Muon and FFAG

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FFAG2015 @ Kyusyu

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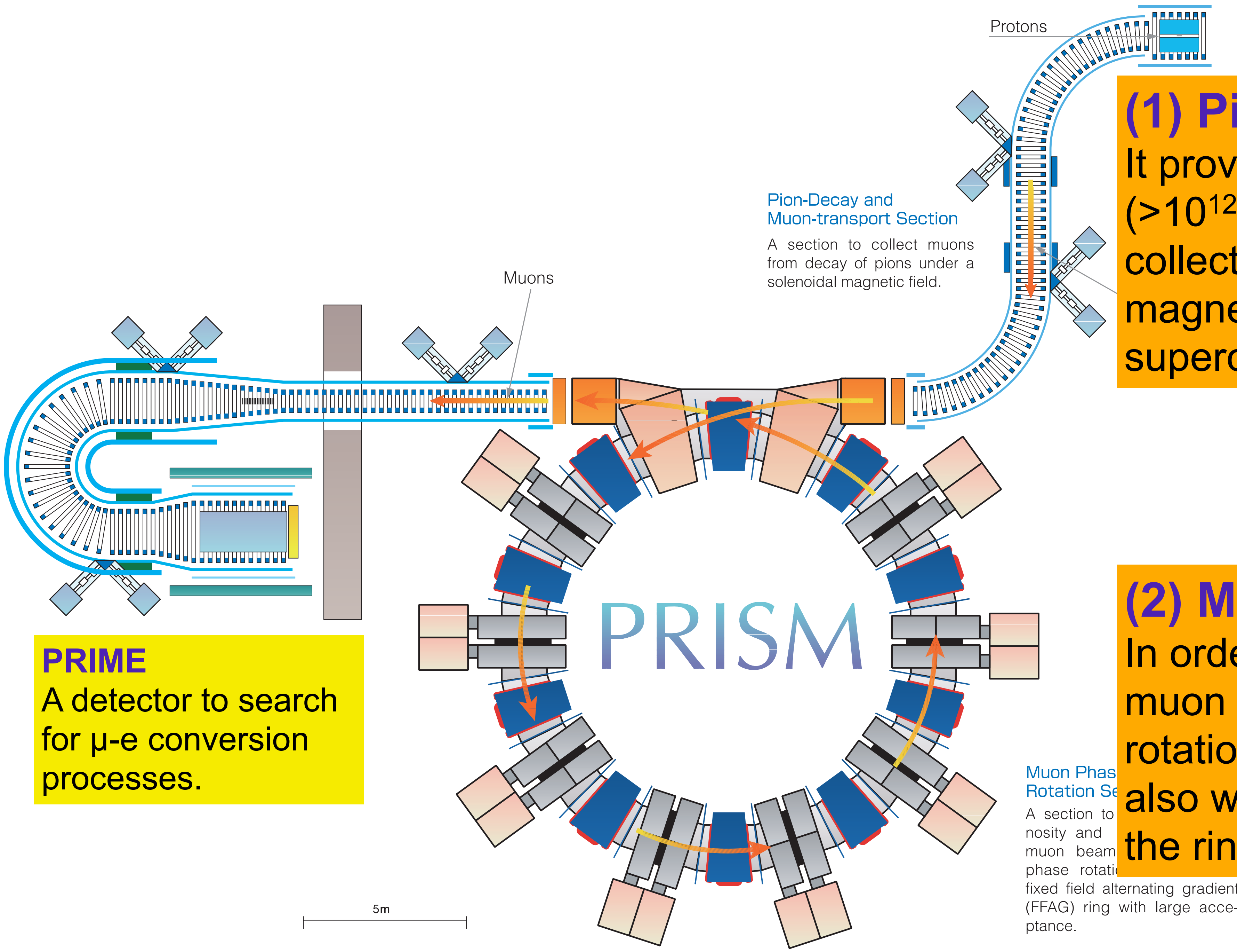
- Ideas for μ-e conv. and nuSTORM/NF
- Some comments to FFAGs
  - Reliability of FFAG design performance
  - Perfect scaling FFAG

Status of my recent projects

- PRISM project is the origin of my interest in FFAG. It is an experiment to search the muon to electron conversion, which is strongly forbidden in the Standard Model of the particle physics, with the ultimate sensitivity.
- The experiment needs an very intense and monochromatic muon beam.
  - μ intensity : 10^{11}~10^{12} μ-/sec
  - momentum : ~40MeV/c with $\Delta p/p$ of ~±2%
  - no pion contaminations

Key components of PRISM/PRIME



(1) Pion Capture System
It provides an intense muon beam ($>10^{12}\mu^-$/sec). Pions and muons are collected effectively by high solenoidal magnetic field produced by superconducting magnets.

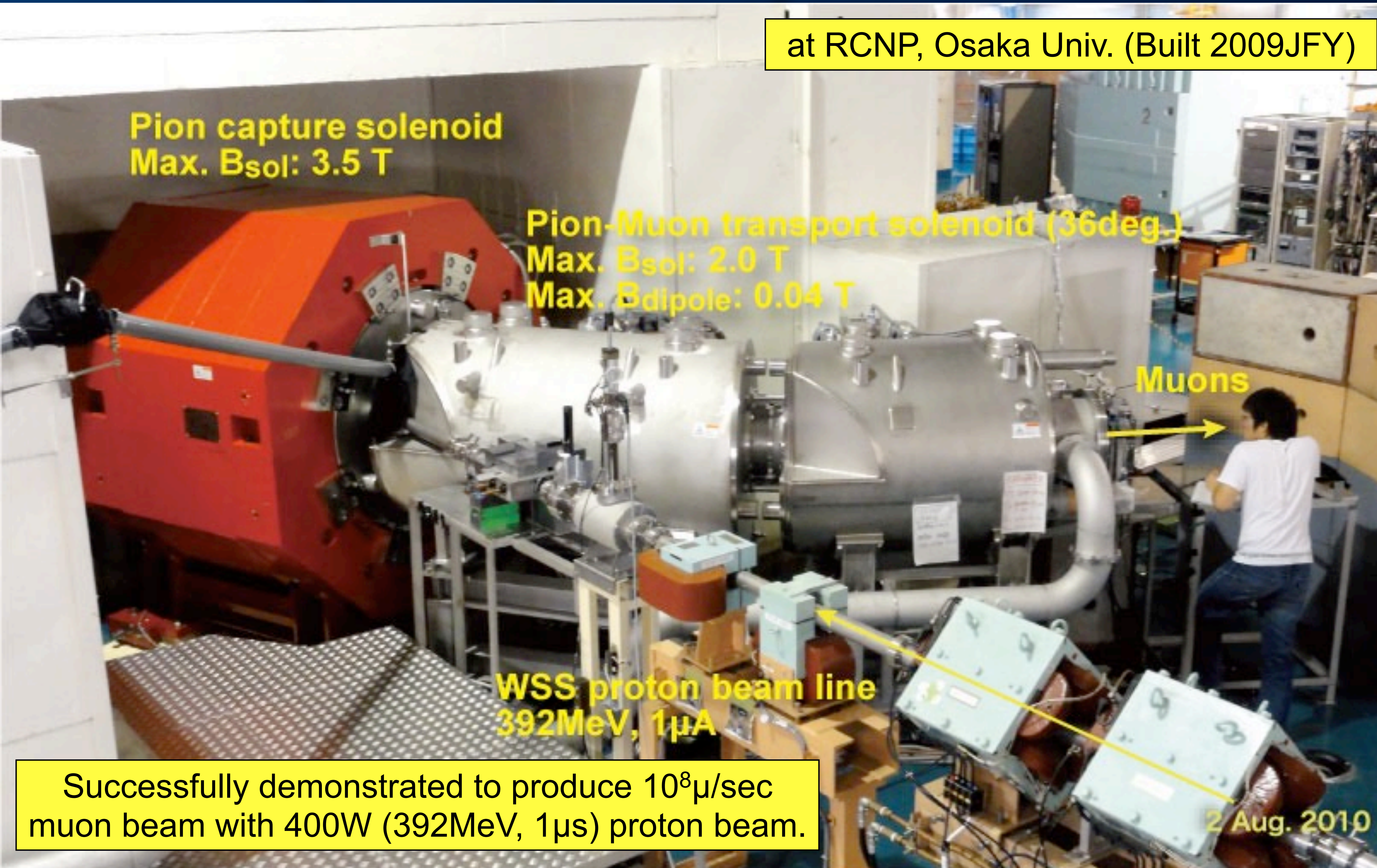
(2) Muon Phase Rotator
In order to realize a monochromatic muon beam of $\Delta p/p \sim \pm 2\%$, a bunch rotation is applied in a FFAG ring. It also work to decay out the pions in the ring.

PRIME
A detector to search for μ-e conversion processes.

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

The 1st pion capture system : MuSIC

at RCNP, Osaka Univ. (Built 2009JFY)



Successfully demonstrated to produce 10^8μ/sec muon beam with 400W (392MeV, 1μs) proton beam.

MuSIC: Development of the pion capture system

(1) Pion Capture System
It provides an intense muon beam (>10^{12}μ-/sec).
Pions and muons are collected effectively by high solenoidal magnetic field produced by superconducting magnets.

The 1st Pion Capture System, MuSIC, was developed and its performance was successfully demonstrated at RCNP, Osaka.

Start COMET experiment at J-PARC
A μ-e conversion experiment was funded by KEK/J-PARC. The experiment named COMET aims the sensitivity of 10^{-16} without the FFAG ring.

Working as the main detector (CyDet) group leader

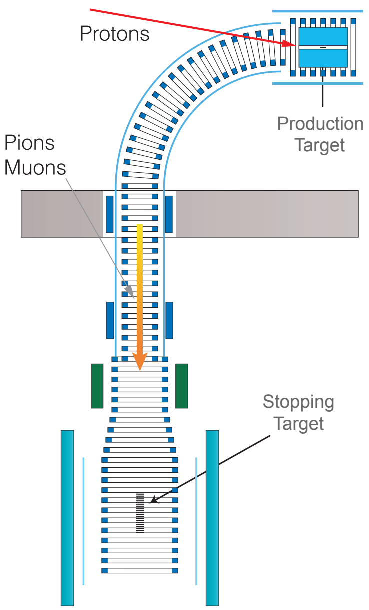
Start construction of μ beamline MuSIC-M1 at RCNP
To start muon experiments for material science, nuclear physics chemical etc, the MuSIC solenoid channel was extended with a normal conducting beam line.

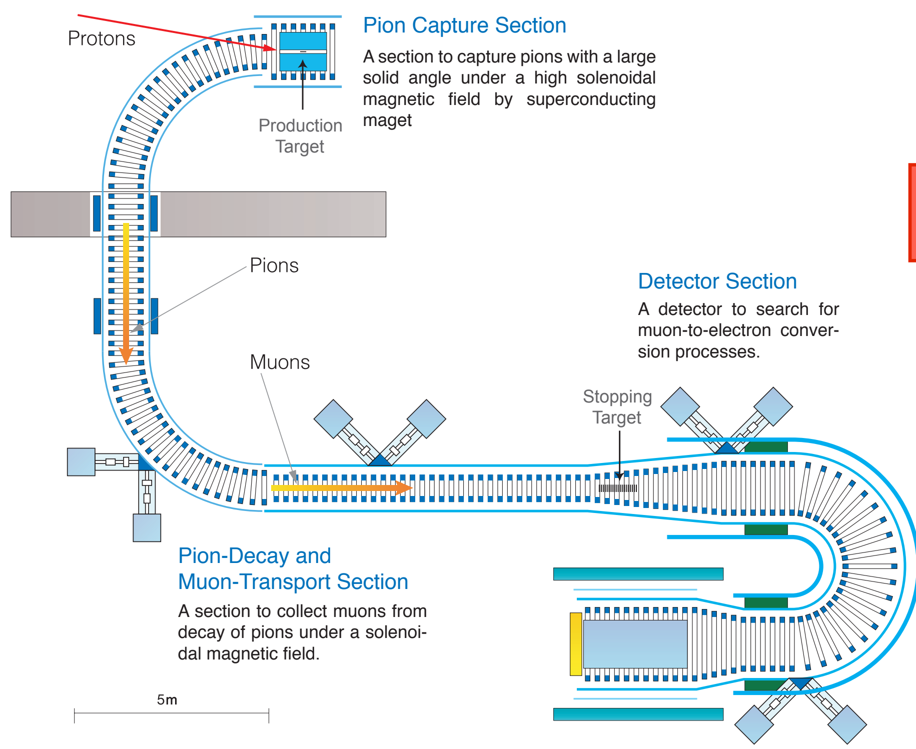
Working as the responsible person of MuSIC

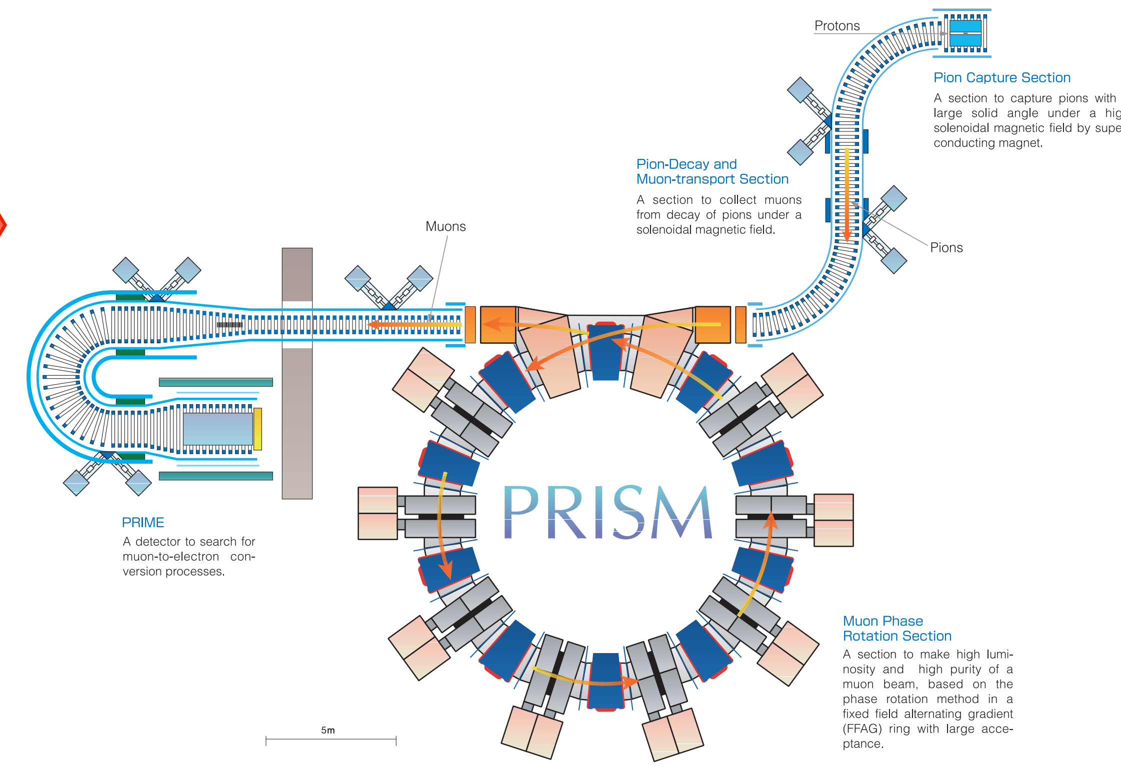
Staging approach of the μ-e conv. experiments

COMET @J-PARC

PRISM







COMET Phase-I :

physics run 2017-

BR(μ+Al→e+Al)<7x10^{-15} @ 90%CL

*8GeV-3.2kW proton beam, 12 days

*90deg. bend solenoid, cylindrical detector

*Background study for the phase2

COMET Phase-II :

physics run 2020-

BR(μ+Al→e+Al)<6x10^{-17} @ 90%CL

*8GeV-56kW proton beam, 2 years

*180deg. bend solenoid, bend spectrometer, transverse tracker+calorimeter

PRISM/PRIME :

physics run 202X-

BR(μ+Ti→e+Ti)<10^{-18} @ 90%CL

*4MW proton beam, 2 years

*180deg. bend solenoid, bend spectrometer, transverse tracker+calorimeter

* FFAG as a phase rotator

Funded!

COMET : Collaboration

164 collaborators, 37 institutes

COMET Collaboration meeting@KEK 26-30 Jan 2015

The COMET Collaboration

(Sep. 2014)

R. Akhmetshin[6,28], V. Anishchik[4], M. Aoki[29], R. B. Appleby[8,22], Y. Arimoto[15], Y. Bagaturia[33], Y. Ban[3], W. Bertsche[22], A. Bondar[6,28], S. Canfer[30], S. Chen[25], Y. E. Cheung[25], B. Chiladze[32], D. Clarke[30], M. Danilov[13,23], P. D. Dauncey[11], J. David[20], W. Da Silva[20], C. Densham[30], G. Devidze[32], P. Dornan[11], A. Drutskoy[13,23], V. Duginov[14], A. Edmonds[35], L. Epshteyn[6,27], P. Evtoukhovich[14], G. Fedotovich[6,28], M. Finger[7], M. Finger Jr[7], Y. Fujii[2], Y. Fukao[15], J-F. Genat[20], M. Gersabeck[22], E. Gillies[11], D. Grigoriev[6,27,28], K. Gritsay[14], E. Hamada[15], R. Han[1], K. Hasegawa[15], I. H. Hasim[29], O. Hayashi[29], M. I. Hossain[16], Z. A. Ibrahim[21], Y. Igarashi[15], F. Ignatov[6,28], M. Iio[15], M. Ikeno[15], K. Ishibashi[19], S. Ishimoto[15], T. Itahashi[29], S. Ito[29], T. Iwami[29], Y. Iwashita[17], X. S. Jiang[2], P. Jonsson[11], V. Kalinnikov[14], F. Kapusta[20], H. Katayama[29], K. Kawagoe[19], V. Kazanin[6,28], B. Khazin[§6,28], A. Khvedelidze[14], M. Koike[36], G. A. Kozlov[14], B. Krikler[11], A. Kulikov[14], E. Kulish[14], Y. Kuno[29], Y. Kuriyama[18], Y. Kurochkin[5], A. Kurup[11], B. Lagrange[11,18], M. Lancaster[35], H. B. Li[2], W. G. Li[2], A. Liparteliani[32], R. P. Litchfield[35], P. Loveridge[30], G. Macharashvili[14], Y. Makida[15], Y. Mao[3], O. Markin[13], Y. Matsumoto[29], T. Mibe[15], S. Mihara[15], F. Mohamad Idris[21], K. A. Mohamed Kamal Azmi[21], A. Moiseenko[14], Y. Mori[18], N. Mosulishvili[32], E. Motuk[35], Y. Nakai[19], T. Nakamoto[15], Y. Nakazawa[29], J. Nash[11], M. Nioradze[32], H. Nishiguchi[15], T. Numao[34], J. O'Dell[30], T. Ogitsu[15], K. Oishi[19], K. Okamoto[29], C. Omori[15], T. Ota[31], H. Owen[22], C. Parkes[22], J. Pasternak[11], C. Plostinar[30], V. Ponariadov[4], A. Popov[6,28], V. Rusinov[13,23], A. Ryzhenenkov[6,28], B. Sabirov[14], N. Saito[15], H. Sakamoto[29], P. Sarin[10], K. Sasaki[15], A. Sato[29], J. Sato[31], D. Shemyakin[6,28], N. Shigyo[19], D. Shoukavy[5], M. Slunecka[7], M. Sugano[15], Y. Takubo[15], M. Tanaka[15], C. V. Tao[26], E. Tarkovsky[13,23], Y. Tevzadze[32], N. D. Thong[29], V. Thuan[12], J. Tojo[19], M. Tomasek[9], M. Tomizawa[15], N. H. Tran[29], I. Trek[32], N. M. Truong[29], Z. Tsamalaidze[14], N. Tsverava[14], S. Tygier[22], T. Uchida[15], Y. Uchida[11], K. Ueno[15], S. Umasankar[10], E. Velicheva[14], A. Volkov[14], V. Vrba[9], W. A. T. Wan Abdullah[21], M. Warren[35], M. Wing[35], T. S. Wong[29], C. Wu[2,25], G. Xia[22], H. Yamaguchi[19], A. Yamamoto[15], M. Yamanaka[24], Y. Yang[19], H. Yoshida[29], M. Yoshida[15], Y. Yoshii[15], T. Yoshioka[19], Y. Yuan[2], Y. Yudin[6,28], J. Zhang[2], Y. Zhang[2]

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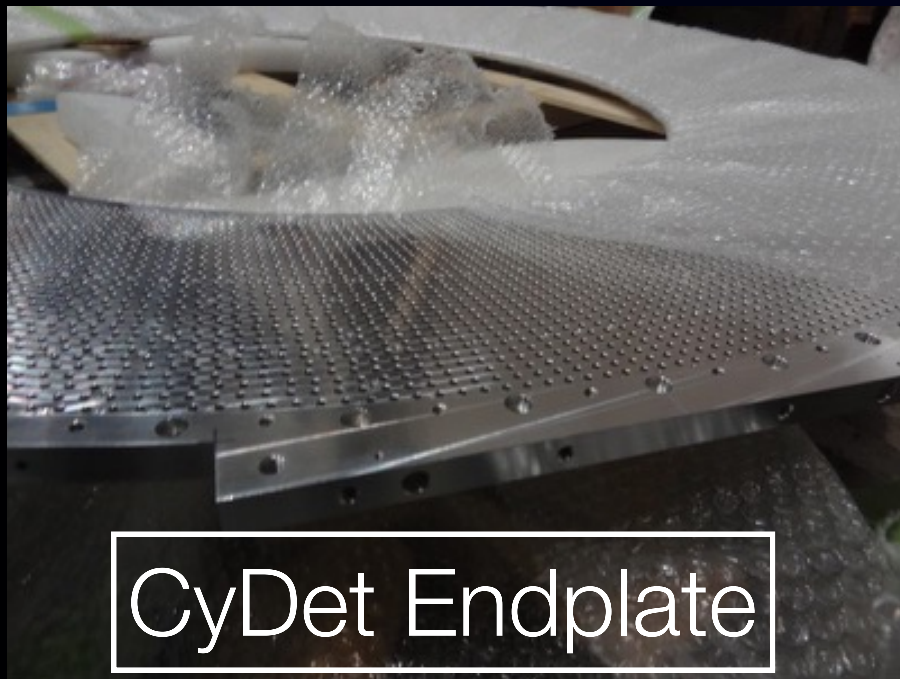
[21] *National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*

COMET : Status

- COMET building completed!

COMET : Status | CyDet


CyDet Endplate


CyDet Outer wall


CyDet assembly


CyDet on wire stringing assembly

Cylindrical Drift Chamber for e$^-$ tracking

MuSIC: Development of the pion capture system

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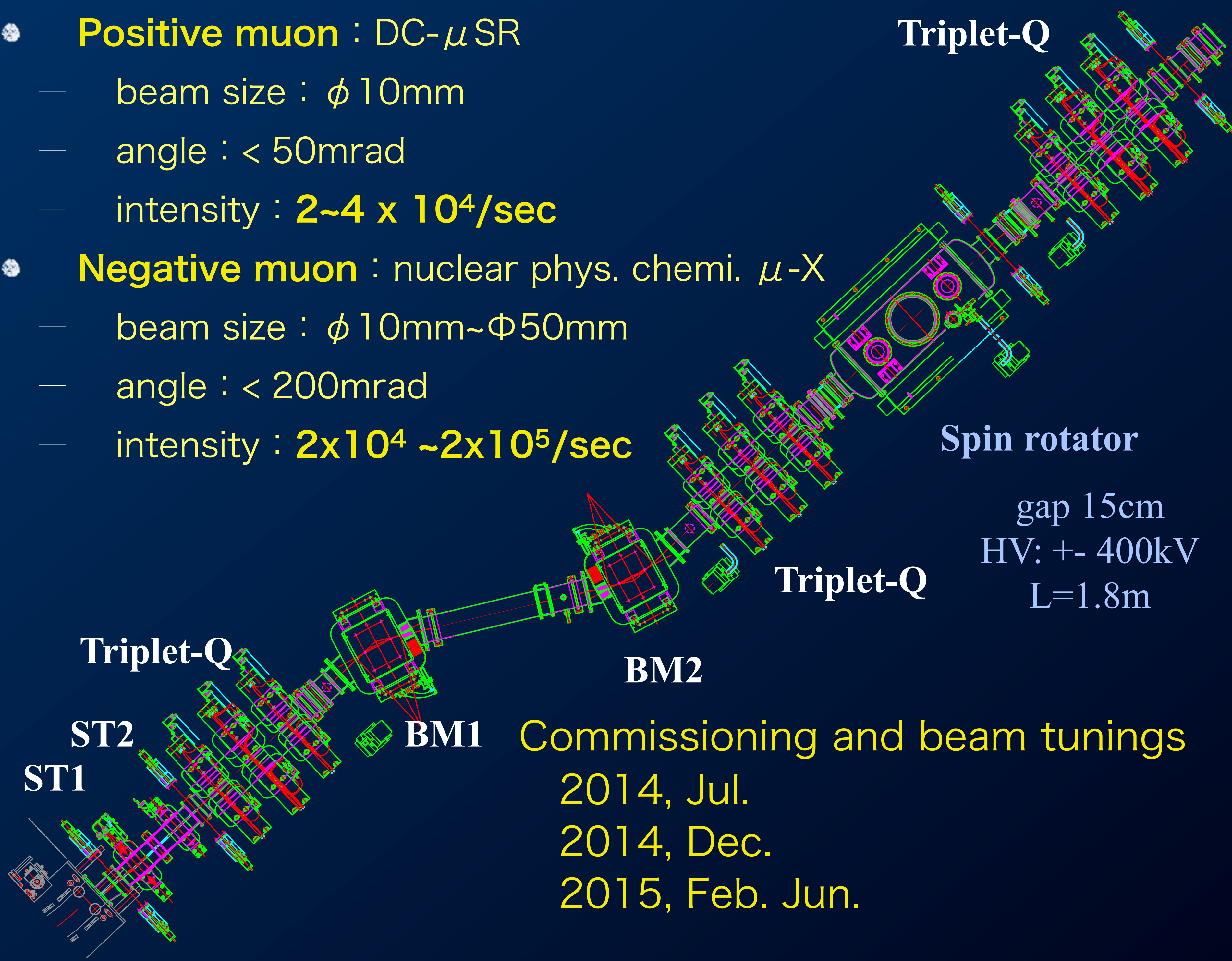
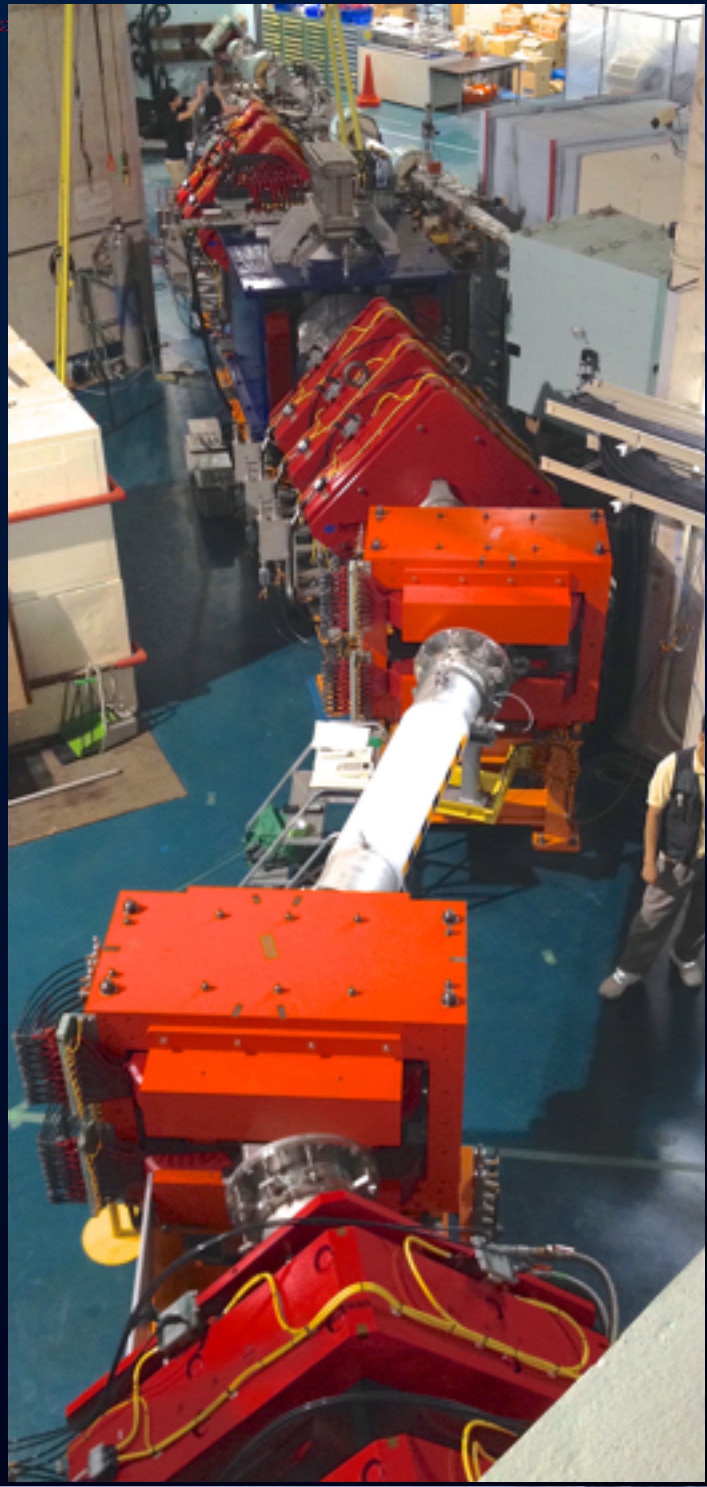
Working as the responsible person of MuSIC

The DC muon beam line in Japan
RCNP-MuSIC-M1 build in 2013JFY

Goal of the beam performance

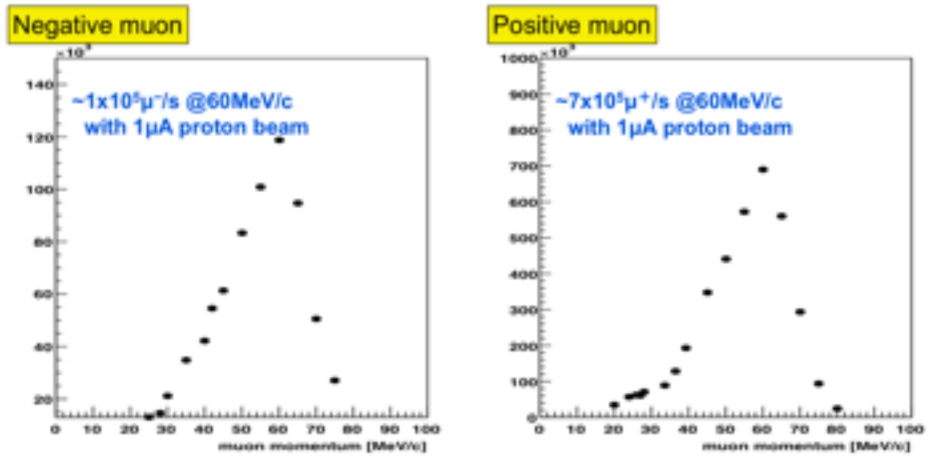
- **Positive muon**：DC-μSR
  - beam size：ϕ10mm
  - angle：< 50mrad
  - intensity：**2~4 x 10^4/sec**
- **Negative muon**：nuclear phys. chemi. μ-X
  - beam size：ϕ10mm~Φ50mm
  - angle：< 200mrad
  - intensity：**$2x10^4$ ~$2x10^5$/sec**



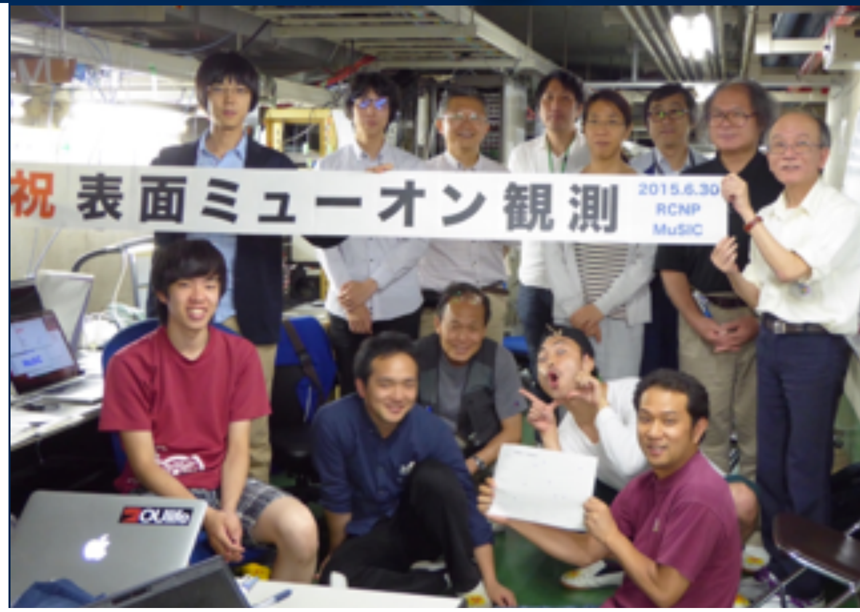


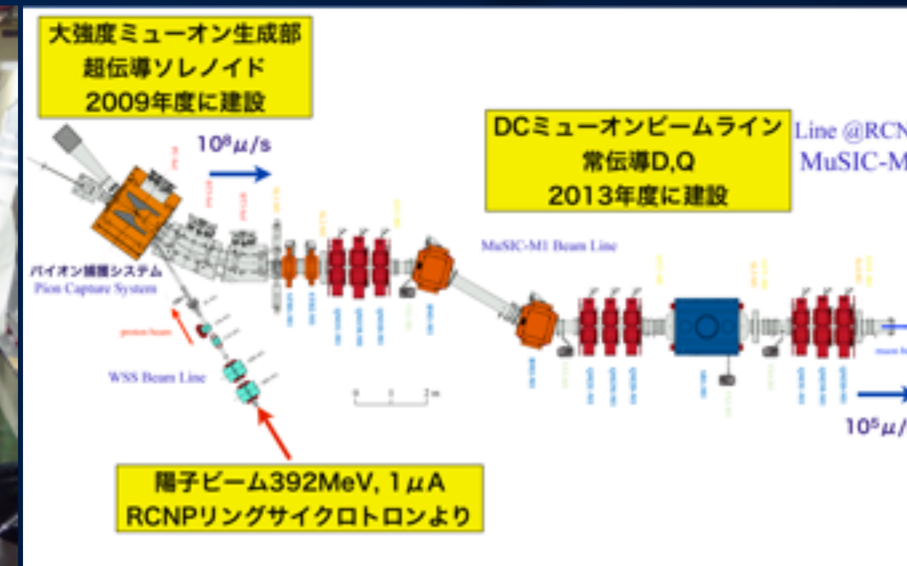
Commissioning and beam tunings
2014, Jul.
2014, Dec.
2015, Feb. Jun.

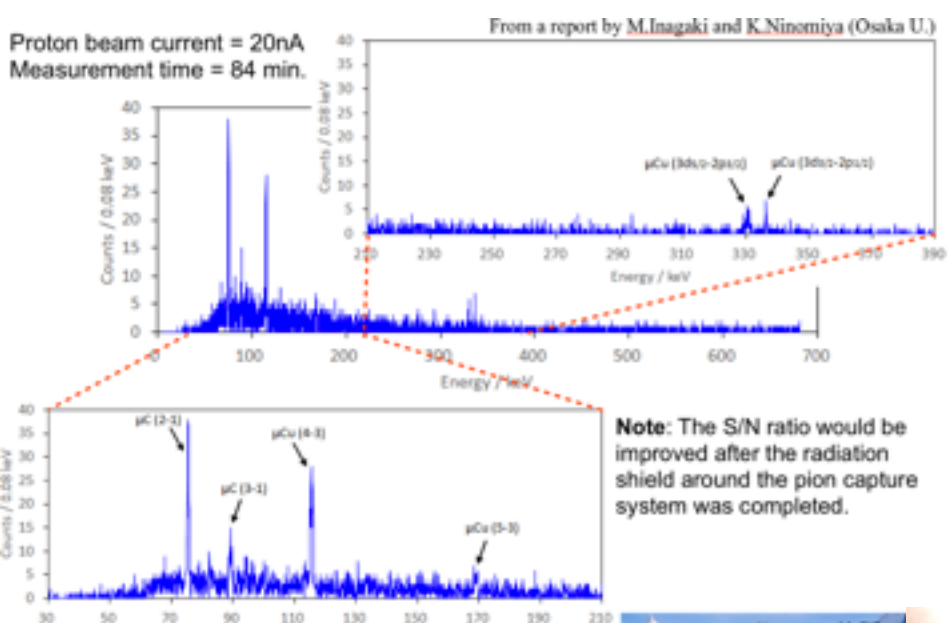
MuSIC-M1: Finalizing beam tuning



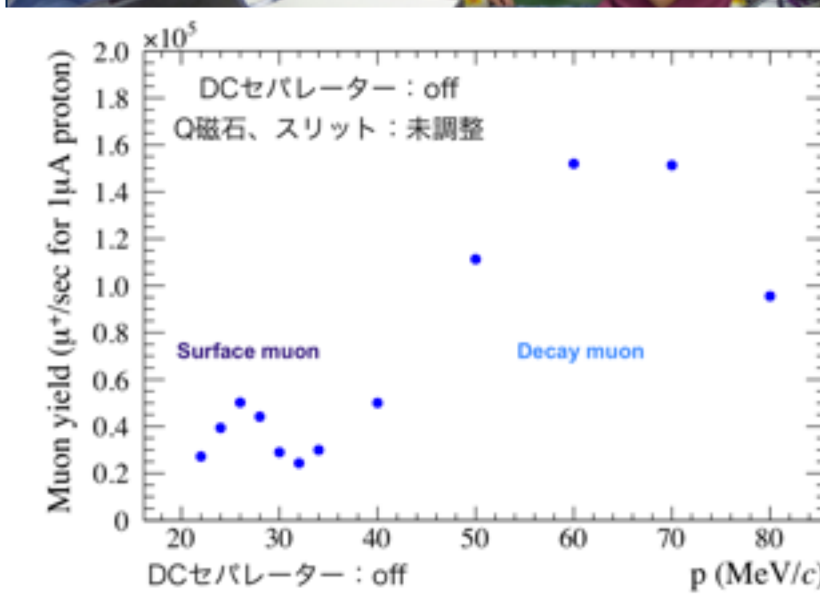
ビーム試験 ：2014年12月、2015年2月　　DCセパレーター：off
- 崩壊ミューオン強度の測定に成功。
- ミューオンX線測定のデモンストレーションに成功



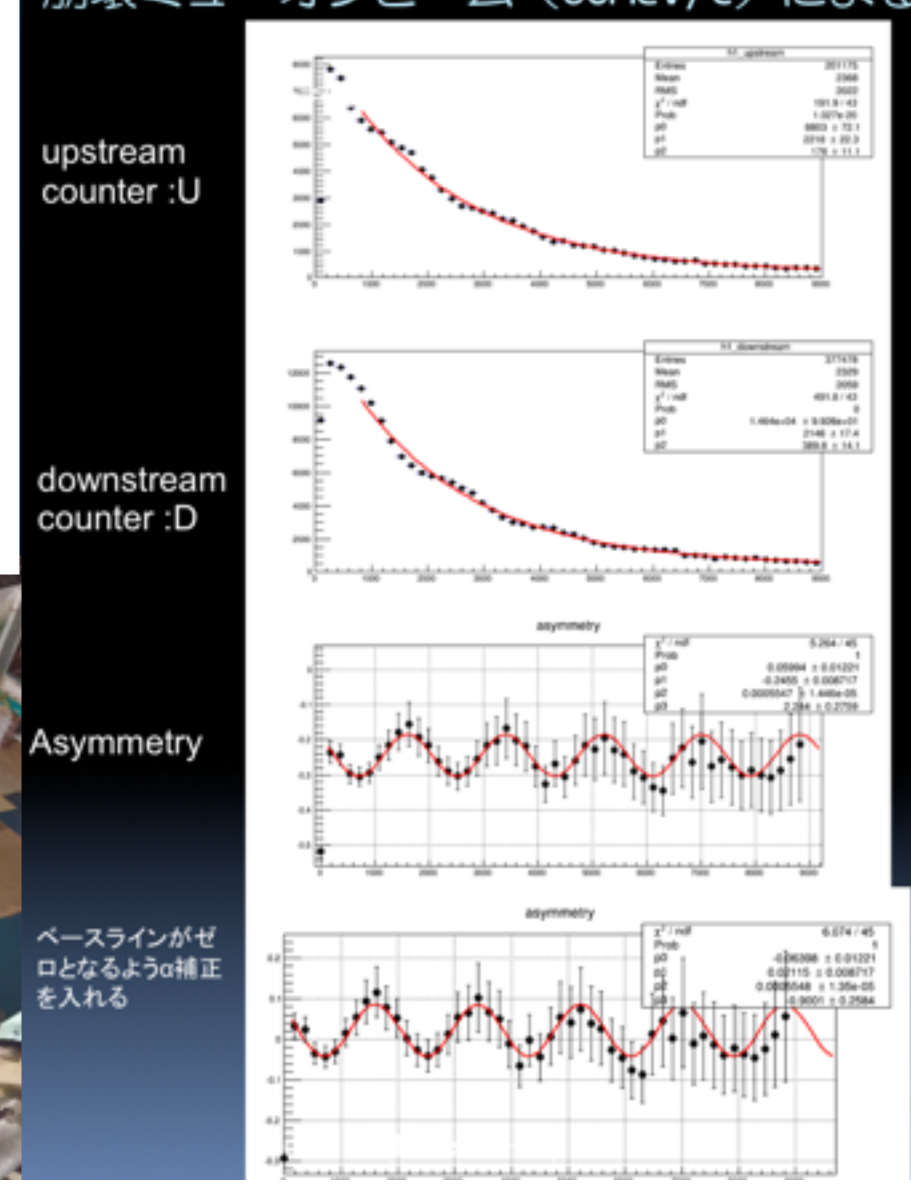


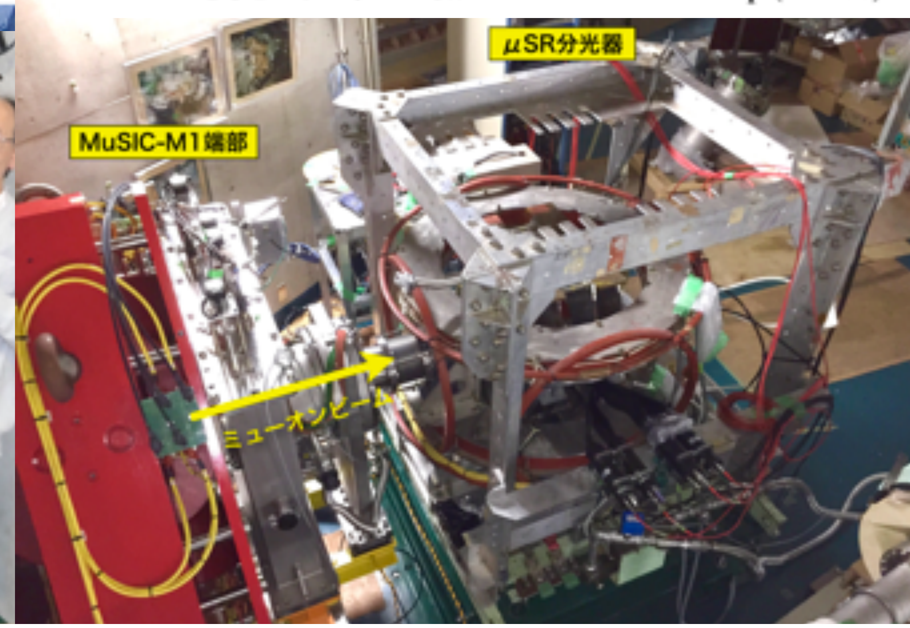


Note: The S/N ratio would be improved after the radiation shield around the pion capture system was completed.



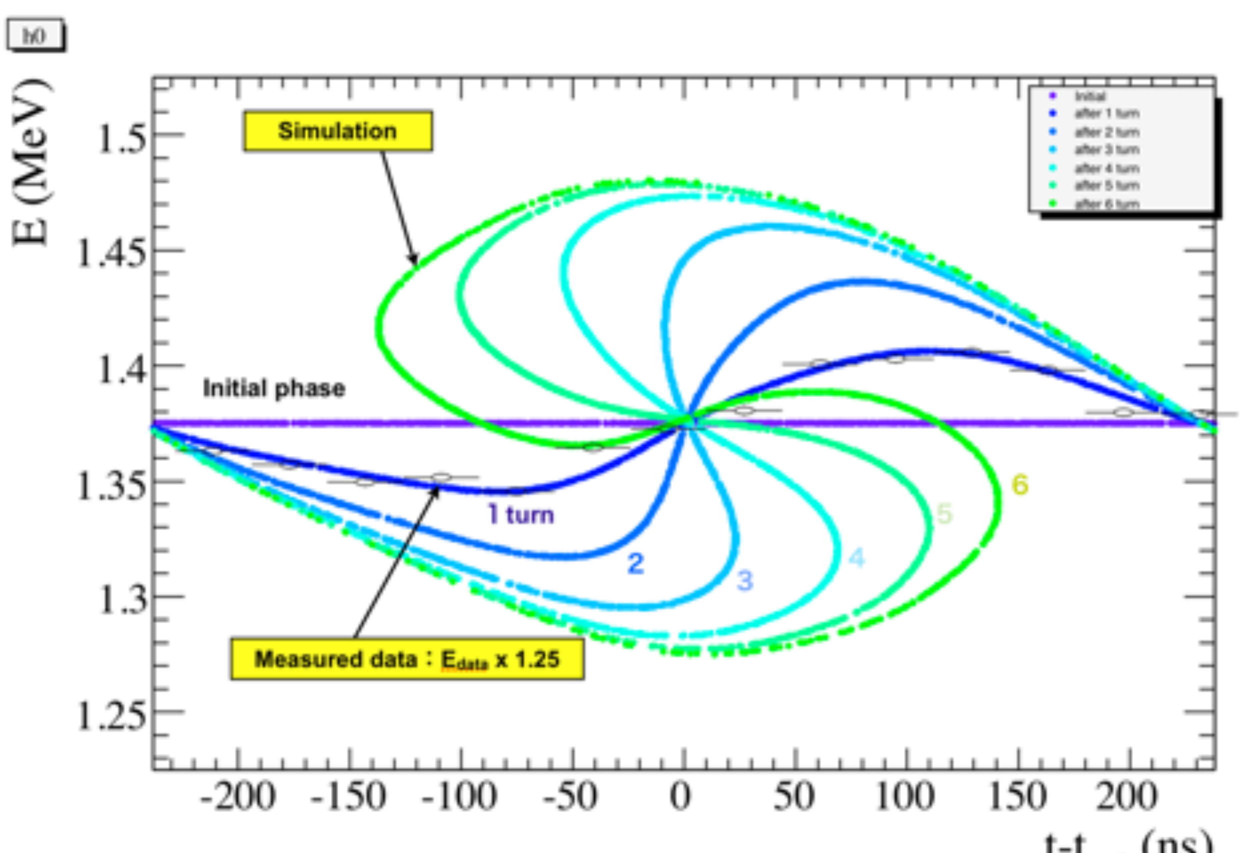
崩壊ミューオンビーム（60MeV/c）による





Toward the PRISM - ultimate μ-e experiment

PRISM-FFAG R&D



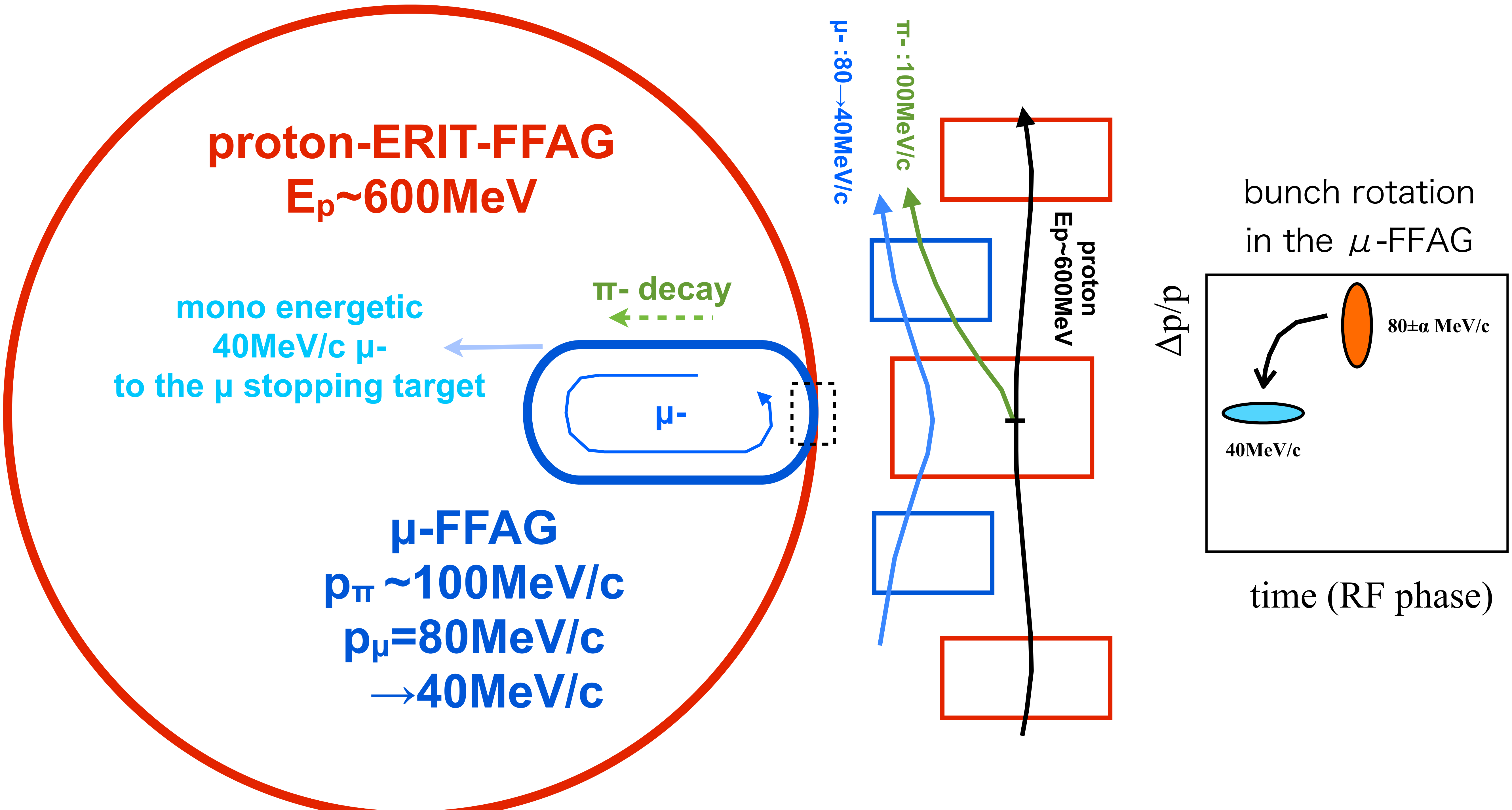
phase rotation of α in the 6-cell FFAG

- PRISM-FFAG was disassembled. It is sleeping at W-exp hall of RCNP.
- The PRISM task force was formed (Jaroslow's talk).

Issues of the PRISM

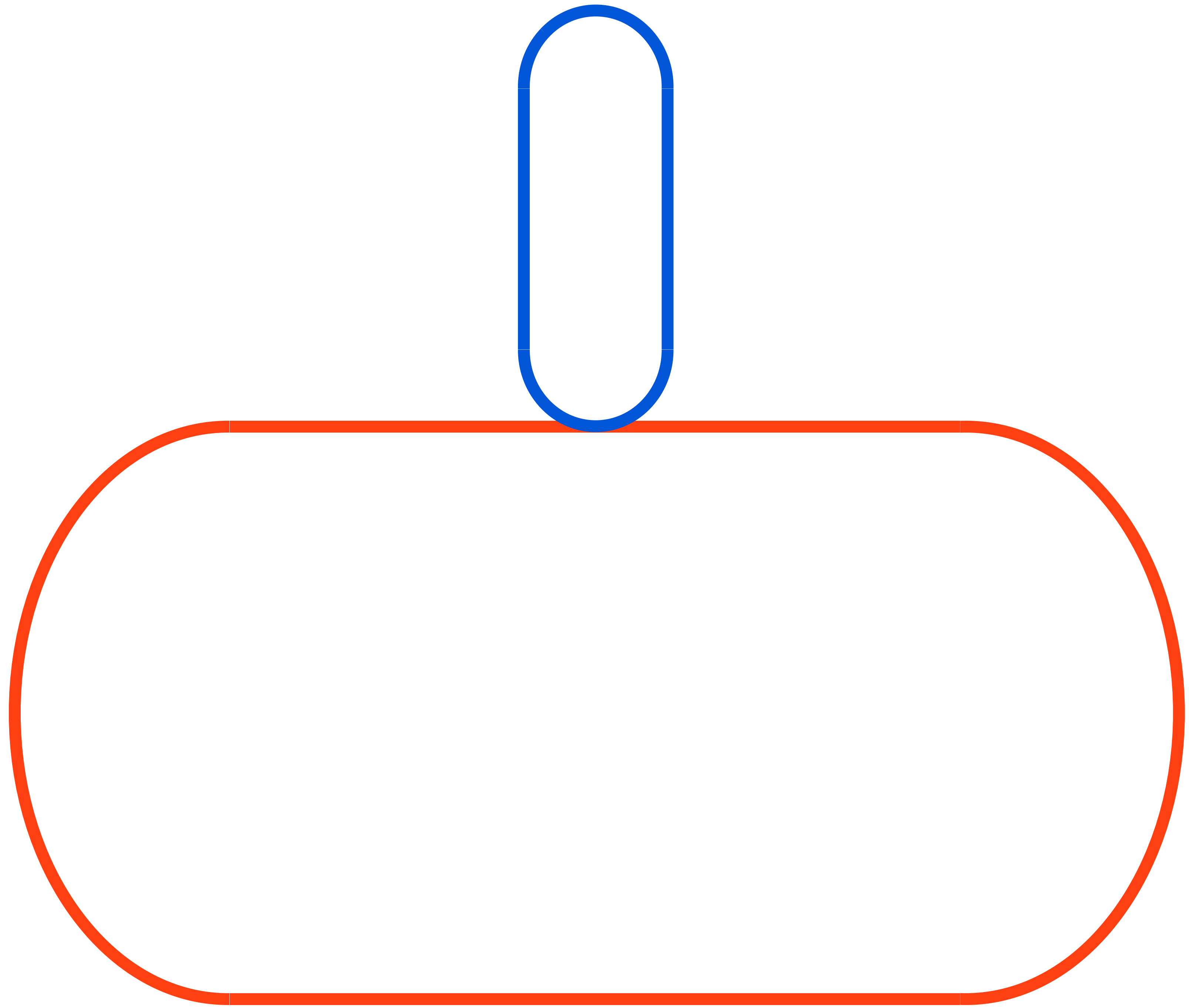
- There are mainly two issues:
  - the transport line from the solenoidal pion decay channel into the FFAG ring
  - the injection and extraction system.
- Need to solve
- I will show conceptual figures to solve some of these issues.

A concept of new PRISM



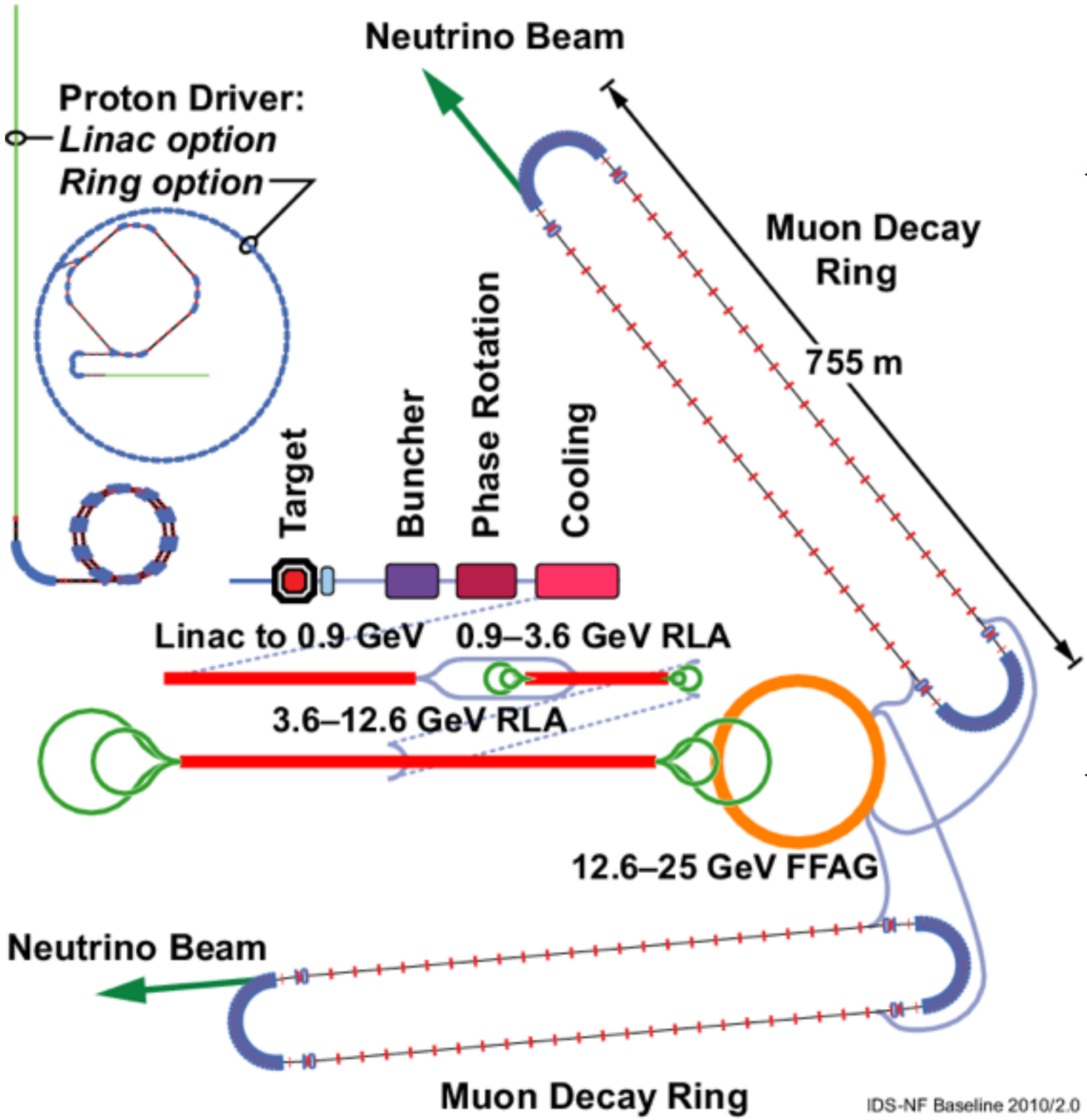
- Muons are decelerated in the μ-FFAG ring.
- V-FFAG or H-FFAG?
- Good solutions for extraction?

A concept of new PRISM



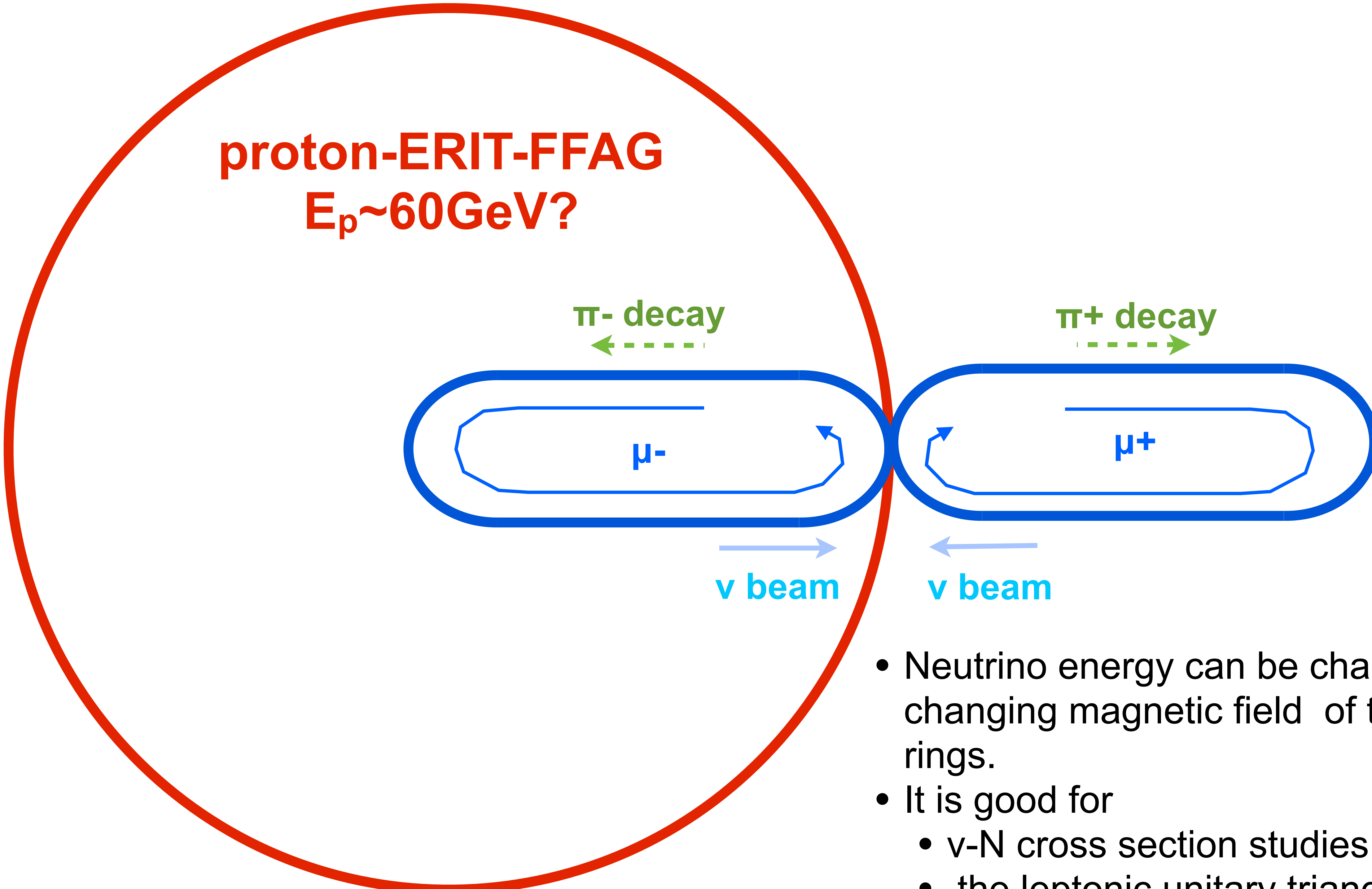
- A racetrack FFAG is better for the proton ring?

IDS-NF baseline 2010/2.0



- After the pion production target, it has
  - buncher,
  - phase rotator,
  - cooling, and
  - muon accelerator ...
- Very complicated and a lot of technical challenges !

MERIT + nuSTORM / NF



- Neutrino energy can be changed by changing magnetic field of the μ-FFAG rings.
- It is good for
  - ν-N cross section studies and
  - the leptonic unitary triangle studies.

- ✦ possible?
- ✦ Is this work as a NF? μ acceleration is not necessary!

Some comments to FFAGs

Comment 1

- We have built many FFAGs and studied many things. We also have many unique ideas which work with FFAG.
- I think it is very important time for future FFAGs, because some projects are considering to use FFAGs as practical accelerators. eRICH, PRISM,,,
- Some people said...
  - "We can not reproduce performance of real built FFAG in computer models", pointed out by Meot.
    - It is very crucial problem. Performance of practical accelerators can be predicted by simulations.
  - "We need to demonstrate many aspects of FFAGs"

Study with booster or ERIT

- Most of people are working with 150MeV-FFAG at KURRI and Kyushyu-U.
  - There are many progress in these years.
  - But, I think still we have a lot of unknown things of the 150-MeV FFAGs.
  - It is the most difficult FFAG,
    - yoke free, saturation in the iron
    - 500Gauss stray field at the center of straight section.
  - There are many 150MeV-FFAG specific issues.
    - We should categorize the issues to
      - (1) FFAG common issues
        - solve and study the issues with the booster FFAG / ERIT FFAG
      - (2) 150MeV specific issues
        - need to work with 150MeV FFAG
      -

Scaling FFAGs operated

	Site	Ion	E_{max} (MeV)	Sector type	Cell	Radius (m)	First Beam	Acc. Scheme	Comments
PoP	KEK	p	1	Radial	8	0.8-1-1	2000	rf	The 1st proton FFAG. Accelerate protons from 50 keV to 500 keV in 1 msec.
150MeV	KEK	p	150	Radial	12	4.5-5.2	2003	rf	100 Hz, 90% extraction
ADSR-Injector	KURRI	p	2.5	Spiral (40°)	8	0.6-1.0	2006	induction	Initial spec : 120 Hz, 1 μA Later : 1 kHz, 100 μA, 200 MeV
ADSR-Booster			20	Radial	8	1.4-1.7	2006	rf	
ADSR-MR			150	Radial	12	4.5-5.1	2008	rf	
ERIT	KURRI	p	11	Radial	8	2.35	2008	rf	70 mA ionization cooling ring to produce a neutron beam for BNCT
PRISM-demo	Osaka-U.	α	1.0	Radial	6	3.0	2008	rf	Demonstrate phase-rotation for the mu-e conv. experiment (PRISM)
EB-FFAG	NHV Co.	e	0.5	Spiral (30°)	6	0.19-0.44	2008	induction	Prototype of electron FFAG for industrial applications
Radiatron	RadiaBeam Technologies, LLC (US)	e	5	Radial	12	0.3-0.7	(2008)	induction	Prototype of a high power accelerator for industrial applications

Scaling FFAG

- Features of the scaling-FFAG
  - beam dynamics dose not depends on the energy
  - zero-chromaticity (constant tune)
- Magnetic field : $B(r,\theta) = B_0\left(\frac{r}{r_0}\right)^k f\left(\theta - \varsigma \ln \frac{r}{r_0}\right)$
  - usually we adjust B at the mid plane.
- But most of FFAG has tune variation
- I propose to make a magnetic field to realize a perfect scaling FFAG.