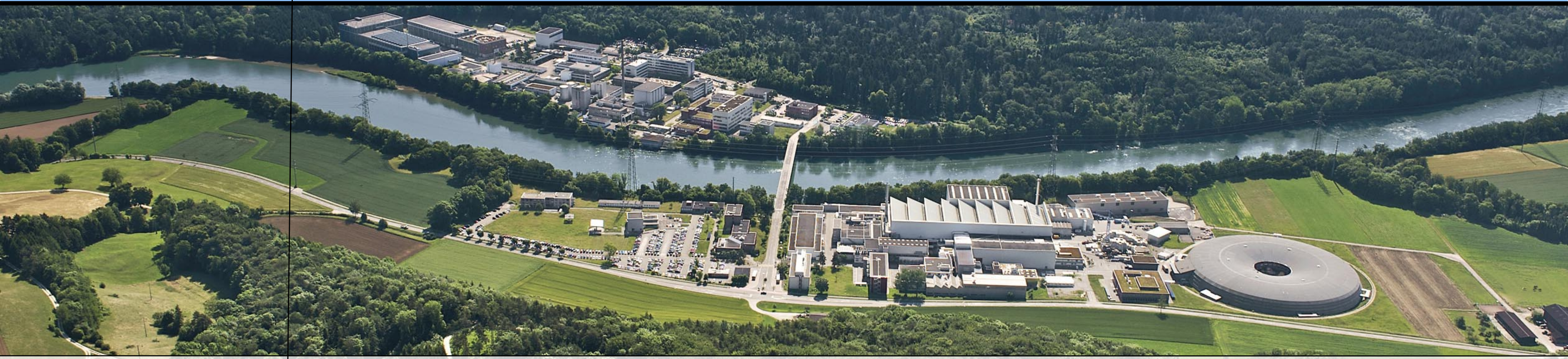


Wir schaffen Wissen – heute für morgen

Paul Scherrer Institut

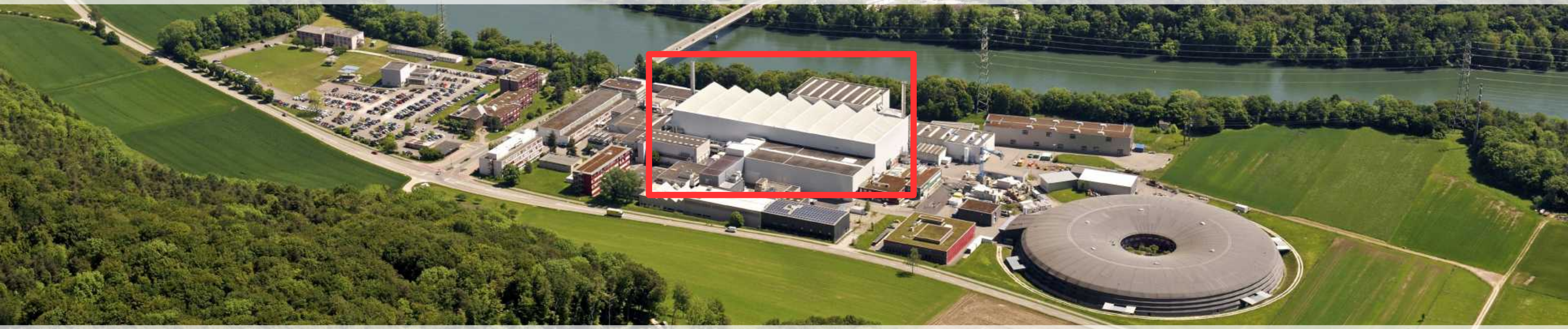
D. Reggiani, B. Blau, R. Dölling, P.A. Duperrex, D. Kiselev, V. Talanov, J. Welte, M. Wohlmuther

Improving Beam Simulations as well as Machine and Target Protection in the SINQ Beam Line at PSI-HIPA

ICANS XXIII, 15.10.2019, Chattanooga, TN, USA

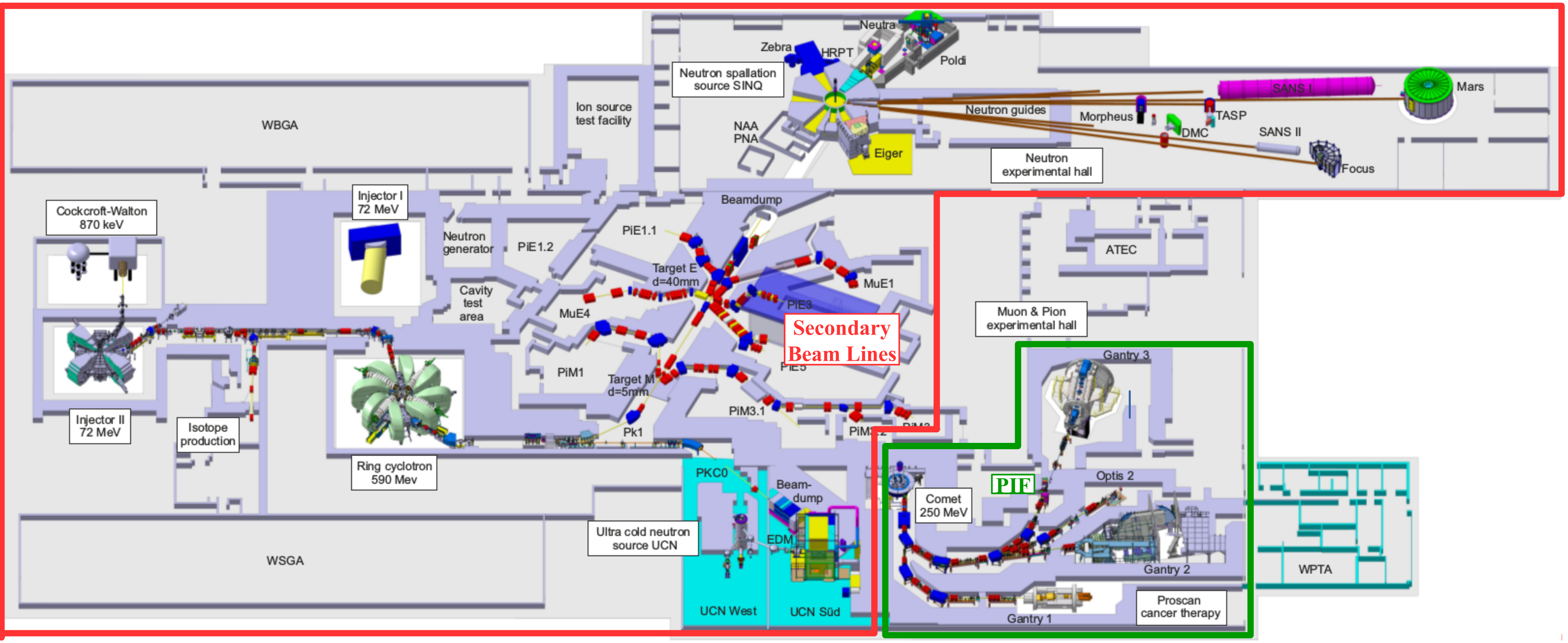
Outline

- Introduction to the PSI High Intensity Proton Accelerator (HIPA) Facility
- Beam Transport to the SINQ Target
- Motivation: Open Issues to be Addressed
- New Beam Diagnostic Tools for Safer Operation
- Understanding Beam Losses through Improved Simulations



- Conclusions and Outlook

The PSI HIPA Proton Accelerator Facility



HIPA (High Intensity Proton Accelerator)

CW, 590 MeV, up to 1.44 MW Beam

2 meson production targets (7 sec. beam lines)

SINQ spallation source

Max 8s Macro-Pulses, up to 3% duty-cycle to UCN

PROSCAN (Protontherapy)

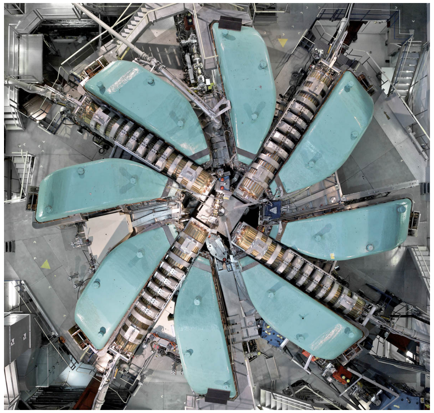
CW, 250 MeV, up to 1000 nA proton beam

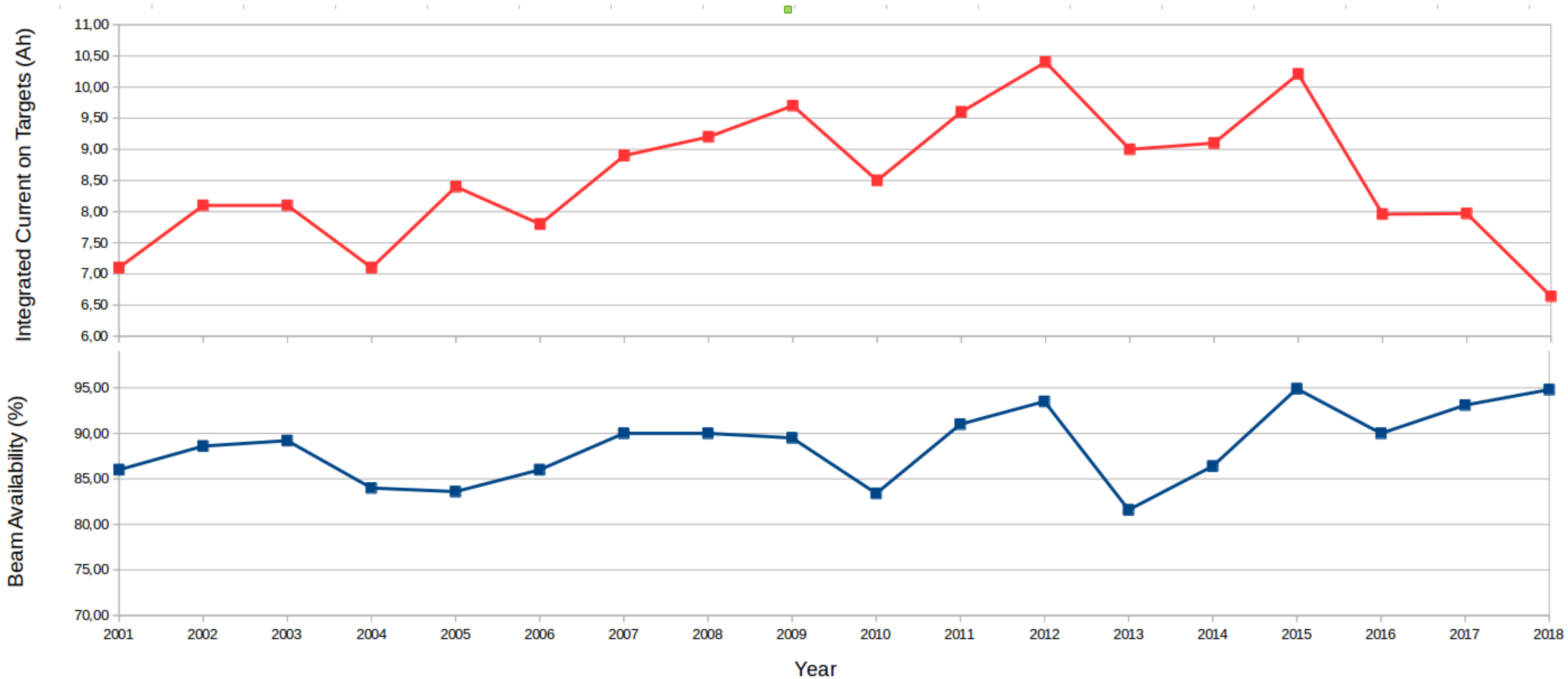
In operation since 2007

2 Gantries, 1 Eye Cancer Treatment Station, 1 PIF

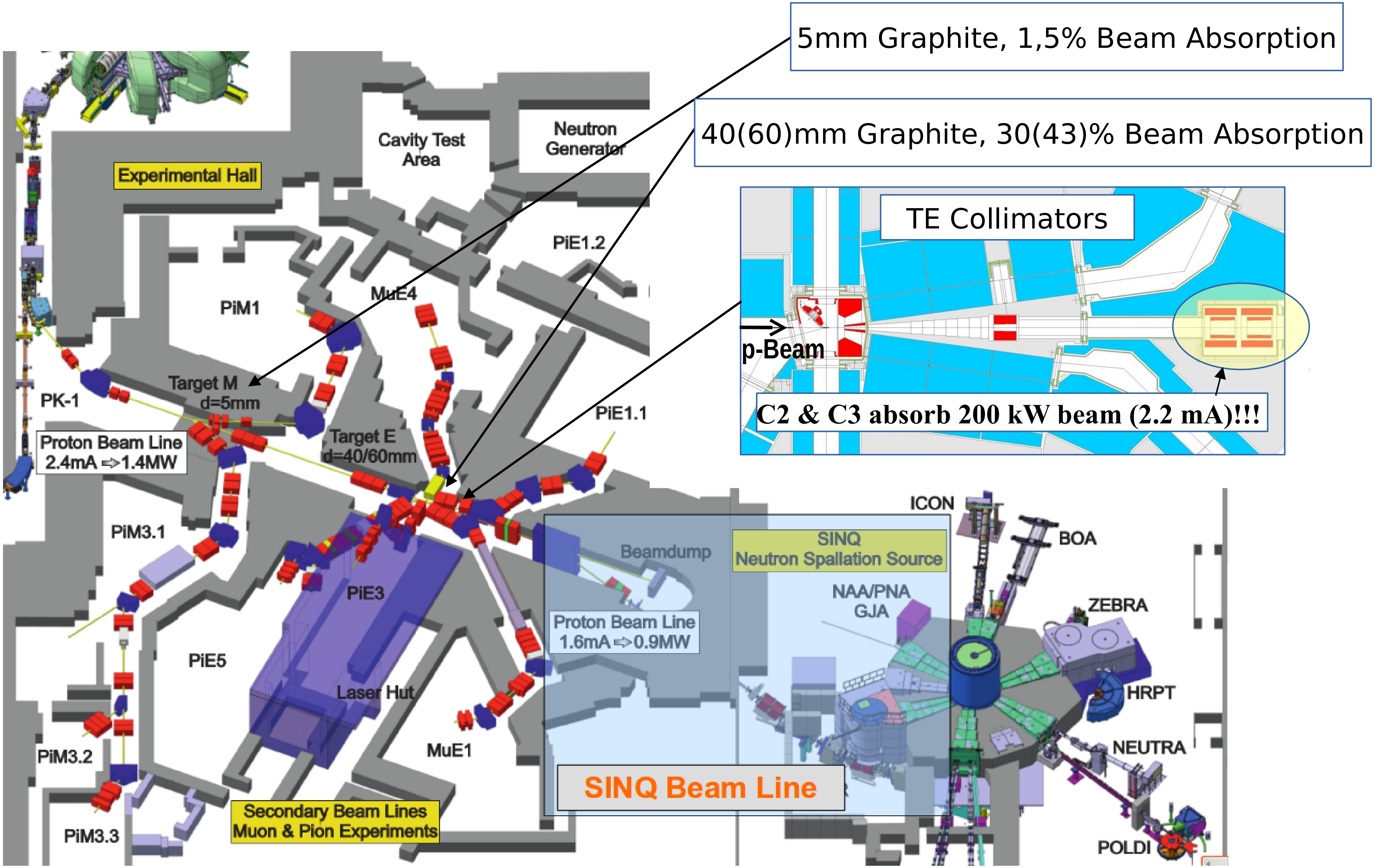
Facts about HIPA

- In operation since 1974, stepwise upgraded
- 1.44 MW max, 1.3 MW routine operation (since mid 2016 limited to ~1MW)
- Low losses, high efficiency ring sector cyclotron (99.98% extracted beam)
- Typical availability: 90%
- Charge delivered to meson production targets: ~9 Ah/year

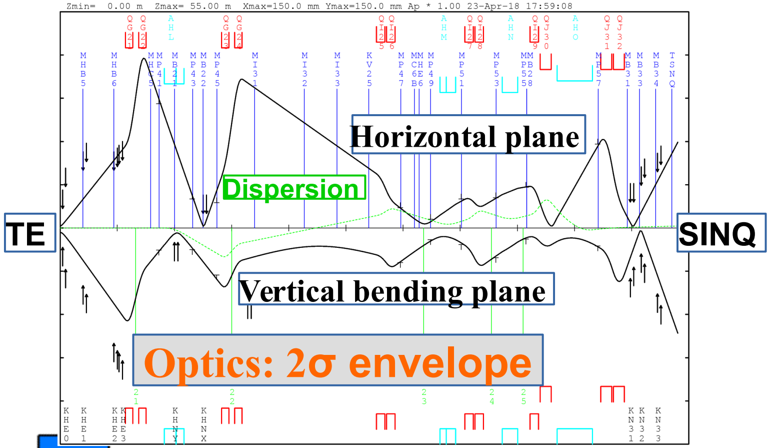




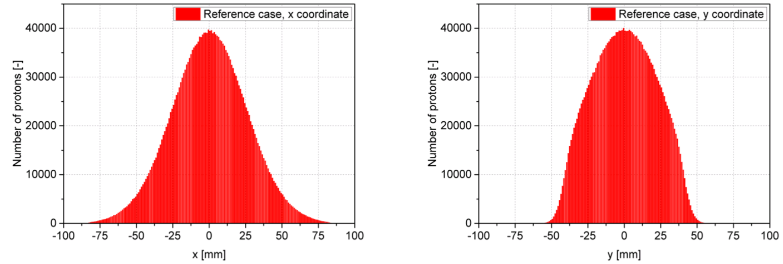
The 590 MeV, 1.4 MW Proton Channel

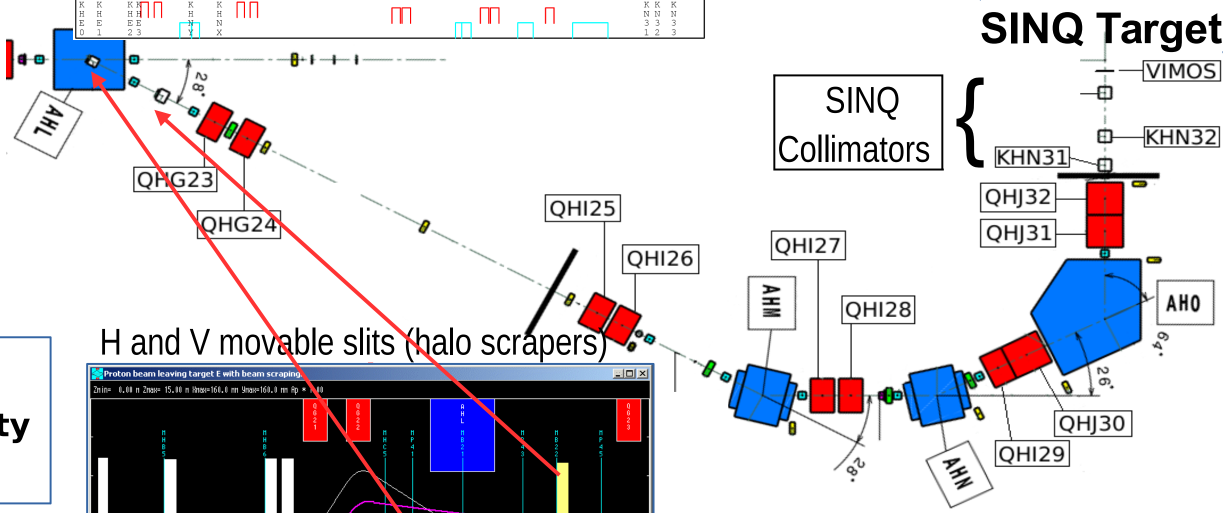


Beam Transport to SINQ



Beam distribution at SINQ target

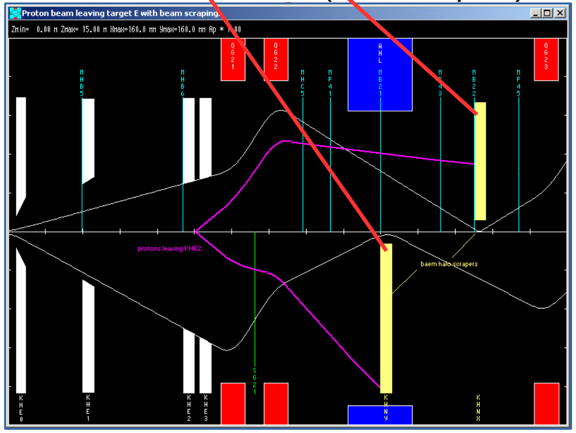




12 Slits in TE:

3% Beam Intensity Modulation

H and V movable slits (halo scrapers)



Beam Diagnostics (until 2016):

- Beam Loss / Intensity Monitors
- Profile Monitors (wire scanners)
- Aperture Foils / VIMOS
- **No BPMs!**

Open Issues of SINQ Beam Transport

Keep stable beam centring on SINQ
→ Difficult because of missing BPMs!
→ Profile monitors help but no continuous measurement

Maintain beam footprint at SINQ
→ VIMOS optical monitor, no quantitative information about footprint
→ Beam envelope fit from profile measurements (~1/week)

Reduce beam line activation due to Halo from TE
→ Manual fine tuning of Halo Scrapers
→ Beam Losses minimization through manual optics and centring adjustments looking at BLMs

Understand Beam Losses through TE and Collimators
→ Two intensity monitors (MHC5/6) need frequent recalibration
i.e. determination of transmission through TE relies on simulations

Target protection
→ Monitor Beam Transmission through TE (5% sensitivity because of TE-Slits)
→ VIMOS (limited speed and tricky image interpretation)
→ KHNY30 vertical slit detecting TE bypassing beam

Key Motivation: Failure of SINQ T11 on 25.06.2016 (see B. Blau's Talk, Mo 11:35)

Potentially Critical Issue: TE-Bypassing Beam

Non-scattered Proton Beam by-passing TE graphite wheel (55m upstream of SINQ) makes it to SINQ Target and creates a hot spot

Simulation Initial Conditions:

Beam width: 2σ=1.5mm, TE width: 6mm

Beam 1.5mm shifted at TE, ~3% Bypassing Beam

Simulation Results:

Hot-Spot direction: Aare (l/r depending on where the beam bypasses TE)

Hot-Spot radius: ~18mm

Hot-Spot Max distance from SINQ-Target center: ~33mm

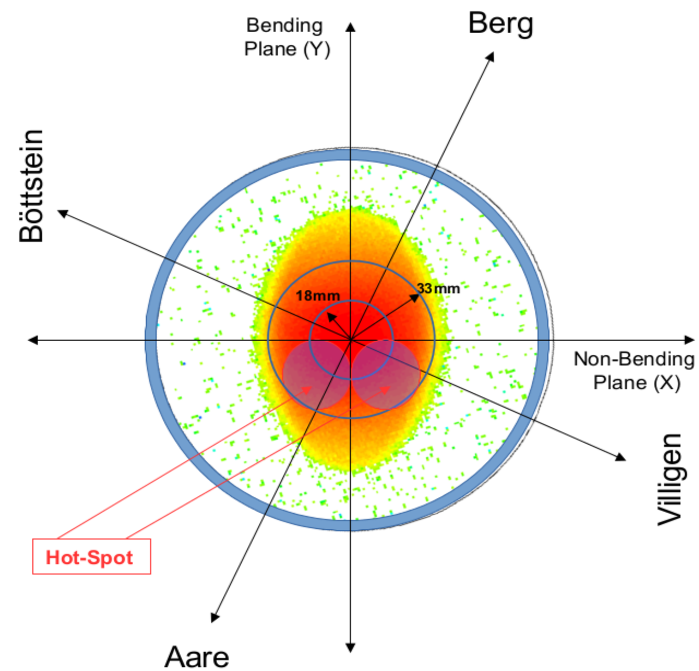
Beam Peak Intensity in the HS: ~2x larger than usual one

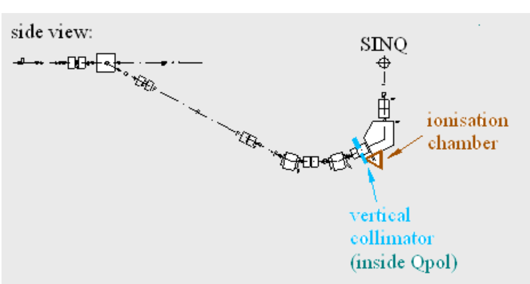
Vertical Slit located in high dispersion region should detect TE-bypassing beam but:

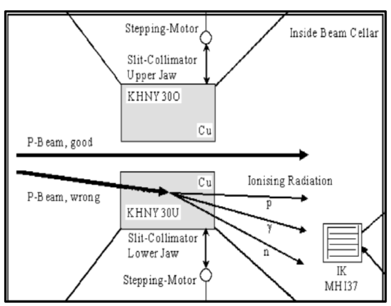
Massive non-cooled copper jaws get hot and active and generate losses if too close to the beam

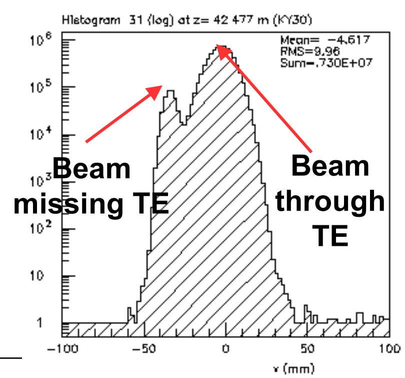
Reliable setting of KHNY30 problematic due to missing BPMs

Hotspots locations at SINQ Bottom View









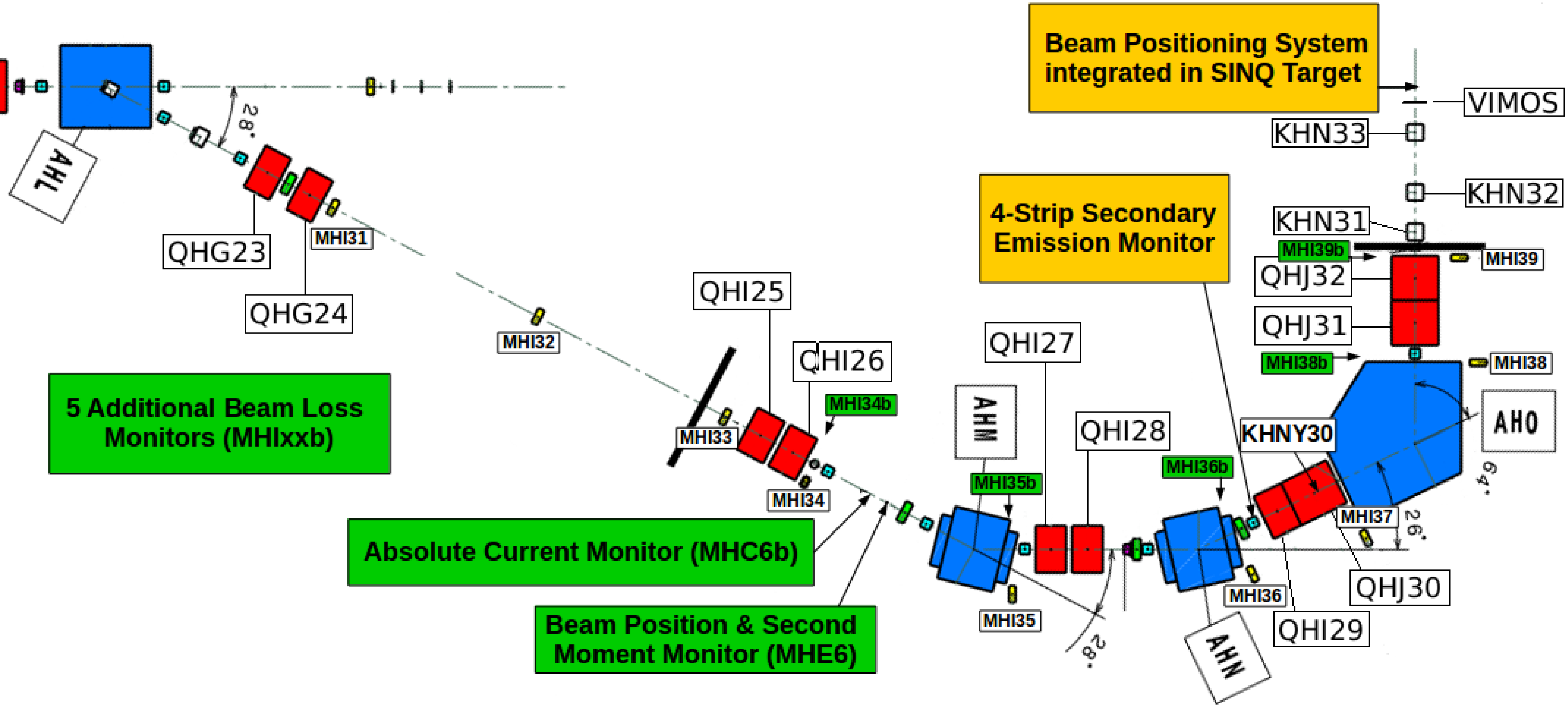
Beam Vertical Distribution at KHNY30 Slit if 3% beam bypasses TE

SINQ Beam Line – Additional Diagnostics 2017 - 2018

From 2016: starting considering additional diagnostics for SINQ beam line:

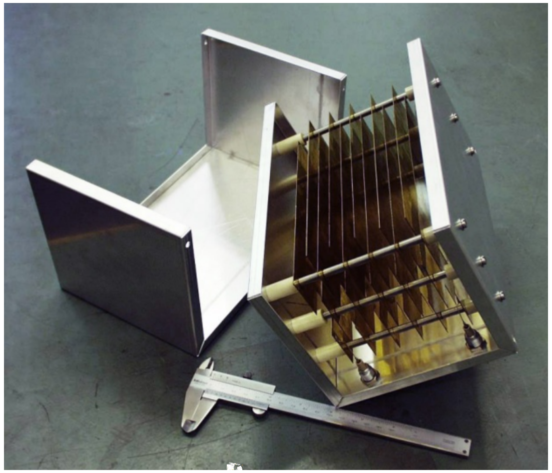
New elements installed during 2017 and 2018 shutdowns.

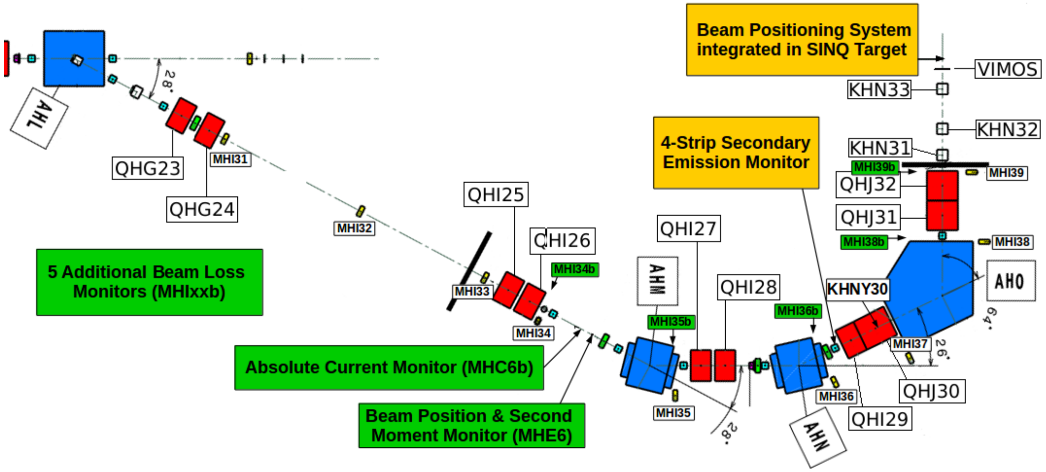
More to come!



Additional Beam Loss Monitors

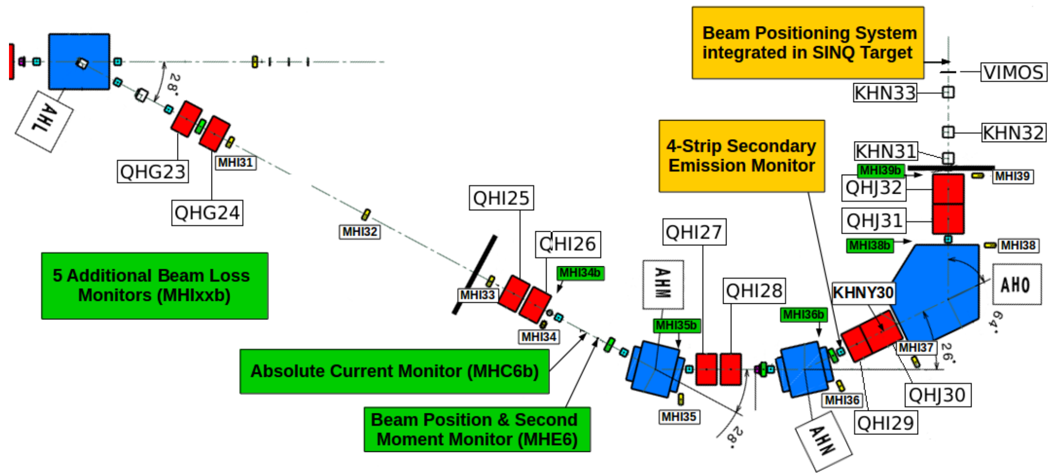
5 new BLM installed in SD2017





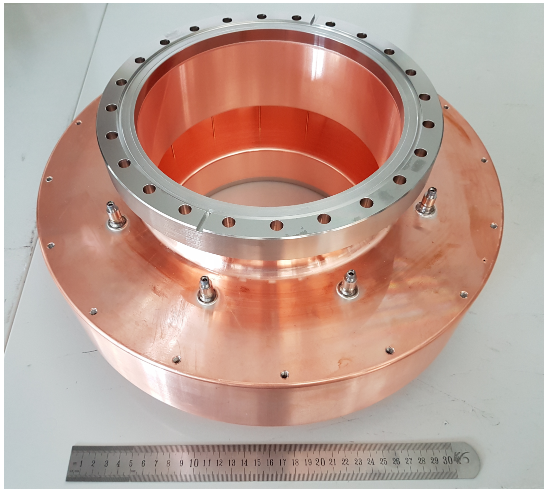
- Original BLMs mainly installed on the bottom side of beam line (**MHI34-39**)
- Top/Bottom beam loss asymmetry expected due to dispersion function
- Additional **b** monitors assess this asymmetry
- Measurements by MHB34b, MHB35b and MHB39b meet expectations

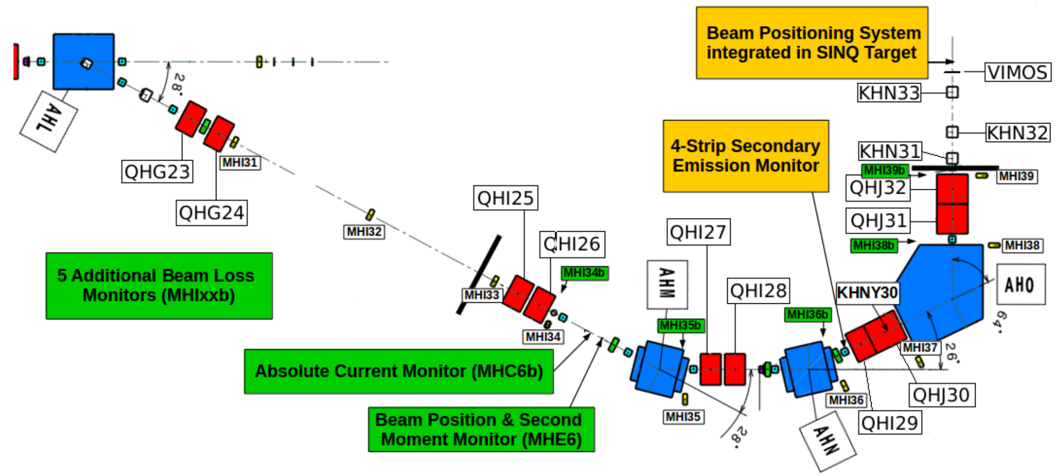
Absolute Bergoz Current Monitor installed in SD2017



- 2^{nd} harmonic resonators provide fast but **relative** beam current measurement
- Beam transmission not precisely measurable
- One Bergoz® absolute current monitor installed in 2009 upstream of TM
- **Second Bergoz® installed in 2017 in SINQ beam line**
- Idea: **Precise transmission measurement** and reliable calibration procedure for the resonators

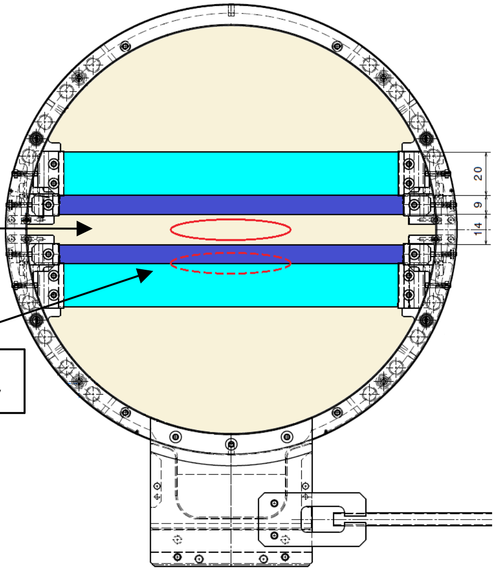
New Beam Position and Second Moment Monitor (SD2017)

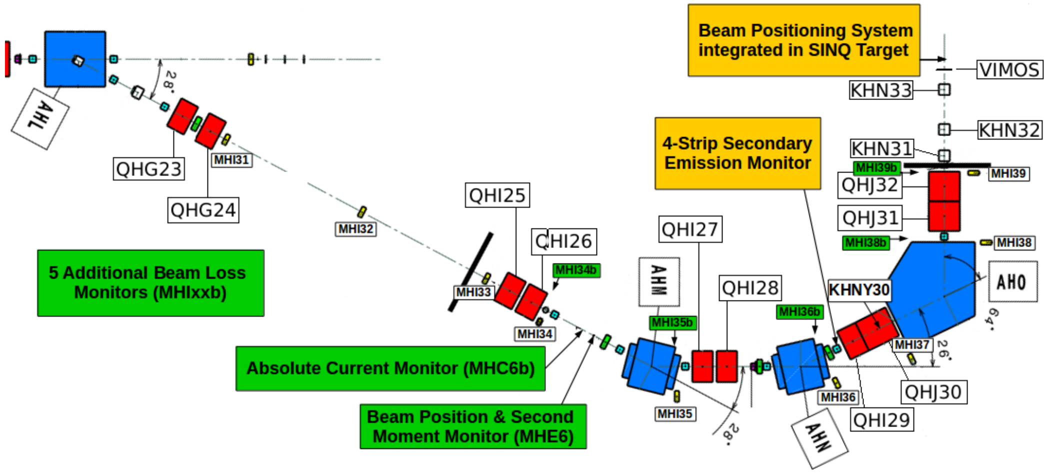




- New monitor **conceived and built at PSI**
- 8 broad-band magnetic pickup coils
- **Measures the moments M=0, 1, 2** of the proton beam magnetic field
- First prototype for potential integration of BPMs in SINQ-BL
- First measurements of **beam current and position** in 2017
- Calibrations for determination of **Beam "Ellipticity"** (M=2) still ongoing

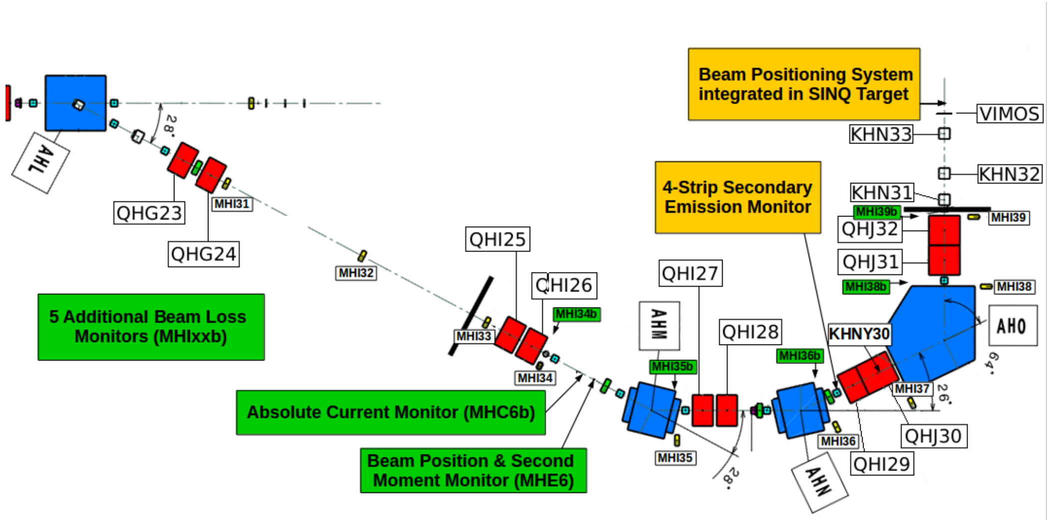
New 4-Strip SE-Monitor as TE-Missing Beam Monitor

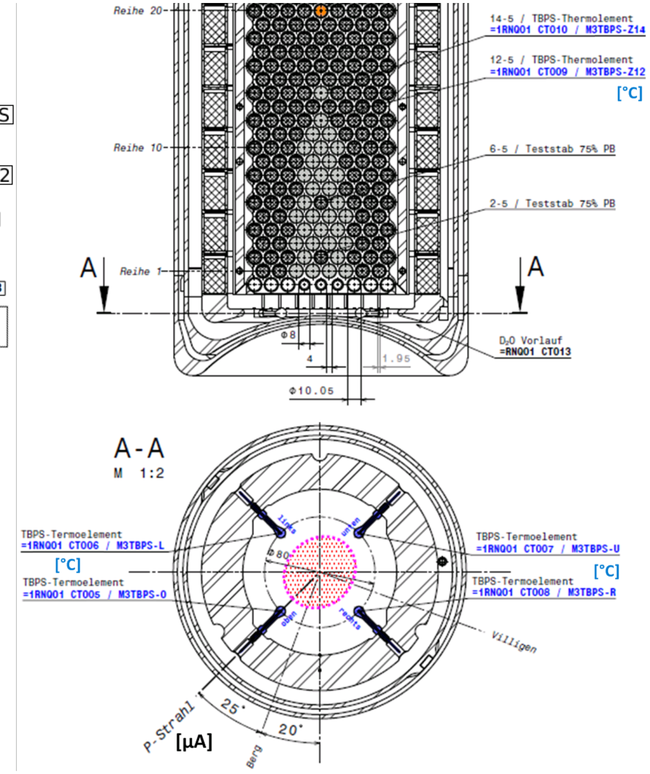




- **Protons missing TE shifted vertically** according to dispersion function
- New SE-Monitor installed in SD-2018 closed to KHNY30 slit
- Idea: assist (eventually replace) bulky and loss generating KHNY30 slit
- Setup: 4 – **20µm Molybdenum foil strips** on both sides of the beam generate SE-electrons when hit by proton beam
- **~1% protons missing TE reliably detected**
- Negligible beam losses according to simulations and measurements

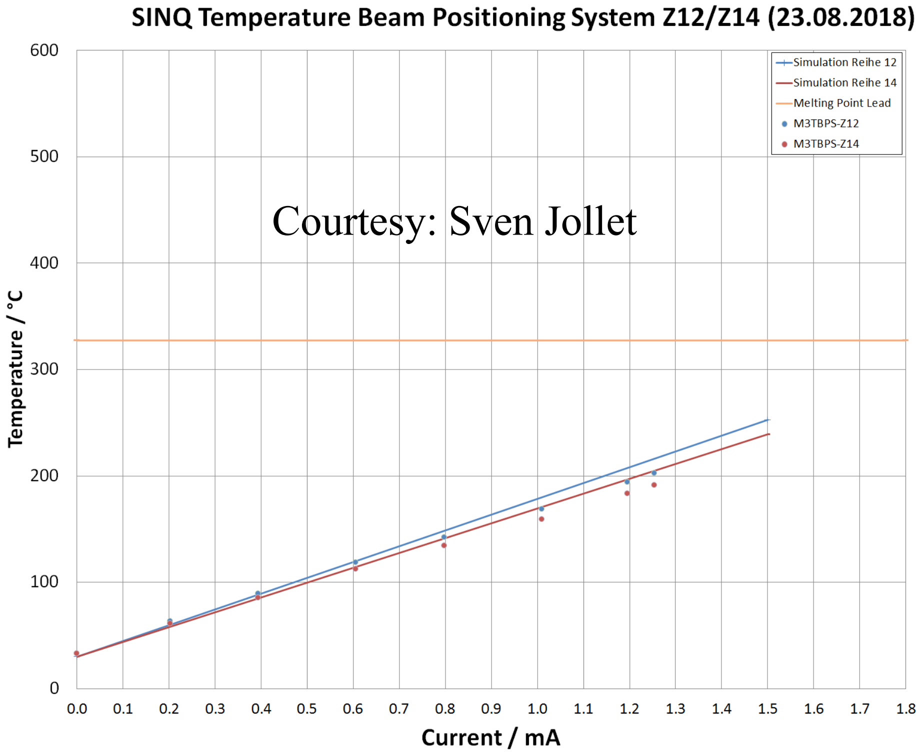
SINQ Temperature Based Beam Positioning System

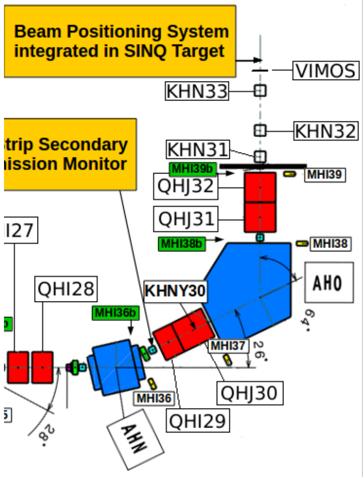


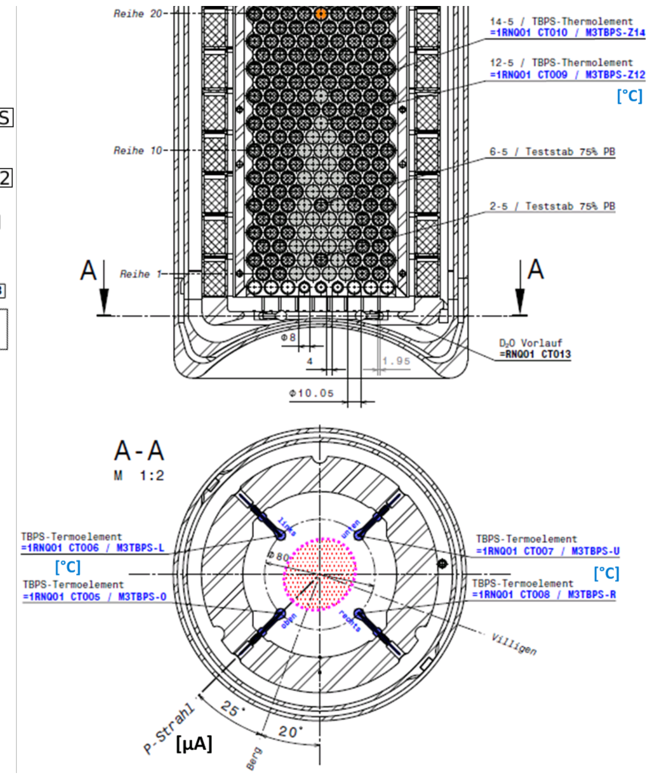


- SINQ Target **T13** furnished with **temperature based beam positioning system**
- **4 Sensors at the Target rim / 2 Sensors in the center** (row12 and 14)
- Reliable **determination of beam position**

SINQ Temperature Based Beam Positioning System

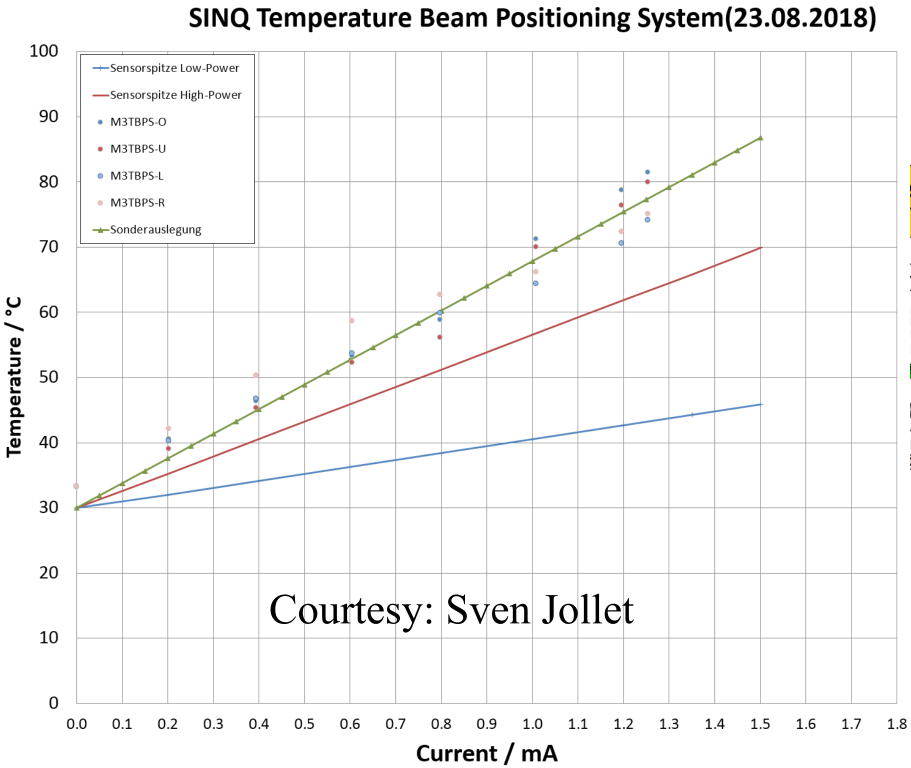


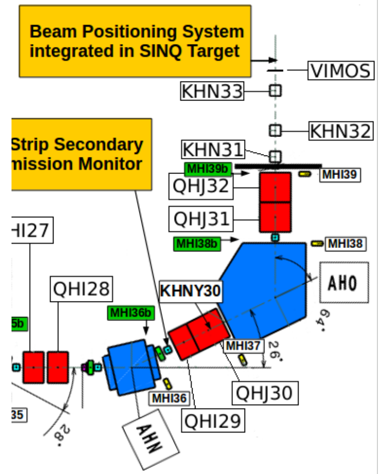


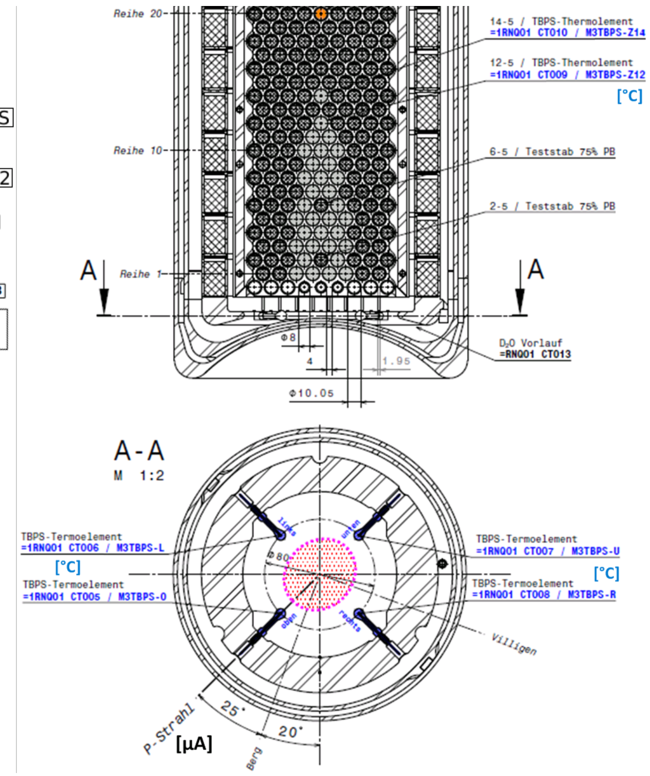


- SINQ Target **T13** furnished with **temperature based beam positioning system**
- **4 Sensors at the Target rim / 2 Sensors in the center** (row12 and 14)
- Reliable **determination of beam position**
- Good simulations/measurements agreement for 2 central sensors

SINQ Temperature Based Beam Positioning System







- SINQ Target **T13** furnished with **temperature based beam positioning system**
- **4 Sensors at the Target rim / 2 Sensors in the center** (row12 and 14)
- Reliable **determination of beam position**
- No simulations/measurements agreement for 4 outer temperatures: larger halo than expected

New Method to Center the Beam on TE

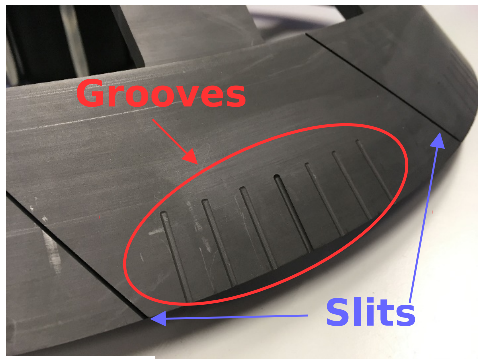
Issue: horizontal centering of proton beam (2σ=1.5mm) on 6mm wide graphite wheel TE

Risk: TE-missing beam delivers hotspot at SINQ target

Method (so far): transmission measurement not very sensitive due to slits in TE

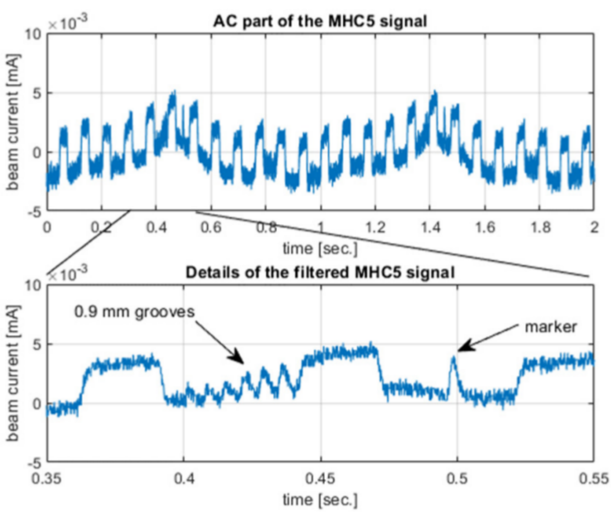
New Idea: grooved TE introduces sizeable modulation of beam current if beam not centered

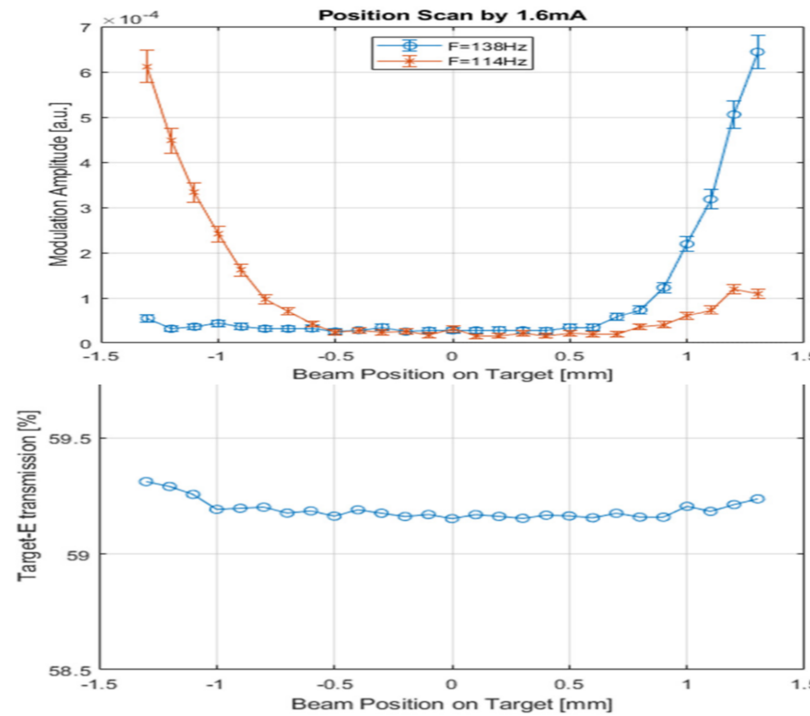
First Tests with Prototype TE: July-September 2019



Groove Depth: 0.3, 0.5, 0.7, 0.9 mm

Modulation Freq: 114Hz (left), 138Hz (right)





Improving Beam Line Simulation: Motivation

Motivation: understanding beam losses on Target and Collimators essential step to

- determine and keep beam transmission under control
- determine beam intensity at SINQ
- Further beam line development
- cross check measurement of newly installed Bergoz Monitor

Tool employed so far: **Turtle** → poor geometry modelling, lacks inelastic scattering

New Idea: **complement Turtle with MCNPX** for TE and collimation sections

Simulation approach:

Start with 10M protons at TM-IN

Turtle between TM-IN and TE-IN

MCNPX between TE-In and KHE3-OUT (last TE collimator)

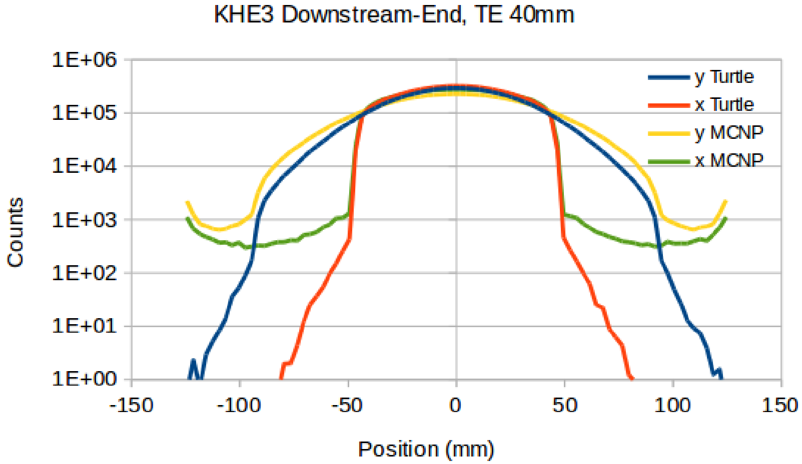
Turtle between KHE-OUT and KHN31-IN (first SINQ collimator)

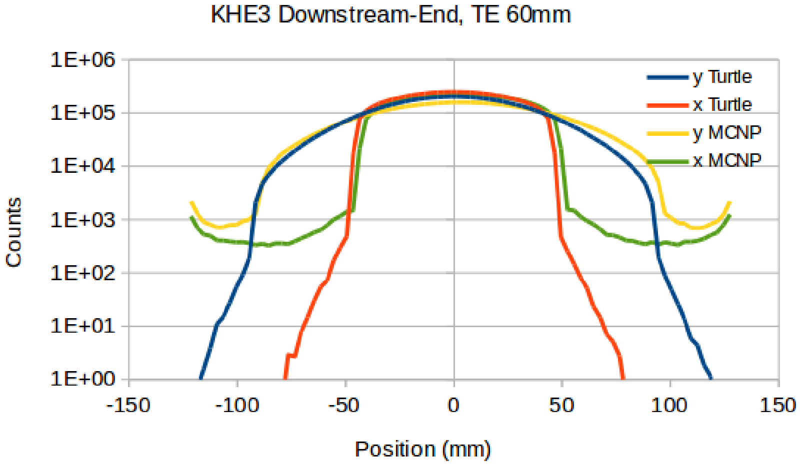
MCNP between KHN31-IN and SINQ target

Comparison: pure Turtle, MCNPX/Turtle and measurements

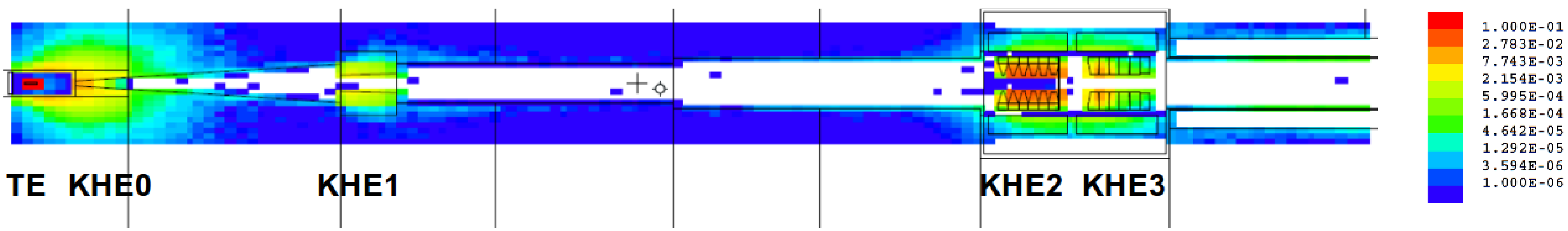
Improving Beam Line Simulation: Results (I)

KHE3-OUT

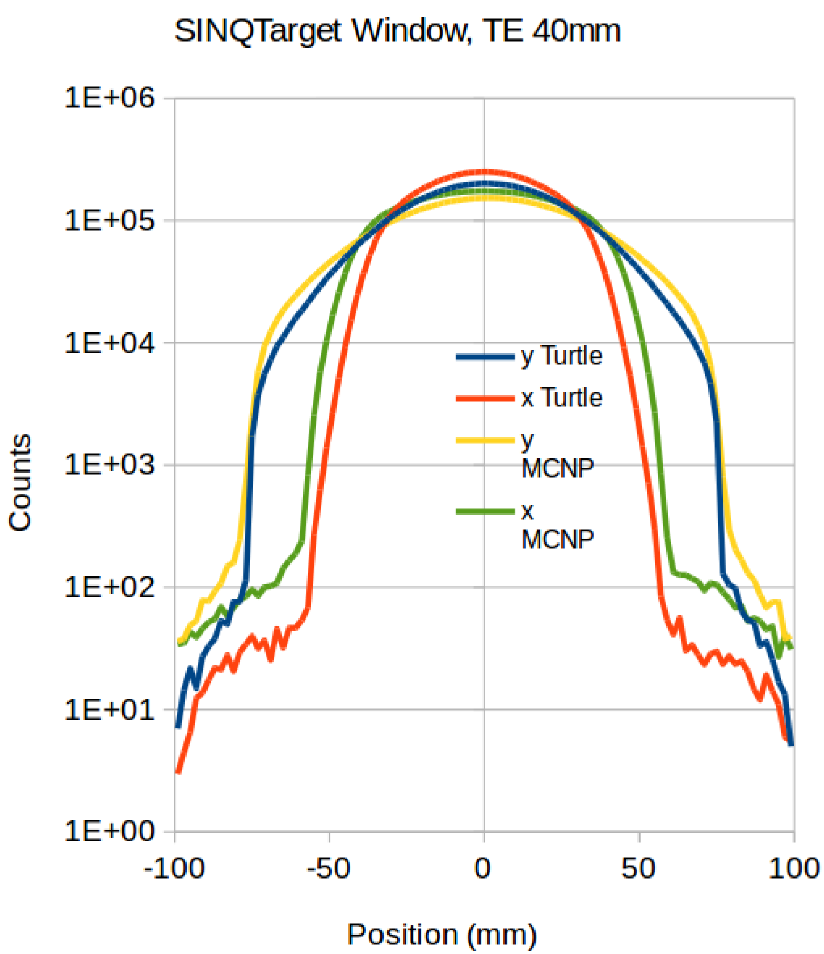


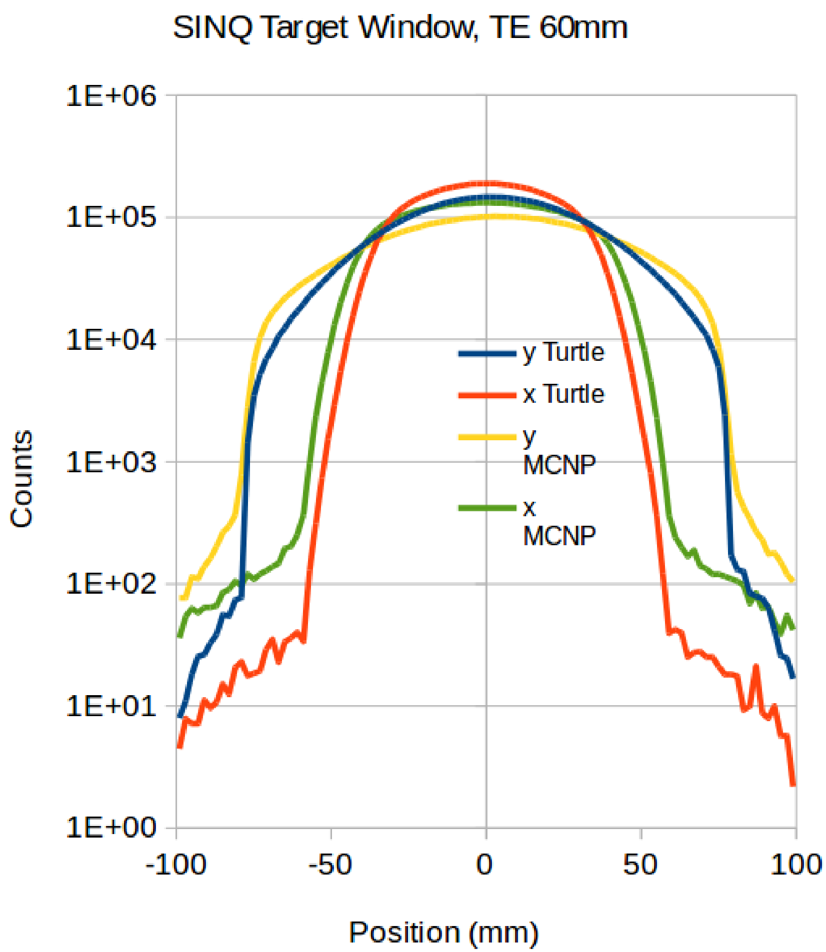


Energy Deposition (MeV/cm^3/particle) calculated with MCNPX2.7.0



SINQ Target Window





Improving Beam Line Simulation: Conclusions

- MCNPX/Turtle predicts **larger losses and huge tails** after TE collimators
- MCNP/Turtle tails produce **higher losses between KHE3 and MHC6**
- MCNPX/Turtle distribution matches the beam envelope in the x plane at SINQ Target
- Beam transmission compilation (in %):

Location	Beam Trans. (TE40)			Beam Trans. (TE60)		
	Turtle	MCNP	Meas.	Turtle	MCNP	Meas.
TM in	100	100	100	100	100	100
TE in	97.7	97.7		97.7	97.7	
KHE3 out	69.9	65.9		57.3	52.6	
MHC5	69.2	63.7		56.5	50.2	
MHC6	68.6	62.0	65.9	55.9	48.6	53.3
KHN31 in	68.6	62.0		55.9	48.6	
SINQ	68.4	61.1		55.7	47.4	

- **Neither Pure Turtle nor MCNPX/Turtle in agreement with measurement**

→ Further investigation necessary!

Conclusions

- After SINQ T11 failure, a campaign towards an improved control and thorough understanding of the proton beam delivery to SINQ has been launched
- New diagnostic elements already installed allowing
  - Better understanding of beam losses
  - Monitoring of beam position / width at SINQ target
  - Improved detection of TE-bypassing beam
  - Absolute measurement of beam intensity
- New beam line simulations making use of MCNP(X) are being carried out in order to assess losses on targets and collimators

PAUL SCHERRER INSTITUT

Outlook

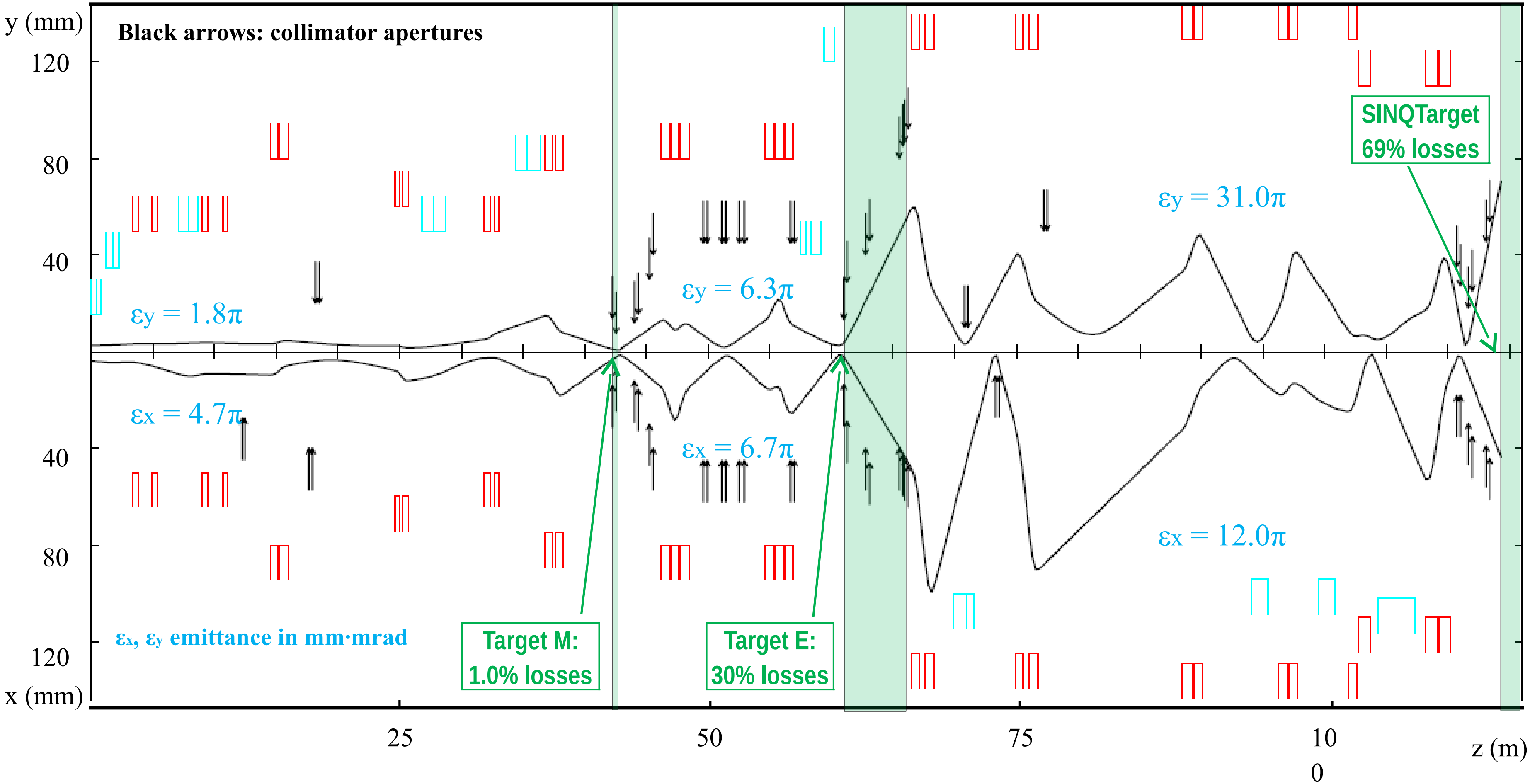
- First tests of fast detection of off-center beam at TE look very promising and will be pursued aiming at its implementation in the MPS.
- Temperature based SINQ beam centering system will be further developed
- Possible future implementation of BPMs in the SINQ beam line under study
- New fast and more flexible electronics for beam loss monitors being developed, commissioning of first prototypes foreseen for 2021
- Further development of beam losses simulation ongoing
- Machine Learning project aiming at automatic control of beam footprint on SINQ as well as beam interlock forecasting started beginning 2019

→ Still a lot of work (and fun!) to come!

Thank you!

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

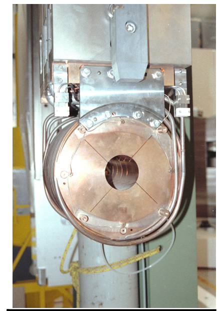
Average losses away from targets: 0.6 W/m

Target E Region

Target Wheel
9% beam loss

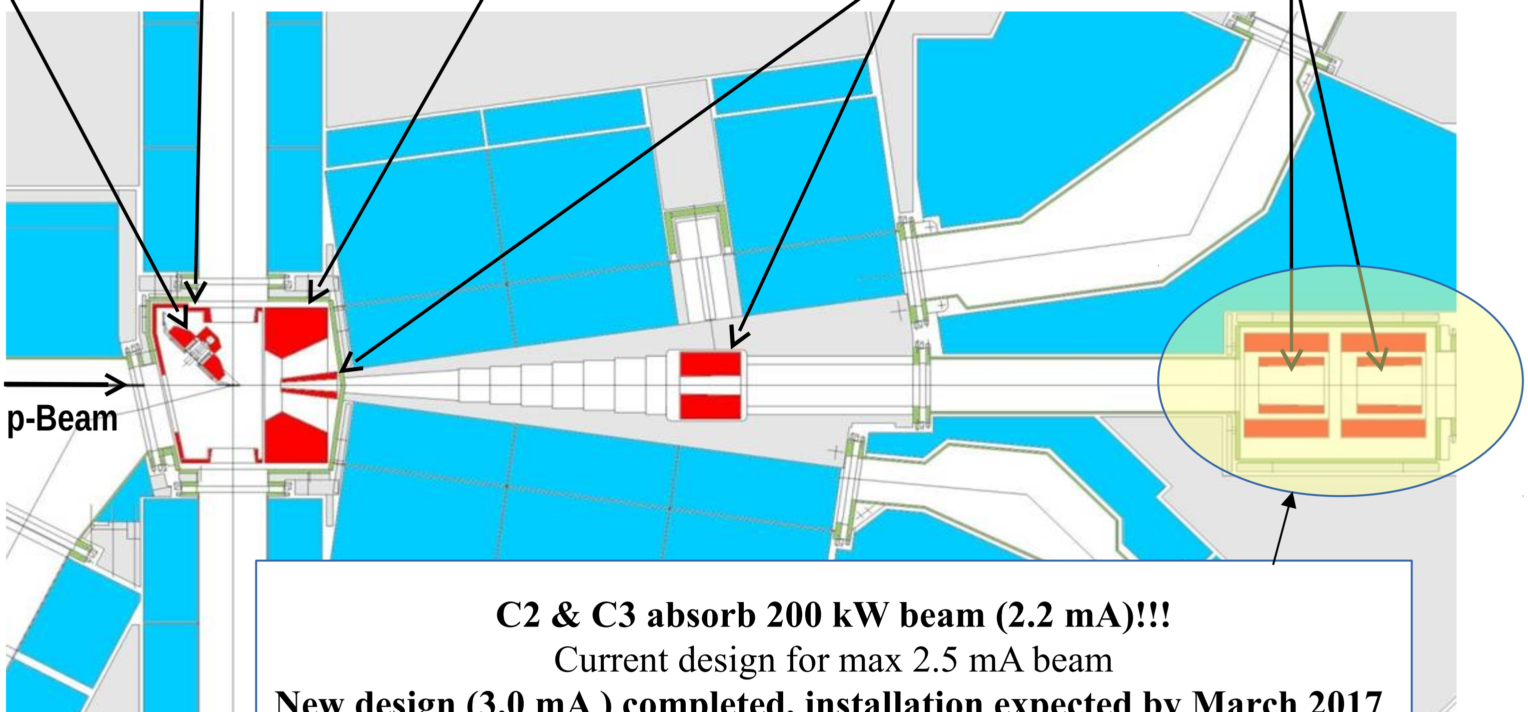
Backward
Schielding

Target
Chamber



Collimators 0&1
6% beam loss

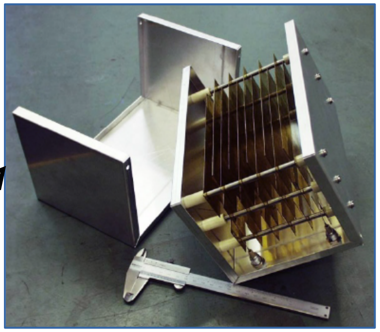
Collimators 2&3
15% beam loss

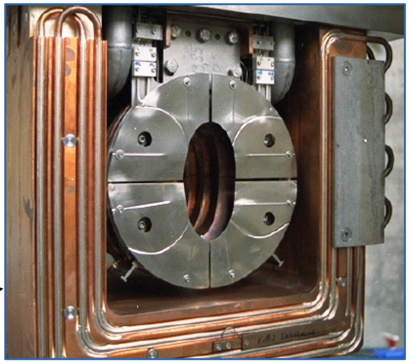


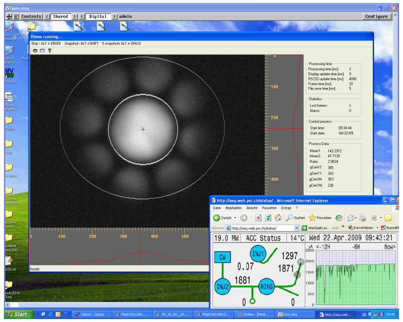
C2 & C3 absorb 200 kW beam (2.2 mA)!!!
Current design for max 2.5 mA beam
New design (3.0 mA) completed, installation expected by March 2017

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)

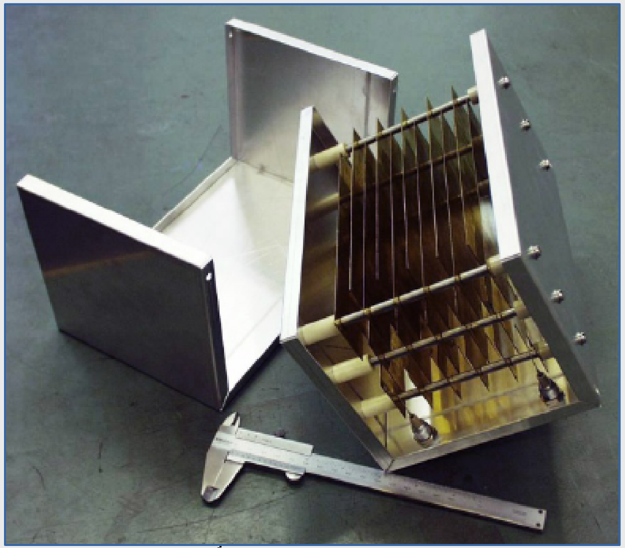


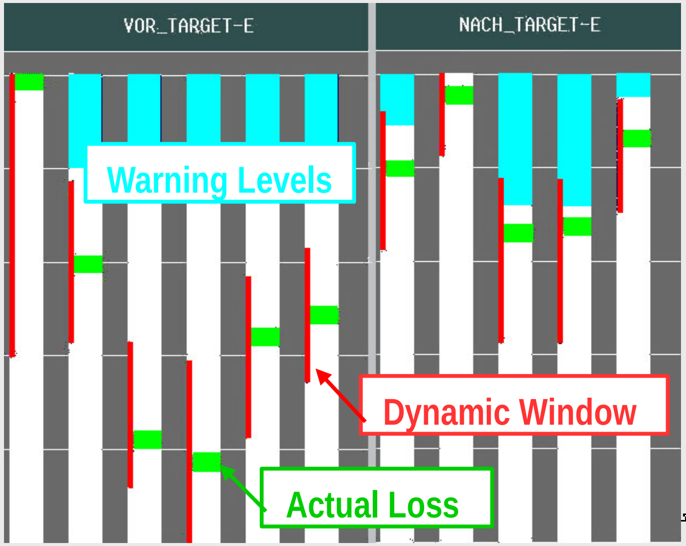


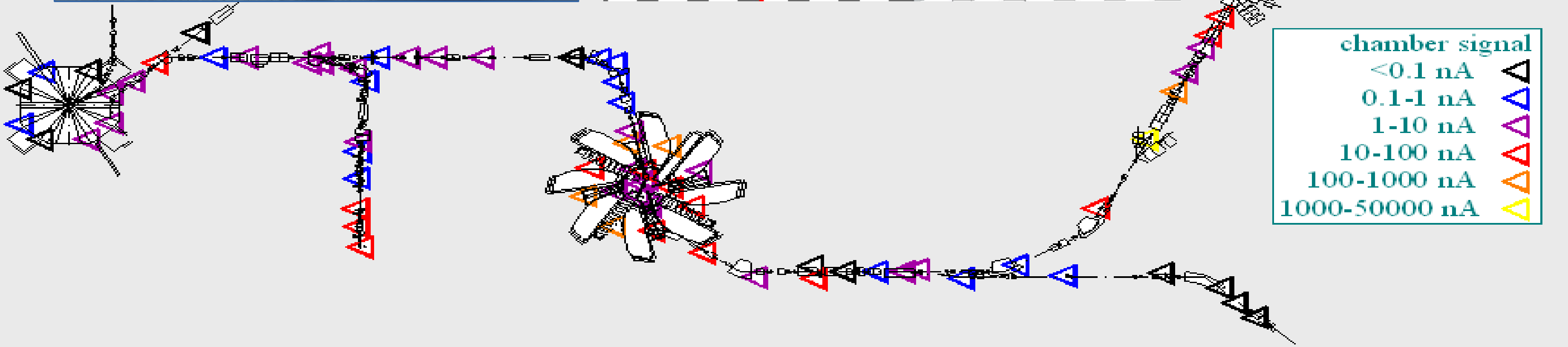


Setup and Monitoring: Beam Loss Monitors

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



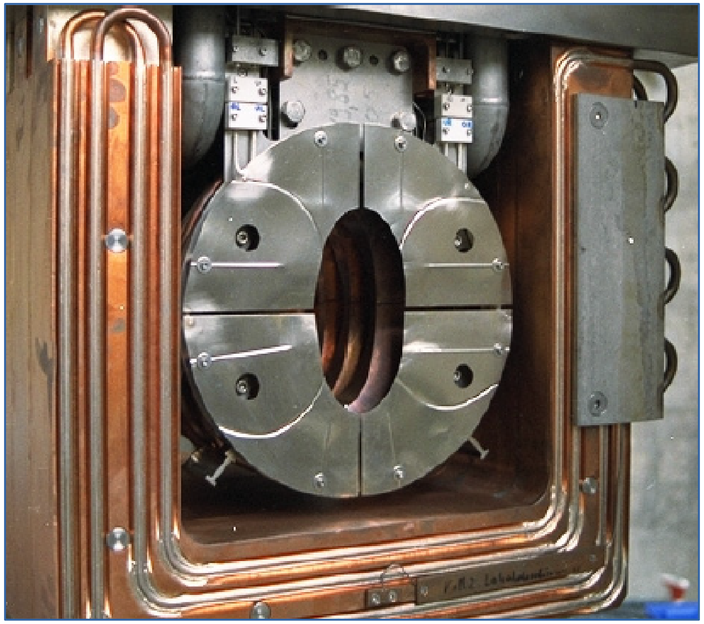


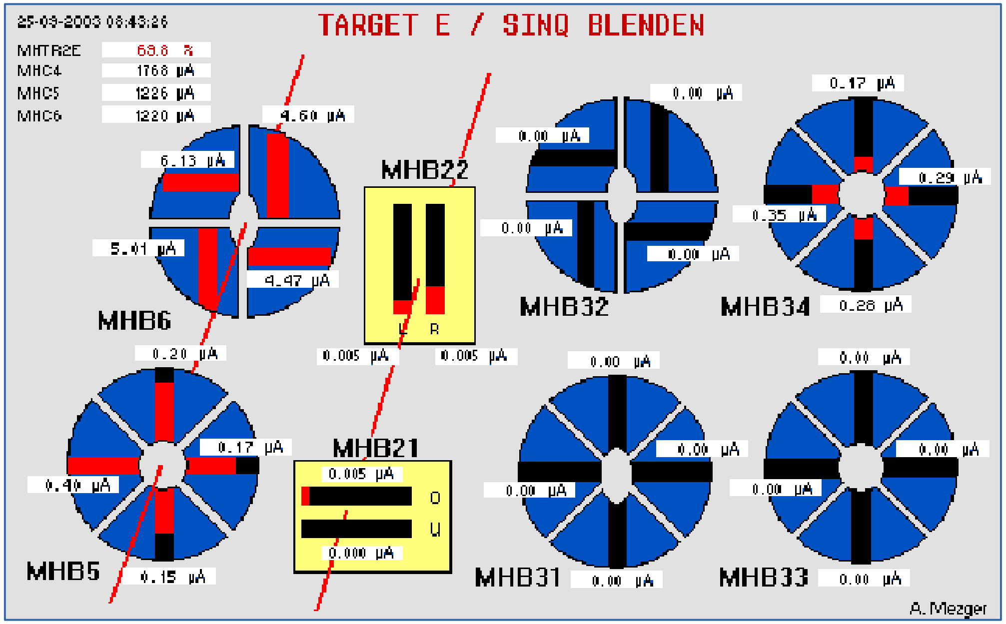


Loss Measurements employed for a fast machine setup!

Setup and Monitoring: Aperture Foils

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

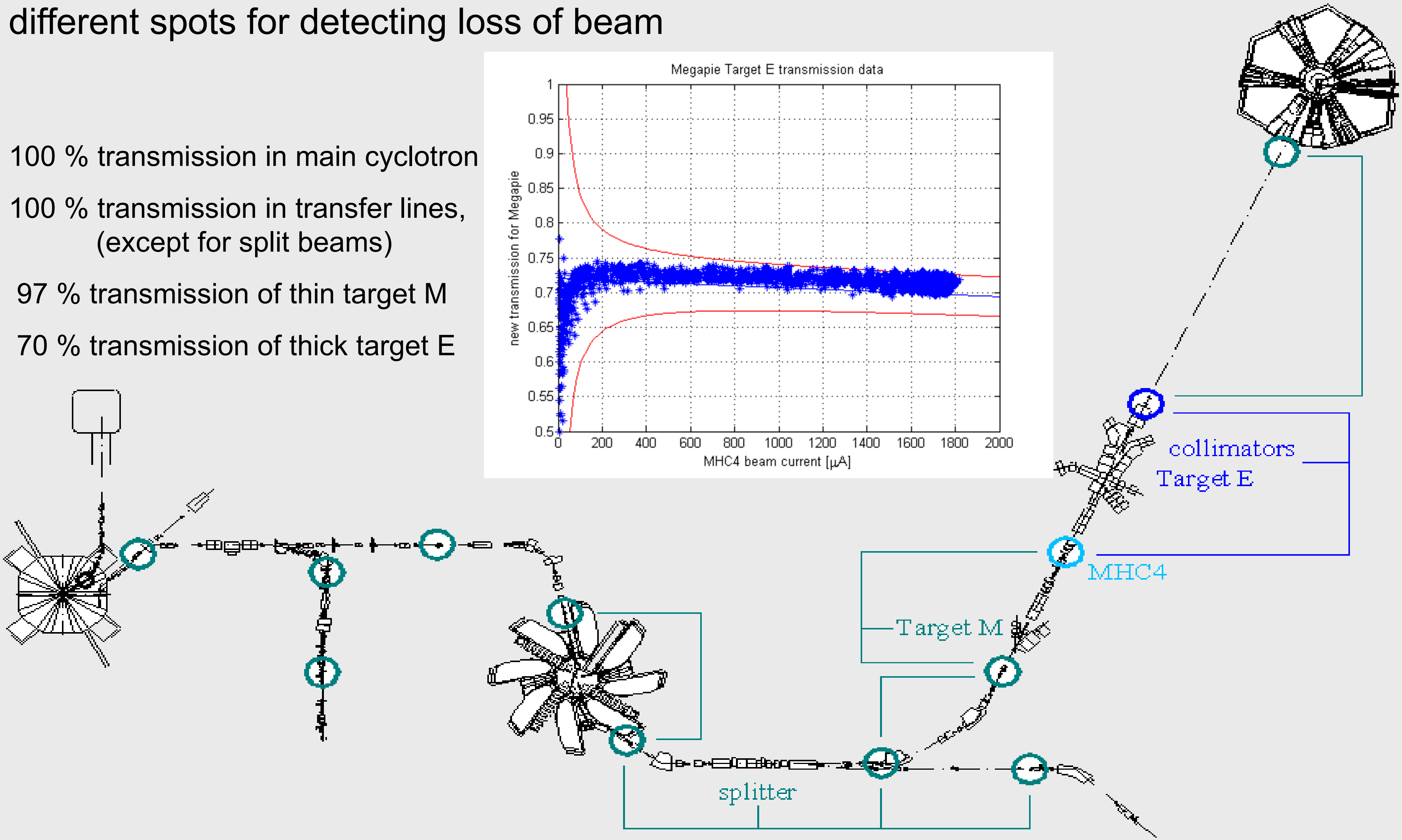
Beam current transmission monitors compare the beam current at different spots for detecting loss of beam

100 % transmission in main cyclotron

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

97 % transmission of thin target M

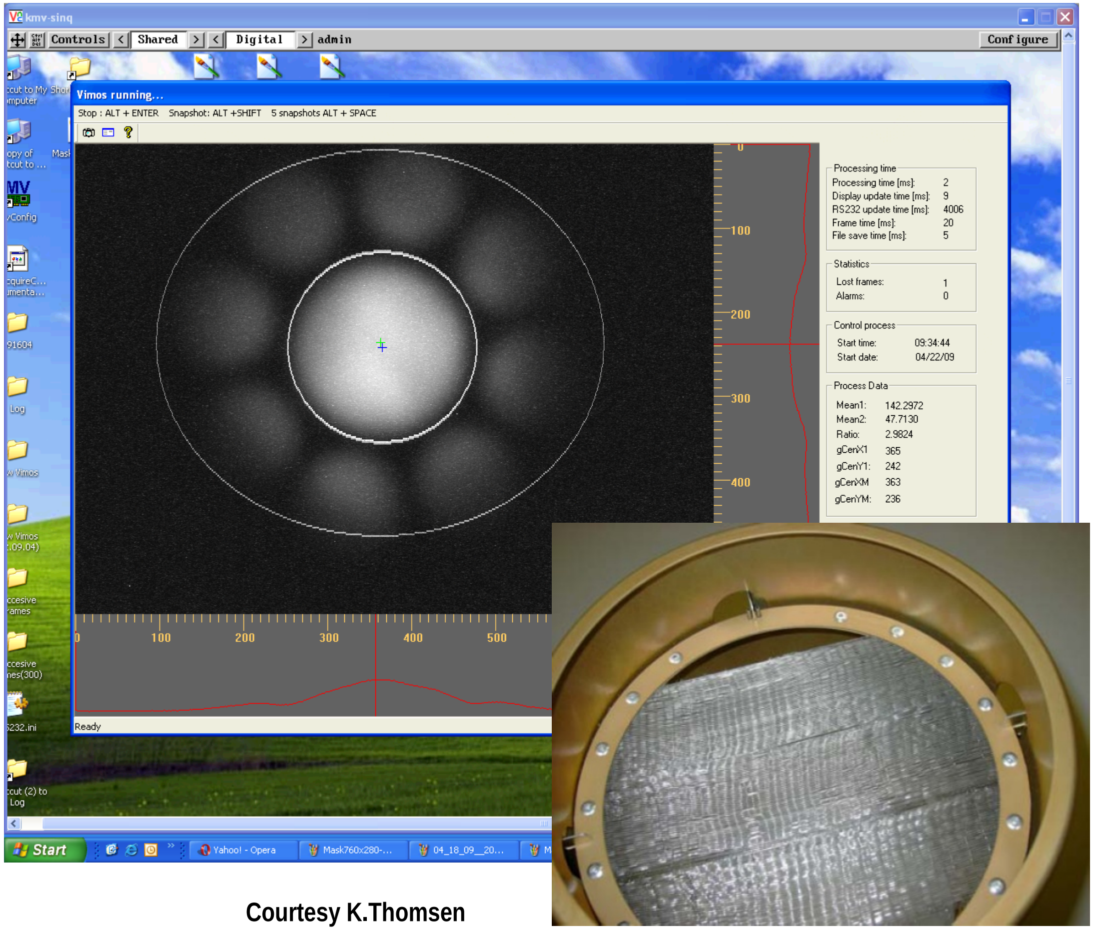
70 % transmission of thick target E



Setup and Monitoring: VIMOS

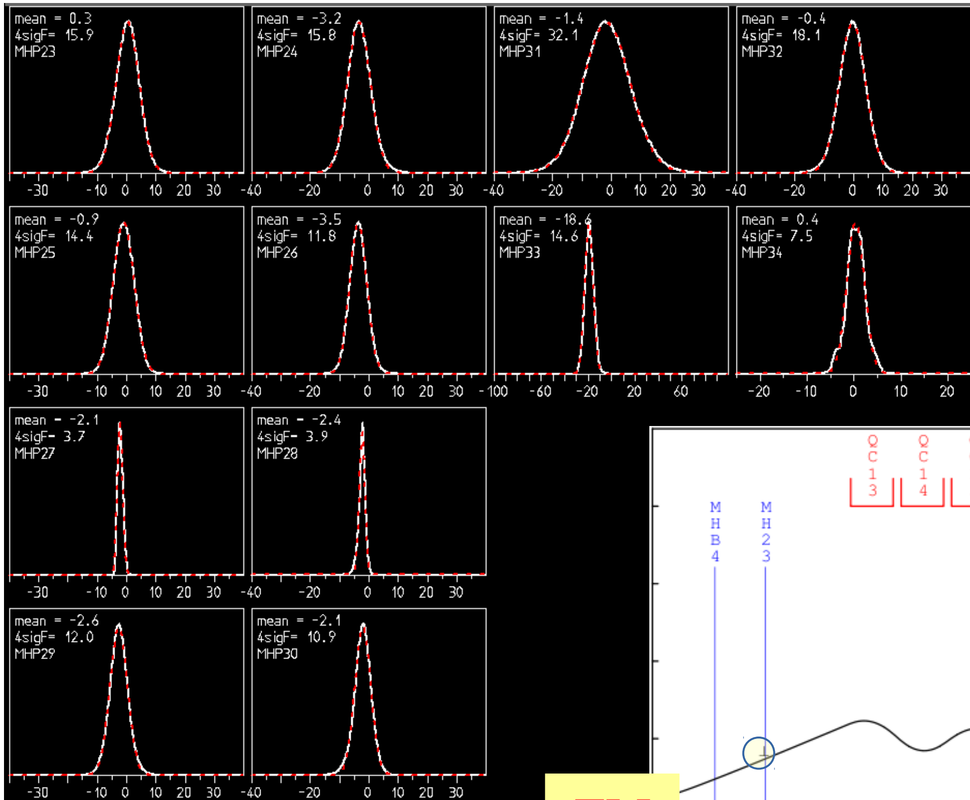
Tungsten Grid located 40 cm upstream of the SINQ Target visualized by optic-fibers and camera gives an image of the thermal radiation

- 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.



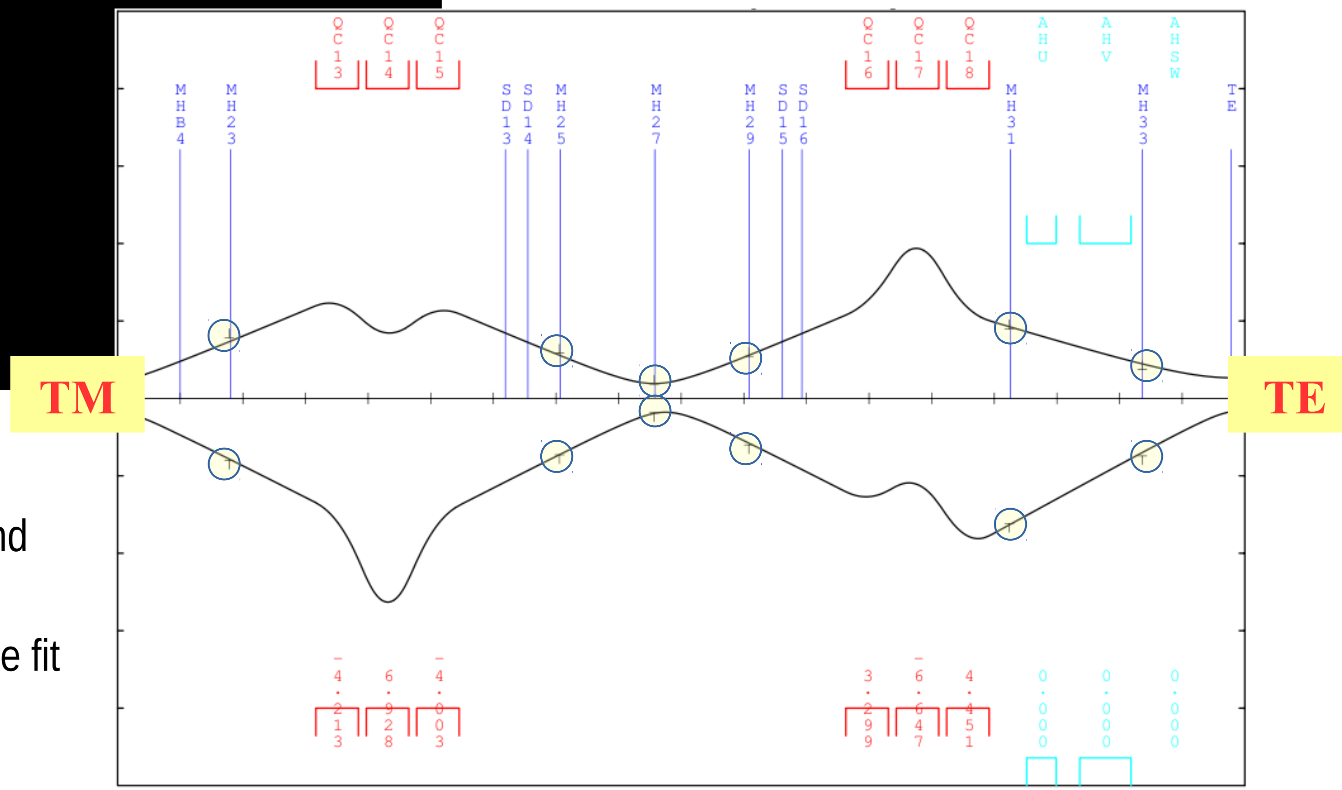
Courtesy K.Thomsen

Beam Optimization: Optics Determination



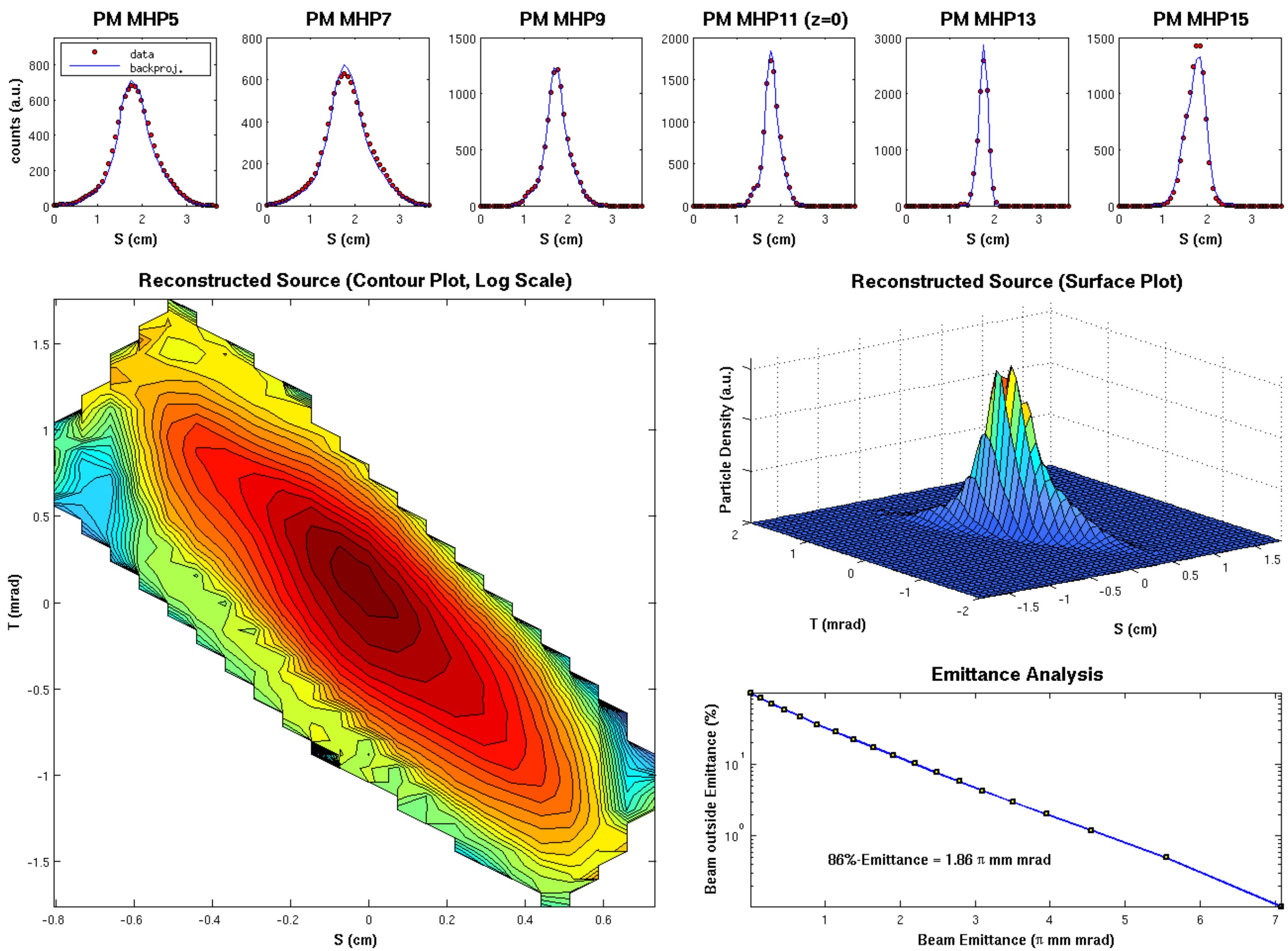
Beam Profile Monitors determine beam widh at several locations along beamline

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



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

Further Improvement: Beam Tomography



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