Wir schaffen Wissen – heute für morgen

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The PSI HIPA Beam Lines

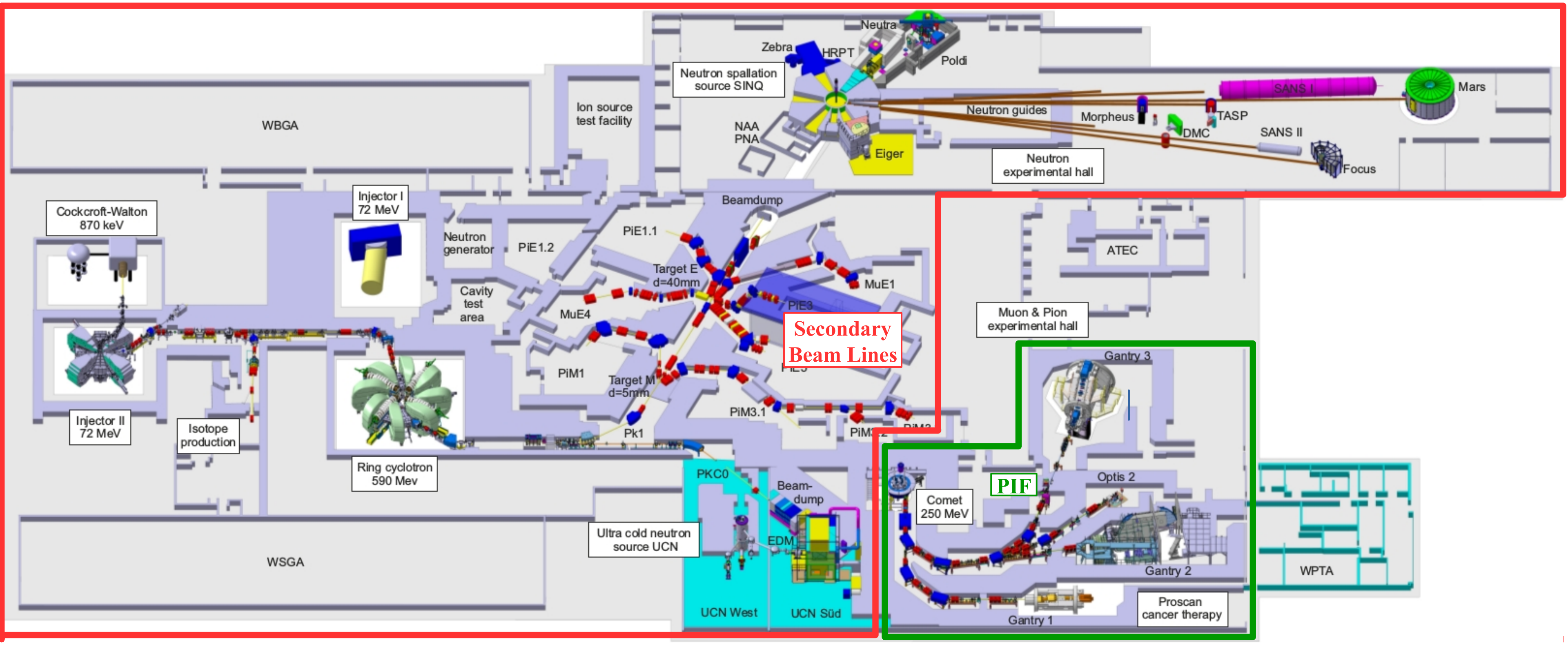
6th Beam Telescopes & Test Beams Workshop, 17.01.2018, Zurich, Switzerland

PAUL SCHERRER INSTITUT PSI

Outline

- Introduction to the PSI High Intensity Proton Accelerator (HIPA) Facility
- Secondary beam lines (PiM1, PiE1, PiE5)
- Other “useful tools” (Wien Filters, Beam Scanners, Control System)
- Conclusion

The PSI HIPA Proton Accelerator Facility



HIPA (High Intensity Proton Accelerator)

CW (50.63 MHz), 590 MeV, up to 2400 µA (1.44 MW) to 2 meson production targets (7 sec. beam lines) and SINQ spallation source

Macro-Pulses, up to 3% duty-cycle to UCN source

High availability, stable operation.

PROSCAN (Protontherapy)

CW, 250 MeV, up to 1000 nA proton beam

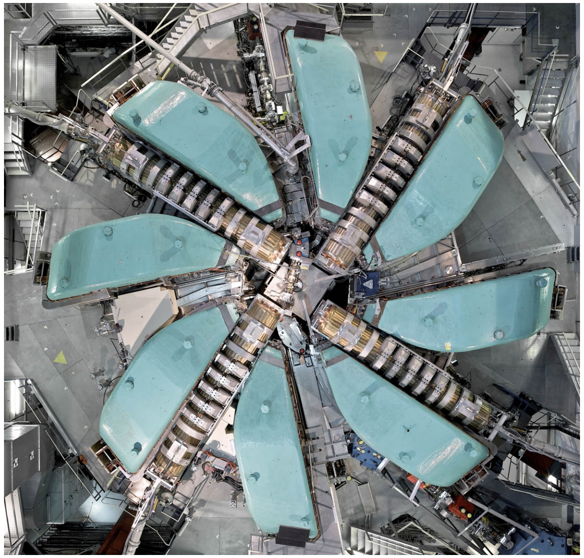
In operation since 2007

3 Gantries, 1 Eye Cancer Treatment Station, 1 PIF

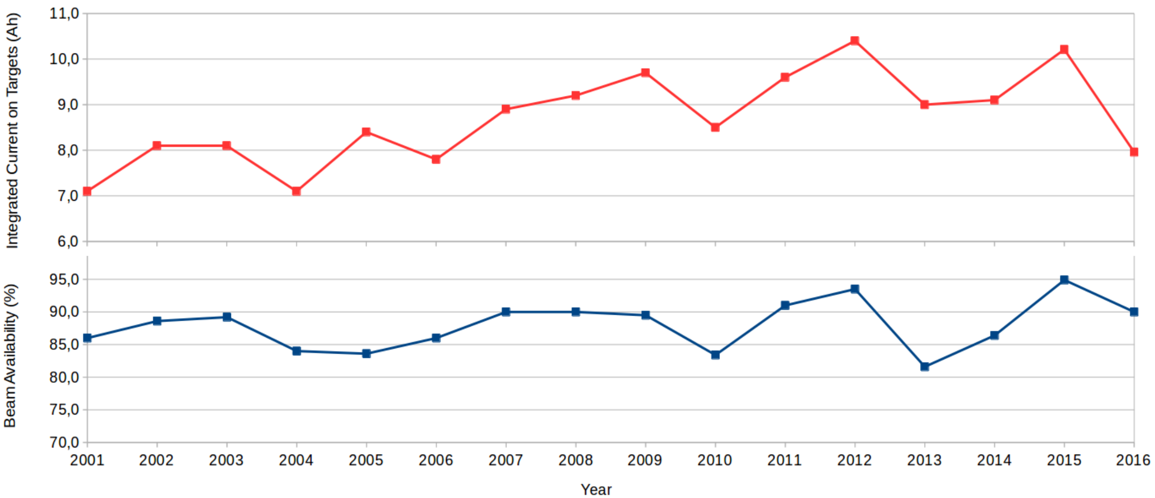
Facts about HIPA

- In operation since 1974, stepwise upgraded
- Most powerful CW beam worldwide so far
  (1.44 MW max, 1.3 MW routine operation)
- Low losses, high efficiency accelerator (99.98% extracted beam)
- Typical availability: 90%
- Charge delivered to meson production targets: ~9 Ah/year
- CW beam, 50.63 MHz (spacing between bunches: 19.75 ns)

Carbon Target Wheel



590 MeV Ring Sector Cyclotron

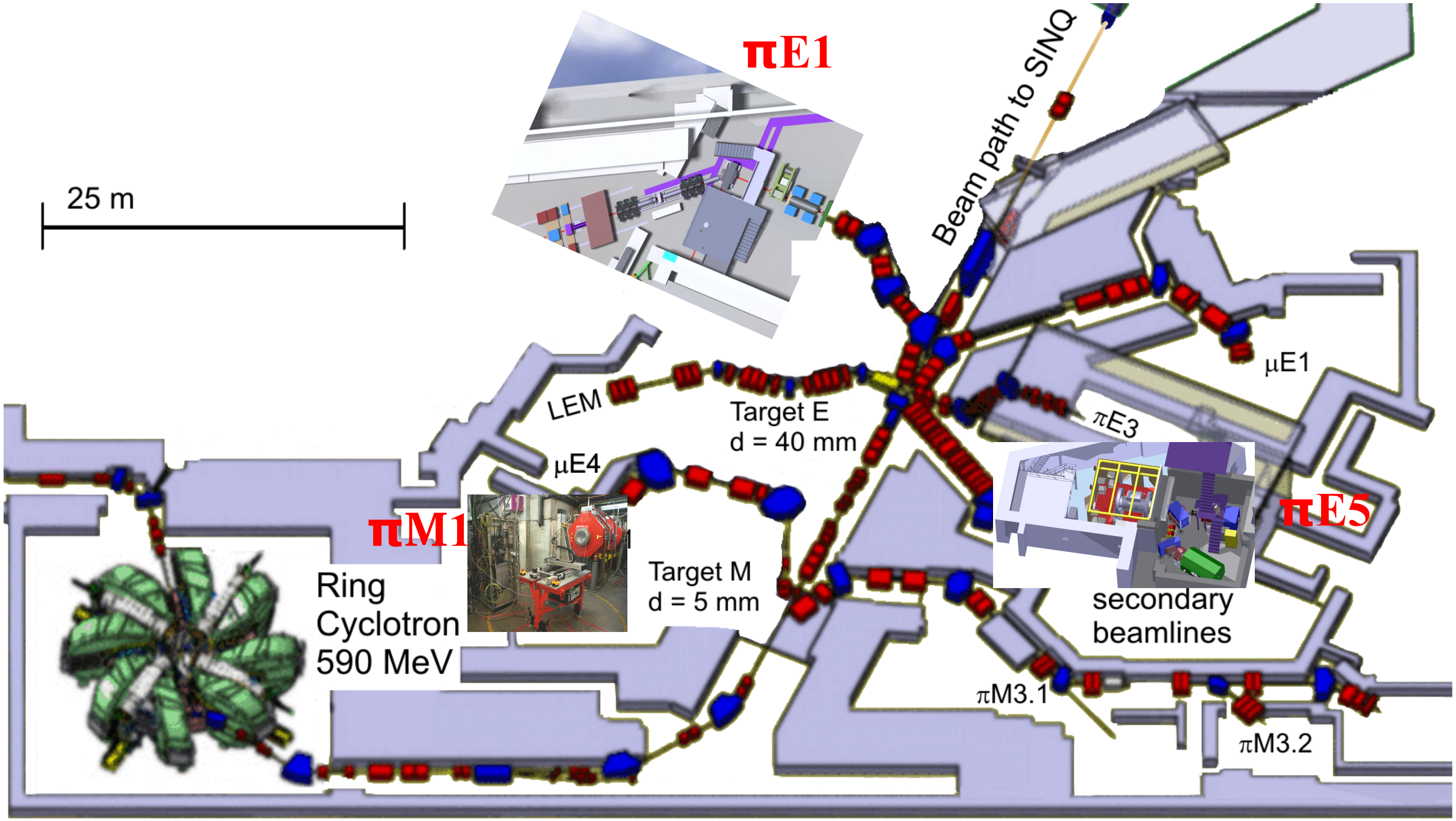


HIPA Performance 2001-2016

HIPA Secondary Beam Lines

Two meson production targets:

- **TM** (5 mm), 2 beam lines: **PiM1**, PiE3
- **TE** (40 mm), 5 beam lines: **PiE1**, MuE1, PiE3, MuE4, **PiE5**

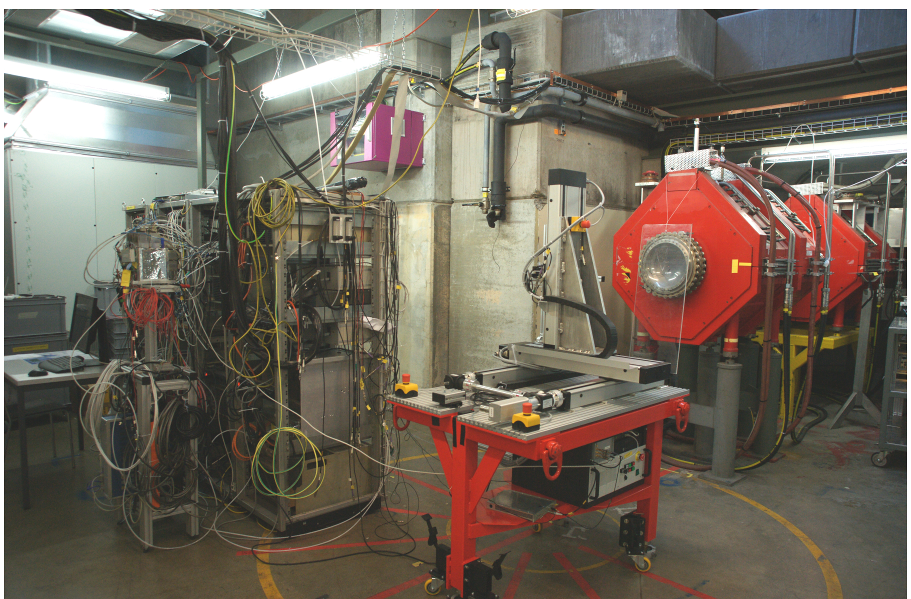


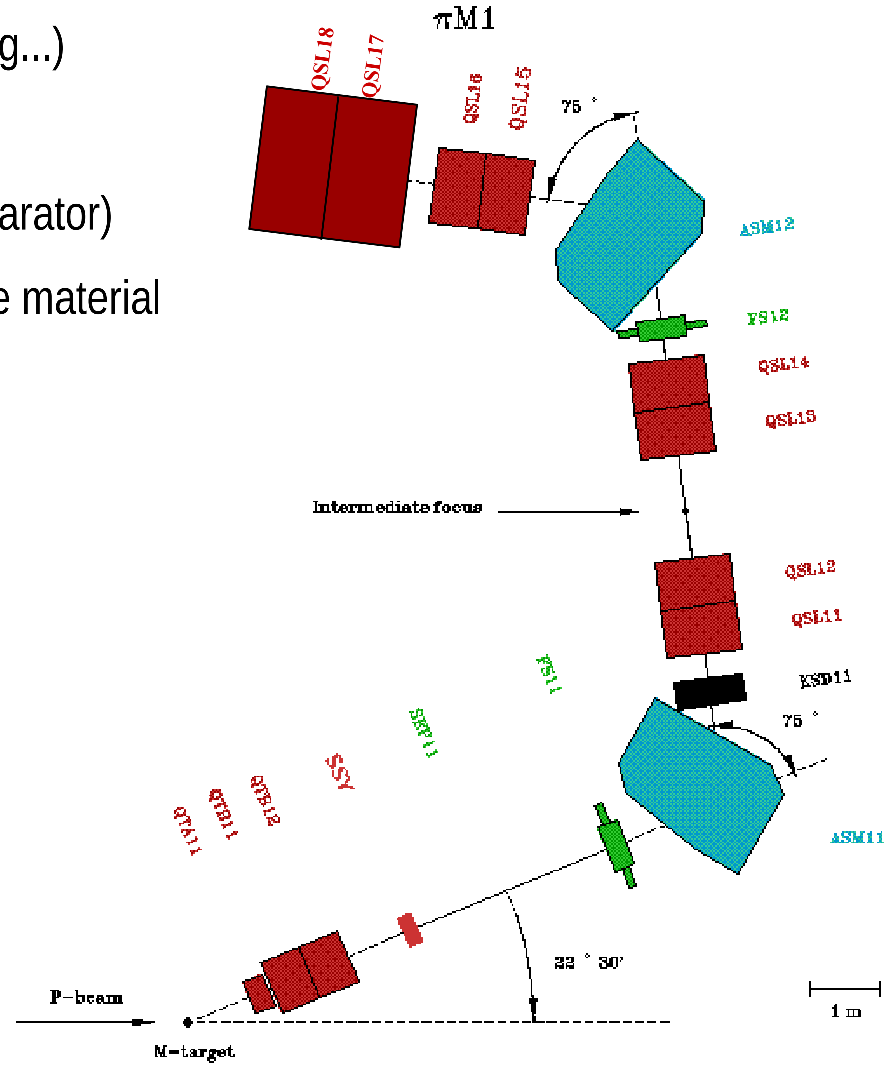
Overview of Secondary Beam Lines Features

	PiM1	PiE5	PiE1 Redesigned in 2012	PiE3 Redisigned 2010/2011	PiM3 New S-Rot in 2017	MuE4	MuE1
Target	M	E	E	E	M	E	E
Particle Type	e/μ/π/p	μ/π	π/μ/p	μ (surface)	μ (surface)	μ (surface)	μ (cloud)
Momentum Range	10-500 MeV/c	10-120 MeV/c	10-500 MeV/c ustream ASK 10-120 MeV/c downstream ASK	10-40 MeV/c	10-40 MeV/c	10-40 MeV/c	60-120 MeV/c
Typical Momentum	15-350 MeV/c	28-85 MeV/c	PP: 10-50 MeV/c μSR: 28 MeV/c Irrad: 300 MeV/c	28 MeV/c	28 MeV/c	28 MeV/c	60-125 MeV/c
Max Rate [$s^{-1}mA^{-1}$]	$2x10^{8}$	$6x10^{9}$	$4x10^{9}$	$3x10^{7}$	$3x10^{6}$	$4x10^{8}$	$6x10^{7}$
Typical Use	Particle Physics Test Experiments, Detector/Material Irradiation	Particle Physics Experiments	μSR Dolly Facility Particle Physics Experiment, Detector Irrad.	μSR HAL 9500 (High Field) Facility	μSR GPS and LTF Facilities	μSR LEM Facility	μSR GPD Facility
Users	- MUSE Coll. - PSI-PIF group - INFN Det. Group - ETH Detector Gr. - PSI HE Section - ETH Students - Others	- MEG Collab. - Muonic Helium Exp - Prot. Radius Exp - μ3E Collab.	- MuSun Collab. - Dolly Group - CERN/PSI Detector - PSI PP Group	μSR-SμS GPS/LTF	μSR-SμS High Field μSR	μSR-SμS Low Energy Muon	μSR-SμS GPD group

PiM1 Overview

- 22m long beam line located at TM (22.5° forward angle)
- **“The” Test Beam line** at PSI (but MUSE is coming...)
- **Momentum range: 10 – 500 MeV/c**
- Beam mixture of **e/μ/π/p** (no “active” particle separator)
- 60 cm Air gap at intermediate focus allows to place material for passive separation

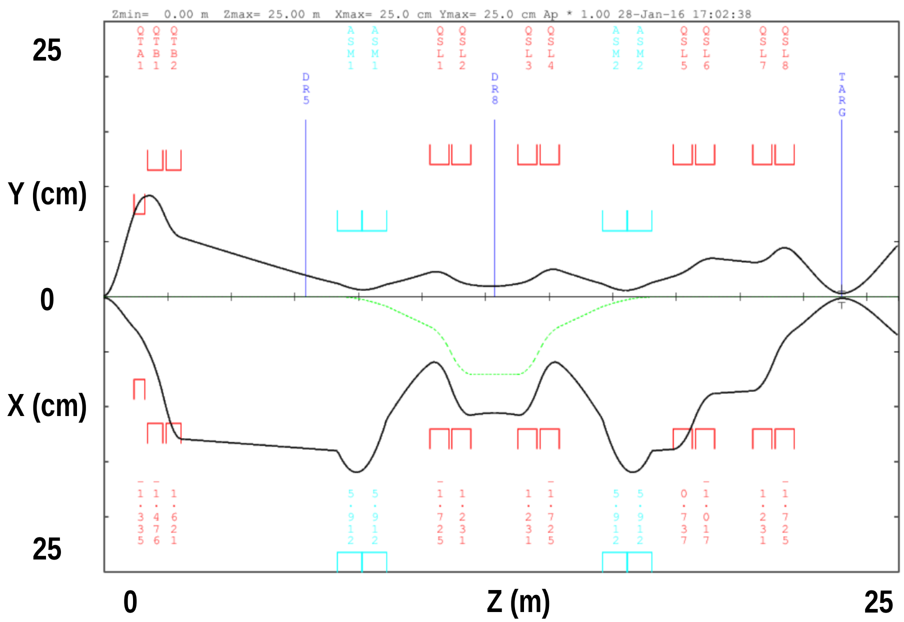




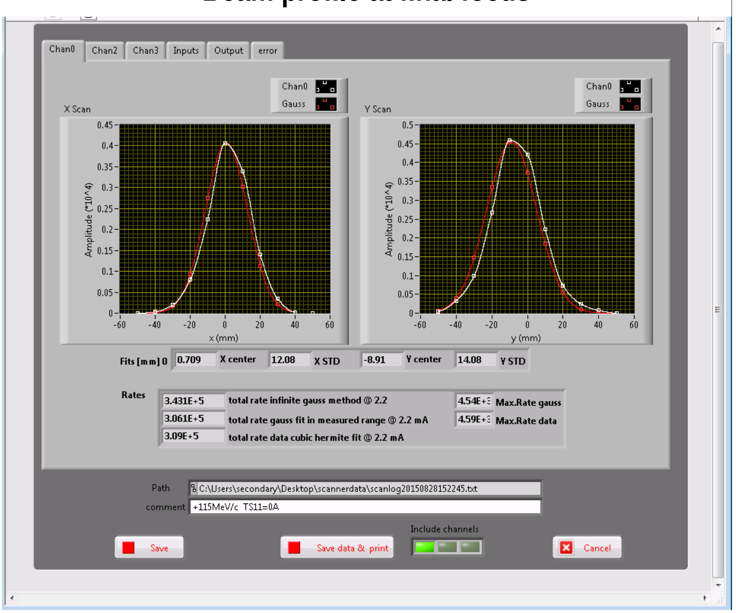
PiM1 Parameters

- Achromatic optics (downstream of last dipole)
- Large dispersion at intermediate focus (air gap): 7cm/%
- Momentum acceptance (1σ): 1.5%
- **Max. particle flux: 2x10^{8} part/s @ 350 MeV/c (positive charge)**
- Beam spot size at final focus (1σ): 18mm (x), 12mm (y)   (>100 MeV/c)
- **Momentum dependent beam composition (no particle separator)**

Beam envelops



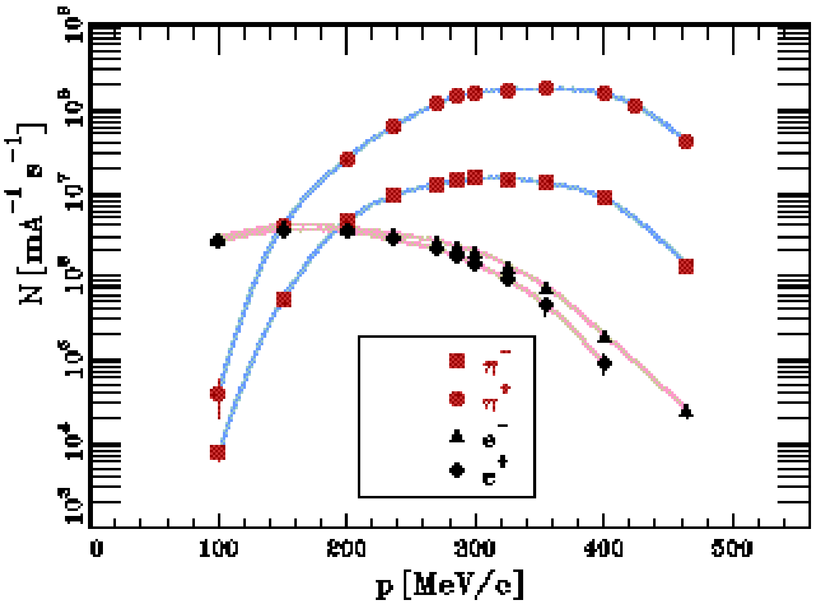
Beam profile at final focus



PiM1 Beam Composition

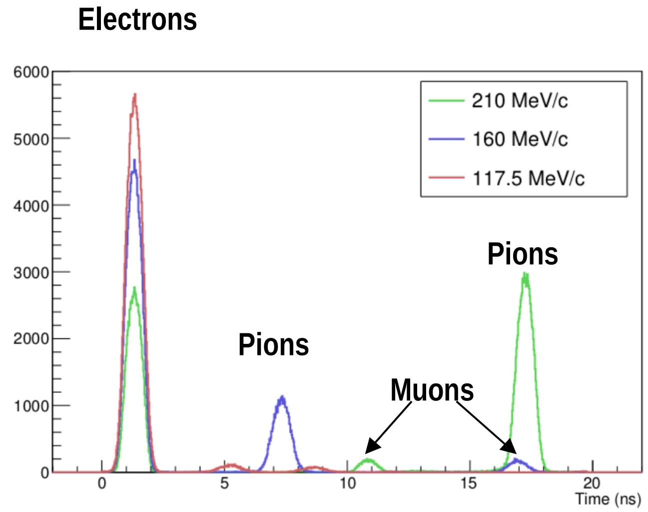
- Beam composition depends upon momentum:
  - < 115 MeV/c: **e**
  - 115 - 200 MeV/c: **e/π/μ**
  - 200 - 280 MeV/c: **e/π**
  - > 280 MeV/c: **π/p/e**
- Beam line originally built for pion physics (1974)
- Beam composition vs momentum measured in 1987 for pions and electrons only and for p > 100 MeV/c
- Recently:
  - Growing interest for low momentum tests (shielding material for space missions): 10 – 100 MeV/c
  - Particle physics moved to muon beams (ex: MUSE, measurement of proton radius)
- **Measurement of beam composition at lower momentum and including muons necessary!**

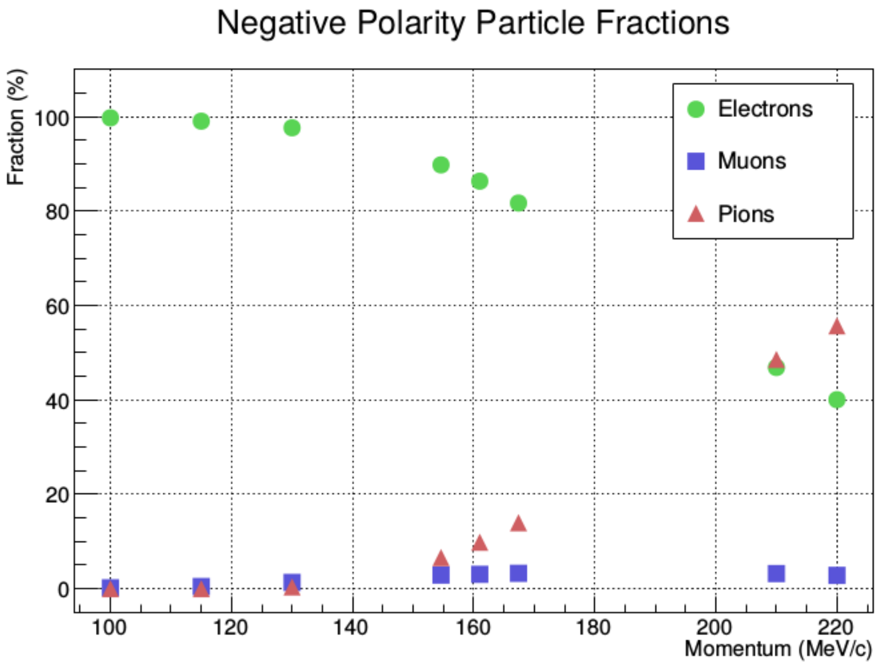
Measured Particle Rates (R.A. Schumacher, U. Sennhauser, 1987)

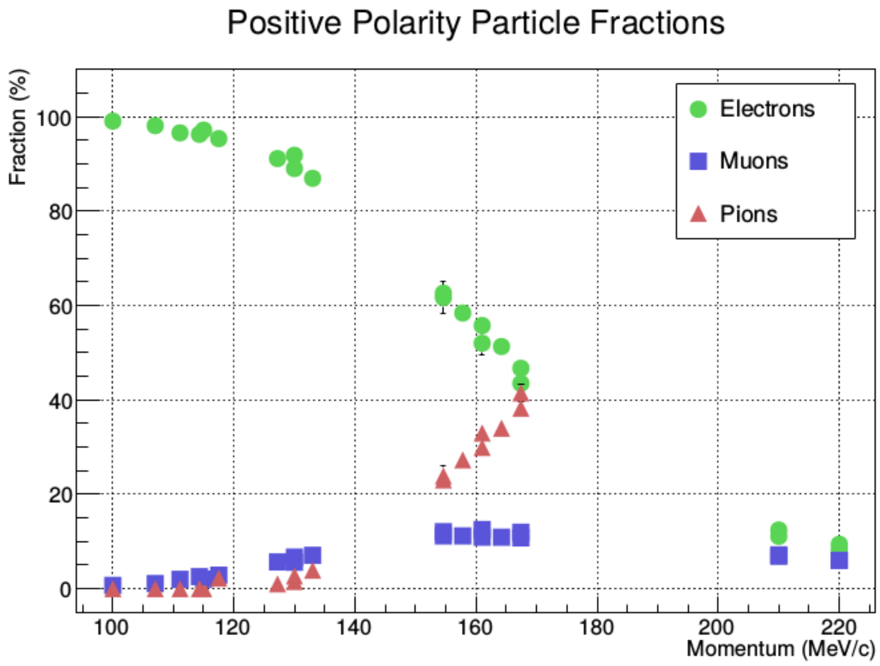


Beam Composition: New Measurements (MUSE)

- **TOF measurements in PiM1 performed by MUSE Collaboration for both negatively and positively charged beam, between 100 and 220 Mev/c**
- **Measurement by PSI Irradiation Group to characterize the PiM1 negatively charged beam between 10 and 230 MeV/c**
- Very good agreement between MUSE and Irradiation Group results (negative charge)

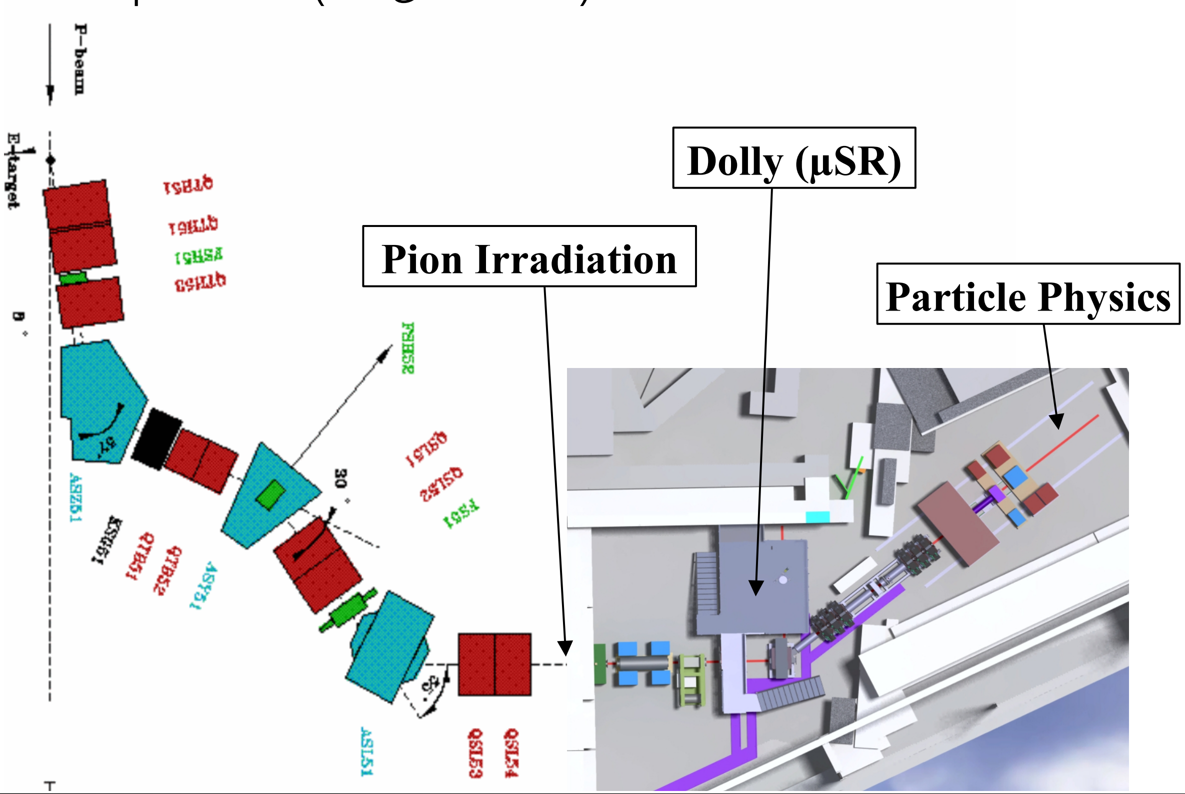


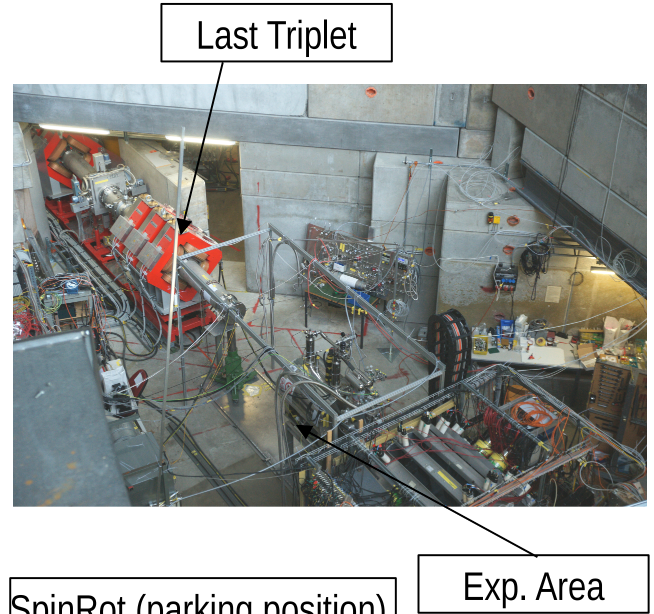


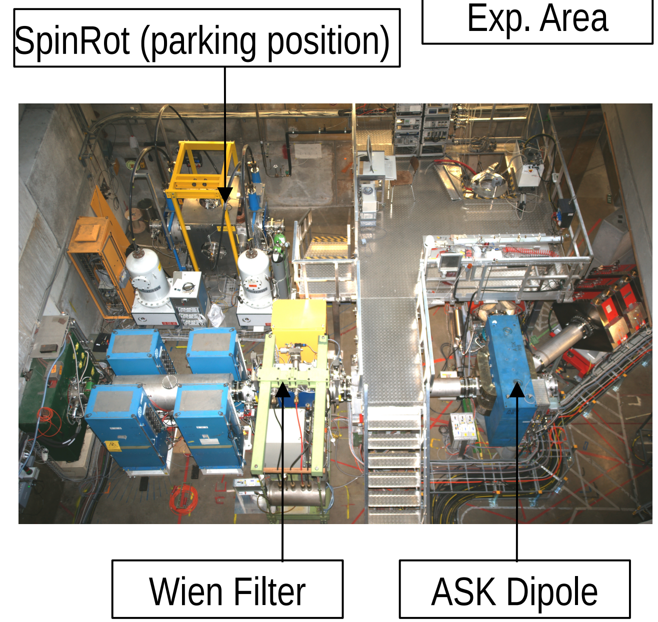


PiE1 Overview

- **High intensity μ/π beam line** at TE (10° forward angle)
- Recently reshuffled (2012)
- 3 operation modes:
  High momentum (max 500 MeV/c) for **Pion Irradiation**
  Surface muons to **µSR** facility (90° bending at ASK)
  Cloud muons (<120 MeV/c) for **Test Beams, Particle Physics**
- Muon Spin Rotator (45° @ 28 MeV/c) or Wien Filter Available

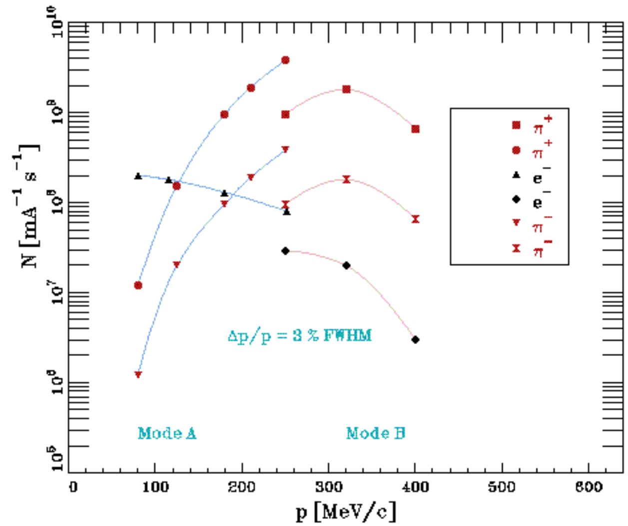


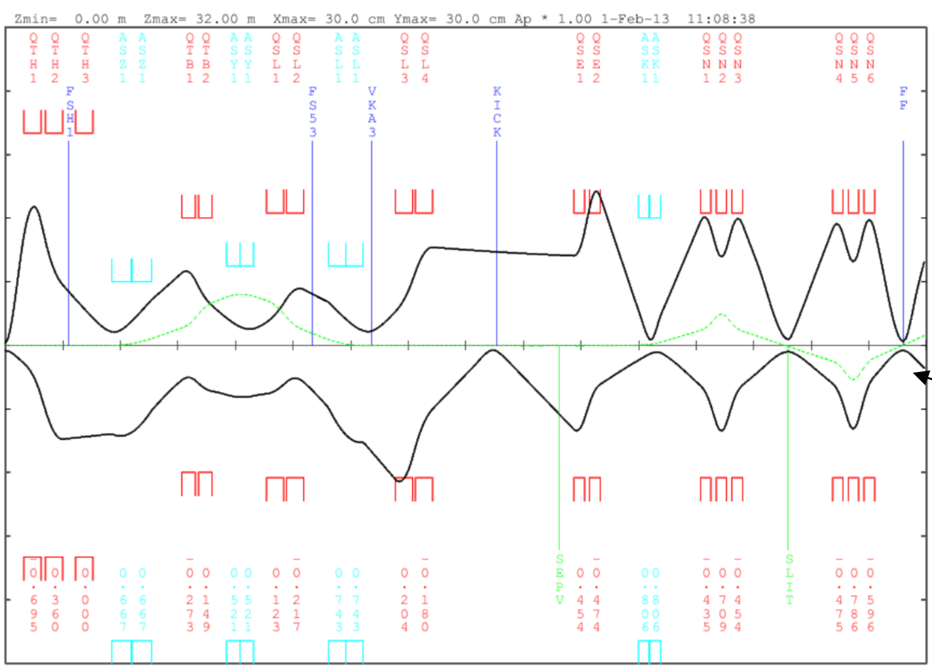


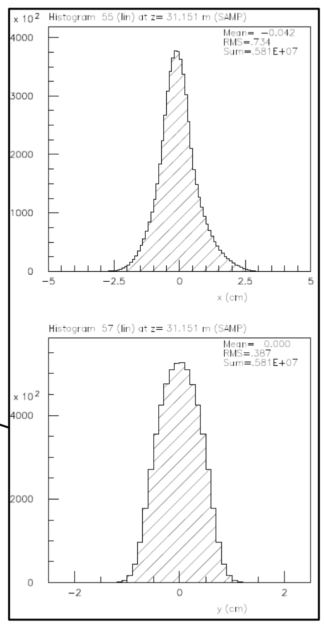


PiE1 Parameters

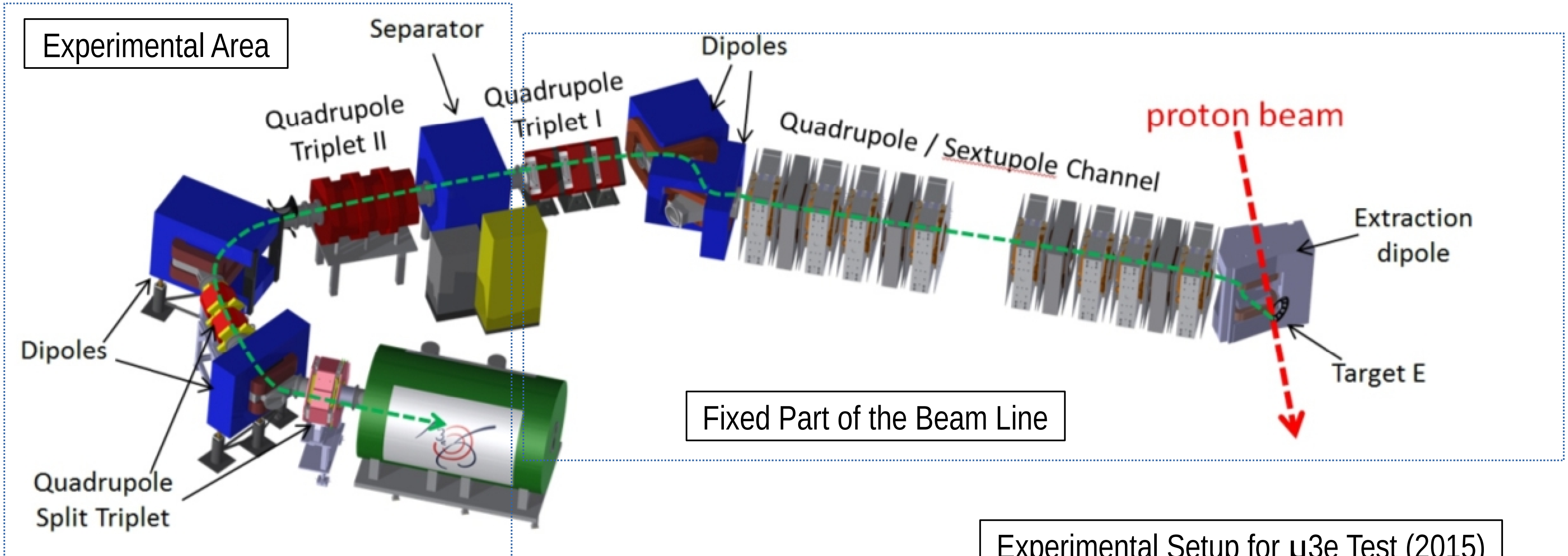
- Achromatic optics upstream of last dipole (ASK)
- **Momentum < 120 MeV/c: Beam dominated by e/μ**
  120 - 280 MeV/c Beam dominated by μ/π
  > 280 MeV/c Beam dominated by π/p
- Momentum acceptance (1σ): 4%
- **Max. particle flux: 4×10^9 π^+ @ 300 MeV/c**
- Simulated Beam spot size at final focus (RMS): 7mm (x), 4mm (y)



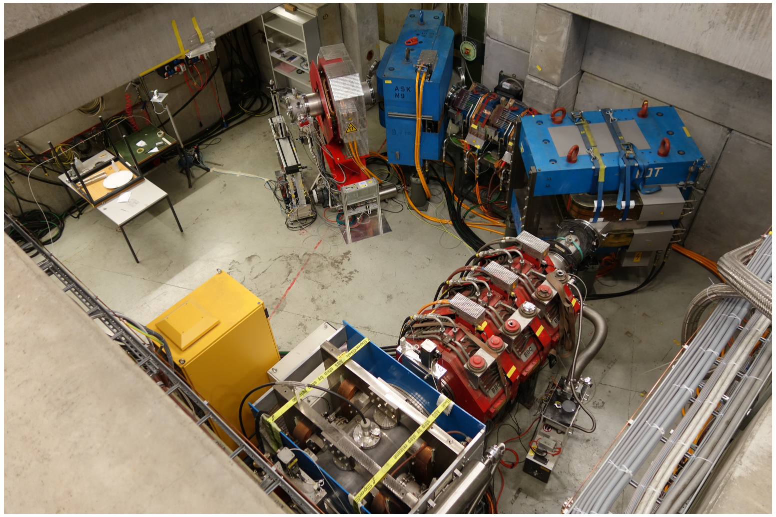




PiE5 Overview



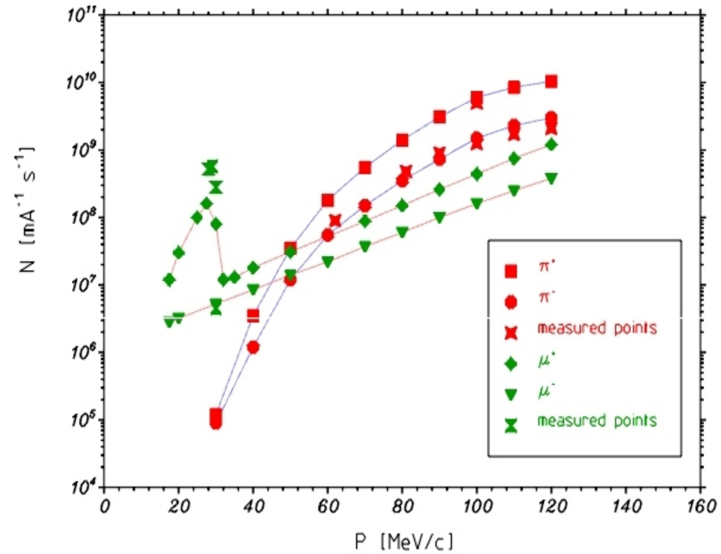
Experimental Setup for μ3e Test (2015)

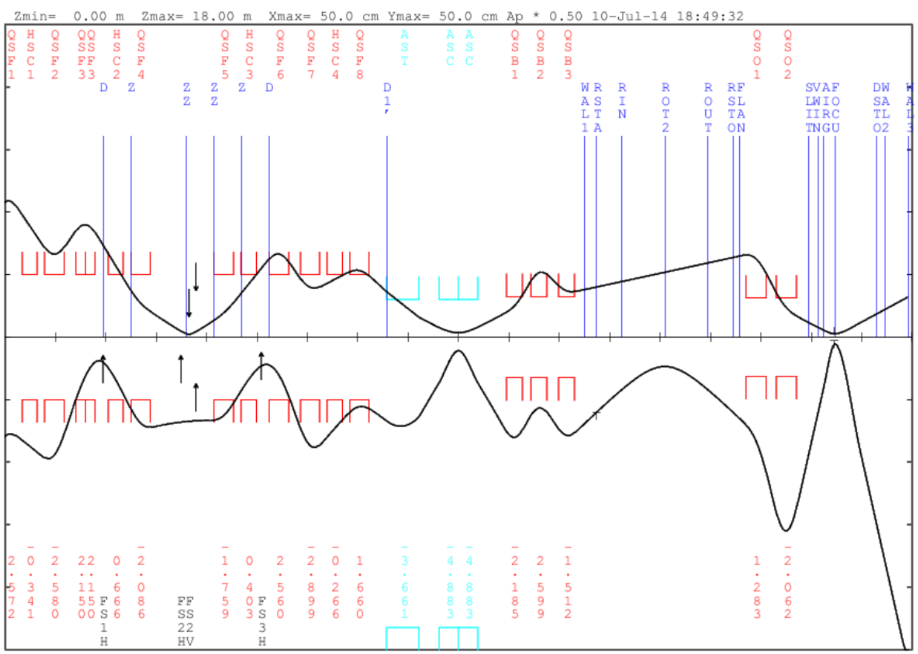


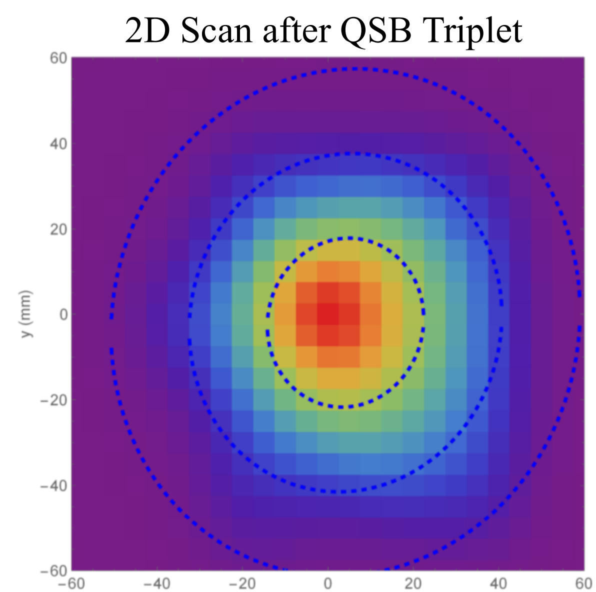
- **Low momentum (10-120 MeV/c), high intensity μ/π** beam line @ TE (175° backward angle)
- Momentum setting done by accelerator control room (affects proton beam)
- Wien Fielter (or Muon Spin Rotator) available
- Tipically employed by **long term PP experiments** (MEG, μ3e)

PiE5 Parameters

- **Momentum Range 15 - 120 MeV/c**
- Momentum acceptance (1σ): 5%
- **Max. particle flux: 6x10^9 π^+ @ 120 MeV/c**
  (decreases if separator or SpinRot are employed)
- Beam spot size after triplet I (RMS): 8mm (x), 10mm (y)
- High neutron background



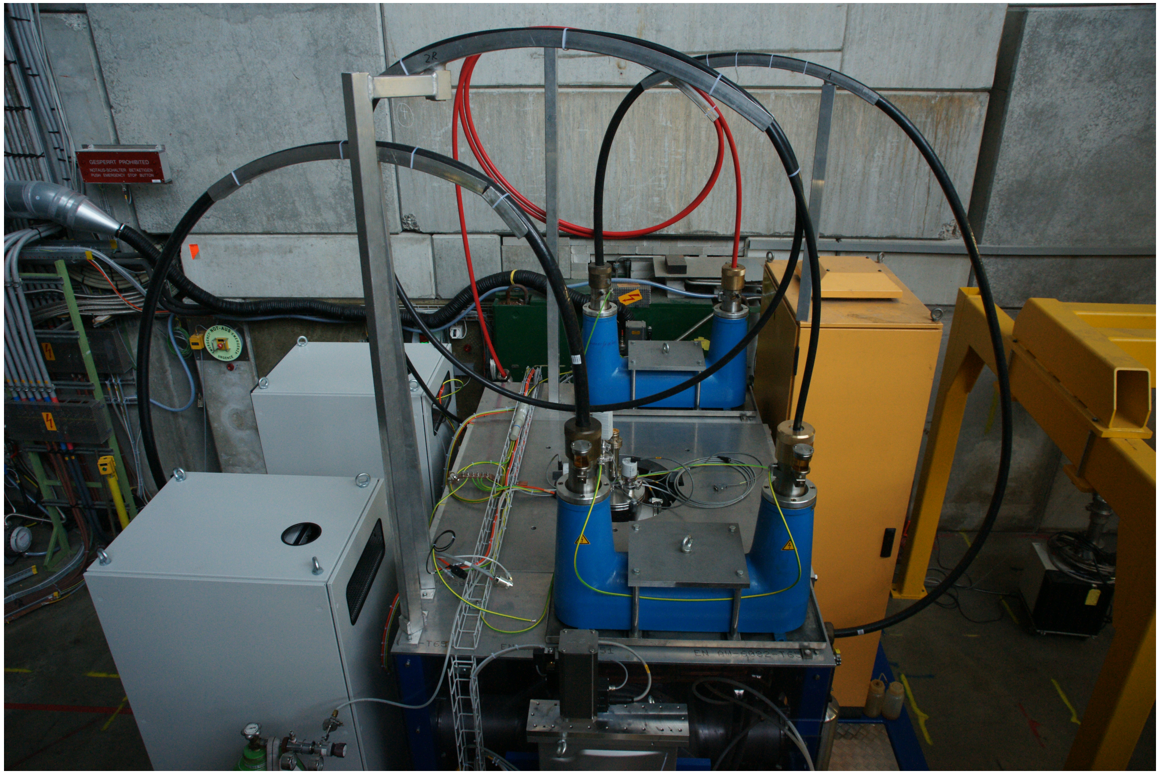




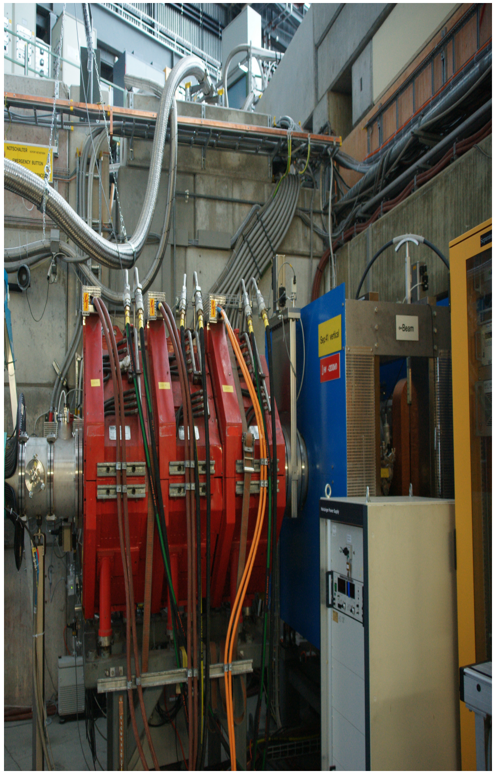
Spin Rotators / Particle Separators

PiE1 and PiE5 equipped with movable Wien Filters employed as:

- Particle separators (i.e. get rid of electron contamination)
- Muon spin rotation (i.e. 28 MeV/c surface muons,)



±300 kV 1.7 m long spinrot / sep inPiE1/PiE5



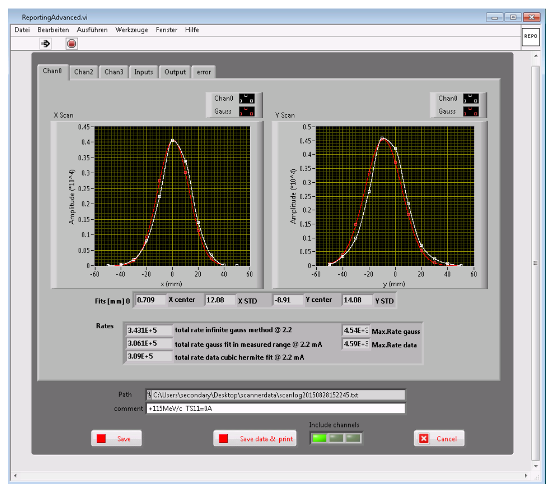
200 kV Separator in PiE5

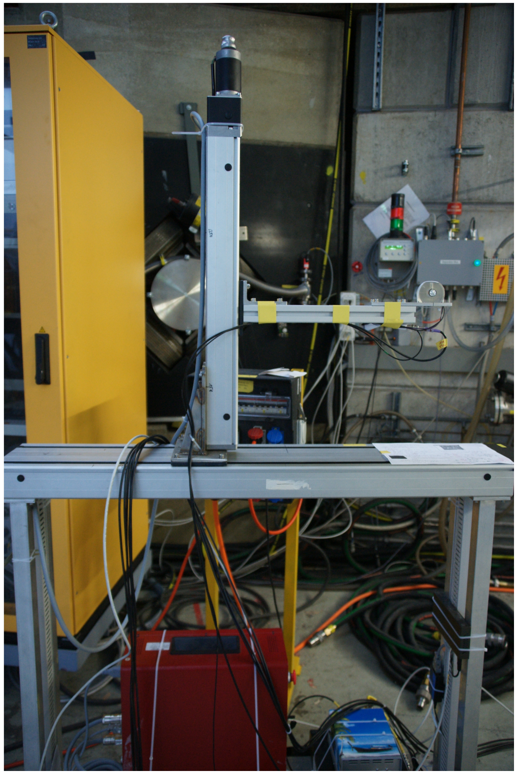
Beam Scanners

2 XY and 1 XYZ movable beam scanners available for beam diagnostics

- 2x2 mm^2 scintillator pill
- Labview based control and readout system
- Determination of beam size and particle rate at final focus

XYZ Beam Scanner in PiM1

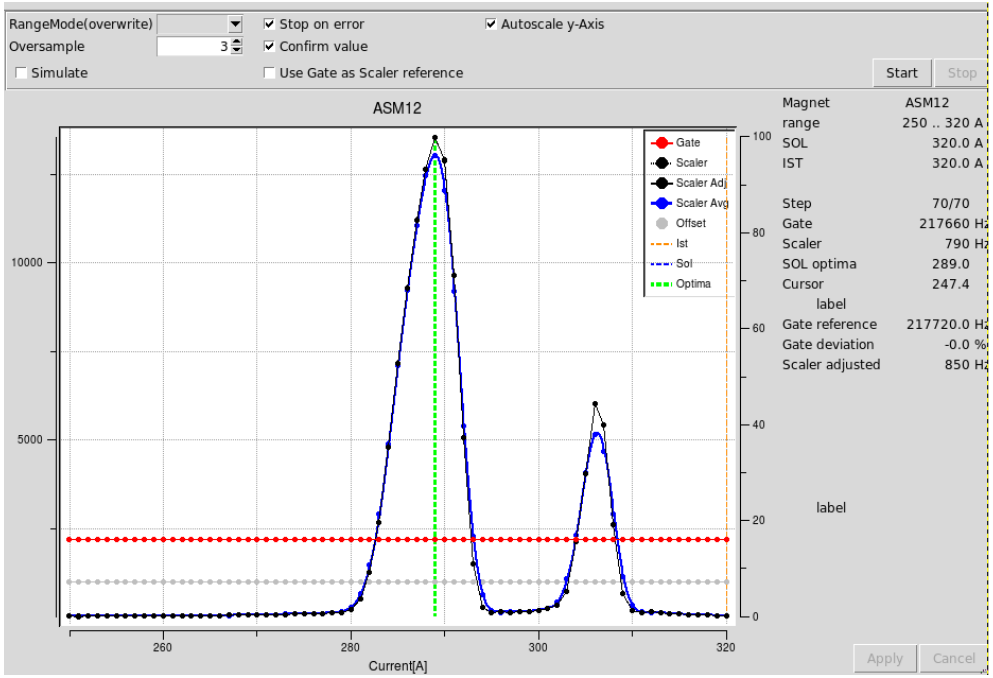




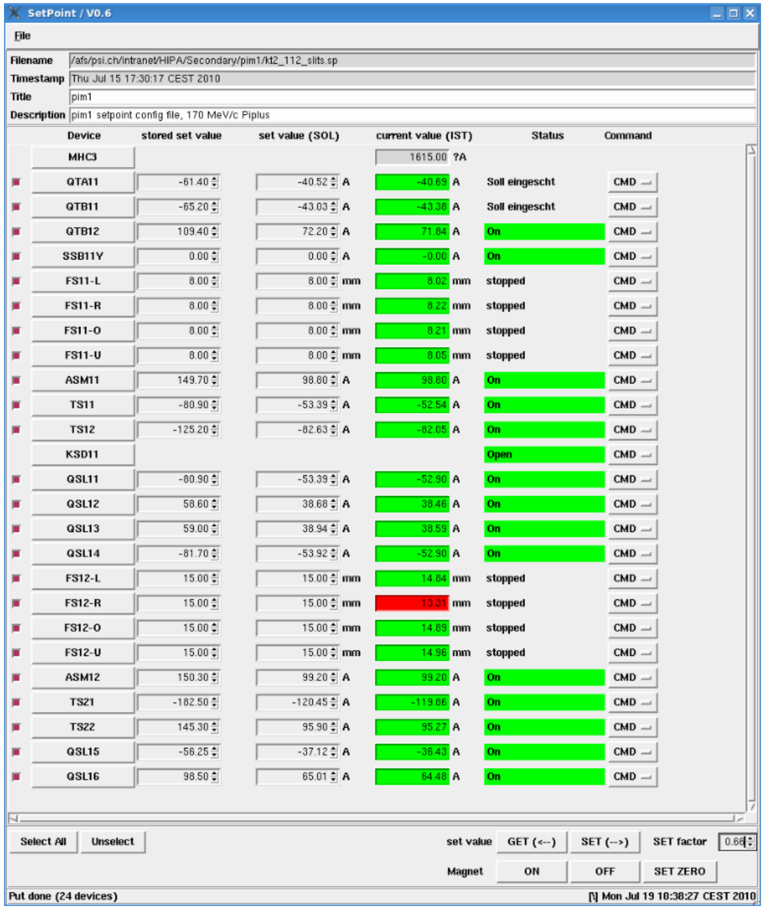
XY Beam Scanner in PiE5

Beam Line Control System

- User Friendly, stand alone beam line control system (magnet currents and slit apertures)
- Users control the beam lines directly (no need to bother the control room except for PiE5 momentum change)
- Beam Optics optimization tool „Optima“

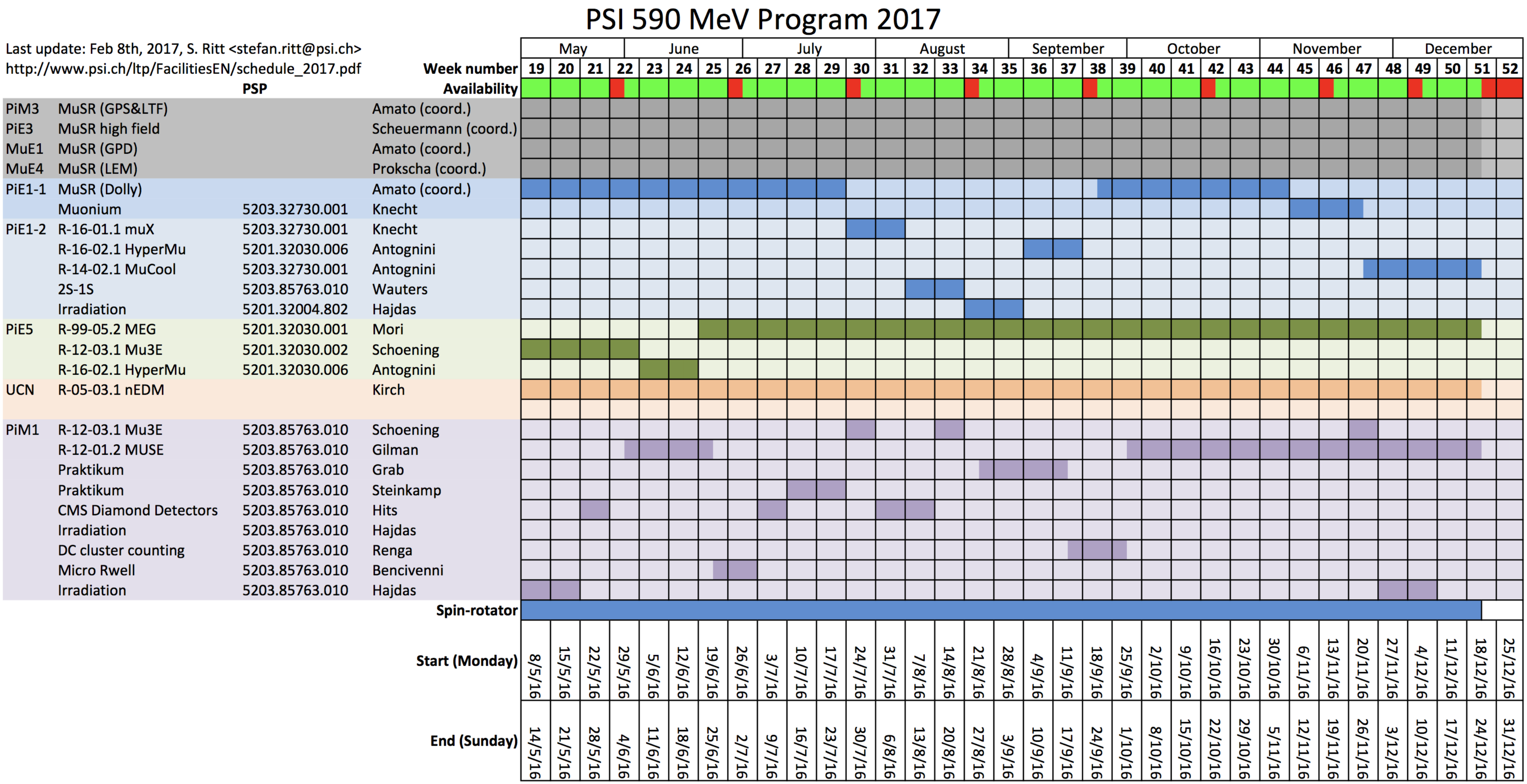


“Optima”: beam rates vs magnet current



“Setpoint”: controls magnets and slits

Beam Schedule



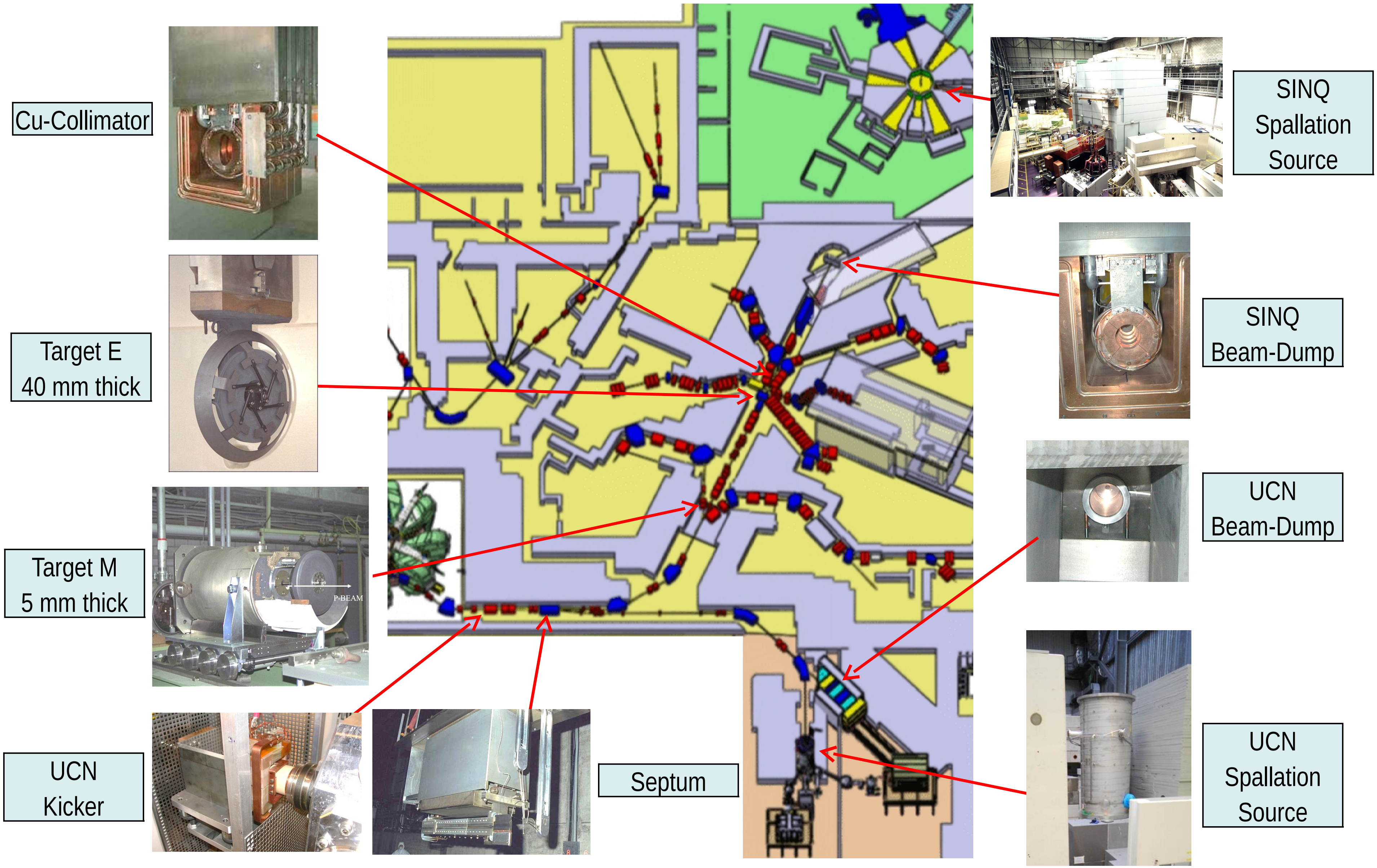
- Instructions for beam request to be found at: https://www.psi.ch/sbl/call-for-beam-time-requests
- Proposals evaluated in February by external review committee (BVR: *BenutzerVersammlung Ring*)

Conclusion

- PSI HIPA is an established and reliable user facility for high intensity particle beams
- Typical beam availability > 90%
- 3 secondary beam lines partially available for tests (20 – 500 MeV/c)
- PiM1 beam-line recently characterized at small and intermediate momentum (10 -230 MeV/c)
- Usual HIPA running period: May through December
- **2018 and 2019: shorter runs from July through December**
- **Proposals for test at HIPA facility to be submitted through:**
  https://www.psi.ch/sbl/call-for-beam-time-requests
- Contact Persons: Stefan Ritt (LTP), Davide Reggiani (GFA)

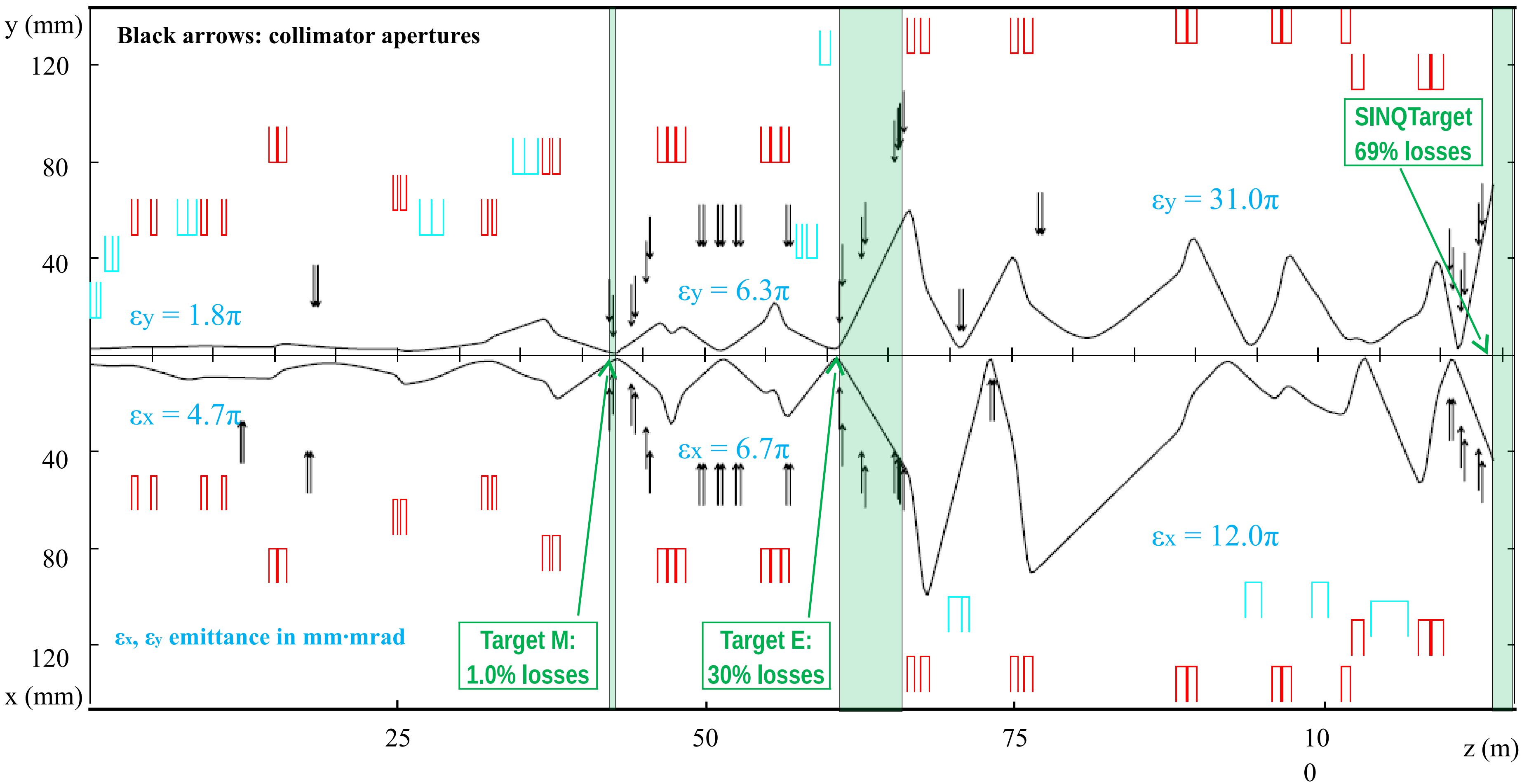
Thank you for your attention!

The 590 MeV Proton Channel



1.4 MW Beam Transport

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



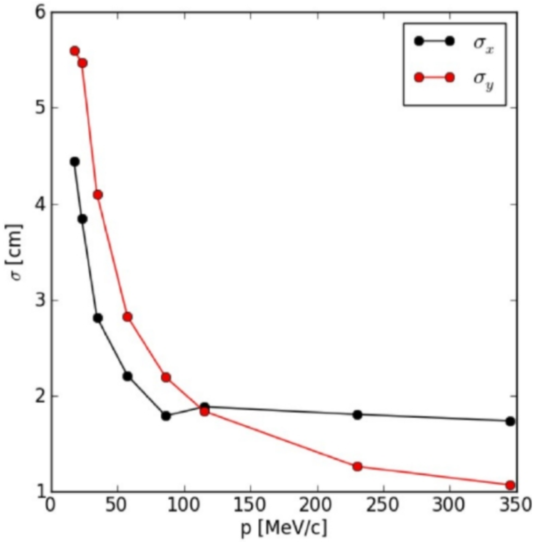
Peak beam current density on target M and E: 200 kW/mm²

Average losses away from targets: 0.6 W/m

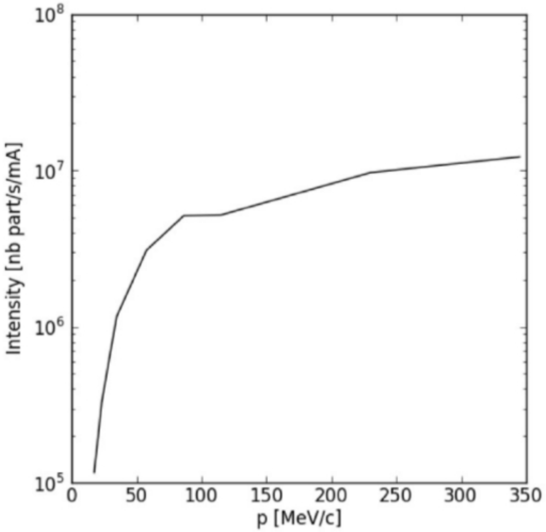
Intensity and Width Meas. (PSI Irradiation Group)

- Between 2014 and 2016: measurement campaign by the PSI Irradiation Group to characterize the PiM1 negatively charged beam (no protons) in momentum range 10 – 230 MeV/c
- **Beam width and intensity:** Beam Scanner furnished with scintillator pill, remotely controlled by LabView program

Beam Width vs Beam Momentum at focal point

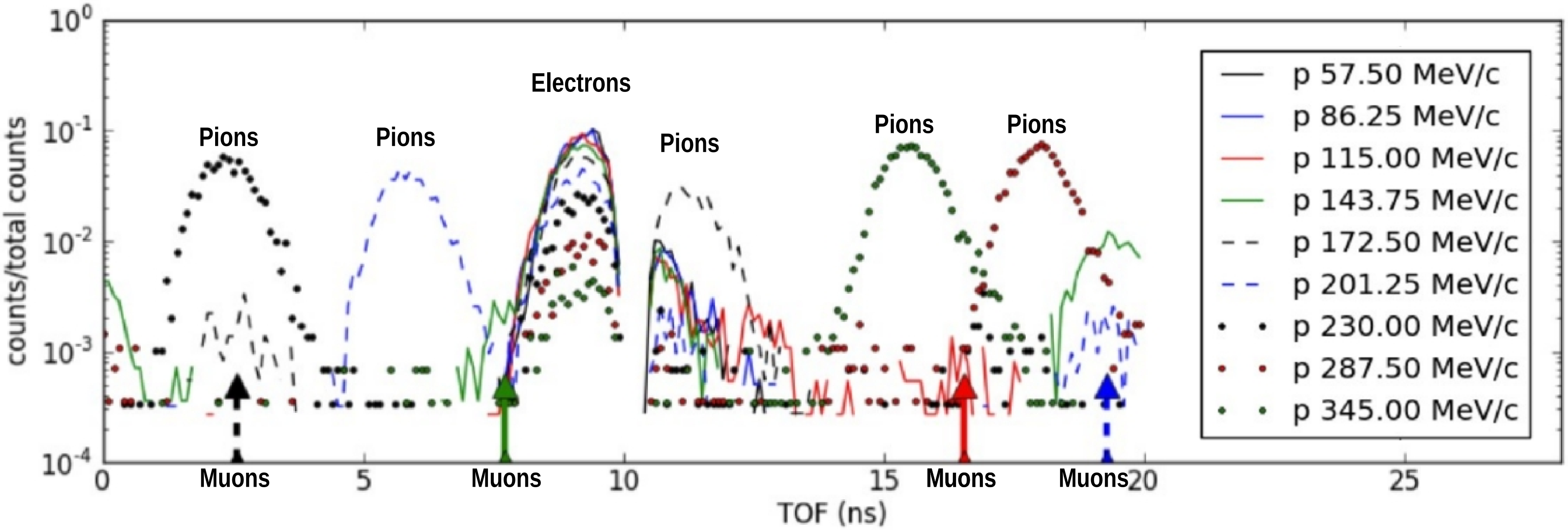


Beam Intensity vs Beam Momentum



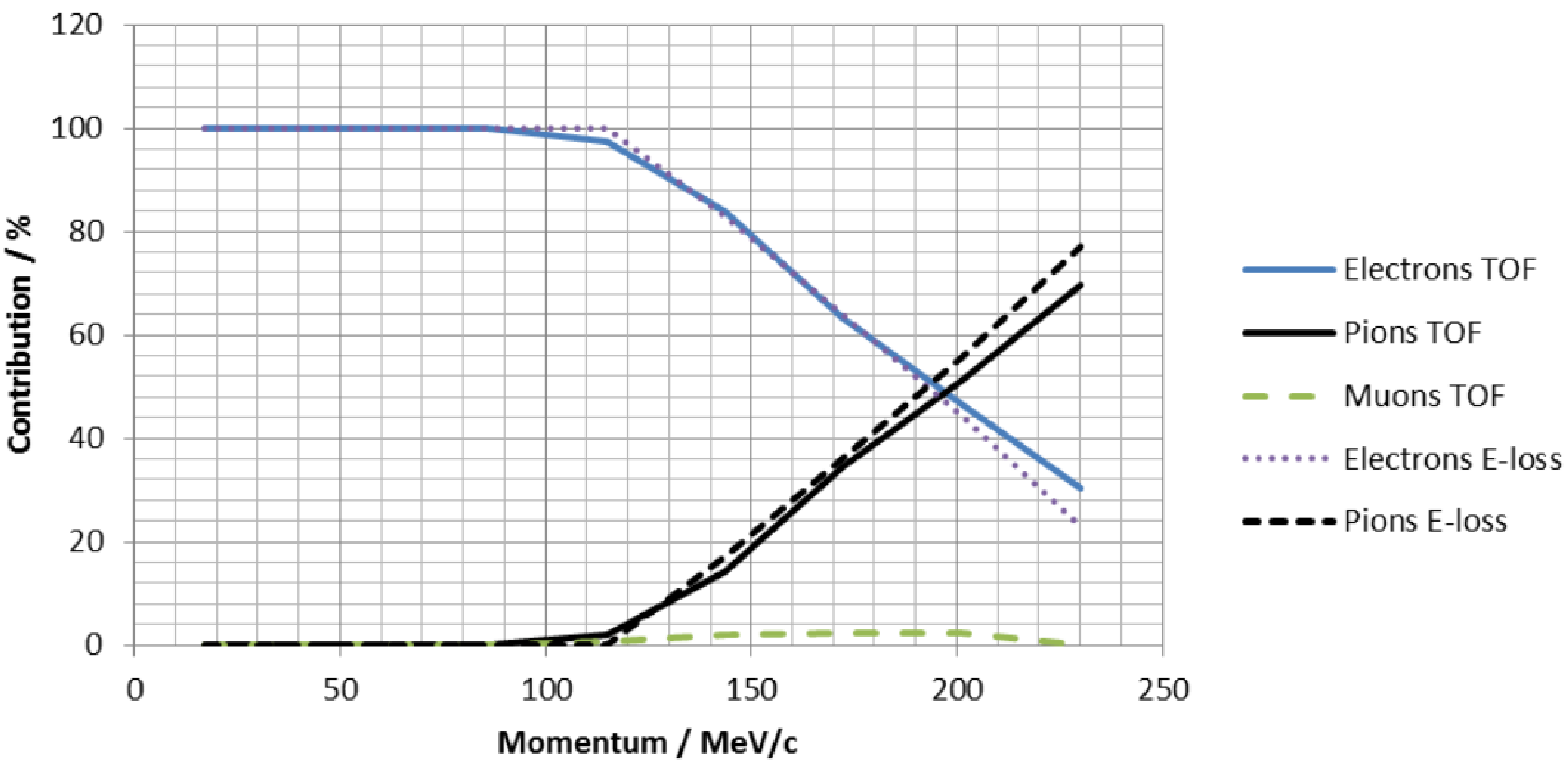
TOF Measurements (PSI Irradiation Group)

- Particles produced in bunches at the Target Station M **every ~20 ns** (proton beam RF structure)
- Accelerator RF signal available in PiM1
- **TOF measurement: time difference between signal from plastic scintillator at the end of the beam line (focus) and closest period of ~20ns modulated accelerator RF-signal (Relative TOF)**
- Electron-TOF NOT momentum dependent, Muon- and Pion-TOF momentum dependent
- Pion/Muon identification through fit of TOF vs 1/β for Muon/Pion hypothesis



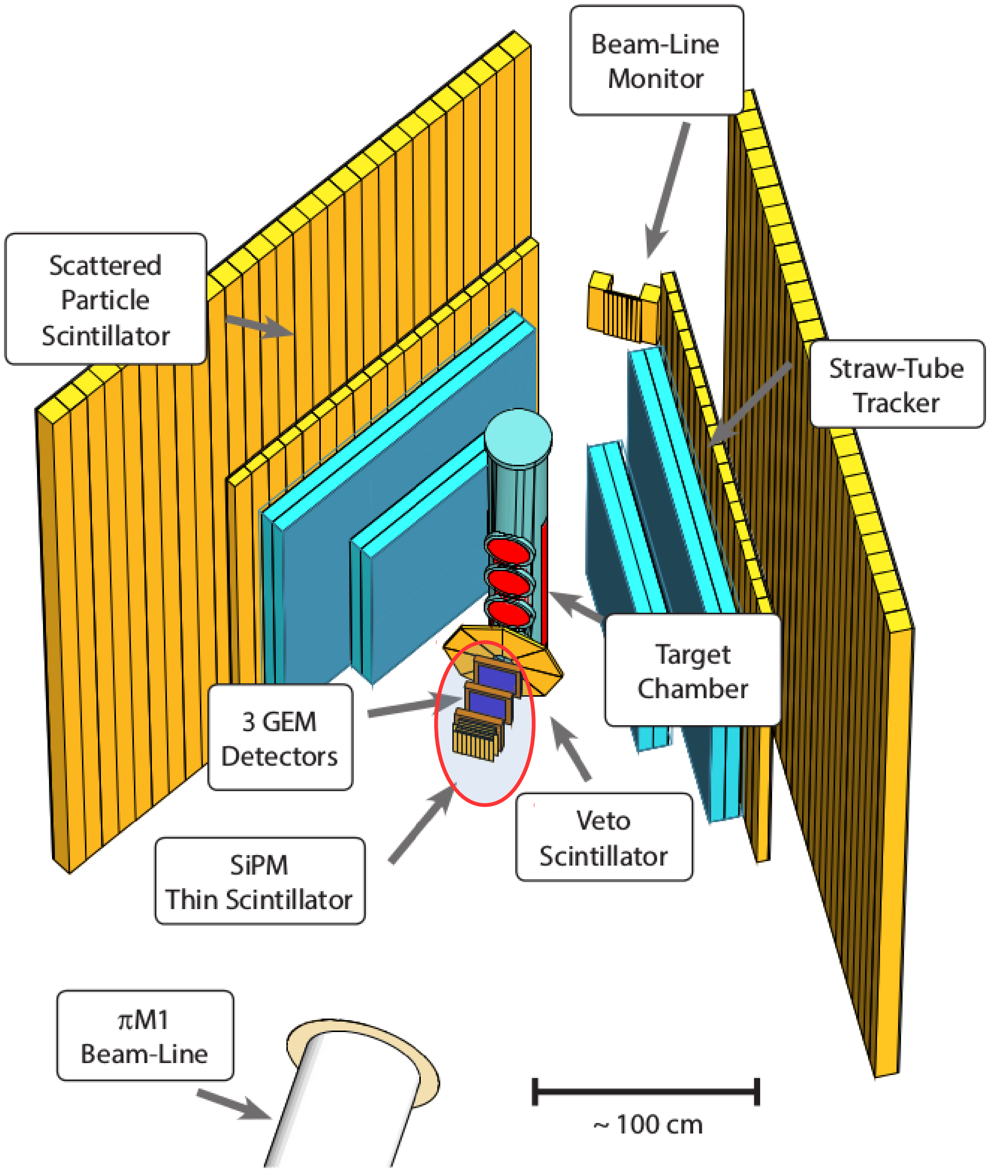
Beam Fractional Composition (PSI Irradiation Group)

- **Beam fractional composition vs momentum from relative contribution of e, μ and π from TOF peaks**
- Electrons dominate between 20 and 150 MeV/c, pions dominate above 220 MeV/c
- Pions and muons start from 115 MeV/c
- Muons always below 3%, disappear above 220 MeV/c
- Comparison with energy loss measurements in thick scintillator (less precise) show good agreement below 180 MeV/c

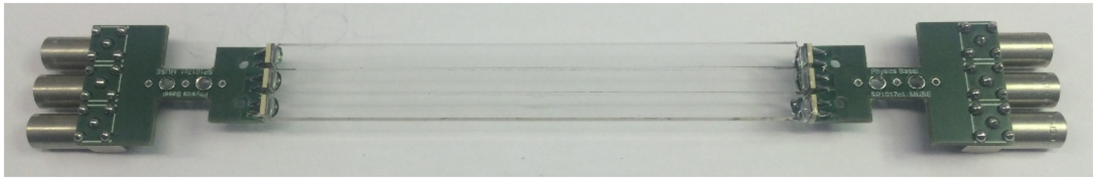


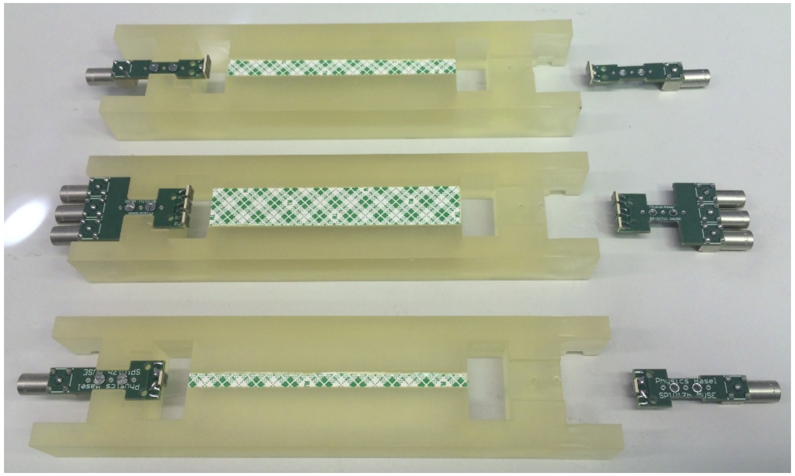
Beam Detectors Design (MUSE Collaboration)

- MUSE: proton radius determination through concurrent muon and electron scattering (LiH Target) needs beam telescope (timing/tracking)
- Expected data taking: 2018-2020
- **PiM1 beam line (and HIPA in general) does not provide a beam telescope**
- Beam detectors currently developed by the **MUSE collaboration**
- **Timing detector: SiPM** (Silicon Photomultiplier) thin hodoscopes
- **Tracking Detector: GEM** (Gas Electron Multiplier) **telescope** (3 planes)
- Such detectors could become the **basis for a future „fixed“ beam telescope system available to all users**



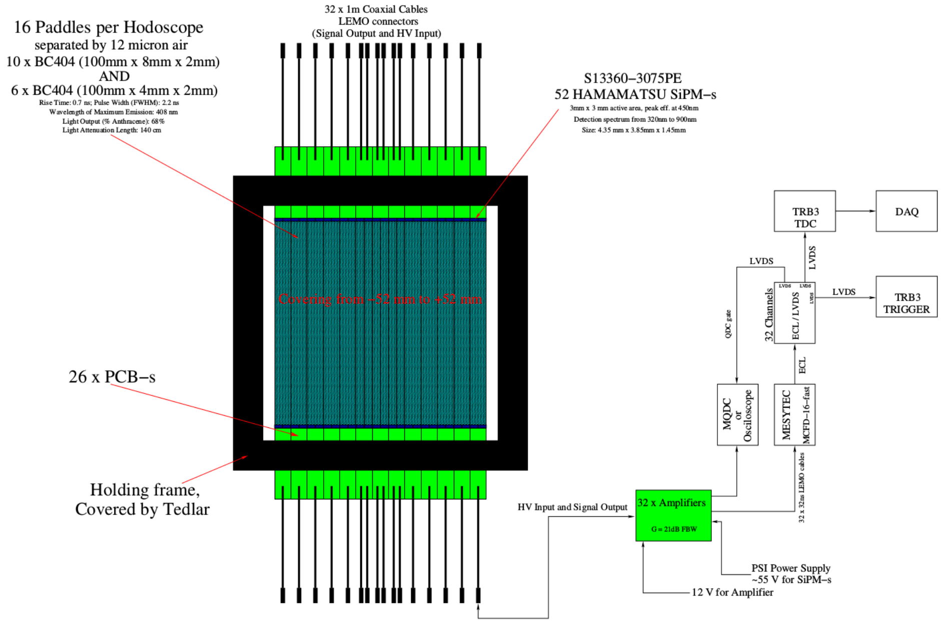
SiPM Hodoscope Design (MUSE Collaboration)





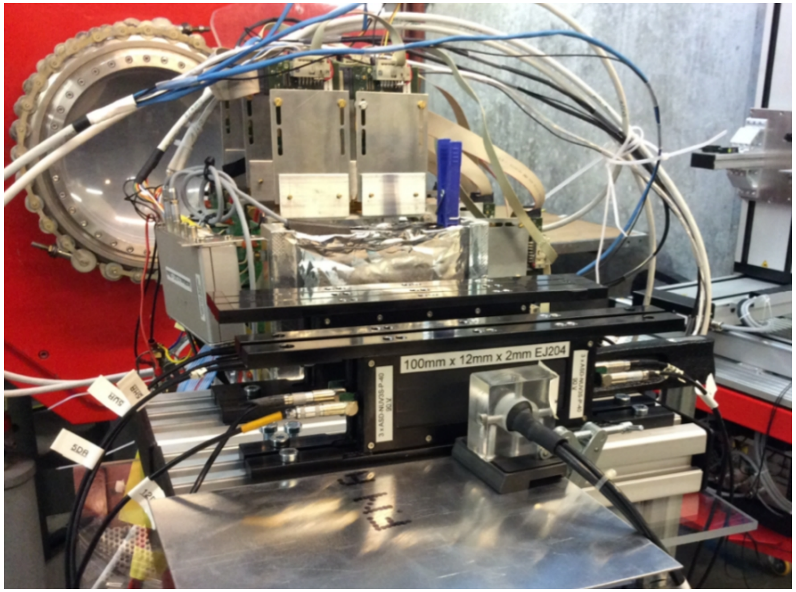
SiPM detectors prototypes 100 mm x (5-12) mm x 2 mm (1 and 3 paddles), without and with frames

Schematics of final SiPM detector with 16 Paddles

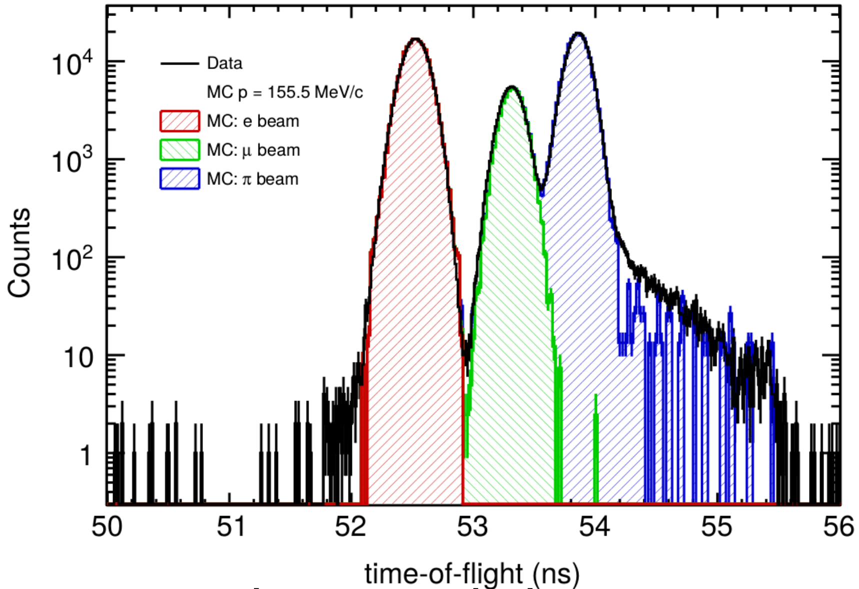


- Goal: **<100 ps resolution** for PID with high efficiency
- **SiPM prototypes designed and built at PSI** with AdvanSiD or Hamamatsu SiPMs
- During tests: analog signals amplified by PSI amplifiers and discriminated by PSI constant fraction discriminators, then sent to TDCs
- **Tests in PiM1 Beam started in December 2015**
- Final hodoscope design: 16 scintillator paddles

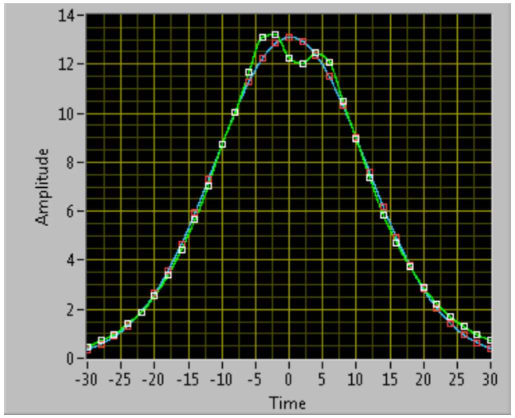
SiPM Hodoscope Tests (MUSE Collaboration)



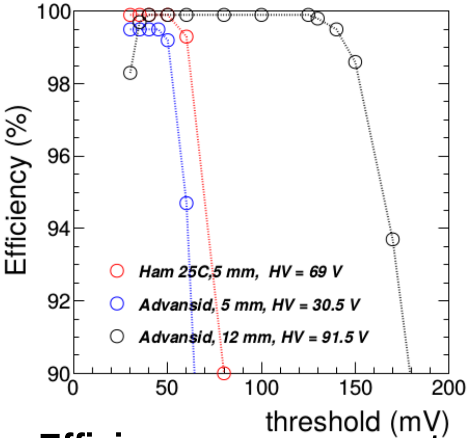
Setup in PiM1 during test in December 2015



TOF between two hodoscopes 50 cm apart (arbitrary x-offset)



Impact on beam profile (3 x 2mm layers)



Efficiency measurement

SiPM Hodoscope Tests (MUSE Collaboration)

- **Two different paddle lengths tested (100 and 162 mm) with similar results**
- **Time resolution: 60 - 80 ps** (dependent upon paddle length, width, type and SiPM type)
- **Efficiency > 99.5%**
- **Hamamatsu SiPMs: more radiation resistant (but more expensive as well!)**
- Radiation damage decreases with larger distance from beam: **longer paddles better suited for high rates**
- **Small effect on beam profile** if 2x2mm or 3x2mm layers employed
- **Particle type on-line triggering** based on SiPMs + RF signals and **FPGA** electronics under study (TOF = SiPM time – Accel. RF Time)

GEM Detectors (MUSE Collaboration)

- **Goal: tracking a 5 – 10 MHz beam with < 100 µm resolution**
- **GEM** (Gas Electron Multiplier): **low-mass detectors** (~0.5% of a radiation length), minimize multiple scattering
- **50 – 100 µm resolution achieved** with a two-dimensional strip readout (~400 µm pitch)
- MUSE to employ a 3 GEMs telescope already in use at the OLYMPUS experiment (DESY): 10×10 cm^2 surface, 70% Ar / 30% CO_2 gas mixture
- Expected rate density for the nominal πM1 tune at the final GEM (upstream of focus): ~ 1 MHz/cm^2 , single-track probability > 90%
- Rearrangement of GEM chambers, electronics and cabling required for PiM1
- GEMs read out based on FPGA-controlled front-end electronics (APV-chip)
- **Read out time to be decreased by factor 10 for PiM1 beam**
- **Electrical noise issues in PiM1 still to be solved**