LABORATORIUM FÜR HOCHENERGIEPHYSIK
LHEP
UNIVERSITÄT BERN

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AEC
ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

R&D and applications of emulsion detectors in Switzerland

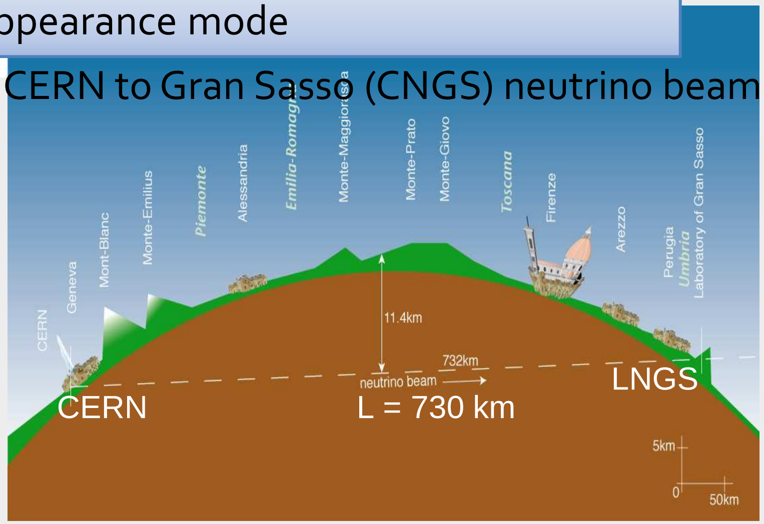
Tomoko Ariga
on behalf of the Bern emulsion group

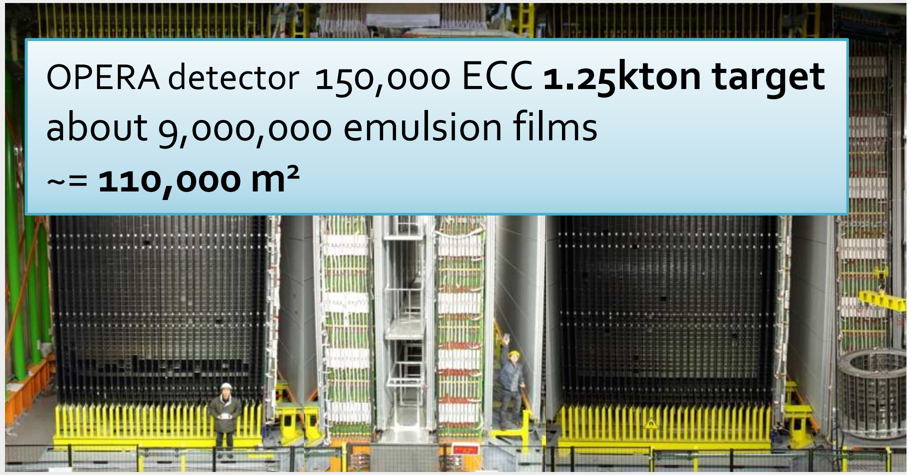
Swiss emulsion activity

- Large contribution in the OPERA experiment
  - OPERA : Biggest-ever enterprise in emulsion experiment

Direct detection of neutrino oscillations in appearance mode

More details in the OPERA talk by J. Kawada



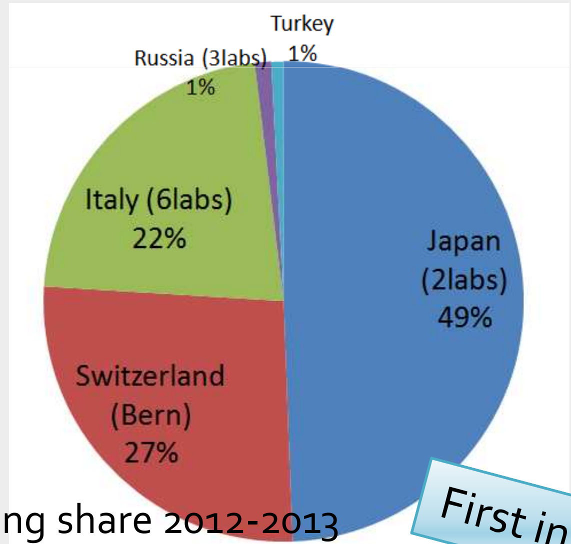


- Exploiting the know-how for the next experiments
  - **R&D on emulsion technology**
  - **Physics applications**

Swiss scanning station

- **6 microscopes with automatic plate changer**
- Scanning and tracking speed
  - 5microscopes for OPERA: **20cm²/h/mic**
  - **6th microscope: see the talk by A. Ariga**

Several hundreds of emulsion sheets analyzed every week

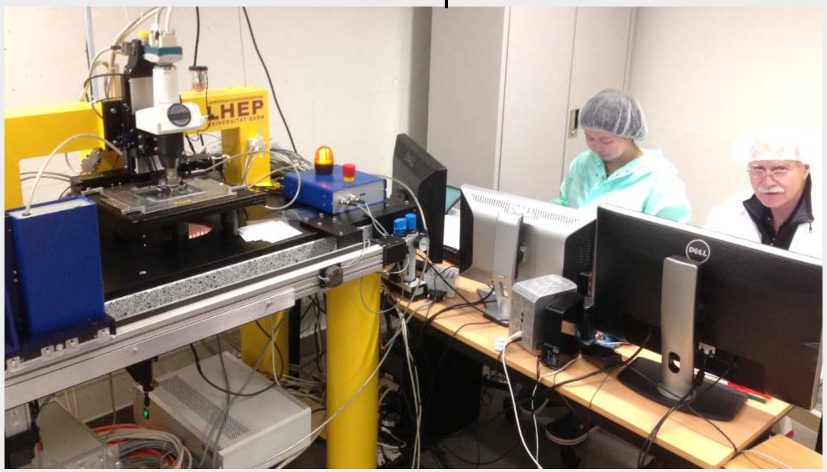


Scanning share 2012-2013

First in Europe

Second OPERA emulsion scanning laboratory in the world

6th microscope for R&D

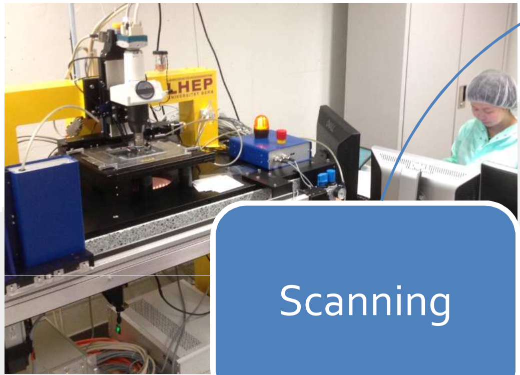


All infrastructures for R&D available in Bern

Strong advantage of our group

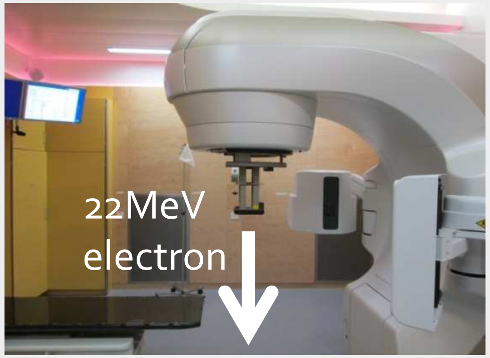
Underground lab, 30 m deep

Film production



Scanning

Performance check



Development

- 22MeV electron and 18MeV proton in Inselspital (hospital in Bern)
- 2.5MeV neutron from D-D fusion

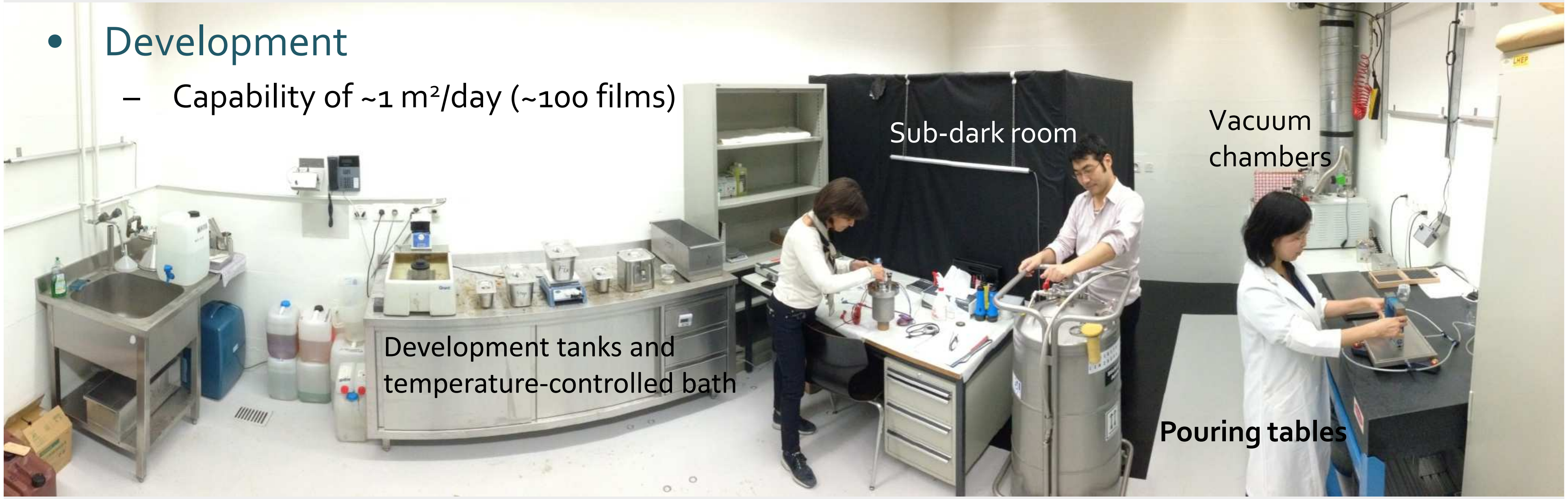
OR

CERN and PSI

Underground emulsion facility

Refurbished in 2013

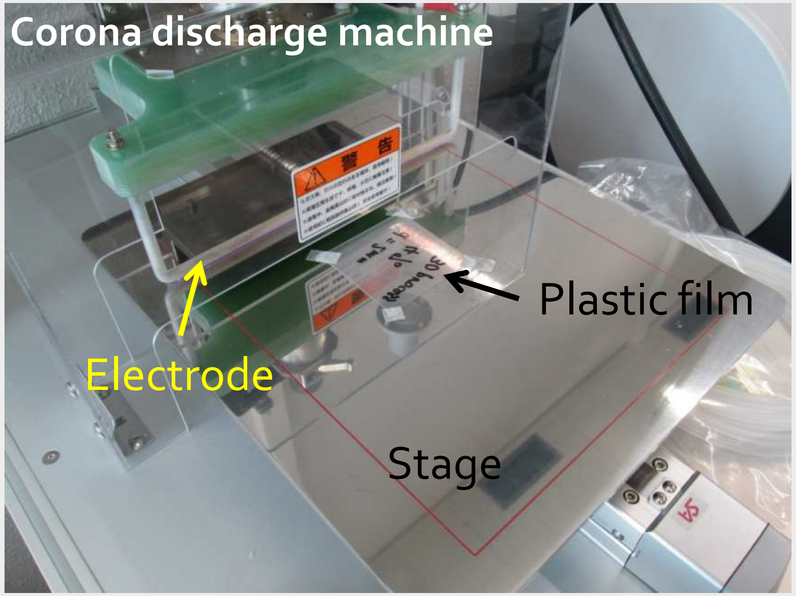
- 3om deep
  - Low cosmic-ray flux, suitable for emulsion film production
- Pouring
  - Custom-made gel from Nagoya Univ. (Japan) and Slavich (Russia)
  - High precision pouring stages
  - Current maximum production rate:
    3 x A4 size (double side coated)/day
- Development
  - Capability of ~1 m^2/day (~100 films)



Equipments for cryogenic tests

Studies on base treatment

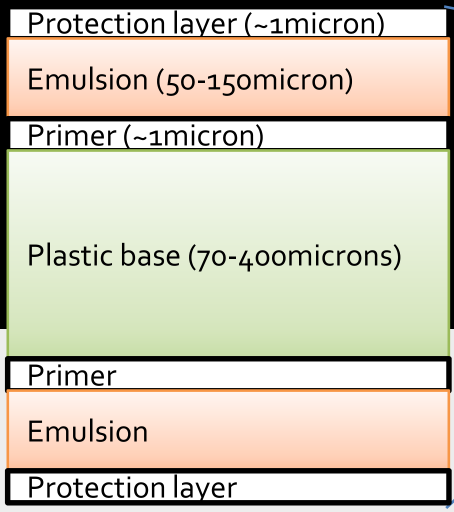
- For acrylic base
  - Chemical treatment (commercial plastic primer)
    - Works but not very strong
  - Corona discharge
    - Study is ongoing
- For glass base
  - Chemical treatment (Dubna recipe)
  - Development in the framework of the INET Project (Switzerland Russia)

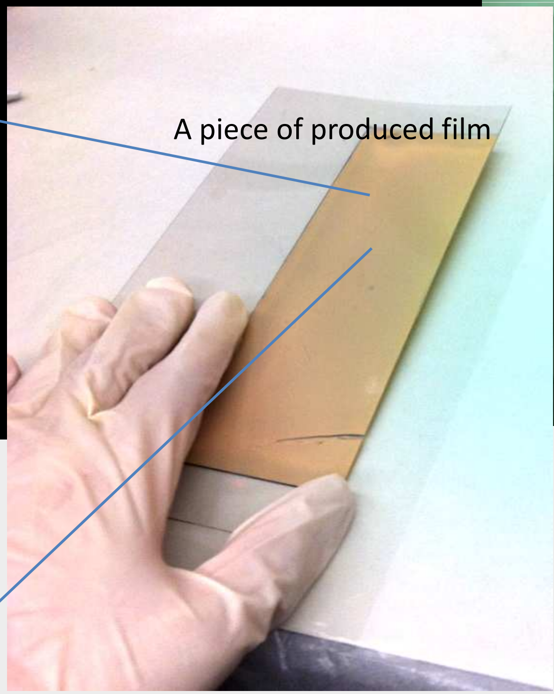


Emulsion film production (pouring)

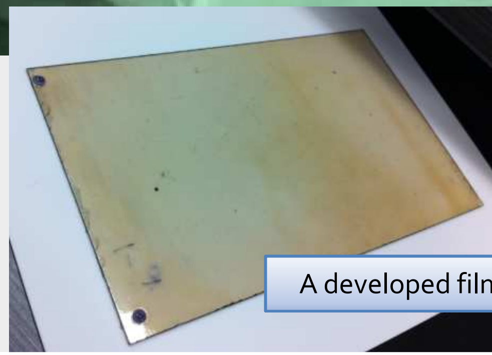
- Gel from Nagoya Univ. (Japan) and Slavich (Russia)
- Multi-layer structure

Cross-section of basic type emulsion film



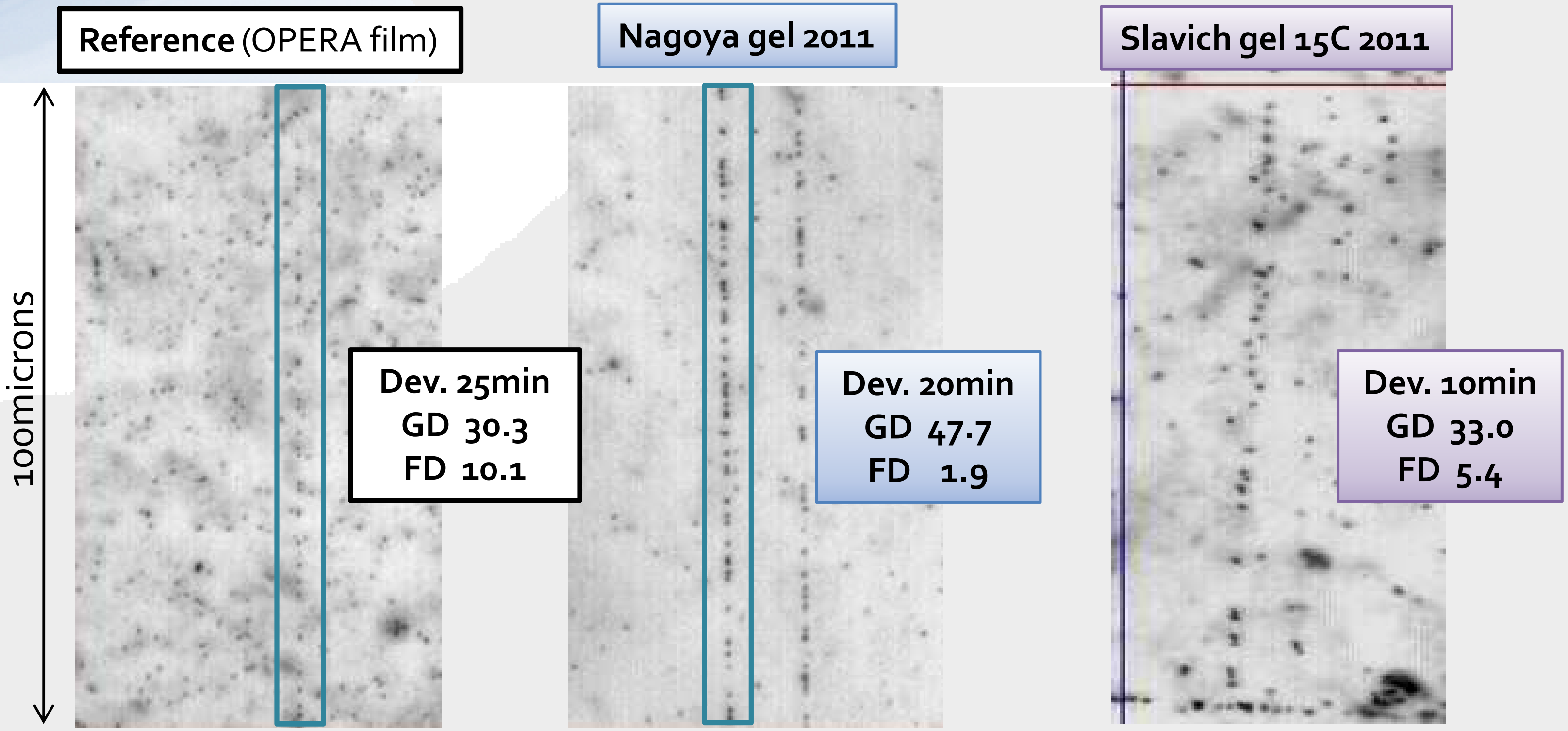


A piece of produced film



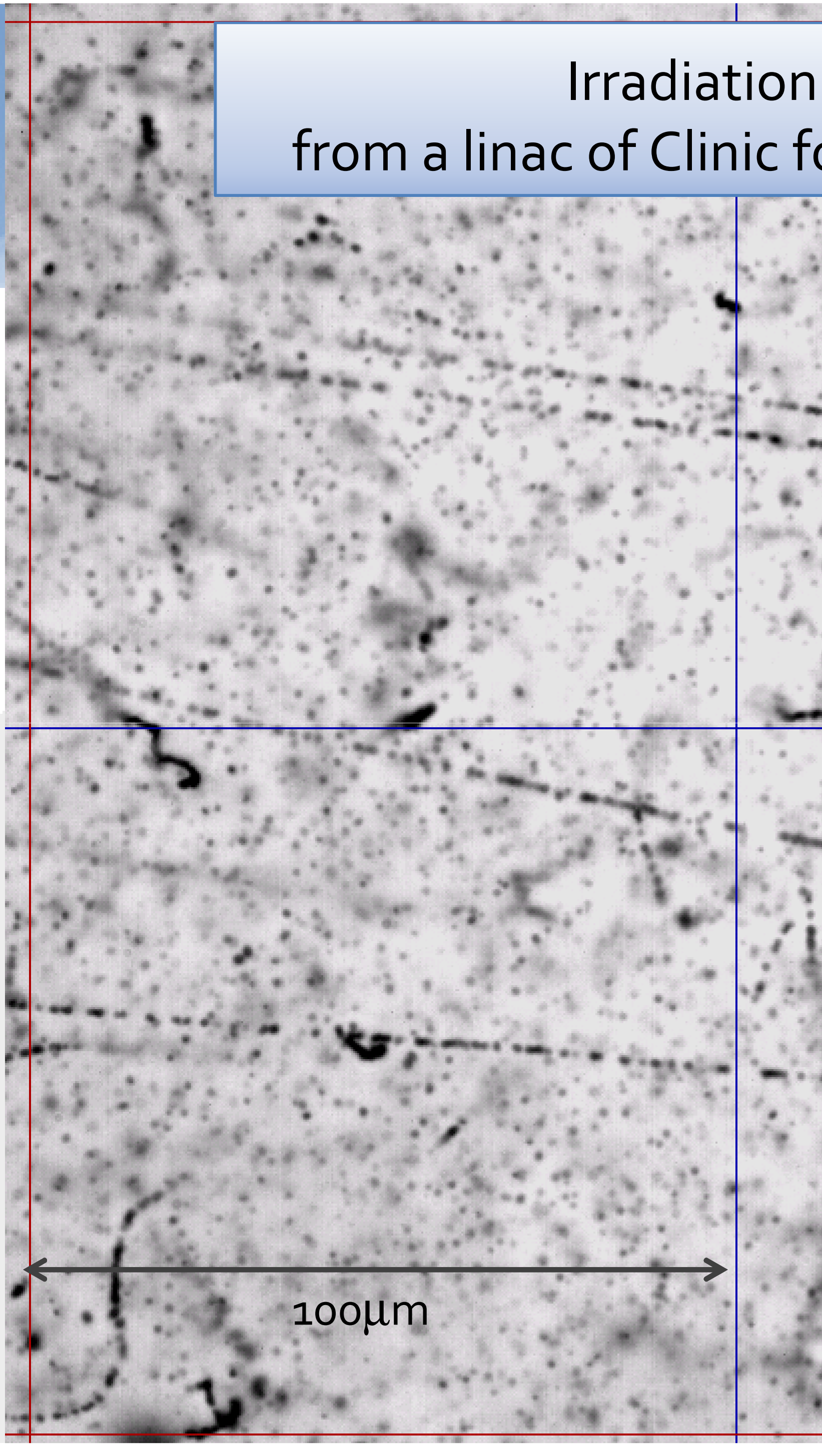
A developed film

Sensitivity evaluation of produced films with CERN Test Beams in 2011



	Beam	Development time	GD (grains/100microns)	FD (grains/10microns cubic)
Reference (OPERA film)	CERN 10GeV pi-	25	**30.3 +- 1.6**	**10.1 +- 0.7**
Nagoya gel	CERN 10GeV pi-	20	**47.7 +- 2.0**	**1.9 +- 0.2**
Nagoya gel	CERN 10GeV pi-	25	**55.1 +- 2.6**	**3.0 +- 0.3**
Slavich gel 15C	CERN 180 GeV pi/mu+	10	**33.0 +- 1.0**	**5.4 +- 0.5**

Irradiation with 22 MeV electrons from a linac of Clinic for Radiation Oncology (Inselspital)

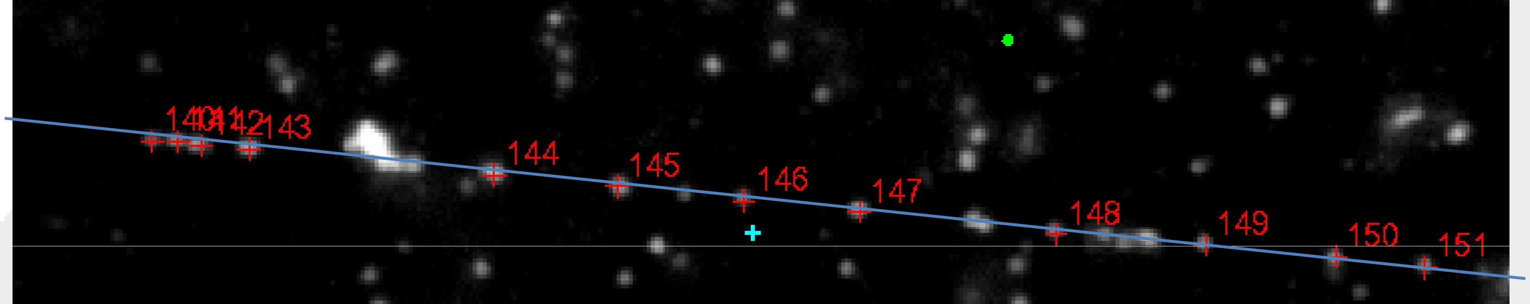


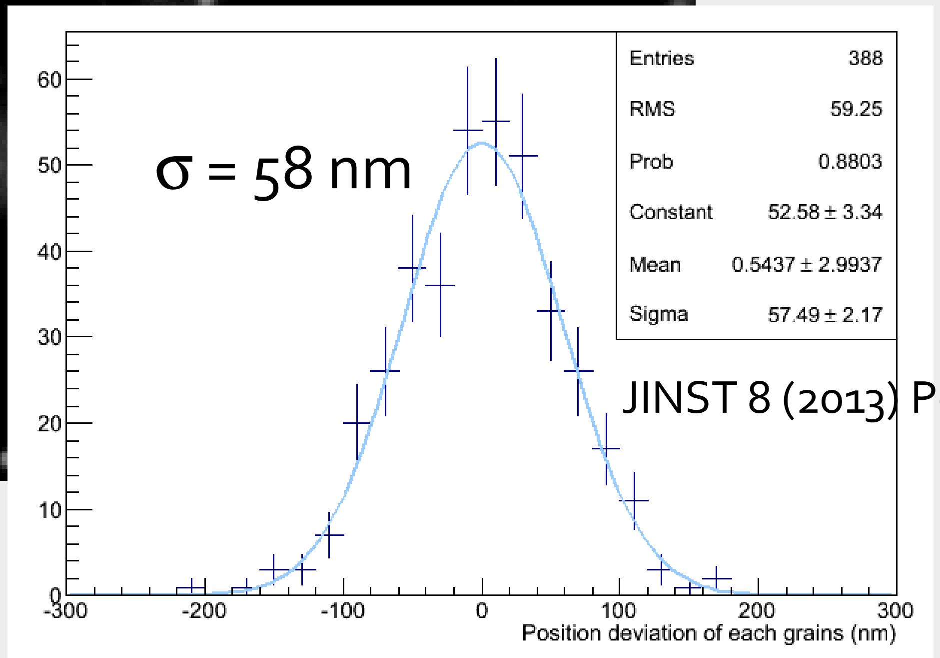
Sensitivity check

Gel type		Grain density (/100μm)
Nagoya A	AgBr30%	39±3
Nagoya B	AgBr45%	47±3
Nagoya C	AgBr55%	**59±4**
OPERA film		30±2

Intrinsic resolution of new film

- Fit a line and evaluate deviation of each grains from the fitted line (line to point distance)
  - Find a straight tracks on the display
  - Measure the grains → Center of gravity calculation
  - (Use only grains near to the center of view ← to minimize optical distortion)
  - (Reject overlapping grains)

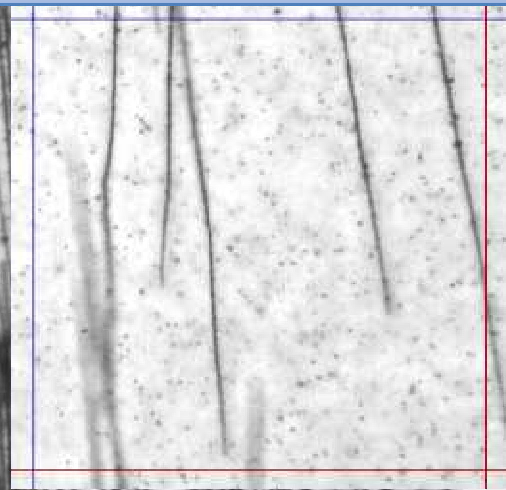




JINST 8 (2013) P08013

Irradiation with 18 MeV protons at the beam transfer line of the new Bern cyclotron laboratory (SWAN, Inselspital)

- Emulsion distortion study
- Particle identification by analyzing the stopping points



100 micron

Emulsion technology

Hardware
- Detector production
- Development

Scanning
- Microscope readout
- Reconstruction

Physics experiments
- OPERA
- T2K
- AEgIS
- ...

Accelerator
- Beam monitoring

Medical application
- Neutron dosimetry
- Proton radiography
- Beam characterization in proton therapy

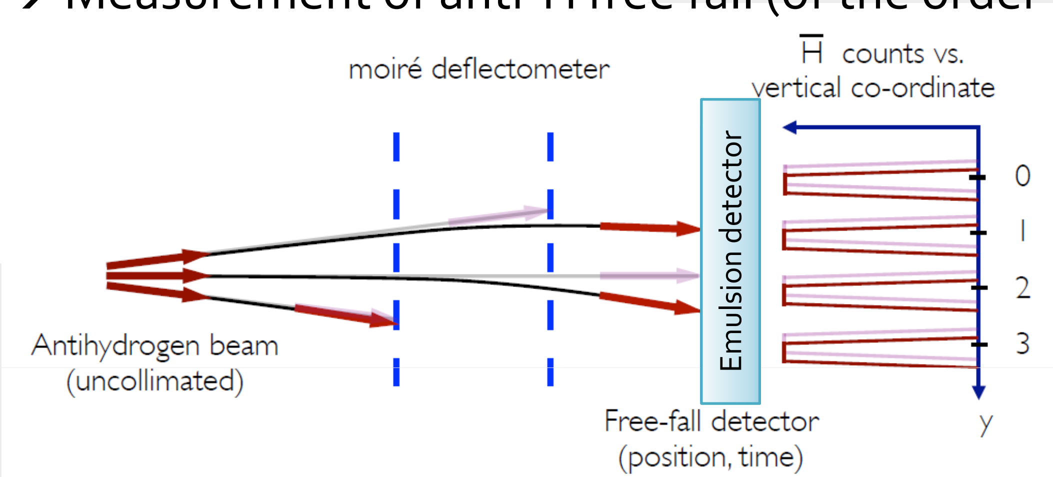
Geosciences
- Muon radiography

xxx
- xxx

AEgIS experiment

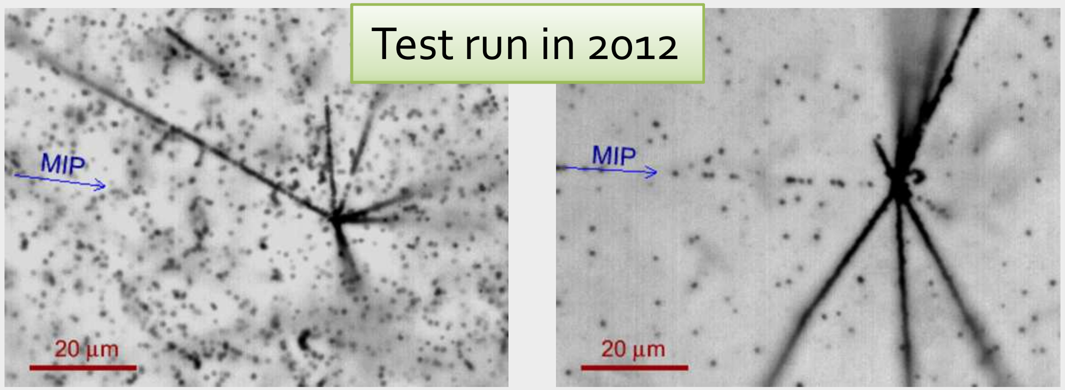
See the talk by A.Ariga

- Measurement of gravitational force on antimatter
  - → Measurement of anti-H free fall (of the order of 10 microns)



- Requirements for emulsion detectors… very challenging!
  - Absolute position resolution (1 micron) over 20cm x 20cm surface
  - Emulsion in vacuum
  - Sensitive at 77K

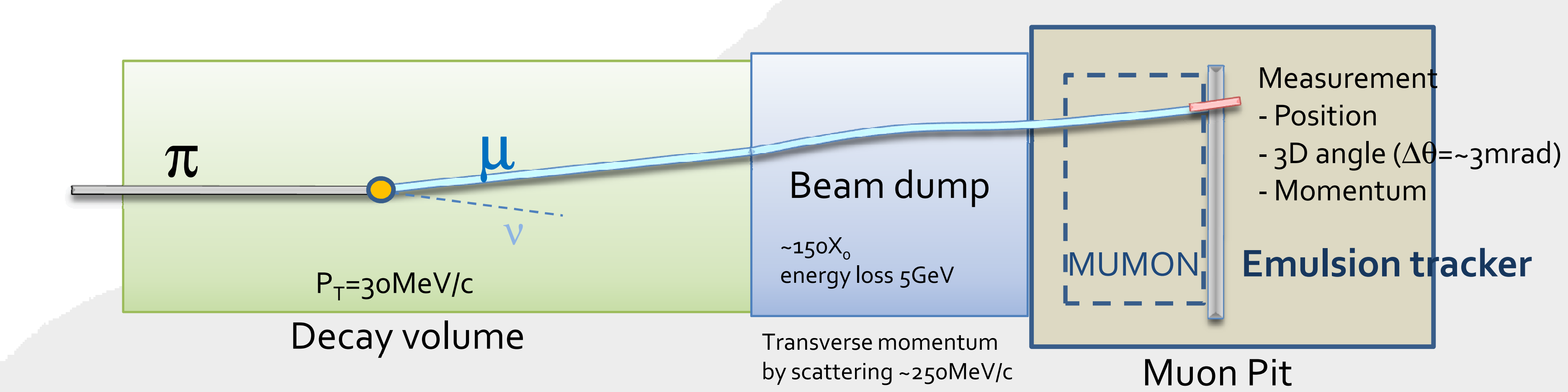
Test run in 2012



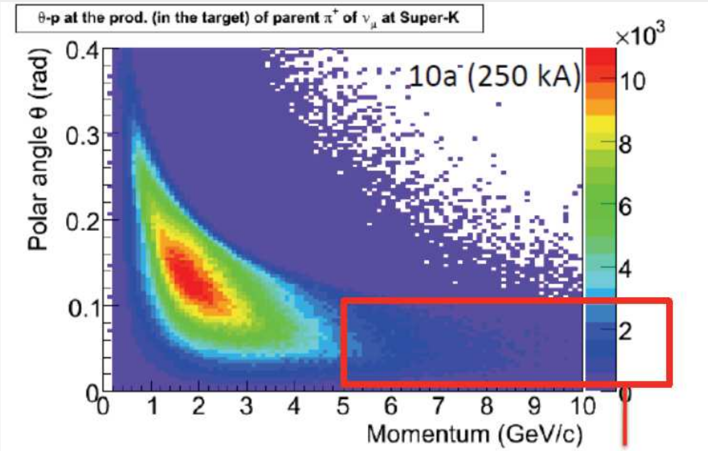
Annihilation vertex in OPERA film (left) and in new film with Nagoya gel (right)

Absolute muon flux measurement at Muon pit in T2K experiment

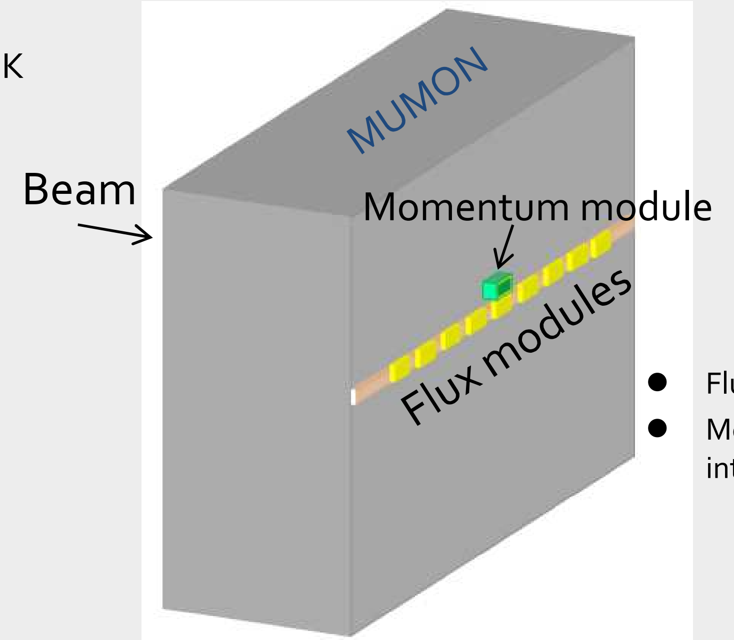
- Measure position, angle and momentum of muons
  - Absolute flux, angular and momentum distribution
- Compare the distributions with beam MC with different hadron production models



Phase space of pions whose daughters reach at SK



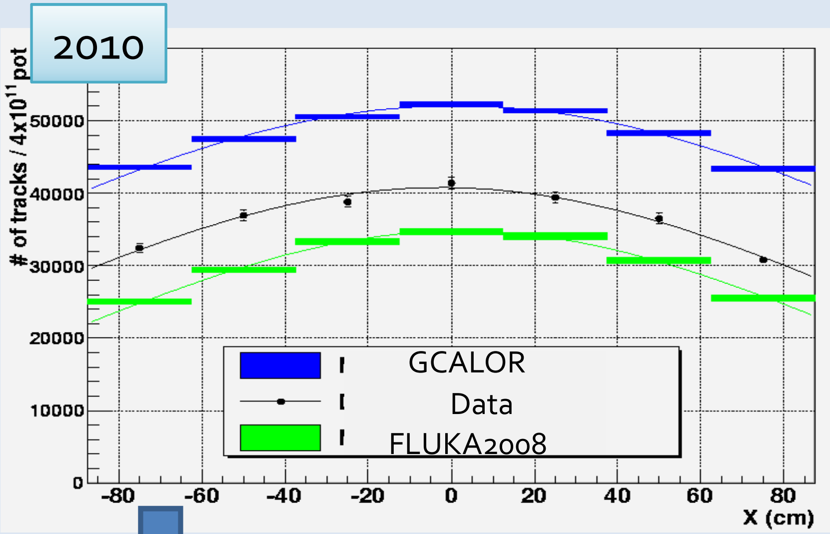
MUMON/Emulsion cover this region



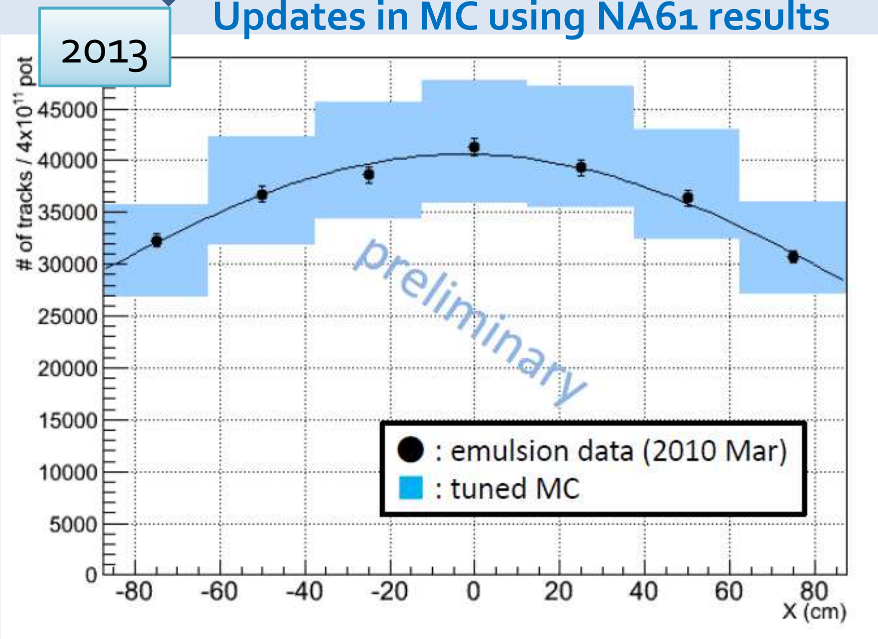
- Flux module : 8 films
- Momentum module : 25 films interleaved by 1mm lead plates

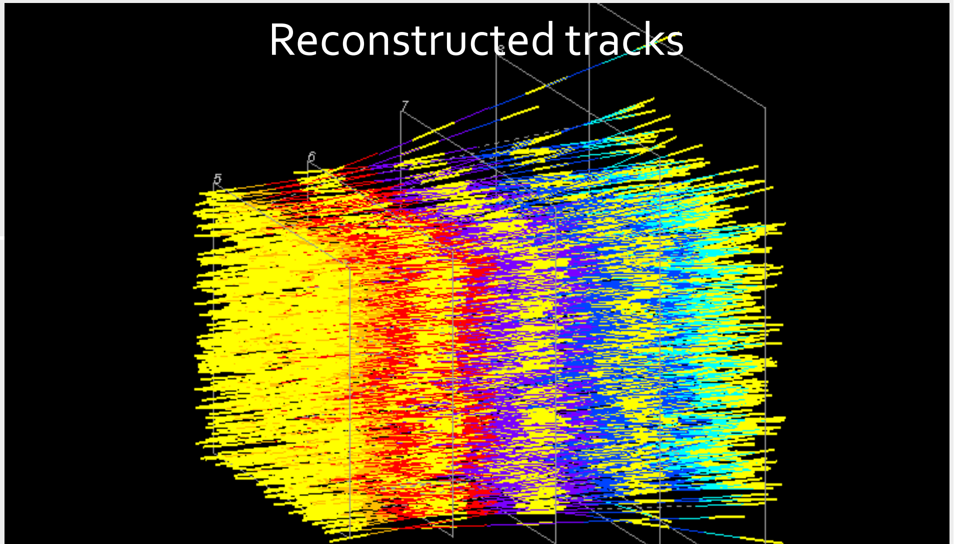
Comparison with MC

Absolute muon flux profile



Updates in MC using NA61 results

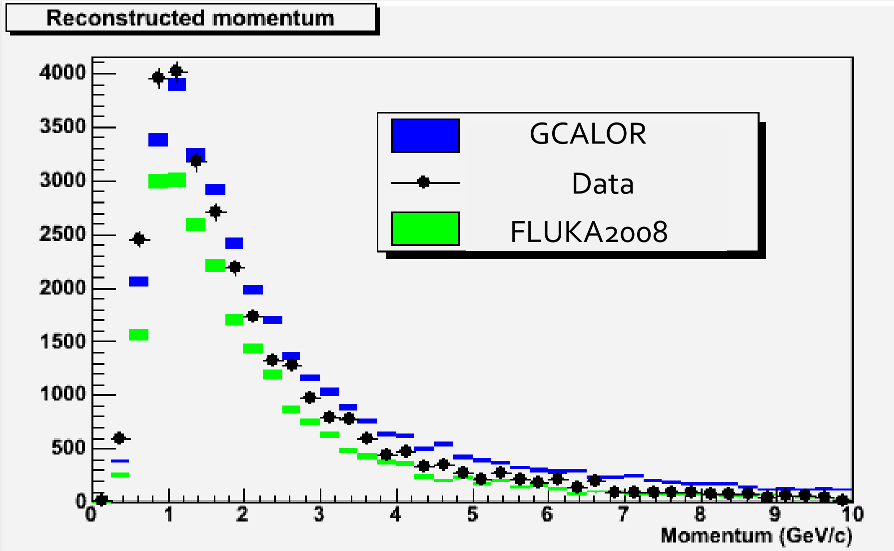




Tracks reconstructed in 2mm x 2mm area (lead module).
Yellow line is emulsion film. The other colored line shows the extrapolation of measured tracks. The color by Z depth in the module.

Momentum distribution

Simulation in emulsion modules was done for MC samples.
Here we compare the reconstructed momentum for both MC and data.



Medical application: neutron spectroscopy with emulsions

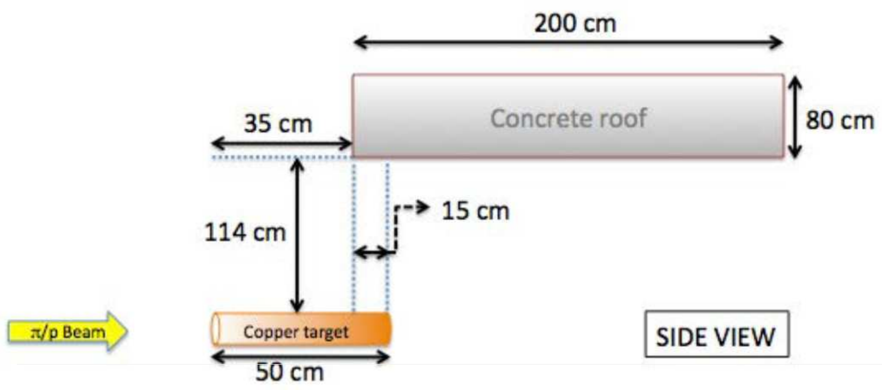
Secondary neutrons in clinical proton radiotherapy is a crucial issue for possible secondary cancer induction, causing an extra-dose to the whole body of the patient.

It is important to assess and minimize, the potential for second cancer induction by these secondary neutrons. (*D.J. Brenner, E.J. Hall "Secondary neutrons in clinical proton radiotherapy: A charged issue" Radiot. and Oncol. 86 - 2008*)

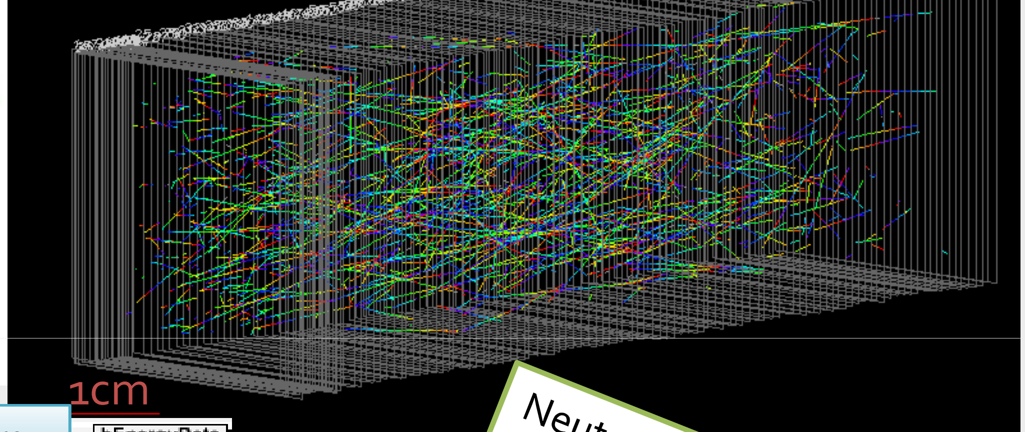
We are investigating the possibility of using the emulsion films to characterize the neutron fields
→ Neutron energy spectrum, Angular information
→ Neutron source imaging (reconstruction of neutron source)

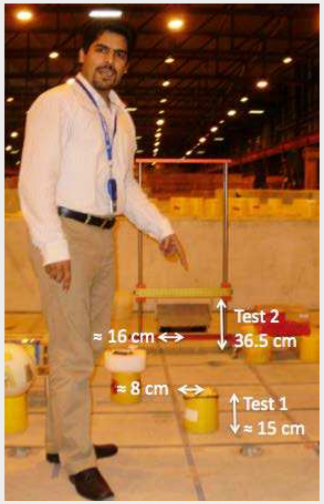
Neutron exposure at CERF facility, CERN

BEAM GEOMETRY

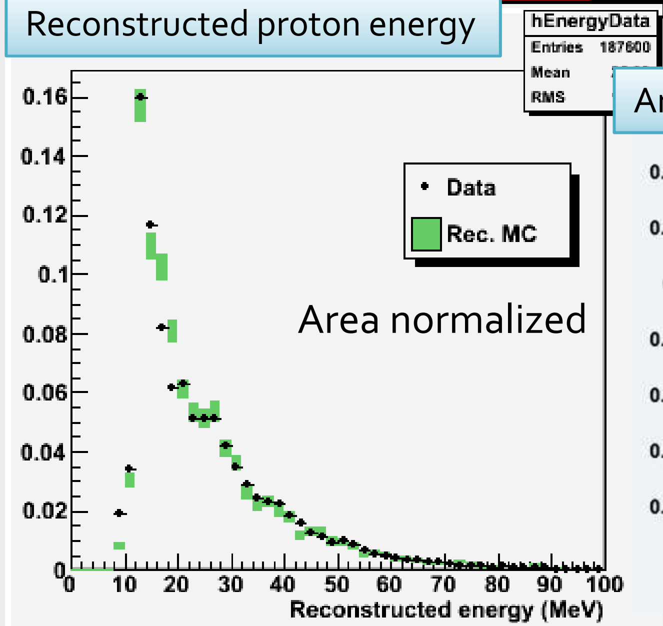


Some of selected tracks
(1track/200tracks are shown)

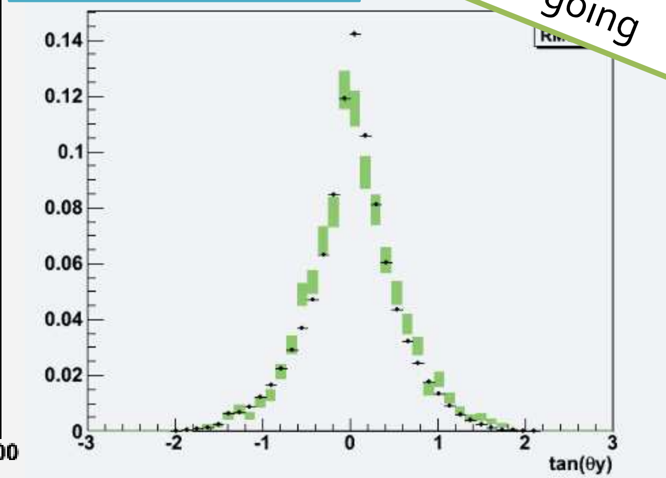




Reconstructed proton energy

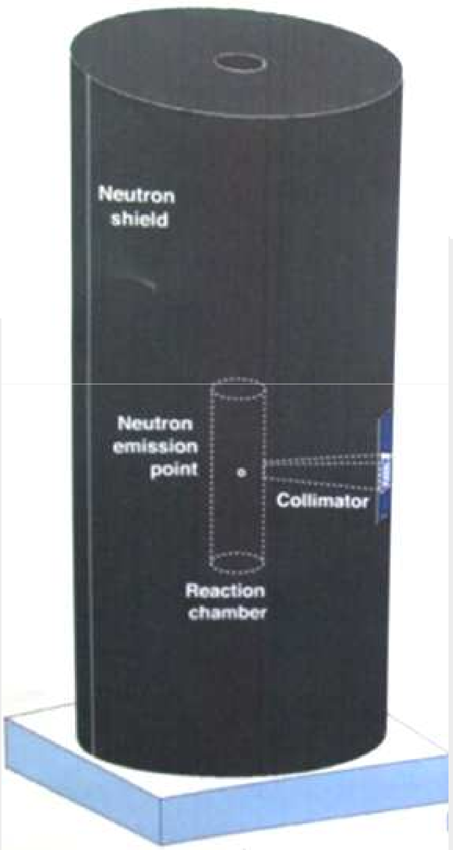


Angular distribution



Neutron spectrum unfolding
On going

Proof of principle for neutron source imaging



2.5 MeV neutron from D-D fusion
→ recoil proton range is about 70 μm

45 cm

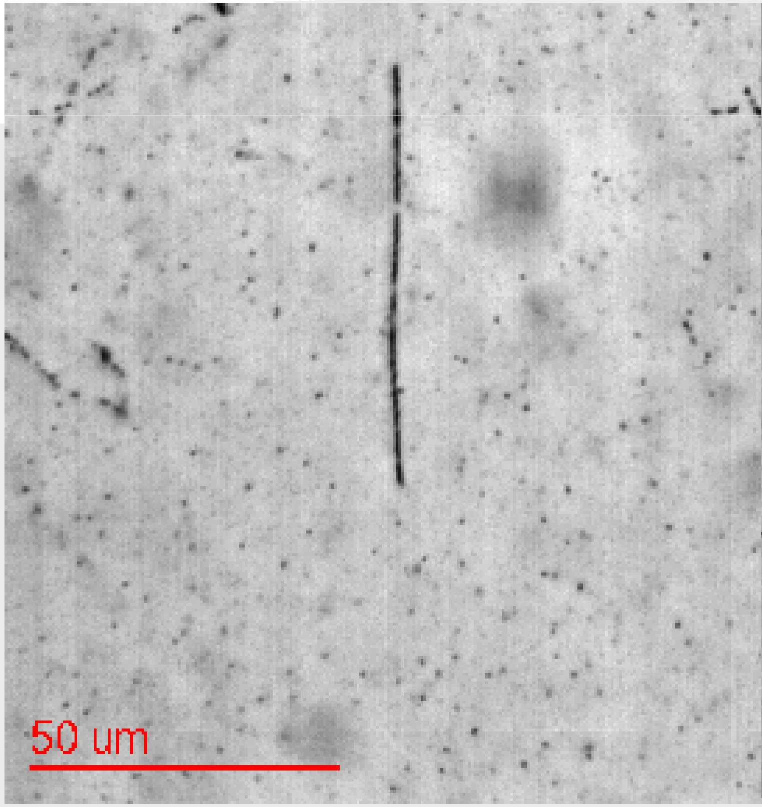
200 cm

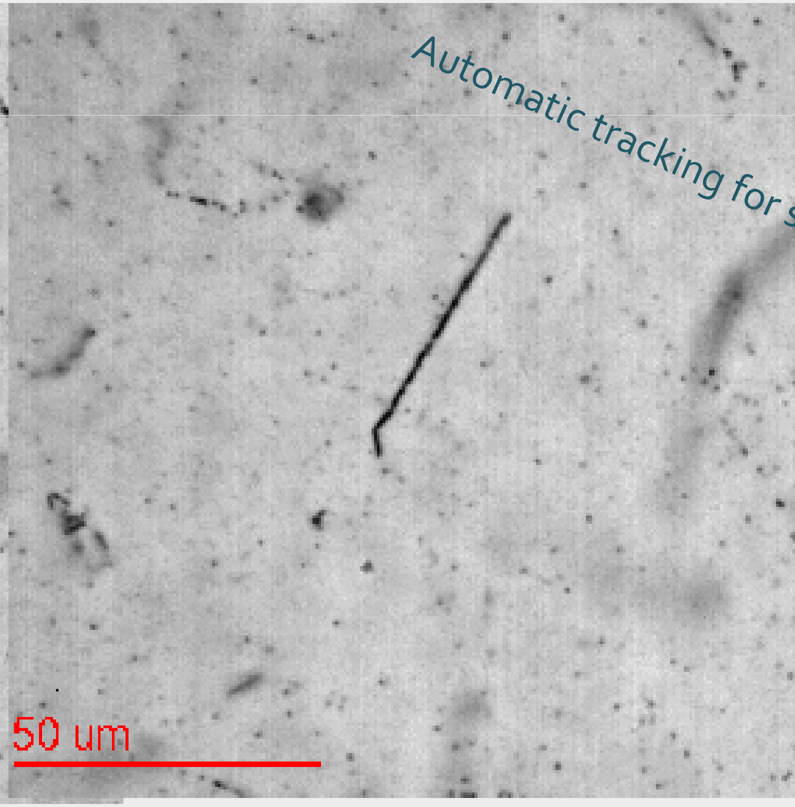
Monochromatic neutron beam
(2.5 MeV neutron from D-D fusion)

Study of imaging of neutron source by using angular information of recoiled protons

neutron

neutron





Automatic tracking for short tracks is ready

Other applications: muon radiography

- Test in Vancouver
  - 3D reconstruction of mineral deposit in Vancouver mine, Canada
  - → Problem in uncertainty of efficiency
  - → Need good quality films for next trials

Set emulsion films in the mine

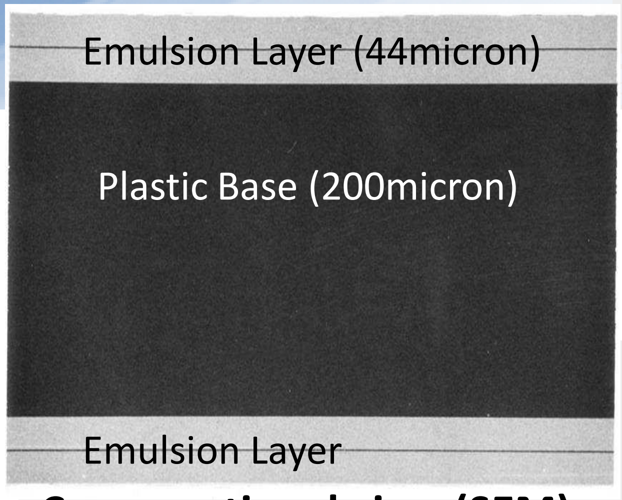
- Further plans for mountains in Switzerland
  - Water content in the mountain, in line of global warming

Summary

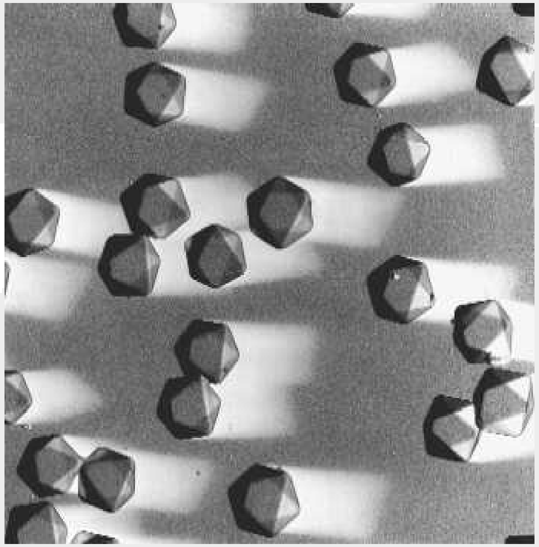
- LHEP Bern is conducting an intensive R&D program on emulsion detectors for wide range of applications.
- Infrastructures for R&D are available in Bern
  - Underground emulsion facility
  - Electron beam for sensitivity measurement
  - Scanning station, largest scale in Europe.
- High sensitivity detector production has been established
- Rich applications in many field
  - Physics: AEgIS, T2K
  - Medical: Beam monitoring, Neutron dosimetry
  - Geography: Mountain structure
  - etc.

Backup

Nuclear emulsion detectors (ex. OPERA film by Fuji Film)



Cross-sectional view (SEM)



A minimal detector

AgBr Cristal,

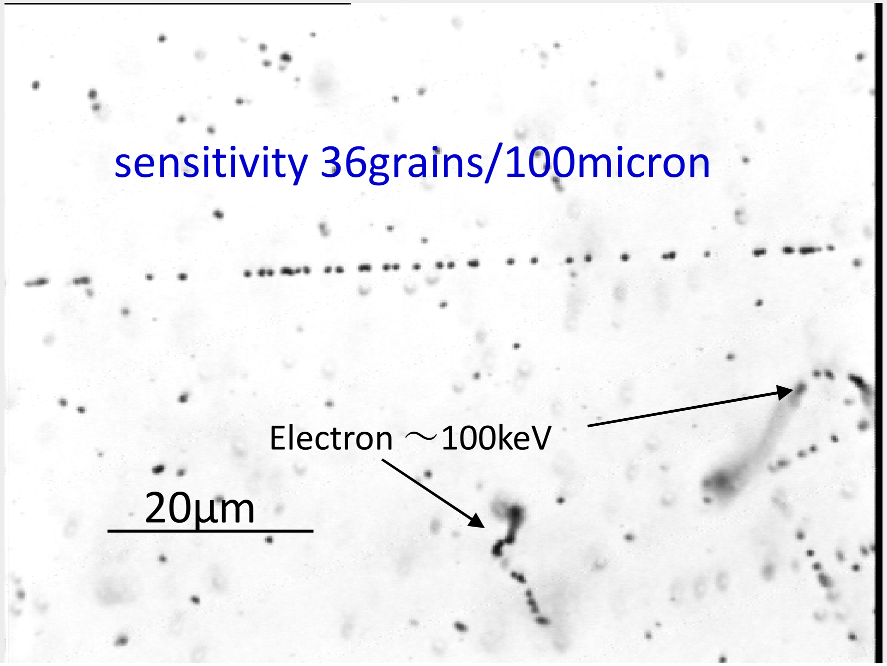
Size = 0.2micron

Detection efficiency

= 0.16/crystal

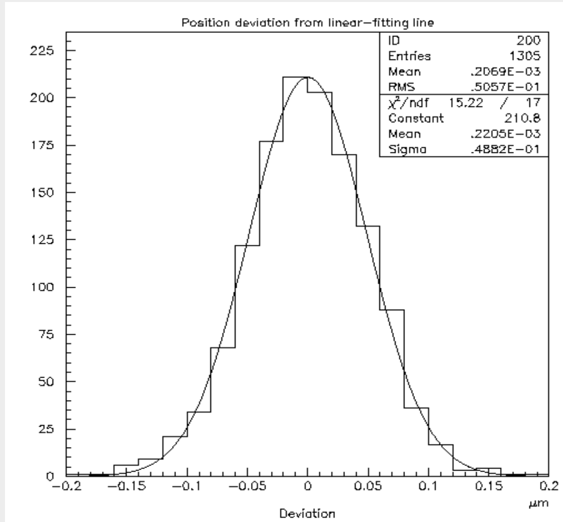
10^{13} channels in a film

π-10GeV/c



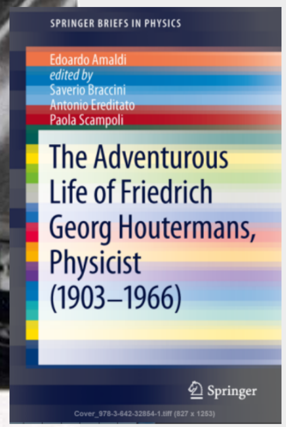
Intrinsic resolution **50nm**

Deviation from linear-fit line (2D)



Emulsion in Bern, Long history…

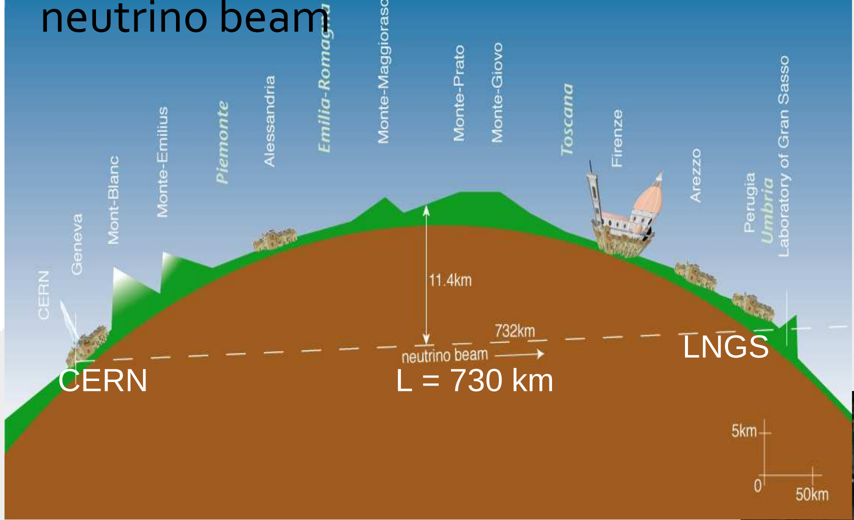
F.G. Houtermans im Kreise seiner Scannerinnen im Physikalischen Institut Bern 1955/56



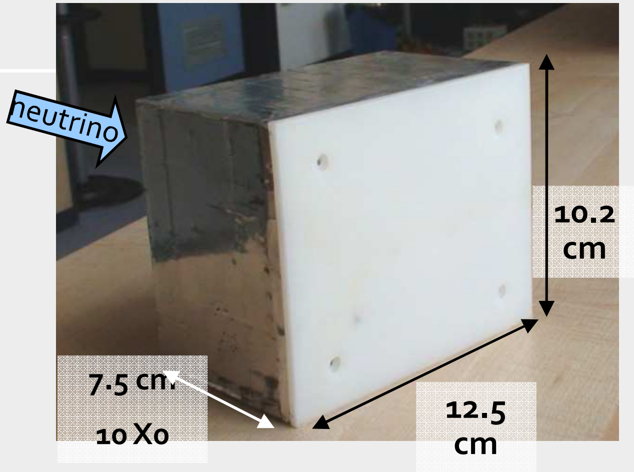
OPERA Experiment

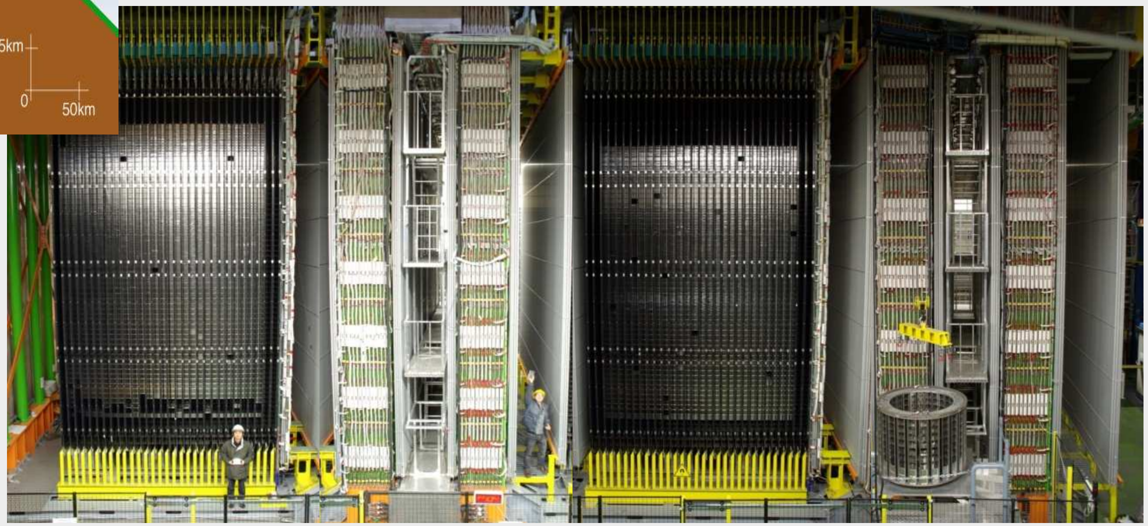
Study neutrino oscillation though appearance of ν_τ in pure ν_μ beam

CERN to Gran Sasso (CNGS) neutrino beam



Basic unit : ECC Brick
57 emulsion films interleaved with 1mm read plates

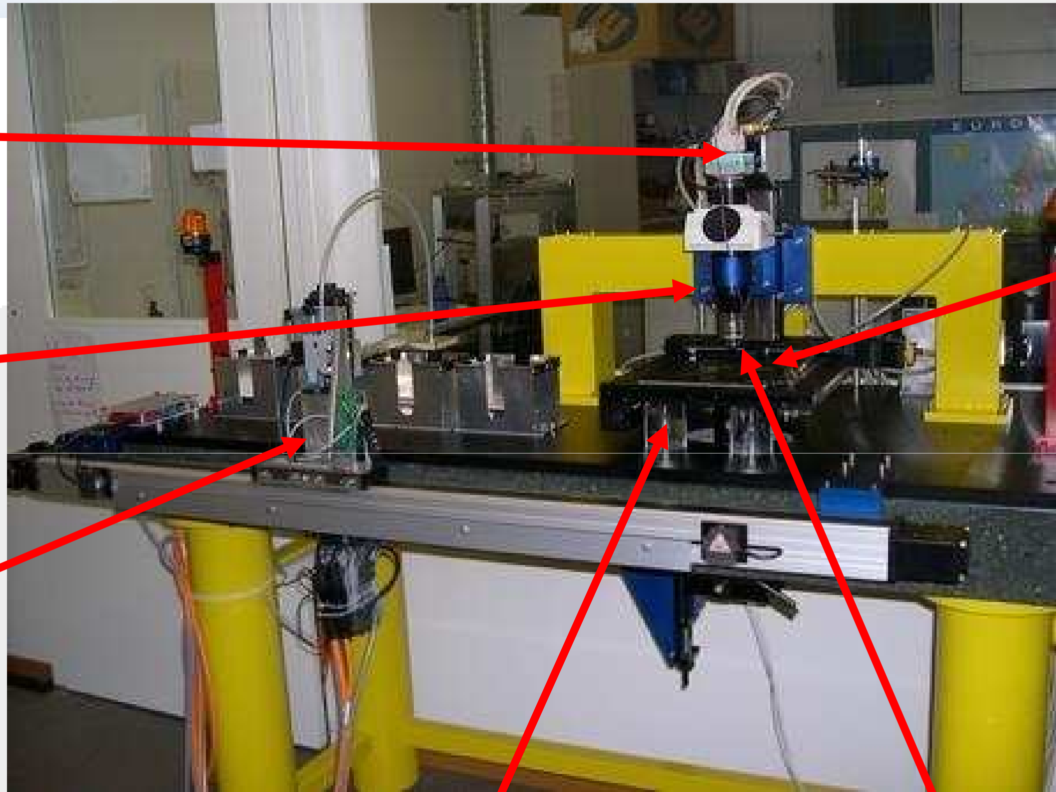




OPERA detector 150,000 ECC 1.25kton target
about 10,000,000 emulsion films ~= **110,000 m²**

OPERA Microscope in Bern

CMOS camera
1280×1024 pixel
256 gray levels
376 frames/sec
(Mikrotron MC1310)



Emulsion film

Z stage (Micos)
0.05 μm nominal
precision

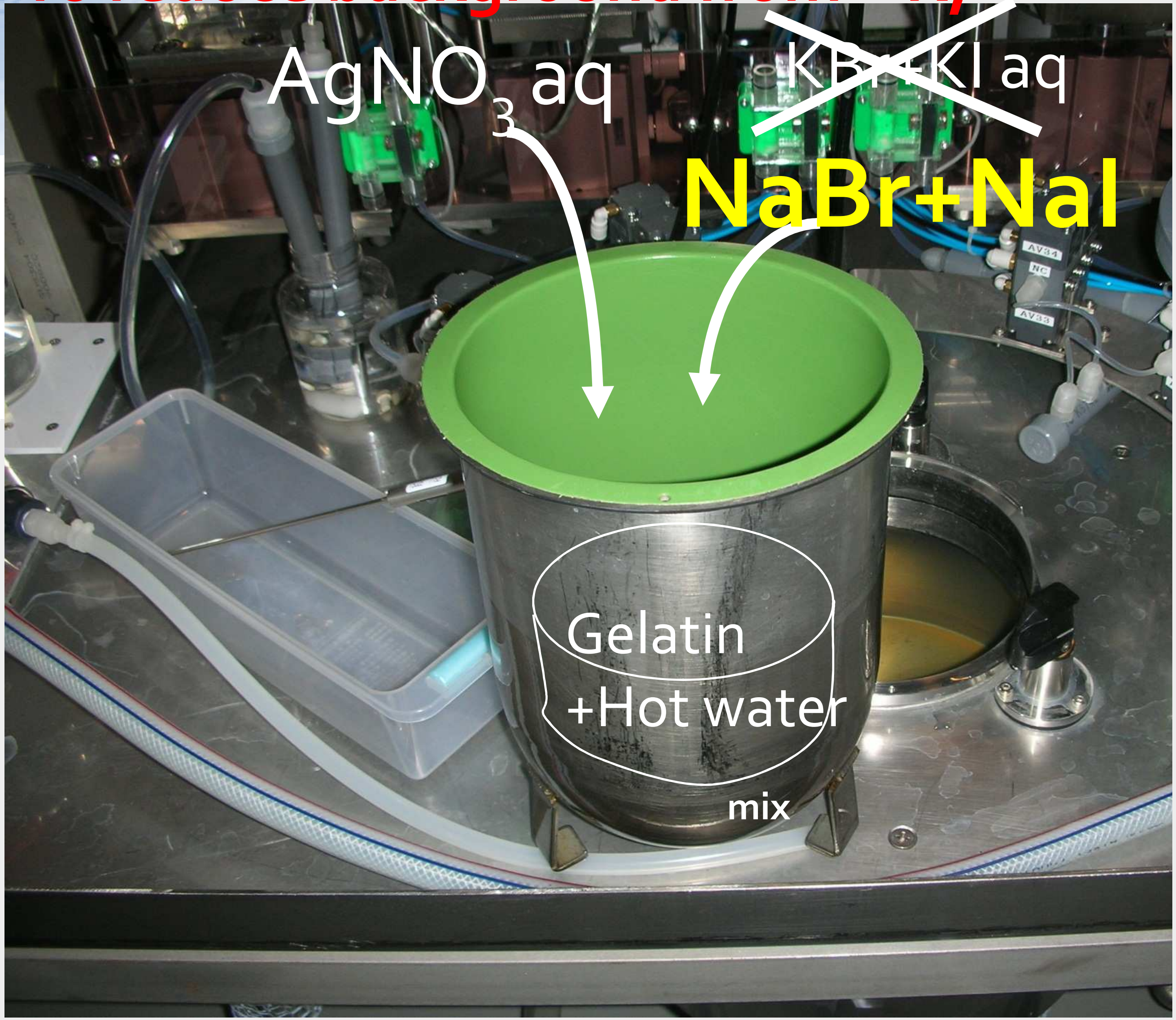
Automatic Plate Changer

XY stage (Micos)
0.1 μm nominal
precision

objective (Dry 50× NA 0.95)

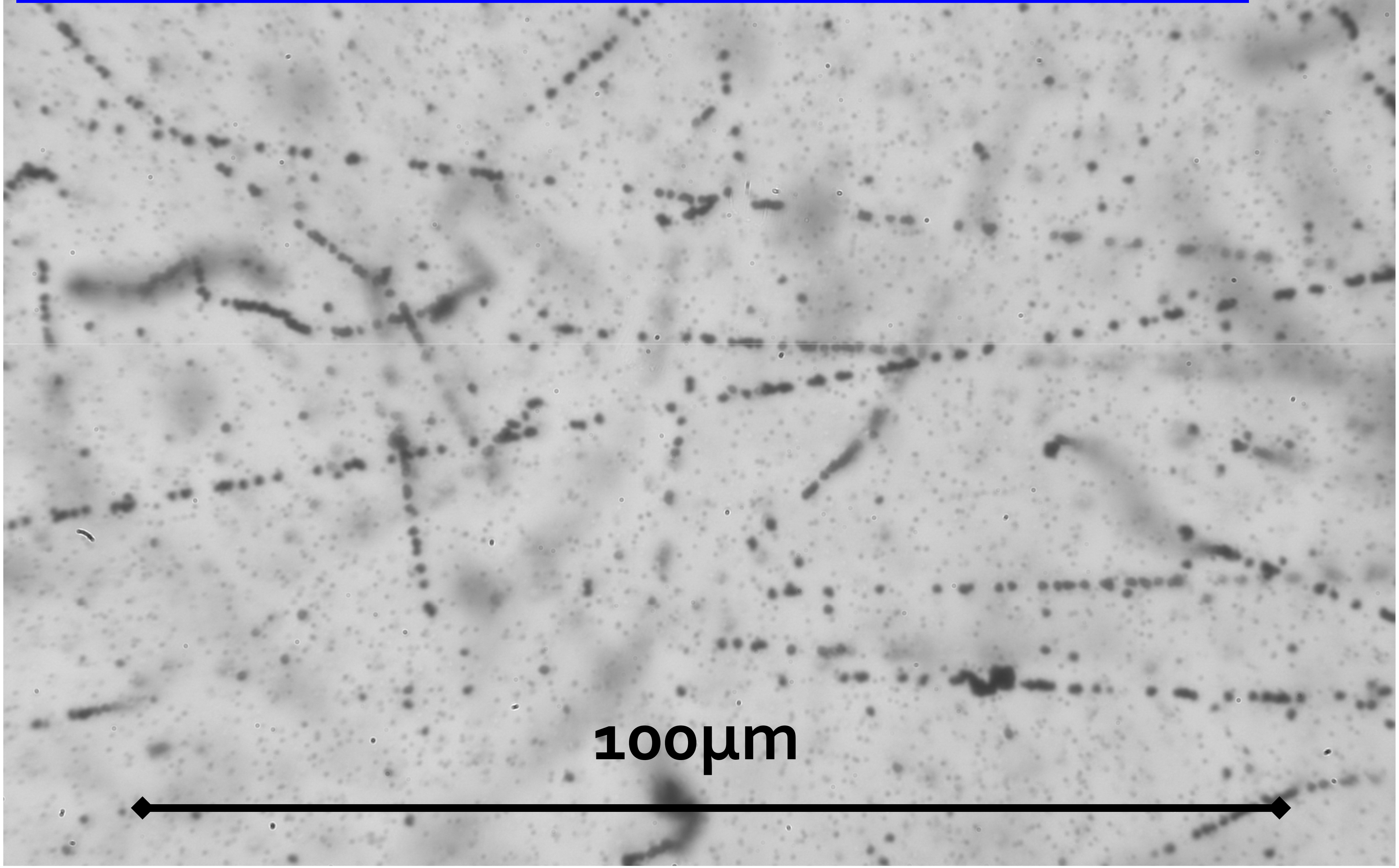
20 min / cm^2

To reduce background from ^{40}K,



Condensed, Na-type 2 (dev 40min)

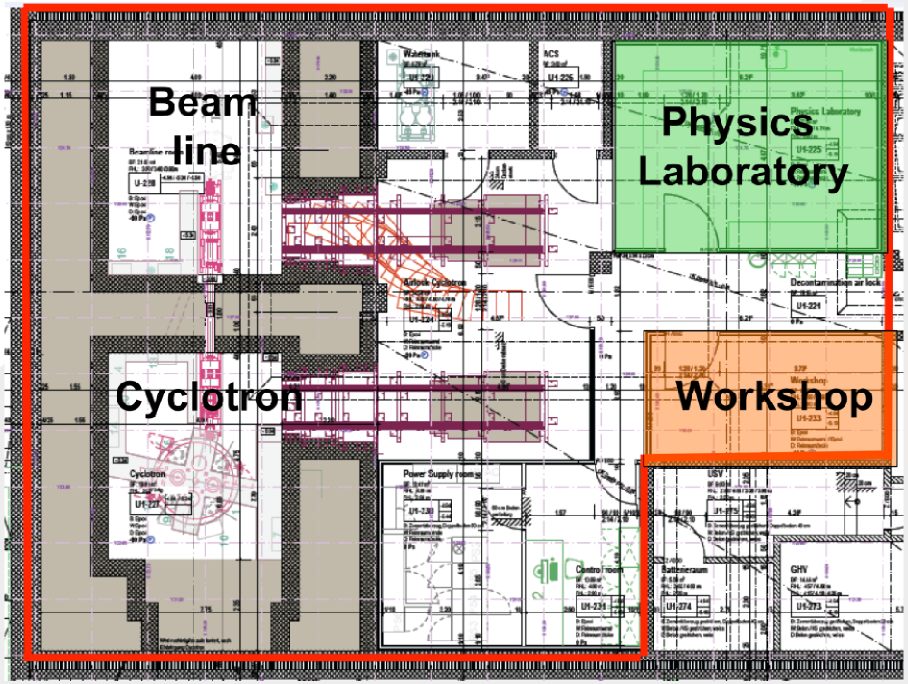
GD=93.9±4.5 FD=2.9±0.9



The SWAN Project in Bern

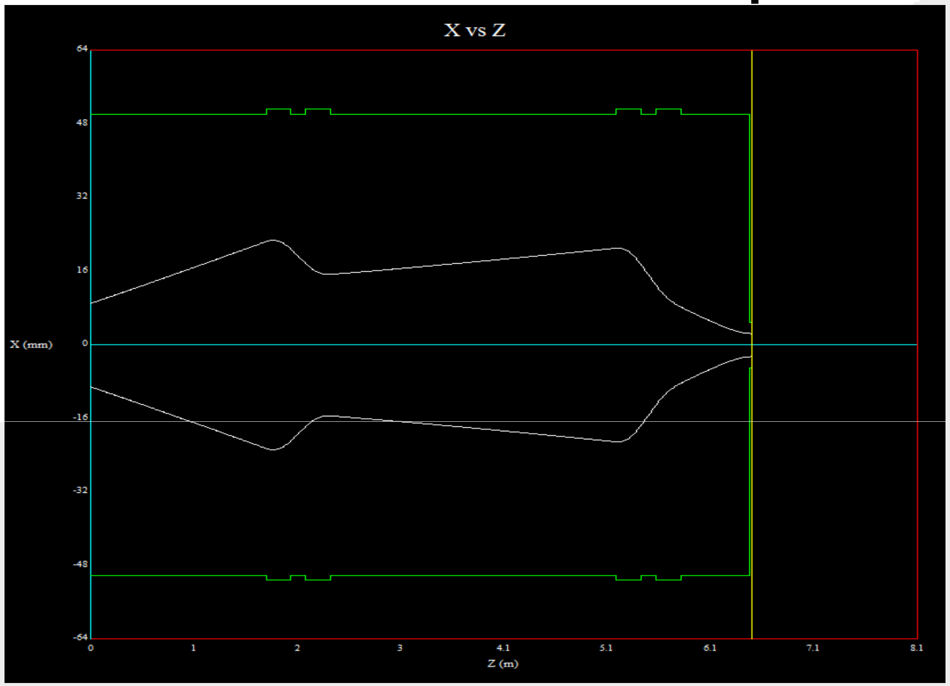
- Initiated in 2007 by the Inselspital and the University of Bern
- SWAN stands for SWiss hAdroNs
- Aims:
  1. Production of radiopharmaceuticals, for PET diagnostics in particular
  2. Proton therapy
  3. Multi-disciplinary research
- Phases:
  1. Cyclotron laboratory for radioisotope production and research
  2. Proton therapy centre

The cyclotron and the Beam Transport Line (BTL)



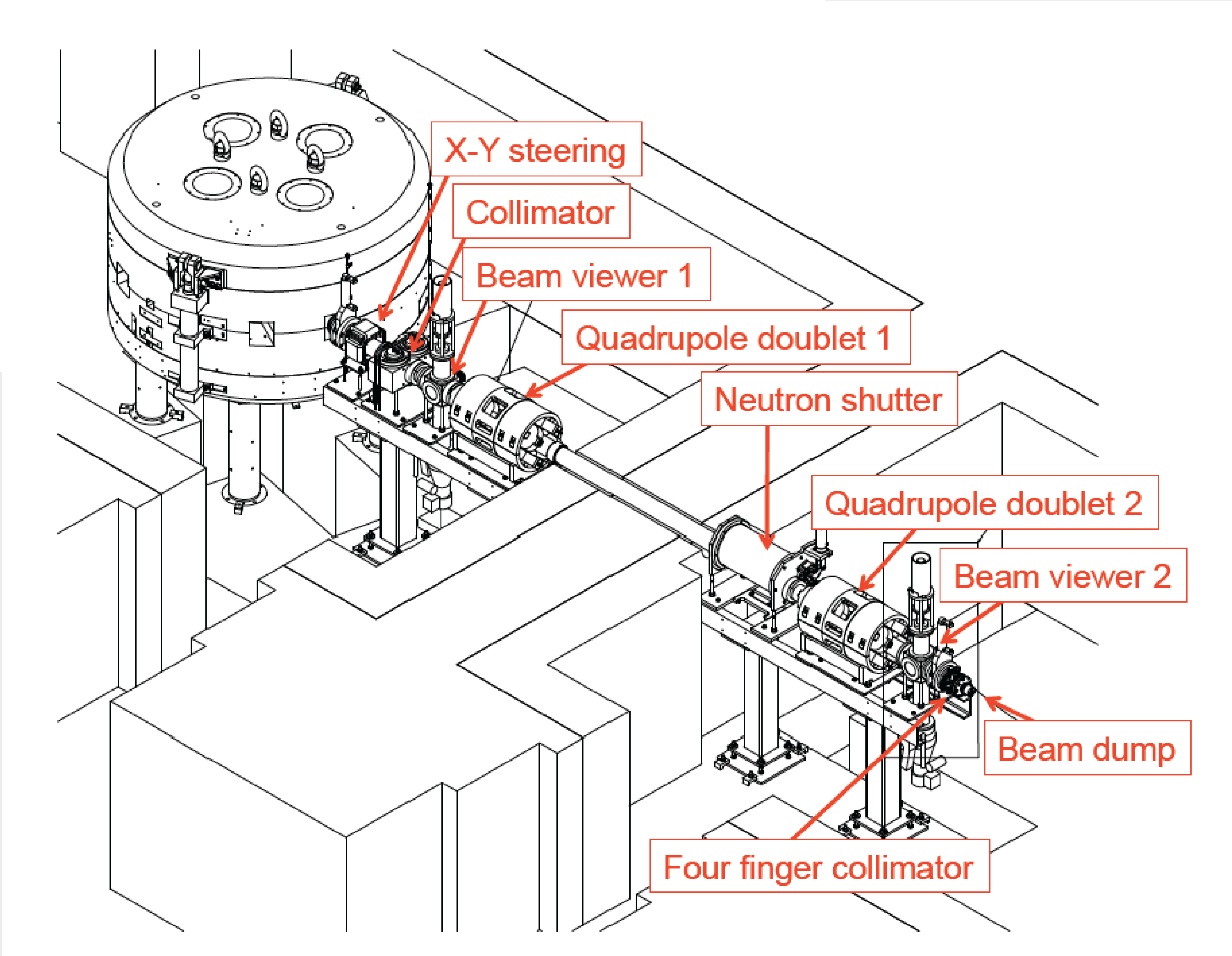
- IBA 18 MeV "twin" high current cyclotron (two H^- ion sources)
- 7 out ports (4 ^{18}F liquid targets, 1 ^{15}O gas target, 2 spare)
- External beam line in a separate bunker: production and research in parallel

The Beam Transport Line (BTL)



- Research and training activities: novel detectors, radiation biophysics, radioprotection, radiochemistry, radio-pharmacy, material sciences, …
- Low currents (1 µA – 1 nA) and high currents (up to 150 µA)
- Beam spots on target: from ≈ 5 mm to 20 mm diameter
- BTL: 6 m long, 2 quadrupole doublets, neutron shutter

Optimized BTL



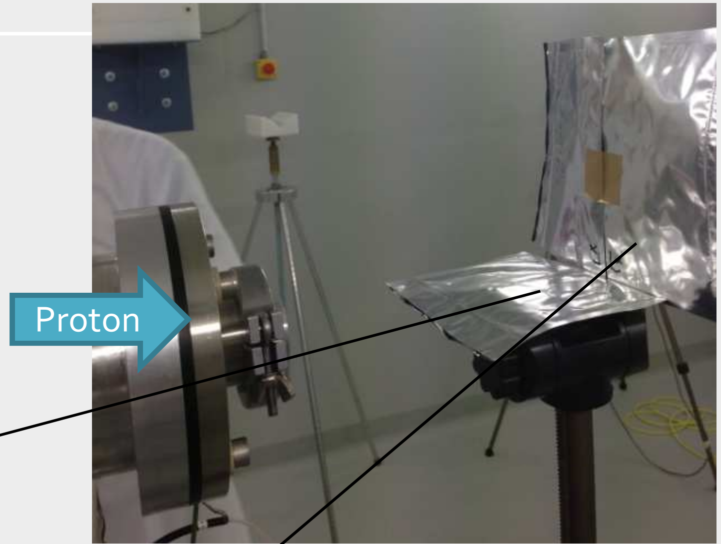
- The optimization of the BTL has been successfully performed
- Transmission of ≈97% at 150 μA stable for 60 minutes has been obtained
- Transmission ≈99% at 10 μA and ≈100% at 1 μA

The new Bern cyclotron laboratory for PET radioisotope production and its beam line for multi-disciplinary research

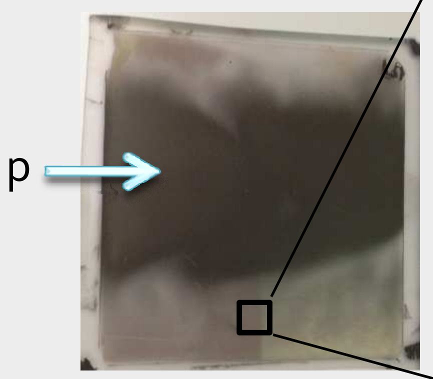
- The new cyclotron laboratory for radioisotope production and research in Bern has been constructed and successfully commissioned
- Routine FDG production has started
- A specifically conceived Beam Transfer Line (BTL) allows multi-disciplinary research in parallel with PET radioisotope production
- Research activities with the BTL have started
  - Detector and accelerator physics
  - Non-intercepting beam monitoring systems
  - Radiation protection

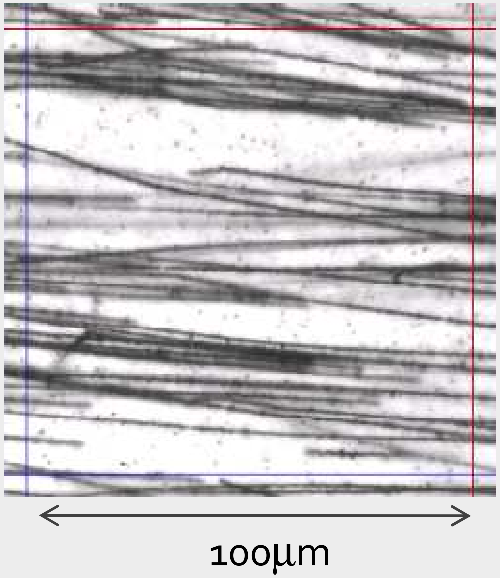
Irradiation with 18 MeV protons at the beam transfer line of the new Bern cyclotron laboratory (SWAN, Inselspital)

- Density
  - Center: too high (cannot measure)
  - 2cm from center: 10^5~10^6 tracks/cm^2

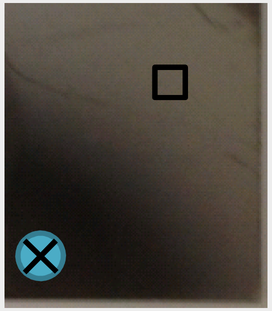


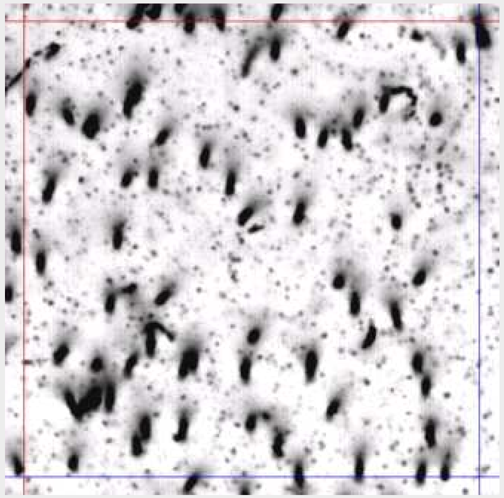
Horizontal exposure





Vertical exposure

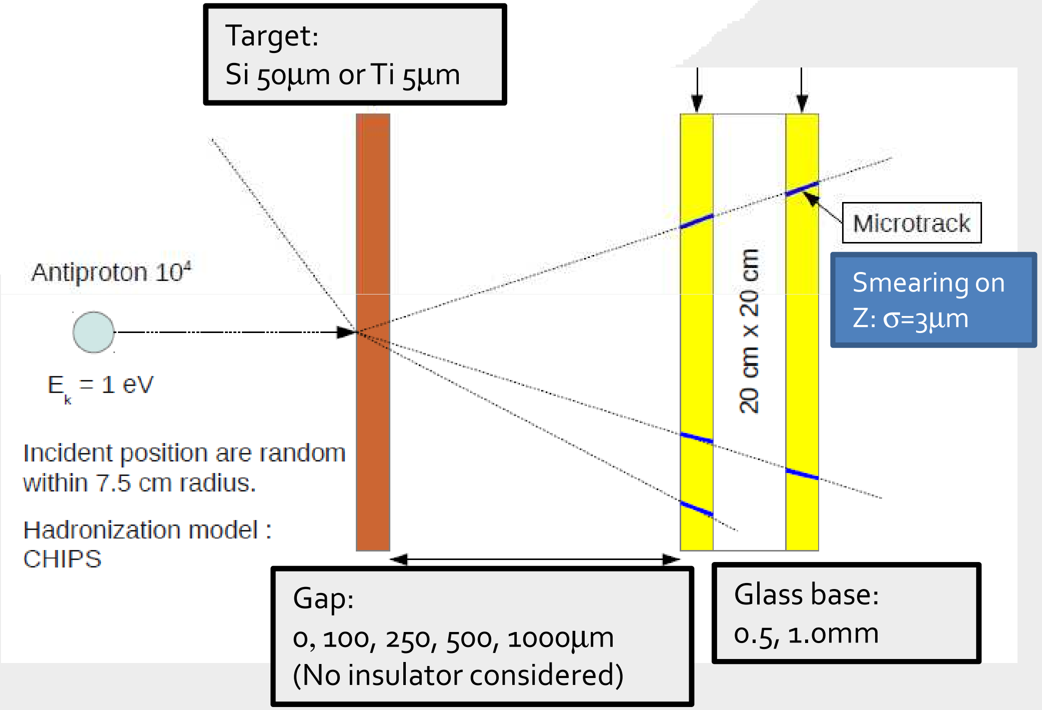




Irradiation with 22 MeV electrons from a linac of the Clinic for Radiation Oncology (KRO) of the Inselspital

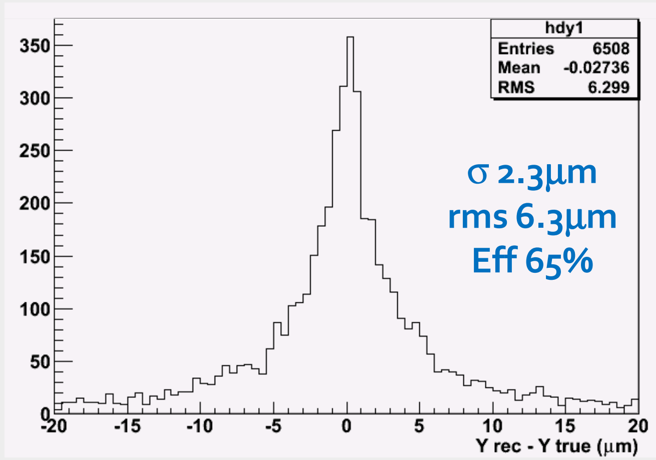
2nd exposure on Jul 15

Resolution before cuts



For the case of
Ti 5µm target, gap 250µm, 1mm glass base

- 10000 antiproton
- → vertices with at least 2 tracks found for 6508 events



Reconstructed vertex Y – true vertex Y

Resolution and efficiency

Selection: Δθ<0.1 & tanθ<3 & ΔZ<10+0.01xGap(μm)

0.5mm glass base

Gap (μm)	Si 50μm		Ti 5μm	
	σ (μm)	Eff	σ (μm)	Eff
0	0.9	0.47	0.7	0.39
100	1.3	0.46	1.1	0.40
250	1.8	0.44	1.7	0.38
500	2.8	0.41	2.5	0.35
1000	4.2	0.38	3.8	0.33

1mm glass base

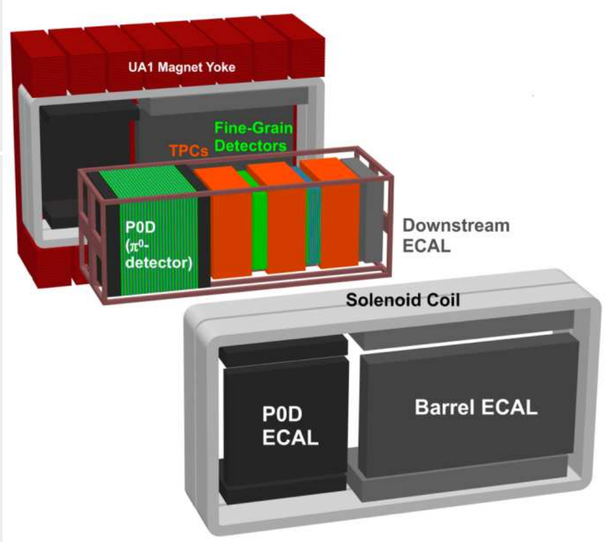
Gap (μm)	Si 50μm		Ti 5μm	
	σ (μm)	Eff	σ (μm)	Eff
0	**0.9**	**0.39**	**0.7**	**0.34**
100	1.3	0.38	1.0	0.33
250	1.8	0.38	1.4	0.32
500	2.2	0.35	2.1	0.31
1000	3.6	0.34	2.8	0.29

- Smaller gap is better → should be less than 250μm
- No significant difference between Si 50μm and Ti 5μm
- Multiplicity for Si is higher than Ti → efficiency for Si is higher

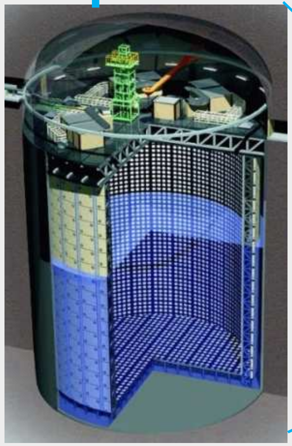
T2K

- Goals
  - Discovery of ν_e appearance
  - Precise measurement of ν_μ disappearance
- Long baseline neutrino oscillation experiment
  - Intense ν_μ beam from J-PARC to Super-K @295km
  - Near detector @280m (ND280)

ND280



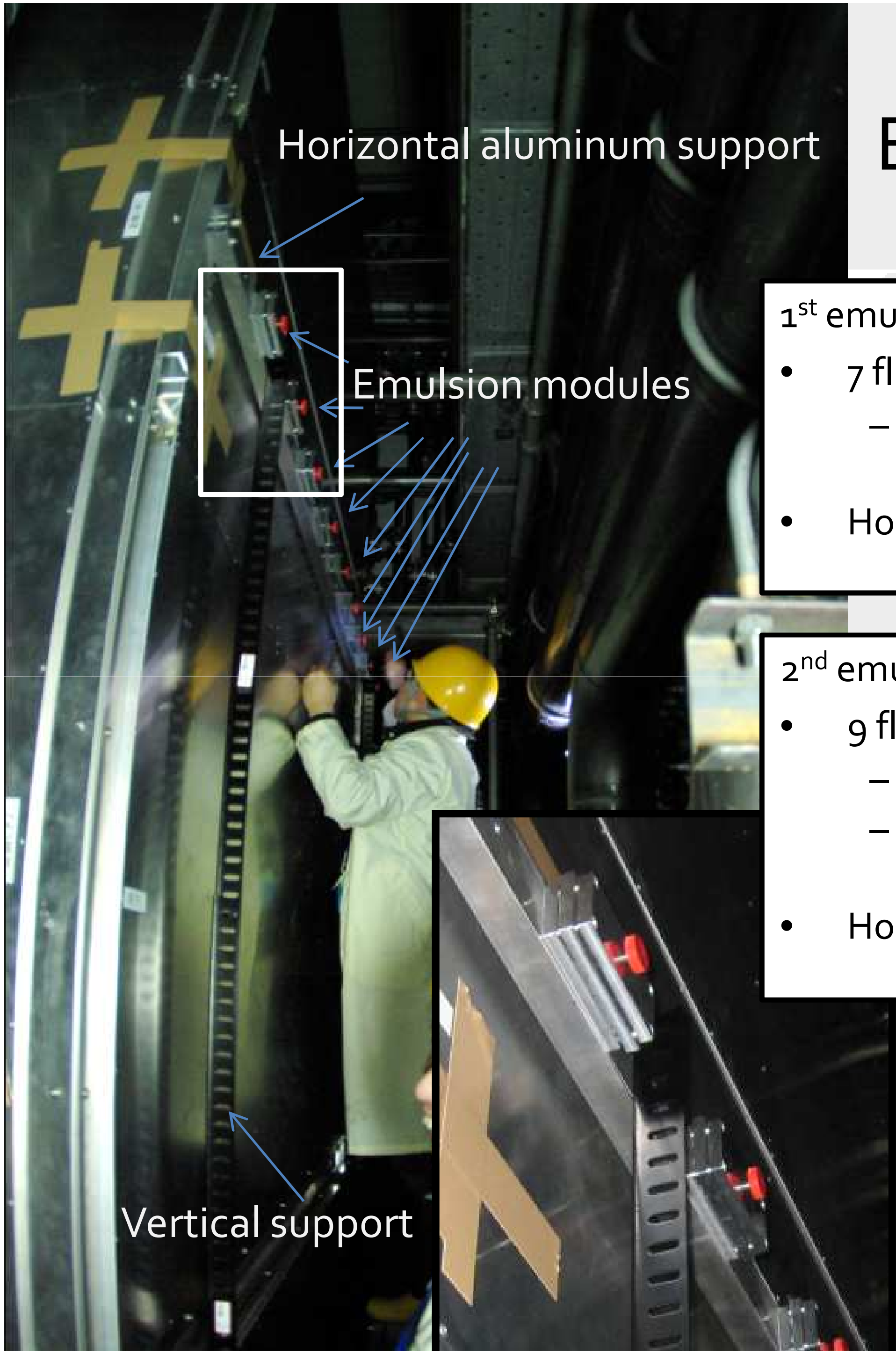
Super-K



50 kton water Cherenkov detector

J-PARC

30 GeV proton beam, design power of 750 kW



Emulsion exposures

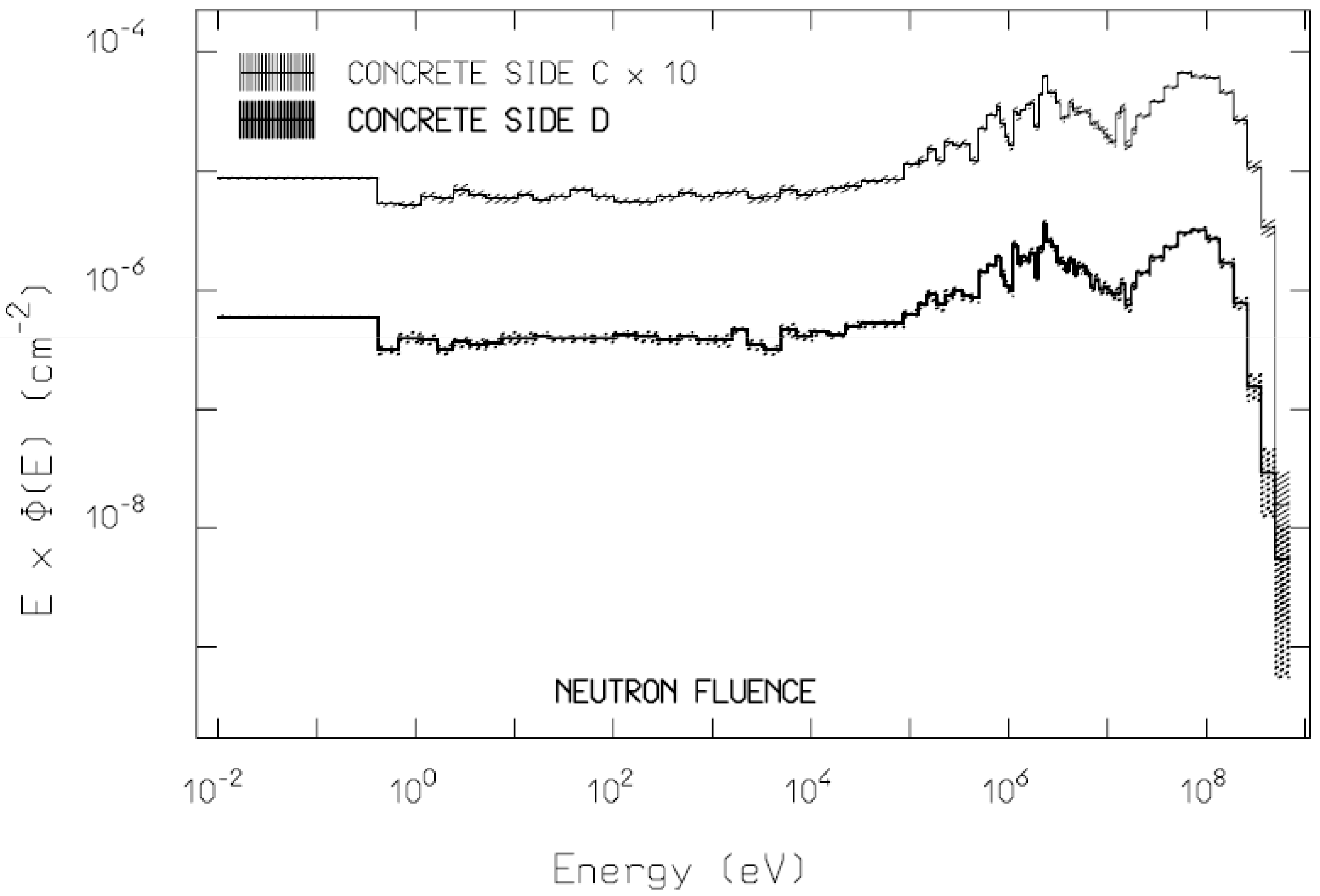
1st emulsion exposure (run24, 27th May 2009)

- 7 flux modules for each shot.
  - Flux module : 5 films + 5 films interleaved by 0.5mm lead plates.
- Horn off (0kA) and horn1 on (I_1 = 200kA, 250kA)

2nd emulsion exposure (run31, 18th Mar 2010)

- 9 flux modules + 1 momentum module for each shot.
  - Flux module : 8 films
  - Momentum module : 25 films interleaved by 1mm lead plates.
- Horn off (0kA) and all horns on (I_1 and I_{23} = 250kA)

Neutron spectrum outside the concrete side-shield



Muon radiography in Vancouver mine

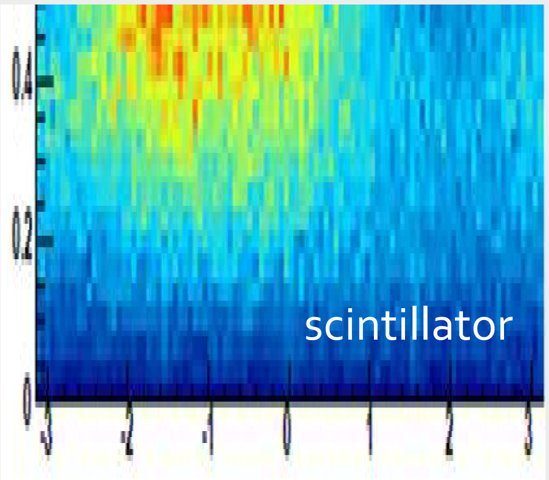
Purpose

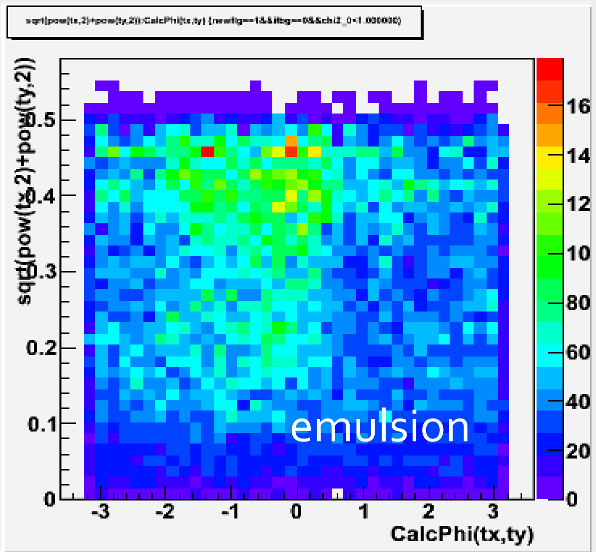
- 3D reconstruction of mineral deposit in Vancouver mine, Canada.

Set emulsion films in the mine

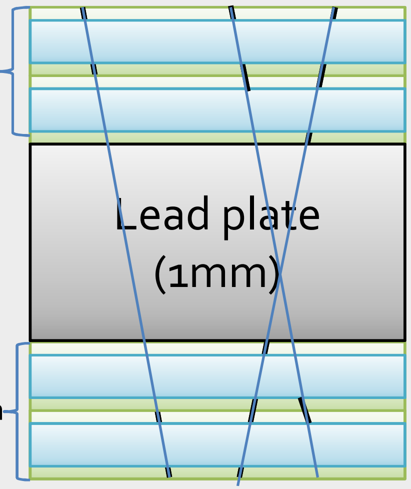
140 days exposure in the mine at 10 places.

→ Exposure was done,
Scanning & Analysis is now on going.





Comparison with scintillator and emulsion result



Detector structure