Beta beams and ion cooling: the future of accelerator driven neutrino oscillations ?

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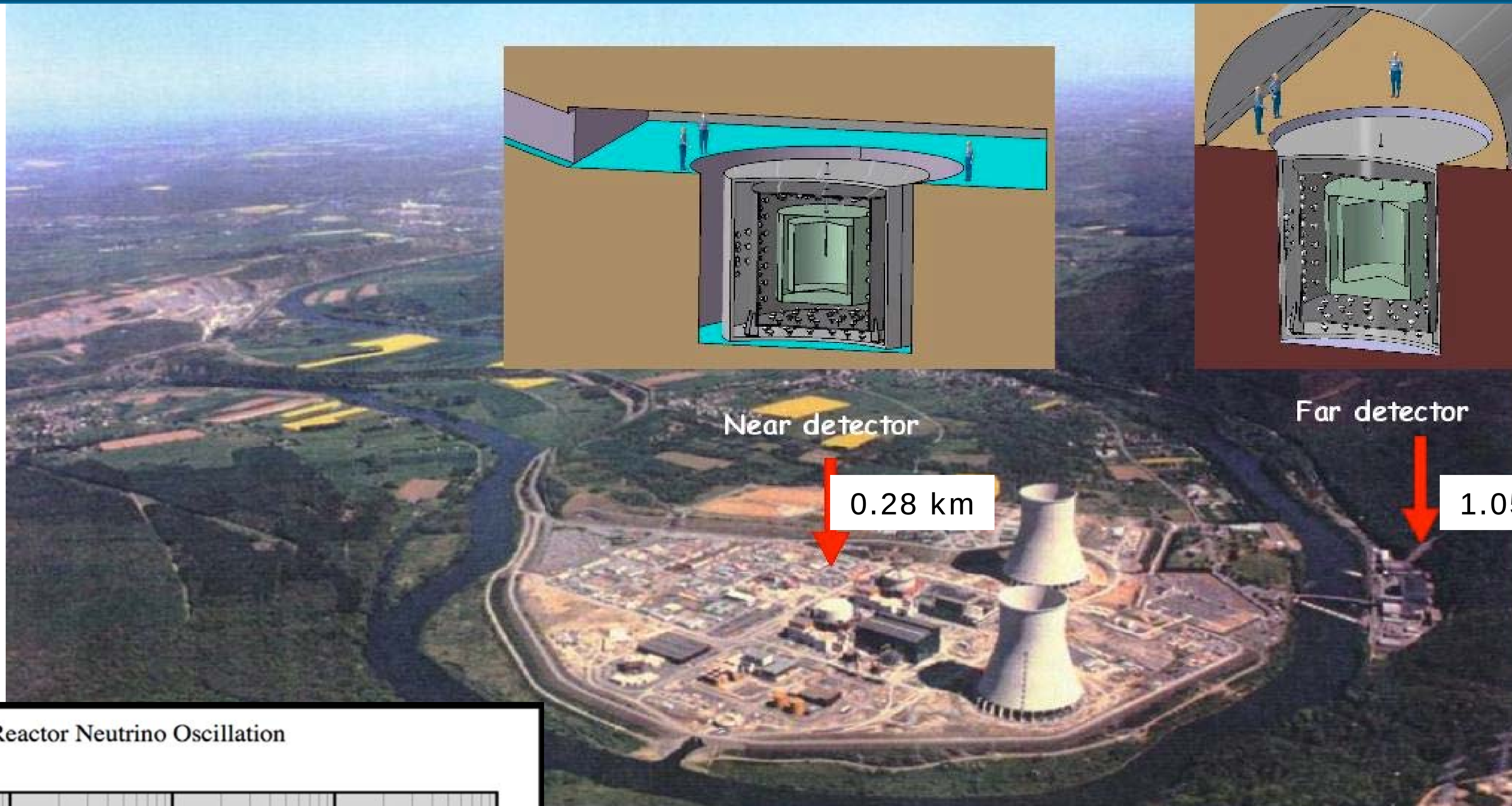
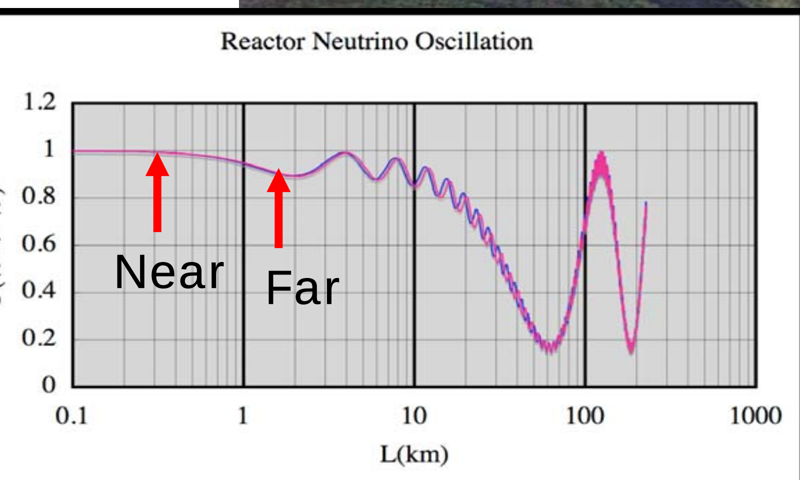
Introduction

- Crucial but very difficult experiments are needed in order to complete the phenomenology of the neutrino sector.
- Such a wide programme demands new accelerated neutrino beams with well identified initial species, long decay distances and novel detection technologies.
- Cosmological arguments have suggested that in order to ensure dominance of matter over anti-matter the CP violation of the quark sector must be extended also to the leptonic sector.
- To this effect, all the three neutrino mixing angles must have non zero values, including the presently unknown θ_{13}, for which the CHOOZ experiment has given the limit $\sin^2(2\,\theta_{13}) < 0.14$ (0.18).
- Provided $\theta_{13} \neq 0$, the leptonic CP violating phase δ becomes accessible with sufficient statistics and in absence of backgrounds.
- Conventional horns and high energy proton beams in MWatt region may be capable of pushing the sensitivity up to $\sin^2(2\,\theta_{13}) > 0.02$, the limit due to the tiny natural ν_e contamination of the horn driven ν_μ beam.
- Entirely new methods are required if $\sin^2(2\,\theta_{13})$ would turn out to have an even smaller value.

Double Chooz in France, Daya Bay in China and so on



Θ_{13}



Suekane DBD07

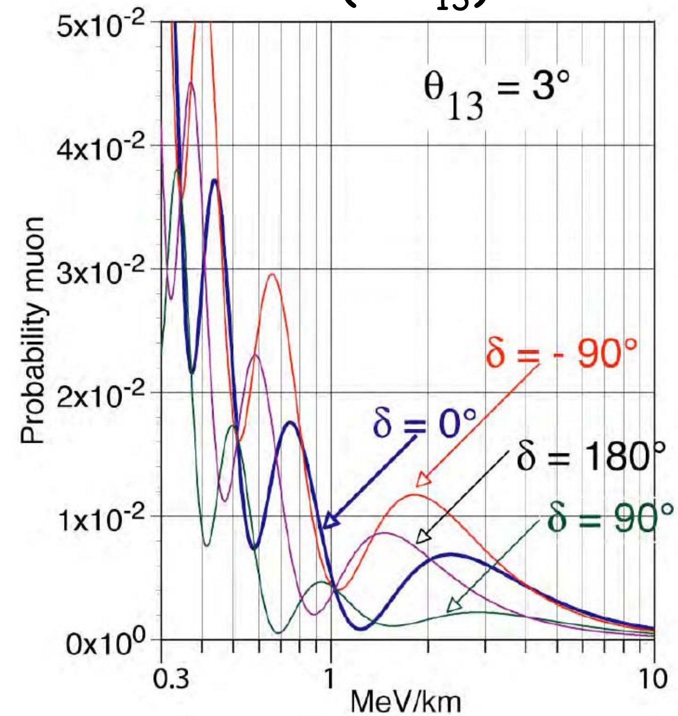
QuickTime™ and a
decompressor
are needed to see this picture.

Future options

- Starting either from an initial high purity ν_μ or ν_e source, the key physical process is the observation of tiny O ($\approx 10^{-3}$) oscillation mixing between $\nu_\mu \leftrightarrow \nu_e$ related to θ_{13}.
- Two advanced methods both based on cooling technologies are being considered:

1) Muon beams, following a method by Skrinsky
   - ➔ 4 MW Proton driver: production target
   - ➔ Target, capture channel: Create π, decay to μ
   - ➔ Cooling: Reduce transverse emittance (1.7 μ/p)
   - ➔ Muon acceleration: ~130 MeV to 20-50 GeV
   - ➔ Decay ring(s): Store for ~500 turn; Long straights
2) Beta-beams: Zucchelli has proposed a neutrino beam from the β-decay of a short lived nucleus followed by acceleration and decay in a dedicated high energy storage ring. It was originally based on He-6 and Ne-19(?), produced by many MW

$\sin^2(2\theta_{13})=2.5\ 10^{-3}$



$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

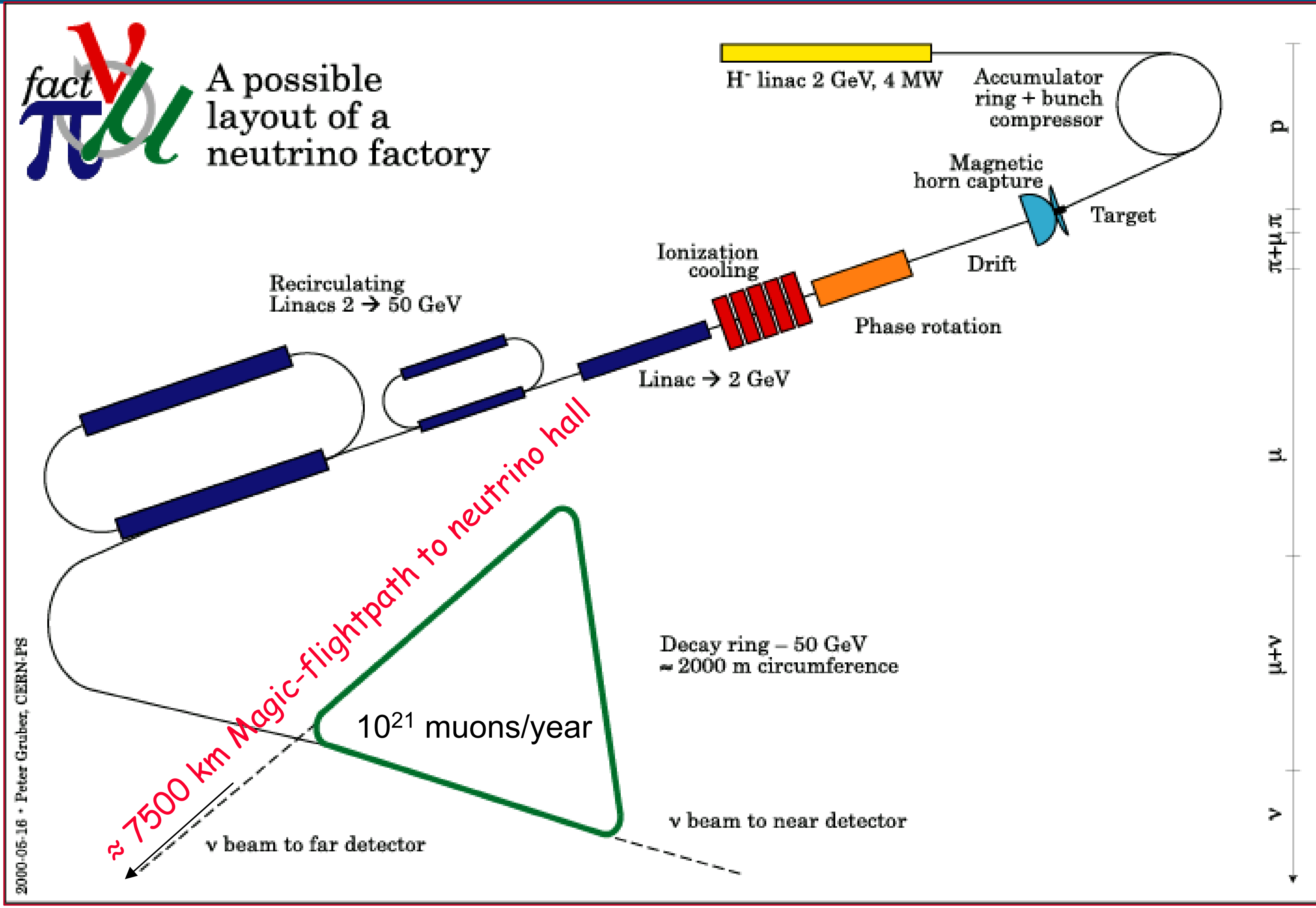
$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

$$\nu_\mu \rightarrow \mu^- [O(1)] \quad \nu_\mu \rightarrow e^- [O(10^{-3})]$$

$$\bar{\nu}_e \rightarrow e^+ [O(1)] \quad \bar{\nu}_e \rightarrow \mu^+ [O(10^{-3})]$$

Lepton sign identification required !

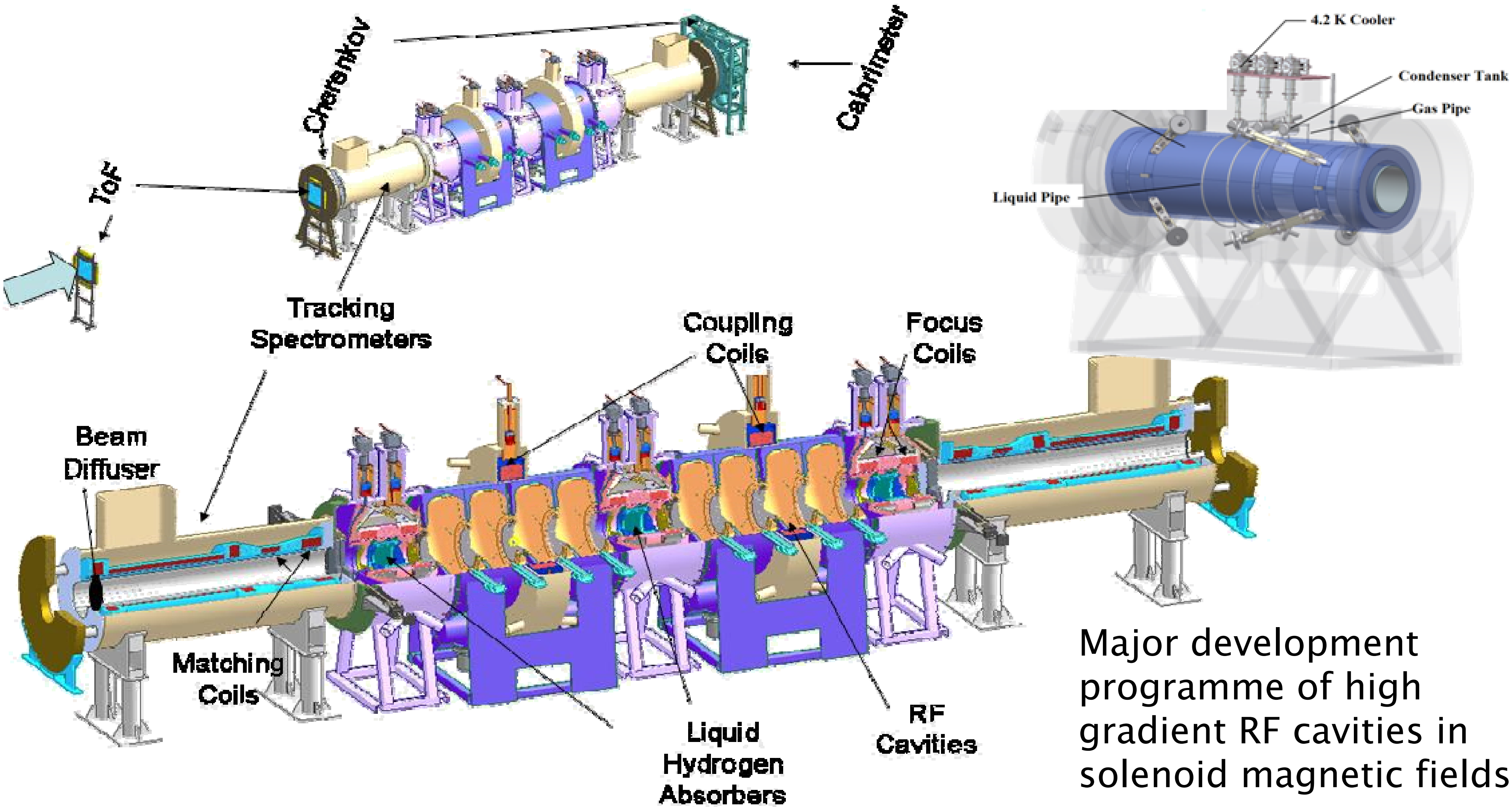
A novel method based on ion cooling of Li-8 and B-8 is here described



fact
A possible layout of a neutrino factory
H⁻ linac 2 GeV, 4 MW
Accumulator ring + bunch compressor
Magnetic horn capture
Target
Drift
Ionization cooling
Phase rotation
Recirculating Linacs 2 → 50 GeV
Linac → 2 GeV
≈ 7500 km Magic-flightpath to neutrino hall
Decay ring – 50 GeV ≈ 2000 m circumference
10^{21} muons/year
ν beam to near detector
ν beam to far detector
2000-05-16 • Peter Gruber, CERN-PS
p
π+μ
μ
μ+ν
ν

Muon Ionisation Cooling Experiment (MICE at RAL)

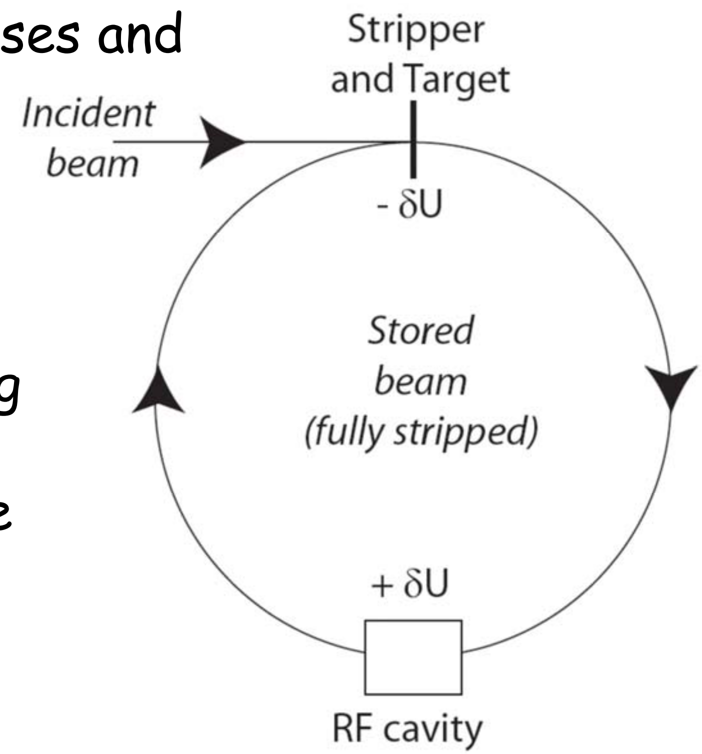
Palmer, BNL 2001

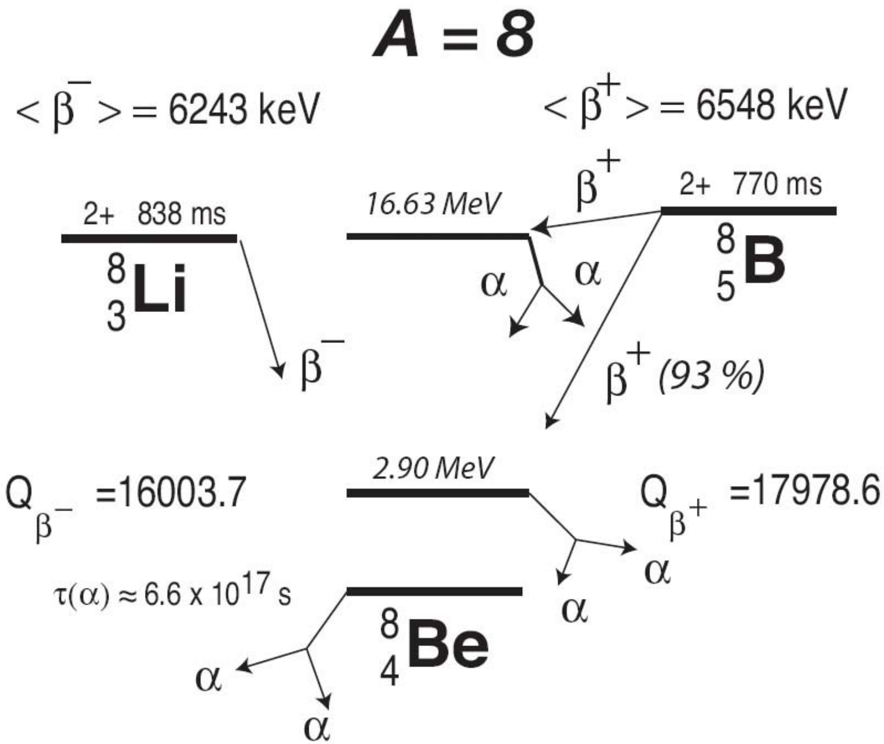


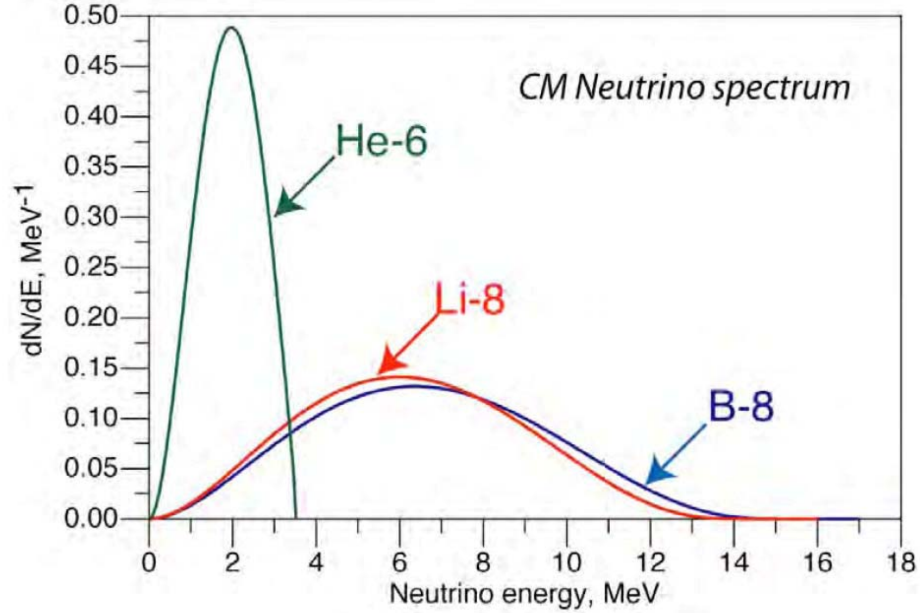
Major development programme of high gradient RF cavities in solenoid magnetic fields

Ionization cooling of slow ($\beta \approx 0.1$) ions

- Stochastic cooling and electron cooling are both well established cooling techniques.
- The unique features of the slow moving, highly ionising and massive ions suggest the development of a novel cooling method based on the non-Liouvillian nature of the dE/dx losses.
- The basic configuration consists of
  - ➔ an appropriate (small) storage ring,
  - ➔ a thin target "foil" which induces energy losses and
  - ➔ an accelerating RF cavity.
- An initially injected ion beam — after being captured by ionisation stripping of the thin target into its highest ionisation state — is permanently stored in the ring. An accelerating cavity of an appropriate voltage and sufficient longitudinal amplitude replaces continuously the energy losses of the stored beam maintaining the equilibrium (orbit) configuration.



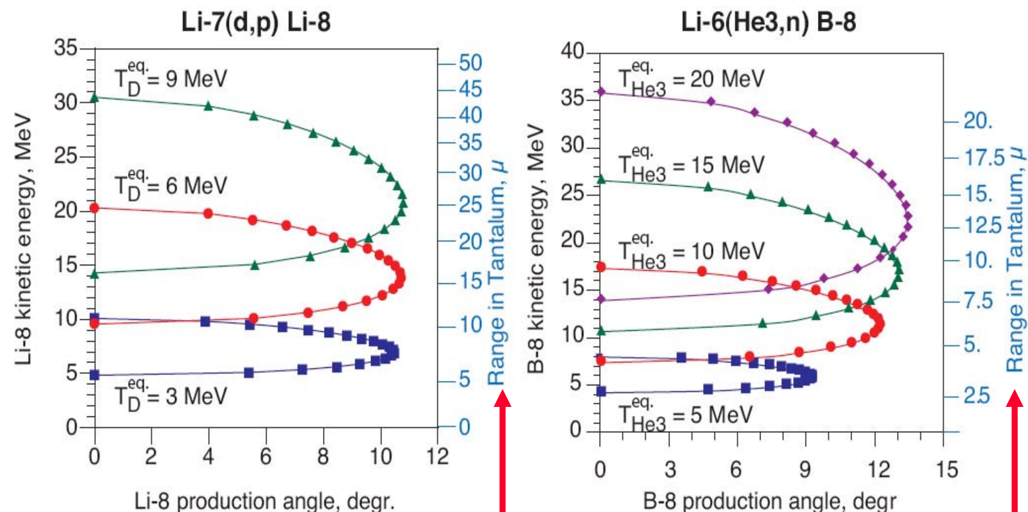




Isospin triplet with A = 8 (Li-8, Be-8, B-8), decaying to the fundamental level of Be-8. In absence of Coulomb corrections, the three states would have identical nucleons configurations because of charge independence. The actual experimental values of the beta decaying doublet Li-8 with = 0.84 s and B-8 with $\tau_{1/2}$ = 0.77 s are respectively Q^* = 16.005 MeV and Q^* = 16.957 MeV.

Exploiting the reverse kinematics

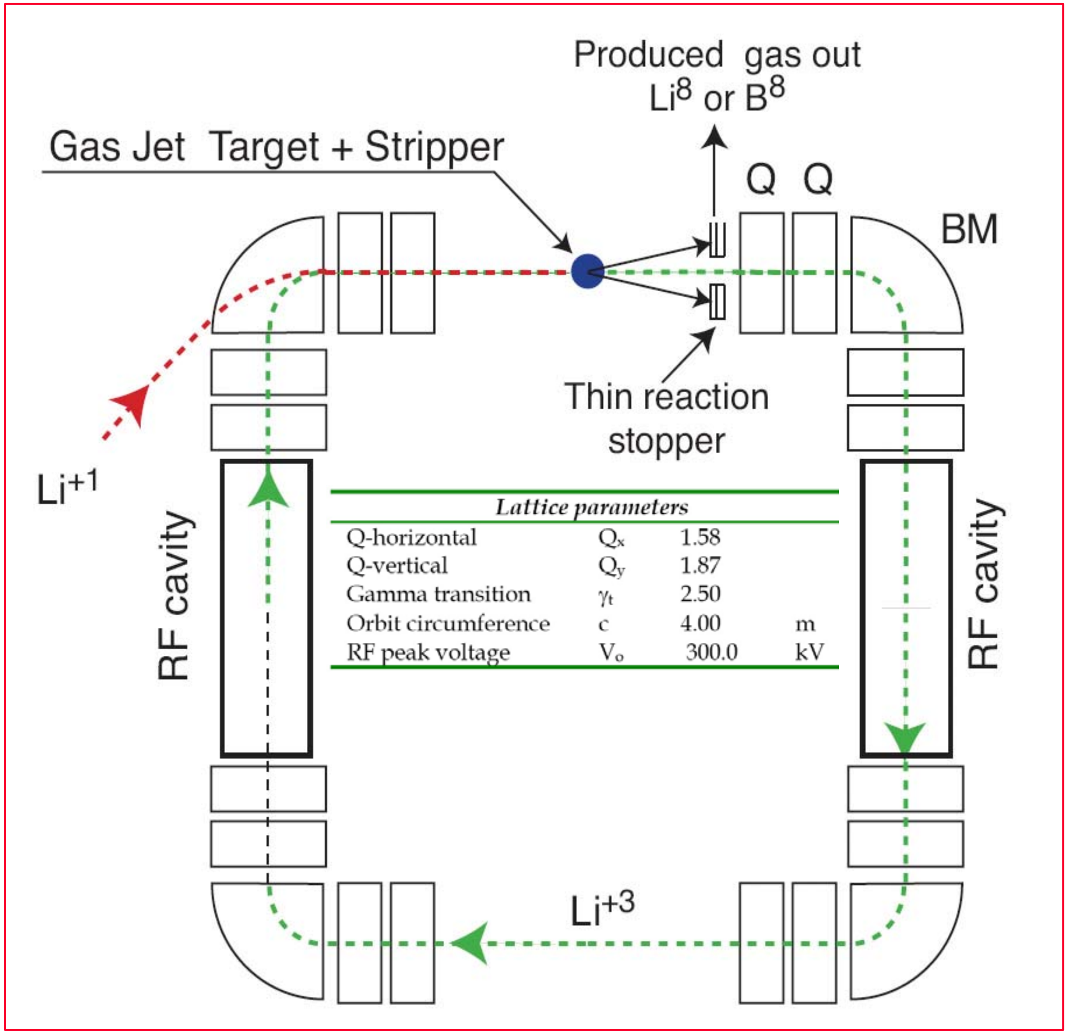
- Reactions are Li-7(d,p) Li-8 and Li-6(He3,n) B-8.
- In the region of few MeV d and He-3, the cross section for the reaction Li-7(d,p) Li-8 is about 100 mb with (a max at 200 mb), while for the reaction Li-6(He3,n) B-8 it is about a fraction 10 lower.
- The products of a D or He-3 beam are emitted over a large angles and very small kinetic energies, (B-8 at 2 MeV is ≈ 0.5 mg/cm²) The power requires a very thin moving Li target in liquid form.
- Therefore choose the "mirror" system, namely a beam of Li-7 or Li-6 hitting a gaseous target either of D or of He-3.
- The emission angles are in a narrow angular cone around about 10° and 12° respectively, with a convenient and relatively concentrated outgoing energy spectrum.



Ion range in Tantalum , micron

The storage ring

- Singly ionized Li-7 injected at 27 MeV are fully ionized by stripping in the gas jet target.
- The circulating beam has a period of P_S=0.136 μs, corresponding to a revolution frequency f_S= 7.35 Mhz.
- At the RF cavities the lattice should be with zero dispersion but at the gas target it should be dispersive.
- The gas target energy loss is U_o = 300 keV and it is wedge shaped. The wedge is adding a linear function to the energy loss, U_o+U'x with $U'x$ = 700 keV/m to damp long. motion.
- Produced secondary particles are collected in the thin reaction stopper foils and brought as neutrals to rest..
- Channelled to an ion source, they are ionised again and accelerated to high energies with conventional methods.

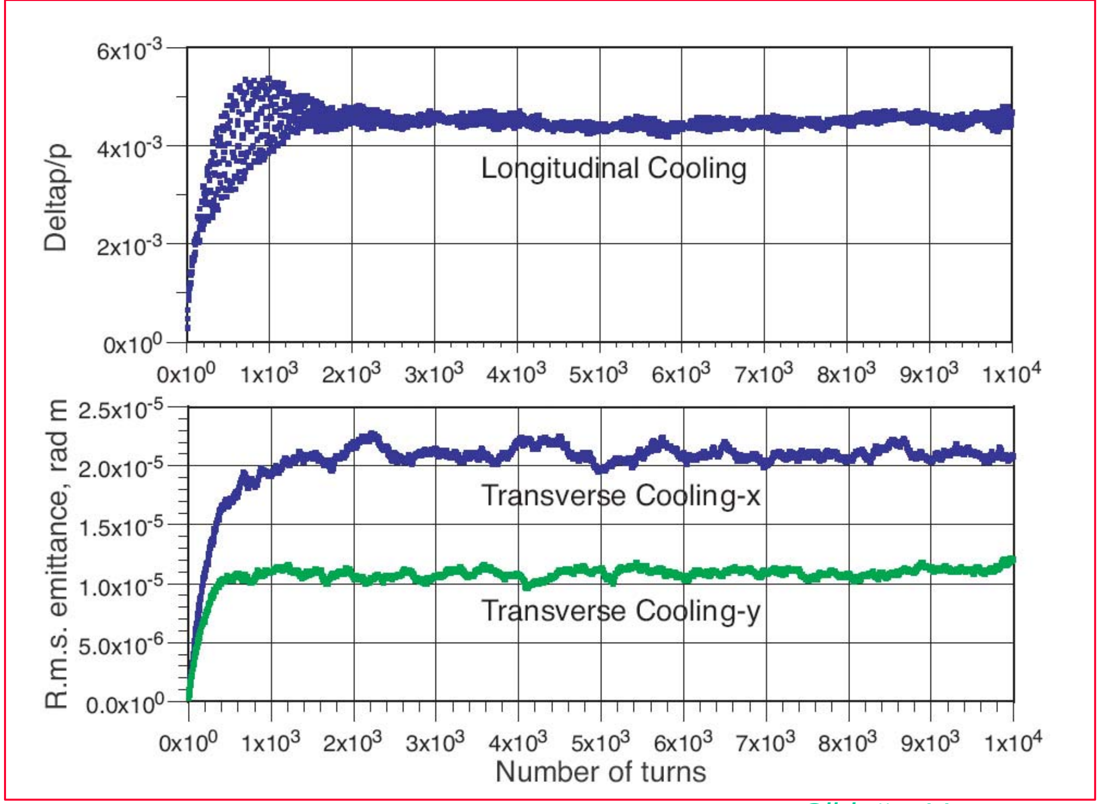


Lattice parameters

Q-horizontal	Q_x	1.58	
Q-vertical	Q_y	1.87	
Gamma transition	γ_t	2.50	
Orbit circumference	c	4.00	m
RF peak voltage	V_o	300.0	kV

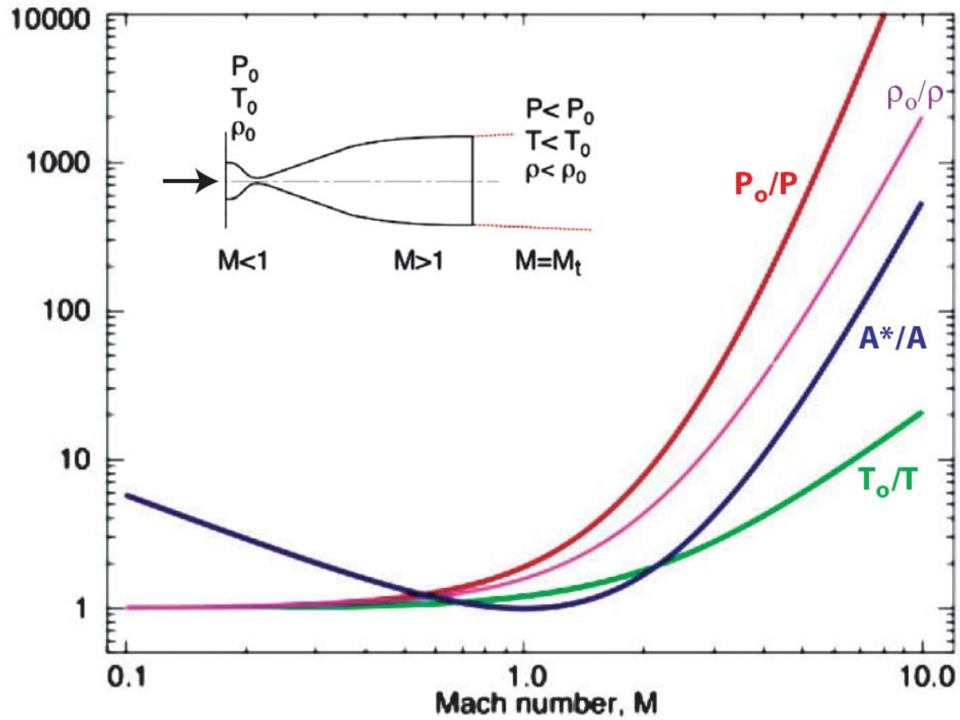
Computer simulations

- In absence of nuclear interactions, particles are circulating indefinitely.
- It is shown a typical evolution of the first 10^4 turns. The equilibrium emittances correspond to extremely small beam sizes, since, for instance $A_y = 10^{-5}$ rad m and β = 15 cm corresponds to an r.m.s. vertical size of 1.2 mm.
- The ratio of the equilibrium transverse emittances in the x- and y-planes are in the ratio 2:1, due to an appropriate x-slope in the foil thickness to ensure longitudinal cooling. The fluctuations are due to the finite number of particles generated.
- Since the transverse heating is due to the Coulomb scattering, the cooled emittance is proportional to β.
- Higher β values generate higher equilibrium emittance and therefore larger beam sizes, which in turn permit higher circulating currents.
- Assuming β = 20 m, emittances are respectively $2.4 \times 10^{-3}\,\pi$ rad m and $1.4 \times 10^{-3}\,\pi$ rad m, i.e. a r.m.s. vertical size of 1.6 cm at the high beta point.
- The number of circulating particles is then $N_{Laslett} = 10^{12}$ for $\Delta Q = 0.25$.



The Laval Nozzle

- The technology is based on the isentropic compressible gas flow, well developed in aero-space, molecular beam research and industry. It is designed on a super-sonic Laval nozzle which produces a highly uniform flow with Mach number $M > 1$, responsible for a low divergence high intensity jet.
- The stagnation volume with P_o, T_o, ρ_o is followed by a narrow throat and a de Laval nozzle, at the end of which the exiting gas has $P<P_o$, $T<T_o$, $\rho<\rho_o$, and a Mach number $M_f>1$. The design is usually done using computational fluid dynamics based on the numerical solution of the Navier-Stokes equations.
- The gas jet target has an approximate thickness of 300 μg/cm², i.e. a target thickness of 5 cm of D_2 at 250 Torr.
- The jet velocity is about 2200 m/s, with a narrow divergence half-angle of ≈ 5° ÷ 12° and $M_f \approx 4$. The volume of gas is 4.3 m^3/s, corresponding to 7.46×10^{25} a/s or 248 g/s.
- Throat = 3.36 mm; inlet = 29 mm; exit diameter = 50 mm; nozzle length = 30.9 cm The pressure at the plenum is 3.3 atm.



Achievable performance

- For an order of magnitude estimate, we may assume to produce 10^{14} reactions/s of Li-7(d,p) Li-8, corresponding to the beam injection of about 10^{15} ion/s. The injected current of singly ionised particles before the stripping is 160 μA. The beam power is relatively small, 4 kW for T = 25 MeV.
- The fully ionised beam in the ring is about a factor 10^{-3} smaller (nuclear beam lifetime ≈ 1 ms), corresponding respectively to circulating intensities of 10^{12} for Li-7(d,p) Li-8, namely to a circulating ion current (Z = 3) of 3.5 Ampere for a revolution frequency f_S= 7.35 Mhz and $\Delta Q_{Laslett}$ = 0.25. With an energy loss of 300 keV in the jet, the power due to the ionisation losses of the gas jet, generated by the re-circulating RF is 1.06 MWatt.
- The radioactivity of such an intense source of the radioisotopes is very strong, of the order of 3400 Curies. The activity is mainly α and β and from neutrons for the (not precisely known) alternate reaction Li-7(d,n) Be-8, which in turn decays instantly into 2 α and Li-7(d,2n) Be-7 with a cross section of about 100 mb. Be-7 has a half-life of 53 days and it decays β+ back to Li-7 with a γ line at 477 keV.
- The beam power is mainly dissipated by the nozzle. The production of 1 MWatt of ionisation associated power corresponds to a temperature increase of 775 K through the passage of the jet. The outlet temperature is then about 570 °C. Such a relevant temperature change has to be carried away by the gas and cooled by an appropriate heat exchanger.

Collection of ions.

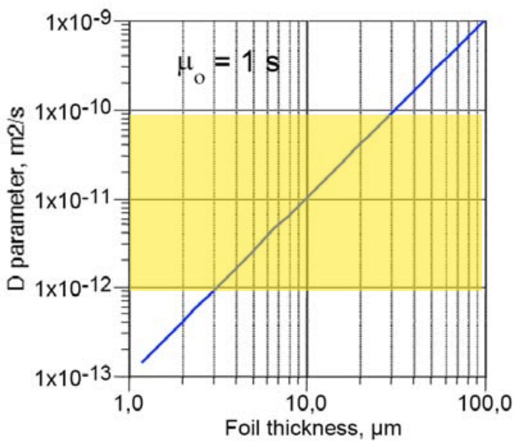
- The nuclear reaction in the gas jet produces a secondary ion within a narrow angular spread (≈ 10°) and with kinetic energy comparable with the one of the incoming heavy beam particle. The range penetration of the secondary ion is very short, typically some tens of micron of solid material.
- The technique of using very thin targets in order to produce secondary neutral beams has been in use for many years. Probably the best known and most successful source of radioactive beams is ISOLDE.
- A critical point is the delay of the collected ions to the catcher-ion-source system (CISS). This requires the understanding of the delay causing processes . The CISS is made of a small ring shaped thin box at about 10 degrees with a hole for the circulating ion beam and with a number of thin catcher foils inside.
- The release of the nuclide proceeds in two subsequent steps: *diffusion* from the place of implantation to the surface of the solid state catcher and *effusion* in the enclosure until the emission as a neutral particle.
- Solid state diffusion is governed by Fick's law. For an initially homogeneous distribution with diffusion coefficient in a thin foil of thickness d, the release efficiency for an ion of half-life $\tau_{1/2}$ is

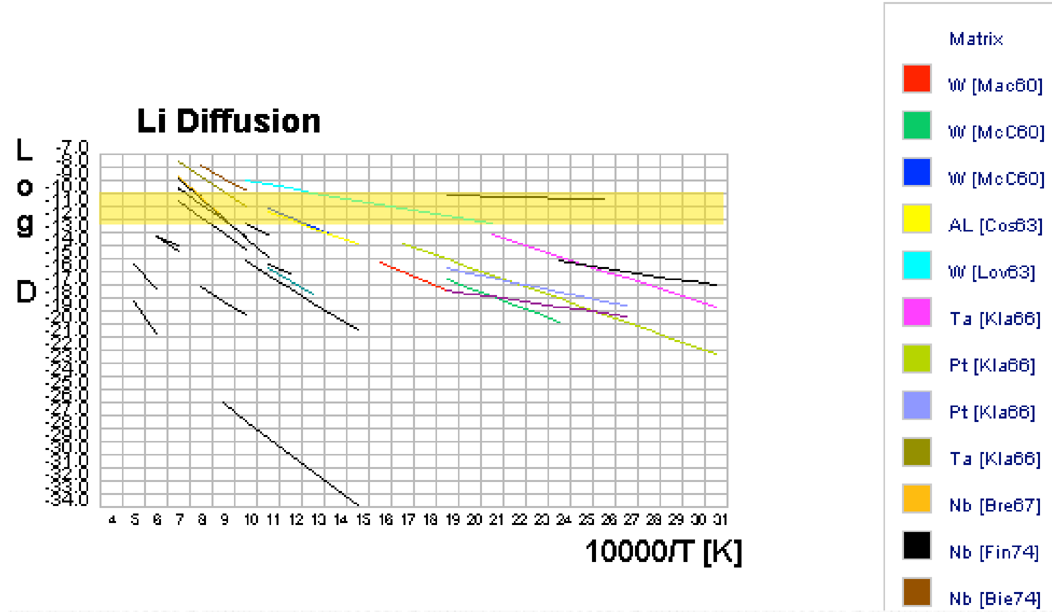
$$Y(\tau_{1/2}) = \tanh\left(\sqrt{\lambda\pi^2/4\mu_o}\right)\Big/\sqrt{\lambda\pi^2/4\mu_o} \approx 0.76\sqrt{\mu_o\tau_{1/2}},$$

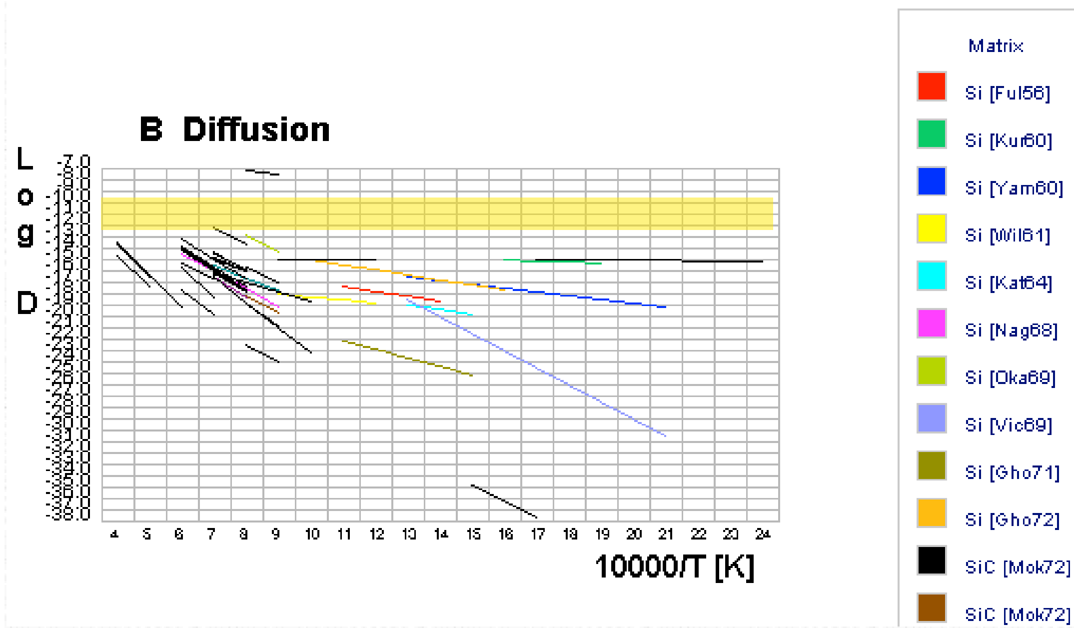
with $\mu_o=\pi^2 D/d^2$ and $\lambda=\ln 2/\tau_{1/2}$.

Ion conversion into neutrals.

- Experimental information on the value for Lithium and Boron in various (hot) materials are presently still contradictory
- Additional work is required before designing an appropriate CISS.
- It is however believed that at sufficiently high temperatures (≈ 2000 °C) an acceptable value is for $10^{-12} < D(m/s) \leq 10^{-10}$.







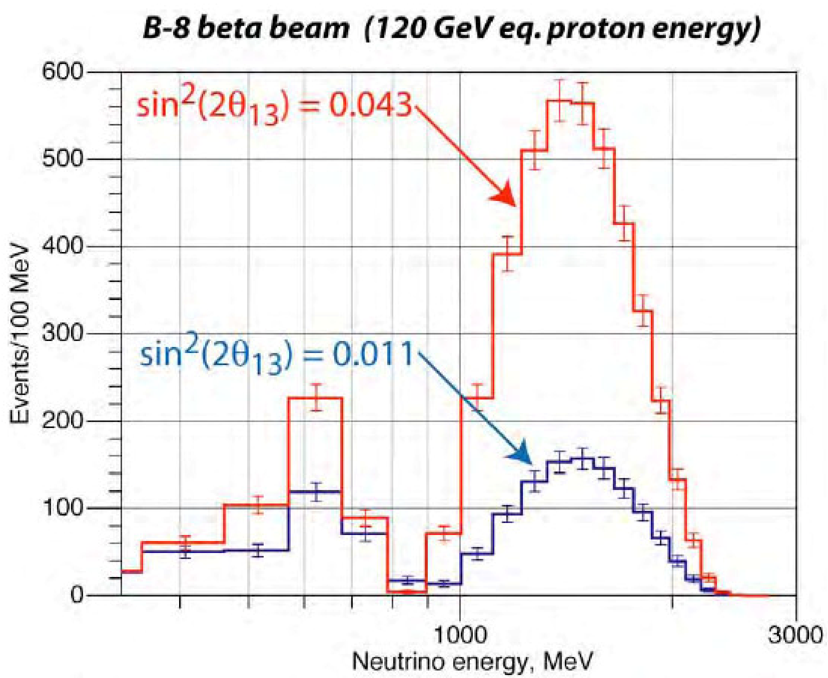
Vogt's symposium, May 4,2008

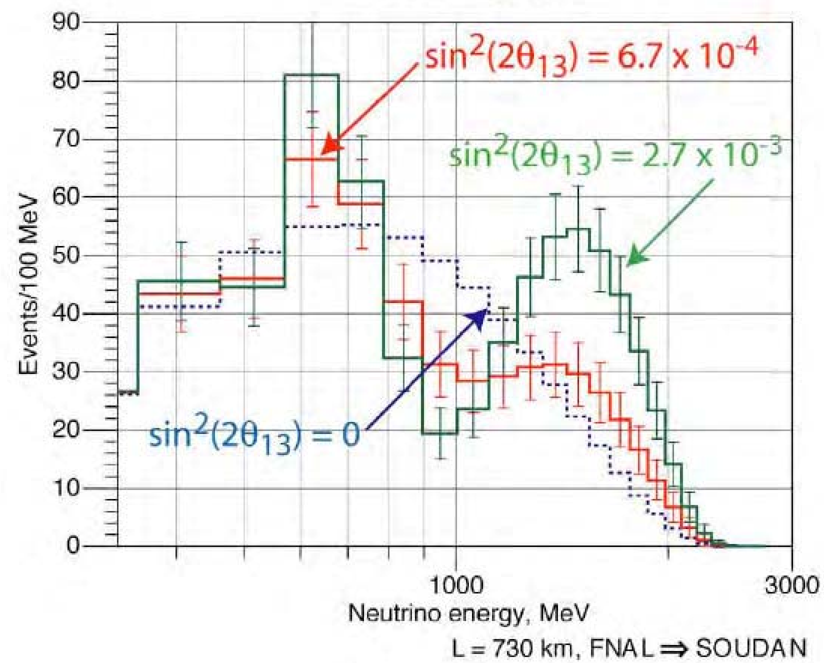
An β-beam configuration based on B-8 and Li-8 decays.

- With B-8, two main factors are reducing the required proton equivalent energy of the accelerator with respect to the Zucchelli/CERN proposal, namely
  - ➔ the higher average CM neutrino energy of 7.0 MeV rather than 1.7 MeV
  - ➔ Z/A = 5/8 = 0.625 rather than 2/6 = 0.333 for He-6, incrementing γ by 1.87.
- For a given magnetic rigidity or proton equivalent momentum, the choice of B-8 produces neutrinos with an average energy 4.11 x 1.87 = 7.7 times larger !
- As a consequence, for instance the existing Main Energy Injector at FNAL with 120 GeV protons may be modified in order to produce fully stripped B-8 beta neutrinos with an end point of 2.5 GeV, perfectly suited for L = 730 km and the Sudan mine. The relativistic factor is $\gamma_{B\text{-}8}$= 80 for the nominal magnetic rigidity.
- We assume that the improved accelerator complex, now being currently improved to accelerate up to a 2 MWatt proton beam, may be also able to accelerate the same circulating current also for B-8, corresponding to 2□ ÷ 3 x 10^{13} ions/s.
- Similar modifications may be at hand at CERN in order to produce a sufficiently large B-8 circulating current and a proton equivalent energy in the interval 100 ÷ 200 GeV in order to send neutrinos to LNGS laboratory.
- The high energy ion beam extracted from the main accelerator is accumulated on a storage ring with one long straight section pointing to the neutrino detector, comprehending 1/3 of the circumference.

Detection rates

- The detector distance is 730 km, corresponding to the Soudan from LNAL or LNGS from CERN.
- We have considered a LAr detector of 50 kton (35'000 m3) if $\sin^2(2\theta_{13}) > 2.7 \times 10^{-3}$, doubled to 100 kton for an ultimate experimental sensitivity as small as $\approx 6 \times 10^{-4}$. Rates before cuts refer to a 5 years exposure with 200 d/y.





Signals and background in LAr

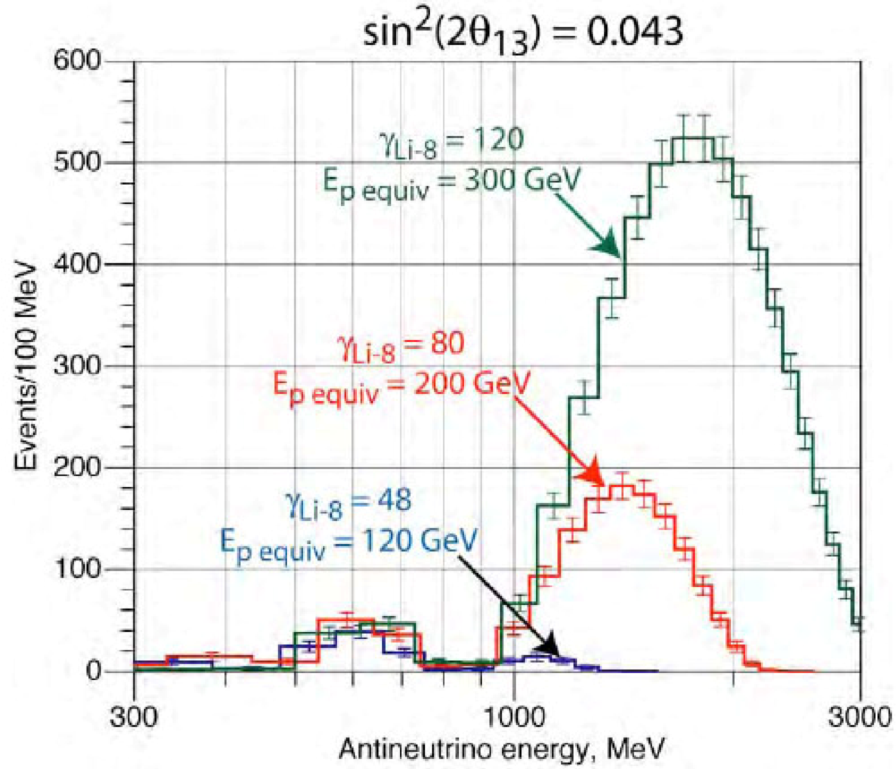
- The signal is a large e-like signal to which a small μ -like signal is superposed.
- The background is rejected selecting the events leading to a muon capture (70% of all cases). The pion background is rejected on the following criteria:
  1) The neutral current signal with a pion faking the muon has a rate of the order of 1/60 of the CC current rate.
  2) The total visible energy deposited along the track as well as the range are accurately measured in LAr. For a given energy, the range of a muon is longer than the one of a pion. Calculations using the FLUKA simulation indicate that a separation better than 1/200 is possible with a few percent loss of the muon track.
  3) About 70% of the negative muons and all pions will undergo nuclear capture at the end of the range but with very different characteristics. Discrimination of the local energy (blob) offers a good identification between π- and μ -(a factor 50 in the $\pi \leftrightarrow \mu$ star identification).

Total background events ≈ 0.5 events for 100 kton LAr and 5 years of running

QuickTime™ and a
decompressor
are needed to see this picture.

Antineutrinos from Li-8

- The situation is generally less favourable than the case of B-8 and this for several reasons.
  - ➔ Because of the smaller charge of Li-8 when compared to B-8, the main Energy Injector at FNAL (120 GeV protons) has however a much smaller the relativistic γ = 48 corresponding to a lower end point of 1536 MeV. In order to bring γ = 120 the energy of equivalent protons must be 300 GeV.
  - ➔ In the case of anti-neutrino initiated events, the most serious concern is caused by the pion background generated by the neutral currents channel, $\nu + \pi^+ + X$. The main surviving criterion of discrimination is the range-energy curve of the relevant track, which may not be sufficient to discriminate unless $\sin^2(2\,\theta_{13})$ is large.



Conclusions

- The completion of the phenomenology of the neutrino sector demands new accelerated neutrino beams with well identified initial species, long decay distances and novel detection technologies.
- The future reactor experiments (Double Chooz, Daya Bay, RENO, Angra) will improve the limit of $\sin^2(2\,\theta_{13})$ to less than 0.01 and presumably set the scale for the CP violation effects.
- Unless the value of $\sin^2(2\,\theta_{13}) > 0.02$-$0.04$, new technologies must be developed to reduce the unwanted "horn" associated e-signal. The way is so far invariably based on "ionization cooling", either for instance
  - ➔ muon beams, from a 50 GeV source with 10^{14} μ/sec at ≈ 7500 km or
  - ➔ beta-beams, from Li-9 or/and B-9 decays and an "almost existing" accelerator complex for few hundred GeV proton eq. at ≈ 800 km.
- A massive detector based on the liquid Argon technologies as developed by the ICARUS collaboration, is probably offering the best opportunities for such future programmes.
- In the case of a muon beam a magnetized massive detector is needed to reject wrong sign particle signs with power of the order of $1{:}10^{-4}$.

Best wishes,

Eric !

A few kinematics facts

- The relation from standard to reverse kinematics is linear over the energies of interest, with energy conversion factors $T_{Li\text{-}7}$=3.483 T_D for the reaction Li-7(d,p) Li-8 and $T_{Li\text{-}6}$=1.994 $T_{He\text{-}3}$ for the reaction Li-6(He3,n) B-8.
- The total nuclear reaction cross sections producing the ejection of the particle from the beam are typically of the order 10^{-24} cm^2, corresponding to a 1/e absorption in D_2 and He-3 of ≈ 3.3 and ≈ 5 g/cm^2. With a typical D_2 target thickness of 0.3 mg/cm^2, the beam lifetime is about n ≈ 10^4 turns.
- **B**eam particle loss by electron capture may occur during the storage, because of wrong charge at the exit of the foil. As equilibrium between stripping and capture, the cross section for electron pickup at the exit of the foil is about $\int_{rec}$= 0.6×10^{-24} cm^2 (He-3 and T = 25 MeV). The shortened lifetime is easily compensated by a higher injected current.
- With δU = 300 keV and T = 25 MeV the gas thickness is about 0.27 mg/cm^2 both for Li-6 on He_3 and for Li-7 on D_2, corresponding to an r.m.s. Coulomb scattering angle $\delta x'$= 0.29 mrad and $\delta x'$=0.20 mrad respectively. The Landau distribution of the energy loss for the values above is in an excellent approximation Gaussian with r.m.s. energy width of δT= 16.1 keV.
- Both diffusion growths are compensated by the “cooling” effect of the RF.

Ion cooling

- At typical energies of nuclear reactions (few MeV/nucleon) the associated ionisation losses are up to several $GeV/(g/cm^2)$. The shortness of the particle range makes nuclear interaction probability very small. A very large number of incoming particles is required in order to produce the chosen nuclear event.
- Storage of cooled beam particles is intended to increment considerably the efficiency of nuclear collisions with the help of a large number of traversals, made stable by the cooling process.
- This method, which we shall call "ion dE/dx cooling" closely resembles to the synchrotron damping of relativistic electrons — with the energy loss in the thin gas target substituting the function of the synchrotron light. The main feature of this method is that it produces an extremely fast cooling, compared to other traditional methods.
- Transverse betatron oscillations are "cooled" by a target "foil" typically few hundred $\mu g/cm^2$ thick. In order to "cool" also longitudinally, chromaticity has to be introduced with a wedge shaped "foil", such as to increase (decrease) the ionisation losses for faster (slower) particles.
- Particles then stably circulate in the beam, until they undergo for instance nuclear processes in the thin target foil.