Future Neutrino Oscillation Facilities

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In Europe
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Why study $\nu$ physics?

- $\nu$s 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-$\nu$s?

- $\nu$s call for an extension to the SM
  - no unique theory of $\nu$ 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 $\nu$ beams?

- easy(!!) way to produce $\nu_s$ and study their properties
  - alternatives: $\nu$ from reactors, beta-decay, $\mu$-decay

- long, very long, or short beam lines depends on the value of the parameters

Typical configuration:

- $\nu$-source:
  - $\pi^\pm$ decay: $\nu$-(super)beam
  - rad-ion decay: $\beta$-beam
  - $\mu^\pm$ decay: neutrino factory

- $\nu$-detectors:
  - near detector
  - far detector(s) (on/off axis)

- Intensity (beam power to produce $\pi, \mu, i ons$) is the key factor
  - high-intensity accelerators and beams
Conventional long baseline $\nu$ beam - CNGS

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

Target Unit

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

Muon detectors

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

Magnetic Horns

- 150(180) kA current
Conventional $\nu$ beams - present

- **CNGS@CERN**
  - design: 500kW (beam), 750kW (infrastructure)
  - OPERA/ICARUS experiments
    - high energy for $\nu_\tau$ appearance
    - no near detector

- **T2K@J-PARC**
  - design: up to 1.6MW (beam), 4MW (infrastructure)
  - near detector + Super-K
    - indication for $\theta_{13}$ non-zero and large

- **NUMI@FNAL**
  - design: 400kW (beam), upgrade
  - near detector + MINOS
    - results support $\theta_{13}$ non-zero hypothesis
    - possible difference in $\nu$, anti-$\nu$ oscillations

Duty factor: $42\text{s}(\text{CNGS})/49.2\text{s (total)} = 85\%$
- 362 kW average power

Beam Intensity: $\sim 2.1\times 10^{19}$ pot/extr
- 423 kW
- 87% nominal

CNGS statistics:
- $11.86 \times 10^{19}$ pot delivered
- $5\times 4.510^{19}$ pot approved program

Note: design and operation of a high-intensity beam facility is always very challenging
Conventional $\nu$-beams – future possibilities

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

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

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

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

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

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

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

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

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

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- $30$ GeV beam from MR
- reach $500$kW in 2013

**NOνA (830km–OA)**
- $120$ GeV beam from MI
- $700$kW with MI upgrade

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

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

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

**LAGUNA–LBNO, EUROv FP7 Design Studies**
ν-beams - Future possibilities : Japan

- T2K beam to Super-Kamiokande

O(1[MWx10^7s]~2e21pot) is major milestone (turning point)
Need to reach ASAP

□ 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

Okinoshima: 50kt LArgon TPC (658km, 0.78deg OA)

Kamioka: 2×500kt water Cherenkov (295km, 2.5deg OA)

Courtesy: T. Kobayashi - KEK
v-beams – Future possibilities: FermiLab

NOvA off-axis experiment @FNAL

- 120 GeV beam from MI like NUMI

LBNE very-long baseline beam to DUSEL

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

- 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/injetcion lines
  - expect: $6 \times 10^{20}$ pot/yr starting 2014

 Courtesy: FNAL - NuMI, LBNE web pages
ν-beams - Future possibilities: CERN

- Long-baseline options - LAGUNA_LBNO Design study

**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

- **... and synnergies:**
  - 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)

- 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”

*graph*
CERN $\nu$-beam to Pyhasalmi - CN2PY

Target
0.5-0.750MW

Near detector
CERN $\nu$-beam to Pyhasalmi - CN2PY

- Target 2 MW
- Near detector
- HPPS
- (LP)-SPL
- CNGS
**v-beams - Future possibilities : CERN**

- **CN2FR : v-sbeam based on HP-SPL to Frejus**

  ![Diagram of HP-SPL block diagram](image)

  **Ion species**  \( \text{H}^- \)
  - **Output Energy** 5 GeV
  - **Bunch Frequency** 352.2 MHz
  - **Repetition Rate** 50 Hz
  - **High speed chopper** < 2 ns (rise & fall times)

  ![Diagram of CN2FR setup](image)

  **MEMPHIS**
  (Water Cherenkov)

  ![Diagram of MEMPHIS installation](image)

  **Courtesy : R.Garoby - CERN**

  **LAGUNA**
  **Courtesy : LAGUNA**
**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**: $4 \times 1 \text{ MW} = 4 \text{ MW} !!!$
  - four target/horn assemblies mounted together in a mechanical frame
  - horn design similar to that of MiniBooNe

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**Beam switchyard**

- 5 GeV, 4MW beam
- 50Hz pulses

**Four horn assembly**

- $4 \times 5 \text{ GeV}, 1 \text{ MW beams}$
- @ 12.5 Hz

**Single horn design**

- 230 cm
- 112 cm
- $\sim 300-400 \text{ kA}$
**Future Possibilities – Neutrino Factory**

- $\nu_s$ from accelerated and stored $\mu^+$ and $\mu^-$
- precision-era facility
  - $\theta_{13}$, CP-violation, mass hierarchy, physics beyond $\text{SM}$

- International Collaborative Effort within
  - IDS-NF : [http://www.ids-nf.org](http://www.ids-nf.org)
  - EURONU/FP7 : [http://www.euronu.org](http://www.euronu.org)

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**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

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**Layout**

- long/very-long baseline beams
- near/far detector combination
  - MIND(MINOS-type), LSND(liquid scintillator), or LArgon-TPC
**v-Factory : Target R&D**

**NF - target station**

**Key results**

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

**MERIT Experimental Setup**

**Hg-jet - beam impact** $16 \times 10^{12} \text{ p, 5T field, 14 GeV/c}$

Hg-jet is restored at the end
v-Factory: Target R&D

Key results:

- Beam power (PS): $3 \times 10^{13}$ protons @ 24 GeV, $115\text{kJ}$ beam pulse energy
- Hg-jet disruption mitigated by magnetic field, disruption length 28 cm, refill time $@ 20\text{m/s} = 0.014\text{s} = 70\text{Hz}$
- Demonstrated operation at: $115\text{kJ} \times 70\text{ Hz} = 8\text{ MW}$

![Diagram of v-Factory Target R&D](image)
**v-Factory : Target R&D**

**NF - target station**

**MERIT Experimental Setup**

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**Key results**

- Beam power(PS): $3.0 \times 10^{13}$ 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
v-Factory : Muon Cooling R&D

- MICE Ionization cooling experiment @ RAL
  - realistic section of the NF cooling channel
**ν-Factory : Rapid Acceleration R&D**

**Rapid μ acceleration**
- rapidly increase $\gamma$ to increase $\mu$ 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 - $\beta$-Beams

- Neutrinos from accelerated and stored radioactive ions, pure $\nu_e$ or anti-$\nu_e$ beams
- Two ion combinations under study: $^{6}\text{He}/^{18}\text{Ne}$ and $^{8}\text{Li}/^{8}\text{B}$
- 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
- $\theta_{13}$, CP-violation study in the absence of matter effects
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

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Future possibilities – Short Baselines

- Short baselines to search for anomalous $\nu$ oscillations – sterile $\nu$’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: $6.13 \times 10^{19} \div 2.1 \times 10^{20}$ pot/y @ 20 GeV, depending on beam sharing
The physics opportunity ...

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

...and of course any unexpected physics !!!
Future v-Oscillation Facilities

... and the challenge

- Future v-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 v-physics and accelerator community defines a prioritized roadmap of facilities to make v-physics a valid option for HEP in // to LHC and its upgrades
Future $\nu$-Oscillation Facilities

- To know more about $\nu$-beams and associated physics:
  - NUFAC11 Workshop @ CERN/UniGe in August 1-6, 2011
  - http://nufact11.unige.ch