Superbeam, Beta Beam, and Neutrino Factory (3)

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3rd Lecture

61st Scottish Summer School in Physics
17 August, 2006

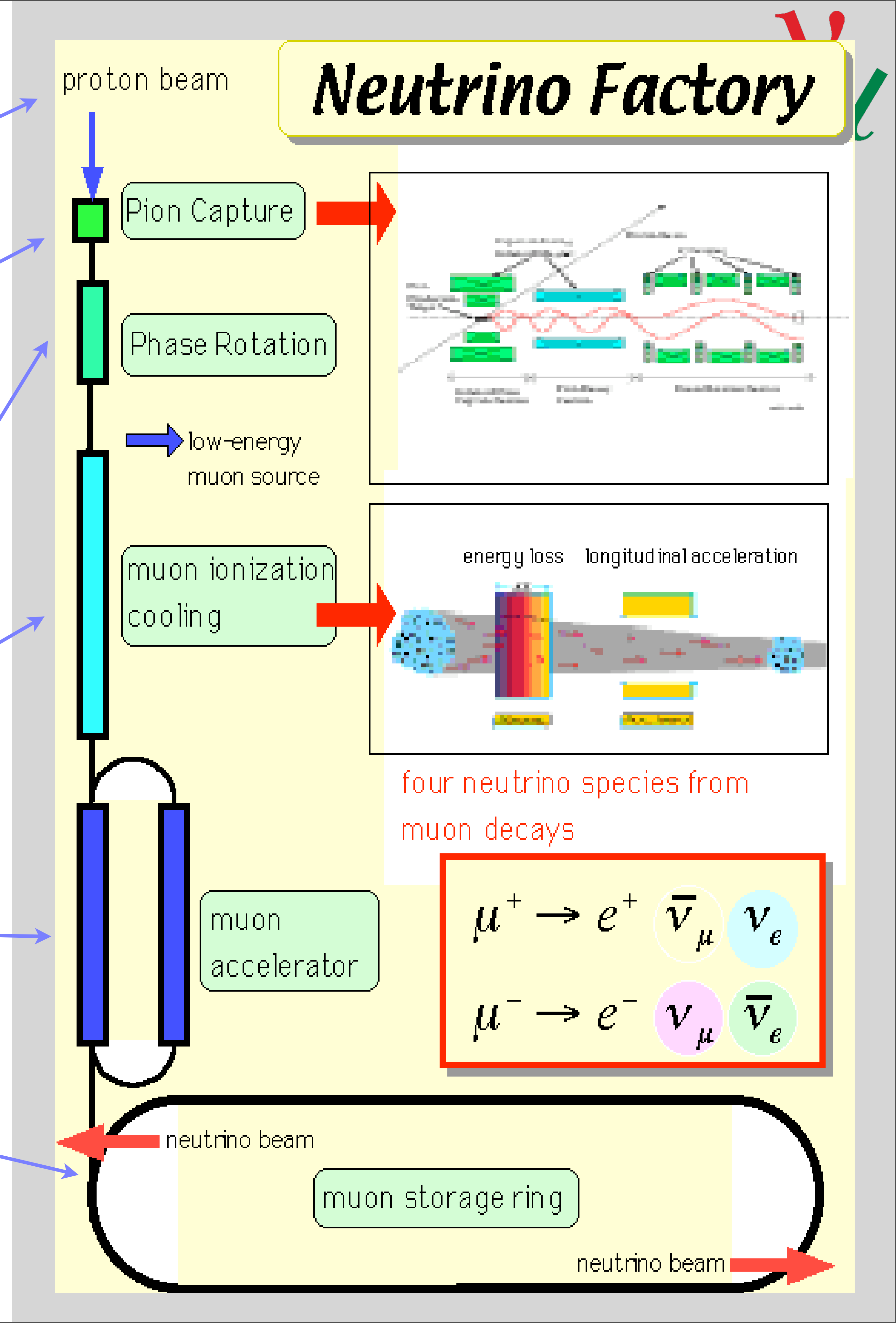
Outline of the Third Lecture

- Neutrino Factory Complex (How it looks like ?)
- Betabeam
- New Physics at Neutrino Factory
- Summary

Neutrino Factory Complex

Neutrino Factory Components

- Proton Driver
  - 1 - 4 MW beam power
- Pion Capture
  - high acceptance
- Phase Rotation and bunching
  - narrow energy spread
- Muon Ionization Cooling
  - reduce beam emittance
- Muon Acceleration
  - accelerate muons
- Muon Storage Ring
  - store muons till decay

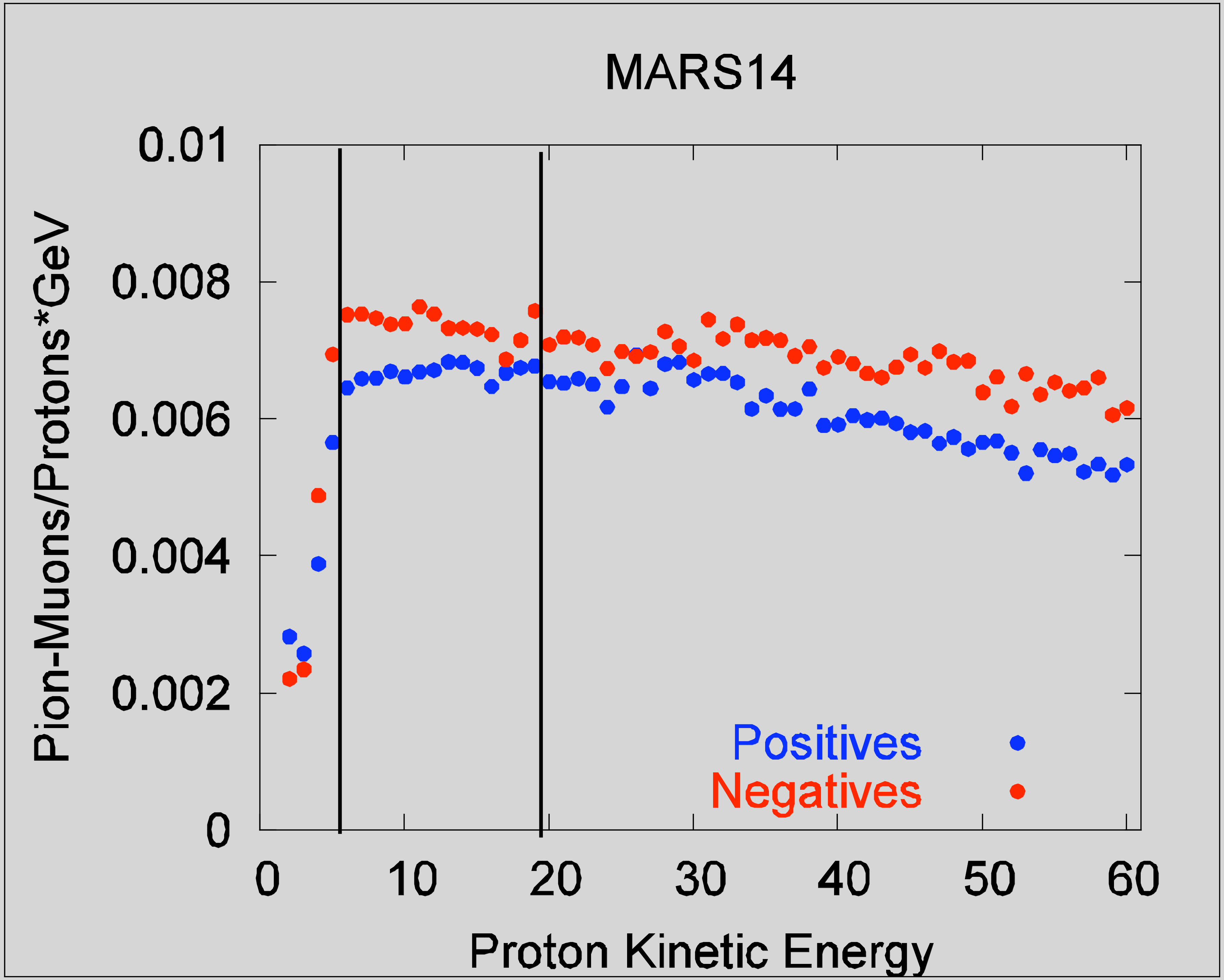


Proton Drivers

- 1 - 4 MW proton beam power is needed.
  - only beam power matters.
  - Proton energy is not important (next slide), but 5-15 (10) GeV would be the best.

- Considerations
  - slow repetition rate with many protons in each pulse (0.1 - 1 Hz).
  - high repetition with less protons in each pulse. (10-100 Hz)

- Options
  - 200 MeV Linac + 3 GeV Booster synchrotron + Proton FFAG (10 GeV)
  - 8 GeV Fermilab superconducting LINAC (20 Hz upgrade) + accumulator buncher
  - SPL at CERN (50 Hz) + accumulator/buncher
  - others (BNL, Japan, etc.)



Optimum proton energy for high-Z target is broad, but drops at low-energy

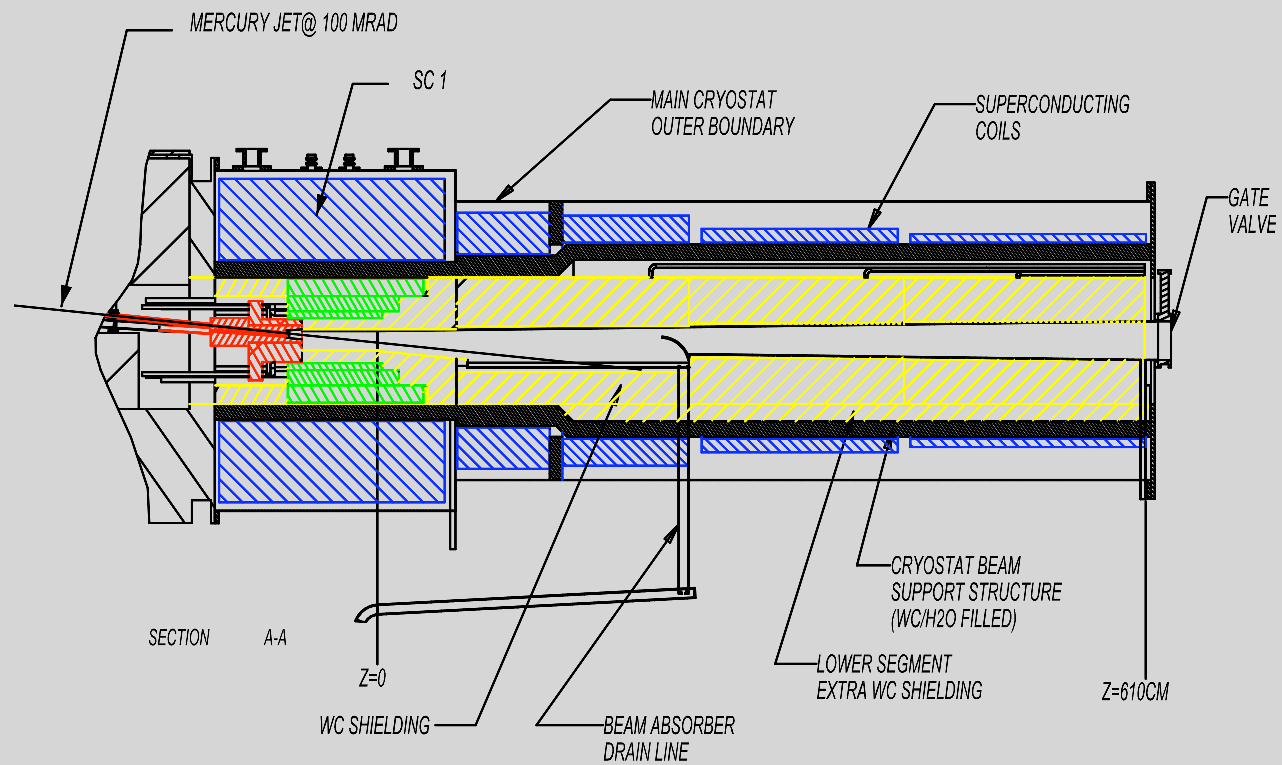
Optimum Proton Energy

Simulation by MARS14

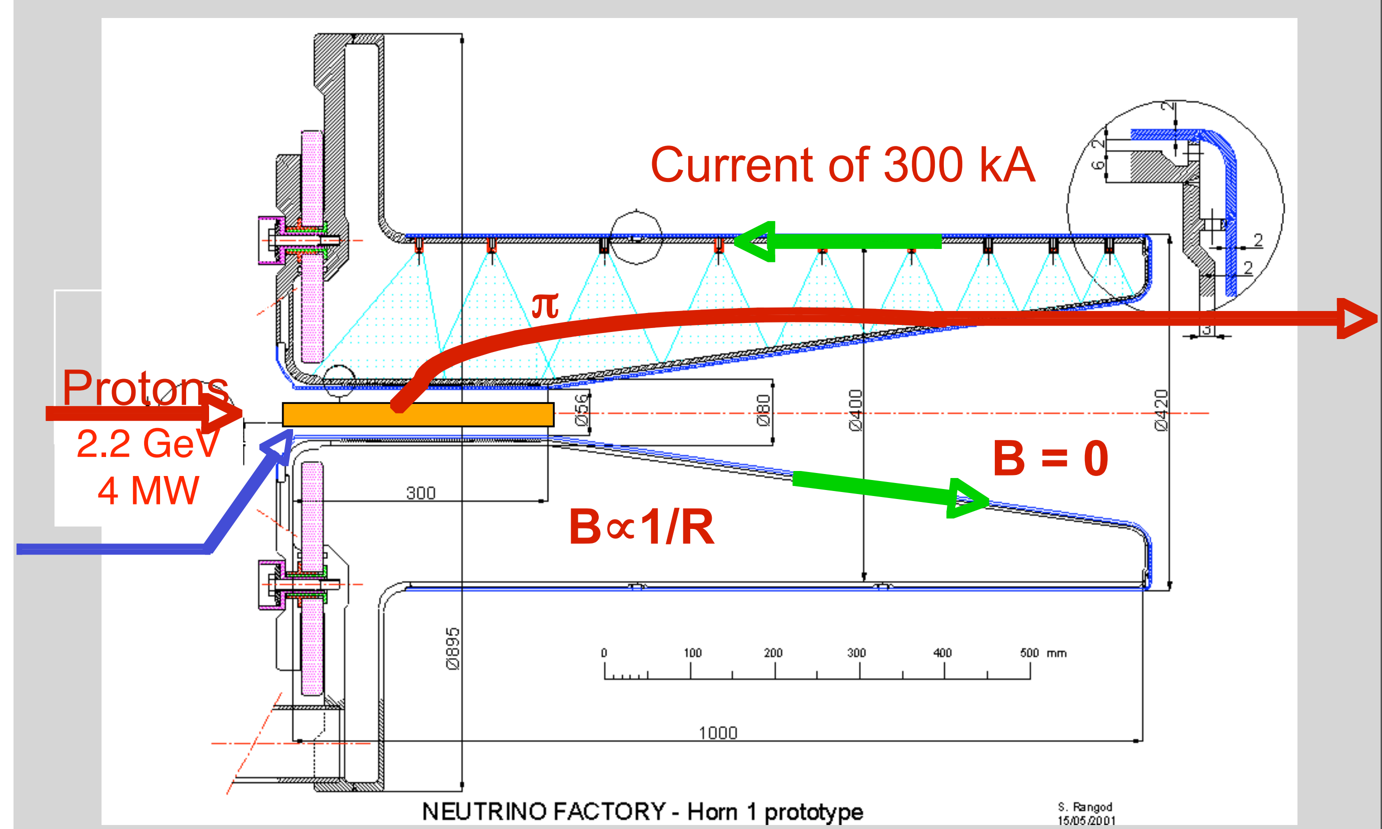
Target and Pion Capture

- Achieve highly intense muon beam by maximizing pion production and collecting as many of them as possible.
  - soft pion production
  - high Z material
  - sustain high beam power (1-4 MW)
- Neutrino Factory Concept
  - Liquid mercury target ?
  - Pion capture system
    - 20 T superconducting magnet.
    - Magnetic horn system

solenoid capture (US,Japan)

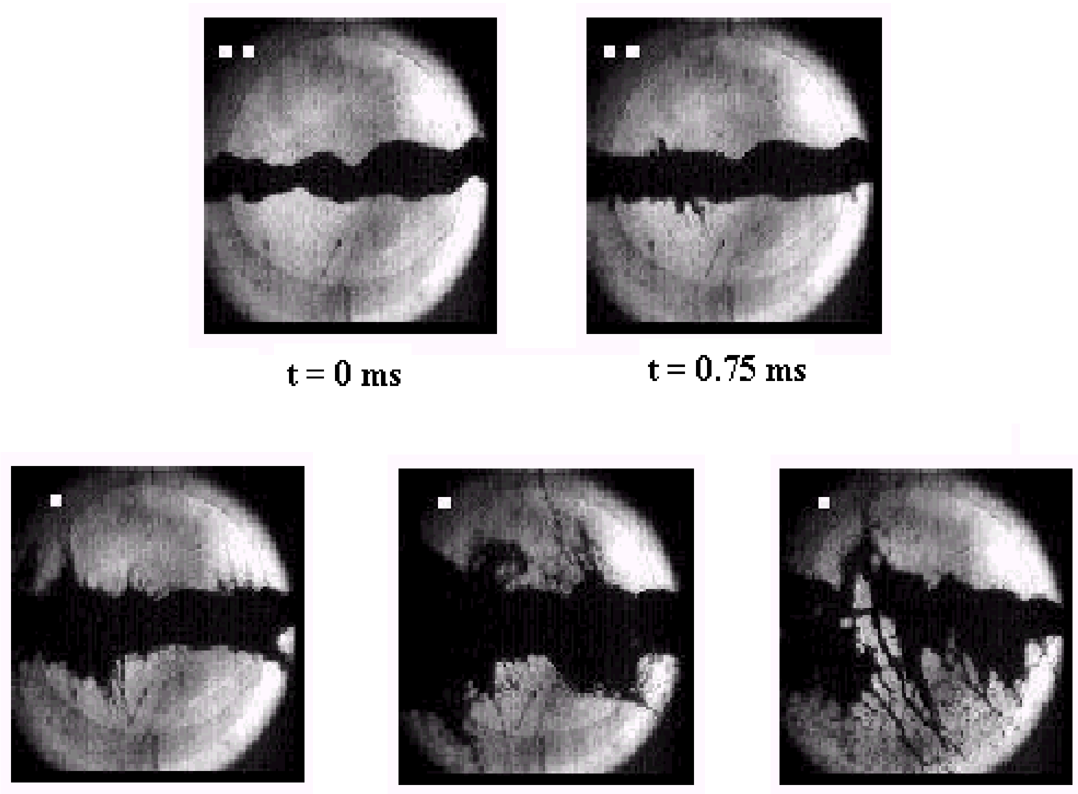


horn capture (EU)



BNL E951 Hg Jet Tests

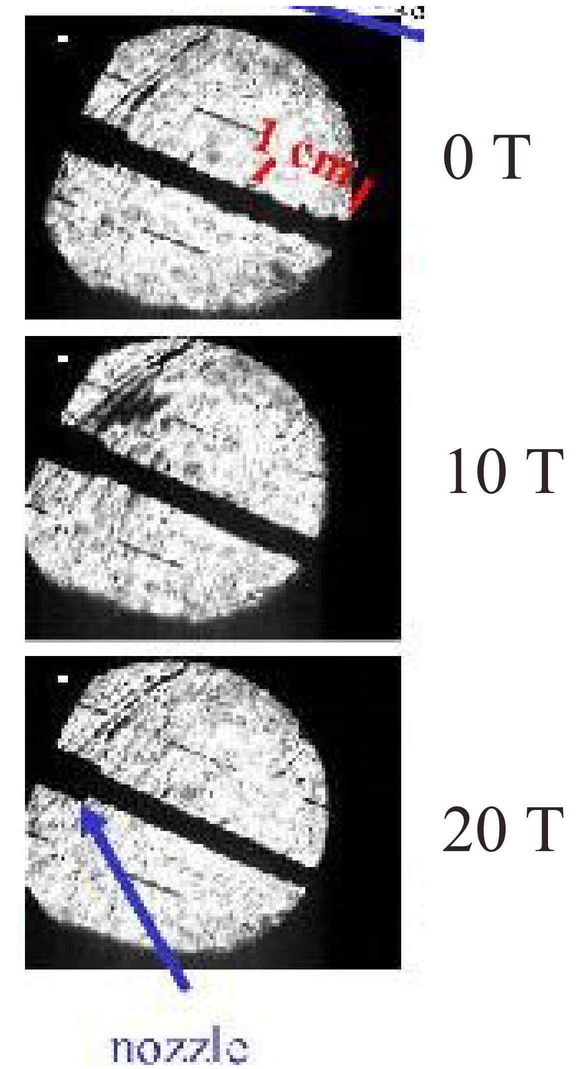
- 1cm diameter Hg Jet
- V = 2.5 m/s
- 24 GeV 4 TP Proton Beam
- No Magnetic Field



t = 0 ms, t = 0.75 ms, t = 2 ms, t = 7 ms, t = 18 ms

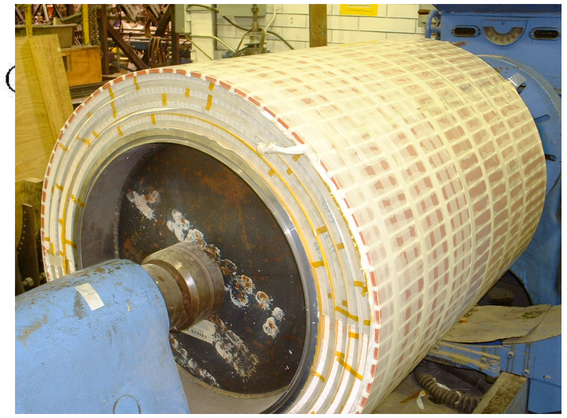
CERN/Grenoble Hg Jet Tests

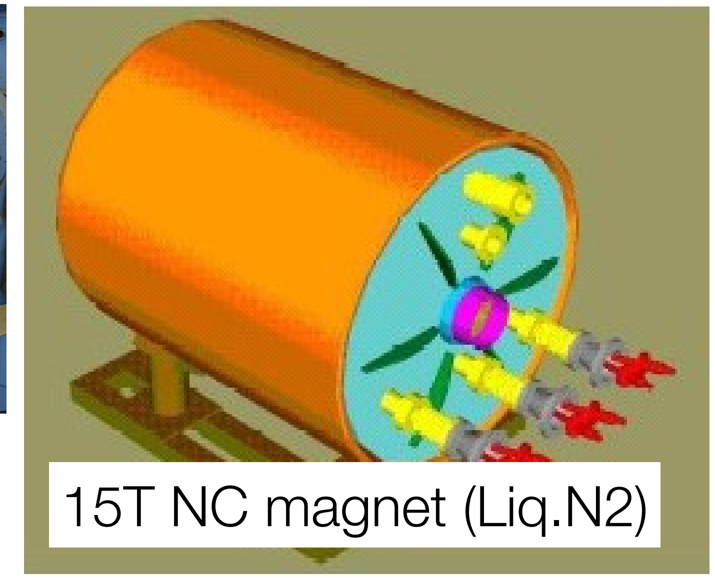
- 4 mm diameter Hg Jet
- v = 12 m/s
- No Proton Beam



Liquid Mercury Tests

A Proposal to
the ISOLDE and Neutron Time-of-Flight Experiments Committee

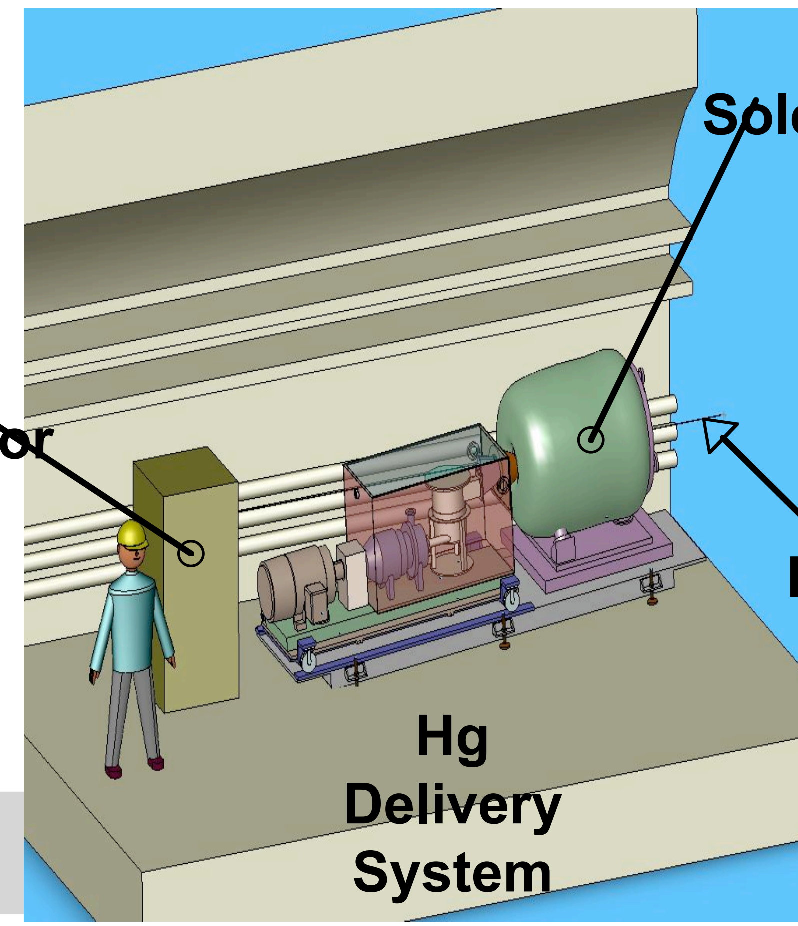




Studies of a Target System for a 4-MW, 24-GeV Proton Beam

J. Roger J. Bennett[1], Luca Bruno[2], Chris J. Densham[1], Paul V. Drumm[1],
T. Robert Edgecock[1], Tony A. Gabriel[3], John R. Haines[3], Helmut Haseroth[2],
Yoshinari Hayato[4], Steven J. Kahn[5], Jacques Lettry[2], Changguo Lu[6], Hans Ludewig[5],
Harold G. Kirk[5], Kirk T. McDonald[6], Robert B. Palmer[5], Yarema Prykarpatskyy[5],
Nicholas Simos[5], Roman V. Samulyak[5], Peter H. Thieberger[5], Koji Yoshimura[4]

Spokespersons: H.G. Kirk, K.T. McDonald
Local Contact: H. Haseroth

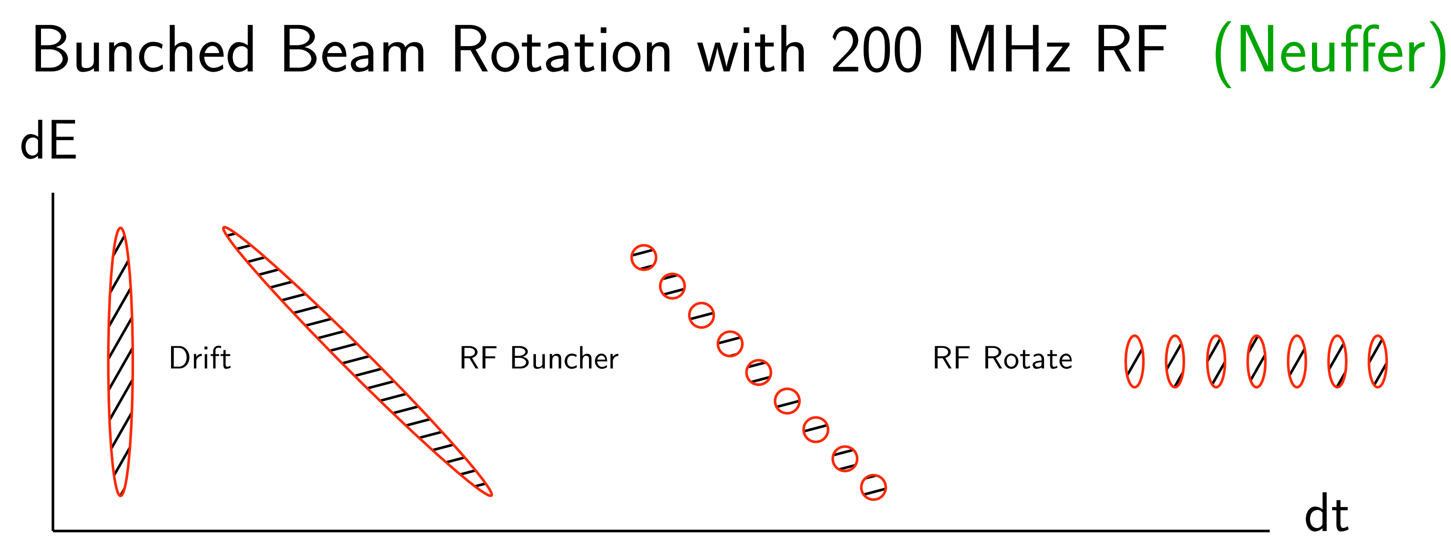


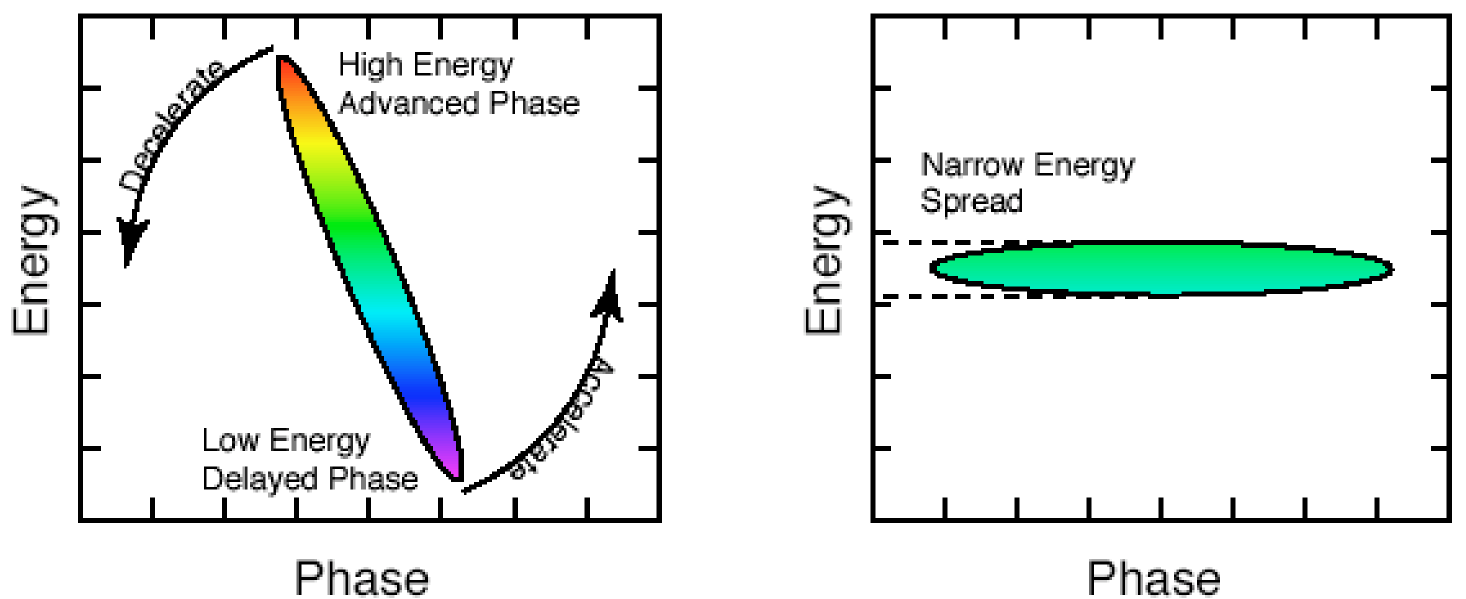
MERIT Experiment at CERN

n-TOF beam line at CERN (nTOF11)

Bunching and Phase Rotation

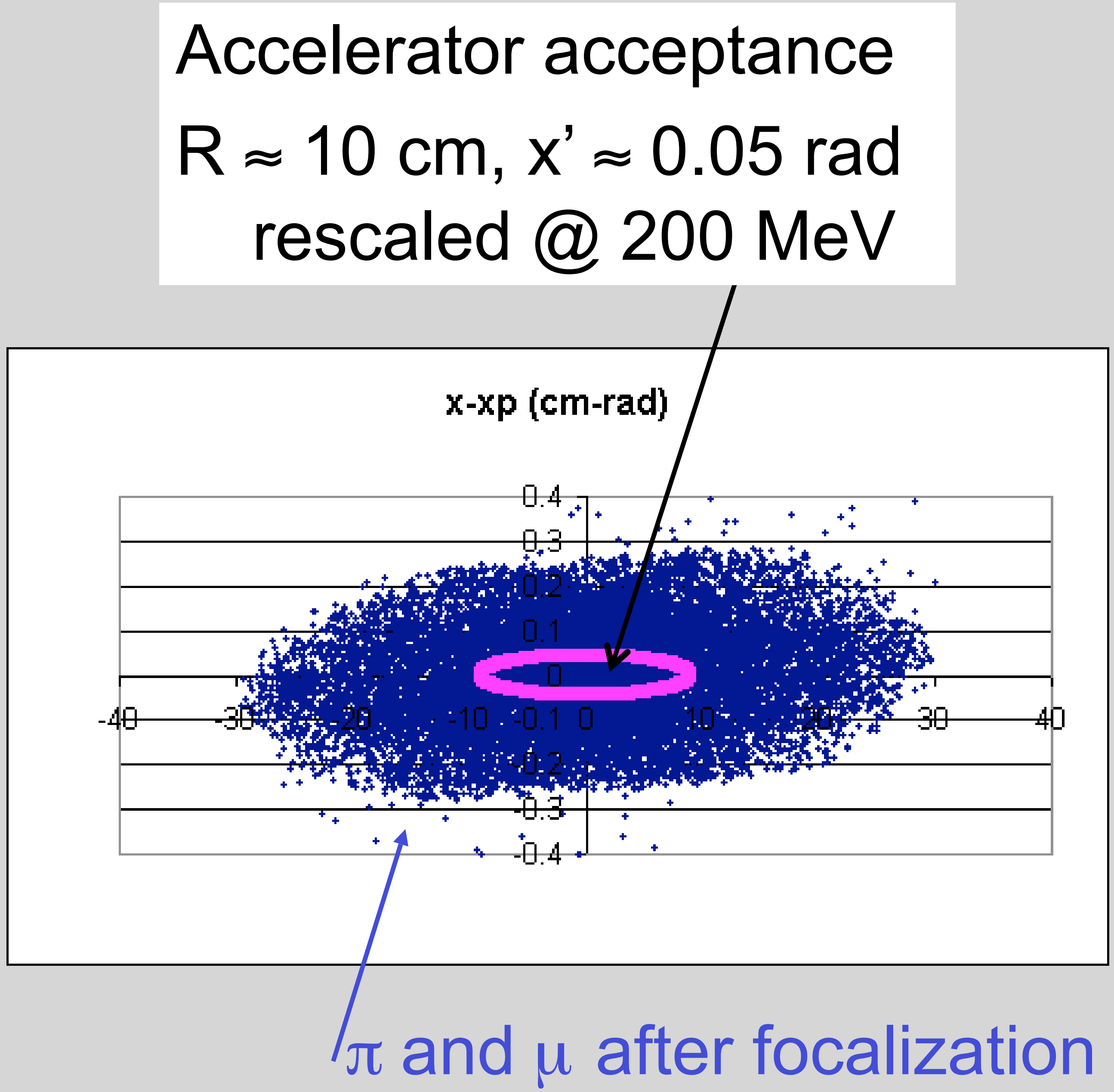
- bunching to fit in an RF system (200 MHz?).
  - originally muon beam spread longitudinally due to different energy.
- Phase rotation : accelerate slow muons and decelerate fast muons to align muon beam energy.





Reduction of Beam Emittance (Cooling)

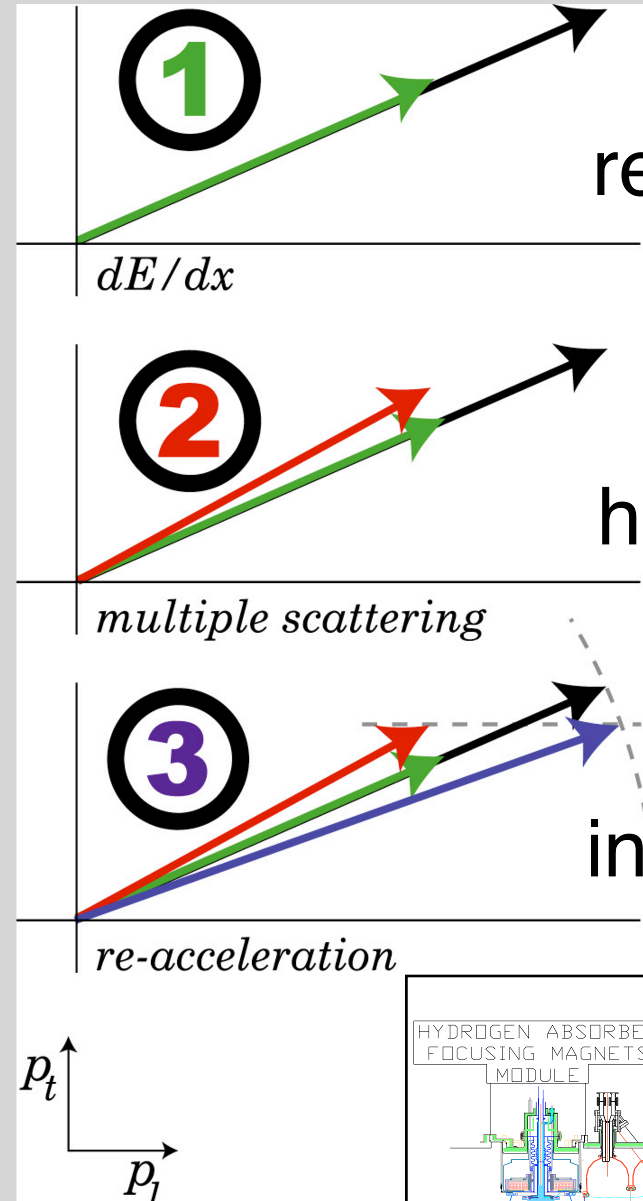
- Emittance = a volume in phase space occupied by beam particles
  - for transverse $(x, \frac{dx}{dz}, y, \frac{dy}{dz})$
- Reduce the muon beam emittance so that as many muons as possible can be accepted in the accelerators following. (Cooling)



Ionization Cooling

- Ordinary cooling (Stochastic cooling etc.) is too slow. A novel method for muons are needed.
- ionization cooling system consists of degraders (absorber) and accelerating RF cavities.
- to minimize heating, degrader should have large radiation length (X_0) and focusing system make the beta function small.

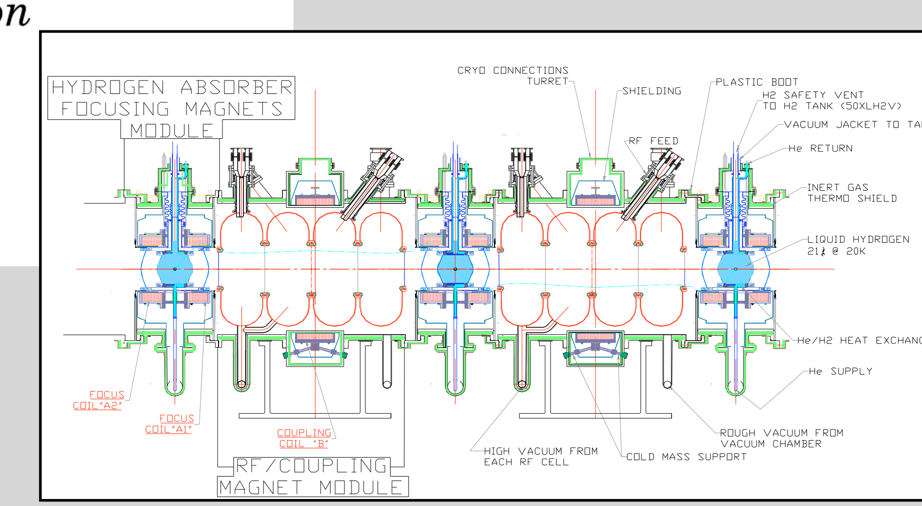
principle



reduce p_t and p_l

heating

increase p_l

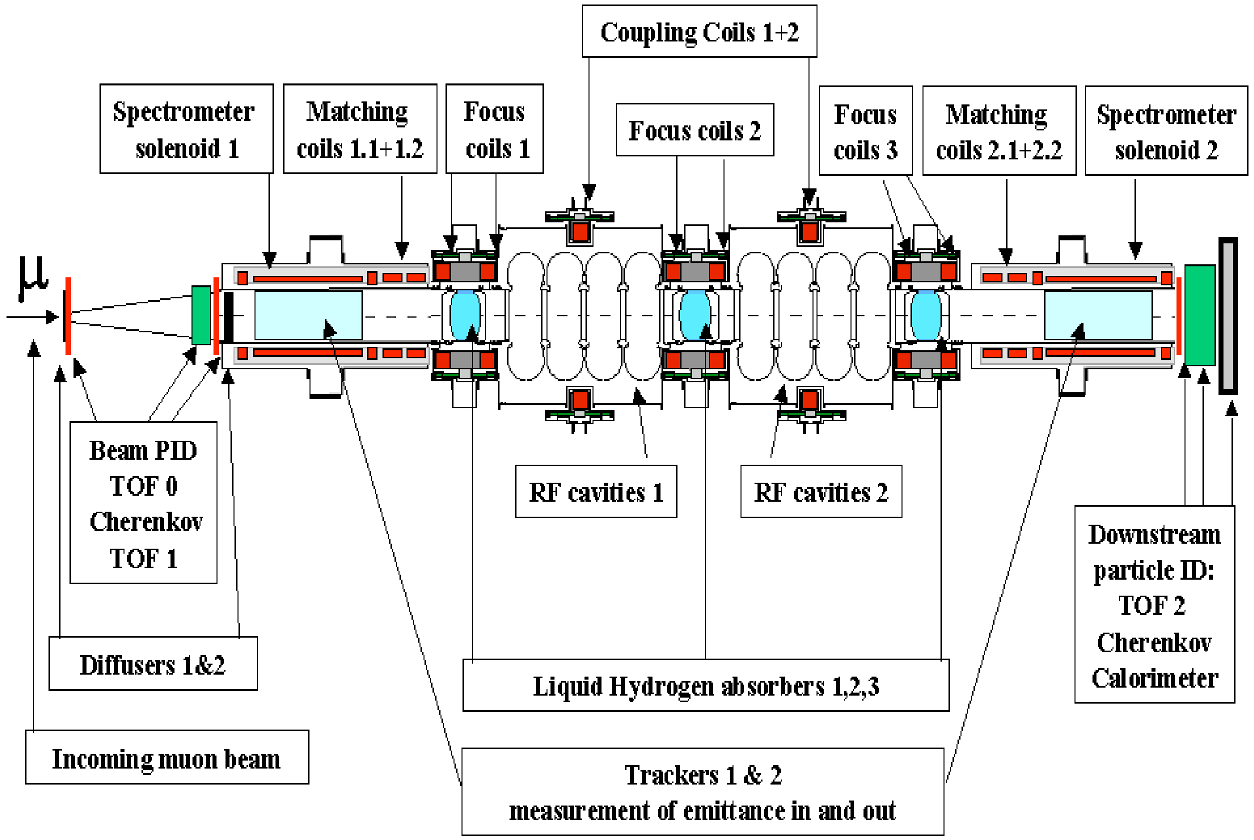


$$\frac{d\varepsilon_n}{ds} = -\frac{1}{\beta^2}\left\langle \frac{dE_\mu}{ds} \right\rangle \frac{\varepsilon_n}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp (0.014)^2}{2E_\mu m_\mu X_0}$$

cooling heating

MICE - Ionization Cooling Demonstration

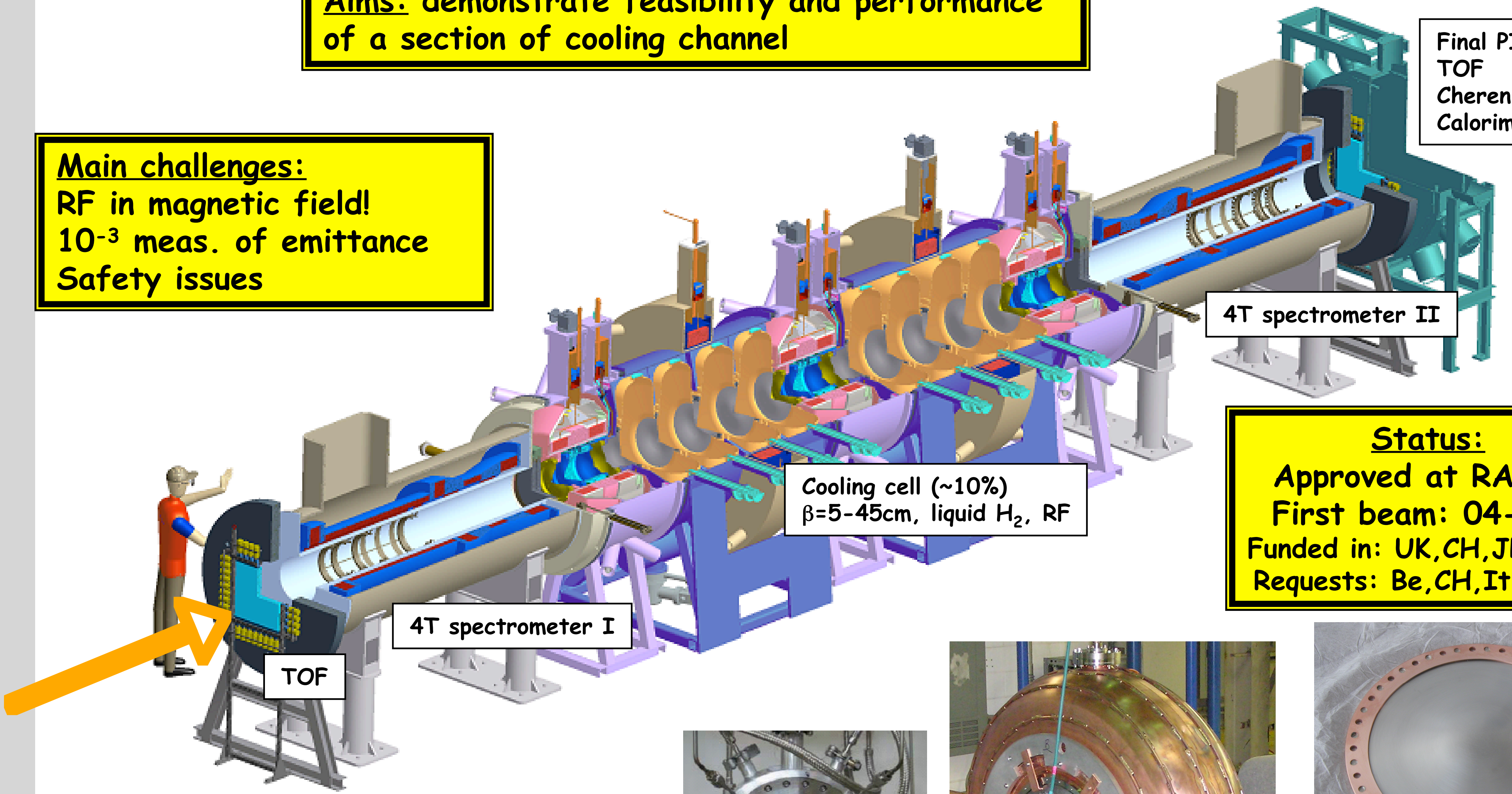
- MICE (= Muon Ionization Cooling Experiment) to demonstrate the principle of ionization cooling.
- Building a section of cooling channel to demonstrate the principle of ionization cooling
- measure : transverse emittance reduction of 10 % with 1 % relative accuracy
- method : single particle measurement (since no ordinary method of emittance measurements available.)
  - measure track parameters before and after cooling channels
- Integration of accelerator and particle physicists.



MICE at RAL

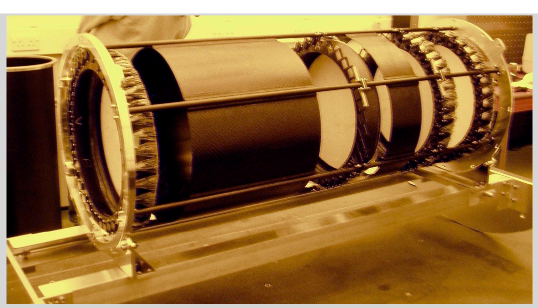
Aims: demonstrate feasibility and performance of a section of cooling channel

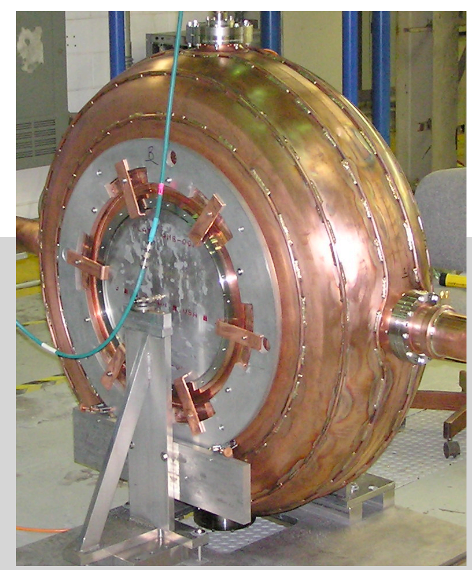
Main challenges:
RF in magnetic field!
10^{-3} meas. of emittance
Safety issues



Status:
Approved at RAL(UK)
First beam: 04-2007
Funded in: UK,CH,JP,NL,US
Requests: Be,CH,It,JP,US

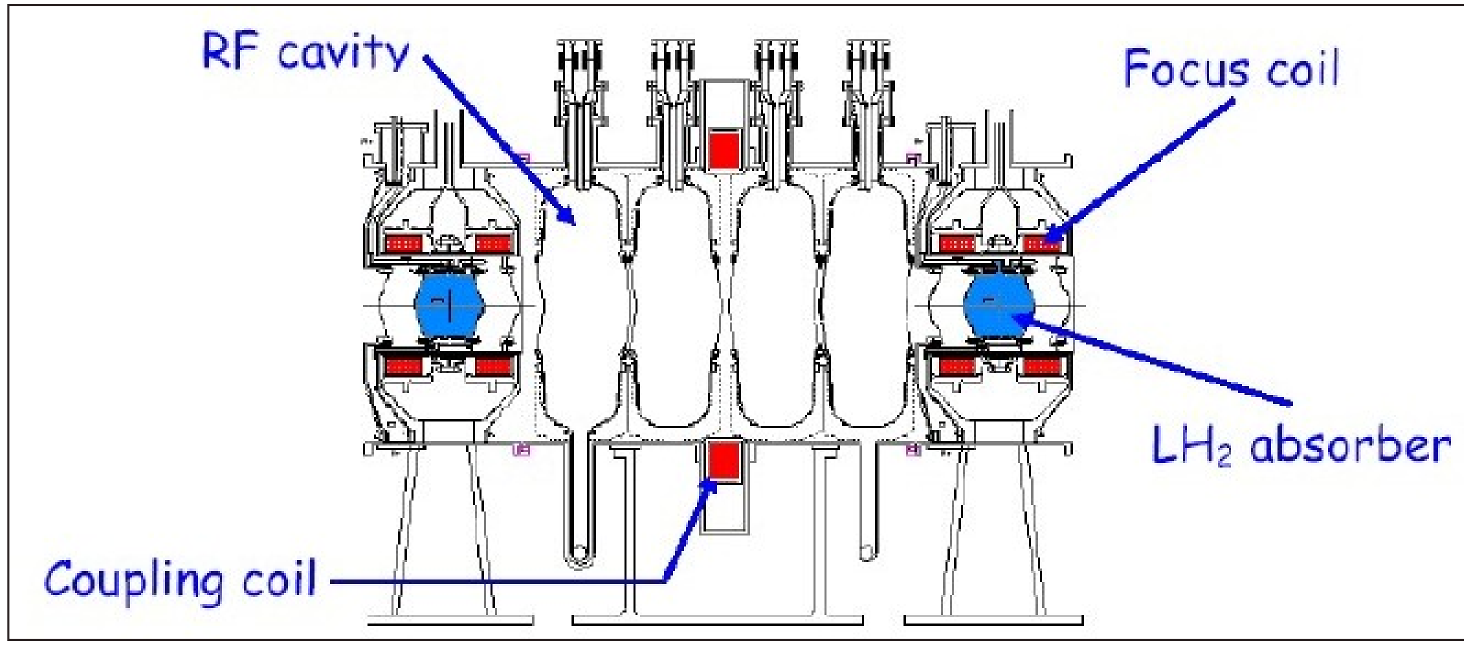
Single-μ beam
~200 MeV/c





Ionization Cooling - MUCOOL

New MUCOOL Test Area Completed – FNAL



LH2 Absorber Cryostat – KEK

Thin absorber windows Tested – new technique – ICAR Universities

201 MHz half-shell ebeam welding of Stiffening – JLab

5T Cooling Channel Solenoid – LBNL & Open Cell NCRF Cavity operated at Lab G – FNAL

MUCOOL at Fermilab

Acceleration

- Rapid Acceleration (to 20-50 GeV) is needed.
  - synchrotron not work.
- Options
  1. Scaling FFAG (Fixed Field Alternating Gradient) accelerator
     - Japanese design
  2. Non-Scaling FFAG
     - US Study 2A
  3. RLA (Recirculating Linear Accelerator)
     - racetrack or dogbone type
     - US Study 2

Scaling FFAG

Non-Scaling FFAG

RLA

Acceleration

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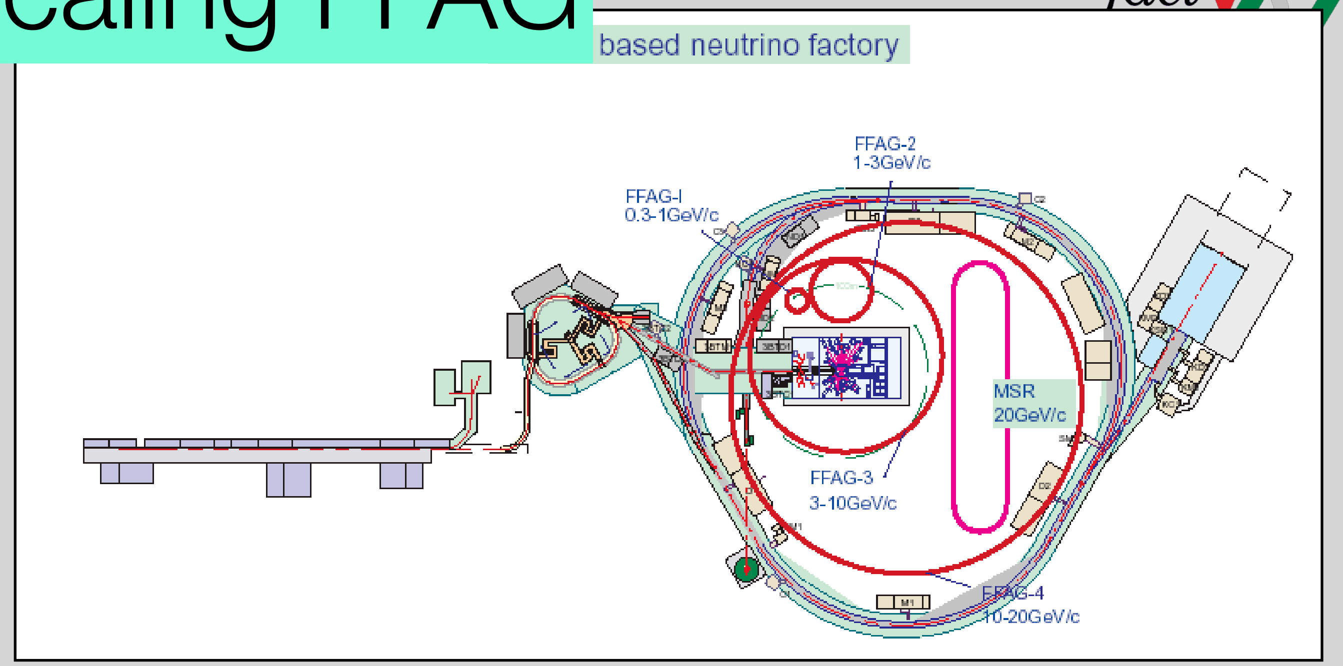
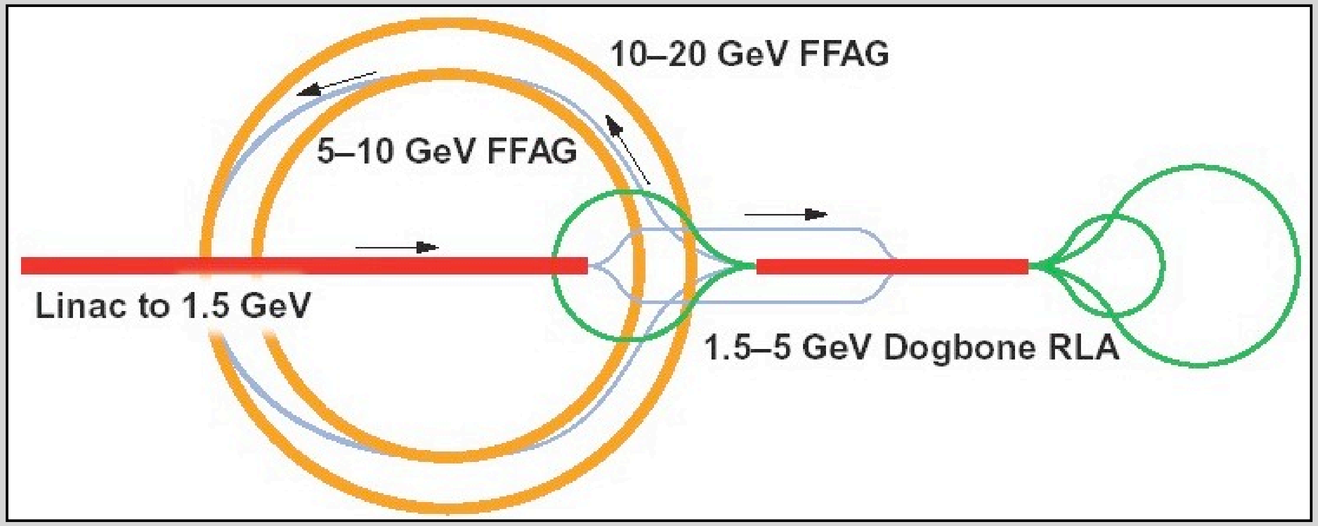
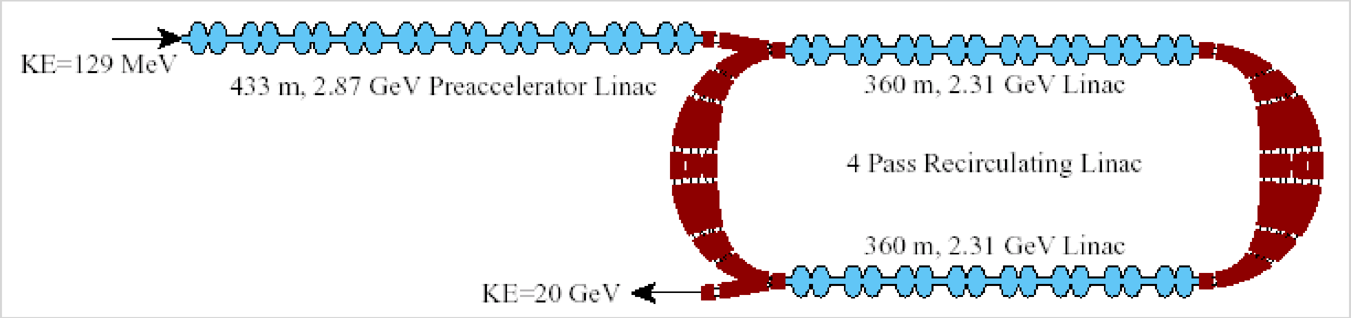
Scaling FFAG



Non-Scaling FFAG



RLA



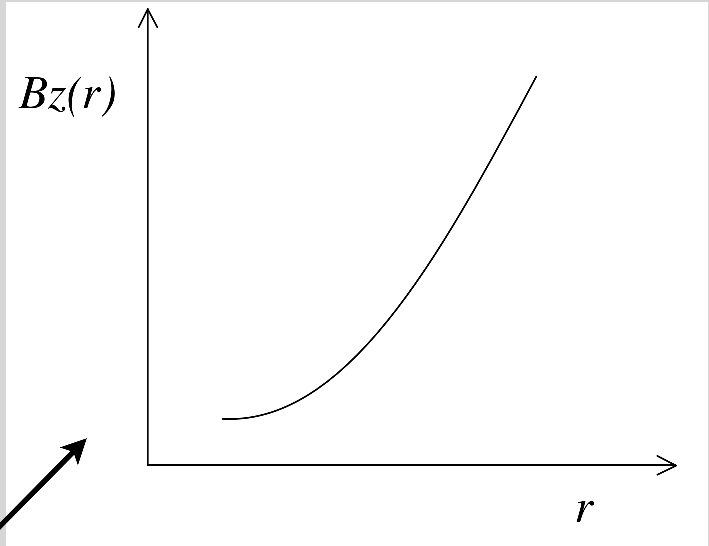
What is a FFAG accelerator ?

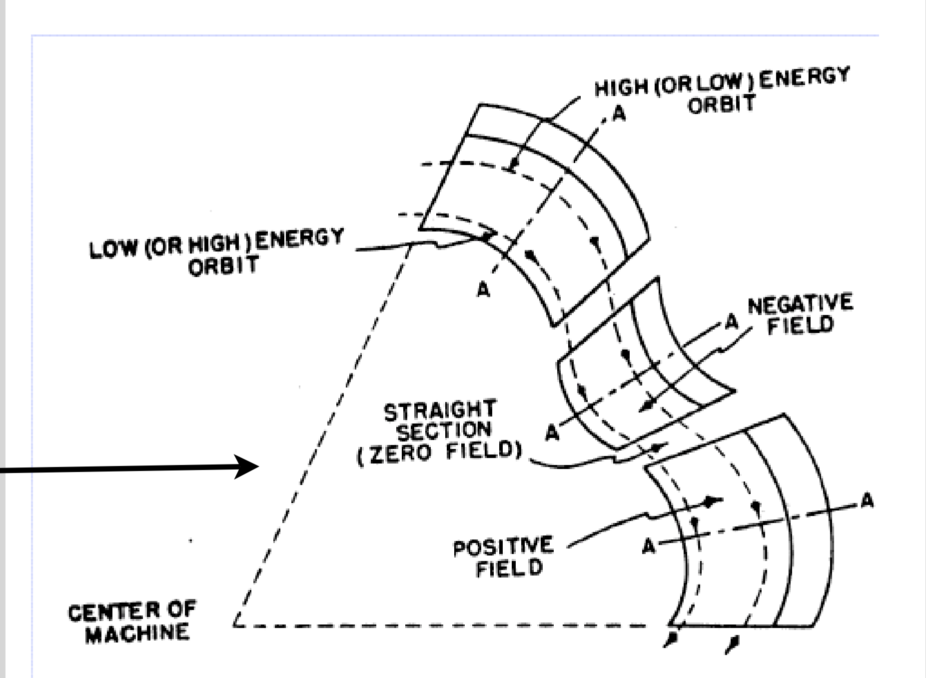
Fixed Field Alternating Gradient synchrotron

- Scaling FFAG
  - quick acceleration due to a fixed magnetic field
  - non-uniform magnetic field

$$B(r) = B_0\left(\frac{r}{r_0}\right)^k \quad (k = 2 \sim 10)$$

  - alternating focus-bending and defocus-bending would provide strong beam focusing
  - large transverse acceptance
  - large longitudinal acceptance
  - invented by C. Okawa in 1950



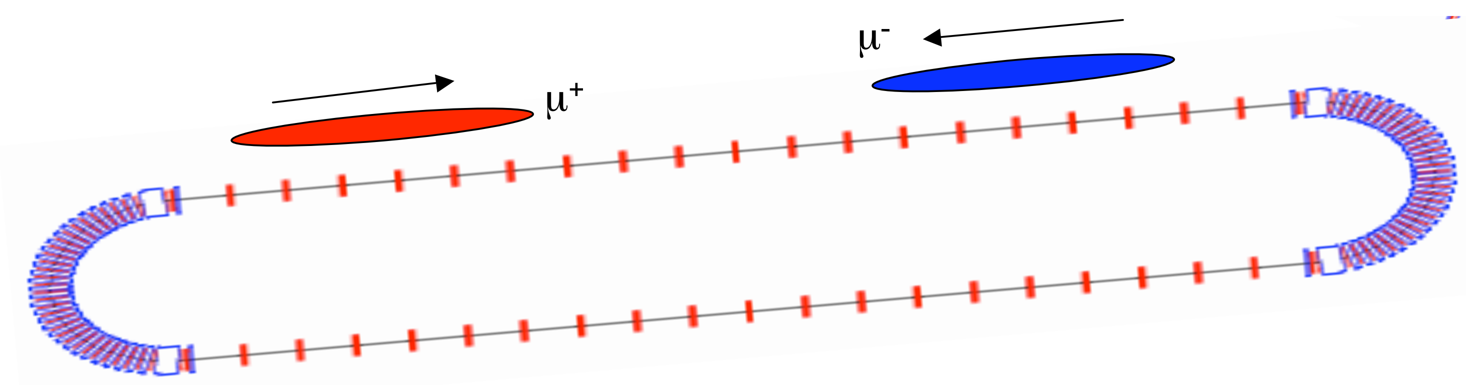


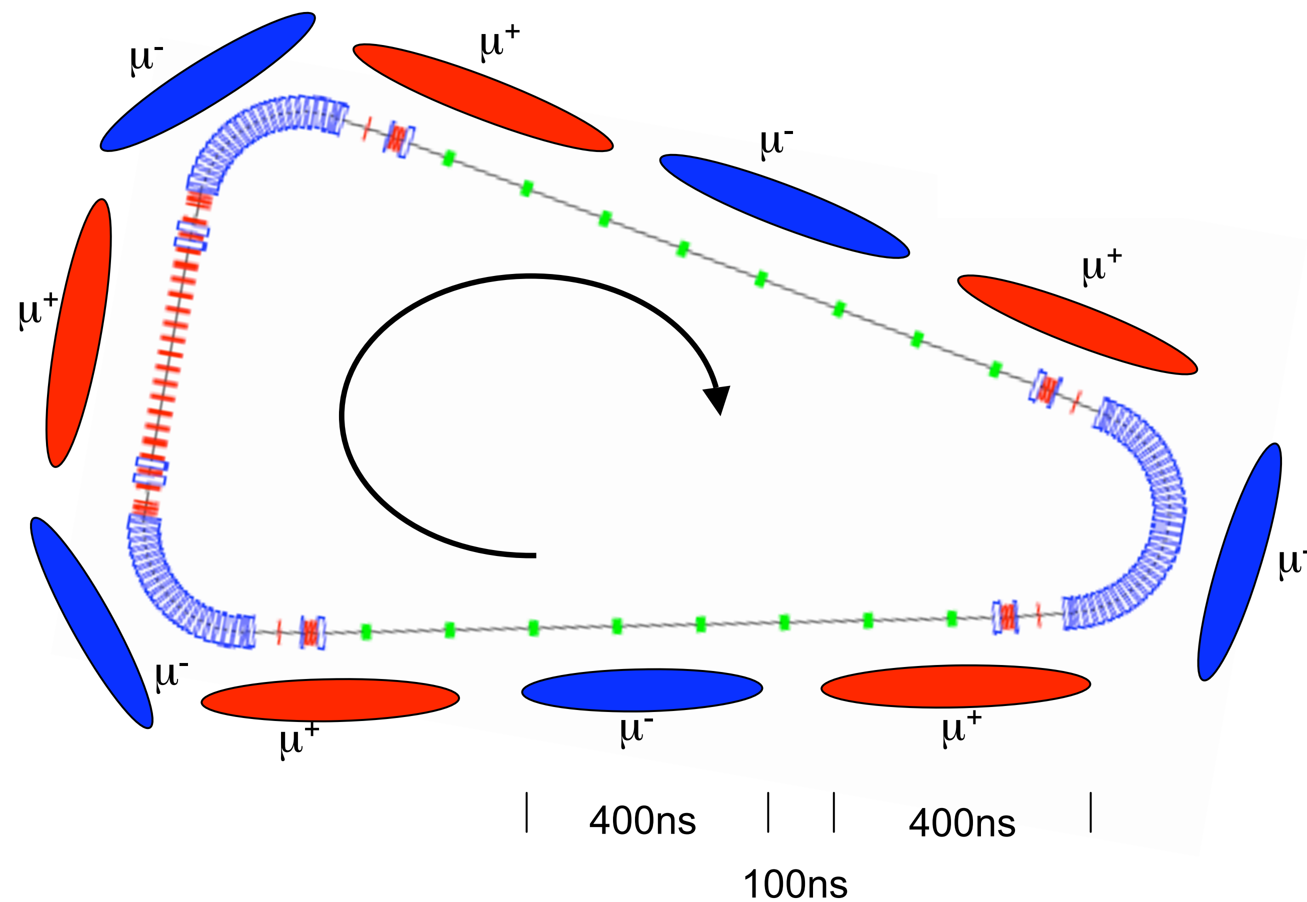
0.5-MeV Proton FFAG POP at KEK

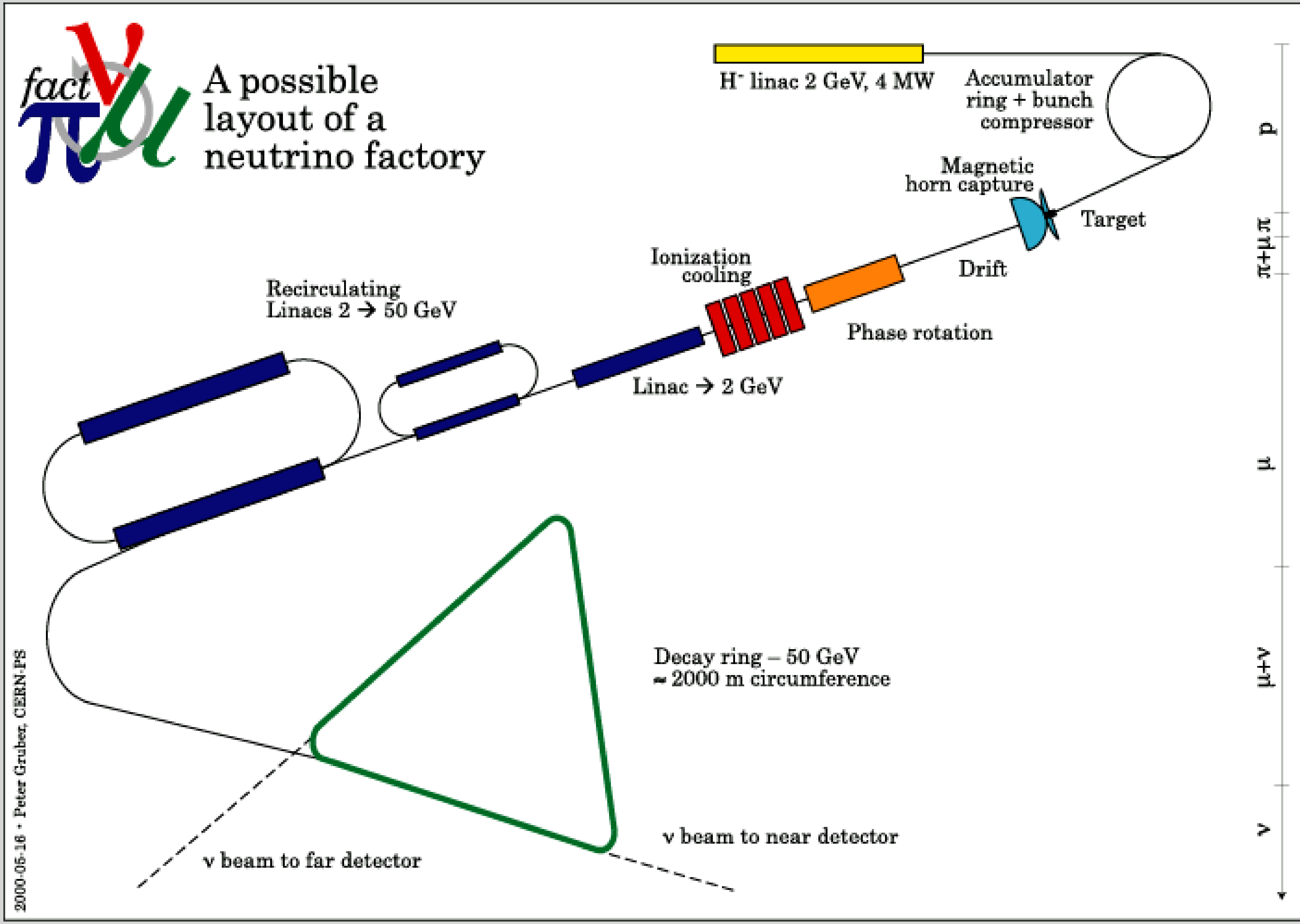
150-MeV Proton FFAG Under construction at KEK

Storage Ring

- Triangle Ring
  - more fraction of straight sections (up tp 48 %), but less flexibility
  - two rings in single tunnel
- Racetrack Ring
  - less fraction of straight section (up to 38 %), but more flexibility to beam directions.
  - one rings in two tunnels.
- Both signed muons are circulated with timing discrimination.
- Dependent on accelerator and detector locations.





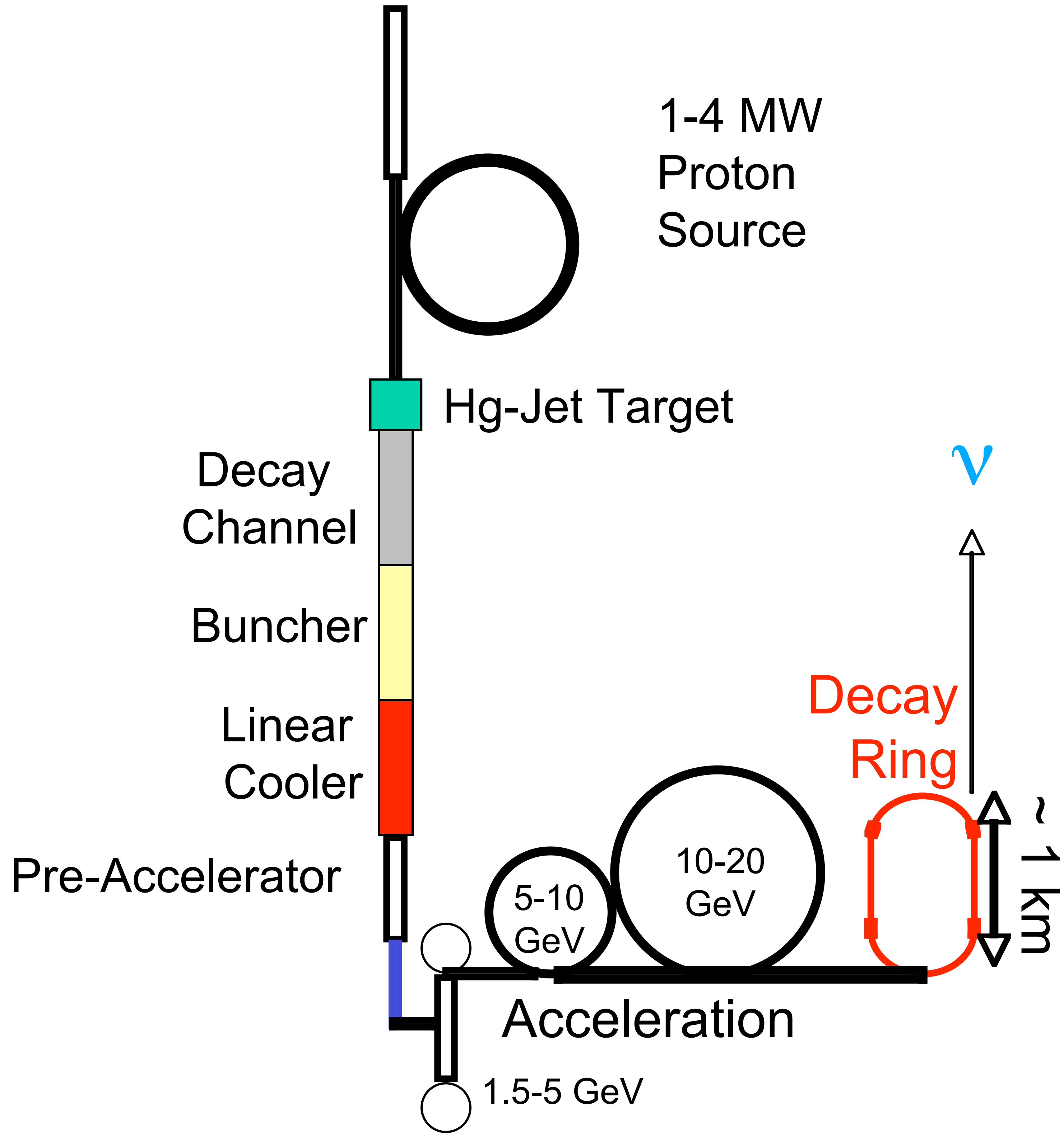


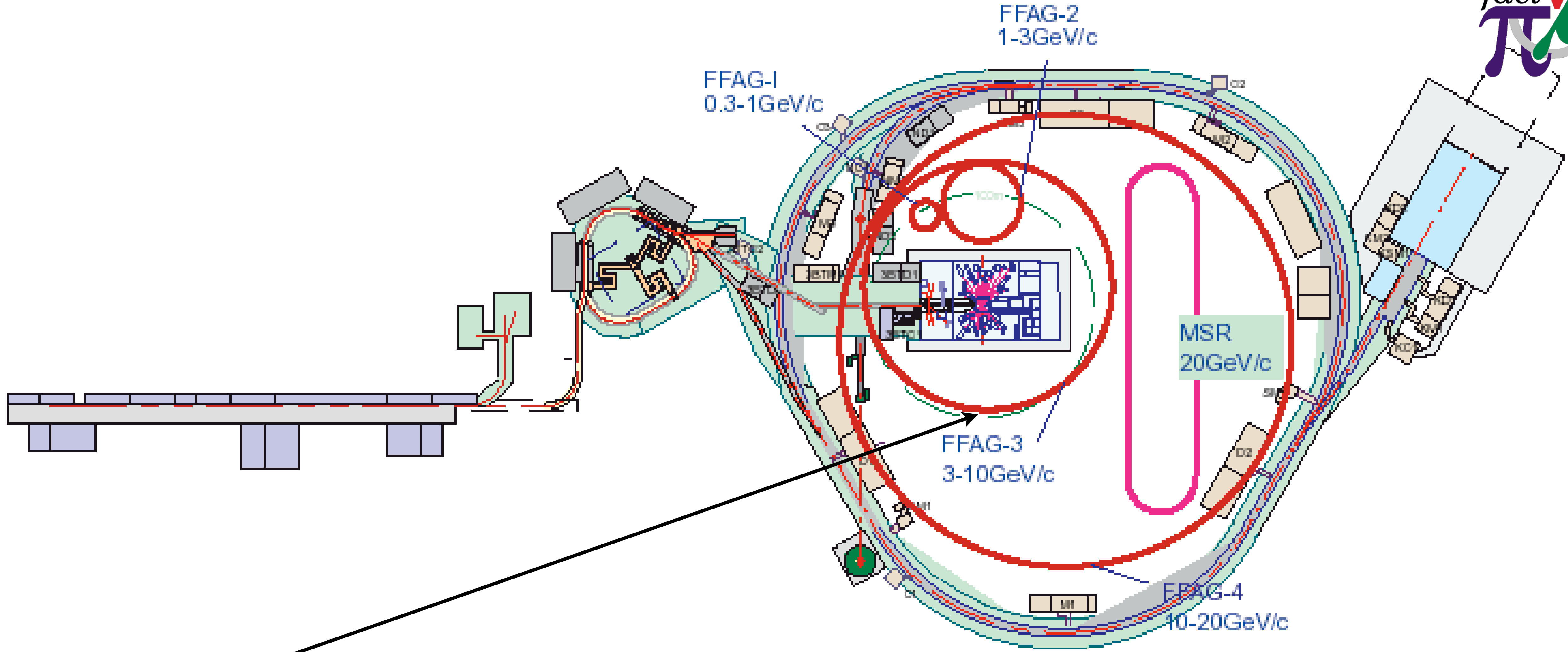
Neutrino Factory

CERN Layout

US Neutrino Factory

- Proton Driver
  - primary beam on production target
- Target, Capture, Decay
  - capture pions, which decay into muons.
- Bunching, Phase Rotation
  - reduce energy spread of bunch
- Cooling
  - reduce transverse momentum
- Acceleration
  - from 200 MeV to 20-50 GeV
- Decay Ring
  - store for about 500 turns
  - long straight sections





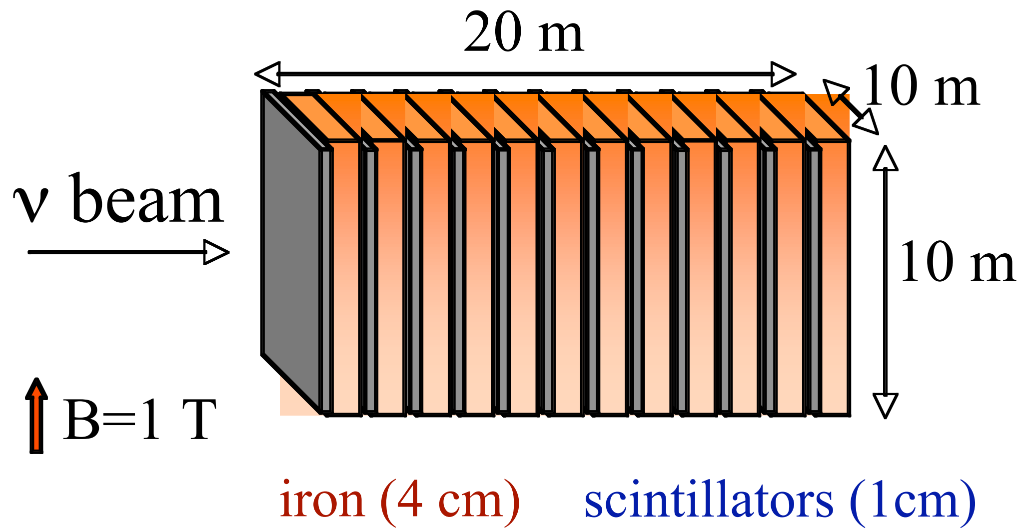
4 FFAG rings + storage ring (no cooling)

Neutrino Factory at J-PARC

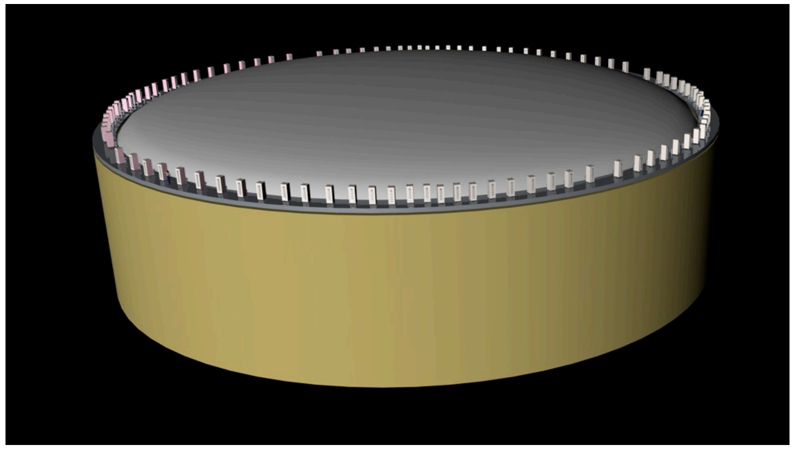
FFAG-based Scenario

Neutrino Factory Detector Options

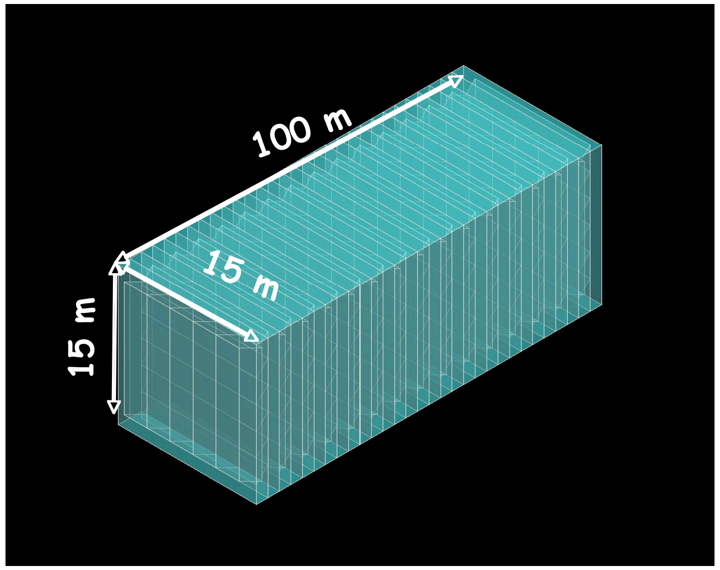
- Segmented Magnetized Detector



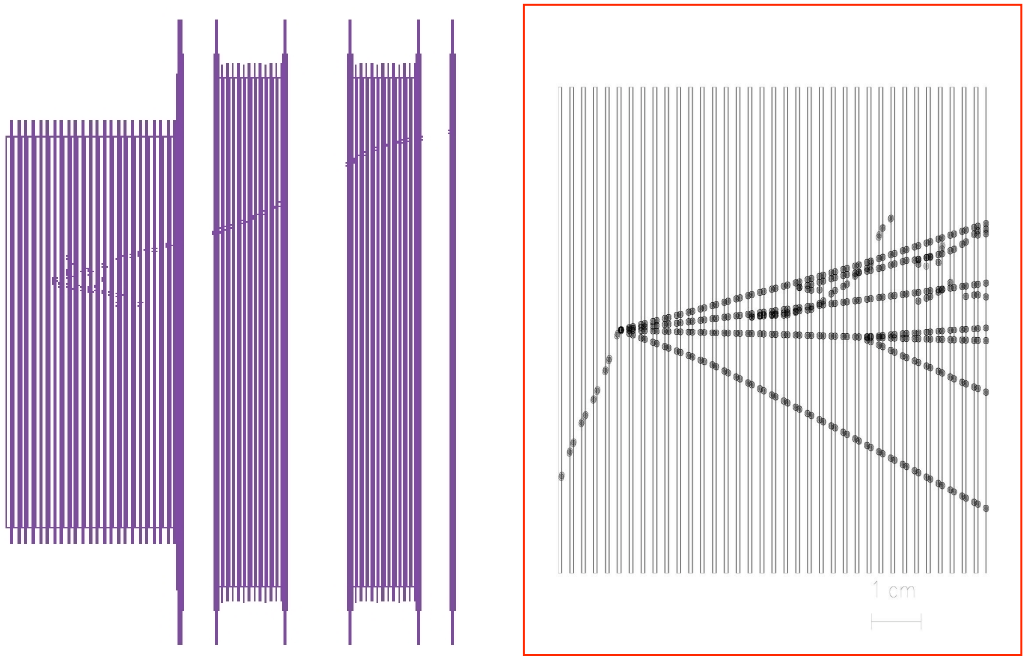
- Liquid Ar Detector



- Totally Active Scintillator Detector



- Emulsion Detector



Beta Beam

What Is a Beta Beam ?

- The "Beta beam" is a future neutrino facility which produce pure and intense (anti) electron neutrino beams, by accelerating radioactive ions and storing them in a decay ring.
- Proposed by Piero Zucchelli
  - Phys. Lett. B532 (2002) 166 - 172.
- Advantages :
  - Energy distribution and normalization of neutrinos can be well known.
  - When radioactive ions with a long lifetime (~sec) are selected, conventional accelerators, not rapid accelerators, can be used.
- EURISOL
  - EURISOL is a project to aim a next-generation facility for on-line production of radioactive isotopes),
  - Beta Beam Design Study is a part of EURISOL Design Study,

Ion Choice for Beta Beam

- Considerations
  - need to produce reasonable amounts of ions.
  - not too short lifetime to get reasonable intensities.
  - not too long lifetime otherwise no decays at high energy.

Electron Anti-neutrinos

$$^{6}_{2}He \rightarrow ^{6}_{3}Li + e^{-} + \bar{\nu}_e$$

average energy = 1.94 MeV

lifetime =

Electron Neutrinos

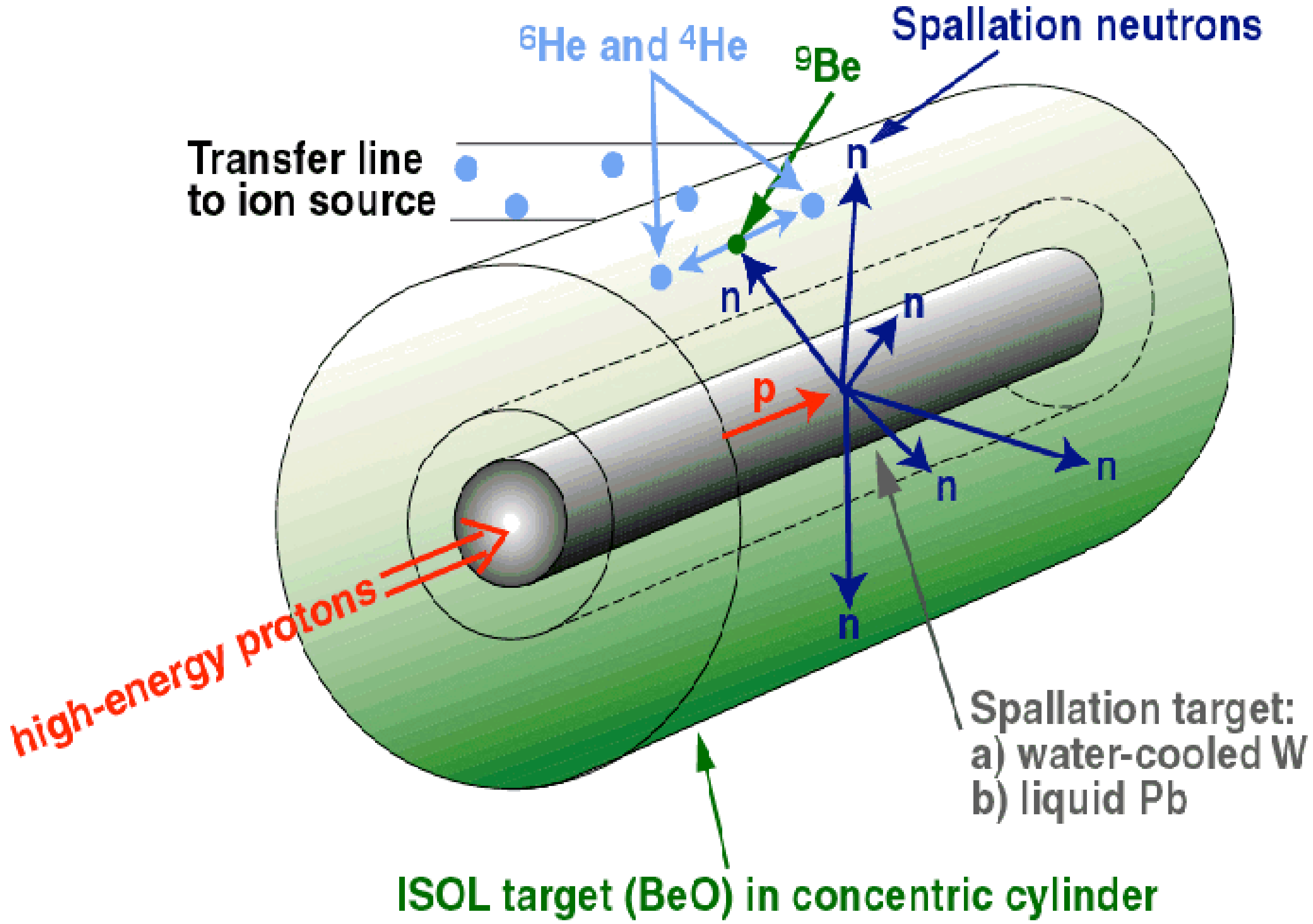
$$^{18}_{10}Ne \rightarrow ^{18}_{9}F + e^{+} + \nu_e$$

average energy = 1.86 MeV

lifetime =

^{6}He Production from ^{9}Be
^{18}Ne Production from Mg0

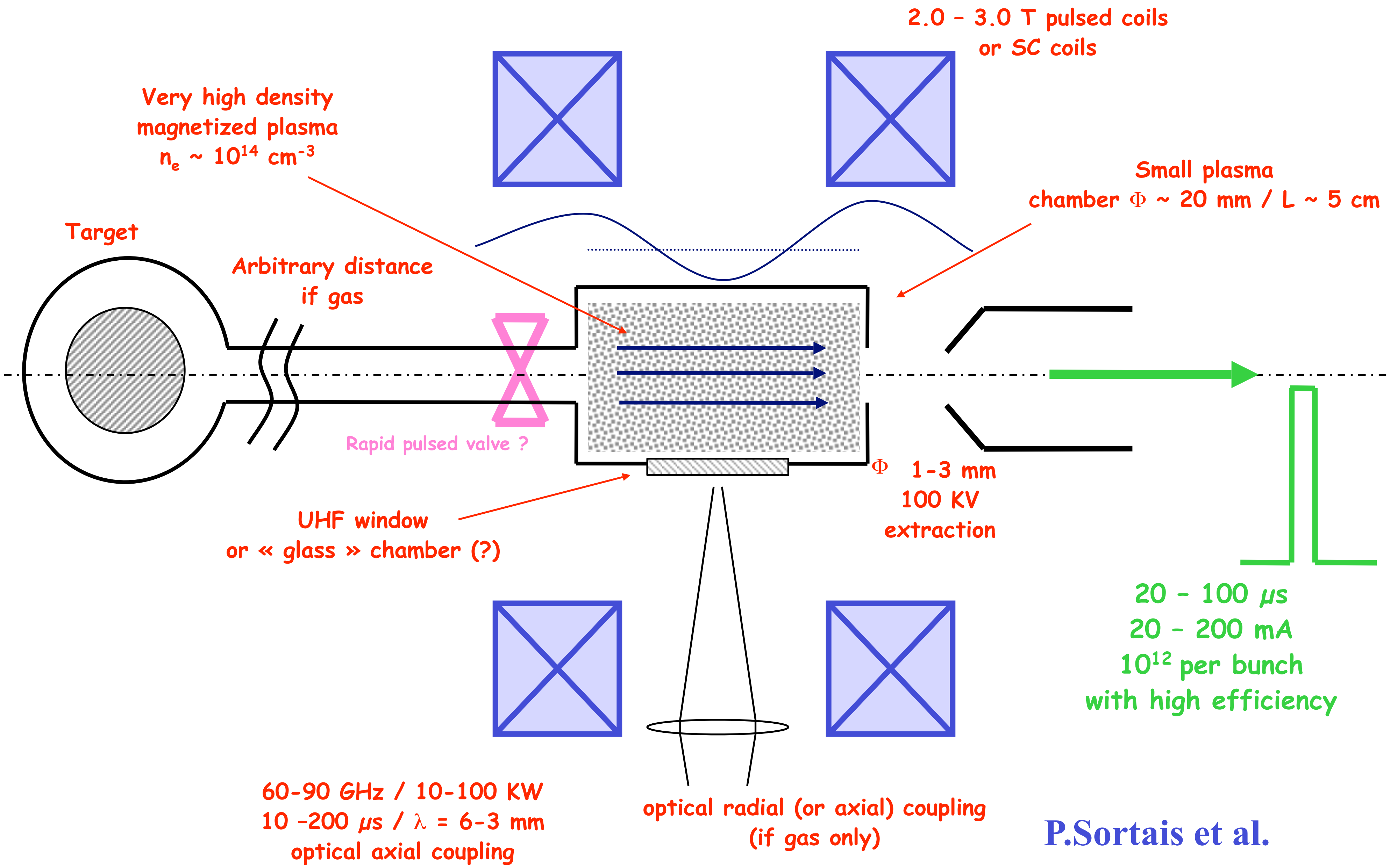
- ^{6}He Production
  - Proton beam impinge on water-cooled W or liquid lead core to produce neutrons. The neutrons hit surrounding BeO to produce ^{6}He.
  - Production rate is ~2×10^{13} ions/sec for 200 kW on target.
- ^{18}Ne Production
  - Proton beam impinge on a MgO target to produce ^{18}Ne.
  - Production rate is 1×10^{12} ions/sec.



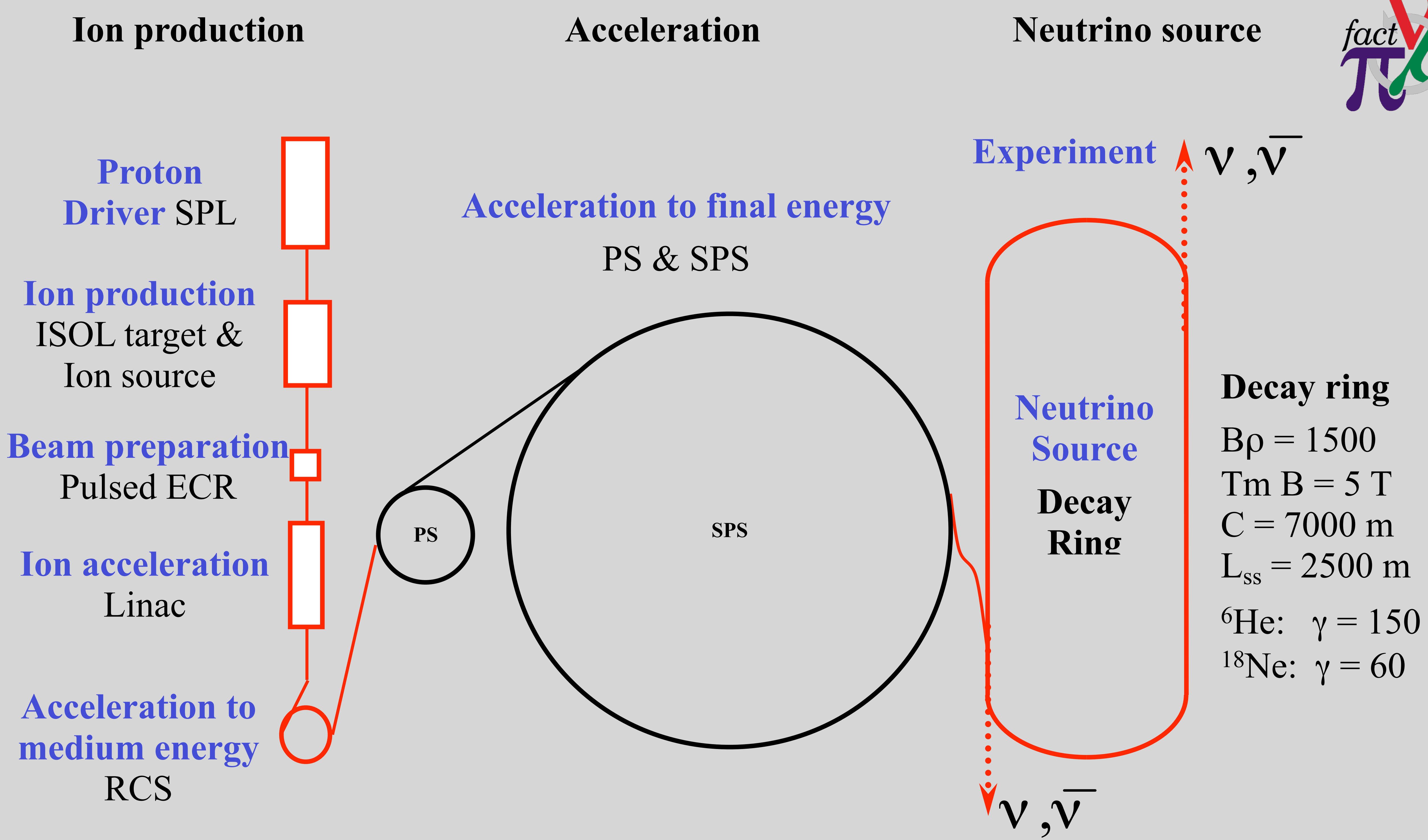
$$^{9}Be(n,\alpha)^{6}He$$

60 GHz ECR Duoplamatron Ion Source

The nuclides of interest are extracted and then ionized based on ion source technology.



P.Sortais et al.



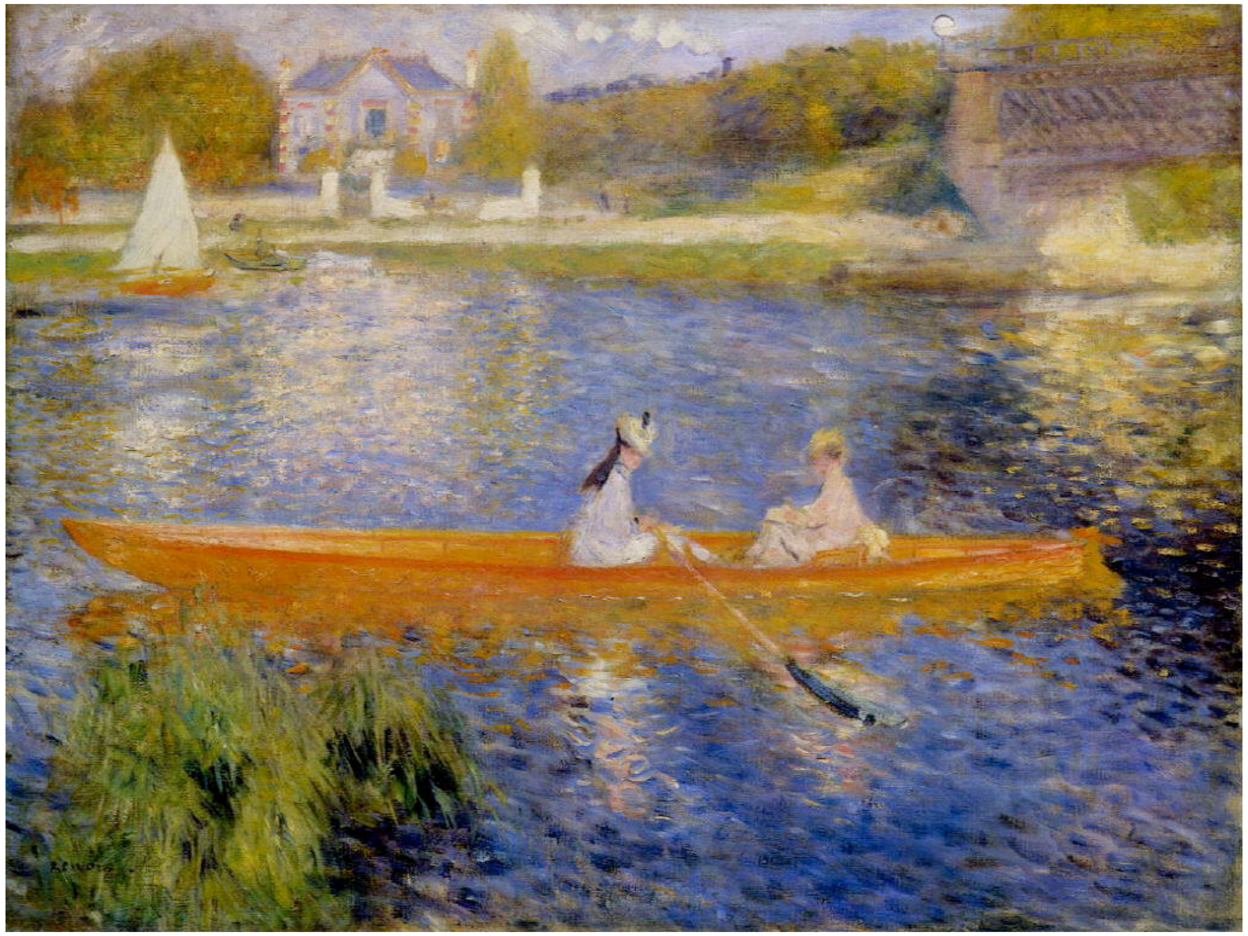
Beta Beam Concept

Monochromatic Neutrino Beam (Electron Capture)

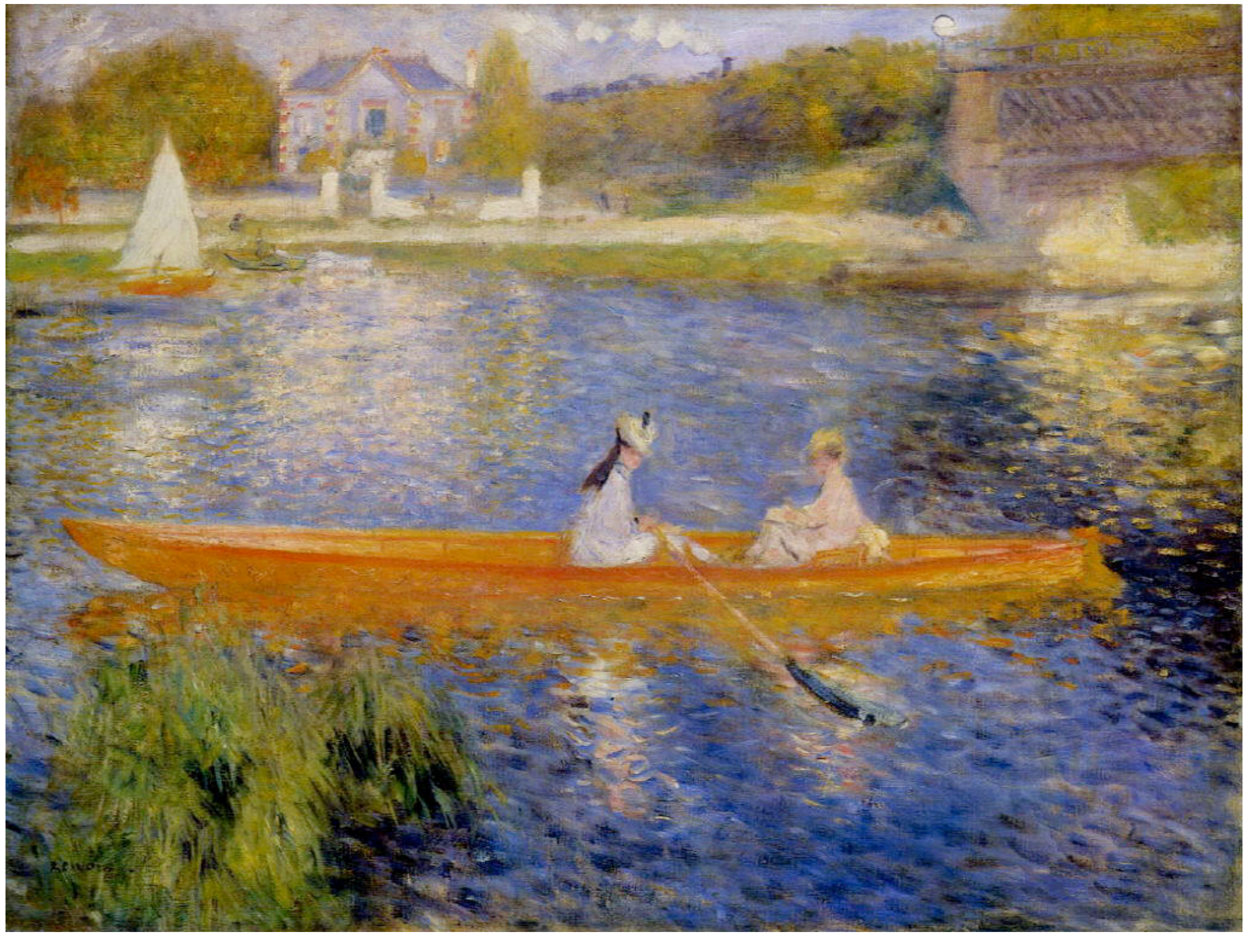
- Radioactive ions with electron capture would give monochromatic-energy neutrino.
- ^{150}Dy
  - possible to produce $1x10^{11}$ of ^{150}Dy atoms/second with 50 micro A proton beam at TRIUMF.
  - 10^{18} decays possible ?

Decay	$T_{1/2}$	BR_{ν}	EC/ν	I^{β}_{EC}	B(GT)	E_{GR}	Γ_{GR}	Q_{EC}	E_{ν}	ΔE_{ν}
$^{148}Dy \rightarrow {}^{148}Tb^*$	3.1 m	1	0.96	0.96	0.46	620		2682	2062	
$^{150}Dy \rightarrow {}^{150}Tb^*$	7.2 m	0.64	1	1	0.32	397		1794	1397	
$^{152}Tm2^- \rightarrow {}^{152}E_T{}^*$	8.0 s	1	0.45	0.50	0.48	4300	520	8700	4400	520
$^{150}Ho2^- \rightarrow {}^{150}Dy^*$	72 s	1	0.77	0.56	0.25	4400	400	7400	3000	400

New Physics
at a Neutrino Factory



New Physics
at a Neutrino Factory



Why do we need high-precision determination
of the lepton mixing parameters ?

The Big Questions

- What is the origin of neutrino mass?
- Did neutrinos play a role in our existence?
- Did neutrinos play a role in forming galaxies?
- Did neutrinos play a role in birth of the universe?
- Are neutrinos telling us something about unification of matter and/or forces?
- Will neutrinos give us more surprises?

Big questions ≡ tough questions to answer

Is the Lepton Mixing Matrix Unitary ?

- So far, the neutrino mixing matrix is mostly assumed to be unitary. Ten, it can be presented by only 4 parameters (3 angle and 1 phase).
- In principle, the neutrino mixing matrix can have 18 parameters, even in the 3 flavor generation.

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \begin{pmatrix} e^{-i\frac{\phi_1}{2}} & 0 & 0 \\ 0 & e^{-i\frac{\phi_2}{2}} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$V = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \times \begin{pmatrix} e^{-i\frac{\phi_1}{2}} & 0 & 0 \\ 0 & e^{-i\frac{\phi_2}{2}} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

From B Factory to Neutrino Factory

CKM quark mixing:

$$\mathbf{V} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Exp. steps:	θ_{12} →	θ_{23} →	θ_{13} →	δ	**new physics ?**
	~13°	~2°	~0.2°	~65°	**unitarity ?**

MNS lepton mixing:

$$\mathbf{V} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

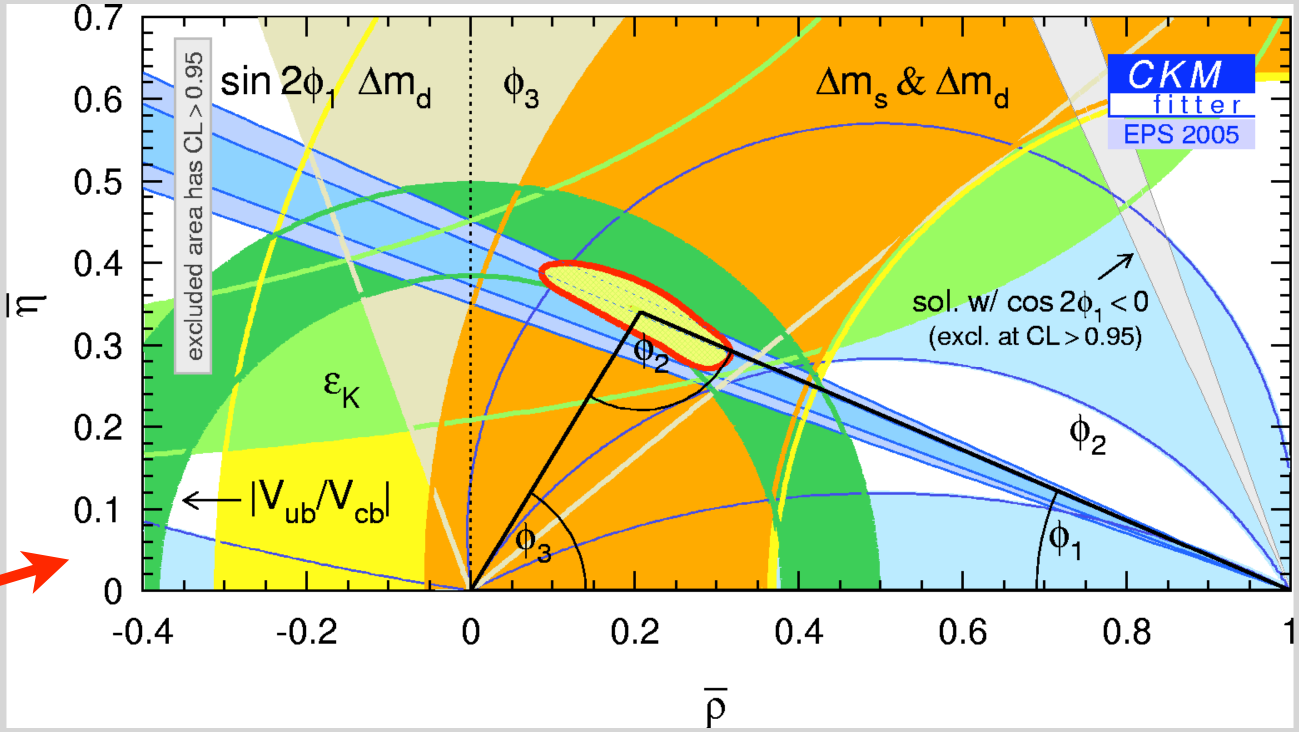
Exp. steps:	θ_{23} →	θ_{12} →	θ_{13} →	$\delta/\rho/\sigma$	**new physics ?**
	~45°	~33°	<10°	~? ? ?	**unitarity ?**

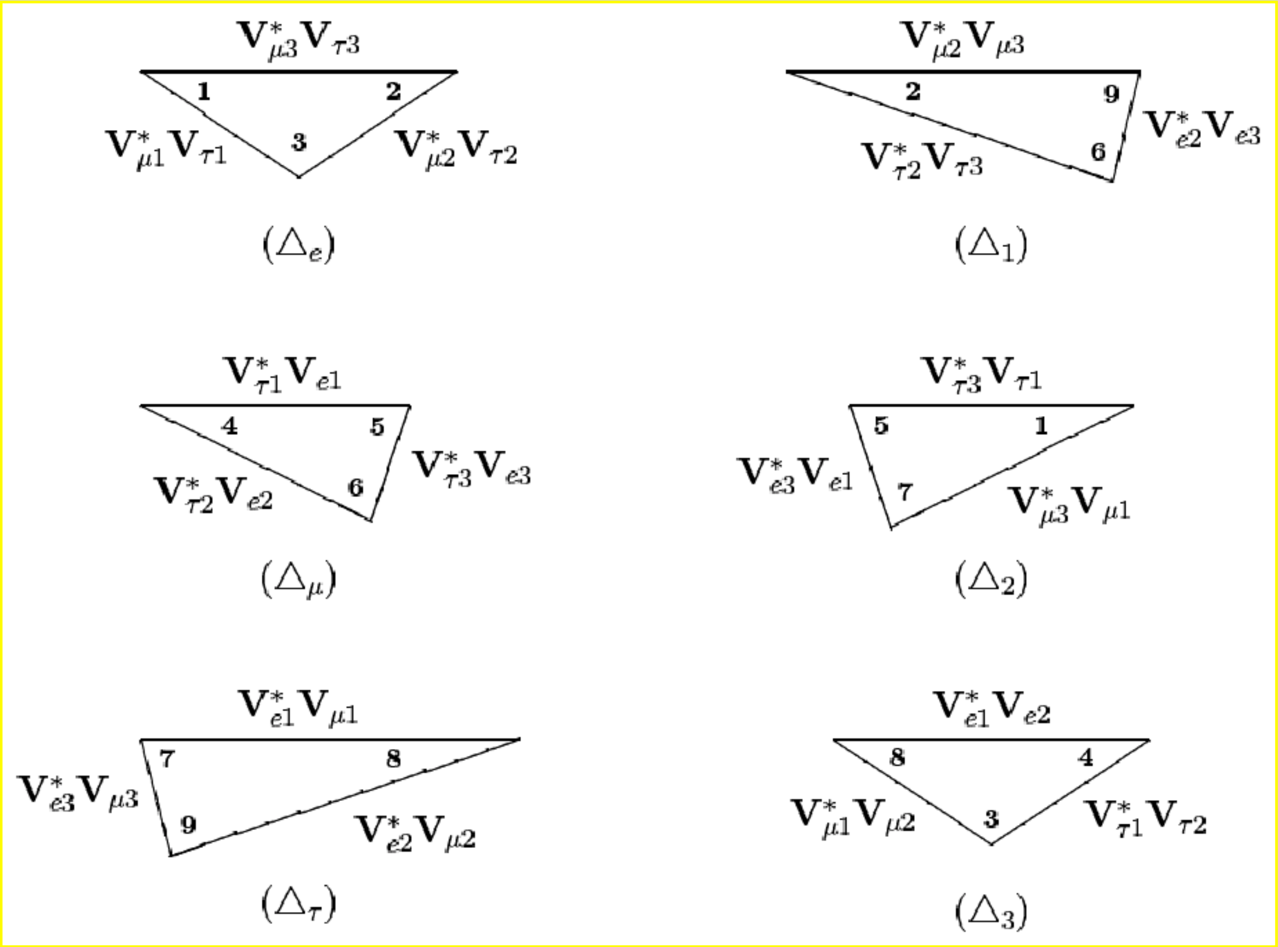
How to Test Unitarity ?

- Normalization Conditions

$$|V_{e1}|^2 + |V_{e2}|^2 + |V_{e3}|^2 = 1$$

- Orthogonality Conditions
  - Examine Unitarity Triangles
  - various combinations of the unitarity triangles for the Lepton mixing.





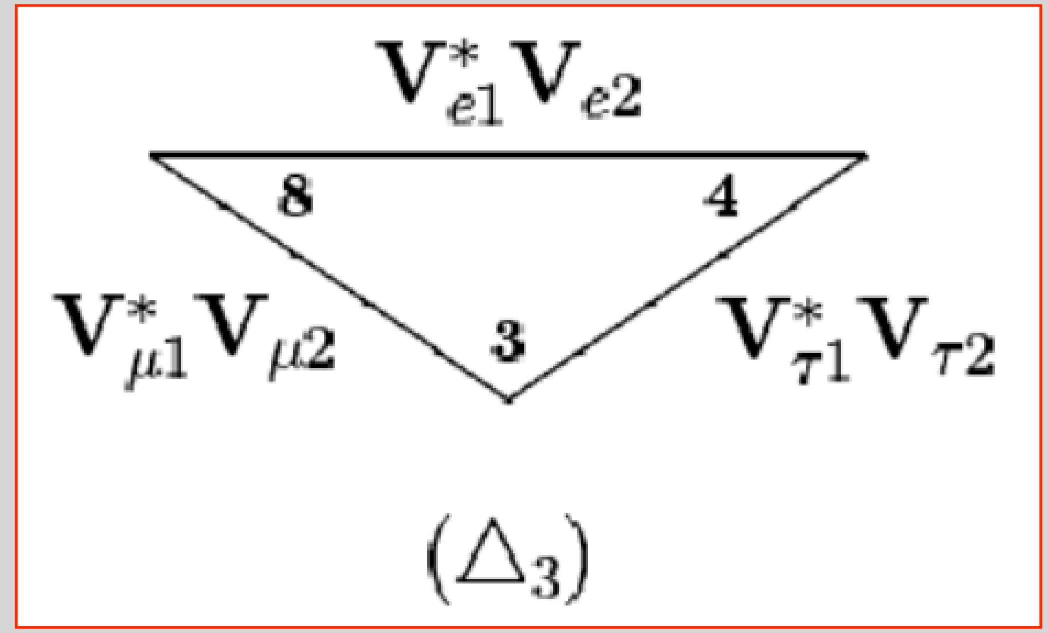
- Neutral Current (total number of active neutrino is conserved ?)

$$\sum_n P(\nu_m \rightarrow \nu_n) = 1$$

Varger, Geer, Whisnant (2004)

Example : Unitarity Triangle

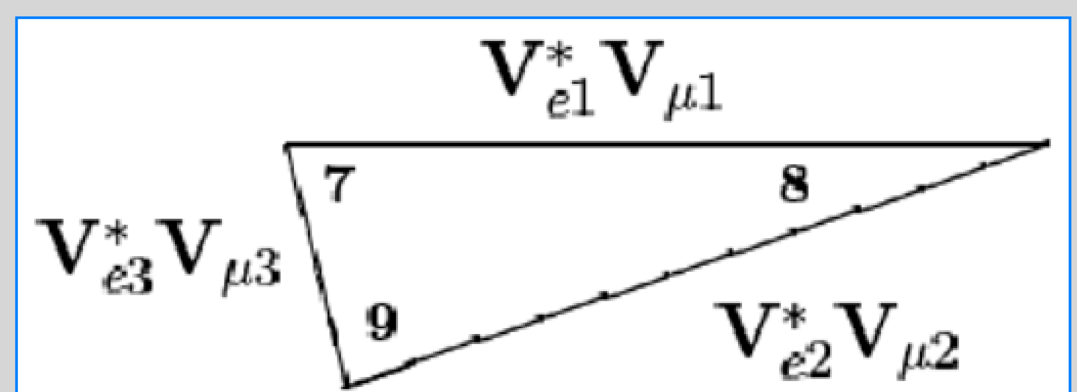
- As in the CKM triangle, the area of the MNS triangle is proportional to the lepton Jarlskog parameter, J.
    - Both $\sin^2\theta_{13}$ and $\sin\delta$ should be large.
    - Physics case for $\sin^2\theta_{13} > 0.01$
- Tau appearance is needed.
- Only a neutrino factory can do a study of the unitarity of the MNS matrix.



$$\alpha_l \equiv \arg\left(-\frac{V^*_{e1}V_{e2}}{V^*_{\mu1}V_{\mu2}}\right)$$

$$\beta_l \equiv \arg\left(-\frac{V^*_{\mu1}V_{\mu2}}{V^*_{\tau1}V_{\tau2}}\right)$$

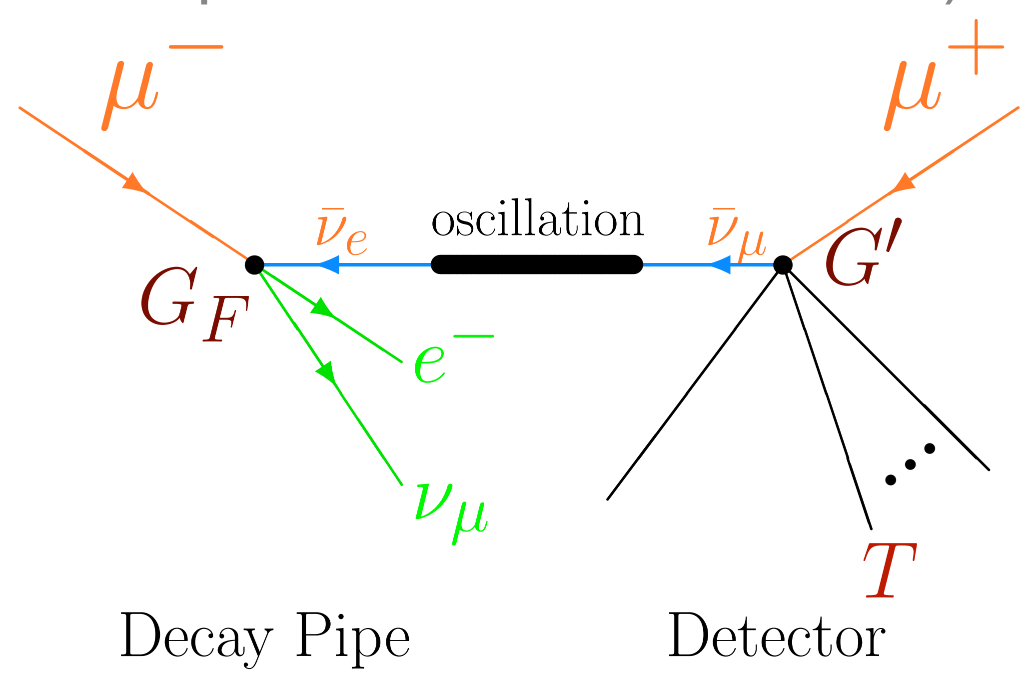
$$\gamma_l \equiv \arg\left(-\frac{V^*_{\tau1}V_{\tau2}}{V^*_{e1}V_{e2}}\right)$$



Sources for Non-unitarity, and new interaction ?

- More than 3 generations
  - sterile neutrinos ?

- New interactions (as in the quark case in B-factories)



new interaction in neutrino production

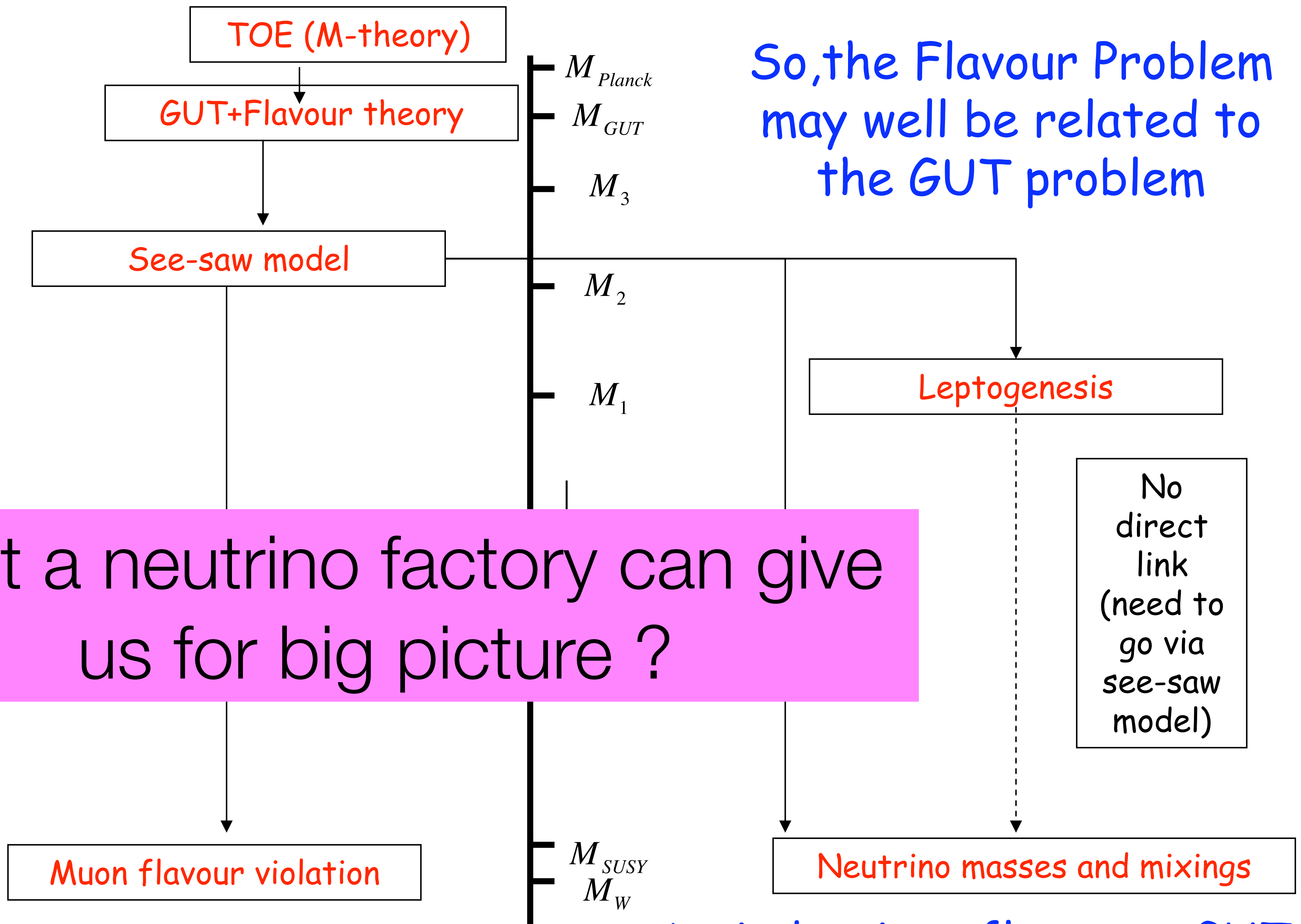
new interaction in propagation in matter

new interaction in neutrino detection

SU(2) assumed, it is related (constrained) by charged lepton flavor violation.

Towards Big Picture

So,the Flavour Problem may well be related to the GUT problem



what a neutrino factory can give us for big picture ?

A window into flavour + GUTs

Summary of the Three Lectures

- Neutrino Oscillation Physics
  - Objectives are
  - Eight-fold Degeneracies
- Future Neutrino Facilities
  - Superbeams
  - Beta beam
  - Neutrino factory
    - Neutrino Factory Complex and R&D
- New physics beyond the standard neutrino oscillation

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Discovery of Leptonic CP Violation δ

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