Design studies for the future μ-e conversion experiment in the PRISM task force

- Synergies between NuFact and Muon Physics -

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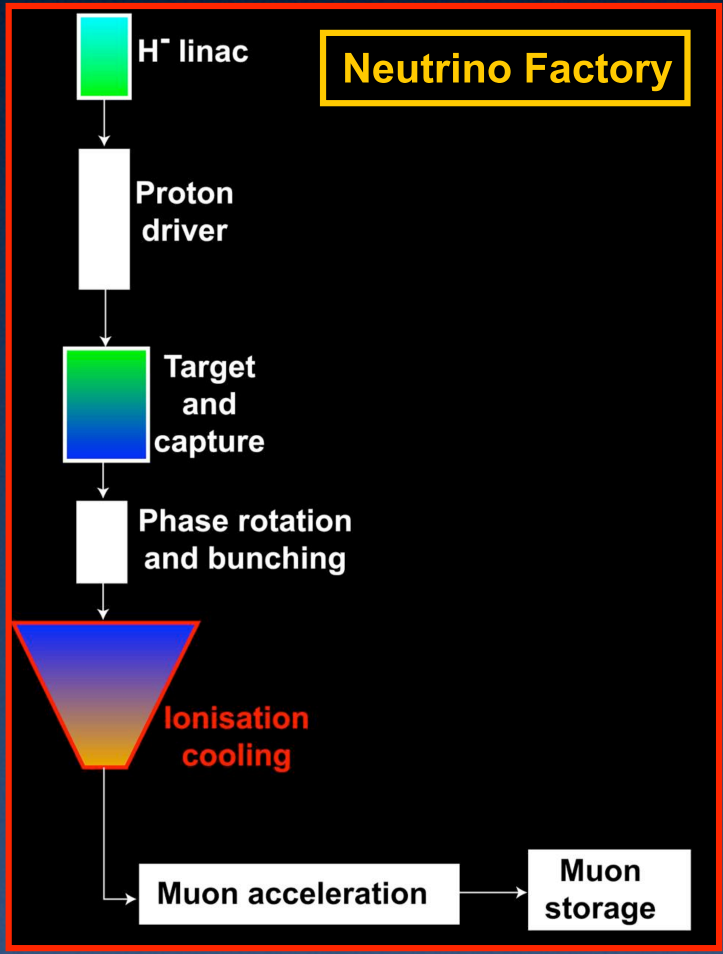
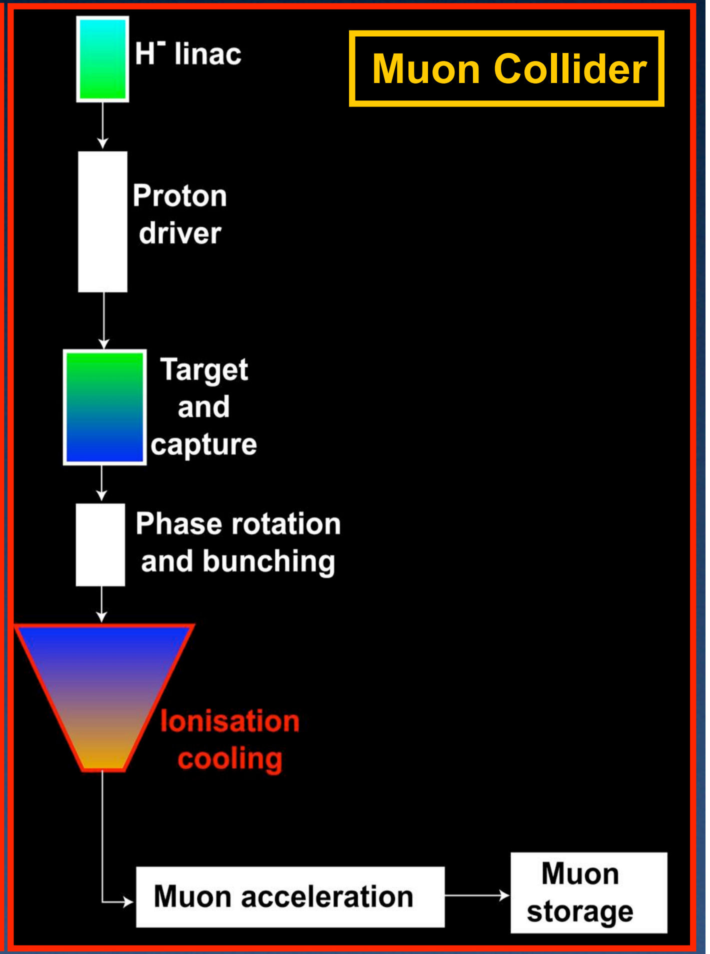
2010/10/22,

12th International Workshop on Neutrino Factories, Super beams and Beta Beams; NuFact10,

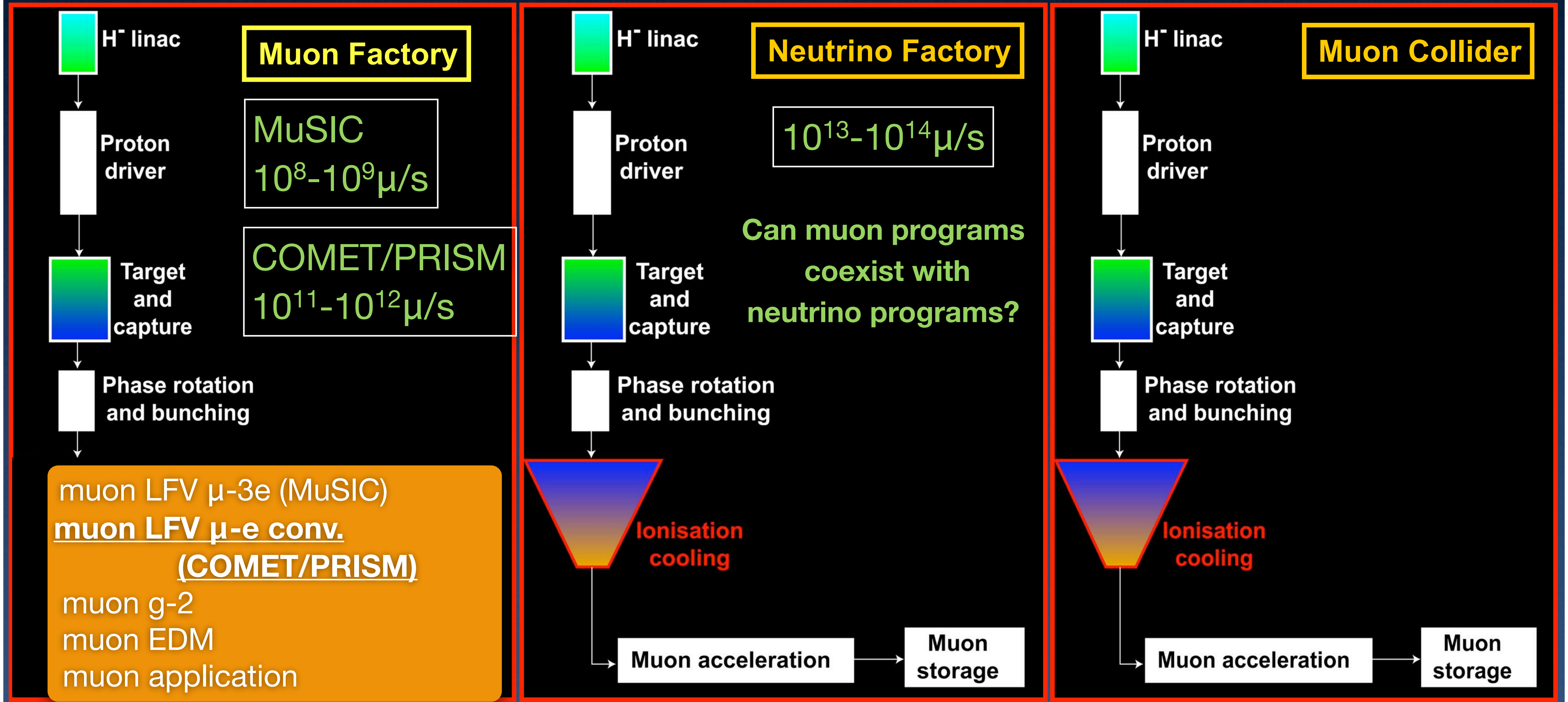
Tata Institute of Fundamental Research, Mumbai, India

Particle Physics Based on Muons



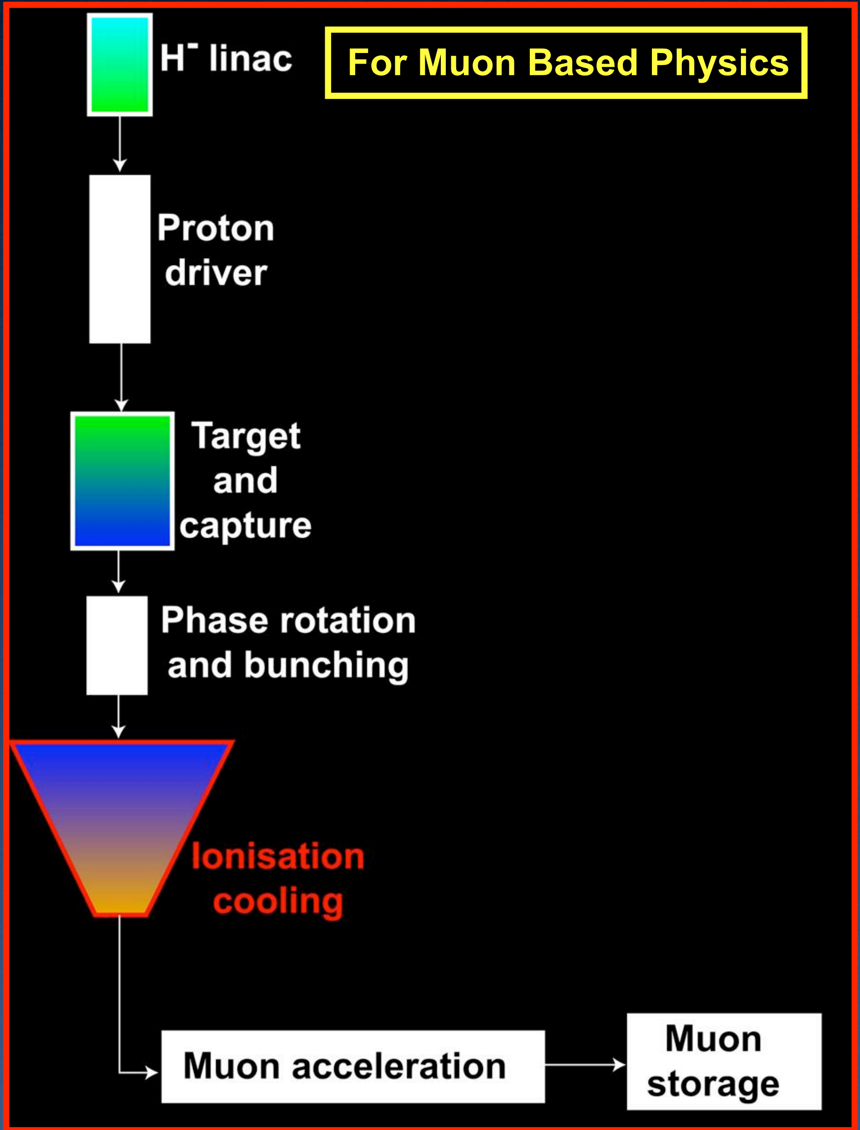


Particle Physics Based on Muons



- There are **excellent synergies** among Muon Factory, Neutrino Factory, and Muon collider on both physics issues and accelerator technologies. Future muon experiments need similar accelerator techniques and devises.
- We need to consider not only the staging scenario from muon factory to neutrino factory but also the co-existence of muon and neutrino programs at the Neutrino Factory facility.

Technological Synergies



- **High power proton driver**
- **Pion production and capture**
  - target system, super-conducting magnet, radiation damage, hadron codes ...
- **Muon beam transport**
  - bend solenoid with a dipole field
- **Phase rotation**
- **FFAGs**
- **Kickers and RF**
- **Techniques in machine design and beam dynamics studies**
- **...**

Studied in MuSIC, COMET and PRISM

Strong relationship b/w NF and muon group is important.

μ-e conversion search is a Hope

- Search for the charged lepton flavor violation (cLFV) is especially promising to probe the TeV-scale physics. In particular, among the cLFV processes, **μ**-e conversion is attractive to carry out with the future high power proton drivers.
- Comparison between **μ**→eγ and **μ**-e conversion (Experimental)

	background	challenge	beam intensity
• μ→eγ	accidentals	detector resolution	limited
• μ-e conversion	beam	beam background	no limitation

  - μ→eγ : Accidental background is given by $(\text{rate})^2$. The detector resolutions have to be improved, but they (in particular, photon) would be hard to go beyond MEG from present technology. The ultimate sensitivity would be about 10^{-14} (with about 10^8/sec) unless the detector resolution is radically improved.
  - μ-e conversion : Improvement of a muon beam can be possible, both in purity (no pions) and in intensity (thanks to neutrino factory and muon collider R&D). A higher beam intensity can be taken because of no accidentals.

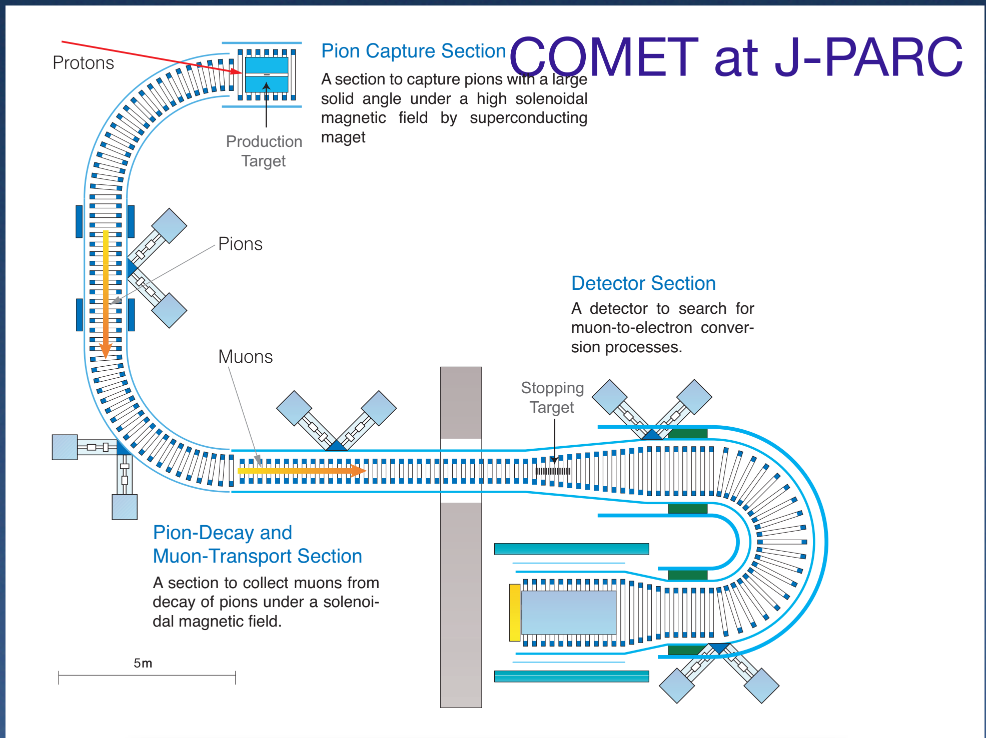
A Next Step should be μ-e conversion

μ-e conv. experiments and R&D programs

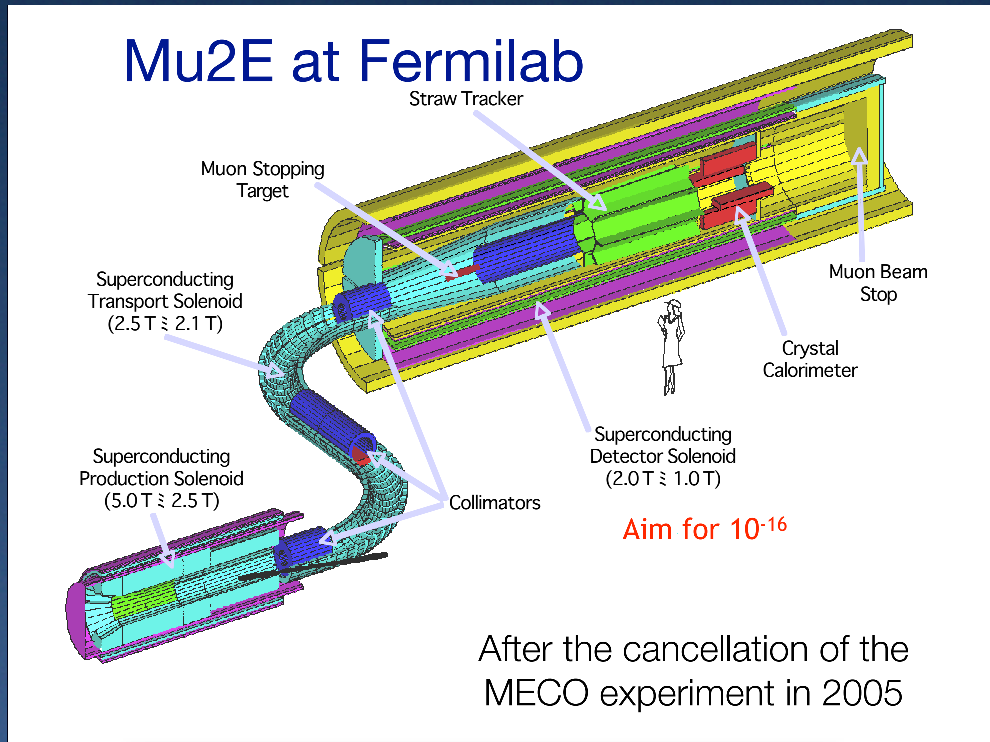
- Proposed experiments
  - COMET at J-PARC and Mu2E at FNAL
  - PRISM at ????
- R&D programs
  - PRISM-FFAG
  - MuSIC
  - R&D programs in COMET/Mu2e
  - **PRISM Task Force**

COMET and Mu2E: S.E.S.~10^{-16}

- To achieve a single event sensitivity (S.E.S.) of 10^{-16}, we need:
  - High intense muon beam: ~10^{11} μ/sec
  - Pulsed muon beam: for the BG rejection
- Two experiments have been proposed to be carried out around 2016.



Stage-1 approval July 2009 at J-PARC



CD0 approval Nov. 2009 by DOE

Limits of COMET/Mu2E

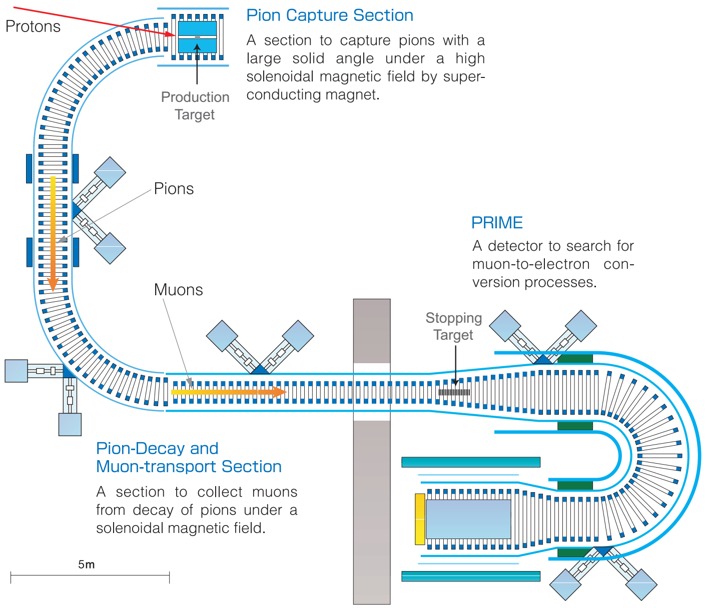
- A single event sensitivity < 10^{-17} would be impossible with the COMET/Mu2E experiments.
  - Signal events can be buried under a large amount of beam related backgrounds, ex. pion radiative decay.
  - A wide energy spread of the muon beam needs a thick stopping target, which makes an insufficient electron energy resolution to separate the signals from backgrounds from muon decay in orbit.
- Measurement efficiency with high-Z stopping targets would be poor.

A mono-energetic and pure muon beam can solve these issues.
The next generation μ-e conversion experiment with PRISM is proposed.

For the detail, please check my presentation of 4th Workshop on Physics with a high intensity proton source, November 9-10 (Monday-Tuesday), 2009
http://indico.fnal.gov/getFile.py/access?contribId=31&sessionId=9&resId=0&materialId=slides&confId=2882

Staging Plan of μ-e conv. in Japan

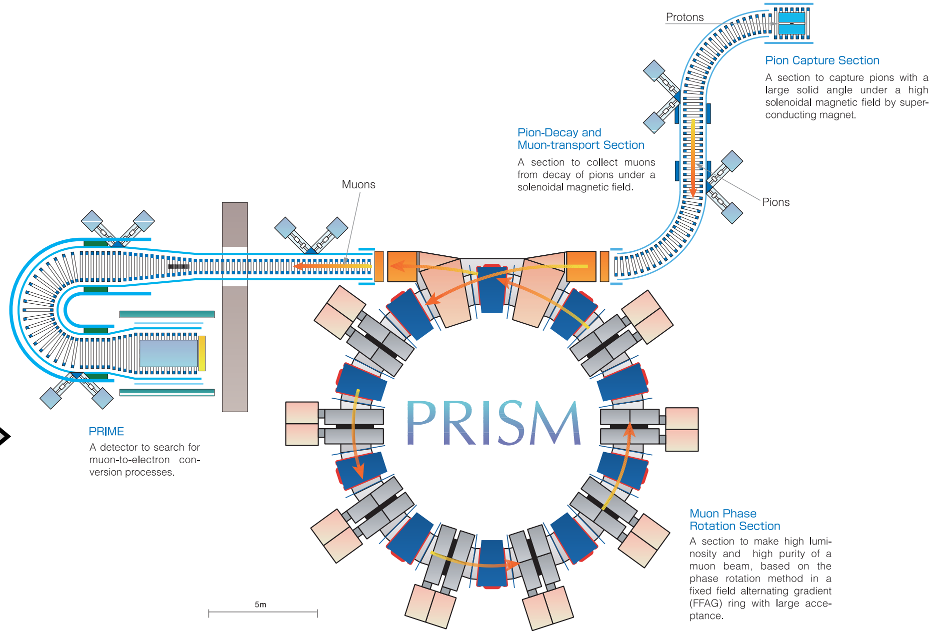
1st Stage : COMET



$$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16}$$

- without a muon storage ring.
- with a slowly-extracted pulsed proton beam.
- doable at the J-PARC NP Hall.
- regarded as the first phase / MECO type
- Early realization

2nd Stage : PRISM/PRIME



$$B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18}$$

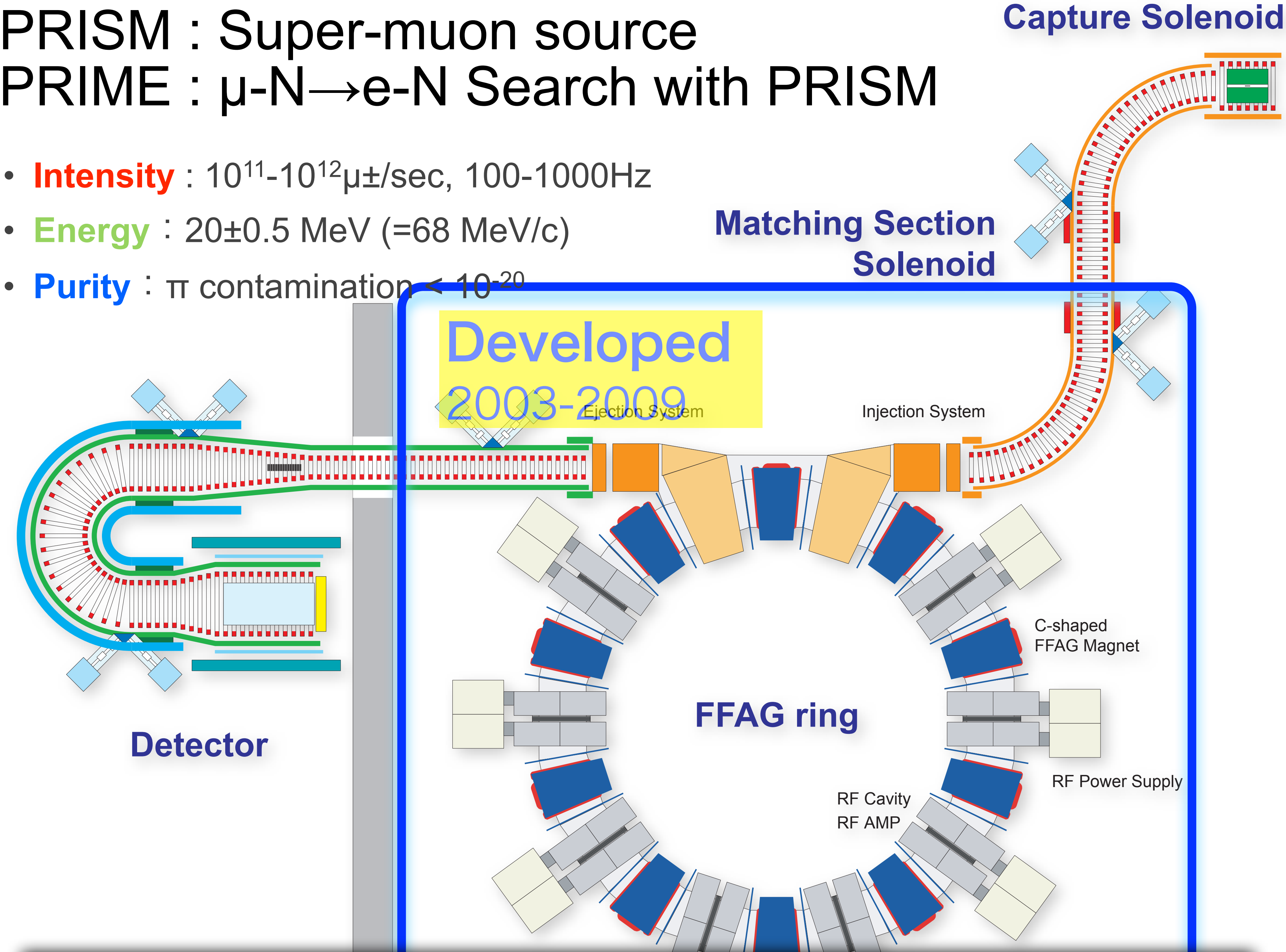
- with a muon storage ring.
- with a fast-extracted pulsed proton beam.
- need a new beamline and experimental hall.
- regarded as the second phase.
- Ultimate search

Staging Programs for the μ-e conversion

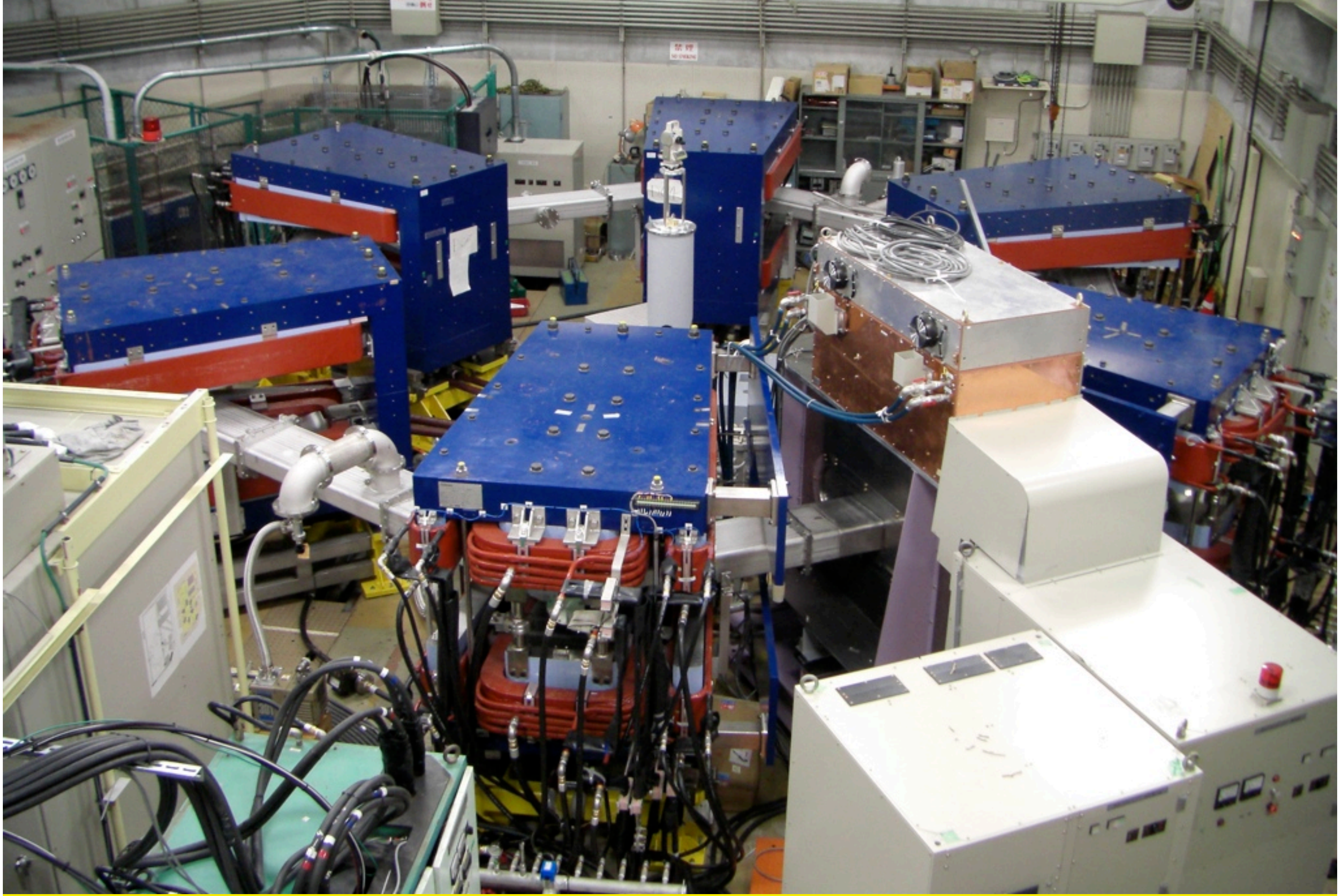
	MuSIC	COMET	PRISM/PRIME
Physics	$\mu \rightarrow eee$ nuclear physics material science	$BR(\mu\text{-}e)<10^{-16}$	$BR(\mu\text{-}e)<10^{-18}$
μ intensity	$10^{8}\mu/s$	$10^{11}\mu/s$	$10^{12}\mu/s$
DC/Pulse	DC	Pulse width<100ns	Pulse width<10ns
Phase Potation?	No	No	Yes
Proton Beam	400W (400MeV, 1μA)	56kW (8GeV, 7μA)	2MW (2-5GeV?)
B_{max} of π Capture Solenoid	3.5 Tesla	5 Tesla	5 Tesla

PRISM : Super-muon source
PRIME : μ-N→e-N Search with PRISM

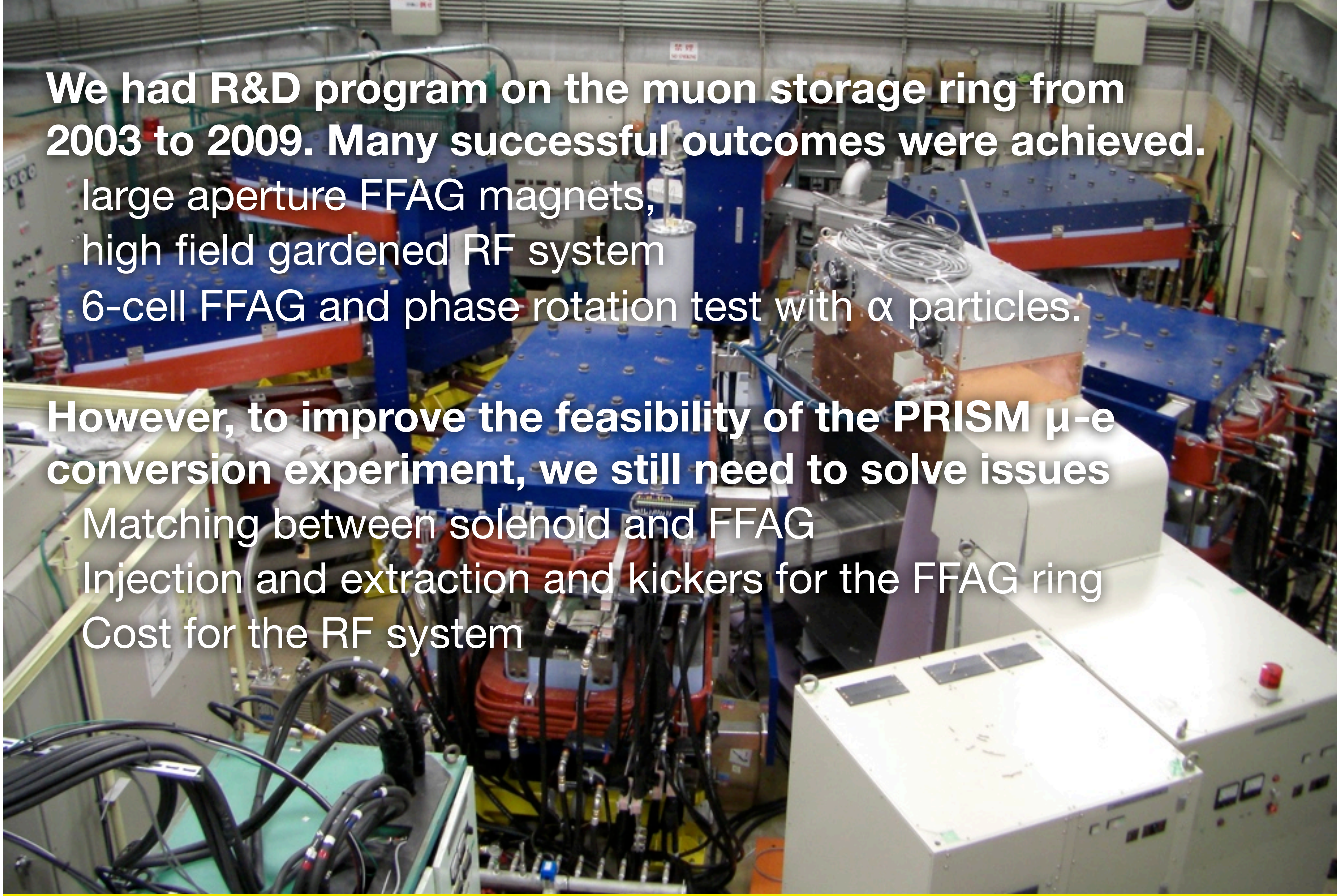
- **Intensity** : 10^{11}-10^{12}μ±/sec, 100-1000Hz
- **Energy** : 20±0.5 MeV (=68 MeV/c)
- **Purity** : π contamination < 10^{-20}



PRISM-FFAG is a key device to achieve the mono-energetic and pure muon beam. Phase rotation is applied in the ring.



6-sector PRISM-FFAG at RCNP, Osaka Univ.



We had R&D program on the muon storage ring from 2003 to 2009. Many successful outcomes were achieved.

- large aperture FFAG magnets,
- high field gardened RF system
- 6-cell FFAG and phase rotation test with α particles.

However, to improve the feasibility of the PRISM μ-e conversion experiment, we still need to solve issues

- Matching between solenoid and FFAG
- Injection and extraction and kickers for the FFAG ring
- Cost for the RF system

6-sector PRISM-FFAG at RCNP, Osaka Univ.

PRISM Task Force

- The PRISM-FFAG Task Force was proposed and discussed during the last PRISM-FFAG workshop at ICL (1-2 July'09).
- The aim of the Task Force is to address the technological challenges in realizing an FFAG based μ-e conversion experiment, but also to strengthen the R&D for muon accelerators in the context of the Neutrino Factory and future muon physics experiments.
- The following key areas of activity were identified and proposed to be covered within the Task Force:
  - - physics of muon to electron conversion,
  - - proton source,
  - - pion capture,
  - - muon beam transport,
  - - injection and extraction for PRISM-FFAG ring,
  - - FFAG ring design including the search for a new improved version,
  - - FFAG hardware R&D for RF system and injection/extraction kicker and septum magnets.
- Studies will continue to obtain a feasible design, aiming on CDR in 2011.

Synergy between PRISM and Neutrino Factory

Members of PRISM Task Force

- **J. Pasternak (contact person)**, Imperial College London / RAL STFC
- L. J. Jenner, A. Kurup, Imperial College London / Fermilab
- Y. Uchida, Imperial College London
- B. Muratori, S. L. Smith, Cockcroft Institute / STFC-DL-ASTeC
- K. M. Hock, Cockcroft Institute / University of Liverpool
- R. J. Barlow, Cockcroft Institute / University of Manchester
- C. Ohmori, KEK/JAEA
- H. Witte, T. Yokoi, JAI, Oxford University
- J-B. Lagrange, Y. Mori, Kyoto University, KURRI
- Y. Kuno, A. Sato, Osaka University
- D. Kelliher, S. Machida, C. Prior, STFC-RAL-ASTeC
- M. Lancaster, University College London

Many young physicists. We are trying to apply our skills, which got thorough the NF related studies, to the muon physics experiment!

Welcome to join us!

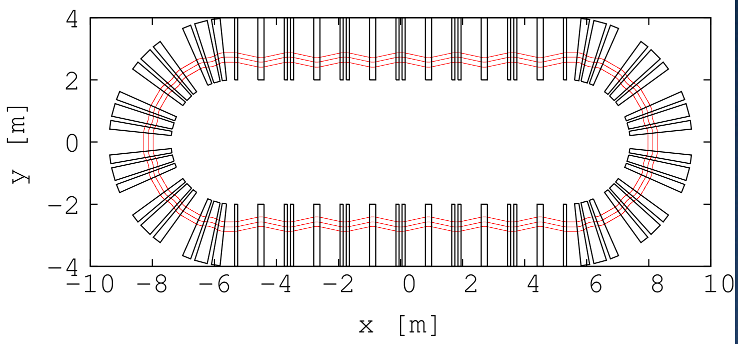
as on IPAC'10 paper

PRISM-TF Design Strategy

- Apply the technologies which studied in the NF related studies to PRISM to solve the issues.
- **Approach 1:**
  - Adopt the original design of PRISM-FFAG and work out injection/ extraction, and hardwares.
- **Approach 2:**
  - Find a new design of the phase-rotator
    - racetrack-scaling FFAG
    - non-scaling FFAG ...
- **Requirements:**
  - High transverse acceptance (at least 38h/5.7v [Pi mm]).
  - High momentum acceptance (at least ± 20% or more).
  - Small orbit excursion.
  - Compact ring size
  - Relax or at least conserve the level of technical difficulties. for hardware (kickers, RF) with respect to the current design.

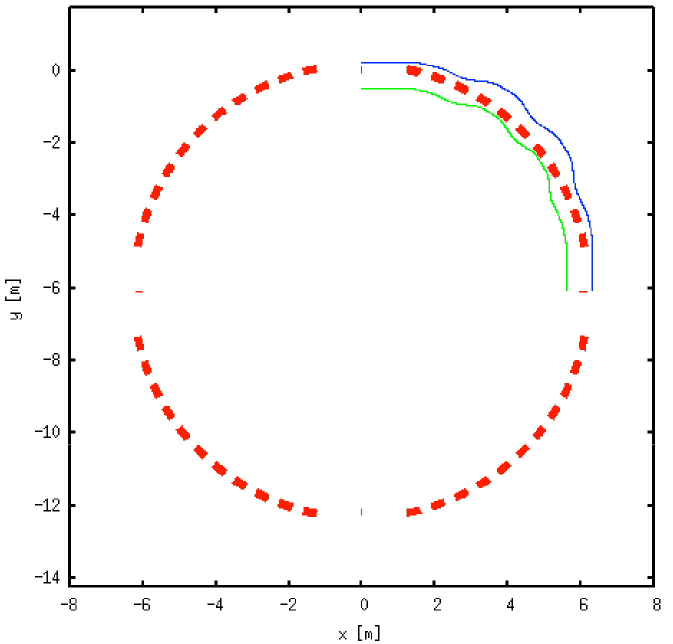
PRISM-TF Progress: Lattice

- One of the issues on the original PRISM-FFAG was injection and extraction.
- New PRISM-FFAG ring designs with longer drifts to install kicker system are proposed.
- Many ideas for scaling and non-scaling FFAGs are being applied to PRISM-FFAG.



Circular section FDF triplet scaling FFAG cell	
k	2.55
Mean radius (at 68 MeV/c)	2.7 m
Horizontal phase advance	60 degrees
Vertical phase advance	90 degrees
Number of circular cells	12
Straight section FDF triplet scaling FFAG cell	
m	1.3 m^{-1}
Cell length	1.8 m
Horizontal phase advance	27 degrees
Vertical phase advance	97 degrees
Number of straight cells	12

Advanced scaling FFAG
(J-B. Lagrange *et al*.)



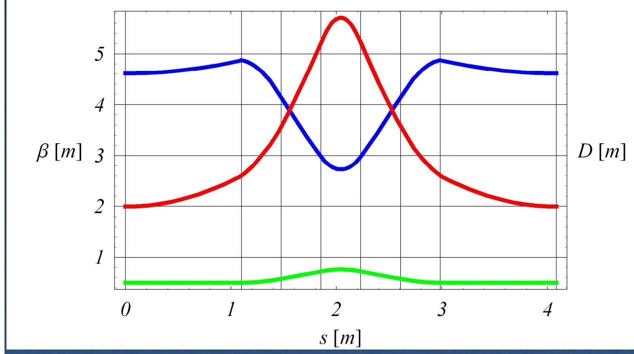
Scaling FFAG machine law:

$$B_z = B_{z0}\left(\frac{r}{r_0}\right)^k F(\theta)$$

Super-periodic solution
(S. Machida)

Some parameters:

- Lattice — Symmetric DFD triplet
- N — 20
- p_0 — 68 MeV/c
- Circumference — 81.68 m
- (Q_H, Q_V)/cell at p_0 — (0.24, 0.155)
- Drif length — 2.2 m
- The same geometry as the previous lattice



non-scaling FFAG
(J. Pasternak)

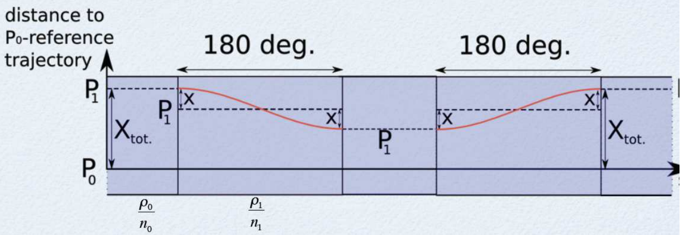
PRISM-TF Progress: Inj./Ext.

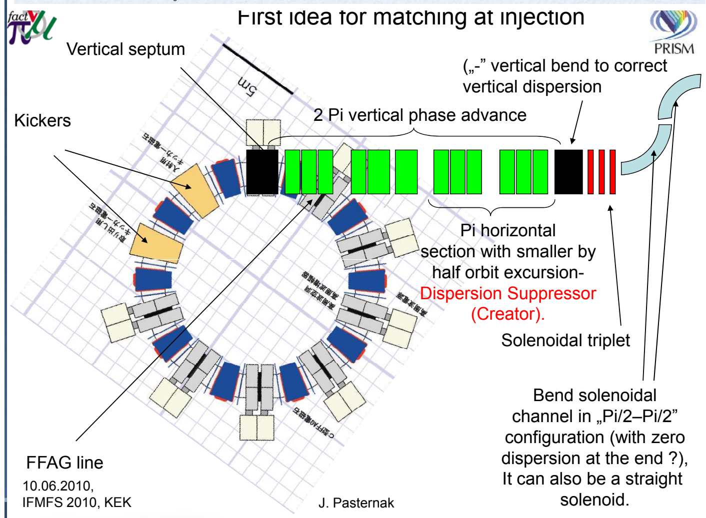
- Matching between the muon transfer solenoid and phase rotator had a difficulty due to a large muon emmitance and dispersion.
- Dispersion suppressor using scaling FFAG magnets and kicker designs based on NF studies are underway.

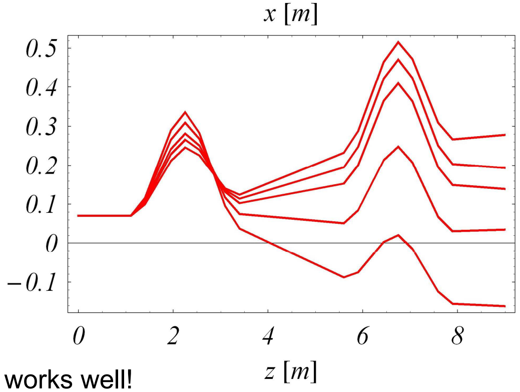
Dispersion suppressor

- Dispersion suppressor (Planche,Lagrange,Mori)
  - successive π-cells in the horizontal plane can suppress the dispersion.

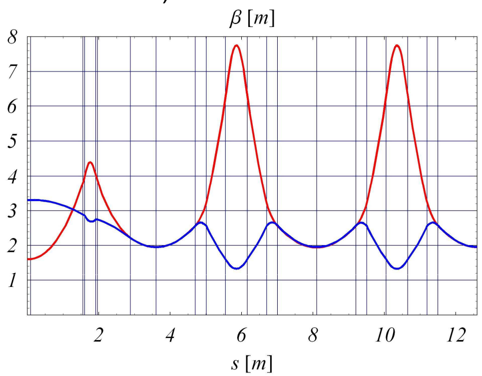
$$X_{tot} = X_1 - X_0 = \frac{1}{n/\rho}\ln\left(\frac{P_1}{P_0}\right) \qquad x = \ln\left(\frac{P_1}{P_0}\right)\left(\frac{\rho_0}{n_0} - \frac{\rho_1}{n_1}\right)$$







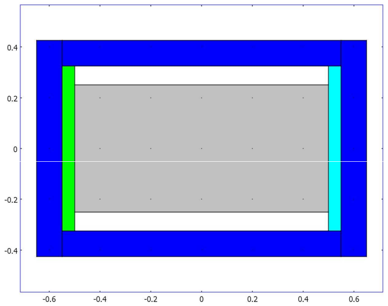
It works well!
The starting position needs to bu adjusted to obtain good results. Here it corresponds to 17 MeV orbit (assuming the periodic condition).



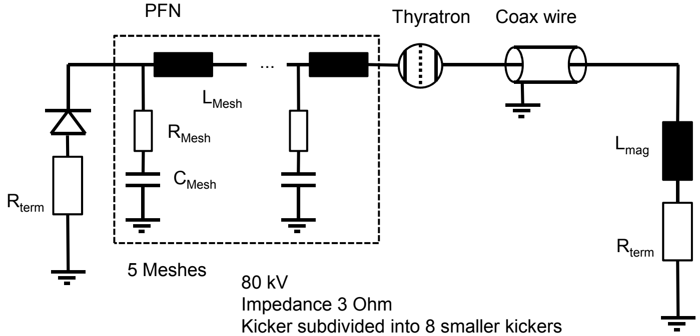
- Dispersion creator is designed and matched to the ring with just one cell.
- Vertical phase advance condition is not rigorously fulfilled (work in progress).

PRISM Kicker, H. Witte

- length 1.6 m
- B vertical 0.02 T
- Aperture: 0.95 m x 0.5 m
- Flat top 40 /210 ns (injection / extraction)
- rise time 80 ns (for extraction)
- fall time ~200 ns (for injection)
- W_{mag}=186 J
- L = 3 uH
- I_{max}=11 kA

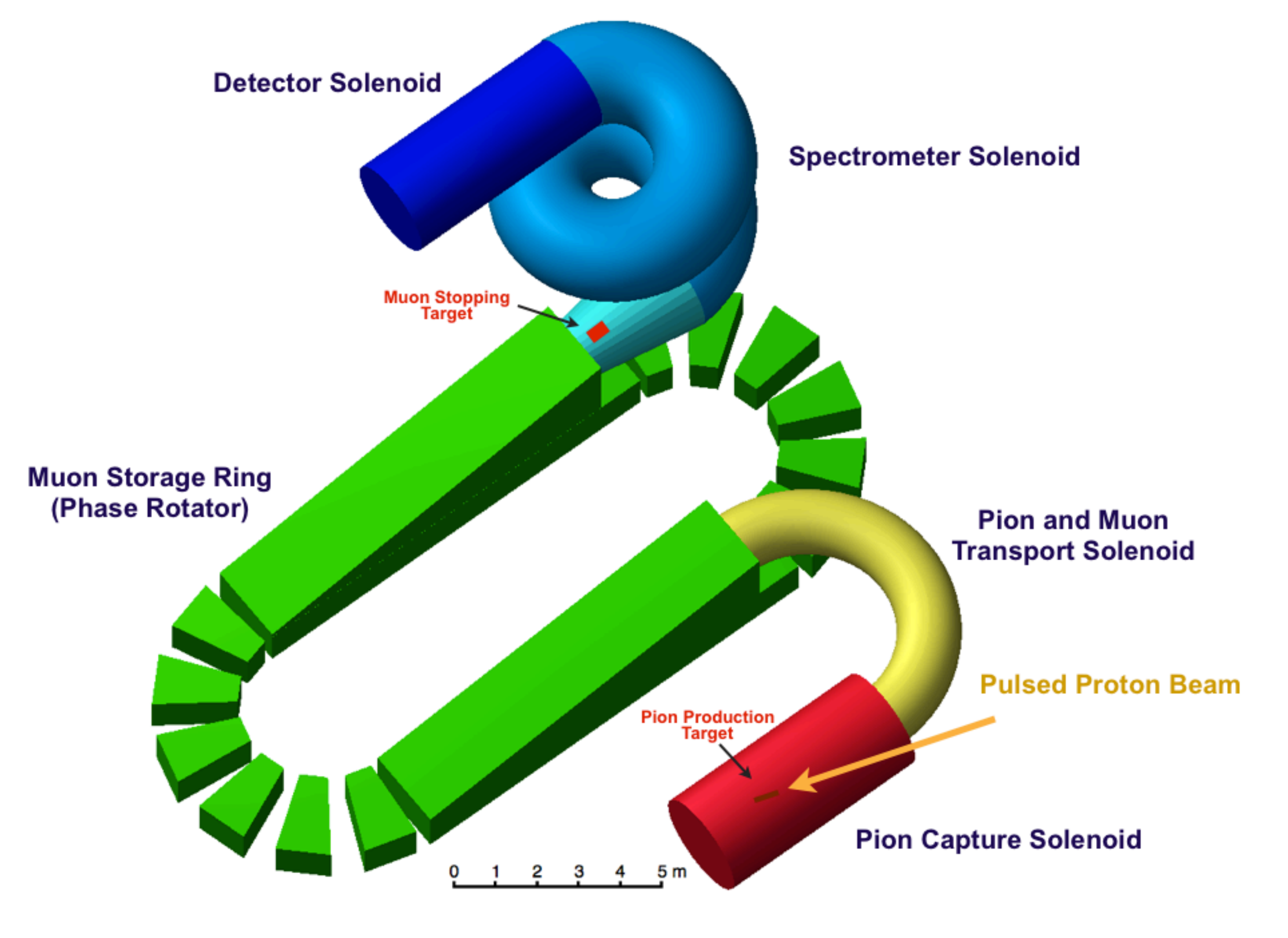


The geometry assumed here corresponds to the horizontal injection, but the kicker parameters for the vertical one will be very similar.



80 kV
Impedance 3 Ohm
Kicker subdivided into 8 smaller kickers
Travelling wave kicker
Each sub-kicker has 5 sections
1 plate capacitor per section

Schematic Layout of New PRISM



PRISM at Project-X?

Fermilab

5th Workshop on Physics
(a series of mini workshops)
with a high intensity proton source, November 2010

Contact Y2K if you have any questions. Last modified:

Workshop (a series of mini workshops) Goal:

Further develop the physics programs and experimental planning for Project X. By the end of 2010, we identify at least one flagship experiment for each beamline and produce an end-to-end (accelerator to detector) conceptual design.

- neutrino beamline - neutrino experiments
- muon beamline - muon experiments
- kaon beamline - kaon experiments
- nuclear beamline - nuclear physics experiments and nuclear energy experiments

Each beamline group has written a document including the end-to-end conceptual design of the experiment and physics potential. They can be found at this page.

Leaders for each beamline / experiment / physics and accelerator liaison

Working Group Document	Workshop Location (FNAL) Agenda	Experiment Coordinators	Accelerator Liaison
Neutrino document	No workshop planned	Stan Wojcicki (Stanford University) Regina Rameika (Fermilab)	Ioanis Kourbanis Phil Adamson
Muon document	Mon, Nov. 8 9am - 5pm WH2E Comitium Agenda	Jim Miller (Boston) Yoshi Kuno (Osaka University, Japan)	Keith Gollwitzer Eric Prebys
Kaon document	Wed, Nov. 3 3pm - 5pm WH2W Black Hole Agenda (tbd)	Bob Tschirhart (Fermilab) Doug Bryman (Univ. British Columbia, Canada)	Mike Martens Herman White
Nuclear Physics document	No workshop planned	Jerry Nolen (Argonne) Guy Savard (Argonne)	Steve Werkema Dave McGinnis
Nuclear Energy document	Tues, Nov. 9 9am - 12:30pm WH1E One East Agenda (tbd)	Shekhar Mishra (Fermilab) Yousry Gohar (Argonne)	Dave Johnson Todd Johnson

http://www.fnal.gov/directorate/Longrange/Steering_Public/workshop-physics-5th.html

Agenda

time	speaker	tentative title
		Morning Sessions (Chair: Yoshitaka Kuno)
Session for Muon Particle Physics at Project X		
09:00 - 09:15	Young-Kee Kim (FNAL)	Welcome and FNAL Future Roadmap
09:15 - 09:45	Steve Holmes (FNAL)	Project X Accelerator Update
09:45 - 10:15	Andre de Gouvea (Northwestern)	Overview of Muon Physics at Project X Era
10:15 - 10:45	Coffee Break	
10:45 - 11:15	Jim Miller (Boston)	Overview of Muon Experimental Programs at Project X
Session for Muon to Electron Conversion Experiment		
11:15 - 11:45	Alejandro Ibarra (TUM, TBC)	Why Muon to Electron Conversion of $<10^{-18}$? (TBC)
11:45 - 13:00	Lunch	
		Afternoon Sessions (Chair: Jim Miller)
13:00 - 13:20	Yoshitaka Kuno (Osaka)	Overview on Muon Storage Ring (PRISM) Option
13:20 - 13:40	Charles Ankenbrandt (Muons. Inc.)	Overview on Cooled RF and Ionization (CRFI) Option
13:40 - 14:10	Keith Gollwitzer (FNAL)	Proton Beam for PRISM
14:10 - 14:40	Eric Prebys (FNAL)	Proton Beam for CRFI
14:40 - 15:10	Coffee Break	
15:10 - 15:40	Jaroslaw Pasternak (Imperial College London)	Muon Beam and FFAG storage ring for PRISM
15:40 - 16:00	Akira Sato (Osaka)	Detector (PRIME)
16:00 - 16:20	Yoshitaka Kuno (Osaka)	Sensitivity and Backgrounds
Session for Synergy of R&D		
16:20 - 16:40	Steve Geer (FNAL)	Synergy with muon collider R&D
16:40 - 17:00	Ken Long (Imperial College London)	Synergy with Neutrino Factory R&D
17:00 - 17:15	Yoshitaka Kuno (Osaka)	Summary

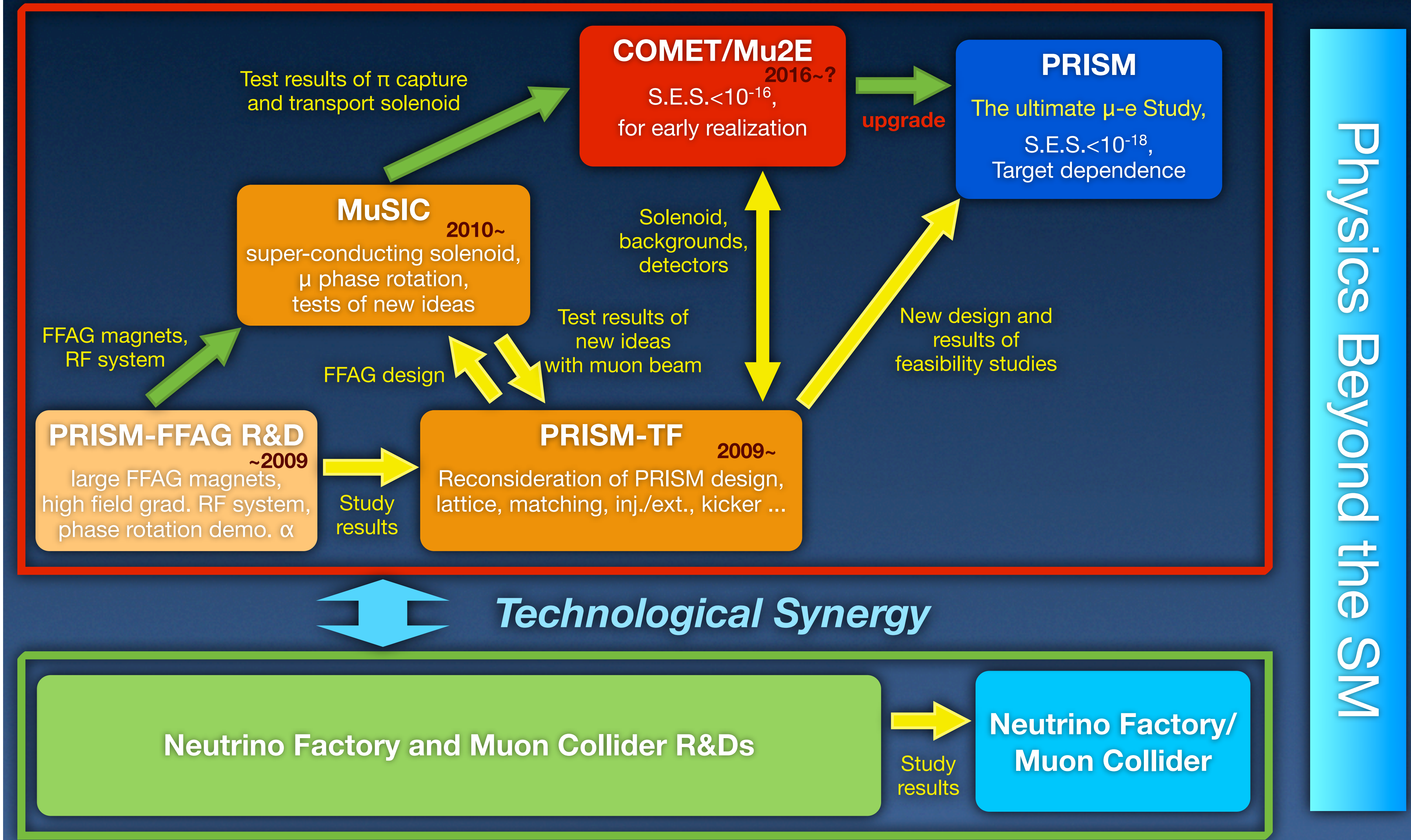
Project-X
5th Workshop on physics,
Muon working group
8th Nov., 2010 at FNAL

Focused on μ-e conv. experiment at SES of 10^{-18}.

PRISM-TF will write a report to show the feasibility of the PRISM based on μ-e conv. experiment.

Relationship among the programs

towards the ultimate μ-e conversion study



Summary

- Search for the charged lepton flavor violation (cLFV), in particular μ-e conversion search, can be a promising probe to the TeV-scale physics in a Neutrino Factory era. We can draw the staging scenario from muon factory to neutrino factory, we need also to consider the possibilities for the co-existence of muon and neutrino programs at the Neutrino Factory facility.
- Neutrino factory and μ-e conversion experiments have a lot of common issues. Therefore, a strong relation ship between neutrino factory groups and muon groups is important to make synergies. PRISM-TF is a very nice example of the good relationship.
- R&D programs for the μ-e conversion are underway. PRISM-FFAG, COMET, PRISM-TF, and MuSIC. Many people from the neutrino factory study join the programs.
- PRISM-TF will make a report on the new PRISM based μ-e conversion experiment in a year. Dellp discussion will be made in comming project-X workshop om muon physics.
- **You are also welcome to join us!!!**