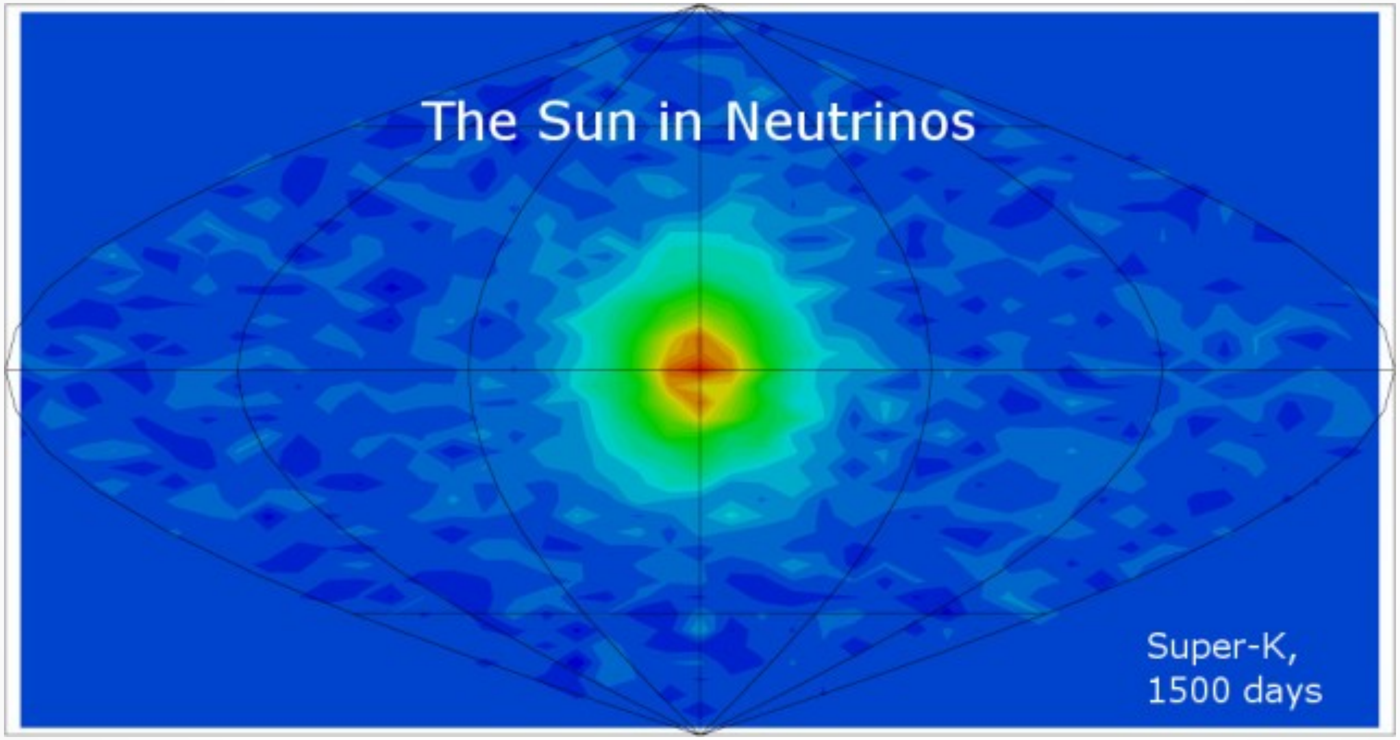
Neutrino Research: For what?



Knowledge about processes in nuclei
Particle physics
With **accelerators** we explore **properties of the neutrino:**
CONTROL of neutrino properties in the detector (flux, energy…)

Leptonic Mixing

The neutrinos $\nu_{e,\mu,\tau}$ of definite flavor

$(W \to e\nu_e$ or $\mu\nu_\mu$ or $\tau\nu_\tau)$

must be superpositions of the mass eigenstates:

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\, |\nu_i\rangle \ .$$

Neutrino of flavor $\alpha = e, \mu$, or τ

PMNS Leptonic Mixing Matrix

Neutrino of definite mass m_i

Pontecorvo–Maki–Nakagawa–Sakata matrix

The PMNS Matrix

- We need to know this matrix (leptonic mixing matrix)
- Information on the matrix elements helps to design the measurement tool (the neutrino facility)
  - For example, recent results from 5 sigma measurements of q_{13} has had important impact on the design of the neutrino facities

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij}$$
$$s_{ij} \equiv \sin\theta_{ij}$$

$$\theta_{12} \approx 34°,\ \theta_{23} \approx 39\text{-}51°,\ \theta_{13} \approx 8\text{-}10°$$

Very Recent measurement!!
We can really start looking for CP Violation

Open Questions

- (θ_{13} is non-zero from recent results: there may be CP violation!)
  - Highly performing new accelerator neutrino facilities may measure this to better precision (Neutrino Factory)
- Is the CP-violating phase δ non-zero, and if so, what is its value?
  - Upgrades of existing accelerator facilities or new better facilities have access to CP violation
- Is the neutrino mass hierarchy "normal" (mass state 1, dominated by the electron neutrino, is the lightest) or "inverted" (mass state 3 is lighter than mass state 1)?
  - Needs long distances from source to detector: "long baseline" (Japan, USA, Europe…)
- Are there any sterile neutrino states, and if so, how many, and how do their masses compare to those of the "active", Standard Model, states?
  - Needs shorter baselines, several experiments are designed to see sterile neutrinos (CERN, FNAL…)
- What is the absolute neutrino mass scale?
  - Not accessible with accelerator based facilities

Neutrino Experiments

- Sources of neutrinos for interactions observed on Earth
  - The Sun
  - Cosmic-ray interactions
  - Reactors
  - Accelerator based neutrino facilities
- Detectors
  - These detectors are often a detector built primarily for astrophysics
  - Synergy with Accelerator Facilities: BUT the Baseline has to fit (E/L)
- The Accelerator based Facilities
  - **Conventional**:
    - A high intensity proton beam is sent to a target
  - **Next generation** neutrino beams
    - "Conventional", but even higher intensities on target**, "Super Beams"**
    - **"Beta Beams"**, radioactive ions decaying in Storage Ring at high energy, high intensity
    - **"Neutrino Factories"**, muons decaying in a storage ring, high energy neutrinos
- **The presentation will focus on future/next generation**
  - The new projects are challenging accelerator projects

Outline

- Conventional Beams & Super-Beams
  - Some Conventional Beams
  - Super Beam Layout
  - Proton Drivers and Accumulators
  - Targets
  - Collection Devices (horns)
  - Target Station
- Neutrino Factories
  - Layout
  - Muon production
  - Collection and Cooling
  - Acceleration
- Beta Beams
  - Layout
  - Isotope Production/Collection
  - Acceleration
  - The Decay Ring
- Costing

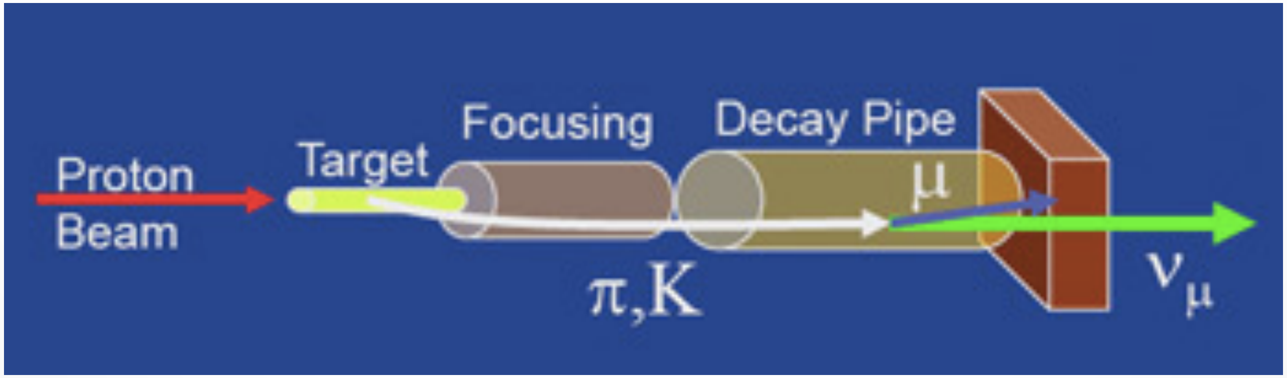
Conventional Beams

- Protons on a target produce pions and kaons
- Pions and Kaons are focused with magnetic horn towards long decay region
- Want to maximize π,K$\rightarrow\mu\nu_{\mu}$ decays for highest ν_{μ} fluxes
- Goals with accelerator beams:
  - Confirm oscillations, both with $\nu_{\mu}\rightarrow\nu_{t}$ appearance and ν_{μ} disappearance
- Proton beam needed

Conventional

D. Harris

Name	Length of run (years)	Max proton Power (kW)	$\int$(protons on target) ($\times 10^{18}$)	Proton Energy (GeV)	Decay Pipe Length (m)	# horns
NuMI	7	350	1571	120	675	2
CNGS	6	480	152	400	1095	2
T2K	1.5	200	301	30	110	3



Conventional Beams , future ?

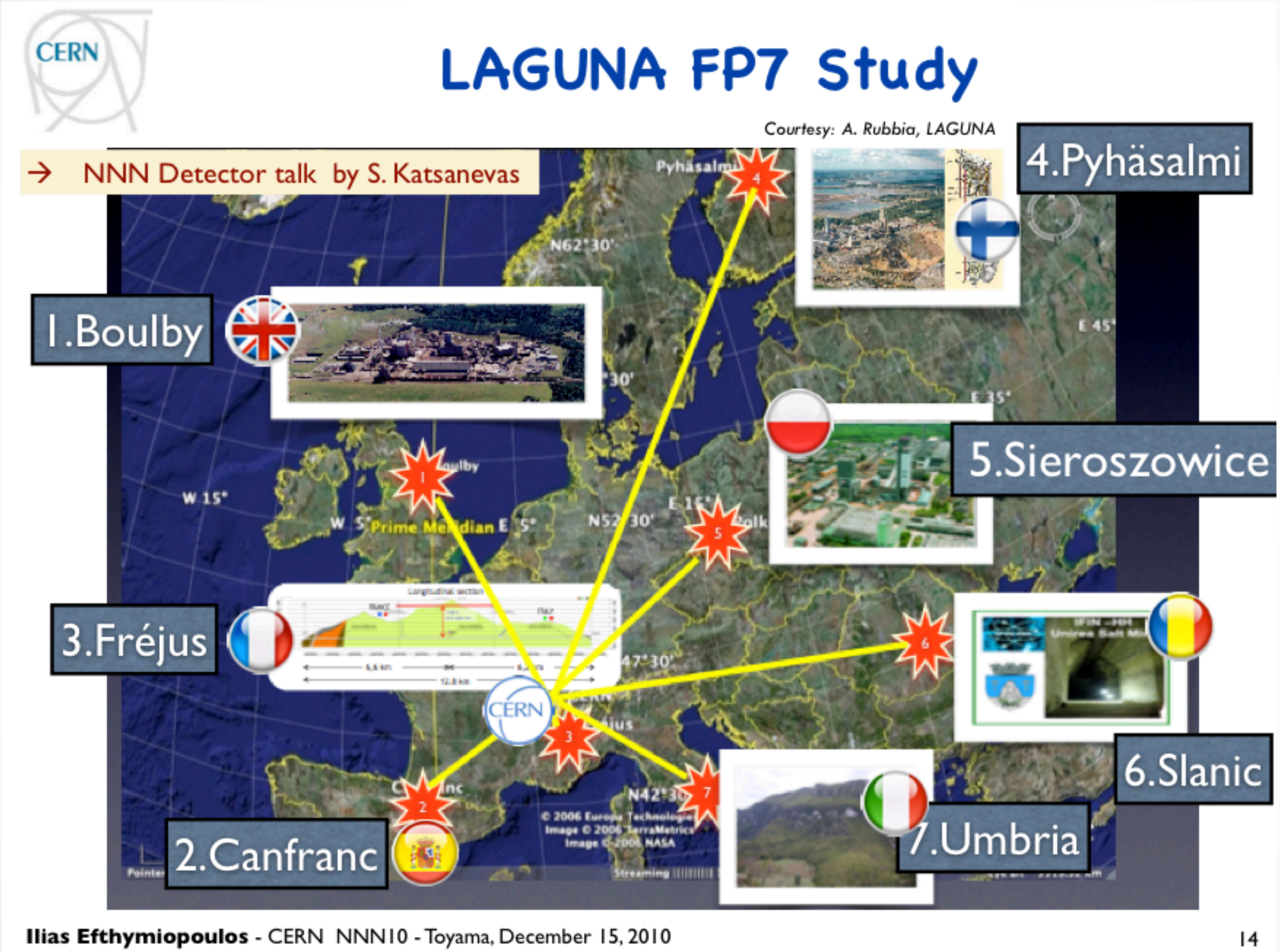
Project	Baseline [km]	Beam Power [MW]	Detector Fid. Mass [kt]	Physics start	Astrophysics
T2HK (JPARC)	2300	0.75	500 (WC)	2023	Yes
LBNE (FNAL)	1300	0.7	10 (Lar)	2022	No
LBNO (CERN)	2300	0.8	20-100 (Lar)	2023	Yes
ESS	365	5	440 (WC)	2019	Yes
CERN-Fréjus or Canfranc	130/650	4	440 (WC)	2020	Yes

I will take one example for illstration: the CERN to Frejus Superbeam

To characterize the n-beam

- Ingredients to flux prediction from upstream to downstream:
  - Proton Dynamics (number of protons on target, spot size, beam scraping)
  - Hadron production off target
    - Need measurements on both thin and thick targets, preferably at similar energy
  - Horn design, horn current, position, angle measurements
- HADRON PRODUCTION most important of these!
- Need to do dedicated hadron production experiments
  - HARP: 8GeV protons on Be (MiniBooNE)
  - NA49: 158GeV protons on thin C (NuMI)
  - MIPP: 120GeV protons on thick C target (NuMI)
  - NA61/SHINE: 31GeV protons on thick and thin C (T2K)

Detectors for the n-beam (EU)

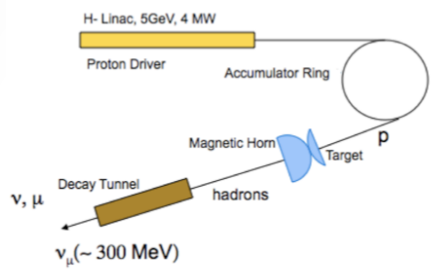
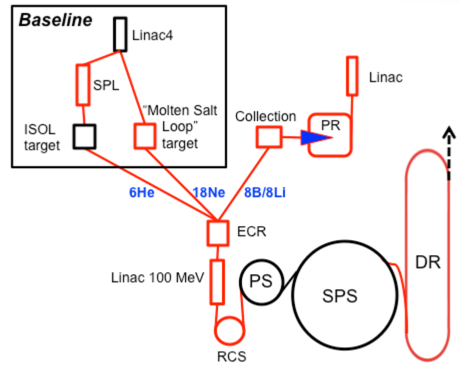
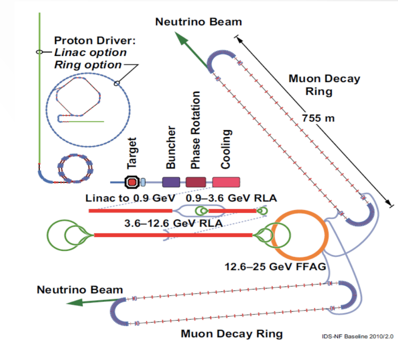
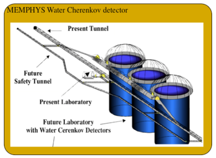
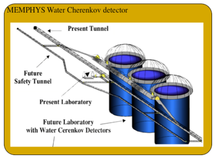
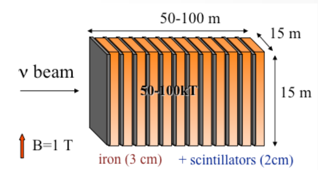
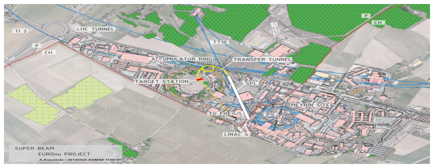
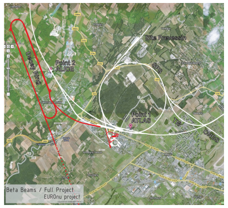


LAGUNA=Large Apparatus for Grand Unification and Neutrino Astrophysics

The following will describe EUROnu projects (FP7)

- Several Other Projects exist:
  - High power proton beams on target
  - Neutrino oscillation also extra neutrinos (steriles)
- EUROnu has studies future precision measurement facilities for CP violation, mass hierarchy and oscillation properties
- Some potential for unknown physics
- The project outcome is part of the European HEP strategy proposals
- The accelerator physics is challenging
- No time to cover all projects and proposals

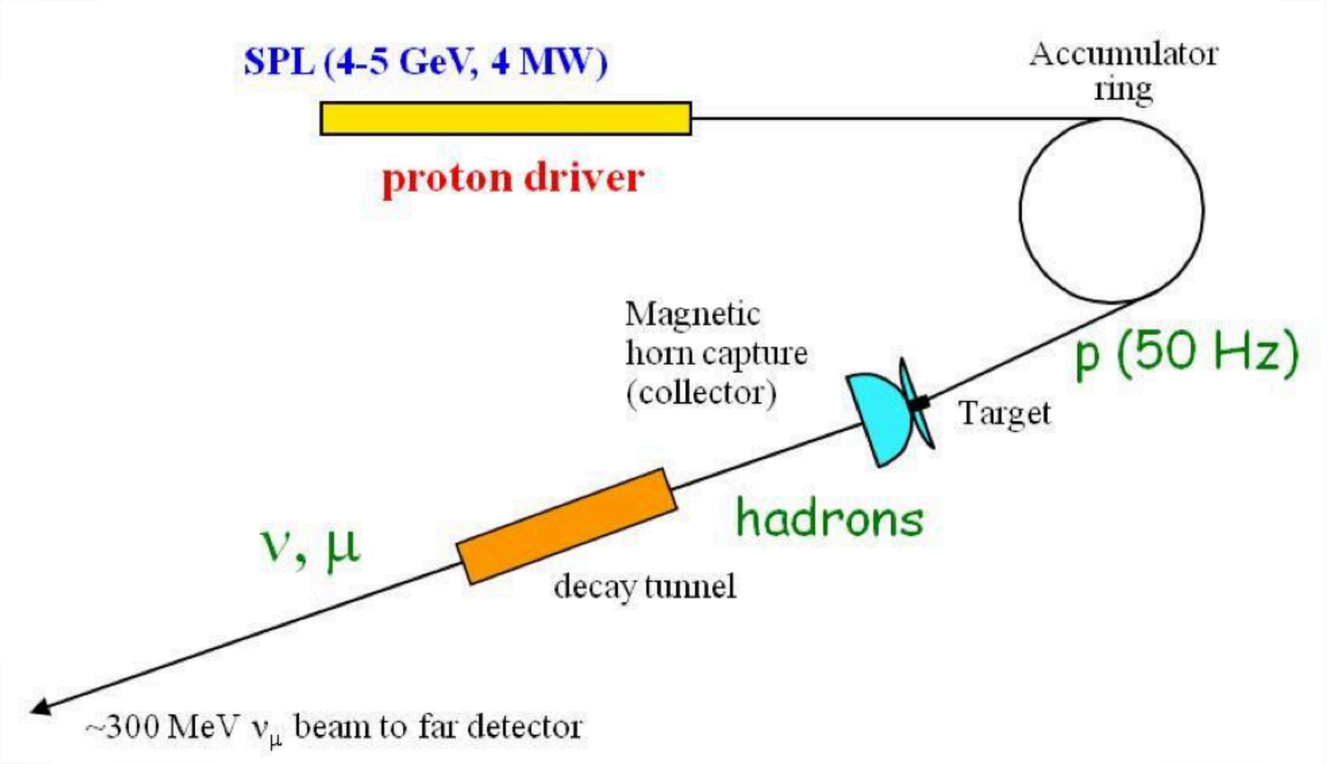
EUROnu

		Super Beam	Beta Beam	Neutrino Factory
Design **Cost** **Safety** **Risk** **Time scale**	Facility			
	Detectors	 =		
Civil engineering				

Comparison: performance – cost – safety – risk

Input to the definition of a Road Map for neutrino physics in Europe
(together with other neutrino facilities studies)
Report to CERN Council via Stragey Group and ECFA

The Super Beam



The SPL

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

Required for low loss in accumulator

Required for muon production

Required for flexibility and low loss in accumulator

	Option 1	Option 2
Energy (GeV)	2.5 or 5	2.5 and 5
Beam power (MW)	2.25 MW (2.5 GeV) <u>or</u> 4.5 MW (5 GeV)	5 MW (2.5 GeV) <u>and</u> 4 MW (5 GeV)
Protons/pulse (x 10^{14})	1.1	2 (2.5 GeV) + 1 (5 GeV)
Av. Pulse current (mA)	20	40
Pulse duration (ms)	0.9	1 (2.5 GeV) + 0.4 (5 GeV)

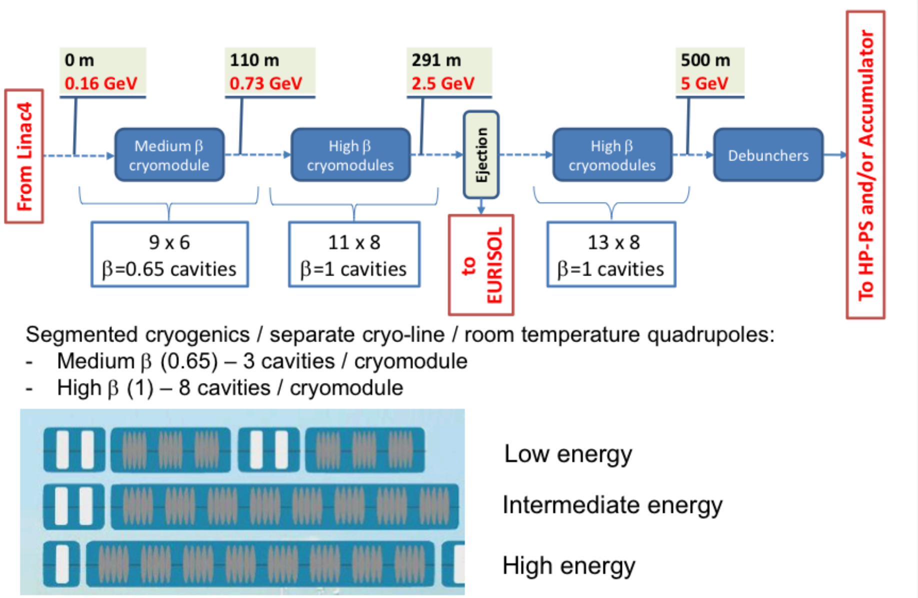
$2 \times$ beam current $\Rightarrow 2 \times$ nb. of klystrons etc .

R. Garoby

The SPL R&D

- ***Low-b cavities => SC***
- ***High Beam Power***

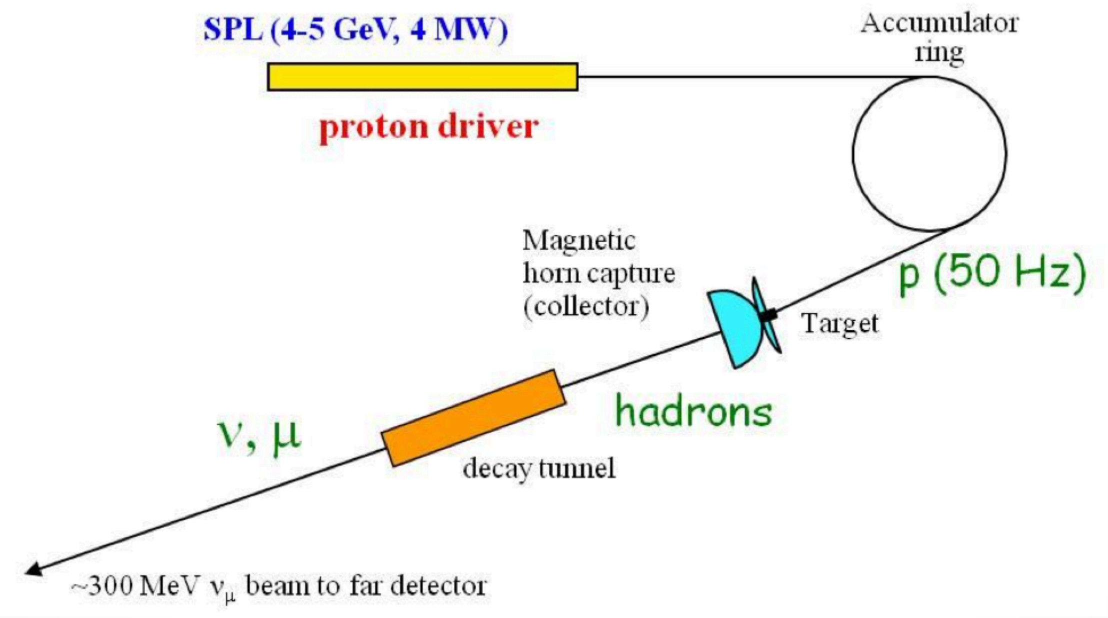
R. Garoby, E. Jensen, F. Gerijk



- ***HOM damper*** for beam stability at high current
- ***SC Cavities*** in view of reaching the expected performance/simplifying fabrication/evaluating alternative solutions (Nb on Cu)
- ***Cryo-module*** towards a full size prototype
- ***RF amplifiers*** for reducing cost
- ***Power supply*** for high power amplifier for reducing cost

Accumulator

- 42 Bunches from the SPL (H^-)
- Charge exchange injection
- 6 Bunches in Accumulator, 120 ns each.

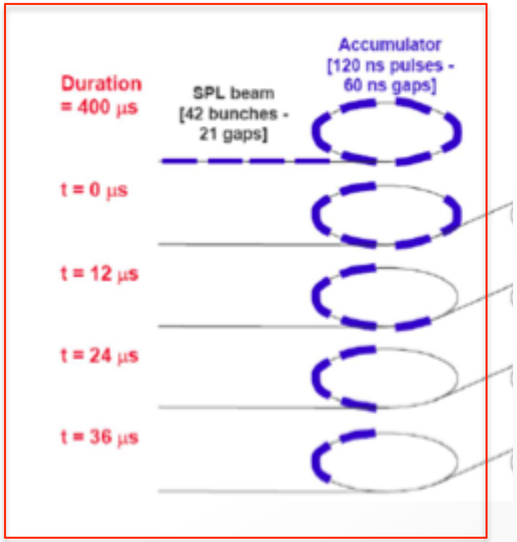


The SPL & Accumulator

SPL type	full-power	low-power
E [GeV]	5.0	4.0
P_{beam} [MW]	>4	0.192
f_{rep} [Hz]	50	2
$I_{average}$ [mA]	40	20
t_{pulse} [ms]	0.4	1.2
$n_{protons/pulse}$ [10^{14}]	1.0	1.5
Max. filling time PS2 [ms]	0.6	1.2
$n_{klystron}$ (Linac4 + SPL)	19+53	19+24
$n_{SC\ cavities}$	234	194
inst. $P_{RF(peak)}$ [MW]	220	100
$P_{facility}$ [MW]	38.5	4.5
$P_{cryo,\ electric}$ [MW]	4.5	1.5
T_{cryo} [K]	2	2
length [m]	534	459

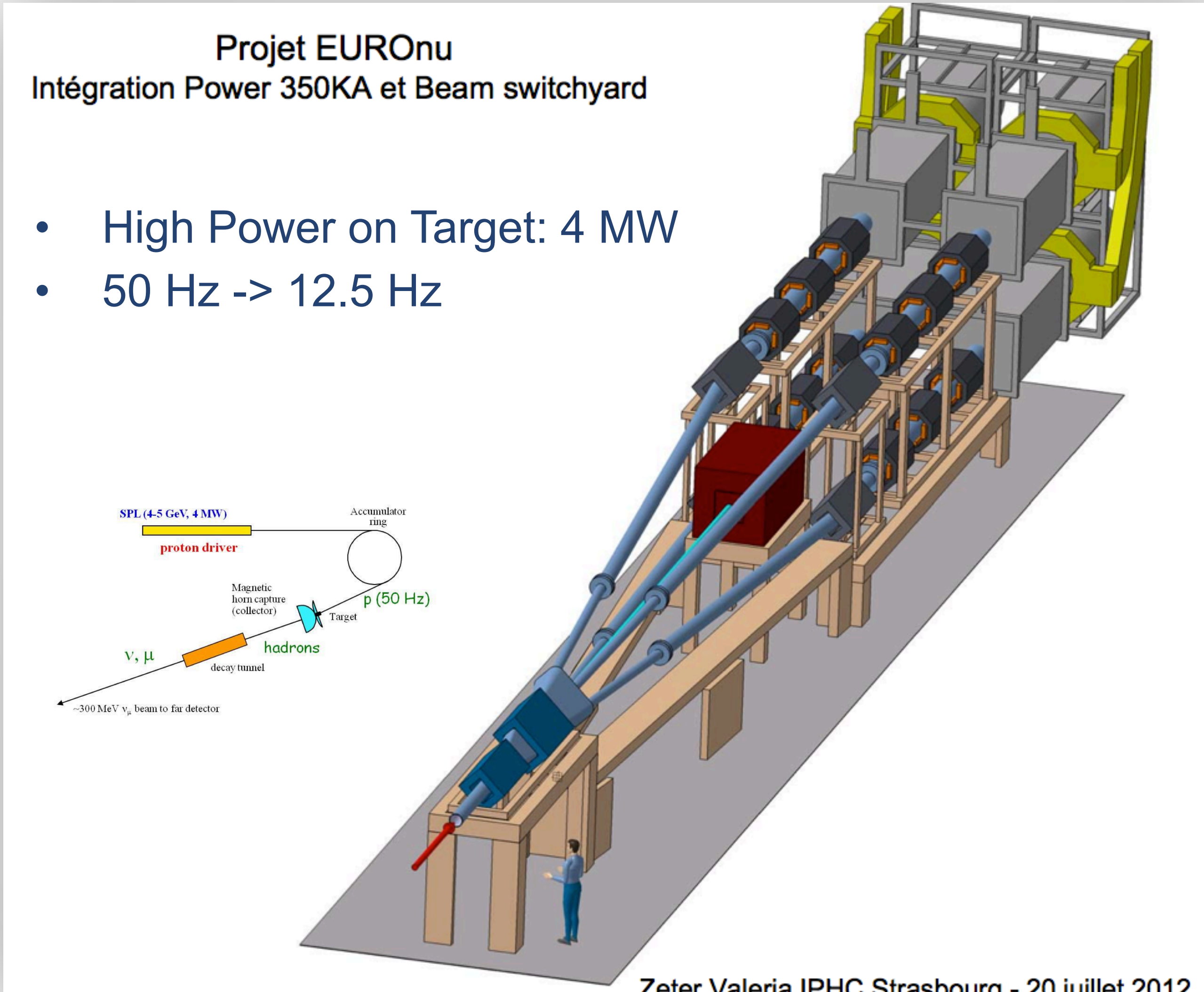
- The SPL beam structure not optimal for the target
- 42 Bunches from the SPL
- 6 Bunches in Accumulator, 120 ns each
- H- charge exchange injection

Super Beam



Proton Beam Distribution

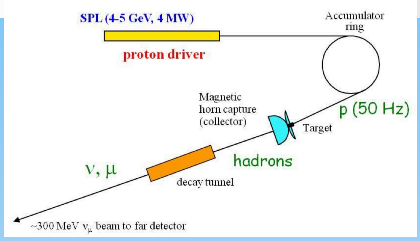
- High Power on Target: 4 MW
- 50 Hz -> 12.5 Hz

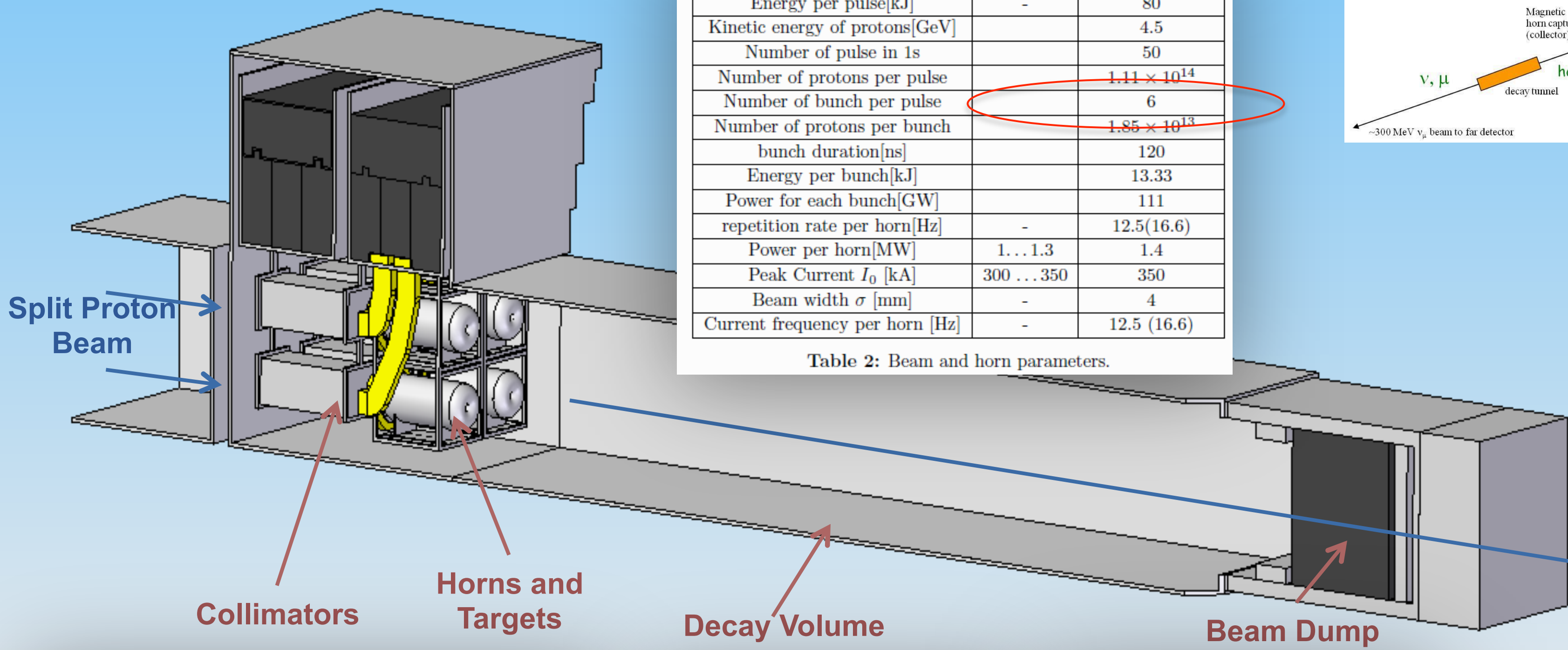


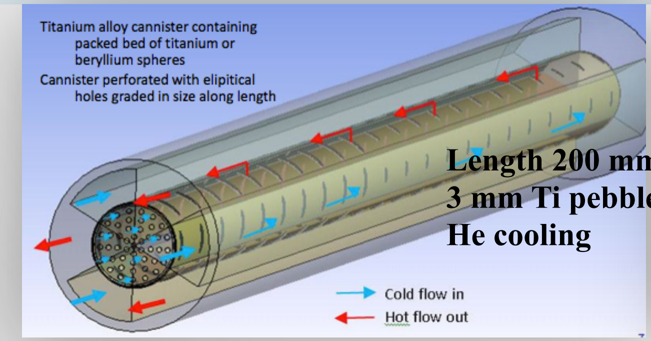
Targets, Horns, Dump

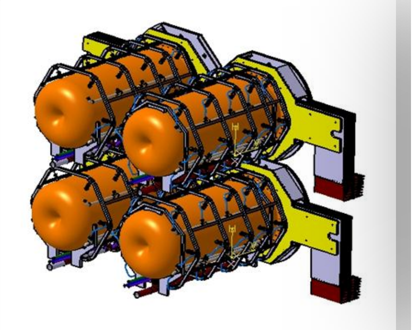
Parameters	Range	Reference value
Beam Power P_{beam}[MW]	-	4
Energy per pulse[kJ]	-	80
Kinetic energy of protons[GeV]		4.5
Number of pulse in 1s		50
Number of protons per pulse		1.11×10^{14}
Number of bunch per pulse		6
Number of protons per bunch		1.85×10^{13}
bunch duration[ns]		120
Energy per bunch[kJ]		13.33
Power for each bunch[GW]		111
repetition rate per horn[Hz]	-	12.5(16.6)
Power per horn[MW]	$1 \ldots 1.3$	1.4
Peak Current I_0 [kA]	$300 \ldots 350$	350
Beam width σ [mm]	-	4
Current frequency per horn [Hz]	-	12.5 (16.6)

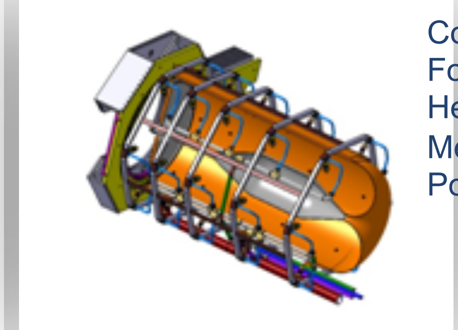
Table 2: Beam and horn parameters.





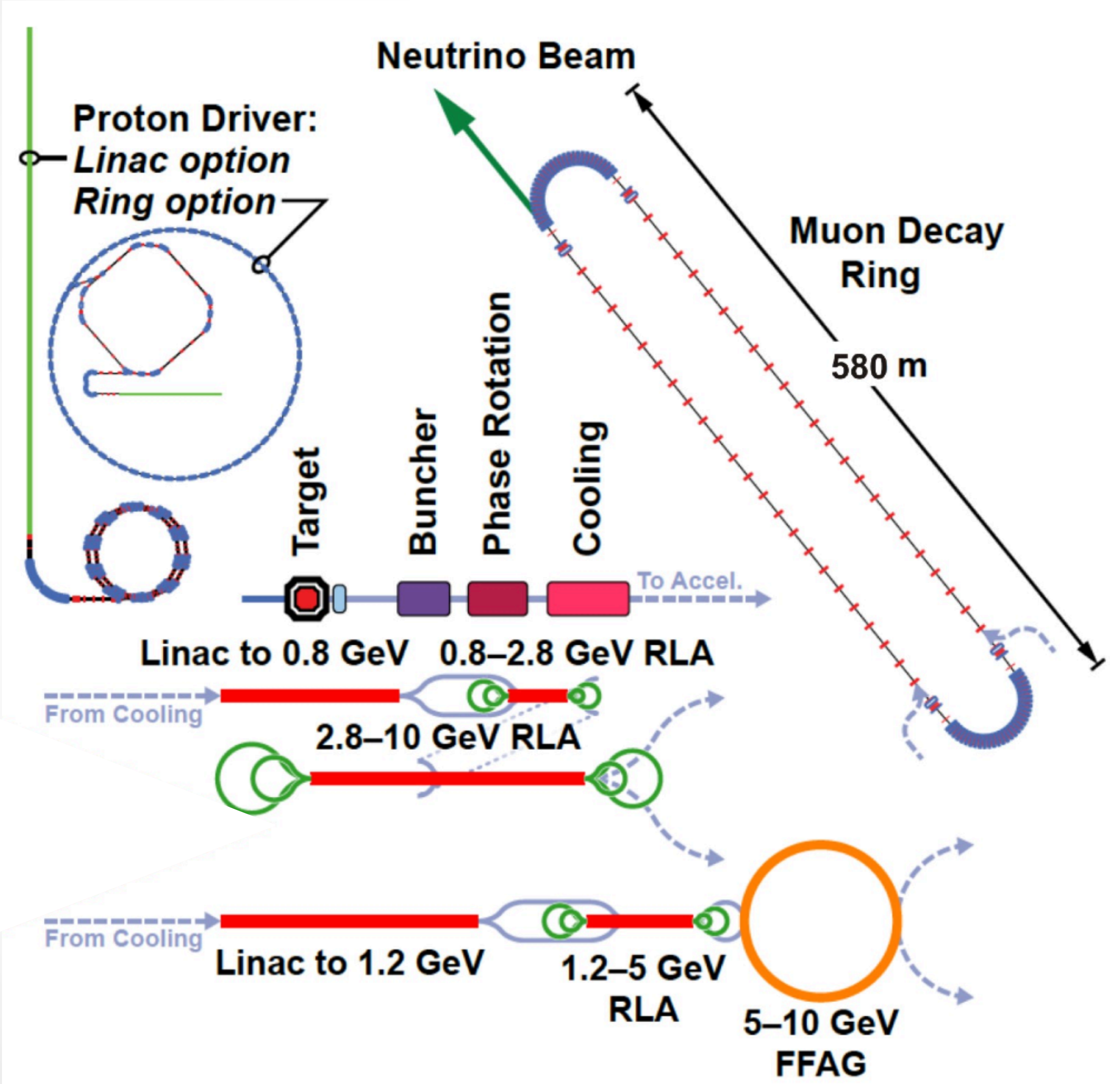






- Considerable R&D
- Focus pions for physics
- Heat Load
- Mechanical Stress
- Power Supplies

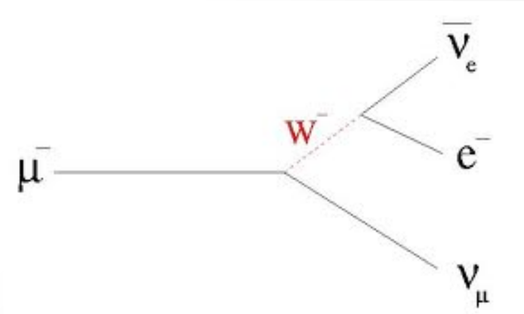
The Neutrino Factory



10^{21} muon decays per year

10 GeV stored muons

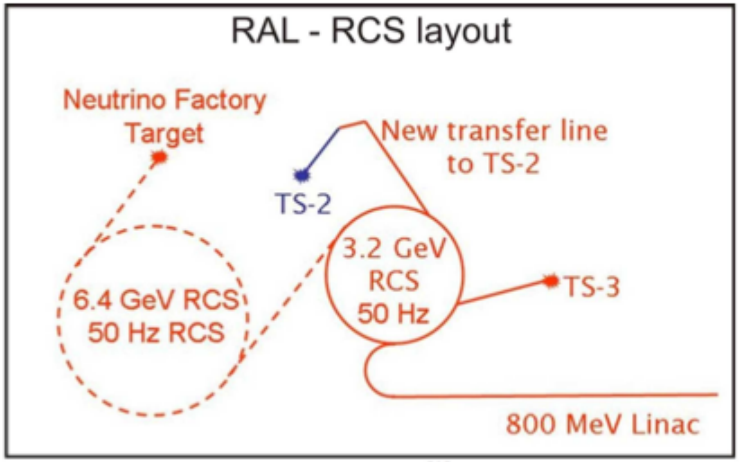
Source-Detector Distance 1500 – 2500 km



NF Proton Drivers

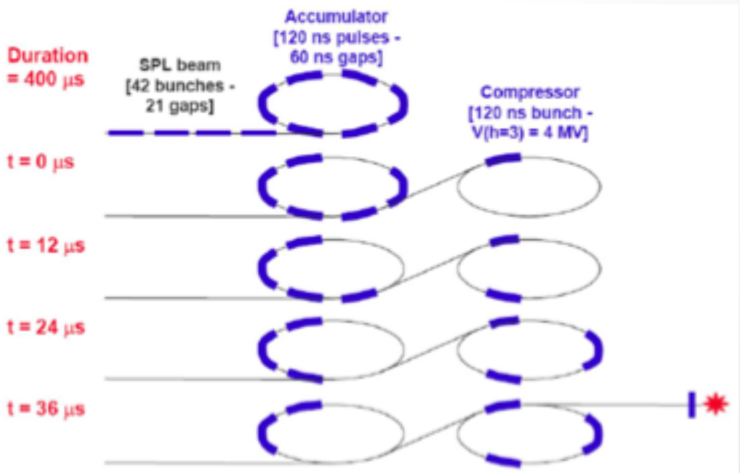
Requirements on target

Parameter	Value
Kinetic energy	5–15 GeV
Average beam power	4 MW
	$(3.125 \times 10^{15}$ protons/s$)$
Repetition rate	50 Hz
Bunches per train	3
Total time for bunches	240 μs
Bunch length (rms)	1–3 ns
Beam radius	1.2 mm (rms)
Rms geometric emittance	$< 5\ \mu$m
β^* at target	≥ 30 cm



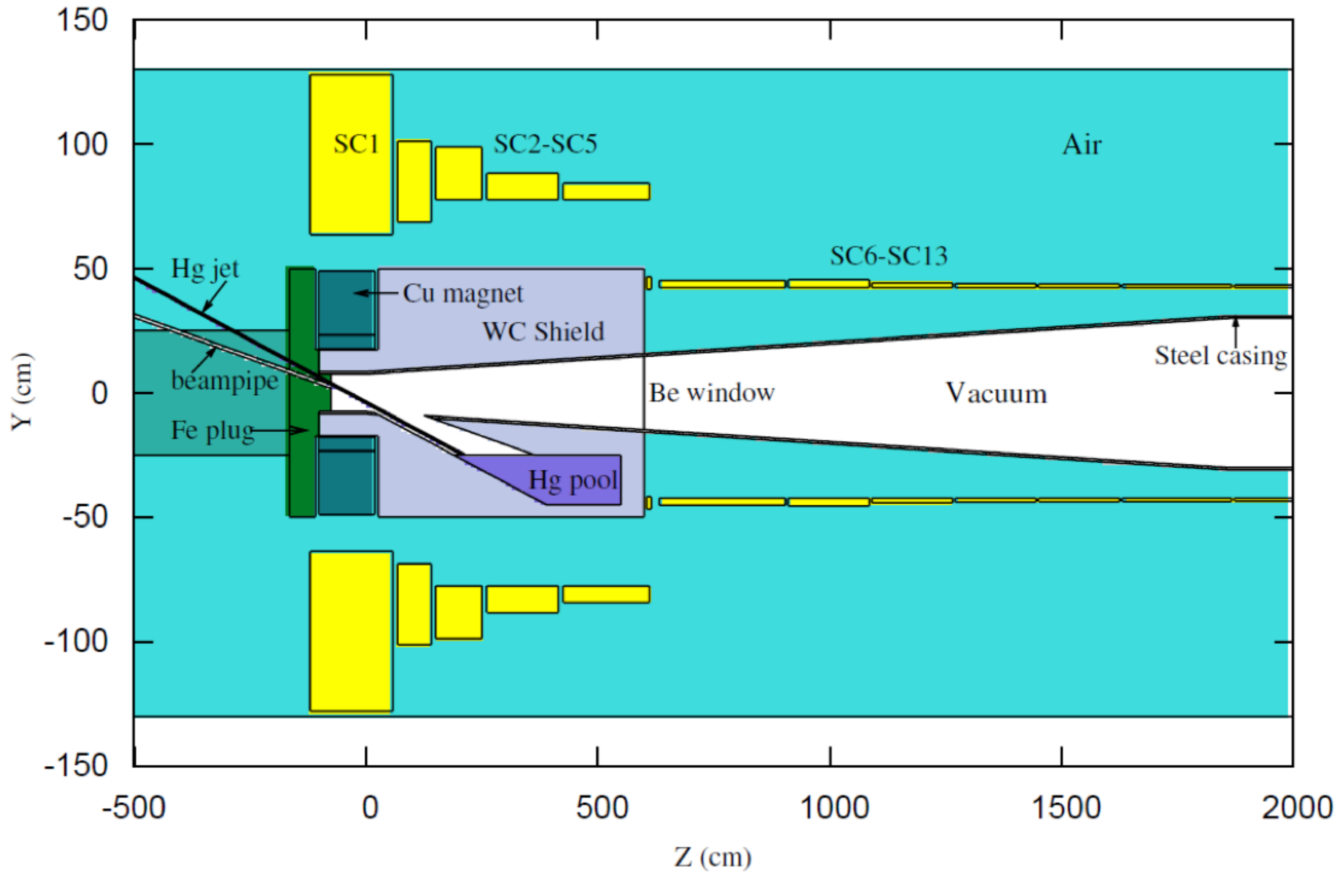
RAL

SPL, charge exchange injection



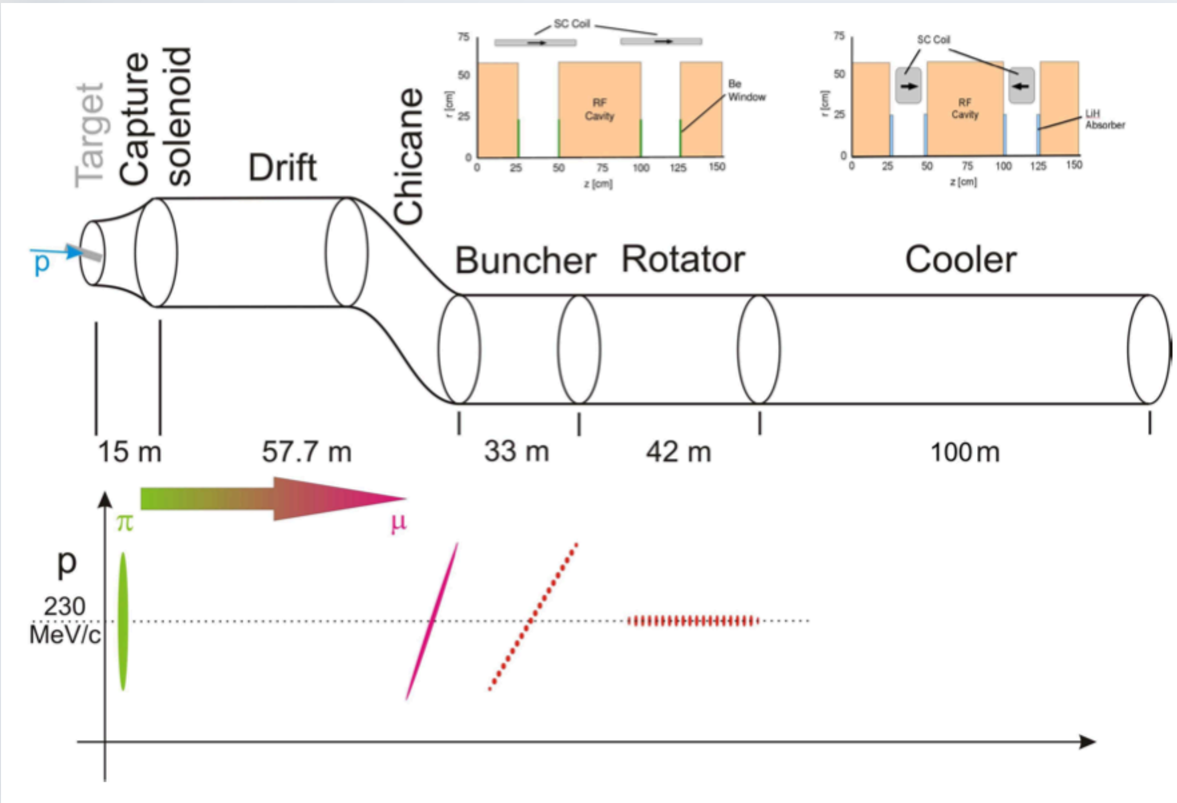
CERN

NF Targets

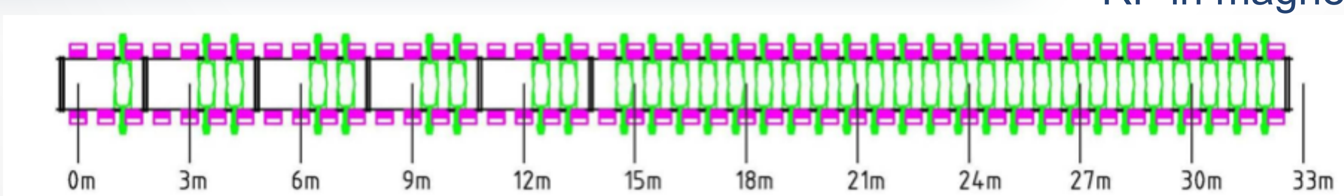


Conceptual layout of the Neutrino Factory pion production target and capture system.

The NF Front End

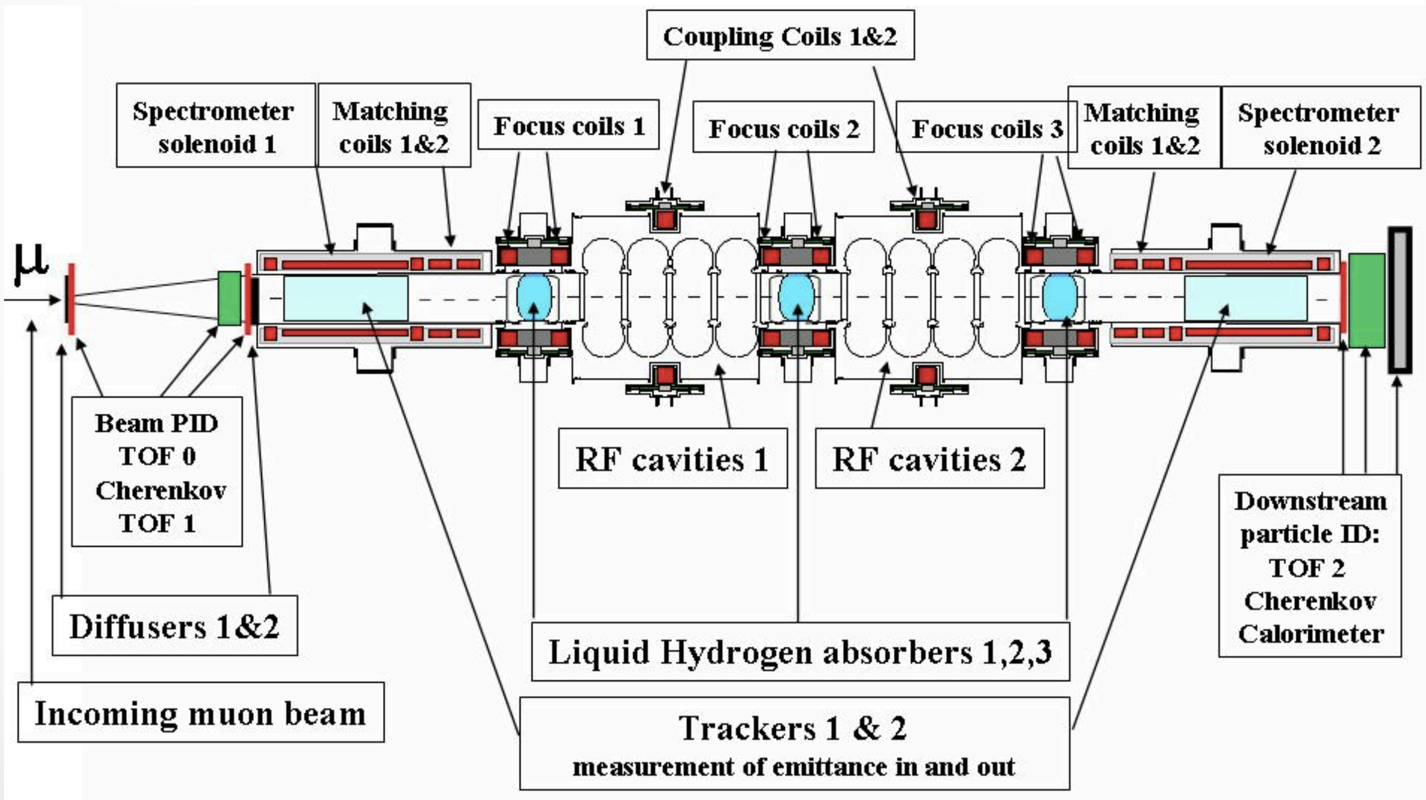


- Chicane: filters out unwanted secondaries, mainly protons, to avoid activation
- The bunching section had to be adjusted to several engineering requirements to allow for a modular setup, rotator with different RF
- The cooling section helps for further acceleration but may have problems with RF in magnetic fields



The Cooling

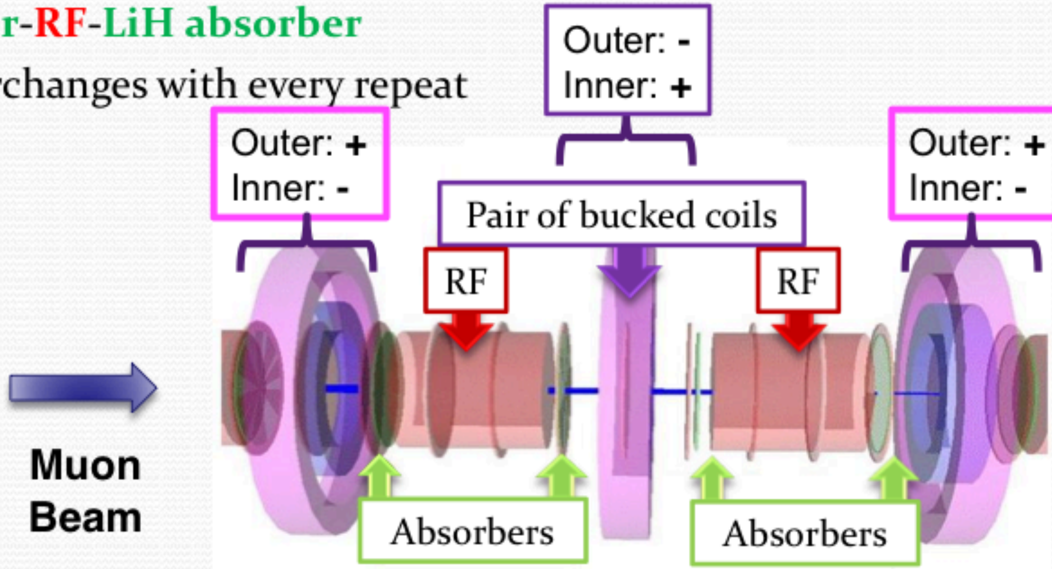
- Ionization Cooling: momentum is decreased by passage through an absorber
- Restored only in longitudinal plane by RF
- Experiment MICE (proton source: ISIS at Rutherford)



New Alternative Lattice: Bucked Coils, BC

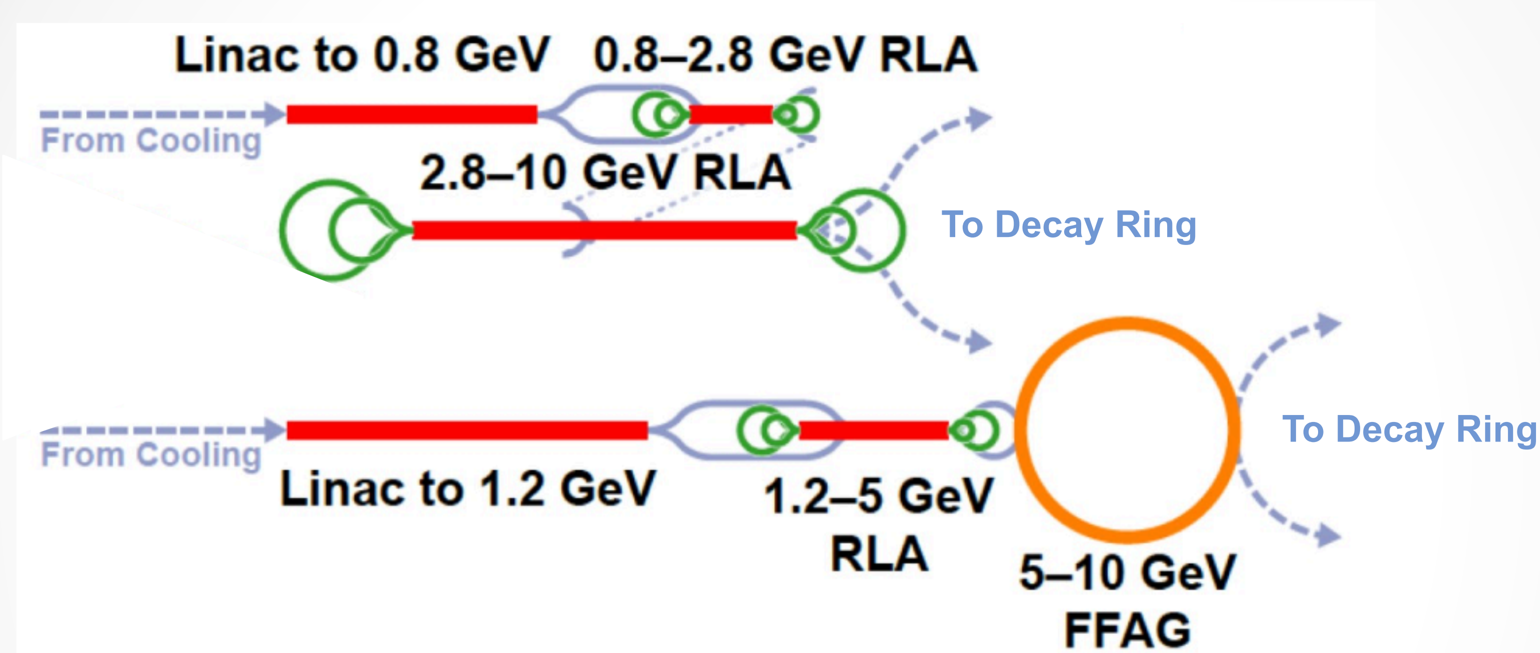
- The magnetic field at the RF cavities can be decreased by:
  - Increasing cell's length
  - Using **Bucked Coils**:
    - Pair of different radius & opposite polarity coils
    - The pair of coils is placed at the same position along the beam axis (homocentric coils)
- BC configuration:
  - **PairOfCoils-LiH absorber-RF-LiH absorber**
  - **PairOfCoils**' polarity interchanges with every repeat

- Magnetic Field in cavities is decreased



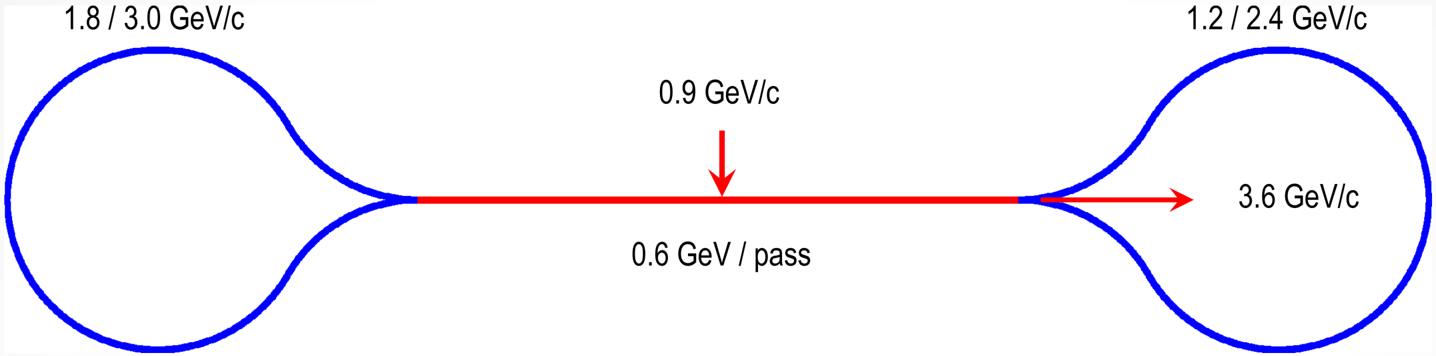
A. Alekou

Acceleration of muons

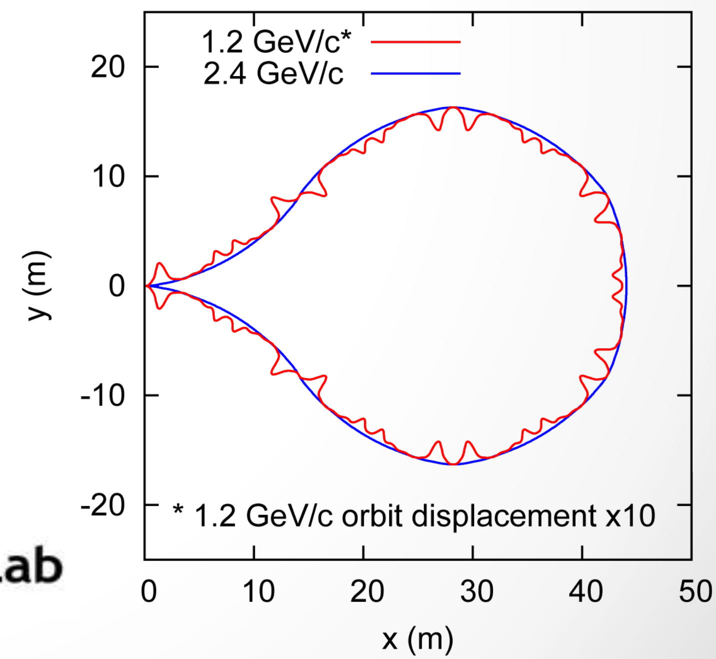


Solenoid Focused Linac up to 0.8 GeV
All Accelerating cavities 201.25 MHz SC
Rapid acceleration is necessary (muon half life-time 2.2 ms)
Transverse phase space acceptance 30 p mm•mrad
Linacs not cost effective after 1 GeV muons

Idea for RLA

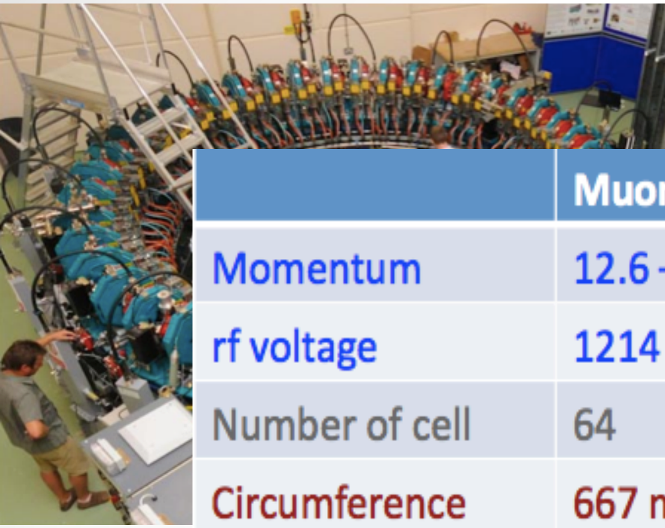


- Innovative 2-pass ‘droplet’ arc composed of symmetric super-cells consisting of linear combined-function magnets
- Large Dynamic Aperture for two discrete energies (up to factor of two energy ratio)
- Synchronization with linac accomplished via path-length adjustment - harmonic jump
- Simultaneous transport of



A. Bogacz Jefferson Lab

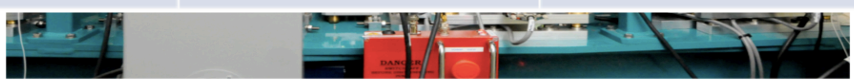
FFAGs



- Isochronous
- Strong focusing, can transport large emittance beams
- Compact magnets thanks to small orbit excursions
- Ring

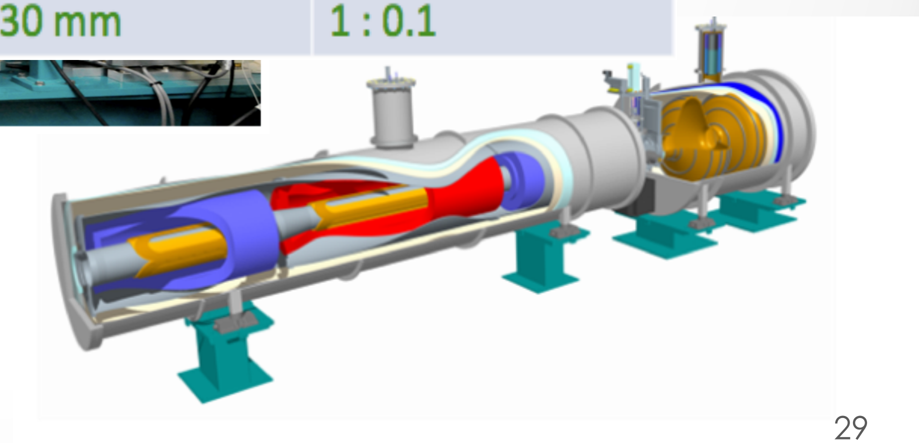
	Muon FFAG	EMMA	Ratio
Momentum	12.6 – 25 GeV/c	10 – 20 MeV/c	1 : 0.001
rf voltage	1214 MV	2.28 MV	1 : 0.002
Number of cell	64	42	1 : 0.66
Circumference	667 m	16.6 m	1 : 0.025
QD/QF length	2.251/1.087 m	0.0777/0.0588 m	1 : 0.035/0.054
Straight section	5 m	0.2 m	1 : 0.04
Aperture	~ 300 mm	~ 30 mm	1 : 0.1

GeV FFAG
328.8
550
49
108.3



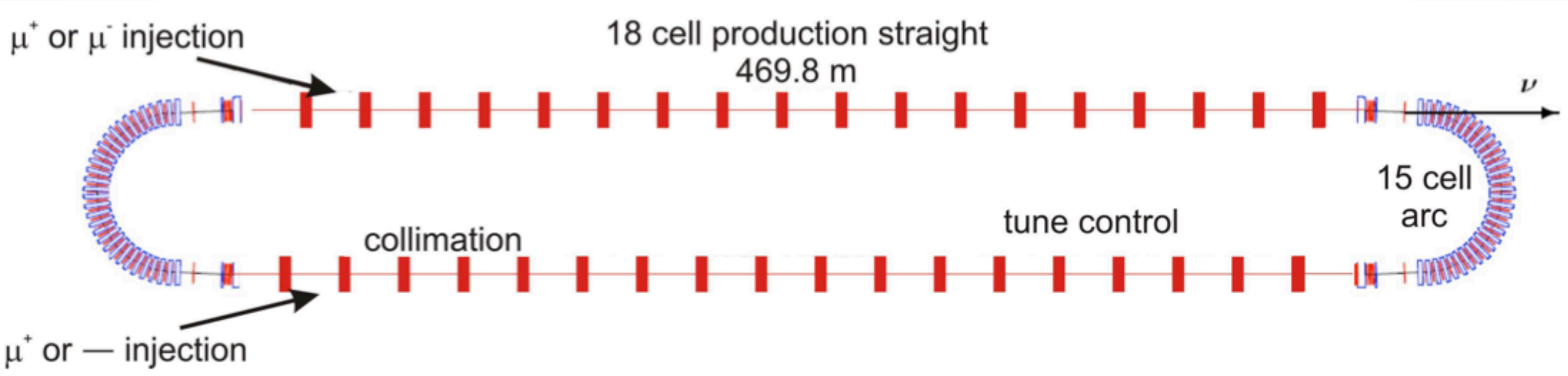
EMMA, proof of principle

Daresbury Laboratory



. Conceptual engineering of the NS-FFAG cell. The main magnets and RF cavity are shown in separate cryostats.

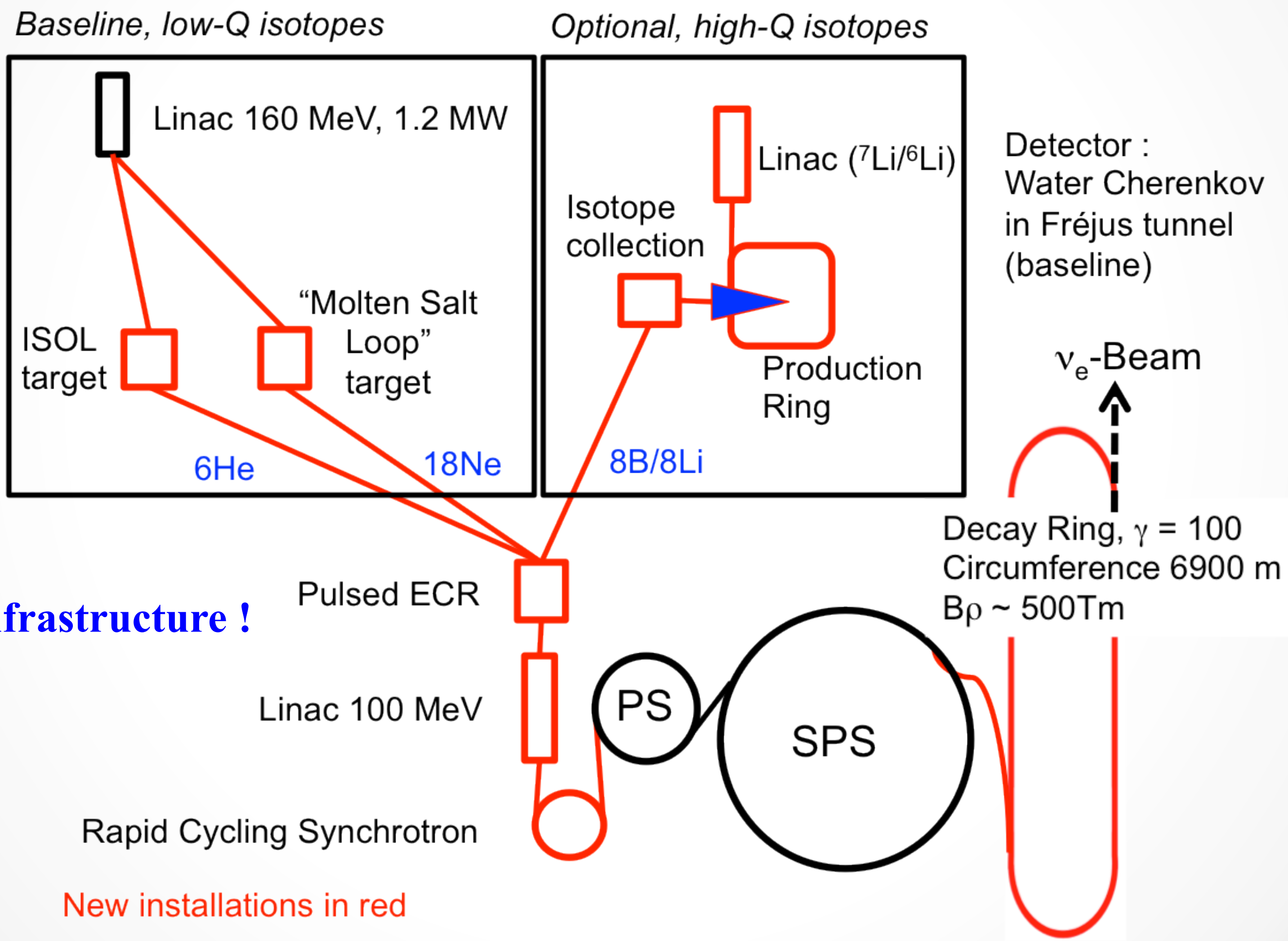
Decay Ring



- Counter-rotating muons of opposite signs

- Ratio length of straights/circumference 37%
- 1300 m in circumference
- Equally-spaced, 250 ns long bunch trains, at least 120 us spaced.
- Depth around 100 m: geological and cost implications

The Beta Beam



CERN infrastructure !

Beta Beam Principle

- **Aim**: production of electron (anti-)neutrino beams from β- decay of radioactive ions circulating in a storage ring
  - *(P. Zucchelli, Phys. Let. B, 532 (2002)166-172)*
- **Produce** suitable beta active radio-isotopes
- **Ionize & Accelerate**
- **Store** them in a racetrack Decay Ring (DR)
- **Let them β-decay** (a straight section of the DR points to detector)
- **Pure** n_e **and anti-**n_e are emitted
  - need a pair of β^+/β^- emitters
- **Spectrum** ($E_n < 2\gamma Q$)
- **Cone** $\theta < 1/g$ in forward direction,
- **Q** = Reaction Energy ~ few MeV

Main research:
- Isotope production
- Beam stability
- Coexistence with LCH

Choice of isotope

- **Need a pair of neutrino and antineutrino emitters**
  - **Lifetime at rest**: $\tau_{1/2}$~1s
  - **Low Z** (minimize accelerated mass/charge & reduce space-charge)
  - **Production rates**
- Stored in a race-track Decay Ring at γ=100
- Q = Reaction Energy

"Low-Q" isotopes

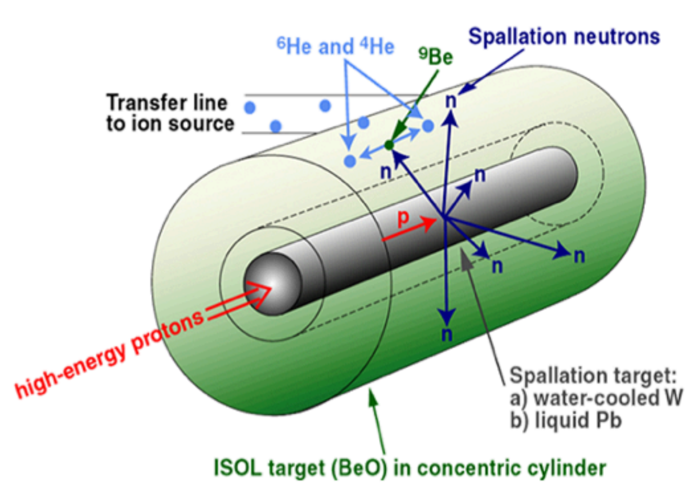
Isotope	^{6}*He*	^{18}*Ne*
A/Z	*3*	*1.8*
emitter	β^-	β^+
$\tau_{1/2}$ *(s)*	*0.81*	*1.67*
Q (MeV)	*3.51*	*3.0*

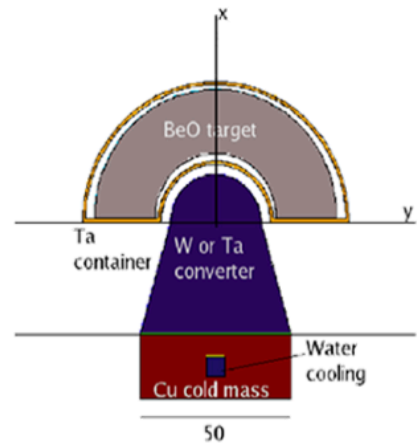
"High-Q" isotopes

Isotope	^{8}*Li*	^{8}*B*
A/Z	*2.7*	*1.6*
Emitter	β^-	β^+
$\tau_{1/2}$ *(s)*	*0.83*	*0.77*
Q (MeV)	*12.96*	*13.92*

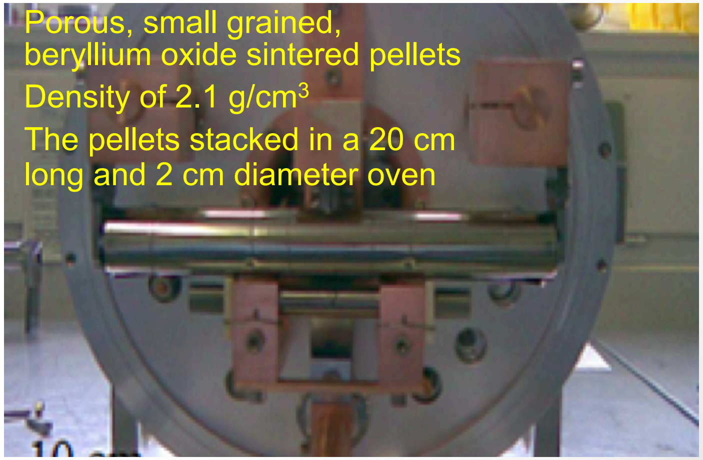
Bird's eye photo in Jan. 2008

Production

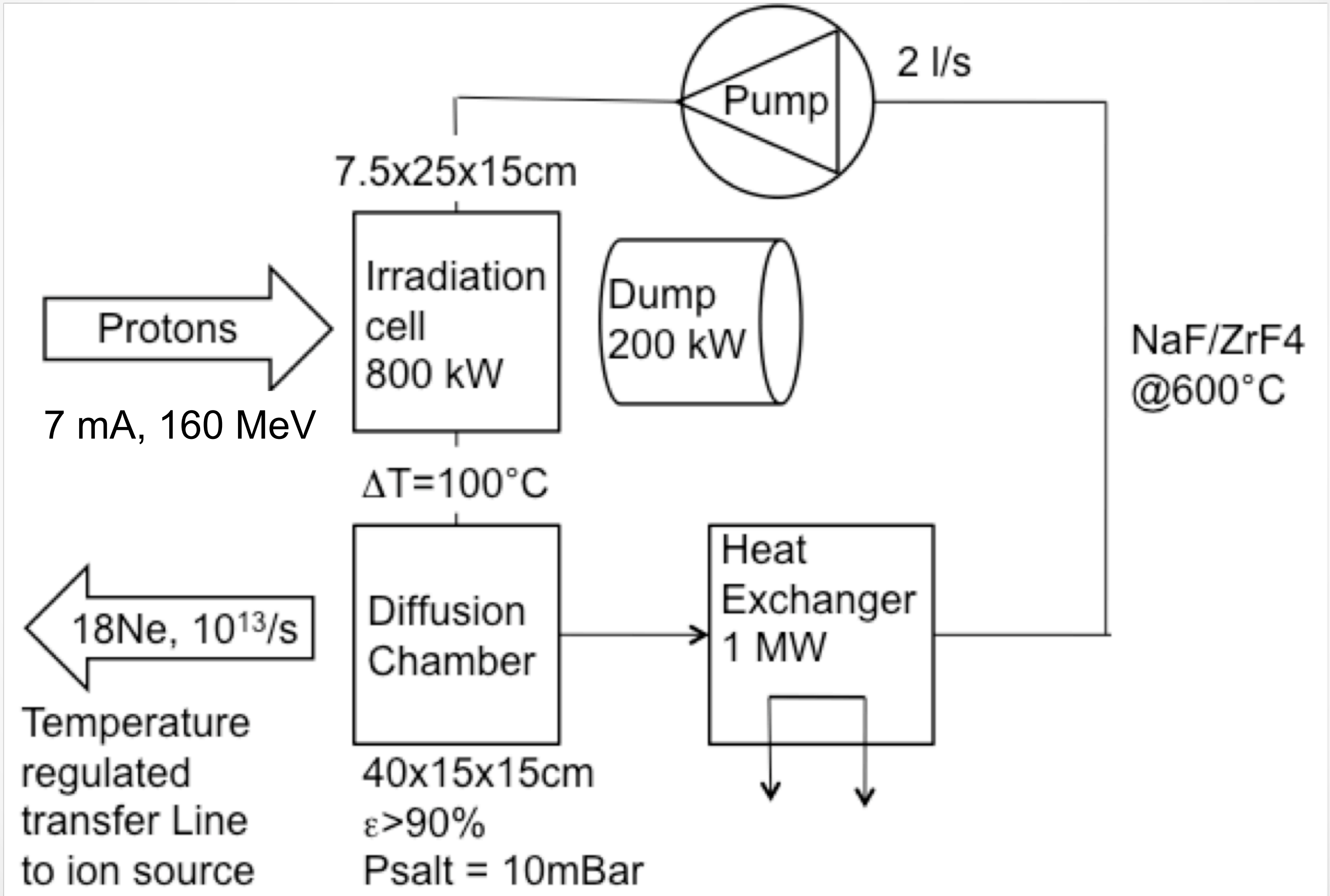




- 10^{14} ^{6}He/s with 100 μA, 1.4 GeV
- ^{9}Be(n,α)^{6}He
- Successful validation at CERN
    - Isotope Separation Online (ISOL) method
- Release at 1400 C: ok for beta Beam

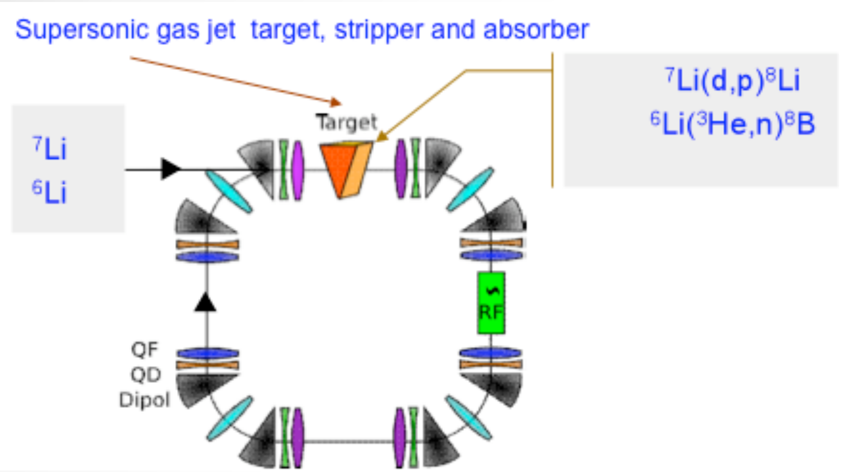


Molten salt loop for ^{18}Ne



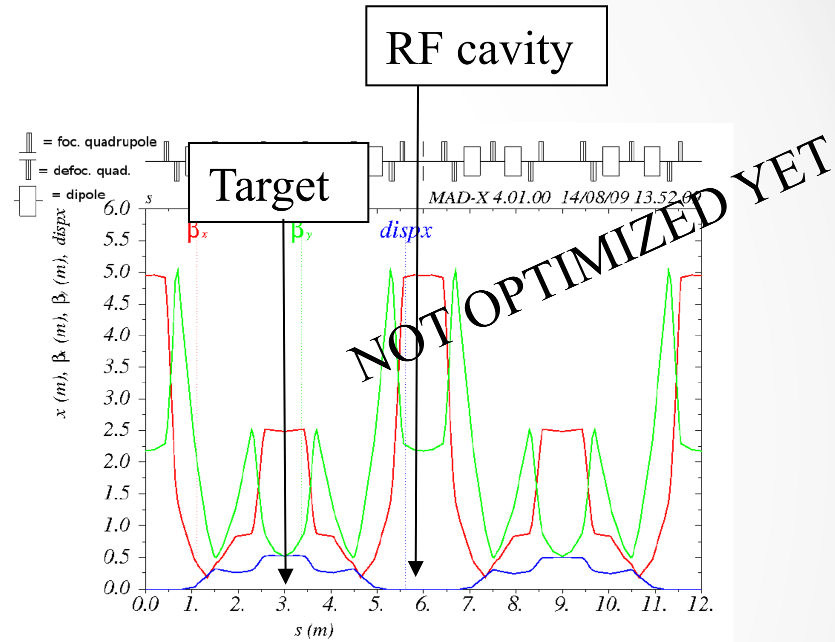
Production of ^{8}B and ^{8}Li

C.Rubbia et al, NIM A 568 (2006) 475–487



Lattice M. Schaumann, Aachen

Particle		^{7}Li
Energy	E_c	25 MeV
Relativistic gamma	γ_r	1.00383
Beam rigidity	$B\rho$	0.636 T m
Transition γ	γ_t	3.58
Tune	$Q_{x,y}$	2.58, 1.63
Natural chromaticity	$Q'_{x,y}$	-3.67, -3.58
β @ target	$\beta^*_{x,y}$	2.62 m, 0.35 m
Dispersion @ target	$D^*_{x,y}$	0.523 m, 0 m
Target thickness	t_0	0.27 mg/cm^2
	n_t	10^{19} atoms/cm^2
Energy losses @ target	E_{BB}	$\sim$ 0.30 MeV



- C=12m
- Normal-conducting magnets
- Lattice → to be optimized
- Charge-exchange injection Li^{+1}
  → to be designed

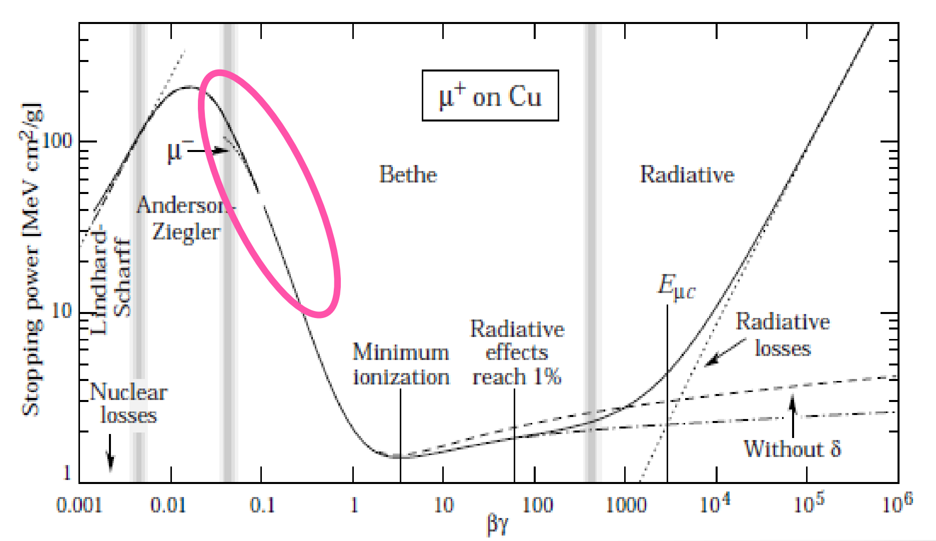
Ionization cooling

- Energy losses (dE/ds) in the target material (Bethe-Bloch)
- Only longitudinal component recovered in RF cavities

  → Transverse emittance shrinks

- Cooling in 6D
  - Heating in longitudinal,
    - Neg. slope for the BB relation
  - Need coupling between transverse and longitudinal:

    → Dispersion & wedge-shaped target



$$\sum J_i = 1 + 1 + \frac{\partial}{\partial E}\left(\frac{dE}{ds}\right)\Big|_{\Delta x=0} \begin{cases} 0.4 \quad \text{for } {}^6\text{Li} \\ 0.01 \quad \text{for } {}^7\text{Li} \end{cases}$$

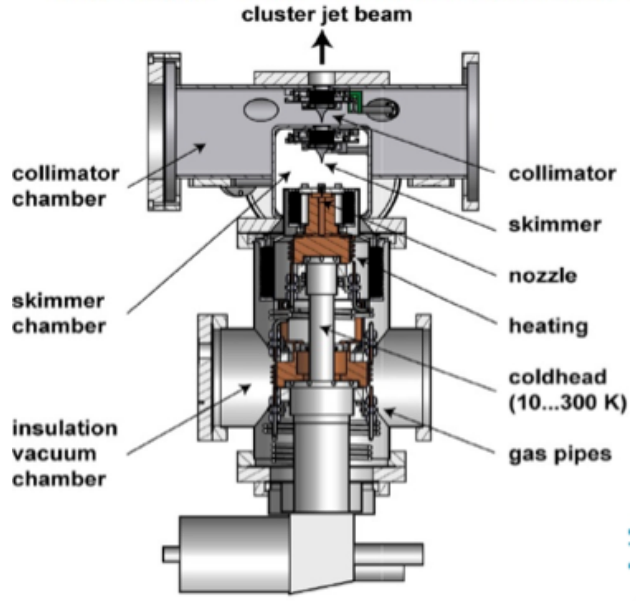
Technological issues & feasibility

- High density gas-jet target (10^{19} atoms/cm^2 thick) in vacuum environment

Factor 10^4 larger !!!
than existing targets

Such gas-jet target densities would be OK in fusion or space applications,

BUT we need good vacuum for the RF cavity!



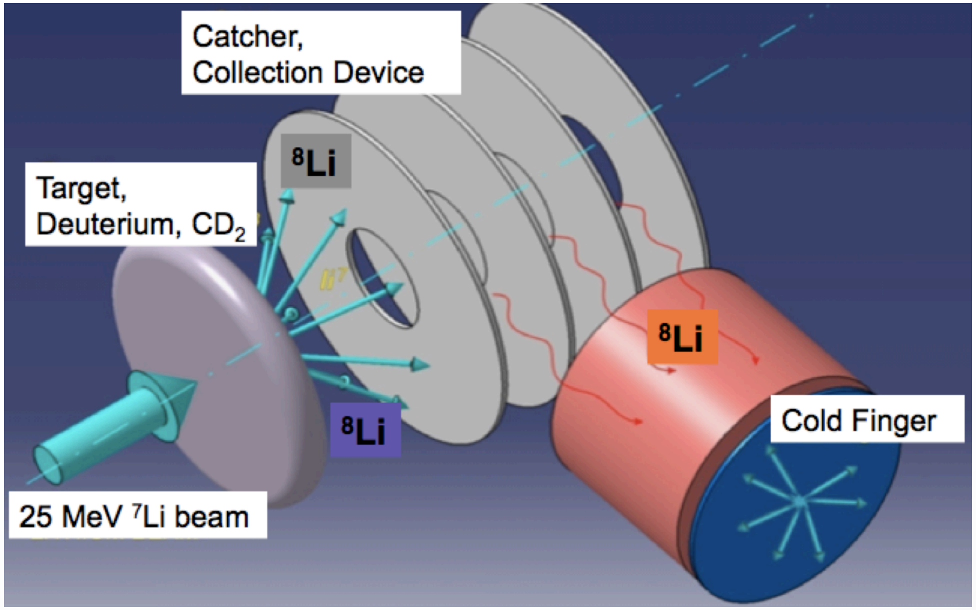
A. Koukaz: Münster Panda Cluster Source Meeting at GSI, 29/10/09

Simulations: Direct kinematics

- Cooling works as expected for reverse kinematics
- With direct kinematics production rates are about 3 orders of magnitude higher than with direct kinematics
- But: Production rates are still lower than originally proposed
  - => Higher beam intensity needed
  - Collection issues not treated in simulations
- Cross section measurements at INFN Legnaro have shown that cross-sections are at least as good as so far in literature

Collection device ^{8}B and ^{8}Li

- Measured collection efficiencies with the prototype device:
- ~30% for ^{8}Li
- 0% for ^{8}B
- 0.53±0.08 % for BF_3 the setup will be optimized during December 2012.



Bird's eye photo in Jan. 2008

Production of beta emitters

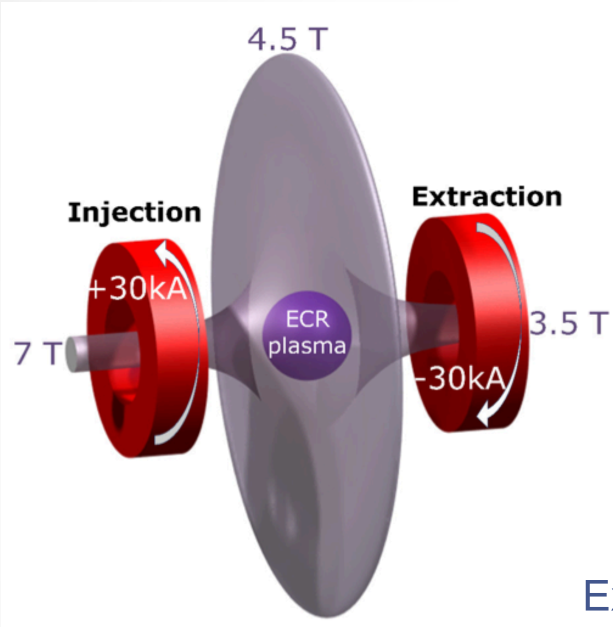
Summary

Isotope	^{6}He	^{18}Ne	^{8}Li	^{8}B
Prod.	ISOL(n)	ISOL	P-Ring	P-Ring
Beam	SPL(p)	Linac4(p)	d	^{3}He
I [mA]	0.07	7	0.160	0.160
E [MeV]	2000	160	25	25
P [kW]	140	1120	4	4
Target	W/BeO	^{23}Na, ^{19}F	^{7}Li	^{6}Li
r [10^{13}/s]	5 (Exp.)	1.0 (Exp.)	0.1	0.08
	2.5 * required	0.5 * required		

Proposal from present results: run 2 years He and 8 years Ne…

Bird's eye photo in Jan. 2008

60 GHz ECR Source

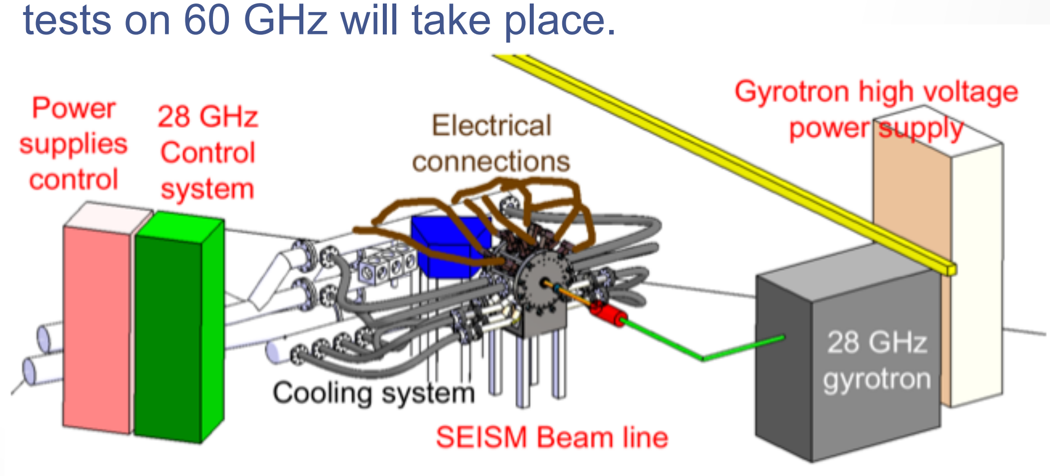


The source is pulsed!
Current density in polyhelix coils 640 A/mm2.
Due to their low resistivity, the coils need 6 MW electrical power and can be cooled with de-ionized water

1+ ions out
50ms pulses at 10 Hz

Efficiencies:
He^{1+} ~ 30%
Ne^{1+} ~ 20%
Li^{1+}, B^{1+} ~ 5%,

Experiment at 28GHz: some adjustments needed before tests on 60 GHz will take place.



Injector chain

Few studies yet

Radioprotection not a show stopper (CERN requirements are fulfilled)

Vacuum ok

Space charge in the PS can be mastered (may need some resonance compensation)

RF of the SPS needs to be further studied

Re-optimization of bunch intensity an distribution is necessary

Studies of beam stability needed

…

Bird's eye photo in Jan. 2008

Decay Ring

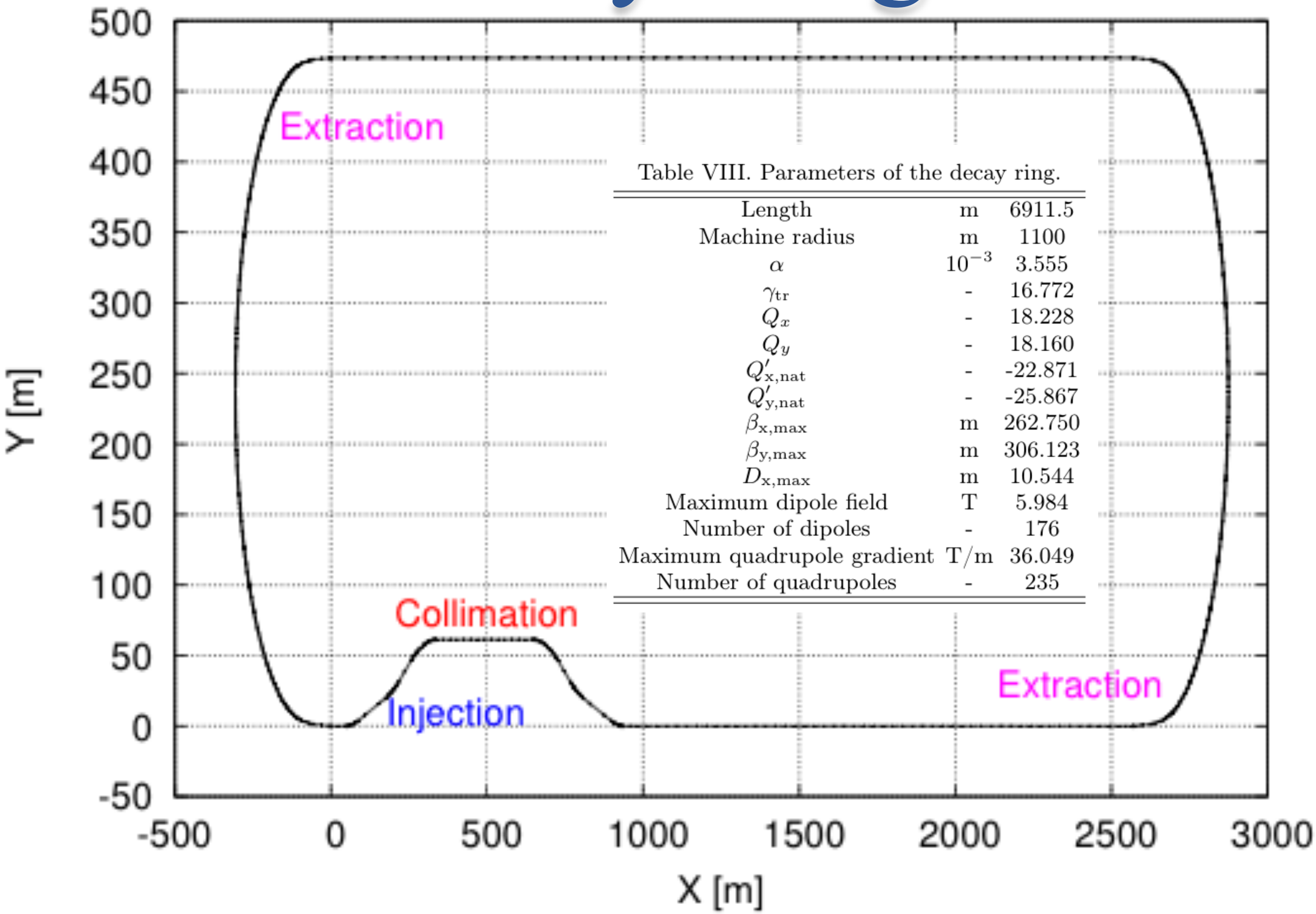


Table VIII. Parameters of the decay ring.

Length	m	6911.5
Machine radius	m	1100
α	10^{-3}	3.555
γ_{tr}	-	16.772
Q_x	-	18.228
Q_y	-	18.160
$Q'_{x,nat}$	-	-22.871
$Q'_{y,nat}$	-	-25.867
$\beta_{x,max}$	m	262.750
$\beta_{y,max}$	m	306.123
$D_{x,max}$	m	10.544
Maximum dipole field	T	5.984
Number of dipoles	-	176
Maximum quadrupole gradient	T/m	36.049
Number of quadrupoles	-	235

Straight/Total ~ 40%

Decay Ring challenges

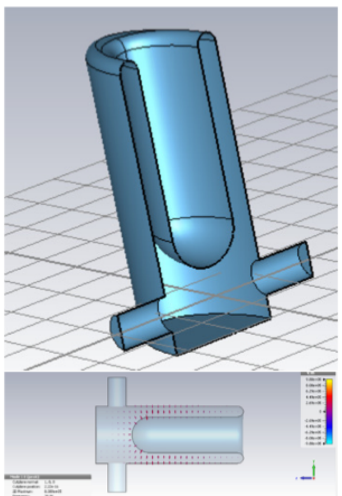
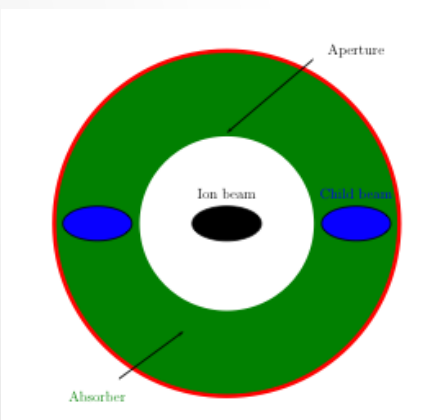


Figure 50. The cavity geometry, top, and the cavity electric field profile for the decay ring 40 MHz RF system, bottom.

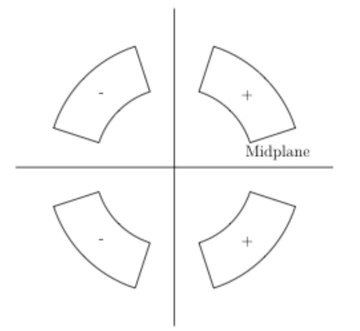
Very short intense bunches (can be relaxed id theta13 is large:
Cavities are 452 mm long
1.9 m height per cavity. Total width 3.8 m, cryostat width around 4.5-5 m wide.

The peak electric field at the design voltage of 600 kV is 30 MV/m.

The R/Q is 2 Ω, and the peak magnetic field is 67.5 mT



Coil Free mid-plane magnets

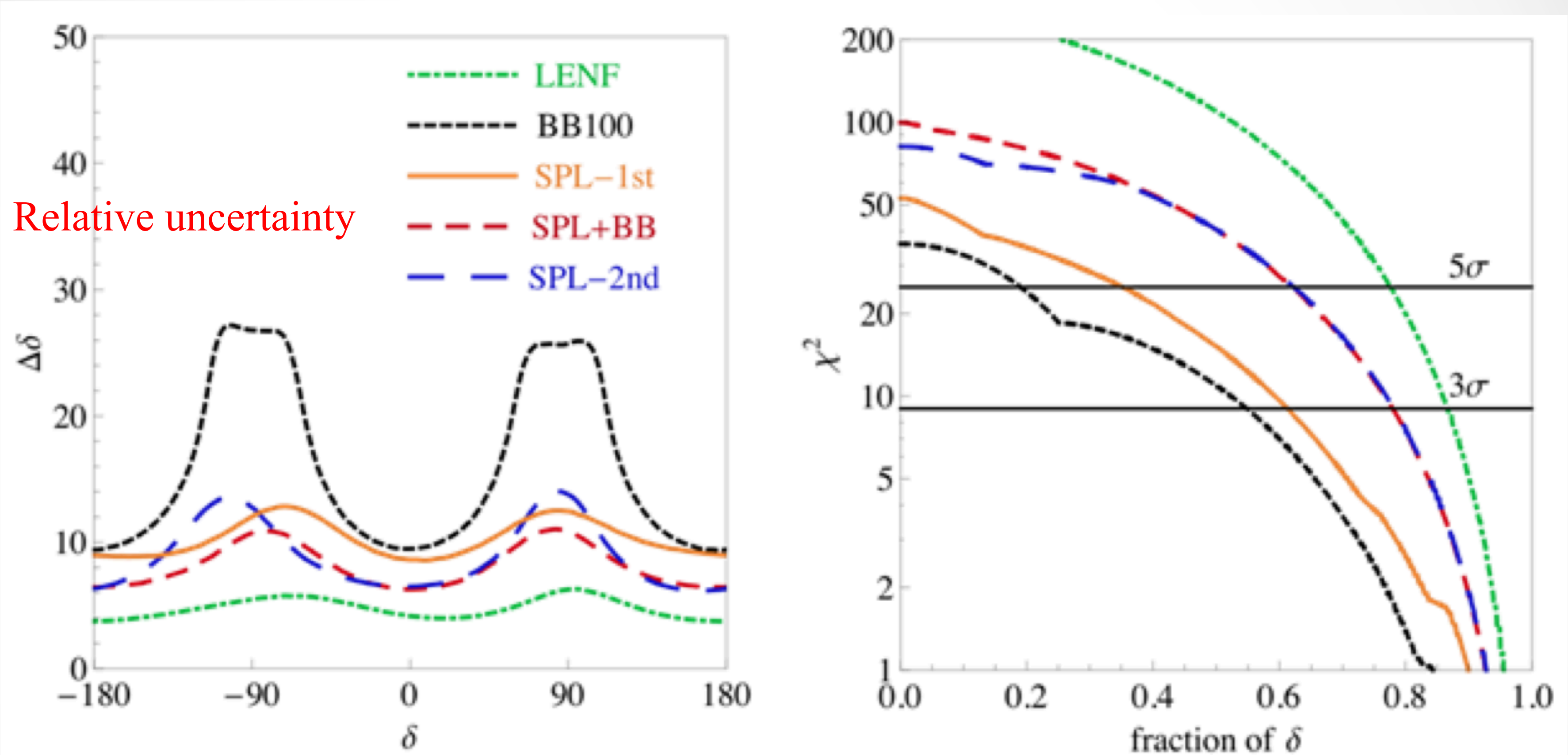


Other challenges: Vacuum, beam stability…

Bird's eye photo in Jan. 2006

Summary: Physics EUROnu

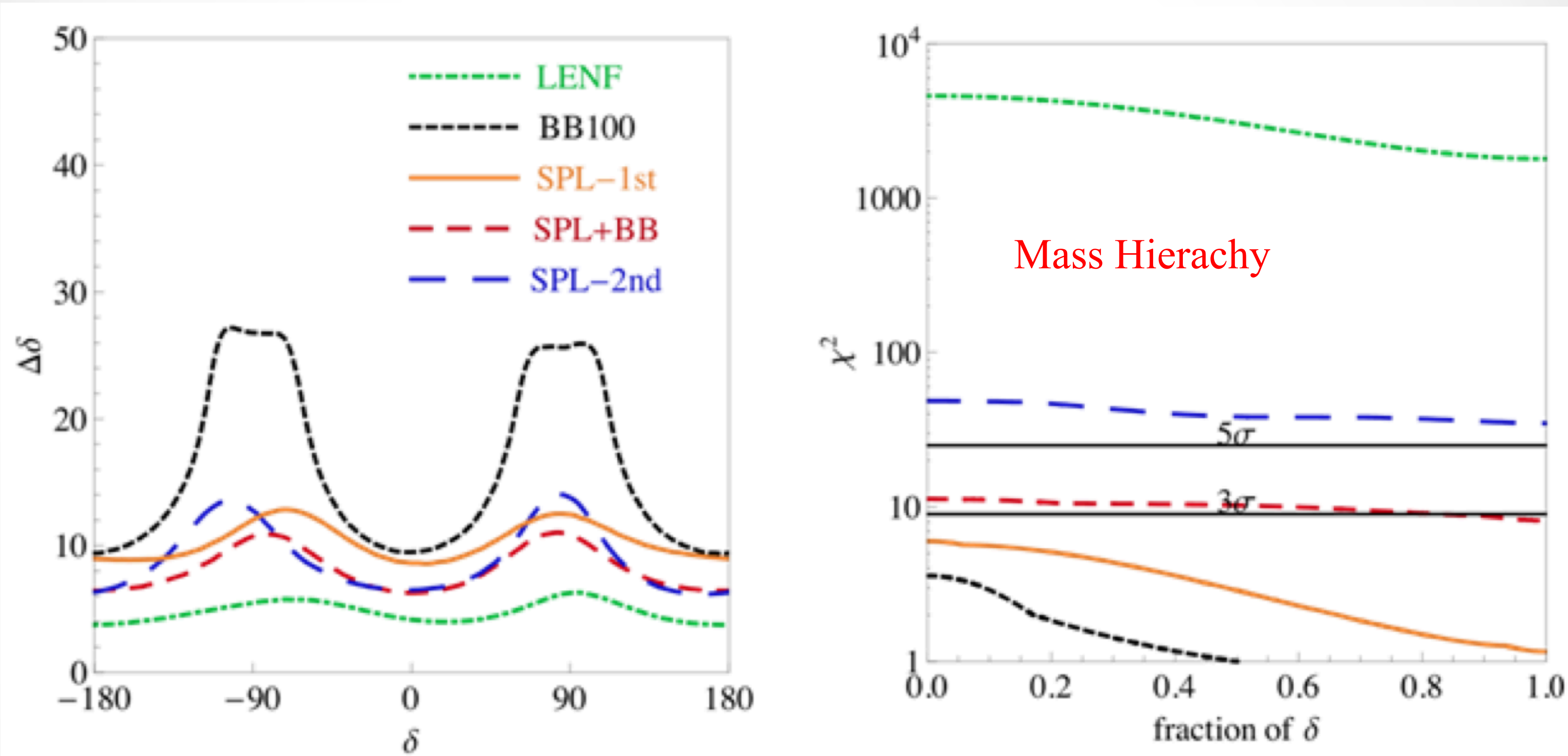
Precision is now (after q_{13} 5 s measurement) what is needed!!!



LENF: Low Energy Neutrino Factory BL=2000 km 10 GeV m energy, 1.4x1021 decays/year, 100 kt mass Magnetised Iron Neutrino Detector (MIND)
BB100: a γ=100 Beta Beam, 1.3/3.5x10^{18} decays per year of Ne/He, 500 kt Water Cherenkov detector (MEMPHYS) Fréjus
SPL-1st: 4 MW SPL Super Beam, 500 kt water Cherenkov detector at Fréjus,
SPL- 2nd: as above, but with the detector at Canfranc, corresponding to approximately the second oscillation maximum;
SPL+BB: the combination of BB100 and SPL-1st.

Summary: Physics EUROnu

Precision is now (after q_{13} 5 s measurement) what is needed!!!



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SPL+BB: the combination of BB100 and SPL-1st.

Summary: Cost EUROnu

Preliminary shallow cost estimations have been done
Not yet official
However the ranking seems to be (high to low)

- NF
- BB
- SB

The NF is the facility of choice
However we could get a good step for physics for a fraction of the money with a SB 2nd

All this to be treated by the European strategy group in a global context
(other physics and other facilities in Europe and around the world)

Bird's eye photo in Jan. 2008

SB n beam composition

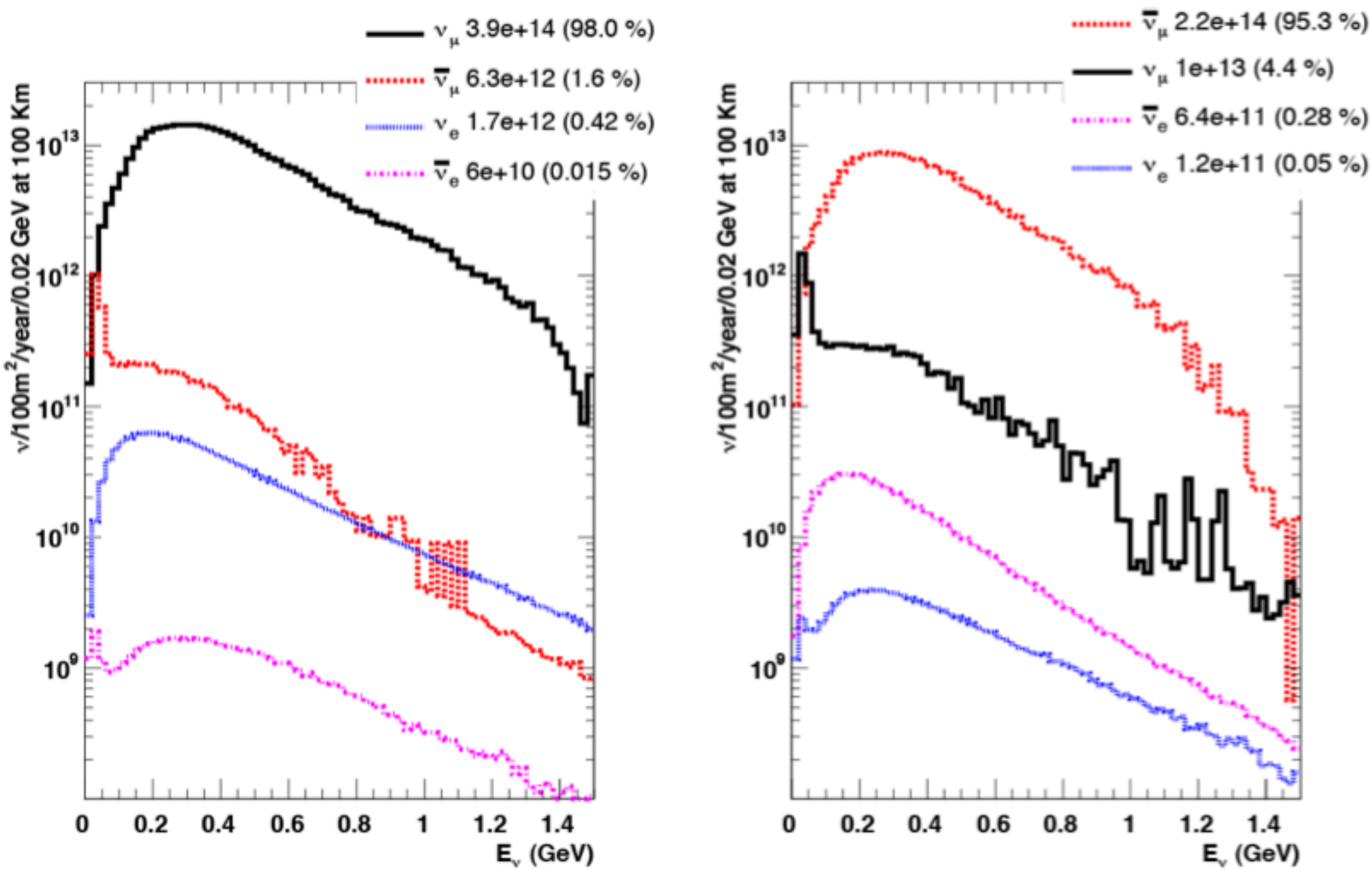


Figure 6: The composition of the neutrino beam produced by the Super Beam facility.

$$Amp(\nu_\mu \to \nu_e) = U^*_{\mu 3}\; e^{i\frac{m_3^2 L}{2E}}\; U_{e3} + U^*_{\mu 2}\; e^{i\frac{m_2^2 L}{2E}}\; U_{e2} + U^*_{\mu 1}\; e^{i\frac{m_1^2 L}{2E}}\; U_{e1}$$

same for ν_2 and ν_1

amp. for finding a ν_3 in ν_μ

amp. for finding a ν_e in ν_3

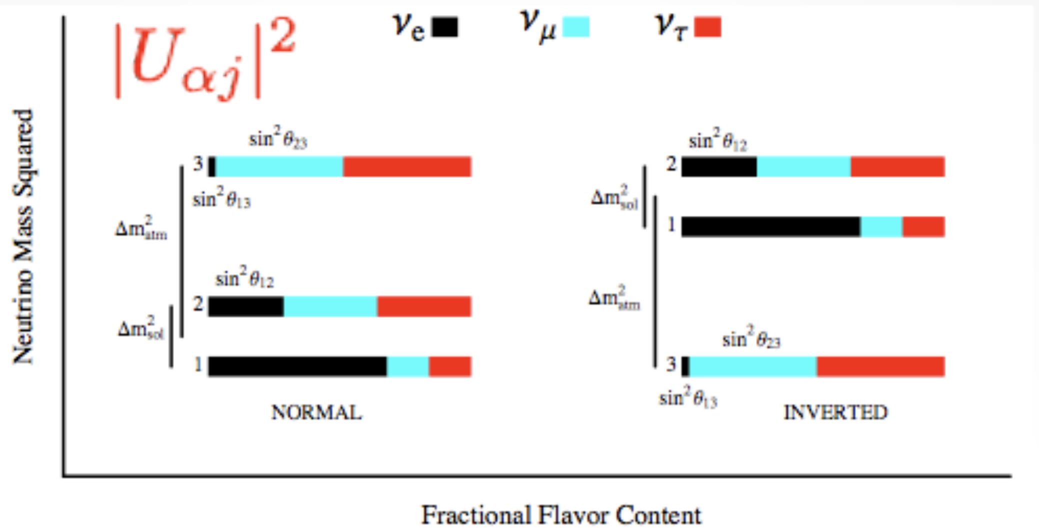
amp. (propogator) for ν_3 to go from production to detection (notice: it's just a phase)

if $\frac{L}{E}$ is small, so that $e^{i\frac{m_3^2 L}{2E}} \approx 1$, then

$$Amp(\nu_\alpha \to \nu_\beta) = U^*_{\alpha 3}\; U_{\beta 3} + U^*_{\alpha 2}\; U_{\beta 2} + U^*_{\alpha 1}\; U_{\beta 1} = \delta_{\alpha\beta}$$

For larger $\frac{L}{E}$: $P(\nu_\mu \to \nu_e) = 4\;|U_{\mu 3}|^2\;|U_{e3}|^2\;\sin^2\frac{\Delta m^2_{31} L}{4E} + \cdots$

$$= \sin^2\theta_{23}\;\sin^2 2\theta_{13}\;\sin^2\frac{\Delta m^2_{31} L}{4E} + \cdots$$



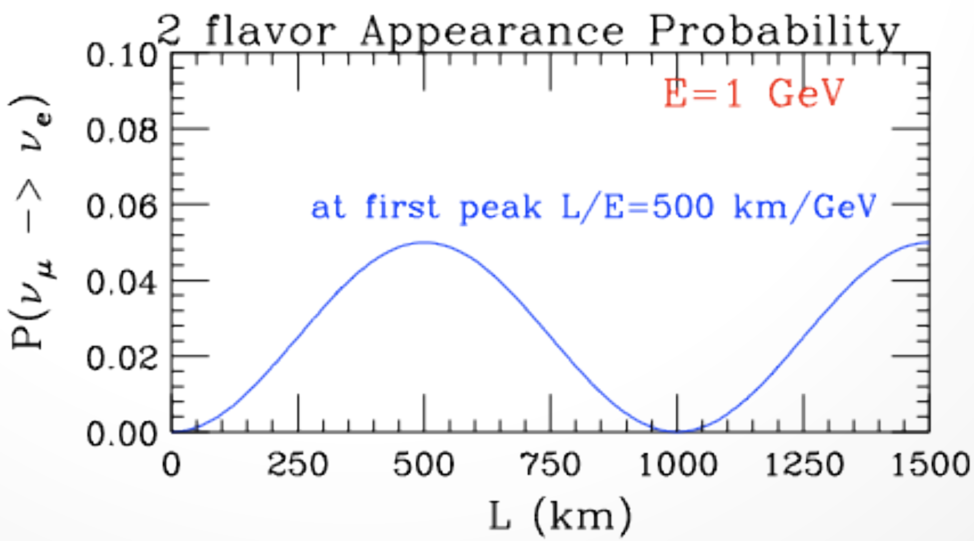
For ν_e appearance in a ν_μ beam:

$$\Delta m^2_{31} = m^2_3 - m^2_1$$

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23} \sin^2 2\theta_{13} \; \sin^2 \frac{\Delta m^2_{31} L}{4E} + \cdots$$

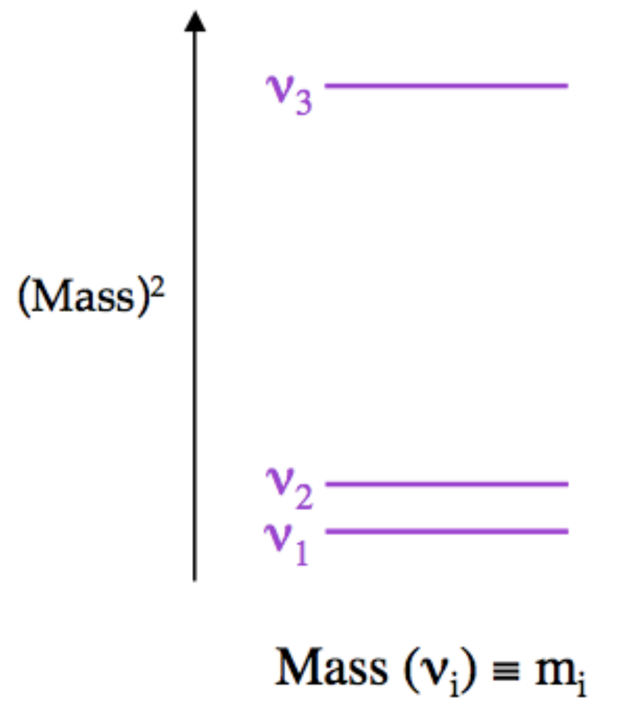
where $\frac{\Delta m^2_{31} L}{4E} \equiv \frac{\Delta m^2_{31} L}{4\hbar c E} = 1.27 \cdots \frac{\Delta m^2_{31}(eV^2) L(km)}{E(GeV)}$

$$\sin^2\theta_{23} \sin^2 2\theta_{13} \approx 0.05$$



Neutrinos have mass

- In the Standard Model neutrinos are mass-less
- But neutrinos have mass: they change flavors!
- We know the differences in mass squared…
- And we also know Sum M_n > 0.05 eV and < 0.5 eV



CP violation

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) - P(\nu_\mu \rightarrow \nu_e) = 2\cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin\delta$$
$$\times \sin\left(\Delta m^2{}_{31}\frac{L}{4E}\right)\sin\left(\Delta m^2{}_{32}\frac{L}{4E}\right)\sin\left(\Delta m^2{}_{21}\frac{L}{4E}\right)$$

δ would lead to $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$. *CP violation*