Proposal for a new Muon Catalyzed ^{3}He-d fusion experiment.

E.M. Maev, O.E. Maev. G.E. Petrov, G.G.Semenchuk, A.A.Vorobyov
Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia.

We report on a possibility to use the setup of MuCap
(Muon Capture by the proton) experiment for
new search of Muon Catalyzed ^{3}He-d fusion reaction:
$^3He\mu d \rightarrow {}^4He(3.66\ MeV) + p(14.64\ MeV) + \mu$
with an ORDER of magnitude higher sensitivity than
in our previous measurements.

Nuclear fusion in $^3He\mu d$ muon molecules.

The nuclear fusion reaction :

$$^3He + d \rightarrow {}^4He(3.66\ MeV) + p(14.64\ MeV)$$

is of interest due to several reasons:

1. As a mirror reaction of the important process of $d+t \rightarrow {}^4He+n$ fusion.
2. As a discussed a perspective source of thermonuclear energy.
3. It is Involved in the primordial nucleosynthesis of the light elements in the early universe.

For all these processes is important to know the cross section of this reaction at low collision energies E<10 keV.
The phenomenon of Muon Catalysis gives the possibility to study this reaction at practically zero collision energy from the muon molecular state $^3He\mu d$-molecule:

$$d\mu + {}^3He \rightarrow {}^3He\mu d \rightarrow {}^4He+p+\mu$$

^{3}*Hedμ molecular formation, decay and fusion:*

1. ^{3}Hedμ-mesomolecule formation (Aristov,Kravtsov,Popov-1981)
   with rate (L_m): dμ+^{3}He→(^{3}Hedμ)(J) , J=1, J - angular momentum
   L_m=124(5) μs^{-1}, T=300 K (PNPI-1992)
   L_m=232(9) μs^{-1}, T=50 K (PNPI-PSI-1999)
2. ^{3}Hedμ decay with L_{dec}~ 7·10^{11} s^{-1},
   ^{3}Hedμ→^{3}Heμ + d+γ (Gamma-emission)
   ^{3}Heμ + d+e$^-$ (Auger transitions)
   ^{3}Heμ + d (predissociation)
3. ^{3}Hedμ transition (J=1) → (J=0) with L_{10} ~5·10^{11} s^{-1},
   chain of ion-molecular reactions (Faifman, Menshikov-1999)
   with formation muon molecular complexes (^{3}HedμD_2)$^+$;
   (^{3}Hedμ)(J=1) → (3Hedμ)(J=0)
4. Nuclear fusion in the ^{3}Hedμ with rate L_f (Bogdanova,Gerstein,
   Ponomarev -1997; Abramov,Gusev,Korobov-1999)
   L_f(0)~2·10^5 s^{-1} , L_f(1)~6.5·10^2 s^{-1}
   (^{3}Hedμ)(J=0) →^{4}He+p+μ
   L_f(eff)= w(0)·L_f(0) + w(1)·L_f(1) ~ w(0)·L_f(0), where
   w(J) is the population of the state with angular momentum J.

Recent experiments for search of Muon Catalysed ^{3}Hed-fusion

1. *MCF- collaboration (PNPI-PSI-TUM-UCLB):*

PNPI : D_2 + ^{3}He(11%); φ=8.7% , L_f(Eff) < $4\cdot10^8$ s^{-1} (1992)

PNPI-PSI: HD+^{3}He(5.6%); φ=9.9% , L_f(Eff) <$1.6\cdot10^6$ s^{-1} (1998)

PNPI-PSI HD+^{3}He(5.6%); φ=9.2%, L_f(Eff) < $6\cdot10^4$ s^{-1} (1999)

$L_f(0) < 5\cdot10^5$ s^{-1} (using theoretical value w(0) – Faifman(1999))

Theory : $L_f(0)\sim 2\cdot10^5$ s^{-1} (Bogdanova, Korobov, Ponomarev(1999)

Experimental method: high pressure ionization chamber (IC).

IC operating as ACTIVE TARGET detecting both the incoming muons and ALL charged products from dd- ,pd- and ^{3}Hed-fusions.

The main idea of experiment is registration of ^{4}He(3.66 MeV) and track of the proton(14.64 MeV) from ^{3}Hedμ-fusion.

Strategy measurements:

a) selection of clean muon stops in the target gas (no muon stops in the wall of the target on the level < 0.1%);

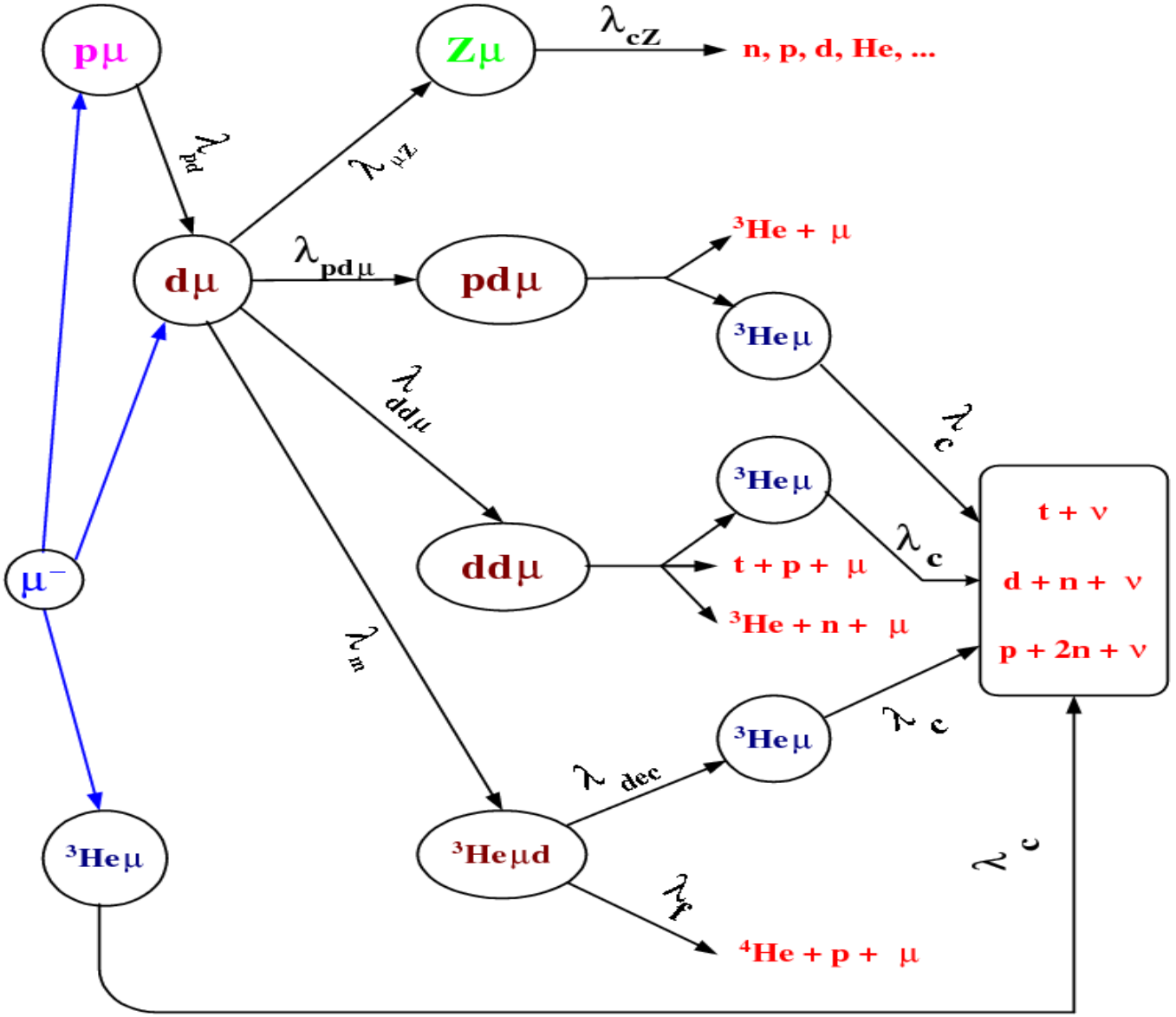
b) HD gas mixture(reduction dd-fusion rate and background process of ^{3}Hed-fusion in flight (dμ+d→ddμ→^{3}He(0.8 MeV)+d→^{4}He+p);

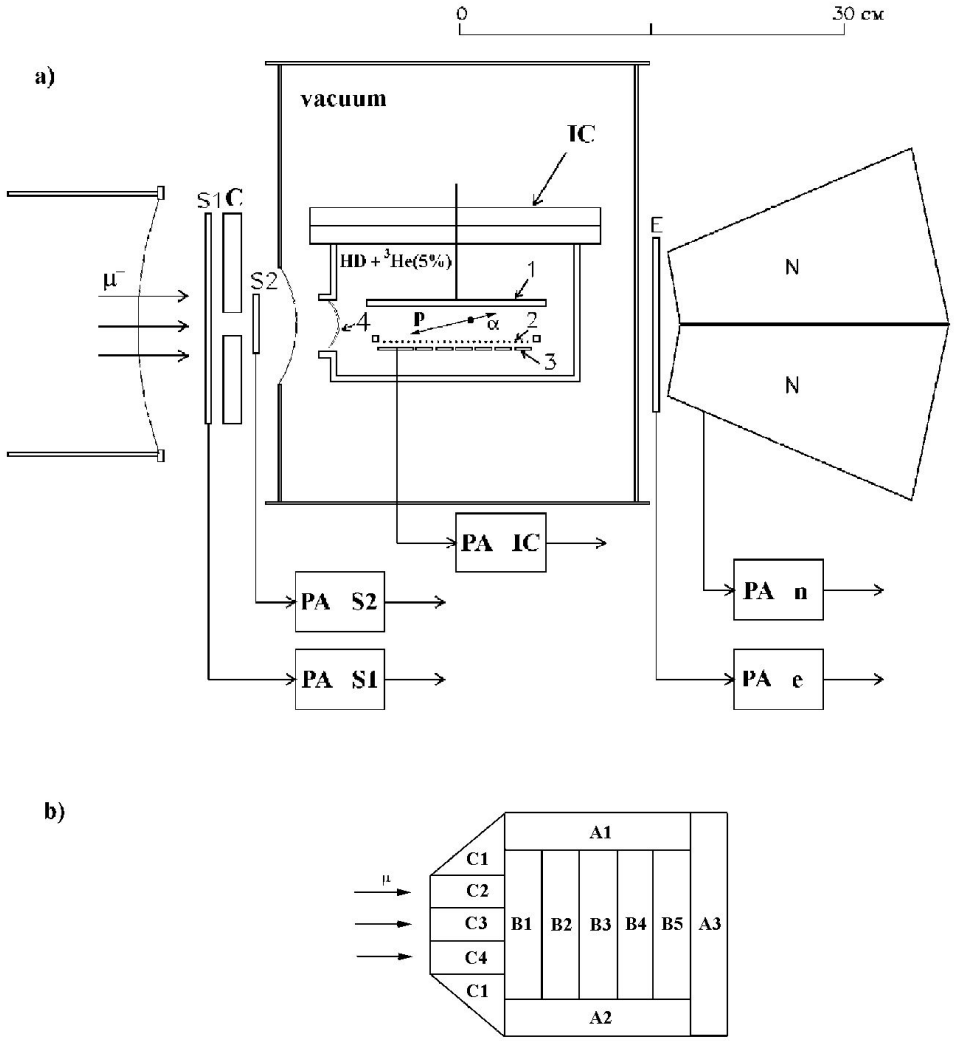
c) energy correlations between the ^{4}He and proton from ^{3}Hedμ-fusion (very power way to eliminate the background).

Previous experiments using the Ionization Chamber:

1. Precision measurement of nuclear muon capture by ^{3}He(1993):
   $^3He + \mu \rightarrow {}^3H(1.89\ Mev) + \nu$,
   Experiment (1999) $L_c = 1496(4)\ s^{-1}$
   Theory (2007) $L_c = 1506(12)\ s^{-1}$
   Proton Pseudoscalar coupling(G_p):
   From our experiment: $G_p = 8.7(6)$ Theory: $G_p = 8.2(2)$;
2. Precision study of muon catalyzed fusion in D_2 and HD (1994-1996)
   a) Muon sticking: W_{dd}(theory)=0.120(4), φ=7%
   W_{dd}=0.1224(6) , φ =8.4%4; W_{dd}=0.1234(7) φ =4.9%.
   b) Branching ratio $R_{res}=Y(^3He+n)/Y(t+p)$ for dd-fusion
   from J=1 ddμ state: R_{res}=1.455(11) .
   c) Spin flip(L_d) rate in dμ-atoms(temperature dependence):
   L_d=37.0(4) μs^{-1} ,T=28.3 K: L_d=35.0(5), T=120.3 K .
   d) ddμ formation rate in pure D_2 and HD gas mixture.
   $L_{dd\mu}$ temperature dependence (T=28-350 K)
   Analysis: E_{11}= 1.9626(4) eV – binding energy
   Theory: E_{11}= 1.9648 eV

Simplified kinetics of the processes in the HD+^{3}He mixture





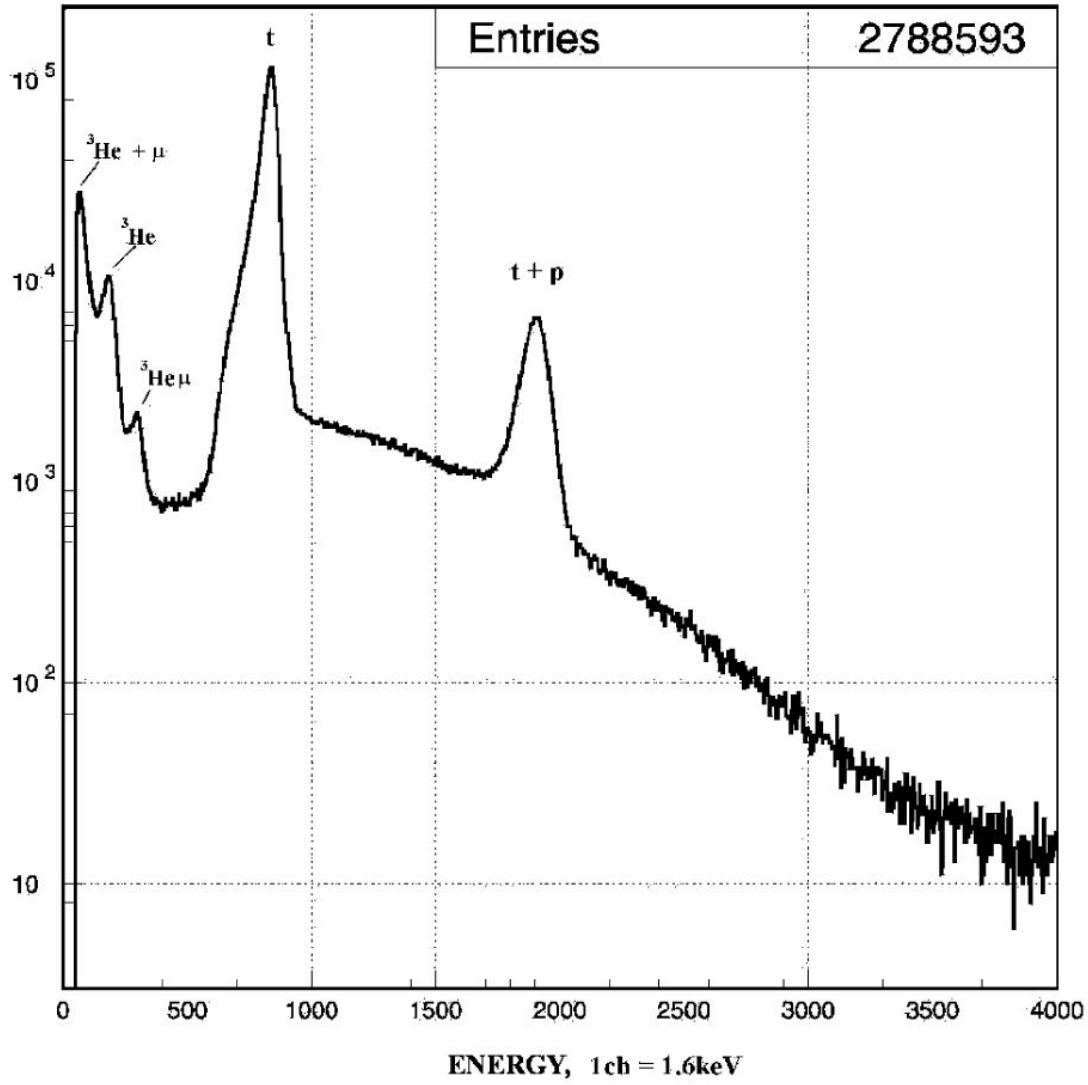
Experimental setup:

(a) Side view on the ionization chamber (IC):

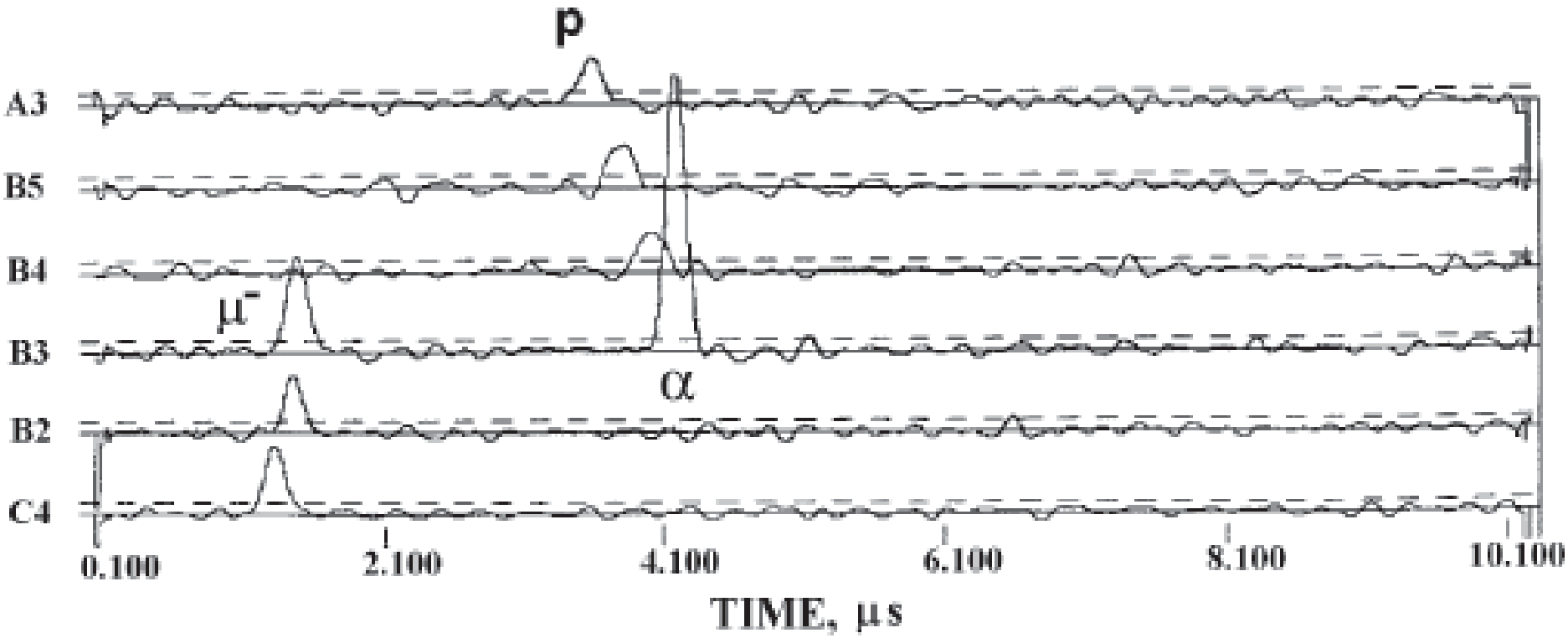
Dimensions: cathode-grid 12 mm, grid-anode 1mm.

N - neutron counters; E - electron counters.

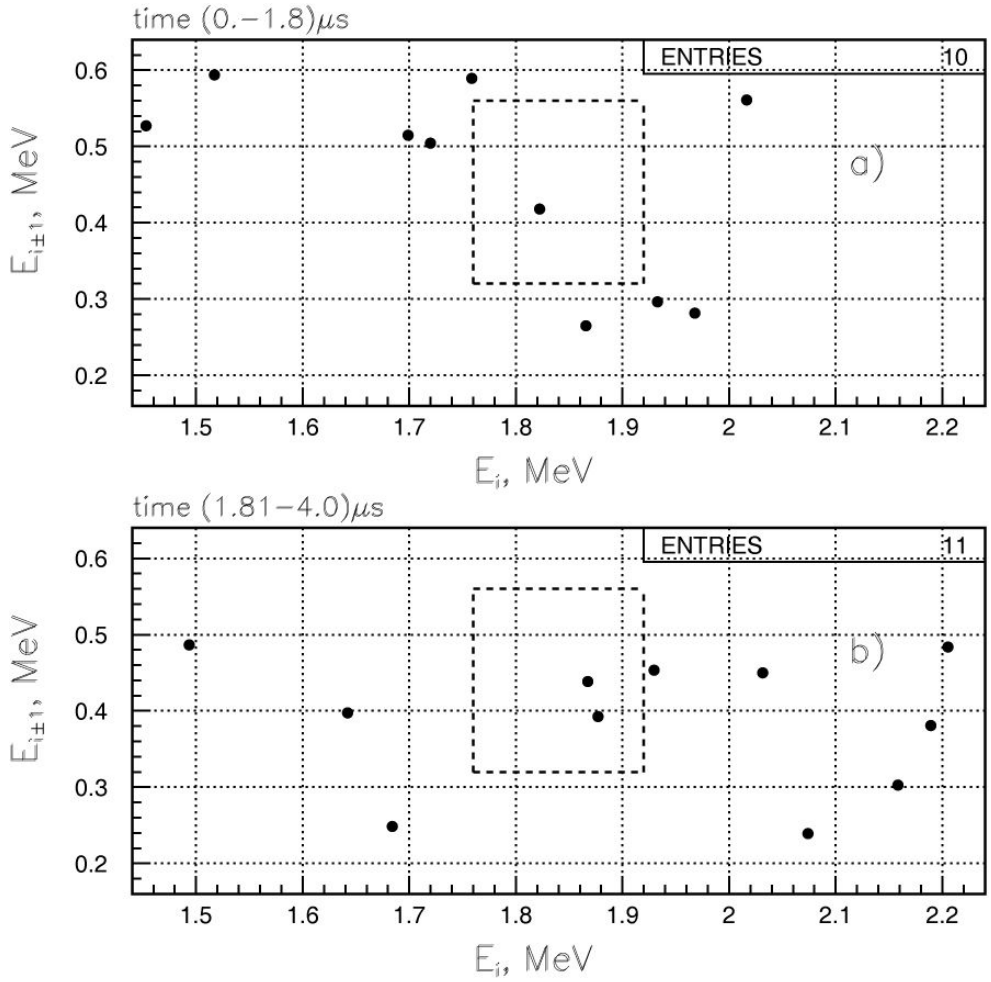
(b) Top view on the block of anodes: Bi-anode size 8x25 mm^2



Energy spectra of pulses which followed the muon signals



Display of the FADCs showing a candidate for ^{3}Hed-fusion



$L_f(Eff)<6\cdot10^4 s^{-1}$

Scatter plots for candidates for ^{3}Hed-fusion events:
The energy correlation between "^{4}He and proton"
a) plot for fusion time (T) <1.8 μs;
b) b) T>1.8 μs
The range for final selection is shown as the boxes.

2. *JINR-PSI-UIUC-INPT-UF collaboration:*

a) D_2+^{3}He(9.8%) , φ=7.9%, L_f(Eff)<5·10^5 s^{-1} (1999)

b) D_2+^{3}He(5%);

φ =5.85% L_f(Eff)=4.5(+2.6,-2.0) ·10^5 s^{-1} (2006)

φ =16.8% L_f(Eff)= 6.9(+3.6,-3.0) ·10^5 s^{-1}

Experimental method: Si(dE-E) telescopes to detect ^{3}Hed –fusion protons (14.64 Mev) and scintillators for detecting of muon decay electrons

Experimental situation:

a) PNPI-PSI-TUM-UCLB collaboration: L_f(Eff) < 6·10^4 s^{-1}

b) JINR-PSI-UIUC-INPT-UF collaboration: L_f(Eff) ~ 5·10^5 s^{-1}

Difference between two experimental results is about ONE ORDER of magnitude

Proposal for a new Muon Catalysed ^{3}Hed-fusion Experiment

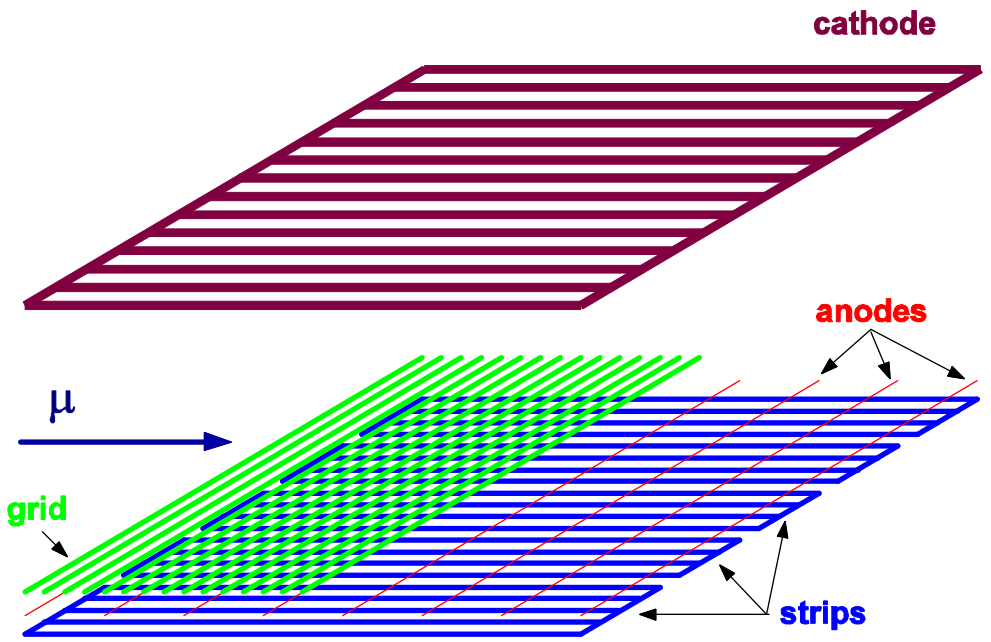
The basic element of the experimental setup – time projection chamber (TPC), operating as an ACTIVE TARGET in ultra clean H_2+HD+D_2+^{3}He mixture.
The TPC allows to detect charge particle inside target with ~100% efficiency.

Experimental conditions.
Gas : H_2(81.25%)+D_2(0.25%)+HD(8.5%)+^{3}He(10%)
equilibrium gas mixture at 10 bar pressure (φ= 1.15% LHD density, T=300K).
The efficiency of registration ^{3}Hed-fusion events ~35%.
The number of clean muon stops (N_μ) in the sensitive volume of TPC:
N_μ ~5-10 kHz; During 4 weeks of data taking ~ 10^{10} muon stops.

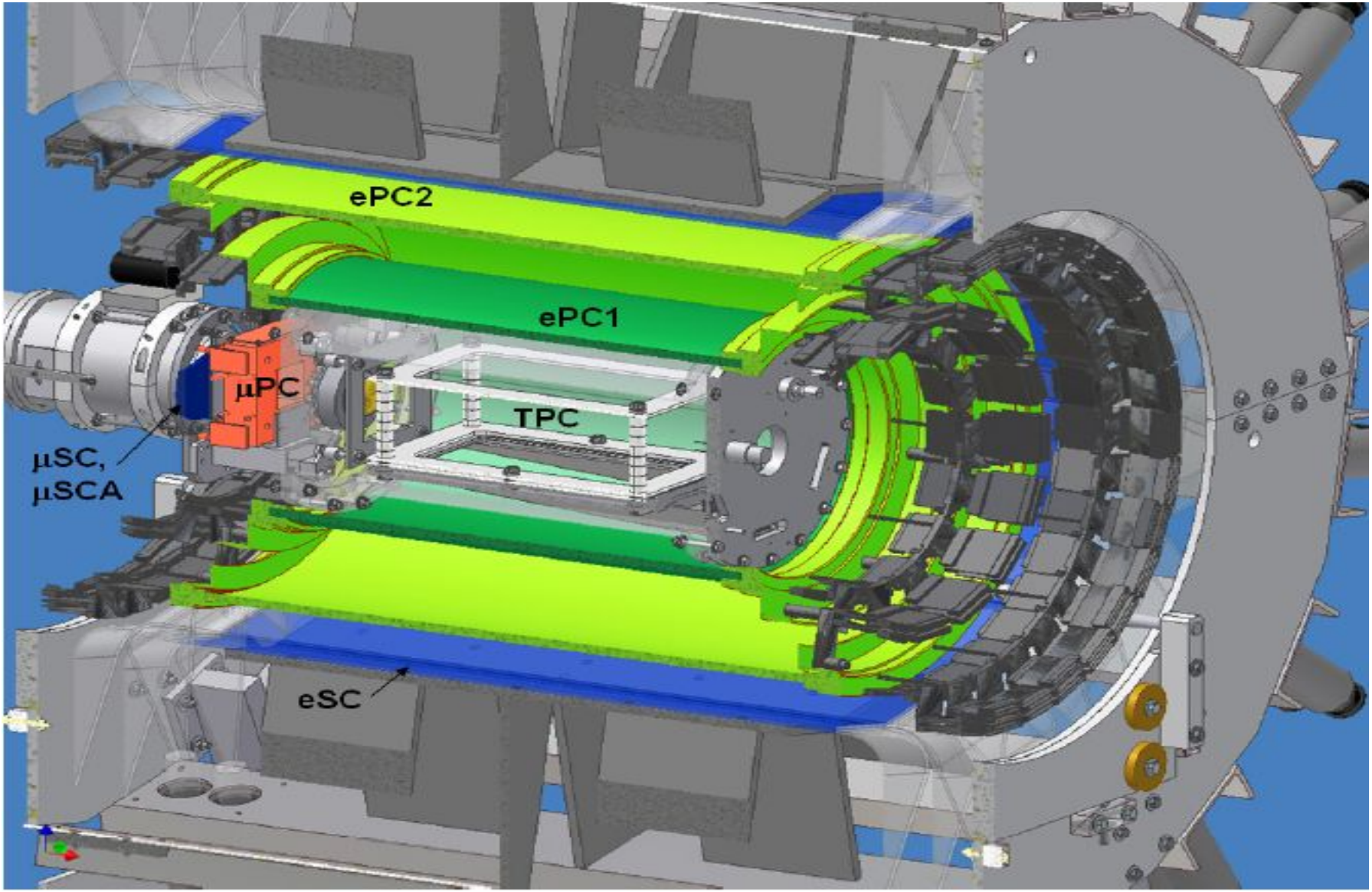
Method of the measurements:
The simultaneous registration of the alpha particle and the track of proton from ^{3}Hed-fusion inside the active target (TPC)

The sensitivity of the new experiment to search ^{3}Hedμ-fusion:
During 4 week data taking we can measure rate ^{3}Hedμ fusion with accuracy about 10% (for theoretical value $L_f(0) \sim 2 \cdot 10^5$ s^{-1}) or obtain new upper limit for this reaction with an ORDER of magnitude higher sensitivity than in our previous measurement

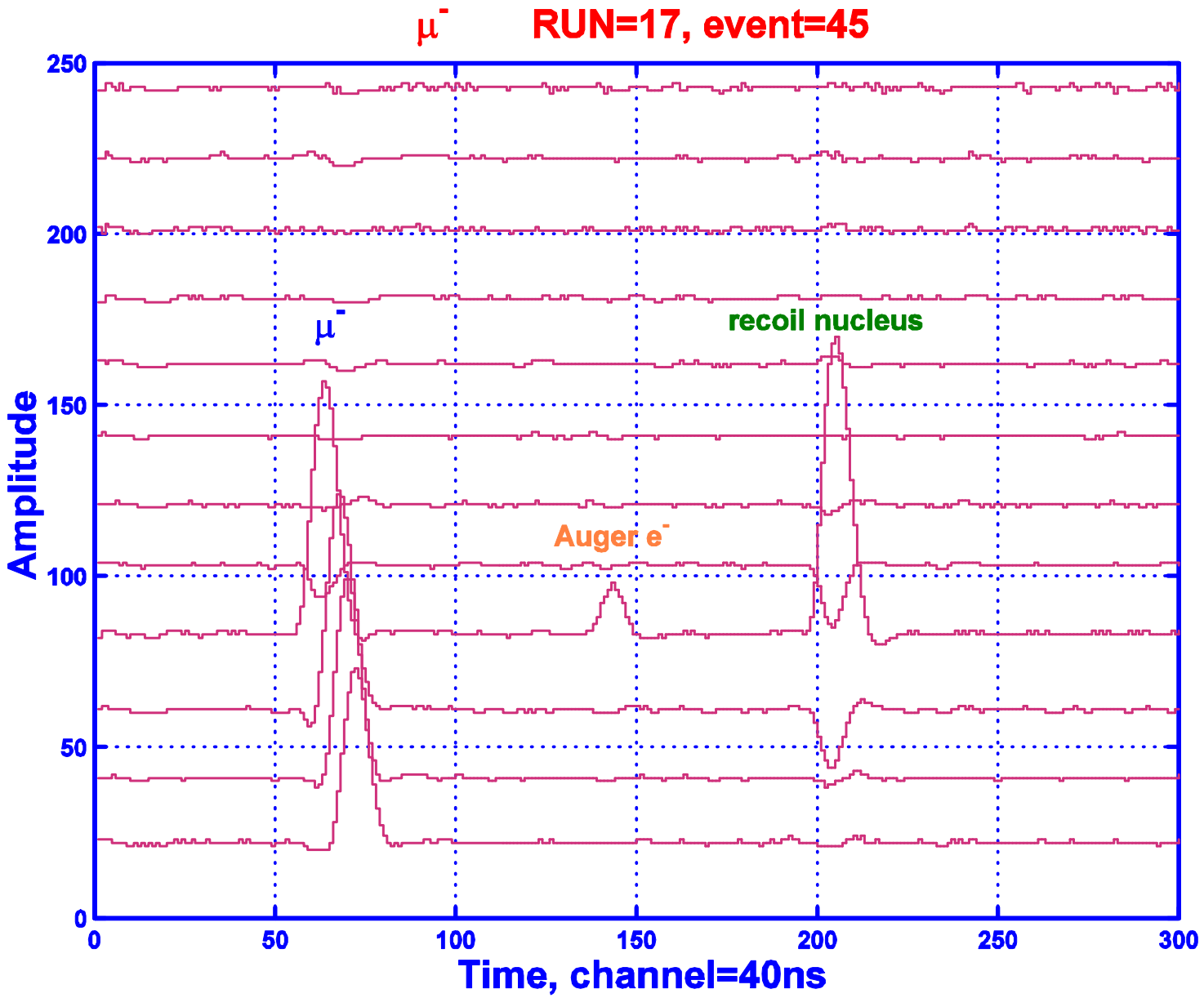
Schematic view of the TPC



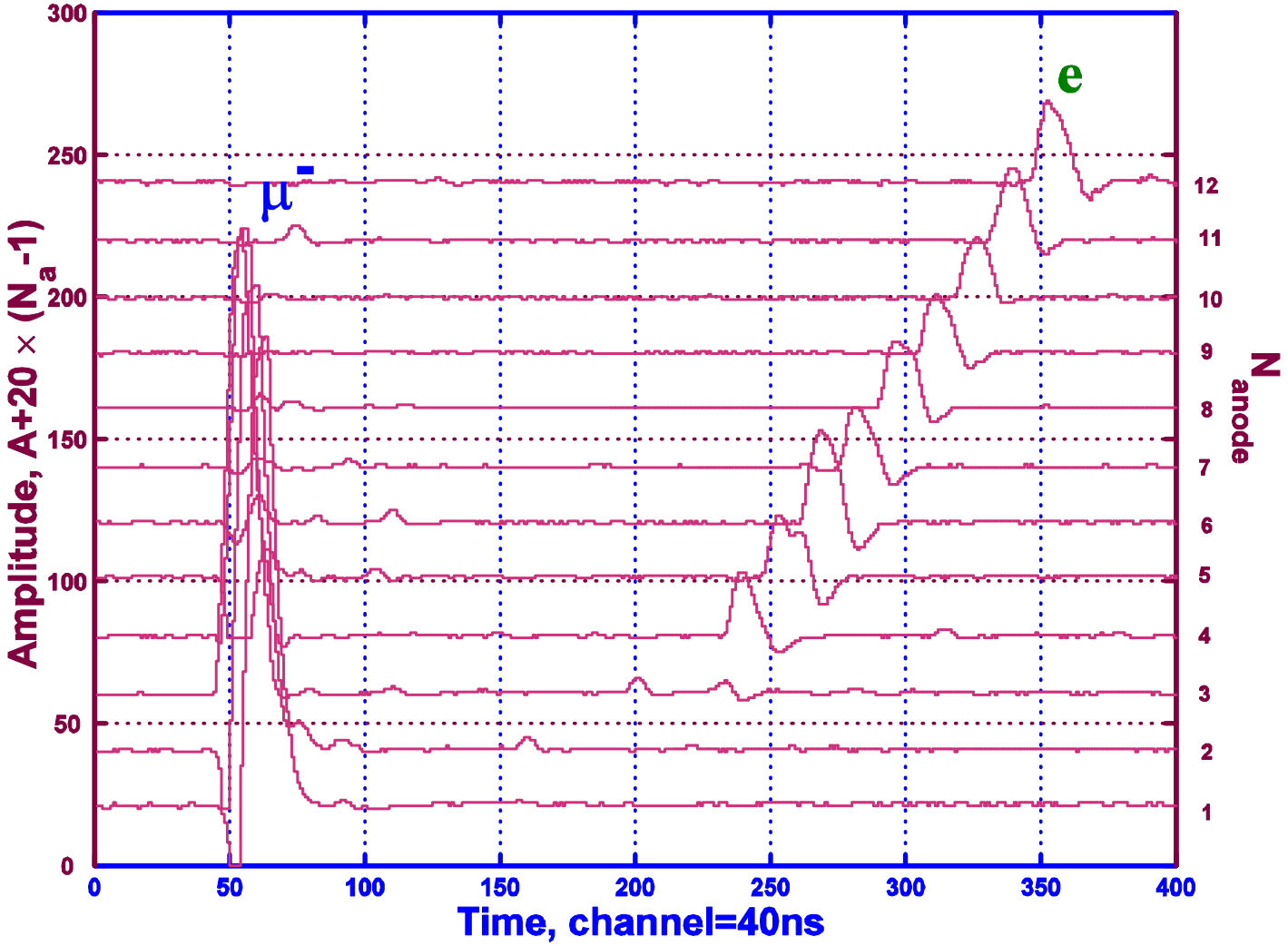
The trajectories of charged particles are measured in 3D space with resolution (σ) 2-3 mm.



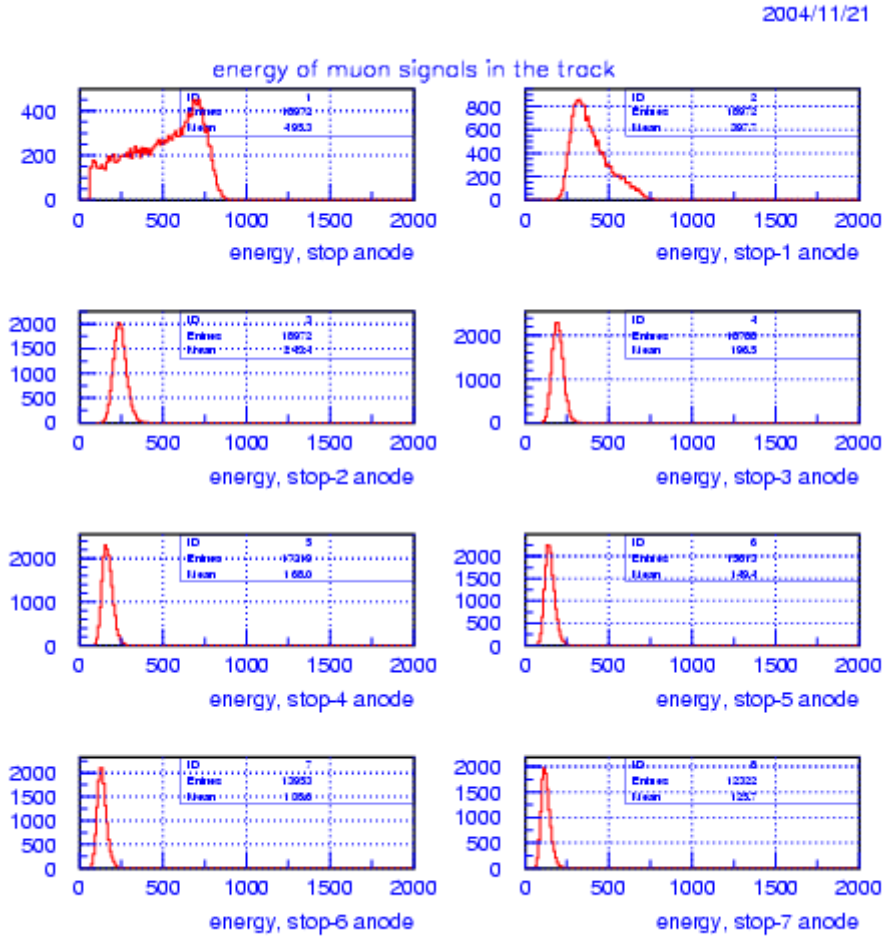
Cross-sectional diagram of the MuCap detector



Display of a typical event with μ-capture reaction on impurity



The signal on TPC anode wires from μ-e decay event



E stop ~ 0 -230 keV
E stop-1 ~ 100 - 200 keV
E stop-2 ~ 90 keV
E stop-3 ~ 72 keV
E stop-4 ~ 66 KeV
E stop-5 ~ 60 keV
E stop-6 ~ 54 keV
E stop-7 ~ 51 keV

For runs:
TPC HV = 5kV,
Attenuation =6dB

From that :
for energy 1ch~0.4keV
for amplitude 1ch~3keV

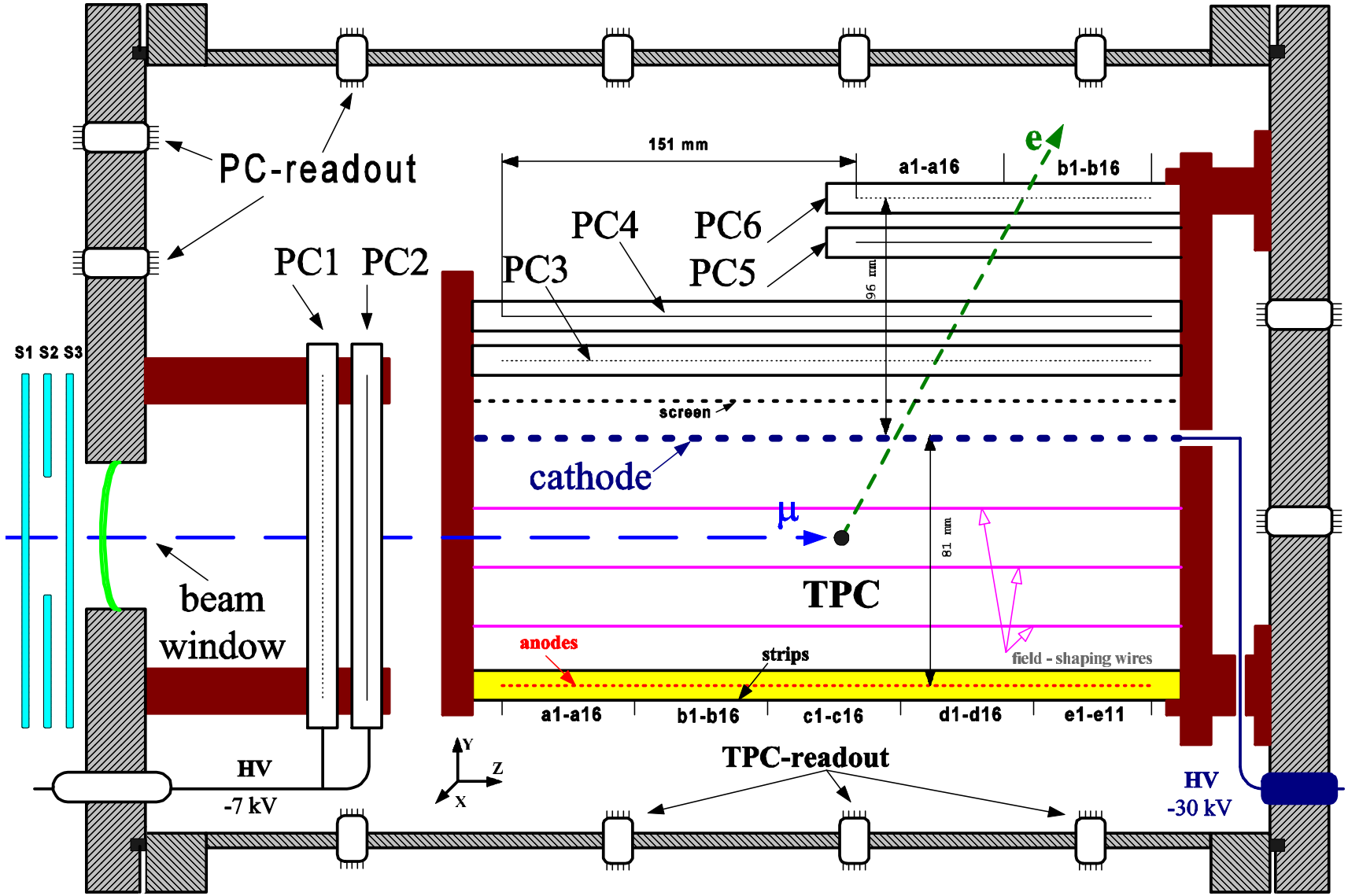
Energy spectra of the muon pulses on TPC anode wires

Conclusion

The proposed experimental method based on hydrogen time projection chamber (TPC) opens the possibility for investigation Muon Catalyzed ^{3}Hed-fusion on new level. The estimations give, that the profit to use the setup of MuCap experiment should be more than 10 TIMES in increasing of the sensitivity to this reaction in comparing with our previous experiments

The TPC operating as an active target in ultra-clean hydrogen helium gas mixture allows to detect any charge particles with about 100% efficiency. All trajectories of charged particles are measured in 3D space with resolution (σ) 2-3 mm.

In principle, such hydrogen TPC is a modern electronic version of a bubble chamber. Because of fundamental nature of the proton as a nuclear/particle target this new instrument might stimulate additional application in other basic or applied experiments.


PC-readout
PC1 PC2
PC3
PC4
PC6
PC5
151 mm
a1-a16
b1-b16
e
96 mm
S1 S2 S3
screen
cathode
μ
beam
window
TPC
81 mm
anodes
strips
field - shaping wires
a1-a16
b1-b16
c1-c16
d1-d16
e1-e11
Y
Z
X
TPC-readout
HV
-7 kV
HV
-30 kV

Search for Muon Catalyzed d^{3}He Fusion.

E.M. Maev [a], D.V. Balin [a], T. Case [b], K.M. Crowe [b], A. Del Rosso [c], V.A. Ganzha [a], F.J. Hartmann [d], S.M. Kozlov [a], B. Lauss [e], O.E. Maev [a], M. Mühlbauer [d], F. Mulhauser [c], C. Petitjean [f], G.E. Petrov [a], S.M. Sadetsky [a], G.N. Schapkin [a], W. Schott [d], G.G. Semenchuk [a], Yu.V. Smirenin [a], M.A. Soroka [a], A.A. Vasiliev [a], A.A. Vorobyov [a], N.I. Voropaev [a] and J. Zmeskal [e]

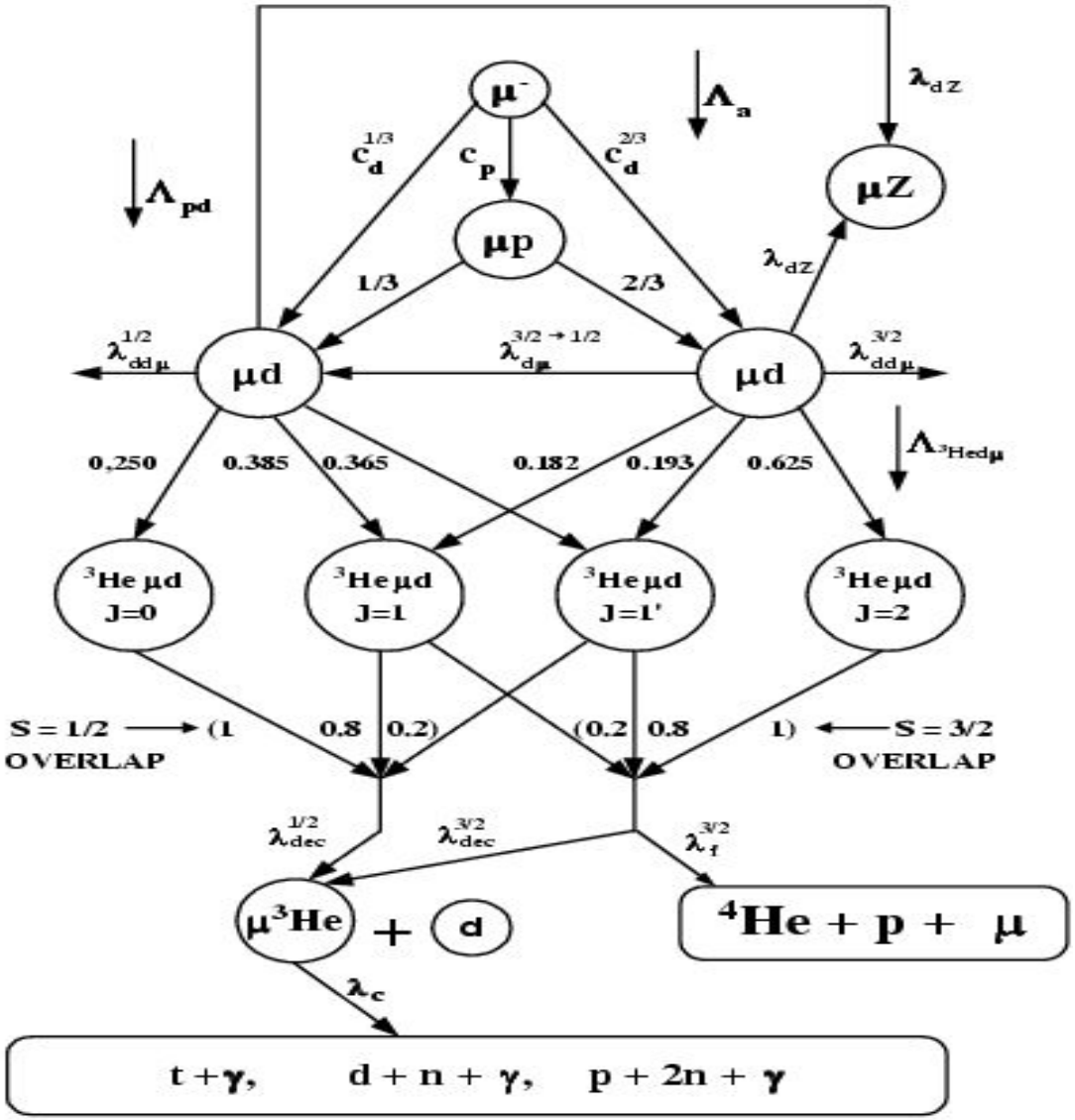
[a] *Petersburg Nuclear Physics Institute (PNPI), Gatchina 188350, Russia*
[b] *University of California and LBNL, Berkeley CA 94720, USA*
[c] *Institut de Physique de l'Université, Pérolles, 1700 Friburg, Switzerland*
[d] *Technical University of Munich (TUM), D-85747 Garching, Germany*
[e] *Austrian Academy of Sciences, A-1090 Vienna, Austria*
[f] *Paul Scherrer Institut (PSI), CH-5232 Villigen, Switzerland*

We report on the results of an experiment aimed at observing muon-catalyzed d^{3}He-fusion with a setup previously used for studies of the muon-catalyzed dd-fusion. The basic element of the setup is a high pressure ionization chamber operating as an active target. In this experiment the chamber was filled with a HD+^{3}He(5.6%) gas mixture at 13.2 bar pressure and 50K temperature. These conditions were chosen as optimal for formation of the ^{3}Heμd-molecules with a low level of background from the d-μ-d fusion. The chamber was exposed to the negative muon beam at PSI. During a 3 week data-taking period 9.7×10^8 muon stops have been selected. The analysis of the data allowed to determine a new upper limit for the d^{3}He-fusion rate in the ^{3}Heμd-molecule ($\lambda_f \leq 6 \times 10^4 s^{-1}$), which is more than three orders of magnitude lower than the previously existed limit.

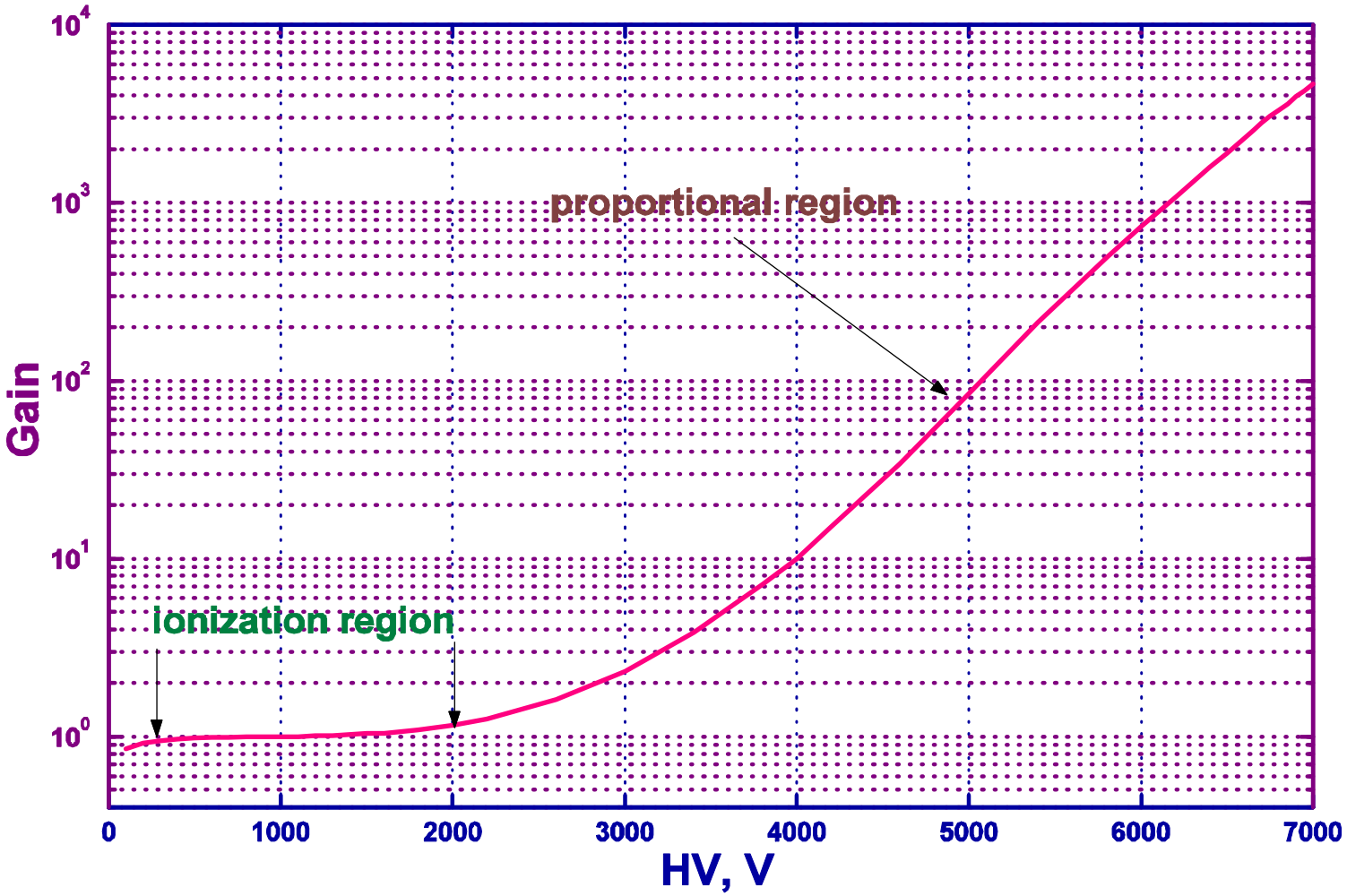
1. Introduction

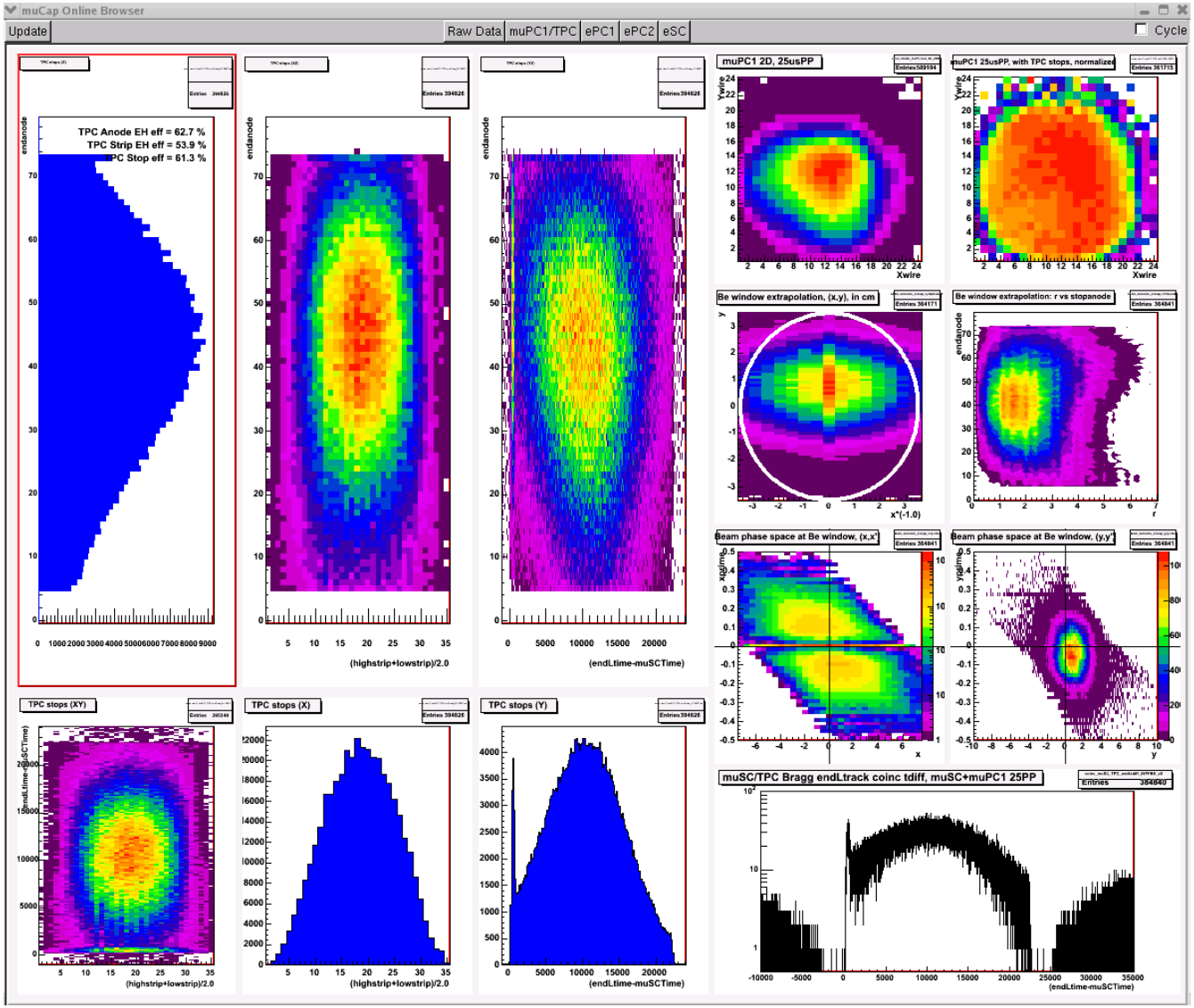
The theoretically predicted [1] and experimentally discovered [2] formation of ^{3}Heμd-molecules allows to search for muon catalyzed d^{3}He-fusion reaction

Учёт кинетики процессов в ^{3}Heμd-молекуле.



J--- спин мезомолекулы
S --- полный ядерный спин


Gain
10^4
10^3
10^2
10^1
10^0
proportional region
ionization region
0
1000
2000
3000
4000
5000
6000
7000
HV, V


muCap Online Browser
Update
Raw Data
muPC1/TPC
ePC1
ePC2
eSC
Cycle
TPC Anode EH eff = 62.7 %
TPC Strip EH eff = 53.9 %
TPC Stop eff = 61.3 %
endanode
(highstrip+lowstrip)/2.0
(endLtime-muSCTime)
muPC1 2D, 25usPP
muPC1 25usPP, with TPC stops, normalized
Ywire
Xwire
Be window extrapolation, (x,y), in cm
x'(-1.0)
Be window extrapolation: r vs stopanode
Beam phase space at Be window, (x,x')
Beam phase space at Be window, (y,y')
TPC stops (XY)
TPC stops (X)
TPC stops (Y)
muSC/TPC Bragg endLtrack coinc tdiff, muSC+muPC1 25PP