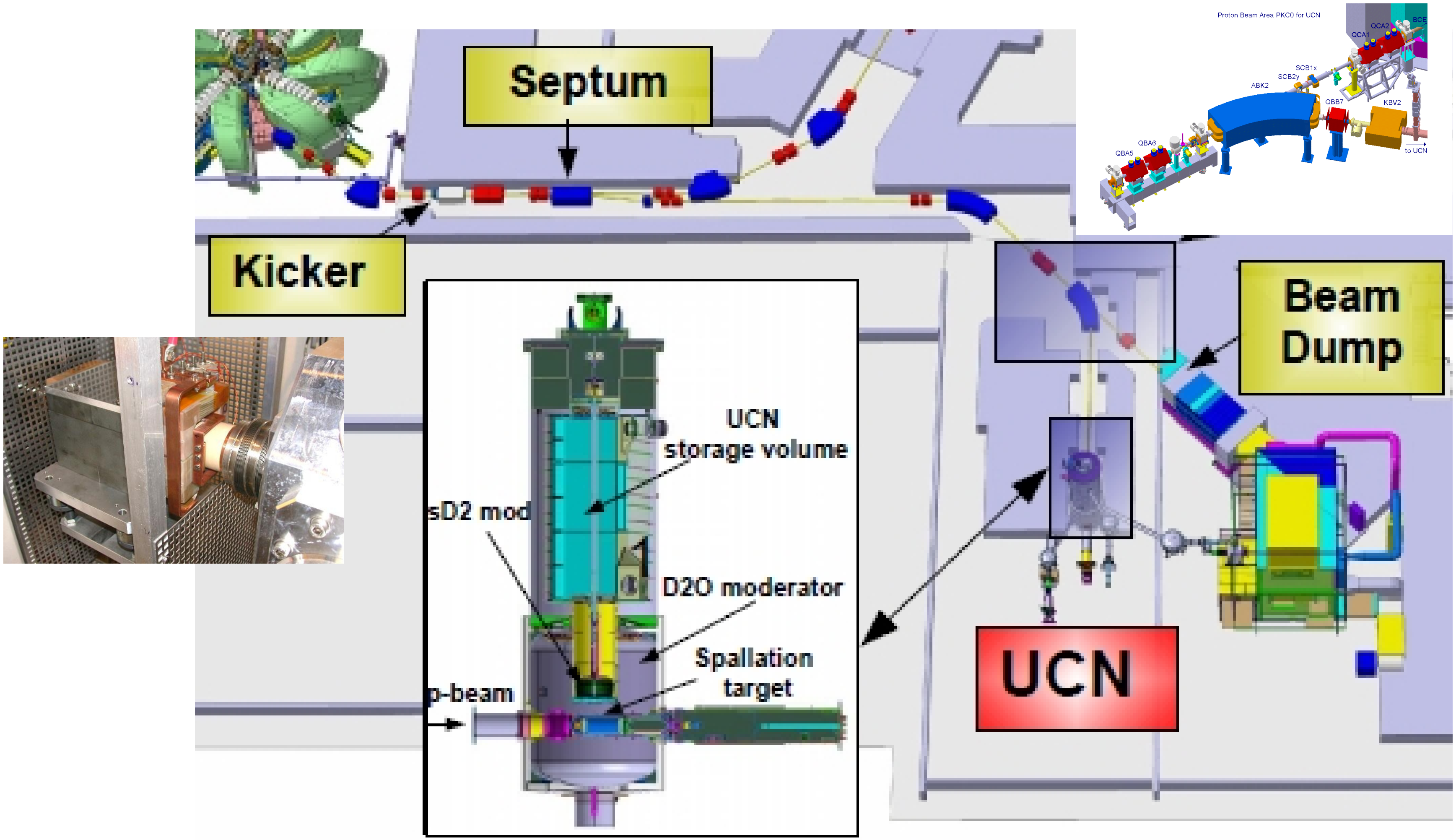


Estimated cold and thermal neutron fluxes do not change wrt to non rotating beam!

Estimated cold (thermal) neutron flux modulation vs rotation frequency: 11% (12%) @ 100 Hz, 1% (3%) @ 1000 Hz

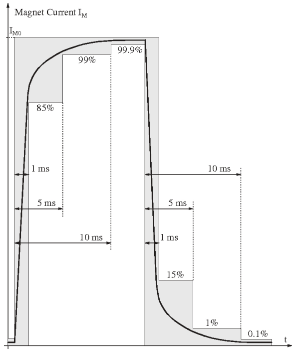
UCN Beam Line (commissioning 2008-2011)

1.3 MW Proton Macro-Pulses diverted to Ultra Cold Spallation Source (1% duty cycle, pulse-length$_{max}$ = 8 s)



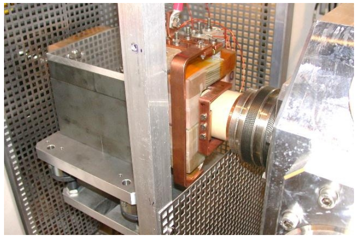
During switchover beam crosses septum collimator causes high losses for a couple of ms!

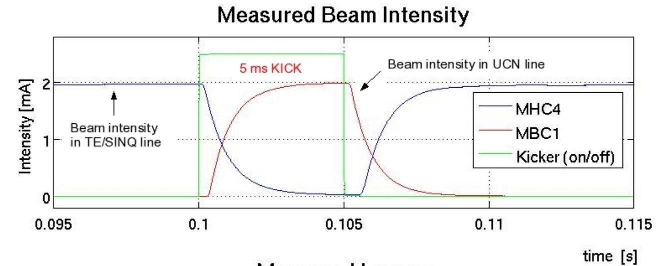
UCN Pulsing Scheme: Requirements and Solutions



Limit beam losses

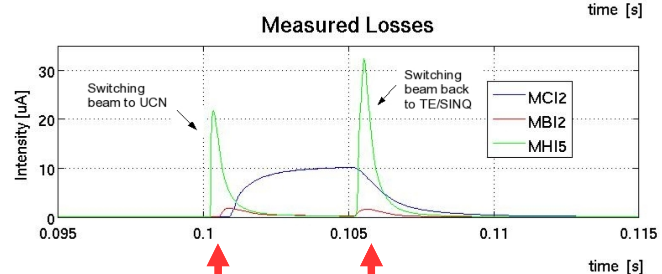
→ Fast Kicker-Magnet (Rise-Time < 1 ms)





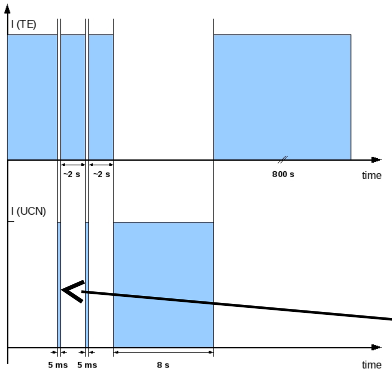
Avoide machine interlock during switchover

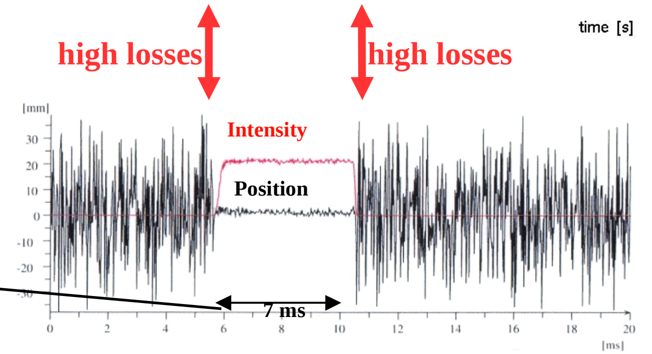
→ Short (3 ms) shift of beam loss monitor interlock thresholds



Check beam centering

→ Perform 7 ms pilot pulse before each long pulse



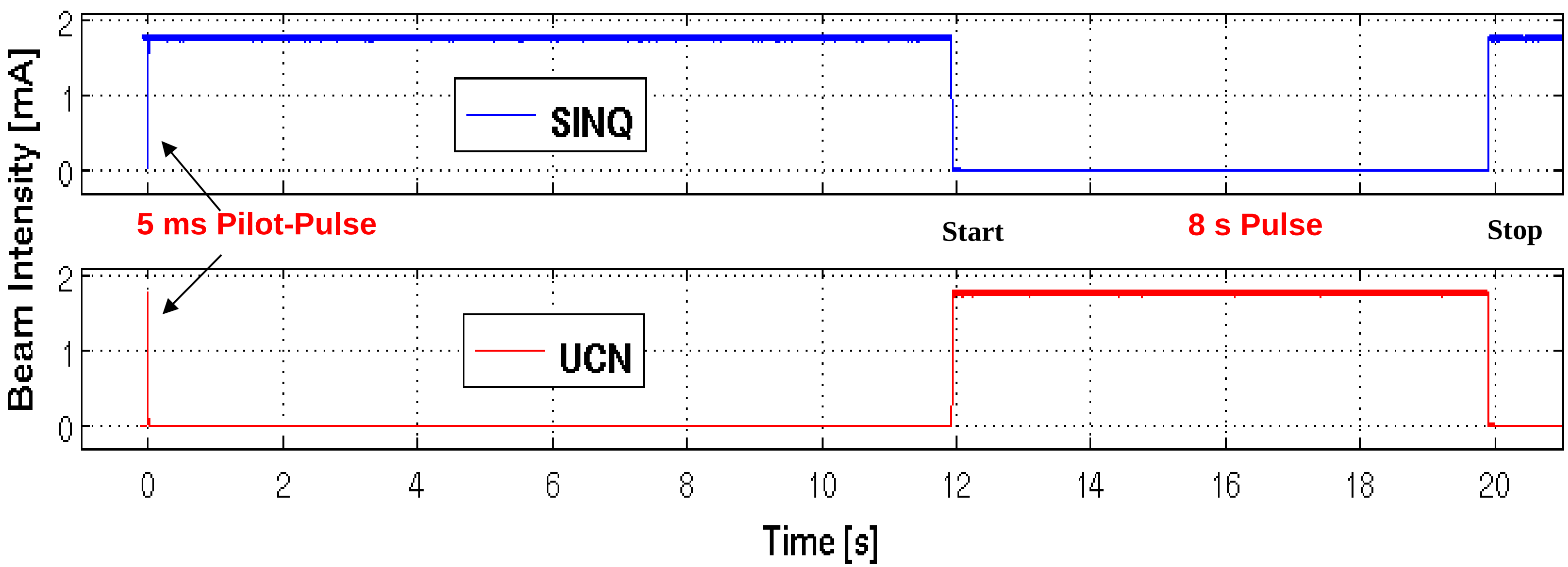


UCN Operation

22 December 2010

First successful 1 MW, 8 s long UCN Beam Pulse

(after three years beam commissioning with the UCN beam dump!)

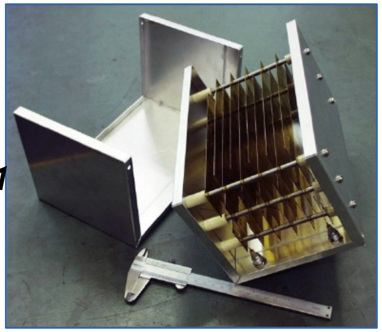


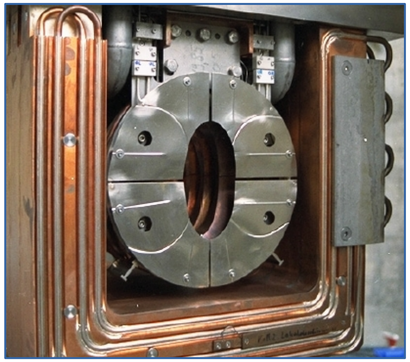
August 2011: Start UCN production

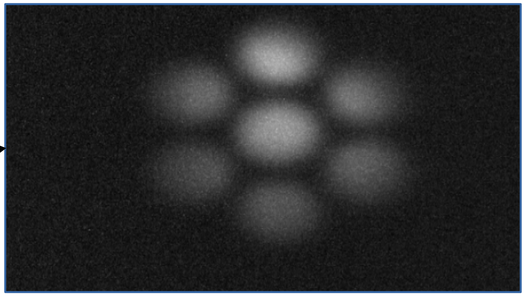
Current kicking scheme: 4 s UCN pulse every 300 s

Machine Protection System

- 1.3 MW proton beam with $\sigma_x = \sigma_y \approx 1$ mm [→ TM and TE regions] melts beam pipe in **≈ 10 ms**
- MPS based on ca. 150 interconnected very fast (<100µs) VME modules treating about **1500 signals**
- PSI MPS can generate a **beam interlock in < 5 ms**
- MPS gets signals from:
  - Magnet power supplies
  - BPMs
  - Beam loss monitors (110 ion chambers)
  - Current monitors (beam transmission)
  - Halo monitors
  - Temperature sensors (collimators)
  - VIMOS tungsten mesh (SINQ beam footprint)

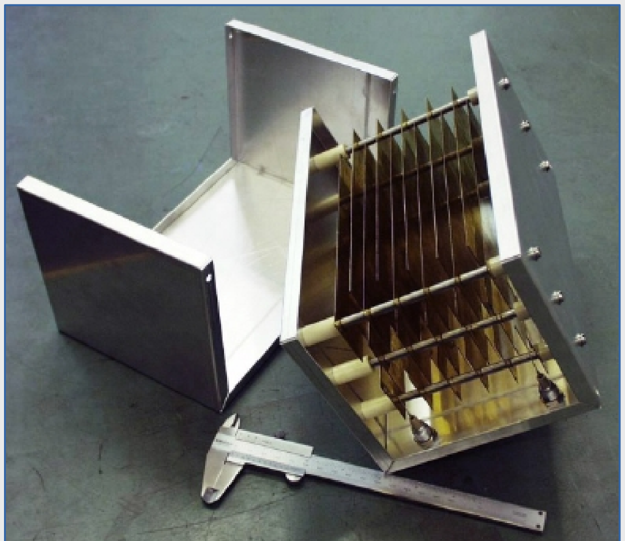


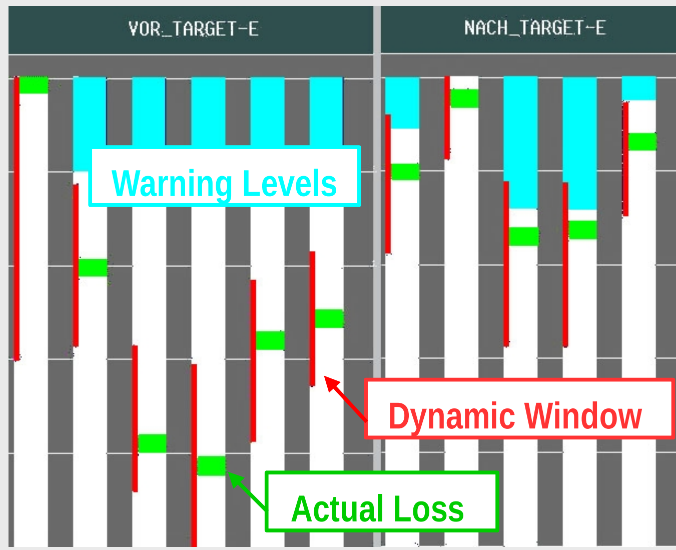


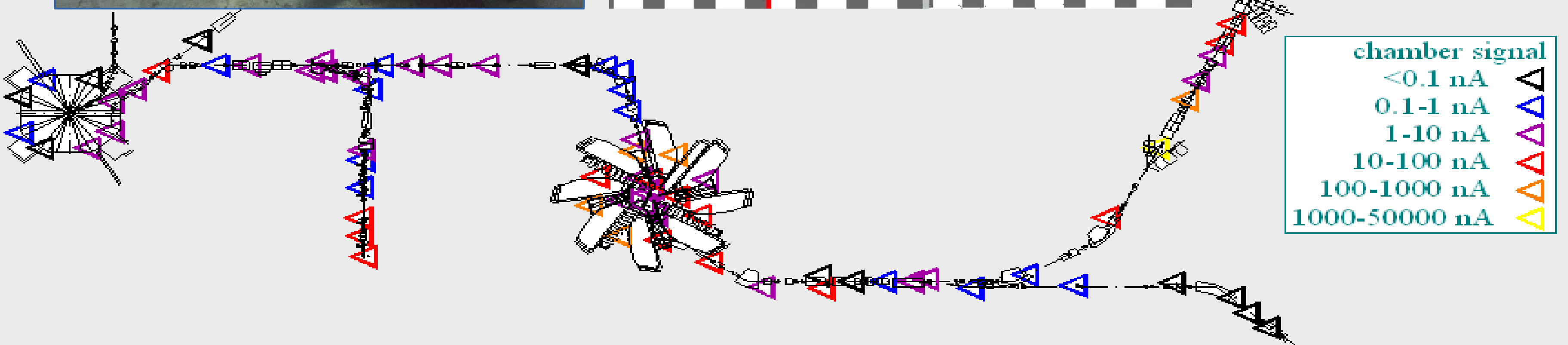


Setup and Monitoring: Beam Loss Monitors

Simple and reliable ion chambers as beam loss monitors with warning and interlock limits



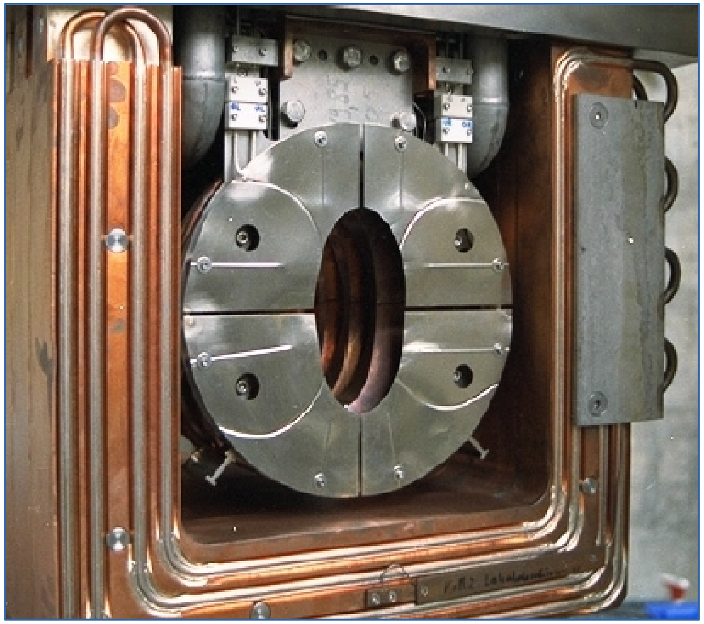


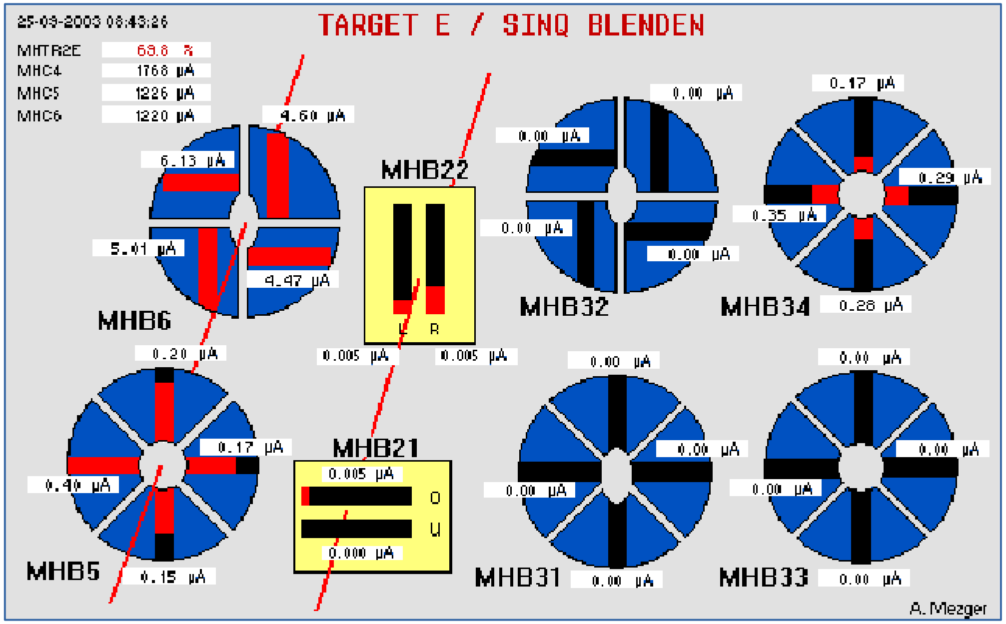


Loss Measurements employed for a fast machine setup!

Setup and Monitoring: Halo Monitors

Segmented foils of nickel/molybdenum installed in front of collimators and measuring the balance of right and left, up and down scraped beam currents (Target E and SINQ Target regions)





Setup and Monitoring: Beam Transmission

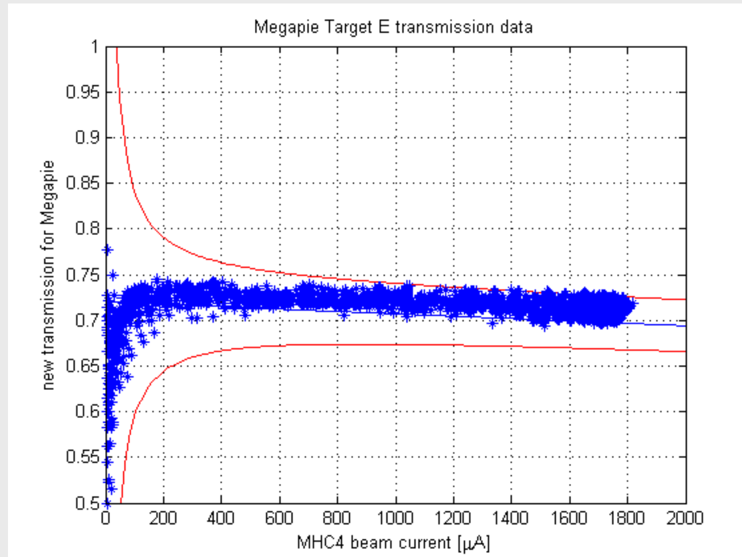
Beam current transmission monitors compare the beam current at different spots for detecting loss of beam

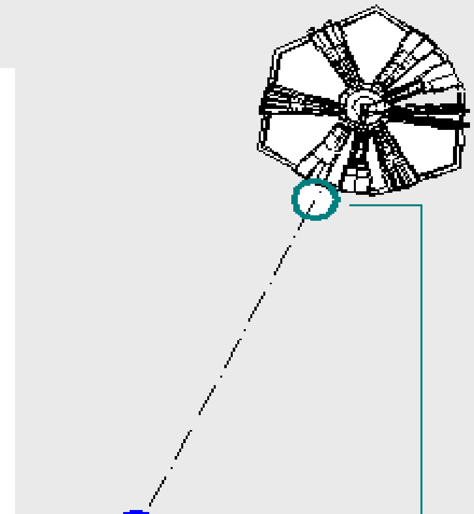
100 % transmission in main cyclotron

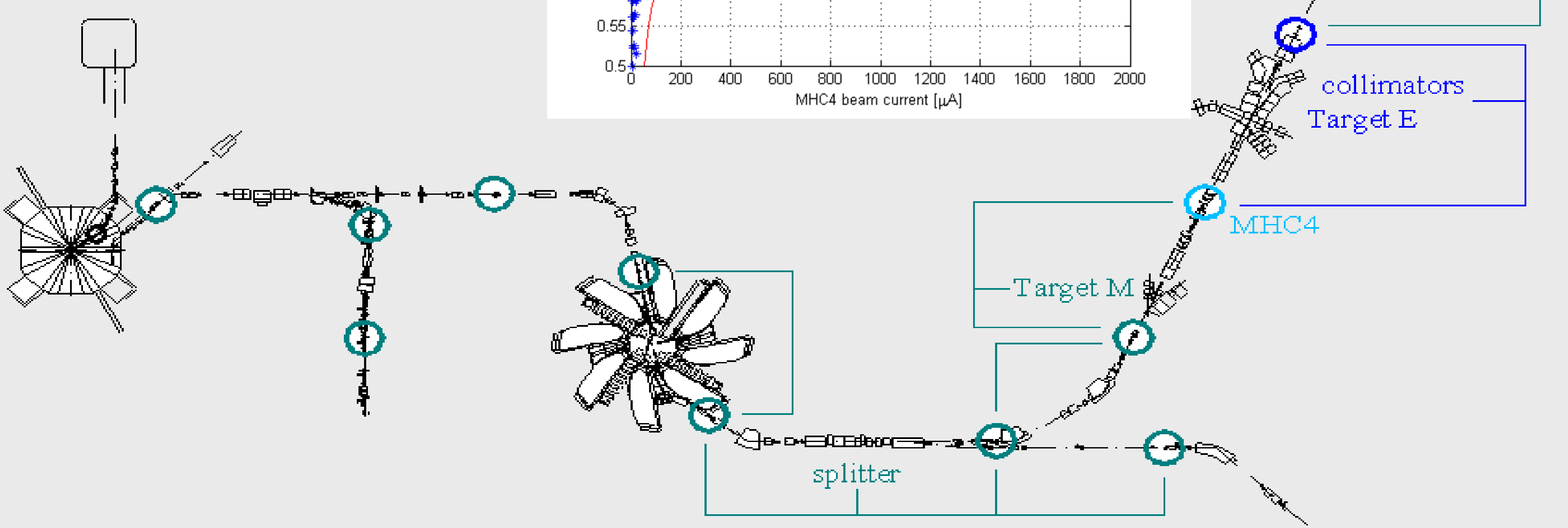
100 % transmission in transfer lines,
(except for split beams)

97 % transmission of thin target M

70 % transmission of thick target E



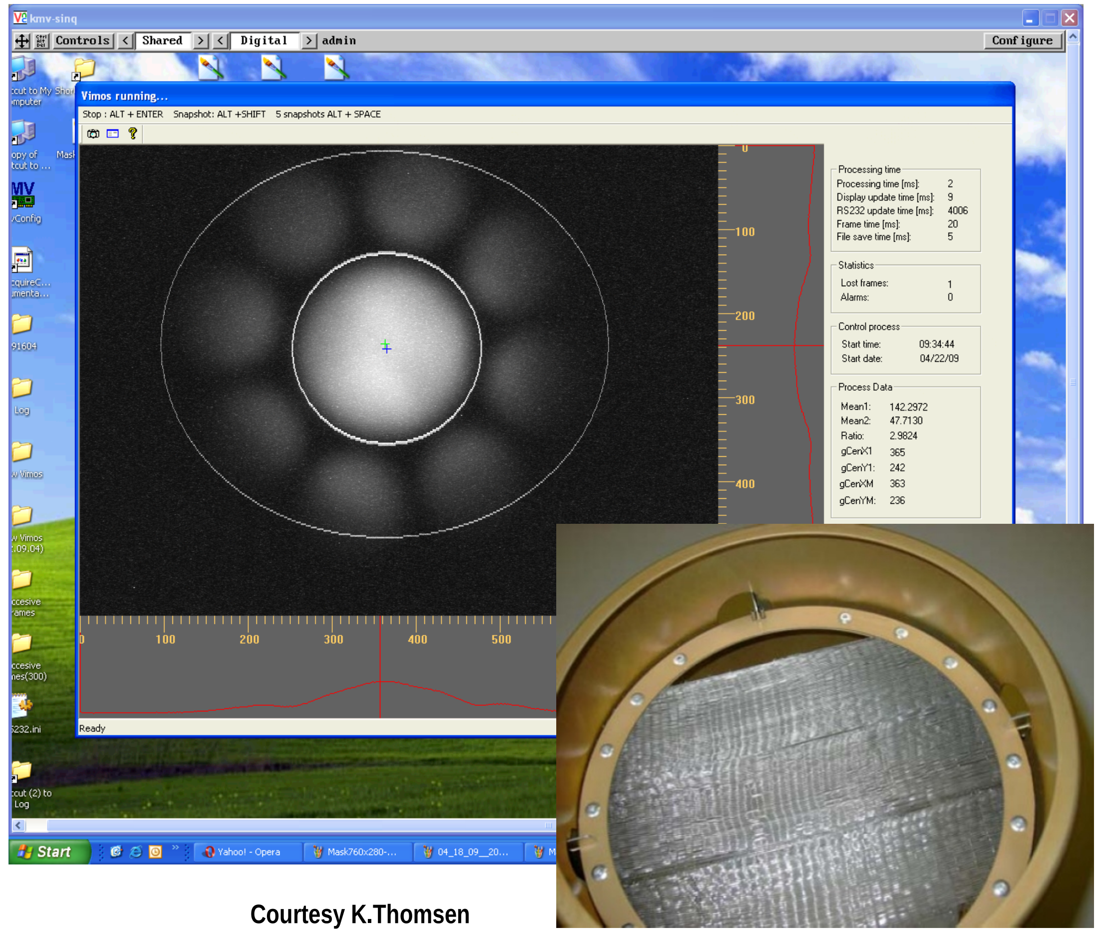




Setup and Monitoring: VIMOS

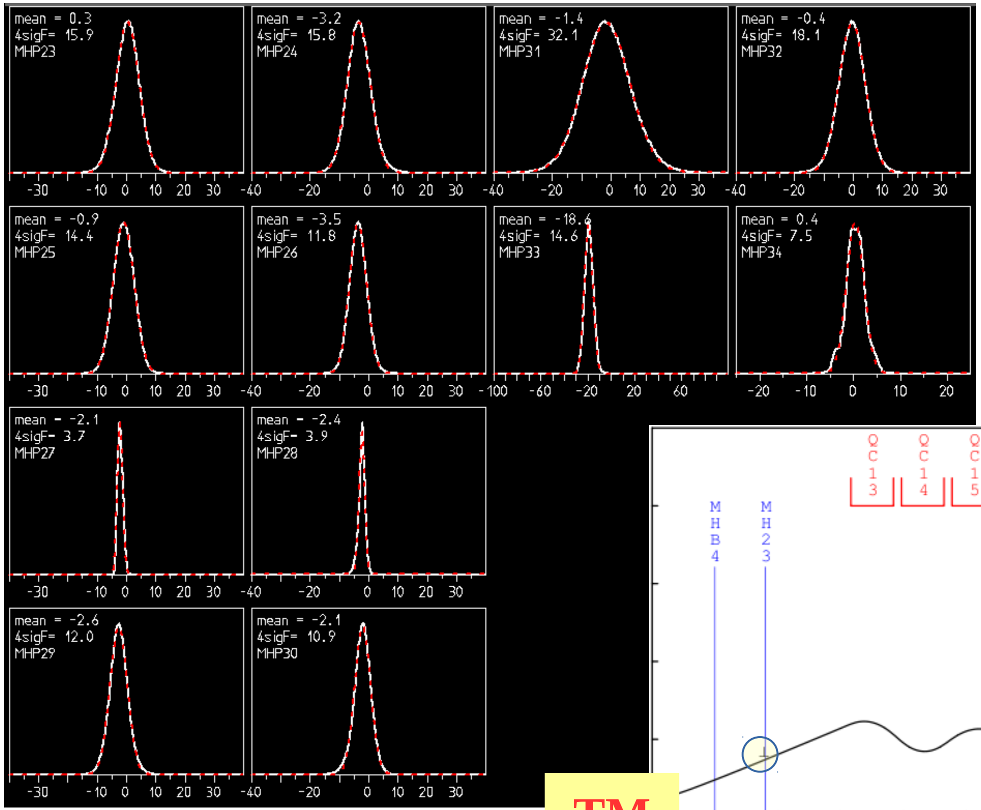
Tungsten Grid located 40 cm upstream of the SINQ Target visualized by optic-fibers and camera gives an image of the thermal radiation

- VIMOS image is digitized to detect abnormal irradiation condition (overfocusing and/or missteering)
- 50 frames / second
- If 4 subsequent frames deviate from thresholds an interlock signal is sent
- Deviation is calculated through intensity ratios and absolute maximum values.



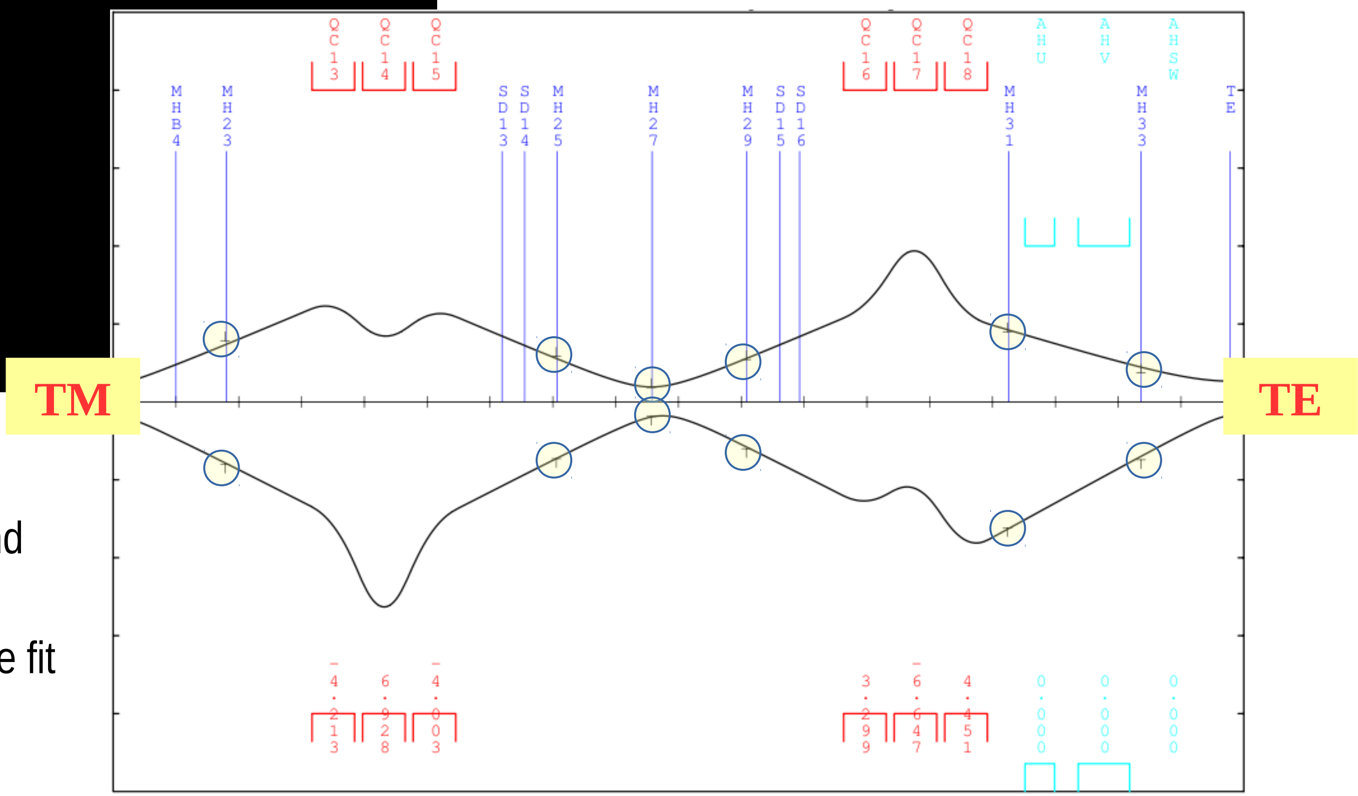
Courtesy K.Thomsen

Beam Optimization: Optics Determination



Beam Profile Monitors determine beam widh at several locations along beamline

~120 monitors in the high power section, mainly Wire Scanner



Fast (off-line) beam optics and emittance determination through TRANSPORT envelope fit

Conclusion & Outlook

- Since many years the PSI 1.4 MW proton accelerator is an established and reliable user facility
- «Production» beam current gradually increased from 100 µA (1974) to 2.2 mA (2009)
- Very low beam loss level (10^{-4}) is a mandatory condition: **beam diagnostics is essential!**
- High current runs at 2.4 mA take place during 2 shifts (16 hours) every 14 days
- **Application for 2.4 mA operation license** under way
- Flat top cavity main source of operation instabilities in the last years
- Towards 3.0 mA beam intensity:
  - **TE collimator redesign completed**; manufacturing expected by 2017
  - **New Injector2 accelerating cavities** to be installed by 2018
  - Studies being carried out to **refurbish FT-cavity** and/or replace it by new design

PAUL SCHERRER INSTITUT

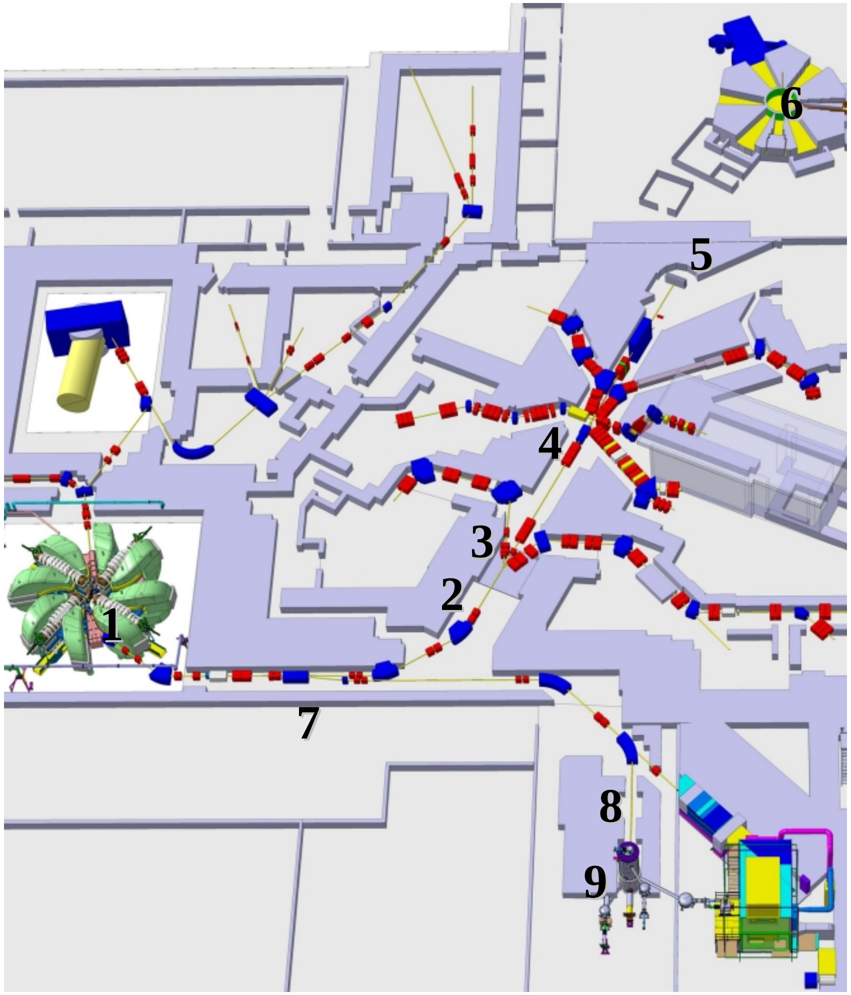
Thank you for your attention!

Acknowledgement

P.A. Duperrex, E. Johansen, U. Müller, M. Schneider, W. Tron, M. Humbel, R. Kan, A. Mezger, M. Seidel, D. Kiselev, M. Wohlmuther, V. Talanov, T. Reiss, R. Sobbia, A. Adelmann, N.J. Pogue, K. Thomsen

Beam Losses along the Proton Channel

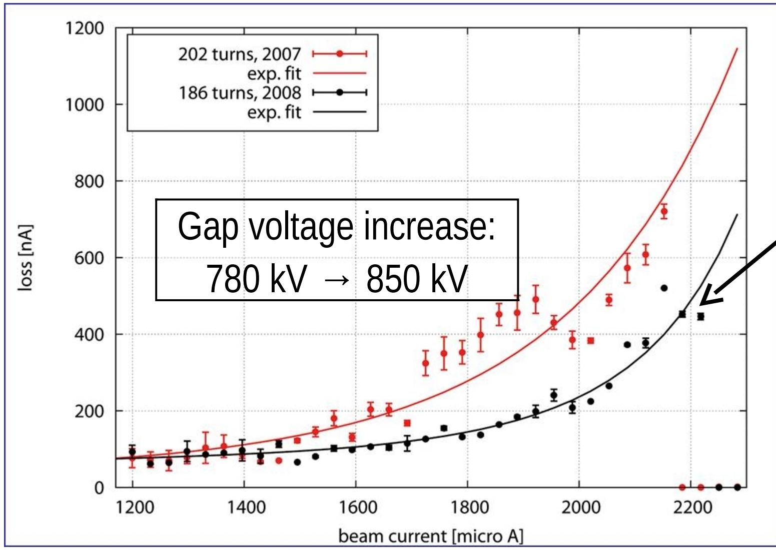
Accelerator Section	kin. energy [MeV]	max. loss [µA]	typ. loss [µA]
1. Ring Cyc., Extraction	590	2	0.4
2. transport Ring-TE	590	0.1	0.01/m
3. Target M (shielded)	590	0.5%	0.5%
4. Target E (shielded)	590	30%	30%
5. transport SINQ	575	2	0.01/m
6. SINQ target (shielded)	575	70%	70%
7. UCN Septum	590	0.02	0.02
8. UCN Colli (shielded)	590	1%	1%



acceptable for service: ~ $2{\cdot}10^{-4}$ relative losses per location

UCN: 1% Duty-Cycle

Extraction Losses and Machine Activation

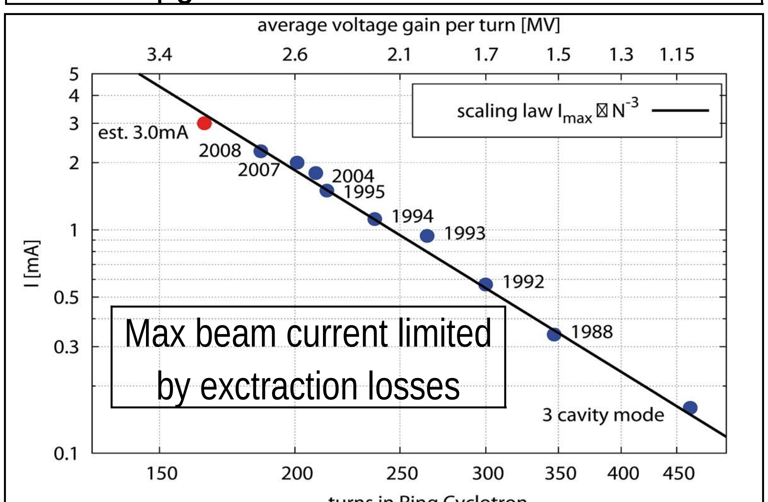


#Turns (since 2008) = 186

Typical extraction losses at 2.2 mA < 500 nA

Extraction Efficency = 99.98 %

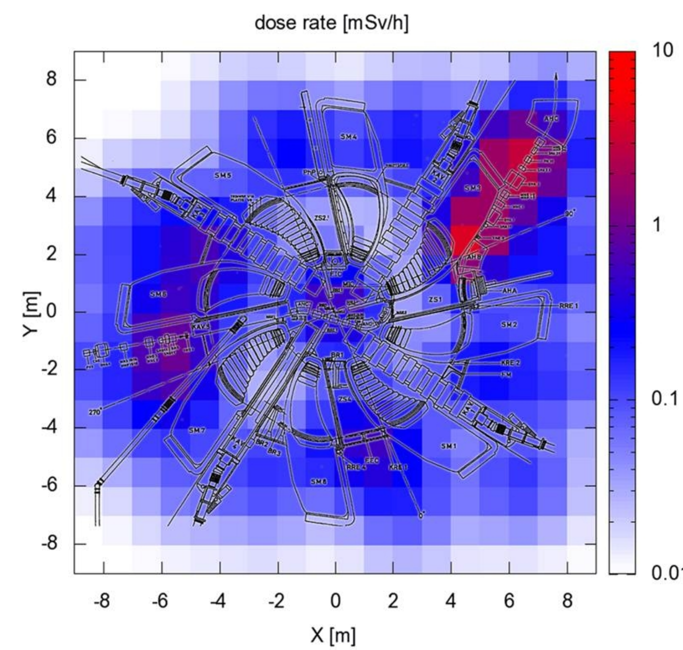
3.0 mA upgrade → Reduce #Turns to ~ 165



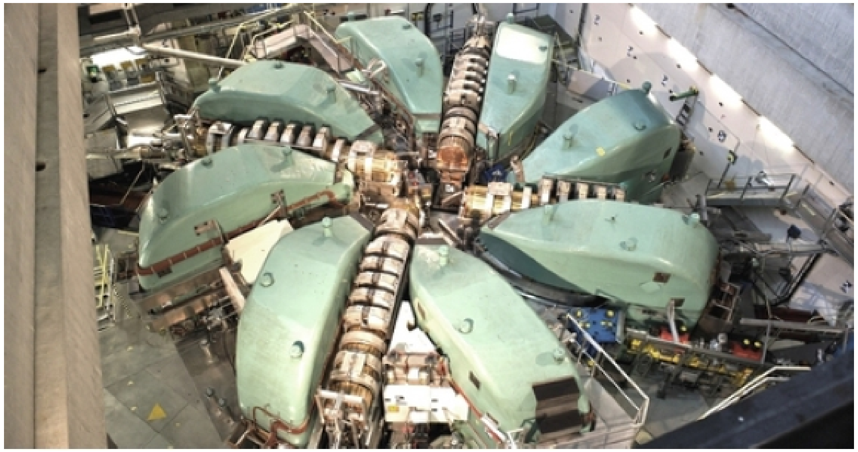
Component activation:

Map interpolated from

30 measured locations



New Phase Measurement System



Based on the so-called “software defined radio” (SDR) **technology.** This digitally based system is replacing a more than 20 years old analog receiver (AR) system, which was based on the conventional heterodyne radio receiver technique.

A SDR presents several advantages compared to the old AR system:

- **Since the signal is digitized already after a first amplification, in the SDR case, there are no spurious effects** due to for instance temperature at the level of the **analog mixer stage or at the baseband detection stage**.

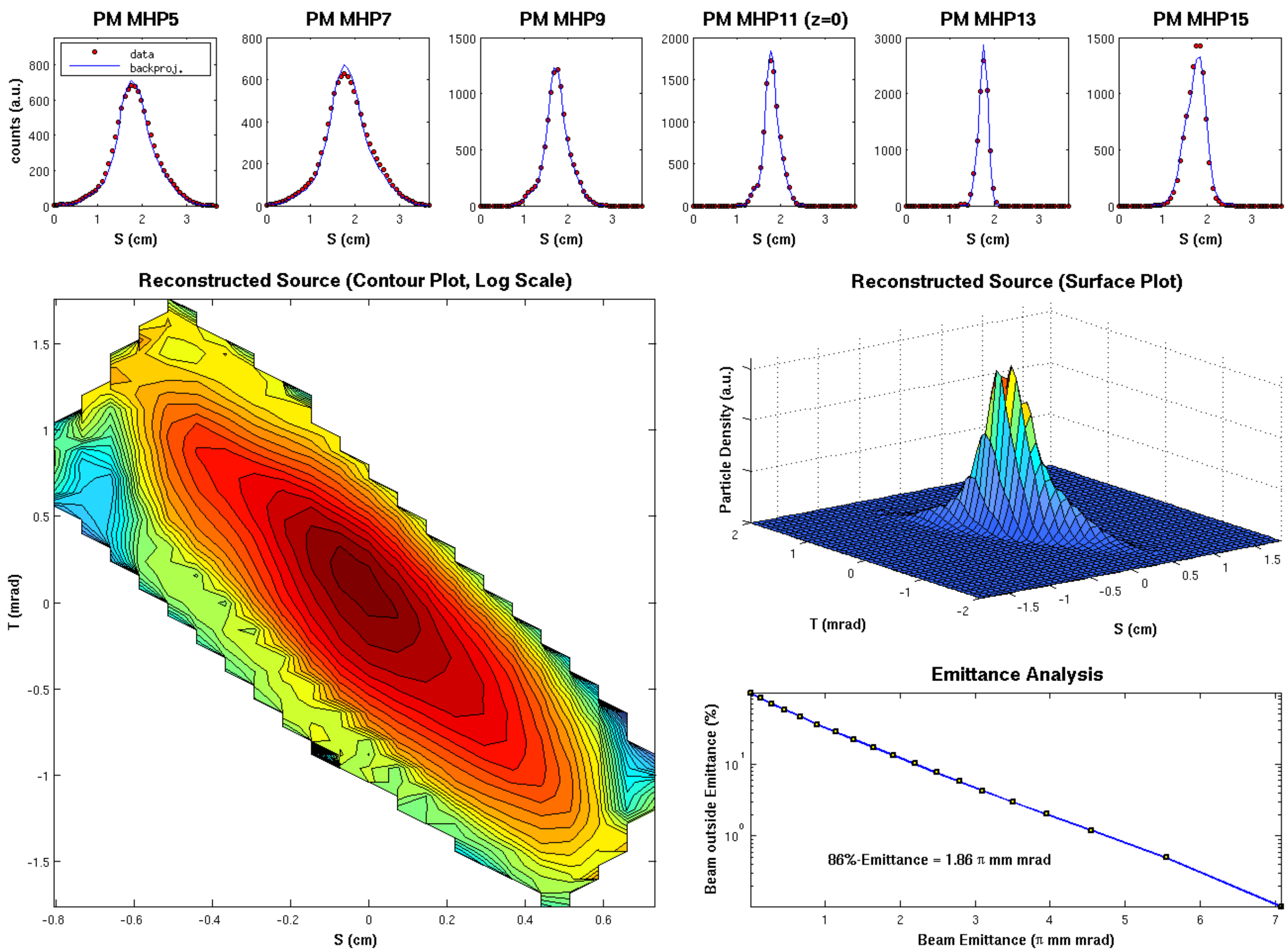
- **For instance the I/Q demodulation in the SDR is performed digitally and temperature drifts have no effect whereas a precise and stable analog 90° shift is very difficult to achieve.**

- Better dynamic range of measurements **thanks high resolution ADCs**, more sensitive at low currents (100 μA up to 3 mA)

- Better signal-to-noise ratio

P.-A. Duperrex, E. Johansen, U. Mueller

Further Improvement: Beam Tomography

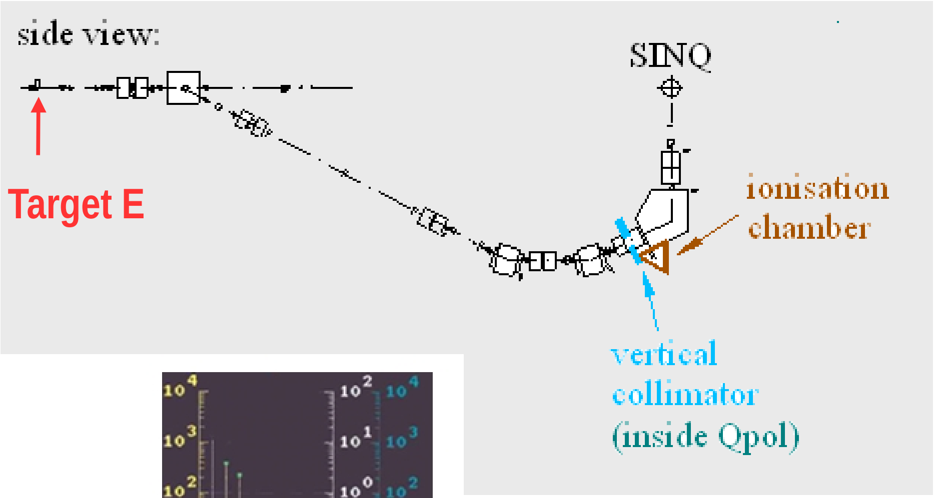


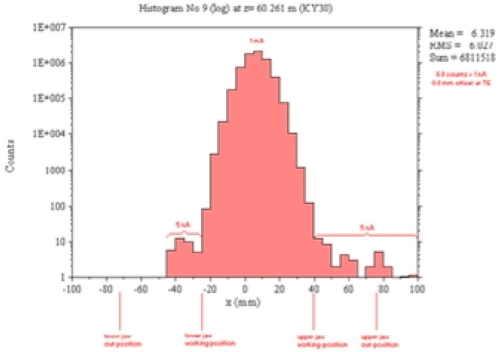
Maximum Entropy Phase Space Tomograpy of 590 MeV beam upstream of Target M (x-Plane)

Controlling Beam Losses

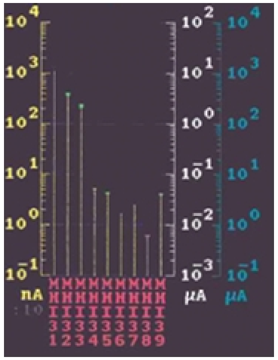
Target E (40 mm C)
- Increases beam divergence
- Decreases beam energy (590 to 575 MeV)

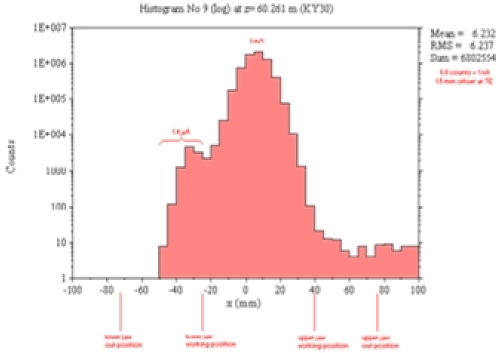
Beam by-passes TE hits a vertical collimator located in dispersive transport section:
Interlocks from collimator current monitor and ionization chambers





Centered Beam





Hor. Beam shift (1.5 mm):
~ 0.1 % protons
by-pass Target E