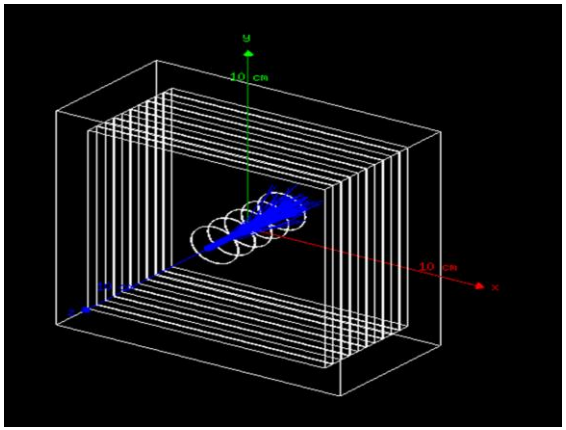
Fundamental Physics and True Muonium Production

Takahisa Itahashi

Faculty of Science, Osaka University, Toyonaka, Osaka, Japan 567-0043

FPUA 2015, RIKEN



Contents

1. *Fundamental Physics - Motivation - Muon problems and True Muonium*
2. *TM - properties the spectrum decay widths mimic the spectrum of positronium scaled by the mass ratio*
3. *Frictional Cooling - principle and present status*
4. *Simulation - GEANT4*
5. *Proton Acc. LEAP-1 - Simulation POP-FRESH*
6. *Summary & Perspectives - Application - muon collider – MAP– neutrino factory*

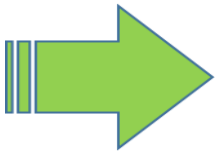
- approach – routine 通例
- break through 開拓
- research direction 創作
- follow Dirac's way 新奇
- large-number-hypothesis 大胆
- fine structure constant (?) 精密

10^{36}

Y. Fujii , A. Iwamoto and H.Hidaka, appeared in BUTSURI 55(2000)

Verification of QED

- Lamb shift of hydrogen $2S_{1/2}$-$2P_{1/2}$ = 1057.86+/-0.06 MHz
- Fine structure $2P_{3/2}$-$2P_{1/2}$ = 9911.38+/-0.03MHz
- Hyperfine structure of hydrogen ground state $\Delta\nu$ = 1420.4057517864(17) MHz
- Hyperfine structure of positronium $\Delta\nu$ =(2.03396+/-0.00005) x10^5 MHz
- Fine structure of muonium $\Delta\nu$ =4463.311(12) MHz
- Anomalous magnetic moment of electron a_e= (1159.65218076+/-27) x10^{-6}
- Anomalous magnetic moment of muon a_μ= (11659209+/-6) x10^{-10}
- Mϕller and Bhabha scattering – recoil effect in propagator



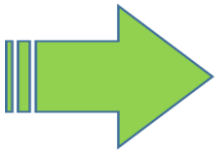
Possibilities
-New Physics-

Muon Problems(?) : *there are several discrepancies between experiment and theory in the muon sector (CODATA)*

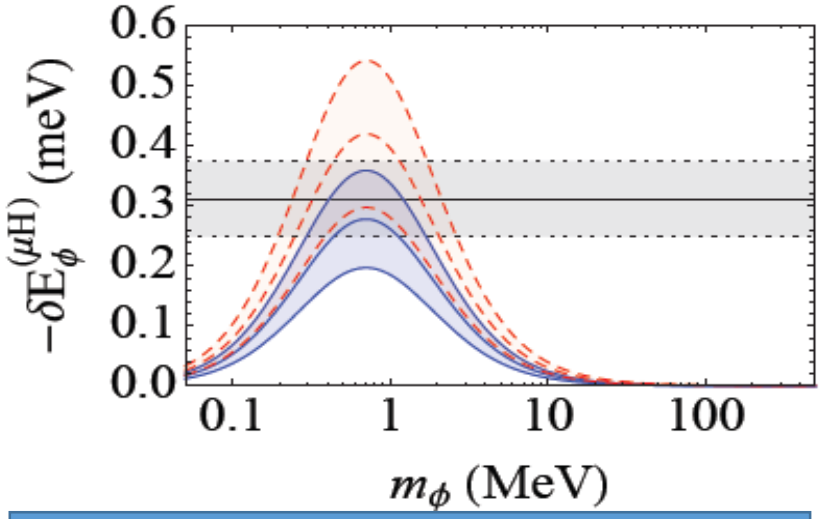
Experiments	Discrepancies	References
a_μ	2.9σ	Phys. Rev D73
r_p	7σ	Science 339 Annals Phys. 331
$R_k B^+ \to K^+ \mu^+ \mu^-$	2.6σ	P.R.L. 113.15
$h \to \mu\tau$	2.5σ	CMS colllab.

BSM ?
EDM ?
g-2 ?
cLFV ?
Dark matter ?
Gravity ?
Relativity ?

- present quest in high energy physics and astrophysics
- *models at hidden sector*
- mediator of a new force
- HPS 10 ~ 1000 MeV *assume a new mediator*



Possibilities -New Physics-



The contribution to the energy shit in μH , plotted against the mass of the mediator

- a new interaction between muons and protons in μH

- Solid-blue , the theoretical deficit, scalar contribution to (g_μ-2) ~ upper and lower +/- 1 s.d. away from the theoretical deficit.
- Solid-red, the vector contribution
- Coupling $g_p=g_\mu$
- Solid horizontal , discrepancy between exp. and th. prediction assuming the CODATA

New physics; discrepancy between the CODATA value of the proton radius and the value deduced the meas. of the Lamb shift in muonic hydrogen,

[ref.] *Muonic hydrogen and MeV forces by David Tucker-Smith and Itay Yavin*

assume a new mediator, the 1st order perturbation theory

$$V_\phi(r) = (-)^{s+1}\left(\frac{g_\mu g_p}{e^2}\right)\frac{\alpha e^{-m_\phi r}}{r}$$

$$\delta E_\phi = \int dr r^2\, V_\phi(r)\left(|R_{20}(r)|^2 - |R_{21}(r)|^2\right)$$
$$= (-)^{s+1}\frac{\alpha}{2a_\mu^3}\left(\frac{g_\mu g_p}{e^2}\right)\frac{f(a_\mu m_\phi)}{m_\phi^2}$$

$$f(x) = x^4(1+x)^4,\quad a_\mu = \left(\alpha m_{\mu p}\right)^{-1}$$

easy comparison

- $\delta E_p = \frac{2\alpha}{3n^3 a_\mu{}^3}\langle r_p{}^2\rangle$
- r_p is the proton radius and

n =2 is the principal quantum number

look for new Physics

- Solid-blue , the theoretical deficit, scalar contribution to (g_μ-2) ~ upper and lower +/- 1 s.d. away from the th.deficit.
- Dashed-red, the vector contribution

assume a new mediator, the 1st order perturbation theory

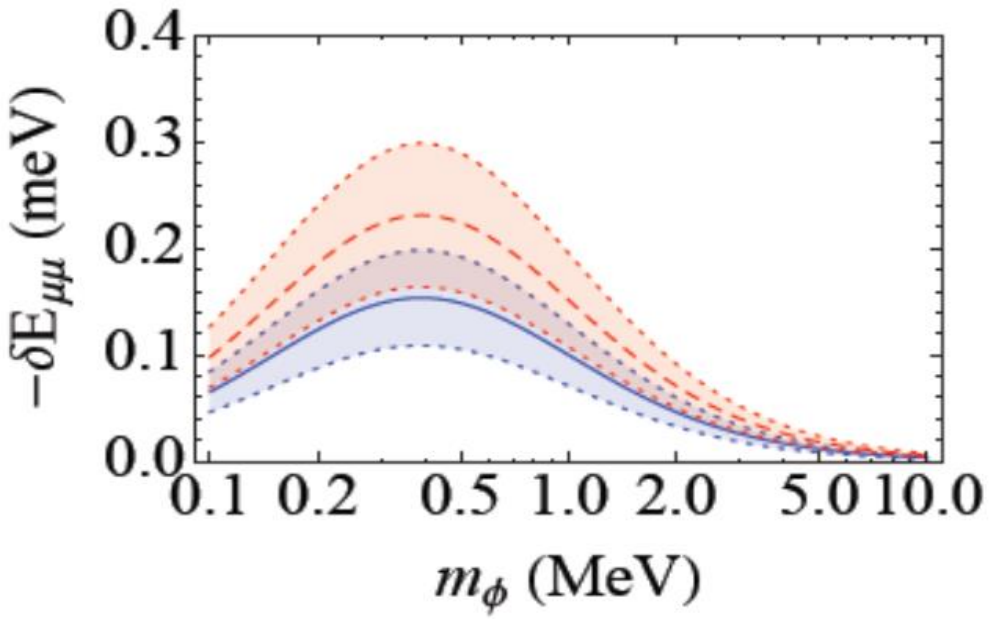
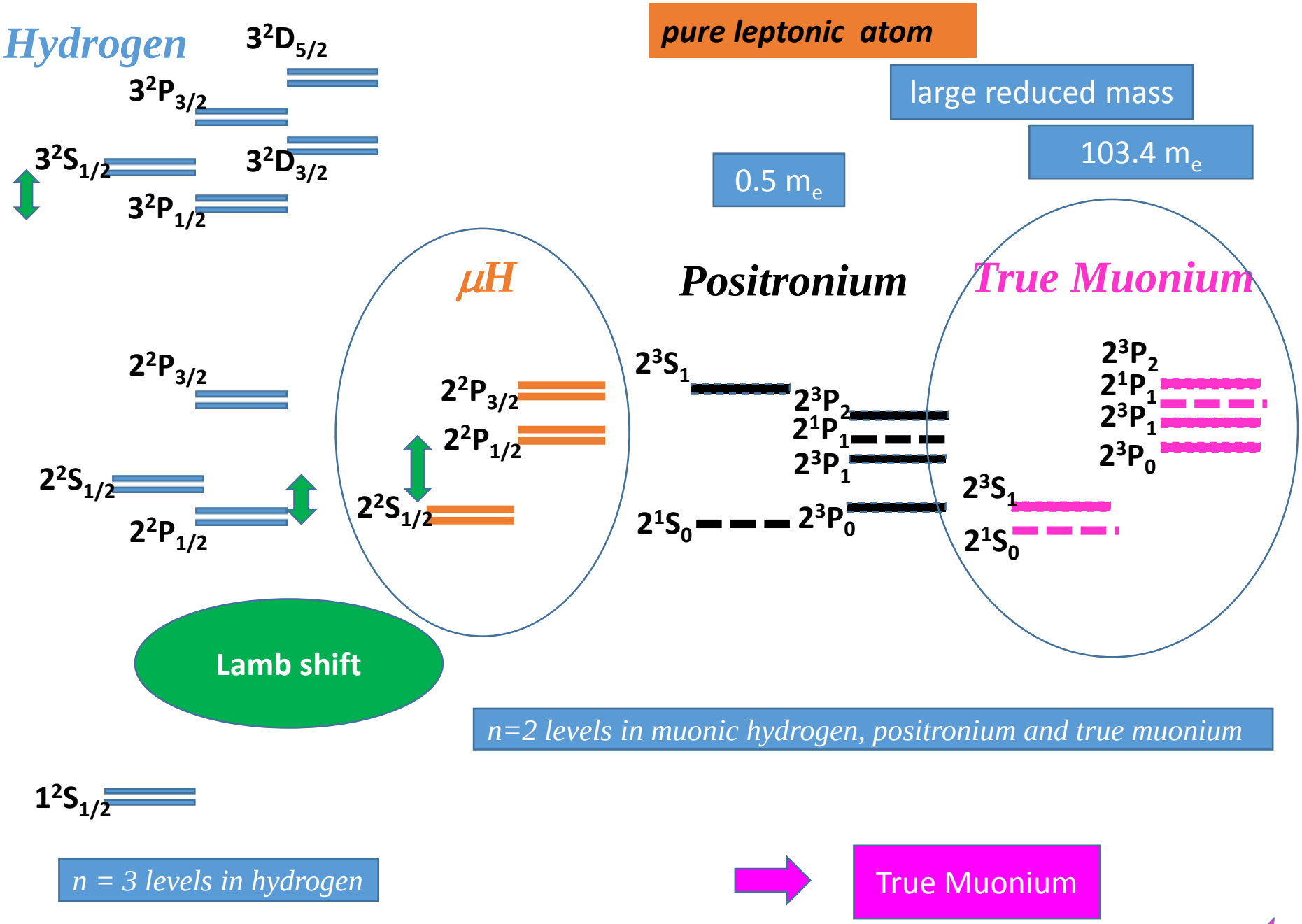


Fig. The contribution to the energy shift in TM as a function of the force carrier mass 2S-2P transition



look for new Physics

How do we produce the true muonium ?

- ***high energy***

Heavy Photon Sear

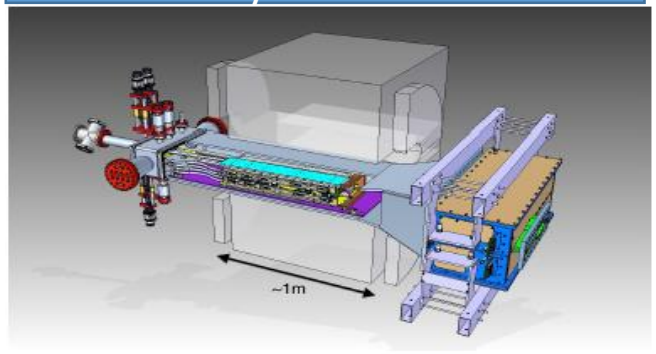


Figure: HPS Experiment at JLab

Dimeson relativistic atom complex

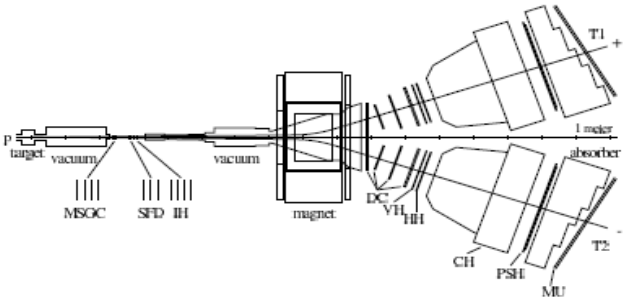


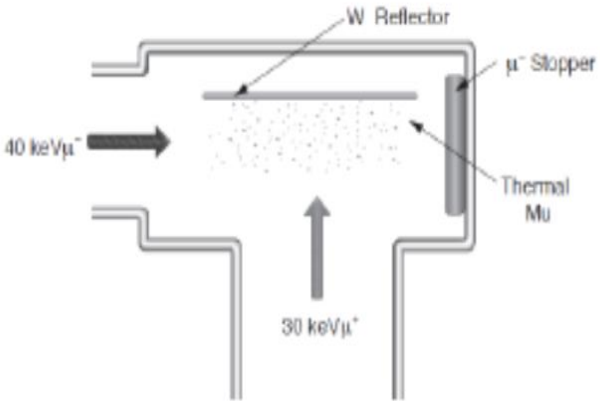
Figure: DIRAC Experiment at CERN

- ***low energy***

K. Nagamine

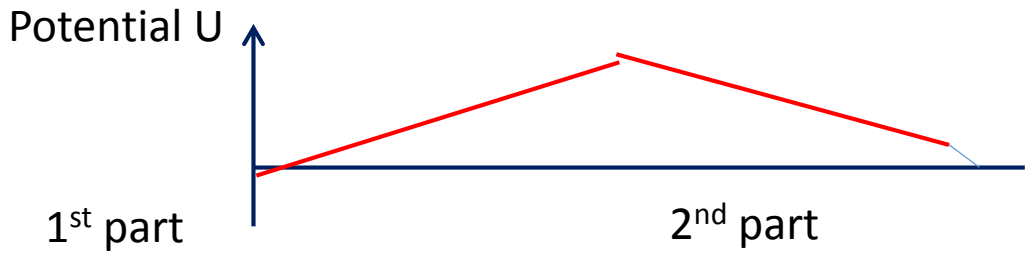
Possible experimental arrangements; detection of formation by K. Nagamine appeared in USM 2013 at Matsue

$\mu^- + Mu \rightarrow (\mu^+\mu^-) + e^-$



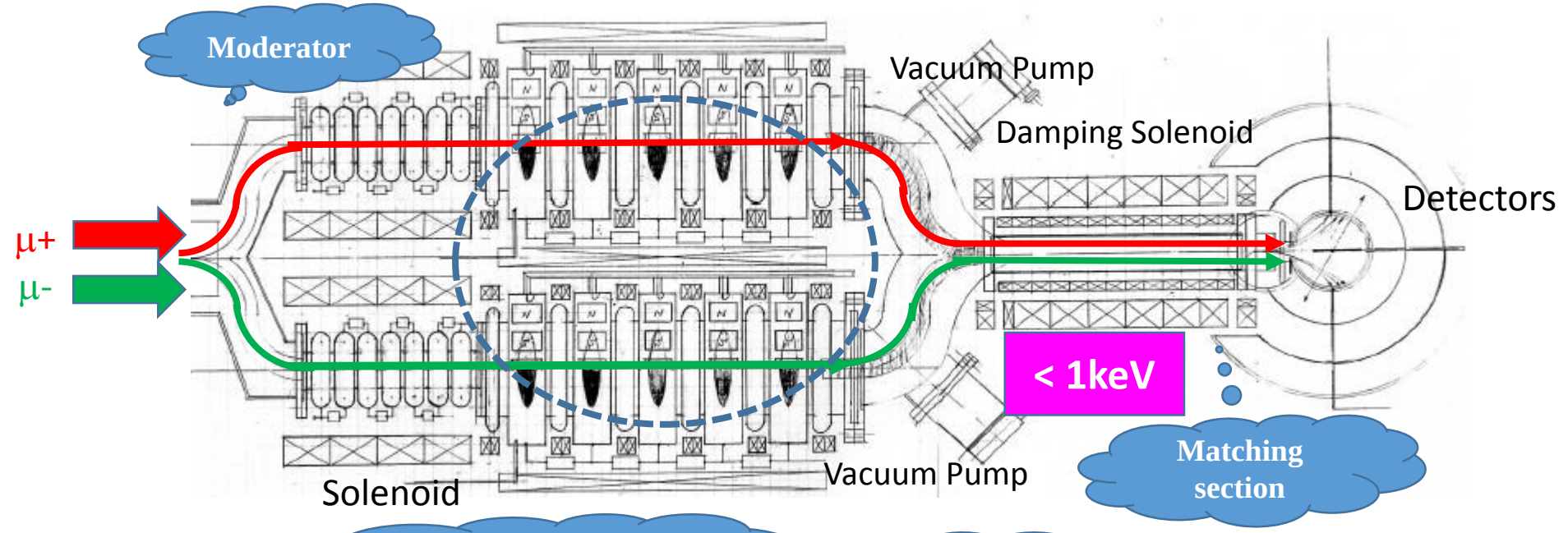
low energy scheme

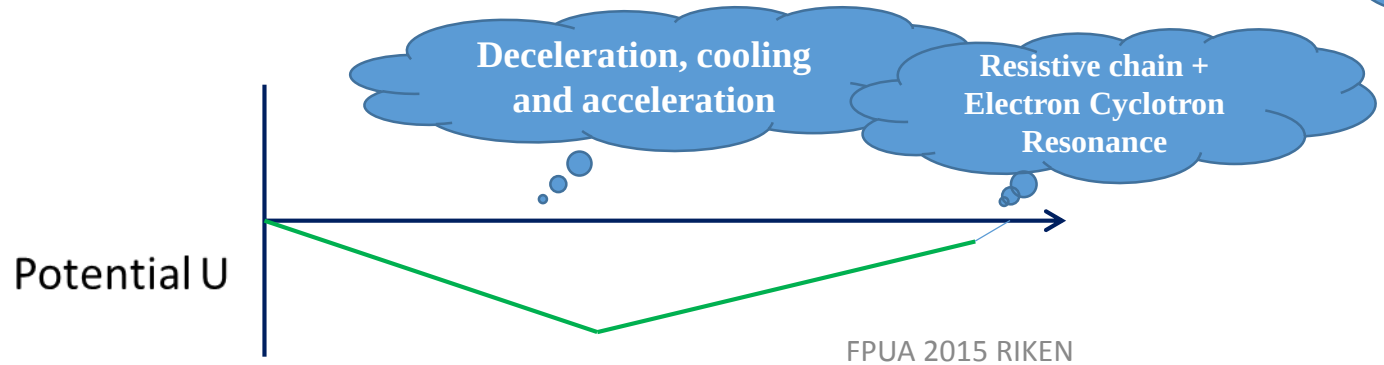
almost the same procedures applied for μ+ and μ-



Deceleration

Friction & Acceleration





preliminary

Strategy for a true muonium production via a low energy collision with μ+ and μ-

Local density approx. for a free electron gas

Many electrons configuration in matter

Dielectric response

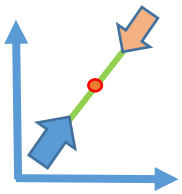
--Lindhard, Scharff (1954)

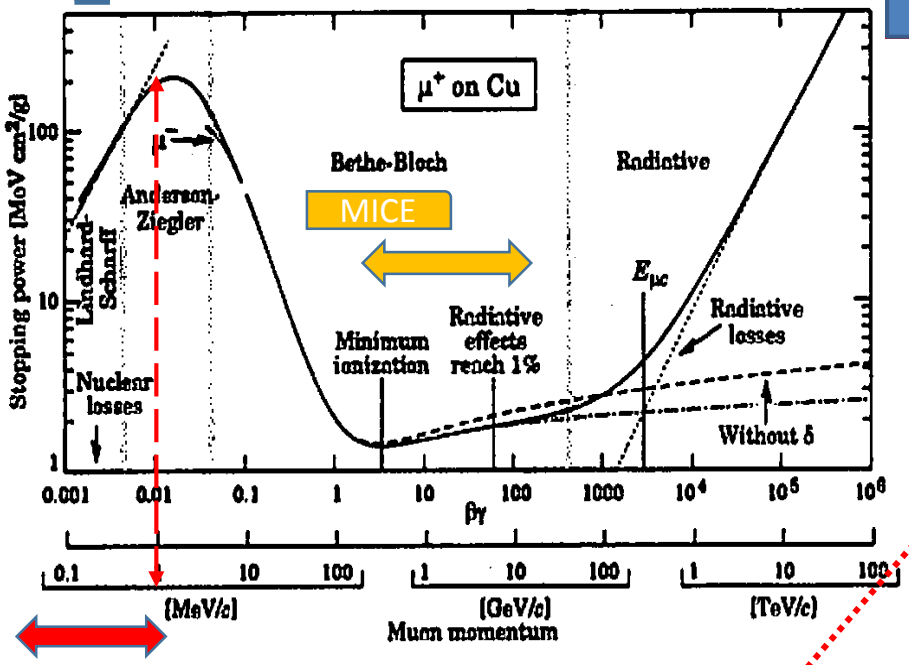
Frictional cooling

Frictional force

$$\vec{F} = q\,(\vec{E} + \vec{v} \times \vec{B}) - \frac{dT}{ds}\hat{v}$$

T is kinetic energy





Frictional cooling

GEANT4 program

LEAP 1 exp.

Free electrons

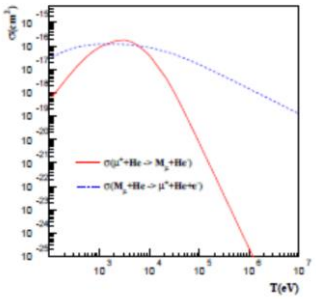
< 1 MeV/c

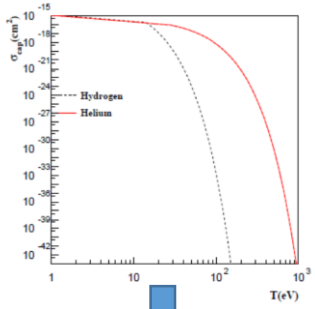
proportional to v

Frictional ECR SHeet – FRESH

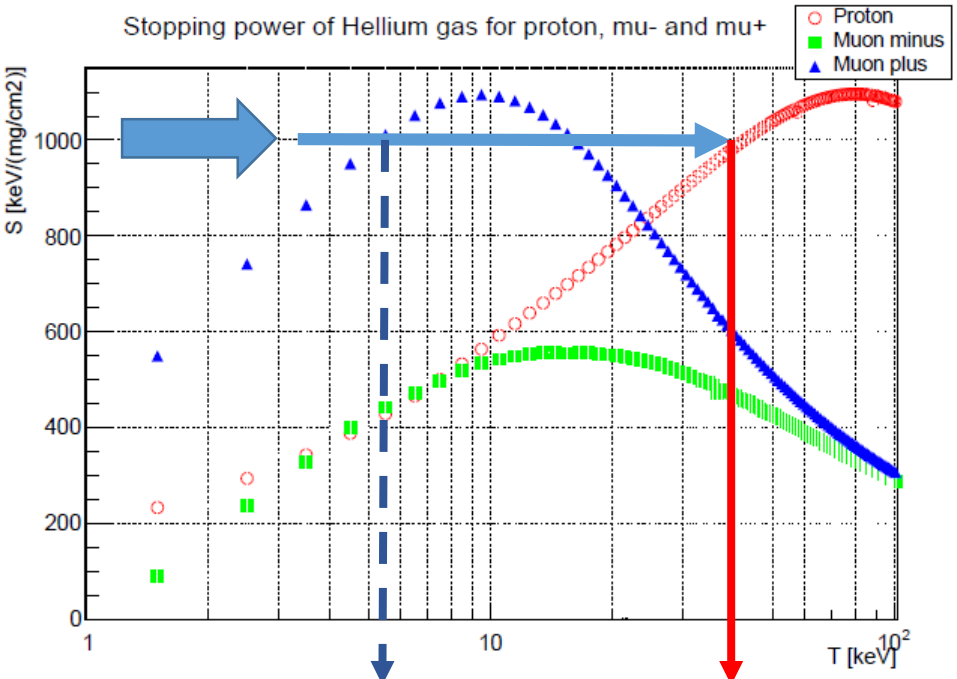
Energy region for frictional cooling of μ+, μ- and proton

Energy region of proton exp. → LEAP 1





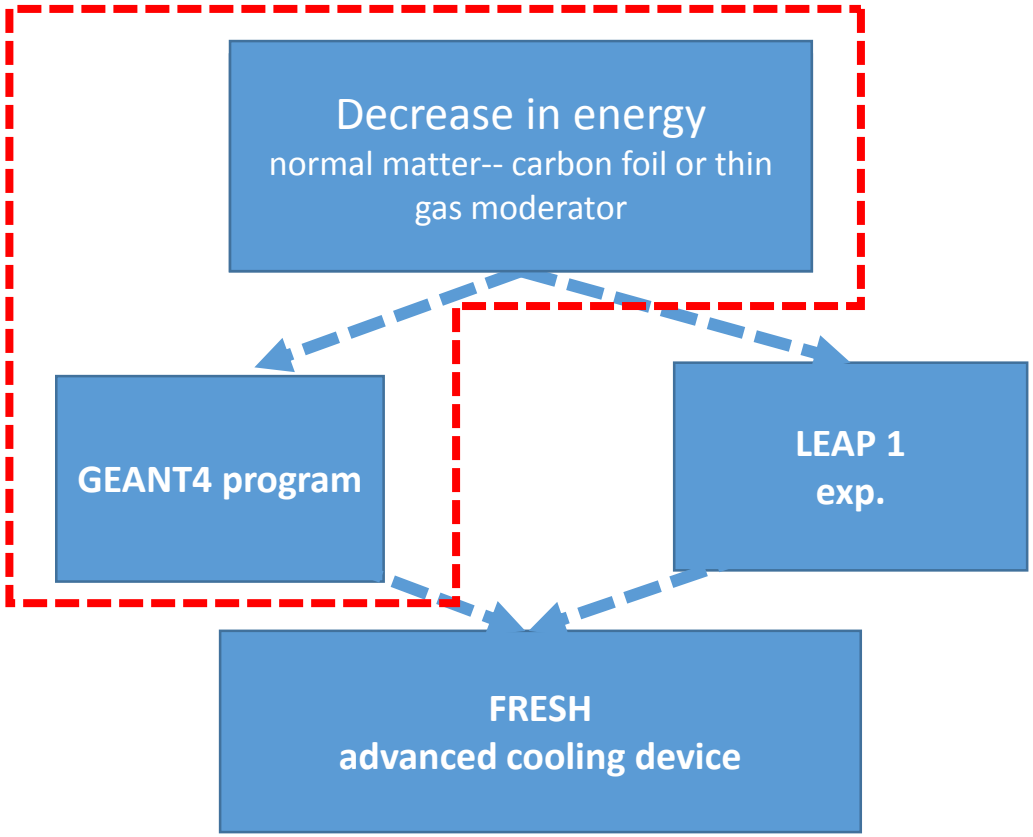
not so low , more than a few 10 eV



formation of few keV μ+ ,μ–

interesting energy region of proton

I. *Numerical simulation with GEANT4*

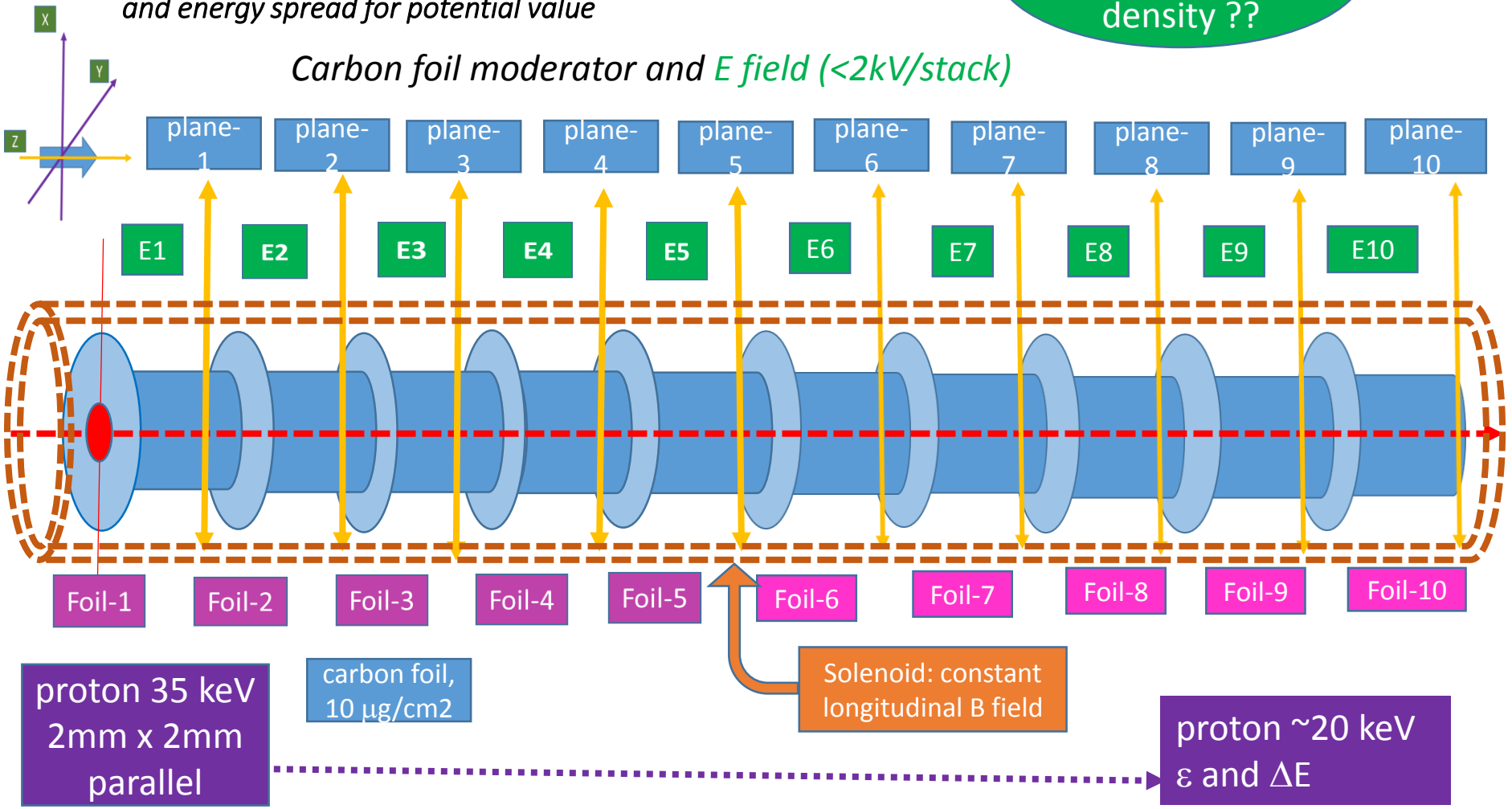


GEANT4 Simulation

GEANT4 Simulation of proton beam emittance and energy spread for potential value

improve the phase space density ??

Carbon foil moderator and E field (<2kV/stack)



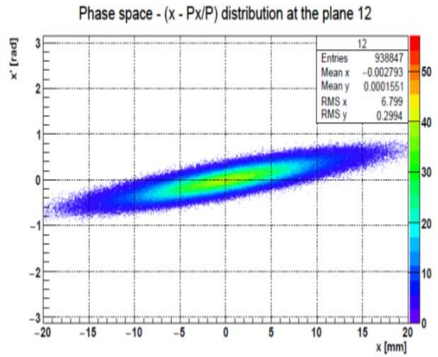
GEANT4 Simulation

35 keV

deceleration

acceleration

Energy of proton beam

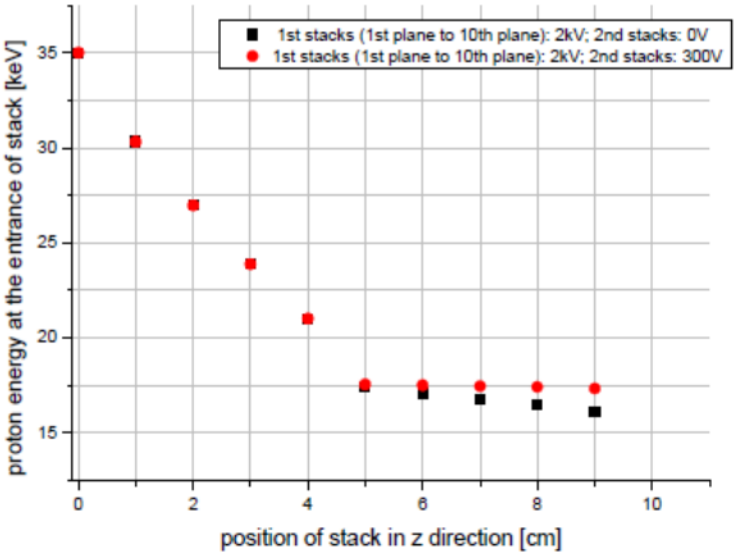


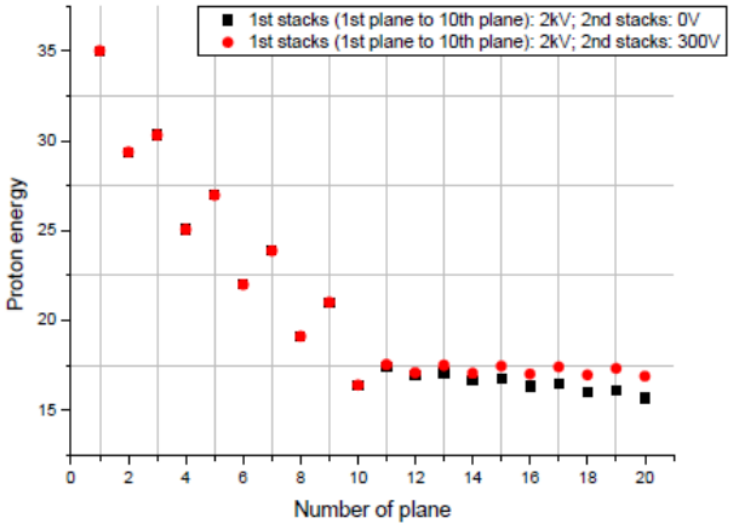
optimization

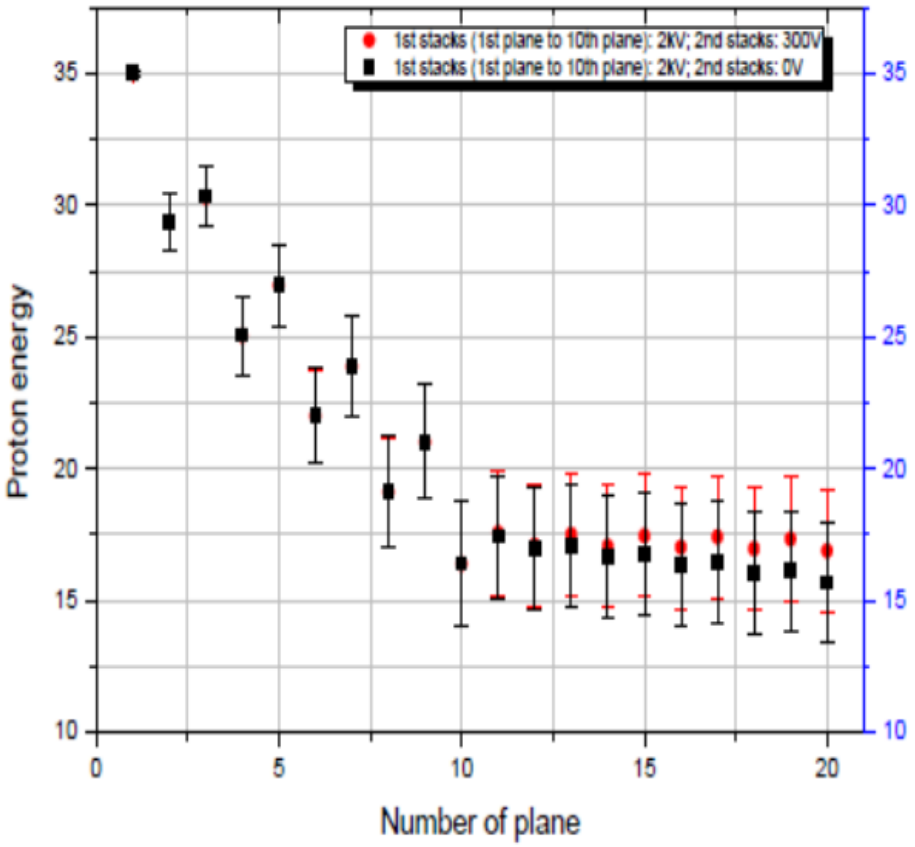
20 keV

GEANT4 Simulation

proton energy at each plane



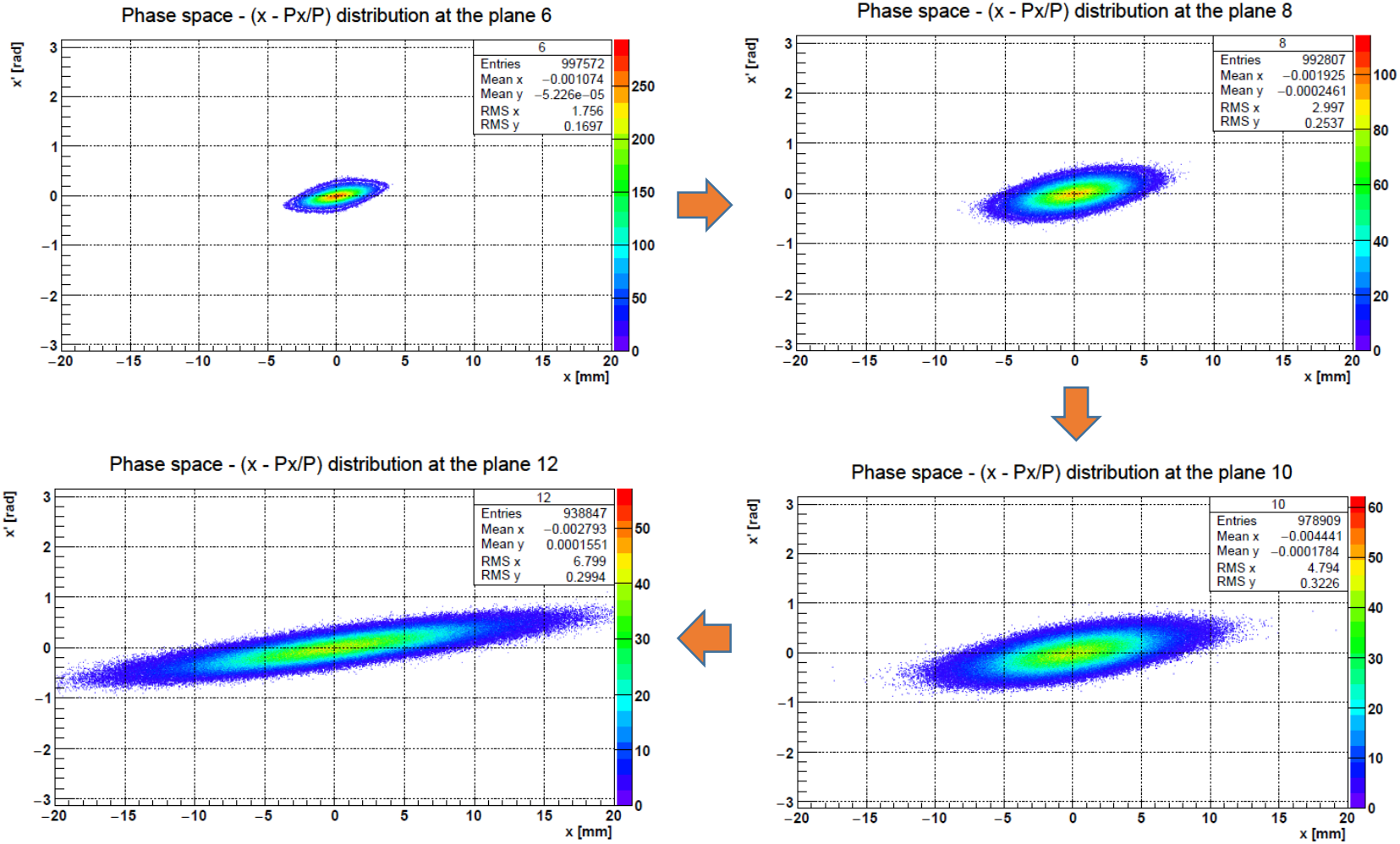




GEANT4 Simulation

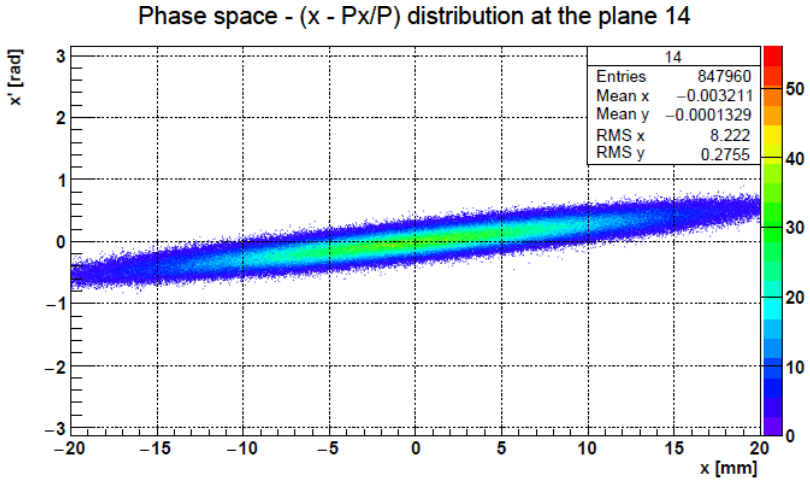
Several results

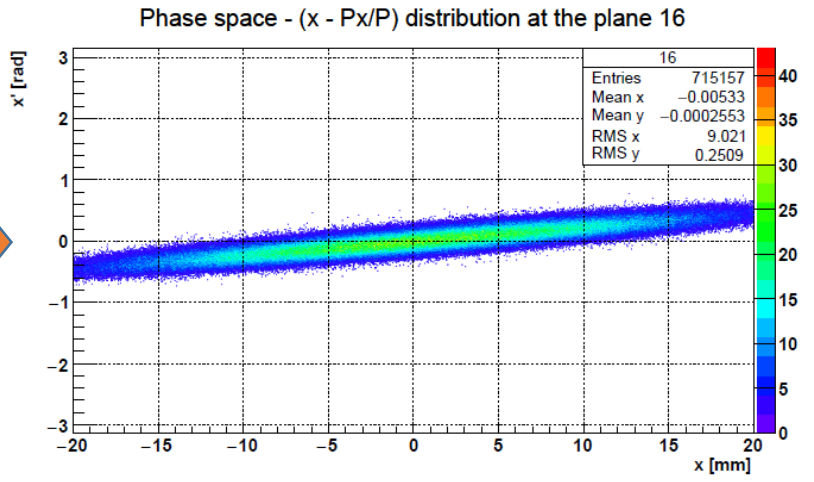
the 1st 5-stacks 2000 V and 2nd 5-stacks 300 V

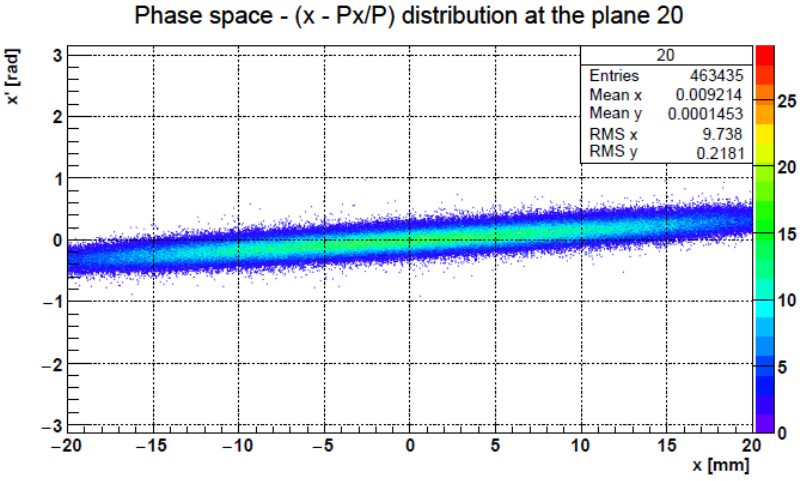


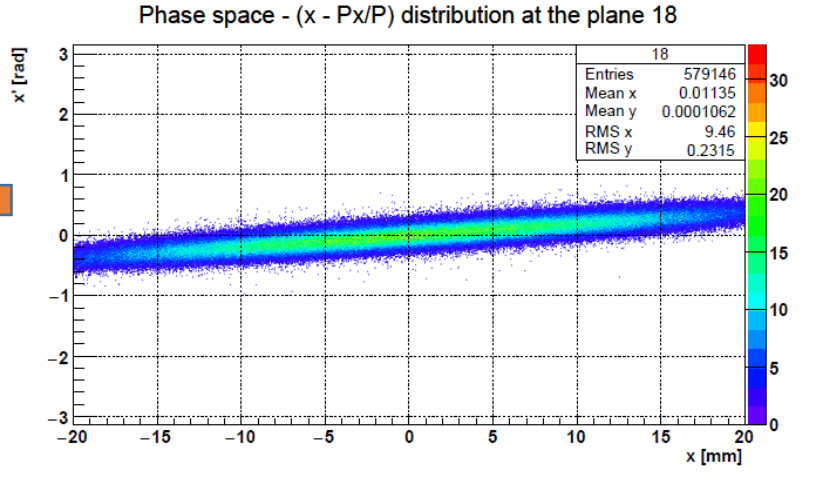
GEANT4 Simulation

the 1st 5-stacks 2000 V and 2nd 5-stacks 300 V









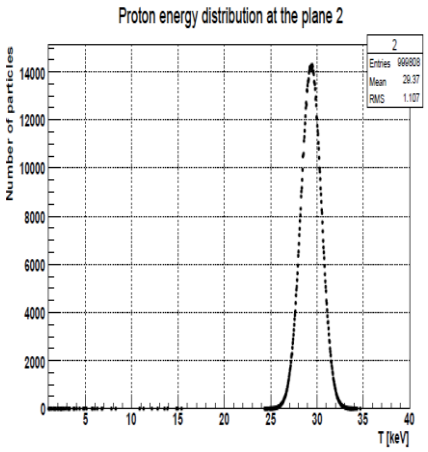
GEANT4 Simulation

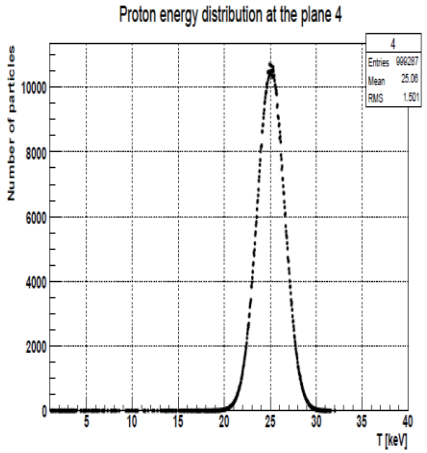
2
29.37keV
1.107keV

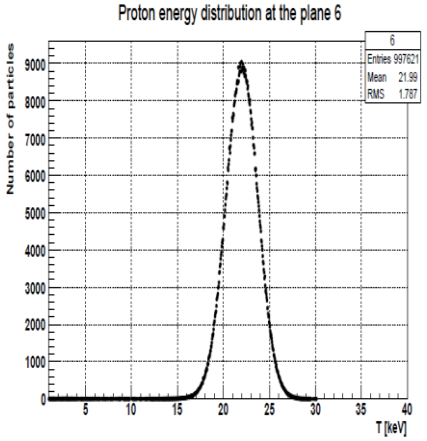
4
25.06keV
1.501keV

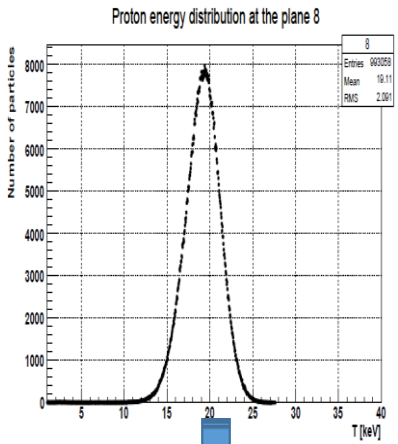
6
21.99keV
1.787keV

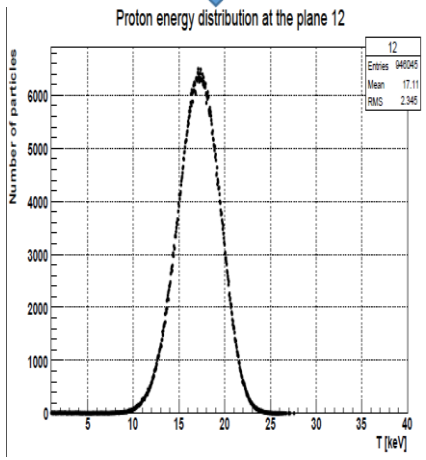
8
19.11keV
2.091keV

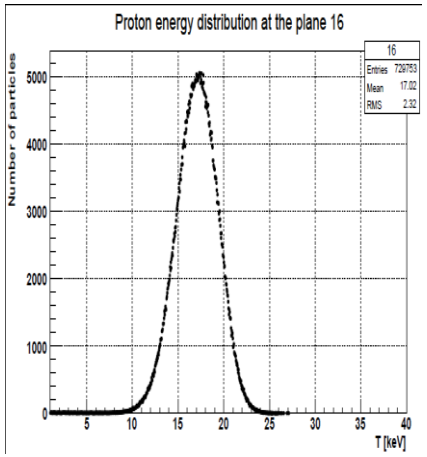


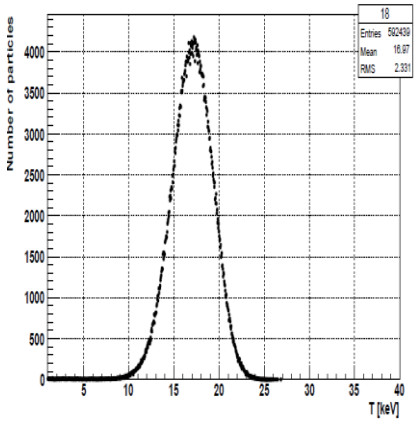


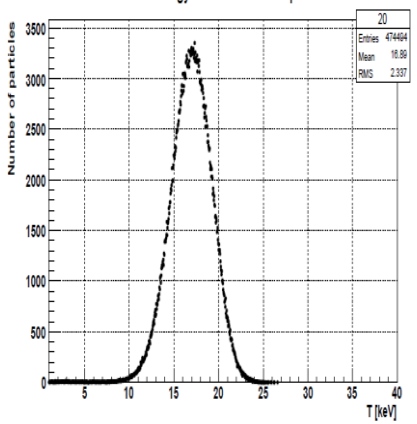












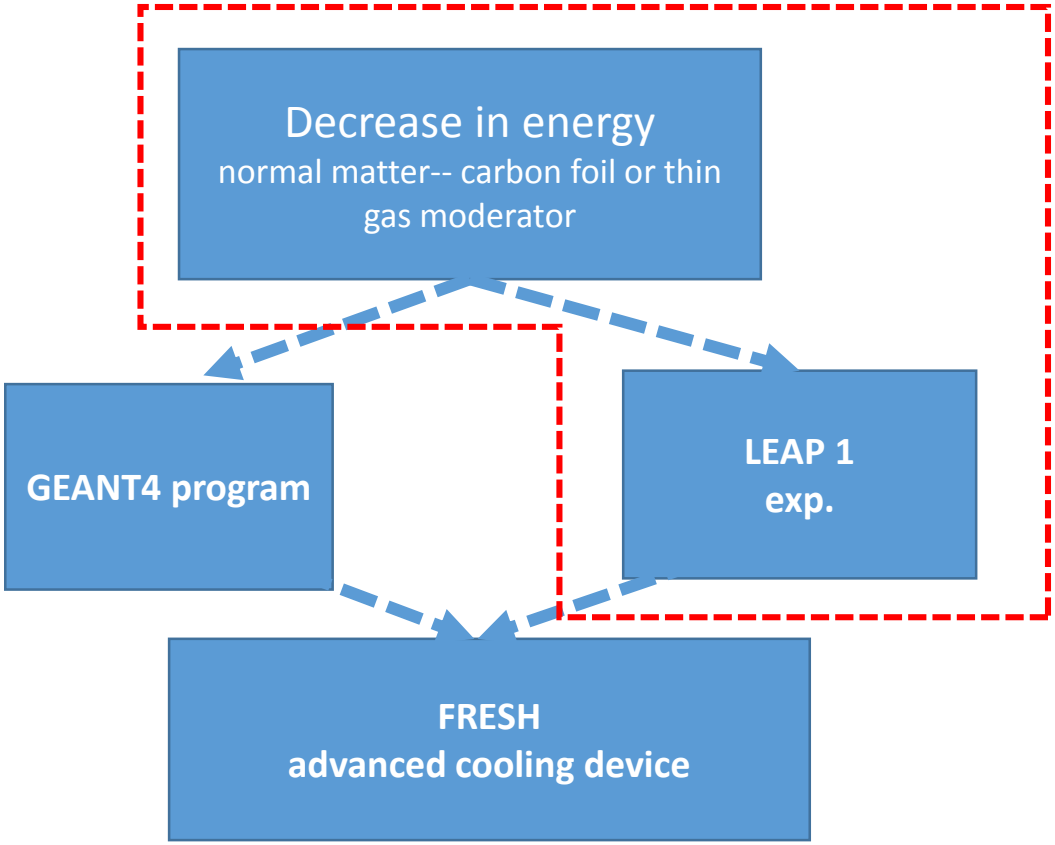
16.39keV
2.337keV
20

16.97keV
2.337keV
18

17.02keV
2.320keV
16

17.11keV
2.345keV
12

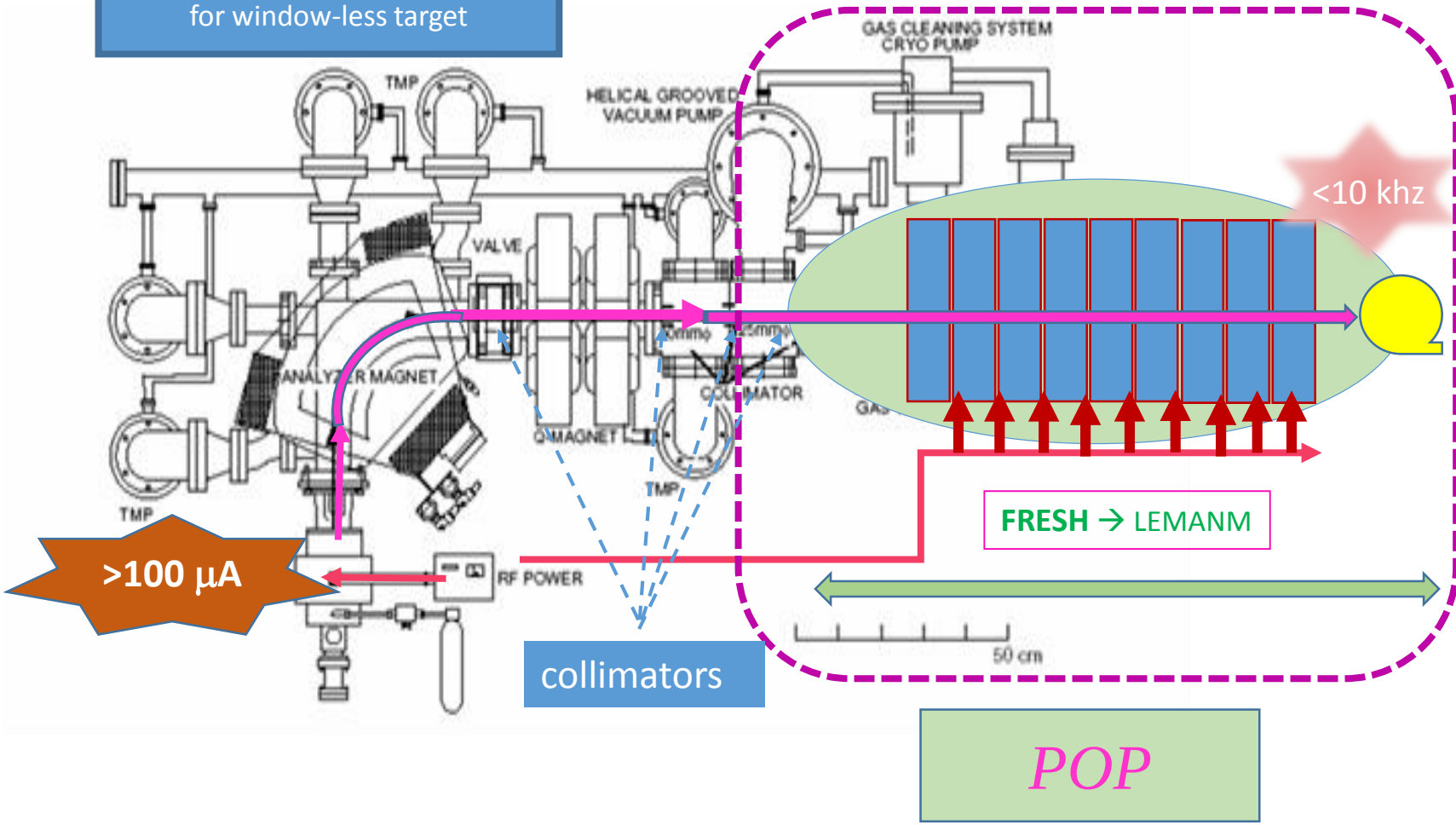
II. Experimental *proof of principle* with proton beam



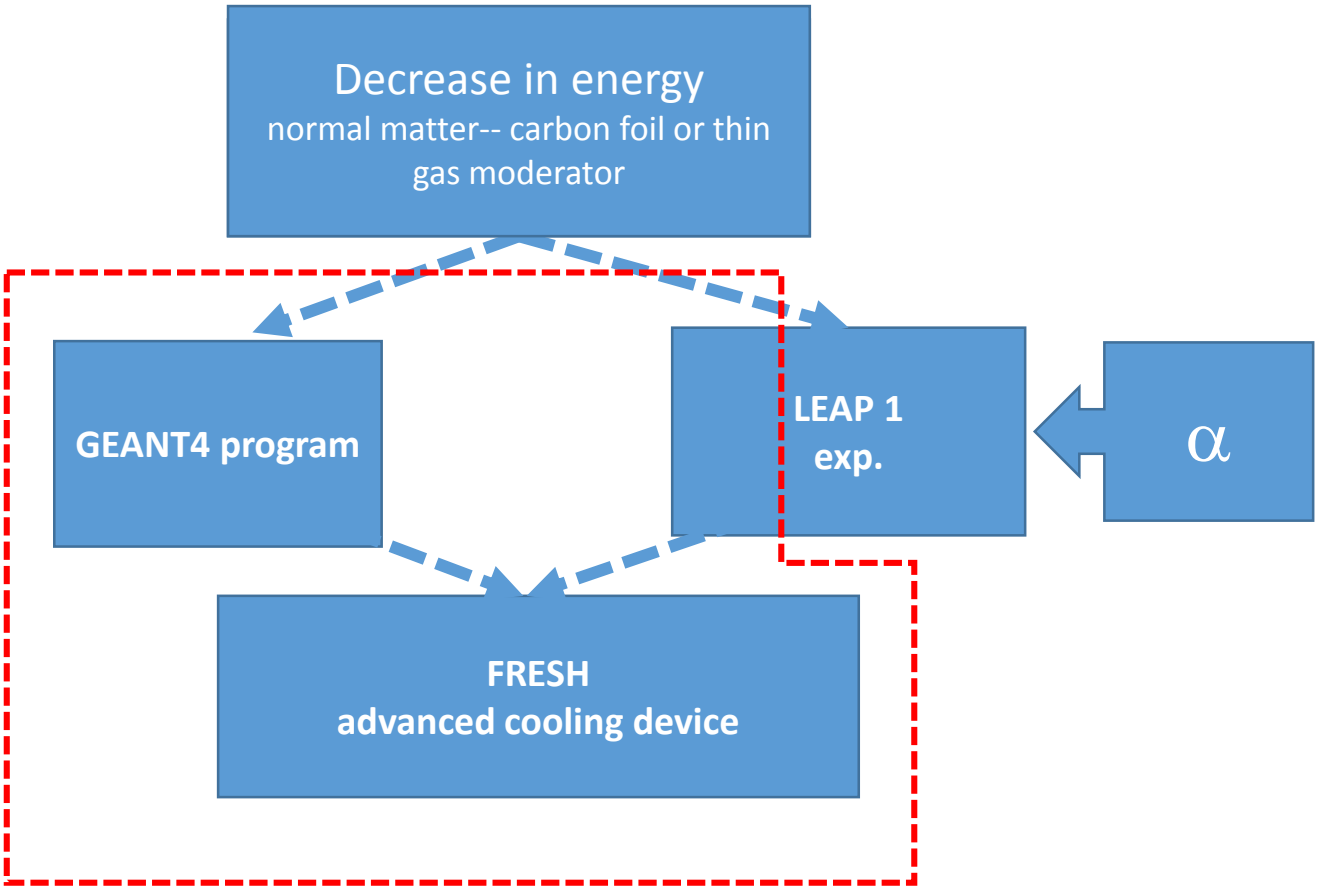
II. *Low Energy Accelerator Project (LEAP 1)*

- Carbon foil
- Helium gas
- Hydrogen gas
- ECR plasma

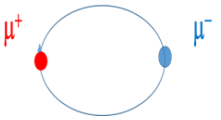
Differential pumping is available for window-less target



III. *FRESH advanced cooling device*



Break through Spectroscopic study New Physics



FRESH – advanced frictional cooling device for muons
--frictional cooling with ECR sheet--

Proof of principle

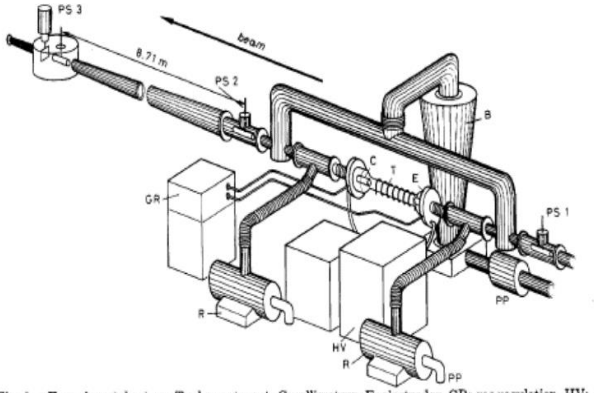
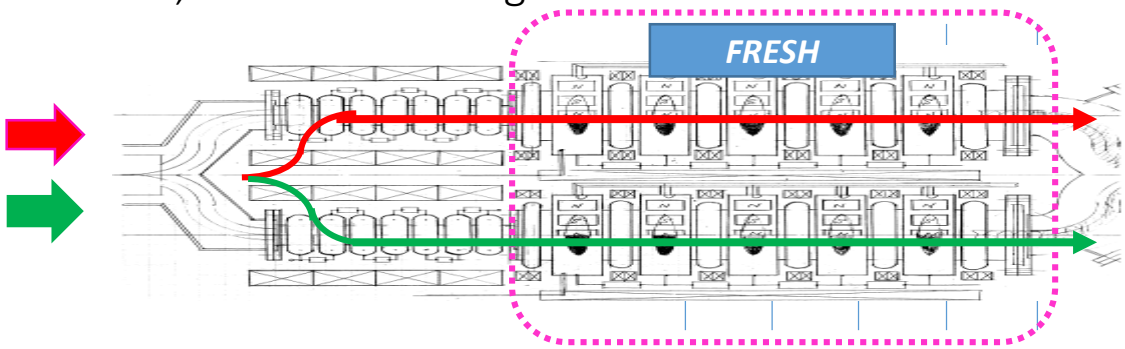
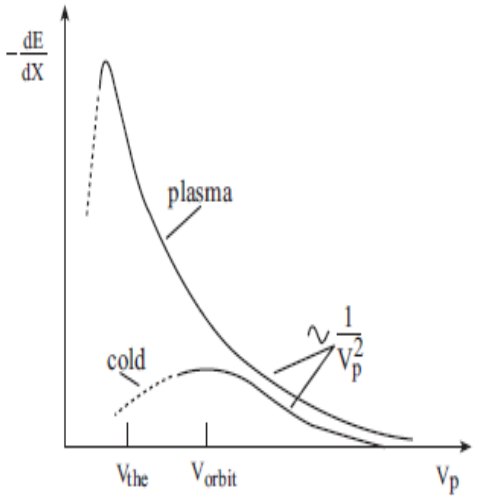


Fig. 1. – Experimental set-up. T: plasma target, C: collimators, E: electrodes, GR: gas regulation, HV: high-voltage supply, PP: primary pumps, R: roots, B: booster, PS1, 2, 3: phase probes.

- FRictional ECR
  SHeet for muon cooling
- Plasma, *dE/dx* --larger stopping power
- Plasma, density --less matter
- Plasma, conductivity--apply potential to
- Plasma, ionization – bring another merit





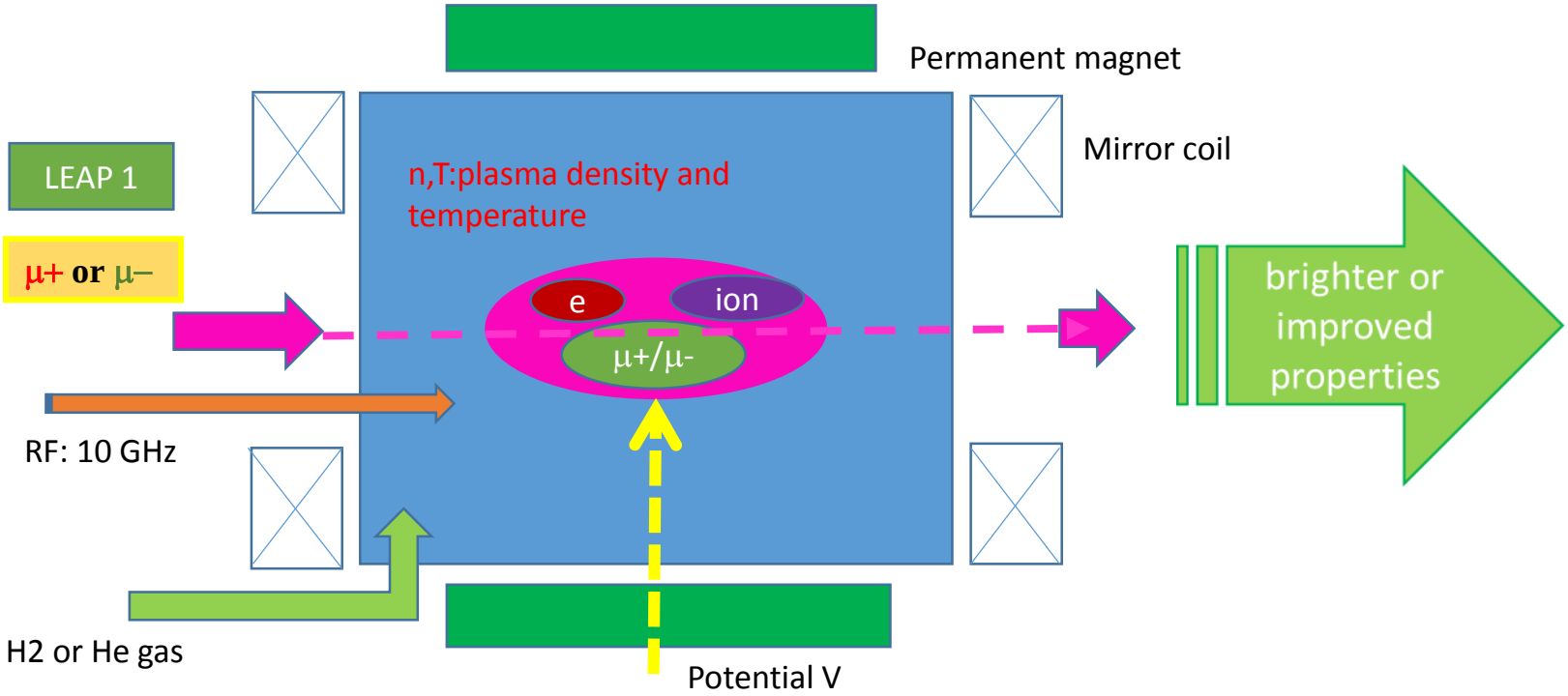
Orsay and TIT exp.

➢Ideas

Atomic, molecular physics/chemistry
and subatomic physics with exotic particles

Basic Plasma physics, with proton, μ+, μ-

- absolute minimum B ECR <--- one example



Ⅳ. TM production and Experiments

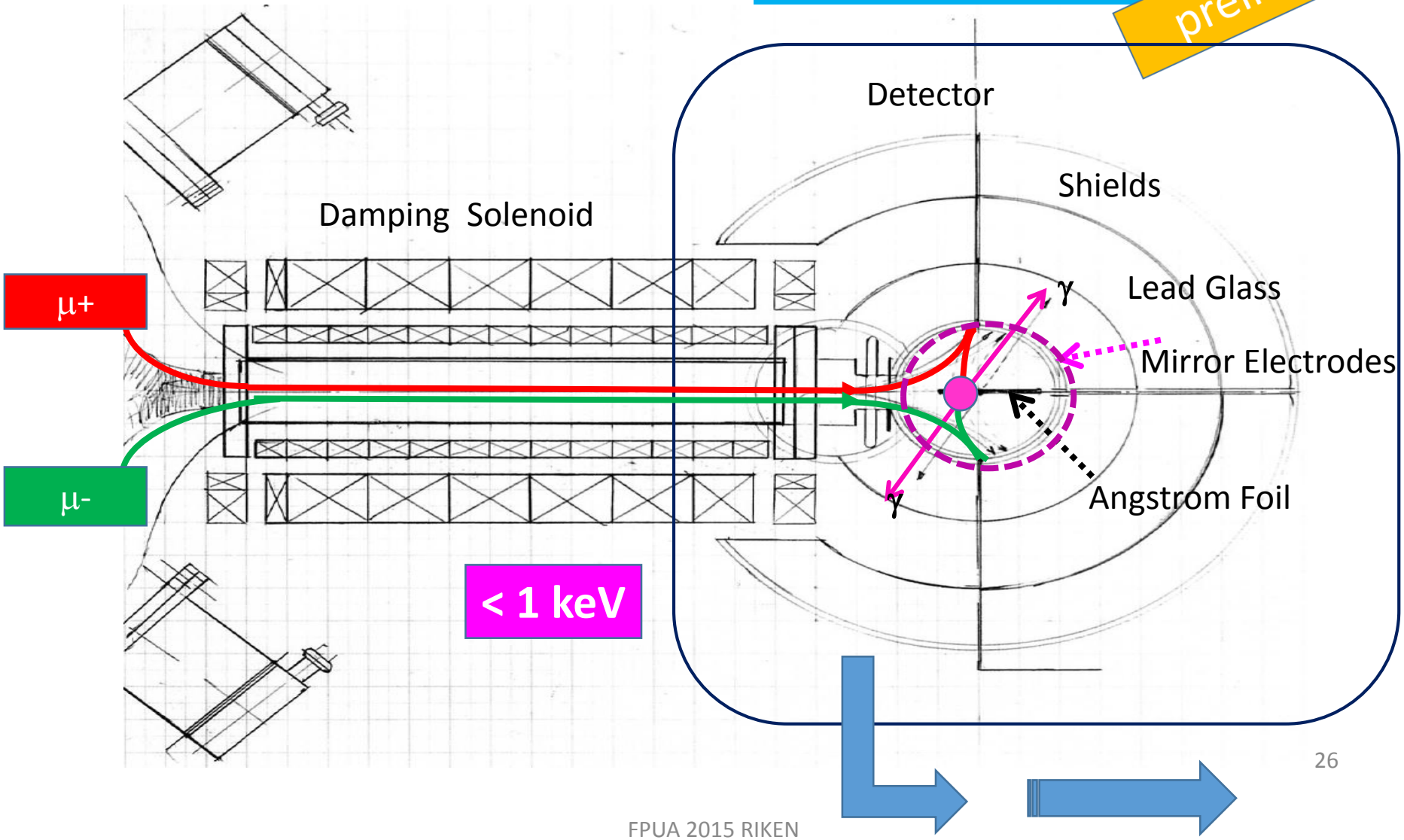
1 year → 2 year

	proton	μ+	μ-
incident energy	~30 keV	expect a few keV	> ~10 keV
beam quality	uniform or Gaussian	uniform or Gaussian	uniform or Gaussian
moderator	Carbon + Helium, H2	Helium	Helium or Hydrogen
gas moderator (nominal)	0.1 Torr (plasma)	0.1 Torr (plasma)	0.1 Torr (plasma)
potential ΔU	1~2 kV	~100 V	~100 V
stack numbers	5 stacks—10 stacks	5 stacks	10 stacks
final energy T	~10 keV	a few keV, <1keV	a few keV, <1 keV
density increase in ε	xxxxx	xxxxx	xxxxx
loss actor	xxxxx	xxxxx	xxxxx

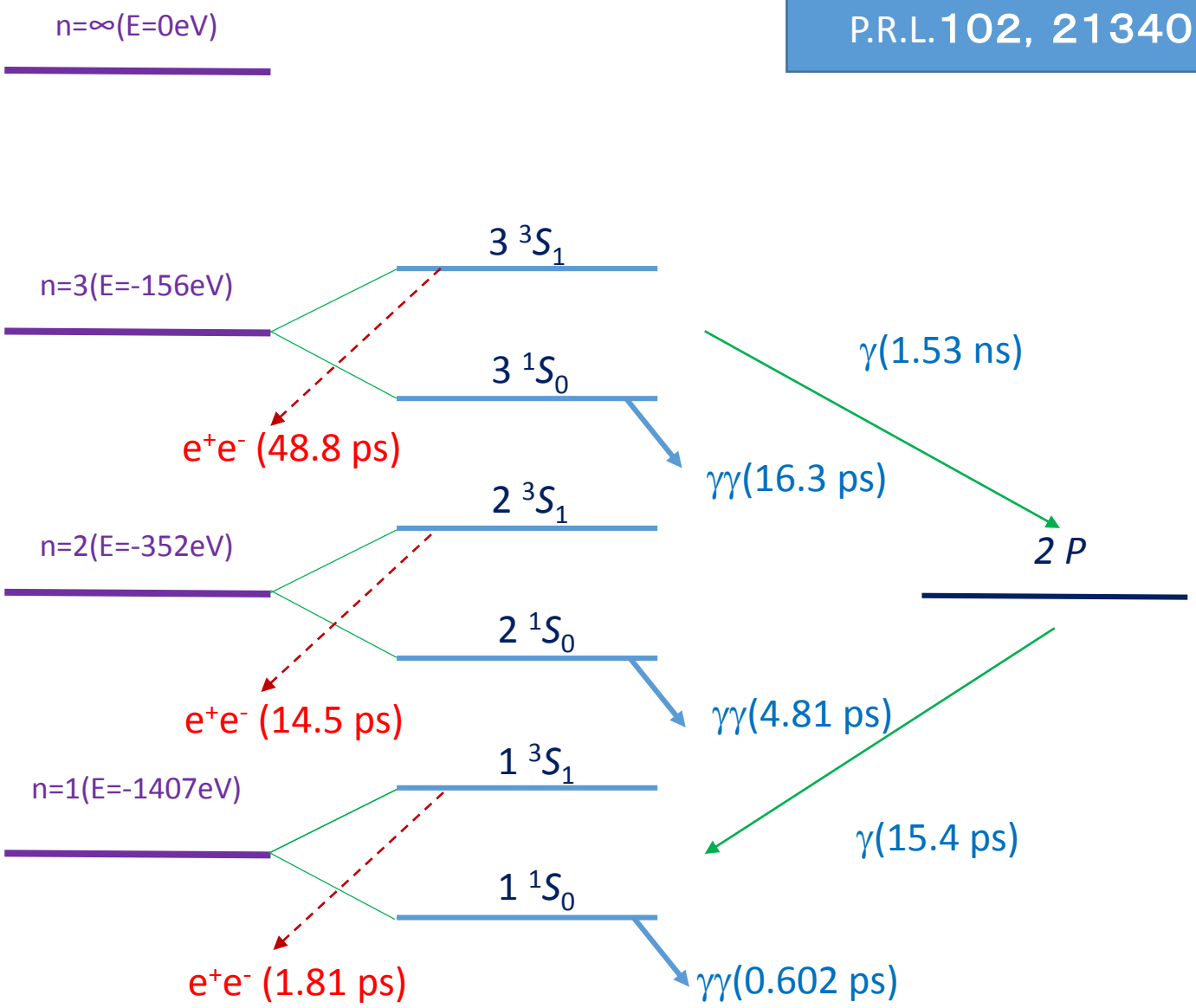
科研費 KAKENHI

Production & Detection

preliminary



True muonium level diagram
P.R.L.102, 213401 (2009)



Summary (要約)

- *quests of several physics interests in TM (探求）*
- *traditional and new physics （伝統）*
- *fine structure, hyperfine structure, Lamb Shift （手順）*
- *strategy of production for TM （革新）*
- *frictional cooling (開拓）*
- *POP facility and simulation study （実行）*
- *FRESH device （創作）*
- *perspectives （飛躍）*