Neutrino Factory R&D and MICE

The International Muon Ionization Cooling Experiment

1. Why, what?

2. MERIT

3. MICE

4. Detector studies

5. Conclusions

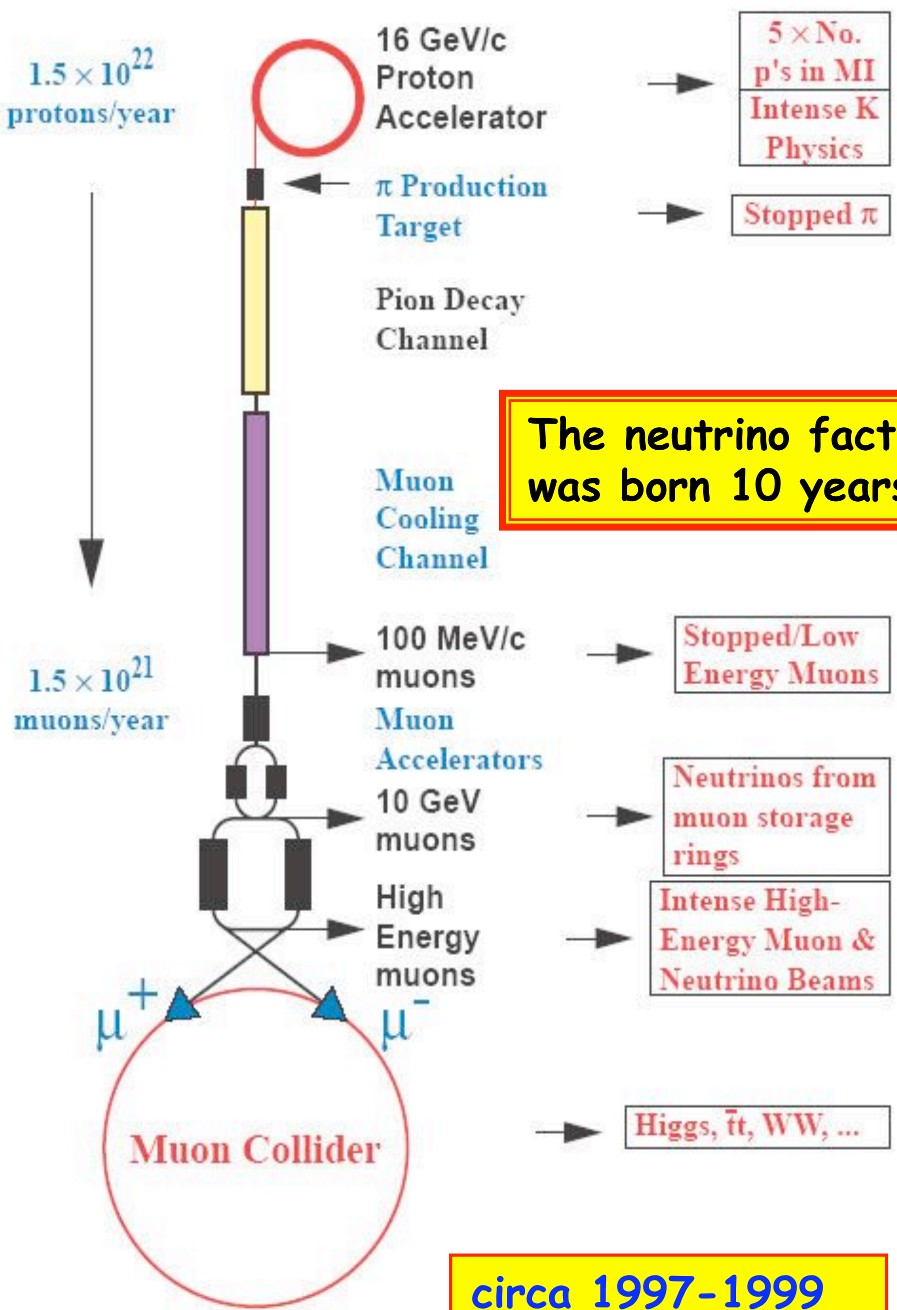
Intense K physics

Intense Low-E muons

Neutrino Factory

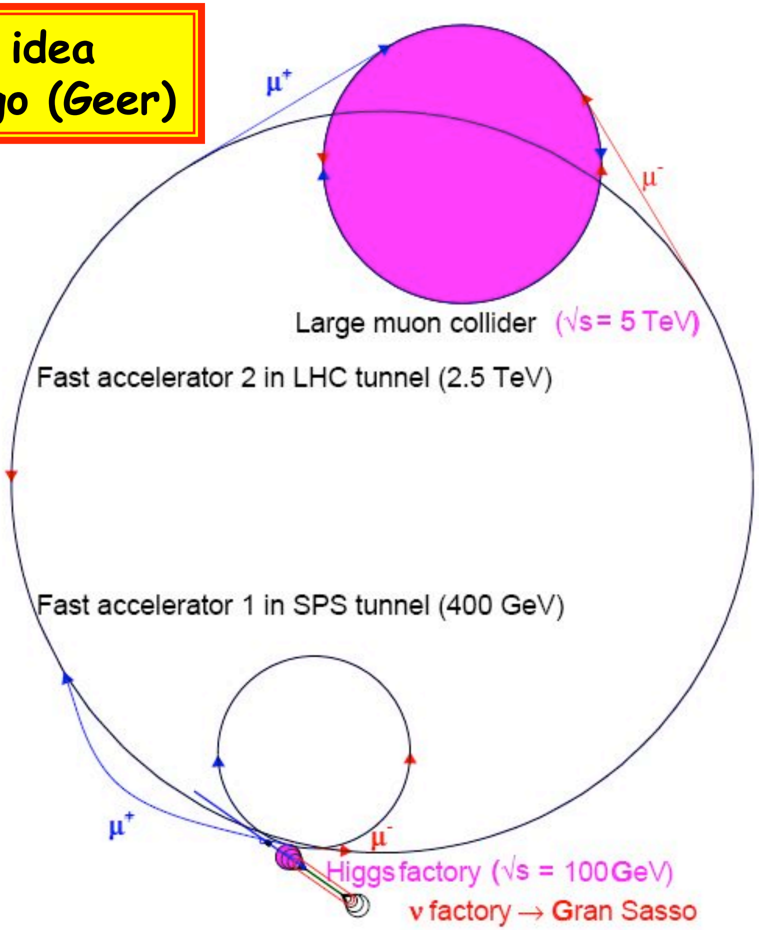
Higgs(es) Factory(ies)

Energy Frontier -> 5 TeV



The neutrino factory idea was born 10 years ago (Geer)

circa 1997-1999
US, Europe, Japan

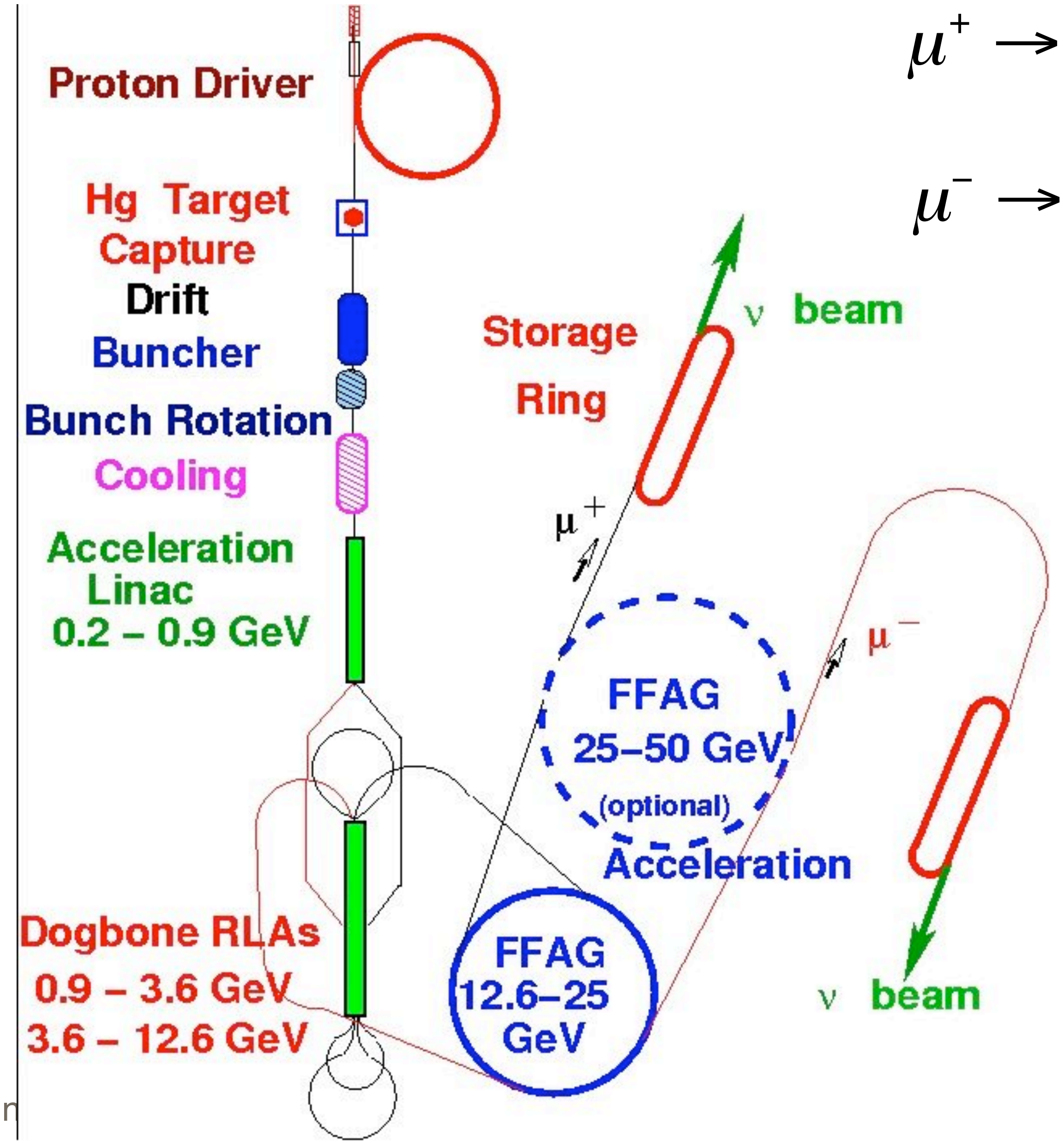


Possible layout of a muon complex on the CERN site.

We do MICE because we want to investigate the feasibility of neutrino factory and muon collider

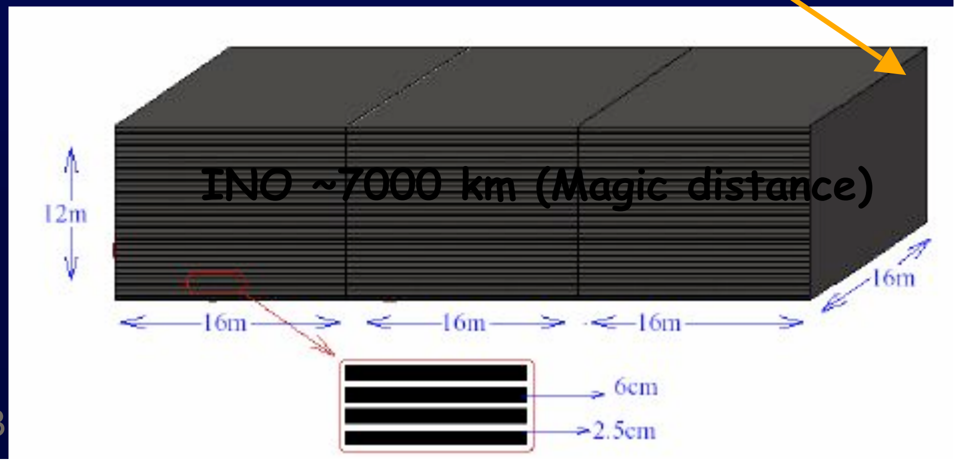
$$\mu^+ \rightarrow e^+ \overline{\nu}_\mu \nu_e$$

$$\mu^- \rightarrow e^- \overline{\nu}_e \nu_\mu$$



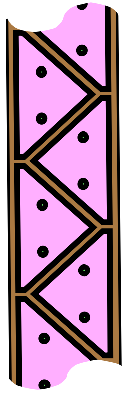
explore neutrino factory
or muon collider
as an option for the future.
Feasibility, cost

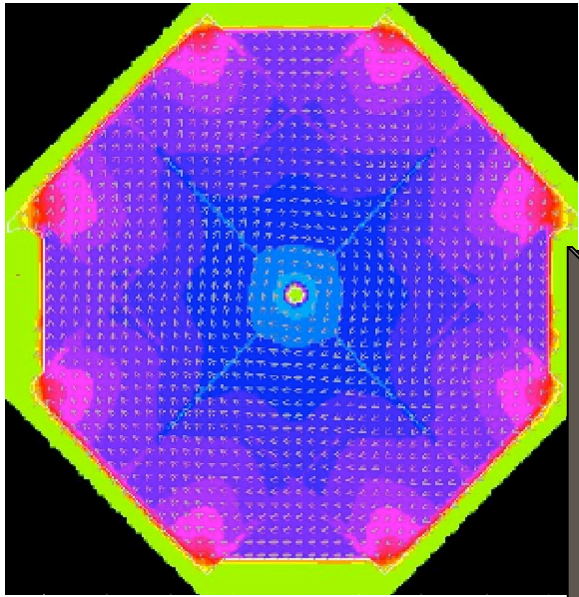
Long baseline detectors: Magnetized Iron, emulsions, liquid argon

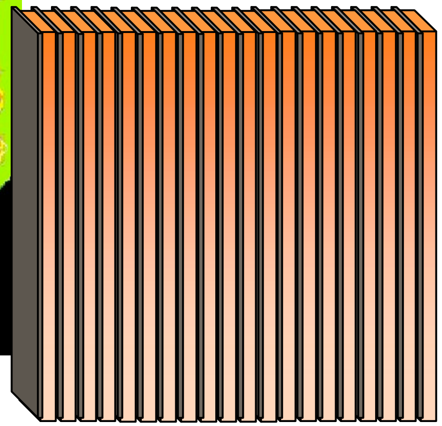


Magnetized Iron calorimeter

(baseline detector, Cervera, Nelson)
B = 1.5 T Φ = 15 m, L = 25 m
t(iron) =4cm, t(sc)=1cm
Fiducial mass = 100 kT
Charge discrimination down to 1 GeV
very similar to MINOS/NOvA/ND280
example. detector:
sci. fi. detector with multipixel APD readout







Event rates for 10^{21} muon decays for 50 GeV beam

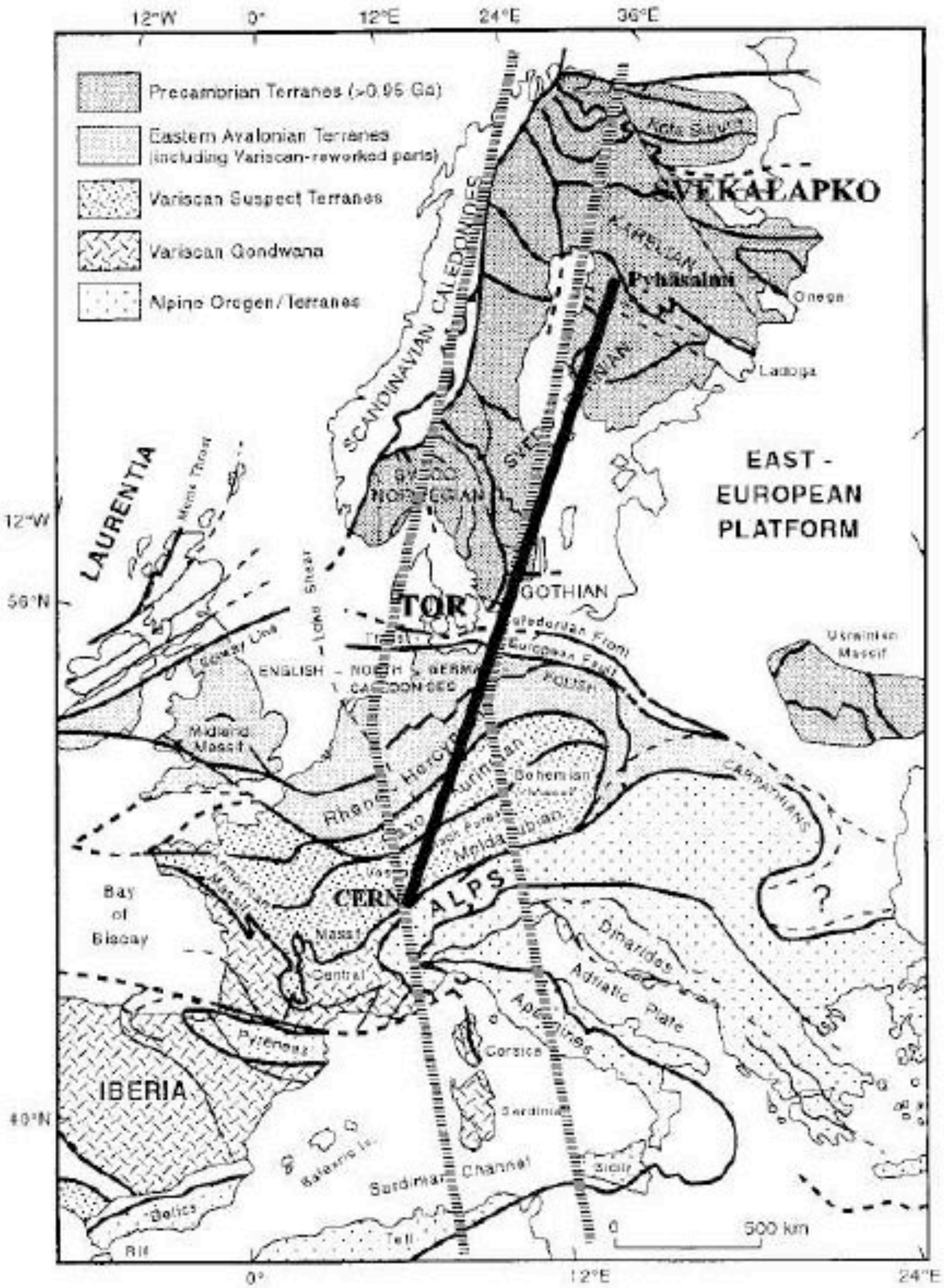
Baseline	$\overline{\nu}_\mu$ CC	ν_e CC	ν_μ signal ($\sin^2\theta_{13}=0.01$)	
732 Km	10^9	2×10^9	3.4×10^5	(J-PARC I→ SK = 40)
3500 Km	4×10^7	7.5×10^7	3×10^5	

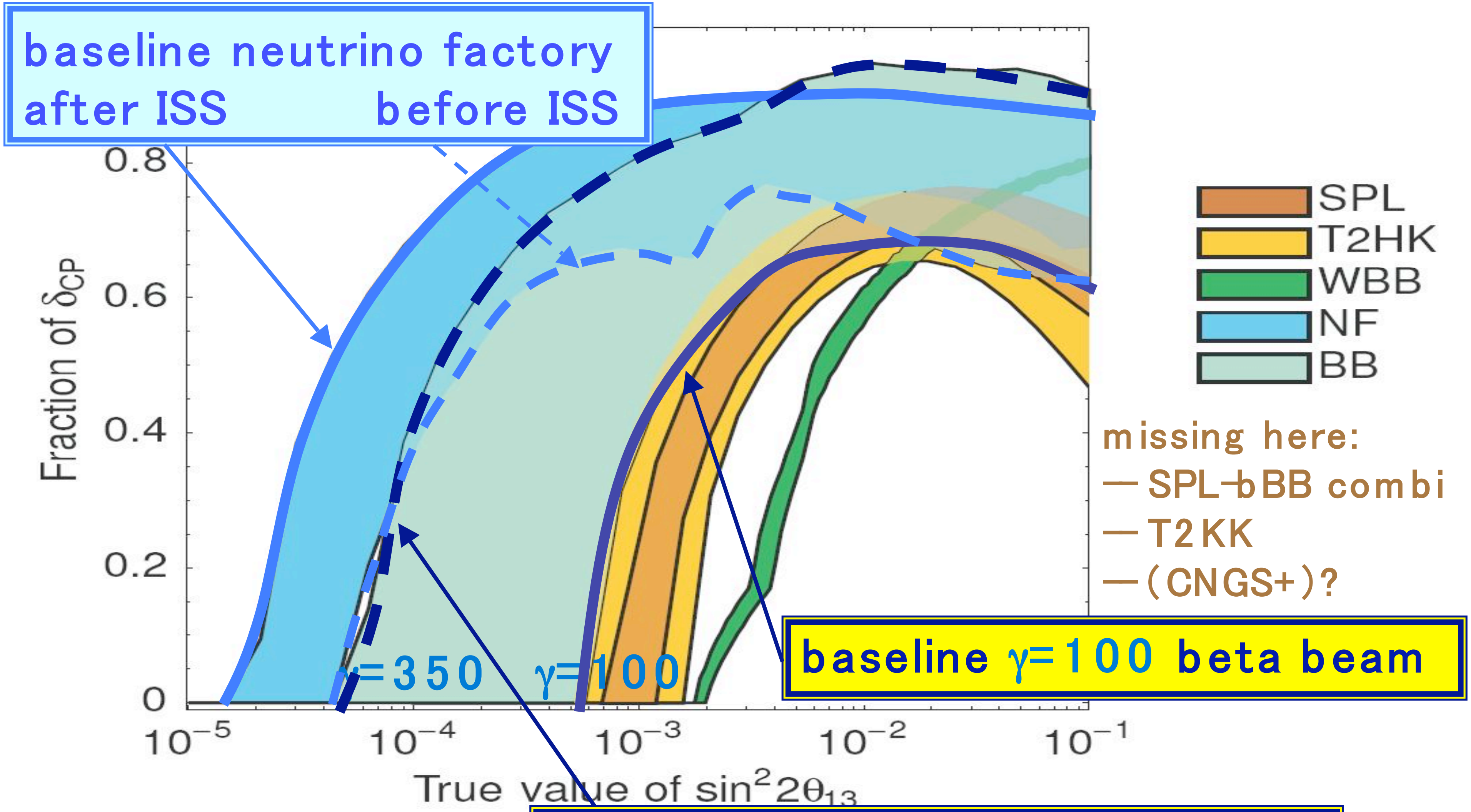
A study was made by

E. Kozlovskaya, J. Peltoniemi, J. Sarkamo,

***The density distribution in the Earth along the CERN-Pyhäsalmi baseline and its effect on neutrino oscillations.* CUPP-07/2003**

→the uncertainties on matter effects are at the level of a few%



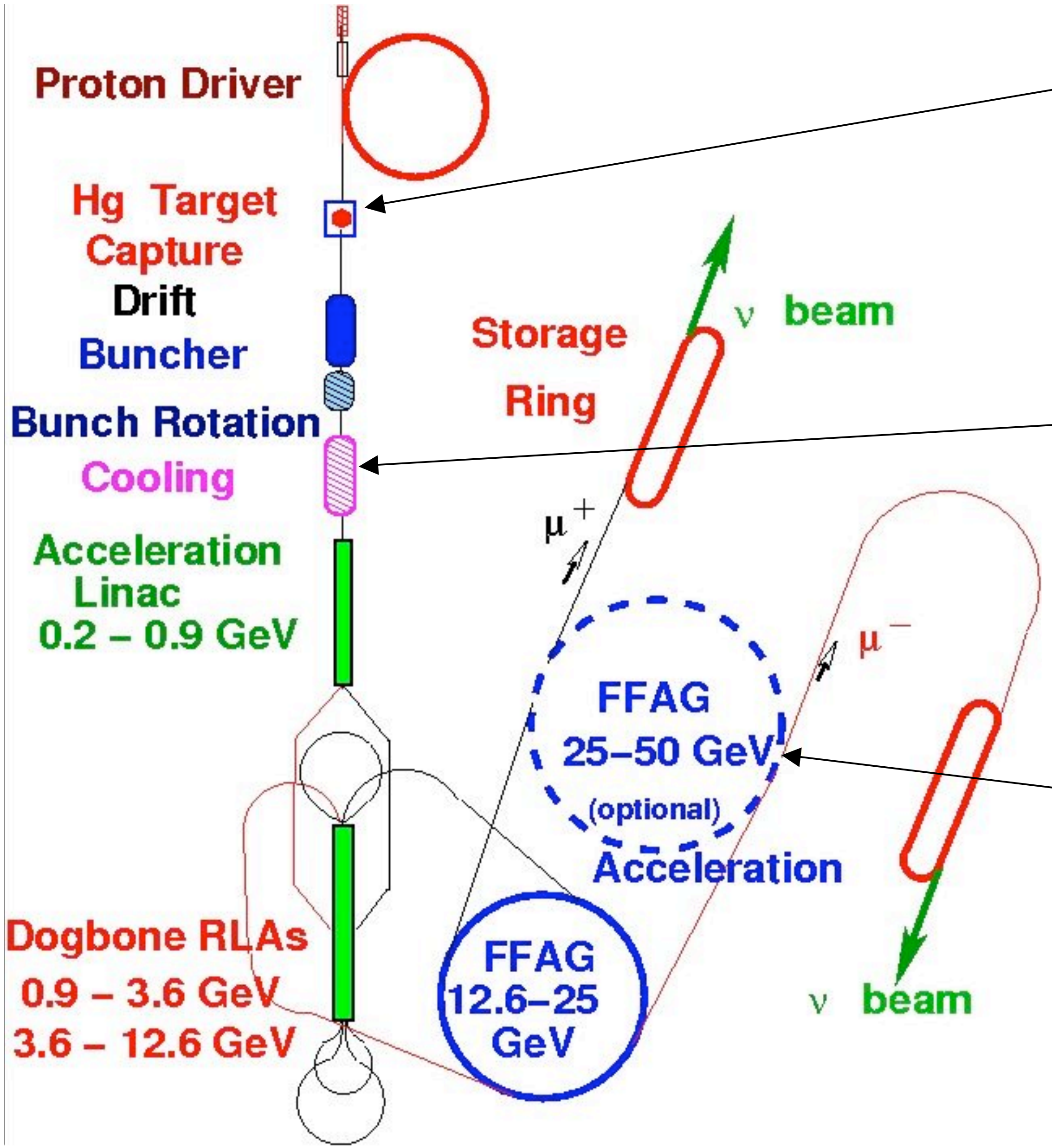


Neutrino factory is the most Powerful device for neutrino CP violation, matter effects, universality, precise measurements of Neutrino mixing parameters

he … he right
excluded at the 3σ confidence level. The discovery limits are shown as a
values of the true value of the CP phase δ ('Fraction of δ_{CP}') and the true
ges of the bands correspond to the conservative set-ups while the left-hand
-ups, as descri…
T2HK as the … as
f the beta-beam is shown as the light green band and the Neutrino Factory
band.

Need to include T2K-'future' in these plots

Major challenges tackled by R&D expts



High-power target
. 4MW
. good transmission
MERIT experiment (CERN)

Fast muon cooling
MICE experiment (RAL)

Fast, large aperture accelerator (FFAG)
EMMA (Daresbury)

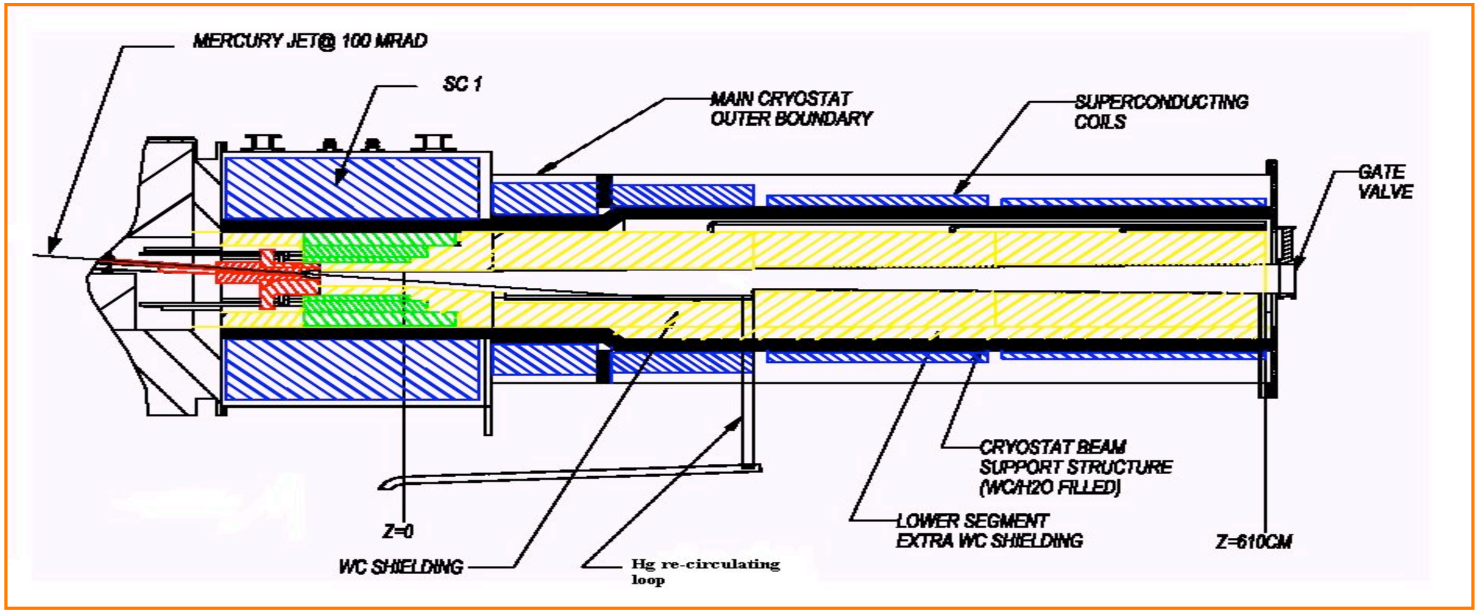
ISS baseline,
(storage rings not to scale)

The Neutrino Factory and Muon Collider target

Solid target systems (graphite, Be, Ta, etc.) limited to ~1MW proton beam

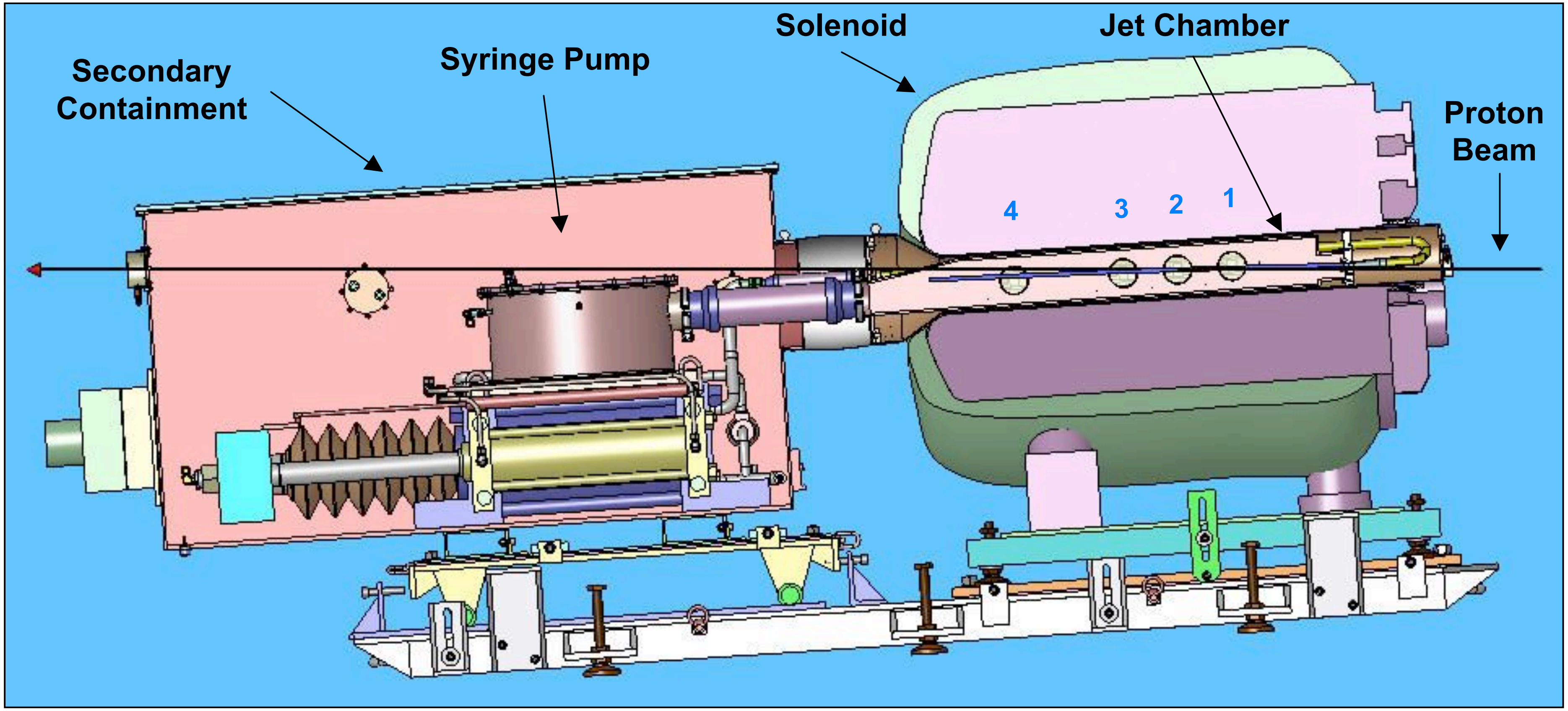
Liquid targets (Hg or PbBi, etc.) avoids beam windows and offers the possibility of re-generation of the target volume at each pulse.

Target must be embedded in magnetic field to collect efficiently secondary particles.



The **MERIT experiment** is designed to validate the liquid target concept

MERIT at CERN (NTOF11)– Experimental setup



The experiment was specially designed to avoid opening the primary container (Hg-wet volume) at CERN

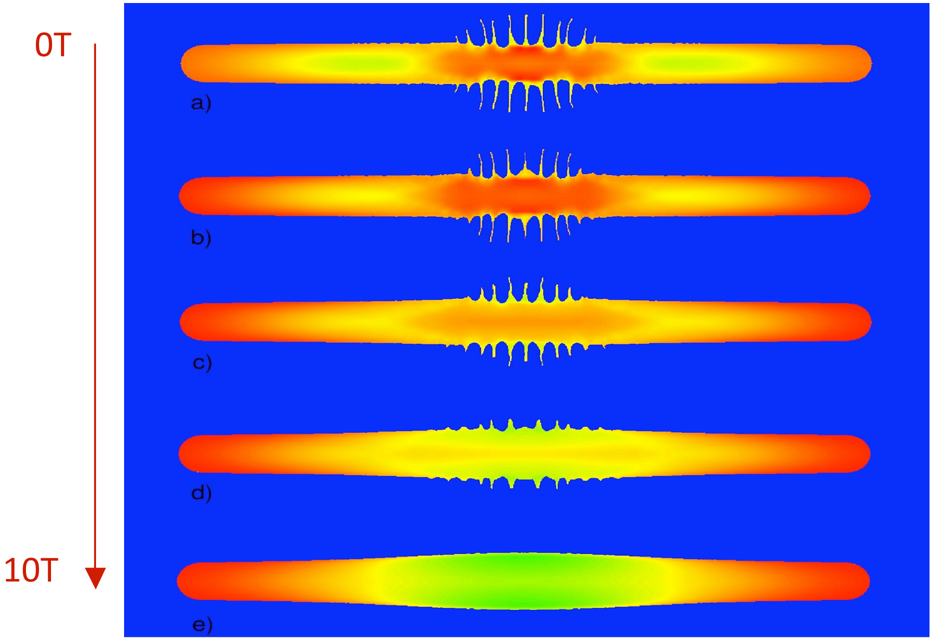
180deg bend in the Hg-delivery piping system upstream; likely cause of deterioration in the quality of the Hg-jet

I.Efthymiopoulos, CERN

MERIT MERcury Intense Target Experiment

Study the impact of an intense proton beam with a free mercury jet, at the presence of high magnetic field

Simulation predicts shrinking of splash with magnetic field



R.Samulyak-BNL

MERIT in the TTA2 beam line:

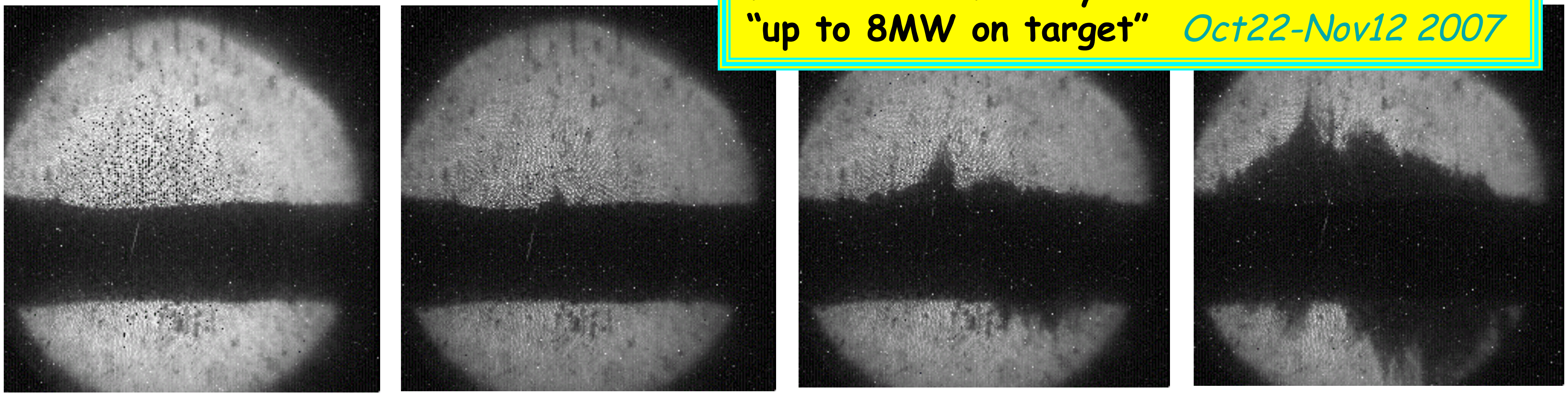
MERIT EXPERIMENT at CERN

BNL, MIT, ORNL, Princeton University CERN, RAL

Splash velocity – 24 GeV beam

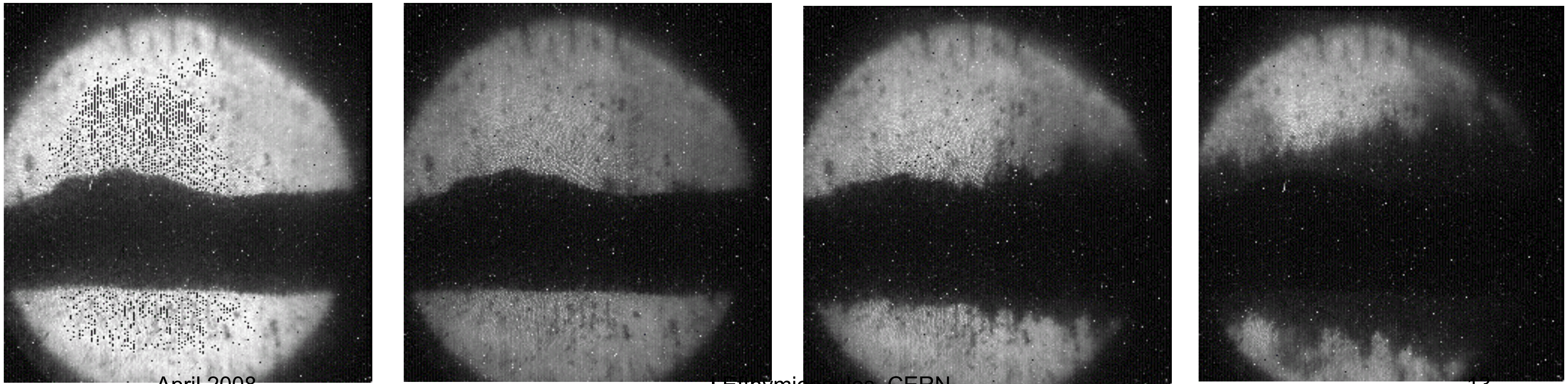
Preliminary conclusion:
demonstrated liquid mercury jet technology for neutrino factory and muon collider "up to 8MW on target" *Oct22-Nov12 2007*

10TP, 10T *V = 54 m/s*



t=0 *t=0.075 ms* *t=0.175 ms* *t=0.375 ms*

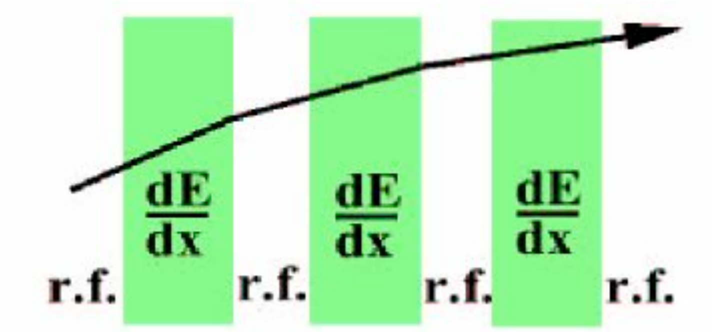
20TP, 15T *V = 65 m/s*



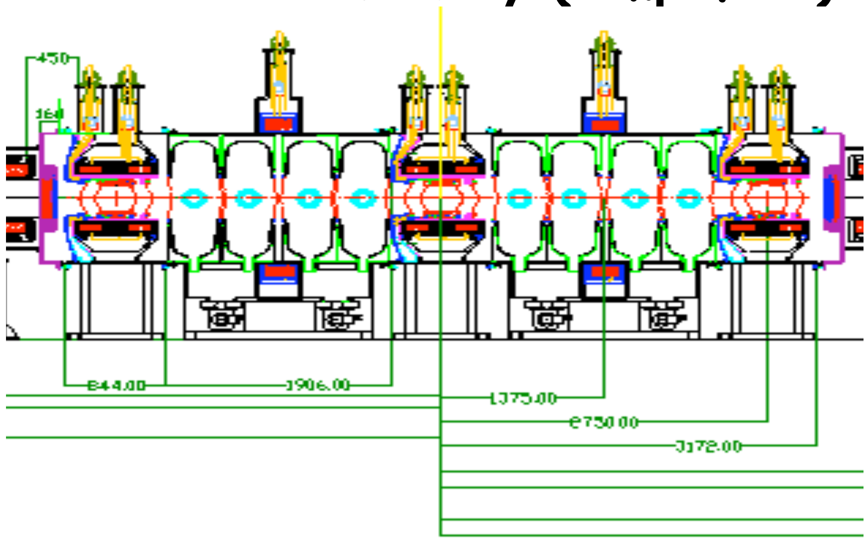
t=0 *t=0.050 ms* *t=0.175 ms* *t=0.375 ms*

IONIZATION COOLING

principle: **reality (simplified)**



this will surely work..!



Front elevation of the Cooling Channel

….maybe…

Cooling is necessary for Neutrino Factory and crucial for Muon Collider.
Delicate technology and integration problem
Need to build a realistic prototype and verify that it works (i.e. cools a beam)

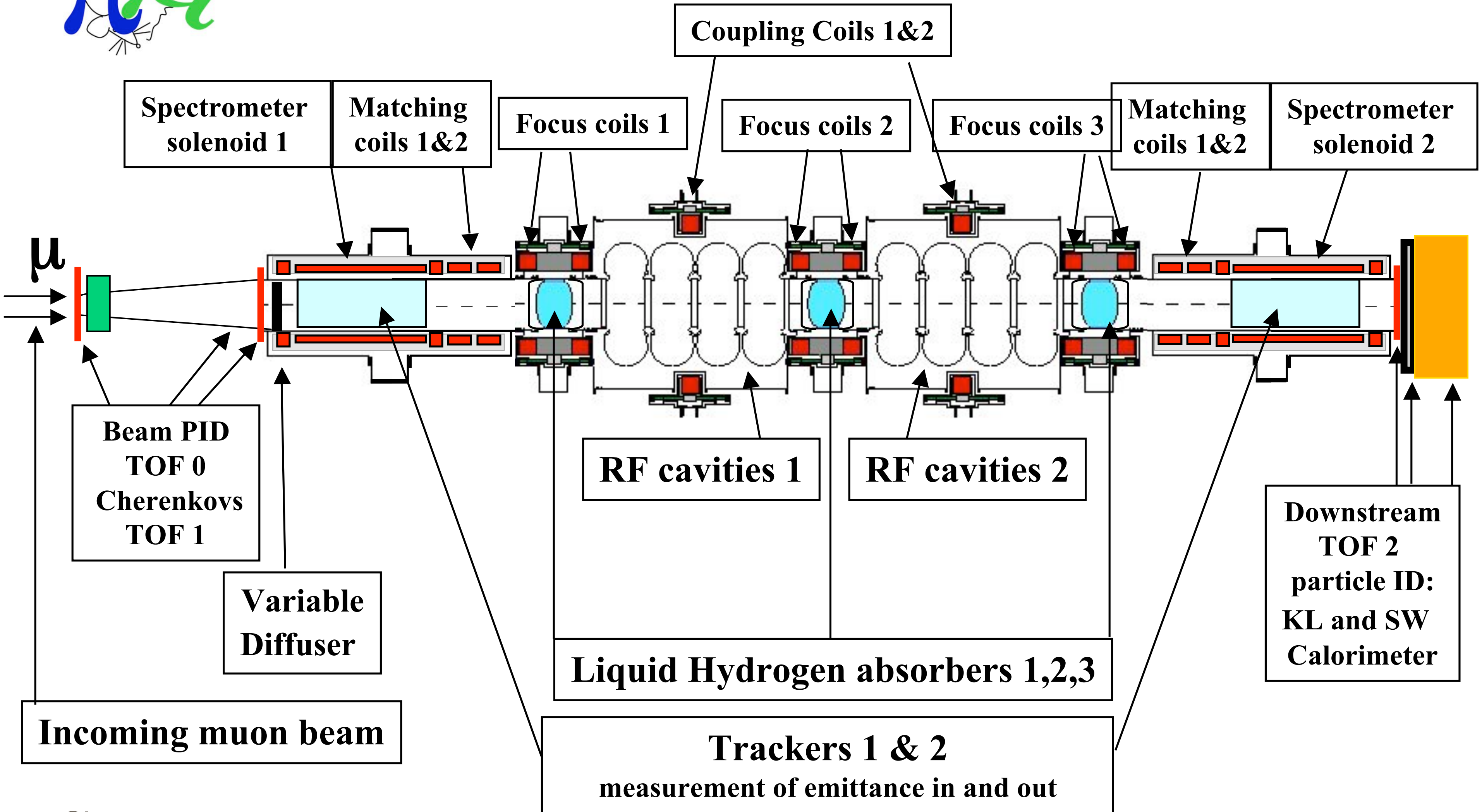
Can it be built? Operate reliably? What performance can one get?
Difficulty: affordable prototype of cooling section only cools beam by 10%, while standard emittance measurements barely achieve this precision.
Solution: measure the beam particle-by-particle

10% cooling of 200 MeV/c muons requires ~ 20 MV of RF

single particle measurements =>

measurement precision can be as good as $\Delta (\varepsilon_{out}/\varepsilon_{in}) = 10^{-3}$

never done before



Cl

Emittance measurement

Each spectrometer measures 6 parameters per particle

$x \quad y \quad t$

$x' = dx/dz = P_x/P_z \qquad y' = dy/dz = P_y/P_z \qquad t' = dt/dz = E/P_z$

Determines, for an ensemble (sample) of N particles, the moments:

Averages $\langle x \rangle$ $\langle y \rangle$ etc…

Second moments: variance(x) $\sigma_x^2 = \langle x^2 - \langle x \rangle^2 \rangle$ etc…

covariance(x) $\sigma_{xy} = \langle x.y - \langle x \rangle \langle y \rangle \rangle$

Covariance matrix

$$M = \begin{pmatrix} \sigma_x^2 & \sigma_{xy} & \sigma_{xt} & \sigma_{xx'} & \sigma_{xy'} & \sigma_{xt'} \\ \cdots & \sigma_y^2 & \cdots & \cdots & \cdots & \sigma_{yt'} \\ \cdots & \cdots & \sigma_t^2 & \cdots & \cdots & \sigma_{tt'} \\ \cdots & \cdots & \cdots & \sigma_{x'}^2 & \cdots & \sigma_{x't'} \\ \cdots & \cdots & \cdots & \cdots & \sigma_{y'}^2 & \sigma_{y't'} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \sigma_{t'}^2 \end{pmatrix}$$

Getting at e.g. $\sigma_{x't'}$ is essentially impossible with multiparticle bunch measurements

Evaluate emittance with:

$$\varepsilon^{6D} = \sqrt{\det(M_{xytx'y't'})}$$

$$\varepsilon^{4D} = \sqrt{\det(M_{xyx'y'})} = \varepsilon_\perp^2$$

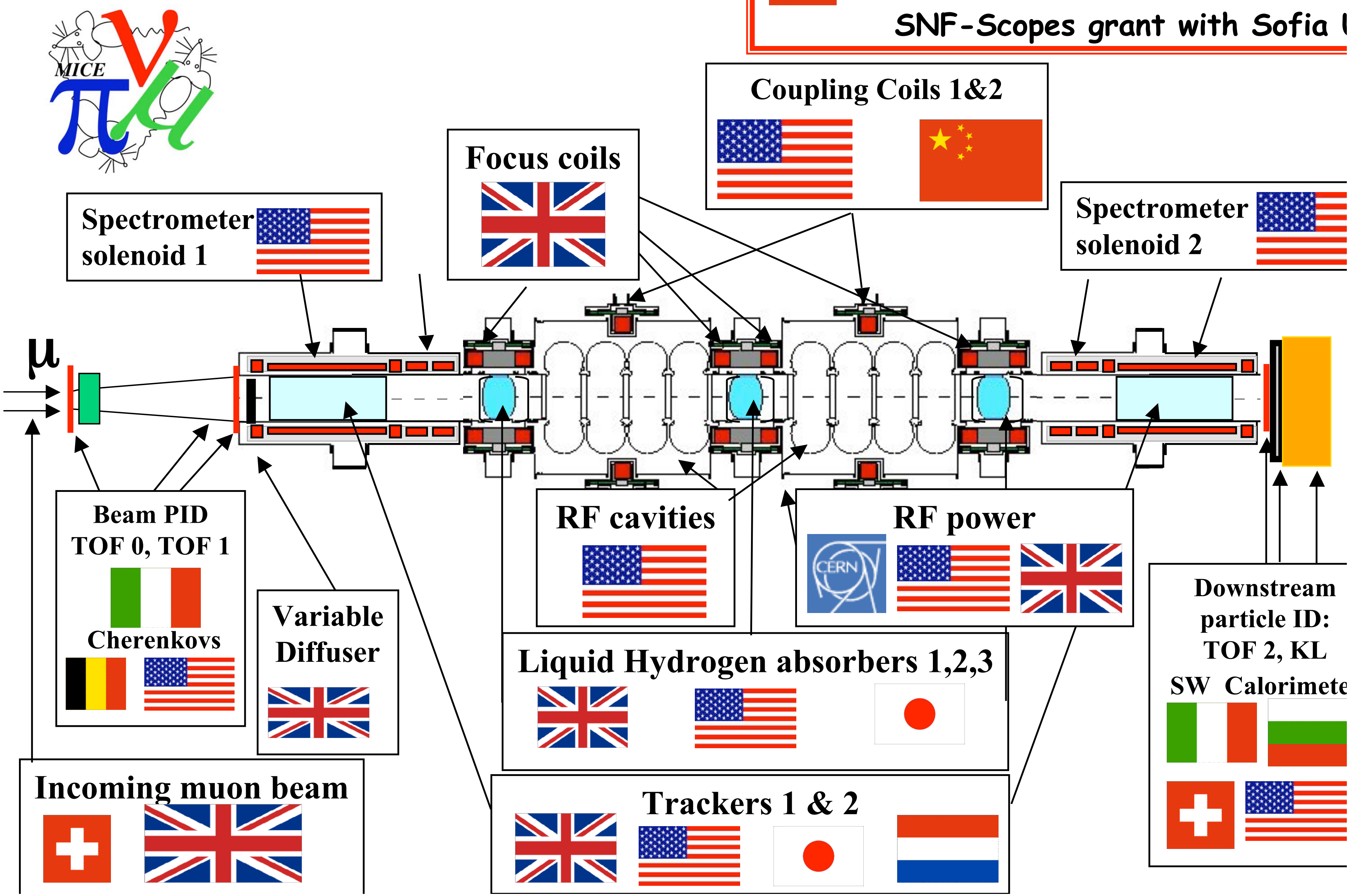
Compare ε^{in} with ε^{out}

MICE Collaboration across the planet

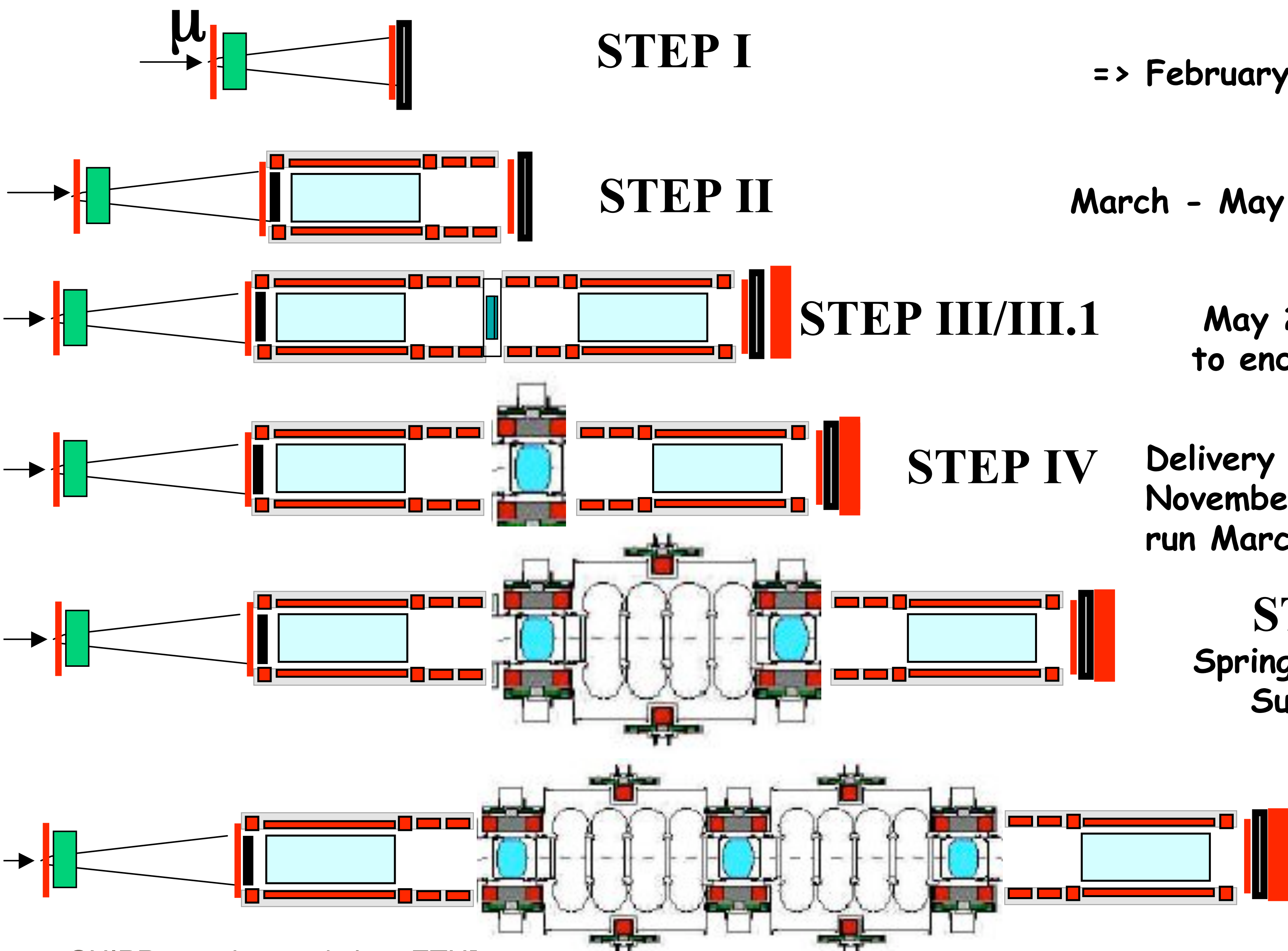
PSI: decay solenoid

GVA: s-mouse, DAQ, soft, SW

SNF-Scopes grant with Sofia



Aspirational MICE Schedule (as of October 2008)



STEP I => February 2009

STEP II March - May 2009

STEP III/III.1 May 2009 to end 2009

STEP IV Delivery of 1st FC November 2009 run March 2010

STEP V Spring - Summer 2010

STEP VI Q4 2010 -2011

Towards a high-intensity neutrino programme

EP2010:

« pursue an internationally coordinated, staged program in neutrino physics »

CERN-SG:

Studies of the scientific case for future neutrino facilities and the R&D into associated technologies are required to be in a position to define the optimal neutrino programme based on the information available in around **2012;** *Council will play an active role in promoting a coordinated European participation in a global neutrino programme.*

Challenges of MICE:

(these things have never been done before)

1. Operate RF cavities of relatively low frequency (201 MHz) at high gradient (nominal 8MV/m in MICE, 16 MV/m with 8 MW and LN2 cooled RF cavities) in highly inhomogeneous magnetic fields (1-3 T)
   dark currents (can heat up LH_2), breakdowns

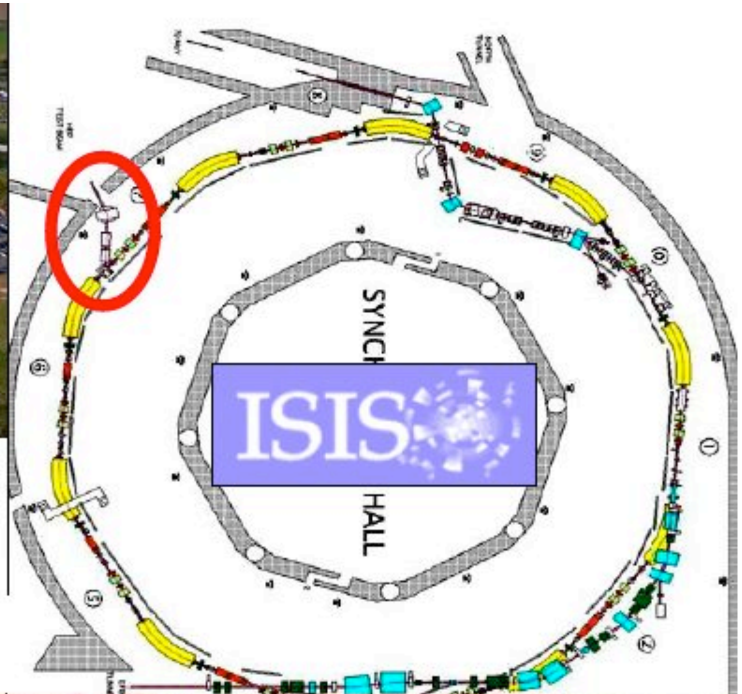
2. Hydrogen safety (substantial amounts of LH_2 in vicinity of RF cavities)

3. Emittance measurement to relative precision of 10^{-3} in environment of RF bkg
   requires
   low mass (low multiple scattering) and precise tracker
   fast and redundant to fight dark-current-induced background
   precision Time-of-Flight for particle phase determination (±3.6^0 = 50 ps)
   complete set of PID detectors to eliminate beam pions and decay electrons

and…

4. Obtaining (substantial) funding for R&D towards a facility that is not (yet) in the plans of a major lab


ISIS
MICE Hall
R5.2

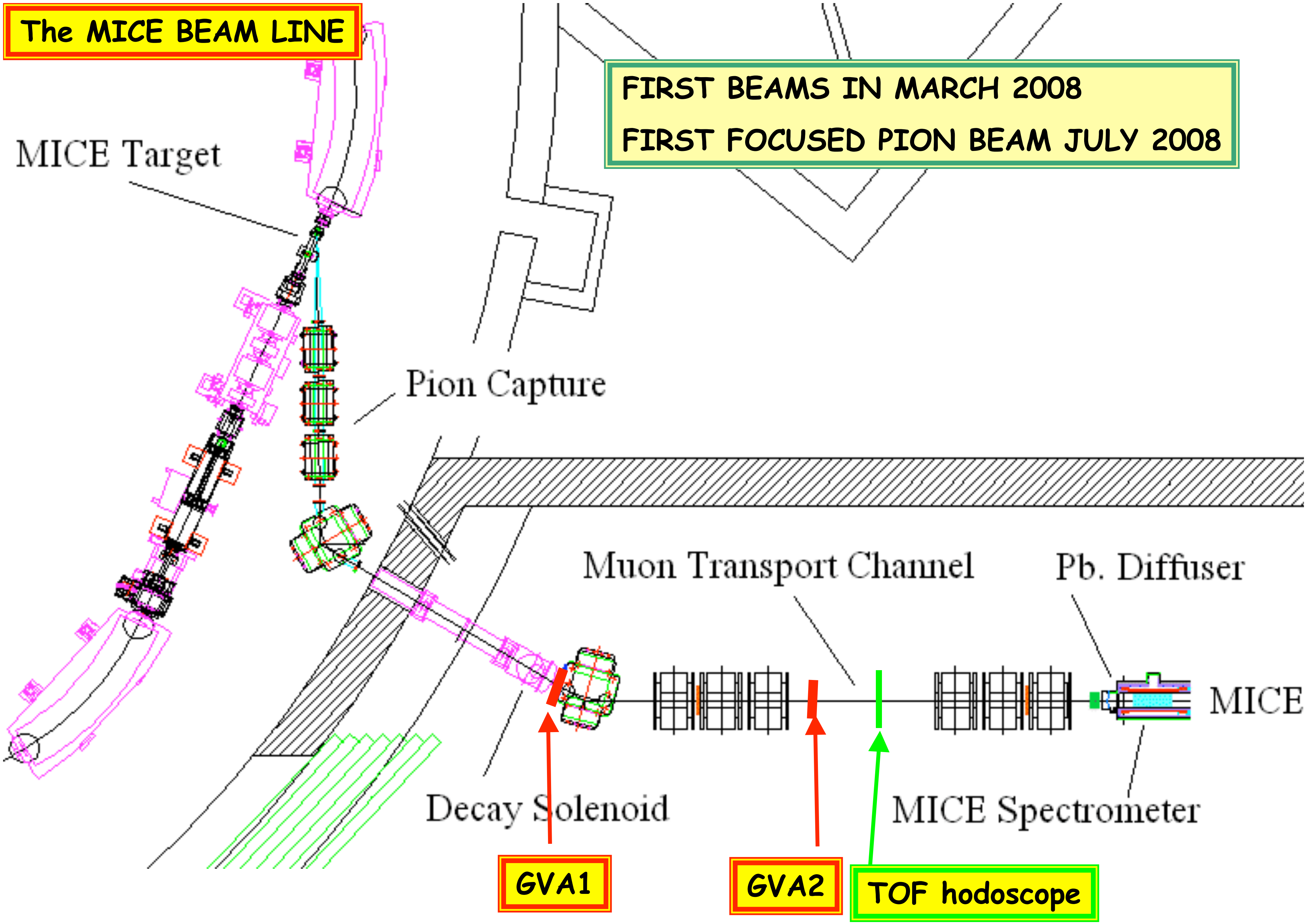


- **MICE is hosted at Rutherford Appleton Laboratory, UK**
  - Brand new muon beam line in construction
  - Built from scratch

The MICE BEAM LINE

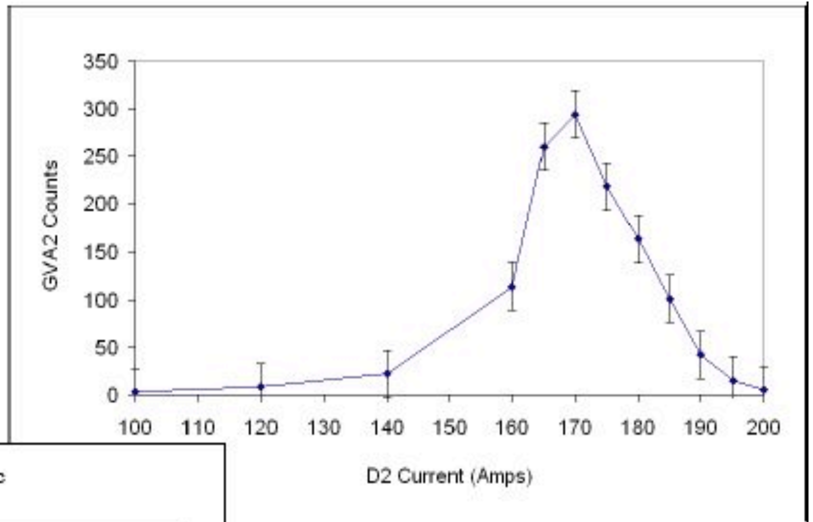
FIRST BEAMS IN MARCH 2008

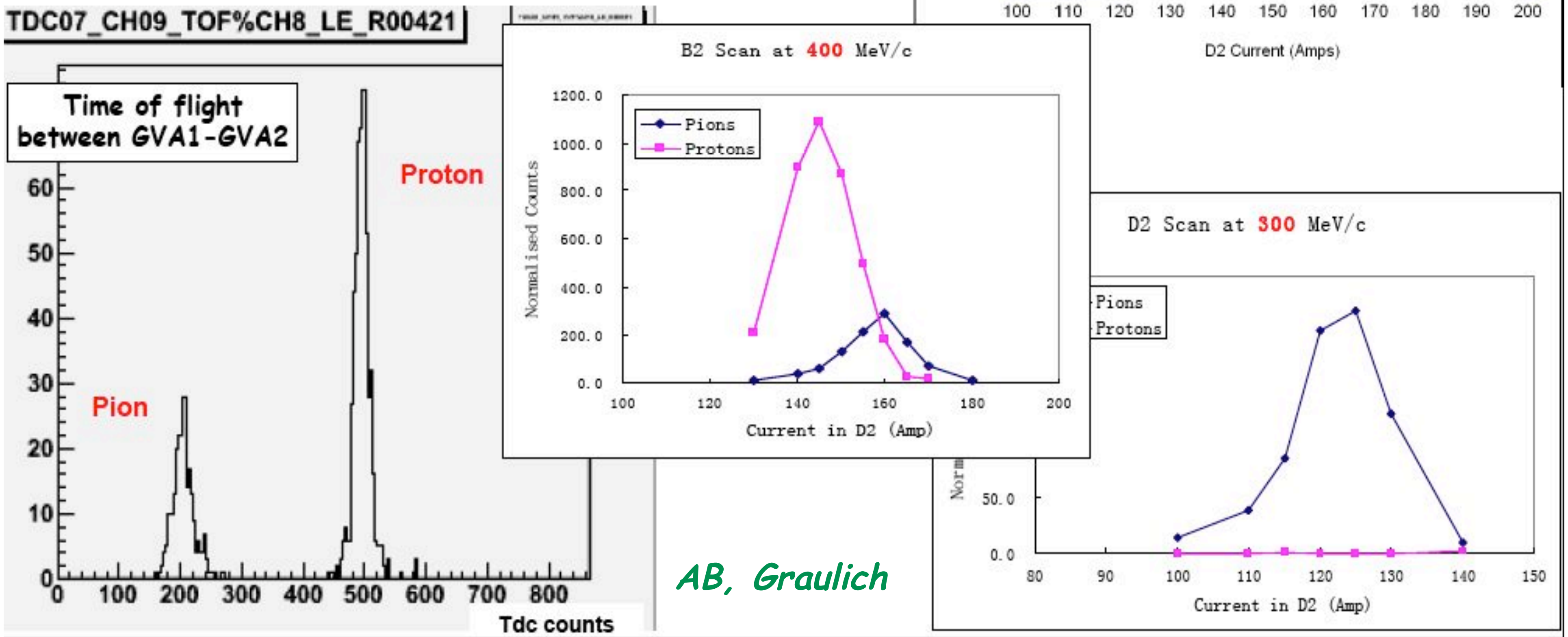
FIRST FOCUSED PION BEAM JULY 2008

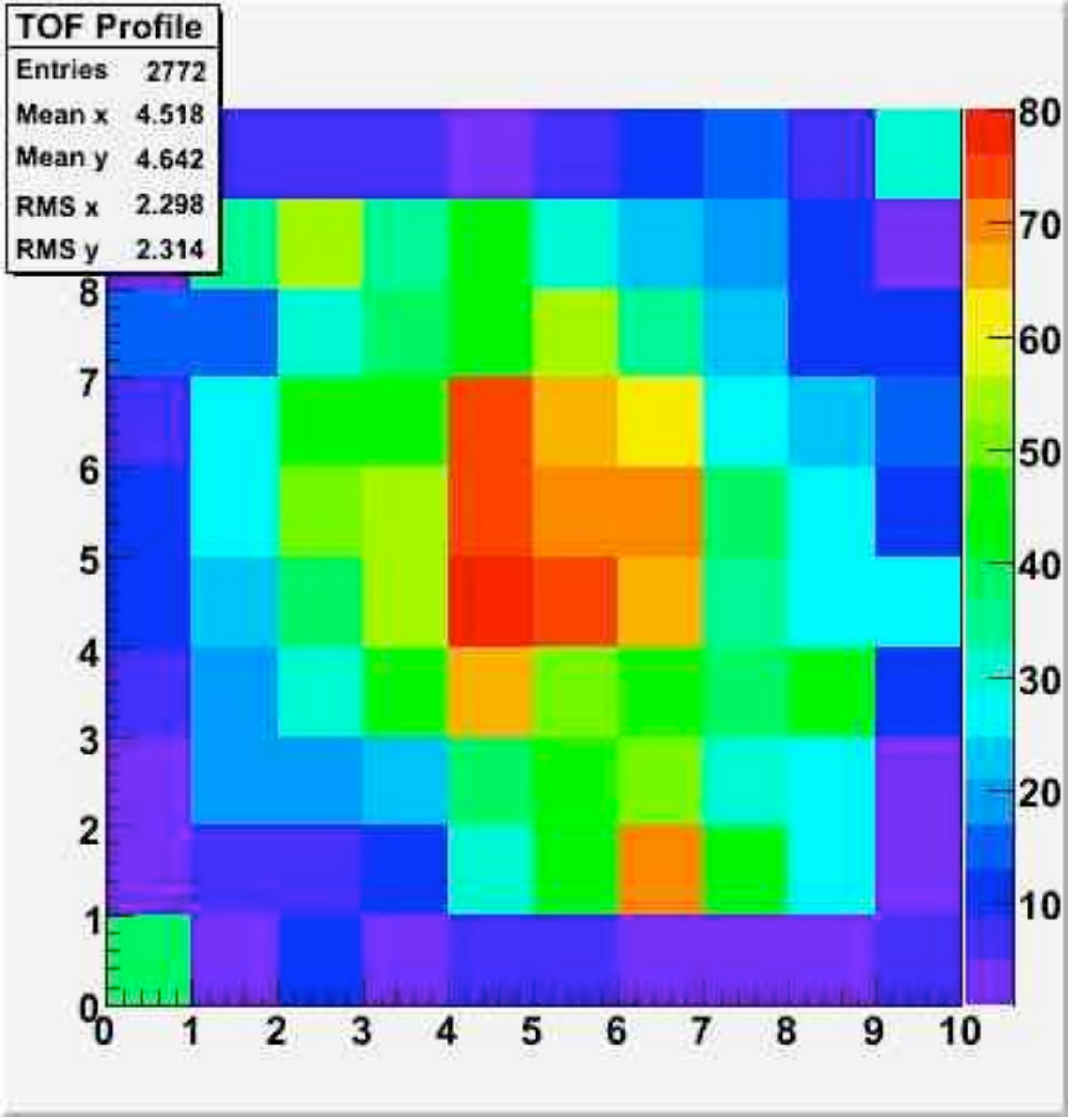


Beam tuning still going on:

- The dipoles behave like expected
- We can separate pions from protons using time of flight between GVA1 and GVA2
- Protons and pions have different momenta when they reach D2
  - Different dE/dX
- Protons at 300 MeV/c are stopped before GVA2







Beam after Q6

With all quads on.

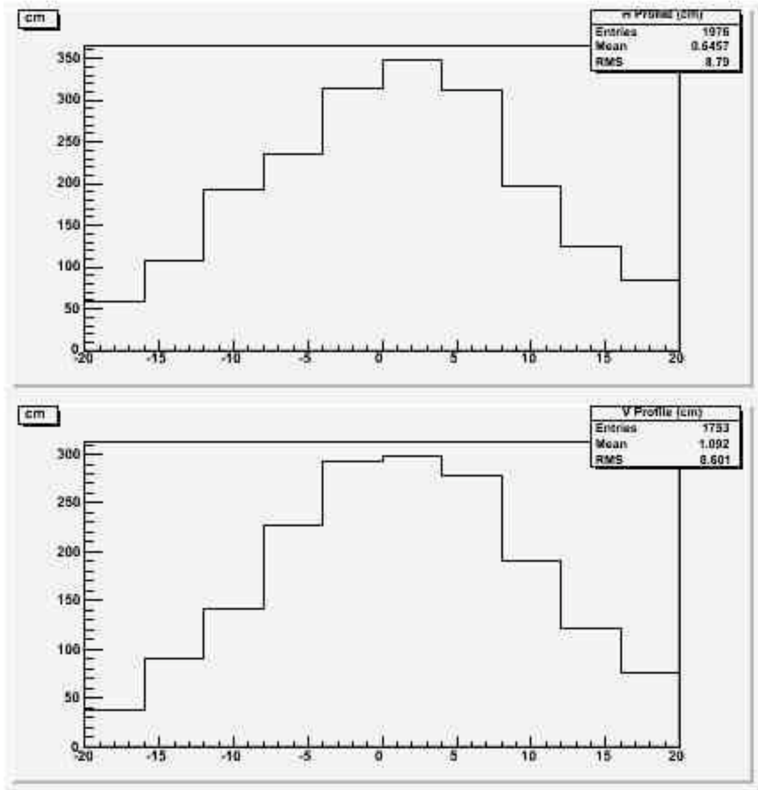
350 MeV/c

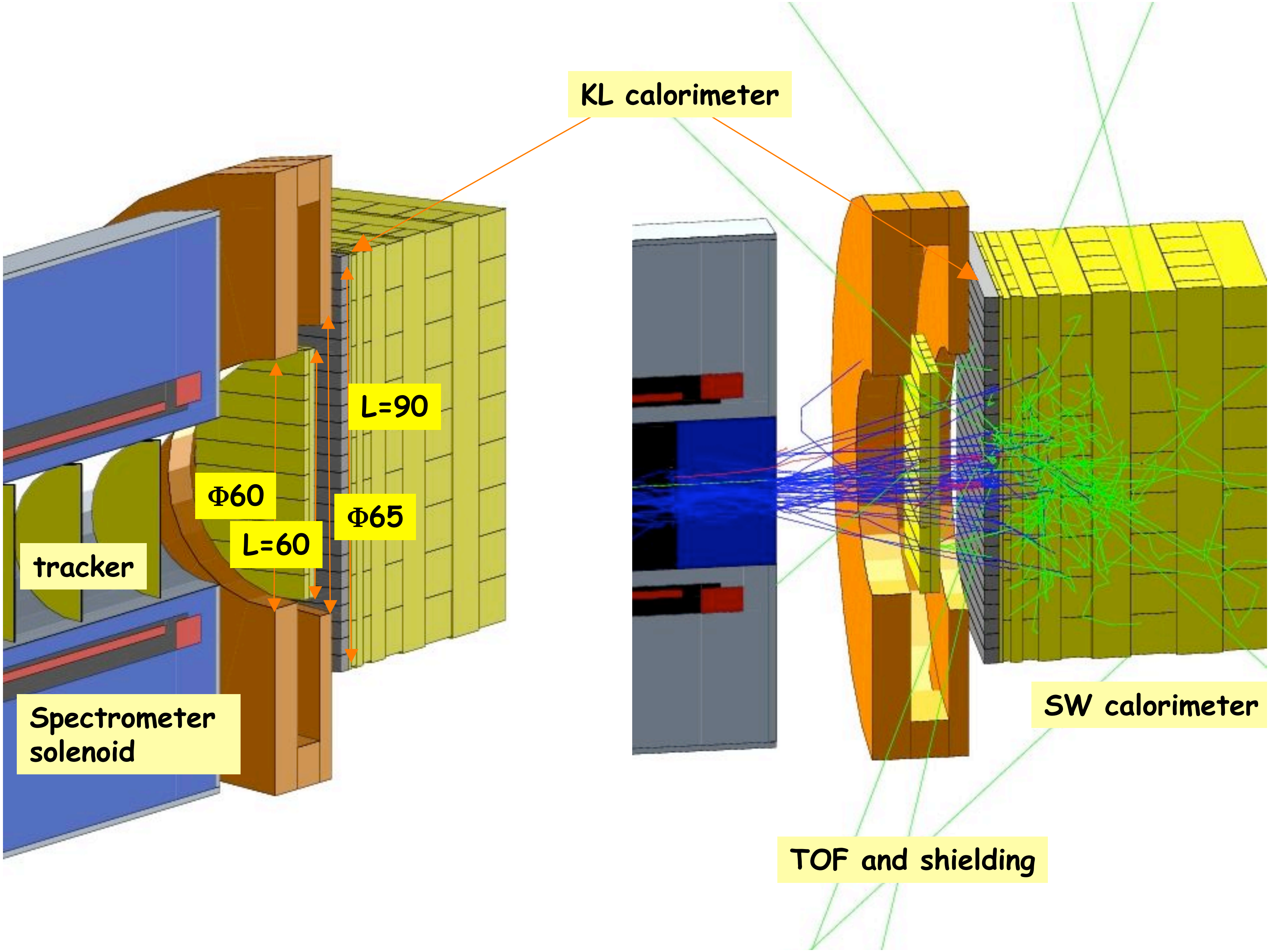
<-- 2D profile

x and y profiles

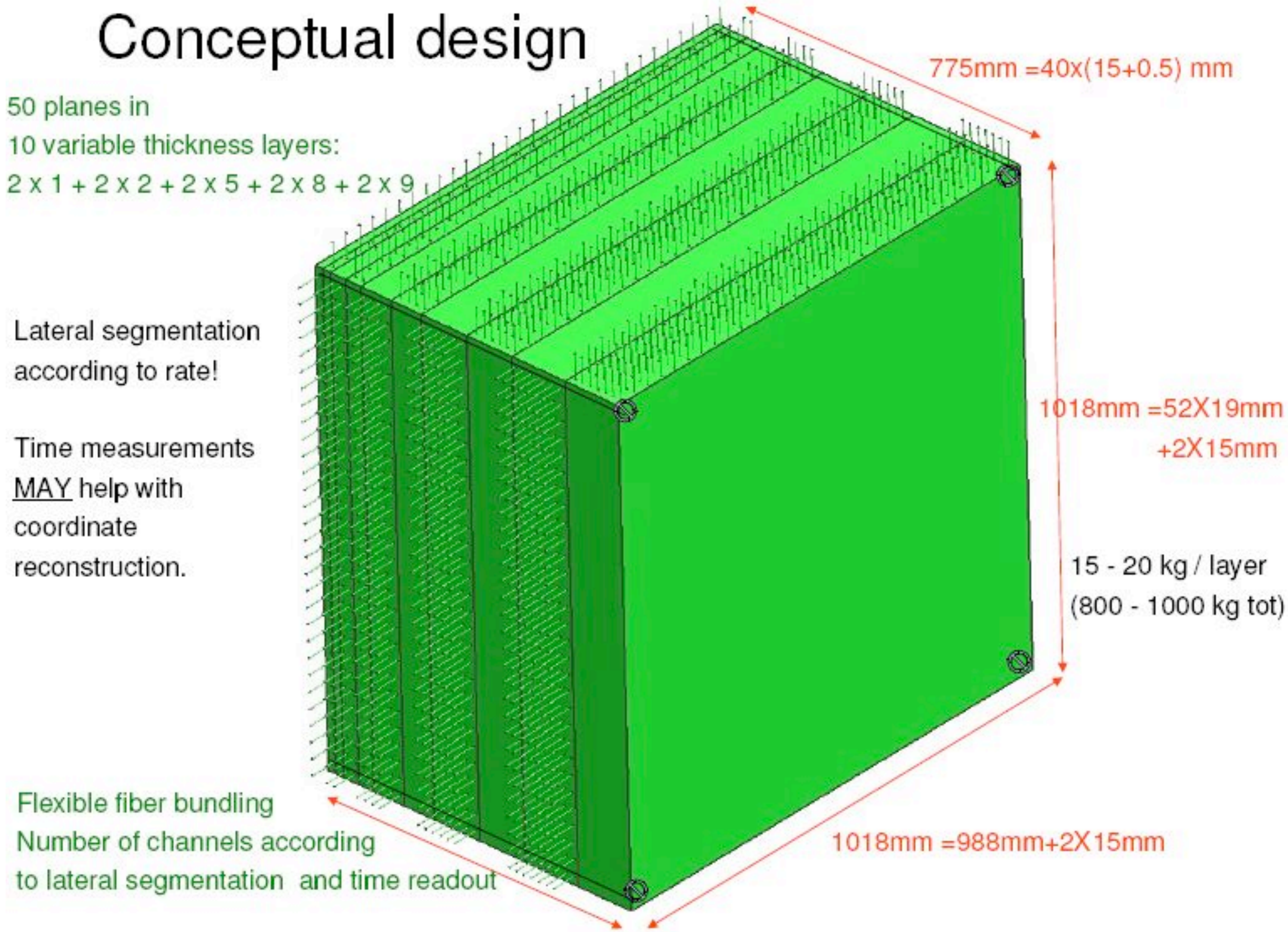
!

V

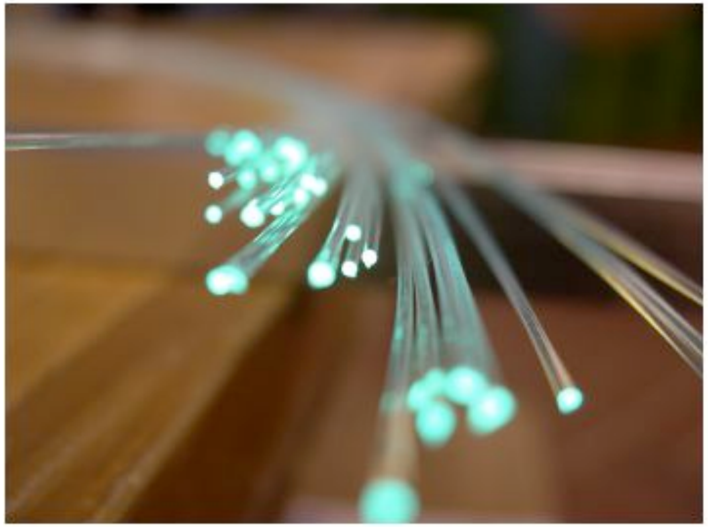


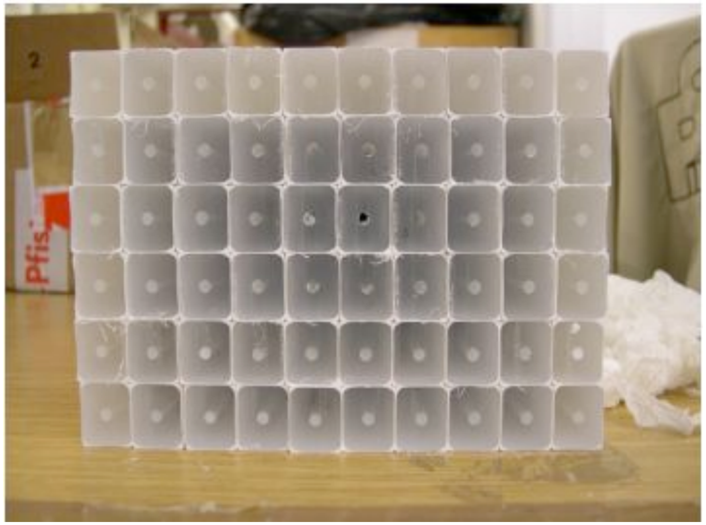

KL calorimeter
L=90
Φ60
Φ65
L=60
tracker
Spectrometer
solenoid
SW calorimeter
TOF and shielding

SW calorimeter

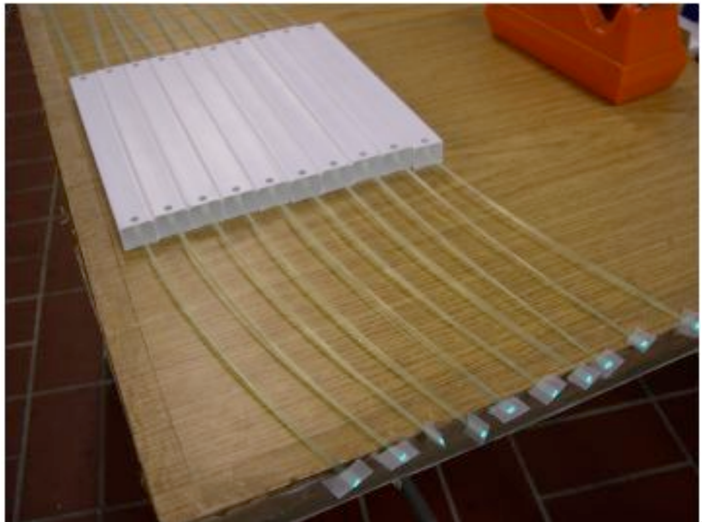


Graulich, Sandström



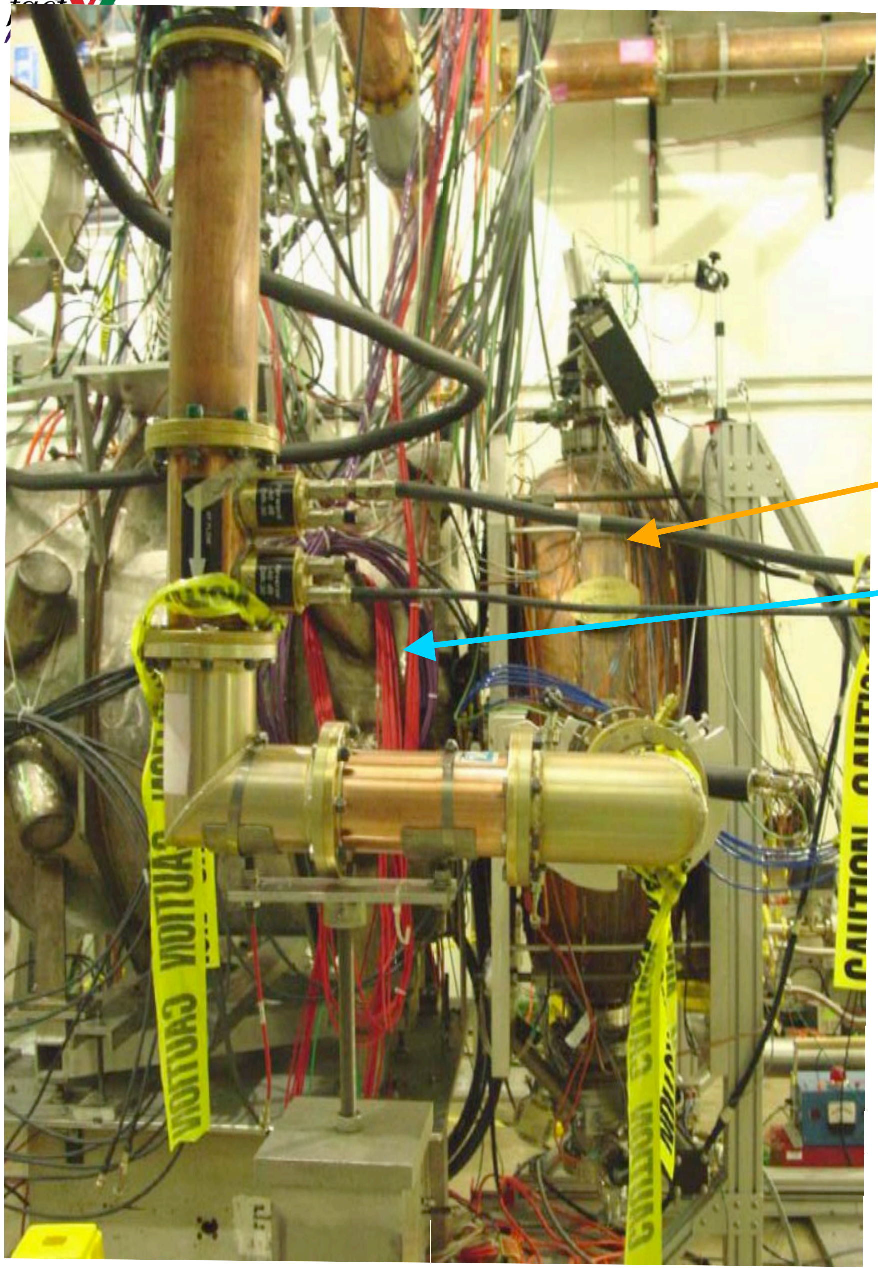


Extrusion provided by Fermilab and mechanical assembly, gluing etc. at INFN Trieste
Electronics and DAQ in Geneva estimated cost 120kCHF



Essential for full precision (10^{-3}) of the experiment over full momentum range

Similar technologies to MINERvA, T2K FGD and P0D



The crucial technological issue:

Field emission by RF cavities in mag. field.

Tests at Fermilab.

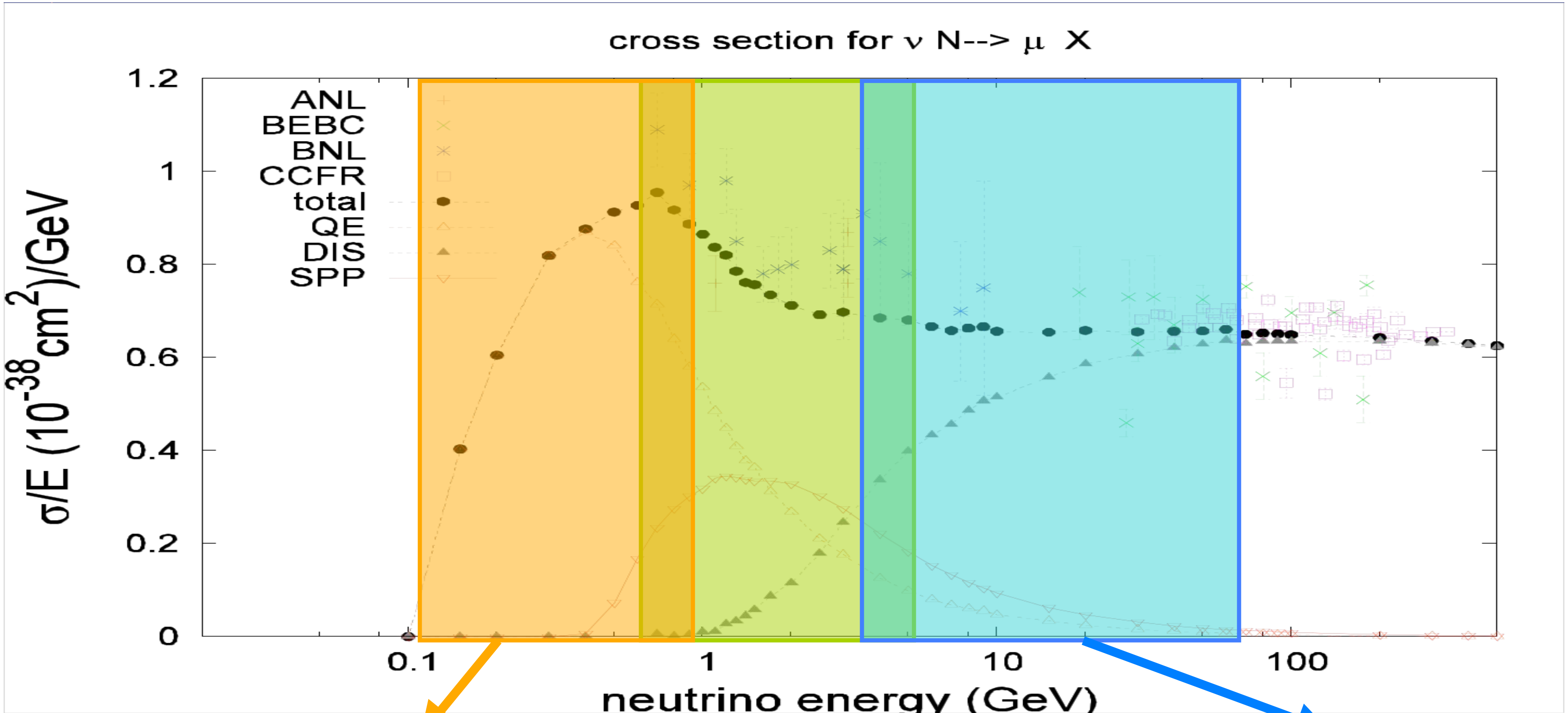
Simulations R. Sandstroem GVA

201 MHz RF cavity (MICE prototype)

SC magnet --> 0.5 T at RF cavity

Cavity reaches 19 MV/m at B=0 without break downs

So far no evidence for strong field emission with 0.5 T.
Next year:
3 T MICE magnet around cavity



Low energy region:
QE dominates

Low energy super beam
(T2K, T2HK, T2KK, Frejus)
Low energy beta-beam
(CERN baseline scenario)

WATER CHERENKOV (Mton)

Mid-energy region:
QE+ 1π + nπ

Super beam
(Numi off, T2KK, CNGS+)
high Energy beta-beam
(CERN highQ or SPS+)

WATER CHERENKOV (Mton)
TASD (NOvA), Larg TPC

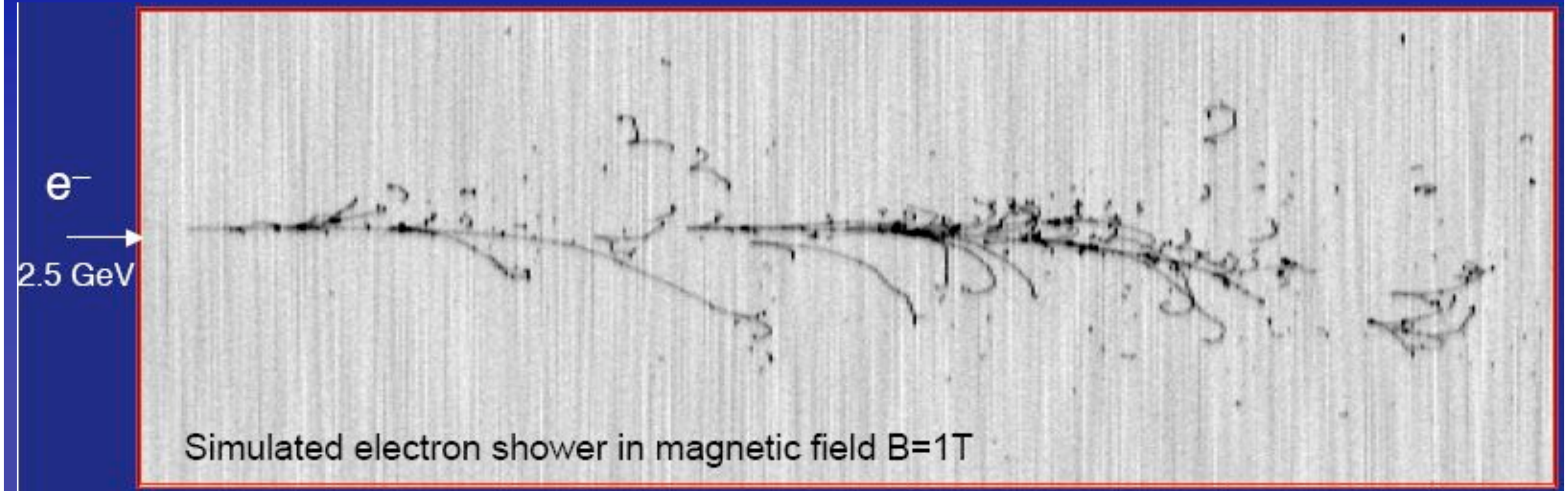
High-energy region:
DIS

Neutrino Factory

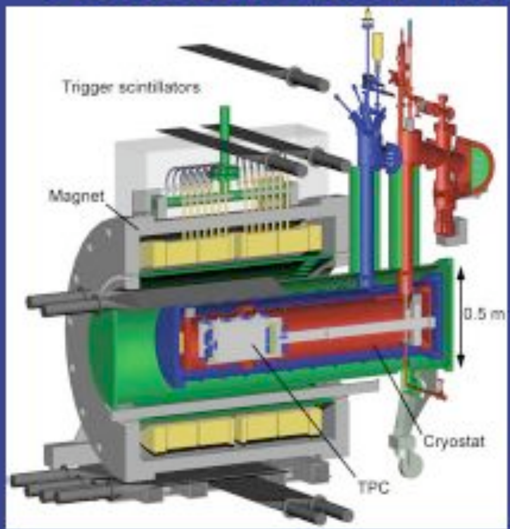
Magnetized Iron
Emulsion

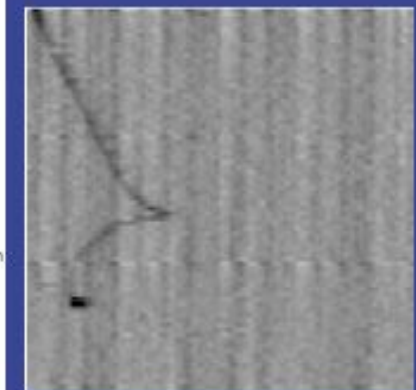
large magnet around:
emulsion, TASD, Larg

A superconducting magnetized LAr TPC detector



First real events in B-field (B=0.55T):





Required field for 3σ charge discrimination:

x=track length

λ=pitch angle

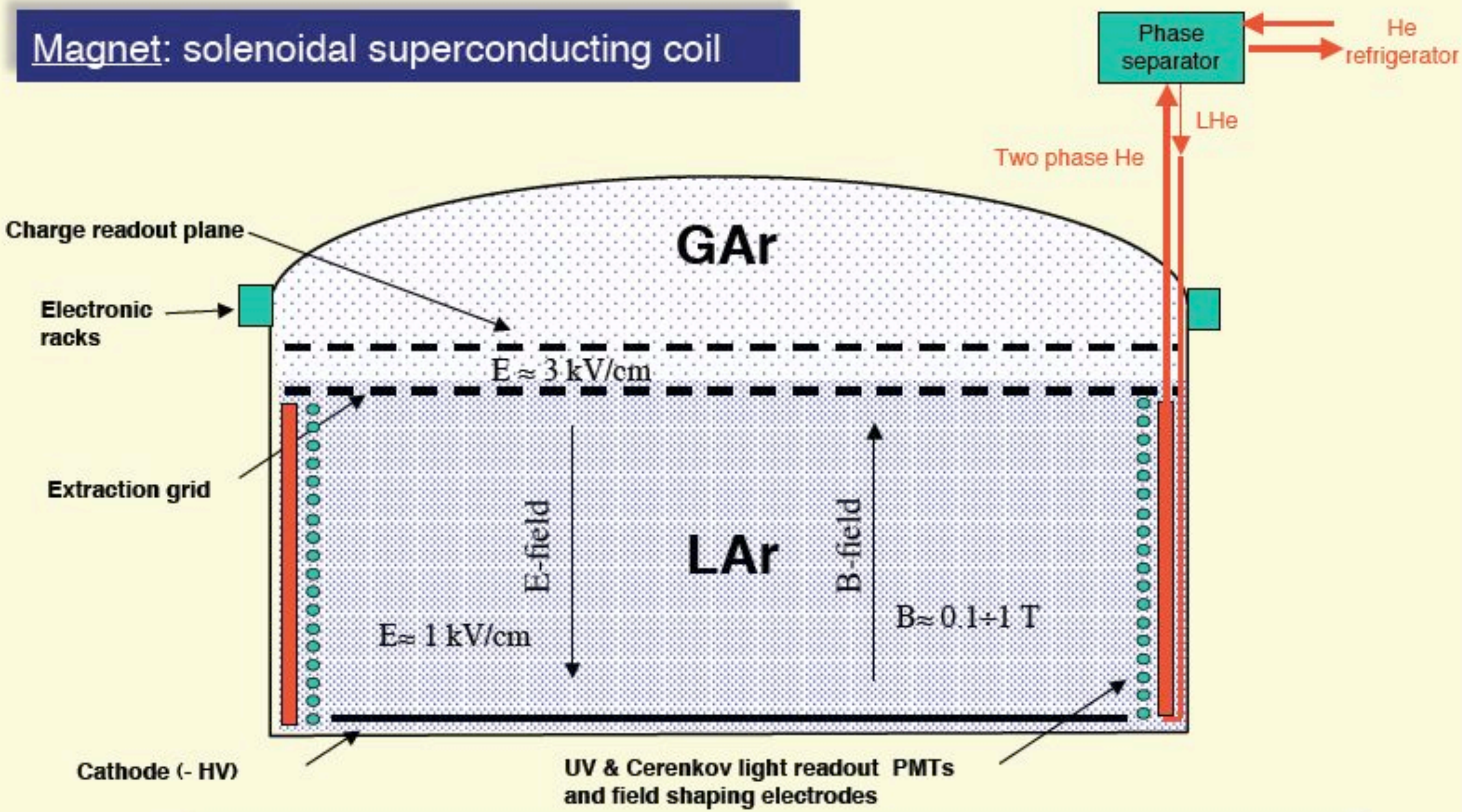
$$B \geq \frac{0.2\,(Tesla)}{\sqrt{x(m)\,\cos^3\lambda}}$$

x ~ a few X0=14cm….

B > 0.5 T

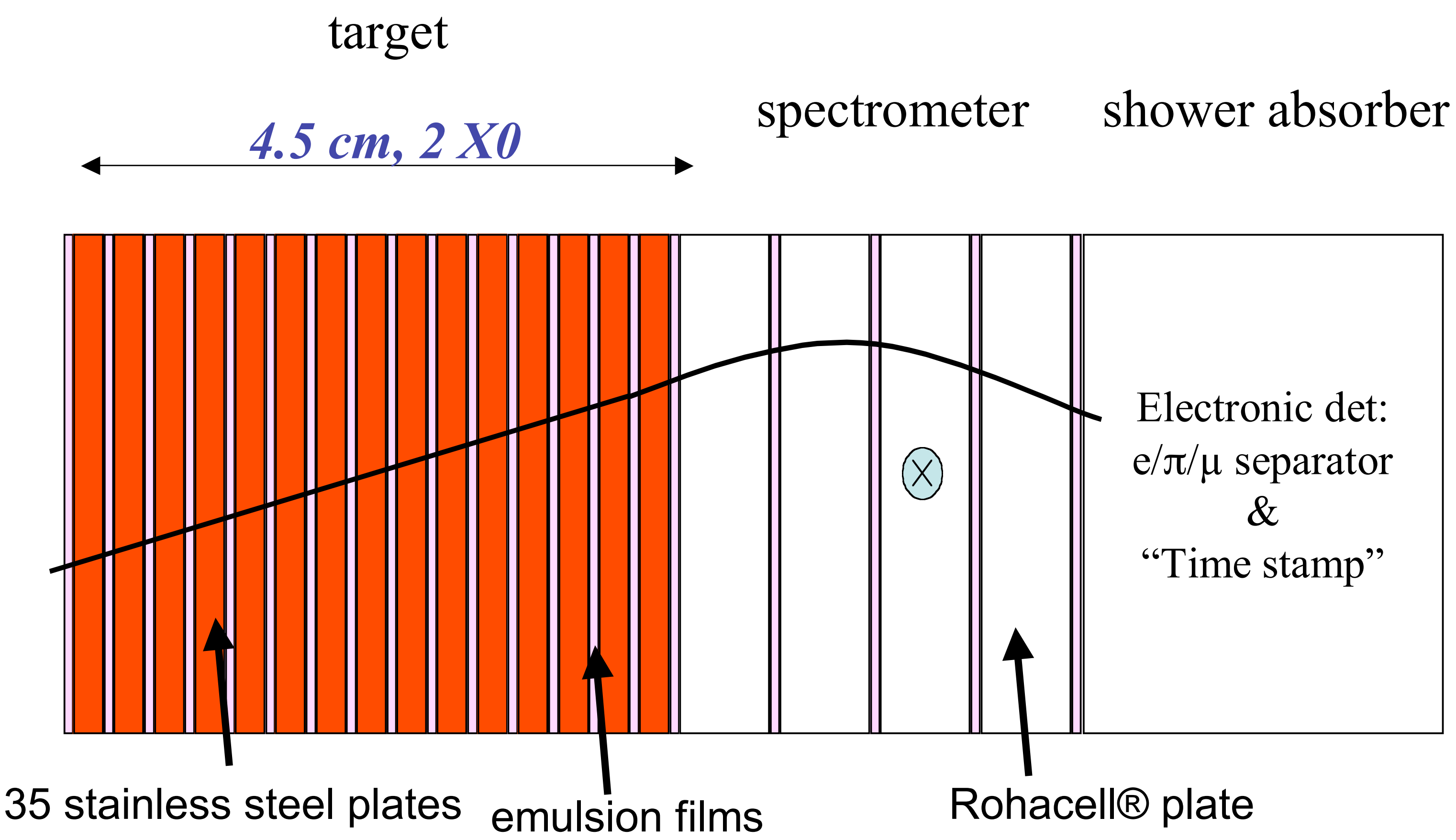
Tentative layout of a large magnetized GLACIER

Magnet: solenoidal superconducting coil



LHe Cooling: Thermosiphon principle + thermal shield=LAr

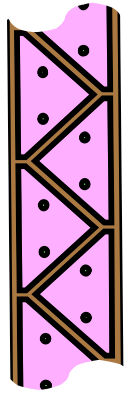
Magnetized ECC structure

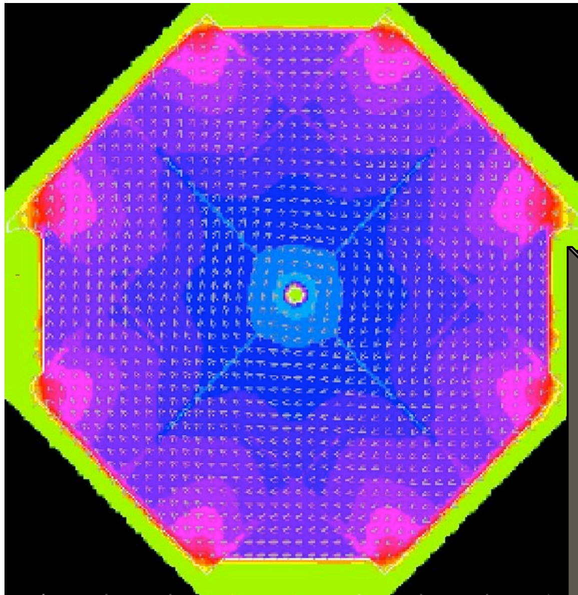


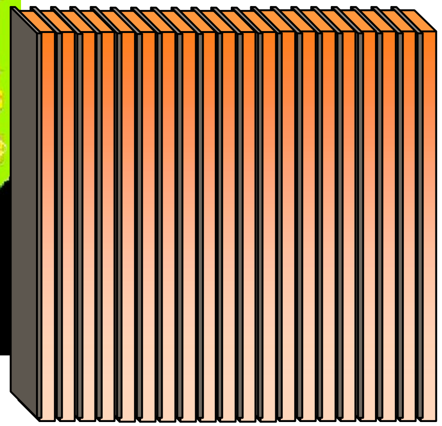
We have focused on the "target + spectrometer" optimization

Magnetized Iron calorimeter

(baseline detector, Cervera, Nelson)
B = 1.5 T Φ = 15 m, L = 25 m
t(iron) =4cm, t(sc)=1cm
Fiducial mass = 100 kT
Charge discrimination down to 1 GeV
very similar to MINOS/NOvA/ND280
example. detector:
sci. fi. detector with multipixel APD readout







Event rates for 10^{21} muon decays for 50 GeV beam

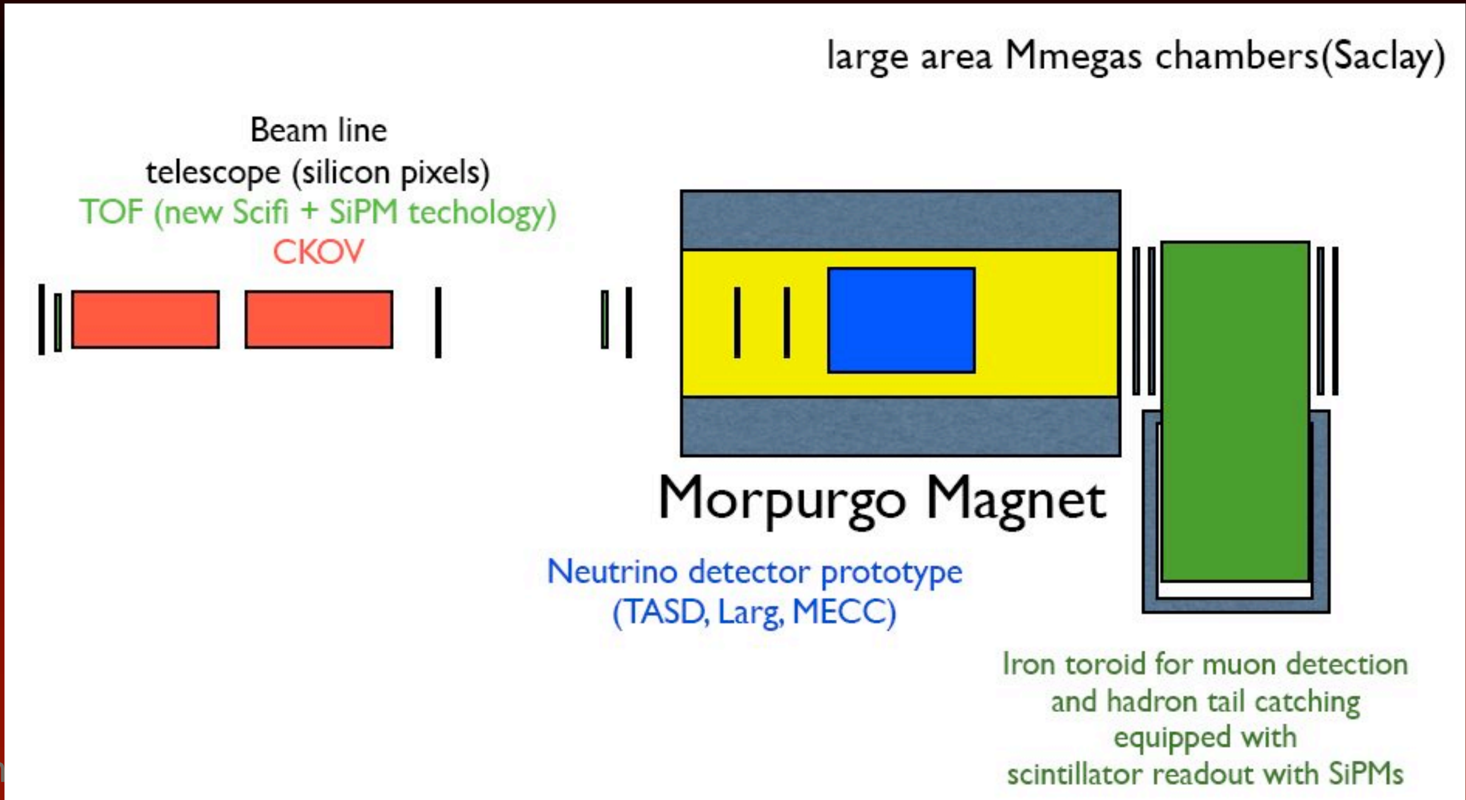
Baseline	$\bar{\nu}_\mu$ CC	ν_e CC	ν_μ signal ($\sin^2 \theta_{13}$=0.01)	
732 Km	10^9	2×10^9	3.4×10^5	(J-PARC I→ SK = 40)
3500 Km	4×10^7	7.5×10^7	3×10^5	

NEUTRINO DETECTOR TEST BEAM

Originally proposed for 'Devdet' detector development in synergy with LHC upgrade and linear collider.

Answer key experimental questions on detectors for future neutrino beams

ex:
- . charge confusion for low energy muons in iron-scintillator sandwich.
- . properties of stopping pions and muons in Liquid Argon and Water
- . Integration of emulsions/Larg/TASD with magnetized iron spectrometer (Hybrid detector)



CONCLUSIONS

Neutrino Factory (and Muon Collider) are challenging machines and require both proof of principle and demonstration experiments and design study/cost evaluation.

MERIT at CERN has demonstrated the validity of the heavy liquid technology for high power targets

MICE is progressing towards demonstration of ionization cooling by 2010/2011.

EMMA is approved in UK for study of non scaling FFAG principle with electrons

By 2012 the feasibility issues of neutrino factory should be clarified and issues of cost and physics optimization (and scientific strategy) can be addressed.

Detectors for future neutrino beams have been charted.
A number of open questions require test beam activity which is extremely well suited at CERN. Lets do it.

Beyond PHASEII -- Ideas for « Phase III »

ONCE PHASEII will be completed, having equipped the MICE hall with
-- spectrometers, TOF and PID able to measure emittance to 10^{-3}
-- 8 MW of 201MHz RF power
-- 23 MV of RF acceleration
-- Liquid Hydrogen infrastructure and safety

MICE can become a facility to test new cooling ideas.

Such ideas were proposed:

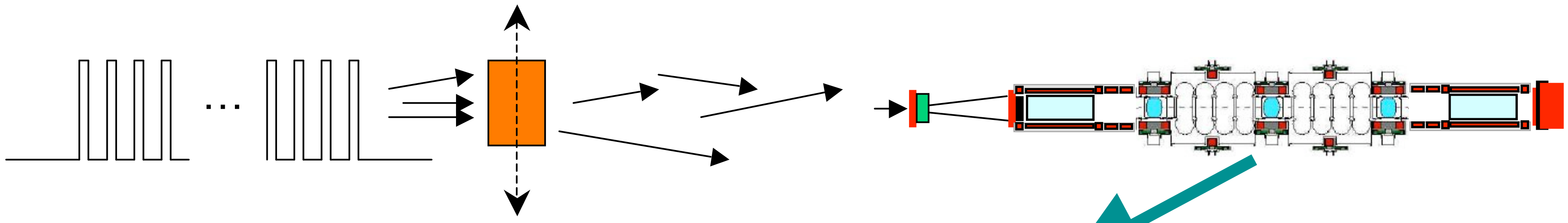
A. with the existing MICE hardware to test optics beyond the neutrino Factory study II:
non flip optics,
low-beta optics (down to 5 cm vs 42 cm nominal)
other absorber materials He, Li, LiH, etc..
LN2 cooled RF cavities

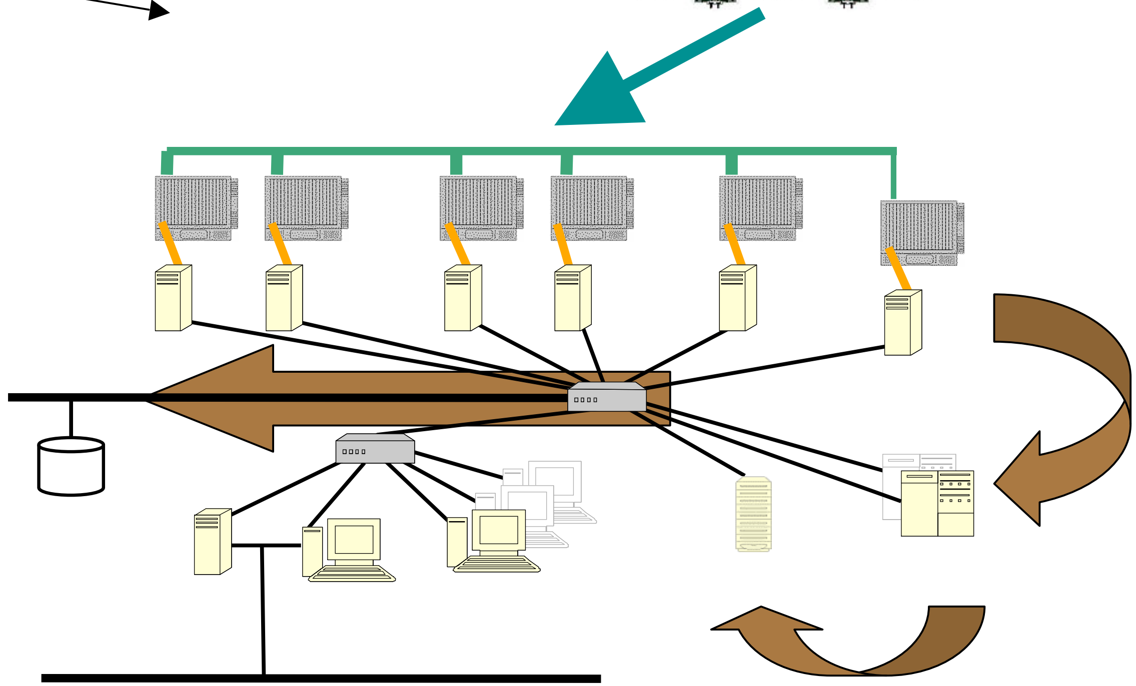
B. with additional hardware:
-- A. Skrinsky to test a lithium lense available at Novosibirsk
-- Muons Inc. to test a section of helicoidal channel (MANX)
-- B. Palmer proposed a poor man's concept of 6D cooling

MICE DAQ & Trigger

Gva, Sofia, UK, IIT, Osaka

data rate ~1MHz





DATE framework (ALICE expt @cern)

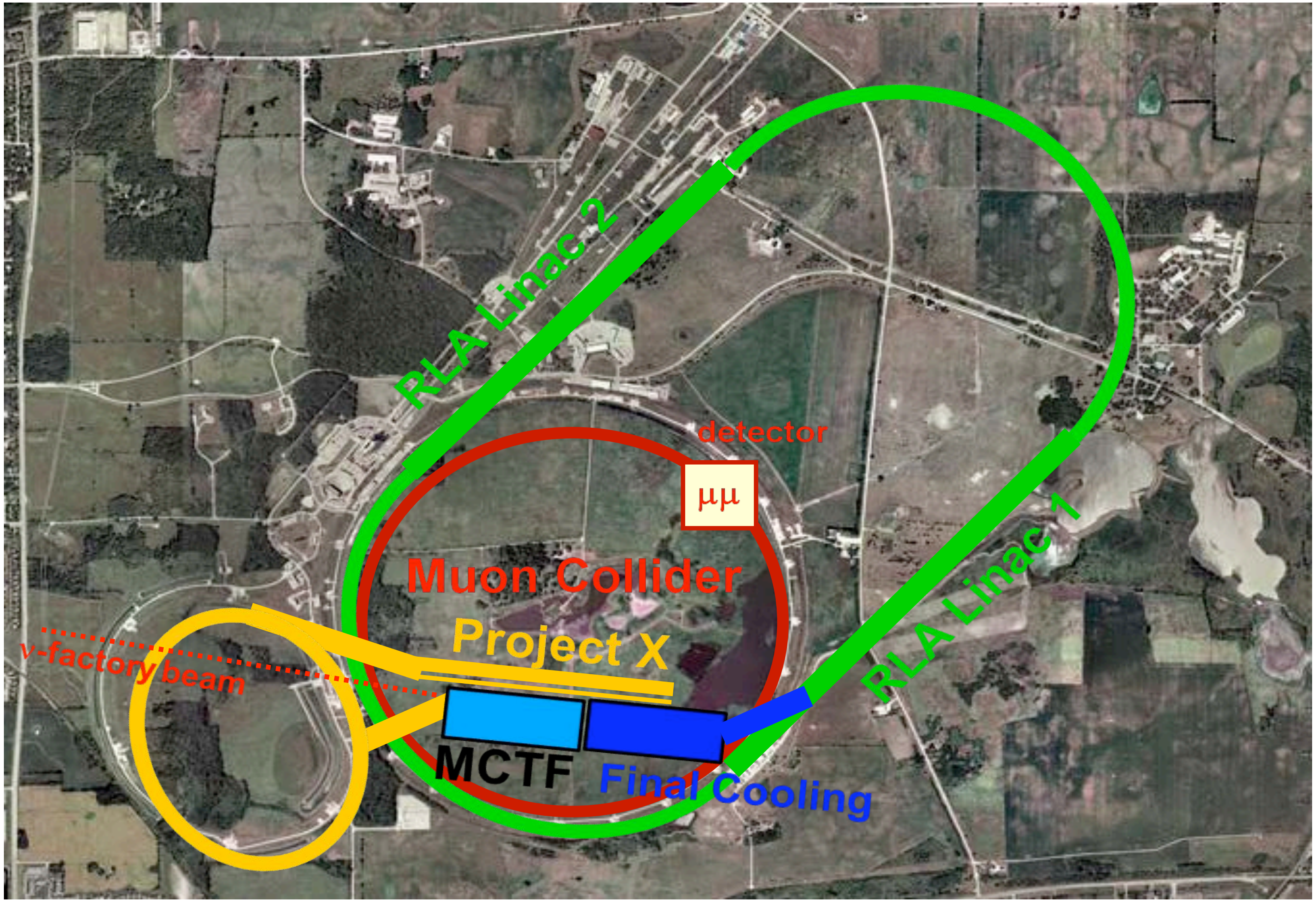
Readout by VME

Trigger signals and run modes established

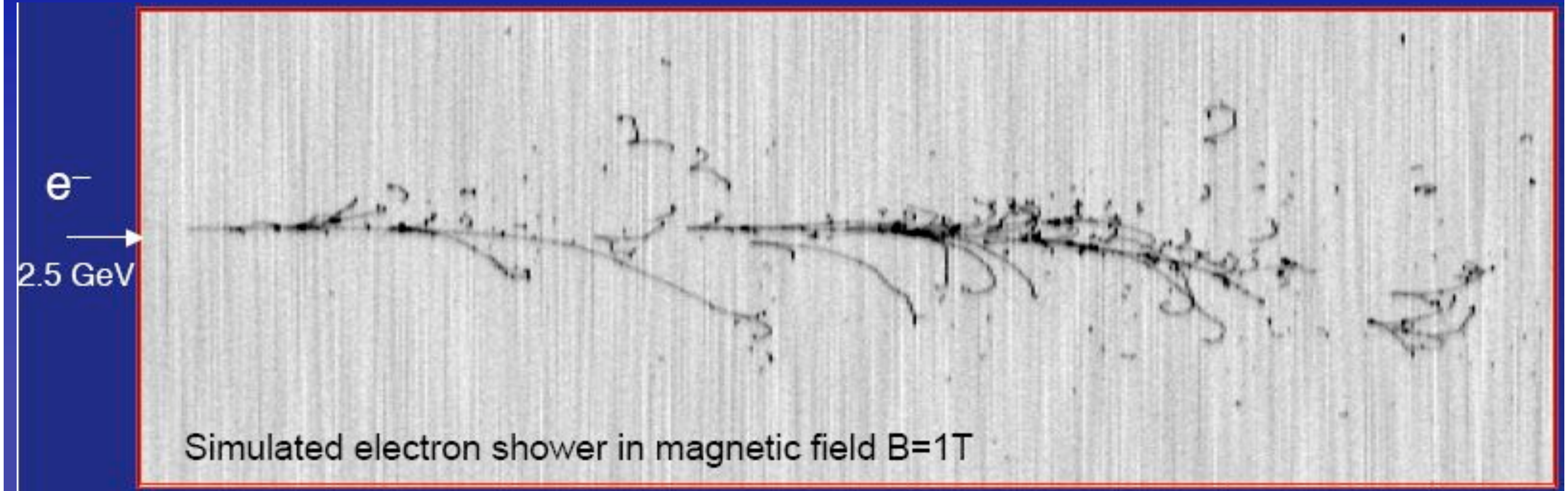
Control and monitoring established (Daresbury)

Controls working for beam magnets, March 14 2008
Electronic Logbook, March 15 2008
DAQ working in MICE Stage 1, 4 April 2008

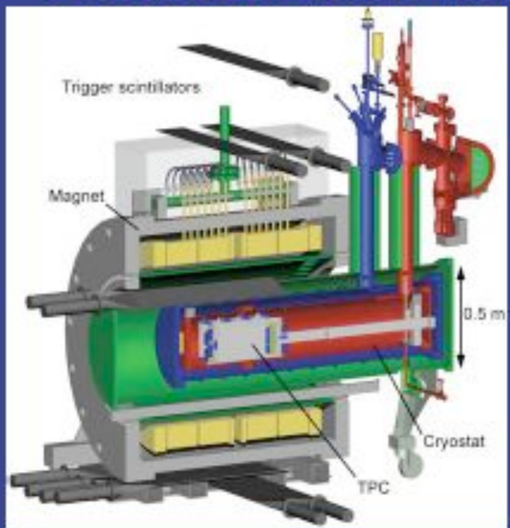
Fermilab Muon Complex - *Vision*

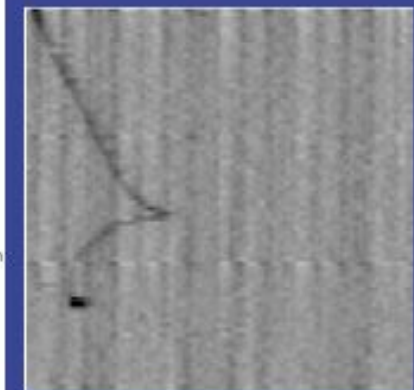


A superconducting magnetized LAr TPC detector



First real events in B-field (B=0.55T):





Required field for 3σ charge discrimination:

x=track length

λ=pitch angle

$$B \geq \frac{0.2\,(Tesla)}{\sqrt{x(m)\,\cos^3\lambda}}$$

x ~ a few X0=14cm….

B > 0.5 T

Requirements on detectors for MICE:

1. Must be sure to work on muons
   - 1.a use a pion/muon decay channel with 5T, 5m long decay solenoid
   - 1.b reject incoming pions and electrons
     - TOF over 6m with 70 ps resolution+ threshold Cherenkov
   - 1.c reject decays in flight of muons
     - downstream PID (TOF2 + calorimeter set up)

2. Measure all 6 parameters of the muons x,y,t, x', y', β_z=E/Pz
   tracker in magnetic field, TOF

3. Resolution on above quantities must be better than 10% of rms of beam at equilibrium emittance to ensure correction is less than 1%.
   + resolution must be measured

4. Detectors must be robust against RF radiation and field emission

Design of MICE detectors and beam test results have satisfied the above requirements

MICE is an international effort from the start.

NUFACT00	Re-activated the recognized need for muon cooling expt
2000-2001	Workshops on Cooling Experiment (CERN, Chicago, London)
NUFACT01 7:00 am	Steering group formed
Sept. 2001	Workshop at CERN where final experiment took shape.
November 2001	Letter of Intent (LOI) submitted to PSI and RAL
January 2002	PSI cannot host experiment, will collaborate (beam solenoid)
June 2002	RAL IPRP Review Panel encouraged submission of a proposal
January 2003	Proposal submitted
July 2003	Recommendation by International Peer Review Panel
October 2003	'Scientific approval' letter by RAL CEO John Wood
December 2003	Gateway 1 review
June 2004	Gateway 1 passed on 'amber'
20 December 2004	Gateway 2/3 passed (MICE PHASE I)
March 2005	UK phase I funding approved by PPARC and CCLRC 9.7 M£
April 2005	US NFMCC proposes a 5-year plan to fund MICE
June 2006	Harbin ICST joins MICE collaboration
July 2006	UK phase II bid submitted
February 2008	Muons Inc. Joins MICE
March 2008	First beam in MICE step I

THE MICE COLLABORATION -130 collaborators-

Universite Catholique de Louvain, Belgium

University of Sofia, Bulgaria

The Harbin Institute for Super Conducting Technologies PR China

INFN Milano, INFN Napoli, INFN Pavia, INFN Roma III, INFN Trieste, Italy

KEK, Kyoto University, Osaka University, Japan

NIKHEF, The Netherlands

CERN

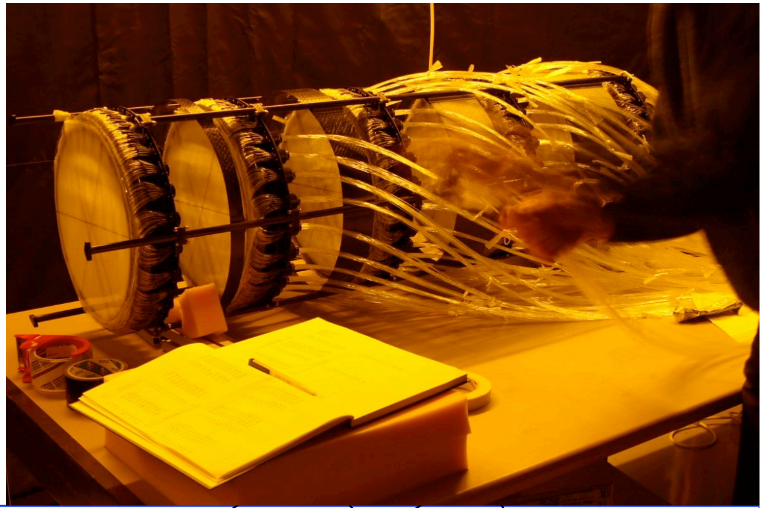
Geneva University, Paul Scherrer Institut Switzerland

Brunel, Cockcroft/Lancaster, Glasgow, Liverpool, ICL London, Oxford, Darsbury, RAL, Sheffield UK

Argonne National Laboratory, Brookhaven National Laboratory, Fairfield University,
University of Chicago, Enrico Fermi Institute, Fermilab, Illinois Institute of Technology,
Jefferson Lab, Lawrence Berkeley National Laboratory, UCLA, Northern Illinois University,
University of Iowa, University of Mississippi, UC Riverside,
University of Illinois at Urbana-Champaign, Muons Inc. USA

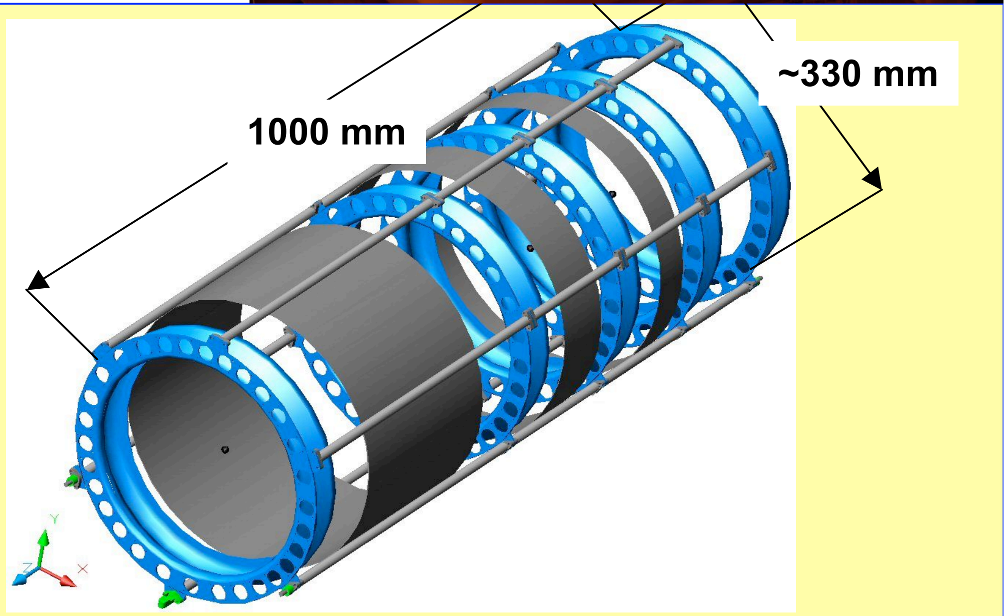
Tracker

resp: Japan,UK,US



two identical trackers with 5 planes of 3-views,
440 μm point resolution achieved
scintillating fiber detector read-out with VPLCs
(7-fold ganging of 350 μm diameter fibers)

Prototypes with 3, 4 triple-planes were built and tested on cosmics and test beam at KEK (in 1 T mag field) ==> curvature measurement OK.



Improved QA procedures for final production

Full production of tracker started in January 2007

TRACKER

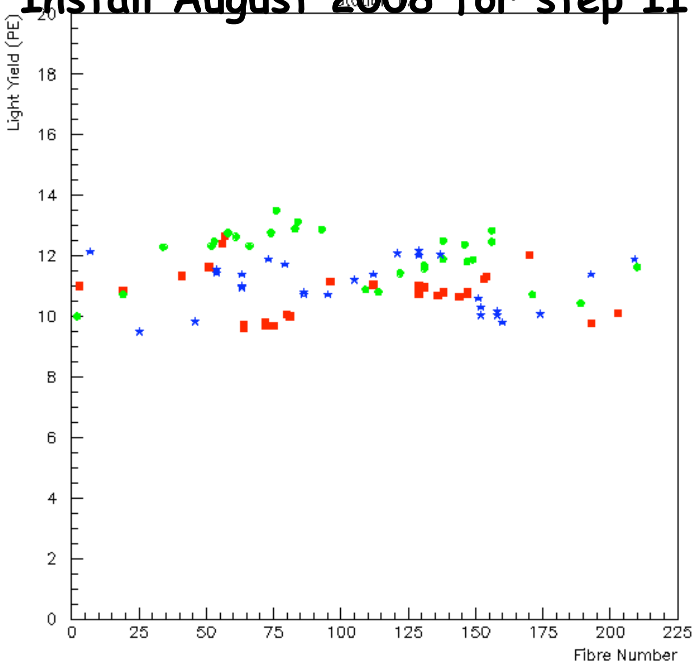
Sci-fi tracker with 5 stations
of 3 views
of 350 microns diam. fibers

Tracker construction complete

Superb quality of construction
(1/5000 channels dead)

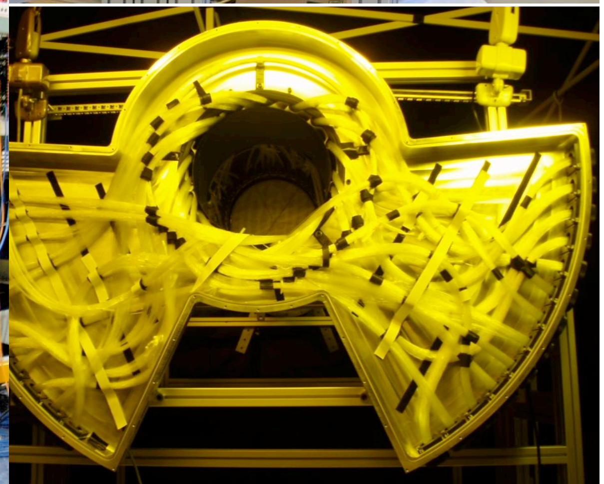
Test on cosmics at RAL

Install August 2008 for step II



Full tracker

VLPC and cryogenics



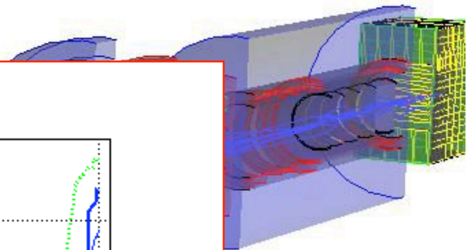
Patch panel

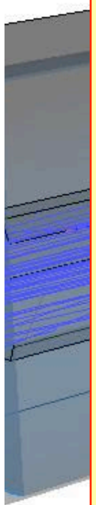
software, analysis & DATA Challenge

1. Basic simulation and reconstruction of MICE is complete for the various steps
Both G4MICE and MUCOOL are used.

2. Putting it all together to do analysis (particle reconstruction, particle ID algorithms
Single particle amplitude and emittance calculations, etc…)

R. Sandström





Example →
Bias on emittance
due to muon decays
Would be ~0.5%
(i.e. 5% error
on cooling meast)
Reduced to <<0.1%
by PID+ tracker
This uses
tracker & TOF info
and PID signals
+Neural Network