Muon Physics in Japan

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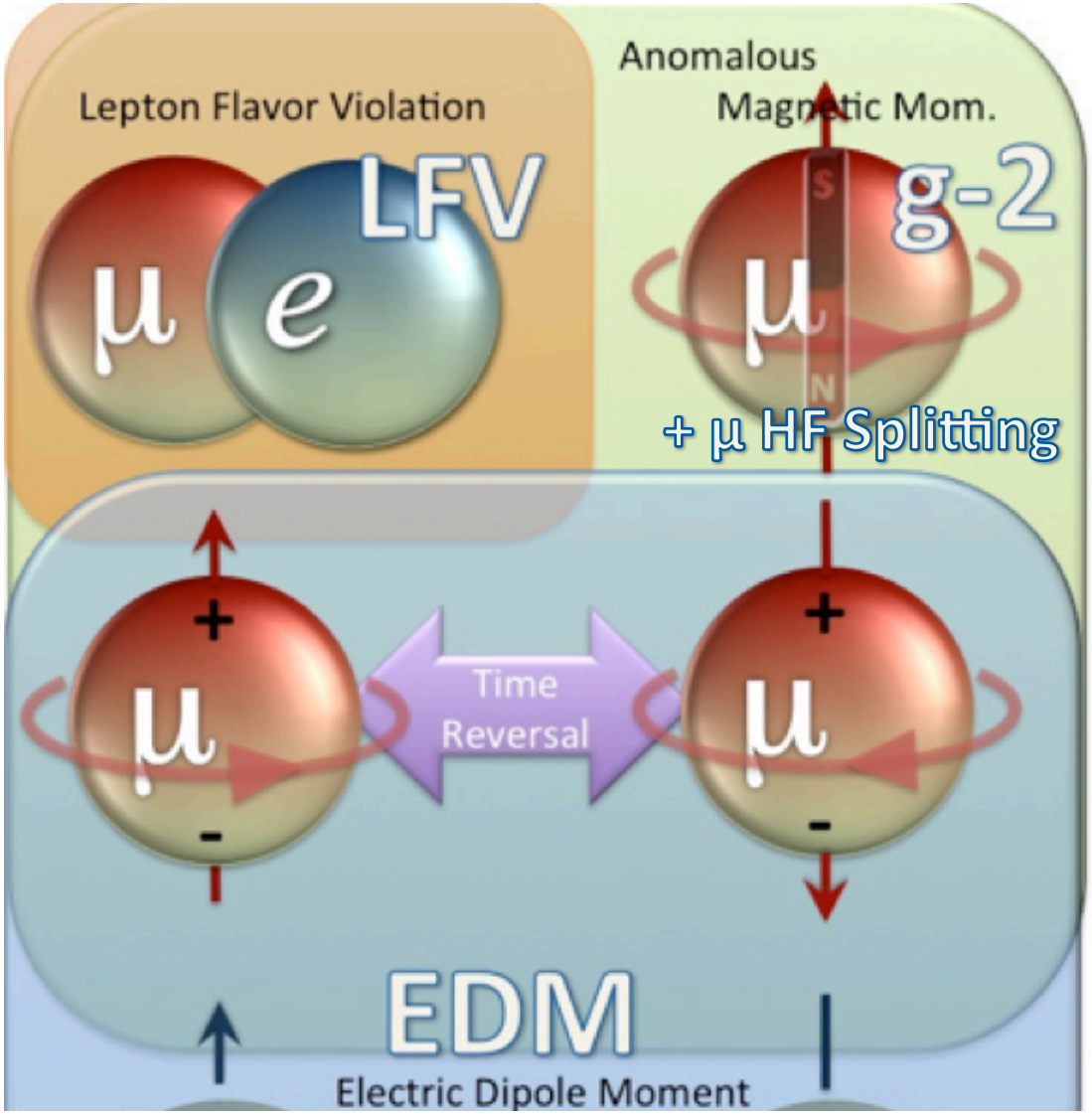
Three Measurements Planned at J-PARC



$$\mathrm{EDM} \propto \mathrm{Im}(m^2_{\tilde{\mu}\tilde{\mu}})$$

$$\mathrm{cLFV} \propto \Delta m^2_{\tilde{e}\tilde{\mu}} + \Delta m^2_{\tilde{\mu}\tilde{e}}$$

$$\mathrm{g-2} \propto \mathrm{Re}(m^2_{\tilde{\mu}\tilde{\mu}})$$

$$M^2_{\tilde{l}\tilde{l}'} = \begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

SUSY Mass Matrix

World Status / Plans

		Funded
		$\mu^+ \to e^+\gamma$
$\mu^- N \to e^- N$ **COMET, DeeMe**	$(g-2),\ EDM_\mu$	$\mu^+ \to e^+e^-e^+$
$(g-2),\ EDM_\mu$ **J-PARC E34**	$\mu^- N \to e^- N$	
$\mu^+ \to e^+e^-e^+$ **MuSic @ Osaka**	$\mu^+ \to e^+e^-e^+$ $\mu^+ \to e^+\gamma$	Time

Funding / Approval Route For Muon Expts

PAC / MuSAC : give approval in two stages
At each stage: Reject, further R&D, recommend, approve.

J-PARC PAC (nuclear/particle)

Advisory Panels

J-PARC MuSaC / KEK Muon

KEK : O($300M)

IPNS particle/nuclear

IMSS materials

$

MuSic @ Osaka

University Funds
Ministry (MEXT)
JSPS etc

Approved Funded Experiment

J-PARC 25% of KEK budget

J-PARC experiment approval status

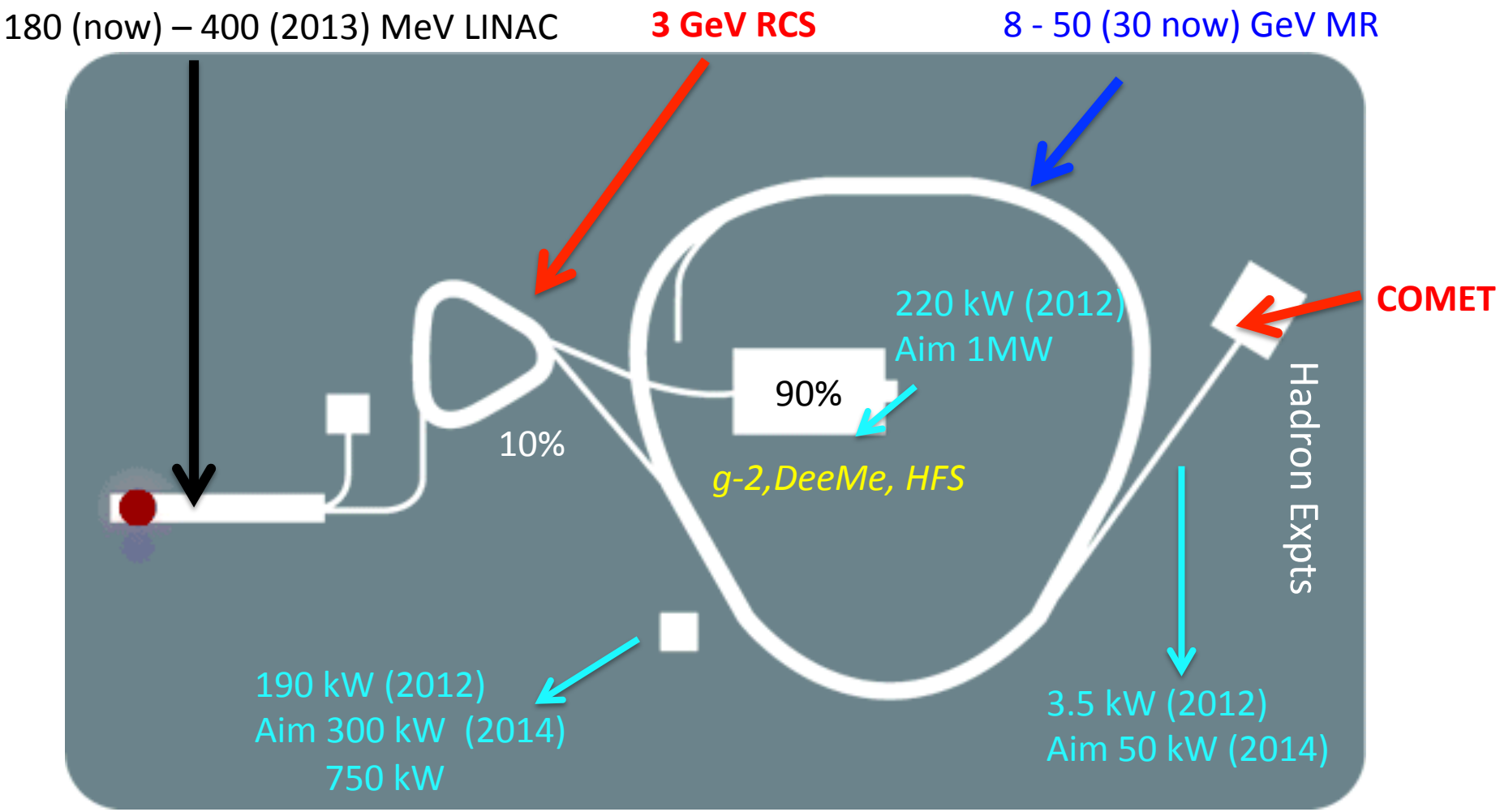
COMET : Stage-1 approved & stage-2 (final) pending TDR.
Phase-1 recommended by PAC and construction of high p_T beamline & first 90^0 of COMET expected to be in 2013 KEK budget
Phase-I "TDR" for July PAC.

MuHFS : Stage-1 approved

DeeMe : Stage-1 IPNS PAC : more R&D requested (extinction)
: Stage-1 IPMSS MuSaC approved

g-2/EDM : Stage-1 recommended for approval by IPNS PAC
Stage-1 approved by IPMSS MuSAC
Specific R&D requests before Stage-2.

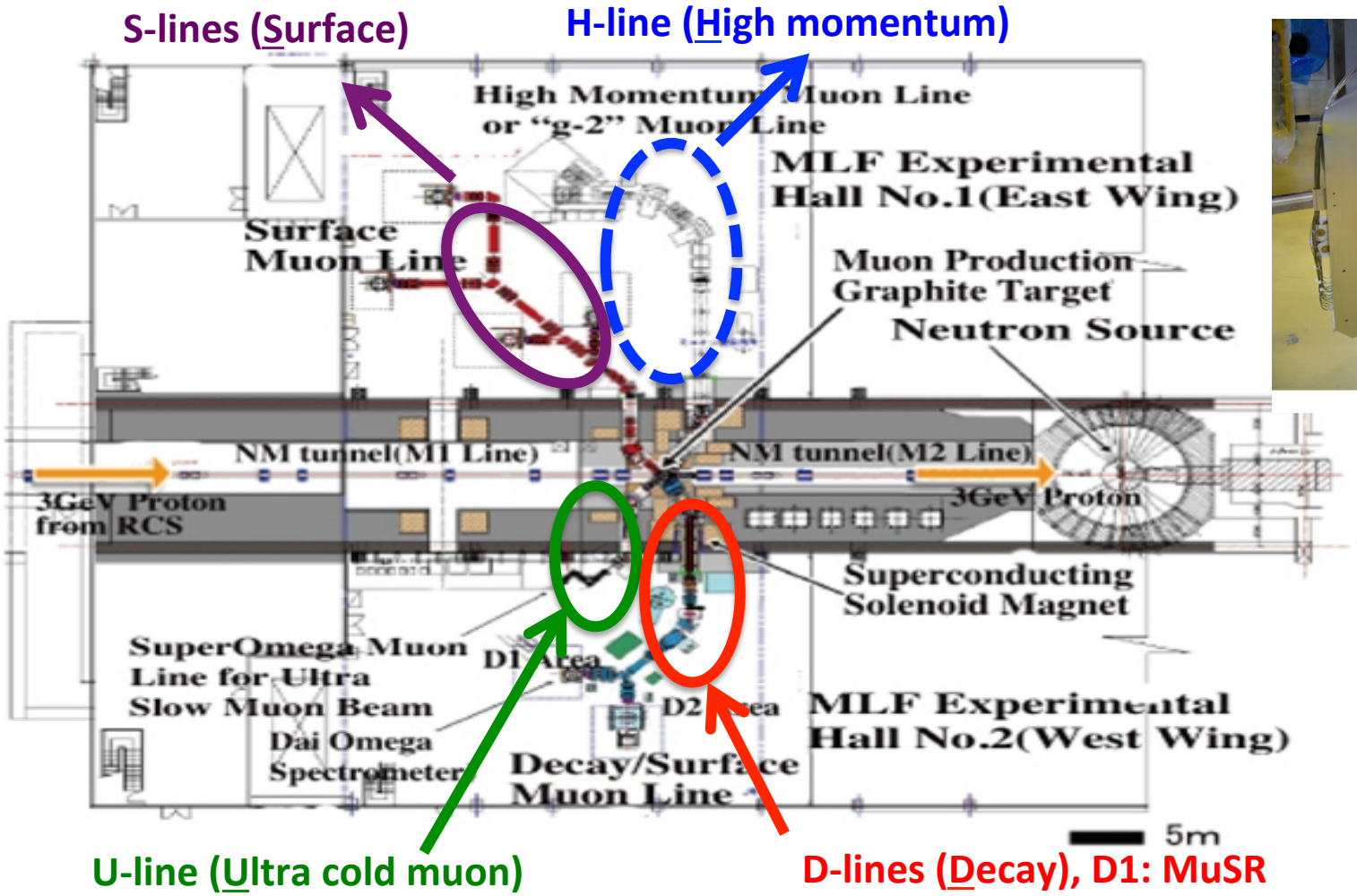
J-PARC Complex

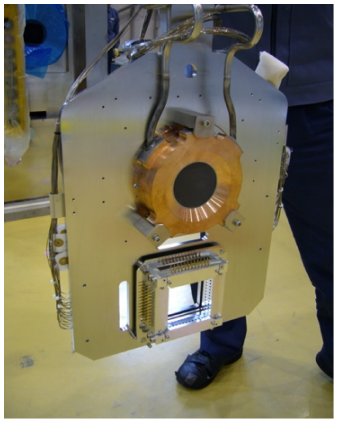


Cannot run COMET (@ 8 GeV) at the same time as the neutrino programme (30-50 GeV)

3 GeV Beam from RCS to MLF Hall

This is where g-2, μHFS, DeeMe experiments are intended to be sited





3 GeV Beamlines

D-line : complete now world's most intense pulsed muon source
(D1 area 10^6 μ^+/s at 220 kW and expect 10^7)

U-line : ultra cold muon beamline (ready end of 2012)
- mostly for μSR but will also be used for some g-2 R&D

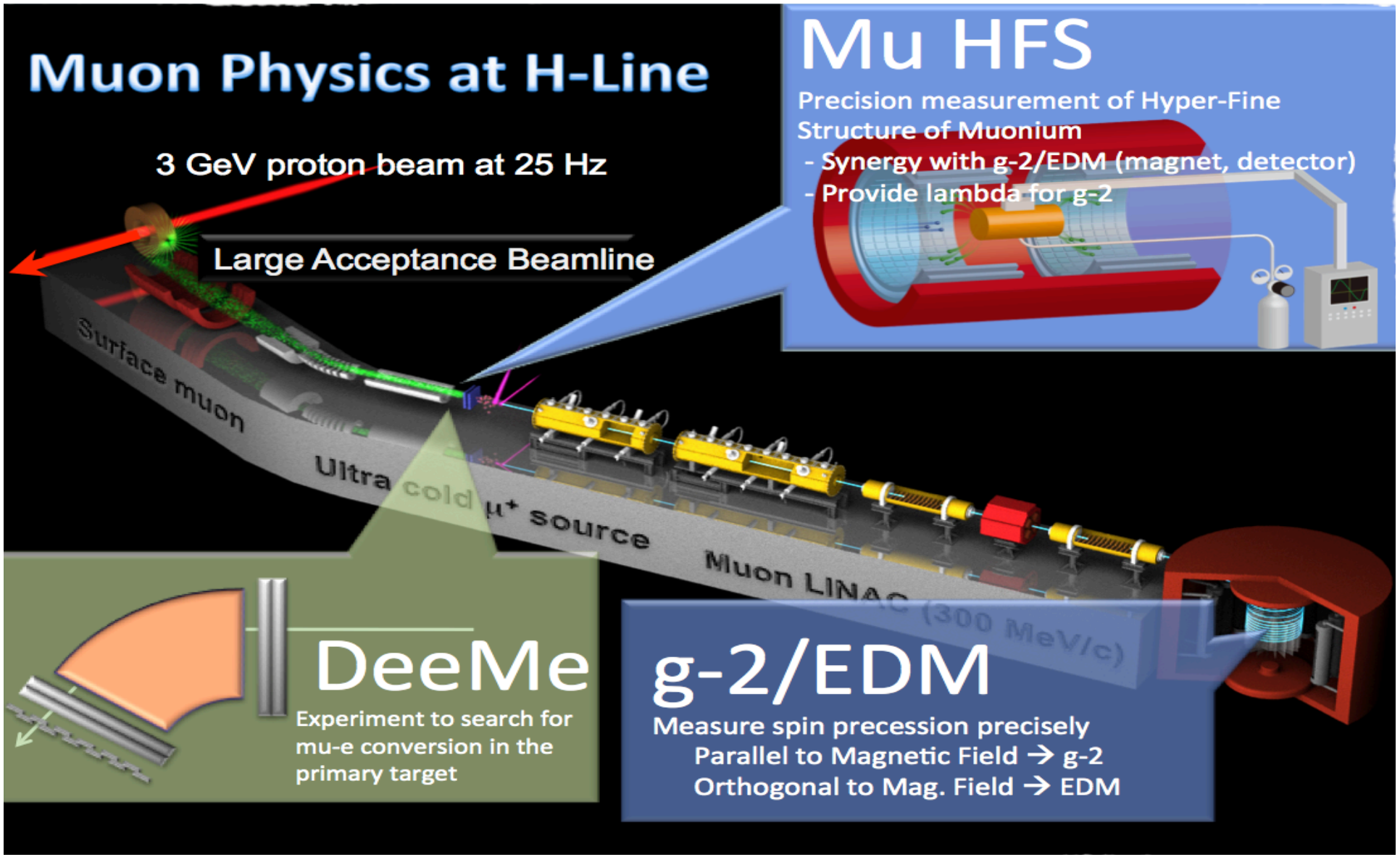
S-line & H-line : portions around target to be constructed this year.

Completion of H- line is high priority for DeeMe, g-2, MUHFS.

U-line, D-line in MLF

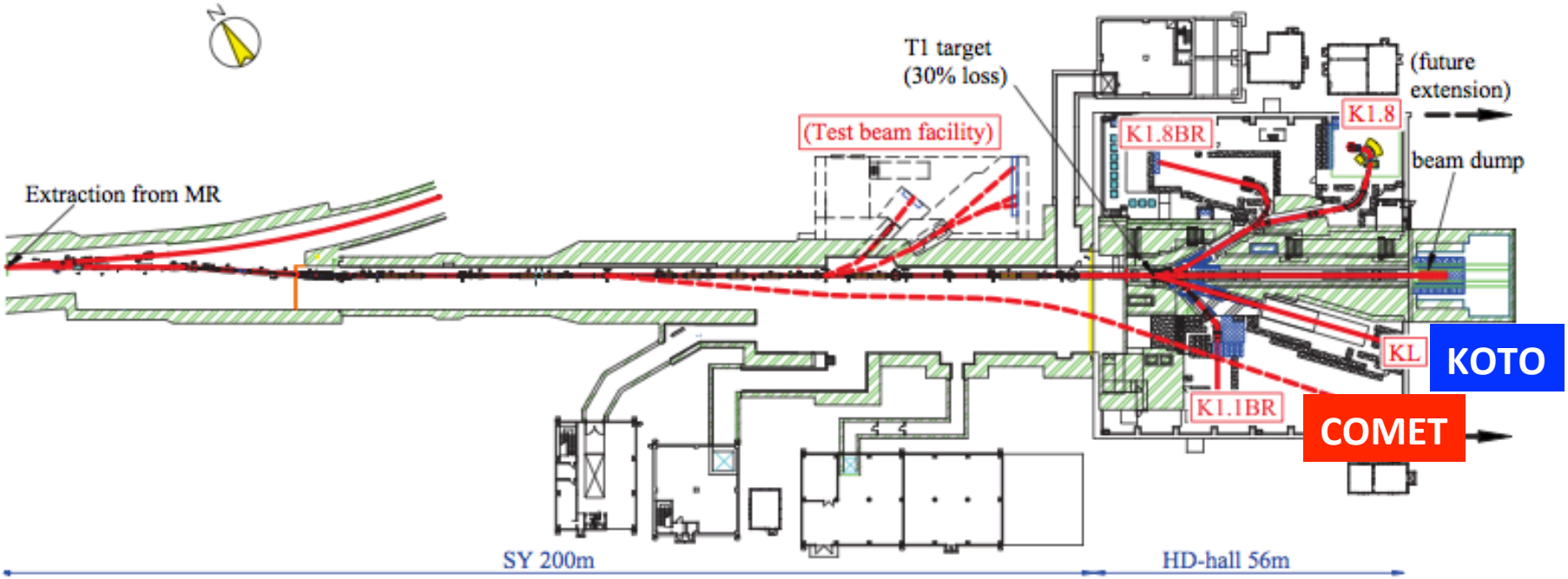
Ultra cold muon tests: both production and acceleration in U-line scheduled for Fall 2012

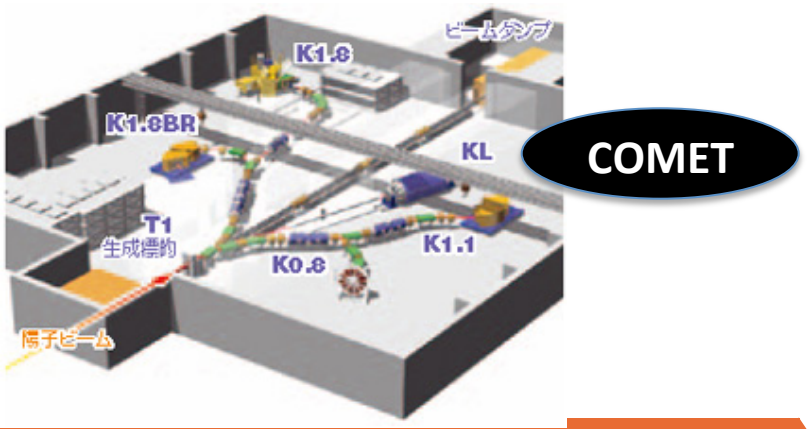
Proposed H-Line



Hadron Hall / NP Beamlines

Presently there are 4 (K1.8, K1.8BR, KL, K1.1BR) from 30 GeV main-ring.





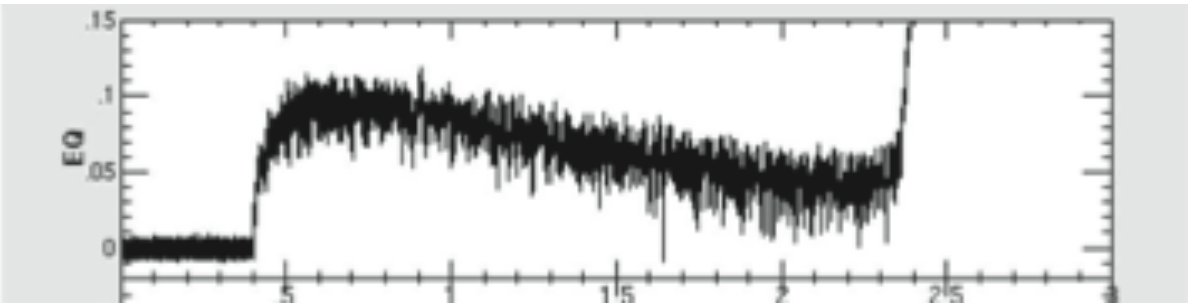
K1.1BR experiments that could jeopardise COMET schedule have been given lower priority.

J-PARC Slow Extraction

Beam fast extracted (FX) for neutrinos.

Bunched slow extraction (SX) @ 8 (-12) GeV crucial for COMET.

Jan 2012 test : "normal" slow extraction at 30 GeV.
3.5 kW delivered to users with duty factor of 43% &
extraction efficiency 99.5%.
Short 10 kW operation at 96% extraction achieved.



COMET extinction and bunched slow extraction (@ 30 GeV) tests presently underway.

In the Fall: move to routine 10kW SX and test run of 50kW extraction.

J-PARC g-2 / EDM

$$H = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

$$\vec{\mu} = g \frac{e\hbar}{2m} \hat{\sigma} \qquad \vec{d} = \eta \frac{e\hbar}{2m} \hat{\sigma}$$

MAGNETIC

$$g = 2(a+1)$$

ELECTRIC

$$\eta = 0$$

a_μ = ½ (g-2) : has SM (strong, weak, EM) contribution + BSM.

η = 0 : any deviation from this is new physics (CP-violating)

g-2 methods

$$\omega = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

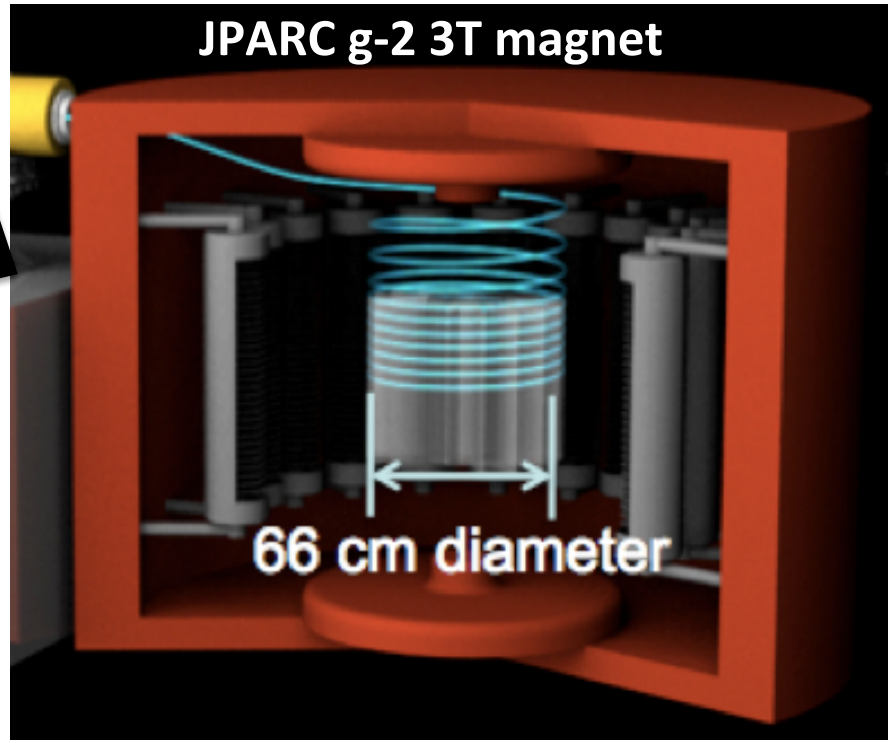
Traditional approach : use magic γ (29.3), p = 3.09 GeV muons.

- BNL measurement and proposed FNAL g-2 measurement

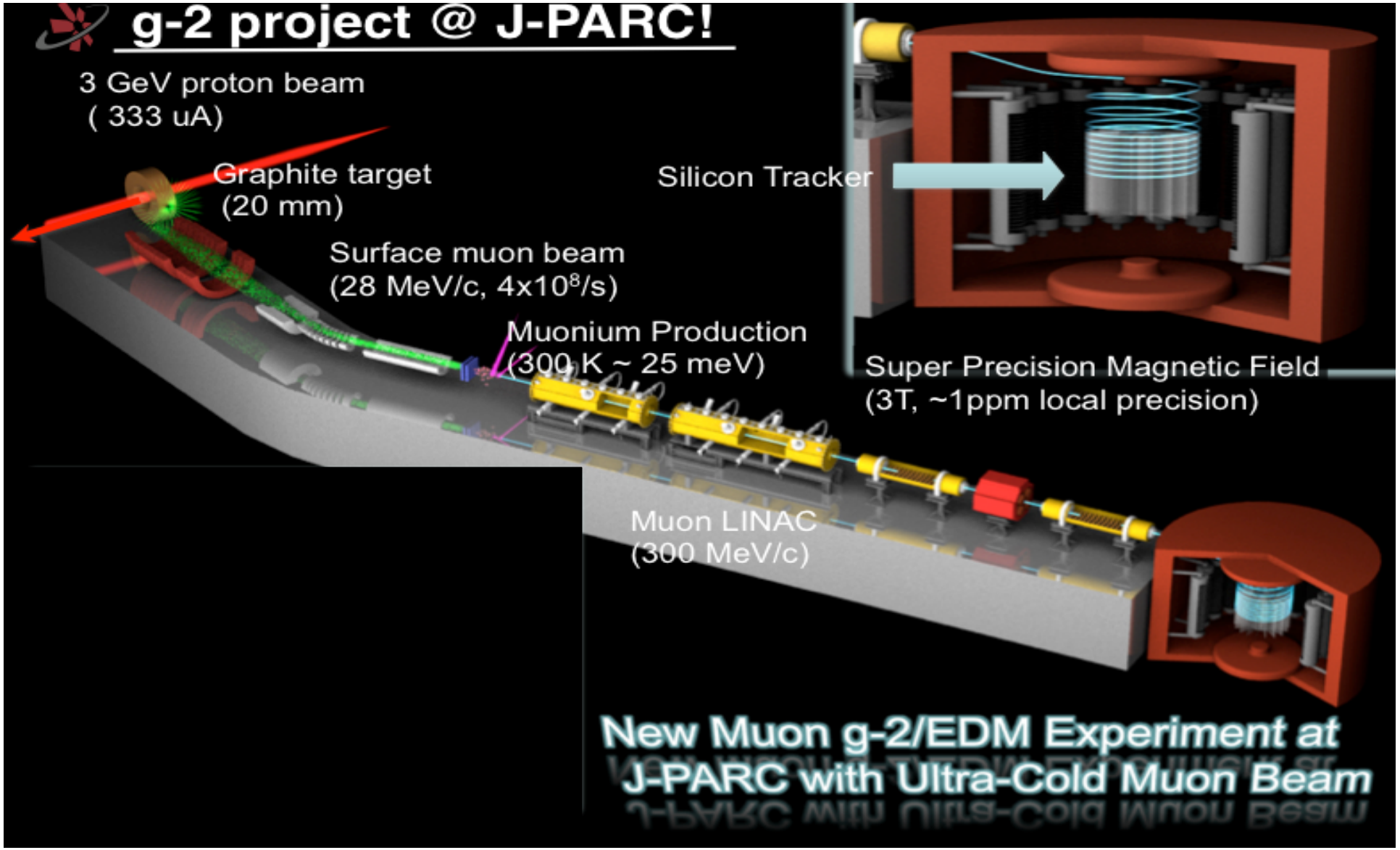
J-PARC proposal : use E ~ 0
: ultra-cold muons (low β)
: larger (and more uniform) B.

Use MRI magnet

MRI magnets uniformity of 1ppm vs 100ppm in BNL experiment.



In dedicated “H” beamline at J-PARC



Several Challenges

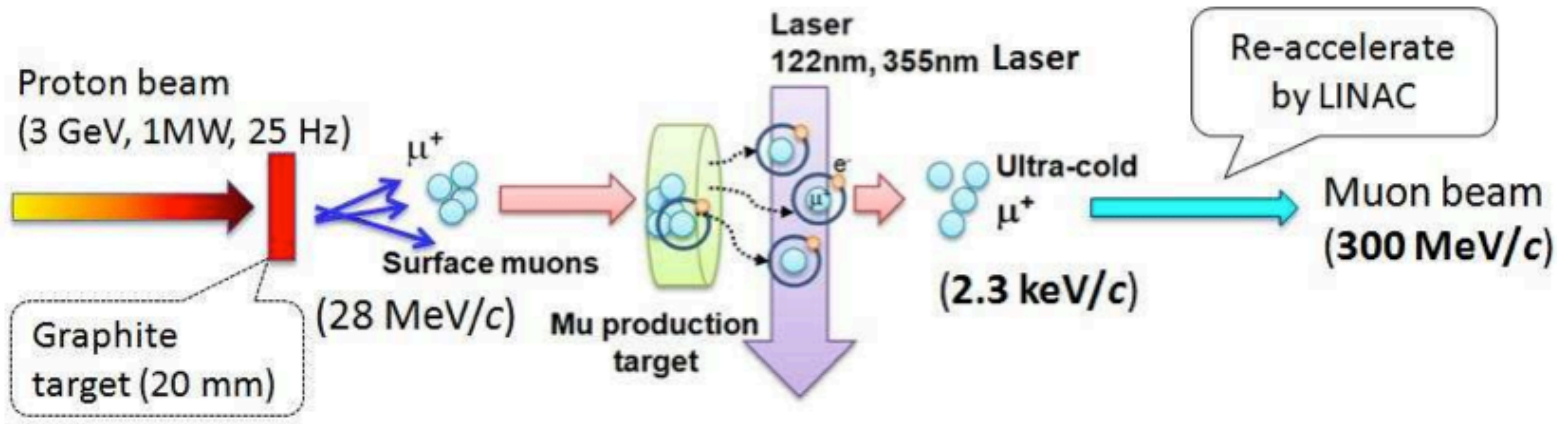
Getting a sufficient rate of ultra cold muons (require 10^6 /sec and 10^{12} e^+)

Avoiding pile-up issues in detector with the high rate

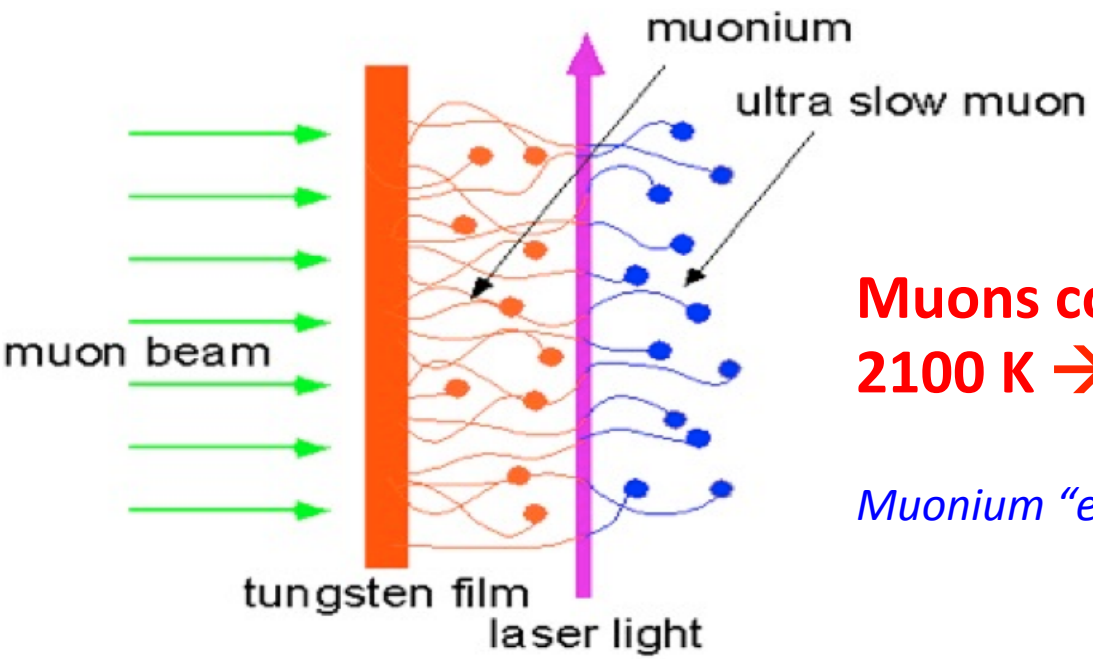
Achieving v. small vertical beam divergence : $\Delta p_T/p_T = 10^{-5}$

Requires advances in "muonium" production

- target materials e.g. nano-structured SiO_2
- lasers (pulsed 100 μJ VUV) to ionise muonium (x100)



JPARC g-2



Muons cooled
2100 K → 300 K

Muonium "evaporates" from surface

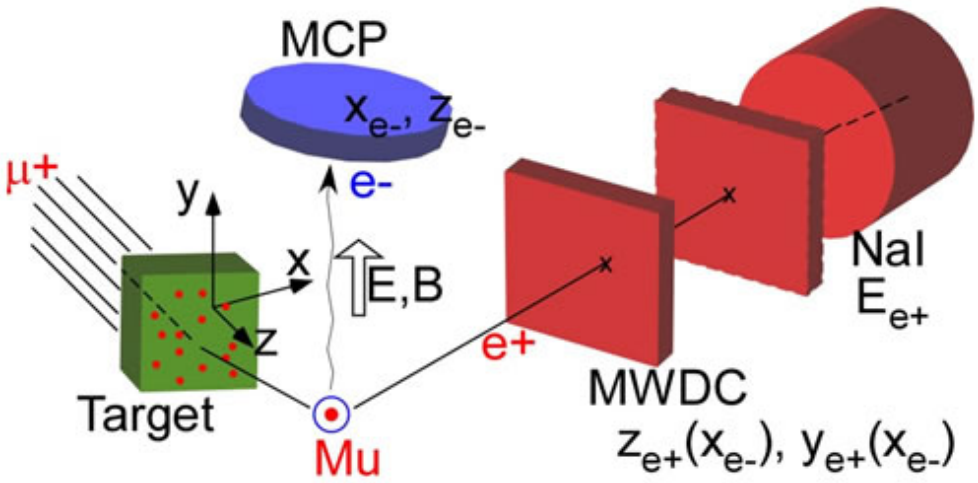
Much R&D on optimising /understanding the muonium yield

Initial studies at RAL with hot tungsten have produced 15 cold μ^+/s but require a room temperature source producing 10^6/s !

JPARC : Increasing the yield

1. Primary muon source intensity x 300 using 1MW power & improved muon collection.

2. Need further factor of 200 from :
   a) Better muonium source (*TRIUMF 2010,2011,…)*
   b) Improved ionisation efficiency & more intense (ionising) laser system (RAL Mar 2012)



TRIUMF S1249 (Runs in 2010, 2011)

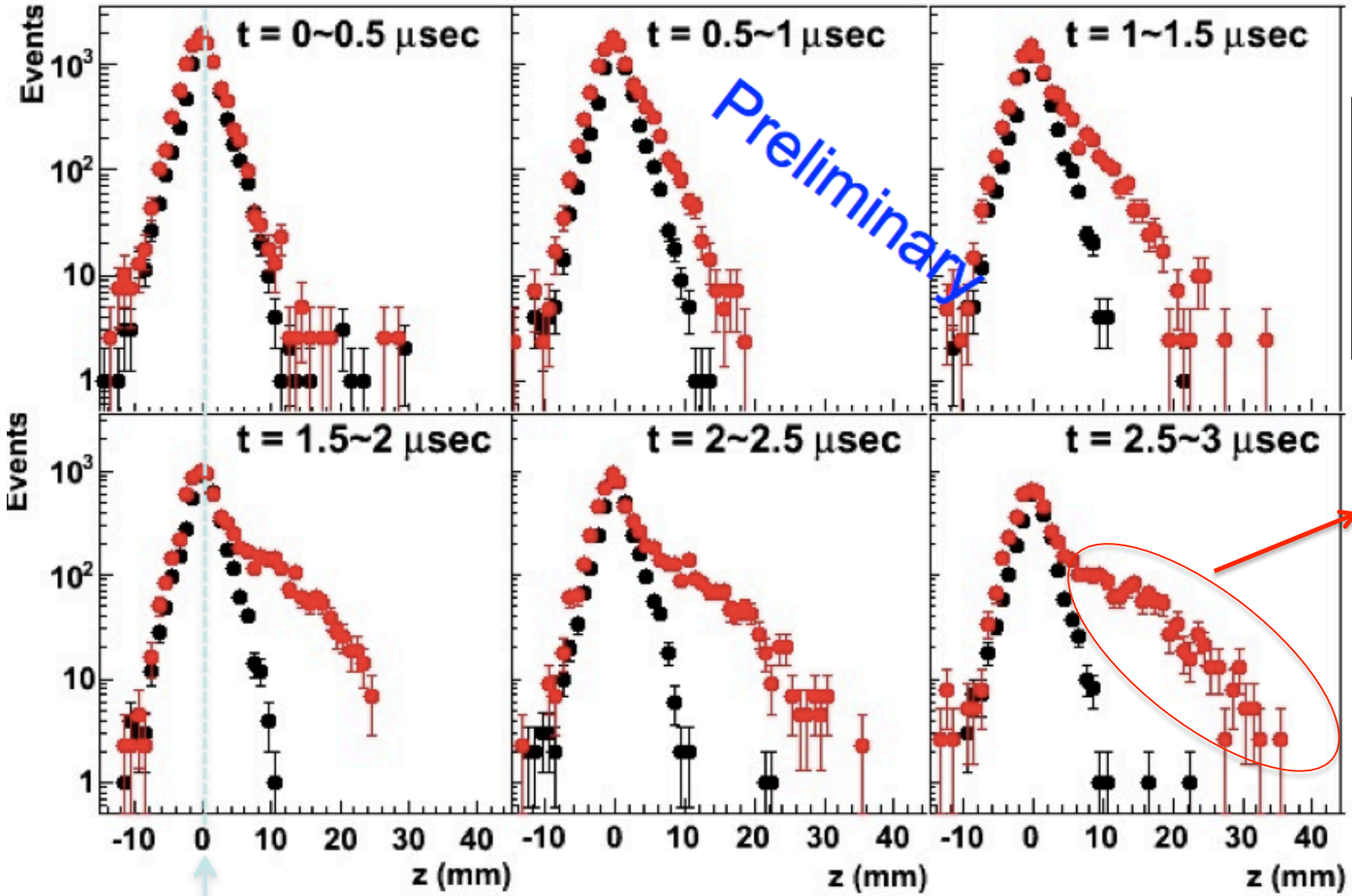
Silica powder, Fused Silica
Silica aerogel, nanogel
Porous silica, alumina

Measure distribution of muonium away from source via e^-, e^+

JPARC g-2 : Material R&D

S-1249 TRIUMF Experiment

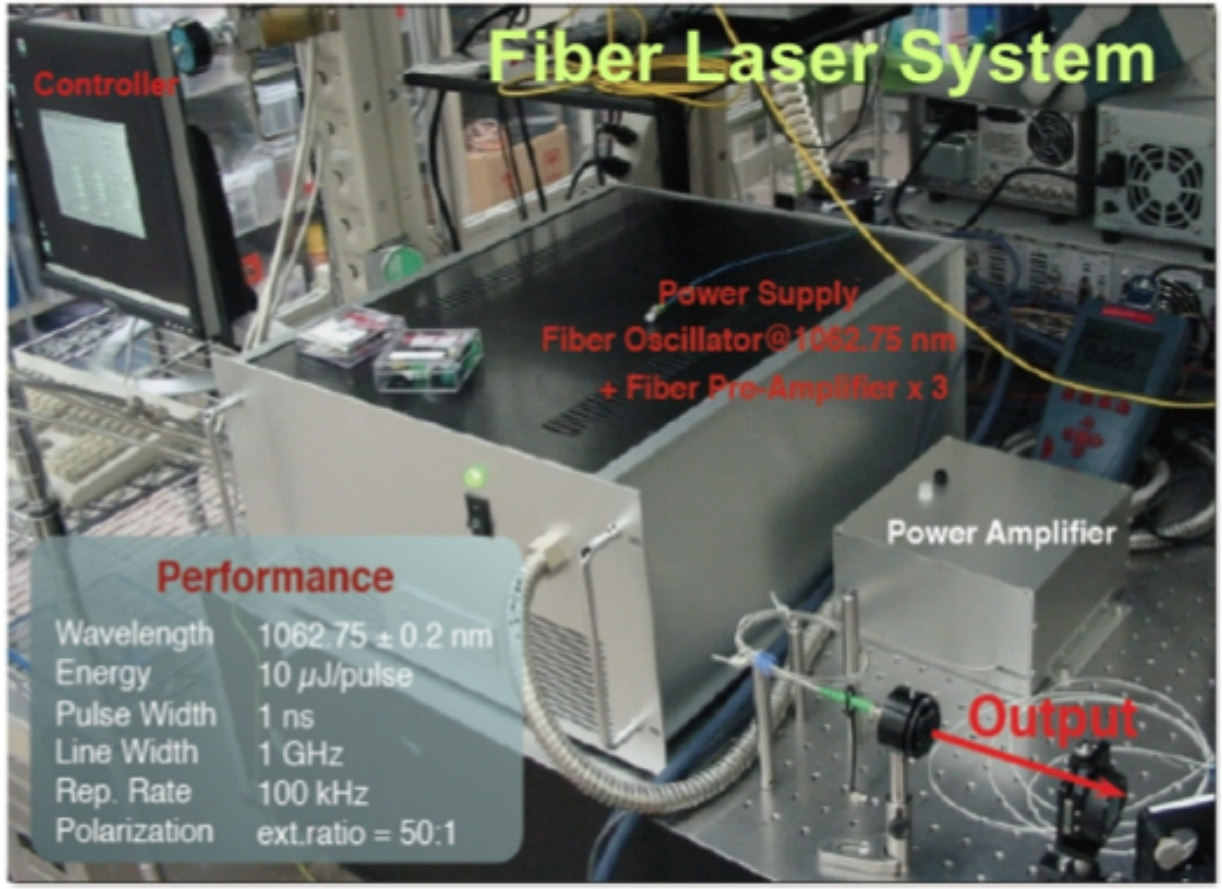
Results from 2011 beam : silica aerogel vs silicon plate (expect no evaporated Mu)



Yield lower than silica powder & no strong density dependence

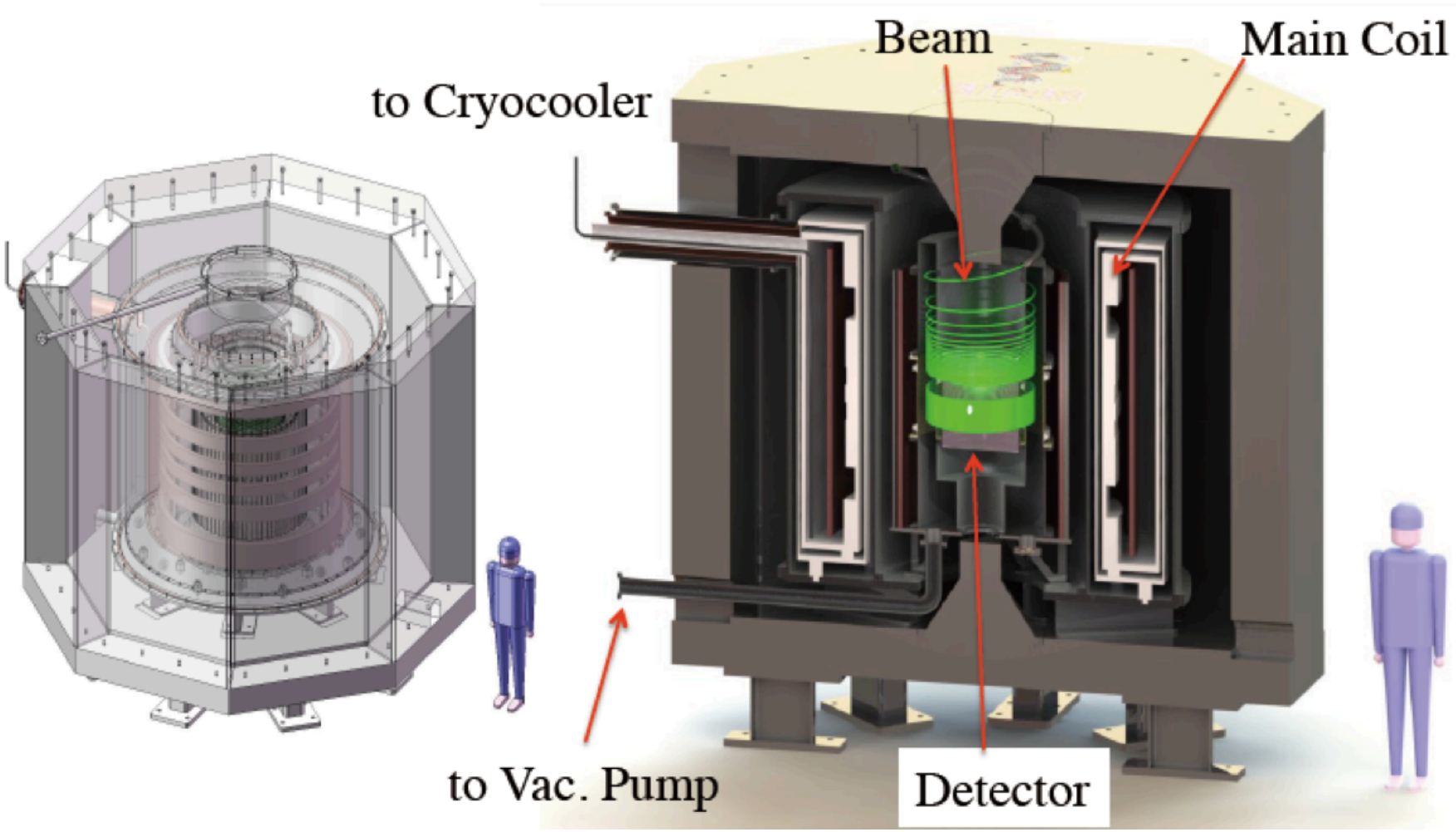
Mu evaporating out from aerogel

Active R&D on laser / target

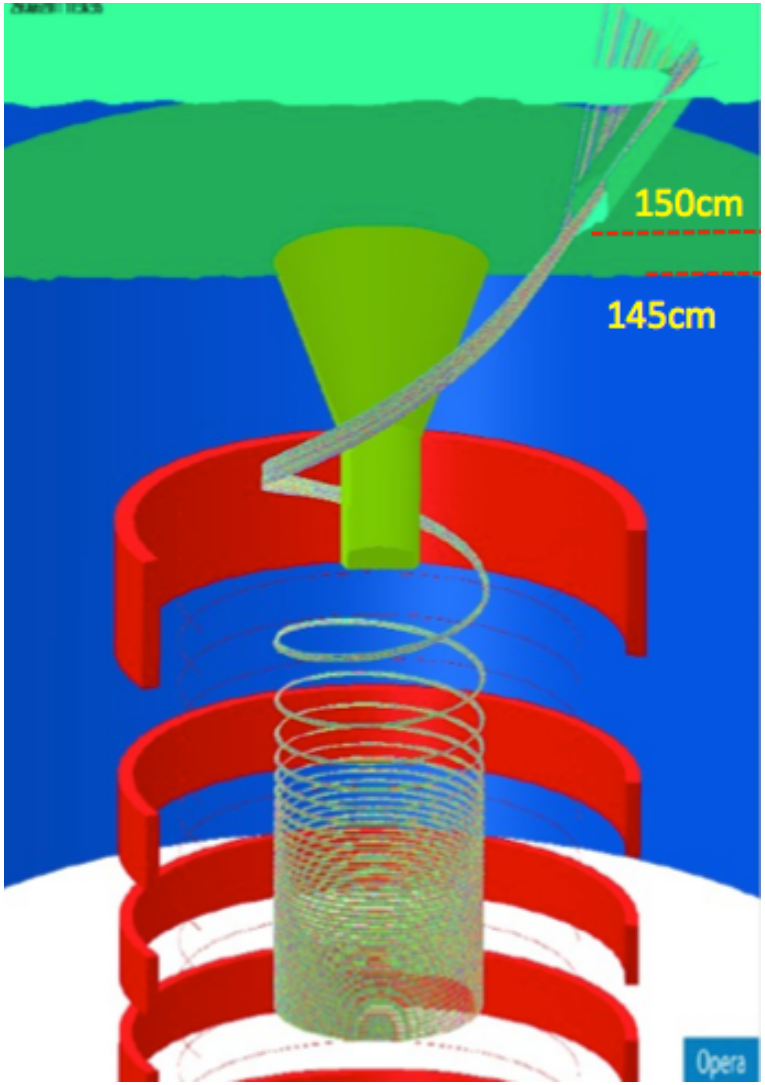


Tests started last month at RAL : delayed from 2011

Detector & Magnet



Beam emittance as injected into magnet

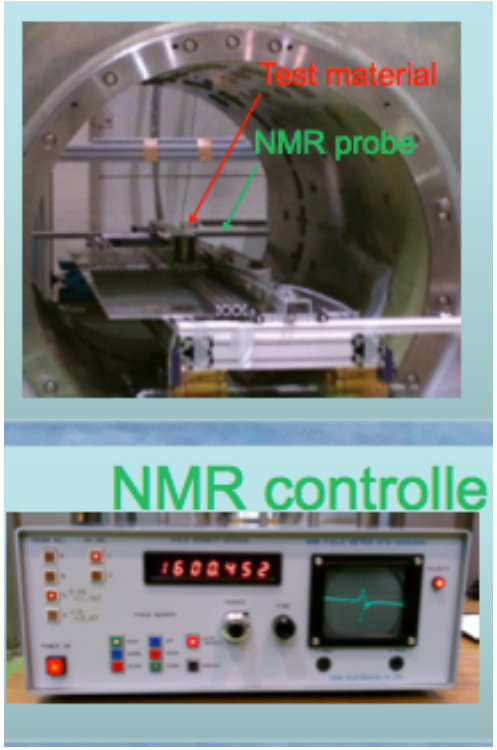


Present Studies

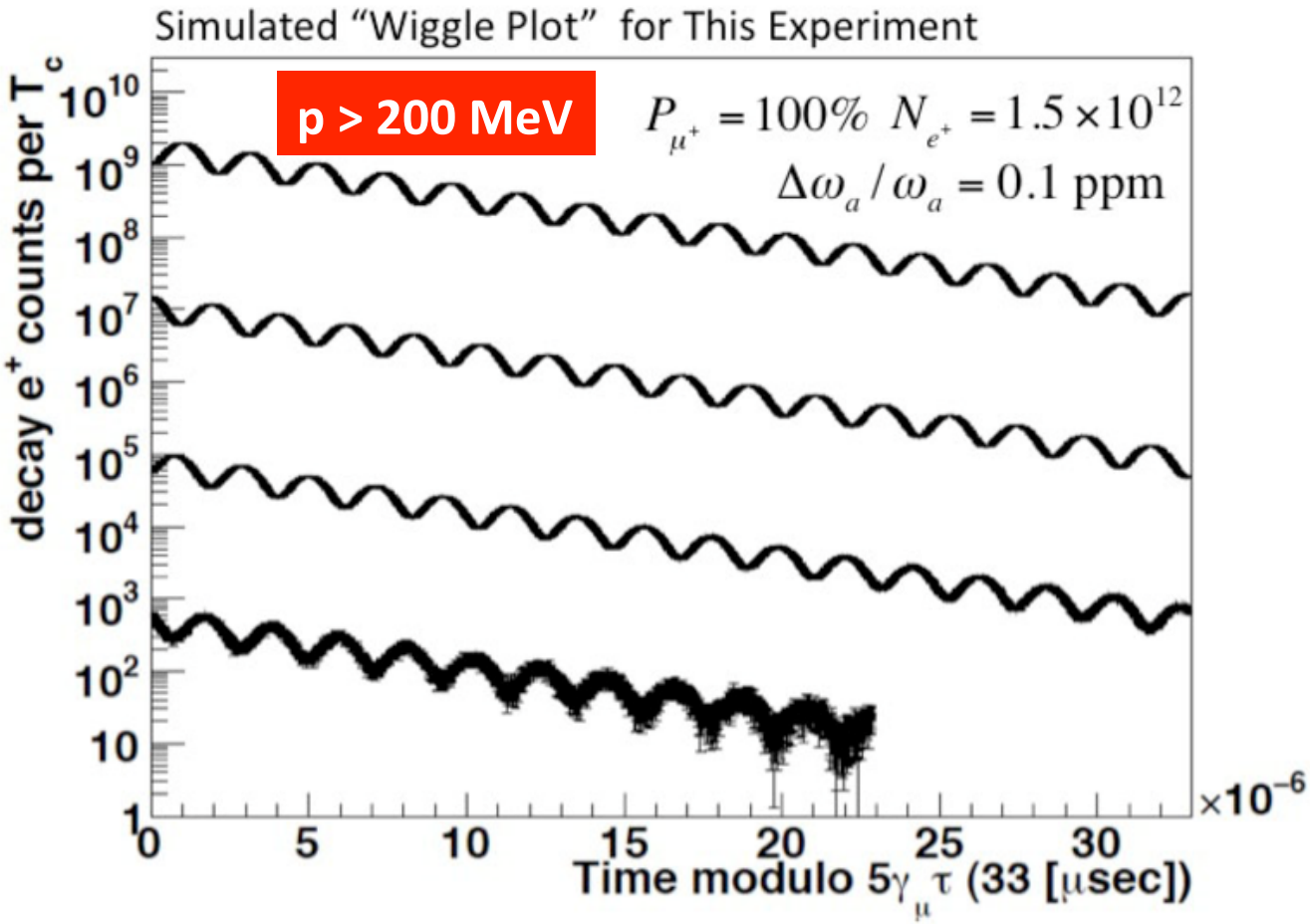
Simulation of beam injection

B-field uniformity : promising < 1 ppm.

Testing of magnetic effect of detector components



Simulated "Wiggle plot" determining g-2



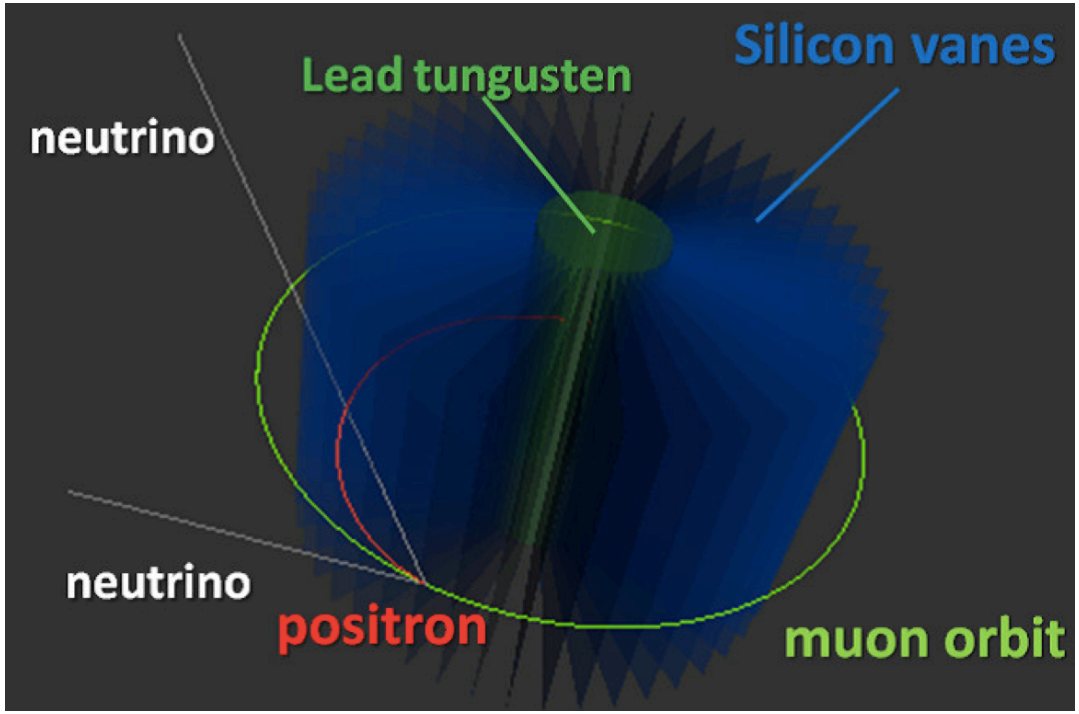
Expect statistical precision of 0.1 ppm i.e. same as FNAL g-2

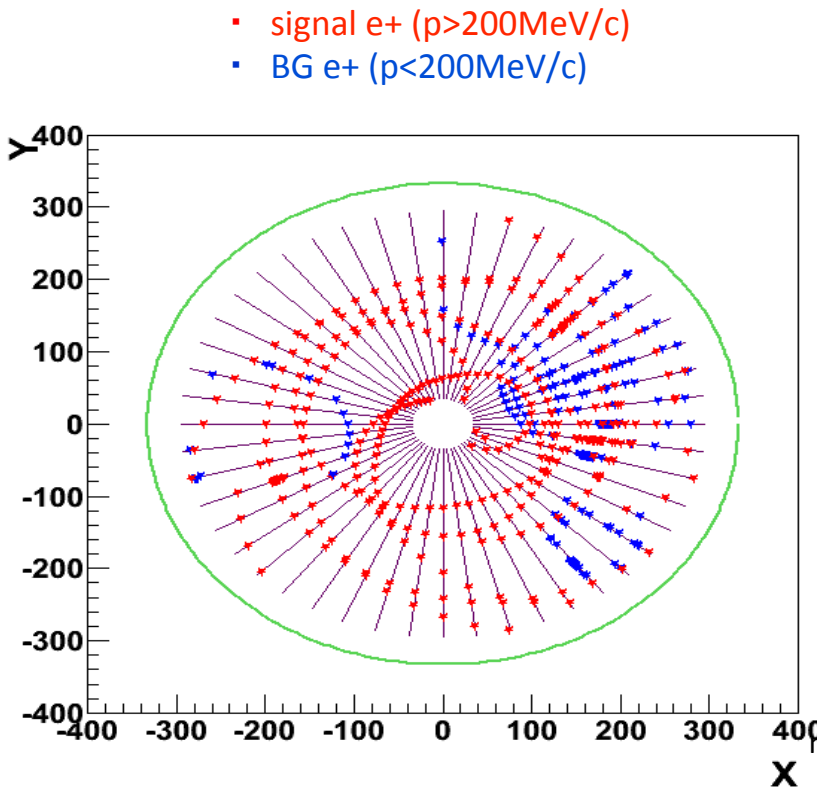
g-2 Silicon Tracker

High granularity Silicon vane tracker (exploiting (Super)KEKB electronics))

Event rate : 1 MHz

Need to reconstruct e+ track from lots of hits, particularly for earliest events.

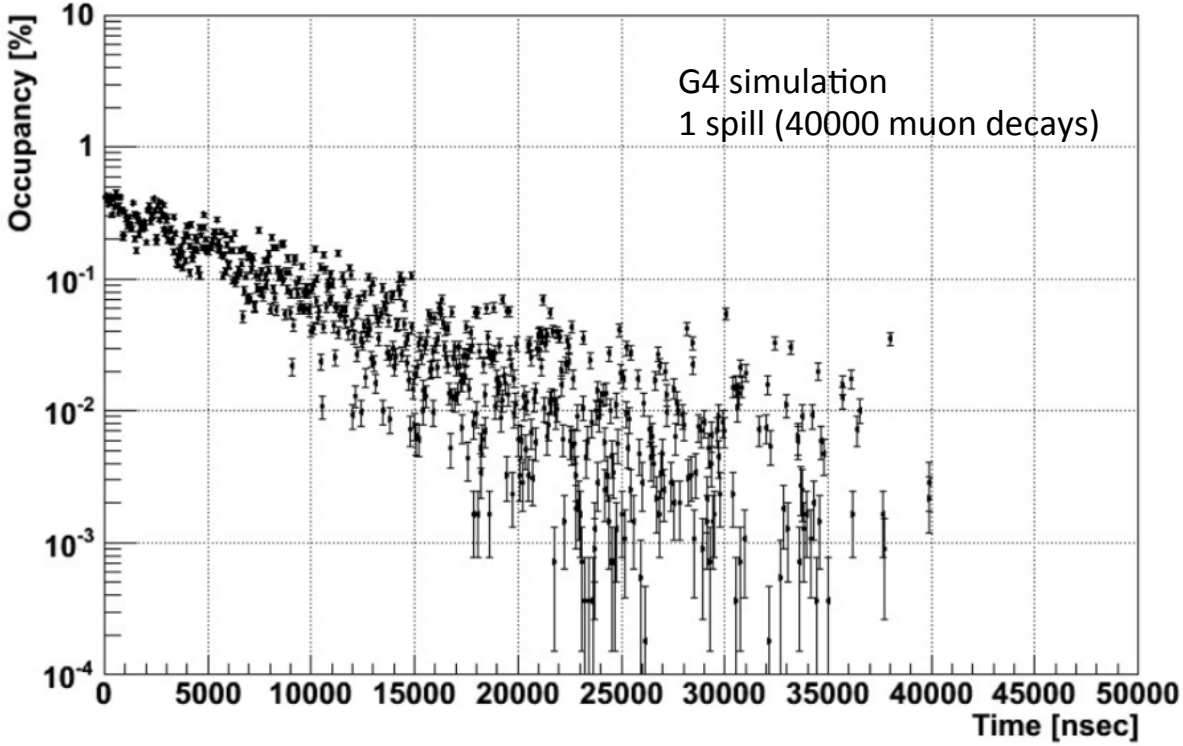




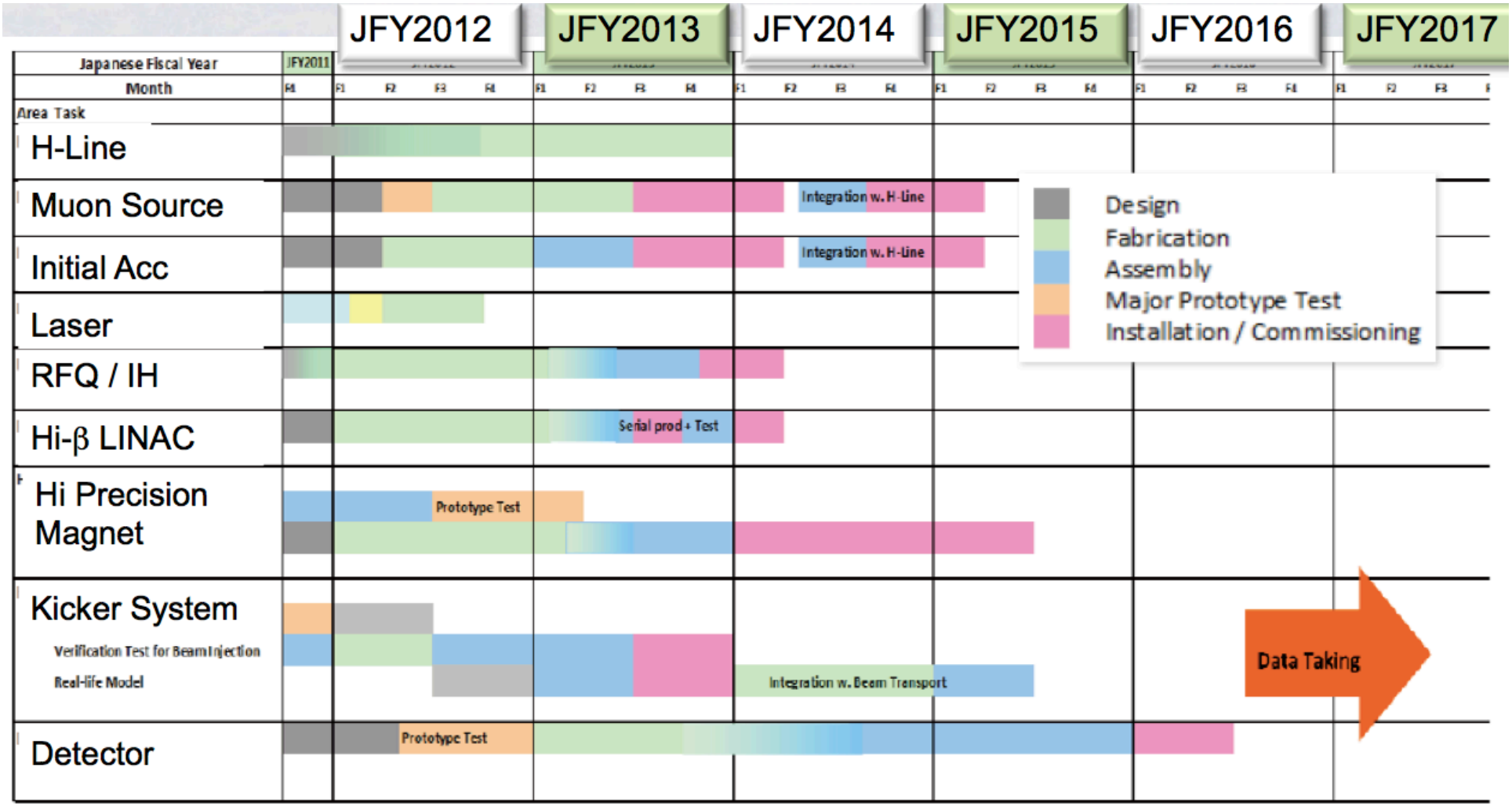
Occupancy Silicon Tracker

Occupancy is less than 0.5% per 5ns time stamp (5 hits/strip/spill).
Positron tracks in first 5ns:

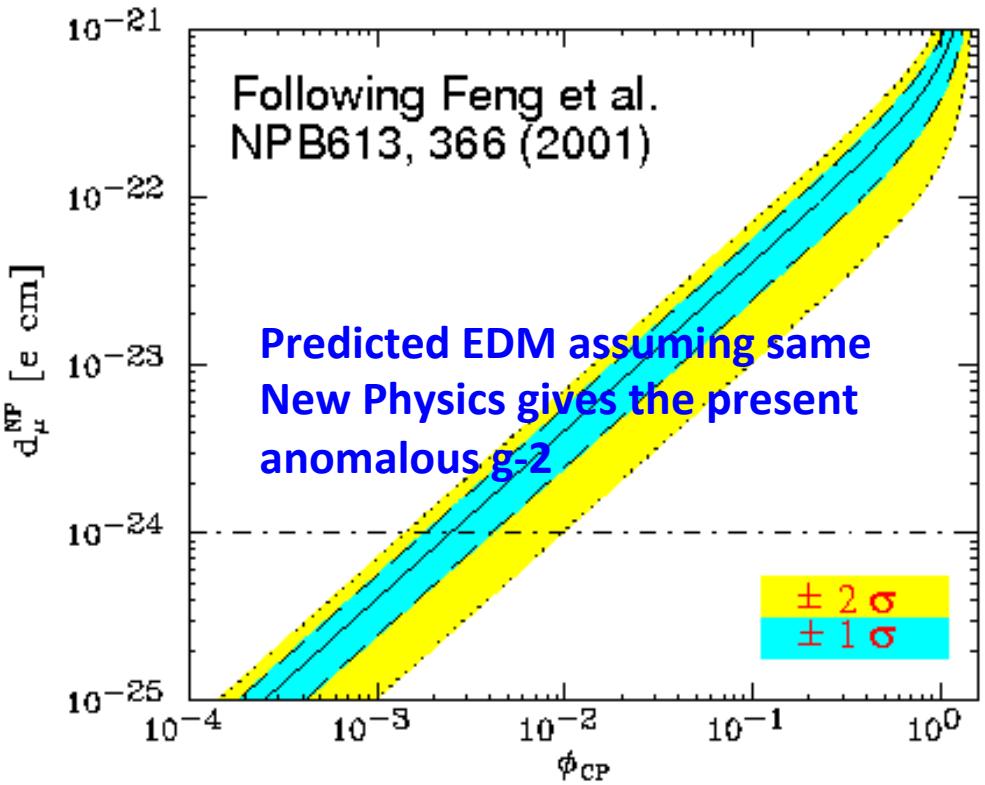
- 15 signal e+ tracks with p>200 MeV in first 5ns
- 30 BG e+ tracks with p<200 MeV in first 5ns

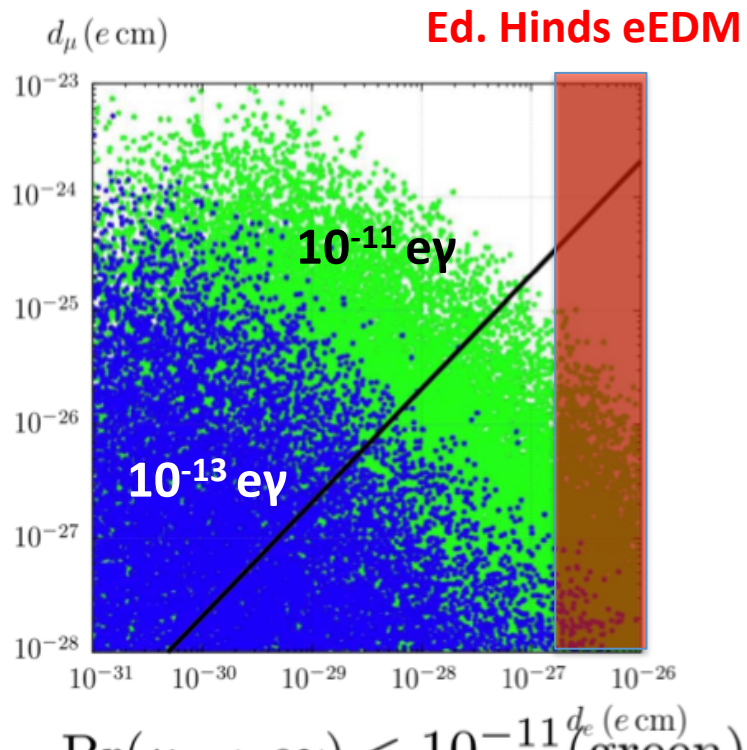


g-2 Schedule : aiming to be competitive with FNAL



Muon EDM





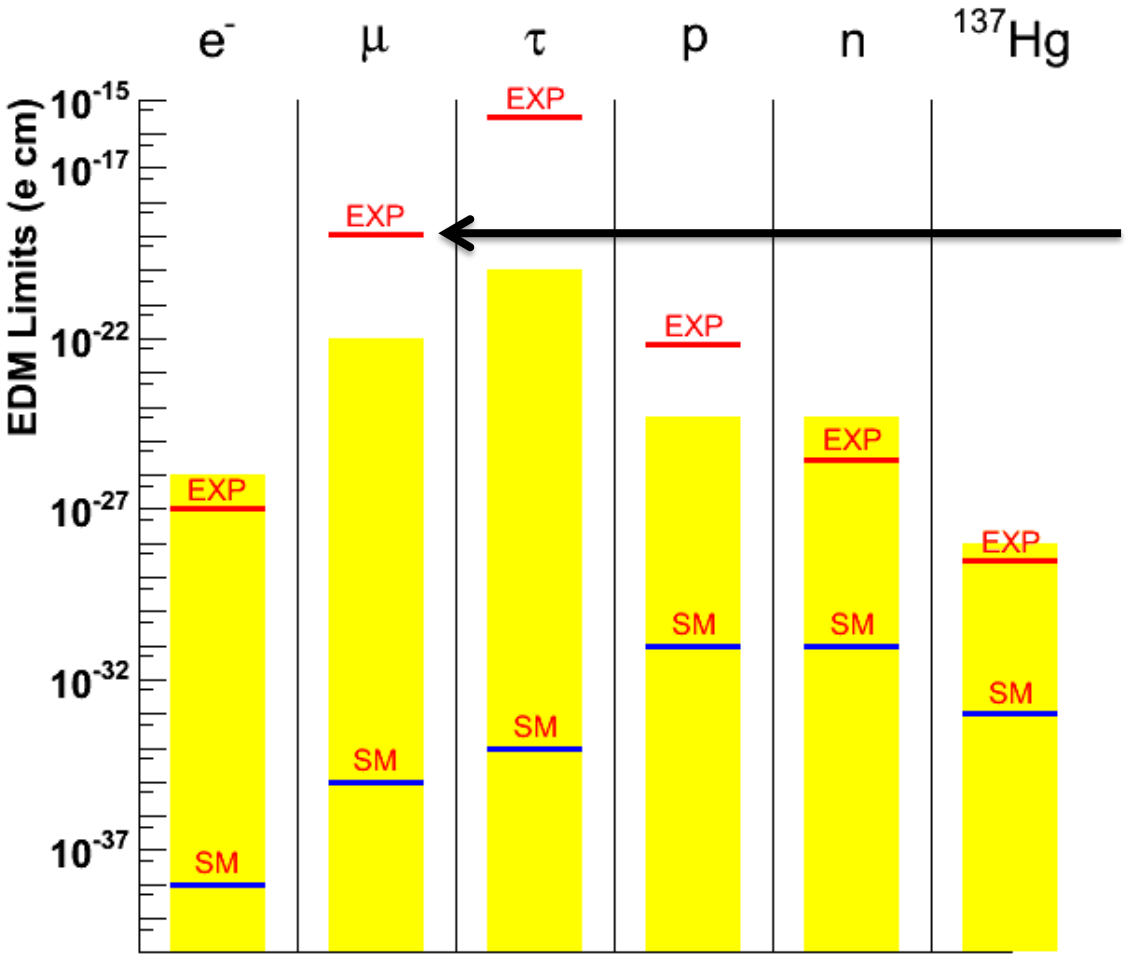
$$\mathrm{Br}(\mu \to e\gamma) < 10^{-11}(\text{green})$$
$$< 10^{-13}(\text{blue})$$

$$d_\mu^{\mathrm{NP}} \simeq 3 \times 10^{-22} \left(\frac{a_\mu^{\mathrm{NP}}}{3 \times 10^{-9}} \right) \tan \phi_{CP} \quad \mathrm{e \cdot cm}$$

where ϕ_{CP} is a CP violating phase.

Muon EDM of $10^{-21\text{-}28}$ are "expected" in many BSM scenarios

Muon EDM from parasitic g-2 running

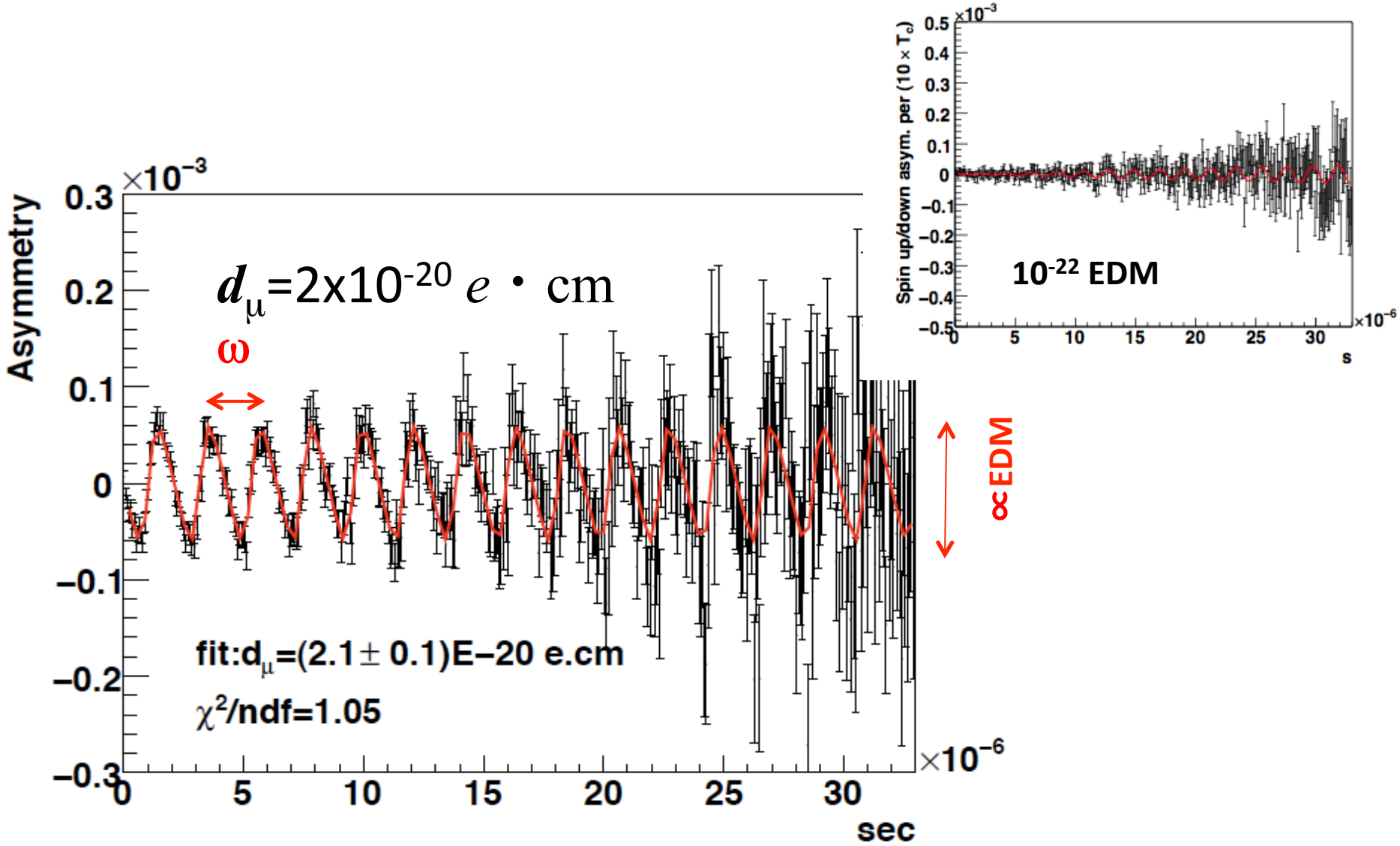


BNL limit (2 x 10^{-19})

FNAL g-2 expects to get to 10^{-21}

JPARC g-2 (Si tracking) quoting 10^{-22} in May 2012 PAC

Vertical Asymmetry to measure EDM



J-PARC Muon EDM beyond 10^{-21}

Parasitic EDM has intrinsic limitation at ~ $10^{-21\text{-}22}$

To go below this : use so-called **"Frozen Spin" technique**

- judicious E and B to cancel magnetic moment contribution

$$\omega = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

Radial E-field without any residual vertical field.

LOI to J-PARC in 2003 to use dedicated 11m FFAG ring with sensitivity @ 10^{-24}

Proof of principle proposed at PSI (2006-2010) with 42cm ring with sensitivity @ 5×10^{-23}

- challenging .....

J-PARC PAC / IPNS favours nEDM (E33) experiment over μEDM although nEDM has not yet got stage-1 approval.

J-PARC Muon Hyperfine Splitting

$$a_\mu = \frac{\mathcal{R}}{\lambda - \mathcal{R}}$$

$$\mathcal{R} = \frac{\omega_a}{\omega_p}$$

Measured by "g-2" experiment

$$\lambda = \frac{\mu_\mu}{\mu_p}$$

Measured from muonium HFS

$$\Delta a_\mu = 0.54 \text{ ppm with } 0.03 \text{ ppm from } \lambda$$

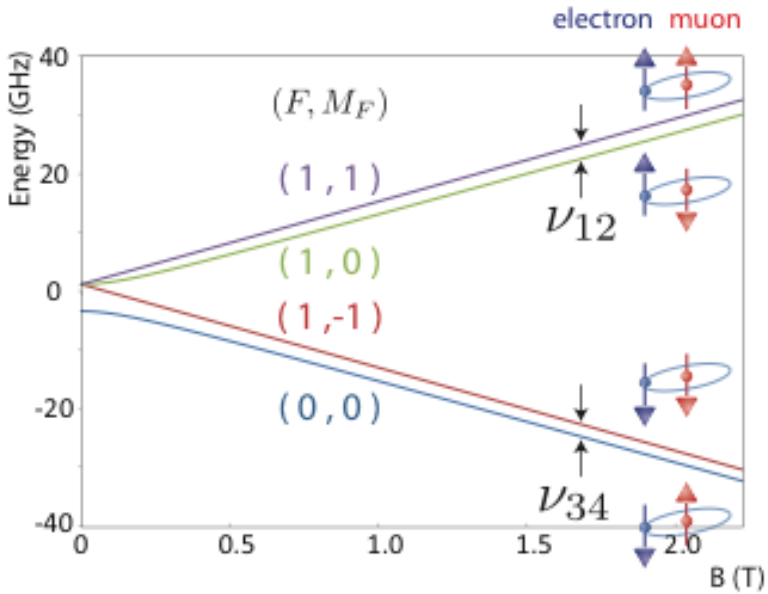
next experiments

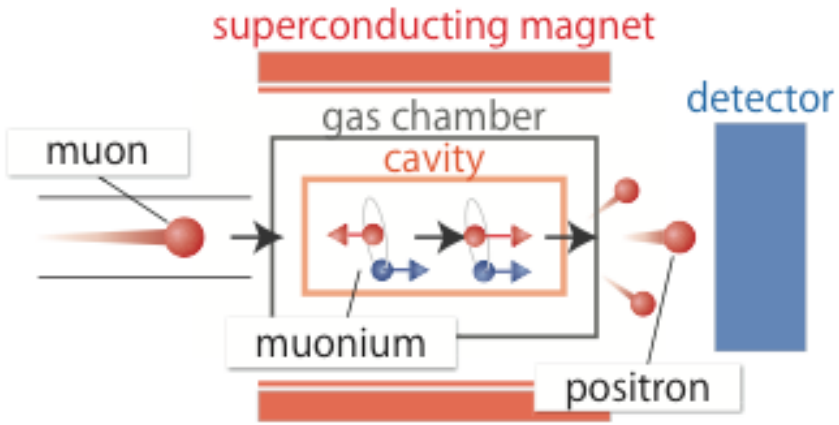
$$\Delta a_\mu = 0.14 \text{ ppm}$$

J-PARC Muon Hyperfine Splitting

Last measured in 1998 at LAMPF, worth measuring :

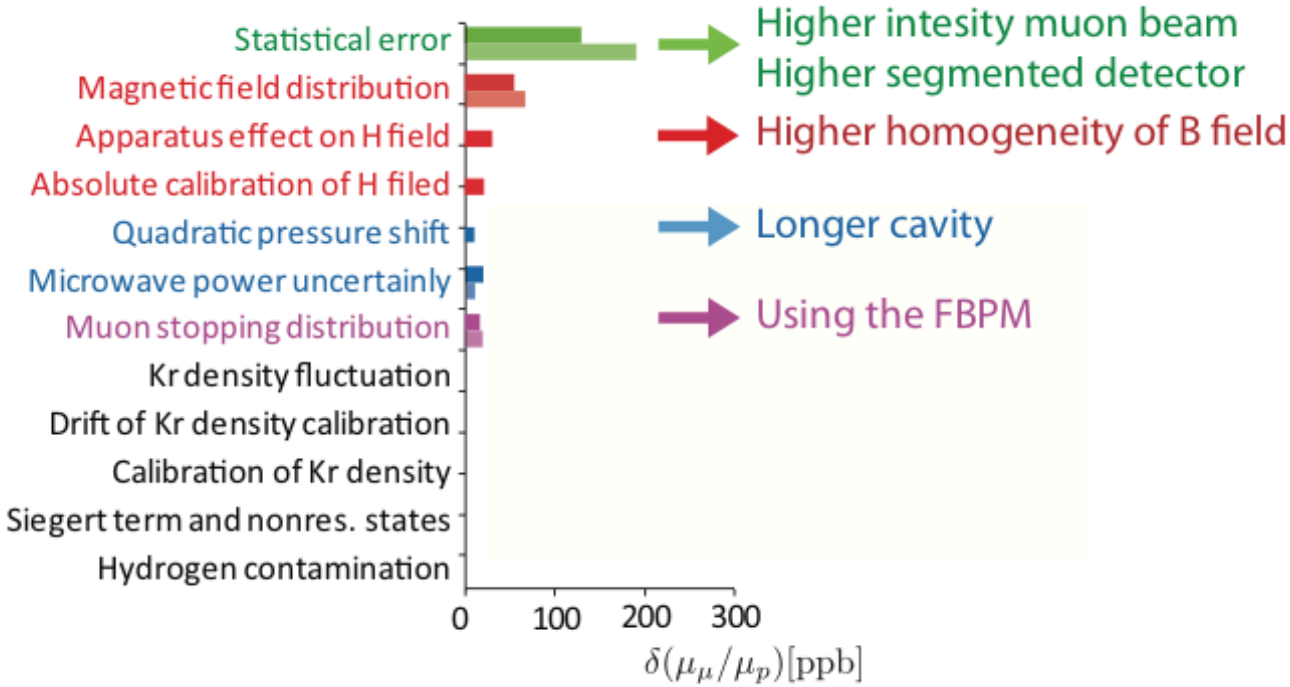
1. To minimise external uncertainties to g-2 determination.
2. Cross check QED : positronium HFS has long standing (3.9 σ) discrepancy wrt SM….





J-PARC Muon Hyperfine Splitting

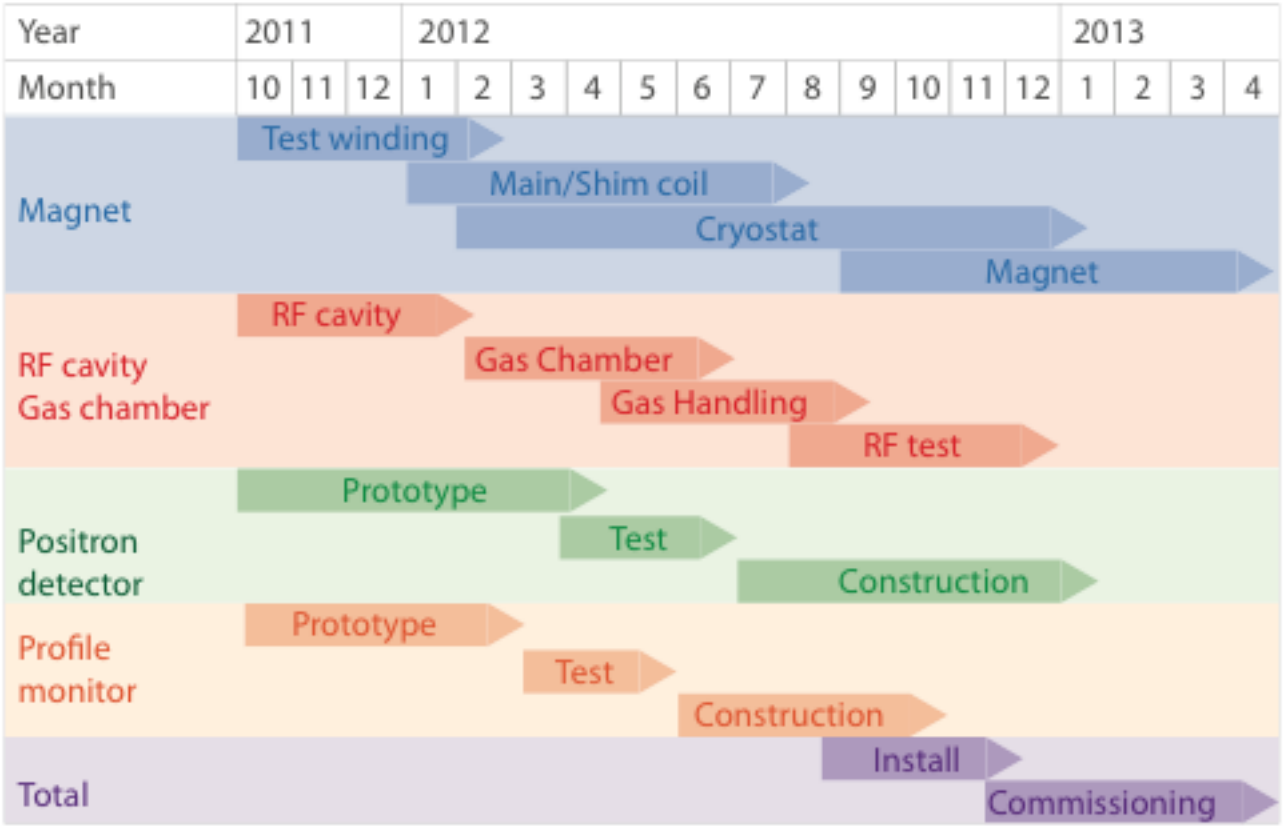
Can use surface muons in D, U, H-line (before cooled).
H-line preferred due to synergy with g-2 (3T uniform B field).
Improvements from the statistics, detector segmentation and more uniform B-field



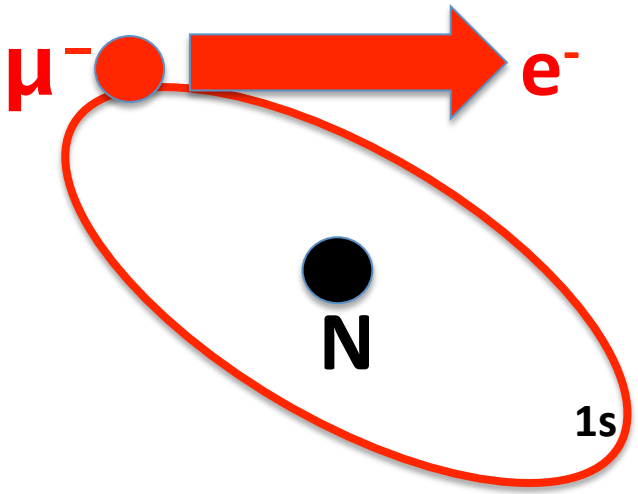
Expect to reduce uncertainty by ~ 40% wrt LAMPF result.

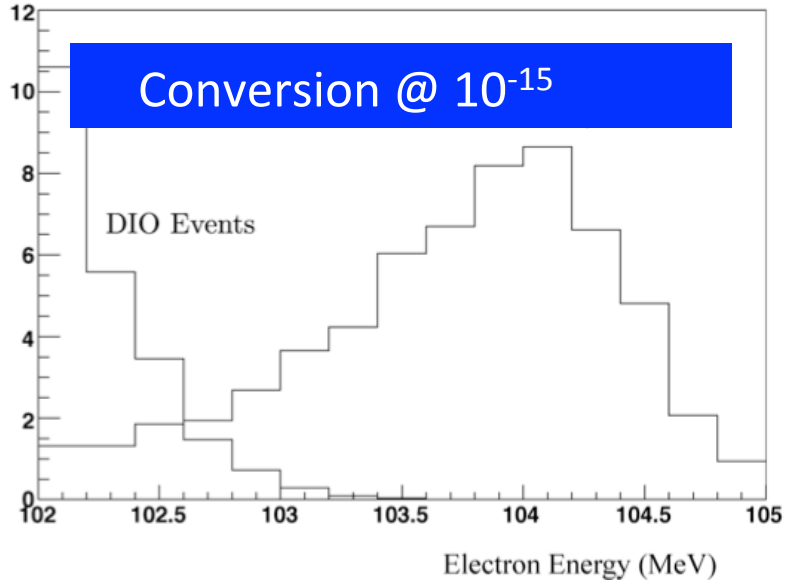
J-PARC Muon Hyperfine Splitting

18 months from stage-2 approval + 100 days of running…



J-PARC Muon to Electron Conversion





1. **COMET** : stage-1 approval with stage-2 expected with TDR in 2012.
   CDR BR sensitivity 6 x 10^{-17} in 2021.

2. **Phase-I COMET** : Beamline+1st 90^0 for COMET has been recommended for inclusion in KEK budget. Sensitivity O(100) better than SINDRUM.

3. **DeeMe** : stage-1 approval from muon PAC but further R&D requested from IPNS PAC
   Would run in MLF without MR in H- line.
   Sensitivity O(100) better than SINDRUM.

COMET Phase-I : Staged Approach

The IPNS proposes, as the first priority item in the next five-year plan, that the upstream part of the high-p beam line be constructed and co-used by the COMET experiment and that the first half of the muon capture solenoid be constructed simultaneously.

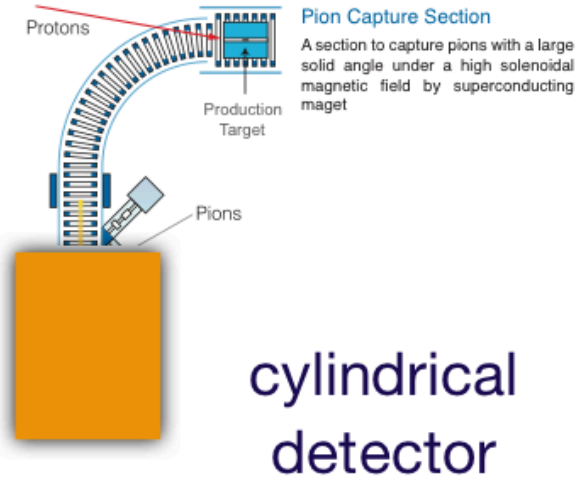
J-PARC PAC APRIL 20102

PAC/IPNS very supportive of a staged approach that will:

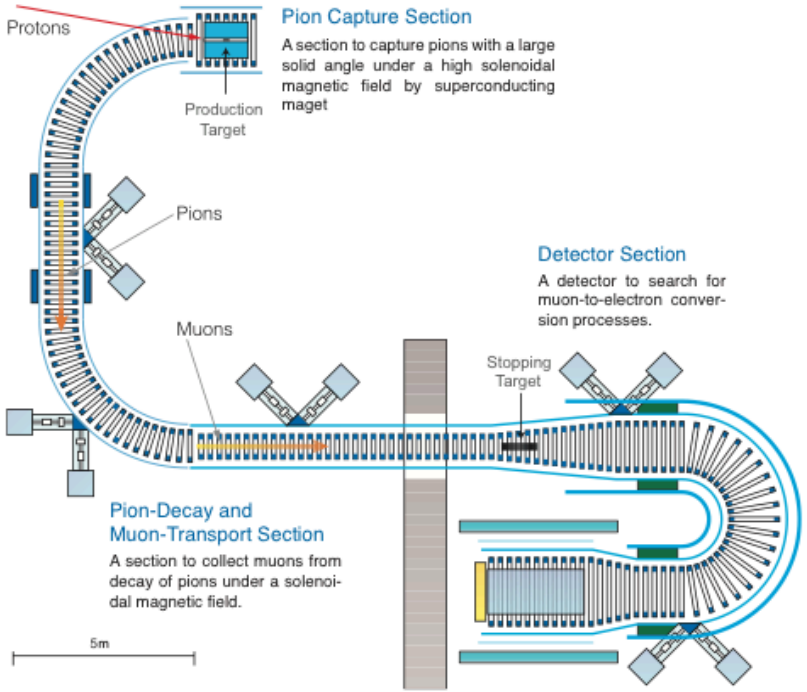
1. Measure key performance parameters (extinction, bgrds)
2. Achieve intermediate sensitivity below 10^{-14}
3. Test prototype detectors
4. Minimise risk in commitment to build rest of COMET

COMET Phase-I

Phase1



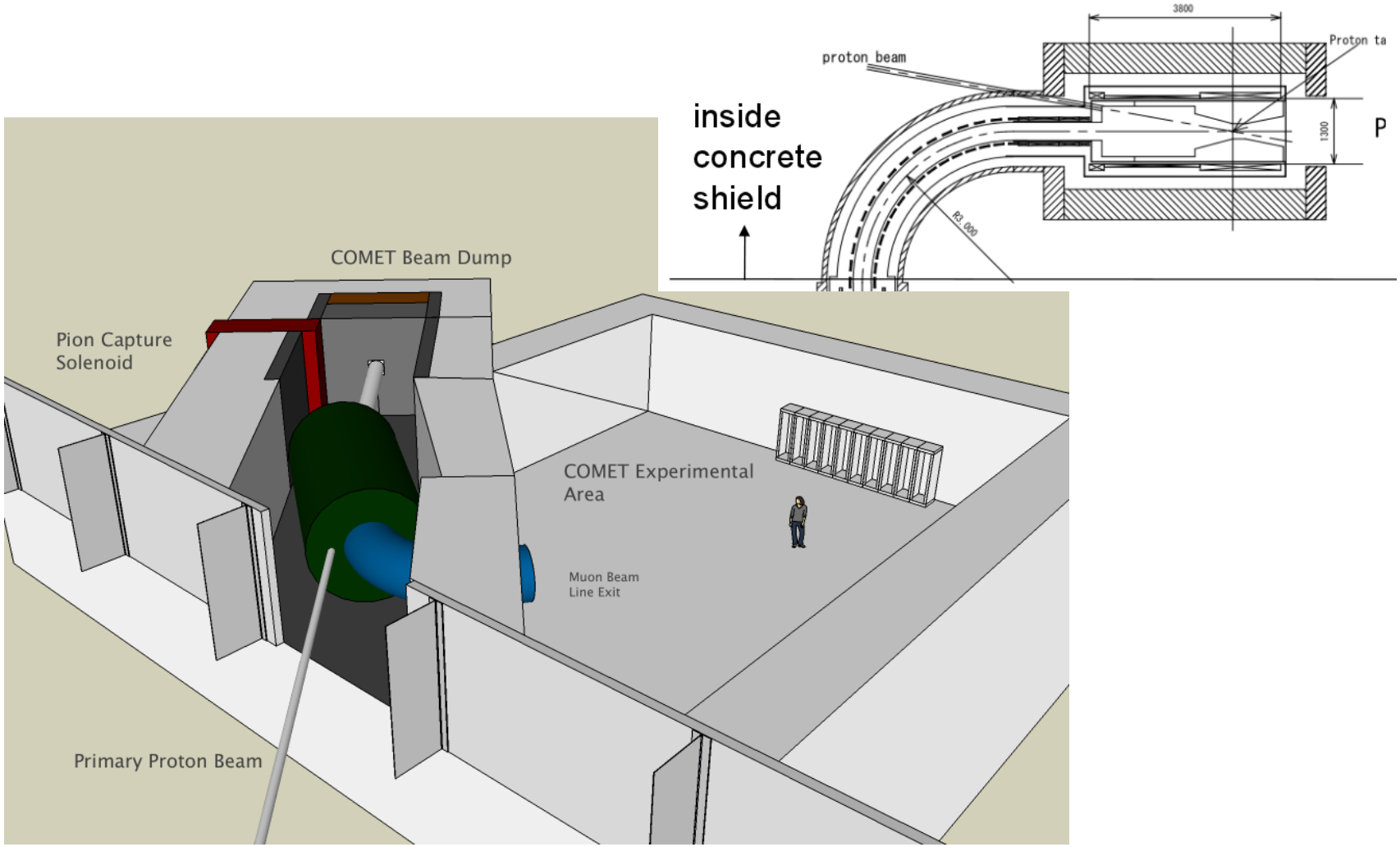
Phase2



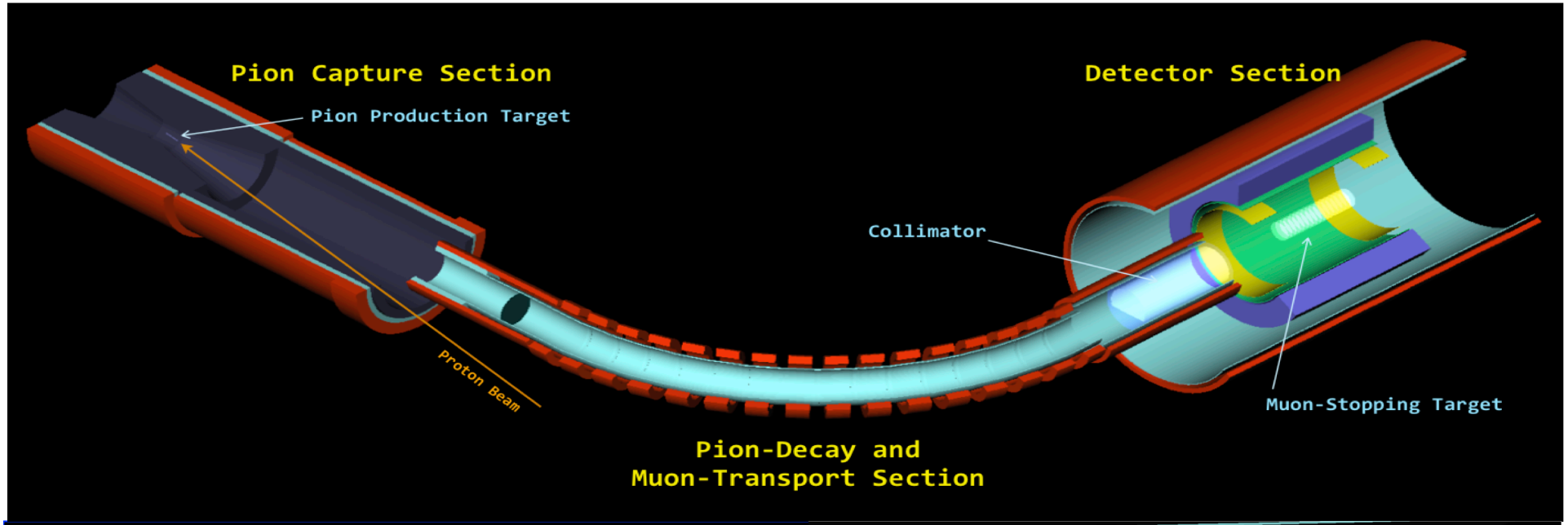
To reach sensitivity below 10^{-14} only need to run at 3.6 kW for 12 days….

Run at 56 kW for canonical 2 years

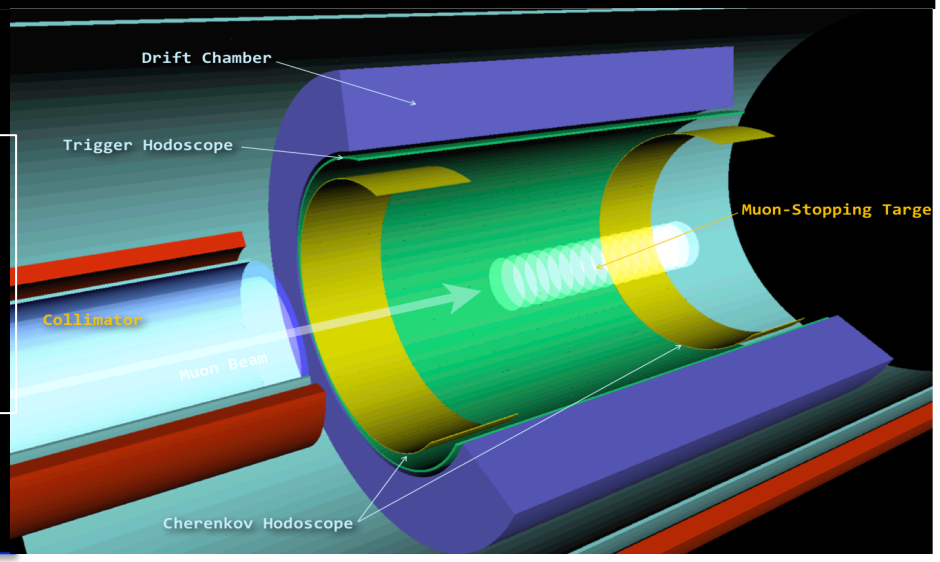
COMET Phase-I



COMET Phase-I



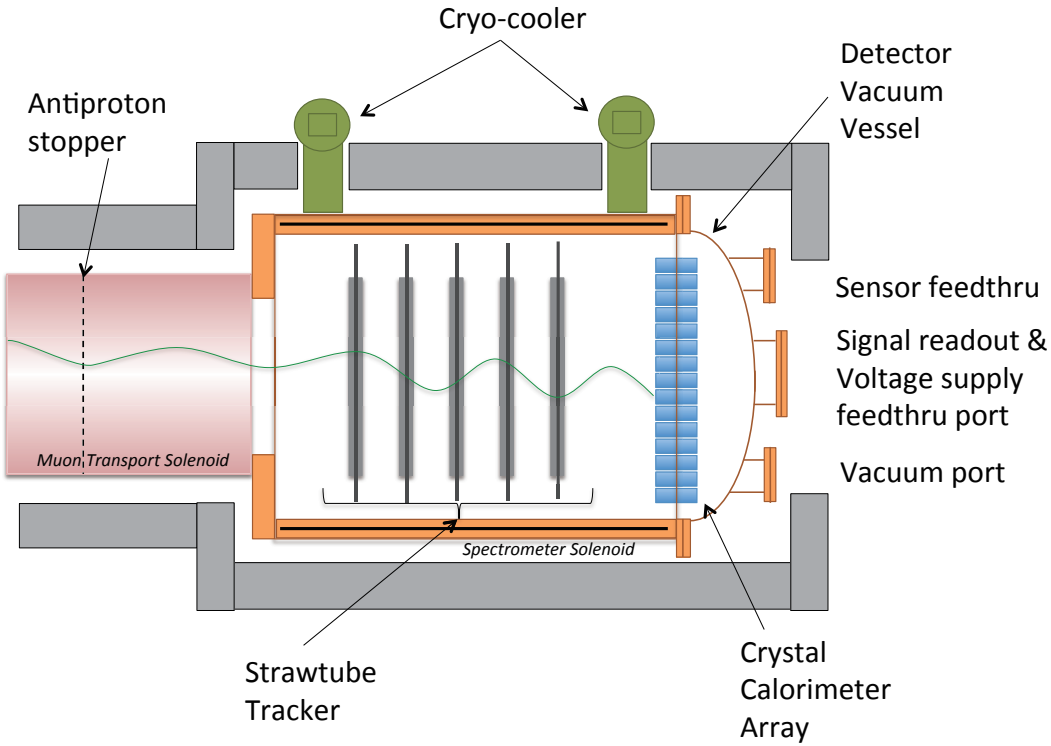
Cylindrical detector (using AMY solenoid) has higher acceptance but poorer resolution compared to transverse/phase-II detector



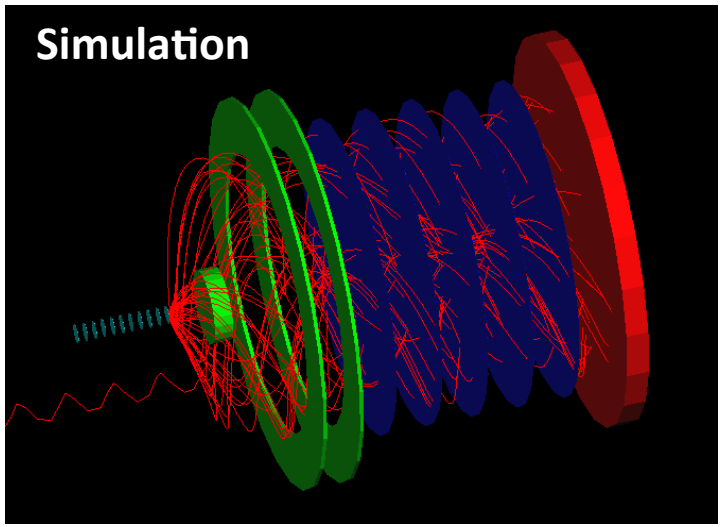
COMET Phase-I BG Detector ?

Use prototypes of final straw tracker and crystal calorimeter.

Run at low power (in non-pulsed mode) and possibly over range of proton energies.

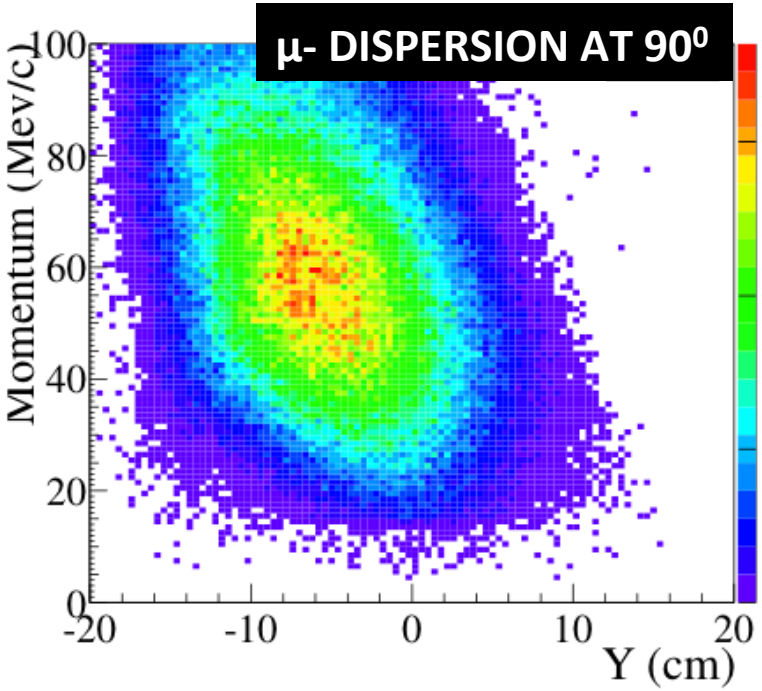


Estimate pbar contamination of beam.



COMET Phase-I

Studies of performance of Phase-I still evolving

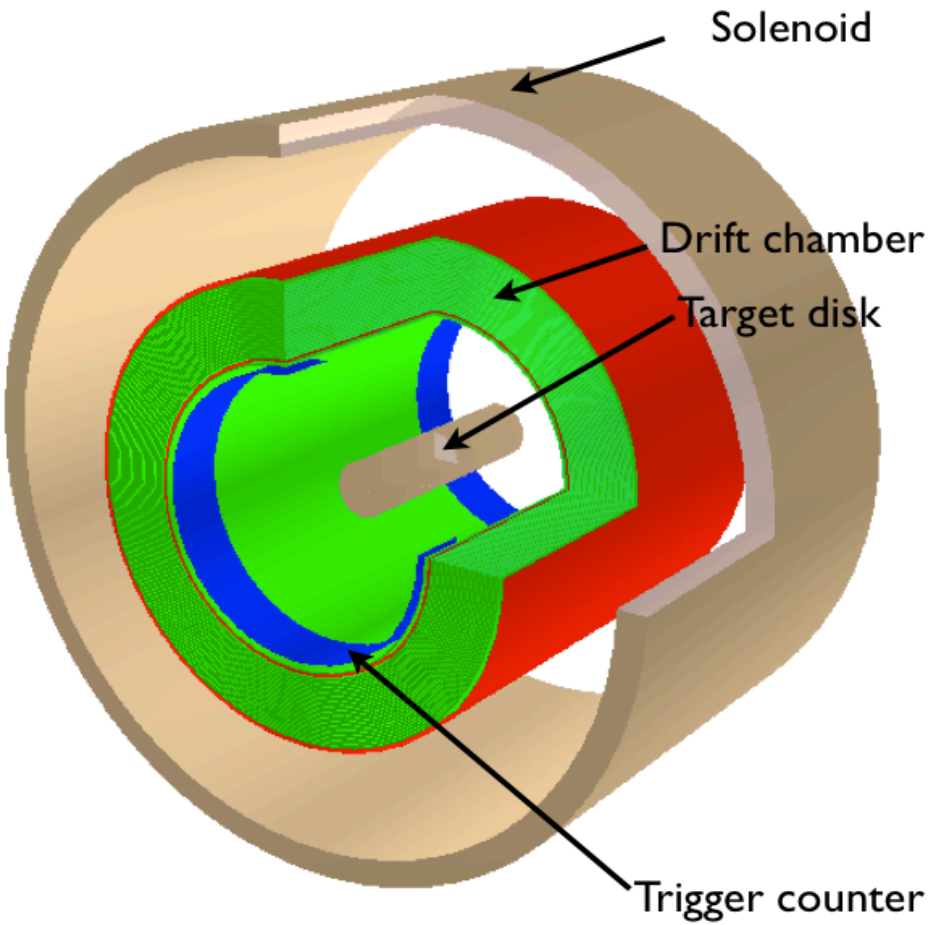


Clearly with only partial beamline:
- pion extinction is reduced
- momentum (and charge) selection reduced (augment with collimator)
- no charge selection of e^-, so (?) $\mu^- N \rightarrow e^+ N'$

Larger backgrounds

Detector with poorer resolution vs final detector

COMET Phase-I



Solenoid (1T) :
- radius = 1.2m, length = 1.5m

Tracker
- gas region : 55-80 cm
- 5 superlayers (5 wires each)

Non stopping particles pass through.

Effective pT cut of 70 MeV.

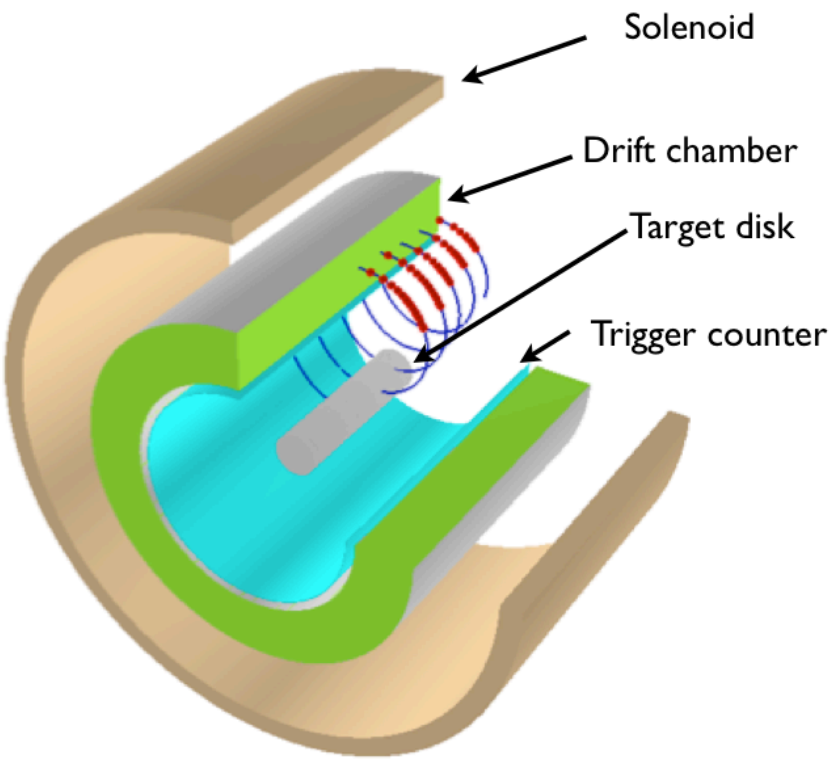
Dominant hit-rate from p emitted after nuclear capture (1.5 kHZ/wire)

Aim to study this at TRIUMF with Mu2e

COMET Phase-I

Sensitivity is strong function of tracker resolution (and acceptance).

For geometric + tracking efficiency of 50% and p-resolution of ~ 700 keV then 90% BR upper limit is 7 x 10^{-15} ie (100 x lower than SINDRUM-II).



p-resolutions closer to 400 keV look achievable (gas choice, extent of trigger counter)

COMET Phase-I

		Budget request	KEK internal	External funding	Optional	Future funding	Comments
Building		8.0					
Beam dump		1.0	0.5				
SC magnet		8.0					to first 90° bend
						20.0	remaining beam line
	W shield					2.0	for higher power
Power supply					2.0		if purchased
			0.5				installation
						2.5	for upgrade
refrig-erator					2.0		if constructed
			0.5				installation
Beam line	magnet		0.5				installation
						5.0	for higher power
	piping	0.3	0.3				
	cabling	0.6	0.6				
	vacuum	0.6	0.6				
Radiation shielding	NP-hall	1.5					for 3 kW operation
						6.5	for high power
Safety			0.5				
π target				0.8			experimental group
Detector	magnet		0.5	0.5			for Phase-I
	μ target			0.1			experimental group
	μ monitor			1.5			experimental group
	tracker			1.1			experimental group
	ECAL			1.6			experimental group
	CR veto			5.7			experimental group
	DAQ			0.5			experimental group
Total		20.0	4.5	11.8	4.0	36.0	72.3+4.0

building 9.5M€

magnet 9.0M€

beam line 6.3M€

detector 11.5 M€

budget request 20 M€

J-PARC project budget 4.5 M€

Experimental Group 11.8 M€

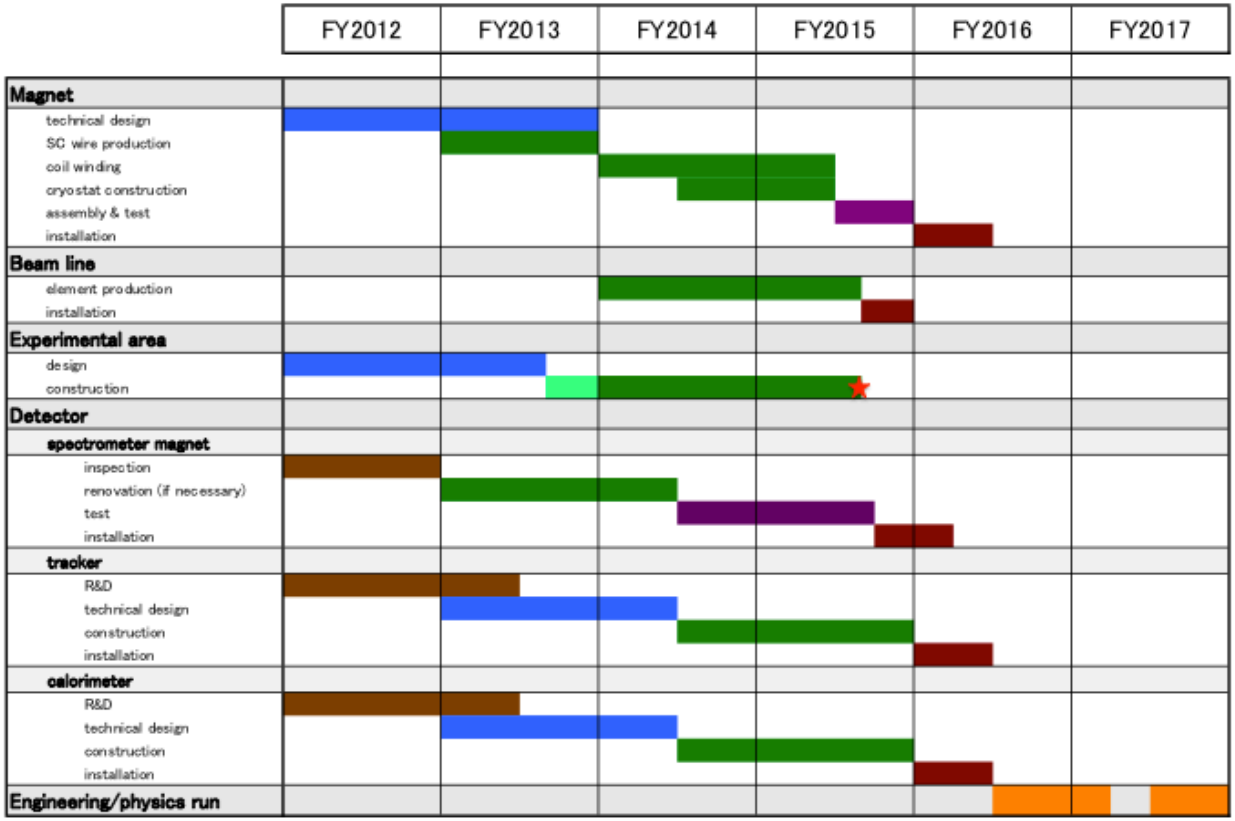
Collaboration ~ 100

11 countries with recent engagement from India & China

Running costs added when budget approved

COMET Phase-I

Phase-I data-taking in 2016/2017



Full beamline & transverse-detector ready 2020/1 & then data over 2 yr.

Recent COMET Phase-II Activities

TDR in final stages of preparation for stage-2 PAC approval.

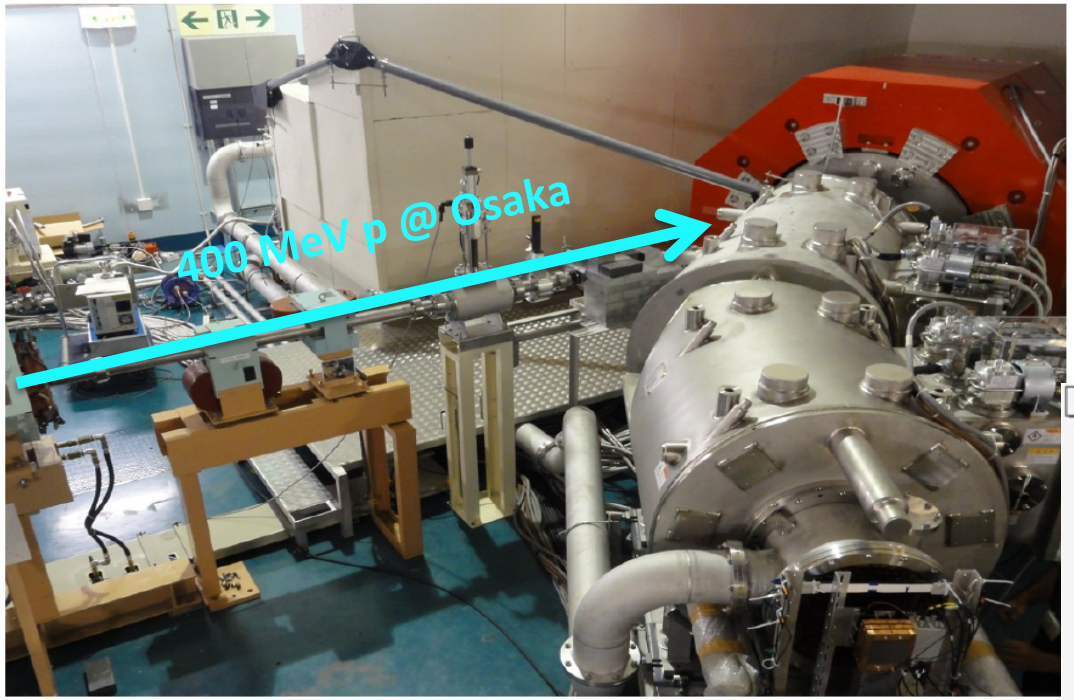
Extinction measurements being carried out @ J-PARC at the moment

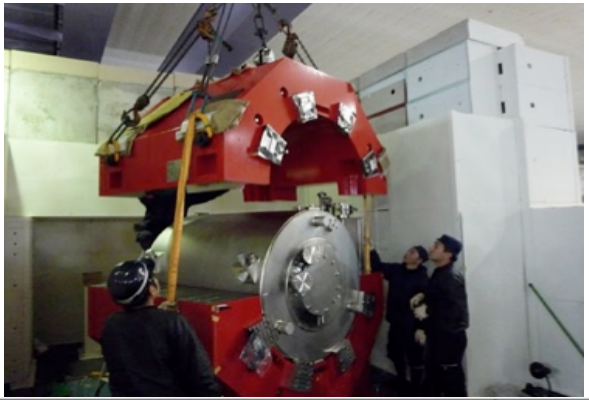
Pion capture solenoid studies (this week) at Osaka with MuSiC

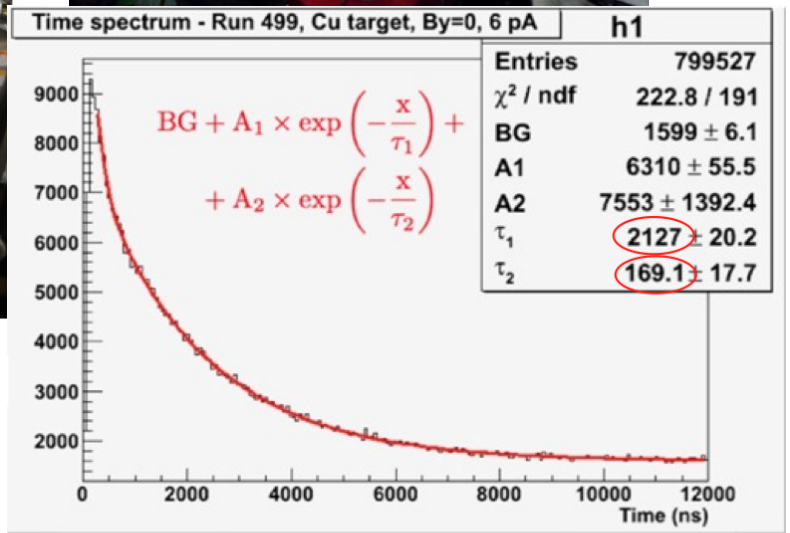
Prototype straw tracker tests at KEK

Preparations for (50-crystal) calorimeter test beam at Novosibirsk in November

MuSiC : Pion Production





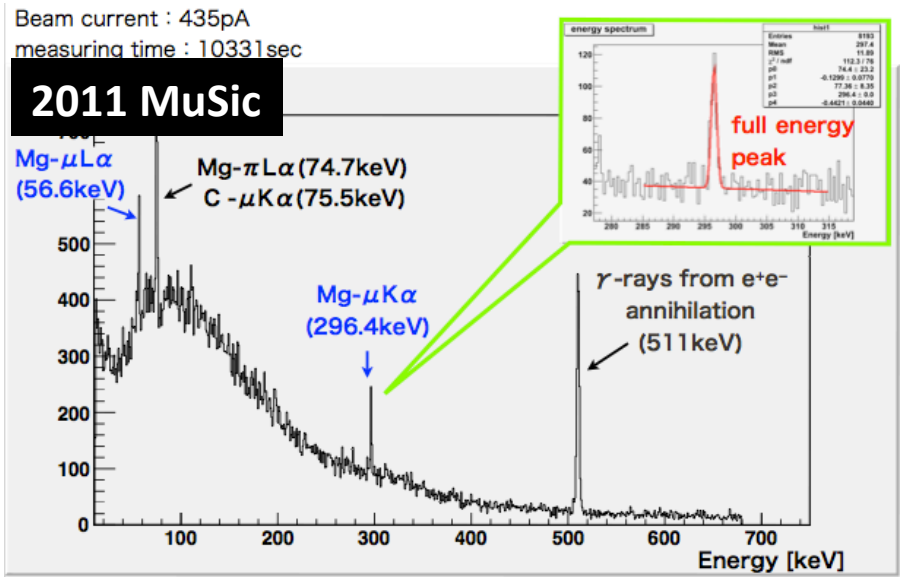


	Free muon*	Cu**	Plastic scint.**
τ (ns)	2197.03 ± 0.04	163.5 ± 1	2026.3 ± 1.5

Observed muons at rate O(1000) x PSI per W of beam power.

MUSIC @ Osaka

Current beam test seeking to develop techniques for X-ray measurements for recording # stopped muons.



遮蔽について（外側）

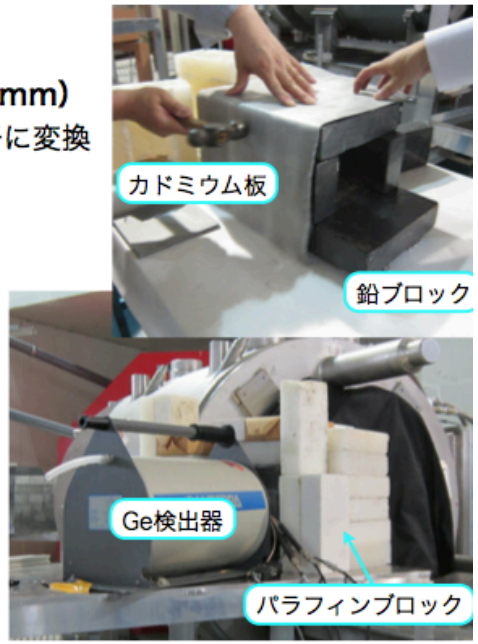
主に中性子の遮蔽が目的

●パラフィンブロック（100~200mm）
比較的速い中性子を熱中性子に変換

●カドミウム板（2mm）
熱中性子を減少させる
※同時にγ線を放出

●鉛ブロック（50mm）
γ線を遮へいする

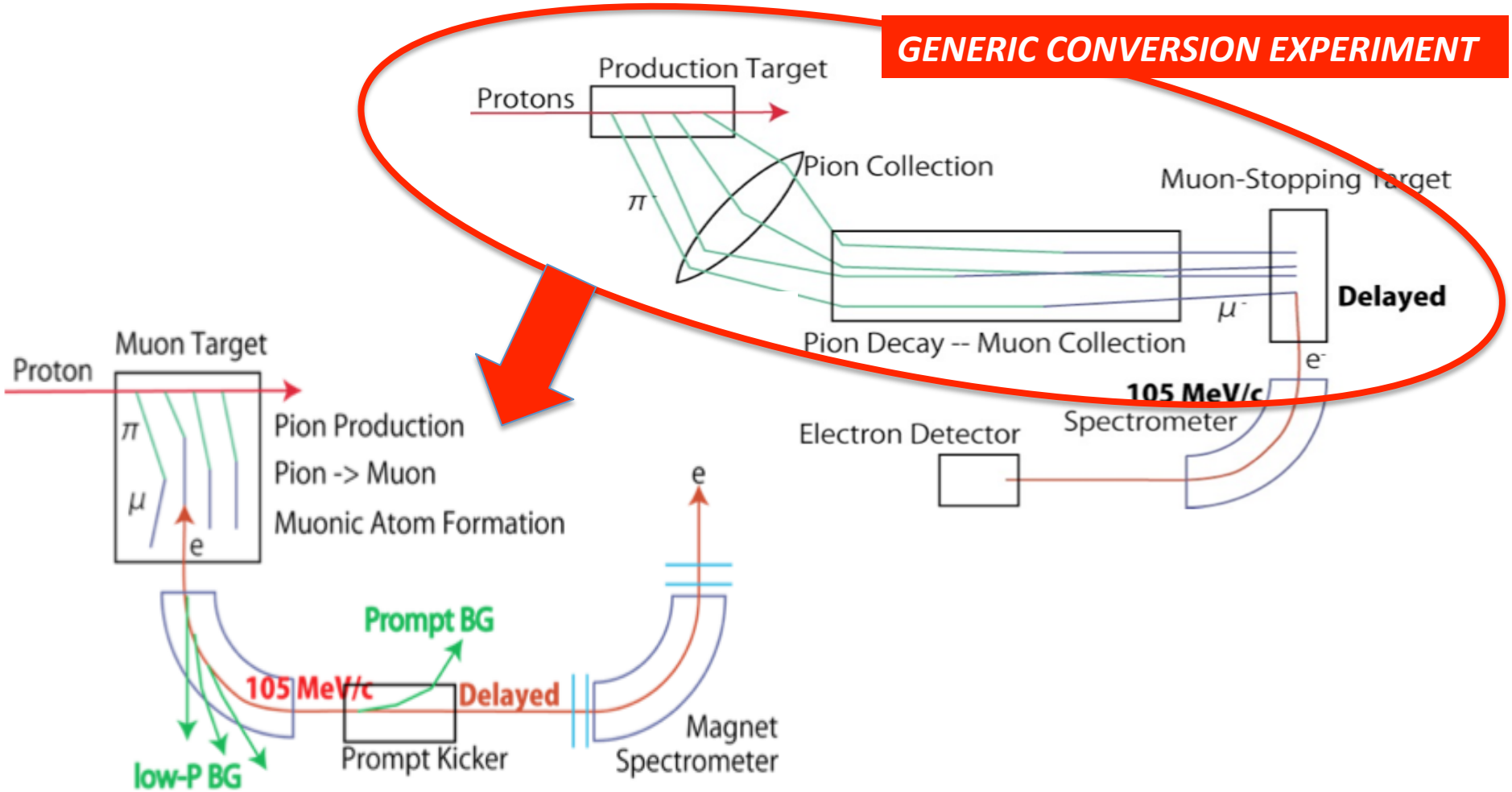
欠点
鉛からの特性X線が低エネルギーのバックグラウンドとなる



This Week ….
Then shutdown for 1-2 years

DeeMe @ JPARC : O(10^{-14})

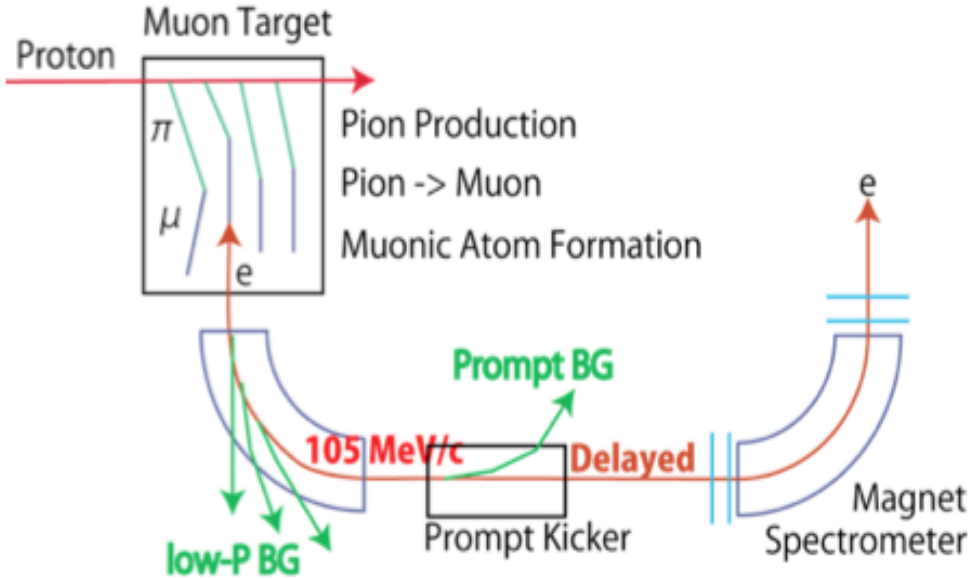
Simpler experiment than COMET/mu2e



DeeMe @ JPARC : O(10^{-14})

3 GeV "fast extracted" beam (cf ~ 8 GeV at COMET/mu2e)
Production & stopping target are combined : "surface muons" –> μ-atom in target
Spectrometer selects only ~ 105 MeV particles.
Prompt background reduced by delay and fast kicker magnet.

Requirement of extinction is : O(10^{-17})



25Hz rep rate, 300 ns fall time, 385 G

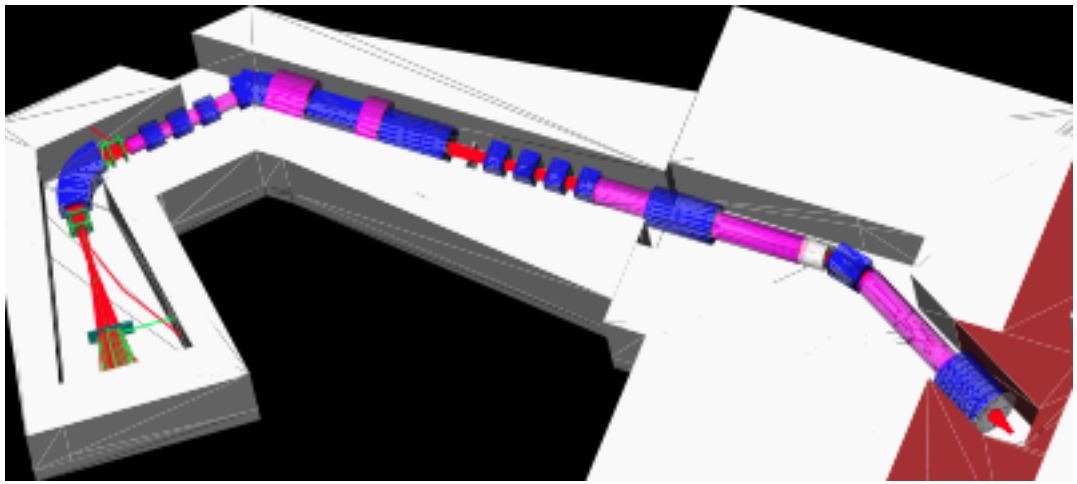
Reduce prompt burst (50 M particles) by factor of 1000.

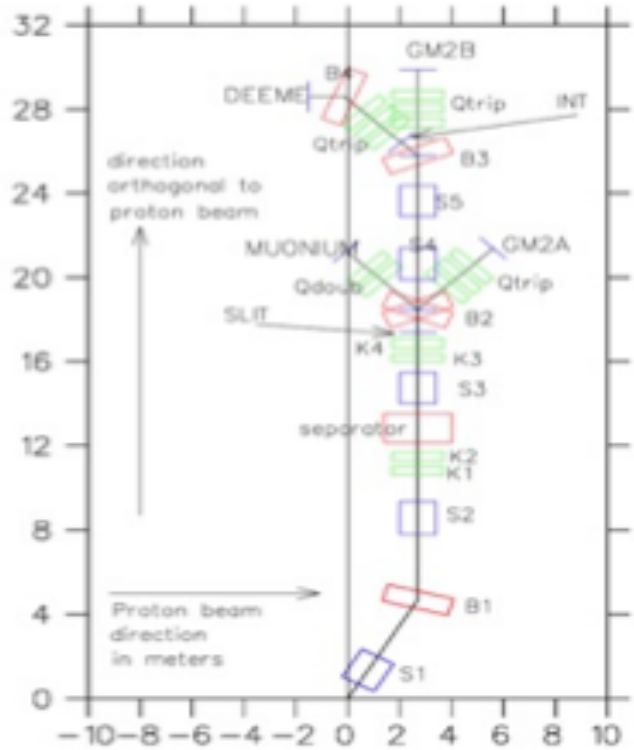
DeeMe @ JPARC : O(10^{-14})

In 2015 : JPARC RCS will provide 1MW @ 3 GeV.

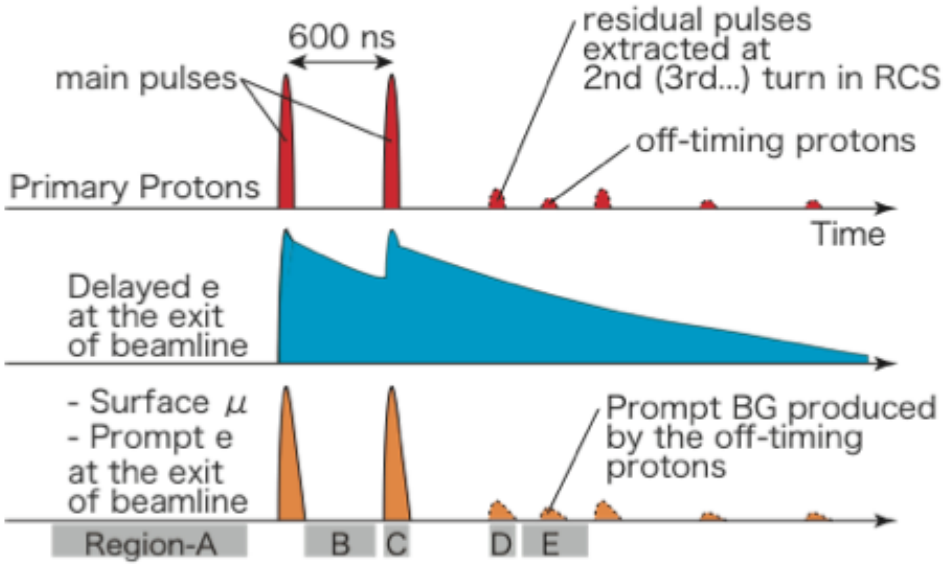
Existing low acceptance (D) beamline and graphite target : 90% BR @ 7×10^{-13}
New high acceptance (H) beamline and SiC target : 90% BR @ 5×10^{-14} for 2×10^{7} s run

Particle yield ($e^{+/-}$ from μ) has already been measured using gated-PMT and agrees well with simulation : **5×10^{9} μ/s/MW (x2 for SiC).**





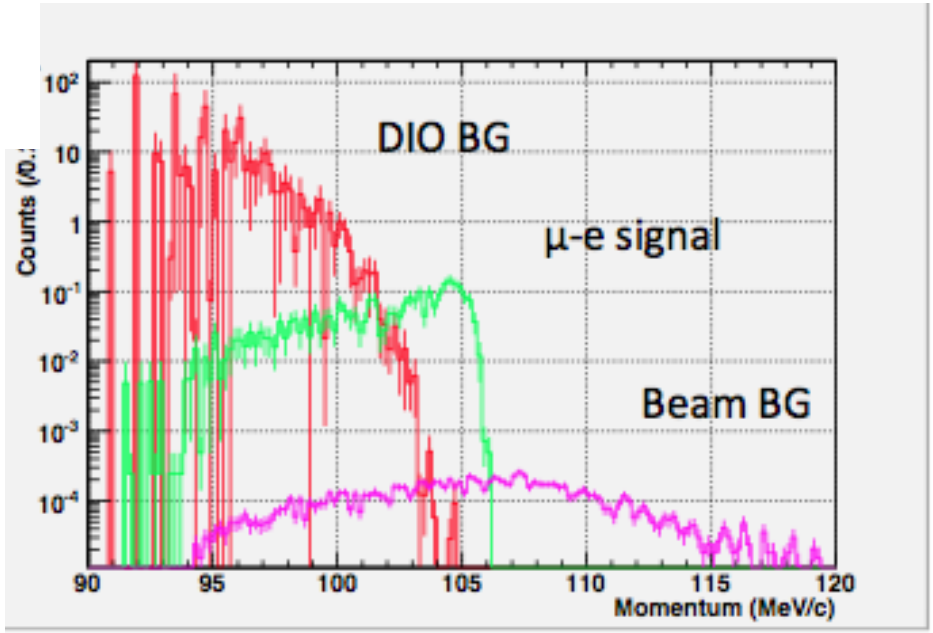
DeeMe @ JPARC : O(10^{-14})



1st extinction measurements performed: no signal recorded from 10^{20} p (258 hrs)

Due to limited momentum acceptance of beamline
DeeMe aims to measure DIO and high-p prompt background in situ

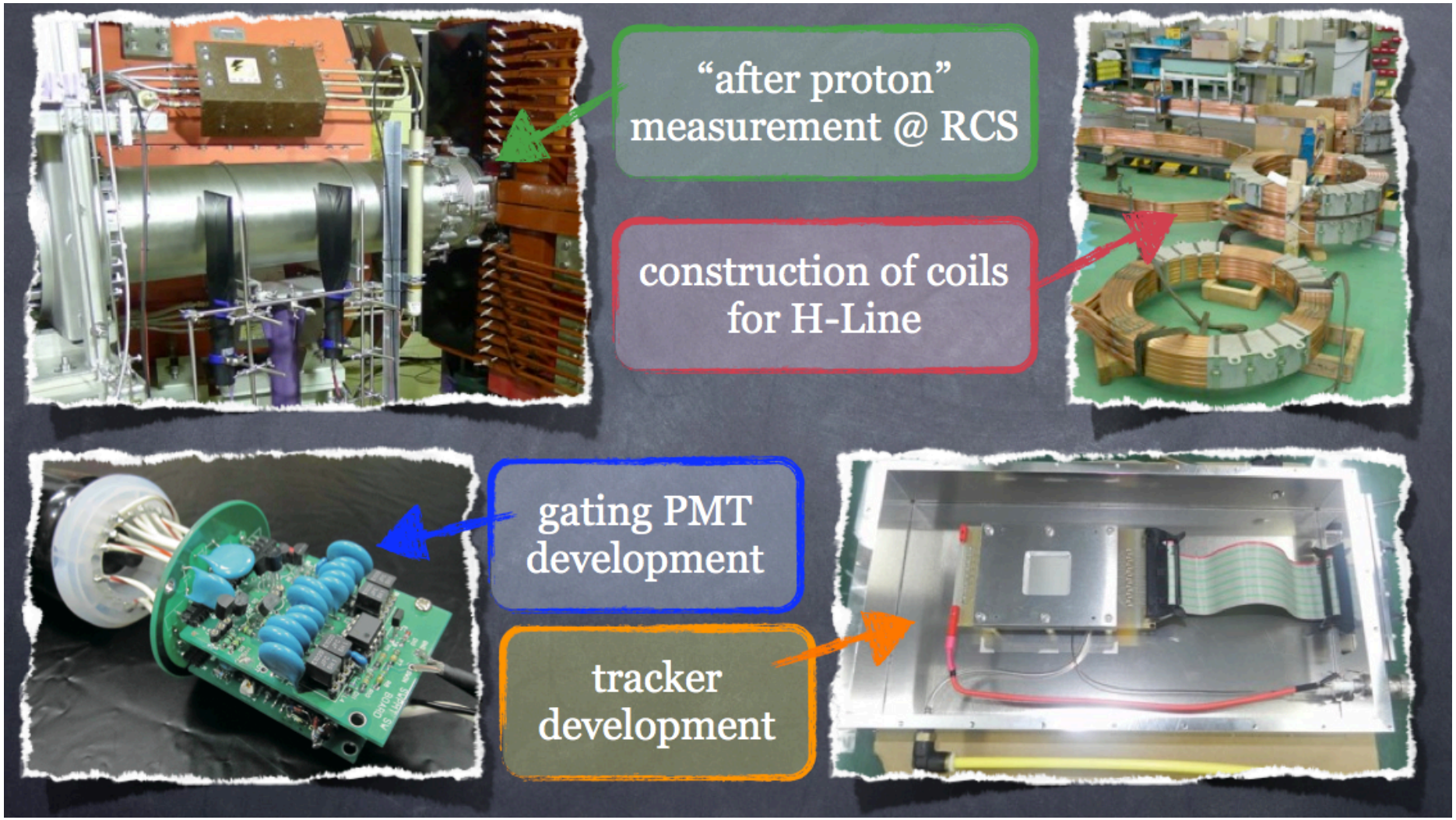
σ(p) < 0.5 MeV (wire chambers)



Signal Region: 102.0 -- 105.6 MeV/*c*

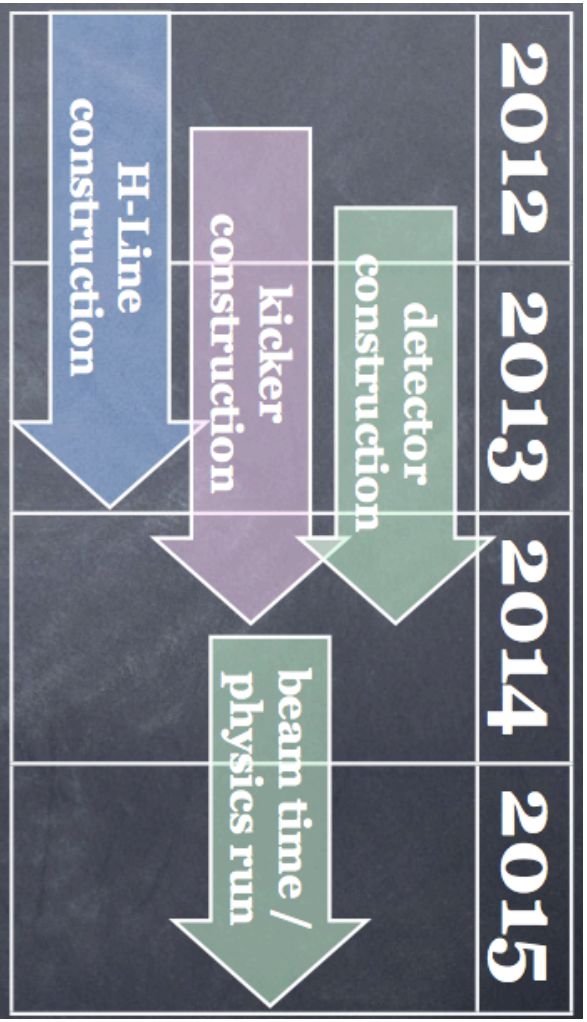
DeeMe R&D Continuing

Critically construction of the coils for the H- line has begun ….



DeeMe @ JPARC

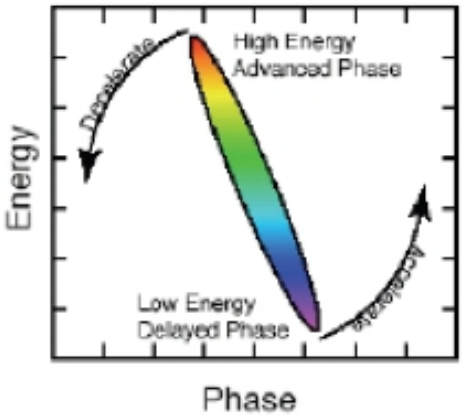
detector	subtotal : 1.03 M€	
	magnet	0.3 M€
	hodoscope	0.1 M€
	tracker (R&D)	0.03 M€
	tracker (prdct.)	0.5 M€
	electronics	0.1 M€
target	subtotal : 0.3 M€	
	SiC target	0.3 M€
Beam line (H-line)	require to the facility side	
kicker	subtotal : 2.2 M€	
	magnet	0.6 M€
	power	1.6 M€
PostDoc	subtotal : 0.75 M€ (for 3 posdocs)	
Grand Total	4.28 M€	

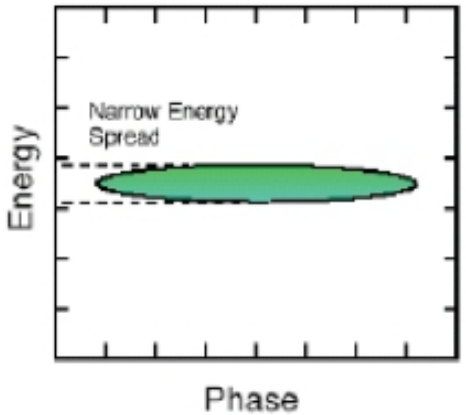


PRISM / PRIME FFAG : O(10^{-18})

Low duty cycle scheme unlike e.g. Project-X

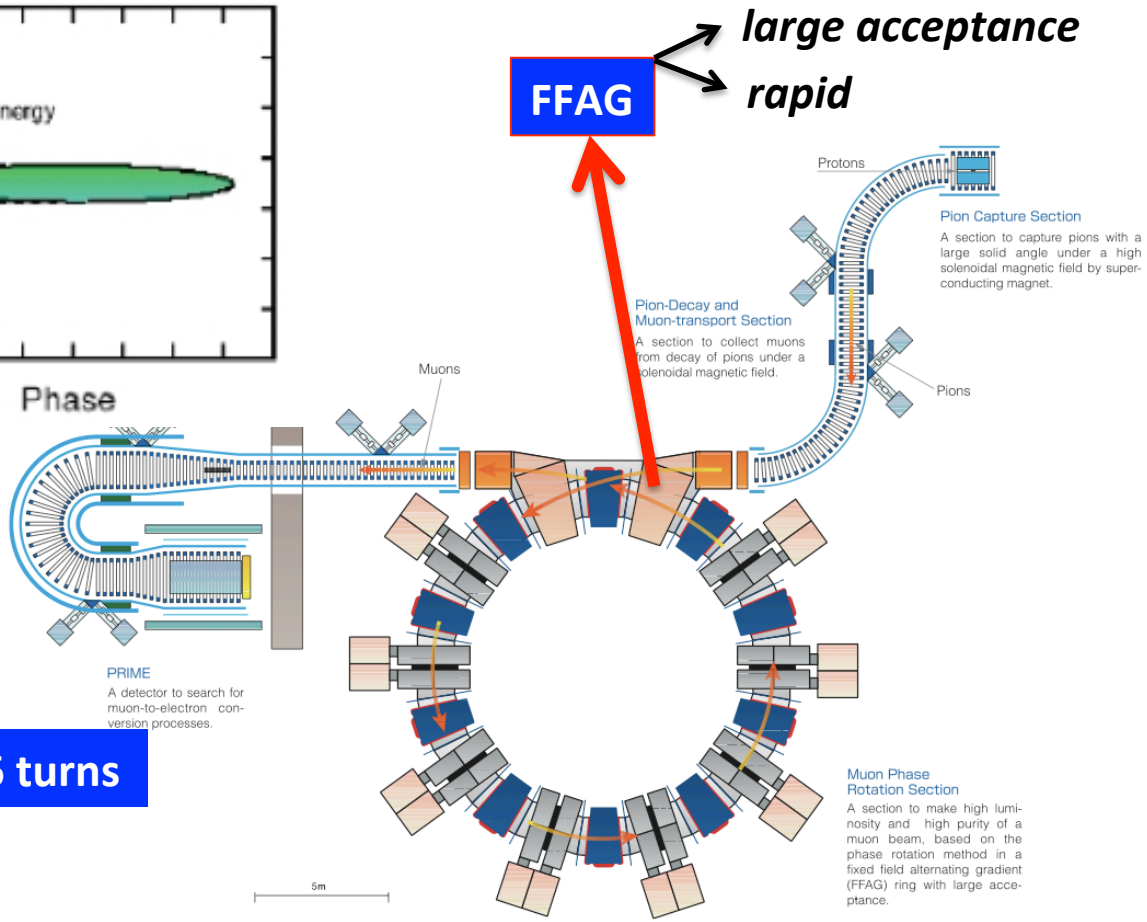
Use initial beam with short pulses (10 ns) and **use phase rotation** to achieve narrow momentum spread at Liouville's expense of longer (220 ns pulse)





Reduce p-spread : 20% to 2% in 6 turns (~1.5 μs).

Pions extinguished below 10^{-20} in 6 turns



PRISM / PRIME FFAG

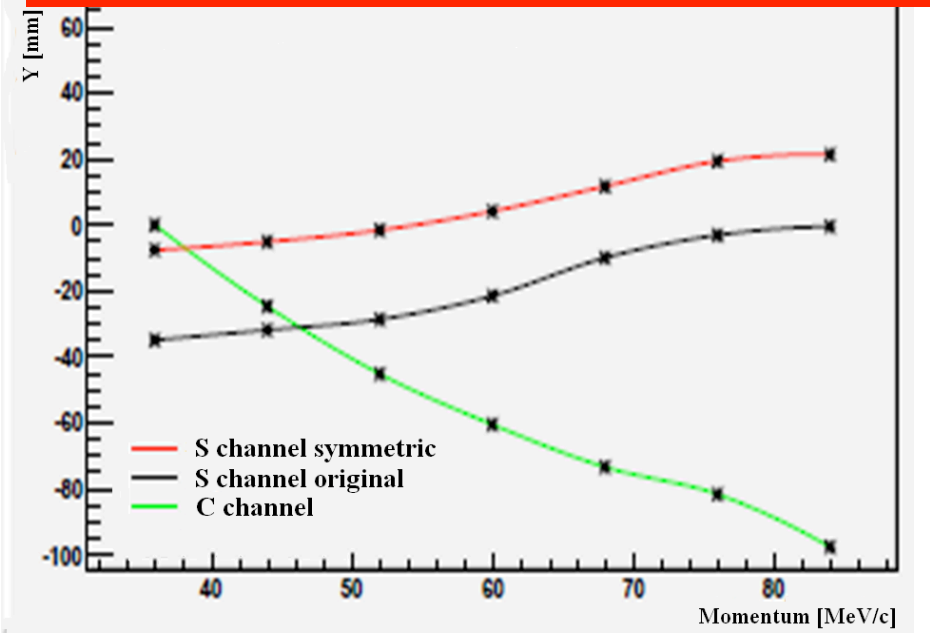
Phase Rotation demonstrated with FFAG at Osaka using α -particles

PRISM : Latest Studies

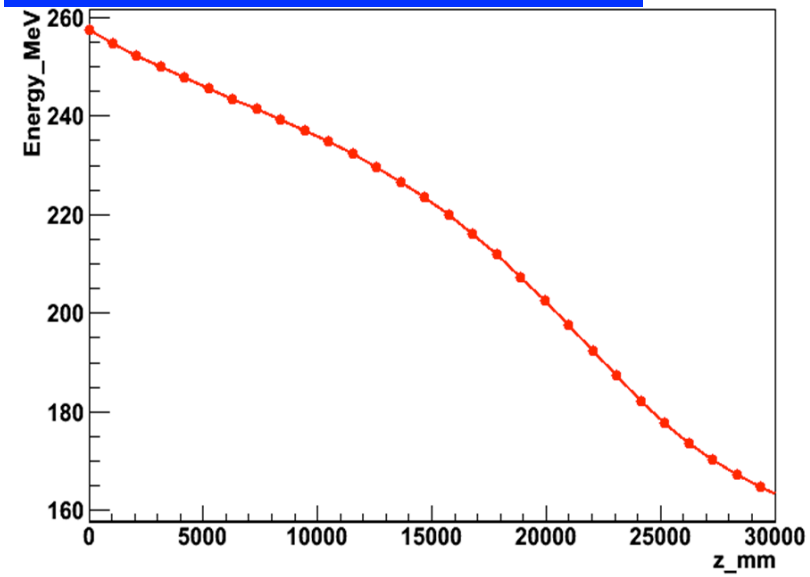
Optimal muon transport solenoid for best transmission into FFAG.

Alternate muon cooling using MICE/NF designs

Beam position at end of transport solenoid



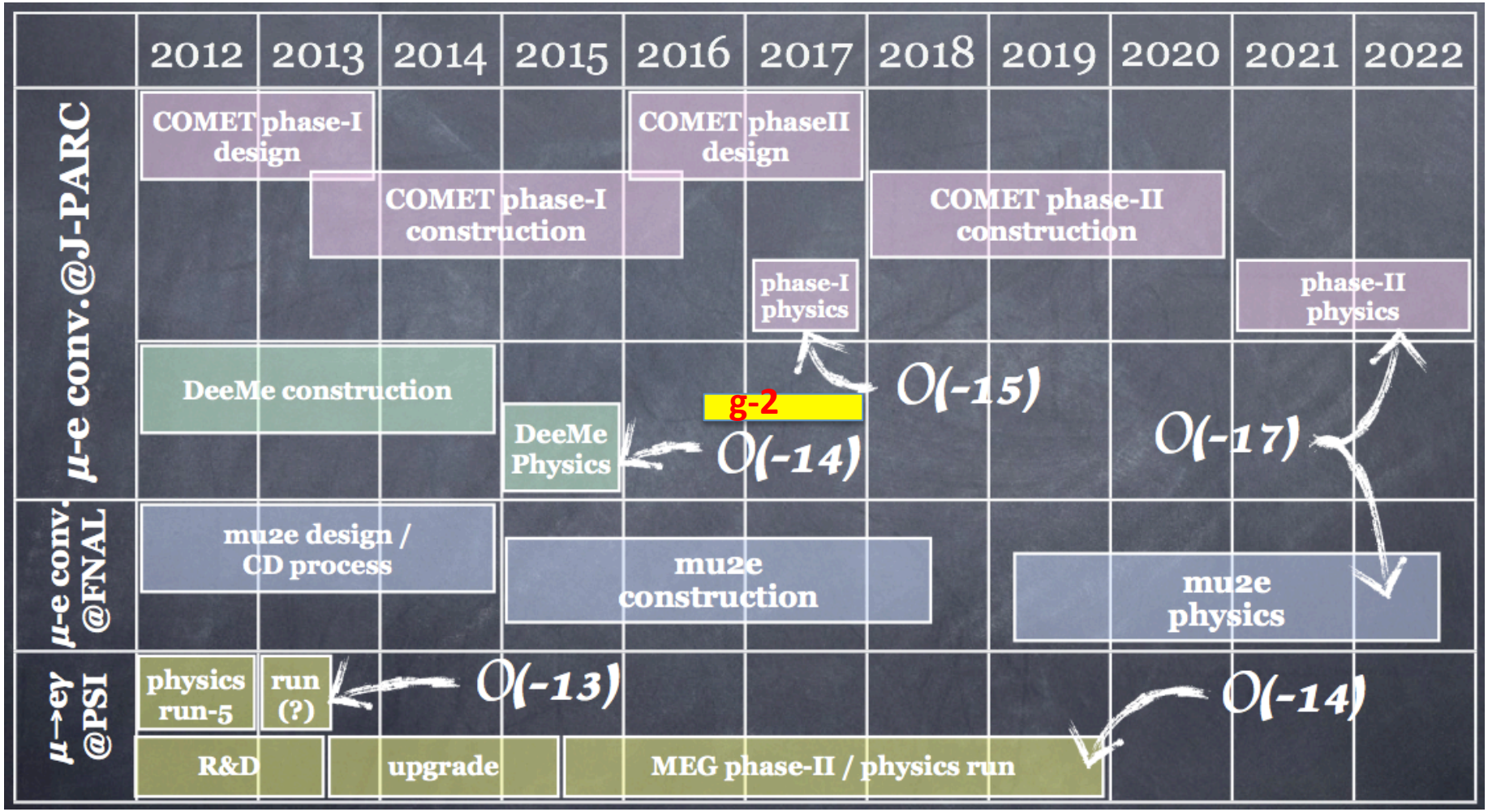
Mu cooling : LiH, 100 MHz RF



Conclusions

Vibrant muon programme in Japan, US and Europe.

Next 10 years promise to be very interesting



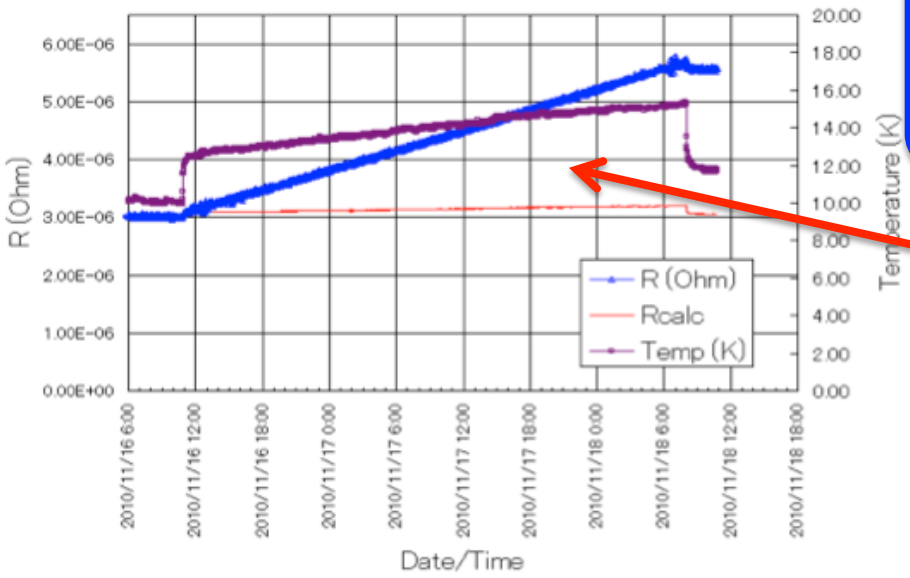
Backup

Silicon Tracker

Item	Specifications
Fiducial volume	240mm (radial) x 400 mm (axial)
Number of vane	48 (still subject for optimization)
Sensor technology	Double- or single-sided Silicon strip sensor
Strip	axial-strip : 188μm pitch, 72mm long , 384 ch radial-strip: 255μm pitch, 98mm long, 384 ch
Sensor dimension	74 mm x 98 mm x 0.32mm
Number of sensor	576 (12 sensors per vane)
Number of channel	442,368 ch
Time measurement	Period : 33μs, Sampling time : 5ns

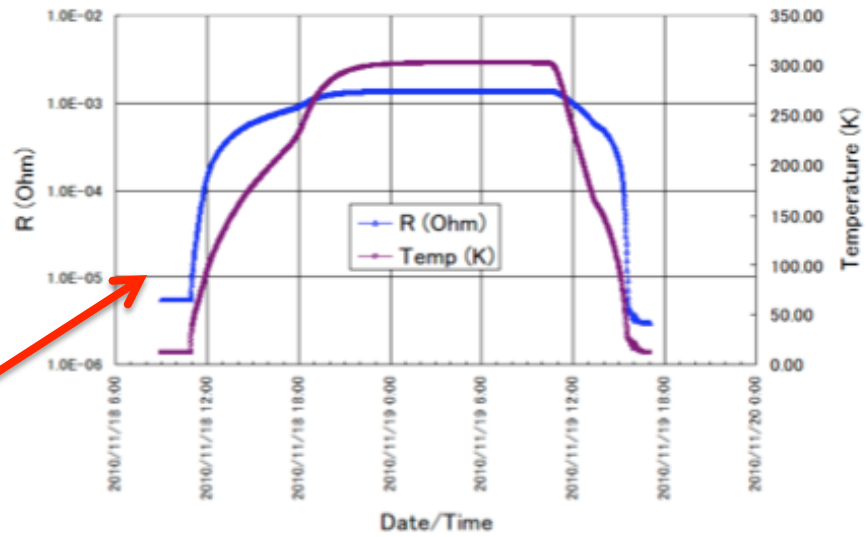
COMET : Irradiation Tests

Pion production solenoid is 1.3m diameter 5T solenoid subject to to 10^{21} n/m^2



Neutron irradiation tests of Superconductor and Al stabiliser at Kyoto nuclear reactor using 10^{20} n/m^2

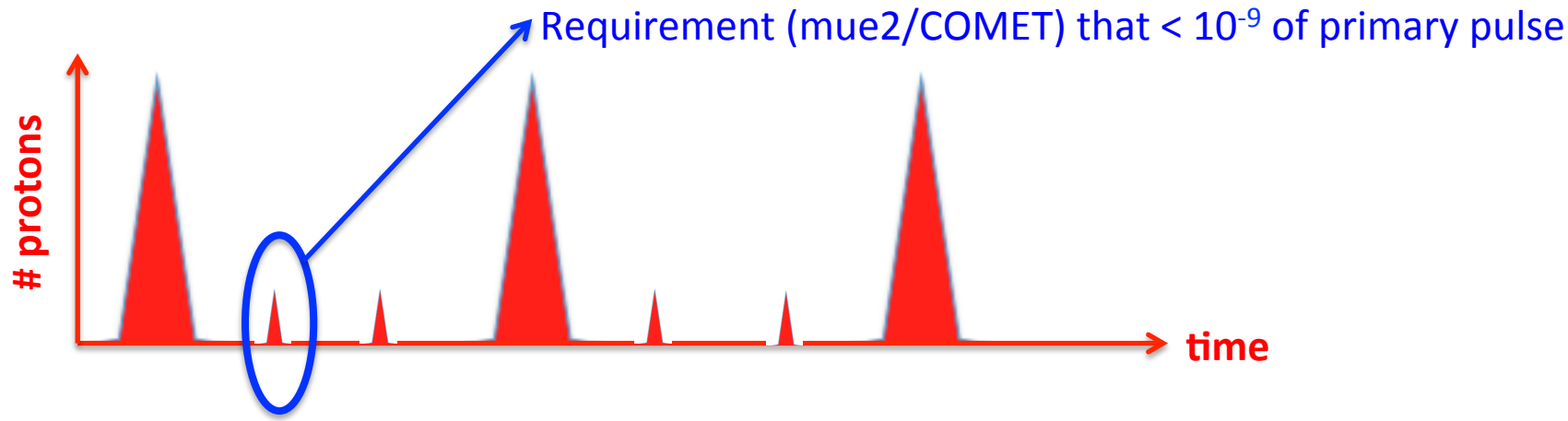
Resistance increased by ~ 2.5μΩ



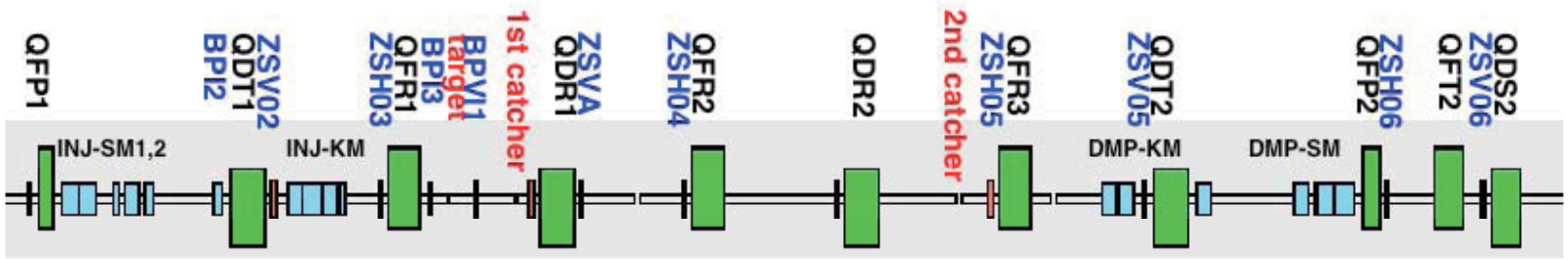
½ day thermal cycling returns resistance to pre-radiated value

Challenges : Proton Extinction / "After protons"

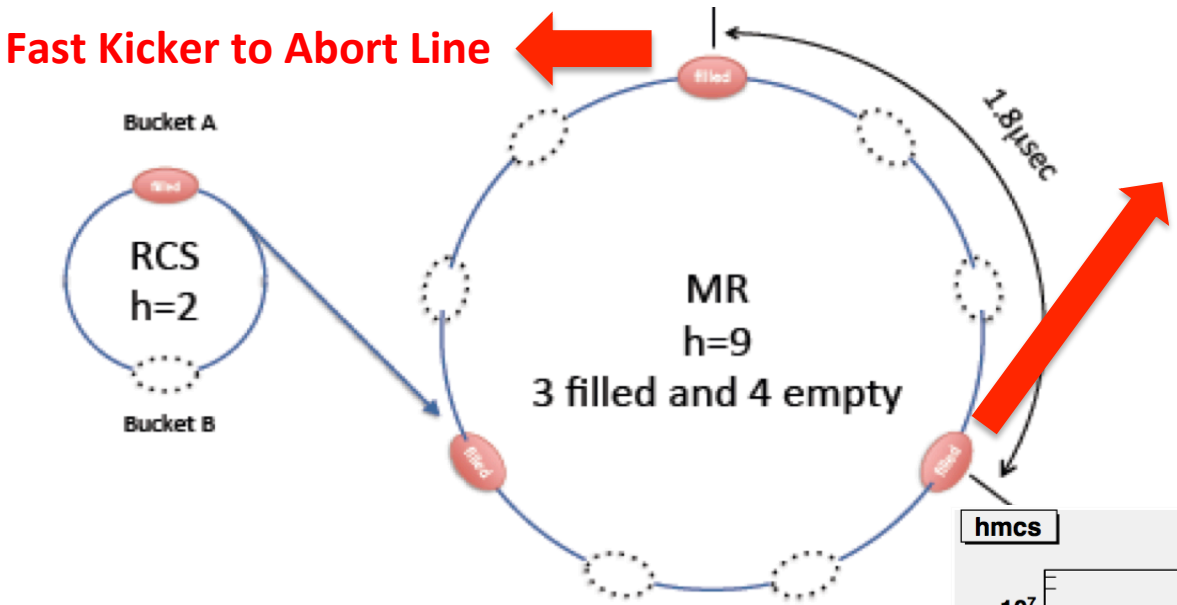
Require that between proton pulses there are no rogue proton pules that could produce a "prompt" background e.g. RPC in the timing window



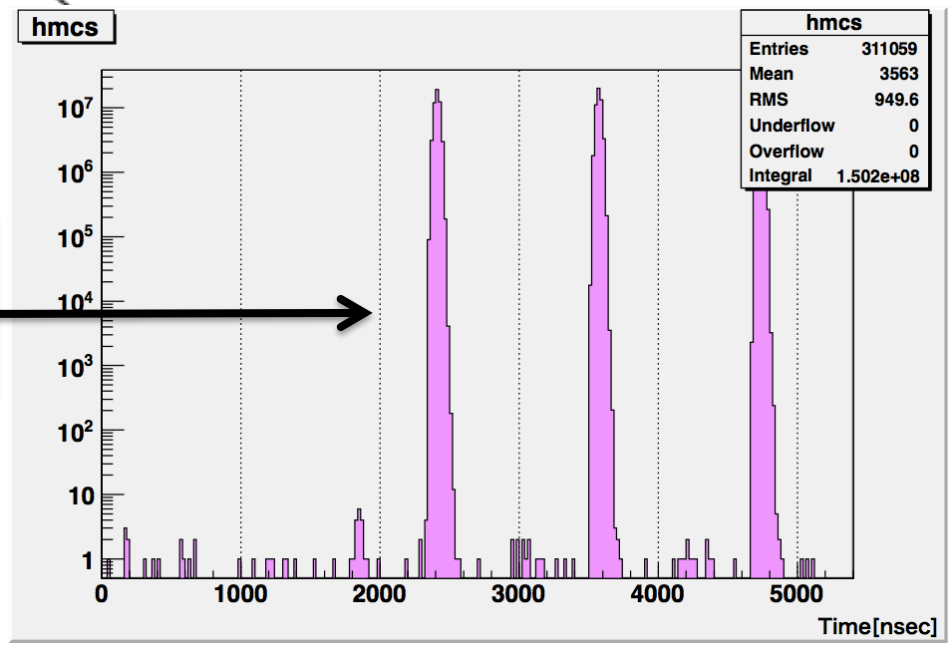
AC dipole/collimator system kicks out the out-of-time particles



COMET : Extinction Studies



Bunched slow extraction using ESS to dedicated target/ secondary beamline

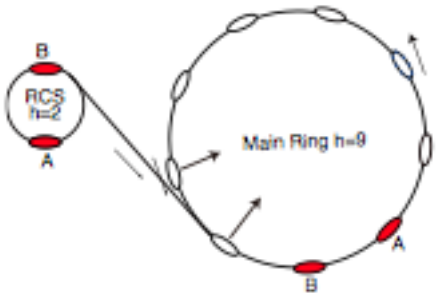


Extinction level of **(5.4 ± 0.6) × 10^{-7}** measured at secondary J-PARC beam line and O(10^{-7}) at abort line

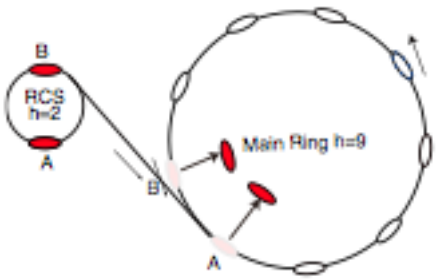
And additional O(10^{-6}) from double kick injection into MR

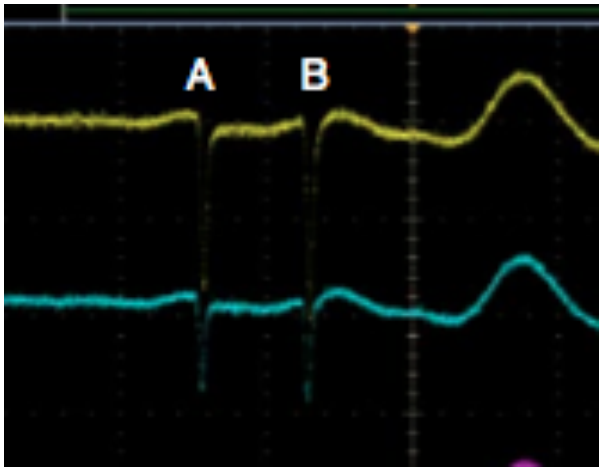
COMET Extinction

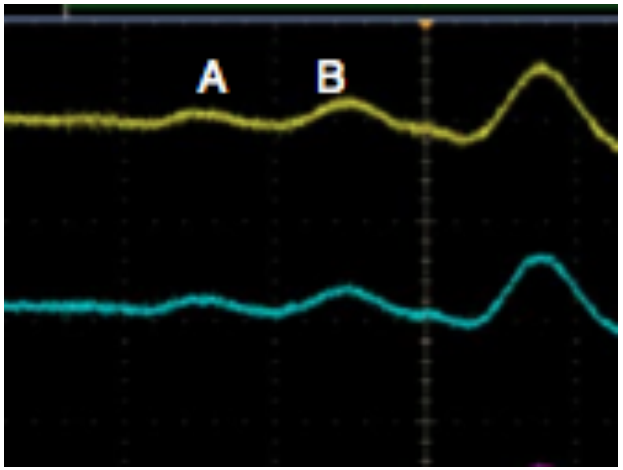
"Double Kicking" injection into the MR



1st measurements show O(10^{-6}) additional extinction can be achieved







Beyond COMET/Mu2E

Strategy depends somewhat on whether signal is seen or not.

If signal is seen

- run with high-Z target to elucidate the underlying physics

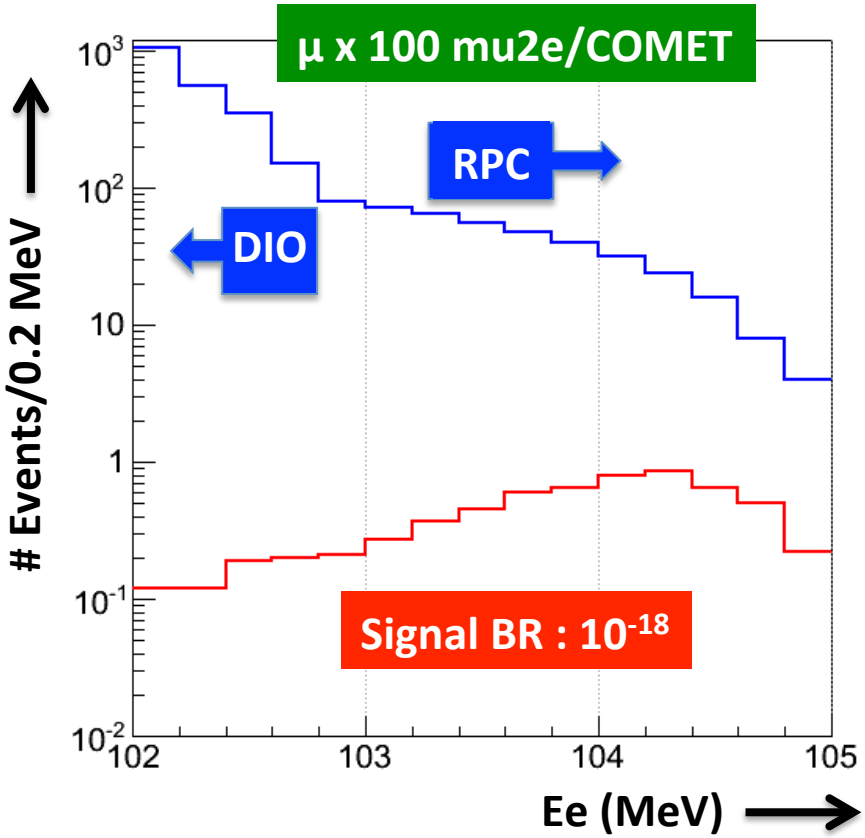
If no signal seen

- push sensitivity down to O(10^{-18})

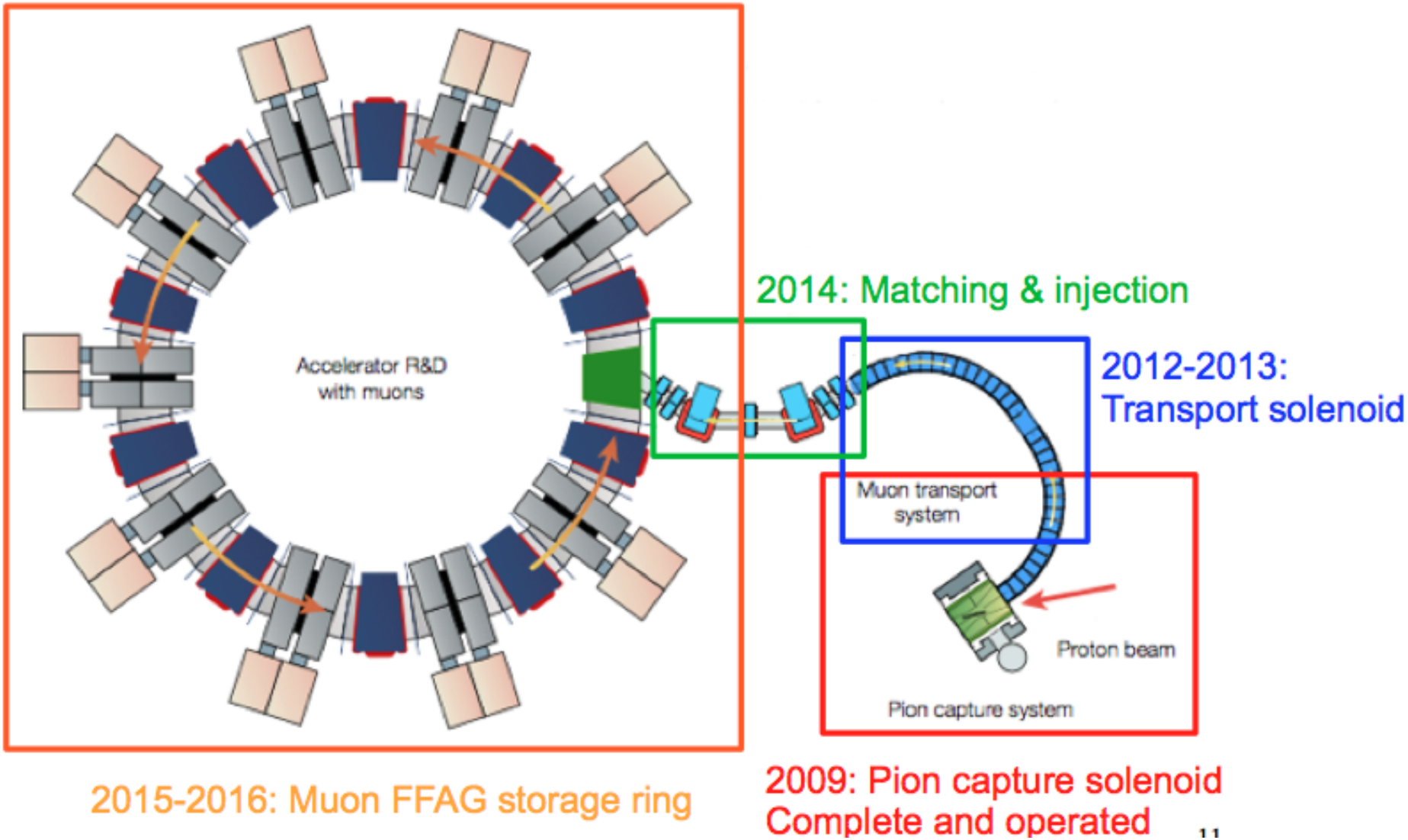
10^{-18} and beyond is difficult with current methodology/detectors since DIO & RPC backgrounds dominate.

Requires:

- reduction in # pions at target by O(100)
- better event localisation (t,pos) at target
- reduced E-loss in target (now ~ 1 MeV)



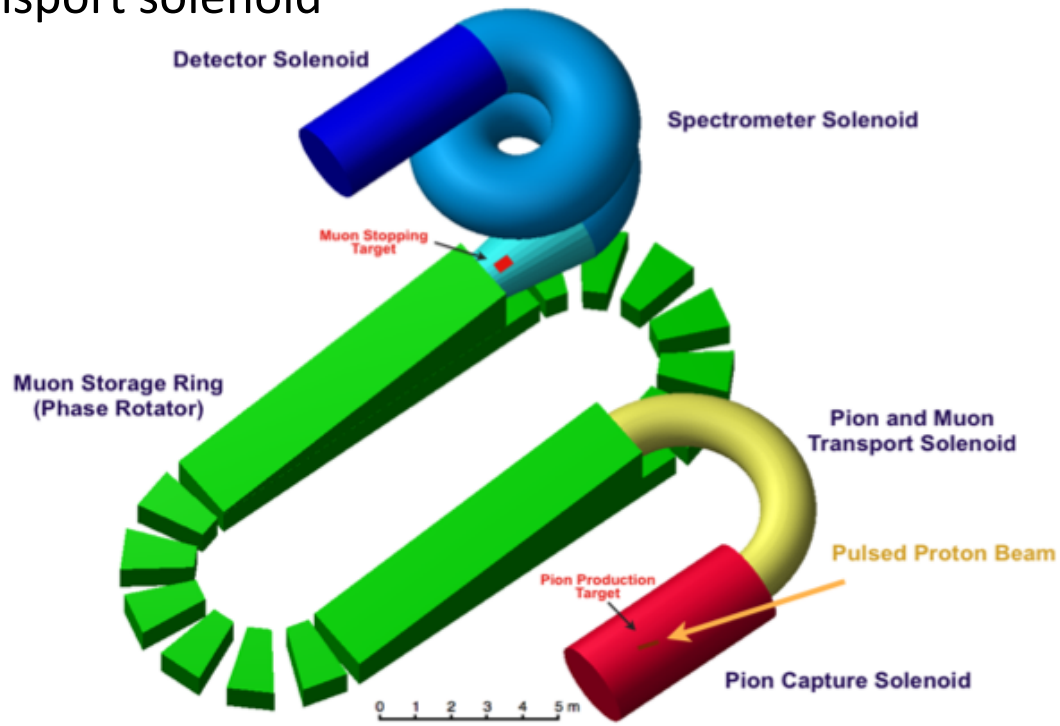
MUSIC Plan (Budget Permitting)



PRISM / PRIME FFAG

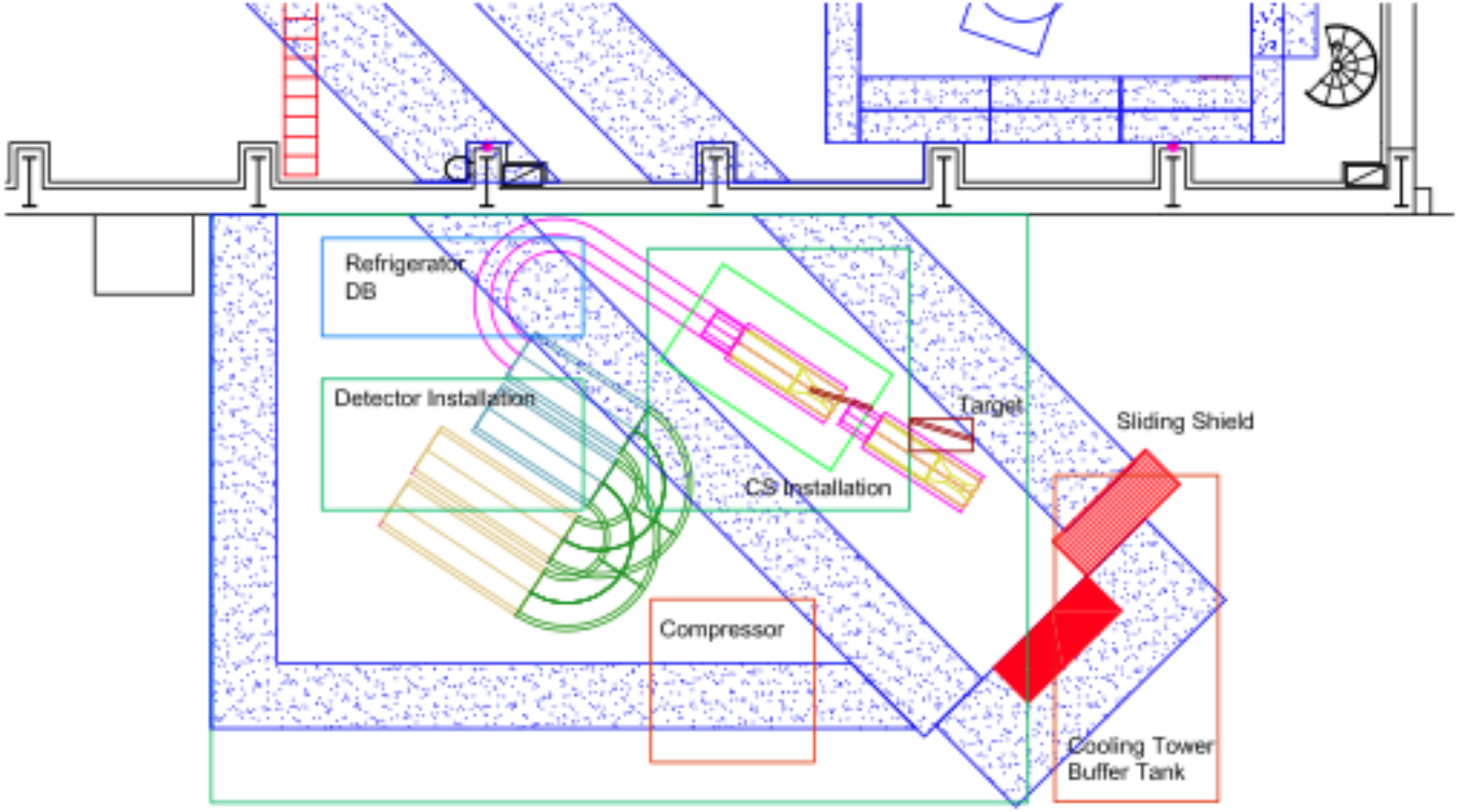
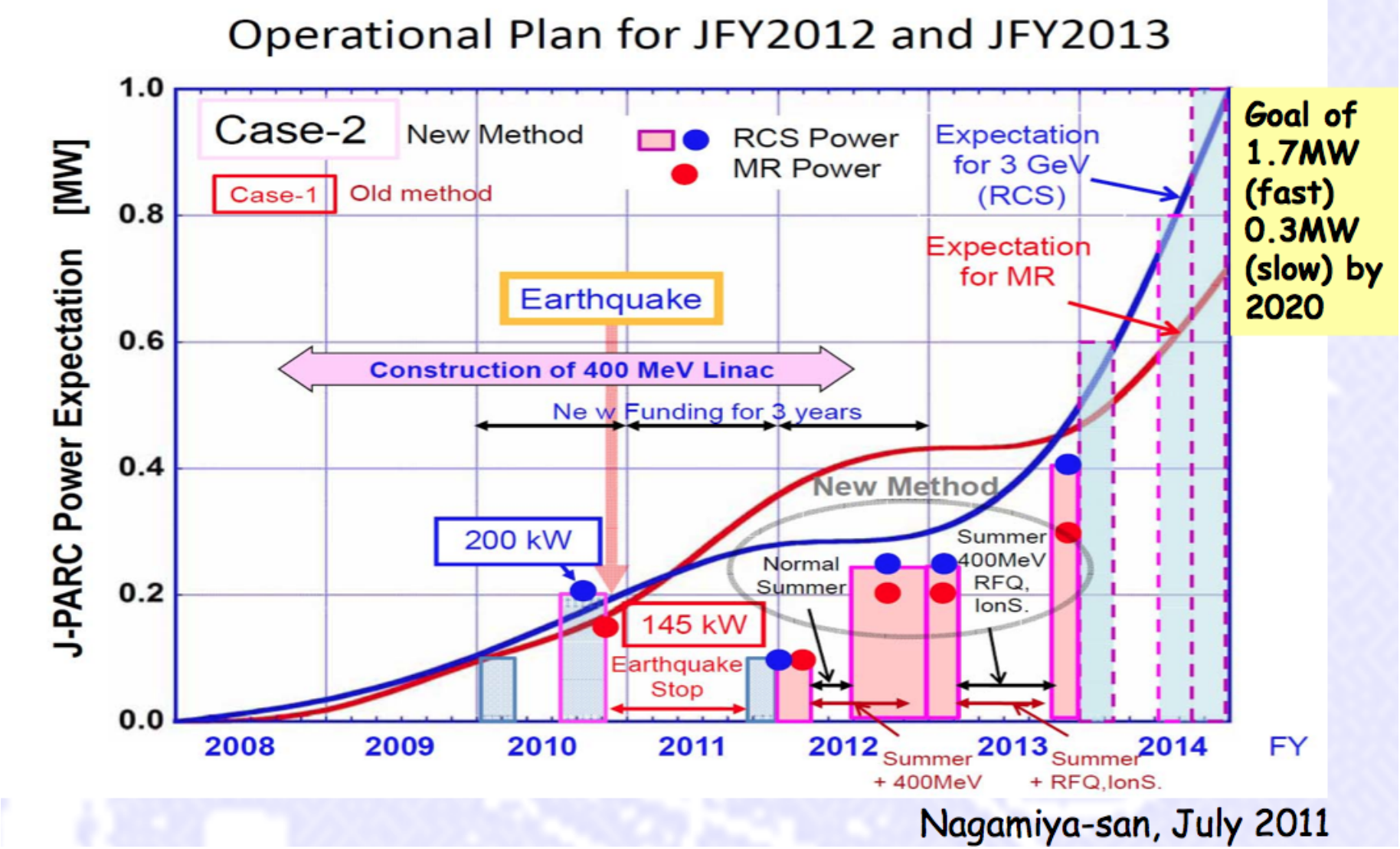
Many issues being worked on:
- injection and extraction (80 ns rise time kicker magnets)
- beamline matching

PRIME is detector concept – employs "Guggenheim" electron (p ~ 105 MeV) transport solenoid



CDR in 2012

COMET Phase-I



J-PARC Timeline