Badanie lekkich egzotycznych jąder w Laboratorium Reakcji Jądrowych ZIBJ w Dubnej. Praktyki dla studentów w ZIBJ

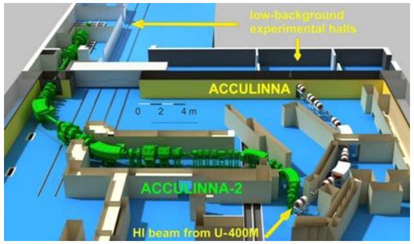
Grzegorz Kamiński
Laboratorium Reakcji Jądrowych, ZIBJ, Dubna
Instytut Fizyki Jądrowej PAN, Kraków

Outline

Flerov Laboratory of Nuclear Reactions

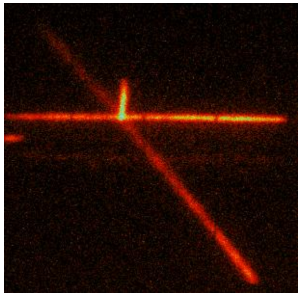
- ✓ The area of study
- ✓ Light exotic nuclei at ACCULINNA
- ✓ Separator: Principle of operation
- ✓ Key equipment
- ✓ Results

„Project" - ACCULINNA-2



- ✓ Status of the project
- ✓ First day experiments

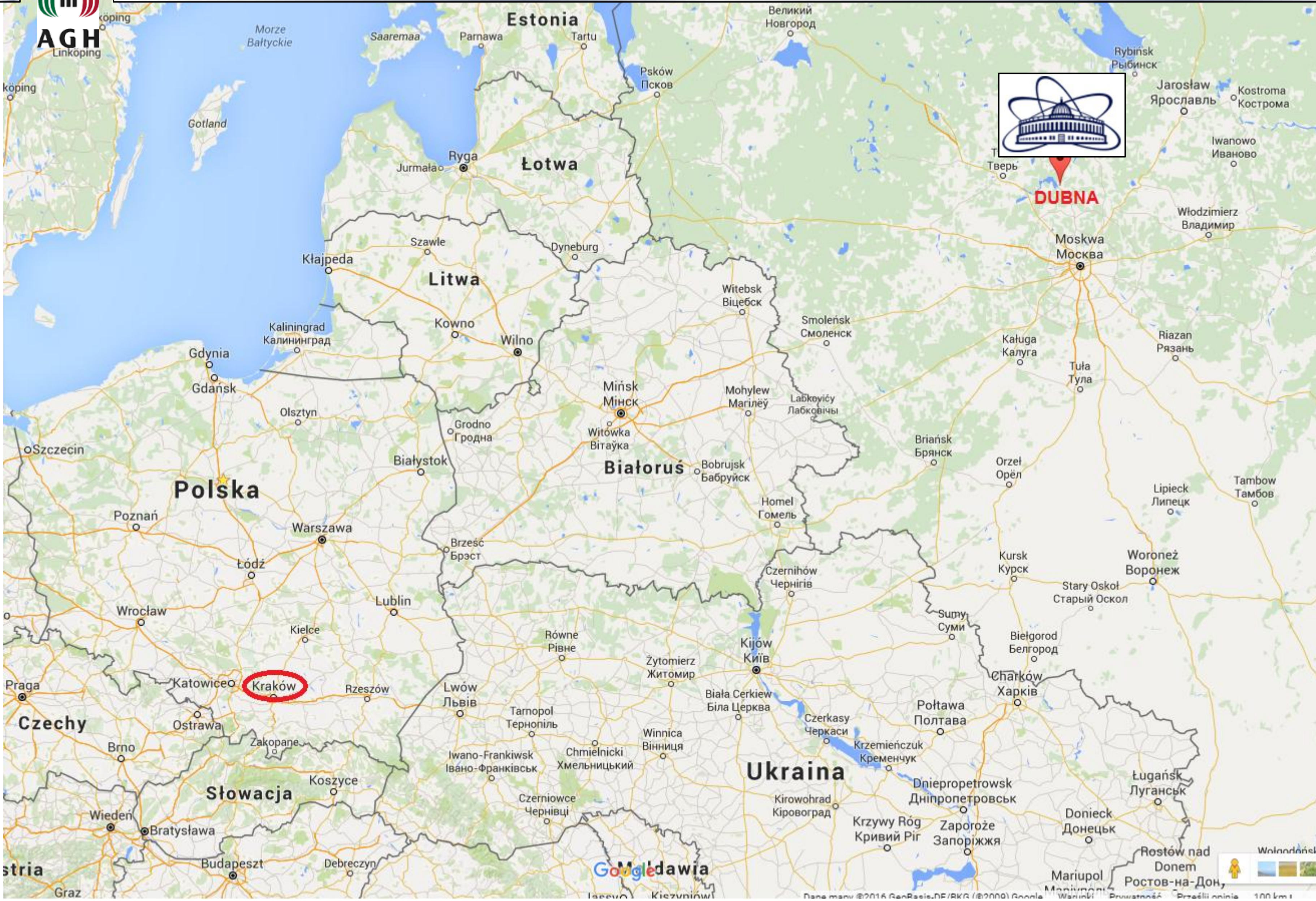
Optical Time Projection Chamber (OTPC)



- ✓ β-delayed particle emmision
- ✓ OTPC – how does it work?
- ✓ Recent studies with the OTPC
- ✓ Nearest plans- β-delayed particle emission of ^{27}S

Possibilities for students at JINR

- ✓ Summer trainings
- ✓ Individual visits
- ✓ Short term & long term contracts


DUBNA
Kraków
Estonia
Łotwa
Litwa
Białoruś
Polska
Ukraina
Czechy
Słowacja
Mołdawia
Morze Bałtyckie
Saaremaa
Gotland
Linköping
Parnawa
Tartu
Psków
Псков
Великий Новгород
Rybińsk
Рыбинск
Jarosław
Ярославль
Kostroma
Кострома
Iwanowo
Иваново
Тверь
Włodzimierz
Владимир
Moskwa
Москва
Ryga
Jurmała
Szawle
Dyneburg
Kłajpeda
Kowno
Wilno
Kaliningrad
Калининград
Gdynia
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Olsztyn
Szczecin
Grodno
Гродна
Białystok
Mińsk
Мінск
Witowka
Вітаўка
Witebsk
Віцебск
Smoleńsk
Смоленск
Mohylew
Магілёў
Łabkovičy
Лабковічы
Kaługa
Калуга
Riazan
Рязань
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Тула
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Bobrujsk
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Homel
Гомель
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Липецк
Tambow
Тамбов
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Warszawa
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Brześć
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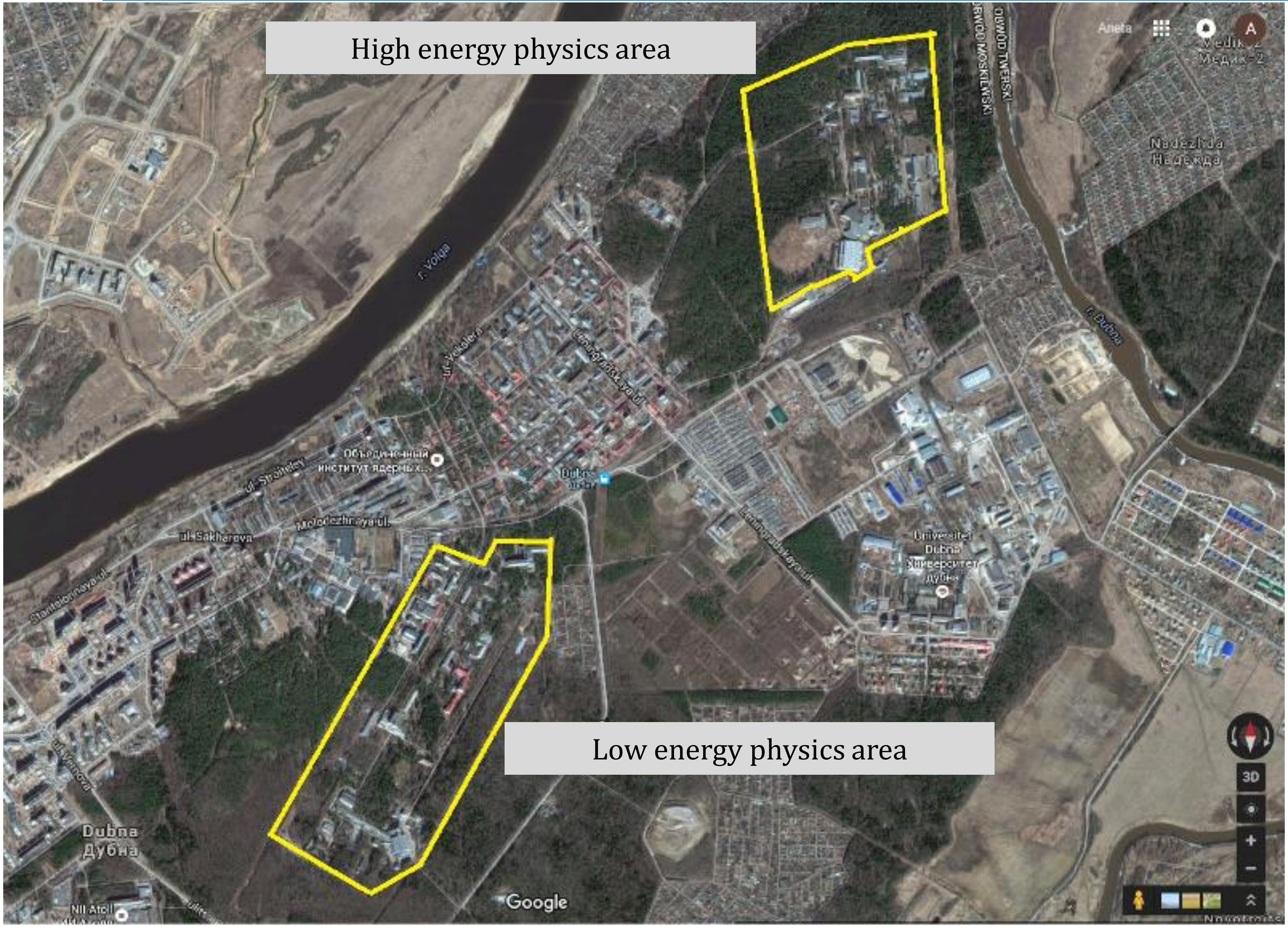
Charków
Харків
Ostrawa
Tarnopol
Тернопіль
Biała Cerkiew
Біла Церква
Czerkasy
Черкаси
Połtawa
Полтава
Brno
Zakopane
Winnica
Вінниця
Iwano-Frankiwsk
Івано-Франківськ
Chmielnicki
Хмельницький
Krzemieńczuk
Кременчук
Ługańsk
Луганськ
Koszyce
Dniepropetrowsk
Дніпропетровськ
Czerniowce
Чернівці
Kirowohrad
Кіровоград
Wiedeń
Bratysława
Doniecк
Донецьк
Krzywy Róg
Кривий Ріг
Zaporoże
Запоріжжя
Budapeszt
Debreczyn
Rostów nad Donem
Ростов-на-Дону
Mariupol
Graz
Kiszyniów

JINR at Dubna map



JINR Laboratories

Veksler and Baldin Laboratory of High Energy Physics

Bogoliubov Laboratory of Theoretical Physics

Laboratory of Information Technologies

Dzhelepov Laboratory of Nuclear Problems

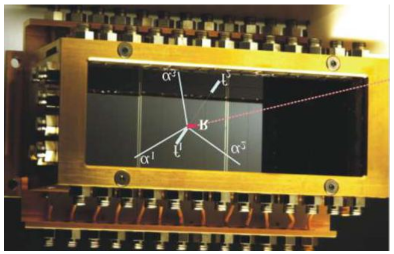
Laboratory of Radiation Biology

Flerov Laboratory of Nuclear Reactions

Frank Laboratory of Neutron Physics

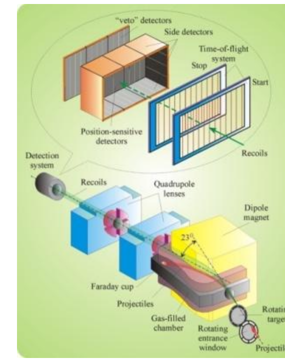
Flerov Laboratory of Nuclear Reactions (FLNR)

The main activities at FLNR



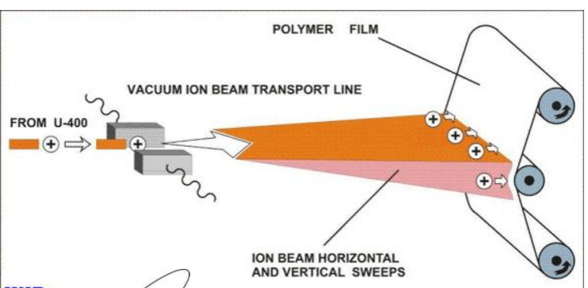
❍ Experiments with heavy ion beams of stable and radioactve nuclei:

- ✓ Synthesis of superheavy elements
- ✓ Study of fusion and fission of atomic niclei
- ✓ Study of nuclear reaction mechanisms
- ✓ Study of the structure of exotic nuclei



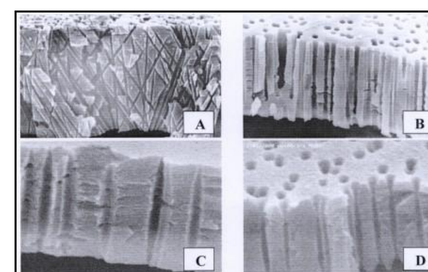
❍ Developpment of acceleration techniques

- ✓ cyclotrons
- ✓ ECR ion sources ECR



❍ Applied study

- ✓ Track membrans
- ✓ Nanostructures
- ✓ Study of materials properties
- ✓ Activations analysis



JINR 114 Flerovium FLNR Dubna

Flerov Laboratory of Nuclear Reactions (FLNR)

FLNR ACCELERATOR COMPLEXES

U400 - Accelerator complex based on U400 isochronous cyclotron was put into operation in 1979. U400 accelerator is Laboratory's basic setup for synthesis of new elements.

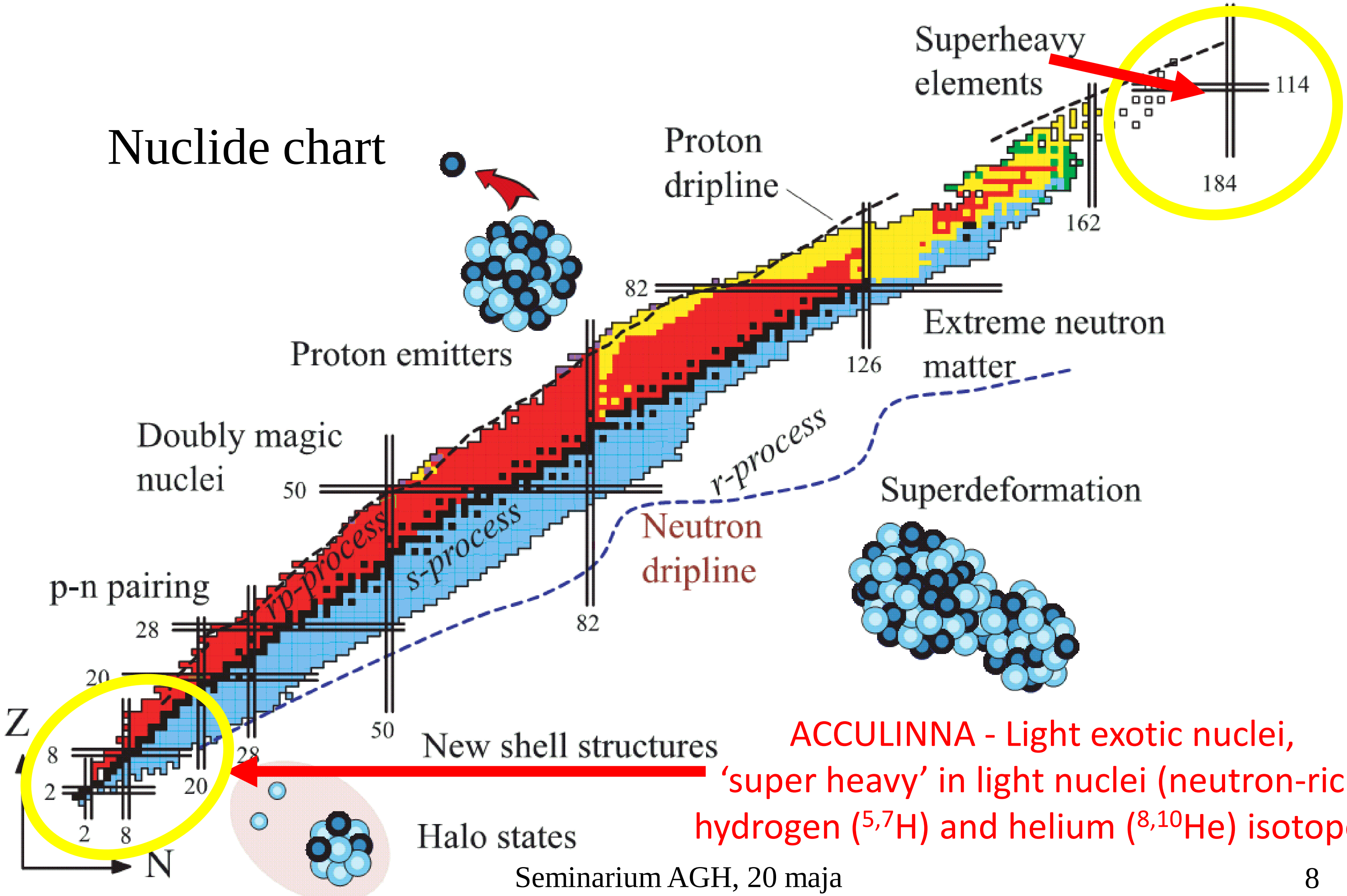
U400M - Accelerator complex based on U400M isochronous cyclotron was put into operation in 1993. In 2002 this cyclotron was included in DRIBs accelerator complex designed for production of radioactive ion beams

U200 - Accelerator complex based on U200 isochronous cyclotron was put into operation in 1968. At present U200 cyclotron is used for production of ultraclean radioisotopes for ecology and nuclear medicine.

DC-40 (IC-100) - Cyclotron complex is the full-scale upgrade of IC-100 cycle implanter. Designed for high technology and applied research.

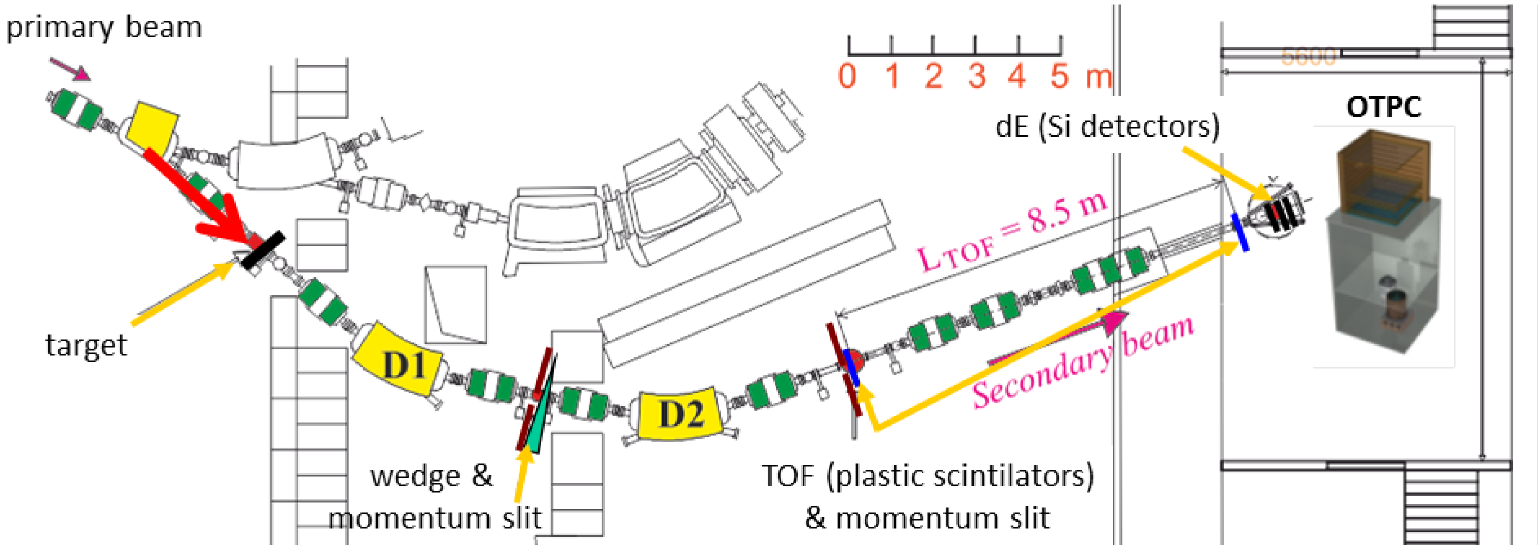
MT-25 - Microtron electron accelerator was put into operation in 1973 (MT-17). It was totally upgraded in 1980 (MT-22) and in 1986 (MT-25). This microtron is used for study and production of ultraclean radioisotopes.

FLNR – the main area of study



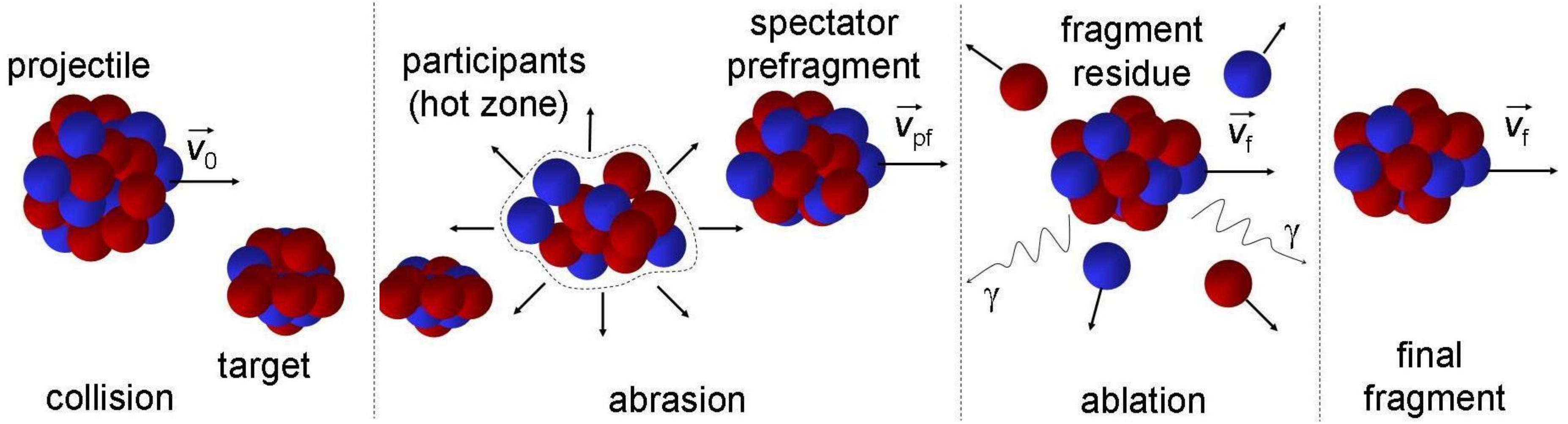
ACCULINNA - Light exotic nuclei, 'super heavy' in light nuclei (neutron-rich hydrogen (^{5,7}H) and helium (^{8,10}He) isotopes)

ACCULINNA


primary beam
0 1 2 3 4 5 m
OTPC
dE (Si detectors)
L TOF = 8.5 m
target
D1
D2
Secondary beam
wedge &
momentum slit
TOF (plastic scintilators)
& momentum slit

Physical tool: projectile fragmentation reaction

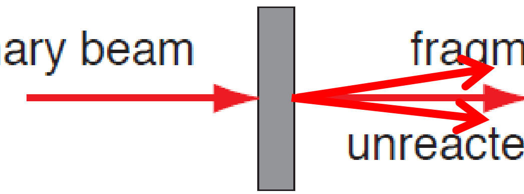
Abrasion/Ablation Model

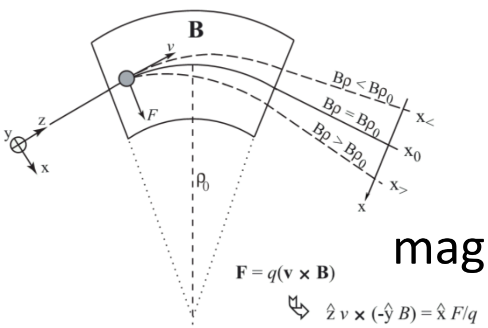


fast Abrasion step
nucleon removal in overlap region of target and projectile

slow Ablation step
equilibration of excited prefragment and evaporation of particles

What is ACCULINNA ?



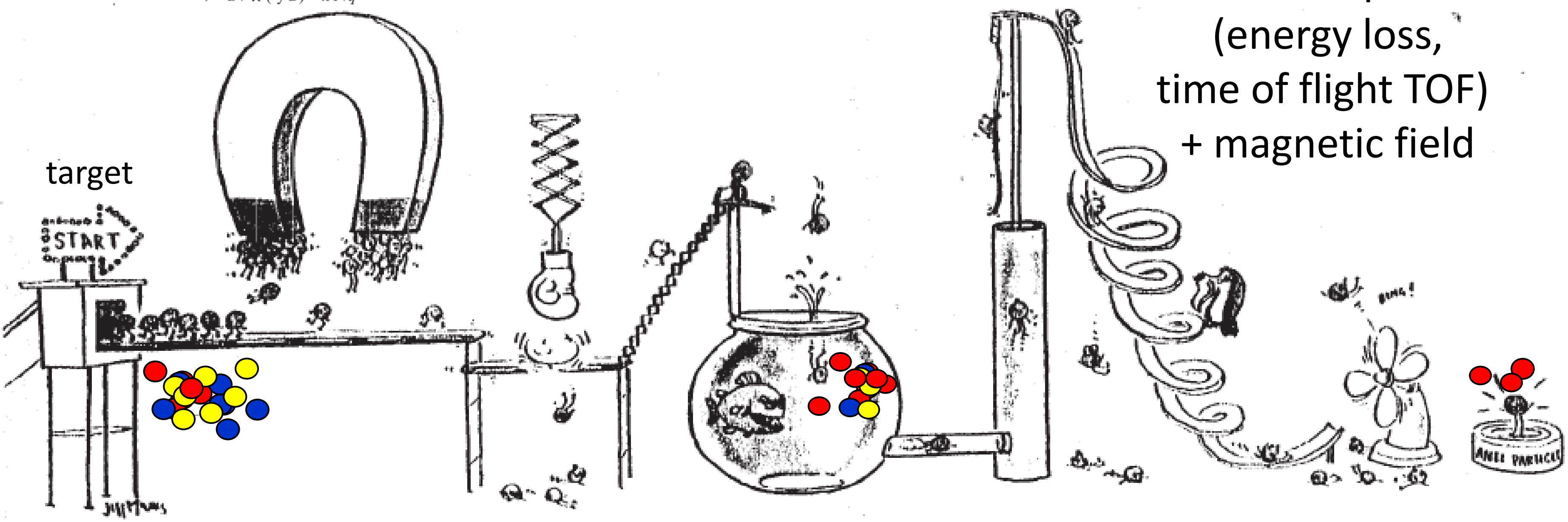


magnetic field

separator of rare isotopes

additonall separation
(energy loss,
time of flight TOF)
+ magnetic field

target

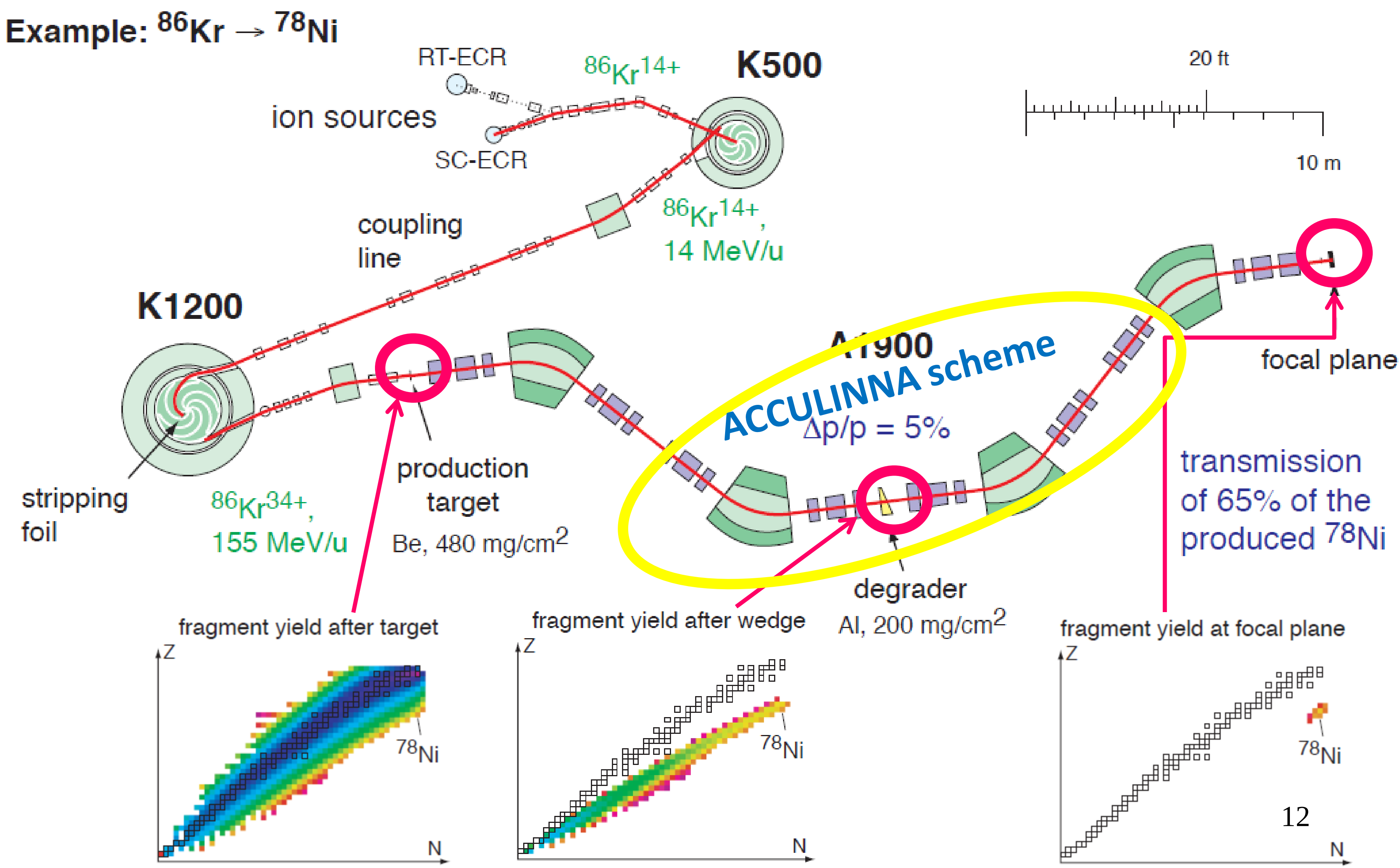


Nuclear reaction -
Many different reaction products

separated by magnetic field

separated products

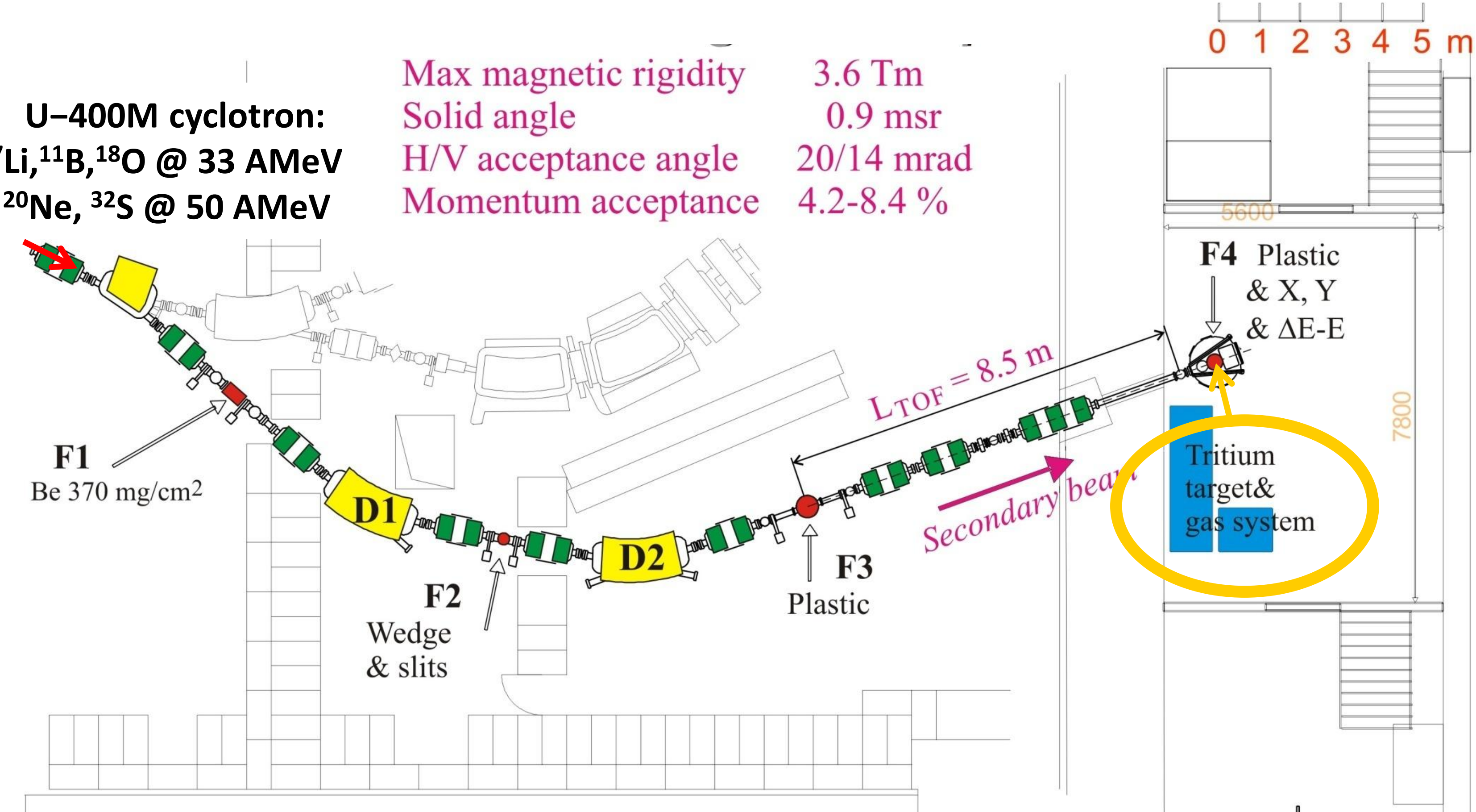
Example scheme of the fragmentation facility



ACCULINNA - separator scheme

U–400M cyclotron:
$^{7}Li, ^{11}B, ^{18}O$ @ 33 AMeV
^{20}Ne, ^{32}S @ 50 AMeV

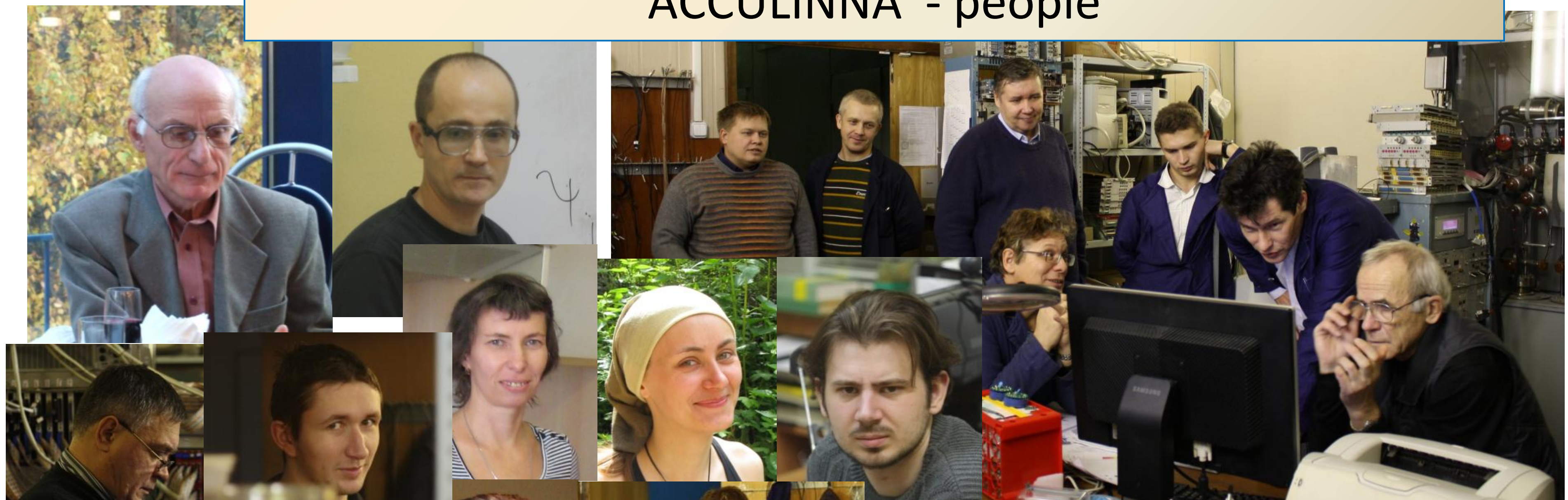
Max magnetic rigidity	3.6 Tm
Solid angle	0.9 msr
H/V acceptance angle	20/14 mrad
Momentum acceptance	4.2-8.4 %



	F2	F3	F4
H/V magnification	0.5/2.0	1.0/1.0	2.25/1.6
Mom. dispersion, mm/%	4.0-18.0	–	–
Mom. resolution	0.003		
H/V RIB size, mm		8/10	20/16

*** 1996 – first experiment**
**** 2000 – last upgrade**
***** 2011 – next step Acc.2**

ACCULINNA - people



THEORY

JINR, FLNR: LG, Yu. Parfenova, P. Sharov

JINR, BLTP: S. Ershov, I. Egorova

Geteborg University: M. Zhukov

EXPERIMENT

JINR, FLNR: A. Fomichev, M. Golovkov, S. Sidorchuk, G. Ter-Akopian, A.Bezbakh, **R. Wolski (IFJ PAN),** A. Gorshkov, V. Gorshkov, R. Slepnev, **G. Kaminski (IFJ PAN)**, S. Krupko, V. Chudoba, **M. Mentel (AGH), P. Pluciński (AGH)**

Kurchatov Institute: E. Nikolskii, E. Kuzmin

RNFC Sarov: A. Yukhimchuk, S. Filchagin, A. Kirdyashkin

PTI St. Petersburg: V. Eremin

saw University: M. Pfutzner, W. Dominik, Z. Janas, L. Janiak, K. Miernik, S. Mianowski, C. Mazzocchi, M.Pomorski

GSI, Darmstadt: H. Simon, I. Mukha, Ch. Scheidenberger

Key equipment of the ACCULINNA separator

✓Cryogenic tritium target system & correlation measurements

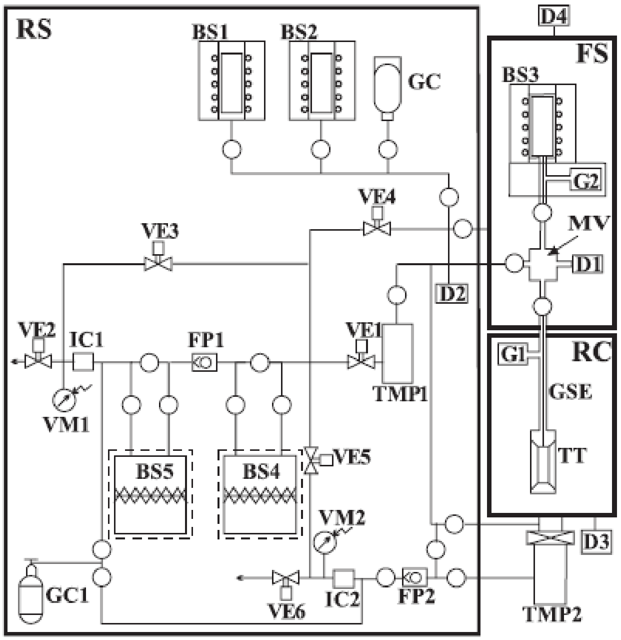
✓Neutron detection system – stilbene crystals

✓Optical Time Projection Chamber (OTPC) at ACCULINNA (collaboration with University of Warsaw)

Cryogenic tritium target

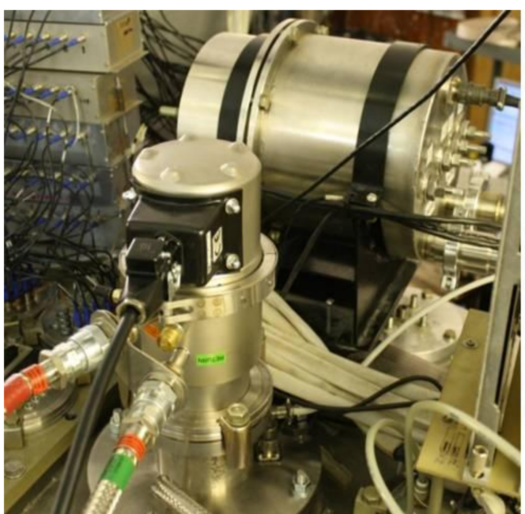
charged particles detectors & neutron detectors, crystal size 80(∅) x 50 mm^3

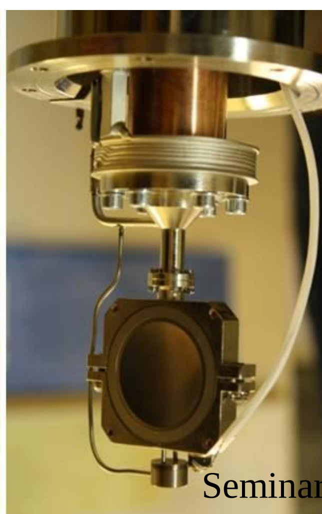
Physical unique targets H, He



Basic scheme of the complex.

FS—filling system; RS—tritium recovery and radiation monitoring system; RC—reaction chamber; TT—tritium target; GSE—gas supply/evacuation line; BS1(2)—hydrogen (deuterium) source; BS3—tritium source; BS4, BS5—traps; GC, GC1—helium gas-cylinders; D1, D2—pressure gauges; D3, D4—vacuum gauges; FP1, FP2—vacuum pumps (BOC EDWARDS GVSP 30); TMP1, TMP2—turbo pumps (STR-300M); MV—measuring vessel (270 cm3); G1, G2—getters; VE1–VE6 valves (open circles show all other valves); IC1, IC2—ionization chambers; VM1, VM2—vacuum gauges blocking the gas release in ventilation in excess of a given level of the gas-specific volumetric activity.





A.A. Yukhimchuk et al.,
NIM A513 (2003) 439.

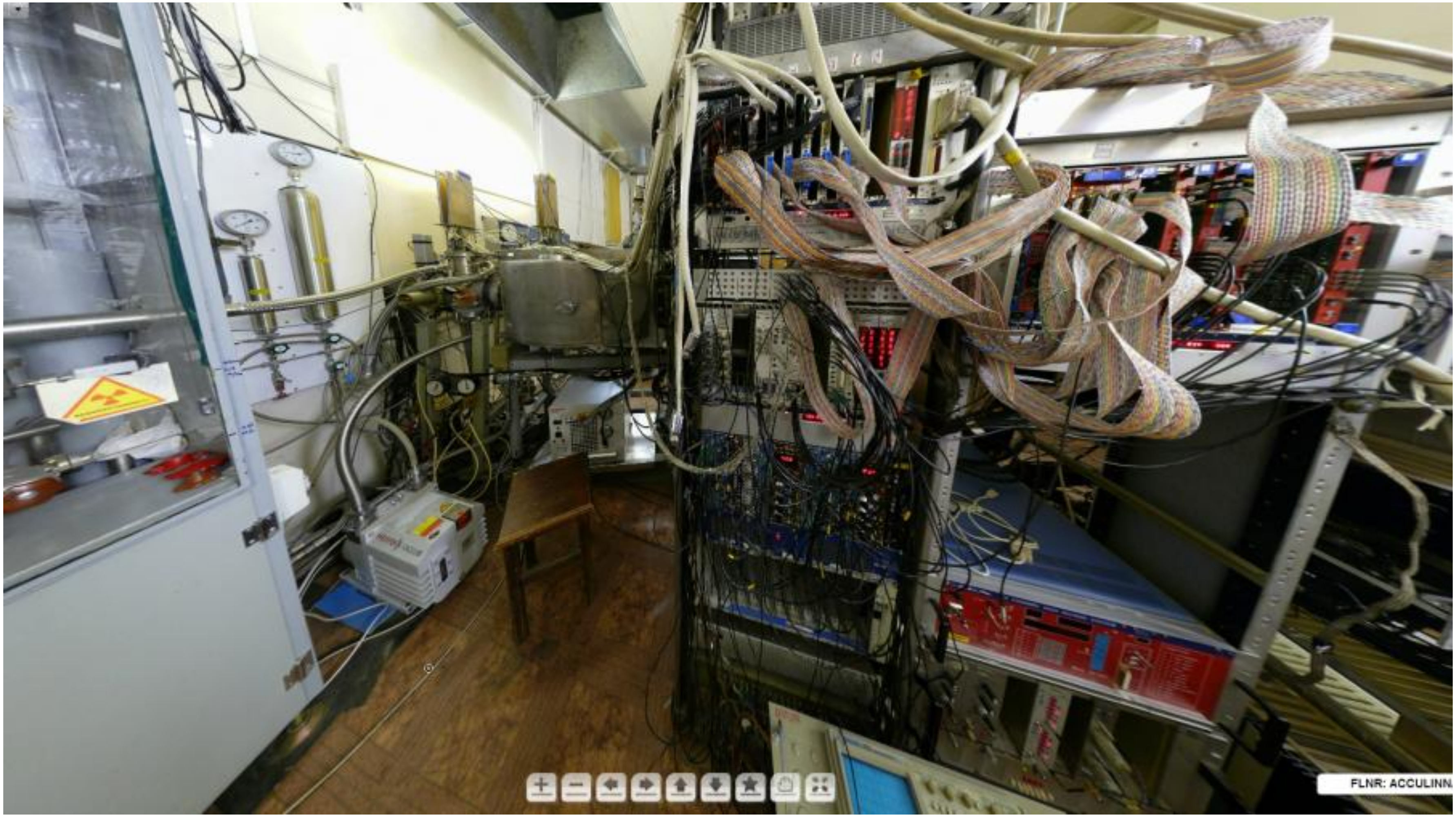
Gas:

ϕ=25 mm, d=3÷6 mm,
T=26 K, P=0.92 Atm,
$x=3*10^{20}$ Atm/cm^2

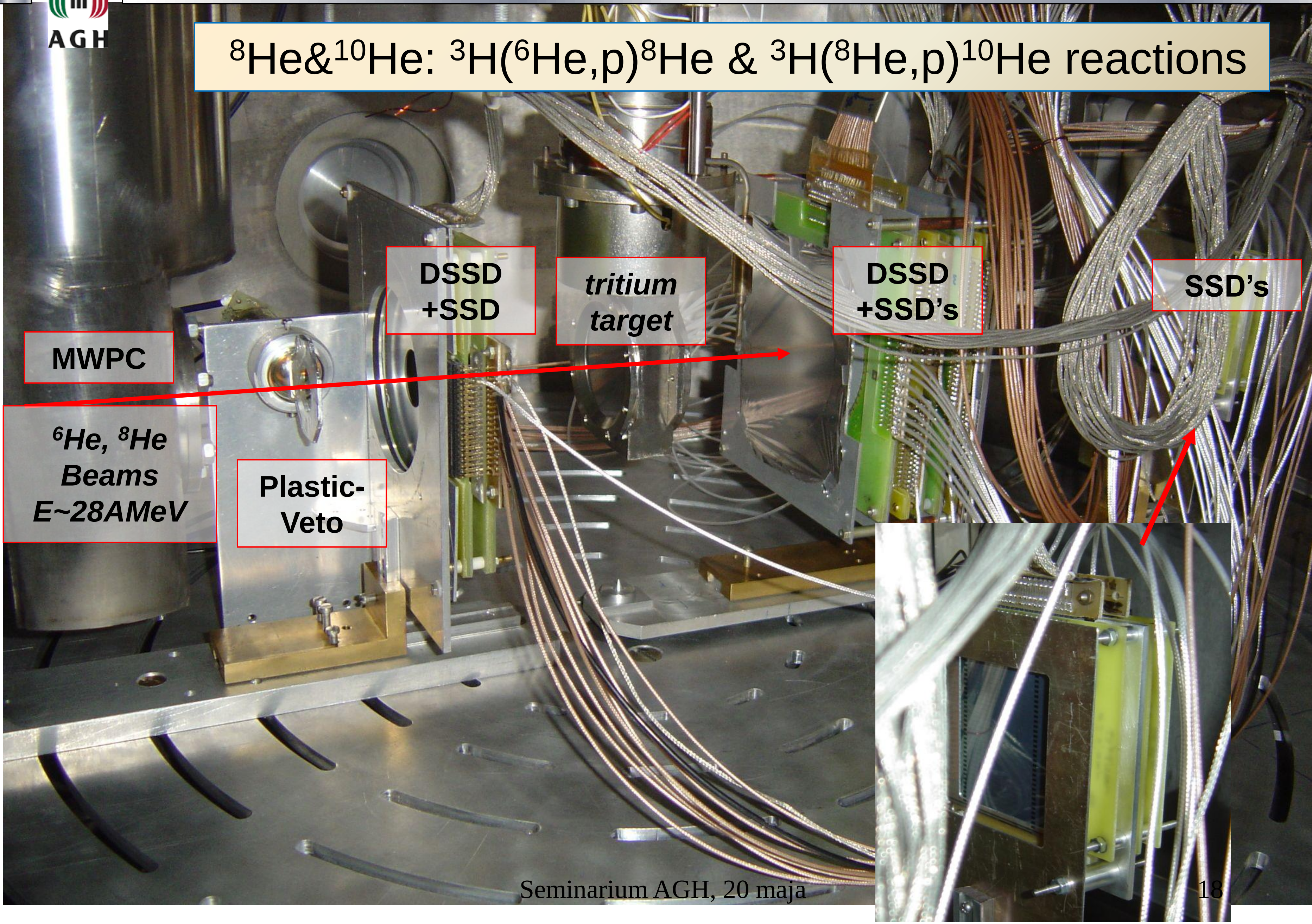
Liquid:

ϕ=20 mm, d=0.4÷0.8 mm,
w=2x8.4 μ stainless steel,
$x=1.1*10^{21}$ Atm/cm^2
I ≤ 960 Ci ($3.54*10^{13}$ Bq)

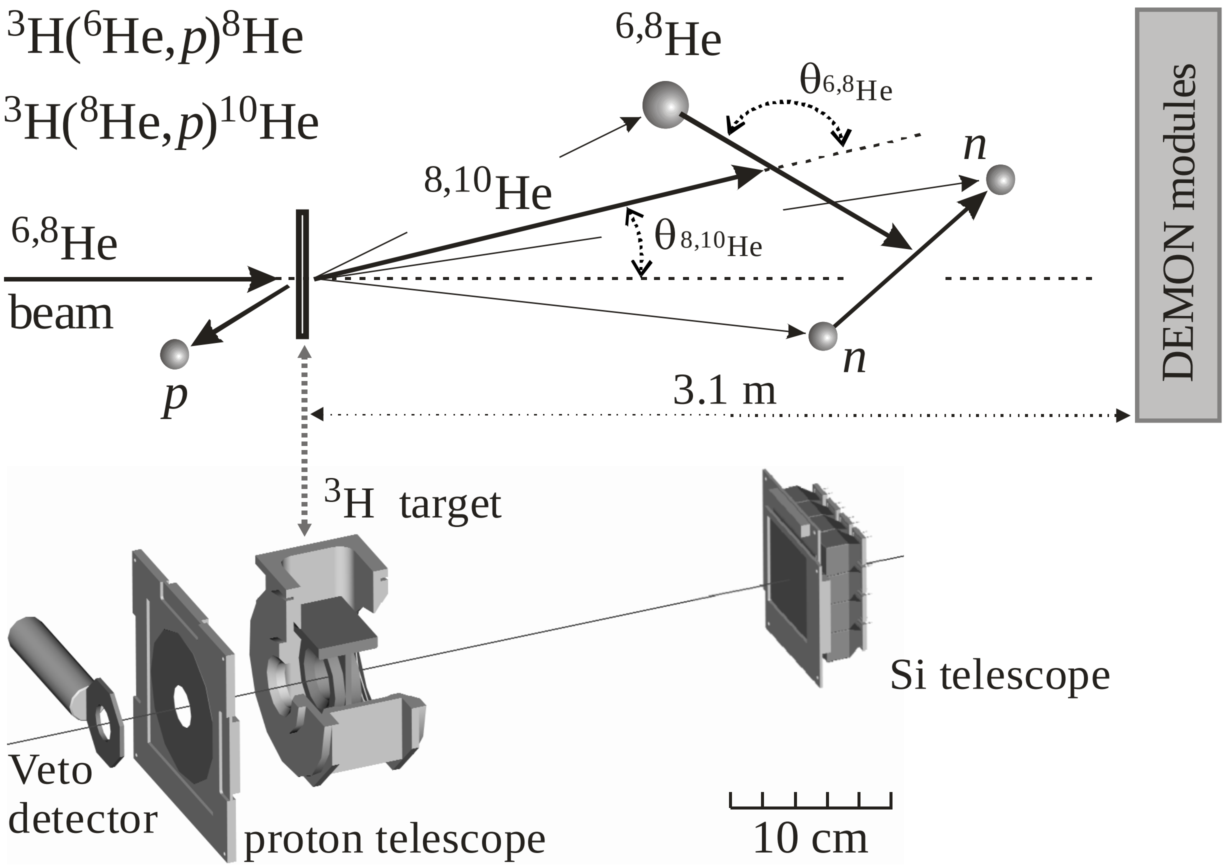
experimental area: reaction chamber, detectors and DAQ



^{8}He&^{10}He: ^{3}H(^{6}He,p)^{8}He & ^{3}H(^{8}He,p)^{10}He reactions



^{8}He&^{10}He: ^{3}H(^{6}He,p)^{8}He & ^{3}H(^{8}He,p)^{10}He reactions



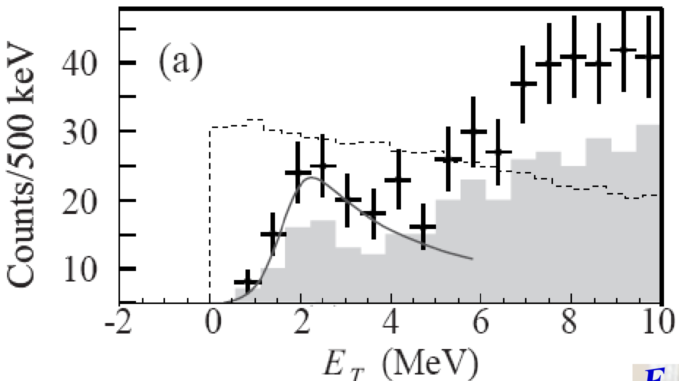
Features:

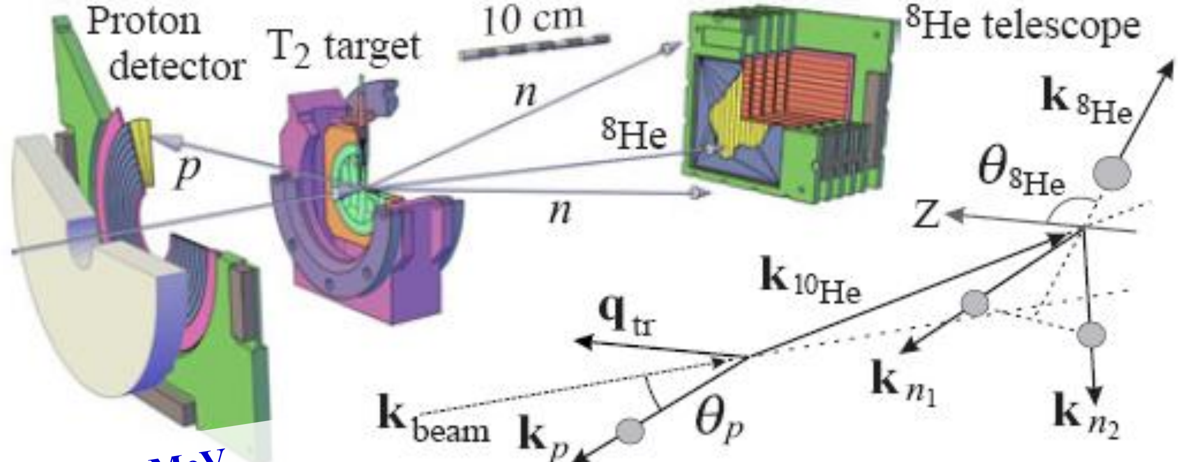
Reasonable energy resolution ΔE~400 keV (FWHM)

Practically background free: very few protons go in the backward lab direction

- Slow protons registered in the backward direction, what limits the maximal ^{8}He and ^{10}He excitation energy to about 14 and 17 MeV.
- ^{8,10}He registered in the forward telescope. Neutrons are registered by 49 DEMON modules.
- It's complete kinematics reconstruction.

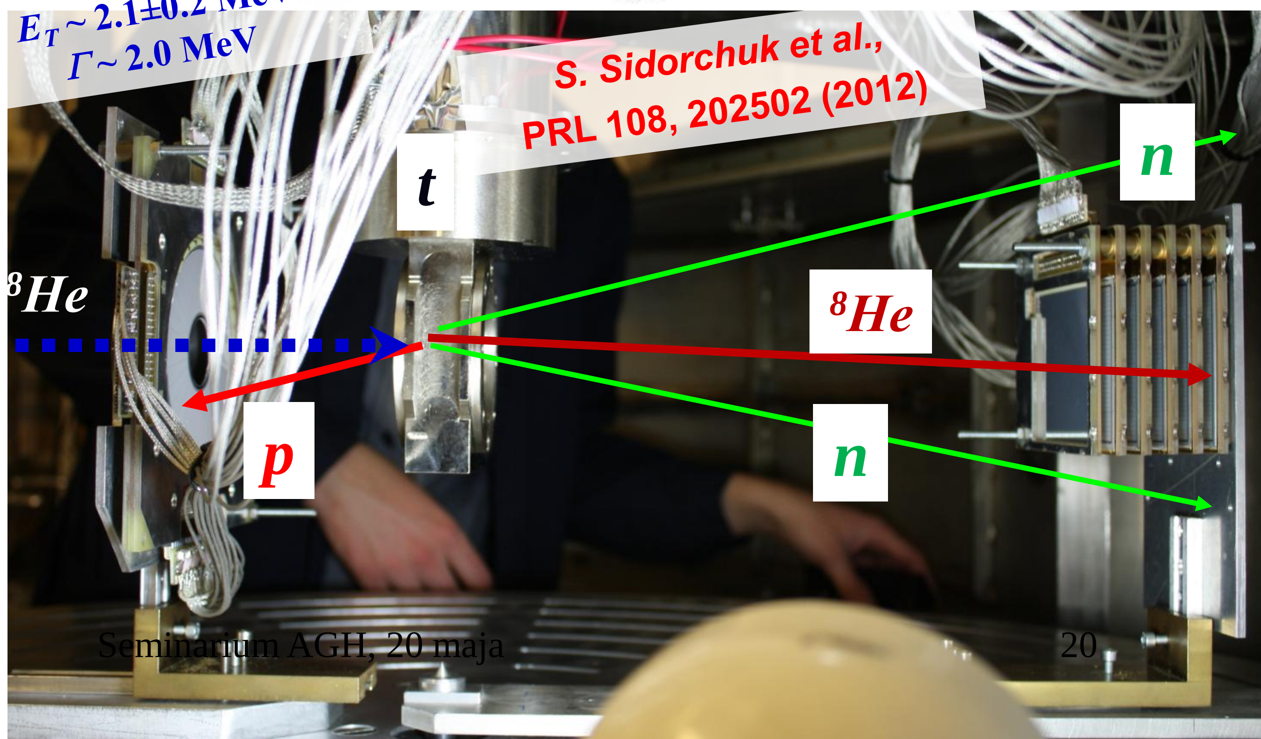
^{10}He: ^{3}H(^{8}He,p)^{10}He





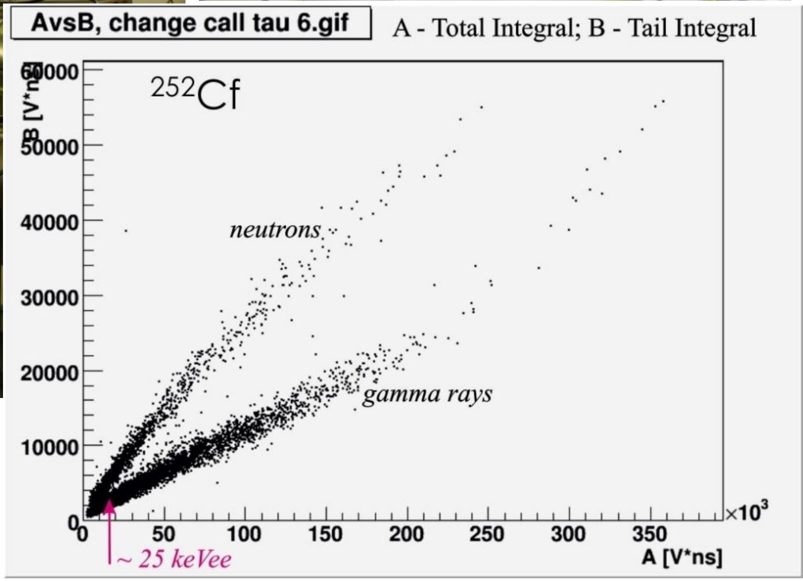
$E_T \sim 2.1\pm0.2$ MeV
$\Gamma \sim 2.0$ MeV

S. Sidorchuk et al., PRL 108, 202502 (2012)



^{8}He beam:
E ~ 23 A·MeV
I ~ 15000 s^{-1}
Tritium target:
6 mm thick @ 99.7 %
0.92 atm @ 26 K

Neutron detection



Neutron detection array

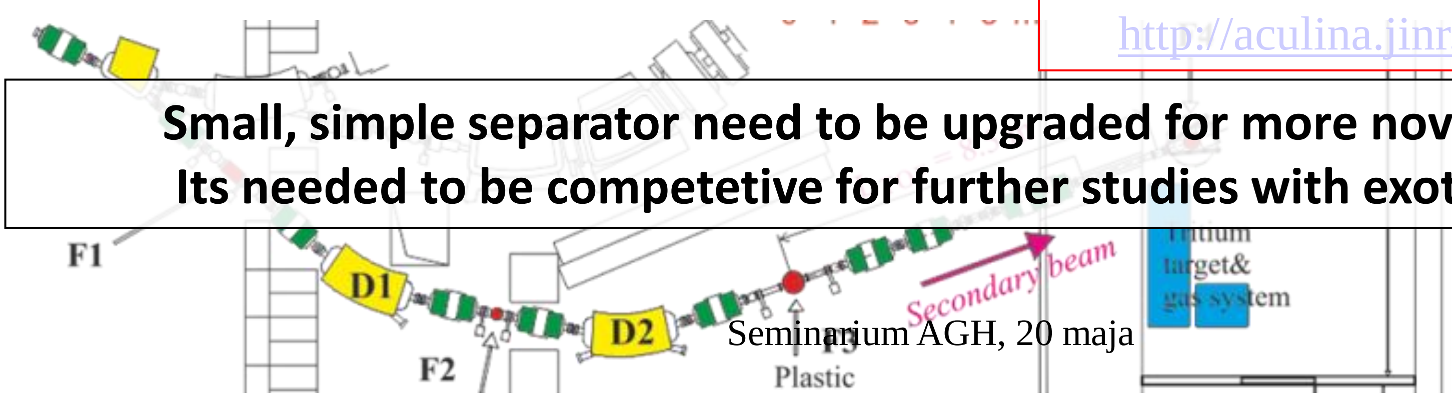
Some results

In the recent years using ACCULINNA separator, new results were obtained for such isotopes as:

^{4}H[1], **^{5}H** [2-4], **^{7}H** [5], **^{6}He** [10], **^{8}He** [6], **^{9}He** [7], **^{26}S** [8], **^{6}Be** [9] and **^{10}He** [6, 11]:

[1] S.I. Sidorchuk *et al.*, Phys. Lett. B 594 (2012) 54;
[2] A.A. Korsheninnikov *et al.*, Phys. Rev. Lett. 87, 092501 (2001);
[3] M.S. Golovkov *et al.*, Phys. Lett. B 566, 70 (2003);
[4] M.S. Golovkov *et al.*, Phys. Rev. Lett. 93, 262501 (2004);
[5] M.S. Golovkov *et al.*, Phys. Lett. B 588, 163 (2004);
[6] M.S. Golovkov *et al.*, Phys. Lett. B 672, 22 (2009);
[7] M.S. Golovkov *et al.*, Phys. Rev. C 76, 021605(R) (2007);
[8] A.S. Fomichev *et al.*, Int. J. Mod. Phys. E 20, 1491 (2011);
[9] A.S. Fomichev *et al.*, Phys. Lett. B 708, 6 (2012);
[10] S.I. Sidorchuk *et al.*, Nucl. Phys. A 840, 1 (2010);
[11] S.I. Sidorchuk *et al.*, Phys. Rev. Lett. 108, 202502 (2012).

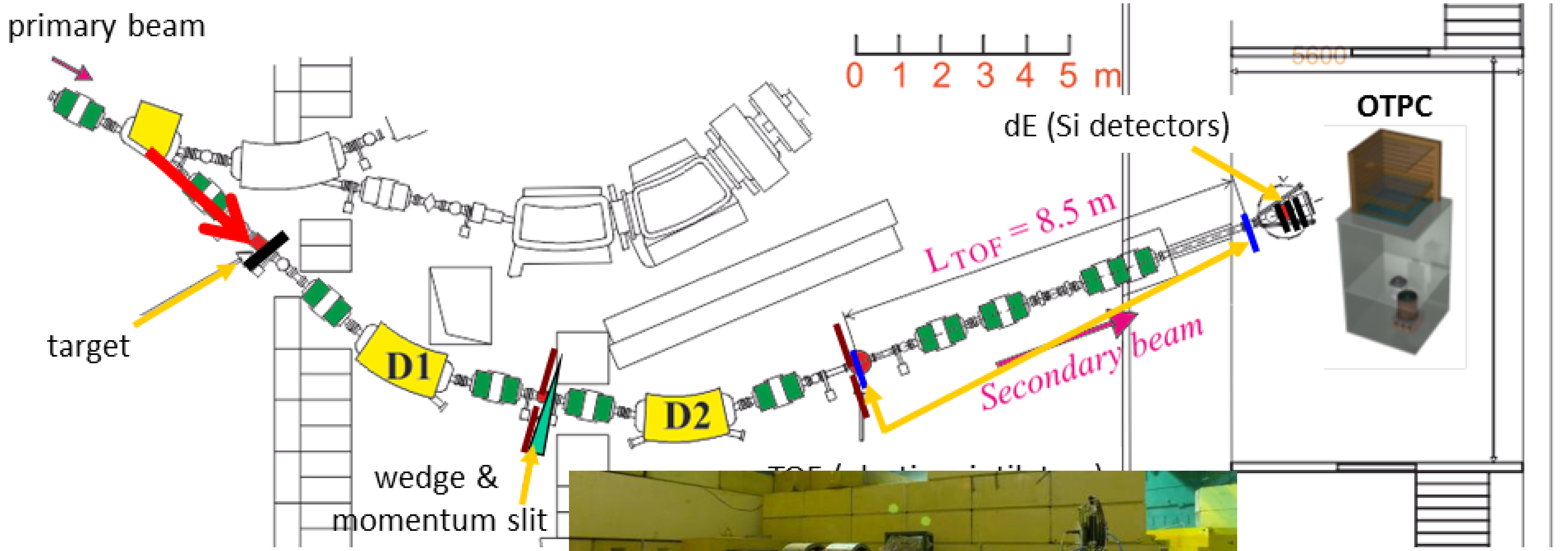
http://aculina.jinr.ru -> publications



Small, simple separator need to be upgraded for more novel results !!!
Its needed to be competetive for further studies with exotic nuclei !!!

Separator ACCULINNA 2

2010 year: Should we upgrade ACCULINNA-1?



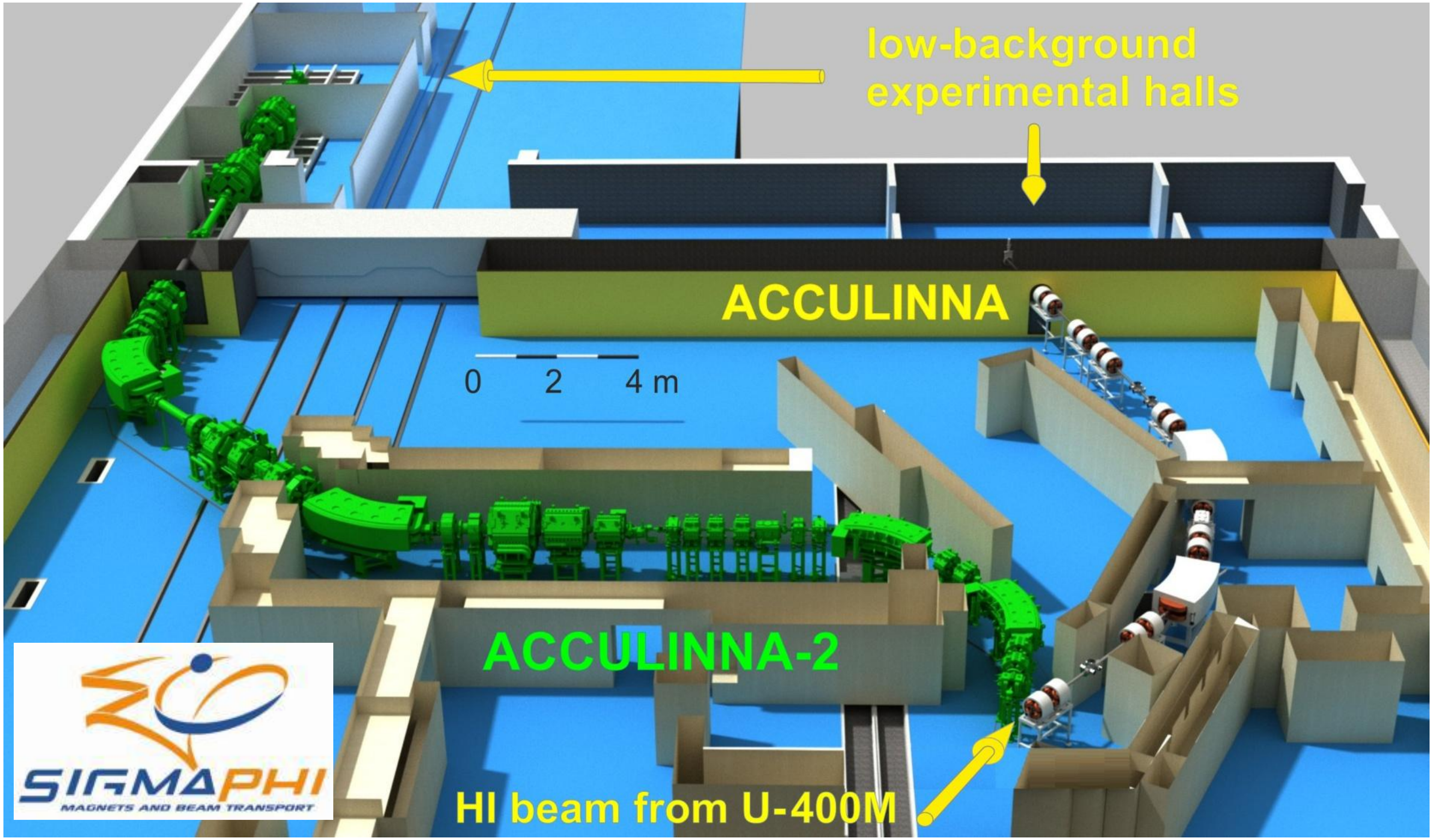
Acculinna2 in perspective

Characteristics of existing and new in–flight RIB separators

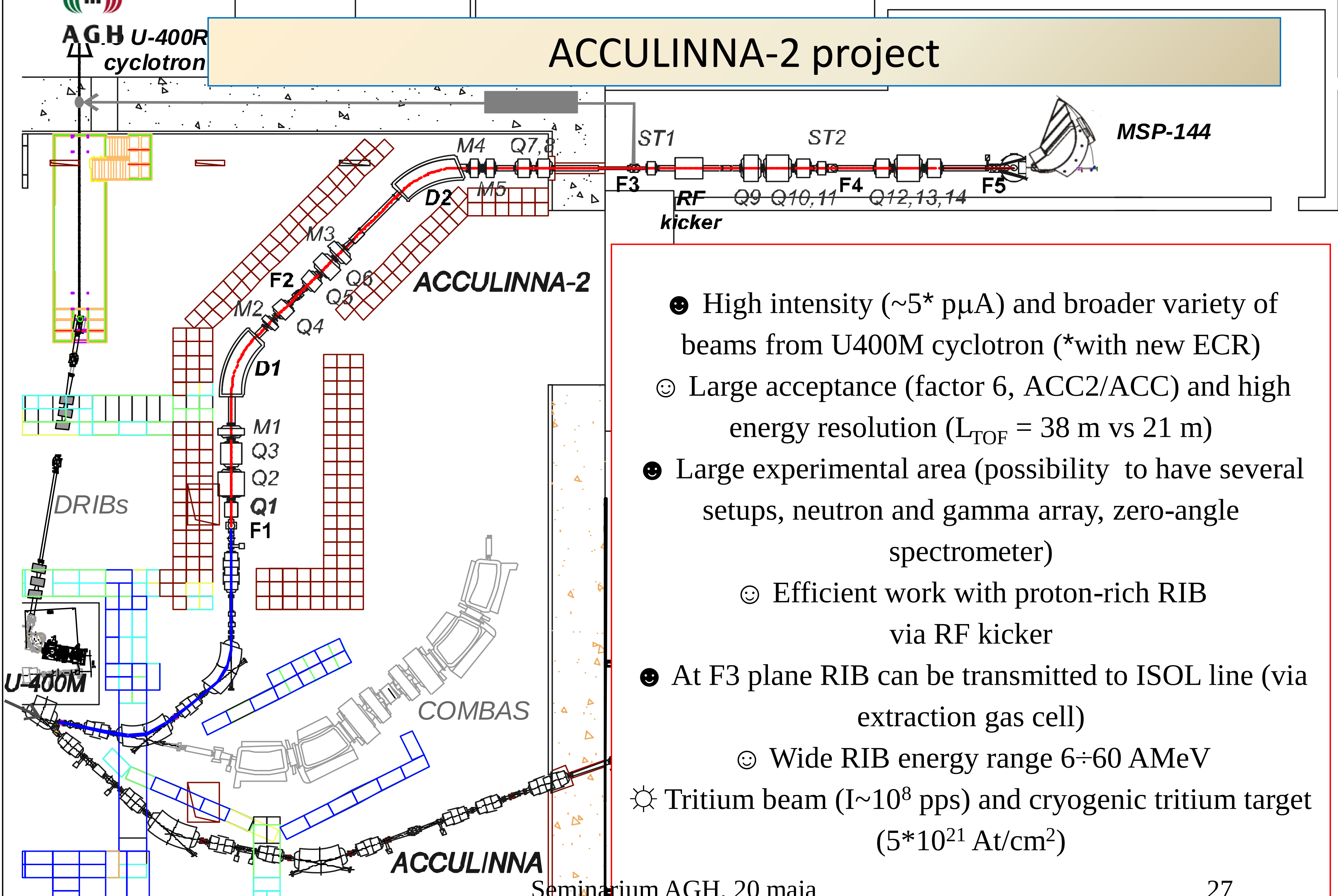
($\Delta\Omega$ and $\Delta p/p$ are angular and momentum acceptances, $Rp/\Delta p$ is the first-order momentum resolution when 1 mm object size is assumed)

	ACC / ACC-2 FLNR JINR	RIPS / BigRIBS RIKEN	A1900 MSU	FRS / SuperFRS GSI	LISE3 GANIL
$\Delta\Omega$, msr	0.9 / 5.8	5.0 / 8.0	8.0	0.32 / 5.0	1.0
$\Delta p/p$, %	± 2.5 / ± 3.0	± 3.0 / 6.0	± 5.5	± 2.0 / 5.0	± 5.0
$Rp/\Delta p$	1000 / 2000	1500 / 3300	2915	8600 / 3050	2200
$B\rho$, Tm	3.2 / 3.9	5.76 / 9.0	6.0	18 / 18	3.2 - 4.3
Length, m	21 / 38	27 / 77	35	74 / 140	19(42)
E, AMeV	10÷40 / 6÷60	50÷90 / 350	110÷160	220÷1000/1500	40÷80
Additional RIB Filter	No / RF-kicker	RF-kicker / S-form	S-form & RF- kicker	S-form / Preseparator	Wien Filter

ACCULINNA-2 project



ACCULINNA-2 project



☻ High intensity (~5* pμA) and broader variety of beams from U400M cyclotron (*with new ECR)

☺ Large acceptance (factor 6, ACC2/ACC) and high energy resolution (L_{TOF} = 38 m vs 21 m)

☻ Large experimental area (possibility to have several setups, neutron and gamma array, zero-angle spectrometer)

☺ Efficient work with proton-rich RIB via RF kicker

☻ At F3 plane RIB can be transmitted to ISOL line (via extraction gas cell)

☺ Wide RIB energy range 6÷60 AMeV

☼ Tritium beam (I~10^8 pps) and cryogenic tritium target ($5*10^{21}$ At/cm^2)

In the beginning of the project at experimental hall

« In the beginning, there was Chaos » Greek Mythology – The Creation

Preparation (area, floor etc.) & 1st delivery

August 2014

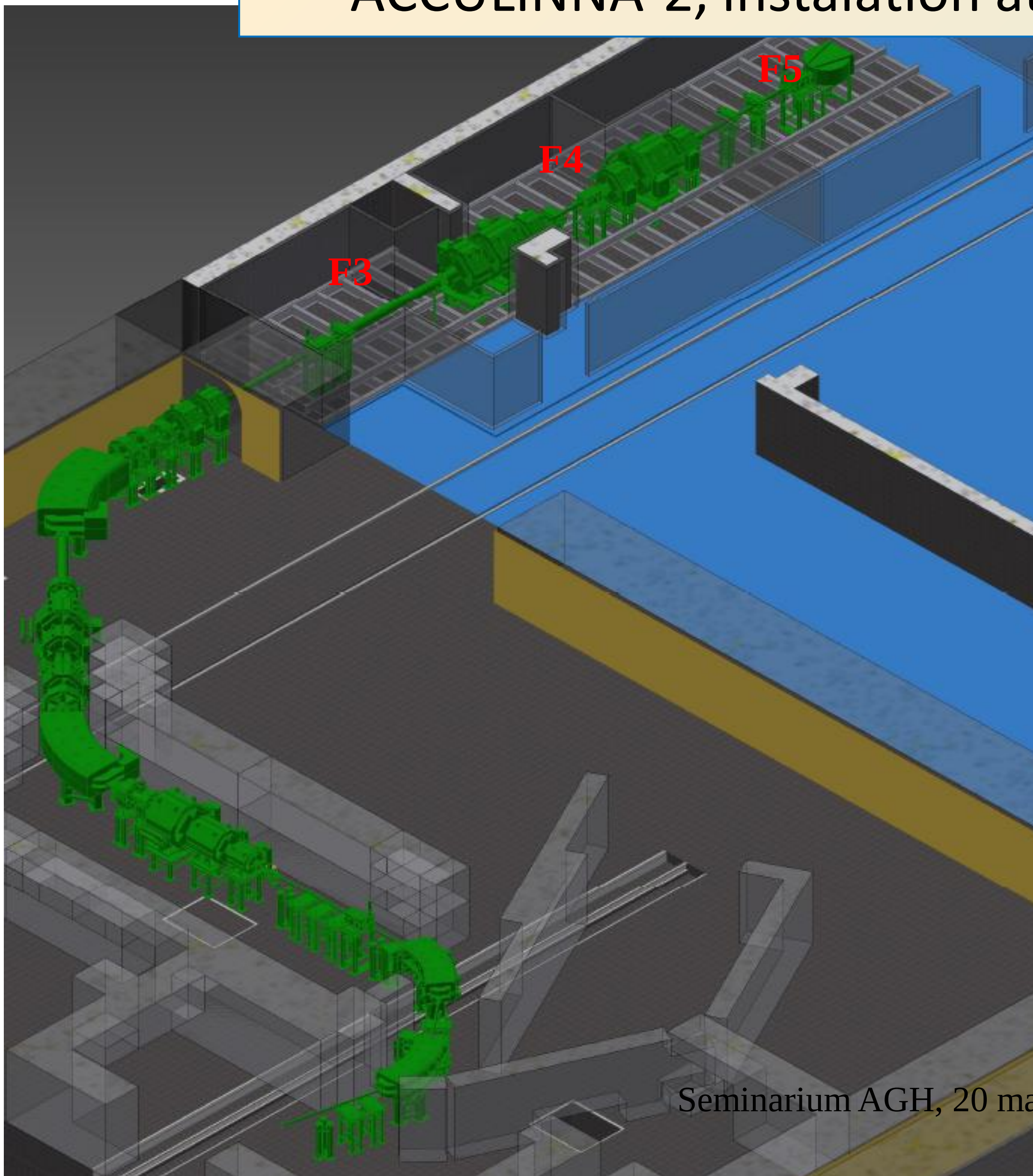
Magnets: some big ones

ACCULINNA-2, instalation of the sections F1-F2

January 2015

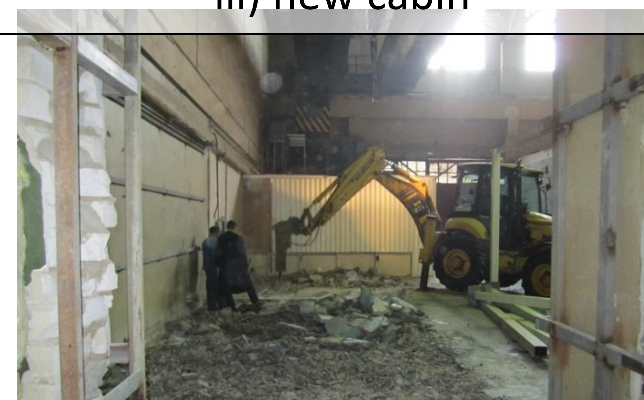
Installation process:
i) all magnets and vacuum chambers in the cyclotron hall;
ii) power supplies

ACCULINNA-2, instalation at the experimental hall



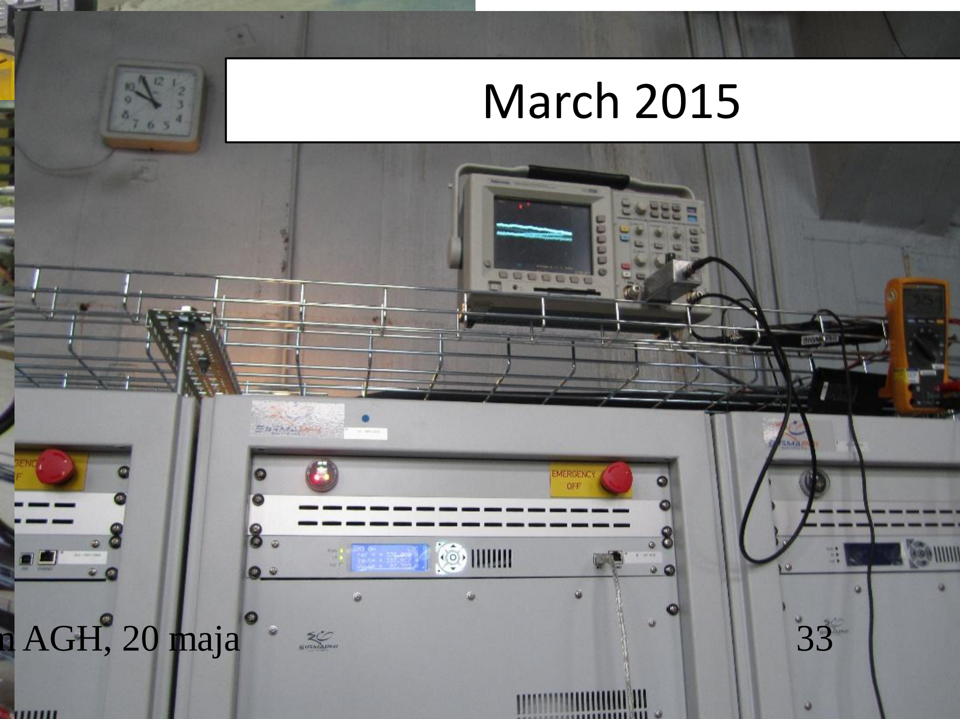
February - March 2015

Installation in F3-F5 area:
i) floor reinforcement
ii) rest magnets & communications
iii) new cabin



ACCULINNA-2, instalation of the section F3 – F5

Vacuum test and first measurements of magnetic fields of the magnets
↓↓
Certificate of Acceptance



March 2015

AGH

ACCULINNA-2: plans for 2016-2017

Proposed scenario

first-first runs:

Possibility to combine commissioning with short experiment @ relatively low RIB intensity

^{27}S; ^{23}Si experiment with OTPC – P(β2p), P(β3p); search for β-^{3}He radioactivity

^{26}S study via ^{28}S(p,t)^{26}S – observation, levels, $T_{1/2}$ **0**

First day experiments:

Maximum advantages of the new separator @ high RIB intensity, average exposure, experience

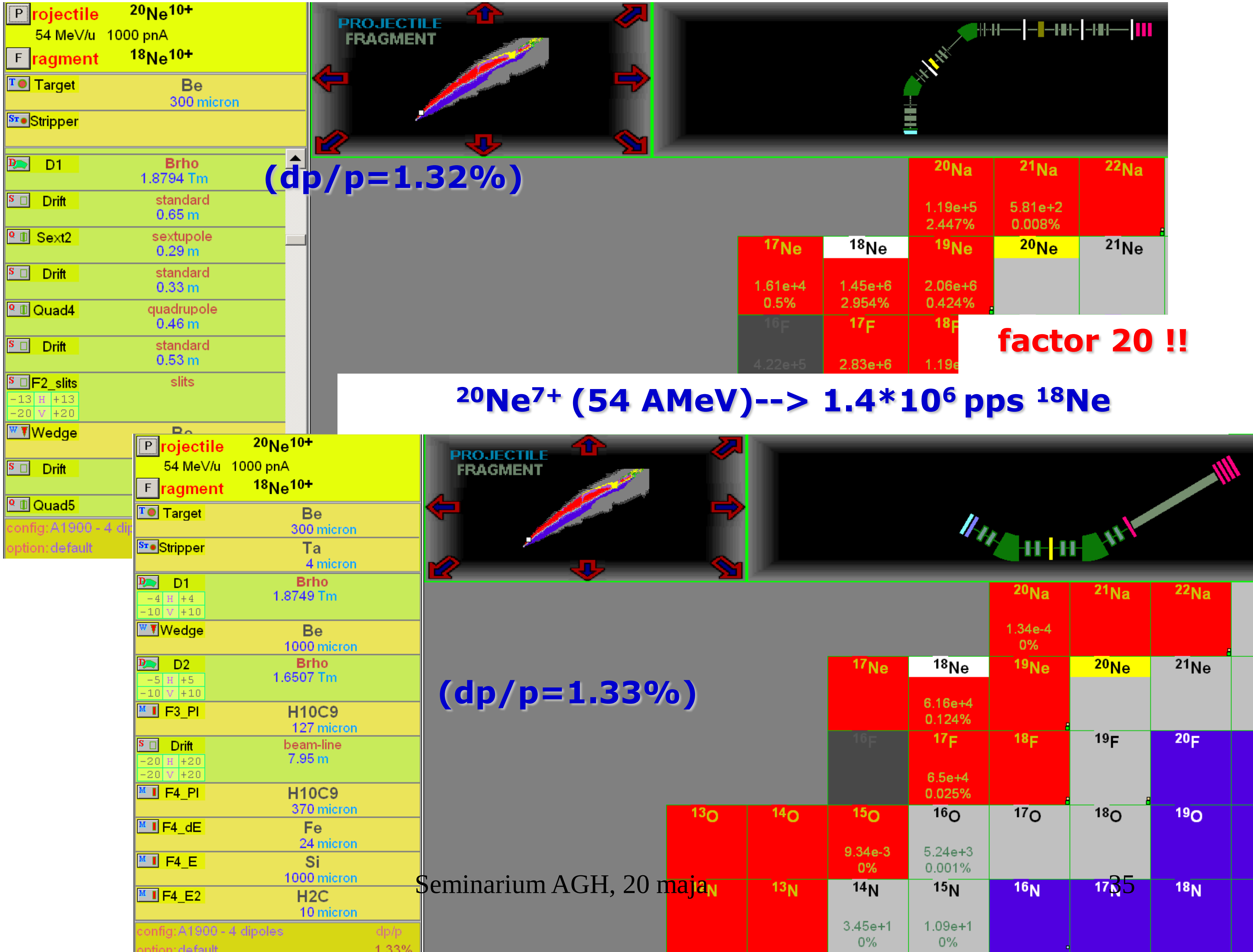
^{17}Ne via ^{18}Ne(p,d)^{17}Ne* – 2p decay for $3/2^{-}$, combined mass
^{16}Ne via ^{18}Ne(p,t)^{16}Ne – level structure, missing mass
^{7}H populated in QFS ^{11}Li(α,2α)^{7}H - observation, E and Γ of the ground state **1**
^{10}Li via ^{11}Li(p,d)^{10}Li E and Γ for ground state, combined mass

Future plans (company with tritium target):

Maximum advantages of the new separator @ high RIB intensity, very long exposure, experience , T-target

^{10}He via ^{8}He(t,p)^{10}He – level structure, decay modes, combined mass
^{16}Be via ^{14}Be(t,p)^{16}Be – level structure, decay modes, combined mass **2**

ACCULINNA-2: beam intensity ~20 time more than@ACCULINA



ACCULINNA-2: Summary and outlook

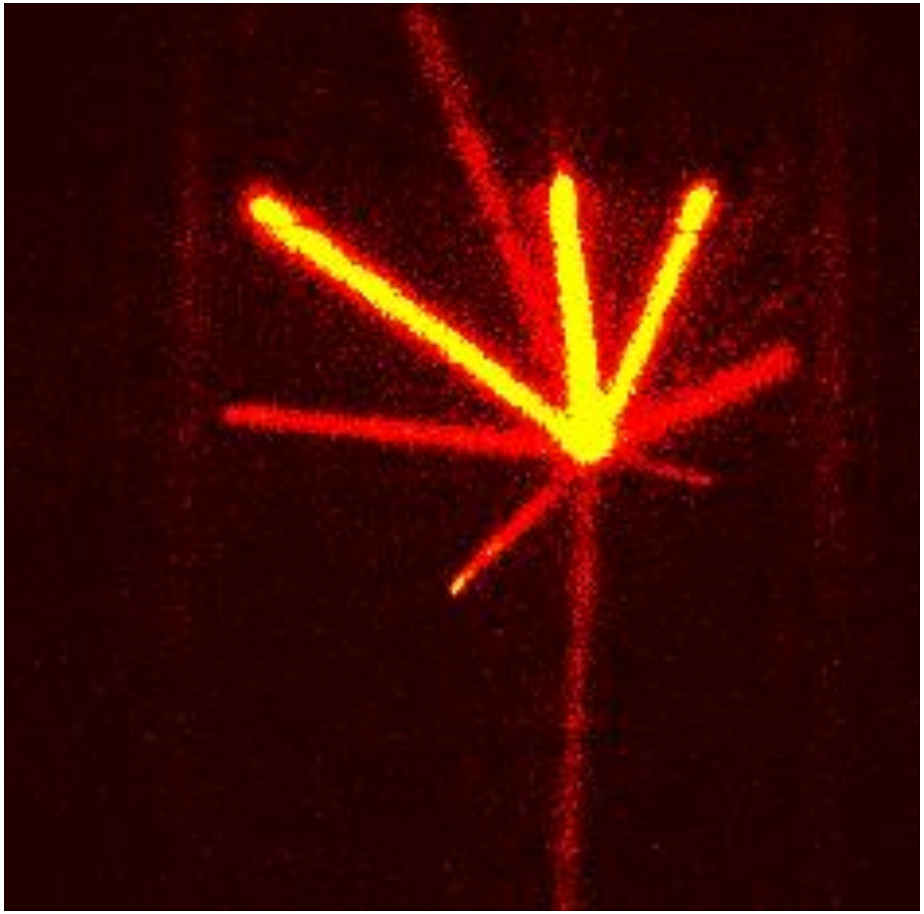
"Acculinna-2" will be put into operation in the end 2016 and first experiments with radioactive beams will be possible.

The scientific program implies an extensive use of advantages of low energy RIB's (E~10-50A MeV), and cryogenic gaseous targets (including tritium) for the study of exotic nuclei with $Z \leq 36$.

Intense radioactive beams available at the new facility will allow us to use experimental approaches developed earlier in studies of ^{4,5}H, ^{6}Be, ^{6,8,9,10}He at the "ACCULINNA" fragment-separator.

Experiments aimed at the studies of the structure of proton rich-nuclei ^{16,17}Ne, ^{19}Mg, ^{23}Si, ^{26,27}S and extremely neutron rich isotopes like ^{7}H, ^{10}He, ^{11}Li, ^{14}Be,^{19}C are foreseen.

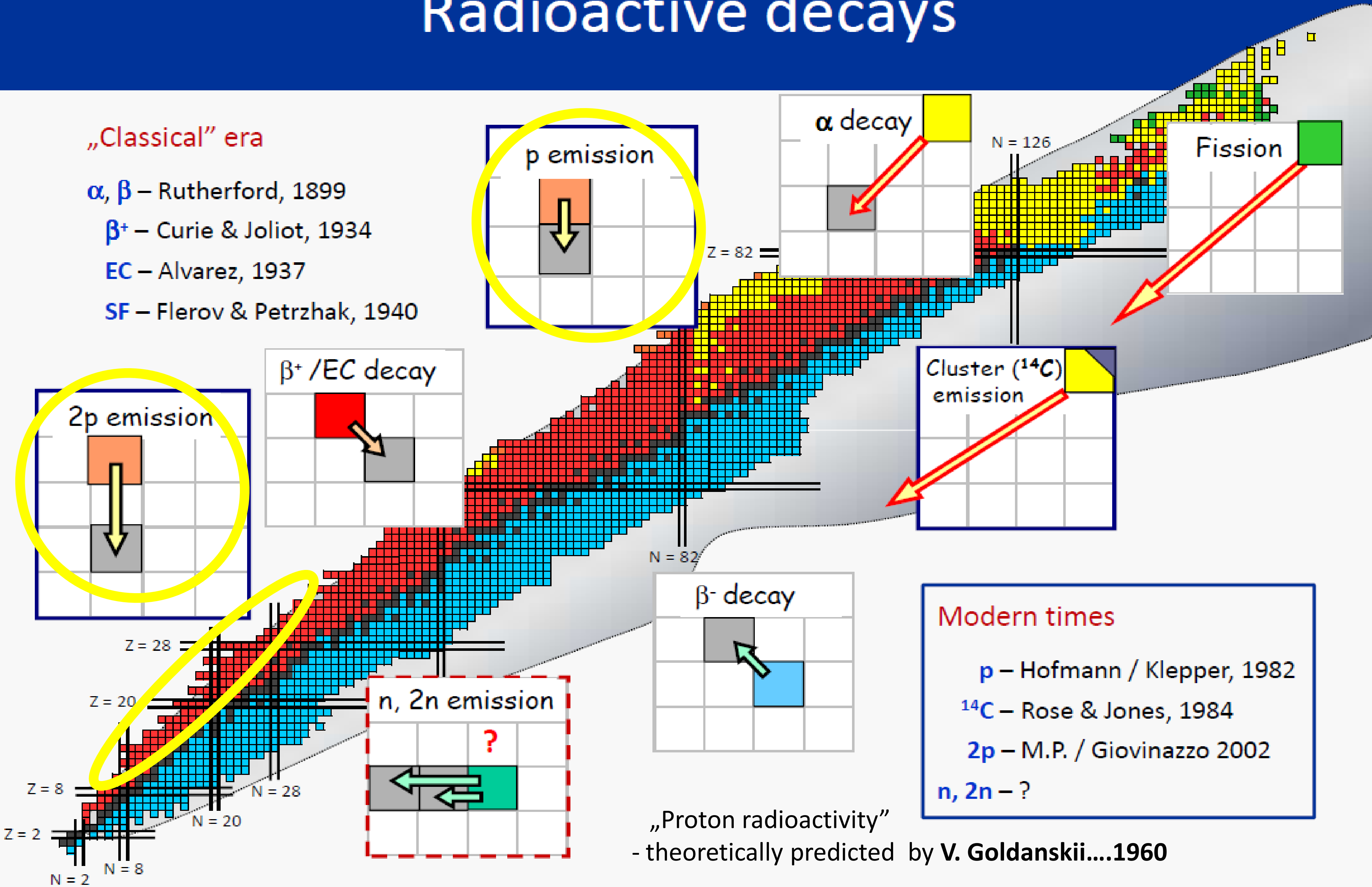
β-delayed particle emission



Radioactive decays

„Classical" era

- α, β – Rutherford, 1899
- β^+ – Curie & Joliot, 1934
- EC – Alvarez, 1937
- SF – Flerov & Petrzhak, 1940

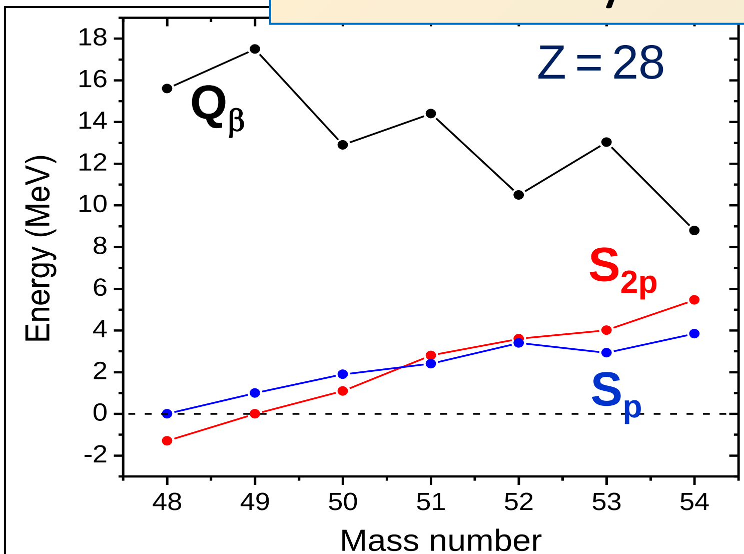


Modern times

- p – Hofmann / Klepper, 1982
- ^{14}C – Rose & Jones, 1984
- 2p – M.P. / Giovinazzo 2002
- n, 2n – ?

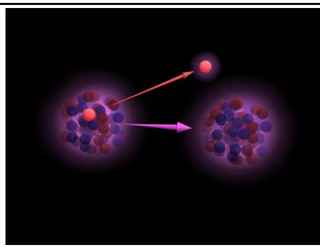
„Proton radioactivity"
- theoretically predicted by **V. Goldanskii….1960**

Radioactivity at the nuclear drip-lines (proton-rich nuclei)

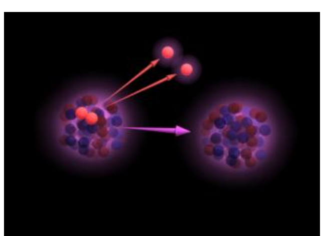


When the β-decay energy is large, many exotic channels are available:

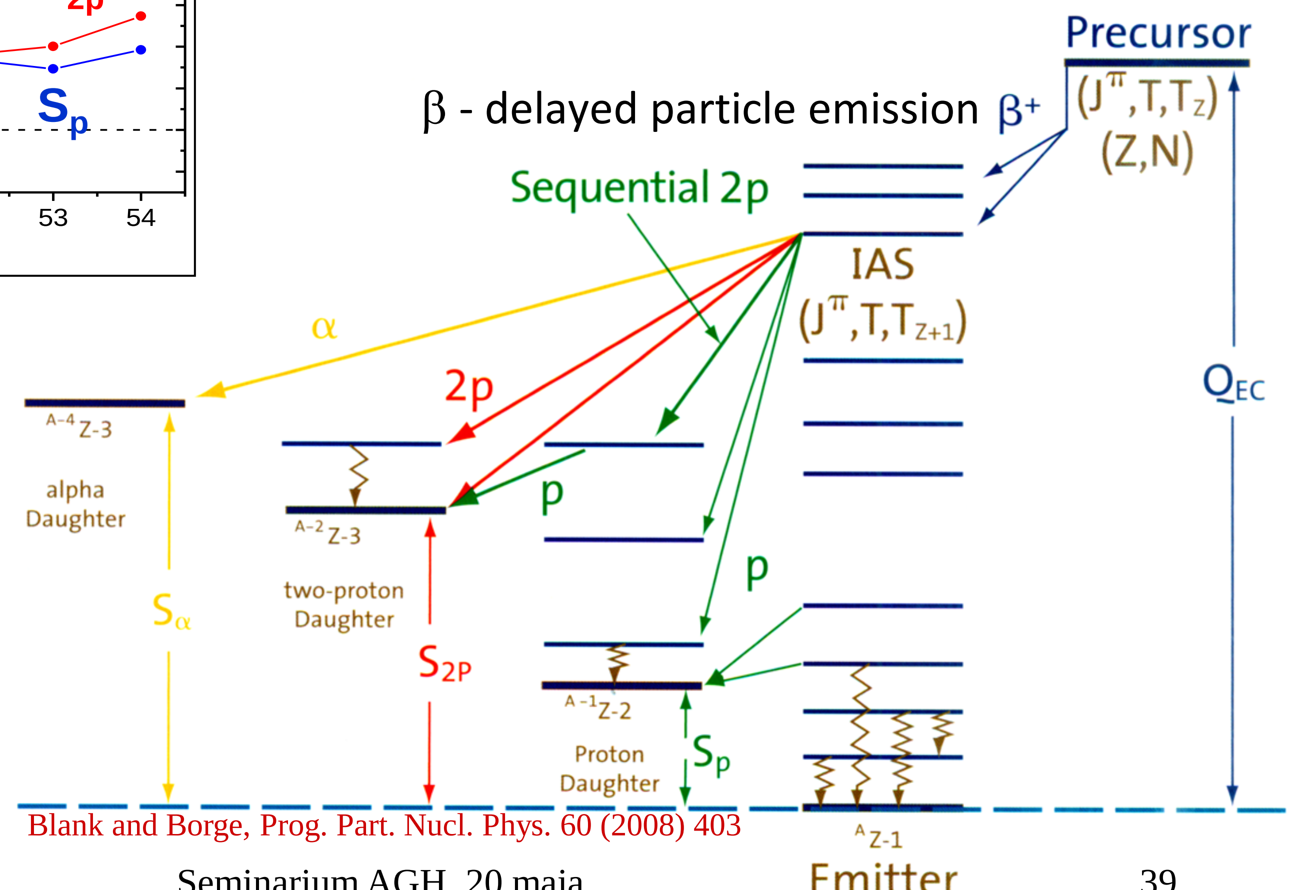
- exotic decay modes (1p, 2p radioactivity)
- multiparticle β-delayed particle emission



1 proton emission



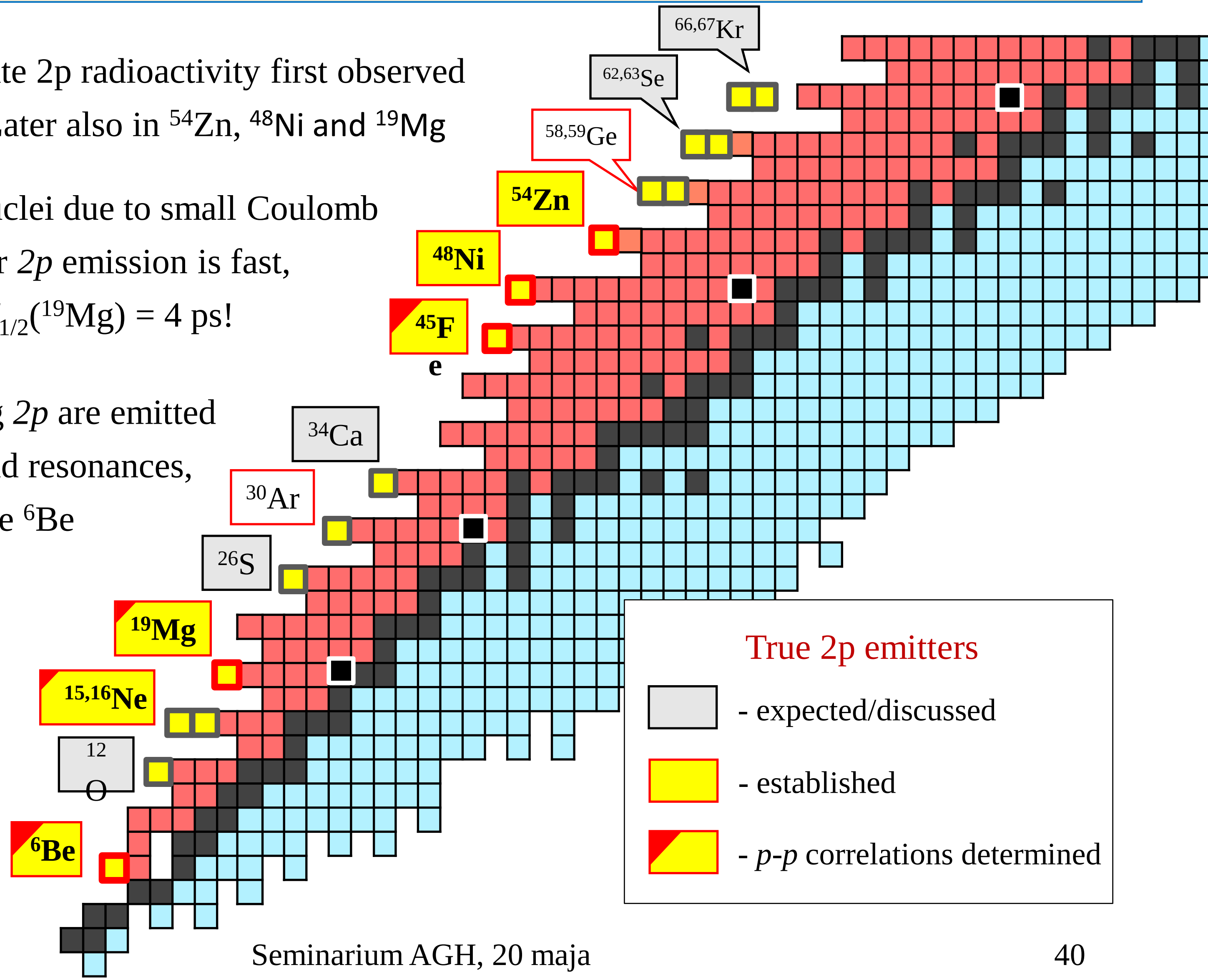
2 protons emission



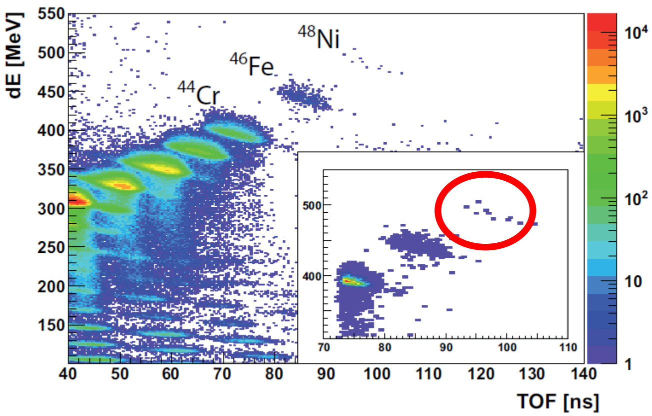
Blank and Borge, Prog. Part. Nucl. Phys. 60 (2008) 403

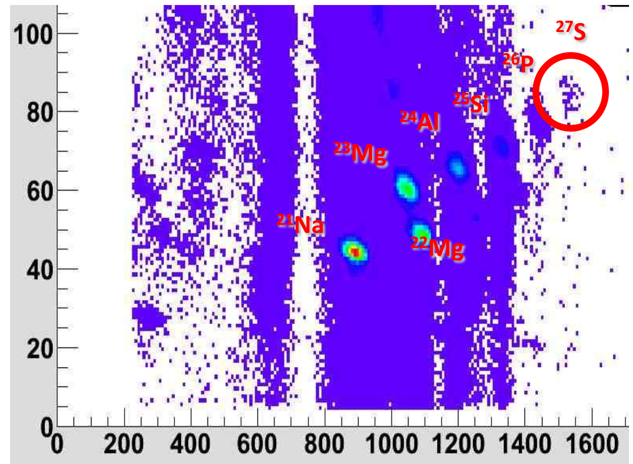
The current status of *2p* emission

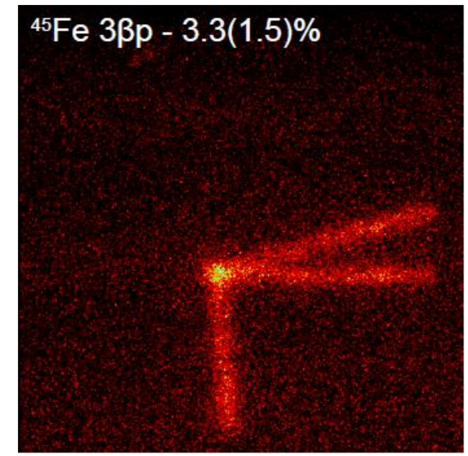
- Ground-state 2p radioactivity first observed in ^{45}Fe. Later also in ^{54}Zn, ^{48}Ni and ^{19}Mg
- In lighter nuclei due to small Coulomb barrier *2p* emission is fast, $T_{1/2}(^{19}\text{Mg}) = 4$ ps!
- Below ^{19}Mg *2p* are emitted from broad resonances, like ^{6}Be



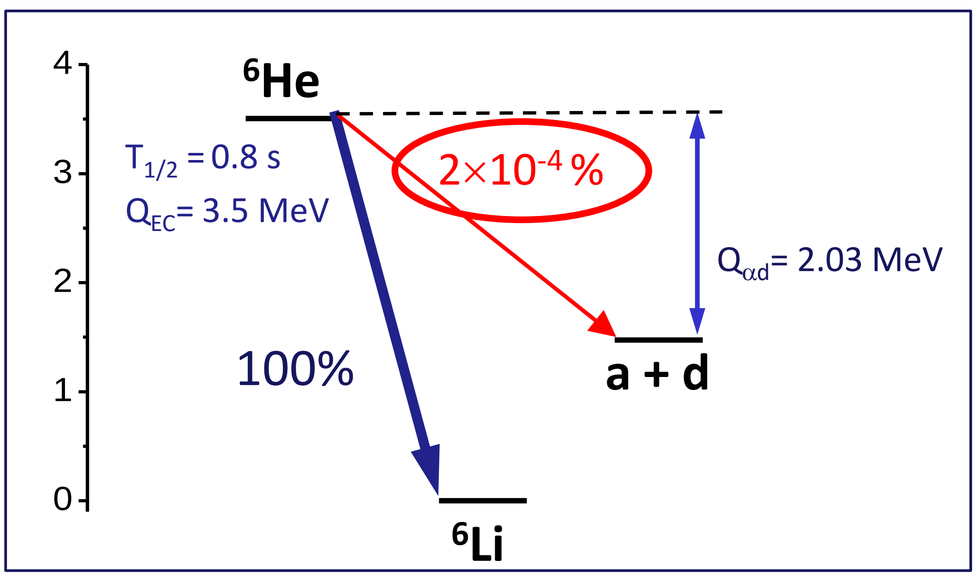
Challenges in spectroscopic studies of drip-line nuclei

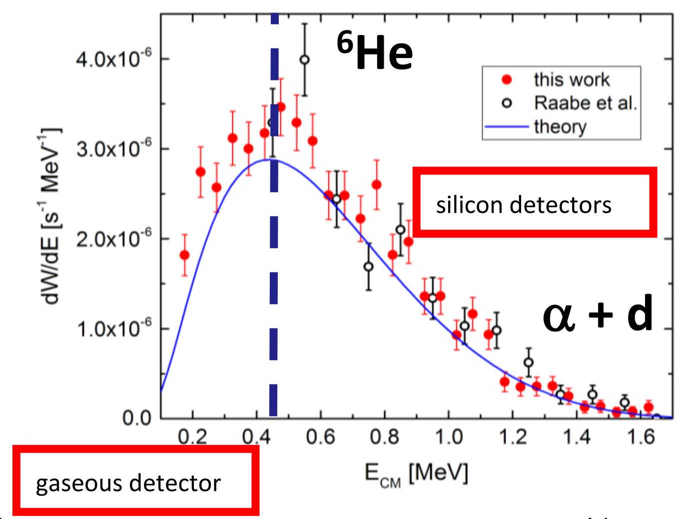






- low production rates
- high background level
- need for particle correlation measurements

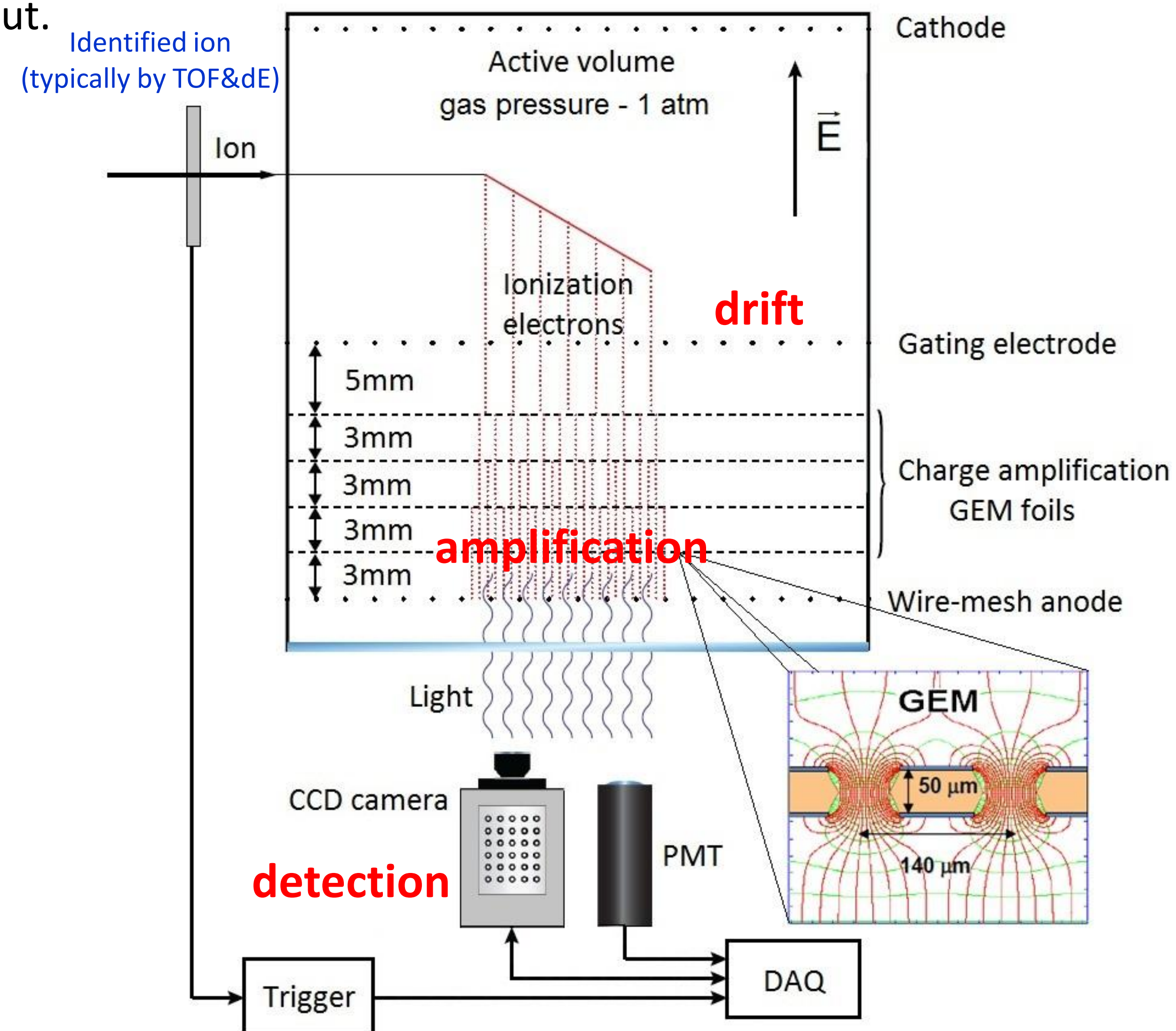




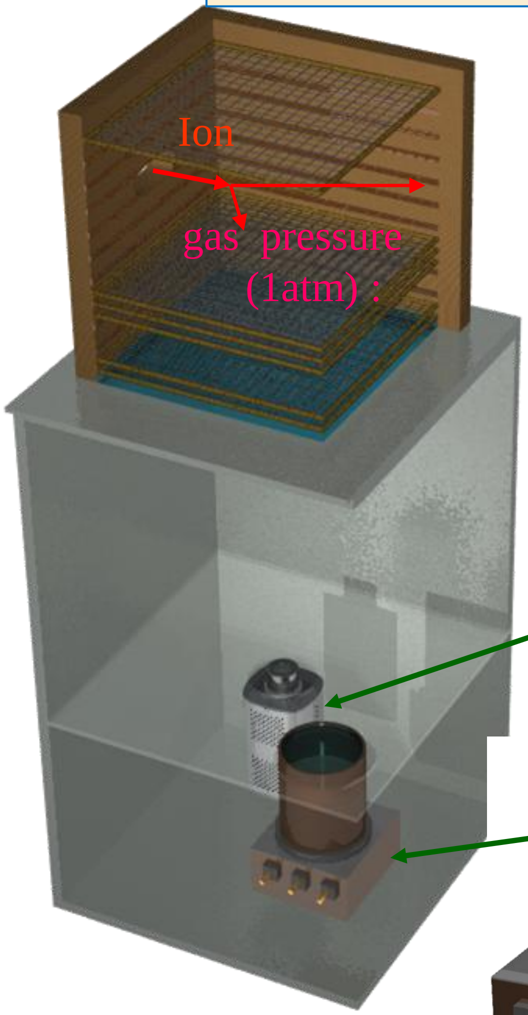
- small branching ratios
- need for low energy particle detection

Experimental tool - Optical Time Projection Chamber

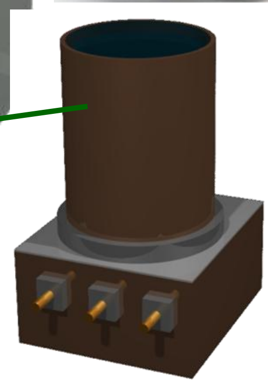
Optical Time Projection Chamber (OTPC) - A new type of modern ionization chamber with an optical readout.



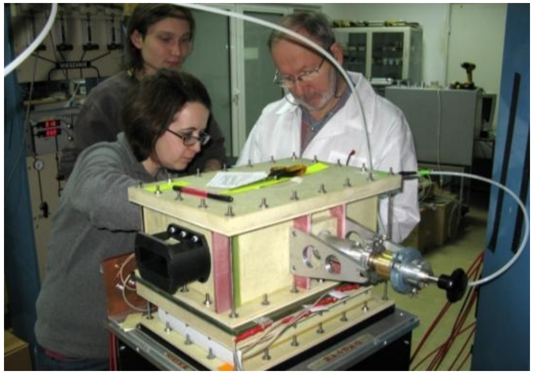
Optical Time Projection Chamber



CCD 2/3”
- 512 × 512 pix
- 14-bits
- image ampl. (× 1200)

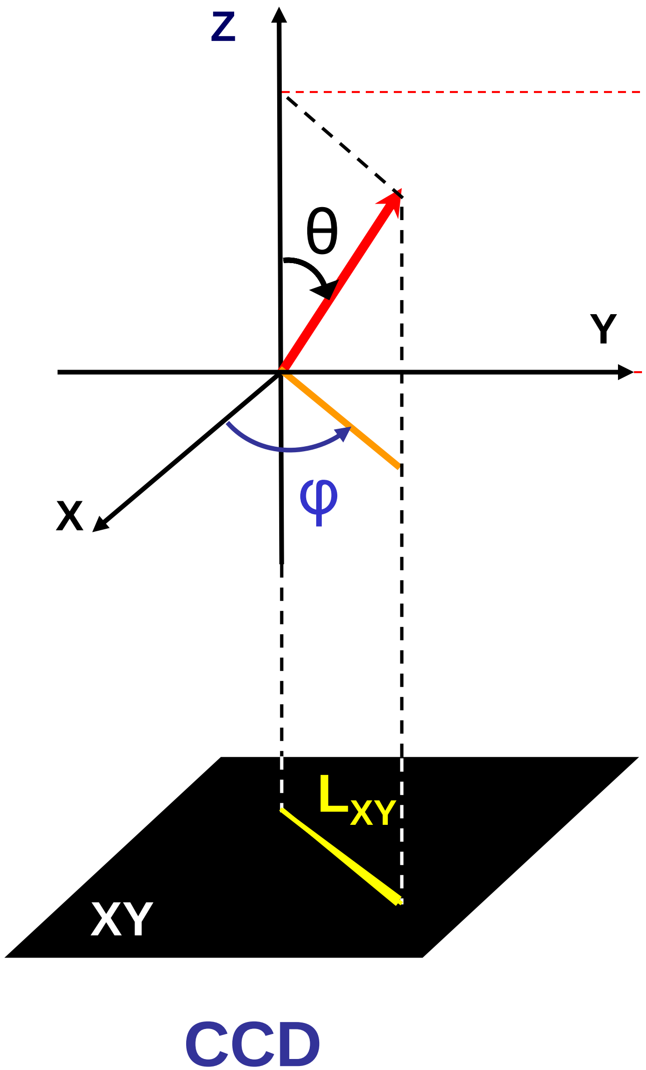


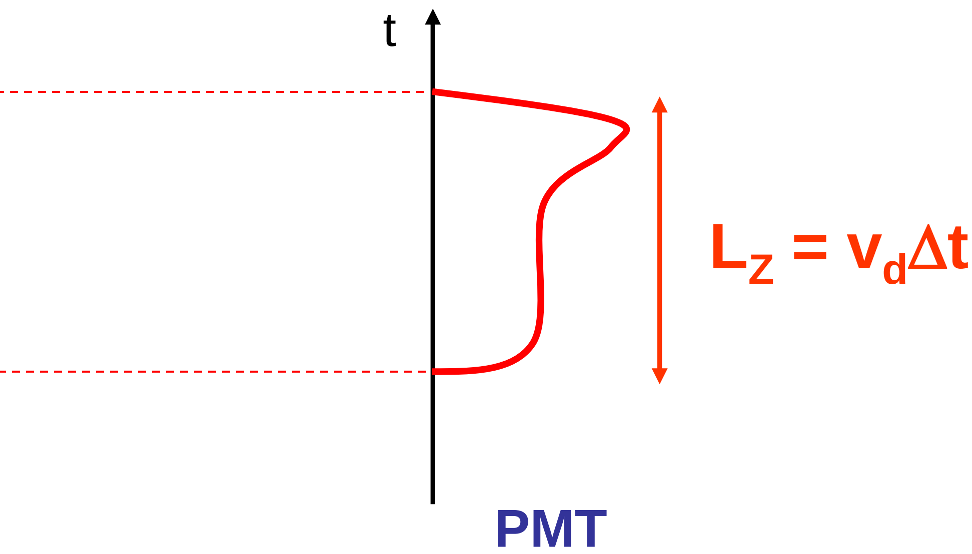
PMT 5”



M. Ćwiok et al., IEEE TNS, 52 (2005) 2895
K. Miernik et al., NIM A581 (2007) 194

Experimental tool - Optical Time Projection Chamber





Track coordinates (r, Θ, φ)

$$L_{XY} = r \sin\Theta$$

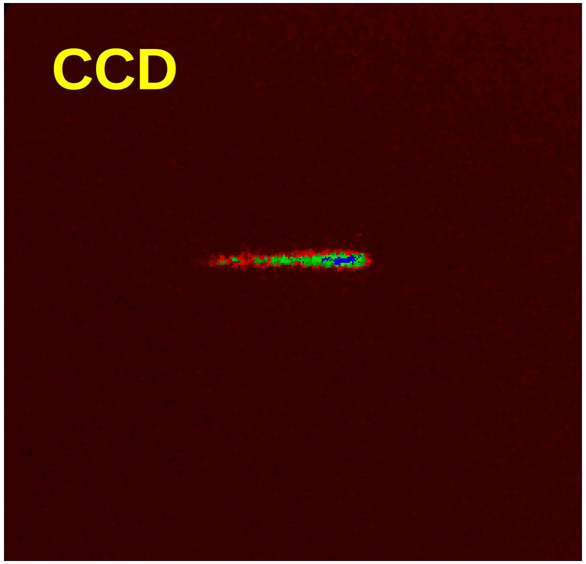
$$L_Z = r \cos\Theta$$

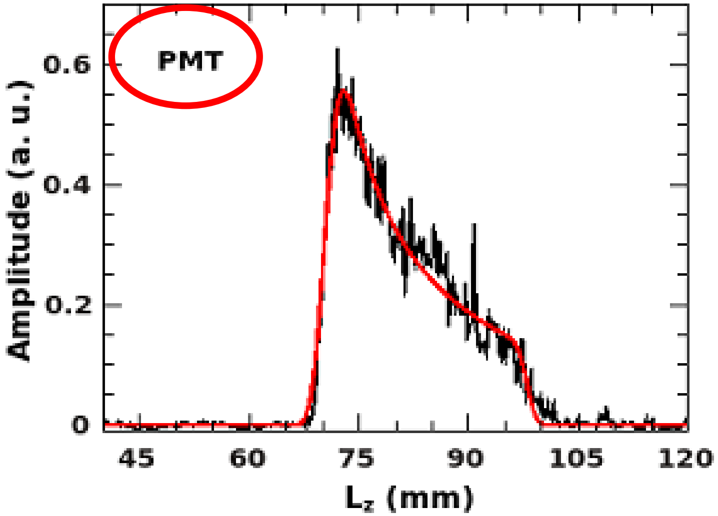
$$r^2 = L_{XY}^2 + L_Z^2$$

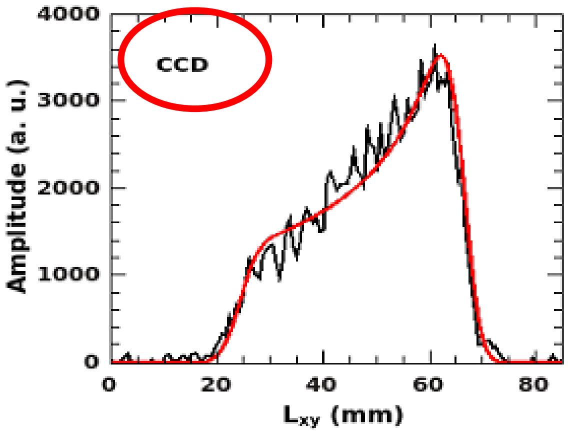
$$\Theta = \arctan(L_{XY}/L_Z)$$

Experimental tool - Optical Time Projection Chamber

- tracks are reconstructed by fitting the data with SRIM simulations







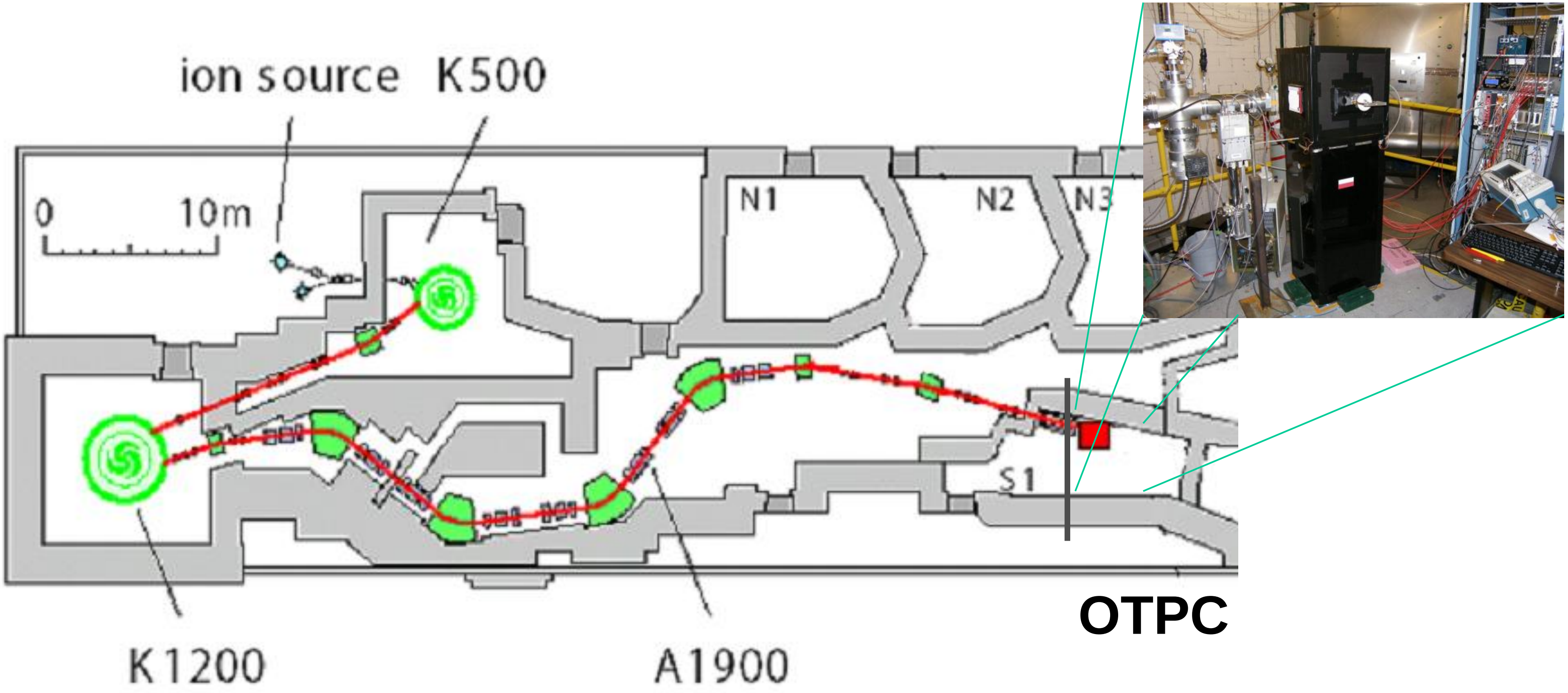
E_α = 4.7 MeV

θ_α = 123°

Experiments

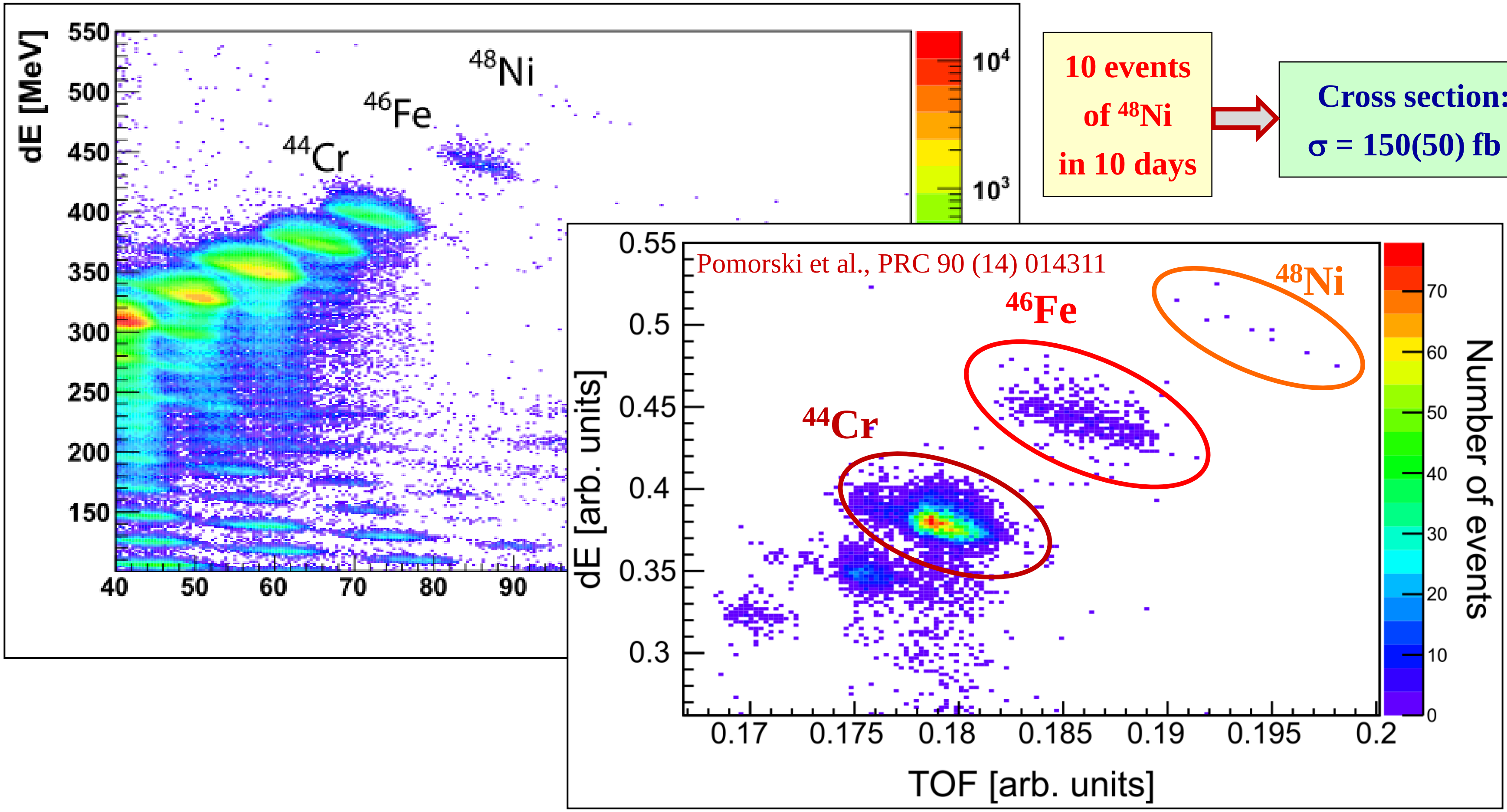
Study of ^{48}Ni with OTPC at NSCL/MSU

- NSCL/MSU, March 2011: ^{58}Ni at 160 MeV/u + ^{nat}Ni → ^{48}Ni



Study of ^{48}Ni

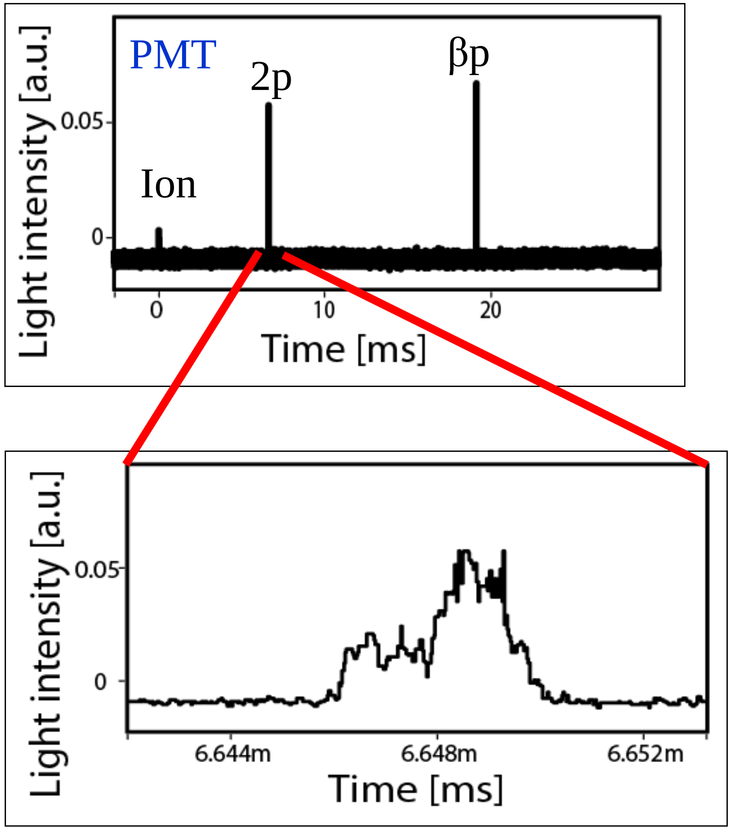
- NSCL/MSU, March 2011: ^{58}Ni at 160 MeV/u + ^{nat}Ni → ^{48}Ni



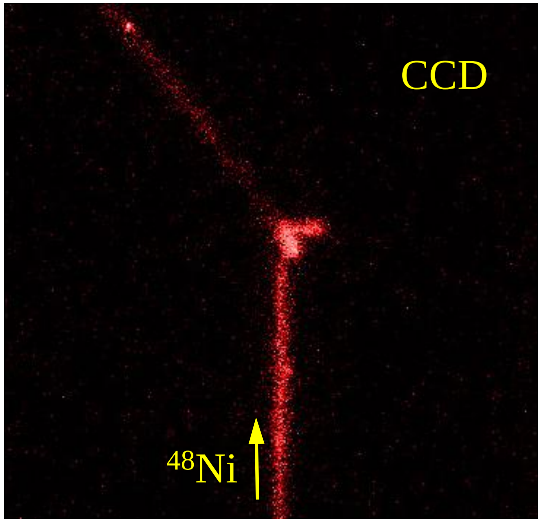
10 events of ^{48}Ni in 10 days

Cross section: σ = 150(50) fb !

Study of ^{48}Ni



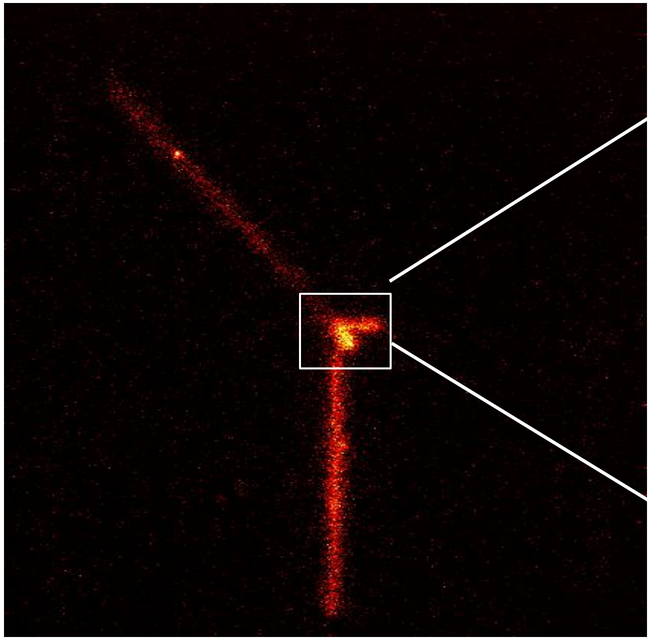
2p decay of ^{48}Ni

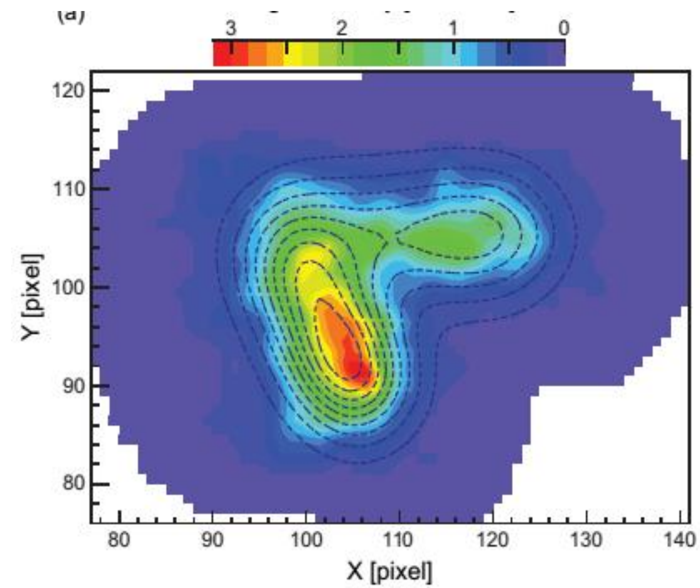


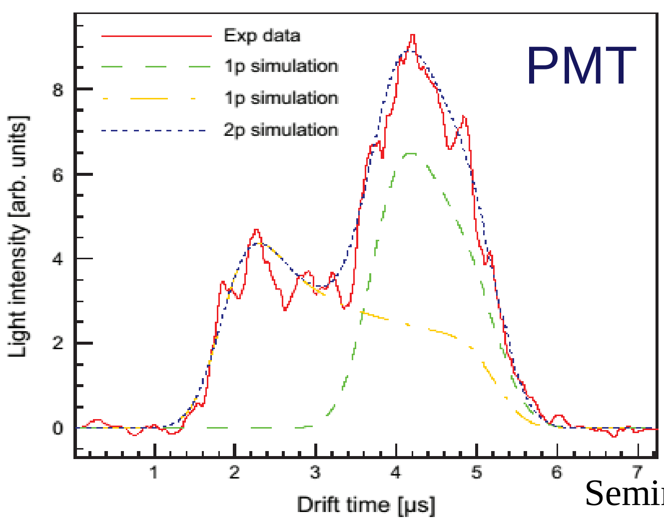
Pomorski et al., PRC 90 (14) 014311

Four 2p events of ^{48}Ni ⇒ Q_{2p} **= 1.29 (4) MeV**

Reconstruction of 2p decay event







E_{p1}= 580(60) keV
θ_{p1}= 117(7)°
φ_{p1} = 0

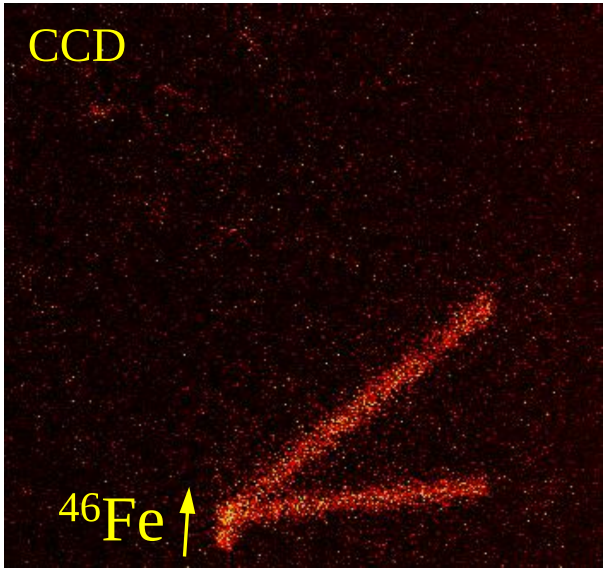
E_{p2}= 665(50) keV
θ_{p2}= 150(6)°
φ_{p2} = -60(7)°

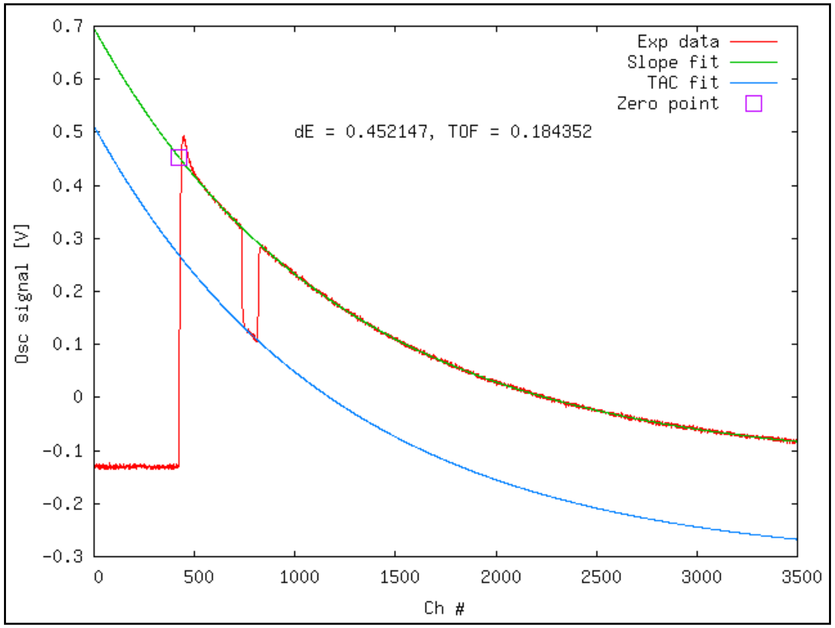
Q_{2p} = 1287(80) keV
θ_{pp} = 51(8)°

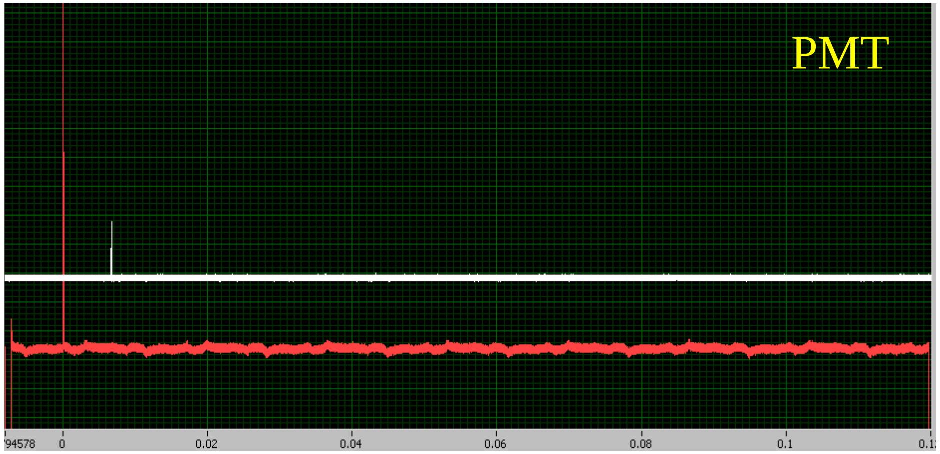
Pomorski et al., PRC 90 (14) 014311

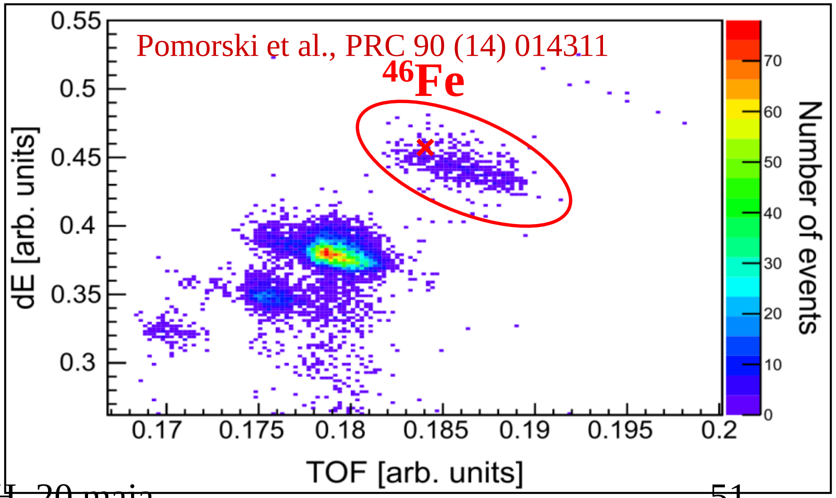
β2p channel in ^{46}Fe

- One good event!

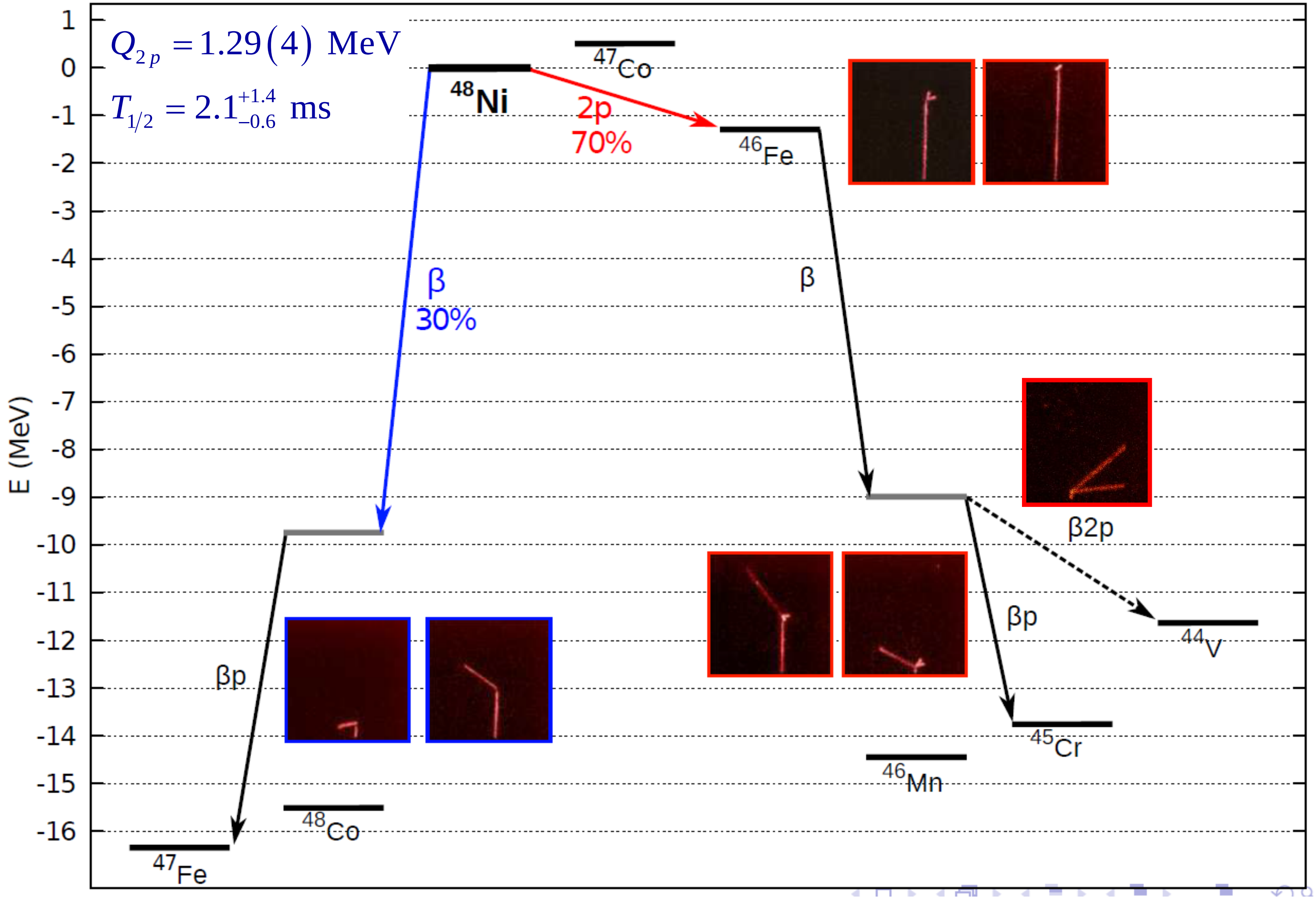




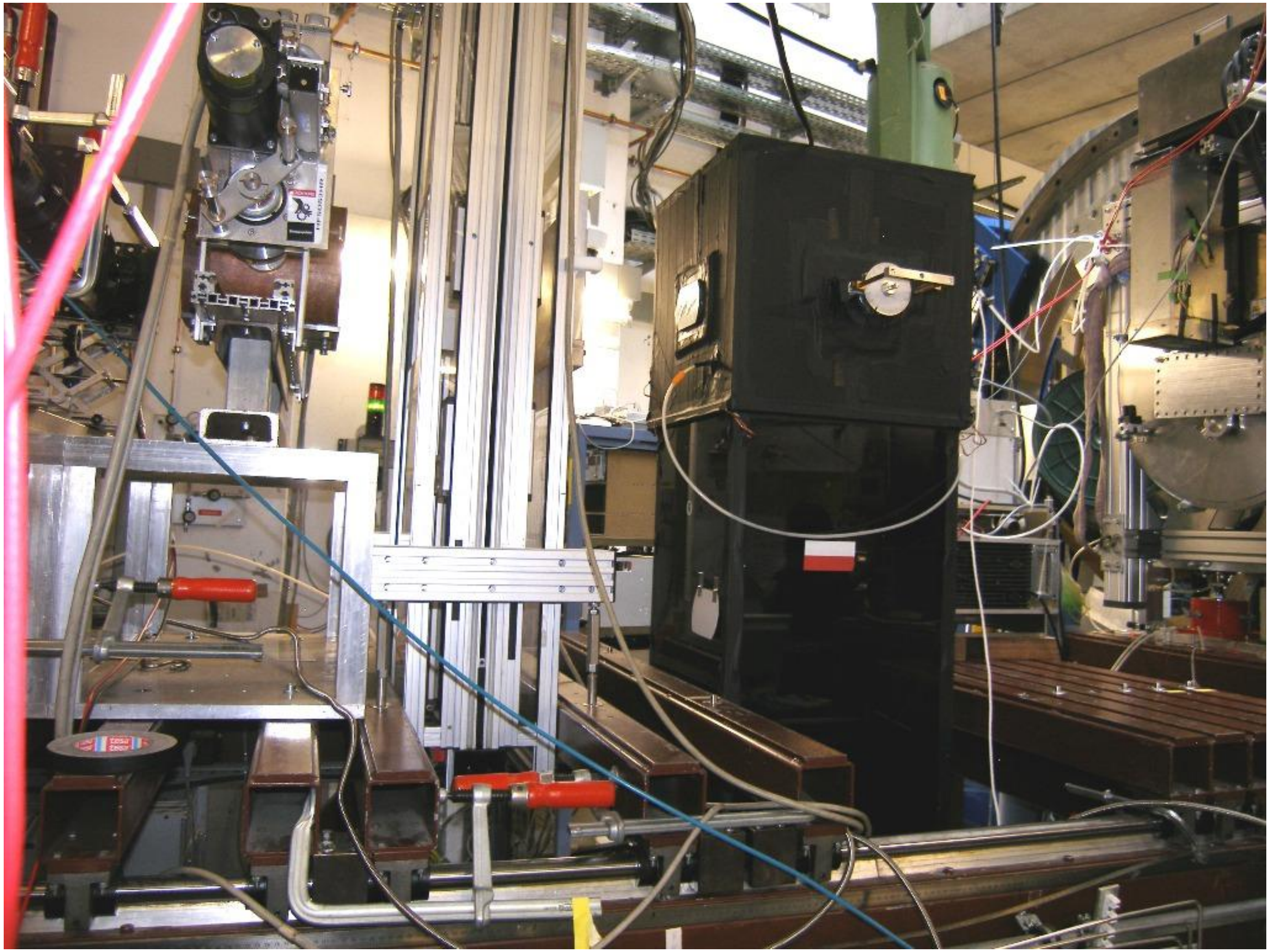




Decay scheme of ^{48}Ni



Study of ^{31}Ar @FRS/GSI



β3p in ^{31}Ar?

PHYSICAL REVIEW C VOLUME 45, NUMBER 1 JANUARY 1992

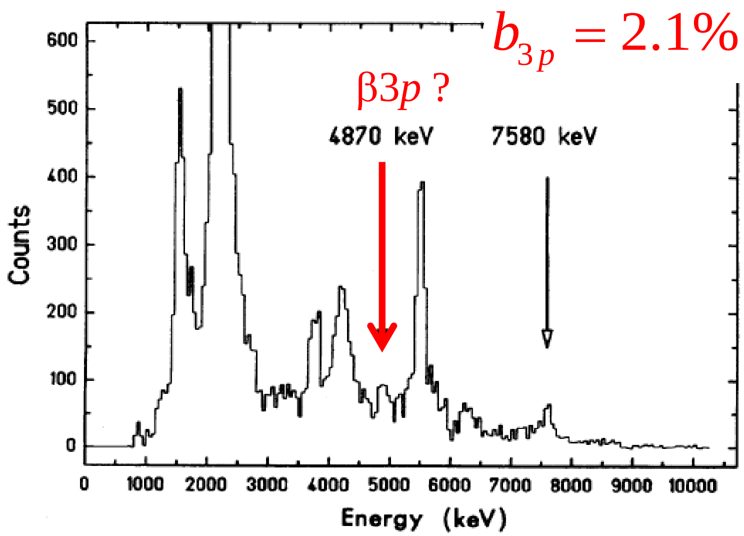
Decay modes of ^{31}Ar and first observation of β-delayed three-proton radioactivity

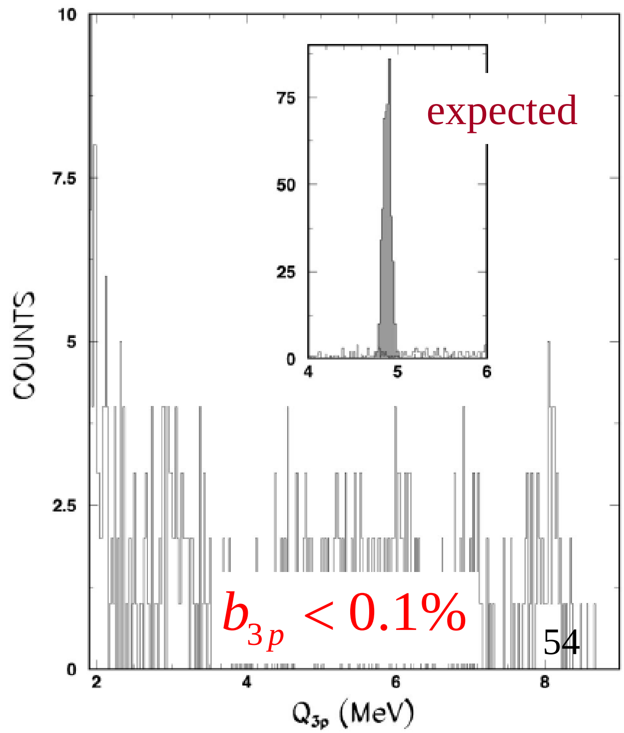
D. Bazin,* R. Del Moral, J. P. Dufour, A. Fleury, F. Hubert, and M. S. Pravikoff
Centre d'Etudes Nucléaires de Bordeaux–Gradignan, Le Haut Vigneau 33175 Gradignan CEDEX, France

PHYSICAL REVIEW C VOLUME 59, NUMBER 4 APRIL 1999

^{31}Ar examined: New limit on the β-delayed three-proton branch

H. O. U. Fynbo,[1] L. Axelsson,[2] J. Äystö,[3] M. J. G. Borge,[4] L. M. Fraile,[4] A. Honk
A. Jokinen,[3] B. Jonson,[2] I. Martel,[5,†] I. Mukha,[1,‡] T. Nilsson,[2,§] G. Nyman,[2] M. Oin
M. H. Smedberg,[2] O. Tengblad,[4] F. Wenander,[2] and the ISOLDE

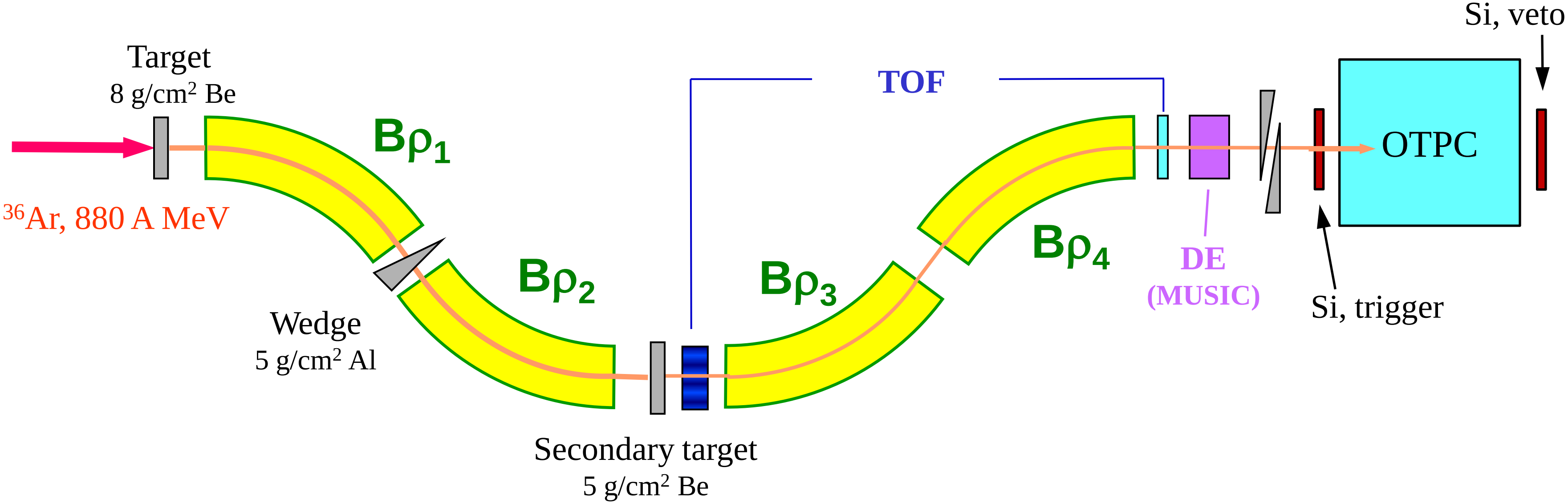


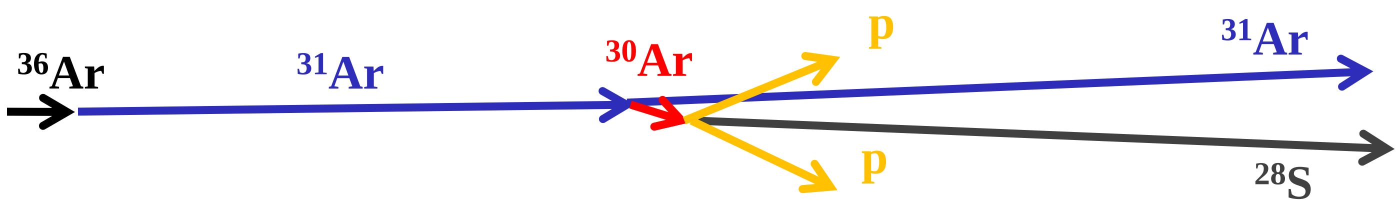


^{31}Ar @ the FRS

- Experiment at GSI-FRS, August 2012

"Search for two-proton decay of ^{30}Ar in flight by the tracking technique" by I. Mukha





- Many ^{31}Ar ions pass to the S4

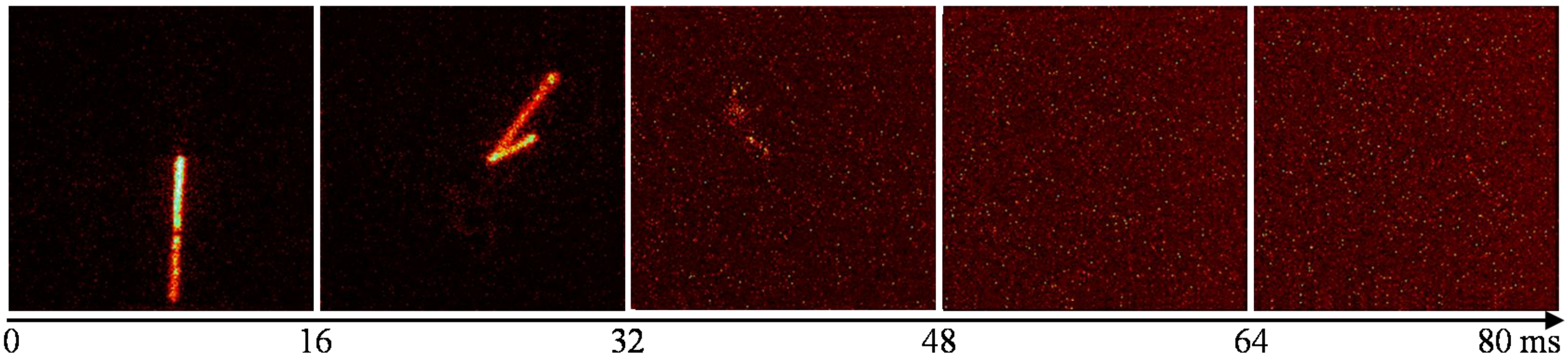
  An idea: stop them in the OTPC and search for β3*p* channel of ^{31}Ar

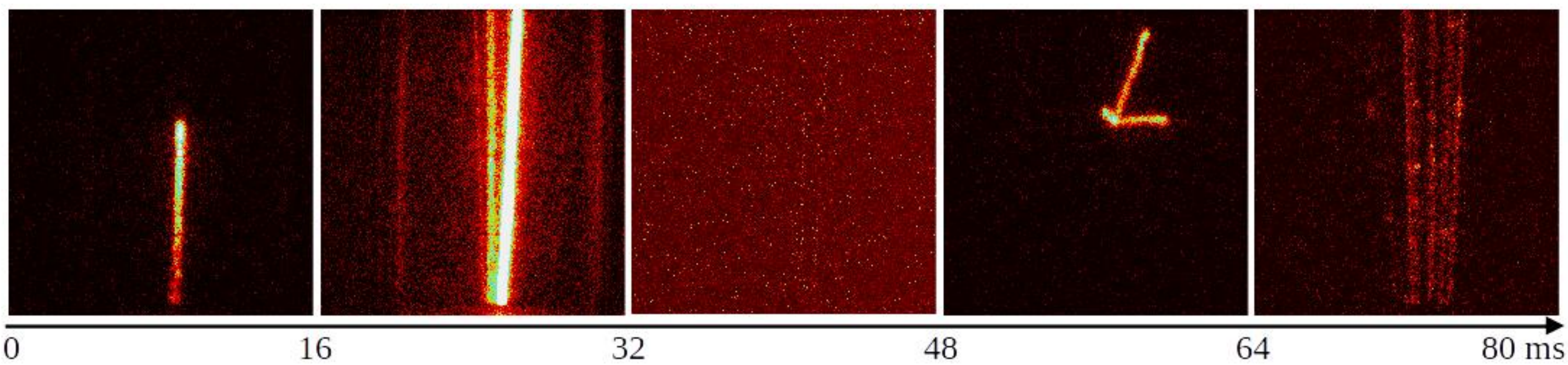
- With the beam of 10^{10} proj./spill we hoped for one ^{31}Ar atom/spill stopped.

  If spill every 4 s → 20 000/day

^{31}Ar @ theYes, β3p in ^{31}Ar! FRS

- A new acquisition mode – a series of shorter expositions („movie”)

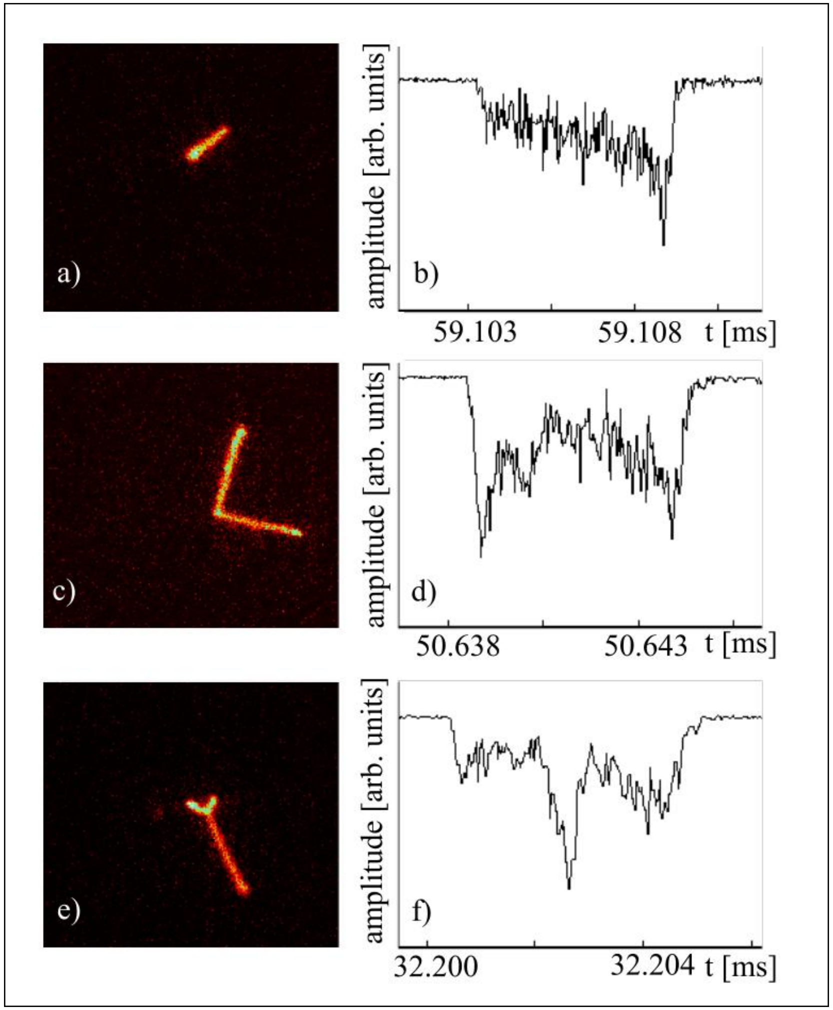




- Selection of events: in the first frame no other ions than well stopped ^{31}Ar present

21 000 events,
all inspected individually
by Ola Lis (now Ciemny)

β3p in ^{31}Ar



Lis et al., PRC 91, 064309 (2015)

- 13 events of β3p decay of ^{31}Ar was observed

TABLE I. The total branching ratios for the observed decays of ^{31}Ar. The given uncertainties are statistical.

Channel	Events	Branching [%]
$\beta 0p$	5984	$22.6(3)^a$
$\beta 1p$	13157	68.3(3)
$\beta 2p$	1729	9.0(2)
$\beta 3p$	13	0.07(2)

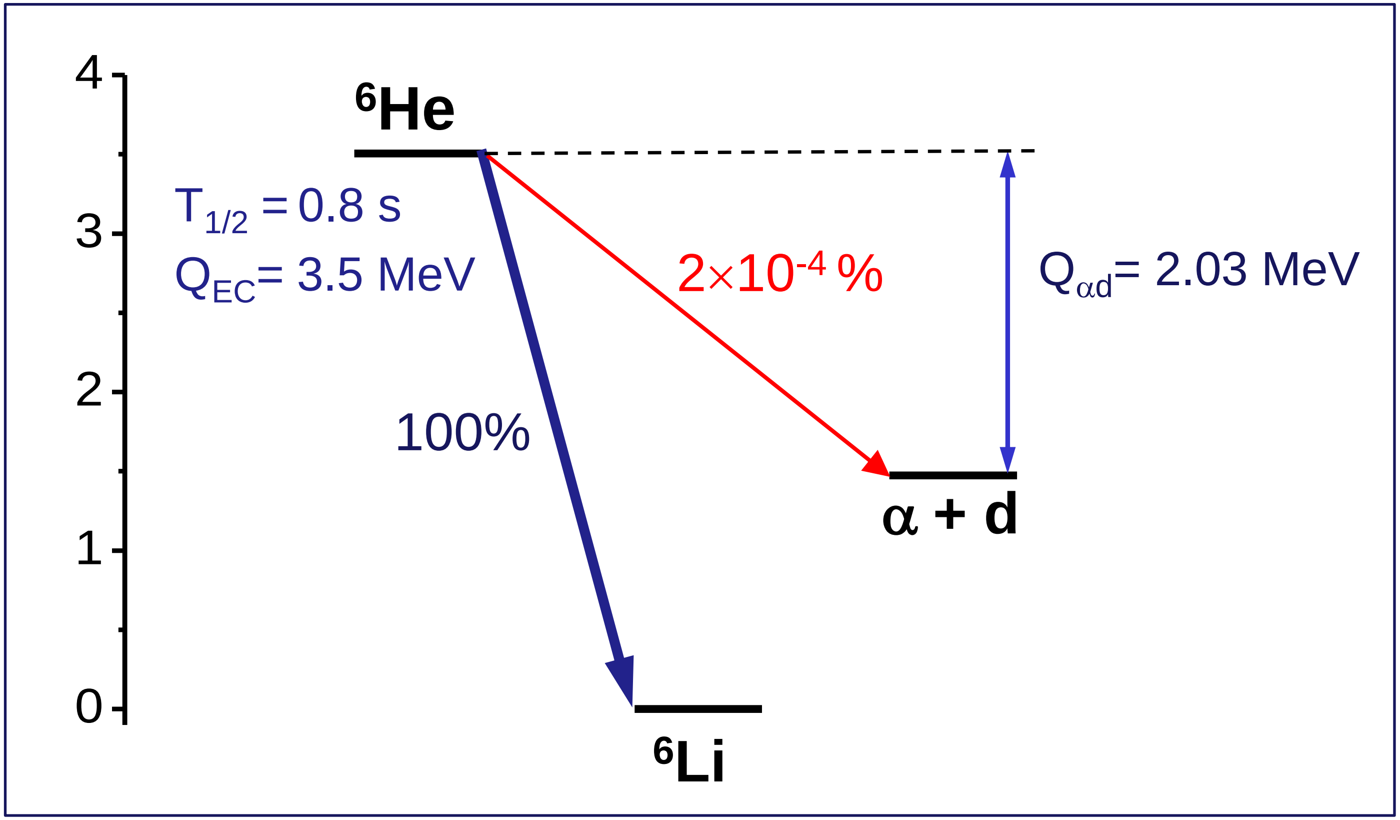
Only 3 cases of β3p known:

- ^{45}Fe (Miernik et al., PRC76, 2007)
- ^{43}Cr (Pomorski et al., PRC83, 2011)
- ^{31}Ar (Lis et al., PRC, 2015)

All discovered with the OTPC!

Study of ^{6}He @ REX ISOLDE/CERN

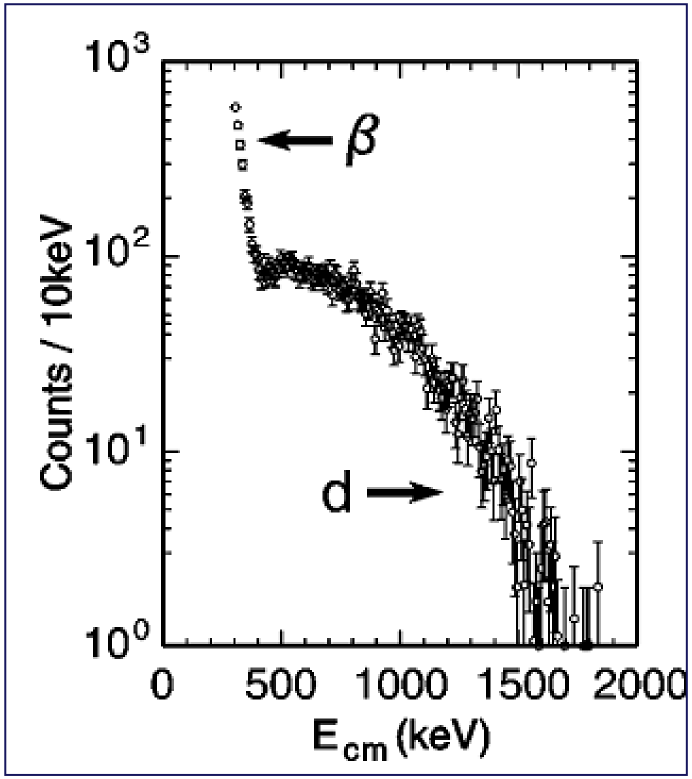
Decay scheme of ^{6}He

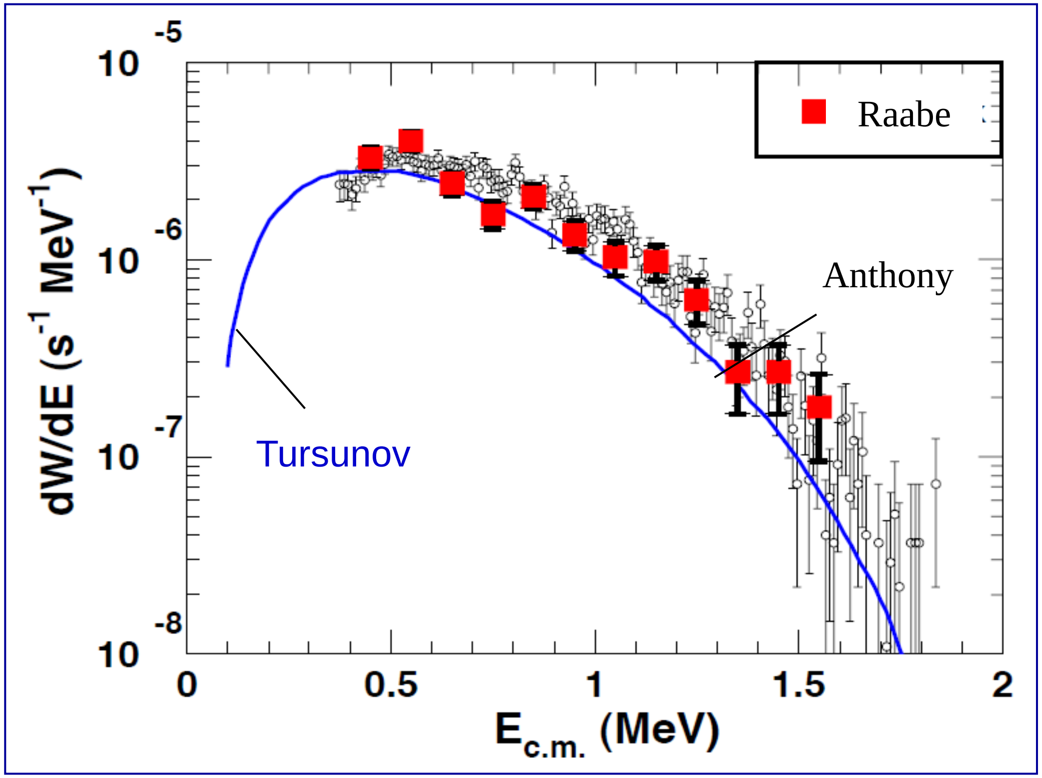


Very small branching for the α+d decay of ^{6}He results from the strong cancelation of the GT matrix elements from internal and external region.

The wave function has to be properly described up to 30 fm.

α+d energy spectrum





Detection threshold ~ 400 keV

E_{α}= 140 keV

E_d = 260 keV

D. Anthony at al. Phys. Rev. C(65) (2002)034310

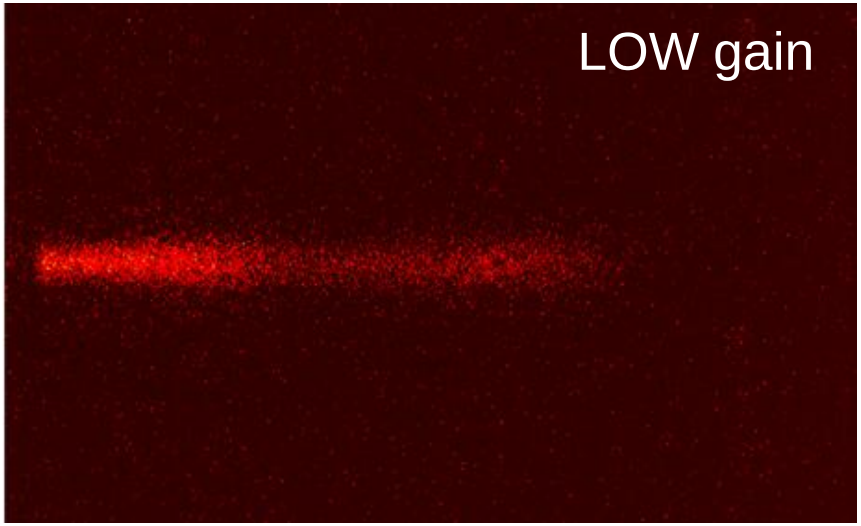
R. Raabe et al., Phys. Rev. C80 (2009) 054307

^{6}He decay studies at ISOLDE

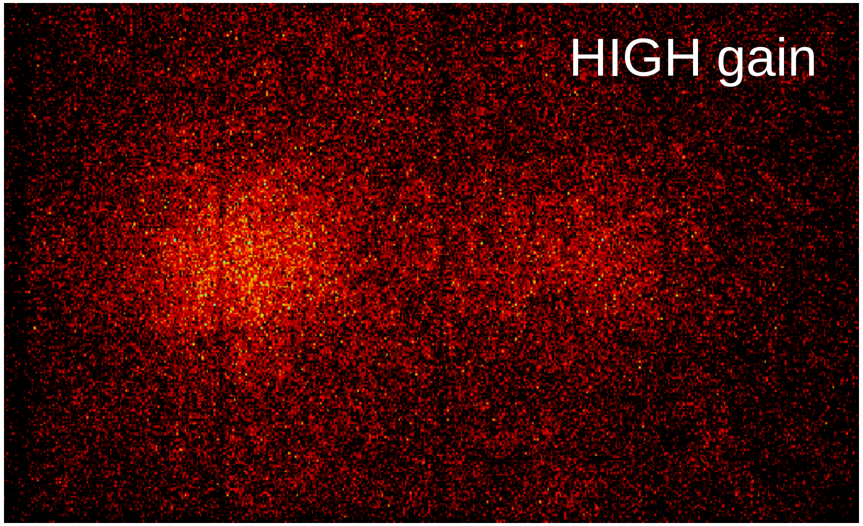
- 2.9 MeV/u ^{6}He beam from REX-ISOLDE

10^4 ^{6}He ions

150 ms bunch



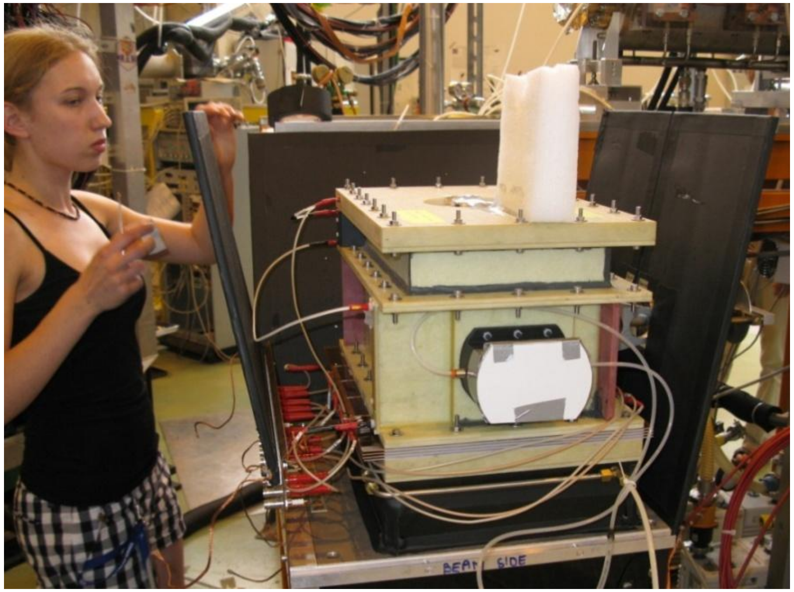
beta particles recorded during 650 ms exposure after the ^{6}He bunch.

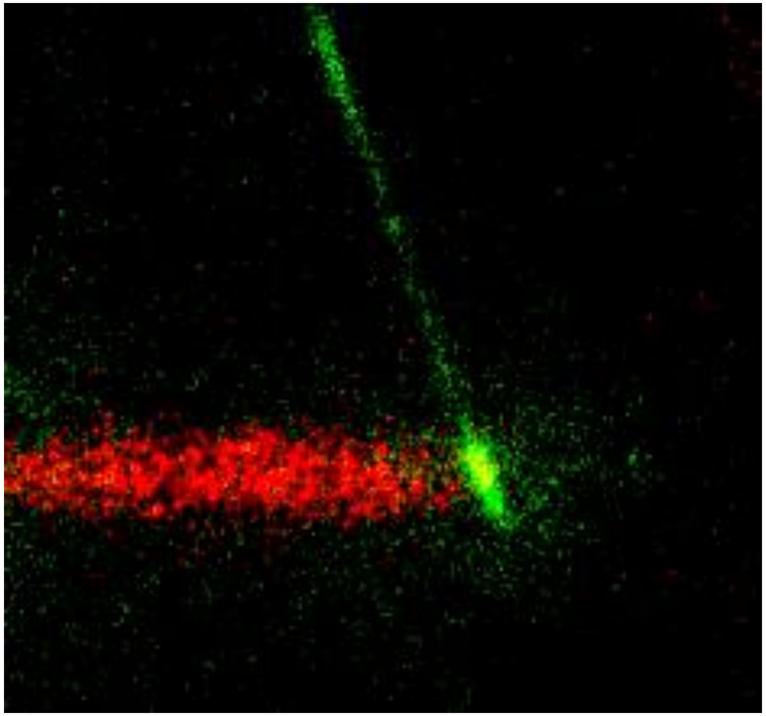


M. Pfützner et al., Phys. Rev. C, **92** (2015) 014316

Probing the 2n halo of ^{6}He

- Weak decay branch ($\approx 10^{-6}$) $^{6}He \rightarrow \alpha + d$ provides insight into the 2n halo of ^{6}He
- Bunches of ^{6}He ions were delivered by **REX-ISOLDE** and implanted into the OTPC
- Clear images of decay events with tracks of an α particle and a deuteron were recorded by a CCD camera



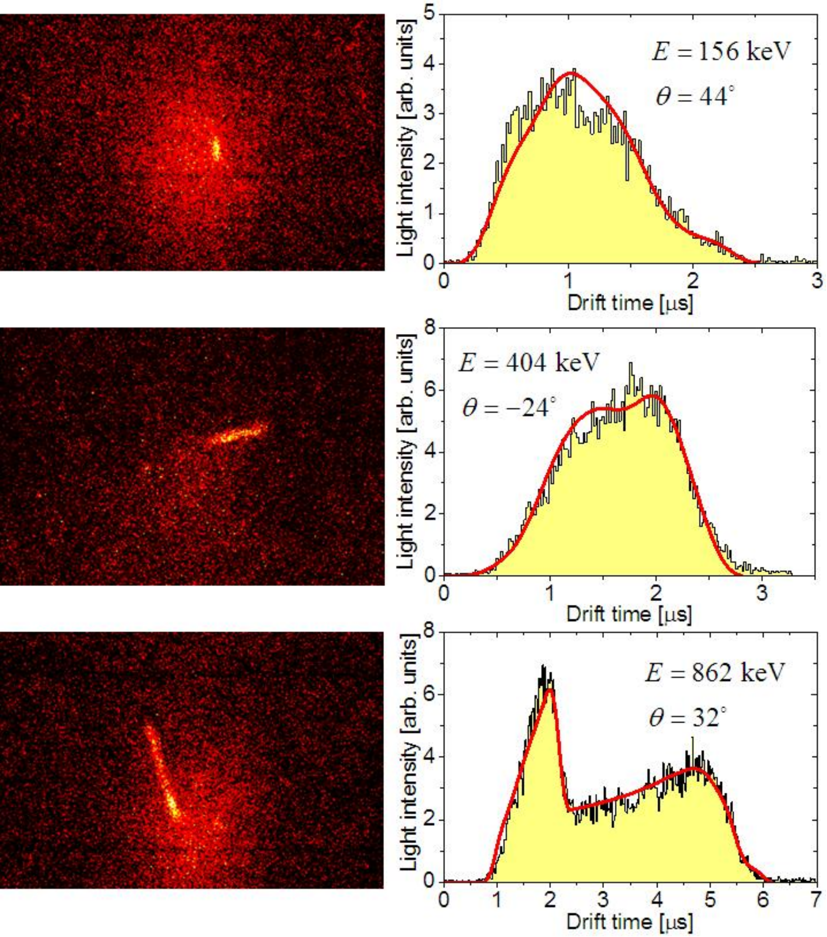


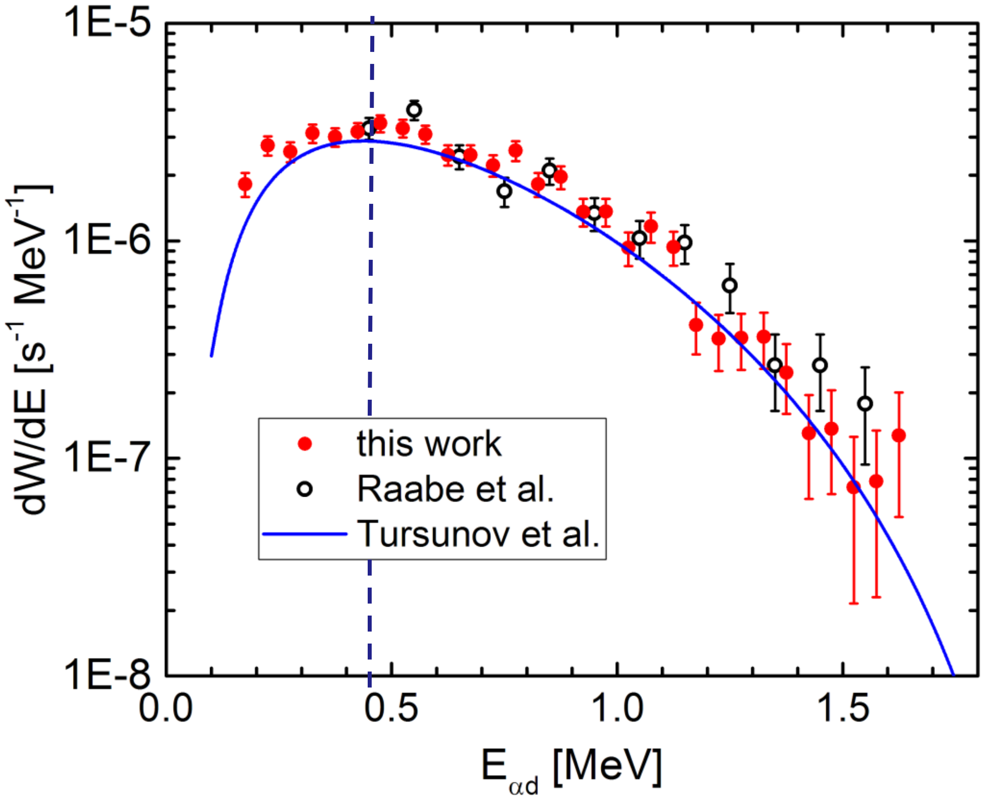
A CCD image showing a bunch of implanted ^{6}He ions (red) and a $^{6}He \rightarrow \alpha + d$ decay (green)

M. Pfützner et al., Phys. Rev. C, **92** (2015) 014316

The spectrum of $\alpha + d$

- 1650 α+d decays of ^{6}He observed in 4.5 days





$B_{\alpha d} = (2.78 \pm 0.07(\text{stat}) \pm 0.17(\text{sys})) \times 10^{-6}$

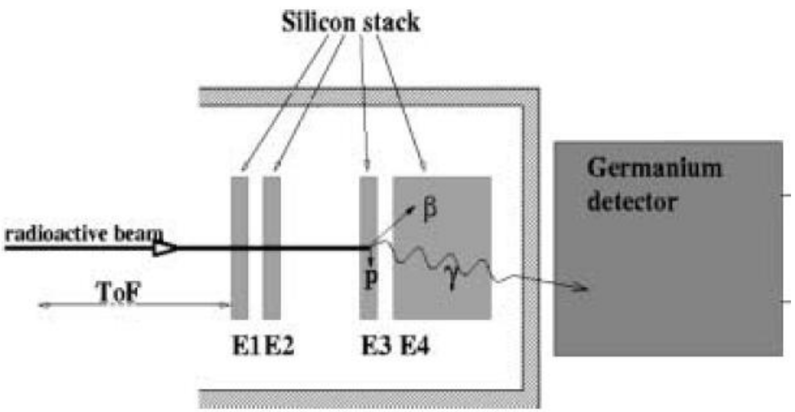
➔ By extending the spectrum do lower energy, we see 70% more intensity

M. Pfützner et al., Phys. Rev. C, **92** (2015) 014316

Last experiment (September 2015)
^{27}S @ ACCULINNA

Study of β-delayed charged particle emission from ^{27}S

^{27}S: Already done



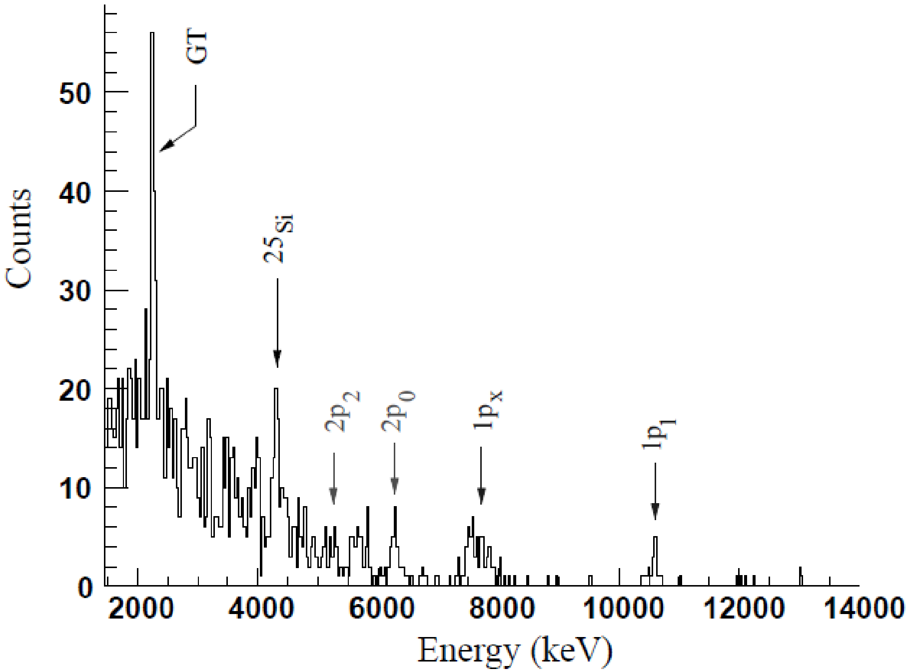
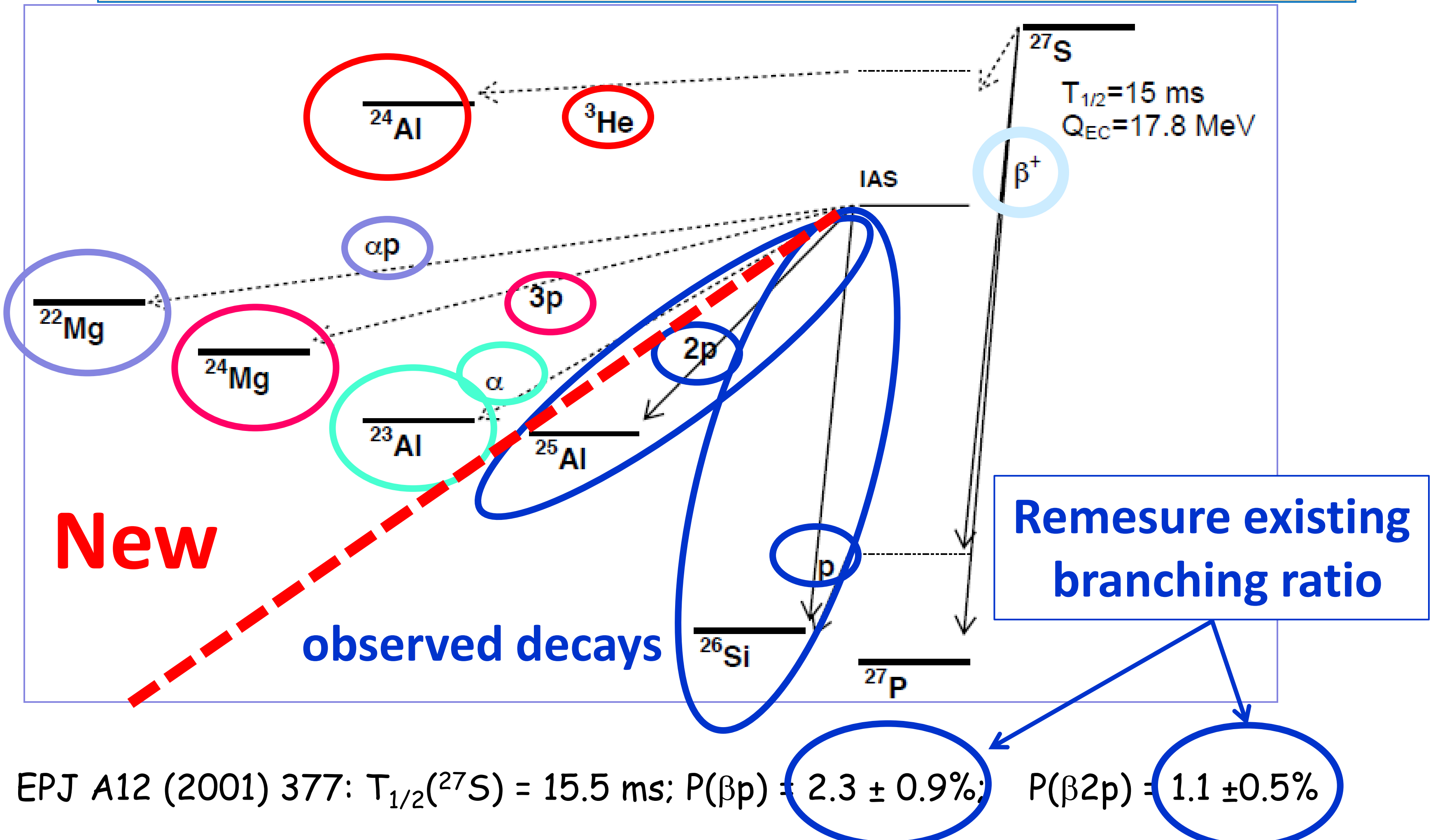


Fig. 3. Charged-particle spectrum of the decay of ^{27}S nuclei implanted in the E3 silicon detector. Proton groups above about 7 MeV have to be reconstructed by summing the energy signals from detectors E3 and E4.

EPJ A12 (2001) 377: $T_{1/2}(^{27}S)$ = 15.5 ms; P(βp) = 2.3 ± 0.9%;   P(β2p) = 1.1 ±0.5%

Study of β-delayed charged particle emission from ^{27}S

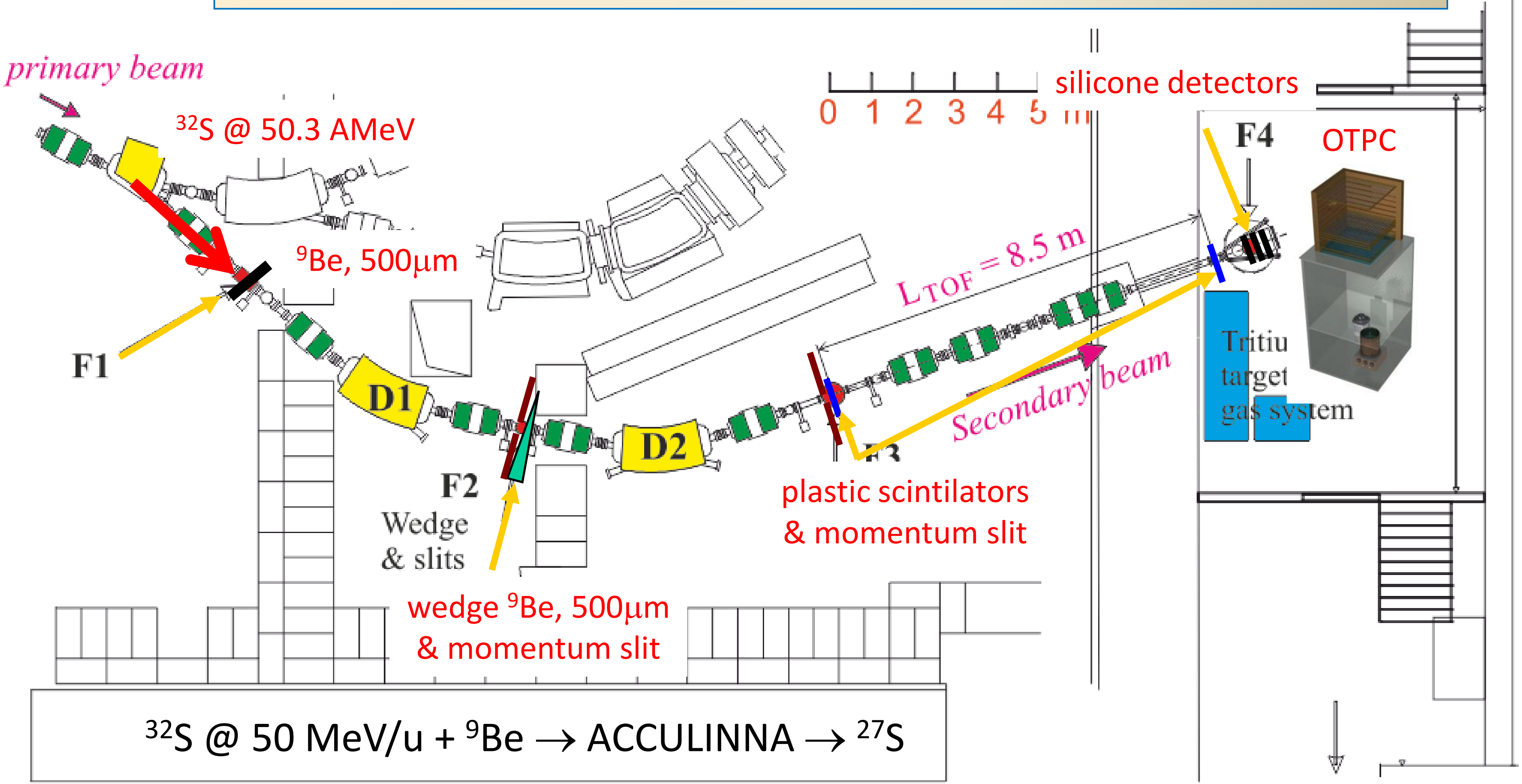


EPJ A12 (2001) 377: $T_{1/2}(^{27}S)$ = 15.5 ms; P(βp) = 2.3 ± 0.9%; P(β2p) = 1.1 ±0.5%

New possible decay channels:
β3p, βα, βαp, β³He

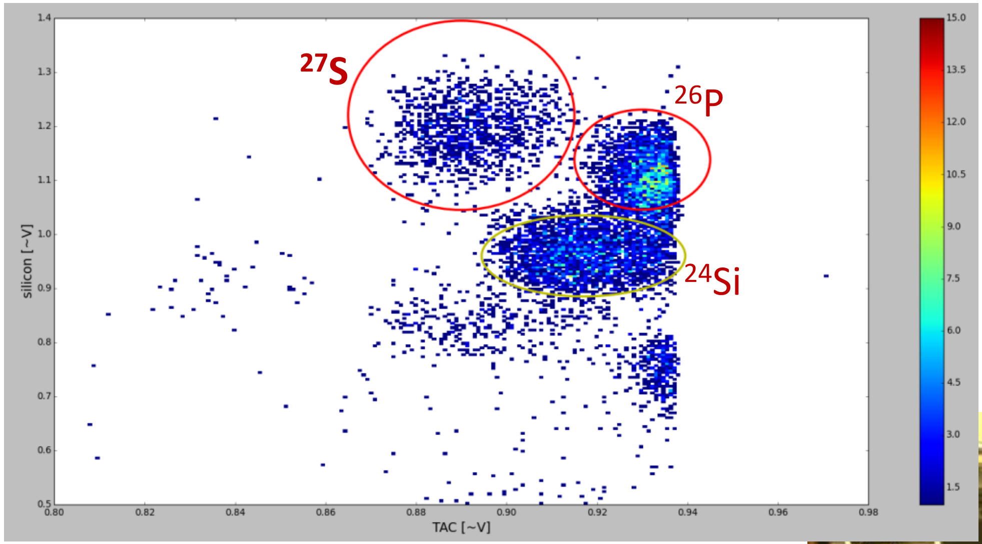
Direct observation of 2p emmision
angular correlations between protons

^{27}S: Study of βp, β2p, β3p, βα, βαp, β^{3}He with OTPC



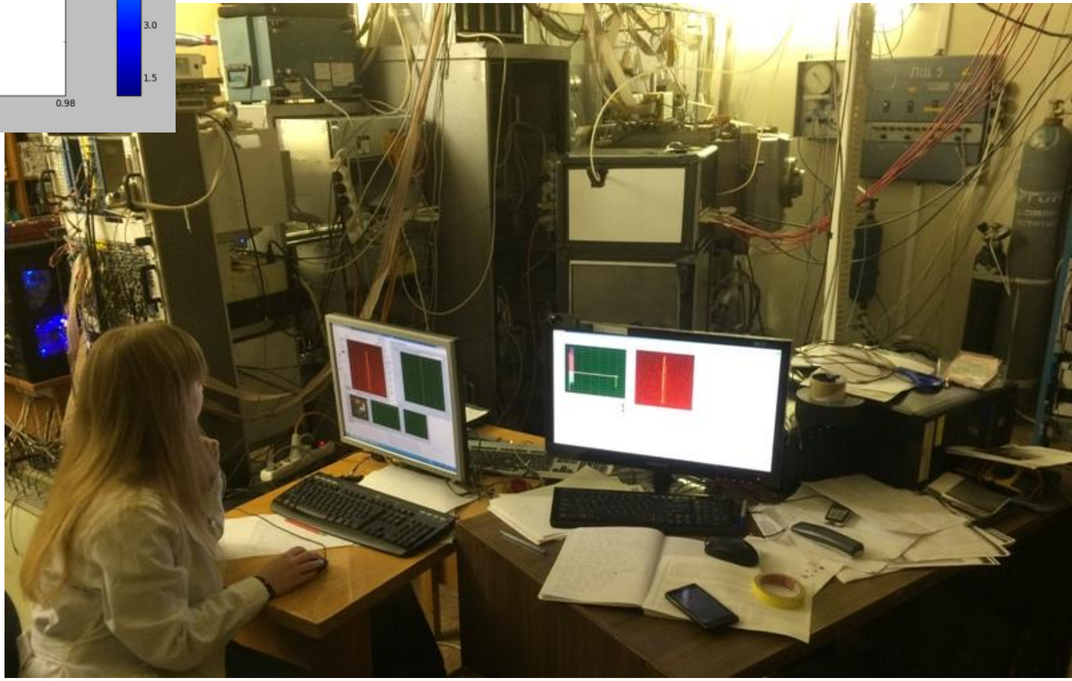
^{32}S @ 50 MeV/u + ^{9}Be → ACCULINNA → ^{27}S

^{27}S: Study of βp, β2p, β3p, βα, βαp, β^{3}He with OTPC

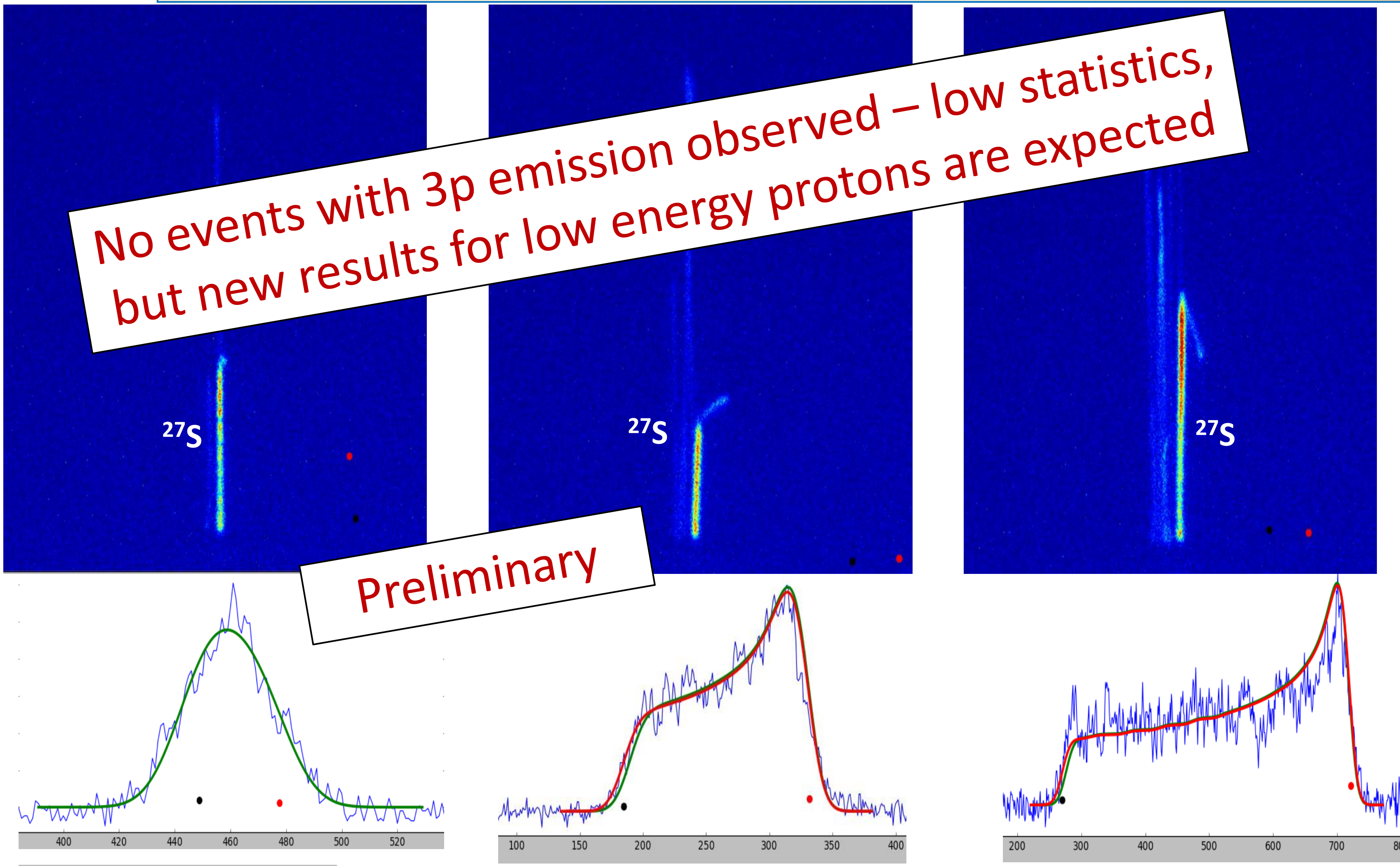


ID plot: dE-0TOF

Data acquisition



^{27}S: Study of βp, β2p, β3p, βα, βαp, β^{3}He with OTPC



Energy from L[keV]=244.5

Angle Θ[deg] =-41

Energy from L[keV]=753.7

Angle Θ[deg] =29.6

Energy from L[keV]=1176.2

Angle Θ[deg] =50.0

Collaboration

University of Warsaw
- W. Dominik
- A. Korgul
- **A. Ciemny**
- L. Janiak
- C. Mazzochi
- K. Miernik
- **S. Mianowski**
- M. Pfutzner
- **M. Pomorski**

JINR Dubna
- A.Fomichev
- A.Bezbakh
- G.Kamiński
- S.Krupko

AGH Krakow
- N. Sokołowska

GSI
- I. Mukha
- H. Geissel
- S. Weick

NSCL
- T. Baumann
- T. Ginter
- A. Stolz
- S. Liddick

Oak Ridge National Lab.
- K. Rykaczewski

University of Tennessee
- R. Grzywacz
- S.Paulauskas

CERN - ISOLDE
- M. Kowalska
- M. Borge

OTPC: Summary

- OTPC was used in connection with different ion delivery systems

- OTPC is a perfect tool to study exotic decays :
  - single event sensitivity
  - low energy threshold
  - low background
  - studies of correlation possible
  - easy to set-up and to use

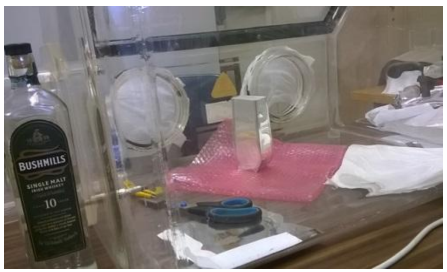
Presented pictures and slides (OTPC part) by courtesy of Marek Pfützner

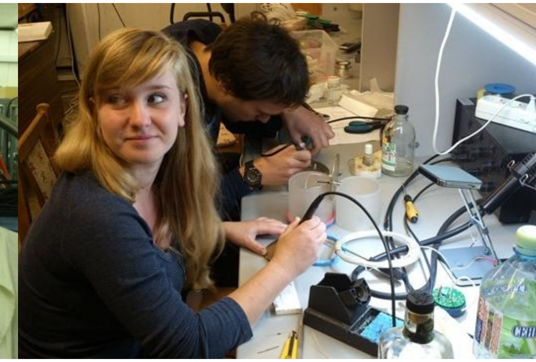
- limitations
  - reconstruction of multi-particle decays (>2) difficult / impossible
  - low counting rate ~2 Hz
  - limited range of measured energies

- OTPC is a perfect instrumentation tool for ACCULINNA-2

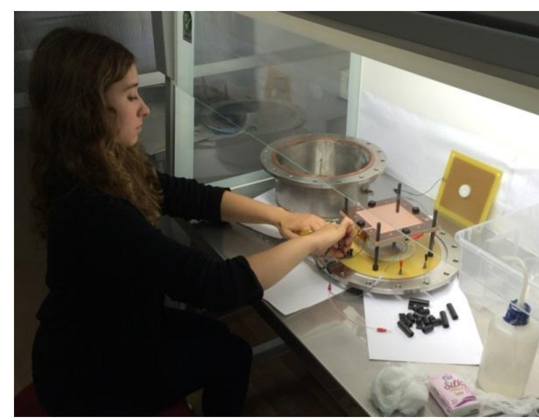
Possibilities for students at JINR

Letnie praktyki dla studentów w ZIBJ





Informacje o praktykach można znaleźć na stronie:
poland.jinr.ru -> Program Bogolubowa-Infelda



Letnie praktyki dla studentów w ZIBJ

Summer Student Practices in JINR Fields of Research w Zjednoczonym Instytucie Badań Jądrowych w Dubnej, 3 do 24 lipca 2016 roku (wyjazd z Polski 2 lub 3 lipca, wyjazd z Dubnej 24 lipca).
Praktyki adresowane są do studentów 3 – 5 roku: - fizyki (specjalność: fizyka jądrowa, fizyka medyczna, nanotechnologia, fizyka ogólna, informatyka) - chemii, biologii i medycyny

Uczestnik praktyki pokrywa:
koszt przejazdu z Moskwy do miejsca zamieszkania w Polsce (około 500 PLN),
koszt dwukrotnej wizy tranzytowej przez Białoruś (15 Euro – opłata za udzielenie wizy, plus opłata około 150 PLN za pośrednictwo w załatwieniu wizy).
koszt ubezpieczenia KL i NNW na okres podróży i pobytu na praktyce (około 70 PLN)

Natomiast ZIBJ pokrywa pozostałe koszty:
zakwaterowania w pokojach 3 lub 4 osobowych w hotelu instytutowym,
programu turystyczno-rekreacyjnego,
transportu z Moskwy do Dubnej w dniu przyjazdu i z Dubnej do Moskwy w dniu powrotu do Polski,
biletu na przejazd pociągiem w wagonie sypialnym II klasy z miejsca zamieszkania w Polsce do Moskwy (łącznie do 150 USD).
Ponadto uczestnik praktyki otrzyma dietę w wysokości 25 USD dziennie i bezpłatne śniadania w restauracji hotelowej.

Część naukowa praktyki składa się z 3 elementów:
Wysłuchanie 4 – 6 wykładów wygłoszonych przez znanych profesorów ZIBJ, przy czym wykaz wykładów zostanie podany w pierwszym dniu praktyki.
Wykonanie wybranego projektu/ćwiczenia.
Przygotowanie prezentacji na temat wykonanego ćwiczenia i przedstawienie jej w ostatni dzień praktyki (szczegóły na stronie "Presentation of the projects by students")

Praktyki indywidualne, staże, eksperymenty

Oprócz letnich praktyk, jest możliwość odbycia praktyk indywidualnych, staży w ramach realizacji prac magisterskich, doktorskich, udział w eksperymentach. Pełne lub częściowe finansowanie na wyjazd uzyskuje się z Program Bogolubowa-Infelda. Warunki ustala się indywidualnie, w zależności od celu wyjazdu i długosci pobytu: głównie są to wyjazdy od tygodnia do dwóch miesięcy

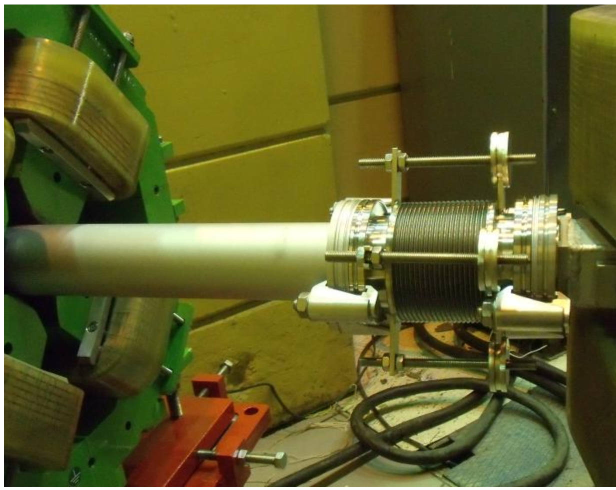
Wyjazdy na okres od 3 miesięcy i więcej

Informacje o formalnościach zwiazanych z wyjazdami na okres dluższy niż 3miesiące można znaleźć na stronie: http://poland.jinr.ru informacje dla przyjeżdżających
Wyjazd organizowany jest na zasadzie zatrudnienia na czas określony, od 3 miesięcy do 2-3 lat z możliwością przedlużenia kontraktu

Więcej informacji : Władysław Chmielowski, email: wchmiel@jinr.ru
Kinga Horodek: kinga.bagazja@uj.edu.pl
Grzegorz Kaminski, Grzegorz .Kaminski@ifj.edu.pl

Możliwość organizacji stażu w grupie ACCULINNA

Prace związane z konstrukcją i testowaniem detektorów, prace związane z programowaniem systemu kontroli próżni na separatorze ACCULINNA-2

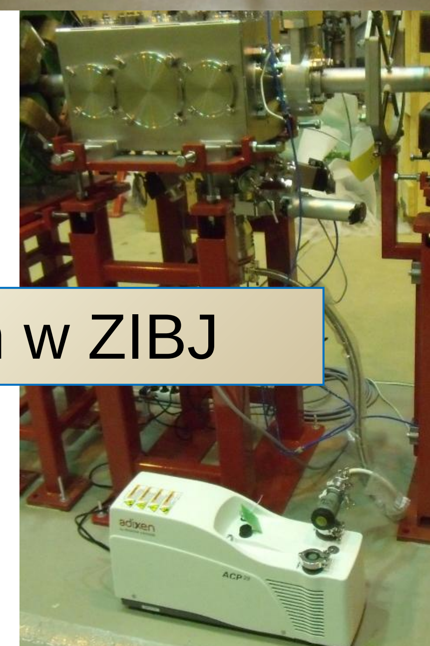


Bellows

Gate valve, diagnostic box and turbopump

Support feet

Controllers



Primary pump

i w innych grupach badawczych w ZIBJ

Dziękuje za uwagę