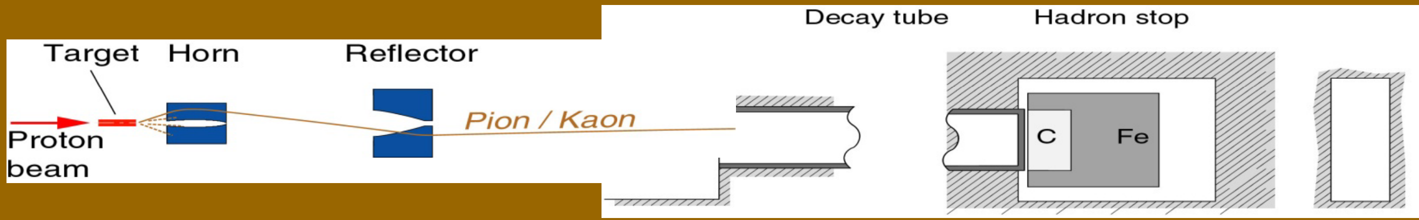
The ultimate neutrino beam(s)

Mats Lindroos

Outline

- Neutrino oscillation physics
  - Super Beams
  - Neutrino factories
  - Beta beams
- Low energy neutrino beams
  - Beta-beams
  - Storage rings
- Acknowledgements to all colleagues in the neutrino beam community!

Neutrino beams and super beams



p + C $\rightarrow$ (interactions) $\rightarrow$ π^+, K^+ $\rightarrow$ (decay in flight) $\rightarrow$ $\mu^+ + \nu_\mu$

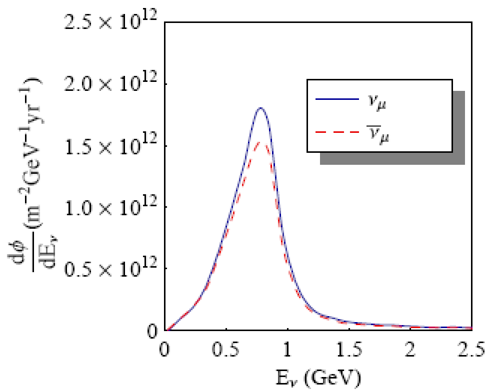
Relative to the main ν_μ component:

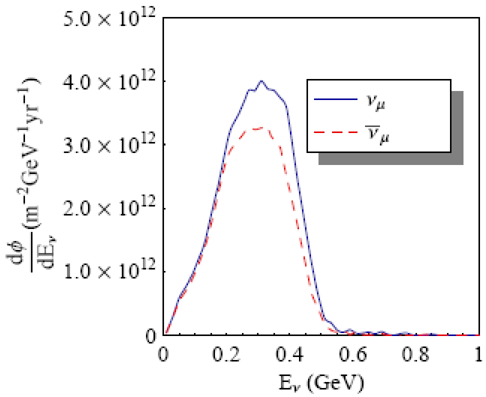
ν_e / ν_μ= 0.8 %

anti-ν_μ / ν_μ= 2.1 %

anti-ν_e / ν_μ = 0.07 %

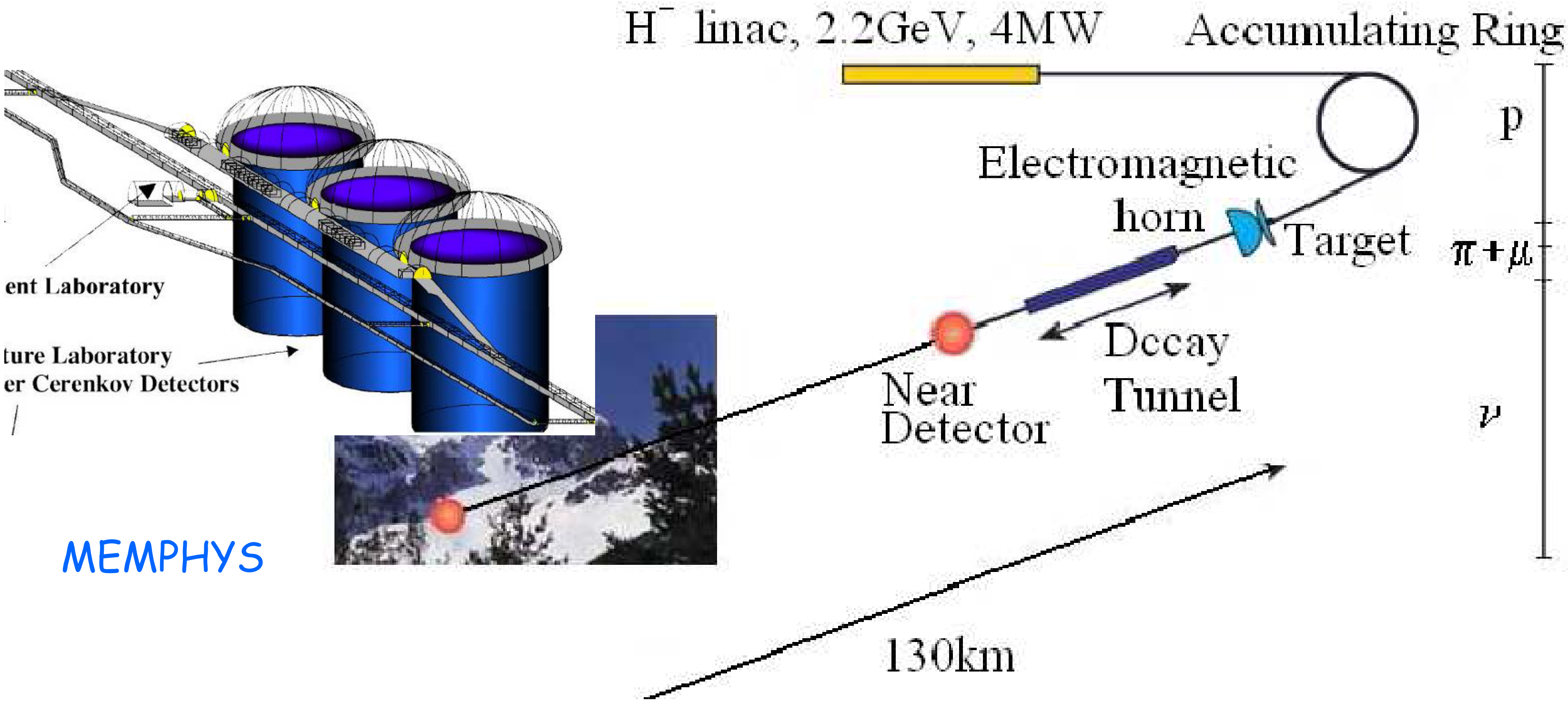
T2HK





SPL to Frejus

Super-Beams

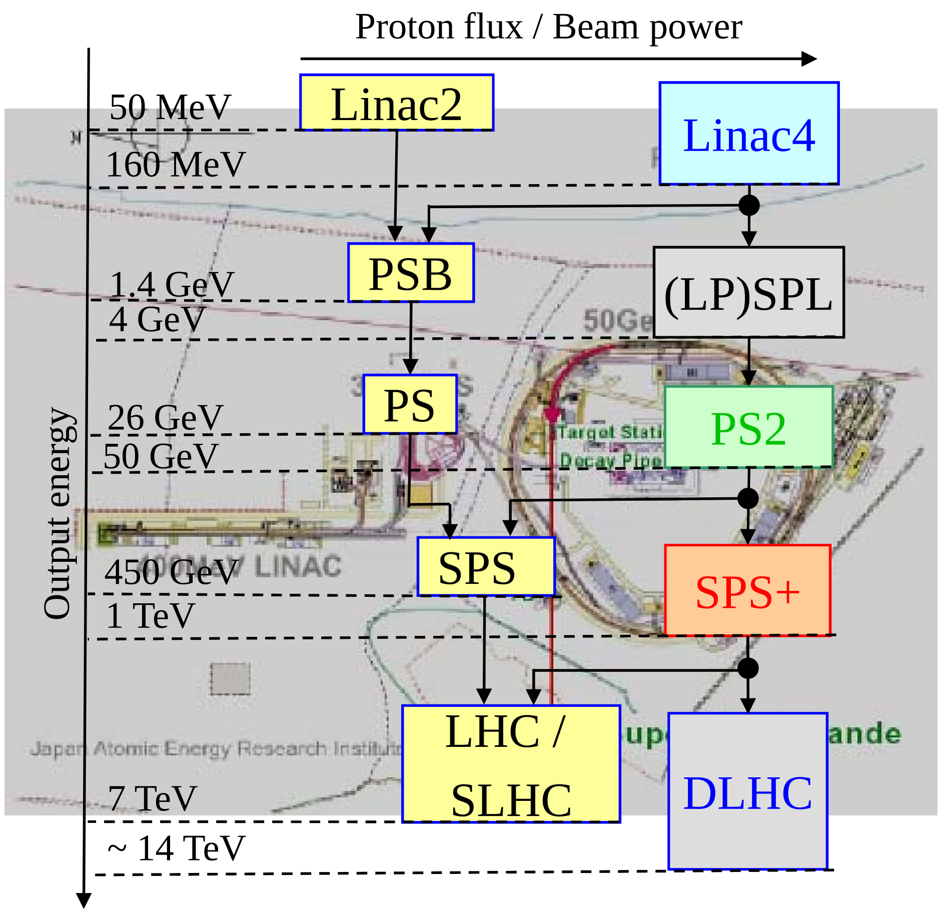


In this project, the planned 4 MW Superconducting Proton Linac (SPL) would deliver a 2.2 GeV/*c* proton beam on a heavy metal target to generate an intense π^+ (π^-) beam focused by a suitable magnetic horn in a short decay tunnel. As a result, an intense ν_μ beam will be produced mainly via the π decay, $\pi^+ \rightarrow \mu^+ + \nu_\mu$, providing a flux of 3.6 x 10^{11} ν_μ/year/m^2 at 130 km distance, and an average energy of 0.27 GeV. The ν_e contamination from kaons will be suppressed by threshold effects and the resulting ν_e/ν_μ ratio (~0.4%) will be known within 2% error. The use of a near and a far detector (the latter at L = 130 km in the Fréjus area) will allow for both ν_μ disappearance and $\nu_\mu \rightarrow \nu_e$ appearance studies.

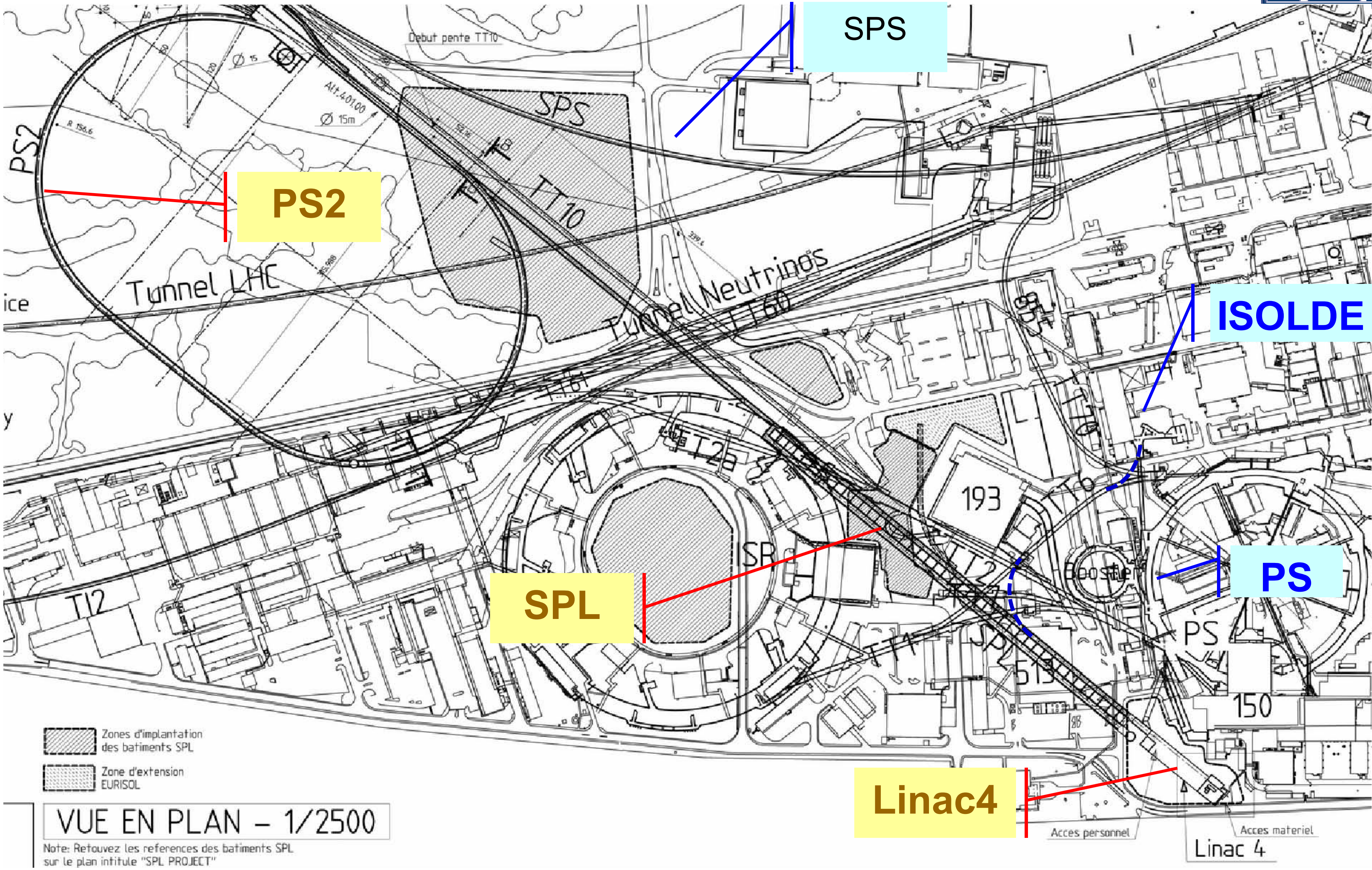
Proton drivers and compressor rings

- **An H- linac with a 50-Hz booster RCS and a 50-Hz nonscaling, non-linear, fixed-field alternating gradient (NFFAG) driver ring**
- An H- linac with pairs of 50 Hz booster and 25 Hz driver synchrotrons (RCS)
- An H- linac with a chain of three non-scaling FFAG rings in series
- An H- linac with two slower cycling synchrotrons and two holding rings
- A **full energy H- linac with an accumulator and bunch Compression ring(s)**

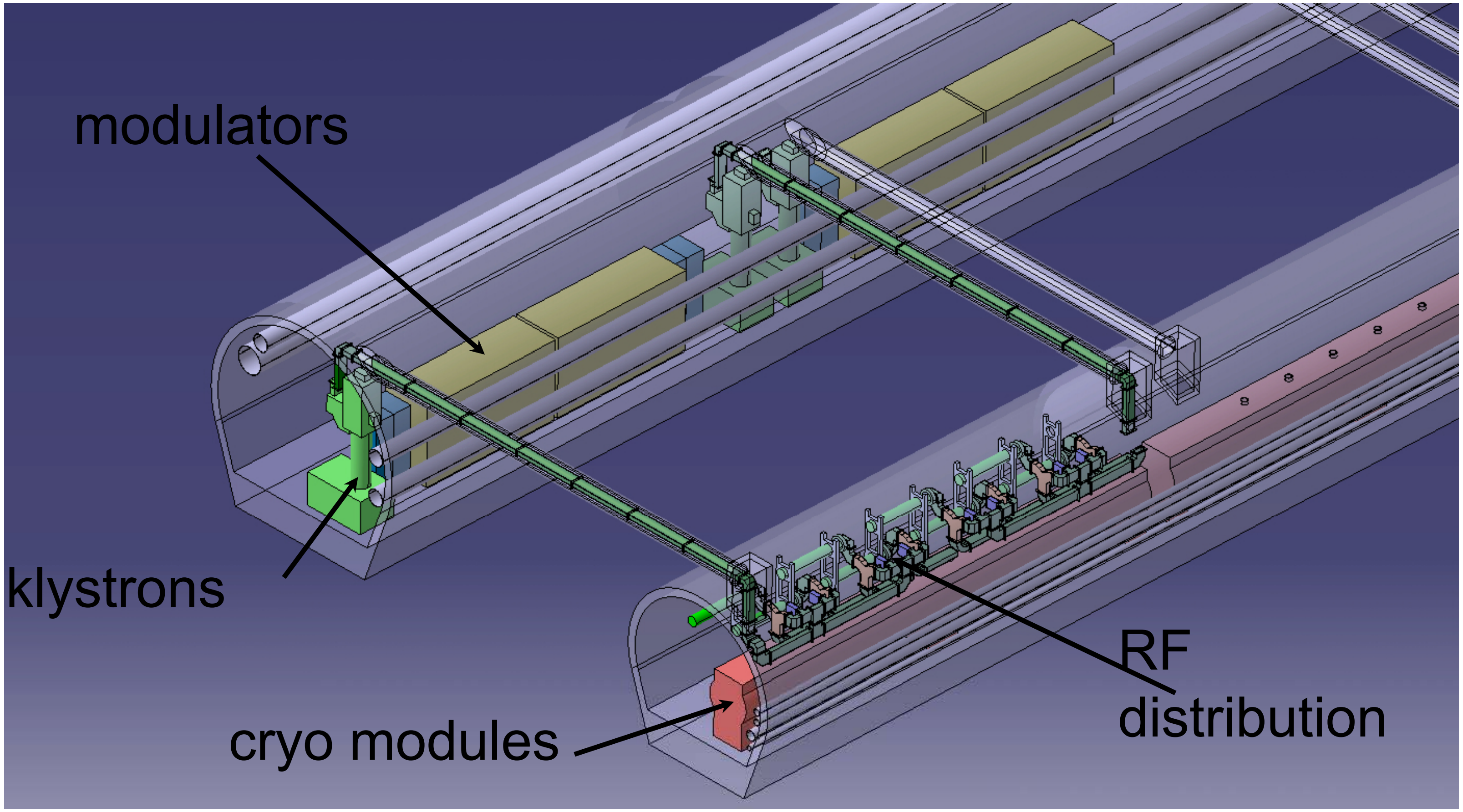
EU-CERN



Layout of the new injectors at CERN



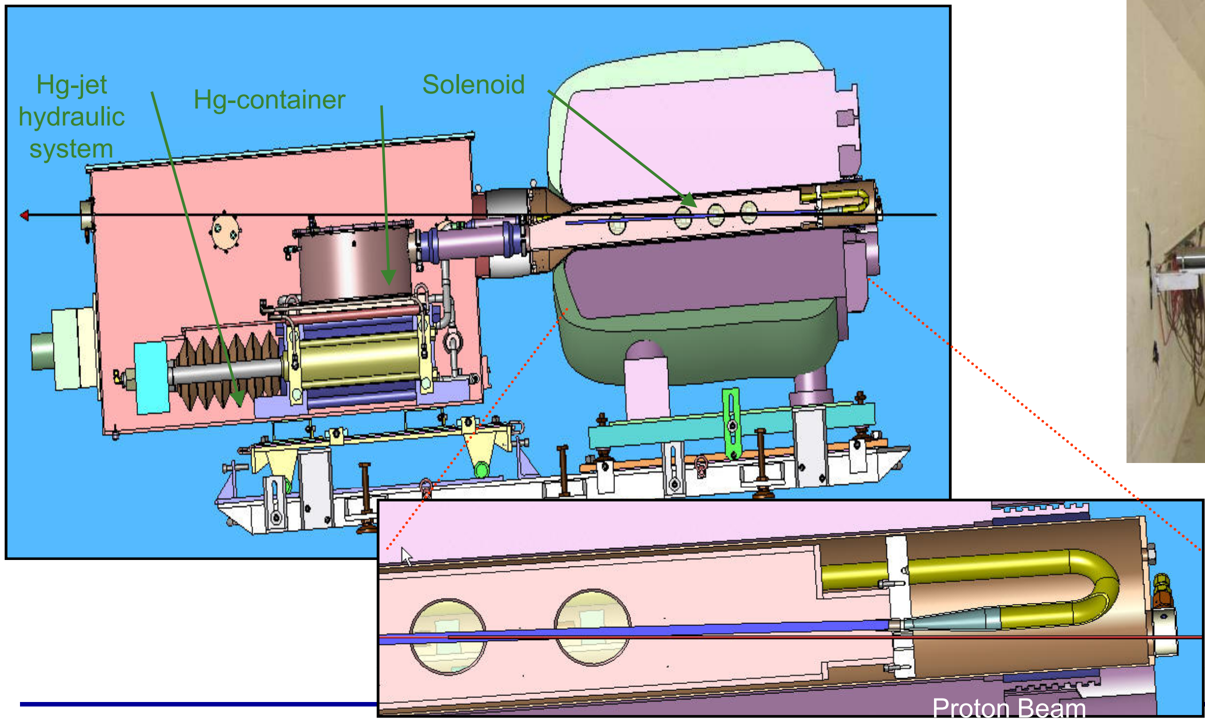
Preliminary tunnel layout



The MERIT experiment

*A **proof-of-principle test of a target station** suitable for a ν-Factory or μ- Collider source*

*PS extracted proton beam of 14(24)-GeV, incident on a **free mercury jet** target located inside a **15-T capture solenoid magnet**.*

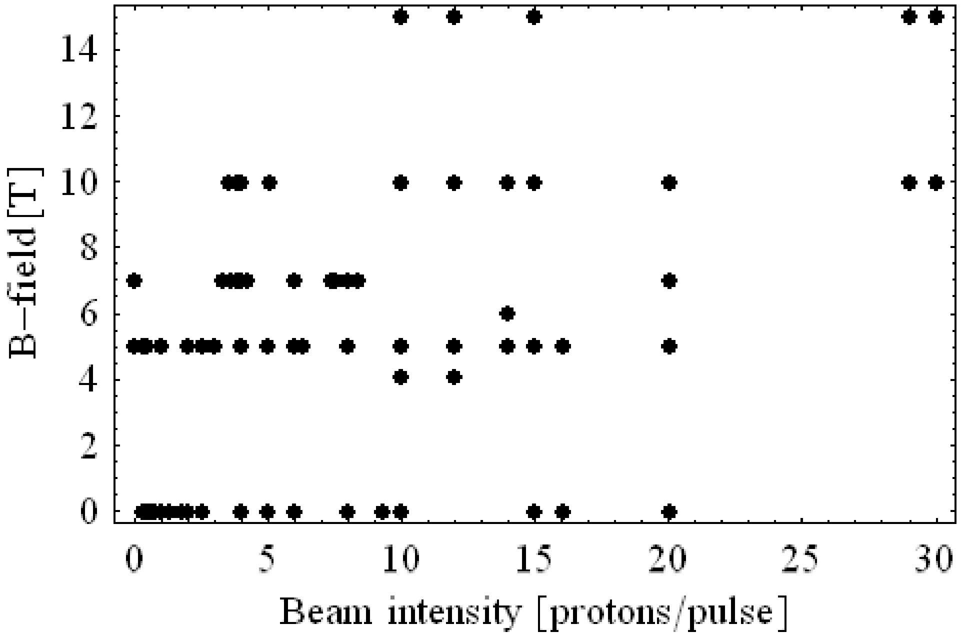


The MERIT experiment

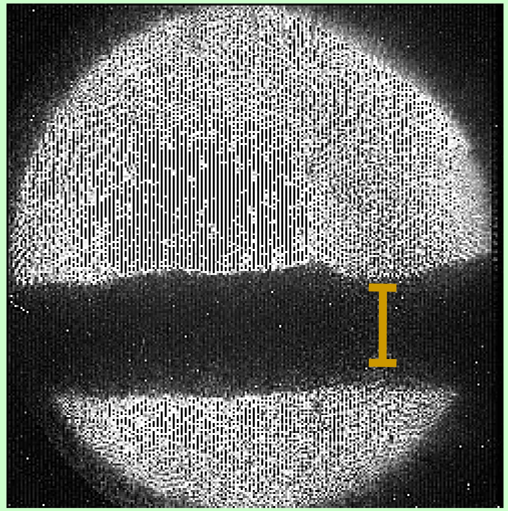
- The experiment could fully exploit the potential of the PS machine to validate the liquid metal target concept

PS record intensity:

- **3 ×10^{13} protons/pulse @ 24 GeV/c**
- Corresponding to **150 kJ per pulse**



Beam-target interaction example



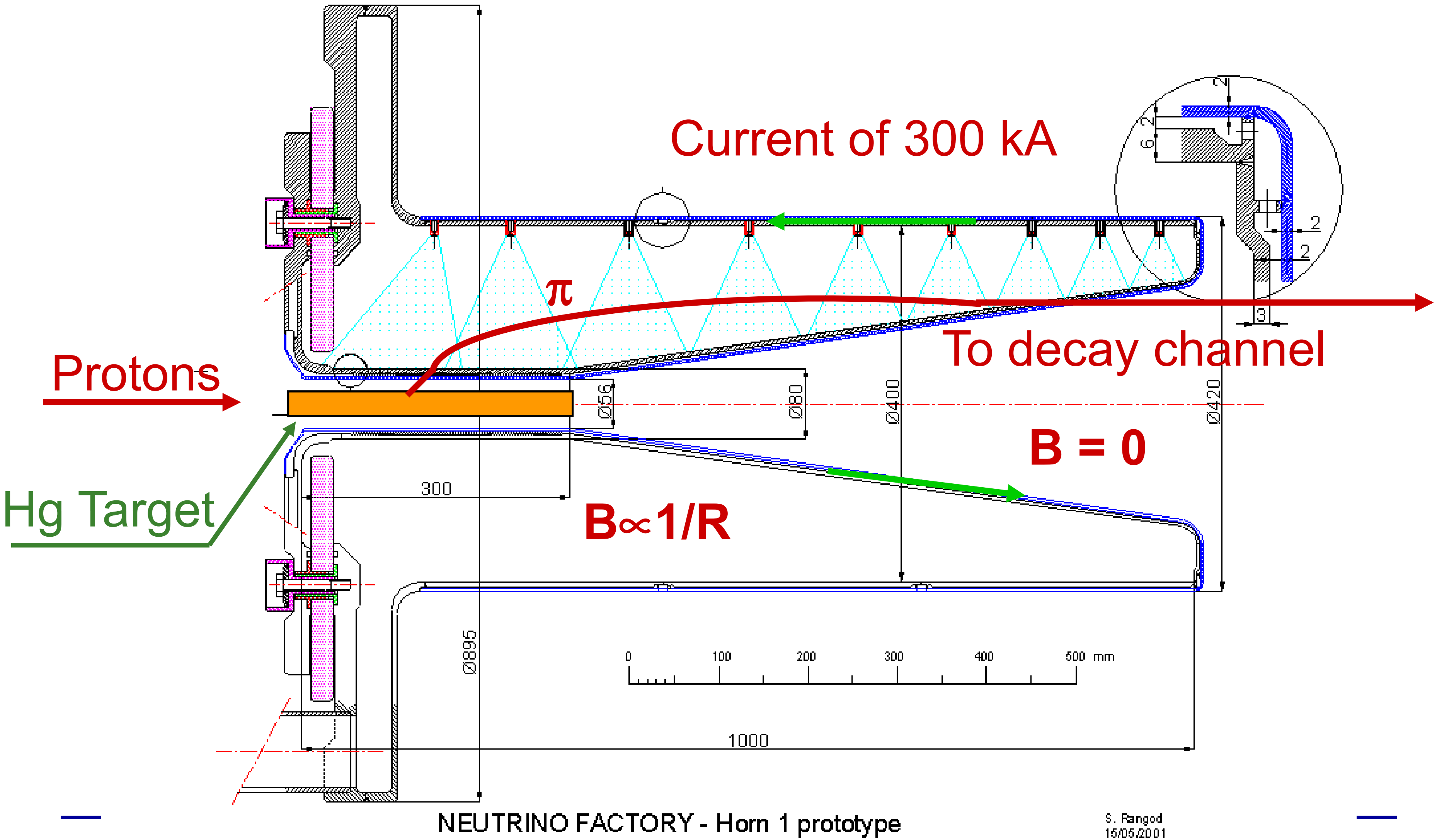
1 cm

- 14 GeV/c beam
- 1.6 ×10^{13} protons/pulse
- 5 Tesla B-field

Images recorded at 2000 frames/sec
Video displayed 400 times slower
Splash velocities up to 60 m/s

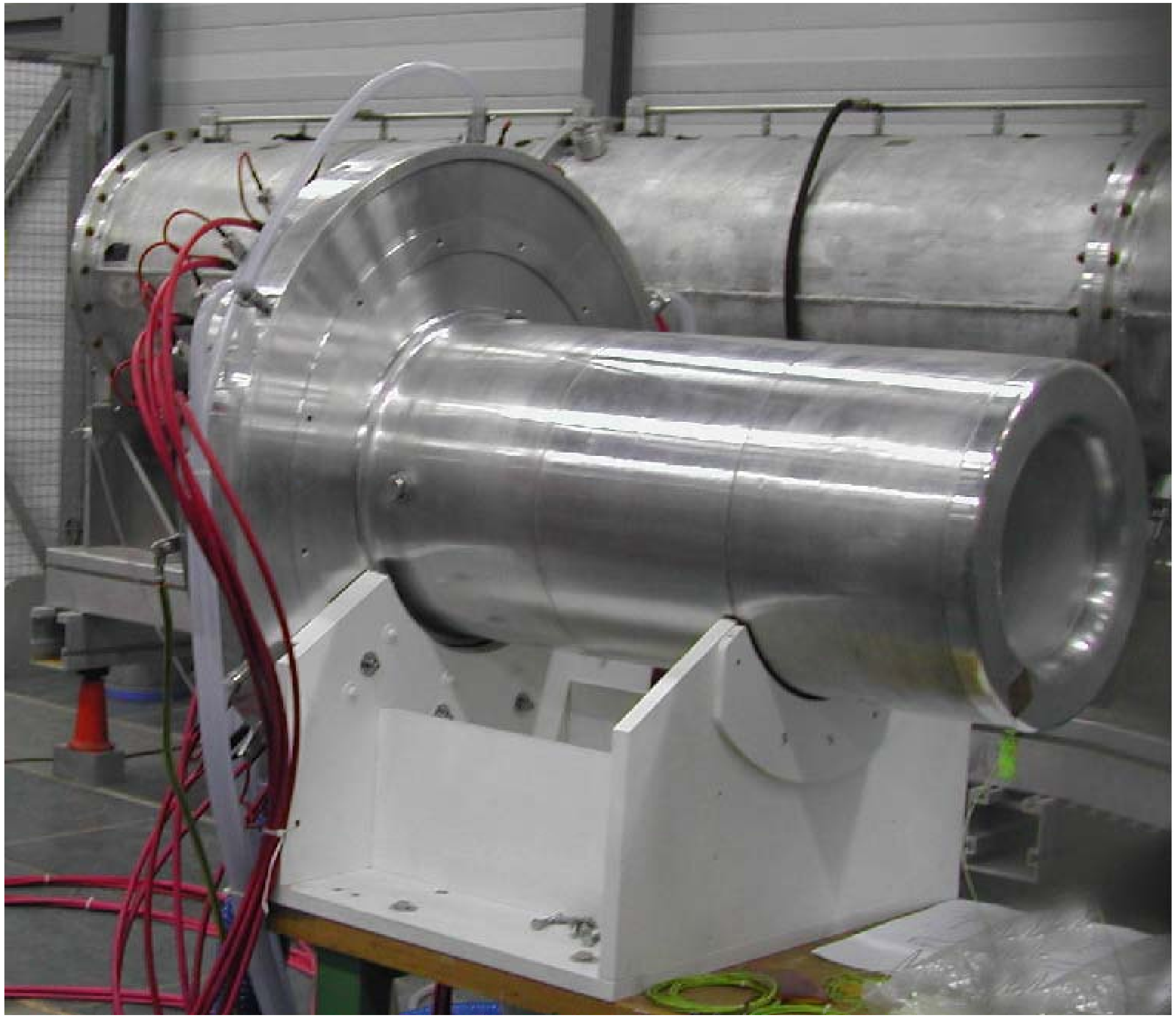
Focusing system: magnetic horn

M. Dracos



Horn prototype ready for tests

M. Dracos



Neutrino factory

- Muons decaying in storage ring:

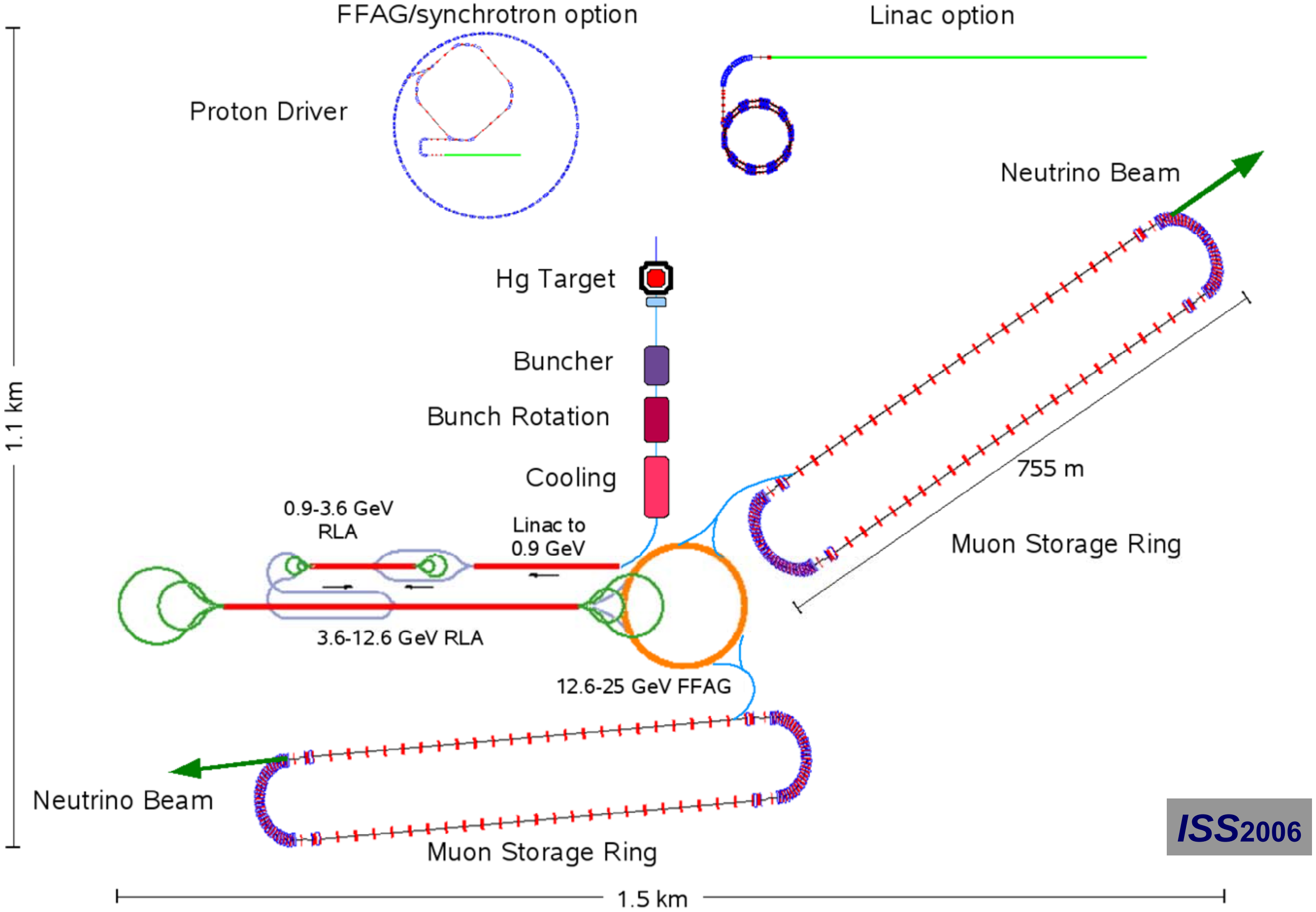
$$\mu^+ \rightarrow e^+ \, \overline{\nu_e} \nu_\mu \qquad \text{and} \qquad \mu^- \rightarrow e^- \, \nu_e \overline{\nu_\mu}$$

ISS DECAY RINGS:

Number of rings (number of baselines)	2
Stored muon energy (total energy, GeV)	25
Beam divergence in production straight (γ^{-1})	0.1
Bunch spacing (ns)	≥ 100
Number of $\mu^\pm$ decays per year per baseline	5×10^{20}

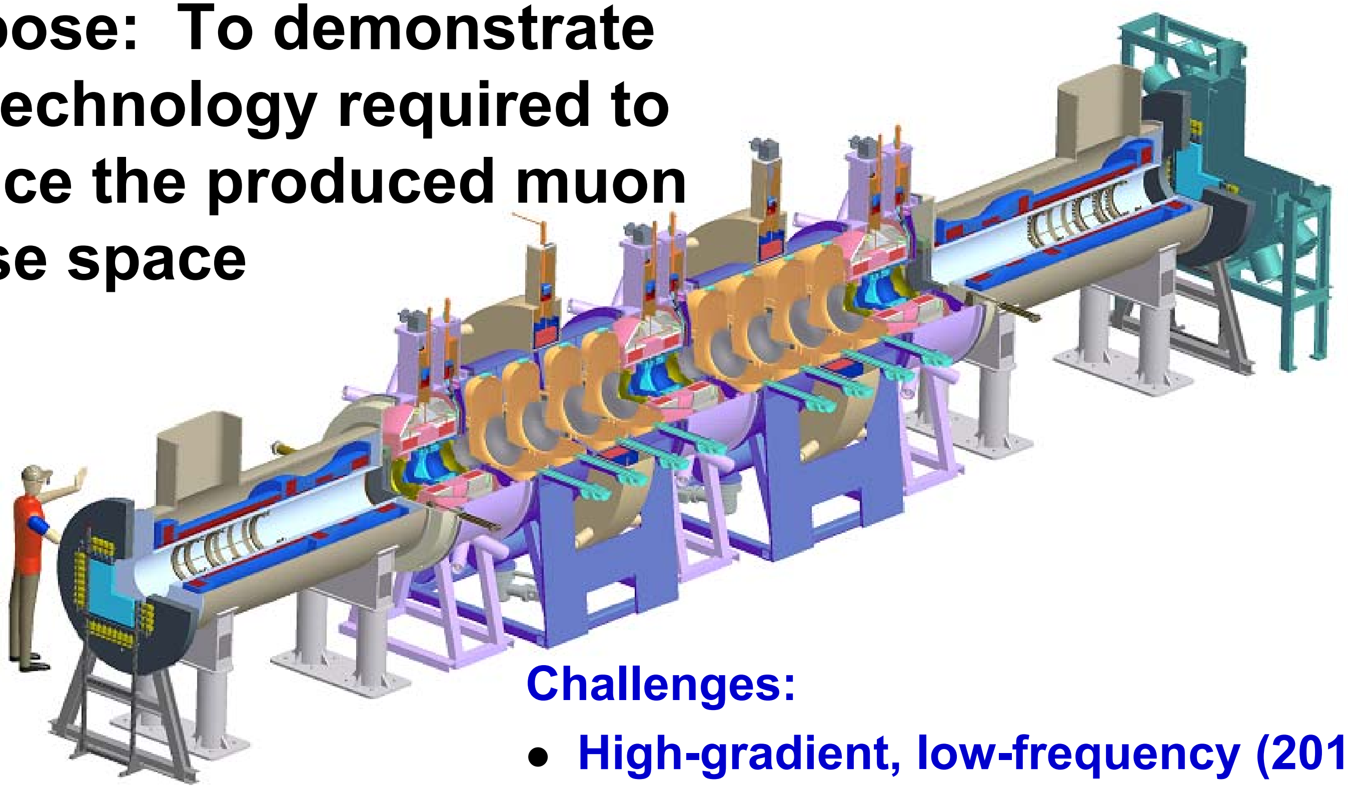
- Well understod high intensity neutrino beam!

Neutrino factories - ISS



The Muon Ionization Cooling Experiment (MICE)

- **Purpose: To demonstrate the technology required to reduce the produced muon phase space**



Challenges:

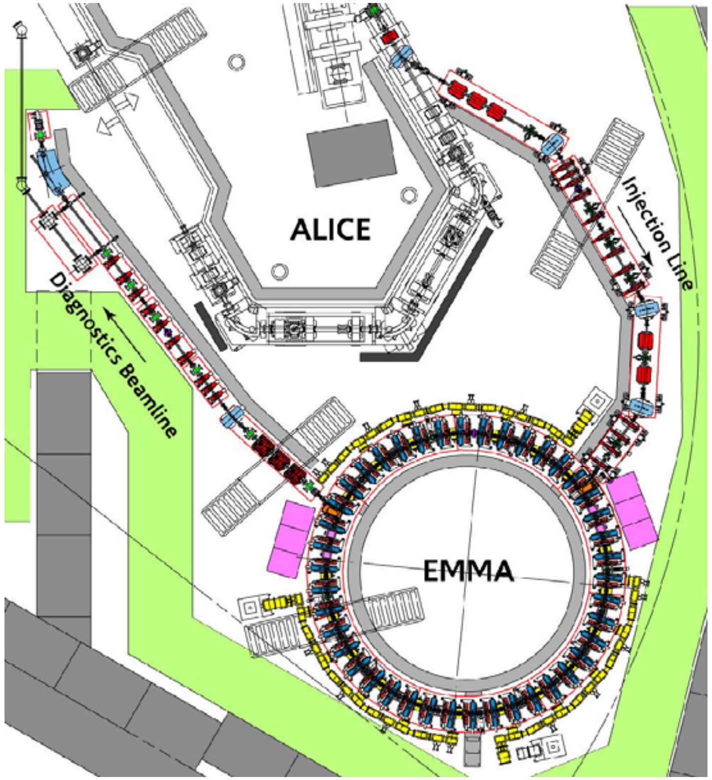
- **High-gradient, low-frequency (201MHz) rf cavities operating in high-magnetic fields (~3T)**
- **Design and safely operated LH_2 absorbers**

EMMA at Daresbury Laboratory

- **Purpose:**
- **Demonstrate the beam dynamics of non-scaling FFAGs**

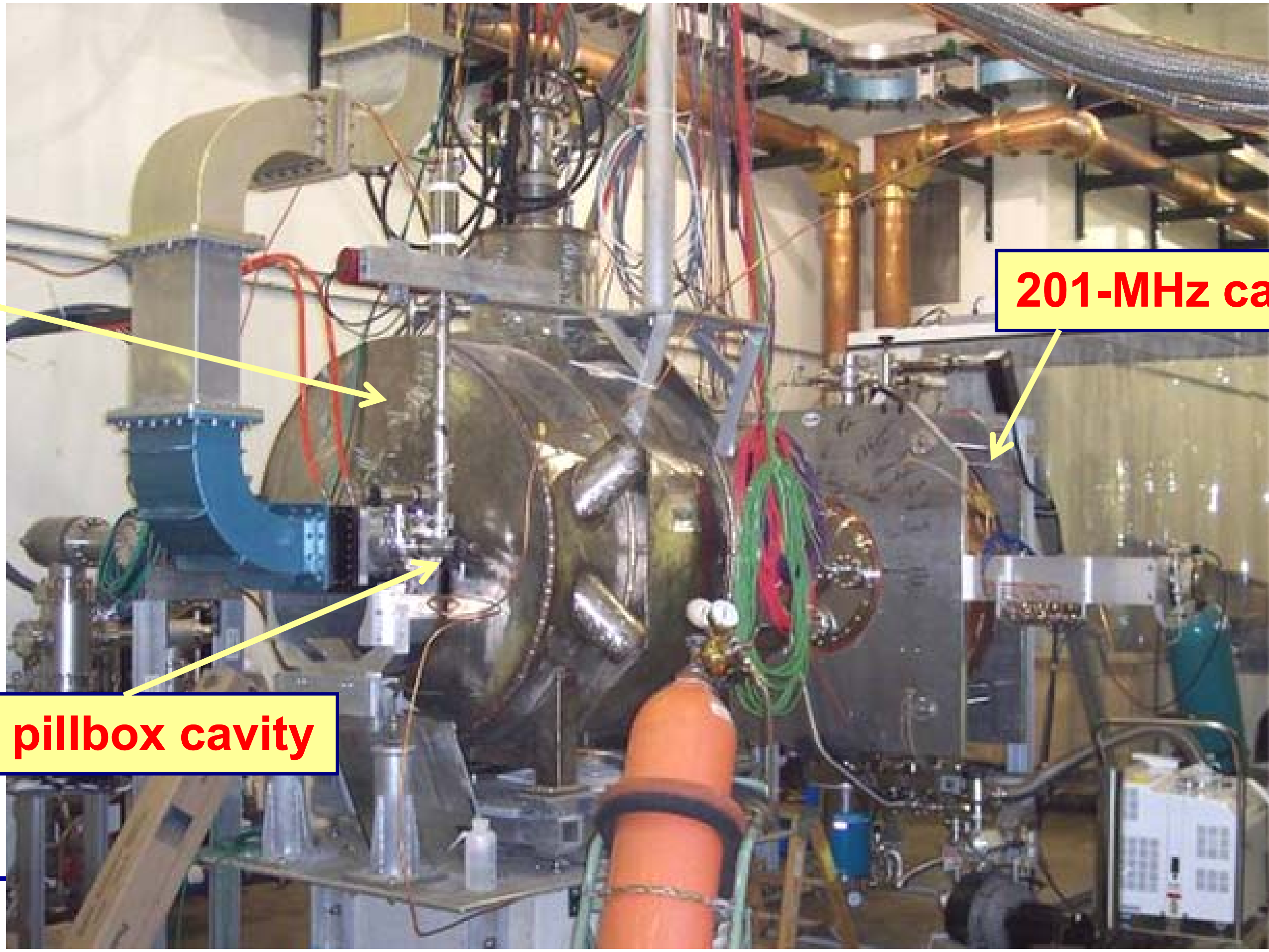
Challenge:

No non-scaling FFAGs have previously been designed, built and operated



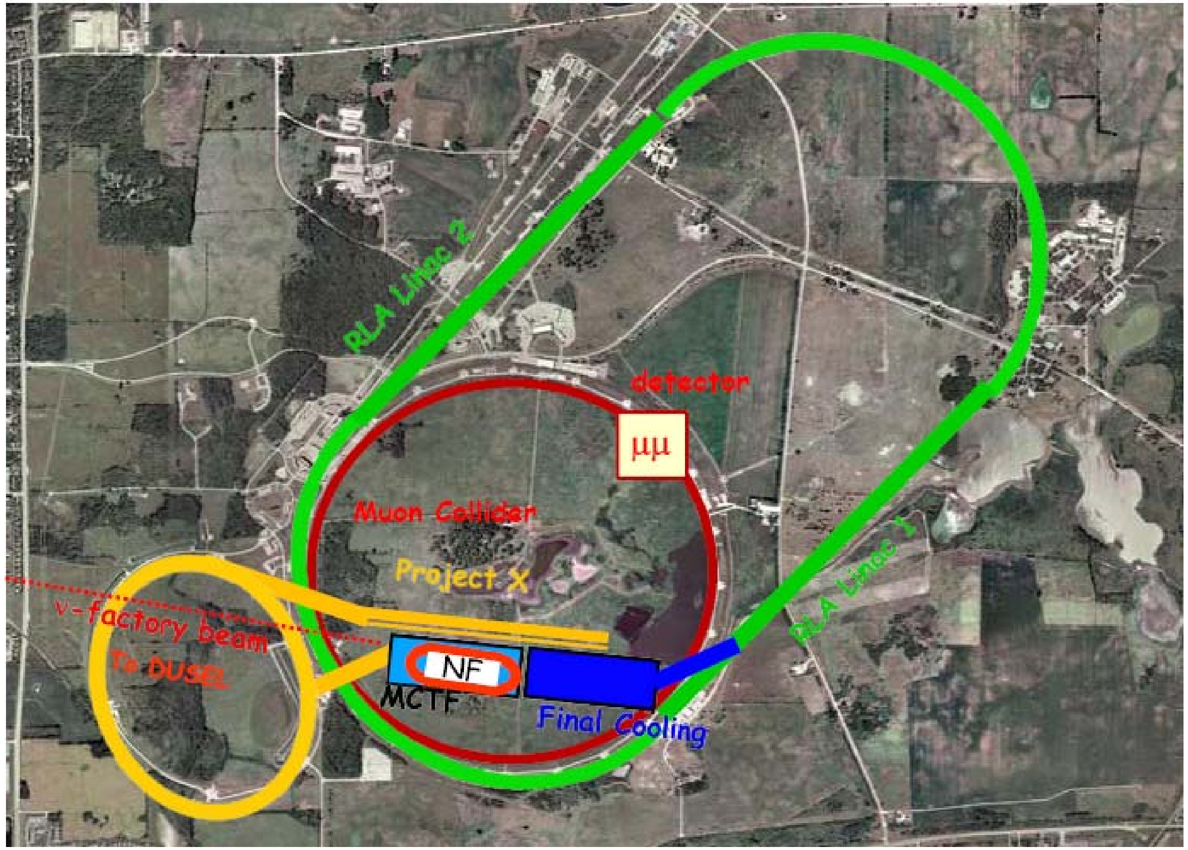
EMMA is an electron analog machine designed for 10-20MeV/c operation

RF breakdown studies with external magnetic fields for 805 and 201-MHz cavities



Neutrino factories - FNAL

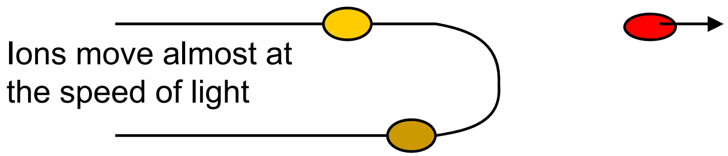
- Can a neutrino factory be the first step towards a muon collider?



Introduction to beta-beams

- **Beta-beam proposal by Piero Zucchelli**
  - ***A novel concept for a neutrino factory: the beta-beam,***
    Phys. Let. B, 532 (2002) 166-172.

- **AIM: production of a pure beam of electron neutrinos (or antineutrinos) through the beta decay of radioactive ions circulating in a high-energy (γ~100) storage ring.**



- **First study in 2002**
  - **Make maximum use of the existing infrastructure.**

Guideline to ν-beam scenarios

based on radio-active ions

- Low-energy beta-beam: relativistic $\gamma < 20$
- Medium energy beta-beam: $\gamma \sim 100$
  - EURISOL DS
  - Today the only detailed study of a beta-beam accelerator complex
- High energy beta-beam: $\gamma > 350$
  - Take advantage of increased interaction cross-section of neutrinos
- Monochromatic neutrino-beam
  - Take advantage of electron-capture process
- High-Q value beta-beam: $\gamma \sim 100$

Accelerator physicists together with neutrino physicists defined the accelerator case of γ=100/100 to be studied first (EURISOL DS).

Low-energy part

Ion production

Proton Driver
SPL

Ion production
ISOL target &
Ion source

Beam preparation
ECR pulsed

Ion acceleration
Linac, 0.4 GeV

Acceleration to
medium energy
RCS, 1.5 GeV

High-energy part

Acceleration

Acceleration to final energy

PS & SPS

Existing!!!

PS
8.7 GeV

SPS
93 GeV

Neutrino source

Beam to experiment

Neutrino
Source

Decay
Ring

Decay ring

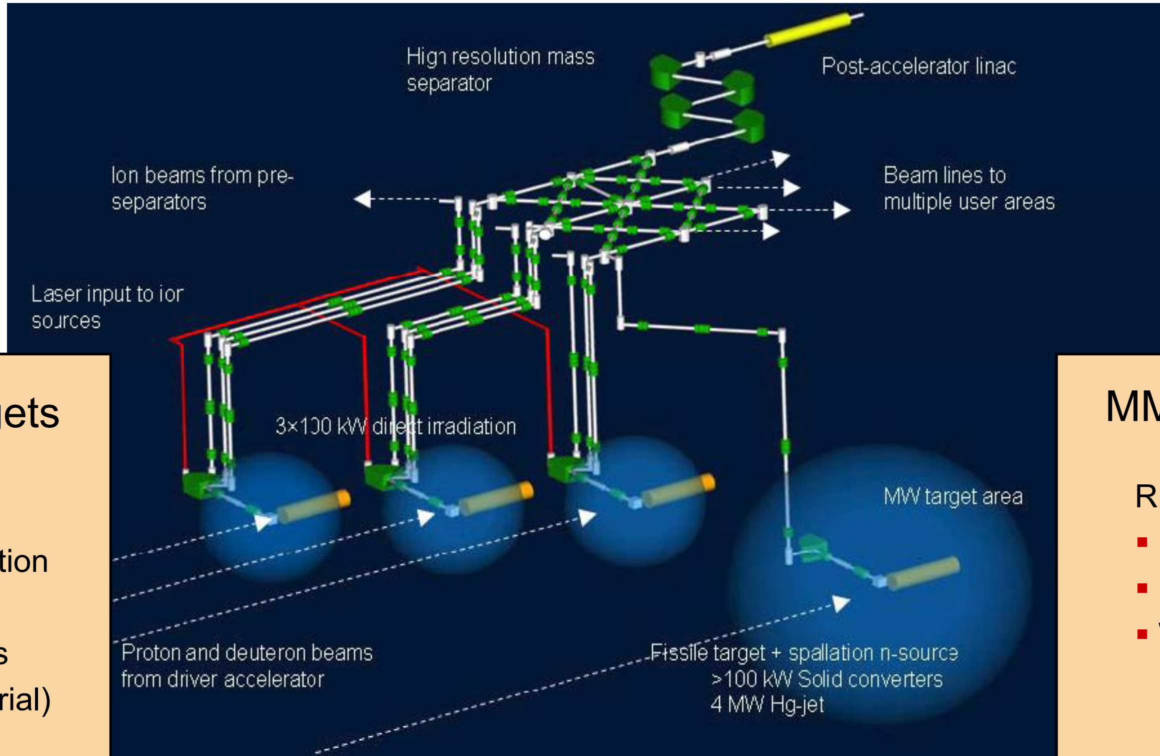
$B\rho$ = 1500 Tm
B = ~6 T
C = ~6900 m
L_{ss}= ~2500 m
^{6}He: γ = 100
^{18}Ne: γ = 100

Detector in the Frejus tunnel

EURISOL Design Study

beam

EURISOL



100 kW direct targets

RIB production:
- Spallation-evaporation
- Main: P-rich
  (10 to 15 elements below target material)
- Residues: N-rich
  (A few elements below target material)

Target materials:
- Oxides
- Carbides
- Metal foils
- Liquid metals

MMW fission target

RIB production:
- Fission
- N-rich
- Wide range
  Z = 10 to Z = 60

Target material:
- U (baseline)
- Th

Converter:
- Hg

Participants:
~20 institutions

Contributors:
~20 institutions

EU suport (~30%):
~9.2 MEuros

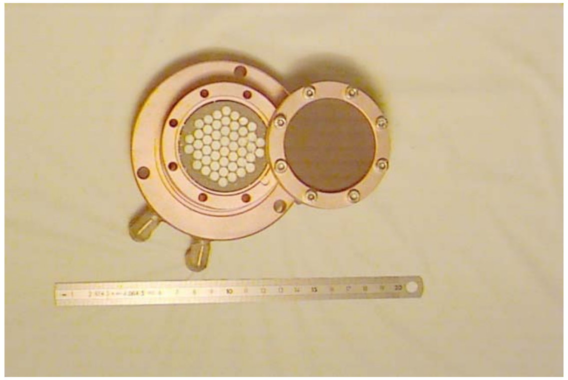
Duration:
2005-2009

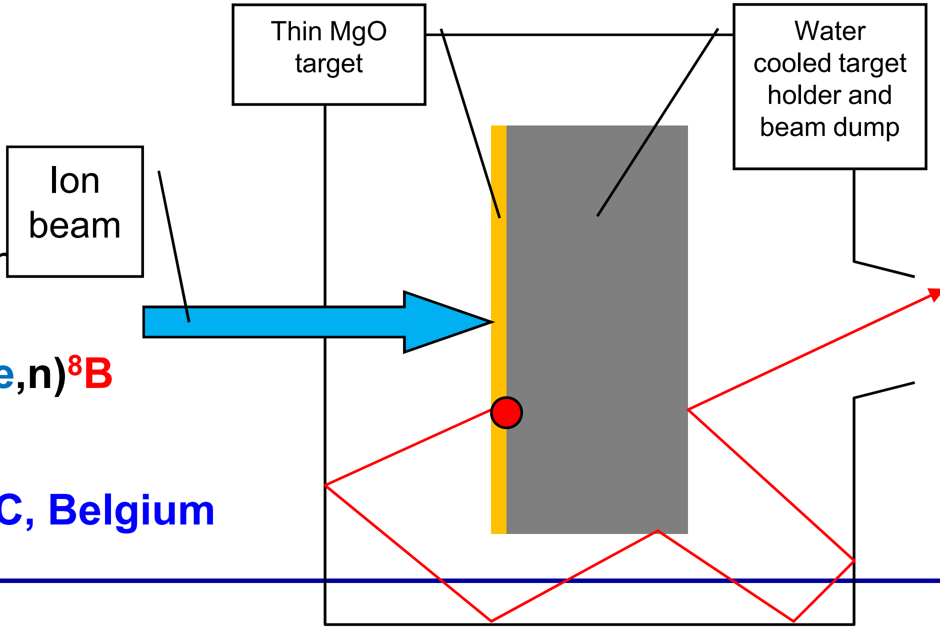
12 Tasks are active

^{18}Ne (Direct Production)

Geometric scaling

- Producing 10^{13} ^{18}Ne could be possible with a beam power (at low energy) of 2 MW (or some 130 mA ^{3}He beam on MgO).
- To keep the power density similar to LLN (today) the target has to be 60 cm in diameter.
- To be studied:
  - Extraction efficiency
  - Optimum energy
  - Cooling of target unit
  - High intensity and low energy ion
  - High intensity ion source
- $^{16}O(^{3}He,n)^{18}Ne$, $^{7}Li(^{2}H,p)^{8}Li$, $^{6}Li(^{3}He,n)^{8}B$ and $^{9}Be(^{4}He,n)^{6}He$





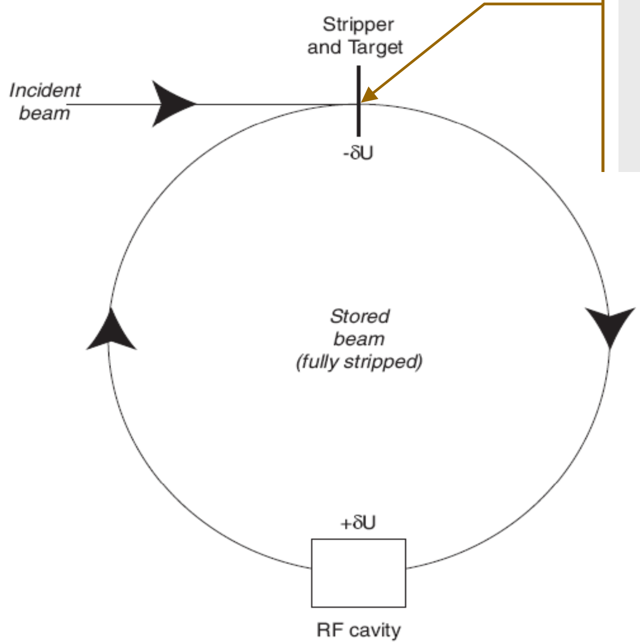
S. Mitrofanov and M. Loislet at CRC, Belgium

A new approach

Beam cooling with ionisation losses – C. Rubbia, A Ferrari, Y. Kadi and V. Vlachoudis in NIM A 568(2006)475

"Many other applications in a number of different fields may also take profit of **<u>intense beams of radioactive ions</u>**."

^{7}Li
^{6}Li

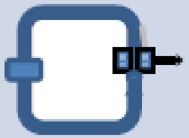
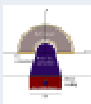
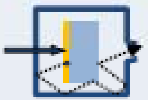


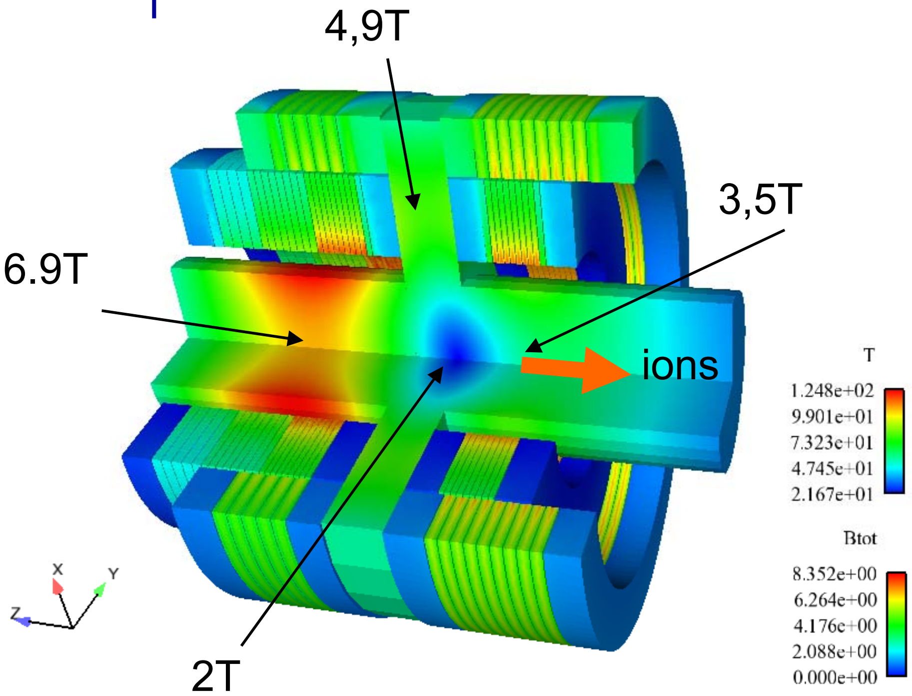
^{7}Li(d,p)^{8}Li
^{6}Li(^{3}He,n)^{8}B

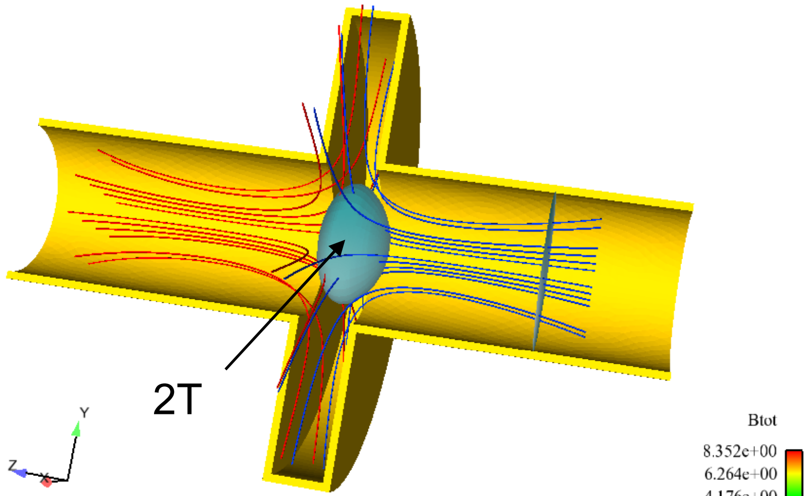
Missed opportunities

See also: Development of FFAG accelerators and their applications for intense secondary particle production, Y. Mori, NIM A562(2006)591

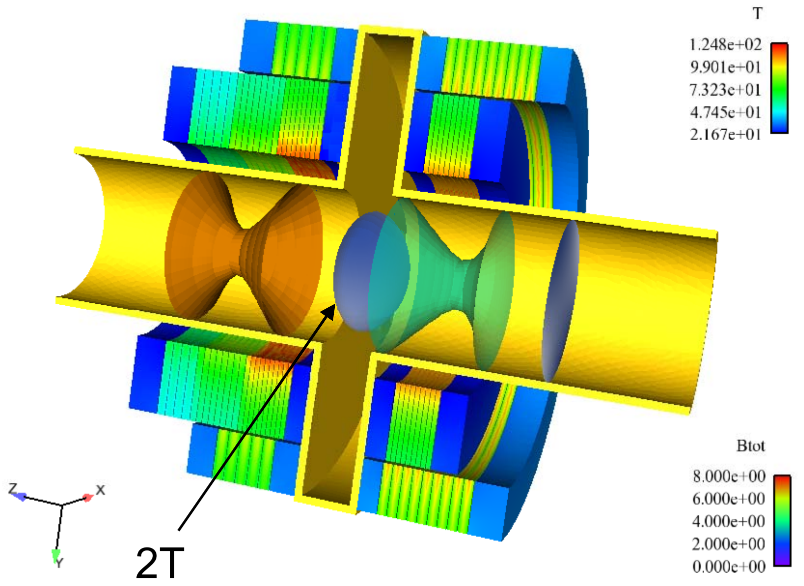
Overview, production

Illustration	METHOD	Advantage	Drawback
	Production ring	-“Re-use” of driver beam thanks to cooling -Huge cross sections for compound nucleus	-Challenging gas target design -Collection device efficiency
	Converter target, with low and high energy driver	Can accept very high intensity driver beam (>1 MW)	Limited to neutron produced isotopes such as ^{6}He and ^{8}Li
	ISOL with >1 GeV protons	Universal, any non-refractory isotope can be produced at high intensity with good beam quality	Can only accepted up to some 100 kW of driver beam
	Direct production	-Low energy and high intensity driver -Huge cross sections for compound nucleus	-Challenging very high intensity driver design -Extraction efficiency





Magnetic field lines



- Max. stress σ~290 MPa <<400MPa
- Simulation fits the specifications

Work on Radiation Issues

- Radiation safety for staff making interventions and maintenance at the target, bunching stage, accelerators and decay ring
  - 88% of ^{18}Ne and 75% of ^{6}He ions are lost between source and injection into the Decay Ring
  - Detailed studies on RCS (manageable)
  - PS preliminary results available (heavily activated, >60 years operation)
  - SPS and Decay Ring ongoing
- Safe collimation of "lost" ions during stacking ongoing
  - ~1 MJ beam energy/cycle injected, equivalent ion number to be removed, ~25 W/m average
- Magnet protection (PS and Decay Ring manageable)
- Dynamic vacuum ongoing
- First study (Magistris and Silari, 2002) shows that Tritium and Sodium production in the ground water around the decay needs to be studied (when site known)

Beta-beam at FNAL

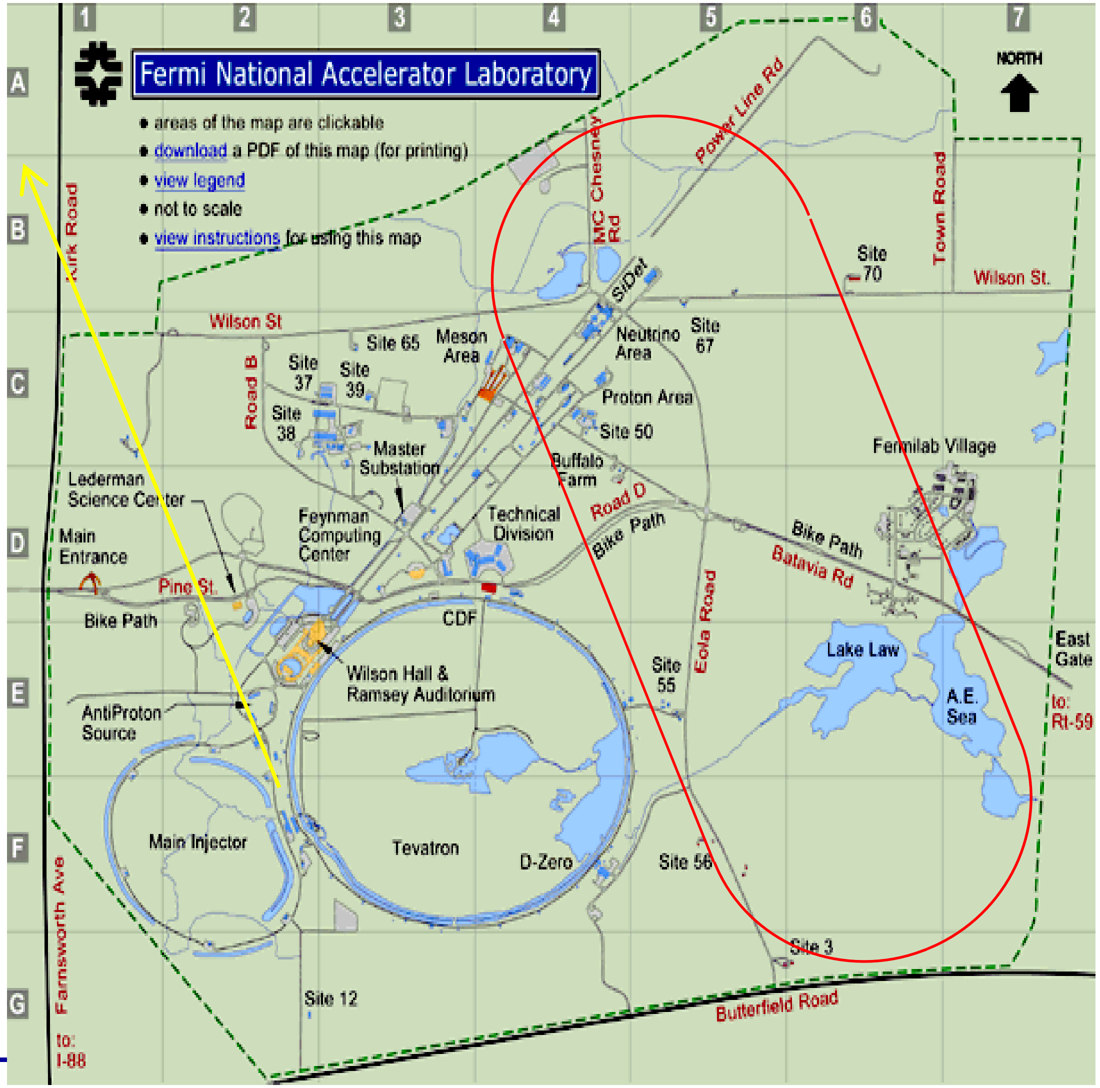
“Stretched Tevatron“

Bρ = 3335 Tm
R = 1000 m (75% 4.4T dipoles)
L_{SS}= ~3500

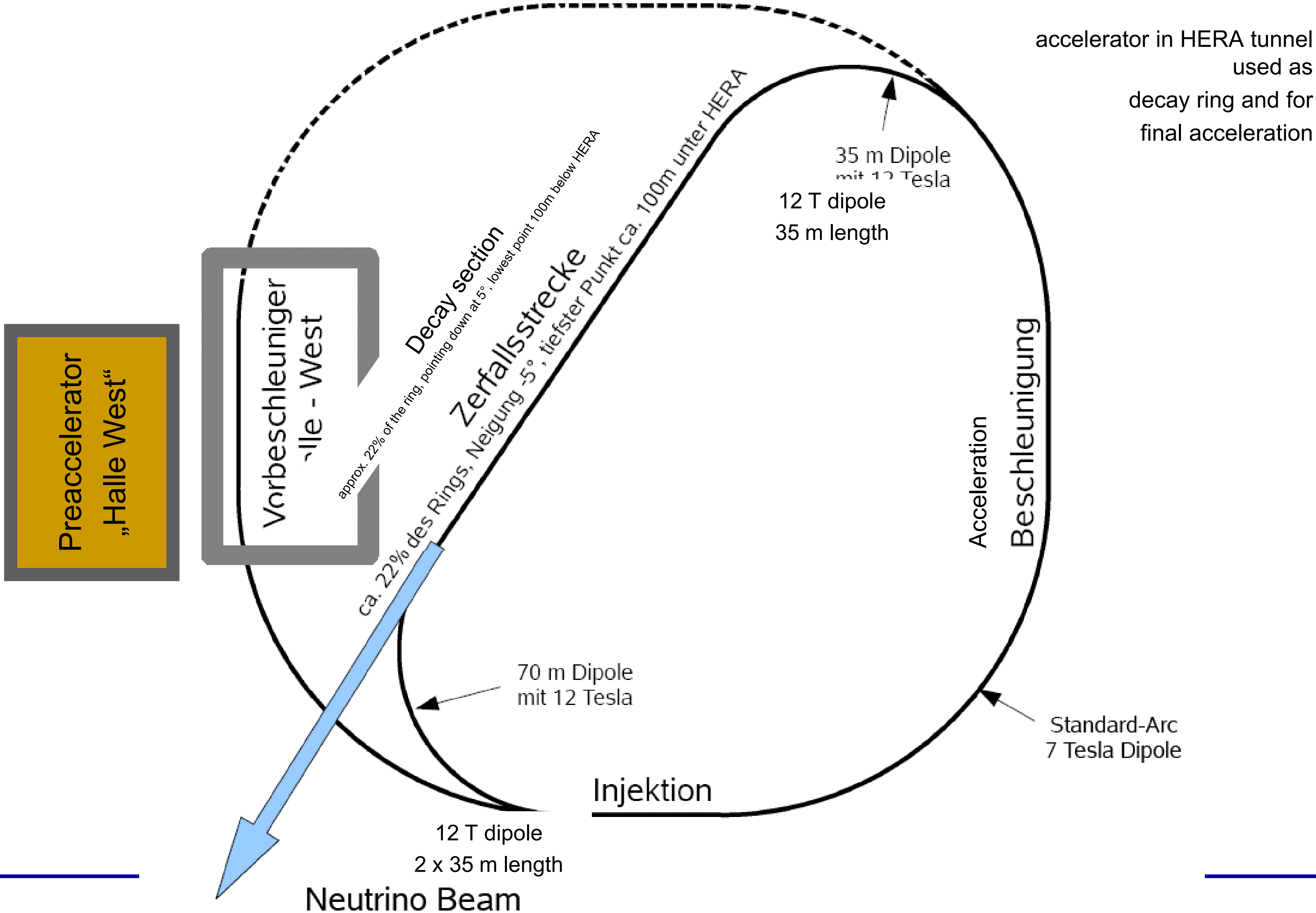
Total circumference:
approximately 2 x Tevatron

320m elevation @ 58 mrad

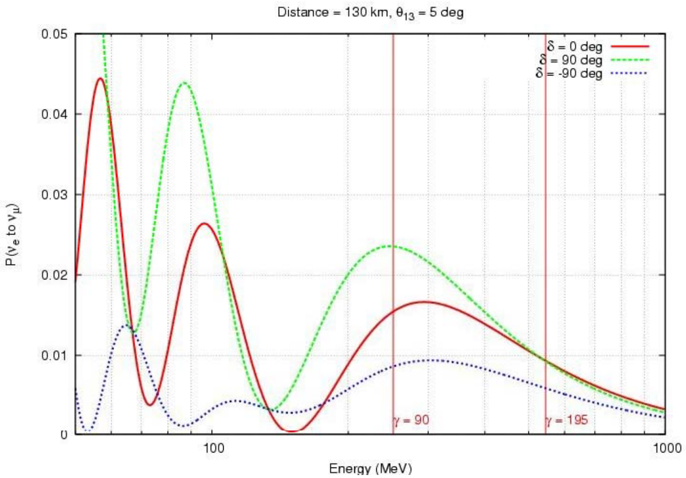
26% of decays in SS

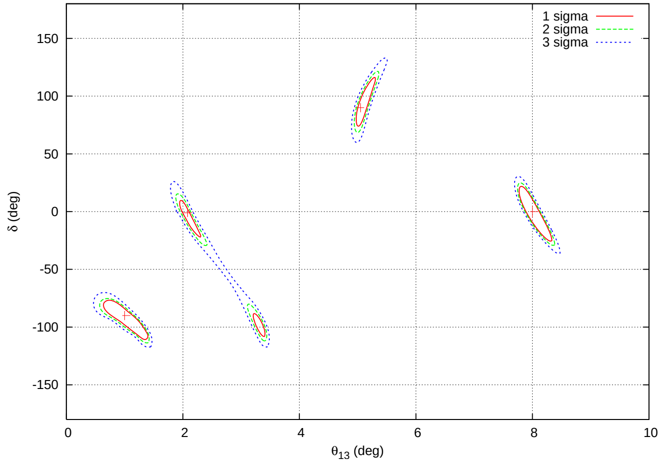


Beta-beam at DESY



EC: A monochromatic neutrino beam





Decay	$T_{1/2}$	BR_ν	EC/ν	I^{β}_{EC}	B(GT)	E_{GR}	Γ_{GR}	Q_{EC}	E_ν	ΔE_ν
$^{148}Dy \to {}^{148}Tb^*$	3.1 m	1	0.96	0.96	0.46	620		2682	2062	
$^{150}Dy \to {}^{150}Tb^*$	7.2 m	0.64	1	1	0.32	397		1794	1397	
$^{152}Tm2^- \to {}^{152}E_T^*$	8.0 s	1	0.45	0.50	0.48	4300	520	8700	4400	520
$^{150}Ho2^- \to {}^{150}Dy^*$	72 s	1	0.77	0.56	0.25	4400	400	7400	3000	400

$$\Delta Q = -\frac{Z^2}{A_p}\frac{3r_p}{4\beta^3\gamma^3 c}\frac{R}{\tau_b}\frac{N_b}{\varepsilon}$$

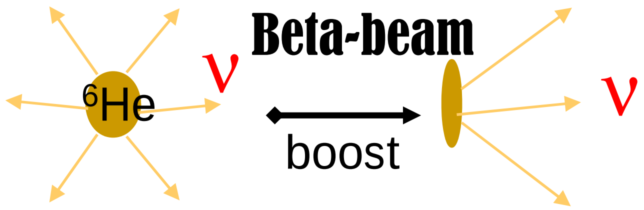
Laslet tune shift

Jose Bernabeu, Jordi Burguet-Castell , Catalina Espinoza and M. Lindroos

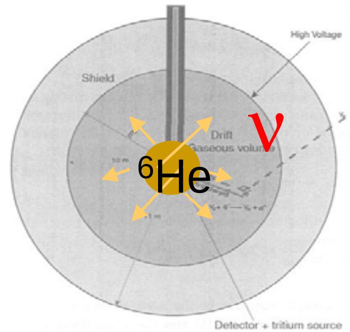
Low energy beta-beam

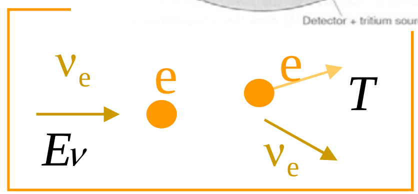
- The proposal
  - To exploit the beta-beam concept to produce intense and pure low-energy neutrino beams (C. Volpe, hep-ph/0303222, Journ. Phys. G. 30(2004)L1
- Physics potential
  - Neutrino-nucleus interaction studies for particle, nuclear physics, astrophysics (nucleosynthesis)
  - Neutrino properties, like n magnetic moment

Courtesy Cristina Volpe, IPN, IN2P3, Fr



$^{6}He \longrightarrow {}^{6}Li + e + \bar{\nu}_e \quad Q_\beta = 4.\ MeV$

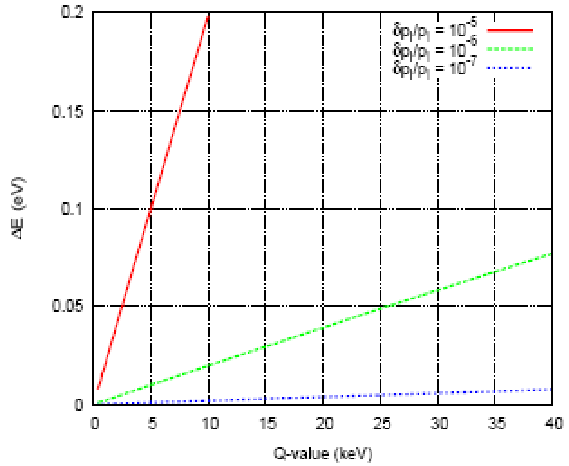


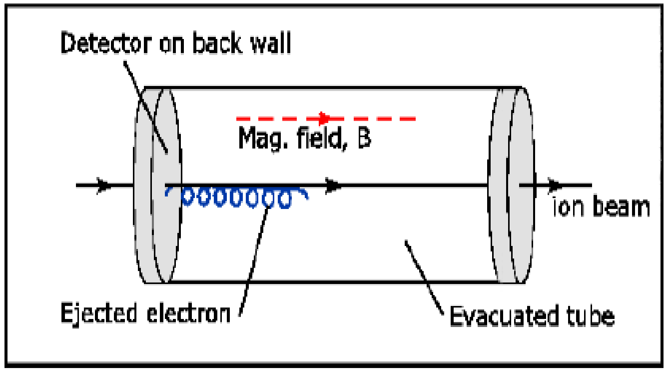


Precision measurements in storage rings

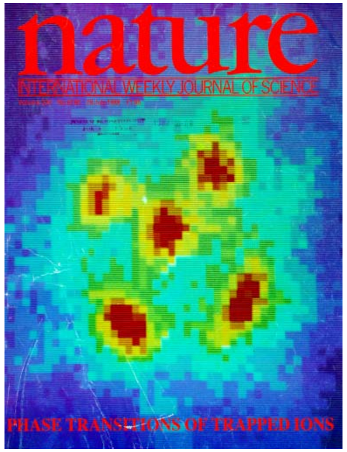
ESR at GSI

Courtesy Chris Orme, Durham U., UK

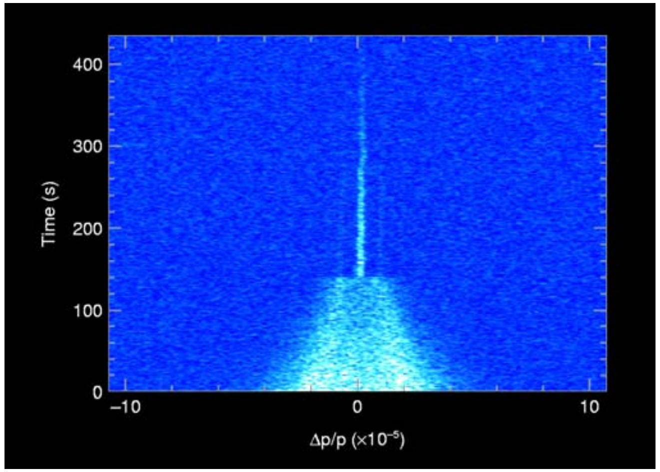


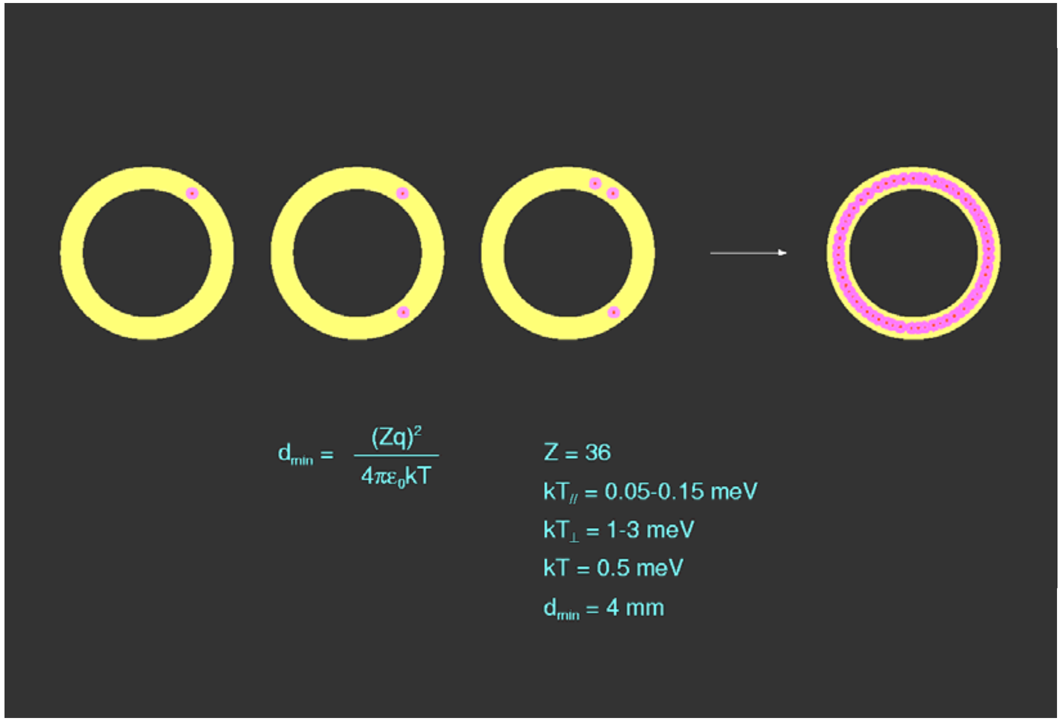


Ordered beams



Nature 1998, Walther et al.



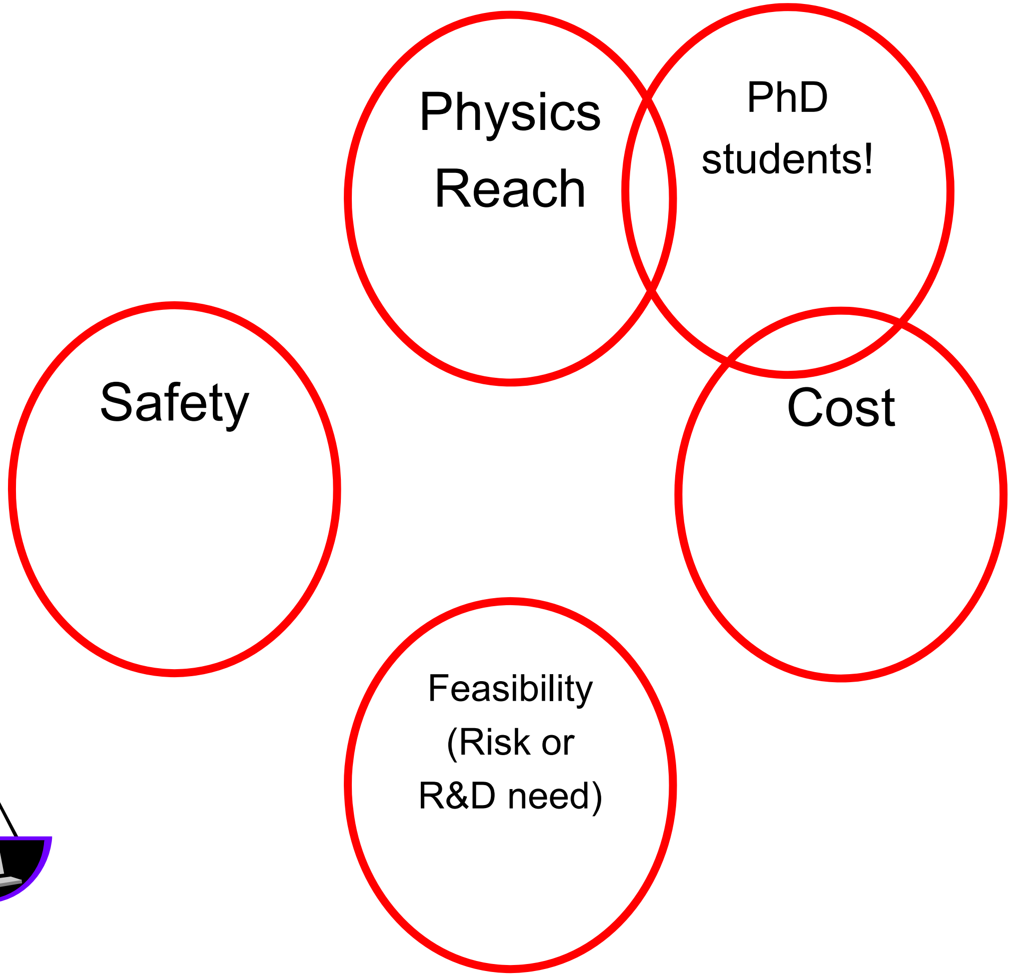


Courtesy Hakan Danared, MSL, Sweden

EURONU DS: Objectives

- **A High Intensity Neutrino Oscillation Facility in Europe**
  - CDR for the three main options: Neutrino Factory, Beta-beam and Super-beam
  - Focus on potential showstoppers
  - Preliminary costing to permit a fair comparison before the end of 2011 taking into account the latest results from running oscillation experiments
  - Total target for requested EU contribution: 4 Meuro
    - 1 MEuro each for SB, NF and BB WPs
    - 1 MEuro to be shared between Mgt, Phys and Detectors WPs
    - 4 year project which started 1st September 2008
- Join us for the First EURONU Town meeting at CERN, 25-26 March 2009

How to chose?



Physics Reach
PhD students!
Safety
Cost
Feasibility (Risk or R&D need)

Conclusions

- We have designs for:
  - Intense and well collimated neutrino beams
  - Neutrino beams of different flavours – single flavour beams
  - Monochromatic neutrino beams
  - Low and high energy neutrino beams
  - High precision neutrino beams

- Let us know what you want and we will build it for you
  - Caveat: We might need some time and money for R&D