Jacques Bouchez

CEA Salay/ APC Paris

NuPAC

Cern, 12/10/2005

Protons at CERN:

synergy with neutrino physics requirements

- Status of neutrino physics
- Future neutrino beams
- CERN-related projects
- Conclusions

What we know and what we want to know

- most probably 3 families of light standard (V-A) neutrinos: ν_e, ν_μ, ν_τ
- neutrinos are massive: we know splittings between square masses
- absolute mass scale?

-> fondamental for cosmology (LSS) and unification scheme of interactions (GUT)

- are neutrinos their own antiparticle (Majorana neutrinos) or not (Dirac neutrinos)

  (for Majorana neutrinos, neutrinos and antineutrinos differ only by their helicity)

- what is the magnetic moment of the neutrinos?
- are neutrinos stable?
- relation between neutrino flavor eigenstates and mass eigenstates (mixing matrix) only partially known
- Is there CP violation in the neutrino sector? (LEPTOGENESIS)

HOW ?

Absolute mass scale: Tritium decay (Mainz/Troitsk, Katrin)

$0\nu\beta\beta$ decay

cosmology: CMB, Large structures

Neutrino nature: $0\nu\beta\beta$ decay (Majorana)

Neutrino mass splittings and mixings : Oscillations

Up to now, flavor oscillations, observed in solar and atmospheric neutrinos, are the only proof that neutrinos are massive and mix.

Flavor oscillations

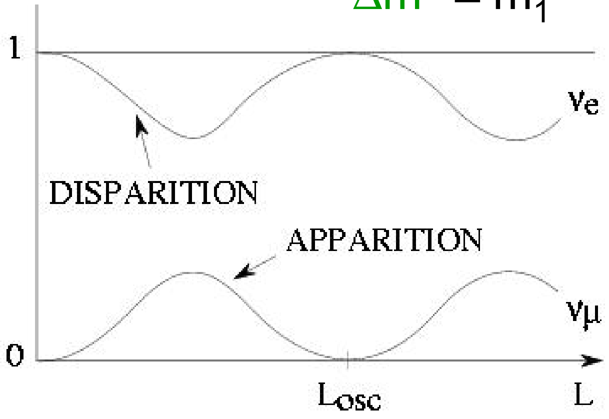
If neutrinos have mass, mass and flavor eigenstates may differ

$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

$$|\nu(t=0)\rangle = |\nu_e\rangle$$
$$|\nu(t)\rangle = \exp(-iE_1 t)\cos\theta\,|\nu_1\rangle + \exp(-iE_2 t)\sin\theta\,|\nu_2\rangle$$

$$P(\nu_e \to \nu_\mu) = |\langle\nu_\mu|\nu(t)\rangle|^2 = \sin^2 2\theta\,\sin^2(\Delta m^2/4E\,t)$$

$$\Delta m^2 = m_1^2 - m_2^2$$



$$L_{osc}\,(m) = 2.5\,E_\nu\,(\text{MeV}) / \Delta m^2(\text{eV}^2)$$

L/E is the right variable if neutrinos have a whole energy spectrun

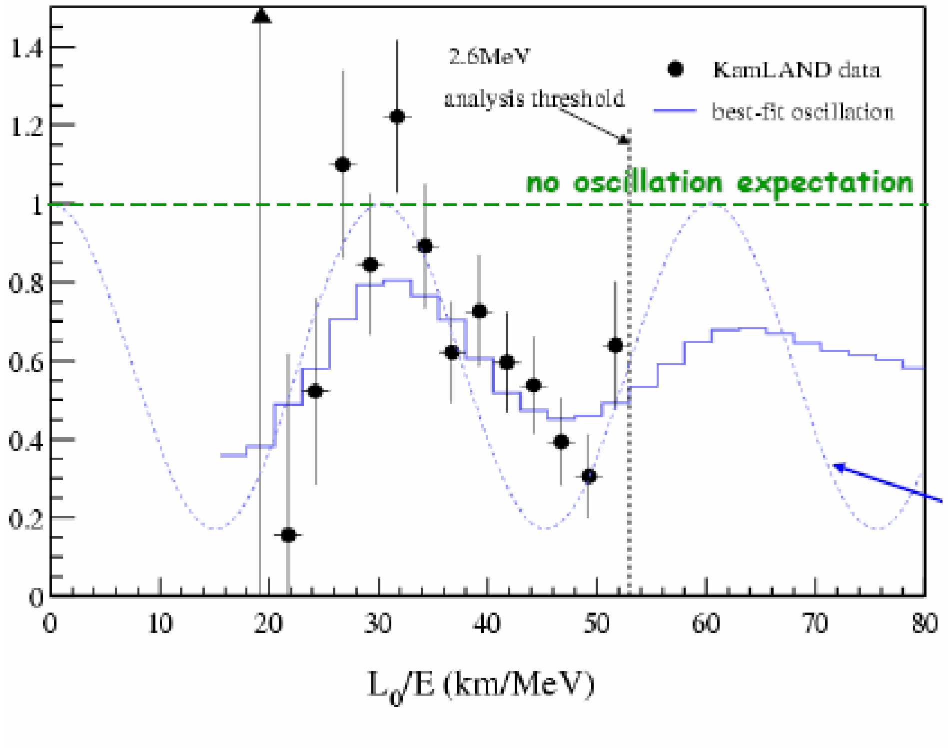
PRESENT EVIDENCE FOR OSCILLATIONS

Solar oscillation: ν_e disappearance

Δm_{12}^2= 8 10^{-5} eV^2

$\sin^2 2\theta_{12}$ =0.85

KAMLAND



Oscillation maximum seen at ~ 30 km/MeV

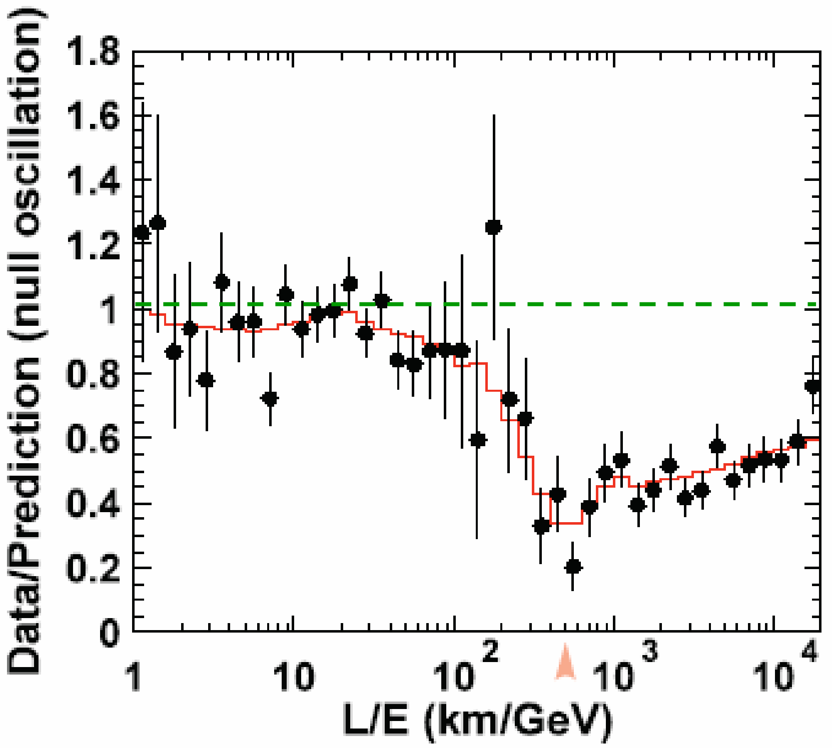
Explains solar neutrino deficit

Atmospheric oscillation: ν_μ disappearance

Δm_{23}^2= 2.5 10^{-3} eV^2

$\sin^2 2\theta_{23}$= 1. 0

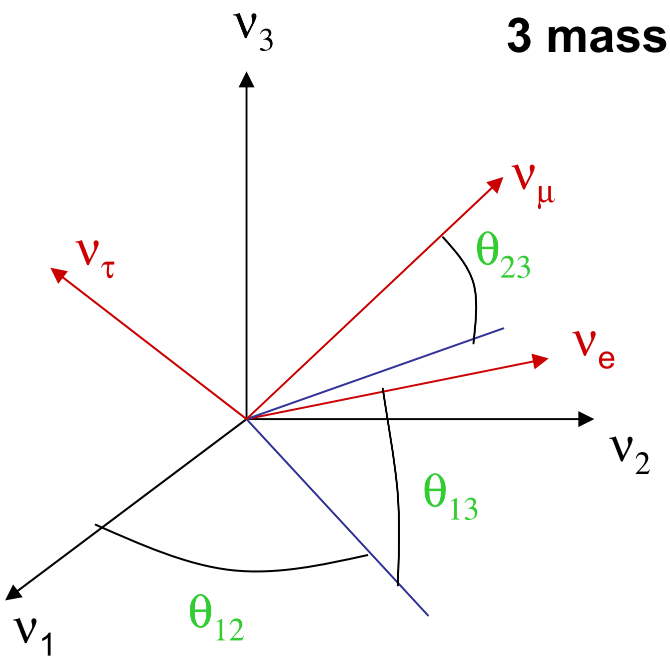
SK



oscillation dip seen at ~500 km/GeV

Studied by MINOS, OPERA, ICARUS

Mixing matrix: the missing parameters



3 masses m_1, m_2, m_3

SUN : $\Delta m_{12}^2 = 8\ 10^{-5}\ eV^2$, $\theta_{12} \sim 35^o$

ATM : $\Delta m_{23}^2 = 2.5\ 10^{-3}\ eV^2$, $\theta_{23} = 45^o$

Missing : θ_{13} and the phase δ

both govern the $\nu_\mu \leftarrow\rightarrow \nu_e$ oscillation at the atmospheric frequency

We know that θ_{13} is < 10^o

$$\nu_l = U_{l\ i}\ \nu_i$$

U is a unitary matrix:

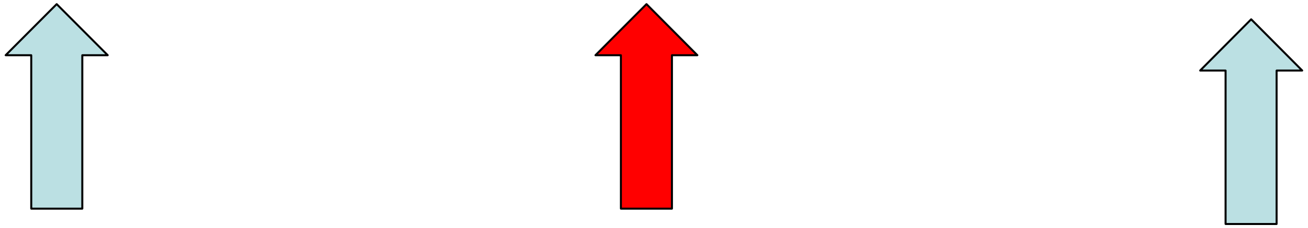
3 angles : θ_{12} , θ_{13} , θ_{23}

plus 1 CP violating phase δ

we have to look for a small oscillation

Another look at the mixing matrix

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



$\nu_\mu \leftarrow\rightarrow \nu_\tau$

ATM.

$\nu_\mu \leftarrow\rightarrow \nu_e$

ATM.

$\nu_e \leftarrow\rightarrow \nu_{\mu,\tau}$

SOLAR.

This “factorization” of effects is due to the smallness of θ_{13} and the strong difference in oscillation frequencies

The quest for θ_{13}…..

- New reactor experiments (double-Chooz, …)
- Neutrino superbeams of first generation (T2K,NOvA)

….and for δ_{CP}

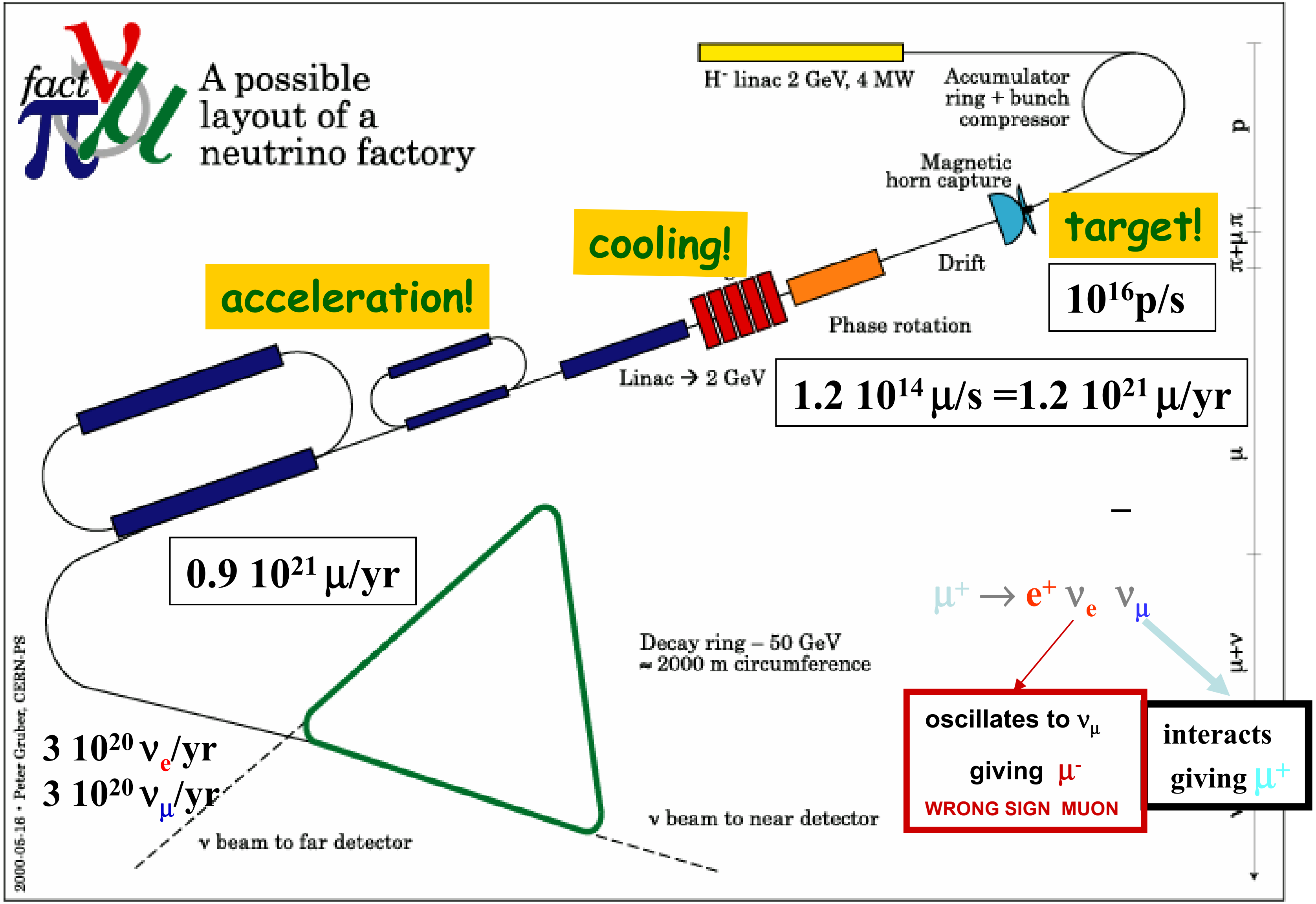
- Megaton detectors and…

CERN

- neutrino superbeams of second generation and/or
- neutrino betabeams and/or
- neutrino factories

(with the possibility to determine the mass hierarchy)

NEUTRINO FACTORY : CERN LAYOUT



target!

10^{16}p/s

cooling!

acceleration!

1.2 10^{14} μ/s =1.2 10^{21} μ/yr

0.9 10^{21} μ/yr

3 10^{20} ν_e/yr

3 10^{20} ν_μ/yr

$\mu^+ \rightarrow e^+ \nu_e \; \nu_\mu$

oscillates to ν_μ

giving μ^-

WRONG SIGN MUON

interacts

giving μ^+

R&D going on for target (MERIT), cooling (MICE) , etc…

Neutrino factory: International scoping study (ISS)

Worldwide effort : Europe, USA, Japan

- Machine: define necessary R&D for different technologies
- Address detector issues:

1. Location of detectors (best combination of distances)
2. Technology of detectors

μ measurement and threshold (fine-grained magnetized detector)	GOLD
e detection capability (Liquid Argon)	PLATINUM
τ detection capability (emulsions)	SILVER

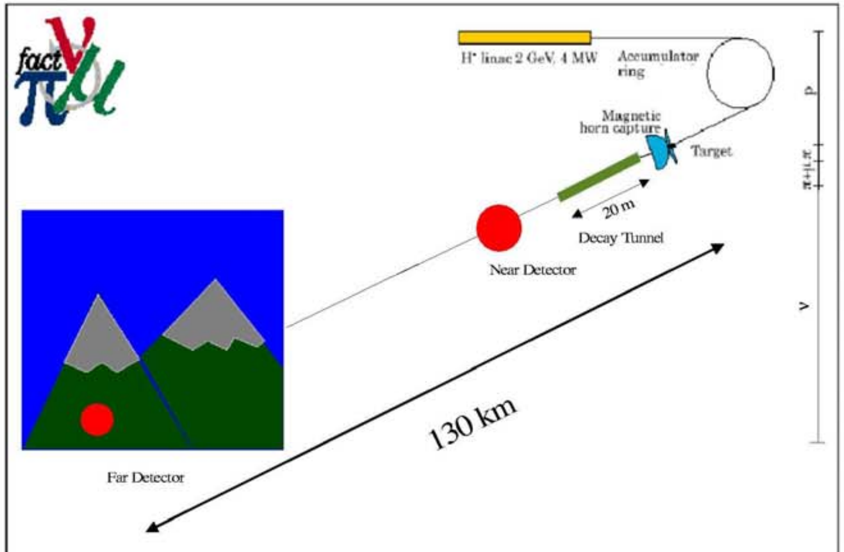
- Estimate performances (trade-off machine/detectors)
- Estimate cost and timescale
- Study alternatives (superbeams, betabeams)

Report due to Nufact06 (August 2006, Irvine)

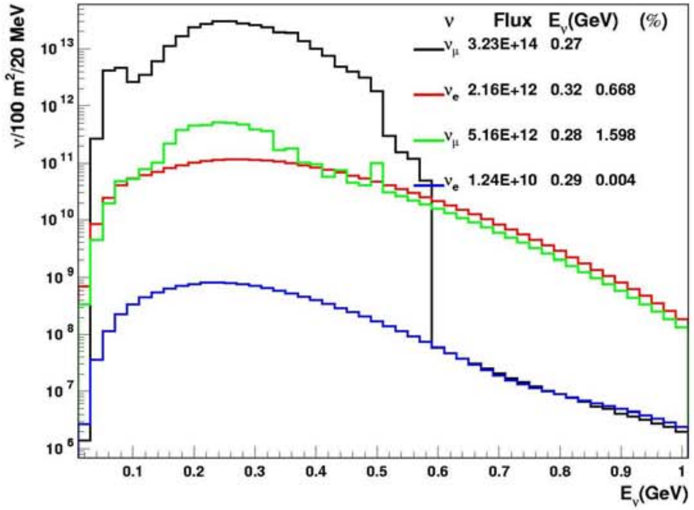
SPL-SuperBeam at CERN

(Initial design)

A feasibility study of the CERN possible developments



Possible Low Energy Super Beam Layout

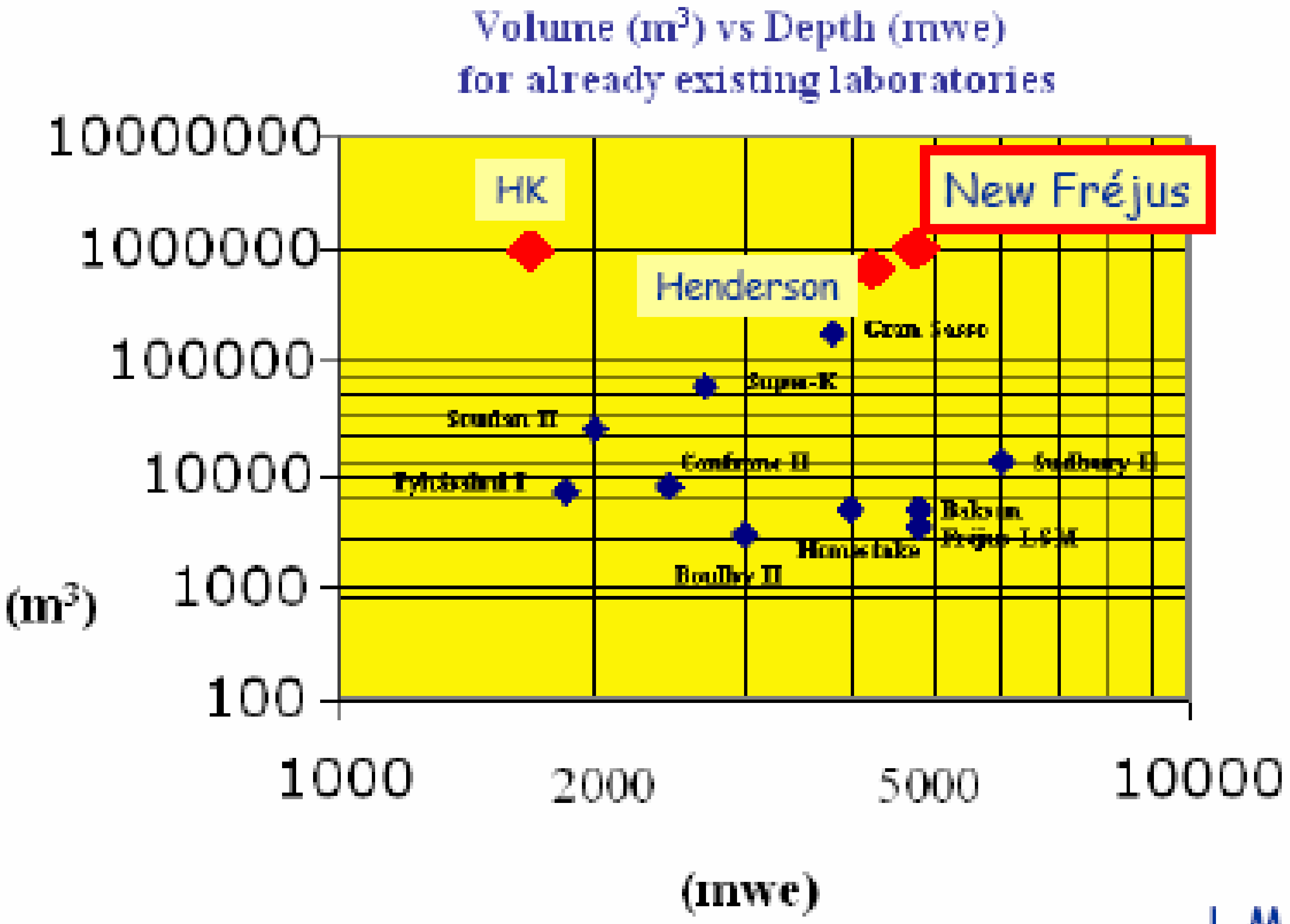


$L_{\mathbf{opt}}$ (km) ~ 0.5 E_ν (MeV)

Flux intensities at 50 km from the target

Flavour	Absolute Flux $(\nu/10^{23}\mathrm{pot}/\mathrm{m}^2)$	Rel. Flux (%)	$\langle E_\nu \rangle$ (GeV)
ν_μ	$3.2 \cdot 10^{12}$	100	0.27
$\overline{\nu}_\mu$	$2.2 \cdot 10^{10}$	1.6	0.28
ν_e	$5.2 \cdot 10^{9}$	0.67	0.32
$\overline{\nu}_e$	$1.2 \cdot 10^{8}$	0.004	0.29

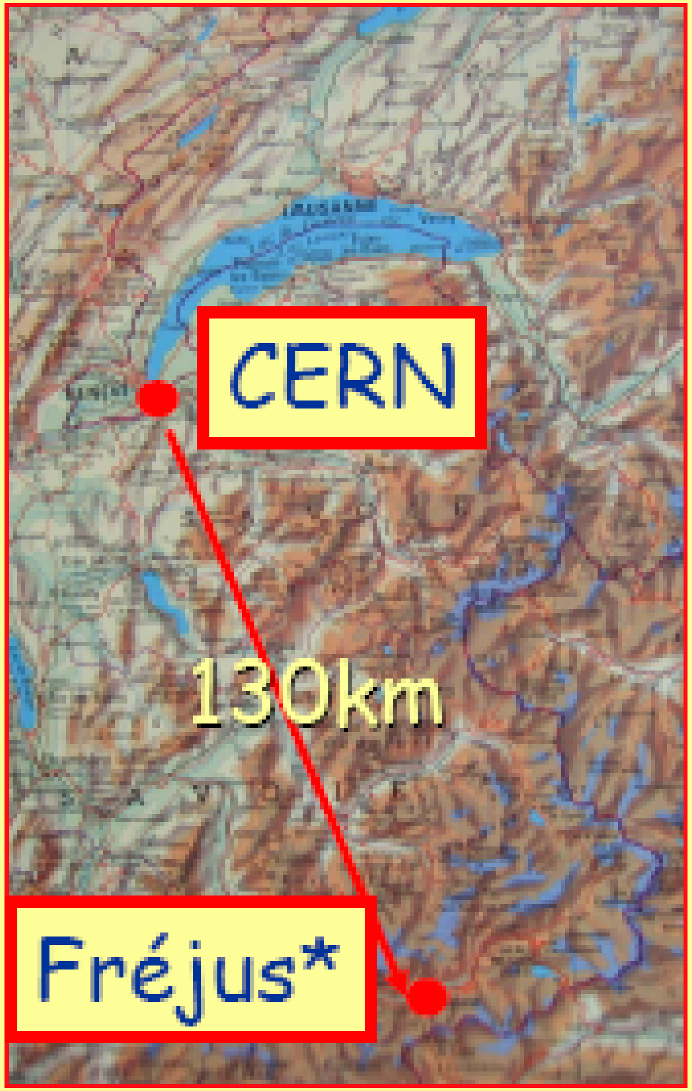
Fréjus site possibility



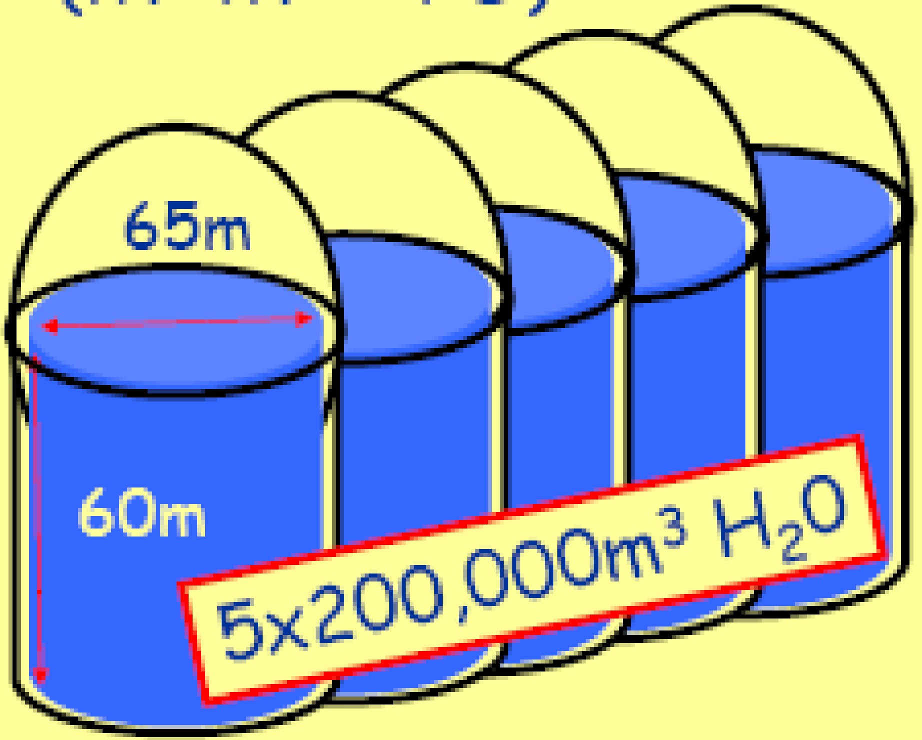
L.M

L.Mosca

New Fréjus Cavern (MEMPHYS)



*: Modane 4800mwe



Based on well experienced civil engineer studies. (September 2005)

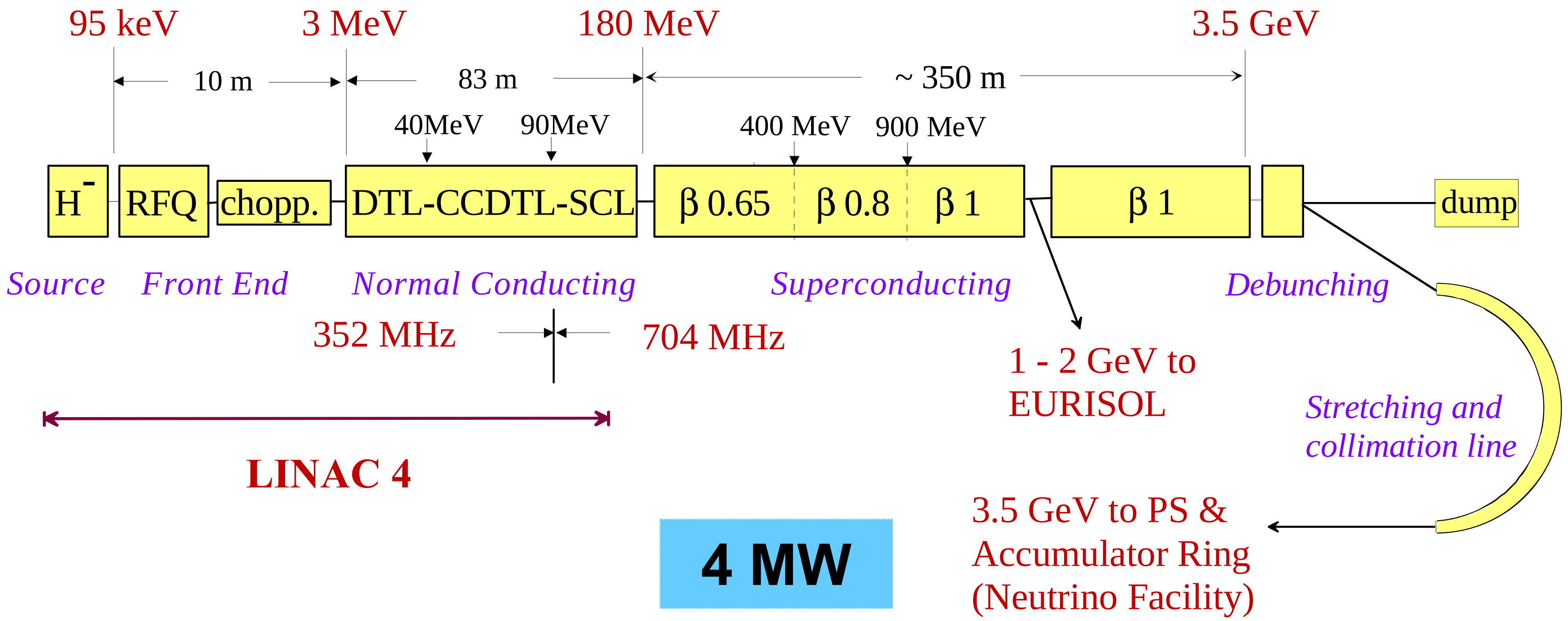
First cost and time estimate will come soon for a dedicated operation.

Beyond that a Design Study is needed

SPL current design

SPL main goals:

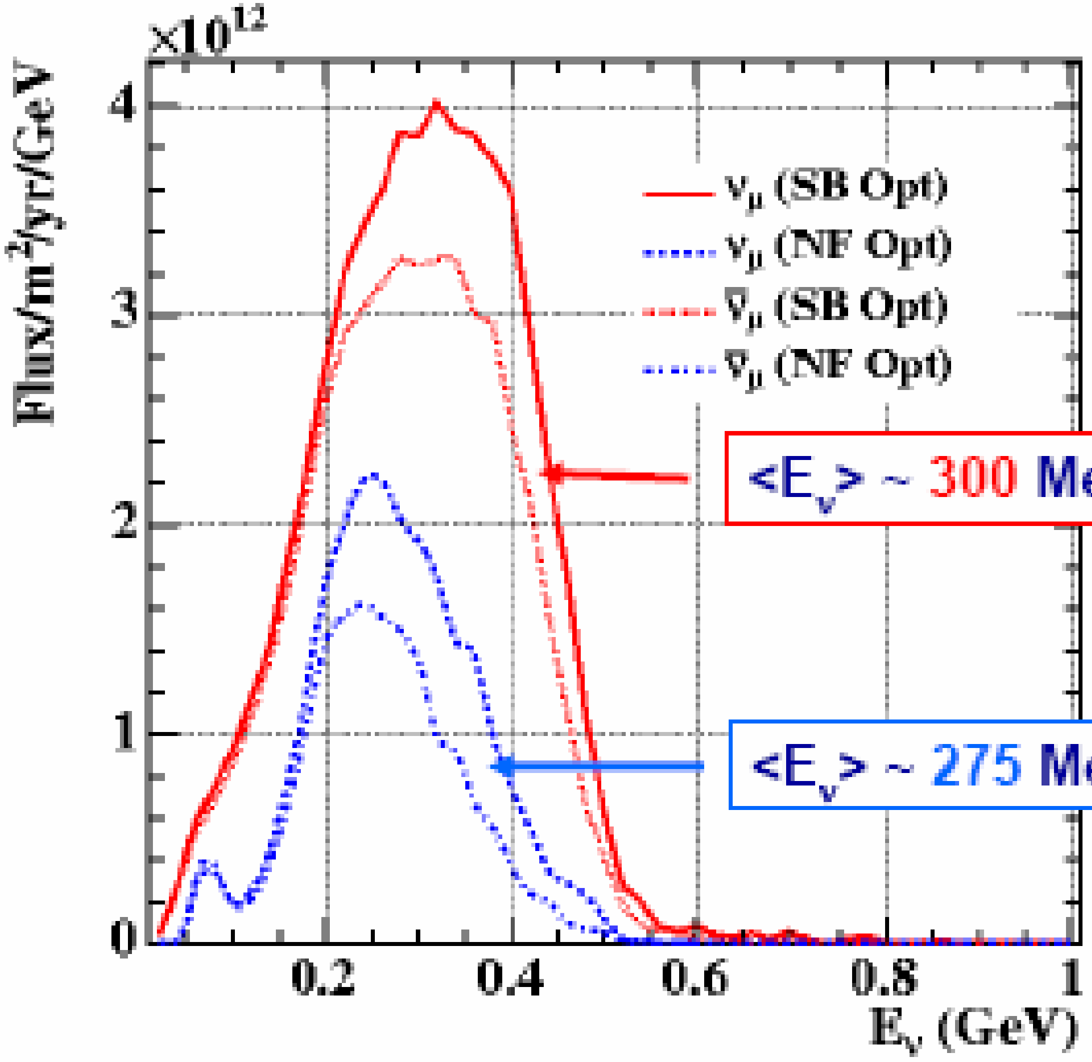
- **increase the performance of the CERN high energy accelerators (PS, SPS & LHC)**
- **address the needs of future experiments with neutrinos and radio-active ion beams**



The present R&D programme concentrates on low-energy (Linac4) items, wherever possible in collaboration with other laboratories.

From R.Garoby

Fluxes comparison @ 130km



$\sim 95\ \nu_\mu^{CC}$/kT/yr*

$\langle E_\nu \rangle \sim 300$ MeV, 1.2 10^{12}/m²/yr

3.5GeV SPL optimum

$\langle E_\nu \rangle \sim 275$ MeV, 4.5 10^{11}/m²/yr

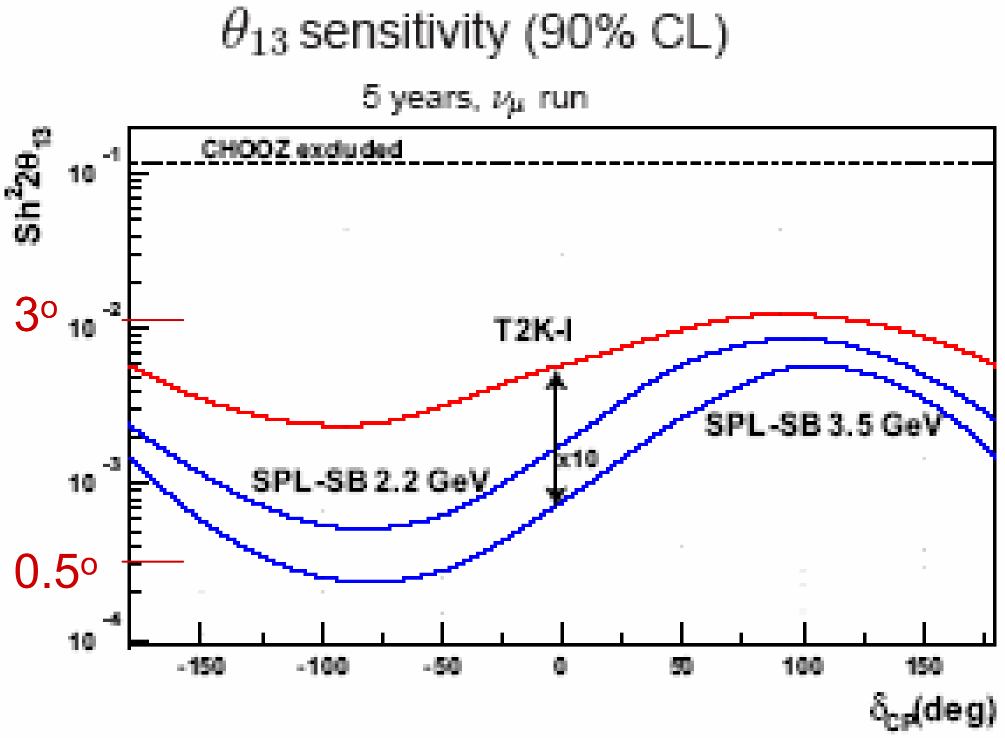
Old νFact optimum

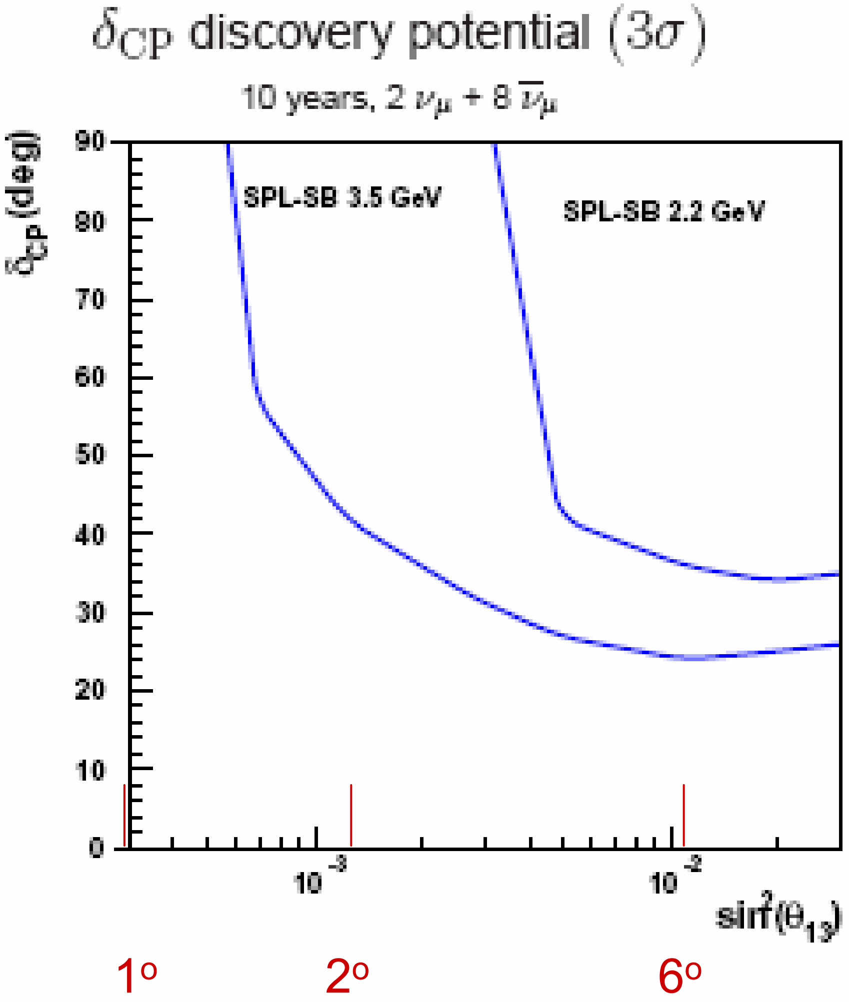
Reflector: 50% of the Flux

*: Lipari x-sect. (see later)

SPL SuperBeam Performances

Computed introducing neutrino energy reconstruction in 200 MeV energy bins.





SPL= 10 x T2K1 + sensitivity on δ

Same performance as T2K2 (megaton)

How to overcome superbeam limitations ?

Main problem :

SPL protons produce less negative pions, so less antineutrinos

antineutrino cross-section ~ 5 times smaller than neutrinos

So 10 SPL years have to be shared as ~ 2 neutrino + 8 antineutrino years

The solution :

Produce a ν_e beam to study $\nu_e \rightarrow \nu_\mu$ oscillation and run it SIMULTANEOUSLY with ν_μ beam from SPL

Compare $\nu_\mu \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_\mu$ (T asymetry, equivalent to CP asymetry)

THIS WAS THE INITIAL MOTIVATION FOR A BETA BEAM

BETA BEAMS

Concept proposed by Piero Zucchelli

- Produce radioactive ions (ISOL technique)
- Accelerate them in the CERN accelerator complex up to Γ of order 100
- Store ions in a storage ring with long straight sections aimed at a far detector

Advantages

- strongly focussed neutrino beam due to small Q value of beta decays (quality factor Γ/Q)
- very pure flavour composition (ν_μ contamination ~ 10^{-4})
- perfectly known energy spectrum

Baseline scenario first studied at CERN (Mats Lindroos and collaborators)
and now part of the EURISOL TDS

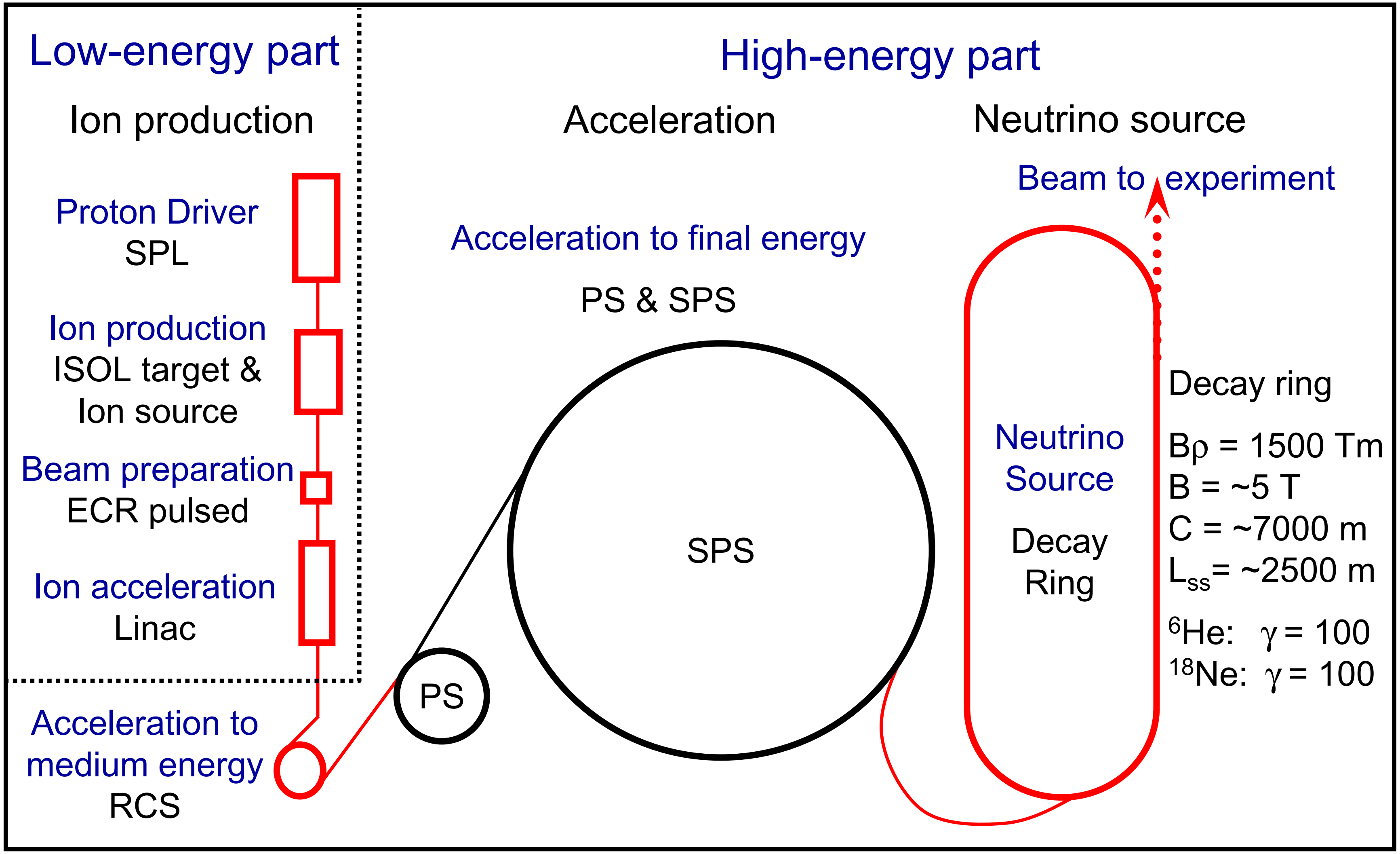
Strong synergy between beta beams and EURISOL

Beta-beam base line design

- **Strategy for the conceptual design study:**
  - Design should be based on known technology.
  - Avoid large number of technology jumps, requiring major and costly R&D efforts.
  - Re-use wherever possible existing infrastructure (i.e. accelerators) for the "first stage" base line design.

- **Major ingredients:**
  - ISOL technique for production of radioactive ions.
  - Use CERN PS and SPS accelerators for acceleration
  - Selected ions: ^{6}He (anti ν_e) and ^{18} Ne (ν_e)

Beta-beam baseline design



M.Benedikt CERN-ISS22/9/2005

Goals - Status

M.Benedikt CERN-ISS22/9/2005

- **For the base line design, the aims are (cf. Bouchez et al., NuFact'03):**
  - An annual rate of 2.9 10^{18} anti-neutrinos (^{6}He) along one straight section
  - An annual rate of 1.1 10^{18} neutrinos (^{18}Ne) at γ=100

  always for a "normalized" year of 10^7 seconds.

- **The present status is (after 8 months of the 4-year design study):**
  - Antineutrino rate (and ^{6}He figures) have reached the design values but no safety margin is yet provided.
  - Neutrino rate (and ^{18}Ne figures) are one order of magnitude below the desired performance. (*)

(*) for a single ISOL target

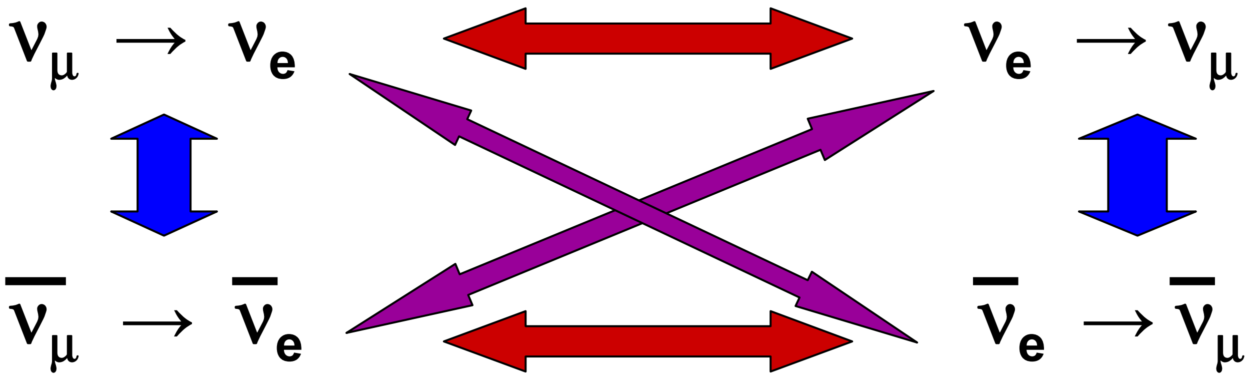
Superbeam + betabeam

SUPERBEAM

2 beams

1 detector

BETABEAM



$\nu_\mu \rightarrow \nu_e$

$\nu_e \rightarrow \nu_\mu$

$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$

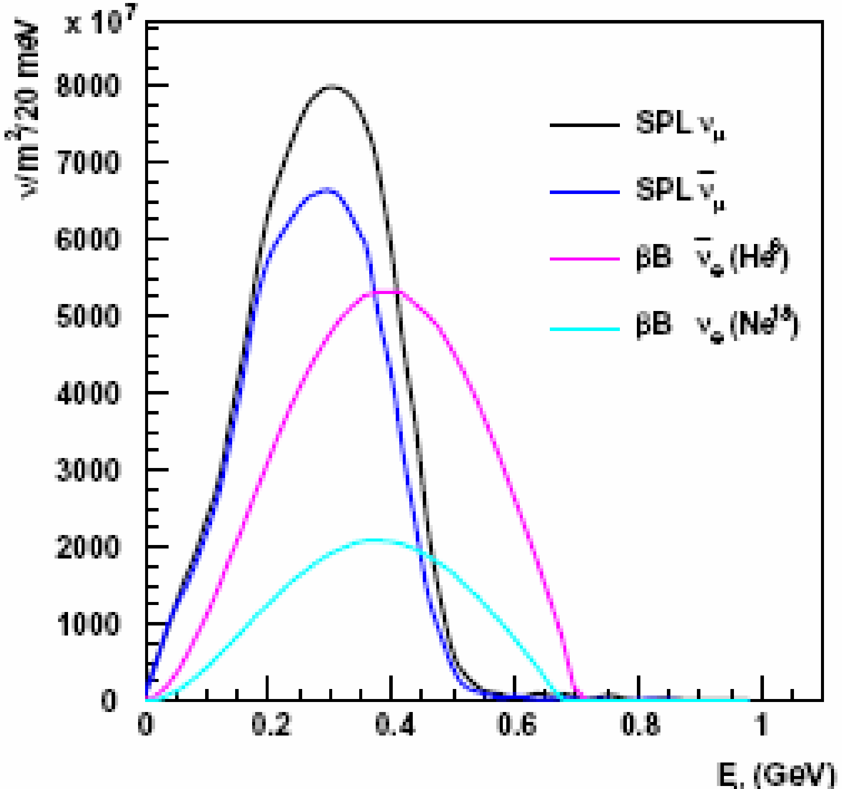
$\overline{\nu}_e \rightarrow \overline{\nu}_\mu$

2 ways of testing CP, T and CPT : redundancy and check of systematics

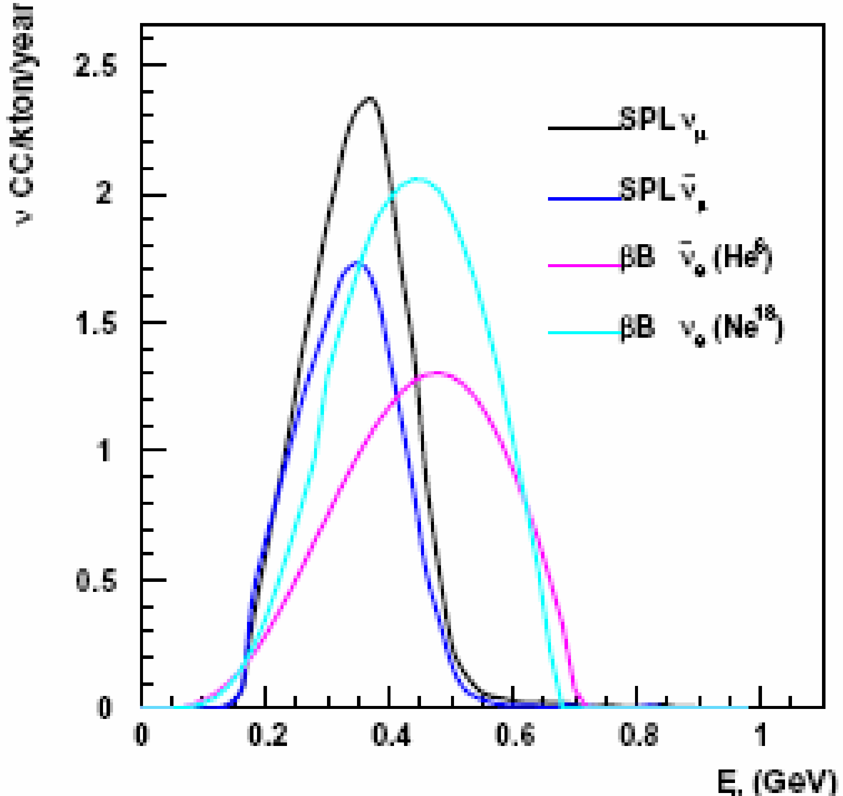
Furthermore: the small signal searched for with one beam is the bulk of events with the other beam:

Better handle on detector response

Yearly Fluxes



Averaged yearly CC rates in a 10 years run for CP

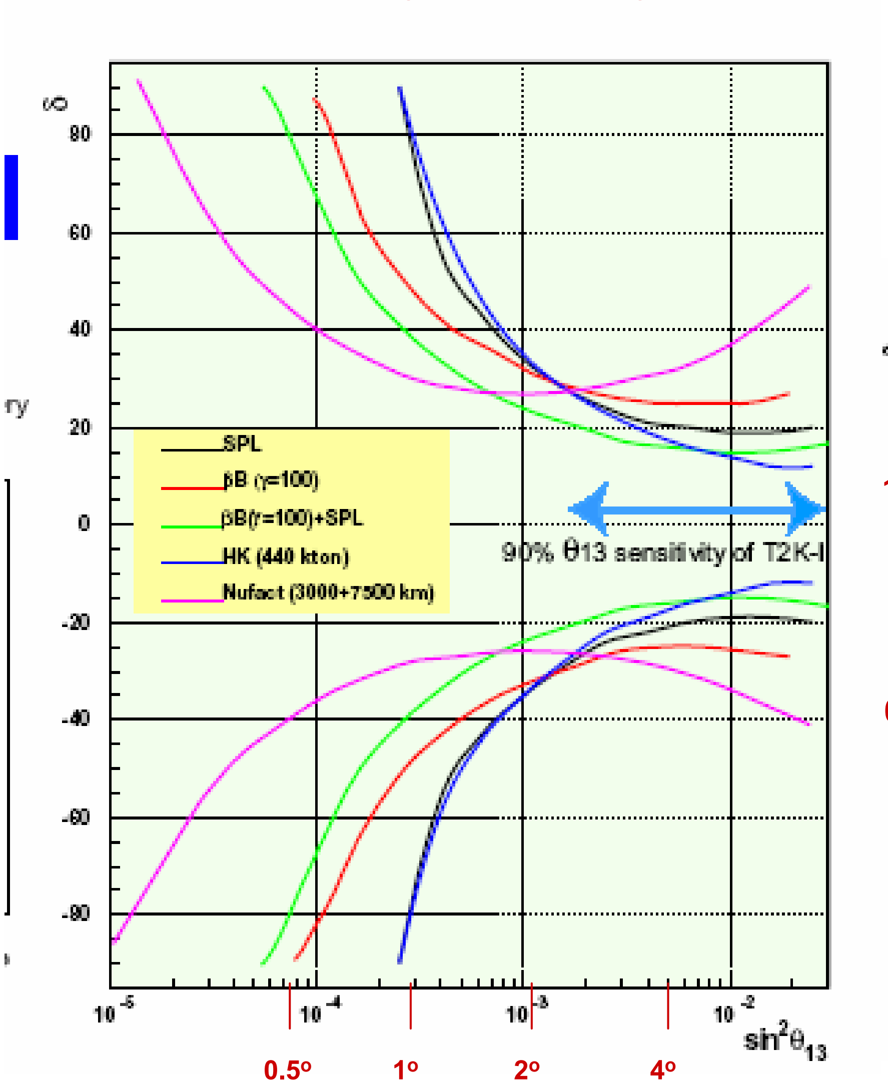


	Fluxes @ 130 km $\nu/m^2/yr$	$\langle E_\nu \rangle$ (GeV)	CC rate (no osc) events/kton/yr	$\langle E_\nu \rangle$ (GeV)	Years	Integrated events (440 kton × 10 years)
SPL Super Beam						
ν_μ	$11.80 \cdot 10^{11}$	0.29	121.7	0.36	2	107127
$\overline{\nu}_\mu$	$9.66 \cdot 10^{11}$	0.28	23.1	0.35	8	81164
Beta Beam						
$\overline{\nu}_e(\gamma = 100)$	$10.92 \cdot 10^{11}$	0.40	46.0	0.46	5	101262
$\nu_e(\gamma = 100)$	$4.06 \cdot 10^{11}$	0.38	65.4	0.44	5	143887

BETA BEAM PERFORMANCES, ALONE and WITH SUPERBEAM

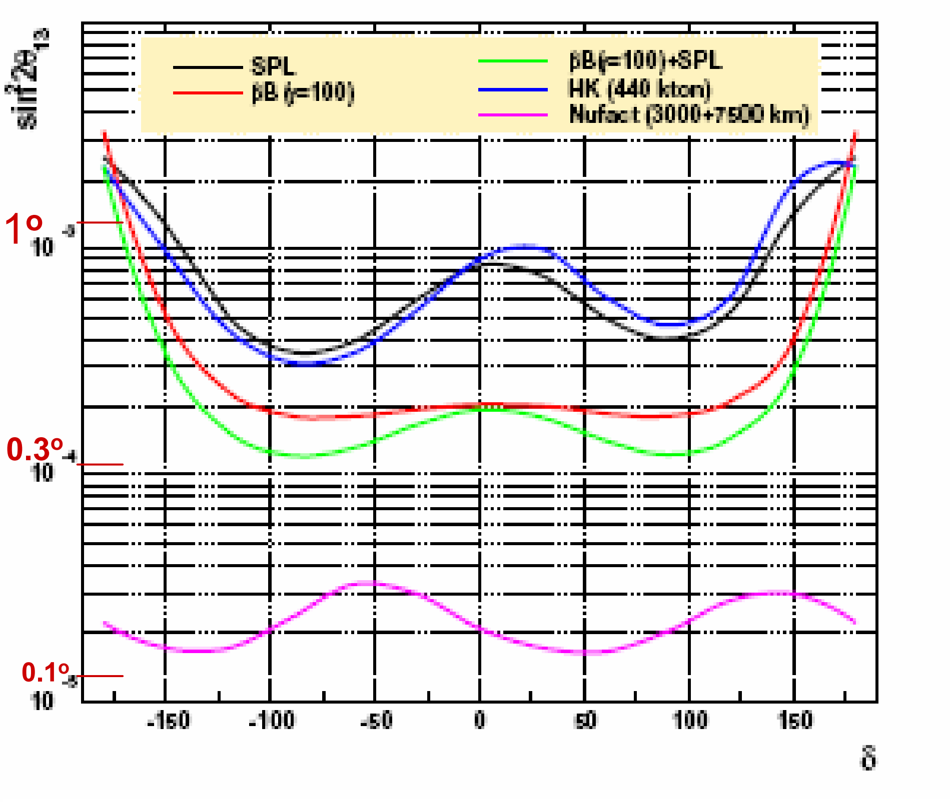
For Frejus detector: 10 year run, 440 kT fiducial mass

Full simulation of signal and backgrounds, based on SK software: results cross-checked using GLoBES

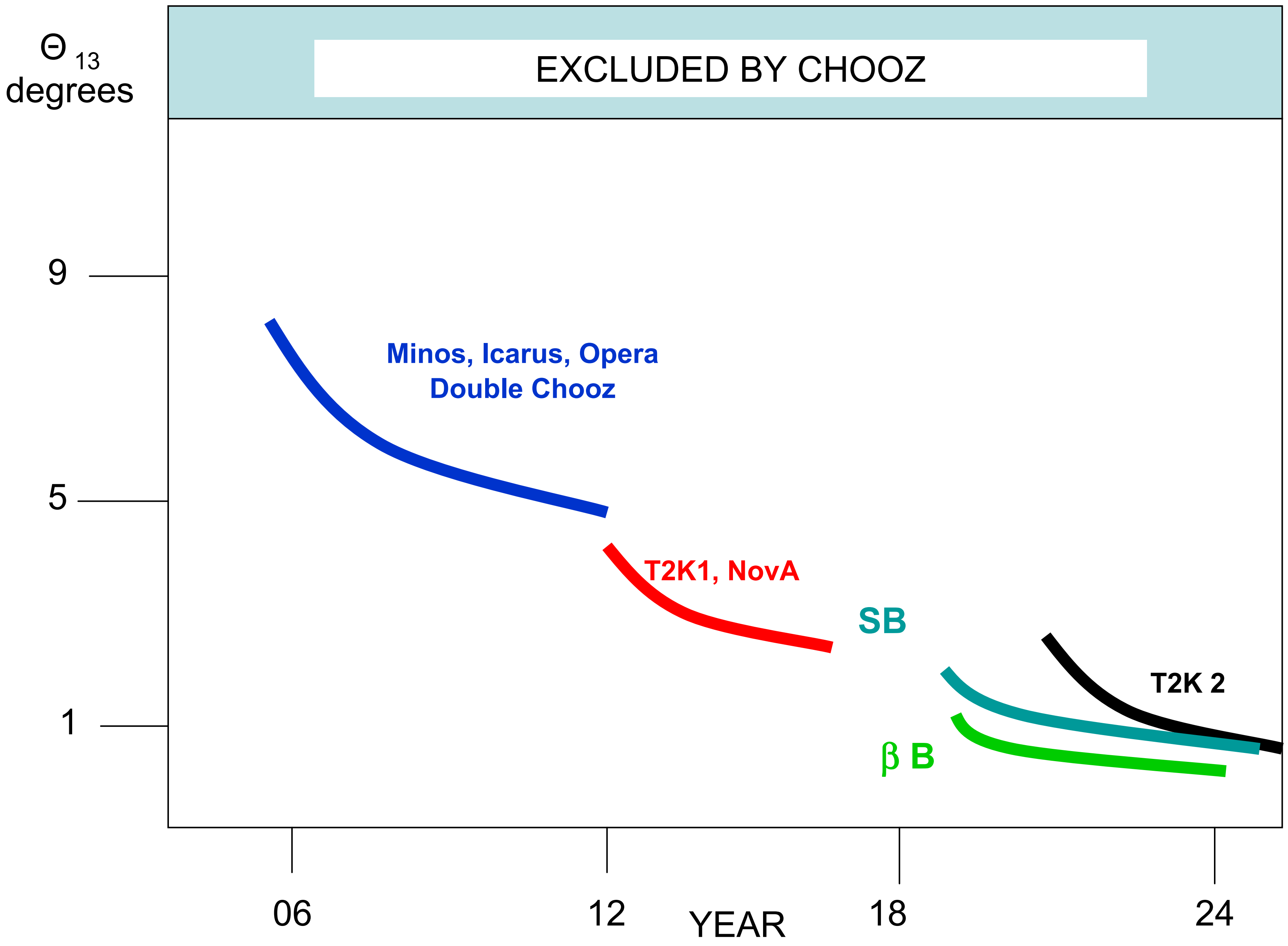


Systematics on signal and background put at 2% on all projects for the same running time

NuFACT; 10^{21} decays/year, 2 x 50 kTdetectors at 3000 and 7500 km, detection threshold 4 GeV

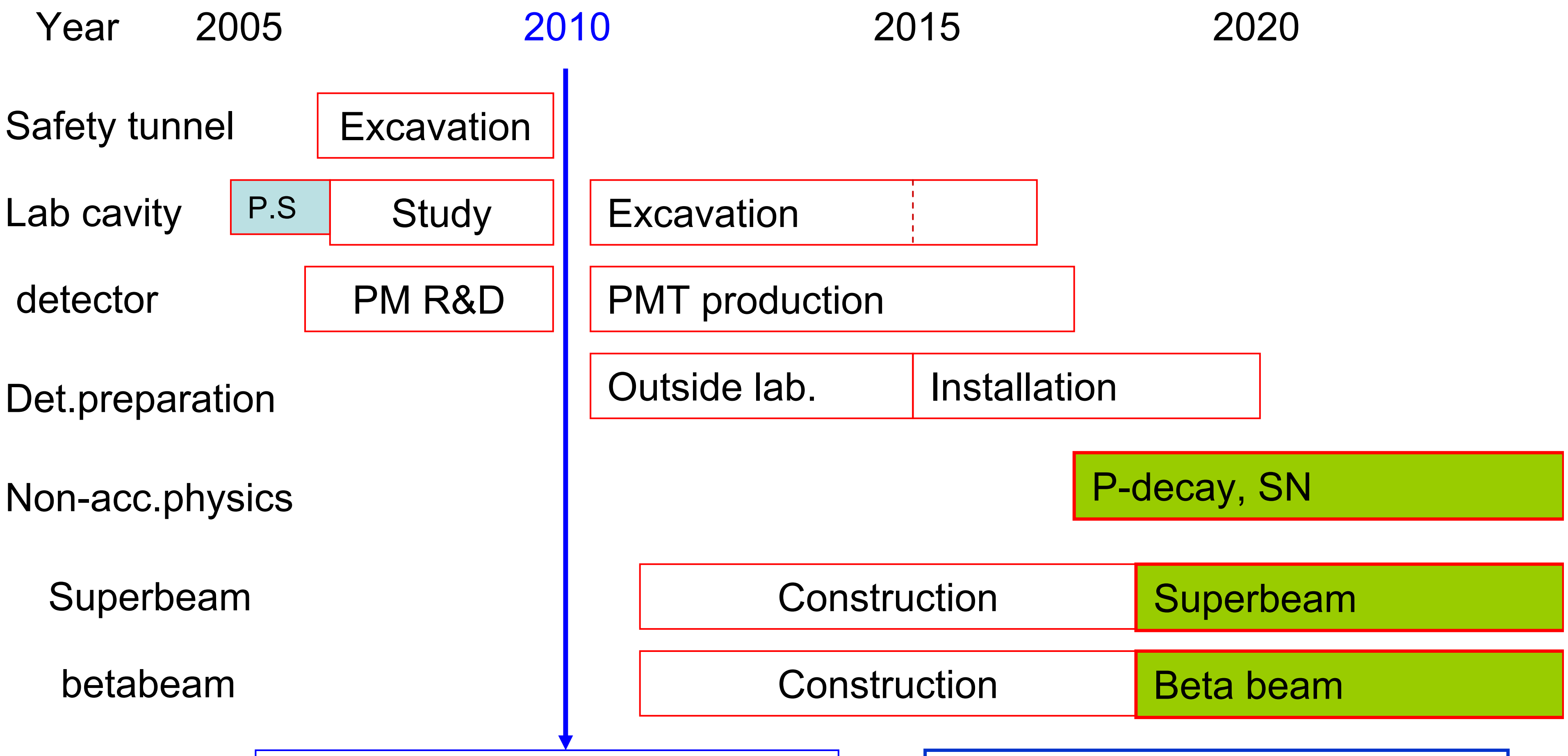


M.Mezzetto TAUP05 Zaragoza



Θ_{13}
degrees
EXCLUDED BY CHOOZ
9
5
1
Minos, Icarus, Opera
Double Chooz
T2K1, NovA
SB
T2K 2
β B
06
12
YEAR
18
24

A possible schedule for a european lab. at Frejus



decision for cavity digging
decision for SPL construction
decision for EURISOL site

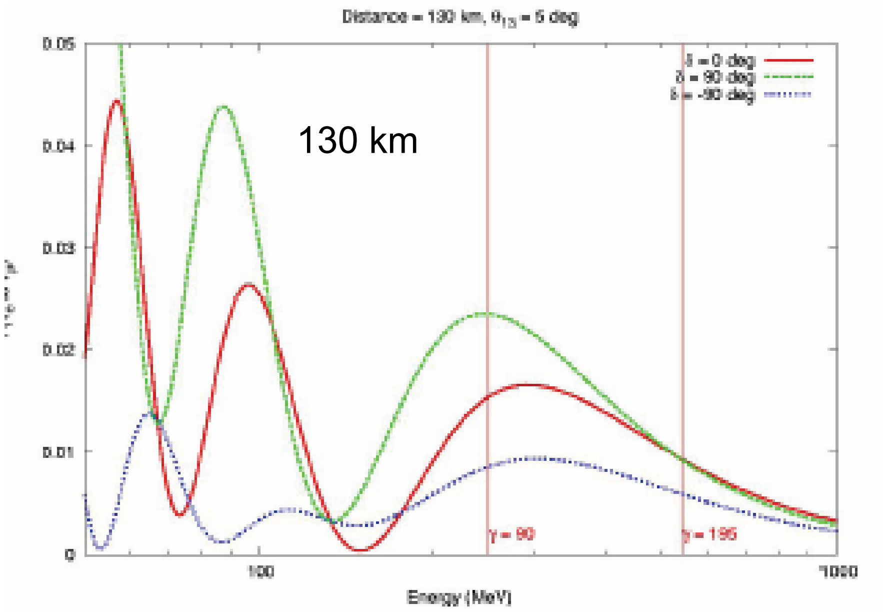
Several modules: physics can start when the 1st is ready

EC ions: monochromatic beams

J.Bernabeu et al, hep-ph/0505054

Candidates: ^{148}Dy $T_{1/2}$ = 3.1 mn EC/β = 96/4 Q_{EC} = 2062 keV

^{150}Dy $T_{1/2}$ = 7.2 mn EC/β = 99.9/0.1 Q_{EC} = 1397 keV



Pending question: achievable flux ?

Run at different γ's, with or without betabeam: interesting potentialities

Even at low flux, ideal beam to measure neutrino cross-sections in a near detector

And also… **intense monochromatic neutron beams**

about 10 ^{11} n/sec (cf. J.Blomberg's talk yesterday)

High energy beta beams

Many papers in the last 2 years have advocated using higher energy beta beams, with γ ranging from 350 (refurbished SPS) to 1000 (greenfield scenario).

Higher energy offers several advantages, in particular to solve some ambiguities through matter effects (mass ordering determination)

ALL STUDIES BASED ON THE HYPOTHESIS THAT THE DECAY RATE IN THE RING STAYS THE SAME, so that the event rate grows like γ

Caveats: phase space limitation => increase bunch length => more background: This needs to be studied carefully

At higher energy, performances of water Cerenkov deteriorate (background increase). Possibility => change technology => smaller mass => less statistics (and loss for non-accelerator physics)

Need a new accelerator, new site and a very big decay ring => cost issue

These projects, if proven feasible and as performant as expected, will arrive much later, but would then be direct competitors to a neutrino factory.

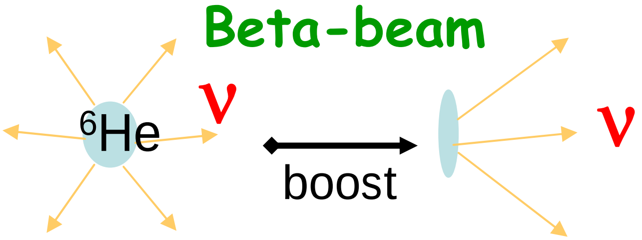
[*see E.Couce and P.Hernandez talks at CERN ISS meeting*]

(very) low energy beta-beams(γ~7-14)

C. Volpe, Journ. Phys. G30 (2004) L1

- The idea

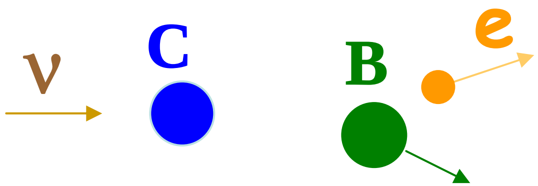
  To exploit the beta-beam concept to produce intense and pure low-energy neutrino beams



- Physics potential

  Neutrino-nucleus interaction studies for:

  - nuclear astrophysics
  - neutrino experiments (oscillations, neutrinoless double-beta decay)
  - nuclear structure



Design study within EURISOL

Design of a small storage ring and possible construction at CERN (in old antiproton storage ring ?)

Conclusions

A megaton water Cerenkov detector ,consisting of several modules, can be installed between 2010 and 2020 at Frejus

It has a very rich non-accelerator program of its own: proton decay, SN explosions, atmospheric, solar, past SN neutrinos

If CERN decides to build the SPL, it offers an excellent superbeam of 2nd generation, with similar performances to the japanese project T2K2 and starting sooner (HK ready by 2020-2025)

If this SPL is the proton machine for EURISOL at CERN, it opens the way to beta beams, with modest added cost, offering better performances than the superbeam and a strong complementarity between the two beams

Concerning neutrino physics, this project is not meant to compete with a neutrino factory, but to arrive sooner and make significant progress on the presently unknown parameters… and bring back ν physics to Europe.
Higher energy beta beams correspond to a different strategy, as an alternative to neutrino factories.

It gives a common interest to nuclear physicists and neutrino physicists to have the SPL at CERN

Union gives strength ! (and allows to save money…)

BACKUPS

HIP WG: long term alternatives (R.Garoby)

Present accelerator	Replacement accelerator	Improvement	INTEREST FOR			
			LHC upgrade	ν physics beyond CNGS	RIB beyond ISOLDE	Physics with Kand μ
Linac2	Linac4	50 → 160 MeV $H^+ \rightarrow H^-$	+	0 (if alone)	0 (if alone)	0 (if alone)
PSB	2.2 GeV RCS* for HEP	1.4 → 2.2 GeV 10 → 250 kW	+	0 (if alone)	+	0 (if alone)
	2.2 GeV/mMW RCS*	1.4 → 2.2 GeV 0.01 → 4 MW	+	++ (super-beam, β-beam ?, ν factory)	+ (too short beam pulse)	0 (if alone)
	2.2 GeV/50 Hz SPL*	1.4 → 2.2 GeV 0.01 → 4 MW	+	+++ (super-beam, β-beam, ν factory)	+++	0 (if alone)
PS	SC PS*/** for HEP	26 → 50 GeV Intensity x 2	++	0 (if alone)	0	+
	5 Hz RCS*/**	26 → 50 GeV 0.1 → 4 MW	++	++ (ν factory)	0	+++
SPS	1 TeV SC SPS*/**	0.45 → 1 TeV Intensity x 2	+++	?	0	+++

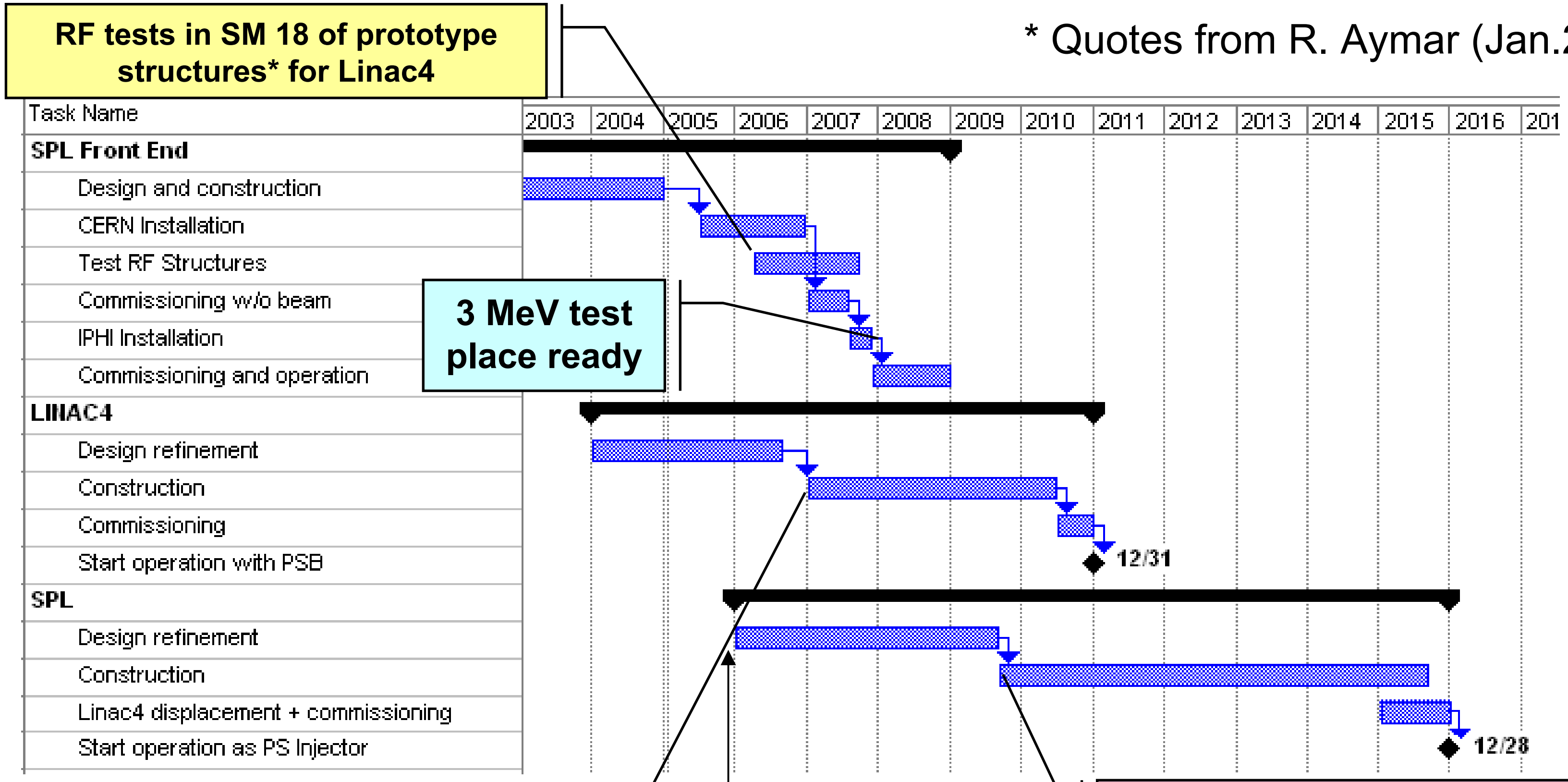
* with brightness x2 ** need new injector(s)

SPSC (Villars) recommendations

- Future neutrino facilities offer great promise for fundamental discoveries (such as CP violation) in neutrino physics, and a post-LHC construction window may exist for a facility to be sited at CERN.
- CERN should arrange a budget and personnel to enhance its participation in further developing the physics case and the technologies necessary for the realization of such facilities. This would allow CERN to play a significant role in such projects wherever they are sited.
- A high-power proton driver is a main building block of future projects, and is therefore required.
- Alone, a direct superbeam from a 2.2 GeV SPL does not appear to be the most attractive option for a future CERN neutrino experiment as it does not produce a significant advance on T2K.
- We welcome the effort, partly funded by the EU, concerned with the conceptual design of a β-beam. At the same time CERN should support the European neutrino factory initiative in its conceptual design.

->

Planning …



RF tests in SM 18 of prototype structures* for Linac4

* Quotes from R. Aymar (Jan.2005)

3 MeV test place ready

CDR 2

Linac4 approval *
"… in 2006-2007, to decide on the *implementation of the Linac 4 and any increased R&D programme*, depending on new funds made available and on a new HR policy"

SPL approval *
"in 2009-2010, *to review and redefine the strategy for CERN activities in the next decade 2011-2020 in the light of the first results from LHC and of progress and results from the previous actions.* "

R. Garoby

SPL & PDAC [1/3]

SPL (CDR2) characteristics

Ion species	**H^-**	
Kinetic energy	**3.5**	**GeV**
Mean current during the pulse	**40 (30 ?)**	**mA**
Mean beam power	**4**	**MW**
Pulse repetition rate	**50**	**Hz**
Pulse duration	**0.57 (0.76 ?)**	**ms**
Bunch frequency	**352.2**	**MHz**
Duty cycle during the pulse	**62 (5/8)**	**%**
rms transverse emittances	**0.4**	**π mm mrad**
Longitudinal rms emittance	**0.3**	**π deg MeV**

R. Garoby

SPL & PDAC [3/3]

SPL (CDR2) + PDAC characteristics

[Extrapolation from PDAC based on the SPL CDR-1]

Mean beam power	**4**	**MW**
Kinetic energy	**3.5**	**GeV**
Pulse repetition rate	**50**	**Hz**
Pulse duration	**1.66**	**μs**
RF frequency	**44.02**	**MHz**
Number of bunches (buckets)	**68 (73)**	
Number of protons per pulse (per bunch)	**1.43 E14 (2.1 E12)**	
Number of turns for injection	**345**	
rms normalized transverse emittances	**50**	**π mm mrad**
Longitudinal emittance	**0.2**	**eVs**

R. Garoby

Linac4

- **Location: PS South Hall and extension**
- **Technical Design report in preparation (publication mid-2006)**
- **Possible planning:**
  - **authorization: December 2006**
  - **construction: 2007-2010**
  - **setting-up & commissioning: 2010**
  - **availability for physics (replacing Linac2): January 2011**

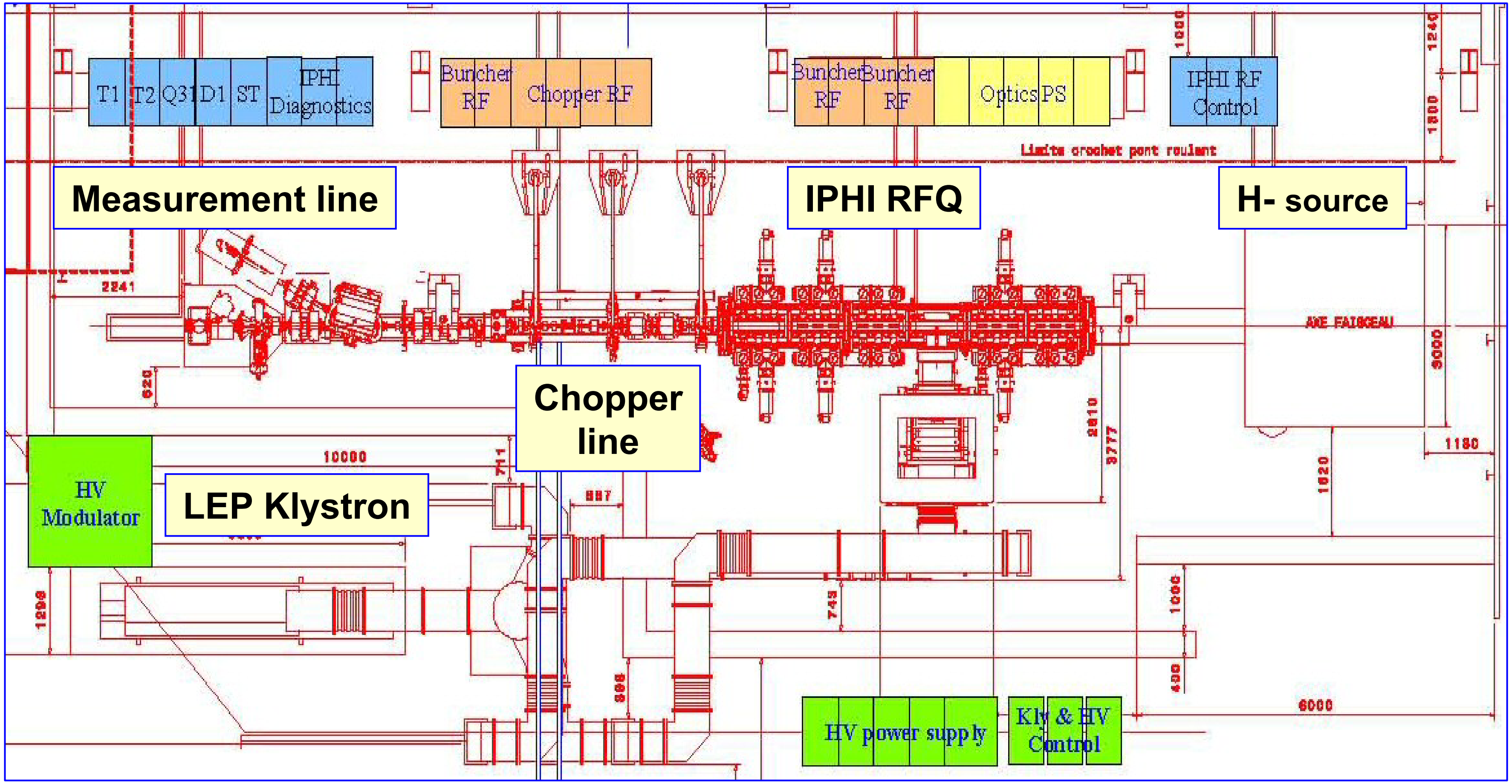
LINAC4 Characteristics

Ion species	**H^-**	
Kinetic energy	**160**	**MeV**
Mean current during the pulse	**40**	**mA**
Pulse duration	**≤ 0.4**	**ms**
Number of particles per pulse	**$\leq 10^{14}$**	
Pulse repetition rate	**≤ 2**	**Hz**
Beam power	**≤ 5**	**kW**
Bunch frequency	**352.2**	**MHz**

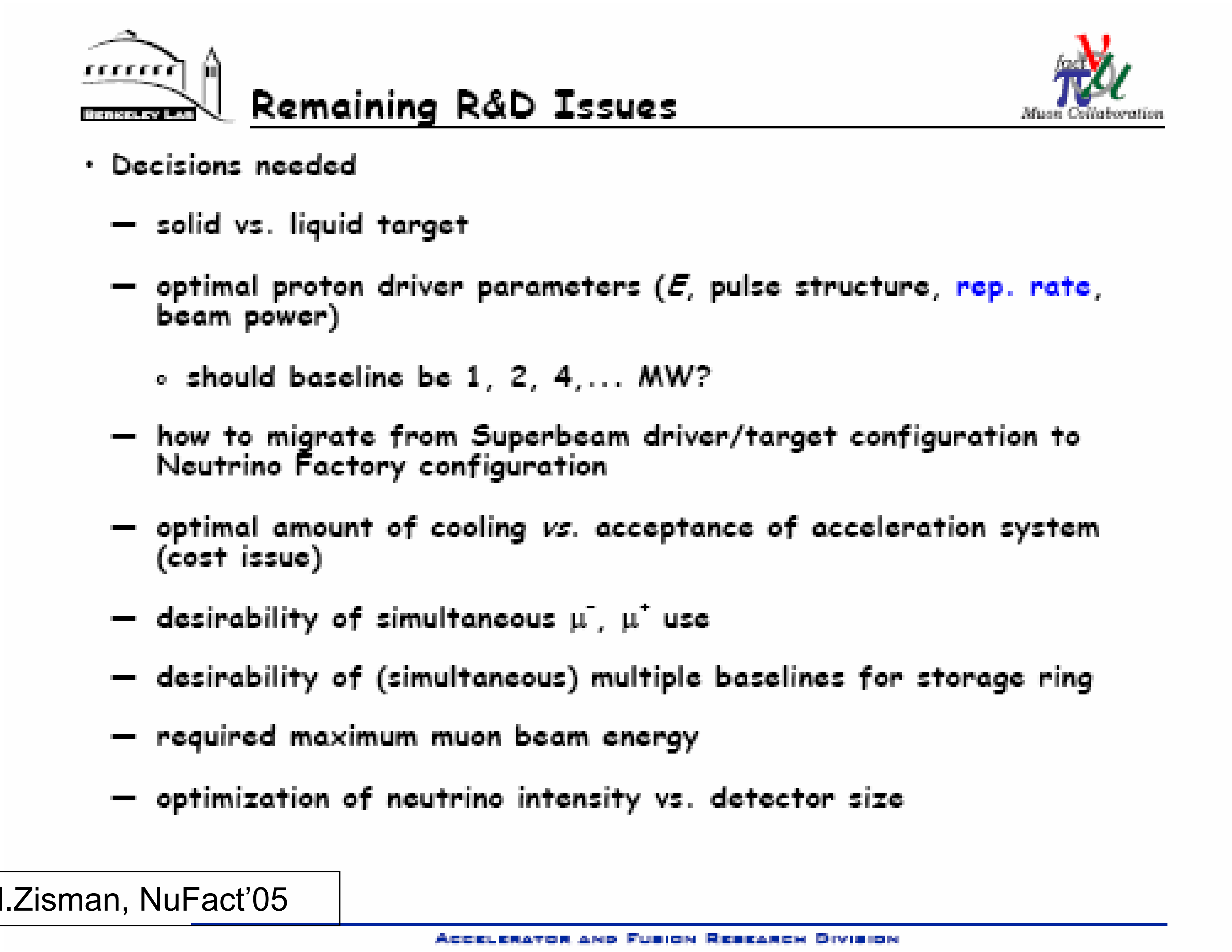
R. Garoby

3 MeV test place (Linac4 front-end)

- **Ongoing project supported by HIPPI (FP6) + IPHI (CEA+IN2P3+CERN)**
- **Location: PS South Hall extension (future location in Linac4)**
- **Test with beam : 2007-2008**



R. Garoby

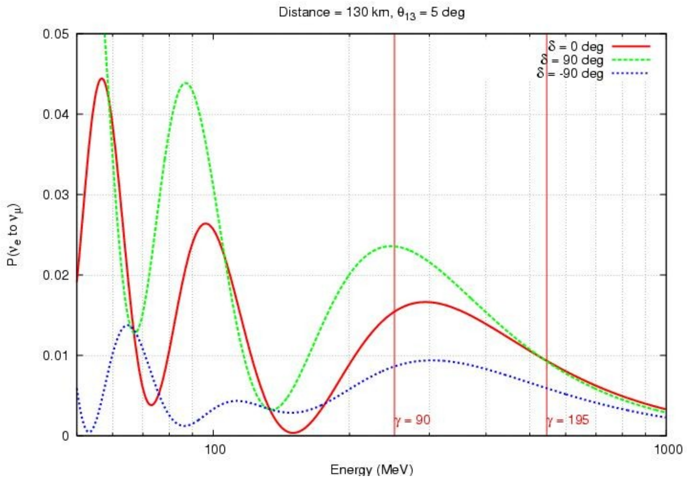


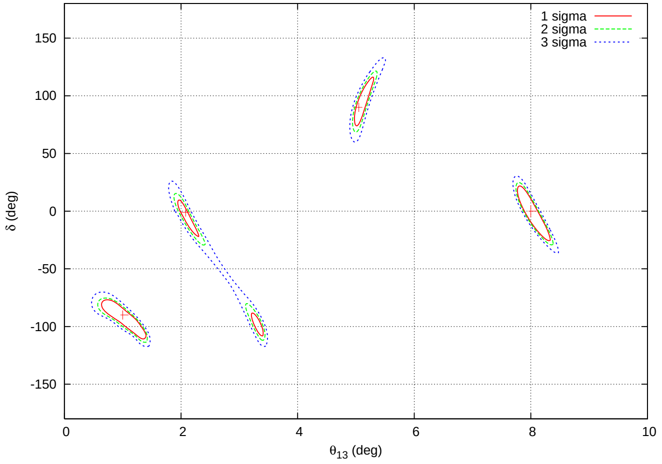
Remaining R&D Issues

- Decisions needed
  - solid vs. liquid target
  - optimal proton driver parameters (*E*, pulse structure, rep. rate, beam power)
    - should baseline be 1, 2, 4,... MW?
  - how to migrate from Superbeam driver/target configuration to Neutrino Factory configuration
  - optimal amount of cooling *vs.* acceptance of acceleration system (cost issue)
  - desirability of simultaneous μ^-, μ^+ use
  - desirability of (simultaneous) multiple baselines for storage ring
  - required maximum muon beam energy
  - optimization of neutrino intensity vs. detector size

M.Zisman, NuFact'05

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→ ^{148}Tb*	3.1 m	1	0.96	0.96	0.46	620		2682	2062	
^{150}Dy→ ^{150}Tb*	7.2 m	0.64	1	1	0.32	397		1794	1397	
^{152}Tm2$^-$→ ^{152}E$_T^*$	8.0 s	1	0.45	0.50	0.48	4300	520	8700	4400	520
^{150}Ho2$^-$→ ^{150}Dy*	72 s	1	0.77	0.56	0.25	4400	400	7400	3000	400

M.Lindroos, NuFact’05

^{150}Dy

- Partly stripped ions: The loss due to stripping smaller than 5% per minute in the decay ring
- Possible to produce 1 10^{11} ^{150}Dy atoms/second (1+) with 50 microAmps proton beam with existing technology (TRIUMF)
- An annual rate of 10^{18} decays along one straight section seems as a realistic target value for a design study
- Beyond EURISOL DS: Who will do the design?
- Is ^{150}Dy the best isotope?

M.Lindroos, NuFact'05