Accelerators for neutrino physics: The Beta Beam

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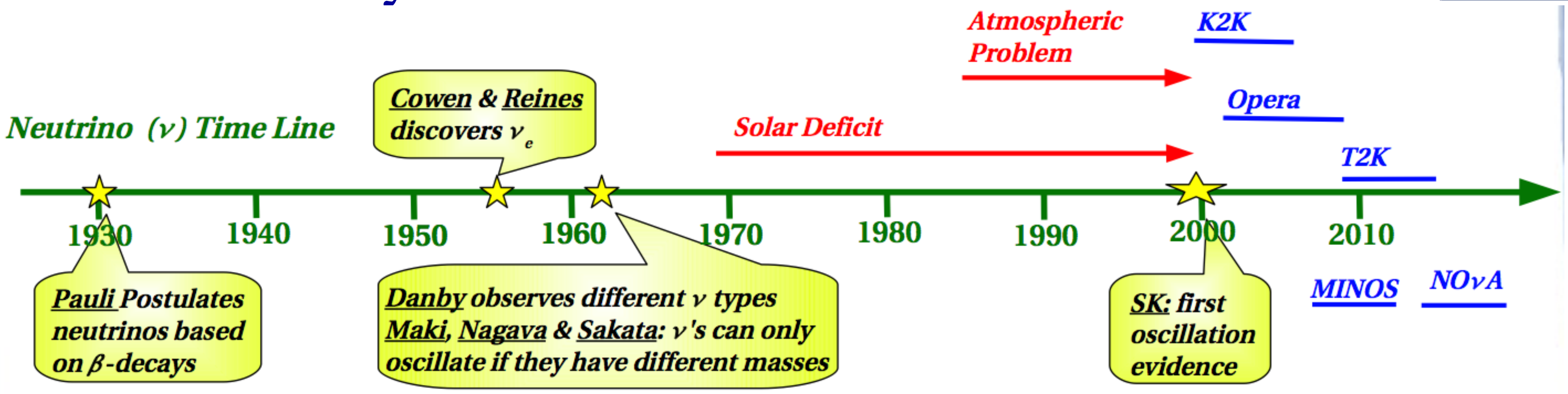
Outline

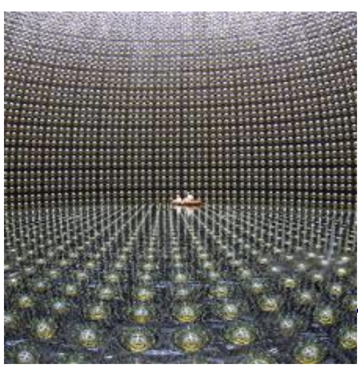
- General:
  - Neutrinos
  - History
  - The Beta Beam concept
- The CERN Beta Beam
  - EU funded development 2005-2009, 2008-2012
- Challenges and Technical Developments
- Outcome of the studies
- Today and the Future
- Summary

History

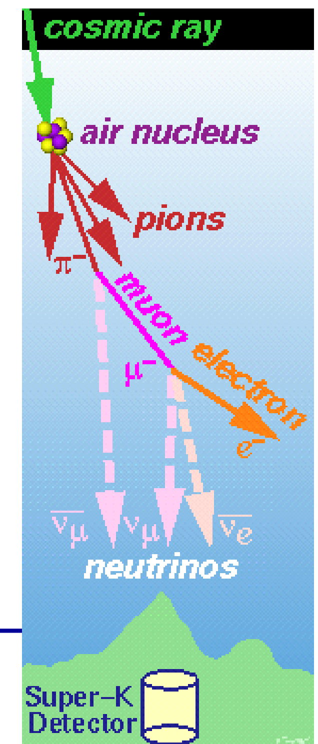


1968 a deficit of solar neutrinos compared to the Solar Standard Model was shown by Davi's experiment (Clorine tank in the Homestake mine) and later confirmed by others.

In late 1980s the number of atmospheric neutrinos seen by Kamiokande indicated a zenith angle dependence.



Kamiokande's results were confirmed by Super Kamiokande (SK) showing results in 1998 that were interpreted as an evidence of Neutrino Oscillation



To choose the Baseline

$$P(\nu_e \to \nu_\mu) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta_{31}L}{2}\right)$$ Atmospheric

$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta_{21}L}{2}\right)$$ Solar

$$+\tilde{J}\cos\left(\delta_{cp}+\frac{\Delta_{31}L}{2}\right)\sin\left(\frac{\Delta_{21}L}{2}\right)\sin\left(\frac{\Delta_{31}L}{2}\right)$$ Interference

$$\tilde{J} \equiv \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13} \qquad \Delta_{ij} \equiv \frac{\Delta m^2_{ij}}{2E_\nu}$$

P -> L/E

Worth to study them ?

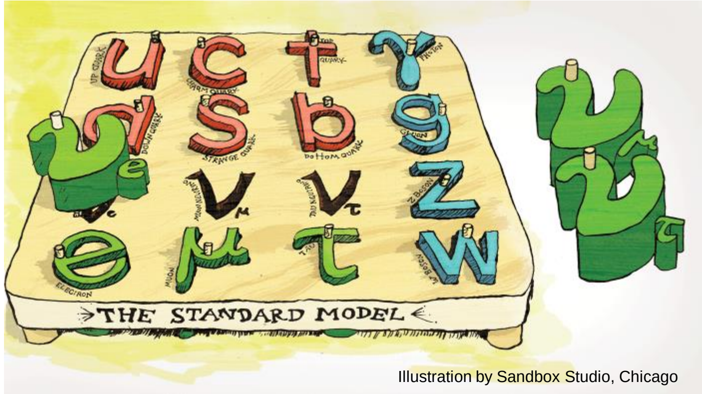
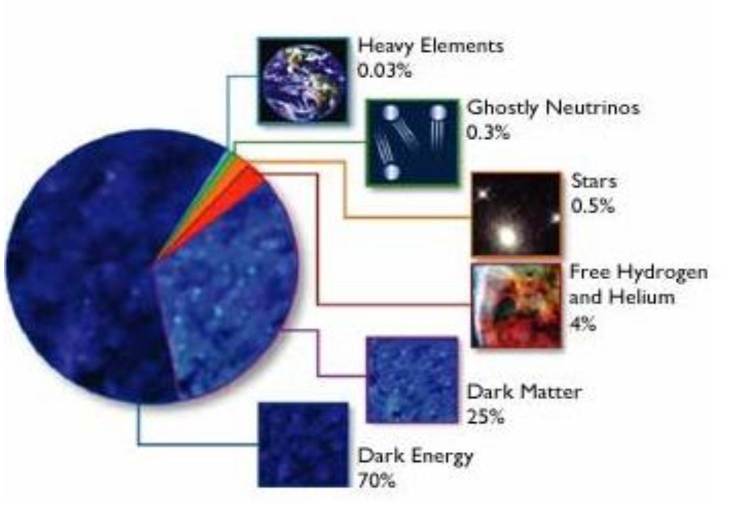


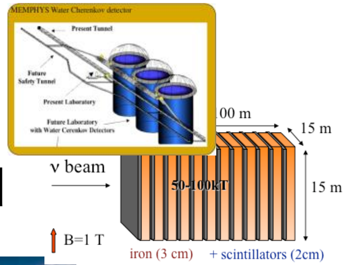
Illustration by Sandbox Studio, Chicago

Do not fit the Standard Model …



- How much would neutrinos weigh?
- Are neutrinos their own antiparticles?
- Are there more than three kinds of neutrinos?
- Do neutrinos get their mass the same way other elementary particles do?
- Why is there more matter than antimatter in the universe?

Neutrino oscillation experiments



- A detector (different for different neutrino energies) is needed
- Neutrinos are created in the atmosphere (collisions)…

- …in the sun…

- From nuclear reactions in the earth

- However, accelerators give intense and controlled neutrino flux

Primary Beam → Target | Collection →

Pions, no acceleration, superbeams
Muons, acceleration, neutrinofactories
Isotopes, acceleration, beta beams

- Nuclear reactors produce neutrinos

crucial measurements !!!

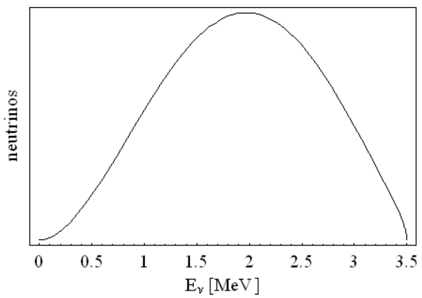
Detectors

- Detectors are normally large and costly
- Should preferably be multipurpose for example
  - Atmospheric
  - Geological
  - Proton decay experiments
- Overburden to protect from atmospheric background
- Cavern: Some old mines can be used
- Located at a certain distance L from the neutrino source
- Technology suitable for the energy and type of the neutrinos
- Has considerable impact on the feasibility of a neutrino oscillation experiment

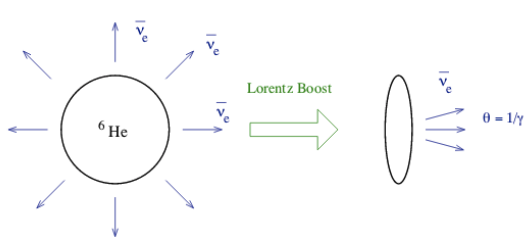
Beta Beams from Beta Decay

The aim is to produce (anti-)neutrino beams from the beta decay of radio-active ions circulating in a race track storage ring with long straight sections (P. Zuchelli, **Phys.** *Let. B, 532 (2002) 166-172*).

The energy of produced neutrinos is important



- Reaction energy Q typically of a few MeV
- Accelerate isotopes, before decay, to relativistic γ_{max}
- Boosted neutrino energy spectrum: $E_\nu \leq 2\gamma Q$
- Forward focusing of neutrinos: $\theta \leq 1/\gamma$
- Two different parent isotopes to produce ν and anti-ν respectively



E_ν: Choice of high Q or high γ ?

- Accelerators can accelerate ions up to Z/A × *the proton energy.*

- $L \sim \langle E_\nu \rangle / \Delta m^2 \sim \gamma Q$, $Flux \sim \gamma^2 L^{-2} \Rightarrow Flux \sim Q^{-2}$

- Cross section ~ $\langle E_\nu \rangle \sim \gamma Q$

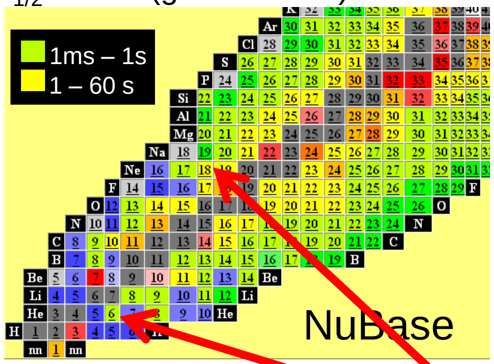
- Merit factor (Flux * Cross-section) for an experiment at the atmospheric oscillation maximum: $M = \gamma / Q$

- Ion lifetime ~ γ
  - longer straight sections in the decay ring to give the same flux for the same number of stored ions in the accelerator if γ is increased

Choice of radioactive ion species

- Beta-active isotopes
  - Production rates
  - Life time
  - Dangerous rest products
  - Reactivity (Noble gases are good)
  - One for neutrinos and one for antineutrinos
- Lifetime at rest
  - If too short: decay during acceleration
  - If too long: low neutrino production
  - Optimum life time given by acceleration scenario
  - In the order of a second
- Low Z (number of protons) preferred
  - Minimize ratio of accelerated mass/charges per neutrino produced
  - One ion produces one neutrino
  - Reduce space charge problems

$t_{1/2}$ at rest (ground state)



6He and 18Ne

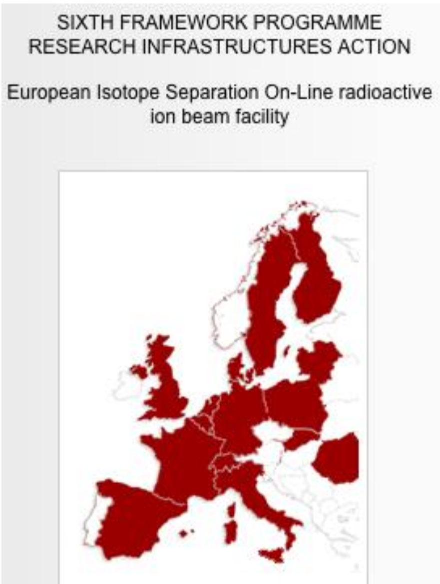
The choice depends on available accelerators (E) and the detector position (L)

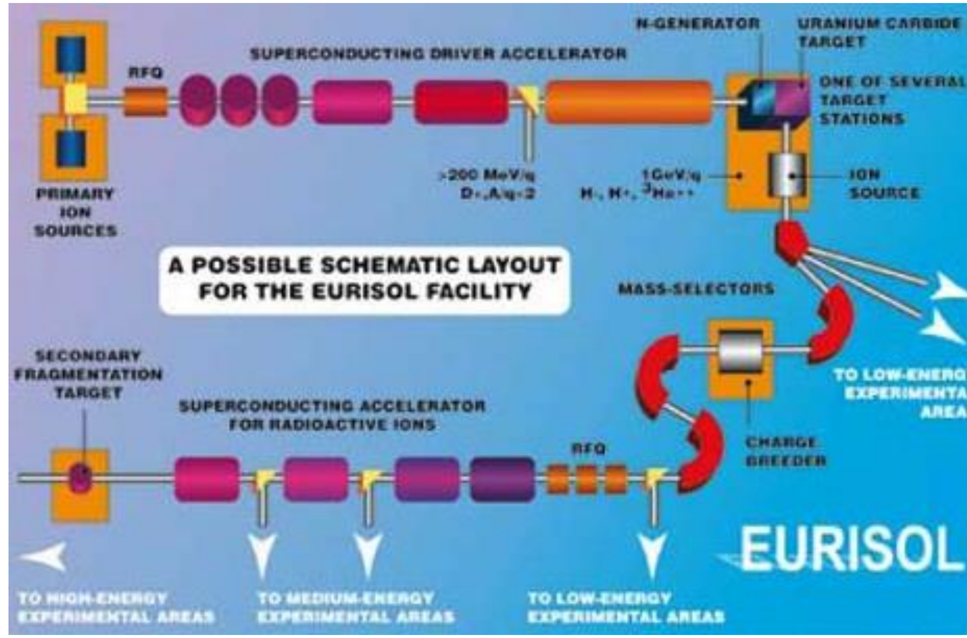
CERN site: where are the detectors?

L/E ~ 500 to get good sensitivity (before 2012)

$E=\gamma Q$, $M = \gamma / Q$

Beta Beam Design Study FP6





EURISOL Design Study

European ISOL radioactive ion beam (RIB) facility

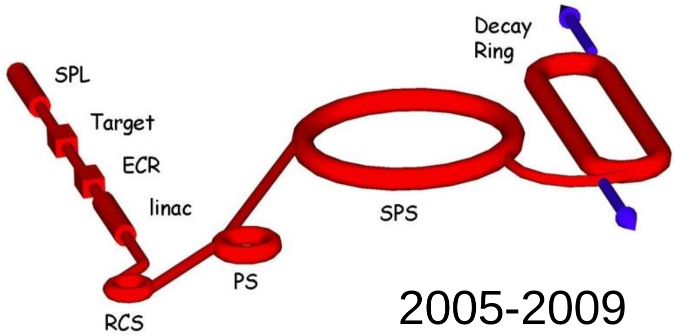
2005-2009
The Beta Beam Design Study was one of the tasks
Task Leader: M. Benedikt

Conceptual Design Report for a Beta Beam facility: The European Physical Journal A, 2011, 47, pp.24.

The EURISOL scenario(*) boundaries

- Based on CERN boundaries
- Ion choice: ^{6}He and ^{18}Ne
- Based on existing technology and machines
  - Ion production through ISOL technique
  - Bunching and first acceleration: ECR, linac
  - Rapid cycling synchrotron
  - Use of existing machines: PS and SPS
- Relativistic gamma =100 for both ions
  - SPS allows maximum of 150 (^{6}He) or 250 (^{18}Ne)
  - Gamma choice optimized for physics reach
- Opportunity to share a Mton Water Cherenkov detector with a CERN super-beam, proton decay studies and a neutrino observatory (Frejus tunnel)

EURISOL scenario



2005-2009

- Achieve an annual neutrino rate of
  - 2.9×10^{18} anti-neutrinos from ^{6}He (produced $3.4\ 10^{13}$/s)
  - 1.1×10^{18} neutrinos from ^{18}Ne (produced $1.7\ 10^{13}$/s)

top-down approach

-> need for good physics

- The EURISOL scenario served as reference for further studies and developments: Euroν (FP7) studied higher Q isotopes: ^{8}Li and ^{8}B

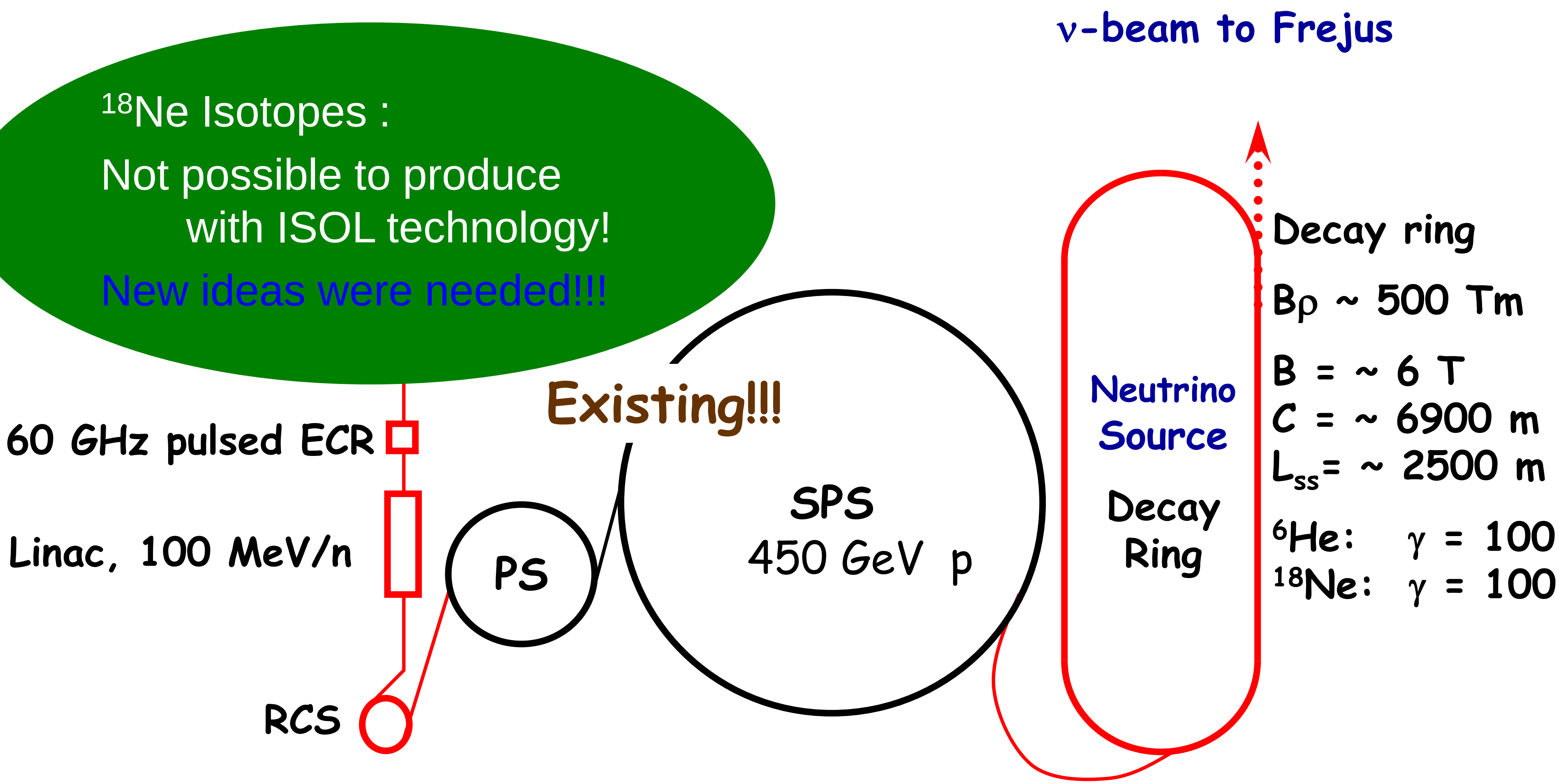
(*) FP6 "Research Infrastructure Action - Structuring the European Research Area" EURISOL DS Project Contract no. 515768 RIDS

Beta Beam scenario 6He/18Ne

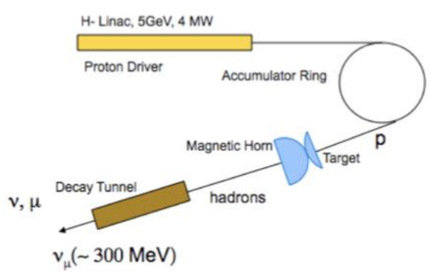
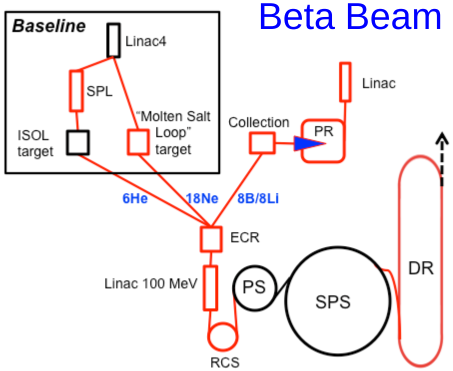
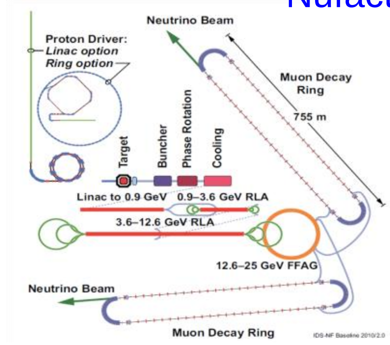
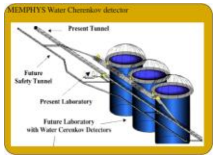
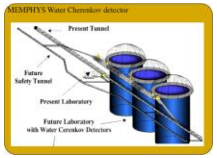
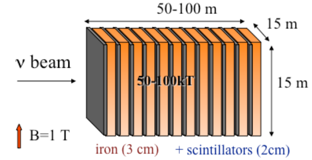
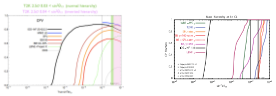
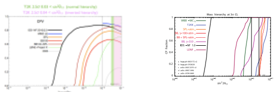
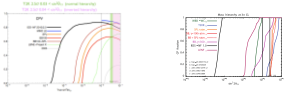
^{18}Ne Isotopes :

Not possible to produce with ISOL technology!

New ideas were needed!!!



EUROnu 2008-2012*)

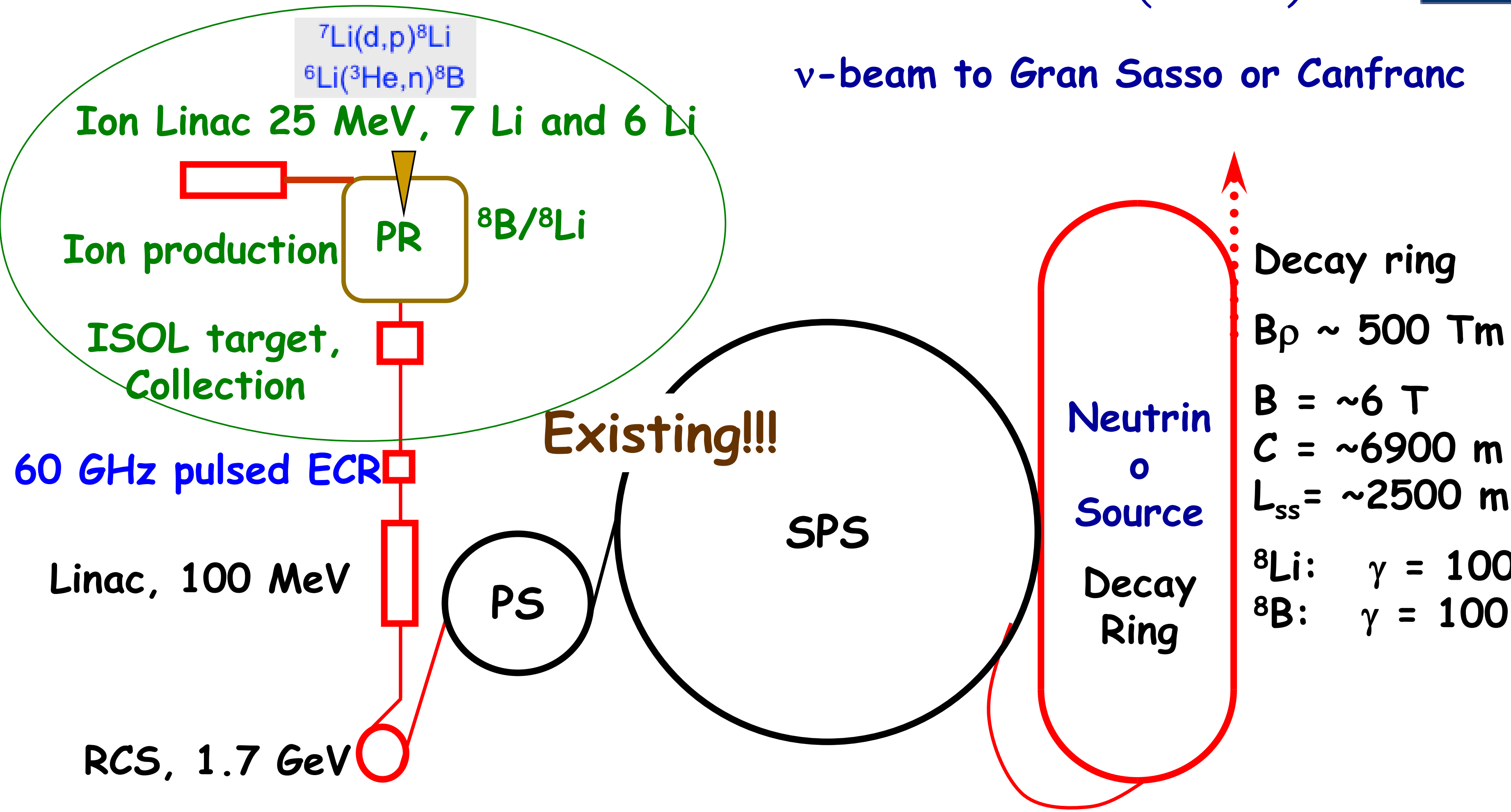
		Superbeam	Beta Beam	Nufact
Design **Cost** **Safety** **Risk** **Time scale**	Facility			
	Detectors		= 	
Physics				

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 the Stragey Group and ECFA

*) *New measurements changed the parameters in 2012*

Beta Beam scenario 8Li/8B (FP7)



New approaches for ion production

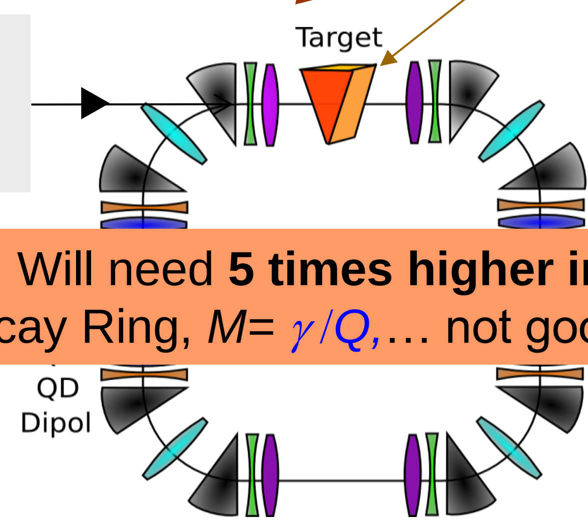
"Beam cooling with ionisation losses" – C. Rubbia, A Ferrari, Y. Kadi and V. Vlachoudis in NIM A 568 (2006) 475–487

"Development of FFAG accelerators and their applications for intense secondary particle production", Y. Mori, NIM A562(2006)591

Supersonic gas jet target, stripper and absorber

^{7}Li
^{6}Li

$^{7}Li(d,p)^{8}Li$
$^{6}Li(^{3}He,n)^{8}B$



However: Will need **5 times higher intensities** in the Decay Ring, *M*= γ/Q,… not good !

Studied within Euroν FP7 (*)

(*) FP7 "Design Studies" (Research Infrastructures) EUROnu (Grant agreement no.: 212372)

High-Q and Low-Q pairs

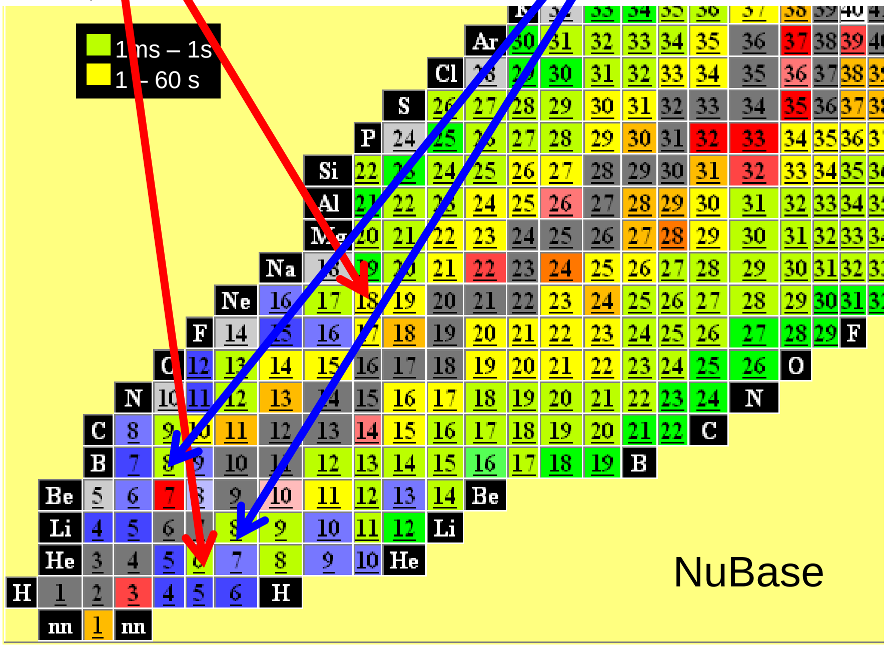
Isotope	^{6}He	^{18}Ne
A/Z	3	1.8
decay	β^-	β^+
$\tau_{1/2}$[s]	0.81	1.67
Q [MeV]	3.51	3.0

Isotope	^{8}Li	^{8}B
A/Z	2.7	1.6
decay	β^-	β^+
$\tau_{1/2}$[s]	0.83	0.77
Q [MeV]	12.96	13.92

6He and 18Ne

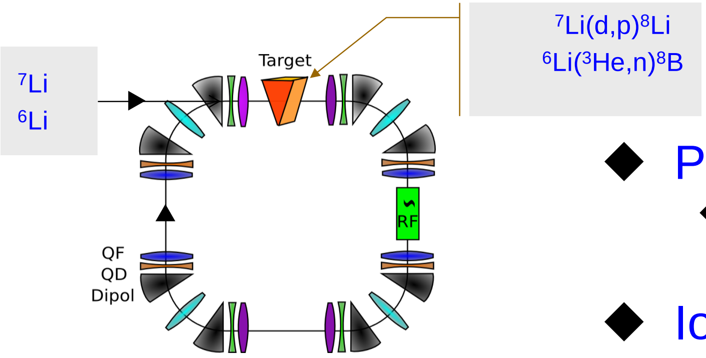
8Li and 8B

$t_{1/2}$ at rest (ground state)



Higher Q-value gives higher ν-energy, better x-sections but needs longer baseline for the same accelerators

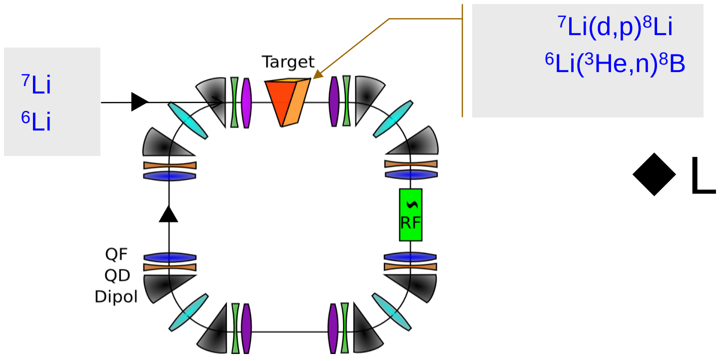
Research topics addressed in EUROnu (FP7)



M. Schaumann, Univ. Aachen

- Production Ring Lattice design
  - RF cavities low dispersion, target low β, dp/p …
- Ionization Cooling feasability
- Target design very challenging
- Cross sections of reactions to measure
- Angular distribution of isotopes, important for collection
- Ion collection device, reverse kinematics
- Ion source (ECR)
- Achievable fluxes/alternative solutions

The production Ring Lattice



M. Schaumann, Univ. Aachen

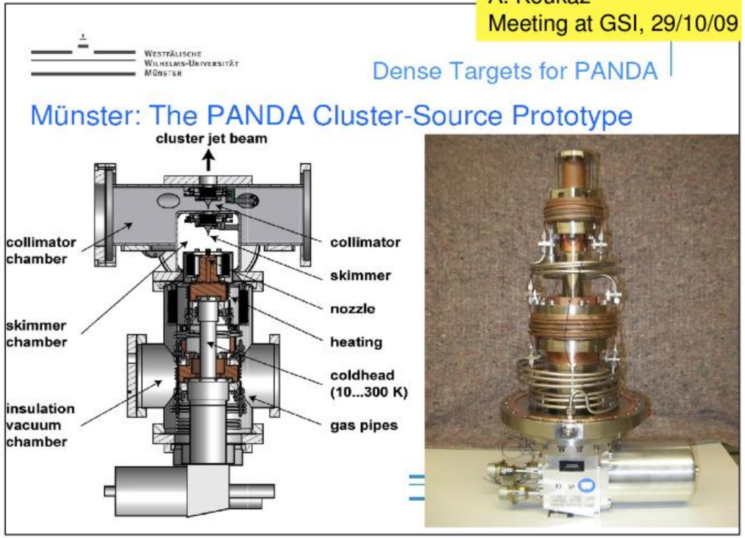
- **Lattice design**
  - RF cavities low dispersion, compensate for energy straggling and multiple Coulomb scattering
  - target low β, dp/p …

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}	~ 0.30 MeV

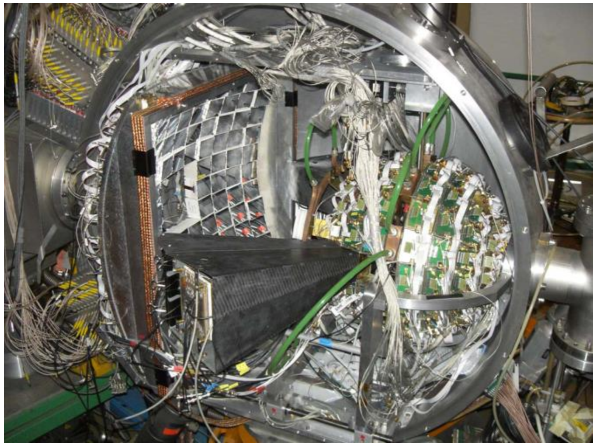
P-Ring results

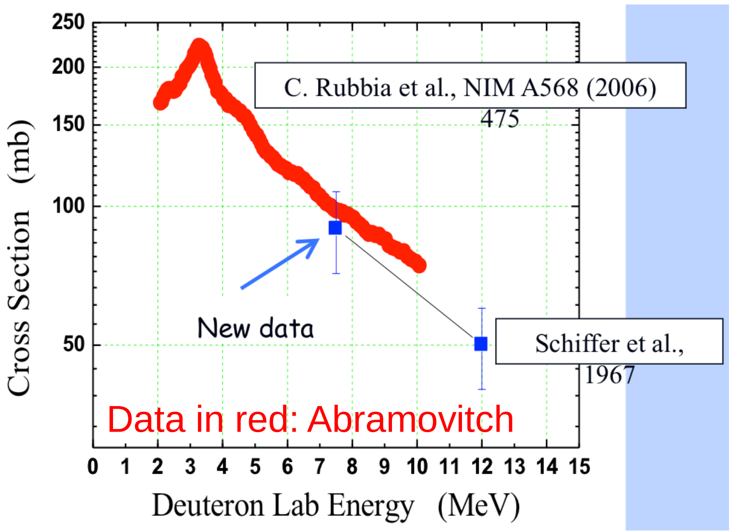
- 6-D simulations (SixTrack) of the cooling shows some cooling, less for Li production (limited dispersion in this energy region), coupling needed
- Need 10^{15} ions/s ^{7}Li ↔ 160μA at the source (10^{14} isotopes needed, 100 mbarn x-section)
  - "Standard" ECR source produces ~30μA!
  - For ^{8}B, need 10 times more of ^{6}Li ... (10 times smaller cross-section ?)
- Gas-jet target needs 10^{19} atoms/cm^{2}, best today 10^{15}: solution is to use solid or liquid targets?
- Liquid film targets: energy deposited ~300kW, 10 μm, heavy ion strippers promising (early R&D)
- Direct kinematics studied, rather promising
- Low frequency Rf cavity
- CERN cavity in AD 9.55 MHz, 750 kV
- 300 kV would allow for cw

A. Koukaz
Meeting at GSI, 29/10/09



X-sections and Angles, ^{8}Li





Inverse kinematic reaction (heavy ion beam on light target):

^{7}Li on CD_2 target E_{beam}=25 MeV

Reaction products in forward cone (~15 degrees), facilitates collection.

Beam traverses target with relatively limited changes (momentum, angle)

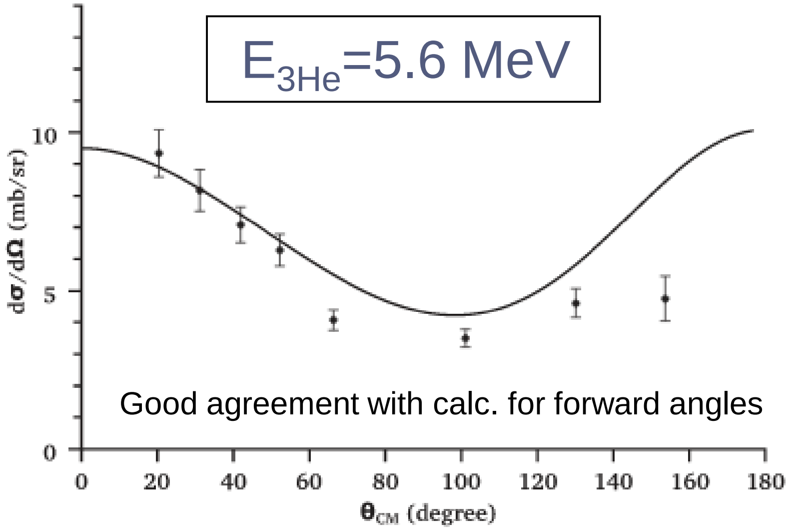
Cross sections in good agreement with literature.

INFN-LNL:

M. Cinausero, G. De Angelis, G. Prete, E Vardaci

Angular distribution and total cross section, ^8B

$^6Li(^3He,n)^8B$



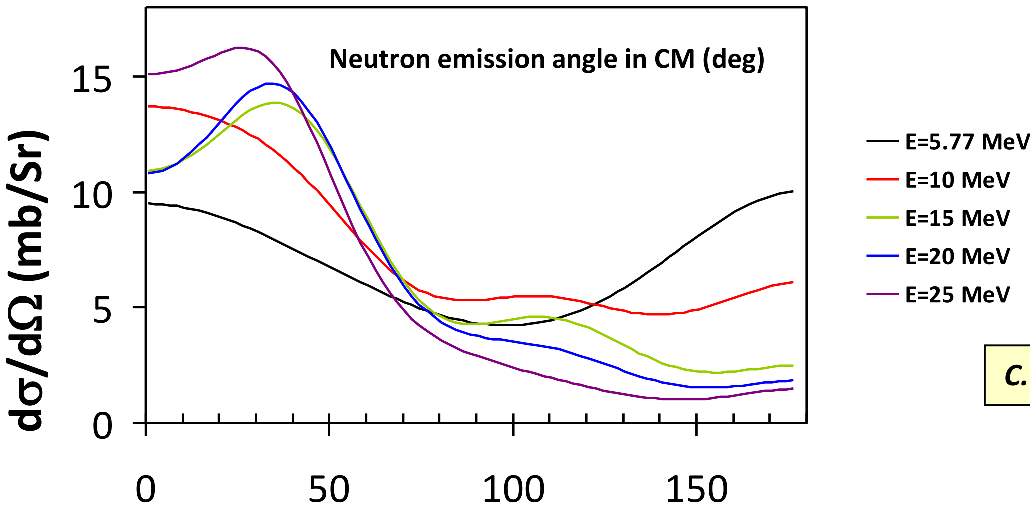
Integrated measured cross sections

Total cross section	Reference
(58 ± 7) mb	**Our result**
75 mb	DWUCK4 calculation
≅65 mb	E_{3He}=5.6 MeV (neutron TOF)

Theoretical Calculations with code DWUCK4
"Zero Range Knock-out Distorted Wave Born Approximation"
S.A. Goncharov, Moscow State University, Russia

Theoretical predictions: Evolution of the cross section with the beam energy

Predictions of the DWUCK4 code at different ^{3}He beam energies



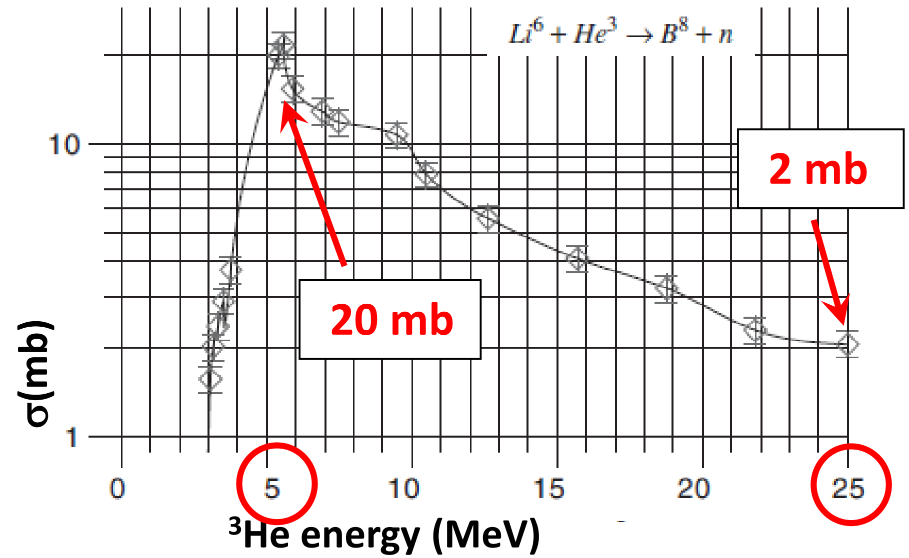
V.L. Kravchuk[1], T. Marchi[1,2], G. Collazuol[2], M. Cinausero[1], F. Gramegna[1], G. De Angelis[1], G. Prete[1]

[1] *INFN Laboratori Nazionali di Legnaro*

[2] *INFN and Dipartimento di Fisica Università di Padova*

Total cross section	^{3}He energy
75 mb	**5.77 MeV**
85 mb	**10 MeV**
79.5 mb	**15 MeV**
74 mb	**20 MeV**
66 mb	**25 MeV**

C.R. McClenahan and R.E. Segel PRC 11 (1975) 370



Confirms disagreement with positron counting experiments

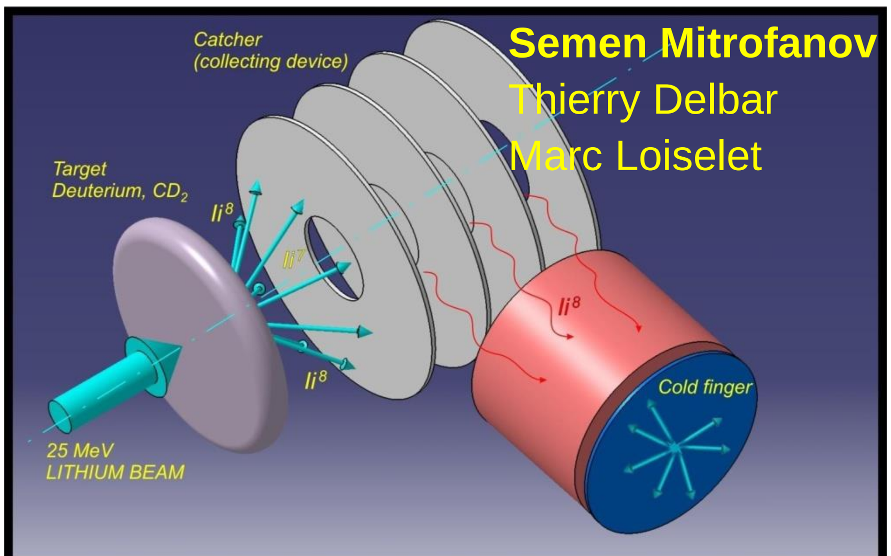
Challenge: collection device

- A large proportion of beam particles (^{6}Li, ^{7}Li) will be scattered into the collection device.

- Production of ^{8}Li and ^{8}B:
  ^{7}Li(d,p) ^{8}Li and ^{6}Li(^{3}He,n) ^{8}B reactions
  using low energy and low intensity ~ 1nA beams of
  ^{7}Li(10-25 MeV) and ^{6}Li(4-15 MeV)
  hitting the deuteron or ^{3}He target.

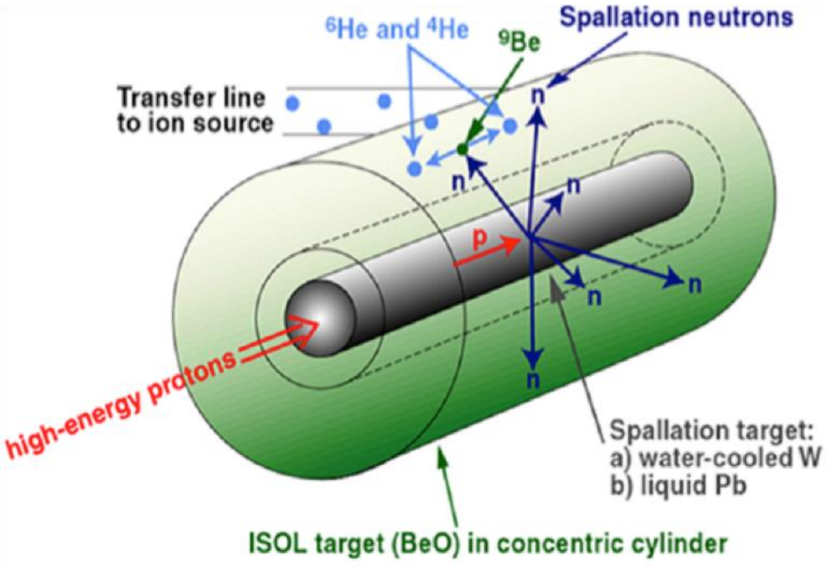
UCL

CRC
Louvain-la-Neuve



End of 2010 - ^{8}Li collection was measured!
Research on B followed, measurements in 2012

Production of low-Q isotopes: ^{6}He



N. Thiolliere et al., EURISOL-DS

Aimed:
^{6}He 3.4 10^{13}/s

- 5 10^{13} ^{6}He/s 200kW, 2 GeV proton beam (ISOLDE 2008, scaling)
- 5 10^{13} ^{6}He/s 600kW, 40 MeV deuteron beam

Can be used also for production of 8Li

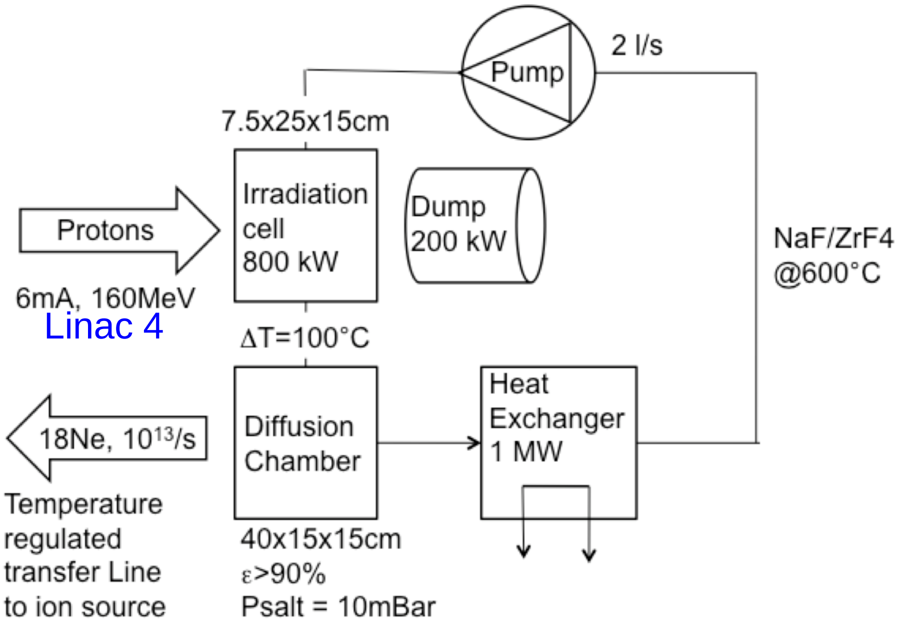
^{18}Ne Experiments for Beta Beams

- Molten salt loop experiment to produce 18Ne
  - experiments at CERN & LPSC (Grenoble)

- The ν_e beam needs production of 2.0 10^{13} ^{18}Ne/s
- Measurements of the cross section

NaF salt loop → 2 reactions

$$^{19}F(p,2n)^{18}Ne + {}^{23}Na(p,X)^{18}Ne$$



^{18}Ne production rate estimated to 1 x10^{13} ions/s (dc) for 960 kW on target.

Some research for doubling this rate, or doubling run-time (He can be run half the time with higher intensities, to be checked for machine performance)

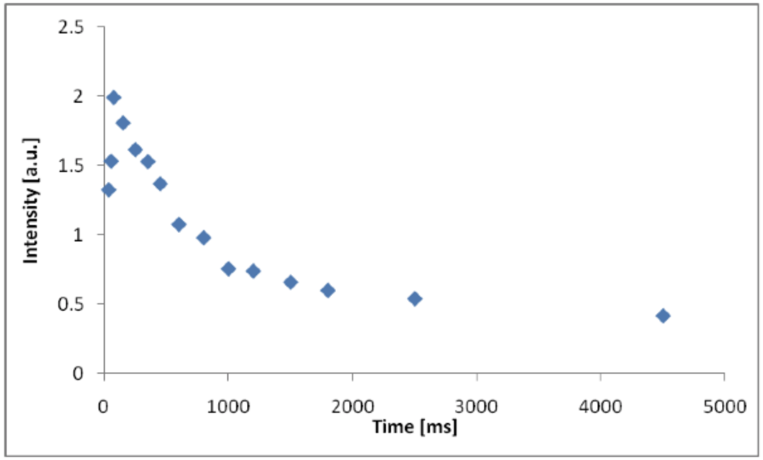
T. de Melo Mendonca et al, Production and Release of ISOL Beams from Molten Fluoride Salt Targets CERN-ACC-NOTE-2013-0009

First ^{18}Ne and ^{19}Ne at ISOLDE

Validation 2012

Thick molten salt targets

Release of 18Ne
Target at 750°C,
Ion source at 1890°C



- Further developments
  - Experiments on diffusion properties
  - Optimization of mechanical design
  - Choice of Salt composition

Today, spinoff :

Salt target tests at Isolde:
^{18}Ne & ^{11}C at high rates (ISOLDE use)
^{11}C hadron therapy (treatment and imaging).

The first ^{8}B ISOL beam worldwide.
Nuclear structure and applied physics !!

Production of Beta Beam isotopes

Aim: 3.4 10^{13} for ^{6}He **Targets below MWatt is a considerable advantage!**

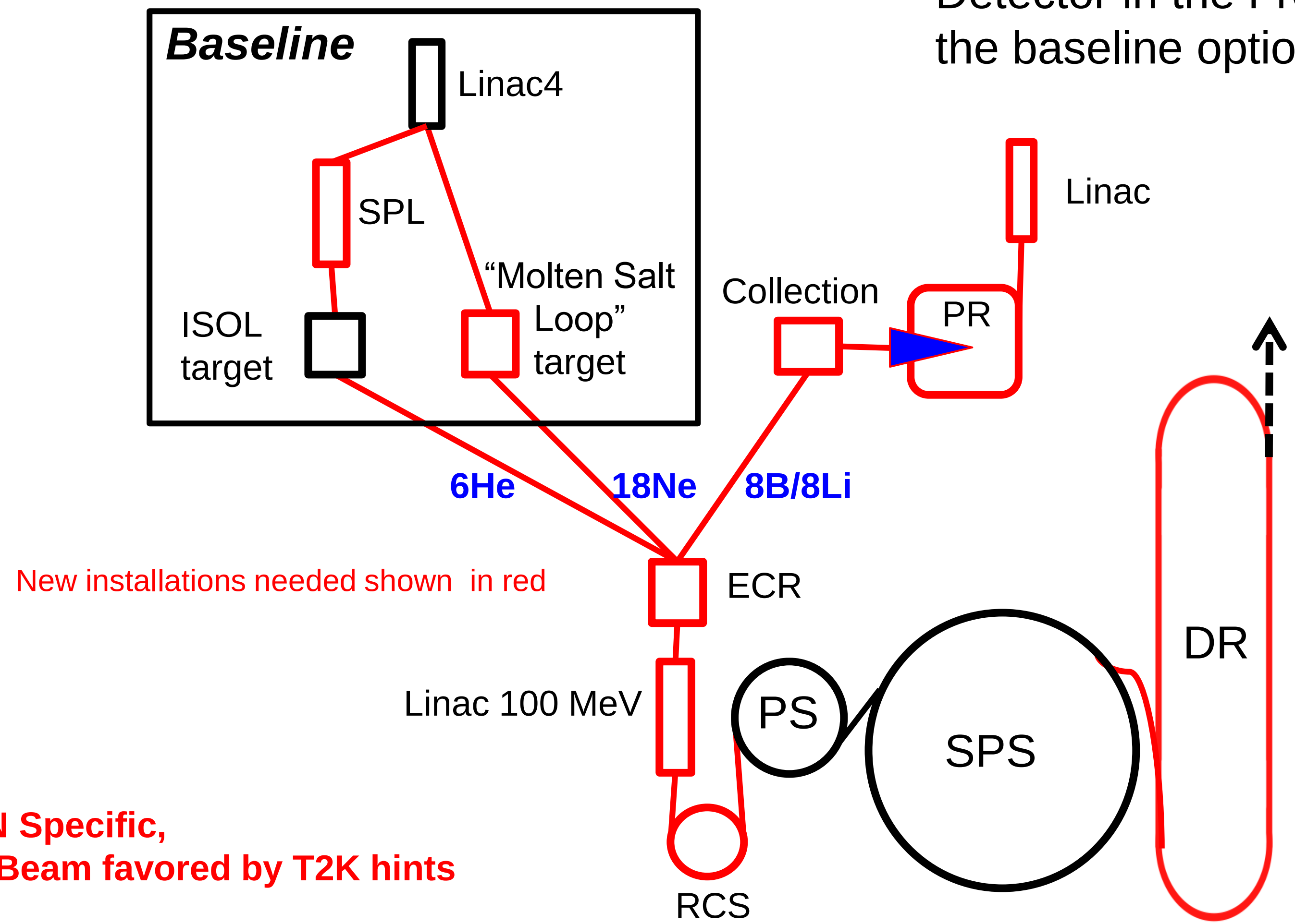
Type	Accelerator	Beam	I_{beam} mA	E_{beam} MeV	P_{beam} kW	Target	Isotope	Flux s^{-1}	
ISOL & n-converter	SPL	p	0.07	2 10^{3}	135	W/BeO	6He	5 10^{13}	
ISOL & n-converter	Saraf/GANIL	d	17	40	680	C/BeO	6He	5 10^{13}	
ISOL	Linac 4	p	6	160	960	23Na 19F Molten NaF loop	18Ne	1 10^{13}	
ISOL	Cyclo/Linac	p	15	60	900	23Na 19F Molten NaF loop	18Ne	1 10^{13}	
ISOL	LinacX1	3He	85	21	1800	MgO 80 cm disk	18Ne	1 10^{13}	
P-Ring	LinacX2	d	0.160	25	4	7Li	8Li	0.1 10^{13}	
P-Ring	LinacX2	3He	0.160	25	4	6Li	8B	0.08 10^{13}	

Aim ^{6}He 3.4 10^{13}/s
^{18}Ne 2.1 10^{13}/s

Source: T. Stora, Proceedings nufact'11

The CERN Beta Beam

Detector in the Fréjus tunnel for the baseline option



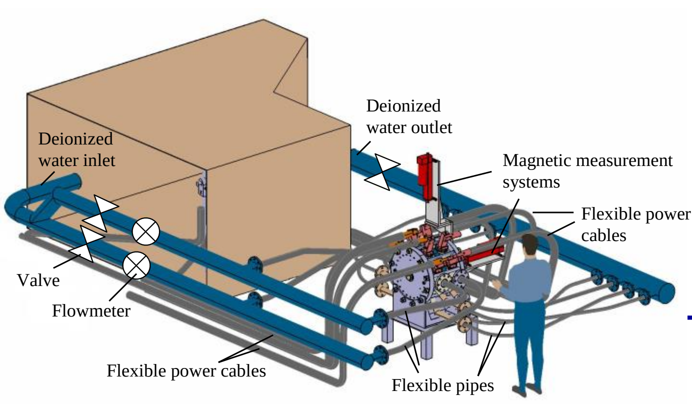
CERN Specific,
Beta Beam favored by T2K hints

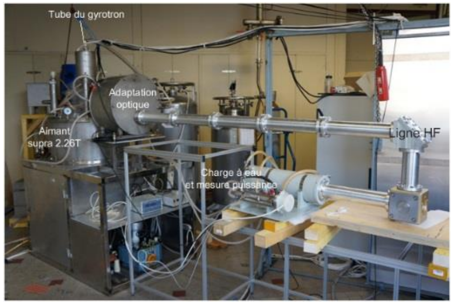
Decay Ring: $B\rho$ ~ 500 Tm, B = ~6 T, C = ~6900 m, L_{ss}= ~2500 m, γ = 100, all ions

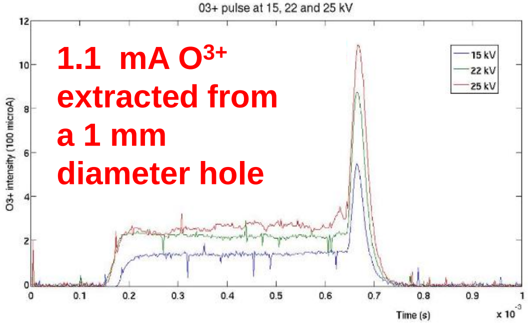
60 GHz ECR Ion Source today

Thierry Lamy, LPSC

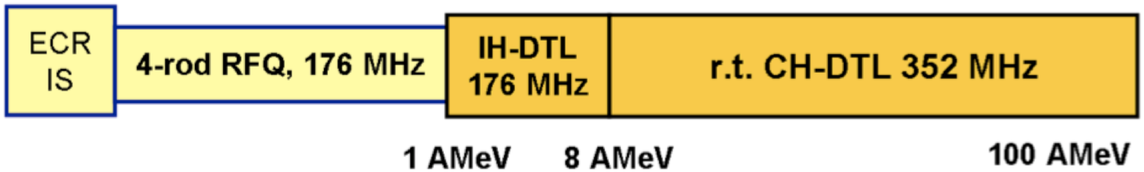
- ECRIS using high field magnet technology (radially cooled polyhelices)
  - Improvement of the magnetic structure cooling at 26000 A
  - Nominal magnetic field reached (> 6.1 T at injection, 3T at extraction, 4.5 T radial)
  - HF injection system designed by Institute of Applied Physics – Russia
- 60 GHz 300 kW pulsed gyrotron (5Hz pulses: 50 µs to 1 ms)
  - Installed and operational at Grenoble High Magnetic Field Laboratory
- First ion beams extracted in 2014
  - First ion beams in the world extracted from a 60 GHz ECRIS (with a closed ECR zone)
  - Oxygen ion beams up to 5+ with high intensity
  - Amperes of beam can be produced, scientific program to be continued

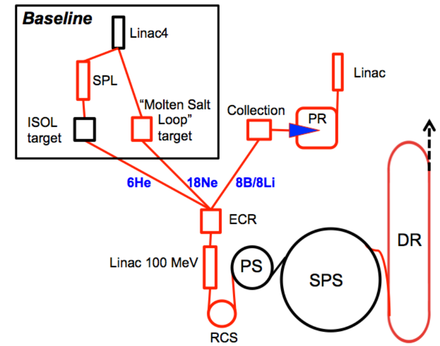






Ion Linac



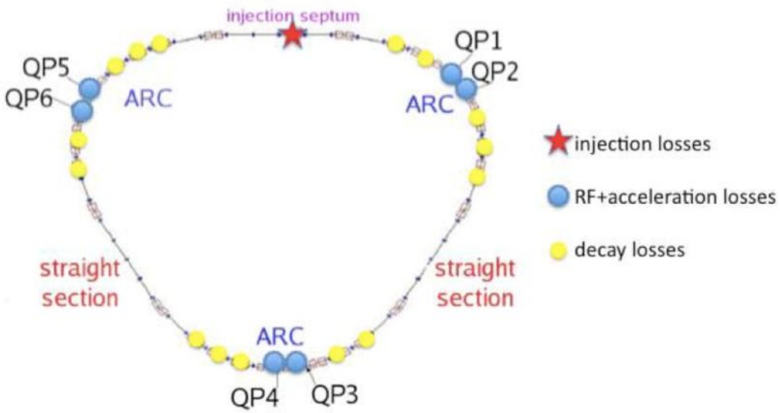


Beta beam linac parameters	
Duty cycle	0.05%
Beam current	13 mA
Mass to charge ratio A/q	3
Input energy W_{in}	8 keV/u
Output energy W_{out}	100 MeV/u
Input emittance $\epsilon_{in,rms,normalized}$	0.2π mm mrad

- Studied within EURISOL FP6
  - Normal conducting rf
  - Ions not fully stripped after ECR
  - Two RFQs may be needed for the different isotopes (not studied)
  - Strip before DTL
  - The linac would be about 110 m long

RCS

- Accelerates He and Ne ion beams from 100 MeV/u to 14.47 Tm (3.5 GeV protons)
- 0.79 MeV for $^{6}He^{2+}$ and 1.65 GeV for $^{18}Ne^{10+}$.



Beta-beam RCS parameters	
Circumference	251 m
Superperiodicity	3
Injection energy	100 MeV/u
Maximum magnetic rigidity	14.47 Tm
Repetition rate	10 Hz
Number of dipoles	60
Number of quadrupoles	48
Max ramping rate	24 T/s
Emittance h/v	$72/39\pi$ mm mrad

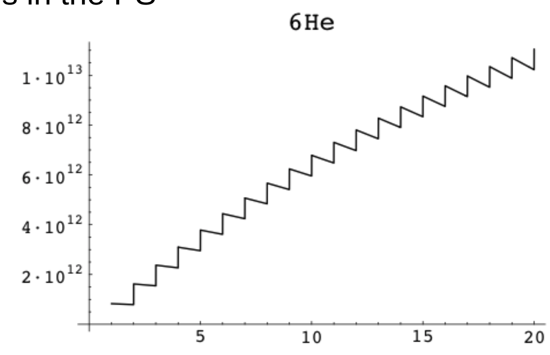
- Multiturn injection of 50 μs long pulse (26 turns)
- Studies of vacuum and radioprotection
- Classified as supervised radiation areas (dose rate constraint 3 μSv/h)
- Concrete shielding 3 to 5 m, depending on the position in the tunnel.

A. Lachaize, EURISOL FP6

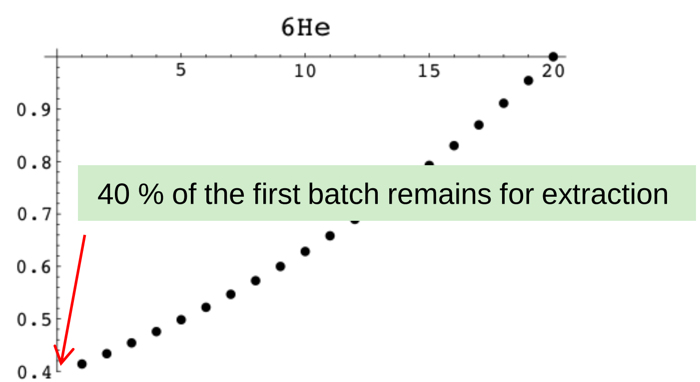
PS

- FP6: 3.5 GeV (space charge ΔQ=0.22)
- FP7: Studies rather consider 2 GeV: 3.5 GeV injection is challenging
- Radiation Studies including Goward road
  - Dose rates lower than today's PS beams
- Some magnets may need remote handling
- Vacuum- pumping can be done with present PS pumps
- Released radioactivity ~0.4 μS (total CERN should be < 10 μS)

Ions in the PS



RCS Batches

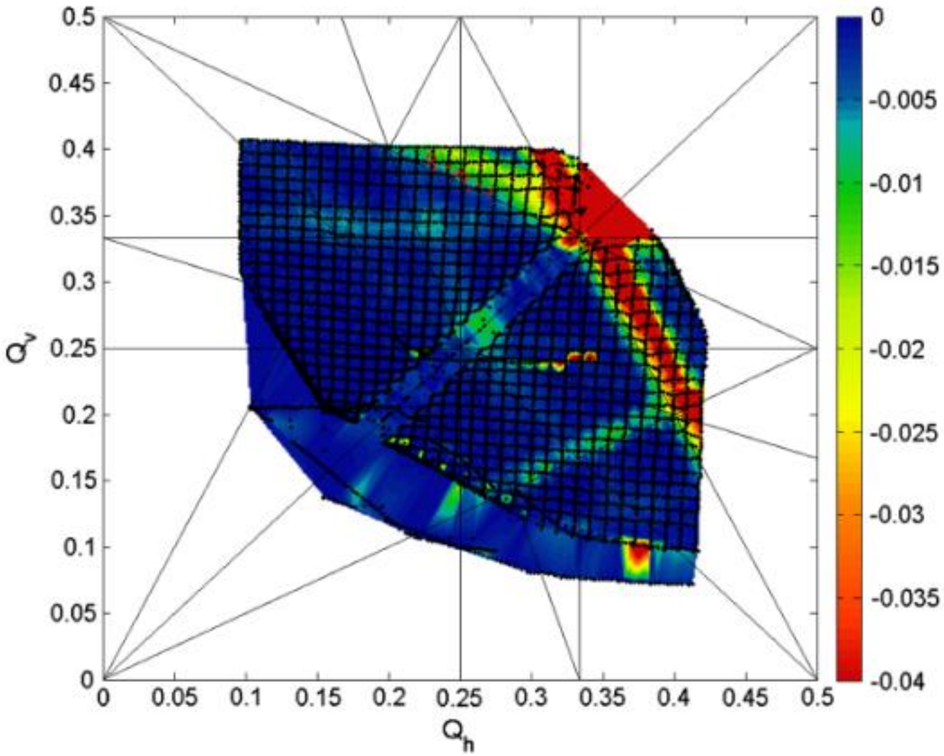


Relative intensity of the PS injected batches

PS extraction kicker random

PS injection tests, Space Charge

- Measurements at 2 GeV with protons suggest that ^{6}He should survive
  - $(\Delta Q_x, \Delta Q_y) = (-0.22, -0.31)$
- ^{18}Ne needs more work (resonance compensation).



SPS

RF:

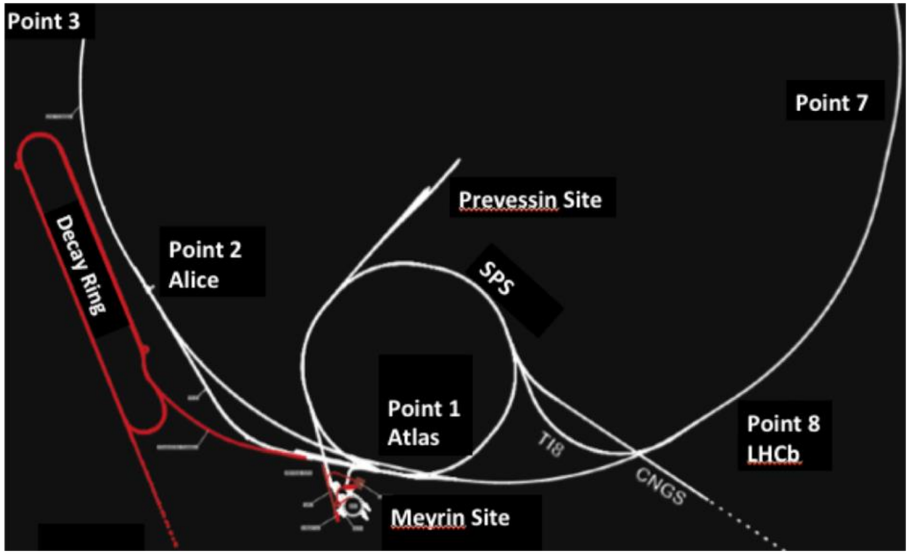
- Space charge bottleneck
  - Add a 40 MHz rf system (allows longer bunches from the PS)
- Several rf considerations for matching, ramp-rates, rf gymnastics close to transition…
- Deliberate mismatch for the injection into the Decay Ring: off momentum into the nonlinear region of the receiving bucket

Vacuum

- Needed pumping rates depend on desorption
- Reduce acceleration time may remedy
- Extended cycle times (6 s)

The Decay Ring (DR)

- Very high intensities
  - 4 10^{12} $^{6}He^{2+}$ and 3.7 10^{12} $^{18}Ne^{10+}$ per bunch
  - Beam Current 50-250 A peak
- Collective effects important
- Head Tail Effects (redesign of the DR necessary)
  - Gain of a factor 2-3 on intensity limit (C.Hansen, Head-Tail & Moses)
- High rf Power
- Beam loading
  - Phase shifting
  - Cavity detuning

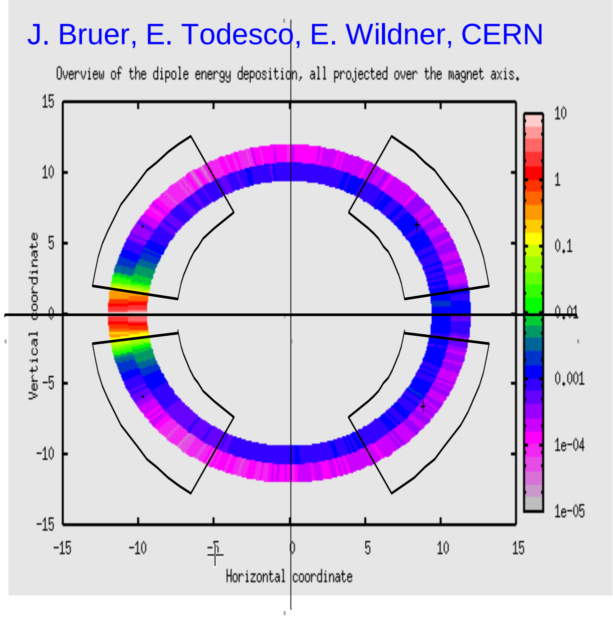


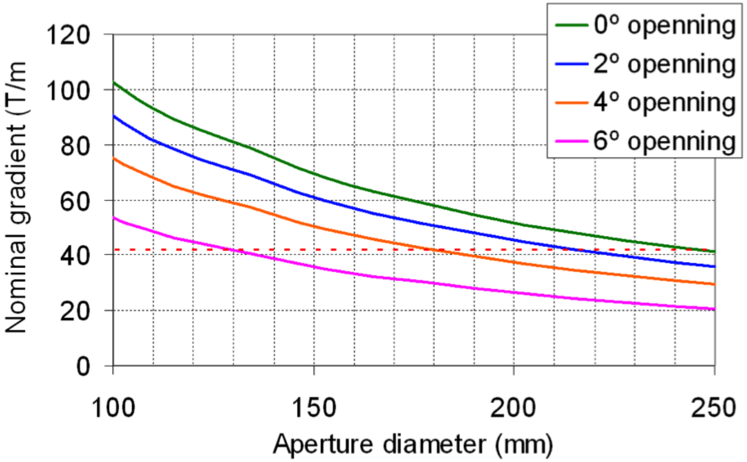
The Decay Ring Magnets

Magnet half-aperture	60 100 (2QP)/120(2QP)	mm
Total number of dipoles	176	-
Dipole length	7	m
Dipole field	6	T
Total number of quadrupoles	236/ 94 SC/ 142 W	-
Quadrupole length	2	m
Max quadrupole gradient	36	T/m
Total number of sextupoles	64	-
Max int sextupole gradient	34	T/m
Total number of kickers	4	-
Kicker length	1	m
Max field of kickers	0.37	T/m
Total number H/V correctors	120/117	-
Total number H/V BPMs	120/117	-
Max int field H/V correctors (3σ)	0.13/0.20	T.m

Decay Ring SC magnets

Cosθ design open midplane magnet



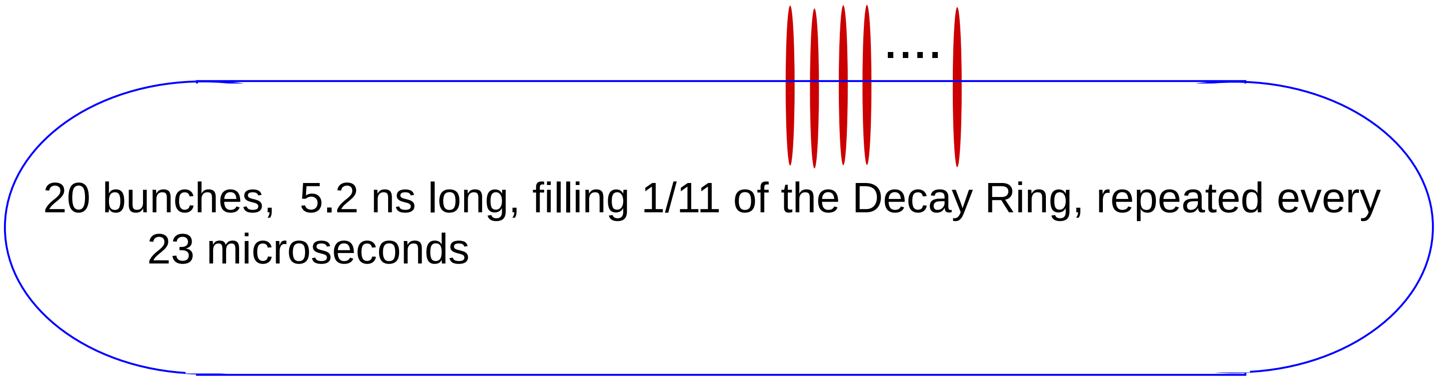


Open Midplane SC Quadrupole

Superconducting Dipole Magnet:
Manageable (7 T operation)
with Nb-Ti at 1.9 K

Duty factor and RF Cavities

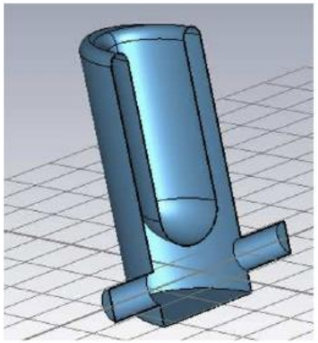
10^{14} ions, 0.5% duty (supression) factor for background suppression !!!



Erk Jensen, CERN

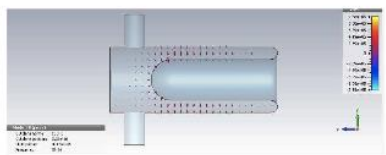
- No net energy transfer to the beam,
  - use a linear phase modulation in the absence of the beam, mimicking detuning-this could reduce gap transients,
- Not conclusive yet
- The heavy transient beam loading is unprecedented
- A high-Q cavity (S.C.) preferable

Low shunt impedance cavity design



- Length: 452 mm
- Height: 1.9 m
- The cavities must flip orientation every other cavity.
- Total width: 3.8 m.
- Total cryostat width: 4.5-5 m.

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



Cost:
5 MCHF per RF station.
56 RF stations
Total cost of 280 MCHF
Total voltage of 32.5 MV

- To keep the cavity on amplitude and phase with the cavity tuned to 40 MHz takes ≈ 9MW
- Bunch charge is varying
  - Cavity frequency will change (Beam Loading/Detuning)
  - $P \sim Q^4$ => Sensitivity to charge errors
- Several Cavity systems studied
- Option: SRF Cavity, low R/Q, only small detuning…

G. Burt

Collective Effects limits, Decay Ring

	Bunch Intensity Limit, N_b^{th}		
	[e12]	[N_b^{nom}]	[N_b^{nom}]
^{18}Ne	0.6	0.1	0.3
^{6}He	5.0	1.0	0.5
^{8}B	1.1	0.1	0.3
^{8}Li	3.0	0.1	0.3

Ions	Fluxes [10^{18}]	Years	$(\sin^2 2\theta_{13})_{min}$	NH,$(\sin^2 2\theta_{13})_{min}$
^{6}He	$\bar{\Phi}_0 = 2.9$	5	5×10^{-4}	No Sensitivity
^{18}Ne	$\Phi_0 = 1.1$	5		
^{8}Li	$\bar{\Phi}_0 \times 5$	5	2×10^{-4}	8×10^{-3}
^{8}B	$\Phi_0 \times 5$	5		
^{6}He	$\bar{\Phi}_0 \times 2$	2	6×10^{-4}	No Sensitivity
^{18}Ne	$\Phi_0/2$	8		
^{8}Li	$\bar{\Phi}_0 \times 2$	5	7×10^{-4}	1.5×10^{-2}
^{8}B	$\Phi_0 \times 2$	5		

Only Transverse Mode Coupling Instabilities

Recent Encouraging results, redesigned decay ring !

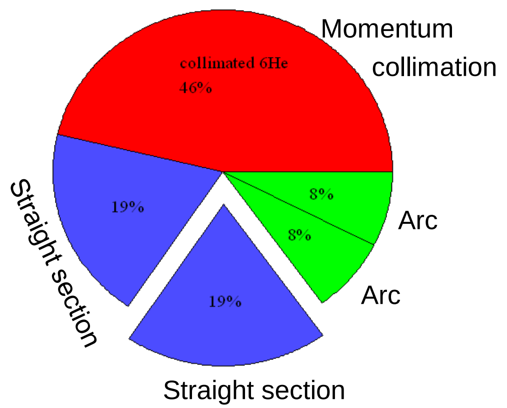
	Bunch Intensity Limit, N_b^{th}		
	[e12]	[N_b^{nom}]	[N_b^{nom}]
^{18}Ne	1.2	0.3	0.6
^{6}He	10	2.1	1.0
^{8}B	2.1	0.2	0.6
^{8}Li	5.9	0.2	0.6

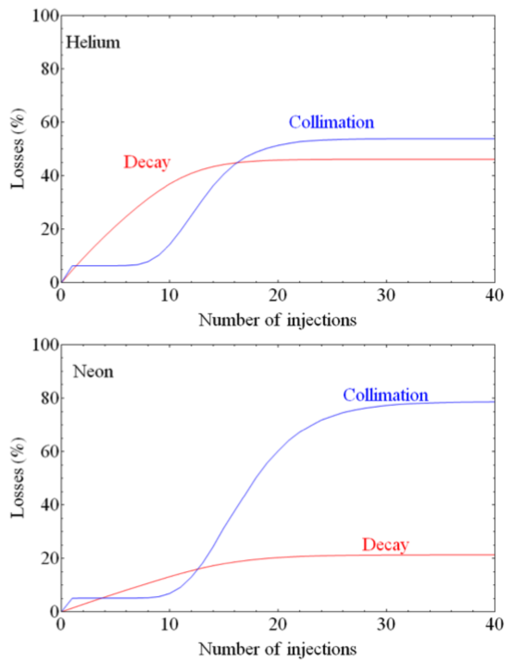
Ions	Fluxes [10^{18}]	Years	$(\sin^2 2\theta_{13})_{min}$	NH,$(\sin^2 2\theta_{13})_{min}$
^{6}He	$\bar{\Phi}_0 = 2.9$	5	5×10^{-4}	No Sensitivity
^{18}Ne	$\Phi_0 = 1.1$	5		
^{8}Li	$\bar{\Phi}_0 \times 5$	5	2×10^{-4}	8×10^{-3}
^{8}B	$\Phi_0 \times 5$	5		
^{6}He	$\bar{\Phi}_0 \times 2$	2	6×10^{-4}	No Sensitivity
^{18}Ne	$\Phi_0/2$	8		
^{8}Li	$\bar{\Phi}_0 \times 2$	5	7×10^{-4}	1.5×10^{-2}
^{8}B	$\Phi_0 \times 2$	5		

Phase slip factor changed

C. Hansen, CERN & A. Chance, CEA

Collimation in DR





Losses:

- Fresh ions which are not captured at the injection.
- Blow-up after injection
- Machine gets "full", large part of the beam is lost
- Two stage collimation system
- Evaluation of dose rates and damage on equipment

Radioprotection

Residual Ambient Dose Equivalent Rate at 1 m distance from the beam line (mSv h^{-1})				
	RCS (quad - ^{18}Ne)	PS (dip - ^{6}He)	SPS	DR (arc - ^{18}Ne)
1 hour	15	10	-	5.4
1 day	3	6	-	3.6
1 week	2	2	-	1.4

Annual Effective Dose to the Reference Population (μSv)			
RCS	PS	SPS	DR
0.67	0.64	-	5.6 (only decay losses)

Stefania Trovati, Matteo Magistris, CERN

Recommendation to reduce!
All machines at CERN should give <10 μSv

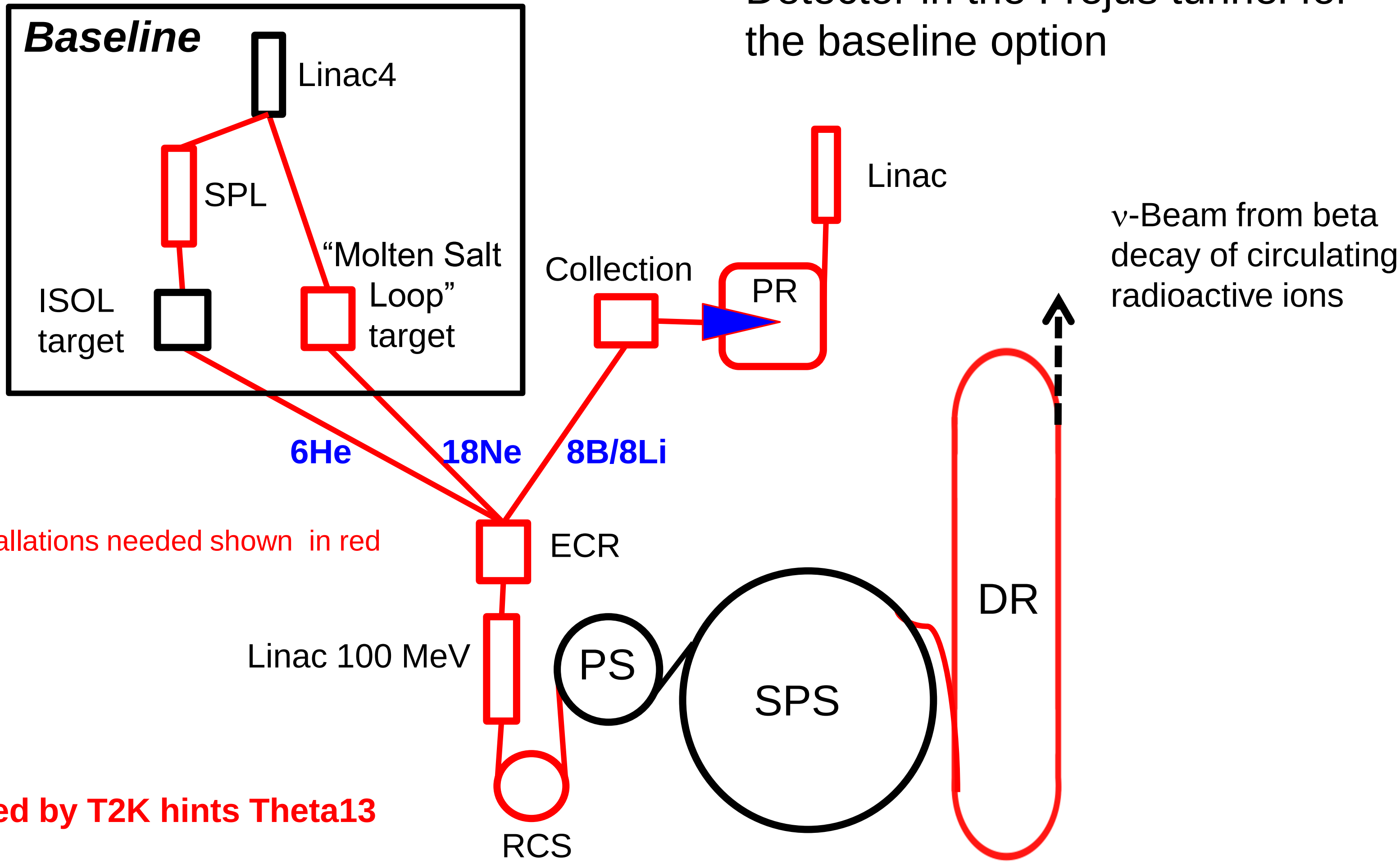
Yacin Kadi et al. , CERN

The beta-beam in EUROnu DS

- The study is focused on production issues for ^{8}Li and ^{8}B
  - Production ring
    - Production and beam cooling are simulated
    - Collection of the produced ions, release efficiencies and cross sections for the reactions (UCL, INFN)
    - Source ECR (LPSC, GHMFL)
    - Supersonic Gas injector, collaboration GSI
- CERN Complex
  - Production Experiments ^{18}Ne and ^{6}He : very good results (ISOLDE)
  - Collective effects, all ions (CERN, CEA)
- Costing and comparison with other neutrino facilities
- Synergy Beta Beams/Superbeams (SPL, good physics)

The CERN Beta Beam

Detector in the Fréjus tunnel for the baseline option



New installations needed shown in red

CERN Specific,
Beta Beam favored by T2K hints Theta13

Decay Ring: Bρ ~ 500 Tm, B = ~6 T, C = ~6900 m, L_{ss}= ~2500 m, γ = 100, all ions

Beta Beam Overviews

FP6: 2005-2009
M. Benedikt et al. :The European Physical Journal A
February 2011, 47:24
Conceptual design report for a Beta-Beam facility

FP7: 2008-2012
E. Wildner et al. : Physical Review Special Topics - Accelerators and Beams
17, 071002 (2014) (~60 collaborators)
Design of a neutrino source based on Beta-Beams

51 +132 articles are referenced in these overviews, of which most are directly related to beta beam research

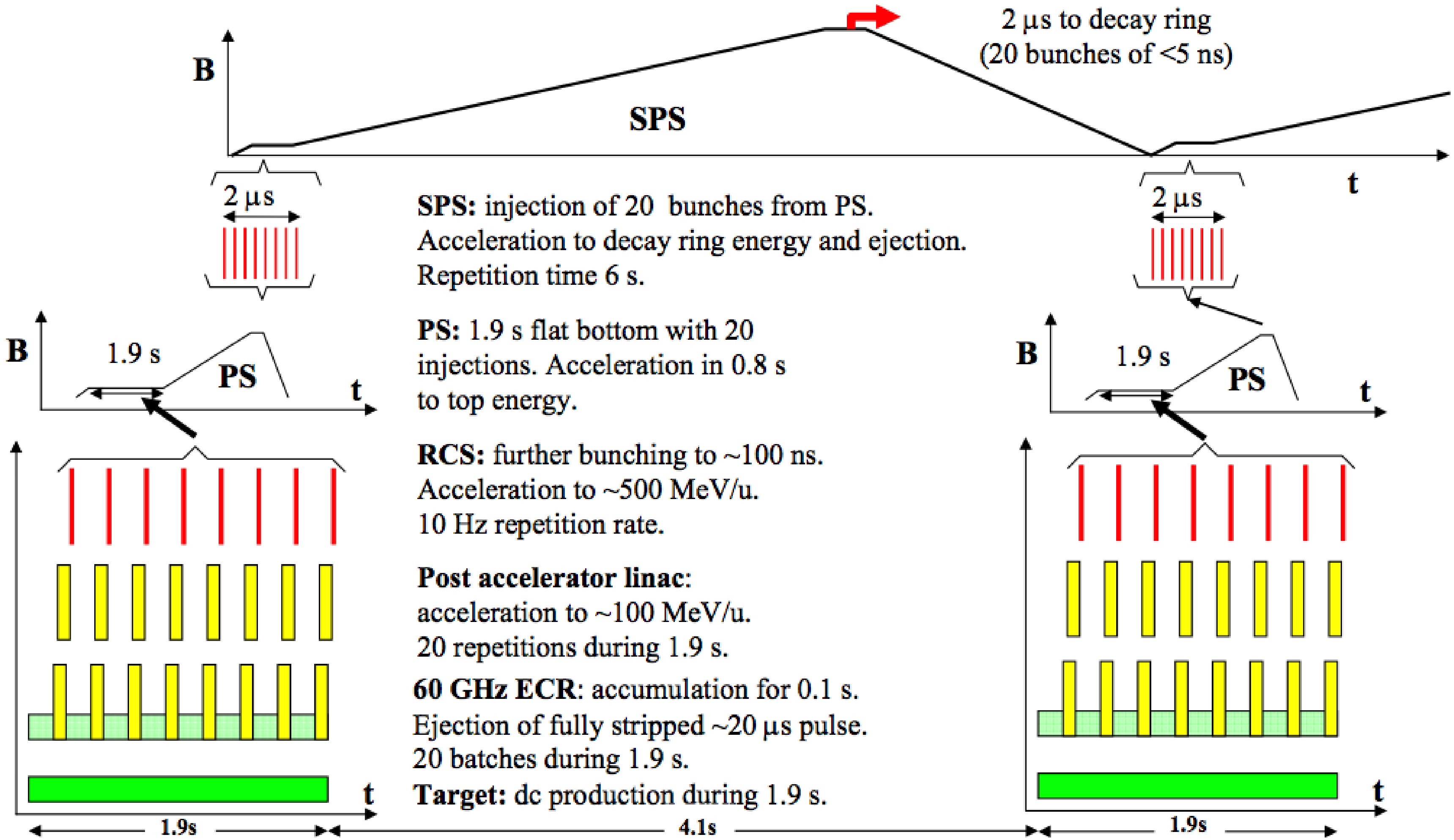
All participants are co-authors, please refer to these publications, more than 50 on each collaboration !

And Now ?

- EUROnu concluded (knowing the measurement of θ_{13})
  - Super-beams have a very good physics potential, relatively cheap
  - Beta Beams have also a very good physics reach, however needs extensive technical development, and sharing the CERN machines. Similar price as a Super Beam. No research on Beta Beams are going on any more (except DAR experiments).
  - The Neutrino Factory is THE tool for accurate measurements, however very expensive > 5 times more and has technology challenges (muon cooling)
- Important now is to estimate systematic errors better
  - Background, fluxes, cross-sections, detectors etc.
- Super Beam projects/studies in Japan (HyperK) and in the US (LBNF/DUNE)
- Will there be any long baseline neutrinos in Europe?
- There is a great opportunity to build a Super Beam in Lund, Sweden, using the 5MW linac of the European Spallation Source (ESS) !!!

Thank you for your attention

The Accelerator cycling



Decay Ring Parameters

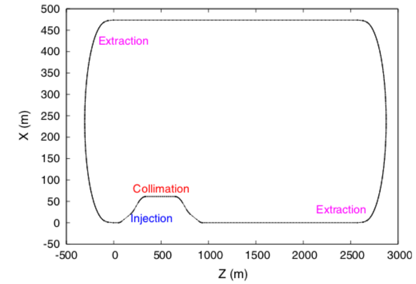
Decay Ring: Bρ ~ 500 Tm, B = ~6 T, C = ~6900 m, L_{ss}= ~2500 m, γ = 100, all ions

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

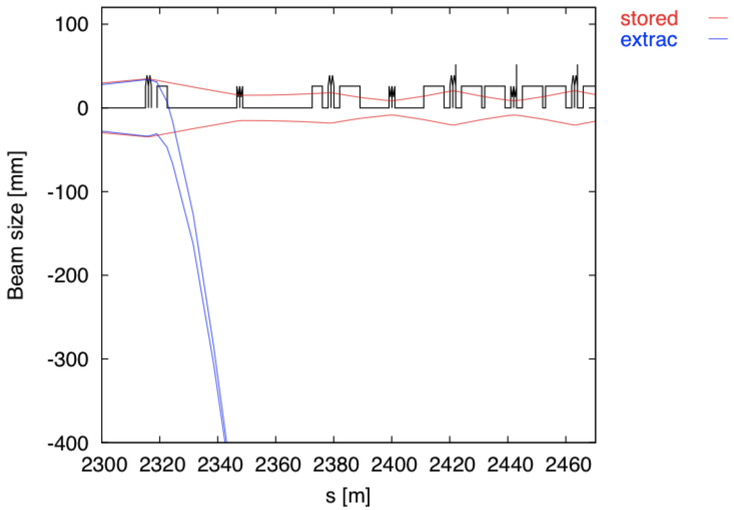
	Units	$^6He^{2+}$	$^{18}Ne^{10+}$	$^8Li^{3+}$	$^8B^{5+}$
Atomic mass A_{eff}	u	6.019	18.006	8.022	8.025
E_{rest}/ion	GeV	5.606	16.772	7.471	7.473
γ	...	100	100	100	100
β	...	1.00	1.00	1.00	1.00
$\beta \cdot \gamma$	...	99.995	99.995	99.995	99.995
Half-life at rest τ	s	0.807	0.167	0.840	0.770
$B\rho$	T m	934.87	559.27	830.64	498.50
Ring length	m	6911.5	6911.5	6911.5	6911.5
Revolution time	μs	23.06	23.06	23.06	23.06
Number of bunches	...	20	20	20	20
Normalized ϵ_x (1 σ)	π mm mrad	14.8	14.8		
Normalized ϵ_z (1 σ)	π mm mrad	7.9	7.9		
Injection cycle time	s	6.0	3.6	4.8	3.6
Nominal annual ν flux	10^{18}	2.9	1.1	14.5	5.5
		Stored beam			
Number of stored ions	10^{13}	9.346	7.178	48.18	16.70
Number of ions/bunch	10^{12}	4.673	3.589	24.09	8.35
Full energy of the beam	MJ	8.3937	19.282	57.668	19.984
Average beam current	A	1.30	4.99	10.04	5.80
Peak beam current	A	227.9	875.0	1762	1017
Longitudinal emittance (full)	eV s	14.4	43.3	19.3	19.3
Bunch length	m	1.97	1.97	1.97	1.97
Momentum spread (full)	10^{-3}	2.5	2.5	2.5	2.5
		Injected beam			
Relative energy difference	10^{-3}	5	5	5	5
Number of ions/bunch	10^{11}	5.57	2.70	27.6	9.17
Full energy of the beam	MJ	0.475	2.99	6.61	2.20
Longitudinal emittance (full)	eV s	1.0	2.2	1.33	1.33
Bunch length	m	1.197	1.197	1.197	1.197
Momentum spread (full)	10^{-3}	0.4	0.4	0.4	0.4

Decay products in the DR

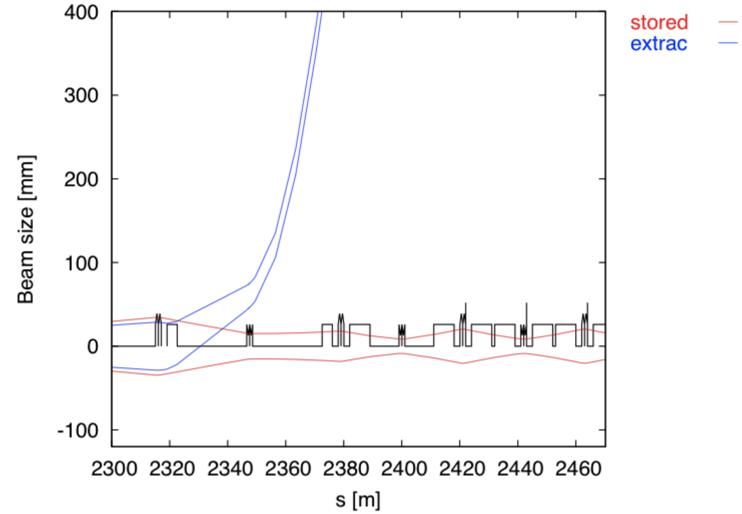
- 37 % of the decays occur in the straight sections
  - 30 kW lost before entrance of arc, must be extracted
- A 0.6 T continuous septum used for this



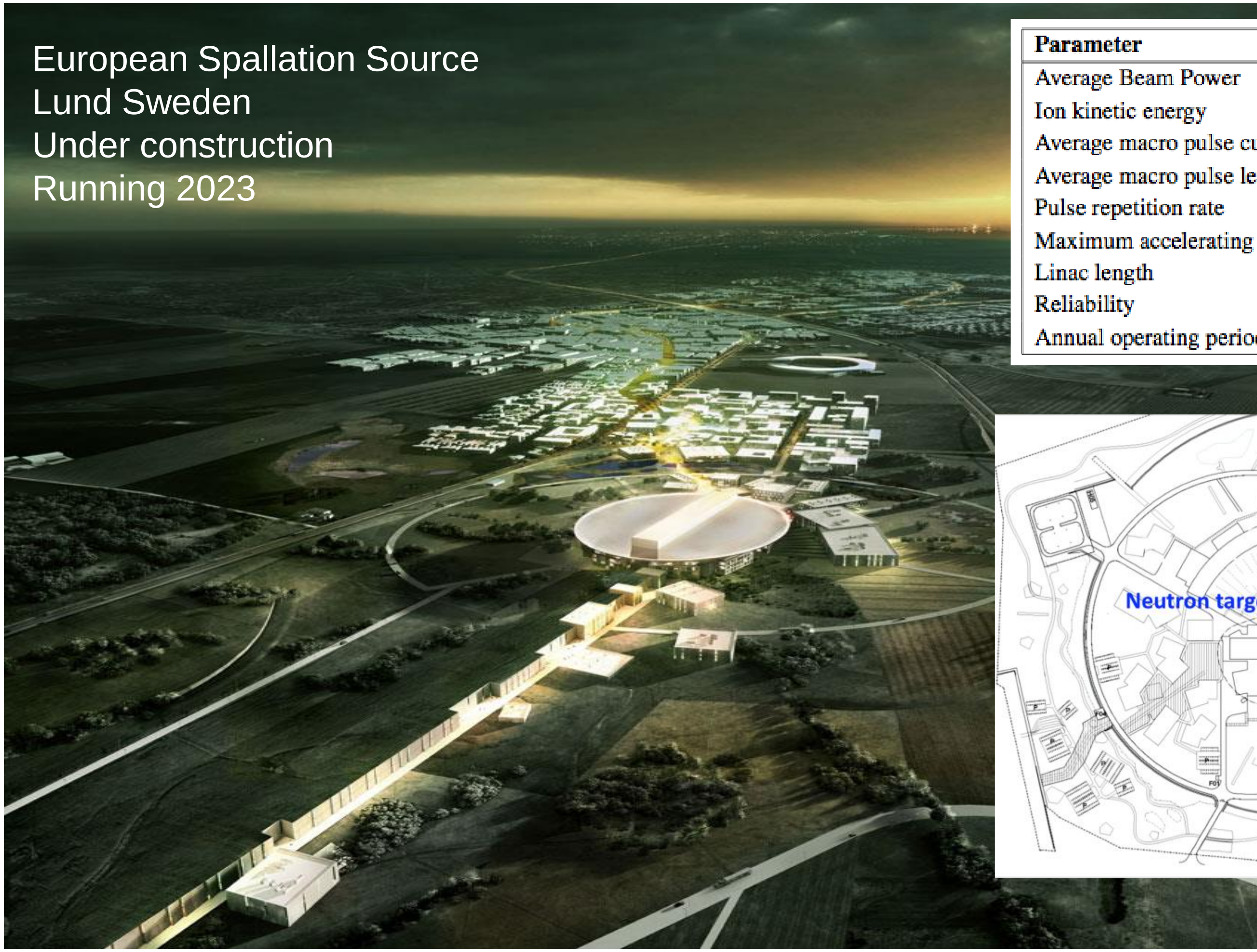
$^{6}He^{2+}$ case



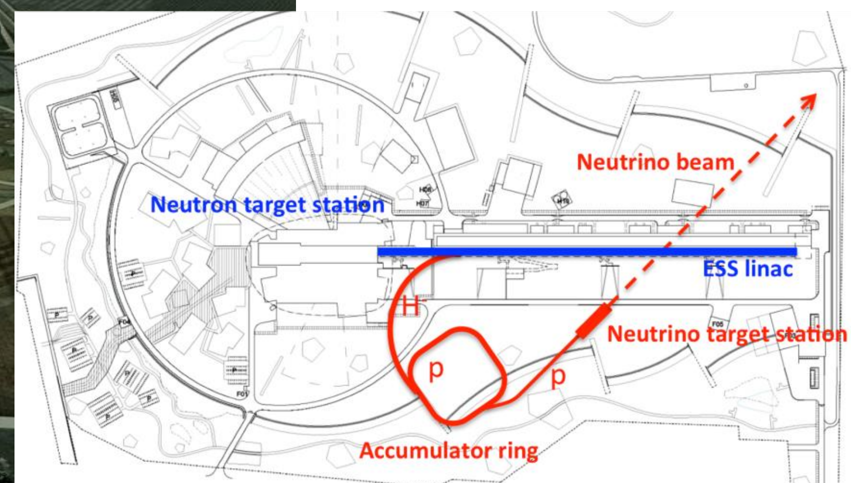
$^{18}Ne^{10+}$ case



Europe: ESSnuSB



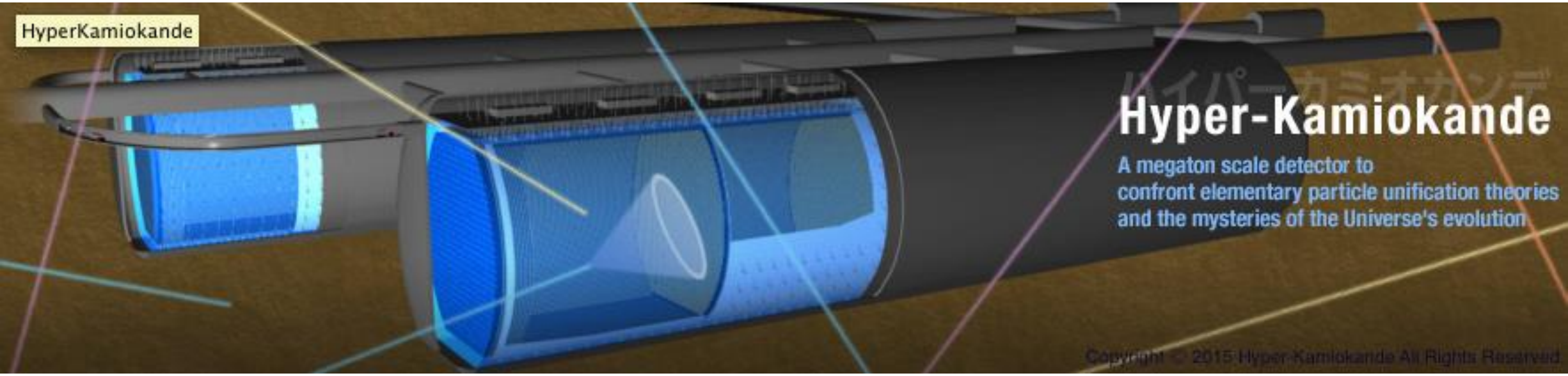
Parameter	Value
Average Beam Power	5 MW
Ion kinetic energy	2 GeV
Average macro pulse current	62.5 mA
Average macro pulse length	2.86/4 ms
Pulse repetition rate	14 Hz
Maximum accelerating cavity surface field	45 MV/m
Linac length	352.5 m
Reliability	95%
Annual operating period	5000 h



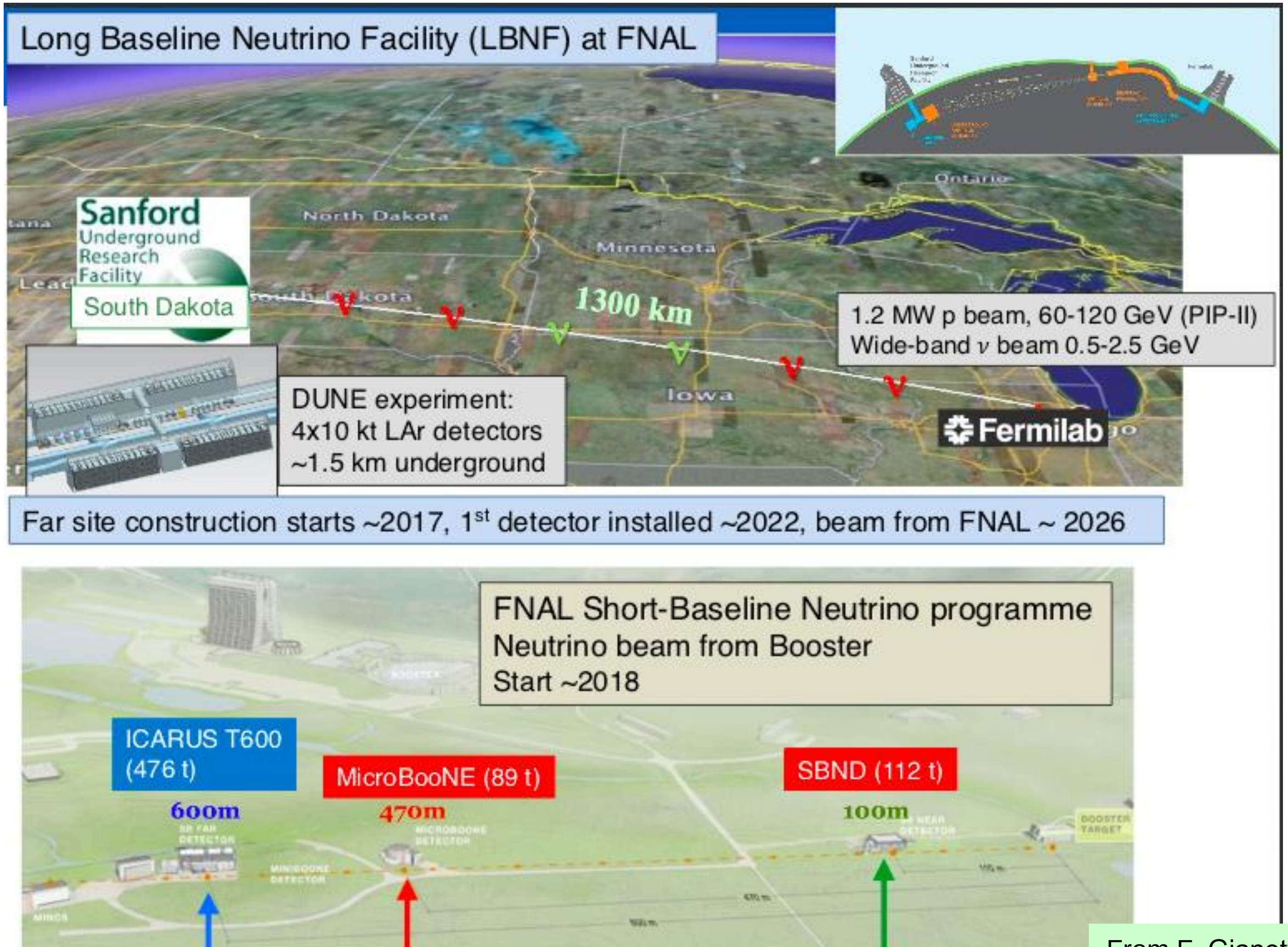
Japan: JPARC

T2K experiment, from JPARC to Super Kamiokande 295km <E> ~ 0.65 GeV off axis experiment.

HyperK, may be built in adjacent mountain, with a similar off axis angle as T2K, Mton Water Cherenkov



US: Fermilab



From F. Gianotti's talk on Monday18/1