Future Neutrino Oscillation Facilities

In Europe

I. Efthymiopoulos , CERN

EPS-HEP 2011
Grenoble - July 23, 2011

Future Neutrino Oscillation Facilities

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*Aegeus, King of Athens consulting the **Delphic Oracle**, Greek Vase, Altes Museum - Berlin, Ge*

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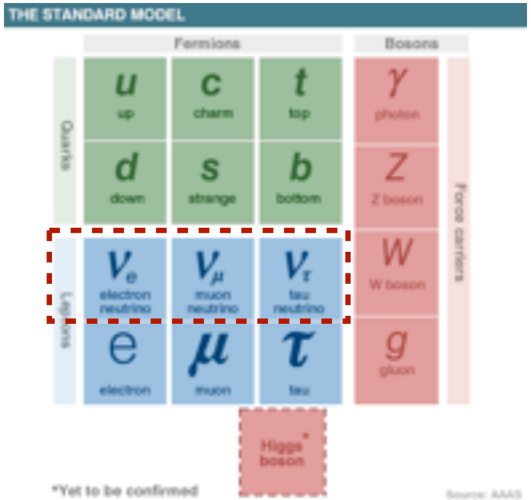
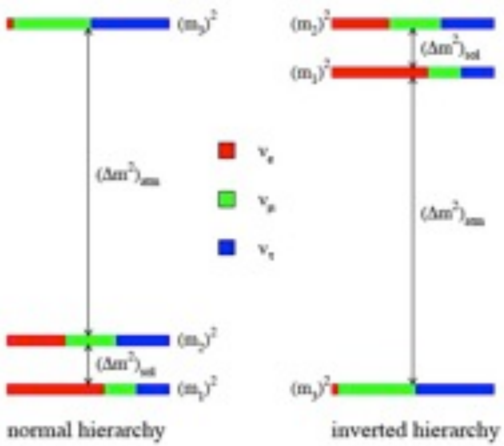
Why study ν physics ?

- νs are part of the Standard Model (SM), yet the least understood particles
  - yet there are in large abundance in the Universe and play an important role in early universe
  - we know they have masses because they oscillate, but which (Majorana mass terms?) and why (hierarchy)? are there only 3-neutrino families of left handed-νs?



- νs call for an extension to the SM
  - no unique theory of ν mass generation - hint for underlying theory?

- is there CP-violation in the leptonic sector as observed for the quarks?
  - this could impact the cosmological models for the matter-antimatter asymmetry in the universe



- the ultimate theory of matter must include quarks and leptons
  - full understanding of the leptons/neutrinos is required
  - can't be done with LHC or ILC, CLIC

Why long baseline ν beams?

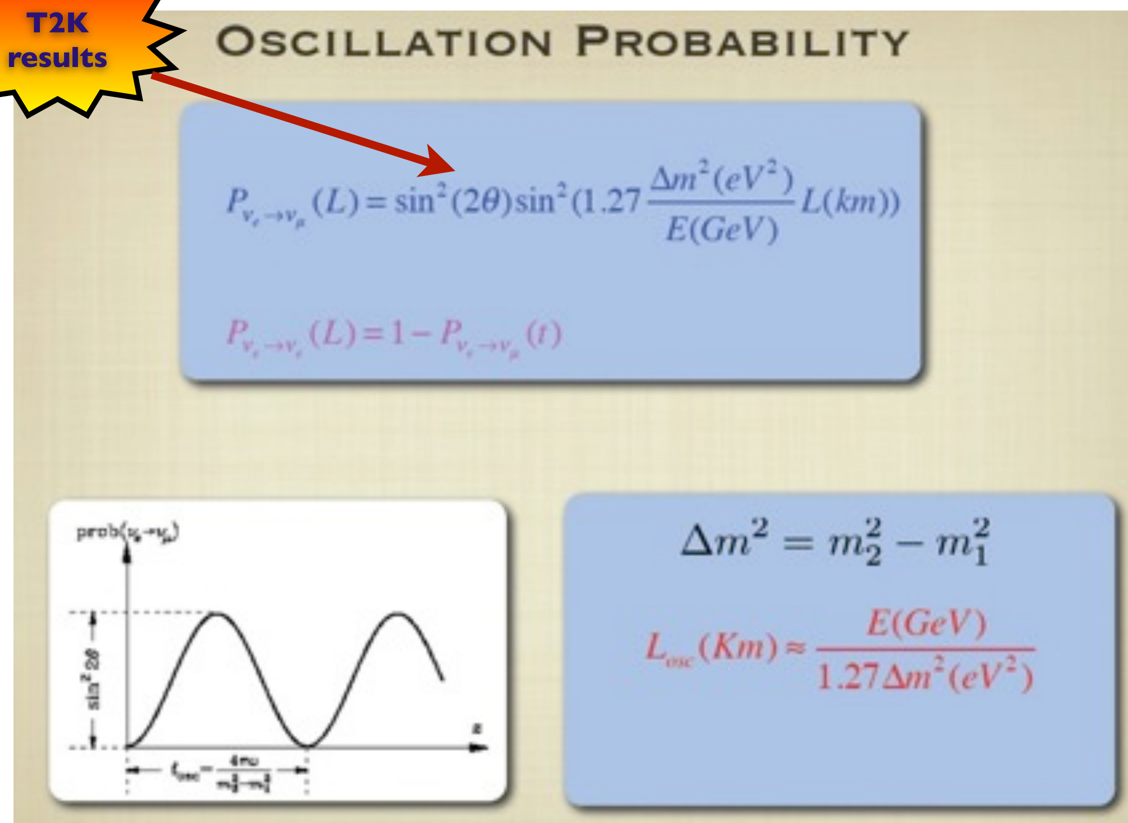
- easy(!!) way to produce νs and study their properties
  - alternatives: ν from reactors, beta-decay, μ-decay
- long, very long, or short beam lines depends on the value of the parameters

Courtesy JJ Gadenas

T2K results

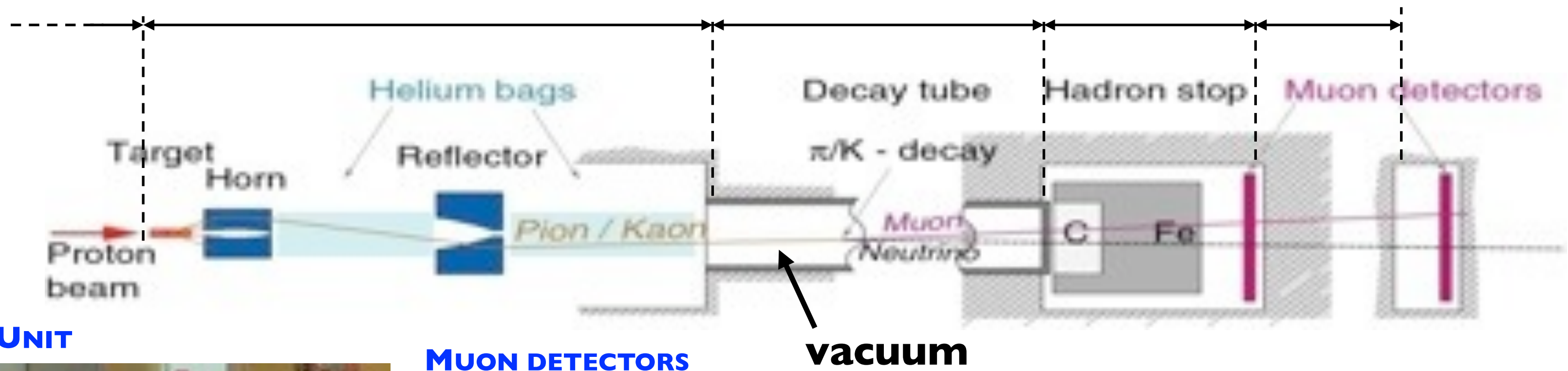
Typical configuration:

- **ν-source:**
  - $\pi^{\pm}$ decay : ν-(super)beam
  - rad-ion decay : β-beam
  - $\mu^{\pm}$ decay : neutrino factory
- **ν-detectors:**
  - near detector
  - far detector(s) (on/off axis)
- Intensity (**beam power** to produce π,μ,ions) is the key factor
  - **high-intensity accelerators and beams**

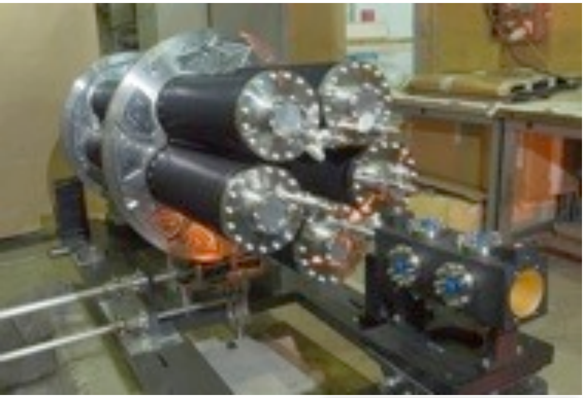


Conventional long baseline ν beam– CNGS

$p + C \rightarrow (\text{interactions}) \rightarrow \pi^+,\ K^+ \rightarrow (\text{decay}) \rightarrow \mu^+ + \nu_\mu$

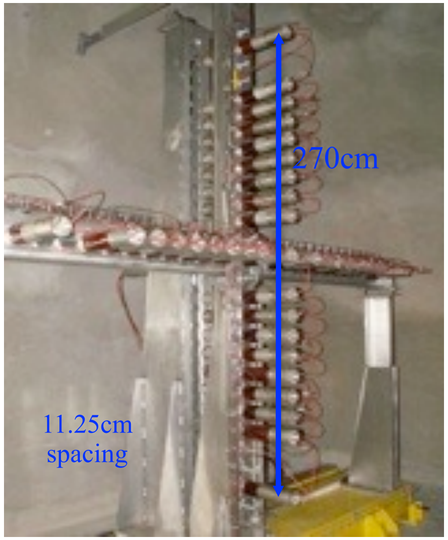


Target Unit



- C rods
- 5(4) mm Ø
- 5 in-situ spares

Muon detectors

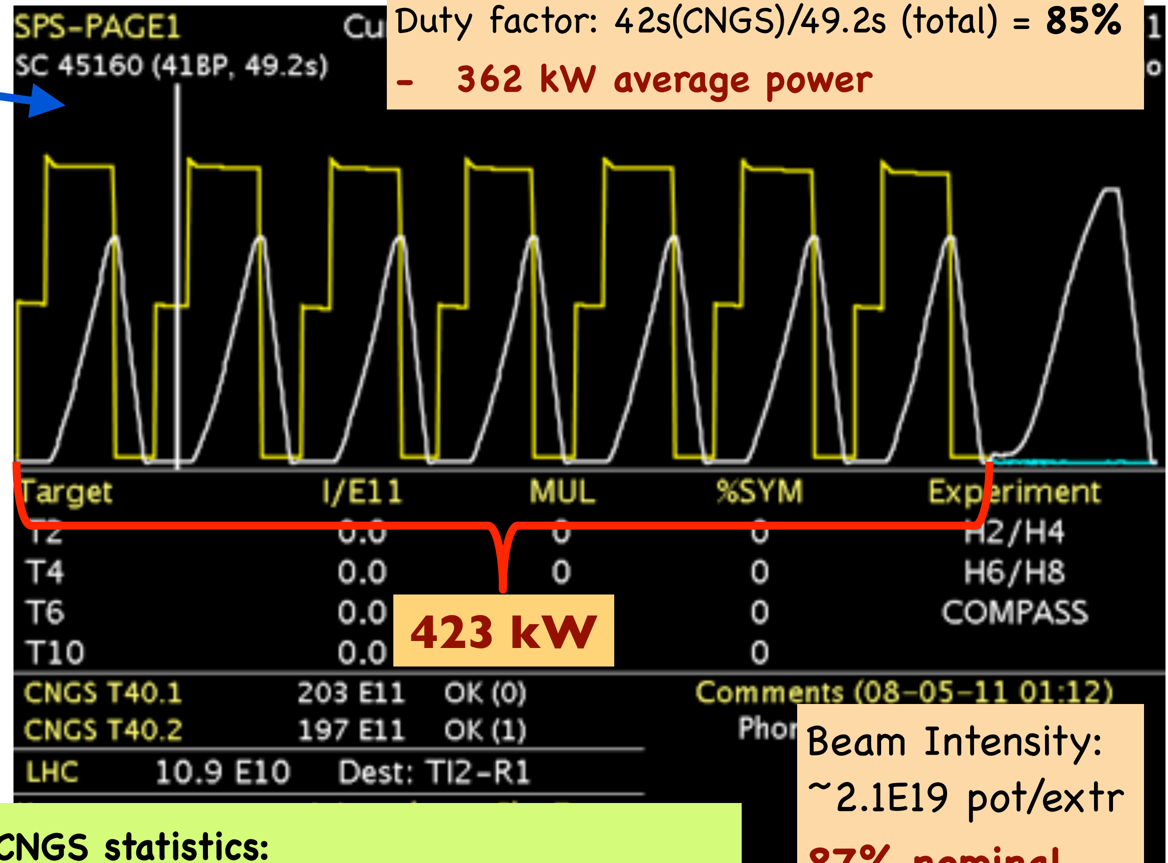


- 2 × 41 fixed monitors
- 2 × 1 motorized monitor

Magnetic Horns

Conventional ν beams – present

- **CNGS@CERN**
  - design: 500kW(beam), 750kW (infrastructure)
  - OPERA/ICARUS experiments
    - high energy for ν_τ appearance
    - no near detector
- **T2K@J-PARC**
  - design: up to 1.6MW(beam), 4MW (infrastructure)
  - near detector + Super-K
    - indication for θ_{13} non-zero and large
- **NUMI@FNAL**
  - design : 400kW(beam), upgrade
  - near detector + MINOS
    - results support θ_{13} non-zero hypothesis
    - possible difference in ν, anti-ν oscillations



Duty factor: 42s(CNGS)/49.2s (total) = **85%**
- 362 kW average power

423 kW

Beam Intensity:
~2.1E19 pot/extr
87% nominal

CNGS statistics:
- 11.86 $\times 10^{19}$ pot delivered
- 5y $\times$ 4.5$10^{19}$ pot approved program

Note: design and operation of a high-intensity beam facility is always very challenging

Conventional ν-beams - future possibilities

Long-baseline beams - a staged approach towards high-intensity

JPARC

T2K (250km)
- **30 GeV** beam from MR
- **70kW** operation in 2010

→

T2K (250km)
- **30 GeV** beam from MR
- reach **500kW** in 2013

→

T2K (250km)
T2O (658km)
- **30 GeV** beam from MR
- **1.66MW** with MR upgrades

FNAL

NuMI/MINOS (735km)
- **120 GeV** beam from MI
- **320kW** operation

→

NuMI/MINOS(735km)
NOνA(830km-OA)
- **120 GeV** beam from MI
- **700kW** with MI upgrade

→

LBNE/DUSEL (1300 km)
- initial: **700kW**
- final: **2MW, 60-120 GeV beam** with Project-X

CERN

CNGS (732km)
- **400 GeV** beam from SPS
- **300-400kW** operation

→

CNGS+ (732km) **or**
CN2PY (2300km)
- **500-750kW,** with SPS and injector upgrade

→

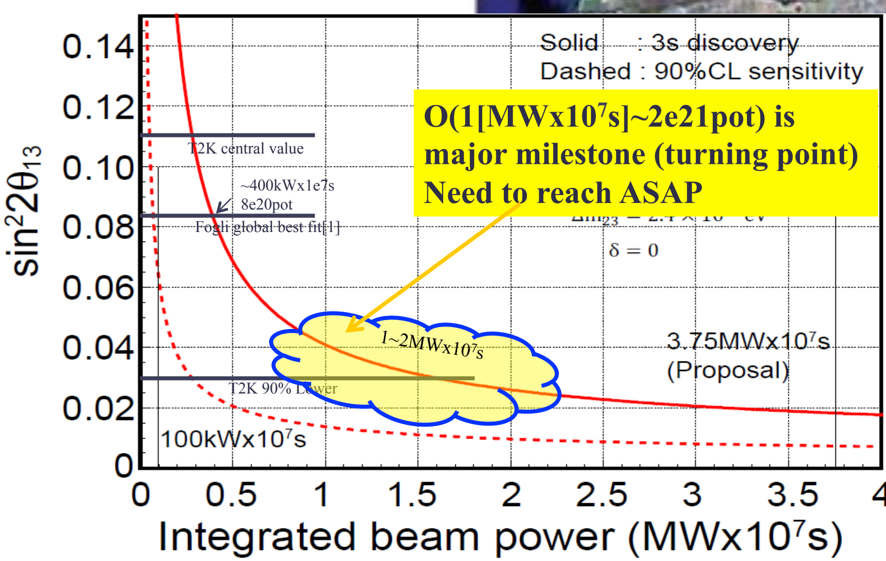
CN2PY(2300km)
- **2MW,** LP-SPL + HPPS

CN2FR(130km)
- **4MW** HP-SPL + accumulator

LAGUNA-LBNO, EUROν FP7 Design Studies

ν-beams - Future possibilities : Japan

- **T2K beam to Super-Kamiokande**

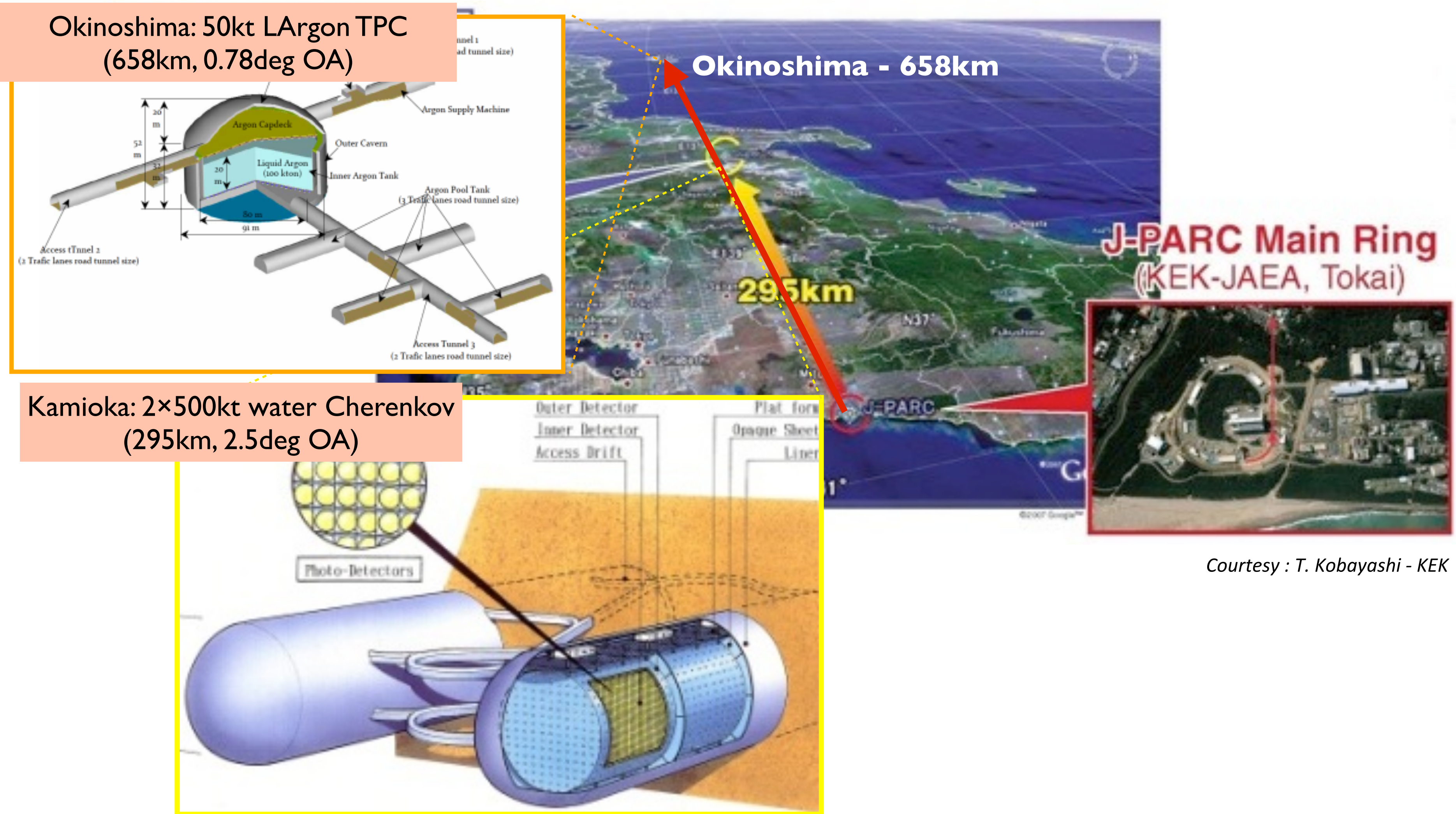


Courtesy : T. Kobayashi - KEK

- recovery from earthquake damages ongoing, expect to restart the J-PARC in **Dec'11**, beam for T2K in **March'12**

ν-beams - Future possibilities : Japan

- **T2K beam to Super-Kamiokande + Okinoshima**

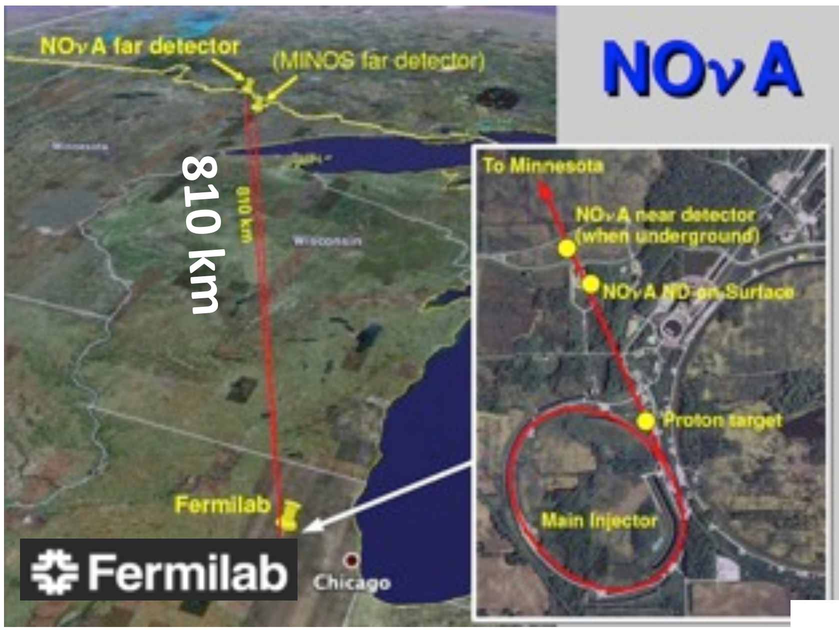


Courtesy : T. Kobayashi - KEK

ν-beams - Future possibilities : FermiLab

NOνA off-axis experiment @FNAL

- 120 GeV beam from MI like NUMI



- **NuMI beam upgrade: 320--> 700kW**
  - use recycler as p-ring
  - reduce MI cycle time from 2.2s to 1.33s
  - new high-power target station
  - new extraction/injeciton lines
  - expect: ~6×10^{20} **pot/yr** starting **2014**

LBNE very-long baseline beam to DUSEL

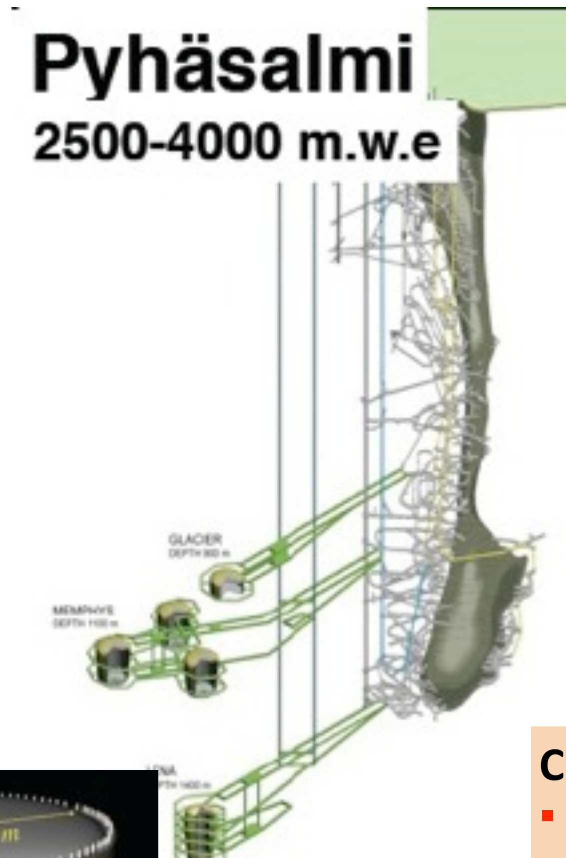
- initial phase: same beam as NuMI-NOνA - **120 GeV** from MI, **700kW**
- upgrade to : **2.3 MW - Project-X**
- far detector : 100kt Water Cherenkov (Super-K technology) or LArgon TPC

Courtesy : FNAL - NuMI,LBNE web pages

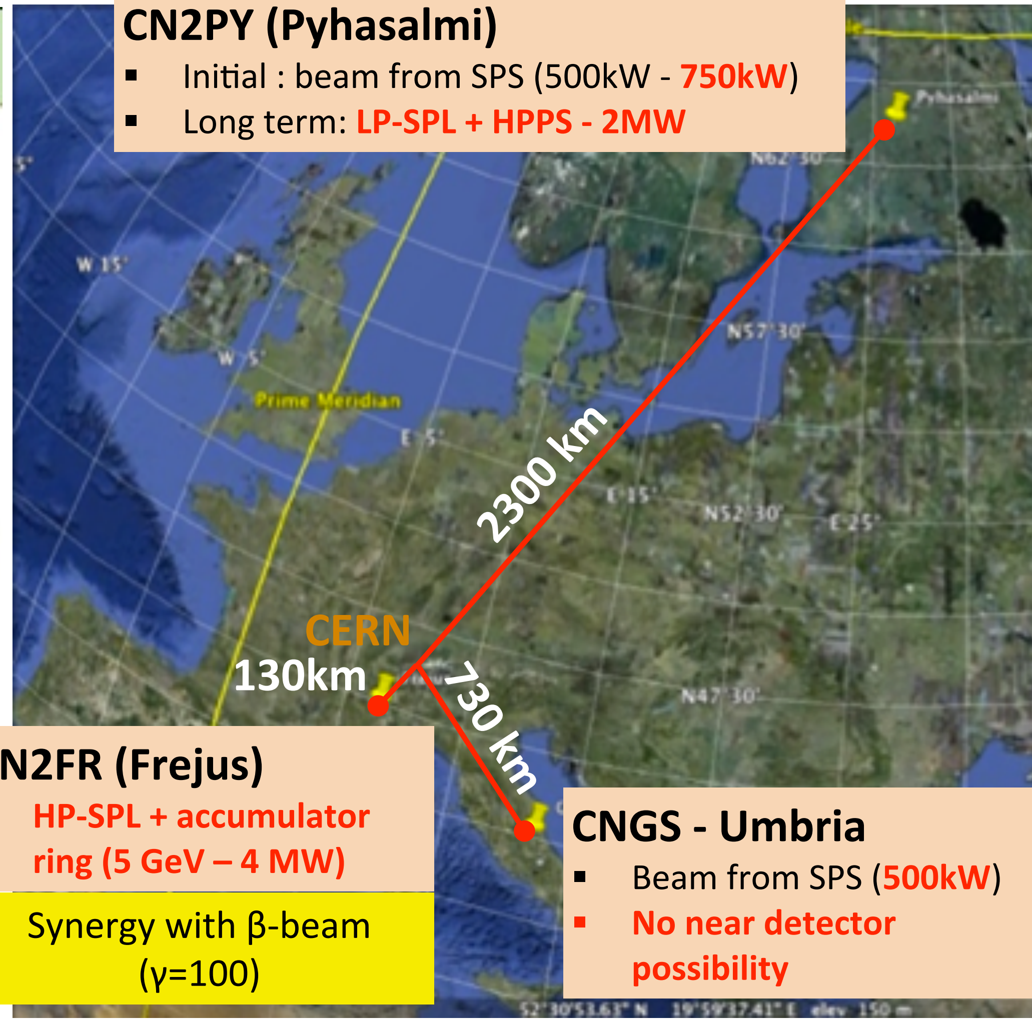
ν-beams - Future possibilities : CERN

- Long-baseline options - LAGUNA_LBNO Design study

LENA
(liquid scintillator)



GLACIER
(LArgon - TPC



CN2PY (Pyhasalmi)
- Initial : beam from SPS (500kW - 750kW)
- Long term: LP-SPL + HPPS - 2MW

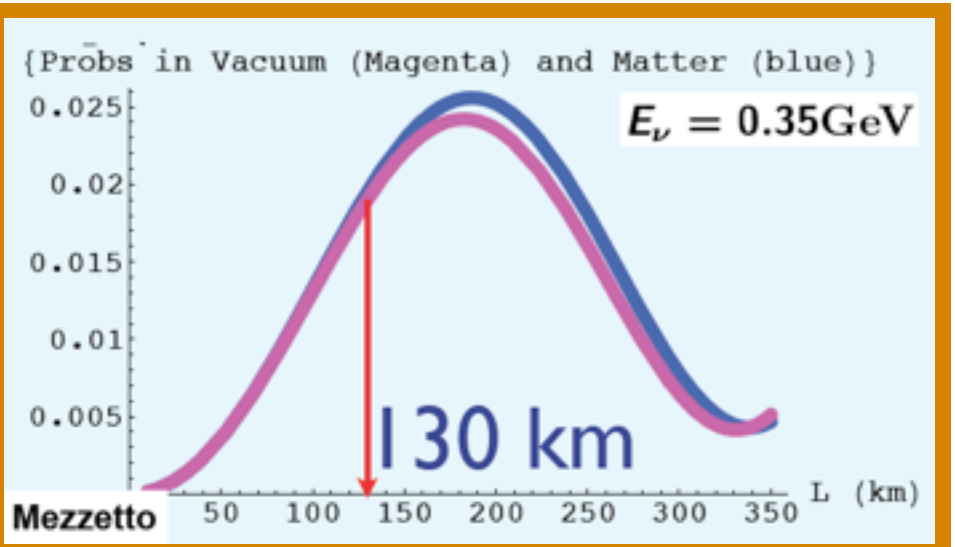
CN2FR (Frejus)
- HP-SPL + accumulator ring (5 GeV – 4 MW)

Synergy with β-beam
(γ=100)

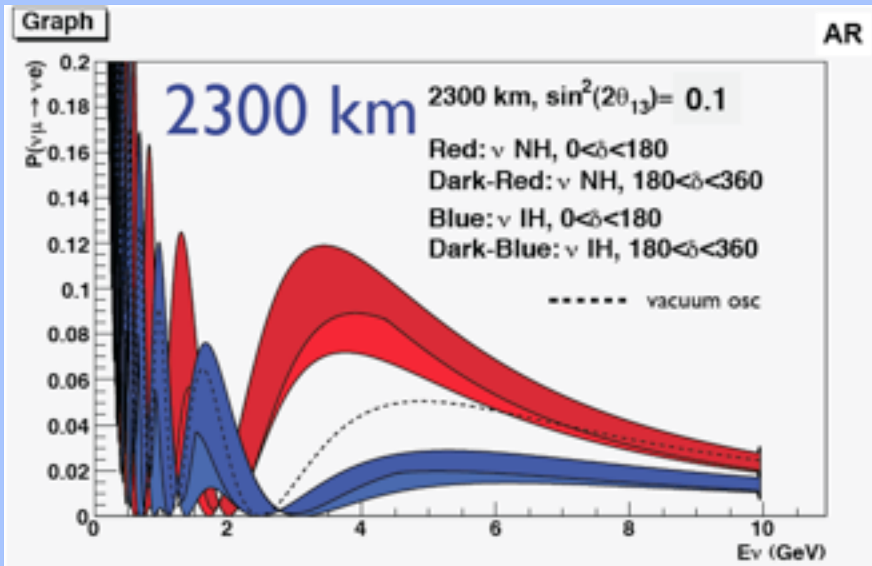
CNGS - Umbria
- Beam from SPS (500kW)
- No near detector possibility

ν-beams - Future possibilities : CERN

- CERN-Frejus-**CN2FR**(130km) & CERN-Pyhasalmi-**CN2PY**(2300km)
  - medium/very-long baseline combination for **unique physics opportunities in Europe**



- Determine CP-violation by comparison of ν/anti-ν in absence of competing matter effects
- Very low energy beam, huge (WC) detector

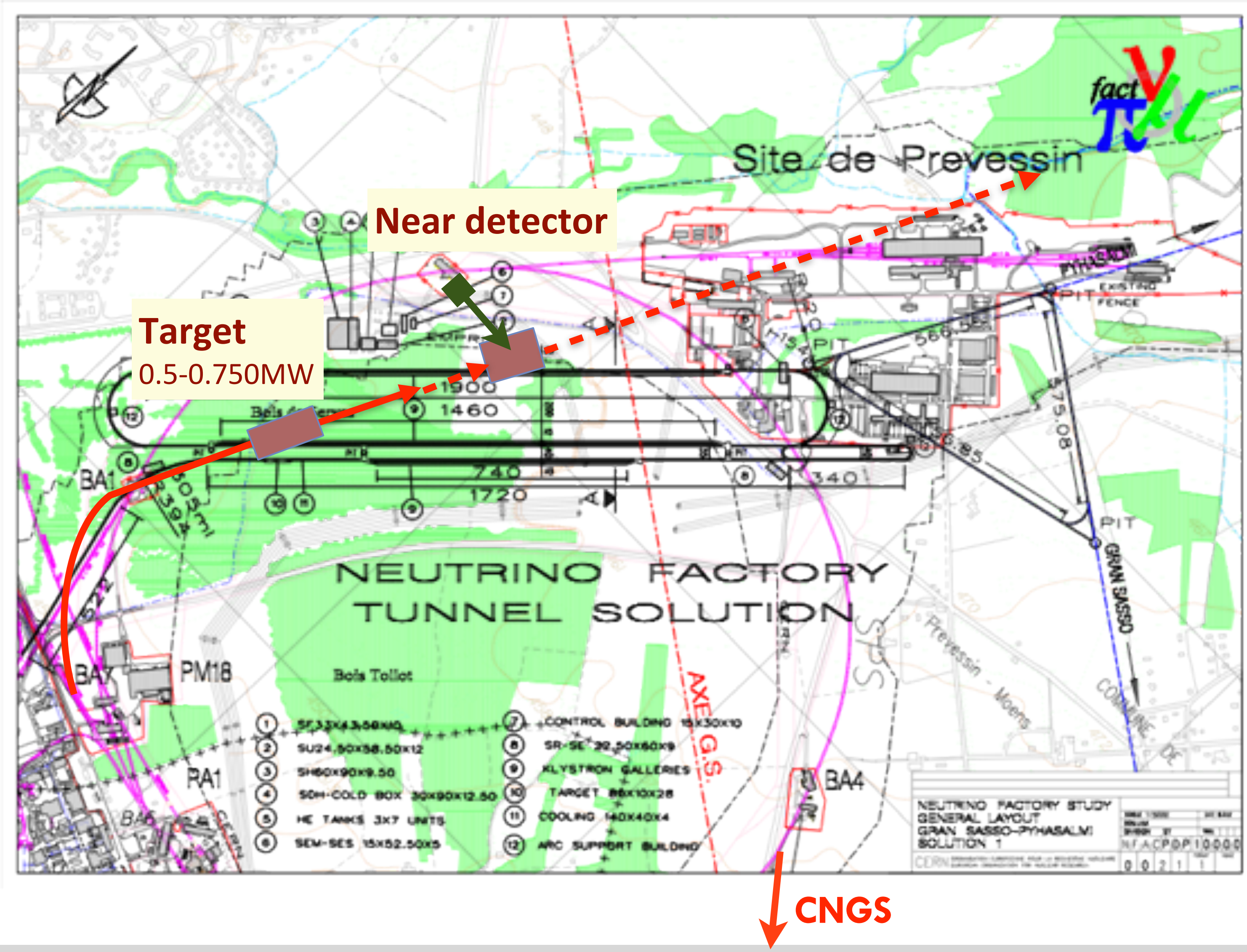


- Determine CP-violation and mass degeneracy by spectrum measurement and resolve degeneracies and so called "π-transit" effect
- arXiv:0908.3741.v1 for "Magic distance"

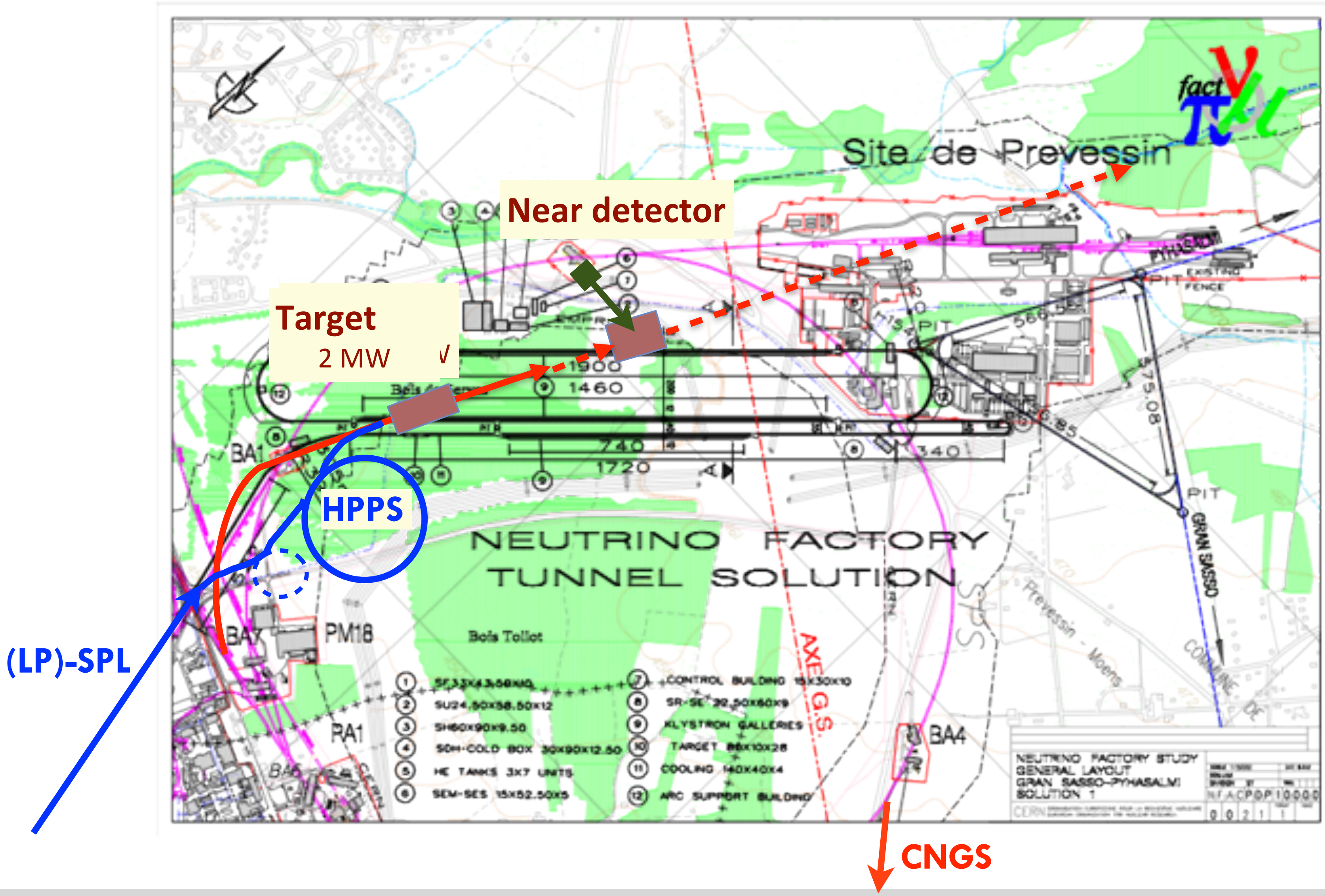
A. Rubbia, LAGUNA

- **... and synergies:**
  - **CERN-Frejus** : adequate baseline/energy for β-beam – **CERN-Pyhasalmi** : adequate baseline for Neutrino-Factory from CERN or other labs (~7'000 km from FermiLab/J-PARC)

CERN ν-beam to Pyhasalmi – CN2PY

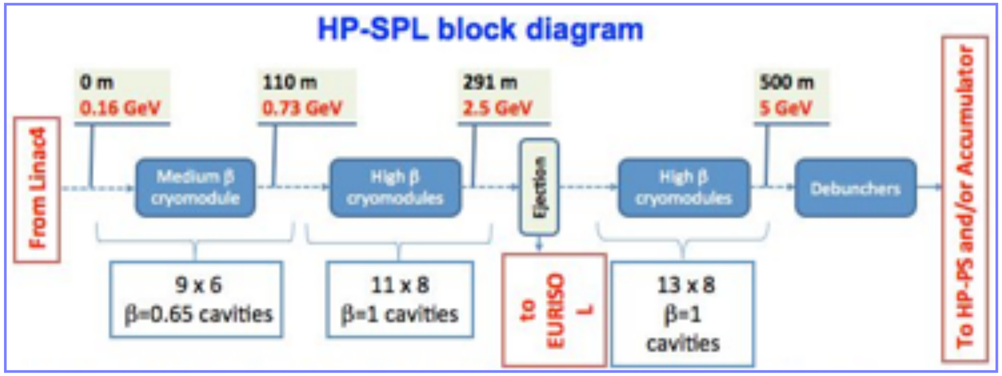


CERN ν-beam to Pyhasalmi - CN2PY



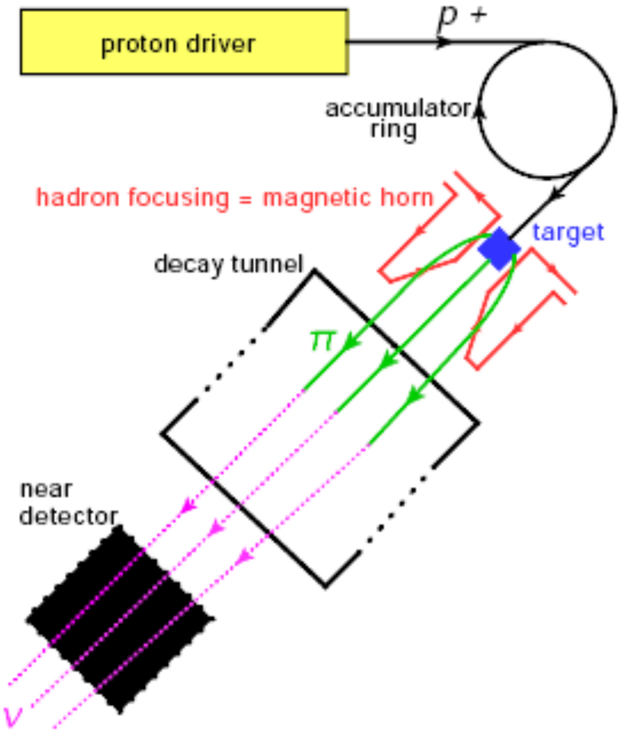
ν-beams - Future possibilities : CERN

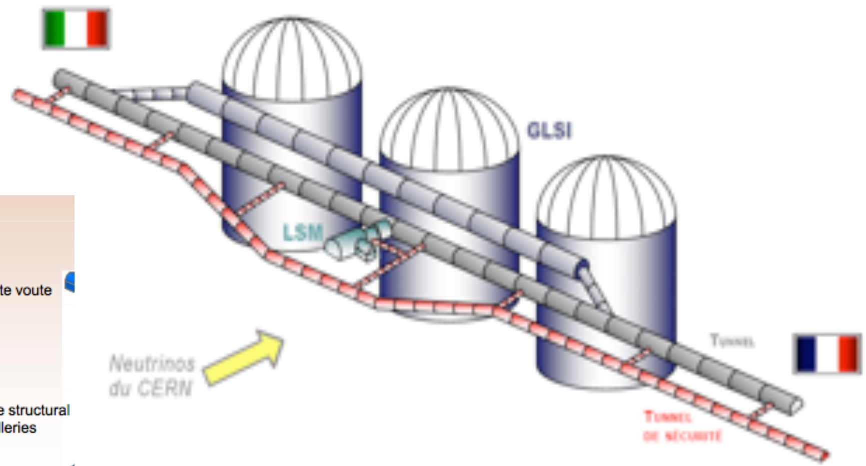
CN2FR : ν-sbeam based on HP-SPL to Frejus



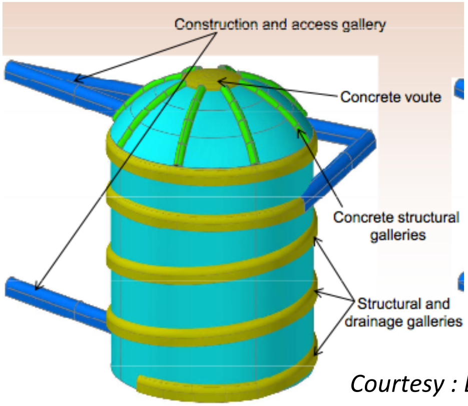
Courtesy : R.Garoby - CERN

Ion species H⁻
Output Energy 5 GeV
Bunch Frequency 352.2 MHz
Repetition Rate 50 Hz
High speed chopper < 2 ns
(rise & fall times)





MEMPHIS
(Water Cherenkov)

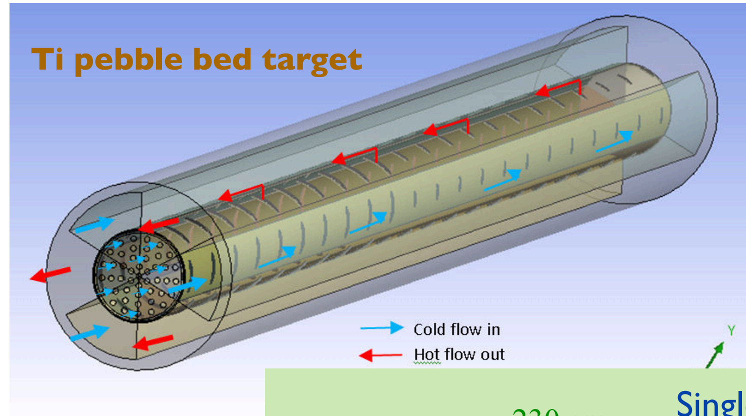


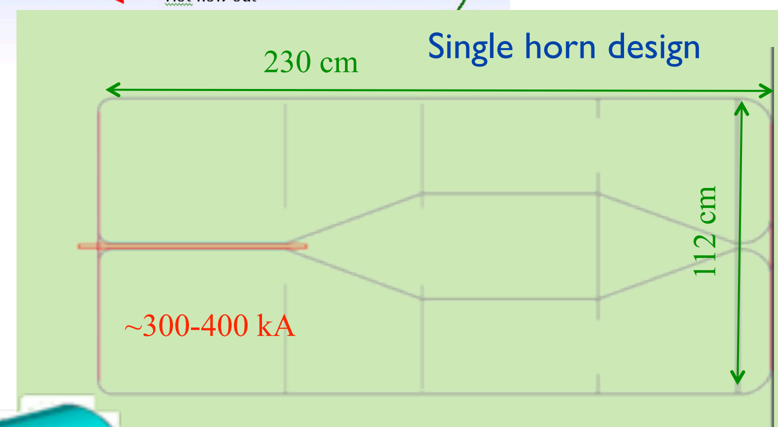
Courtesy : LAGUNA

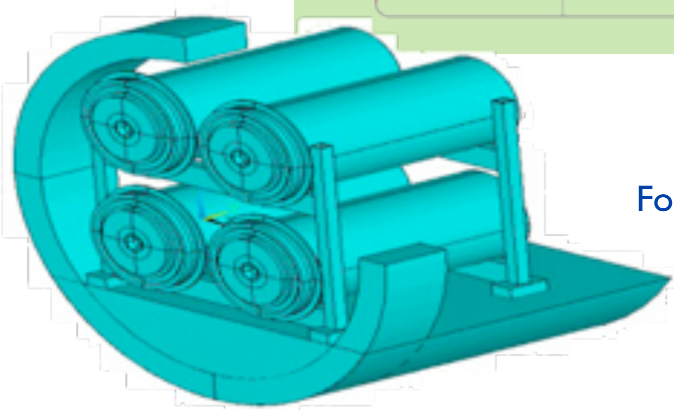
ν-beams - Future possibilities : CERN

CN2FR - Technical challenges:

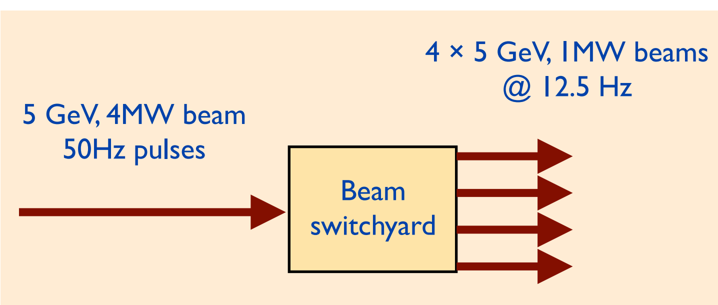
- Target design
  - impact of the 4MW beam
  - baseline : Ti pebble bed target (3mm spheres)
- Horn design
  - high current, mechanical constraints due to physics requirements, radiation, high-current (heating), pulsing
  - **Solution : 4 × 1 MW = 4 MW !!!!**
    - four target/horn assemblies mounted together in a mechanical frame
  - horn design similar to that of MiniBooNe





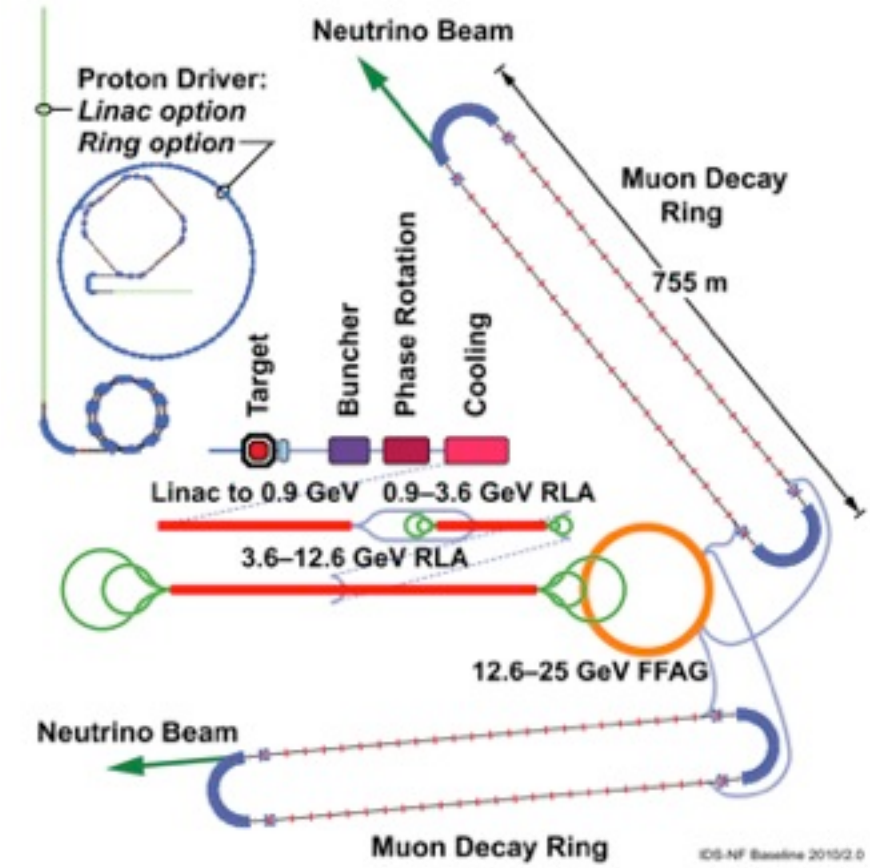


Four horn assembly



Future Possibilities - Neutrino Factory

- ν_s from **accelerated and stored μ^+ and μ^-**
- **precision-era facility**
  - θ_{13}, CP-violation, mass hierarchy, physics beyond SνM



- International Collaborative Effort within
  - **IDS-NF** : http://www.ids-nf.org
  - **EURONU/FP7** : http://www.euronu.org

Key technical challenges

- **Target station - MERIT & CERN**
  - liquid-Hg jet (baseline) @ 20m/s
  - tapered solenoid for pion capture
    - 20T tapering to 1.75T in ~13m
  - Alternatives: tungsten-powder jet, tungsten bars
- **Ionization cooling - MICE & RAL**
  - RF in B-fields
- **Rapid acceleration - EMMA @ Dasebury**
  - Fast acceleration of muons
  - Re-circulating linacs, ns-FFAGs

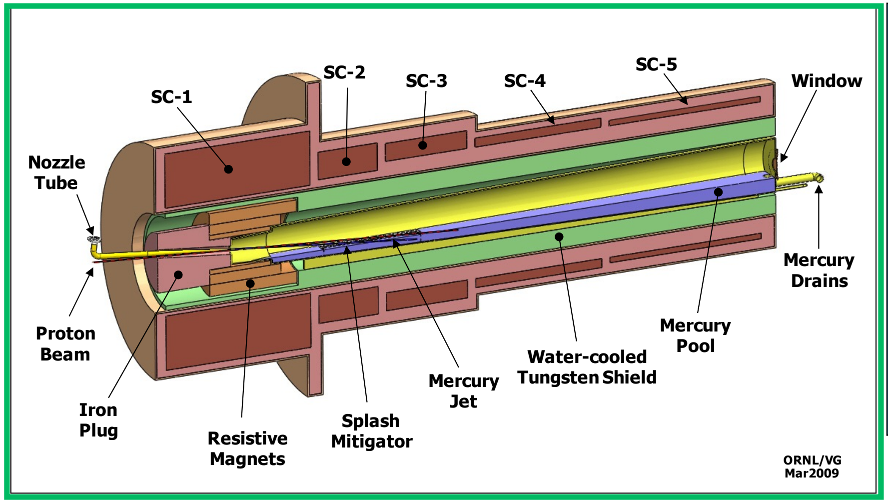
Layout

- **long/very-long baseline beams**
- **near/far detector combination**

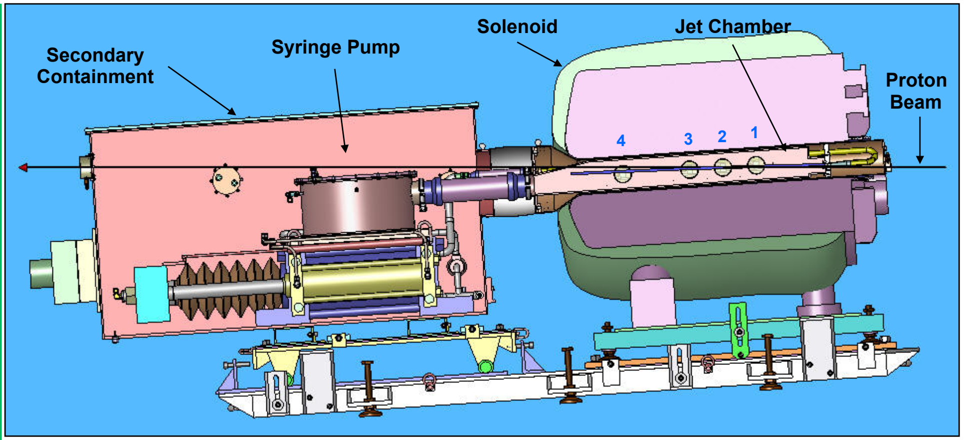
  MIND(MINOS-type), LSND(liquid scintillator), or LArgon-TPC

ν-Factory : Target R&D

NF - target station



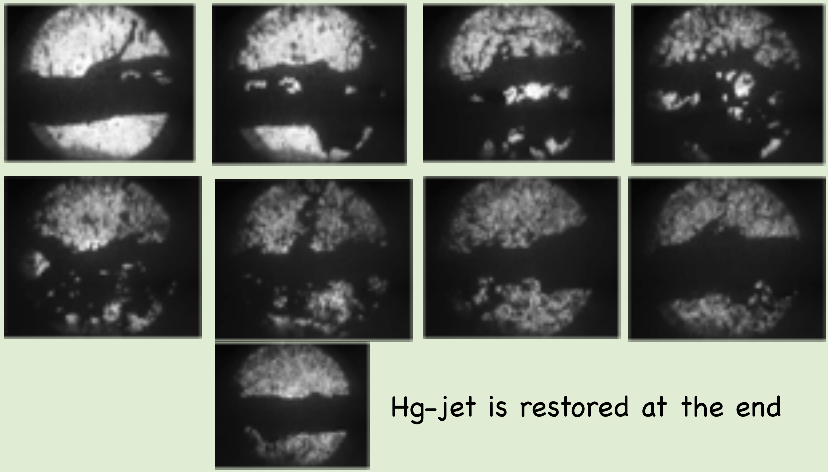
MERIT Experimental Setup



Key results

- Beam power(PS): 3.0×10^{13} **protons @24GeV,**
  - **115kJ beam pulse energy**
- Hg-jet disruption mitigated by magnetic field
- disruption length **28cm**
  - refill time @ 20m/s = 0.014s - **70Hz**
- **demonstrated operation at:**
  - **115kJ × 70 Hz = 8 MW**

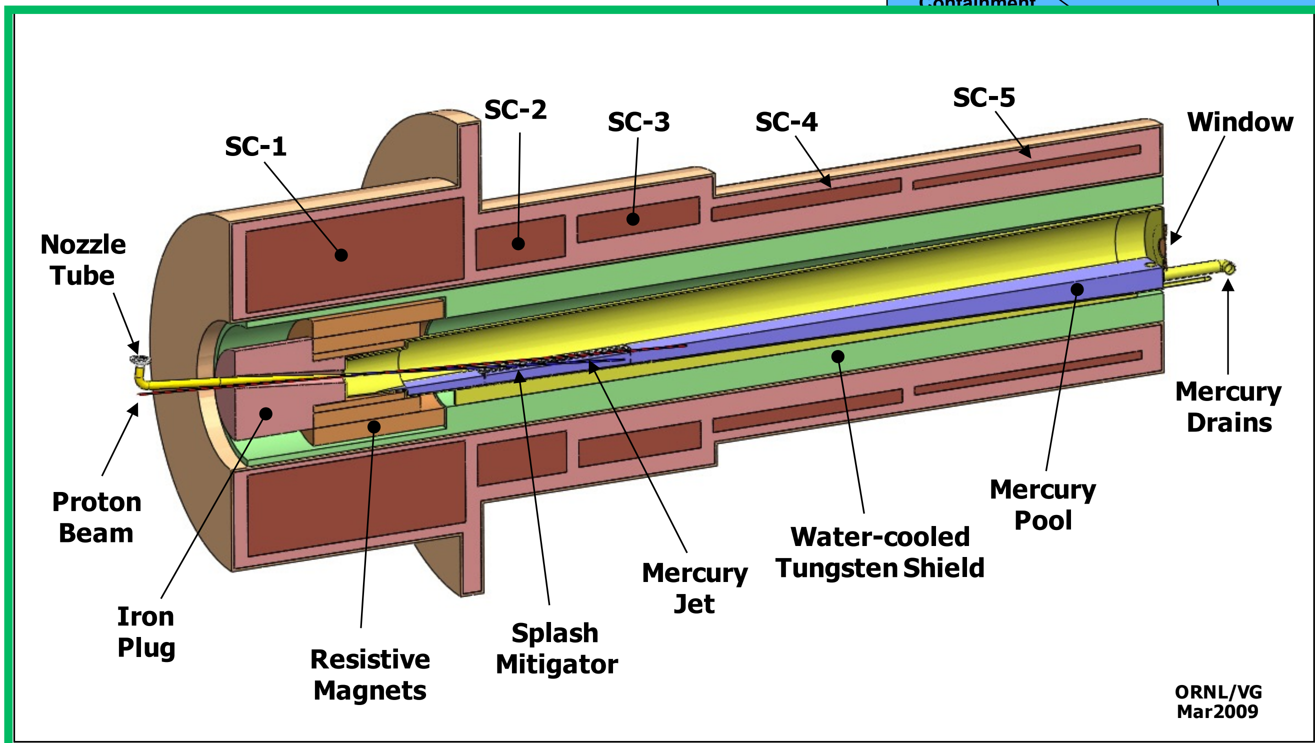
Hg-jet - beam impact 16×10^{12} p, 5T field, 14 GeV/c



Hg-jet is restored at the end

ν-Factory : Target R&D

NF - target station



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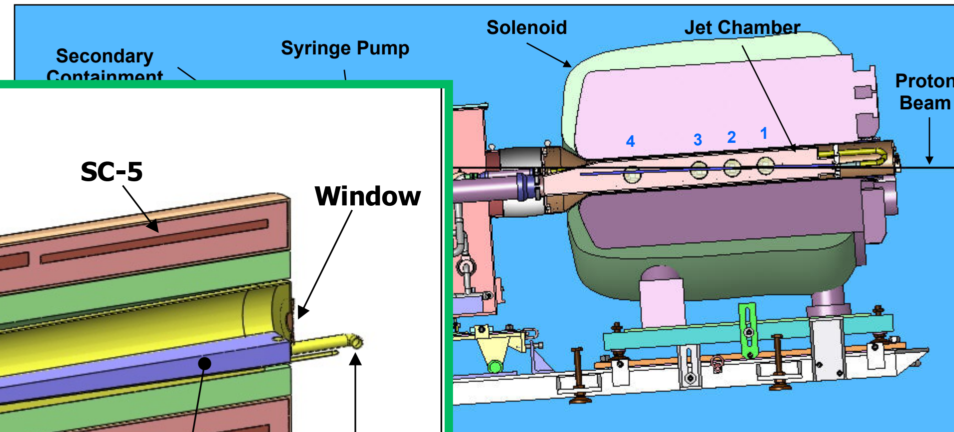

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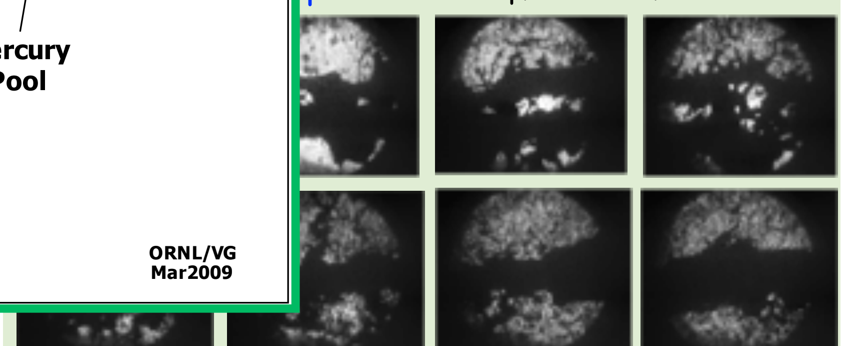

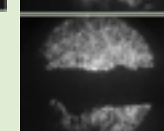

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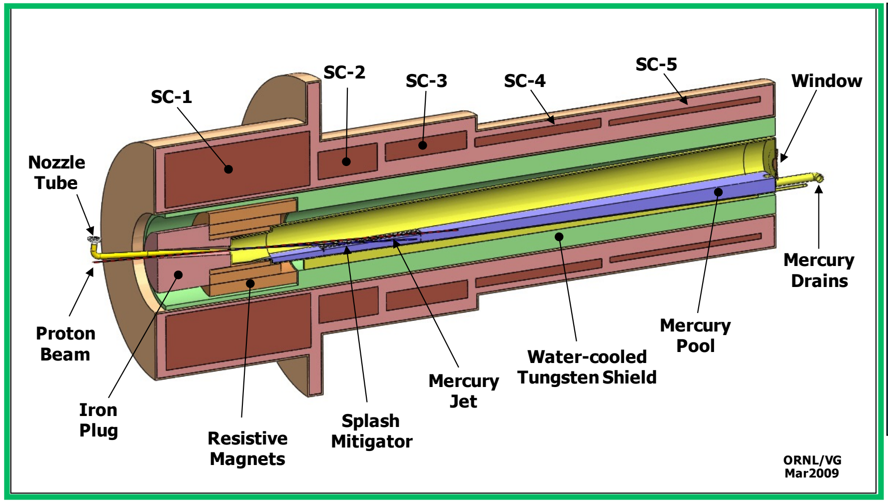
ν-Factory : Target R&D

NF - target station



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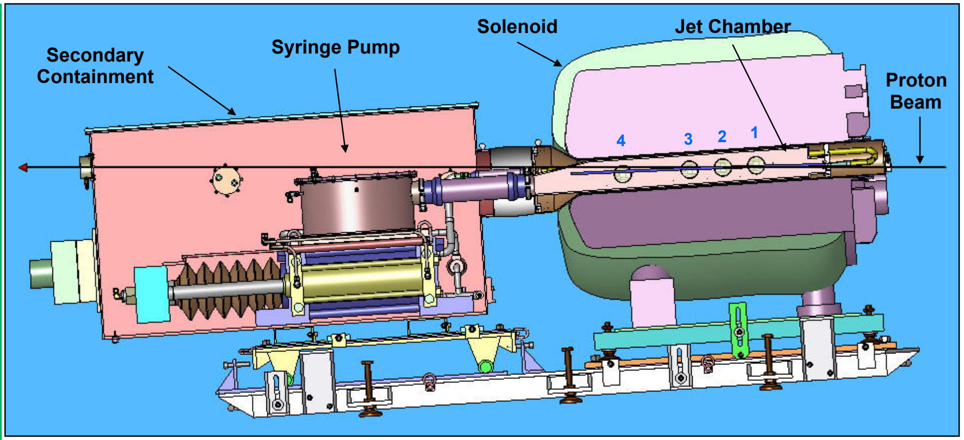

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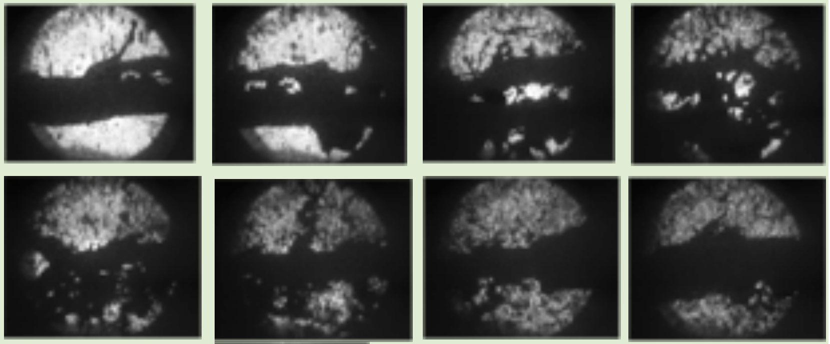
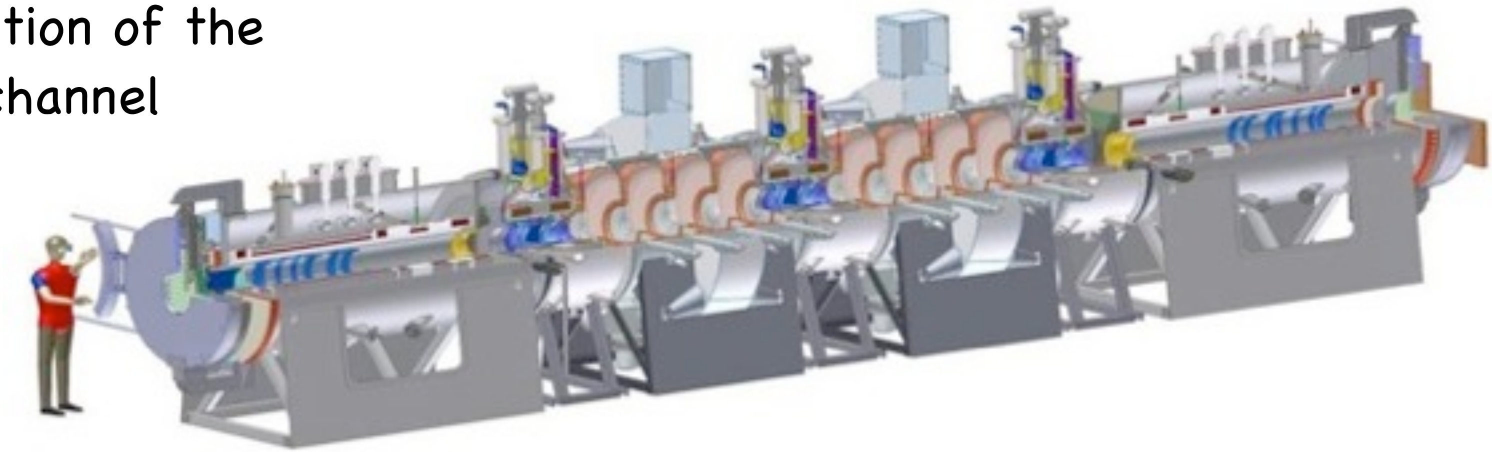
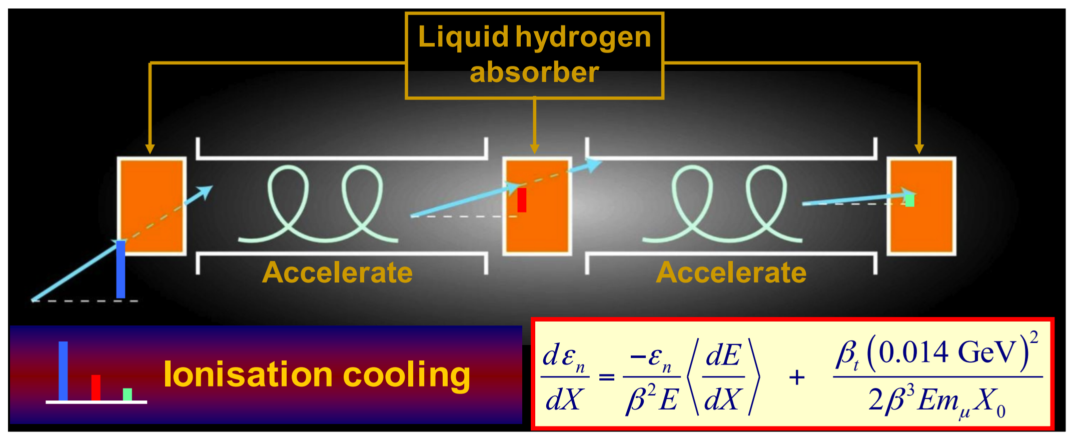


Hg-jet is restored at the end

ν-Factory : Muon Cooling R&D

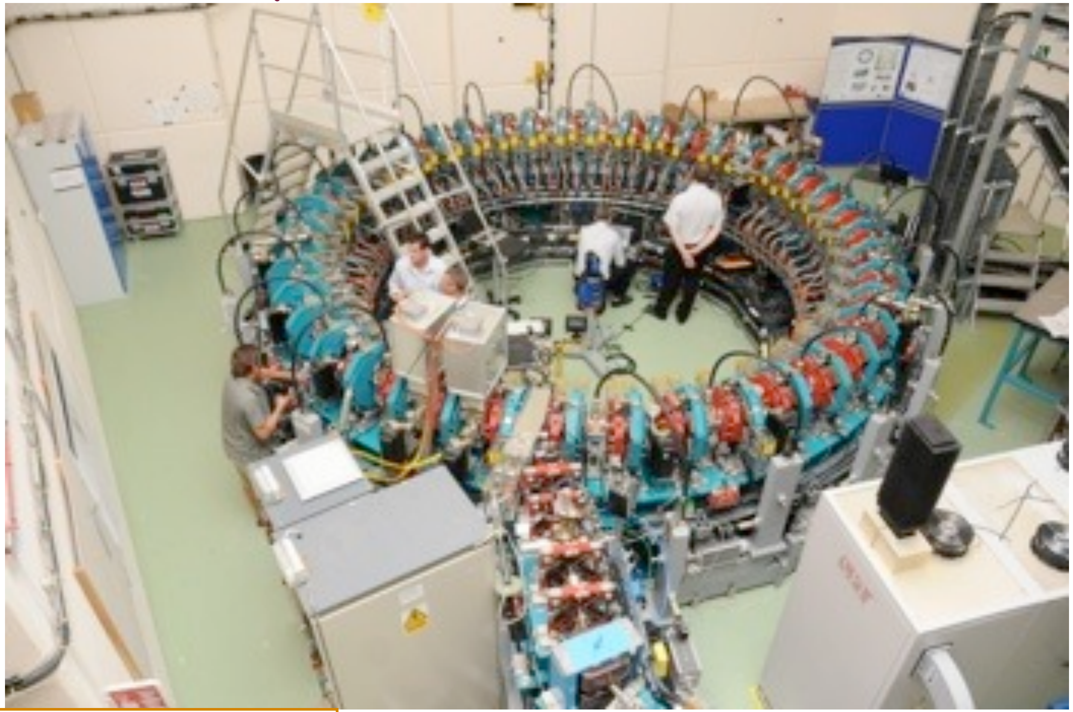
- **MICE Ionization cooling experiment @ RAL**
  - realistic section of the NF cooling channel





ν-Factory : Rapid Acceleration R&D

EMMA setup @ Dasebury

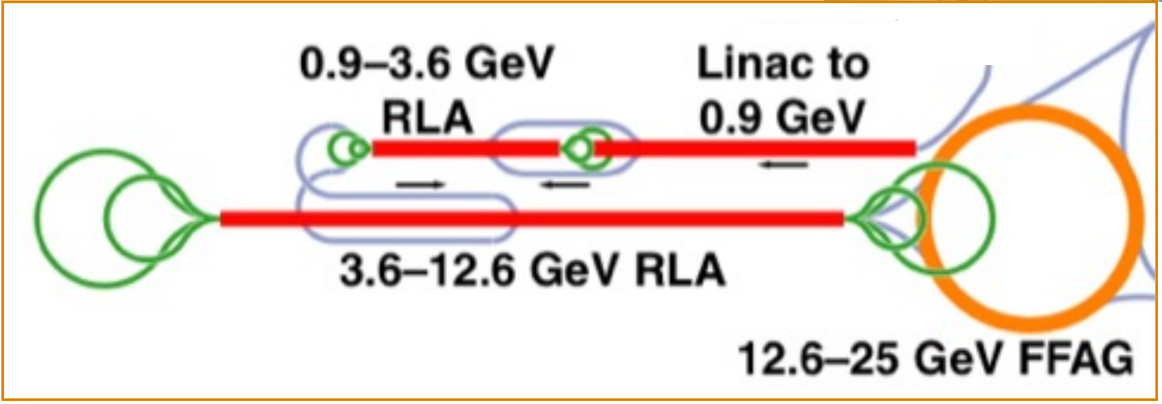


Rapid μ acceleration

- rapidly increase γ to increase μ lifetime

LINAC/RLAs

- **superconducting LINAC**
  - large acceptance
- **Recirculating RLAs**
  - rapid acceleration
  - cost-effective use of RF power



FFAG (Fixed Field Alternating Gradient accelerator)

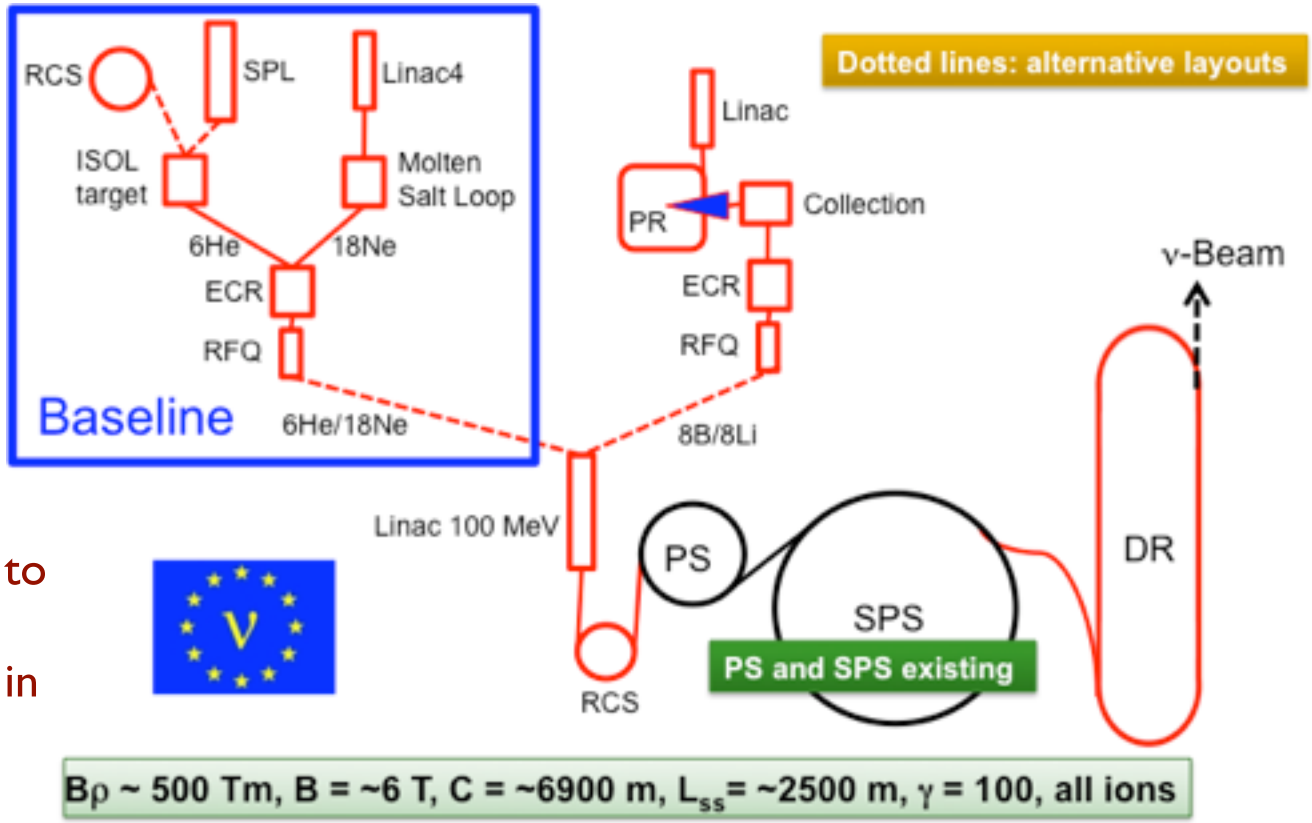
- large aperture magnets with fixed field
  - large acceptance, cost-effective use of RF
- challenging injection/extraction systems

Future Possibilities - β-Beams

- Neutrinos from accelerated and stored radioactive ions, **pure ν_e or anti-ν_e beams**
- Two ion combinations under study: **6He/18Ne** and **8Li/8B**
- **key assets for CERN : existing accelerators and experience in ISOLDE for handling or RIB**

- **Technology challenges**
  - ion production
  - ion collection and bunching
  - ion acceleration
    - collective effects
    - ion decays

✓Synergy with super-beam to Frejus
- θ_{13}, CP-violation study in the absence of matter effects



β-beam: isotope production

Courtesy: E. Wildner, EUROnu

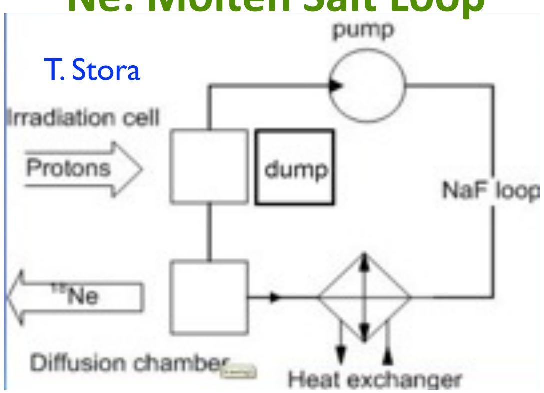
Type	Accelerator	Beam	I_{beam} mA	E_{beam} MeV	P_{beam} kW	Target	Isotope	Flux s^{-1}	Ok?
ISOL & n-converter	SPL	p	0.1	2 10^3	200	W/BeO	6He	5 10^{13}	
ISOL & n-converter	Saraf/GANIL	d	15	40	600	C/BeO	6He	5 10^{13}	
ISOL	Linac 4	p	6	160	700	19F Molten NaF loop	18Ne	1 10^{13}	
ISOL	Cyclo/Linac	p	10	70	700	19F Molten NaF loop	18Ne	2 10^{13}	
ISOL	LinacX1	3He	> 170	21	3600	MgO 80 cm disk	18Ne	2 10^{13}	
P-Ring	LinacX2	7Li	0.160	25	4	d	8Li	?1 10^{14}	
P-Ring	LinacX2	6Li	0.160	25	4	3He	8B	?1 10^{14}	

Experimentally OK
On paper may be OK
Not OK yet

Baseline option (^{6}He and ^{18}Ne). ^{18}Ne production experiments in 2011.

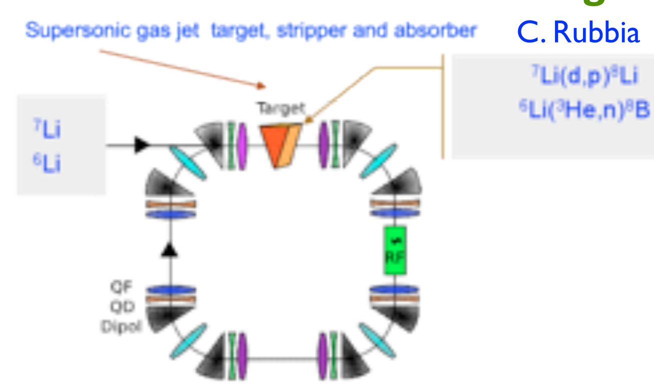
^{8}Li can be produced in sufficient quantities with ISOL & n-converter

^{18}Ne: Molten Salt Loop



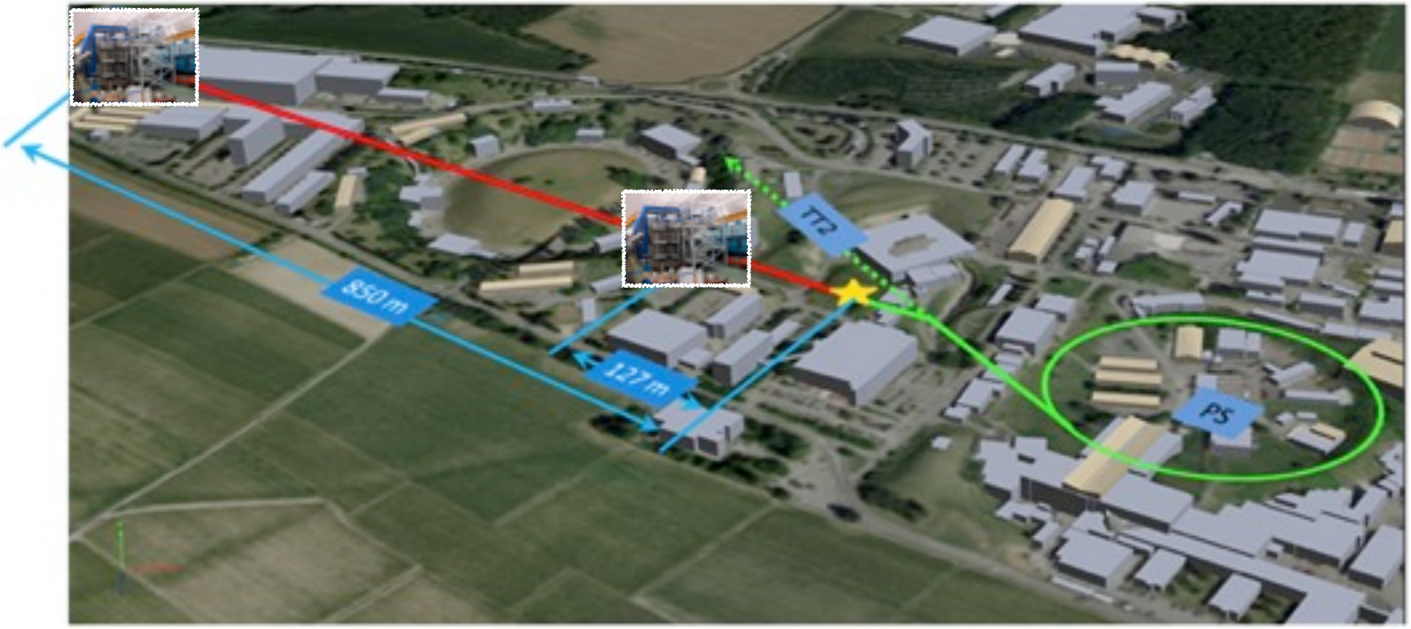
^{6}He & ^{8}Li : ISOL&n-converter

^{8}B & ^{8}Li : Production Ring



Future possibilities - Short Baselines

- Short baselines to search for anomalous ν oscillations – sterile ν's ??
- **FNAL**: Booster beam (8 GeV) to MiniBooNE and upgrades, MicroBooNE
- **CERN** : PS Neutrino Beam



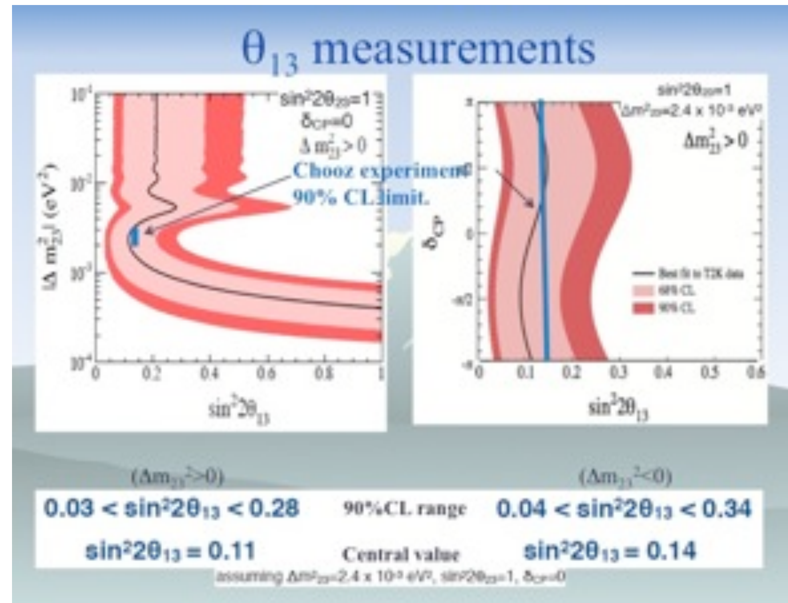
- Beam line originally operated in early 80's for PS169, PS181, PS180(BEBC)
- Near (**150t**) + Far(**600t**) detector with **ICARUS LArgon technology**
- Expect : **$6.13\ 10^{19} \div 2.1\ 10^{20}$ pot/y @ 20 GeV**, depending on beam sharing

- Beam line originally operated in

Future ν-Oscillation Facilities

The physics opportunity …

- New results are coming up that change the ν-physics landscape and will help to better define a future ν-program among the all possible options currently under study
  - **T2K** : θ_{13} non-zero and large
  - **NuMI/MINOS** : θ_{13} , $\nu \leftrightarrow$ anti-ν results
  - **CNGS:** # ν_τ events observed wrt expectations?
  - **Reactor experiments** :
    - θ_{12}, θ_{13} measurement/new limits
  - **LHC** : is there physics beyond the SM?

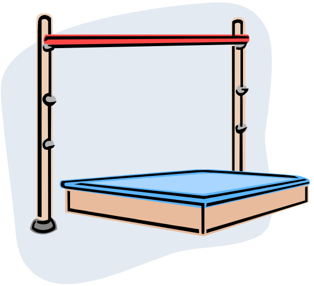


T. Kobayashi - CERN Seminar, July 2011

…and of course any unexpected physics !!!

Future ν-Oscillation Facilities

… and the challenge



- Future ν-facilities will require:
  - Innovative ideas and new accelerator technologies to be developed
  - Collaboration and **coordination** for accelerator and detector R&D at a **global** scale
  - The ν-physics and accelerator community defines a **prioritized roadmap of facilities** to **make ν-physics a valid option for HEP in // to LHC and its upgrades**

Future ν-Oscillation Facilities

- To know more about ν-beams and associated physics:
- **NUFACT11** Workshop @ CERN/ UniGe in **August 1-6, 2011**
- **http://nufact11.unige.ch**