NuSPRASEN

Nuclear Structure Physics, Reactions, Astrophysics and Superheavy Elements Network

Perspectives for study with light radioactive ion beams at ACCULINNA-2

Grzegorz Kaminski[a,g] for the ACCULINNA Collaboration

a – *Flerov Laboratory of Nuclear Reactions, JINR, Dubna, Russia*

b – *Institute of Physics, Silesian University in Opava, Czech Republic*

c – *Bogolyubov Laboratory of Theoretical Physics, JINR, Dubna, Russia*

d – *GSI Helmholtzzentrum fur Schwerionenforschung, Darmstadt, Germany*

e – *National Research Center "Kurchatov Institute", Moscow, Russia*

f – *Institute of Nuclear Physics PAN, Krakow, Poland*

g – *Heavy Ion Laboratory, University of Warsaw, Warsaw, Poland*

h – *Skobel'tsyn Institute of Nuclear Physics, Moscow State University, Russia*

i – *Faculty of Physics, University of Warsaw, Warsaw, Poland*

j – *Fundamental Physics, Chalmers University of Technology, Goteborg, Sweden*

k– *All-Russian Research Institute of Experimental Physics, Sarov, Russia*

l – *Ioffe Physical Technical Institute, St. Petersburg, Russia*

m – *NSCL, Michigan State University, East Lansing, Michigan, USA*

Outline

- Introduction. Light RIB facility at FLNR (ACCULINNA)
- Status of the ACCULINNA-2 project
- First beam at the ACCULINNA-2
- Experimental methods and techniques
- Experiments @ACCULINNA& first day experiments at ACCULINNA-2
- Optical Time Projection Chamber – OTPC at ACCULINNA
- Summary

SIGMAPHI MAGNETS AND BEAM TRANSPORT

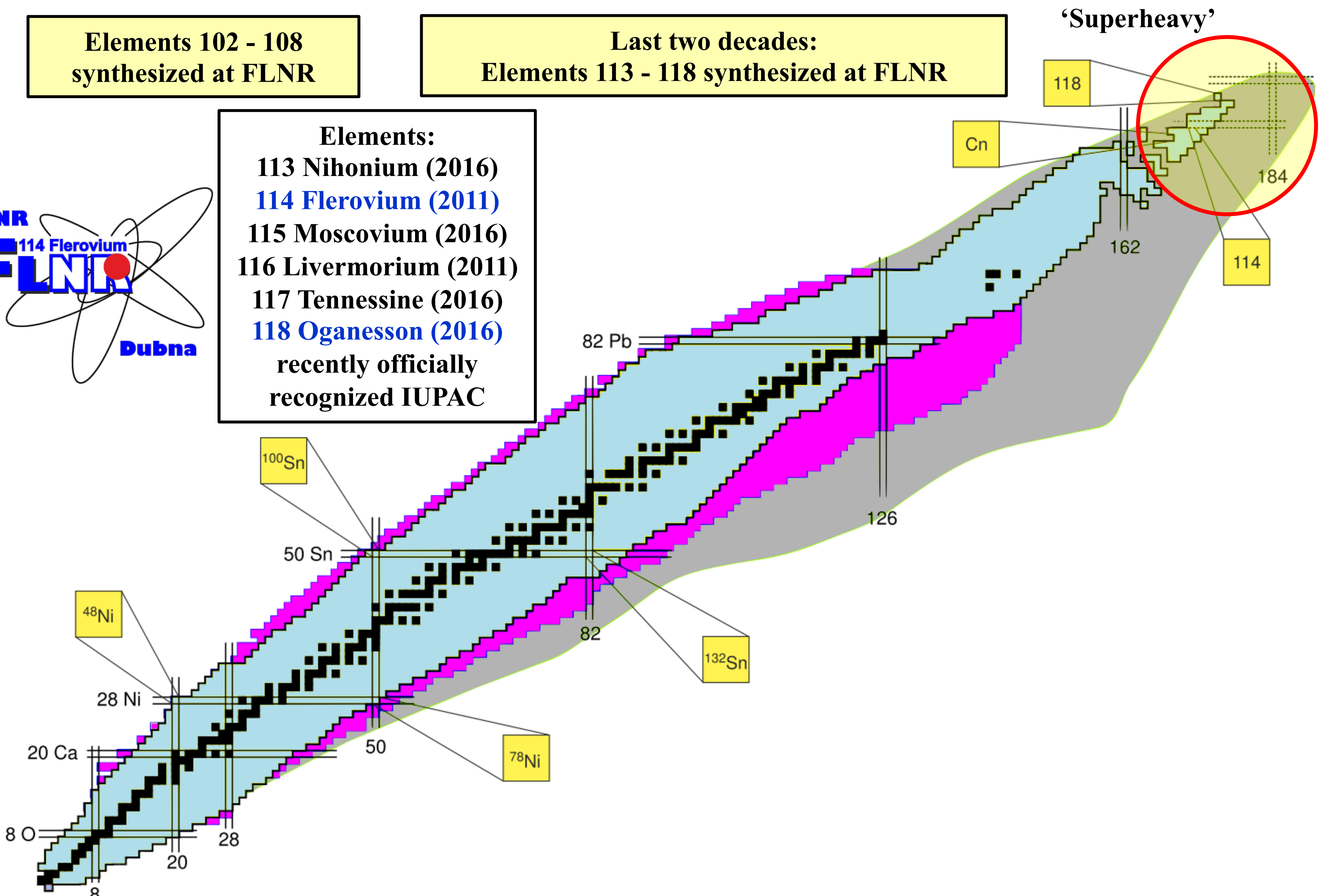
JINR 114 Flerovium FLNR Dubna

Superheavy and "superlight" research at FLNR, JINR

Elements 102 - 108 synthesized at FLNR

Last two decades: Elements 113 - 118 synthesized at FLNR

Elements:
113 Nihonium (2016)
114 Flerovium (2011)
115 Moscovium (2016)
116 Livermorium (2011)
117 Tennessine (2016)
118 Oganesson (2016)
recently officially recognized IUPAC

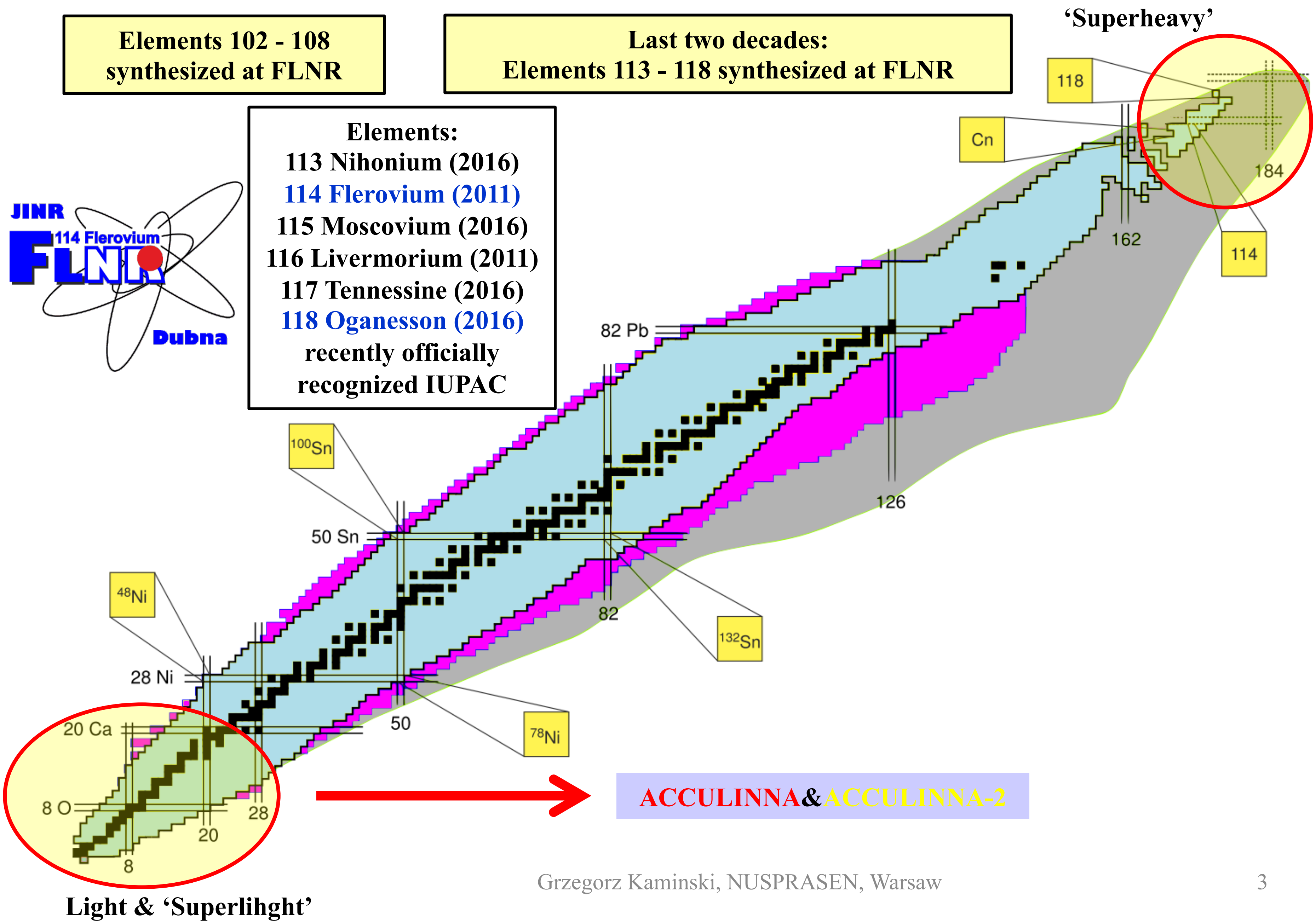


Superheavy and “superlight” research at FLNR, JINR

Elements 102 - 108 synthesized at FLNR

Last two decades: Elements 113 - 118 synthesized at FLNR

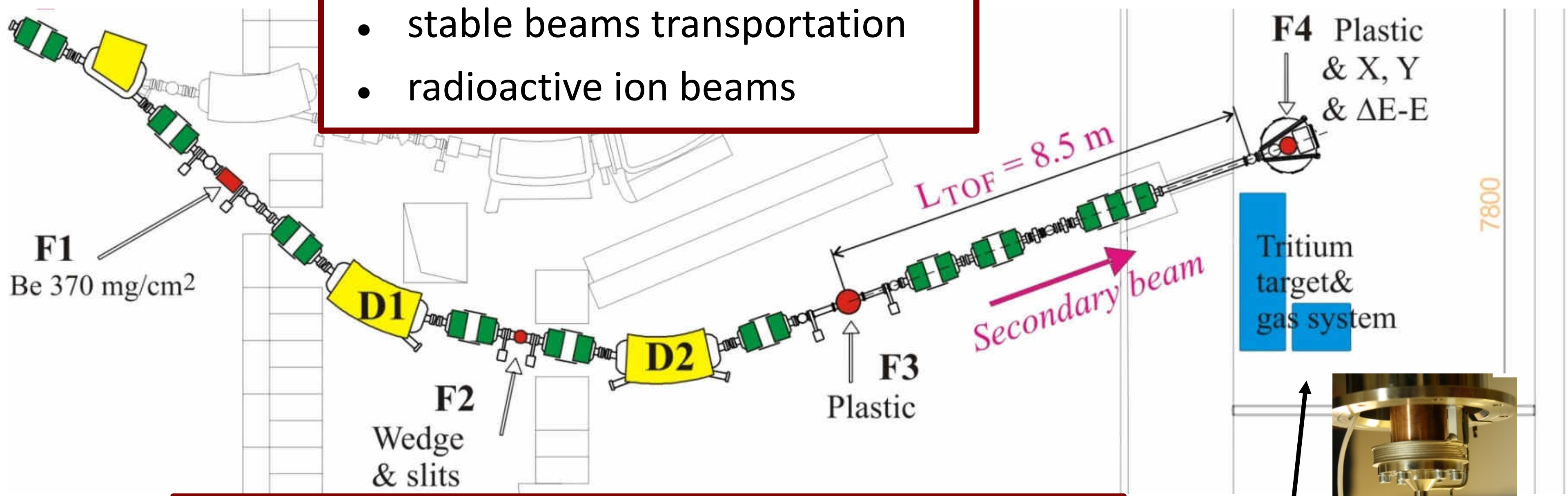
Elements:
113 Nihonium (2016)
114 Flerovium (2011)
115 Moscovium (2016)
116 Livermorium (2011)
117 Tennessine (2016)
118 Oganesson (2016)
recently officially recognized IUPAC



ACCULINNA&ACCULINNA-2

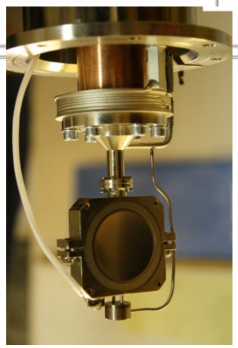
RI beam production at ACCULINNA

- stable beams transportation
- radioactive ion beams



$E_{\text{beam}} \sim 10 – 45$ MeV/A, $I_{\text{beam}} \sim 10^3 – 10^6$ pps

- the only working RIB facility at JINR
- in-flight technique, TOF, ΔE/E, full kinematic
- beams up to ^{26}S



unique combination of tritium beam and target

Study of exotic nuclei in FLNR at the low RI energies

Use of the ACCULINNA fragment separator **has Advantages:**

• The **record intensity** of the primary cyclotron beams (5 pμA of ^{11}B);
• Relatively (to in-flight separators) **low beam energies**, that provide a good energy resolution, high reaction cross section partly compensate the low intensities of secondary beams.
• These **beam energies are optimal** for the nuclear structure studies in transfer, charge-exchange reactions;
• **Complete kinematics method** allows for clean, background-free spectra;
• **Correlation studies** provides possibilities for spin-parity identification of the resonance states.

ACCULINNA open **possibilities** for wide range of experiments
• correlation experiments
• lifetime measurements
• spectroscopic structure studies
• search for new light exotic nuclei and exotic decays

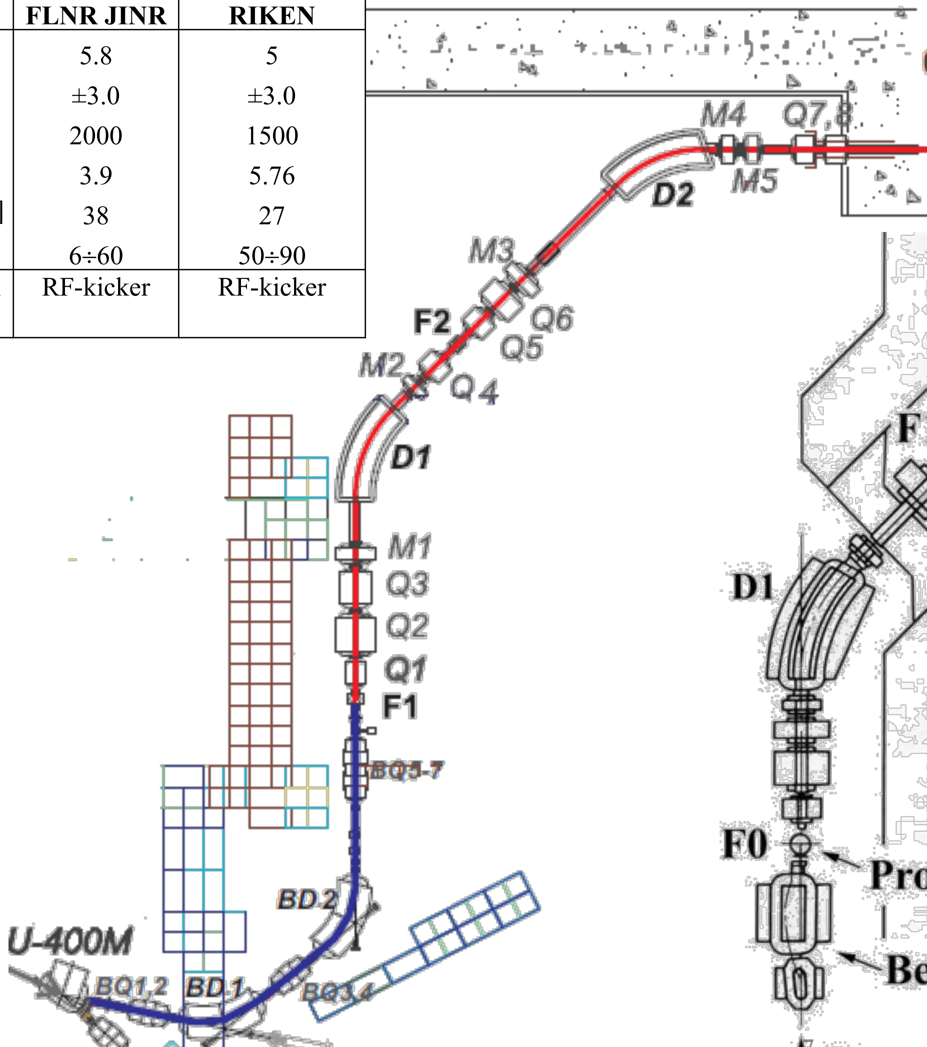
Use of the ACCULINNA fragment separator **has its Disadvantages:**
• It is only efficient with **lightest neutron-rich nuclei**;
• Does not cope with the request of **high intensity clean beams** with Z>8;
• We need **more powerful detector rays**, and a bigger experimental area (for TOF);
• **Small length of the separator** puts limitation on the energy resolution;

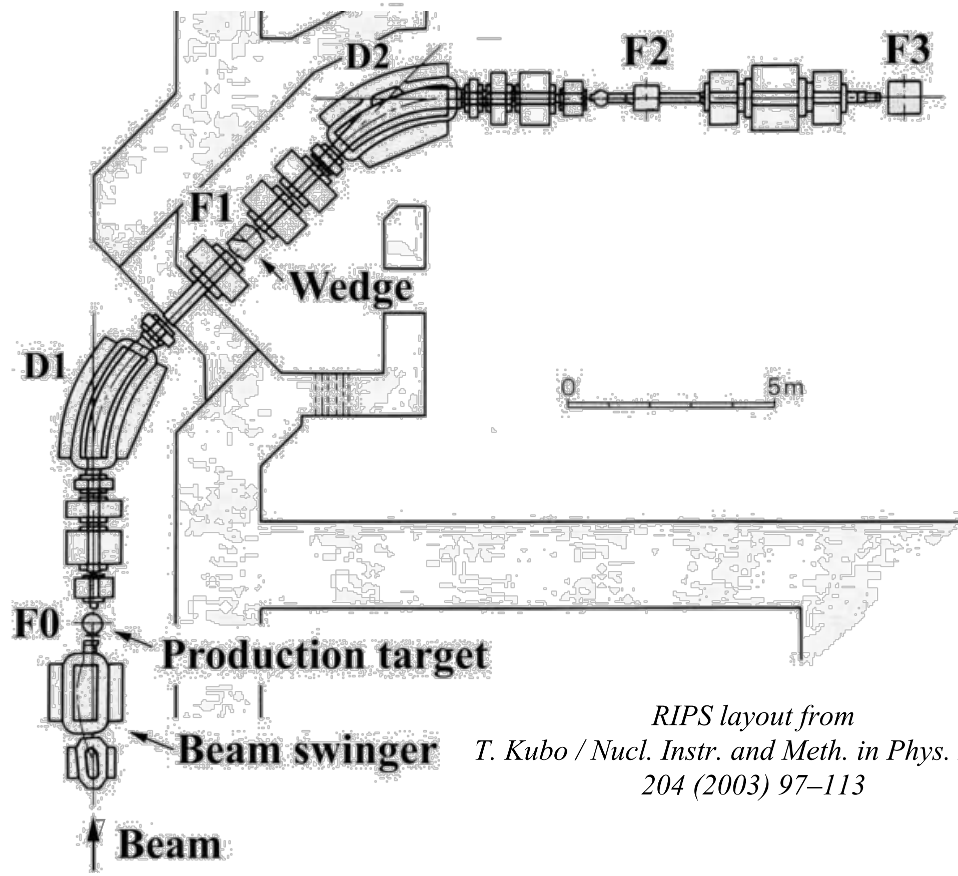
A new separator ACCULINNA-2

Contract with SIGMA PHI to design and instalation of the ACC-2: 2011 - 2015

Layout of ACCULINNA-2

	ACC-2 FLNR JINR	RIPS RIKEN
ΔΩ [msr]	5.8	5
Δp/p [%]	±3.0	±3.0
Rp/Δp	2000	1500
Bρ [Tm]	3.9	5.76
Length [m]	38	27
E [AMeV]	6÷60	50÷90
Additional RIB Filter	RF-kicker	RF-kicker

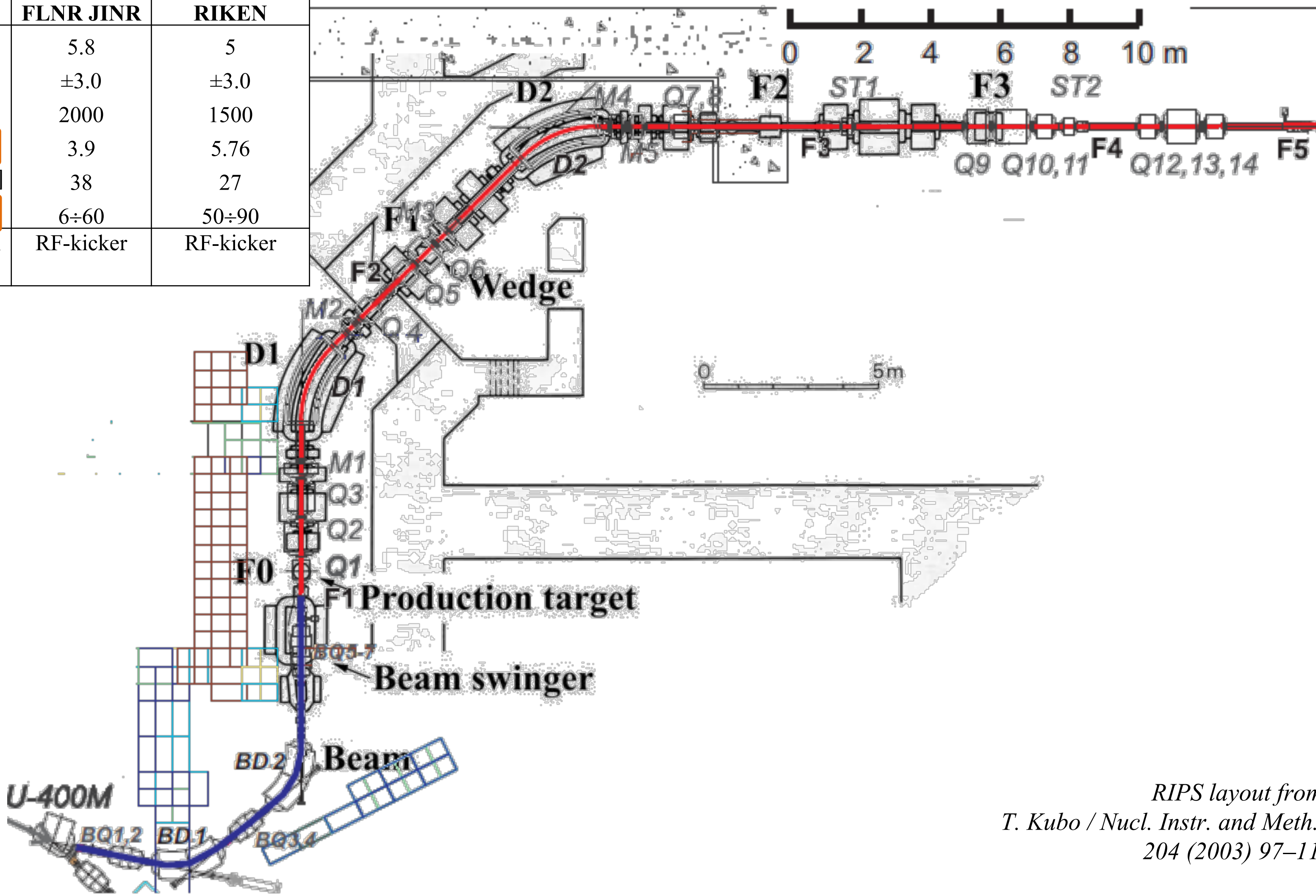




RIPS layout from
T. Kubo / Nucl. Instr. and Meth. in Phys. Res. B 204 (2003) 97–113

Layout of ACCULINNA-2

	ACC-2 FLNR JINR	RIPS RIKEN
ΔΩ [msr]	5.8	5
Δp/p [%]	±3.0	±3.0
Rp/Δp	2000	1500
Bρ [Tm]	3.9	5.76
Length [m]	38	27
E [AMeV]	6÷60	50÷90
Additional RIB Filter	RF-kicker	RF-kicker



RIPS layout from
T. Kubo / Nucl. Instr. and Meth. in Phys. Res. B 204 (2003) 97–113

ACCULINNA-2 in perspective

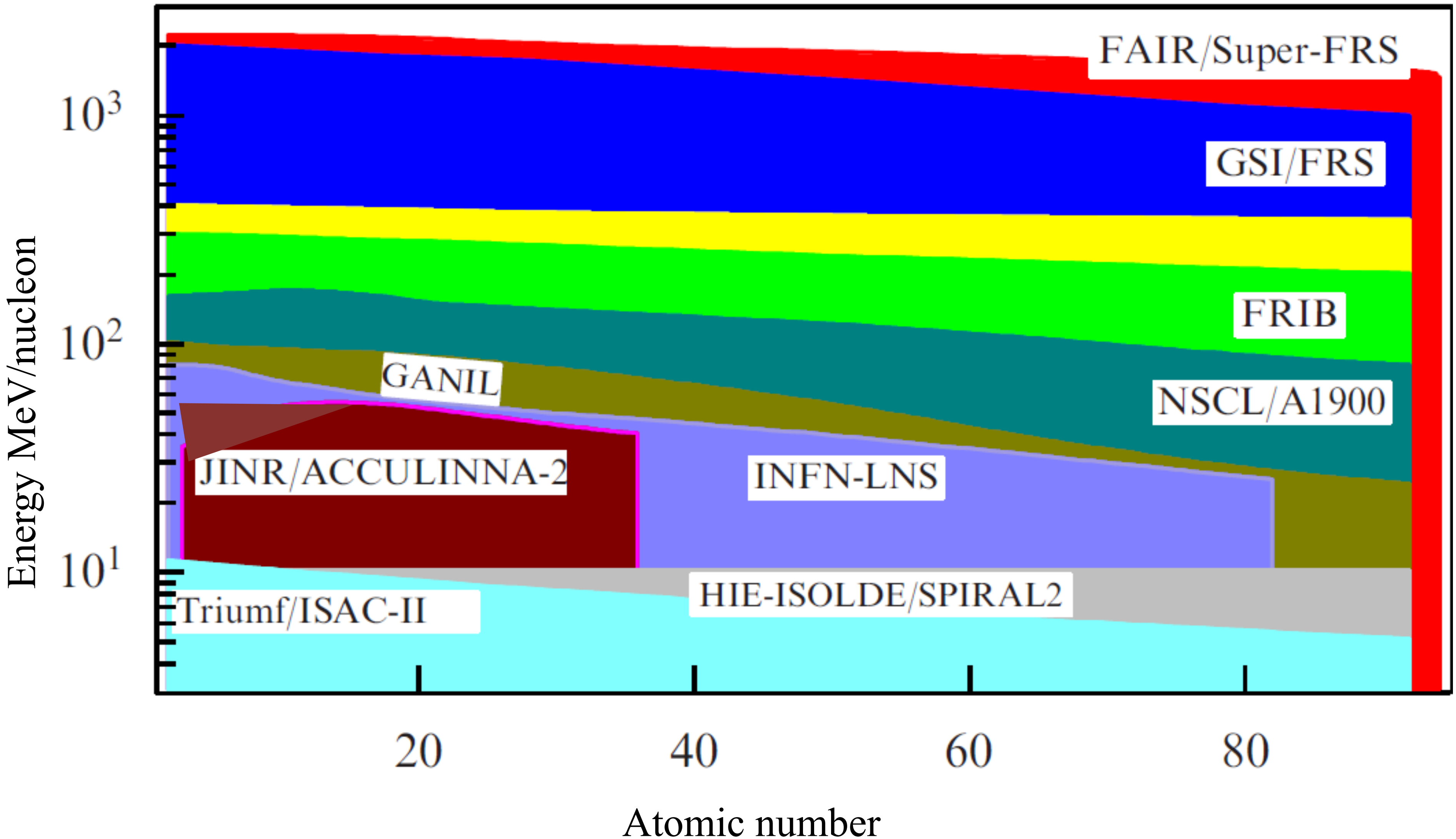
Characteristics of existing and new in–flight RIB separators

(ΔΩ and Δp/p are angular and momentum acceptances, Rp/Δp 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
ΔΩ, msr	0.9 / 5.8	5.0 / 8.0	8.0	0.32 / 5.0	1.0
Δp/p, %	± 2.5 / ± 3.0	± 3.0 / 6.0	± 5.5	± 2.0 / 5.0	± 5.0
Rp/Δp	1000 / 2000	1500 / 3300	2915	8600 / 3050	2200
Bρ, 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

Beams and energies @ ACCULINNA-2

… somewhere among other facilities



RIBs from ACCULINNA-2

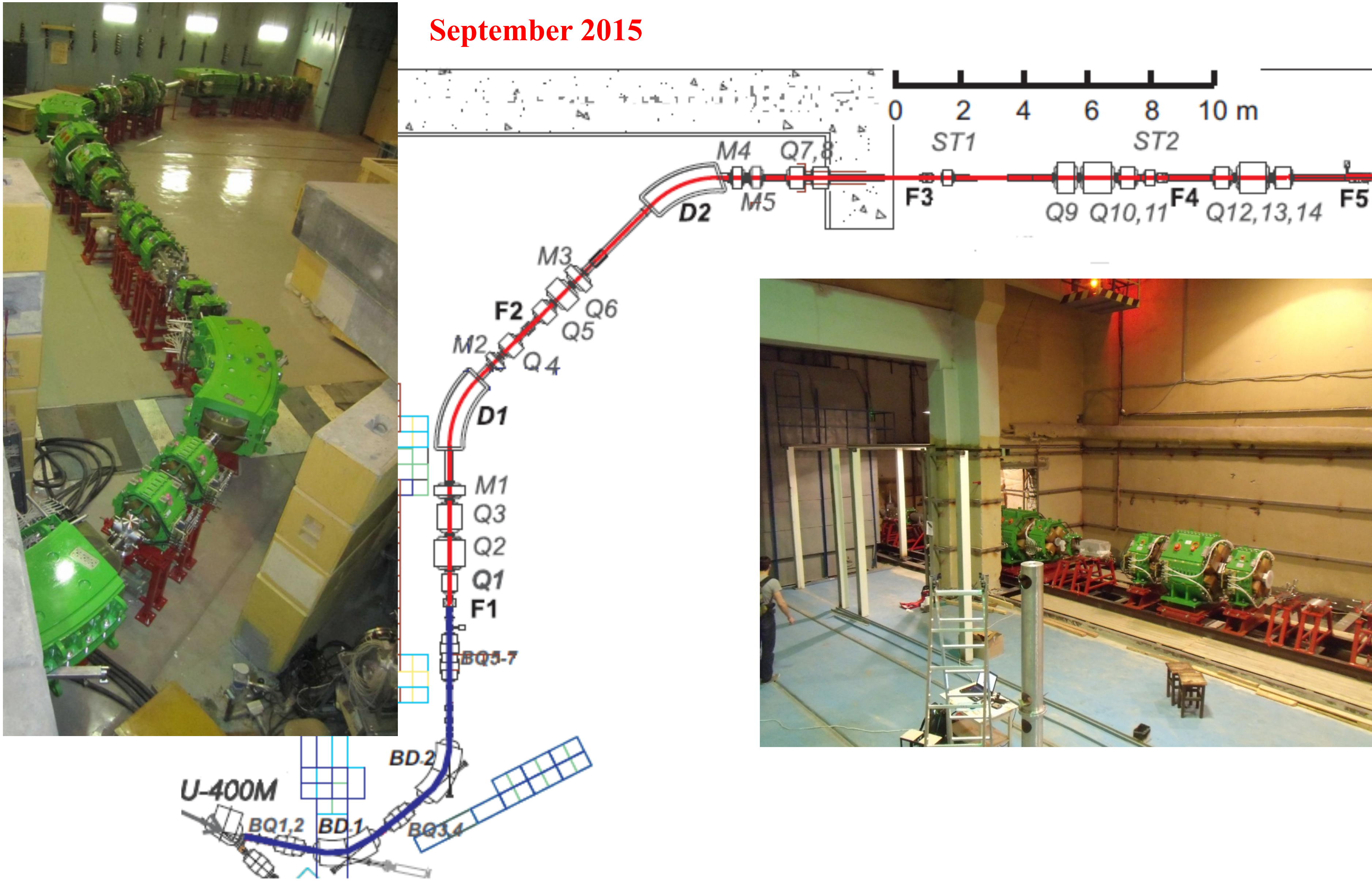
calculations done with LISE++

Primary beam		Radioactive Ion Beam			
Ion	Energy, MeV/u	Ion	Energy, MeV/u	Intensity, s^{-1} (per 1 pμA)	Purity, %
^{11}B	32	**^{8}He**	26	$3*10^5$	90
^{15}N	49	**^{11}Li**	37	$3*10^4$	95
^{11}B	32	**^{10}Be**	26	$1*10^8$	90
^{15}N	49	**^{12}Be**	38.5	$2*10^6$	70
^{18}O	48	**^{14}Be**	35	$2*10^4$	50
^{22}Ne	44	**^{17}C**	33	$3*10^5$	40
		^{18}C	35	$4*10^4$	30
^{36}S	64 (U400M upgrade)	**^{24}O**	40	$2*10^2$	10 (with RF kicker)
^{10}B	39	**^{7}Be**	26	$8*10^7$	90
^{20}Ne	53	**^{18}Ne**	34	$2*10^7$	40
^{32}S	52	**^{28}Be**	31	$2*10^4$	5 (with RF kicker)

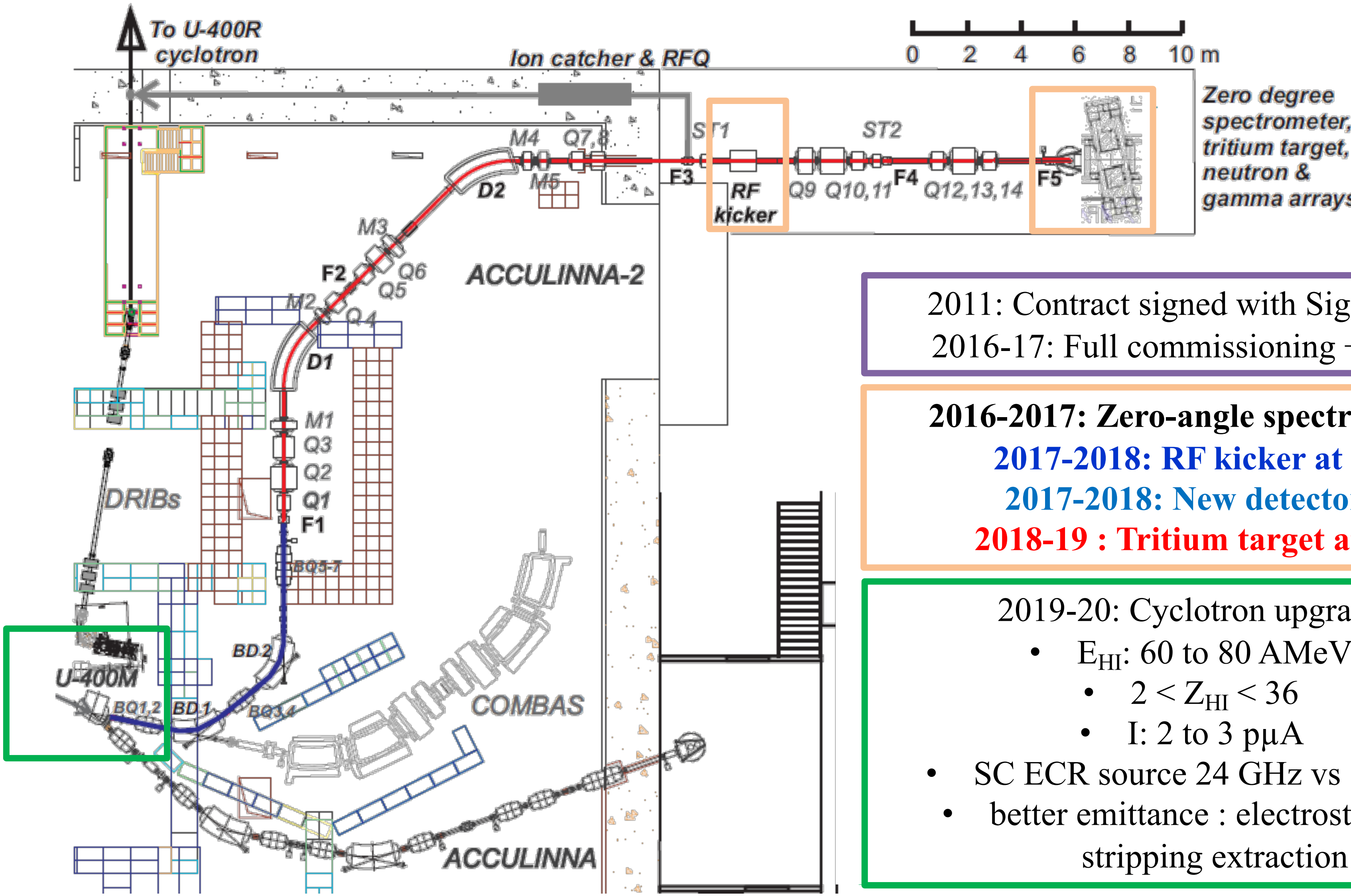
Layout of ACCULINNA-2

Layout of ACCULINNA-2

September 2015



ACCULINNA-2 project: timeline



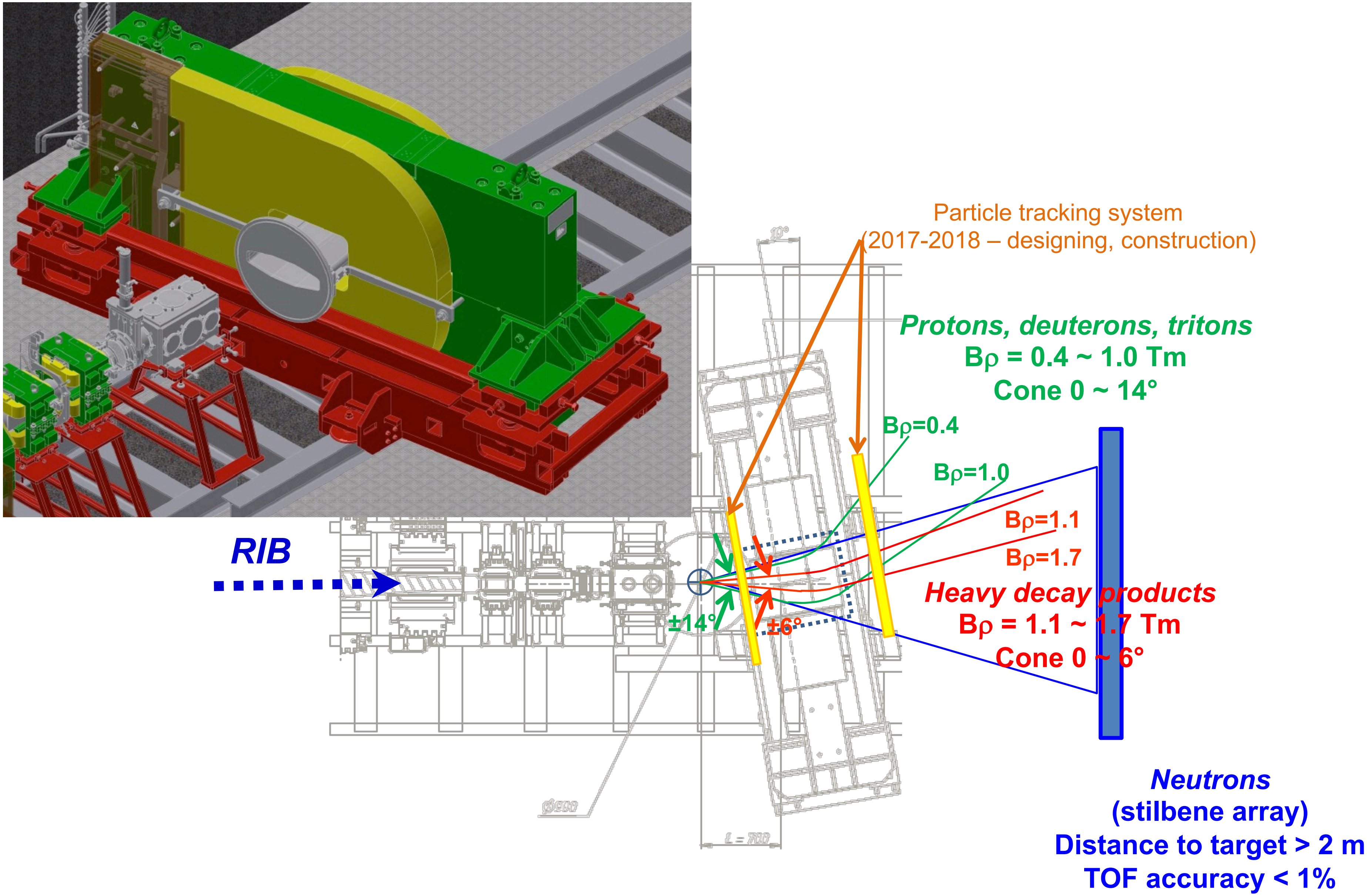
2011: Contract signed with Sigma PHI
2016-17: Full commissioning + Beam

2016-2017: Zero-angle spectrometer
2017-2018: RF kicker at F3
2017-2018: New detectors
2018-19 : Tritium target at F5

2019-20: Cyclotron upgrade

- E_{HI}: 60 to 80 AMeV
- $2 < Z_{HI} < 36$
- I: 2 to 3 pμA
- SC ECR source 24 GHz vs 18 GHz
- better emittance : electrostatic vs stripping extraction

The zero angle spectrometer



The zero angle spectrometer - INSTALLED

February 2017

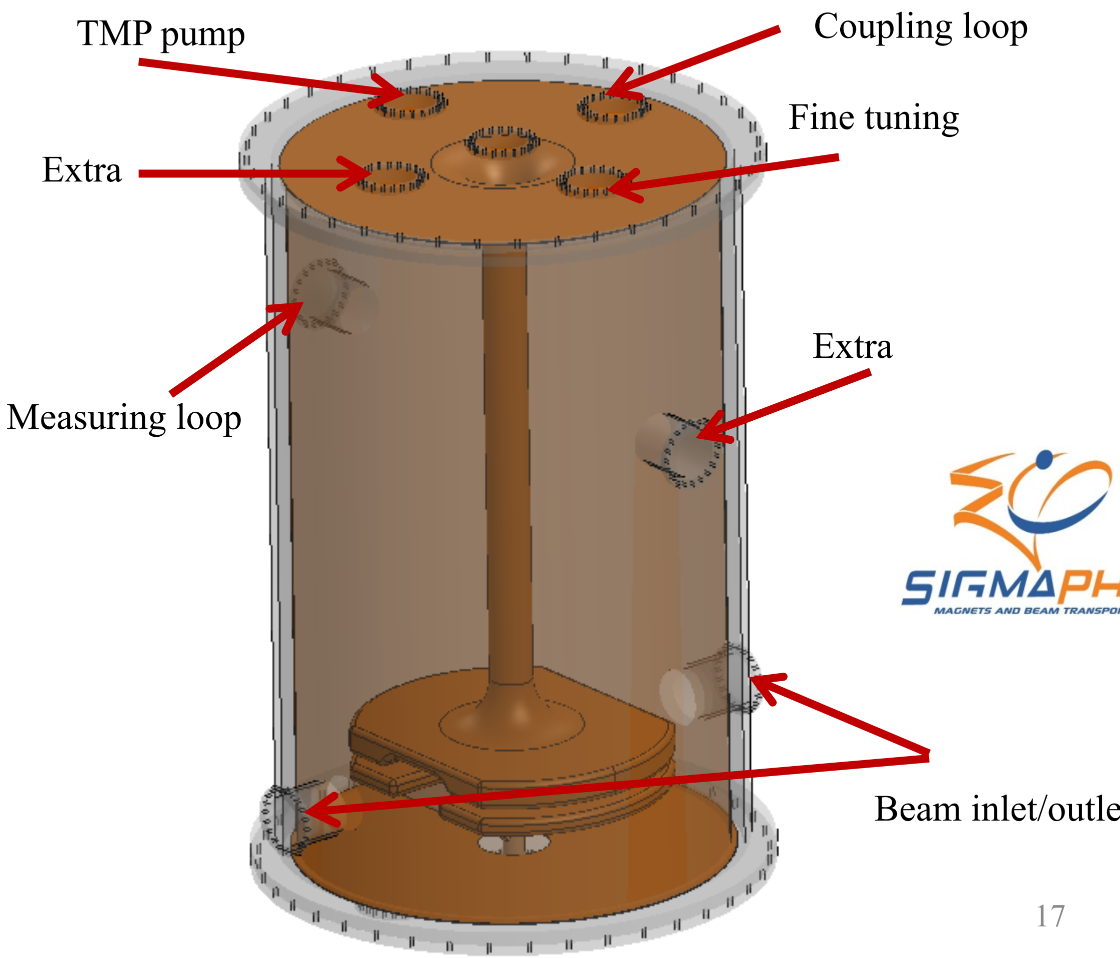
November 2017

RF kicker: started in 2016, installation in the middle of 2018

- The frequency range 14,5 – 20 MHz is the best compromise in term of dimensions and RF power
- We consider some margin on the RF power and a 15 Kwatts amplifier.
- Reducing the copper cavity diameter to 1000 mm and the coaxial line diameter to 100 mm gives a RF power of 12 Kwatts which is still below 15 Kwatts.

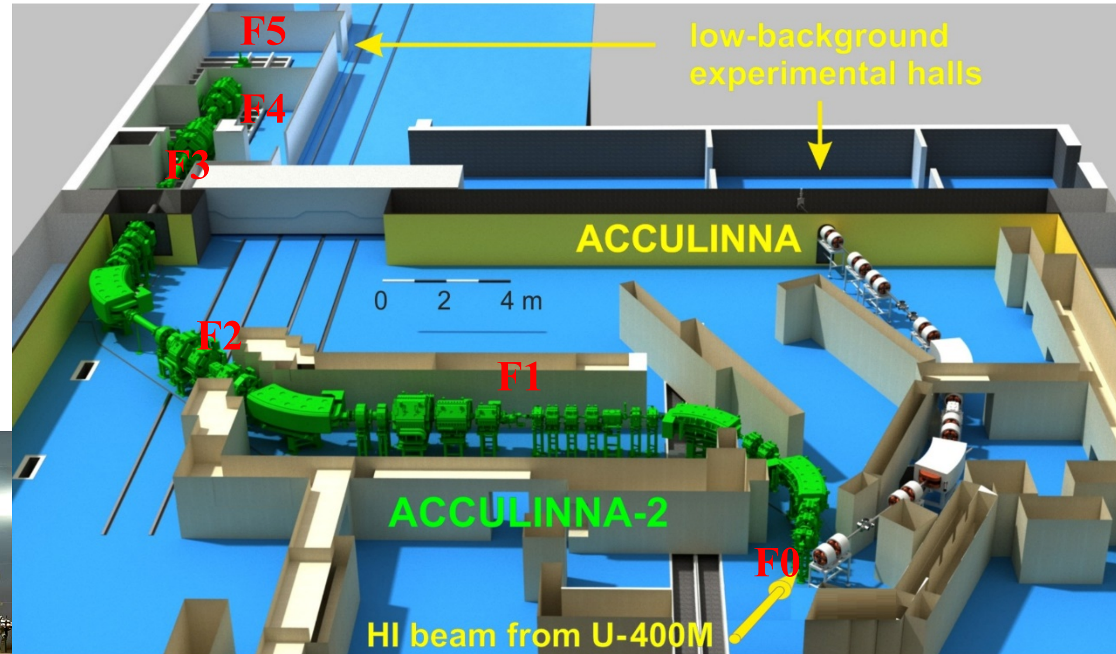
PARAMETERS AND CALCULATION RESULTS

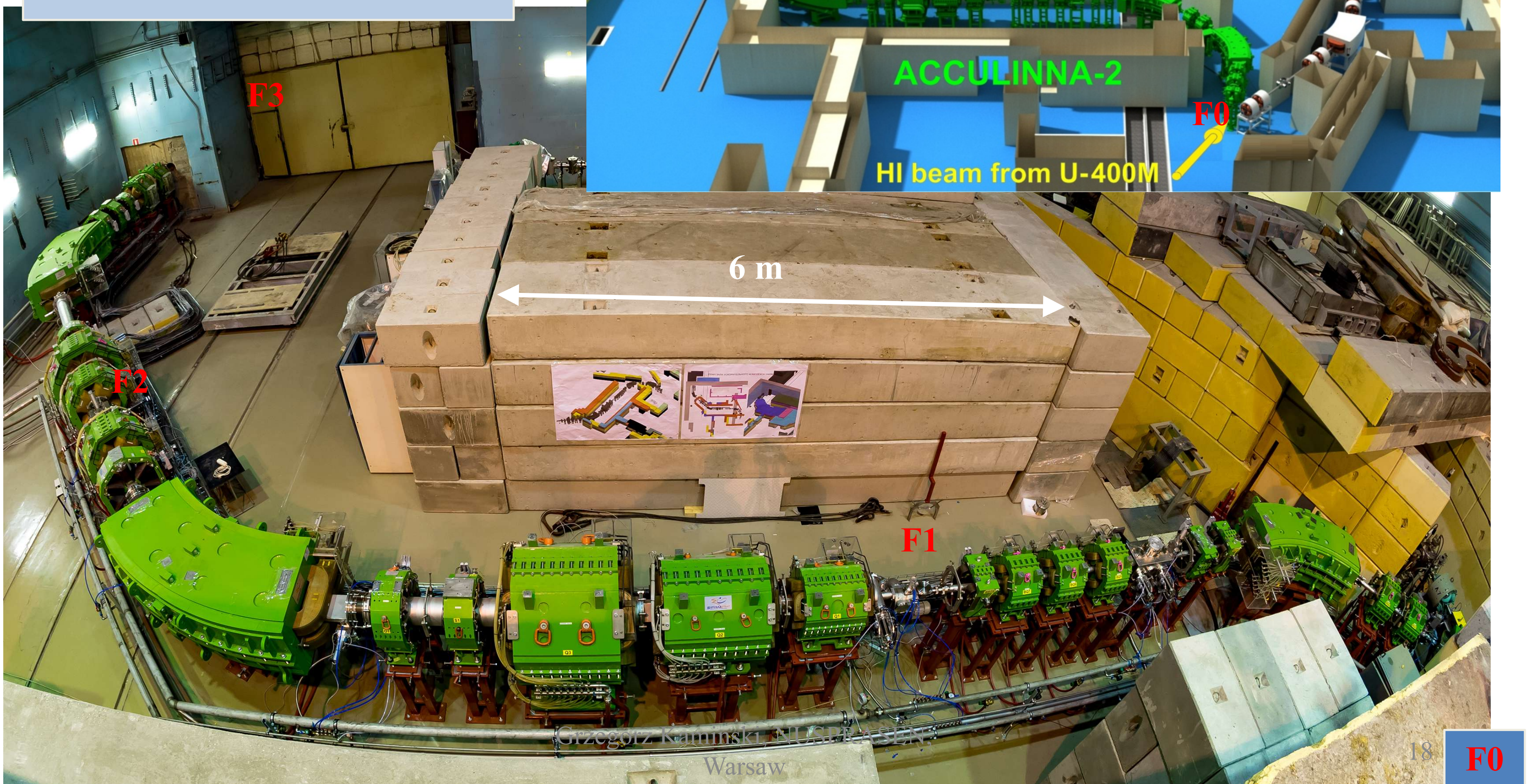
Frequency range (MHz)	14,5 - 20
Peak voltage (KV)	120
GAP (mm)	70
Width of electrode (mm)	120 min
Length of electrodes (mm)	700
Cylinder diameter (mm)	1200 max
Stem diameter (mm)	120 max
Length of coaxial line from beam axis (mm)	1830
Current at junction (A)	990
Current in short-cut (A)	1200
RF power (Watts)	10 000
Reactance Q	8 500
Df (RF tuning) (MHz)	0,66



Setup layout & Today status

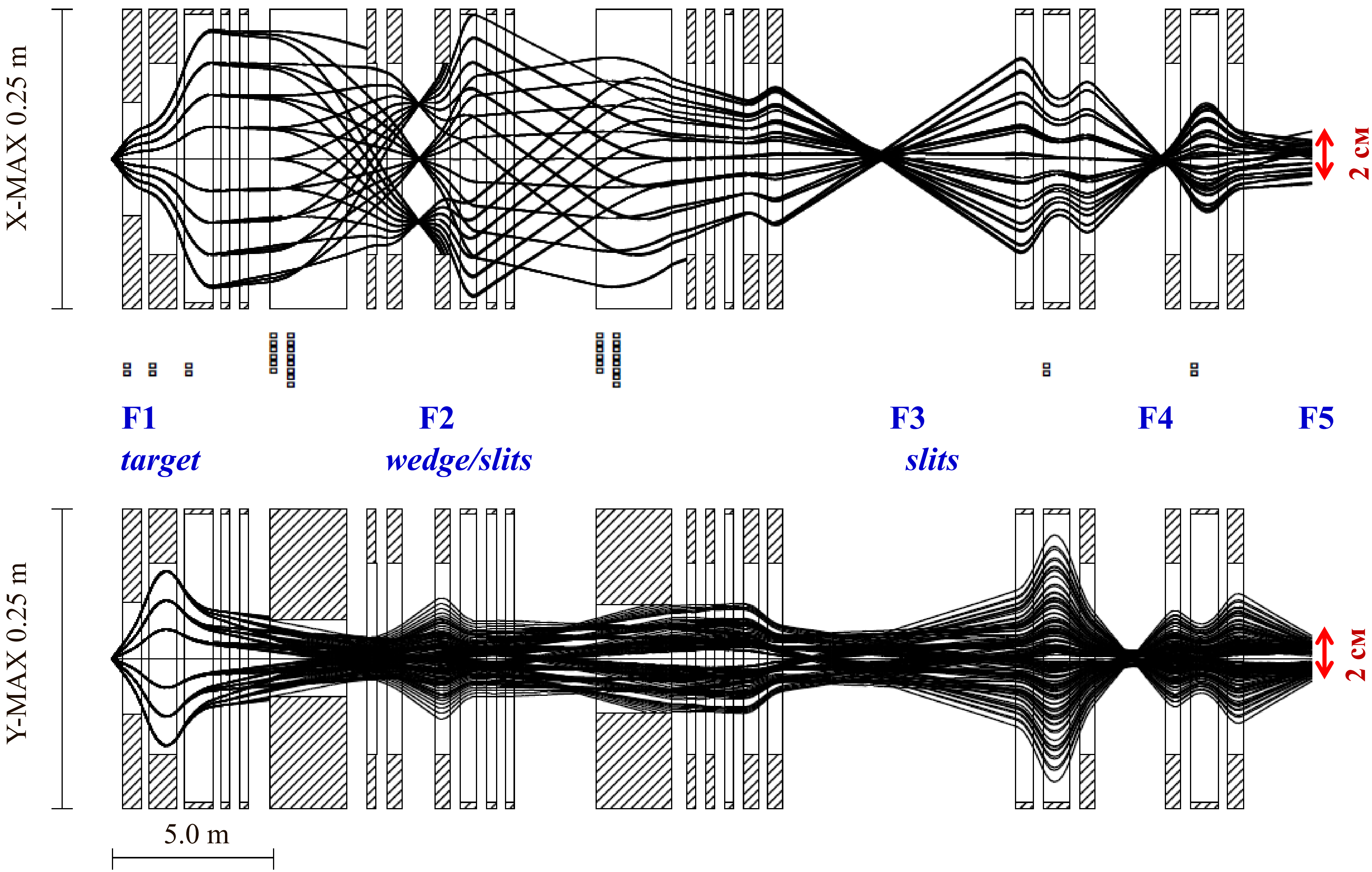
total length F0-F5 ~53m
39 magnetic elements





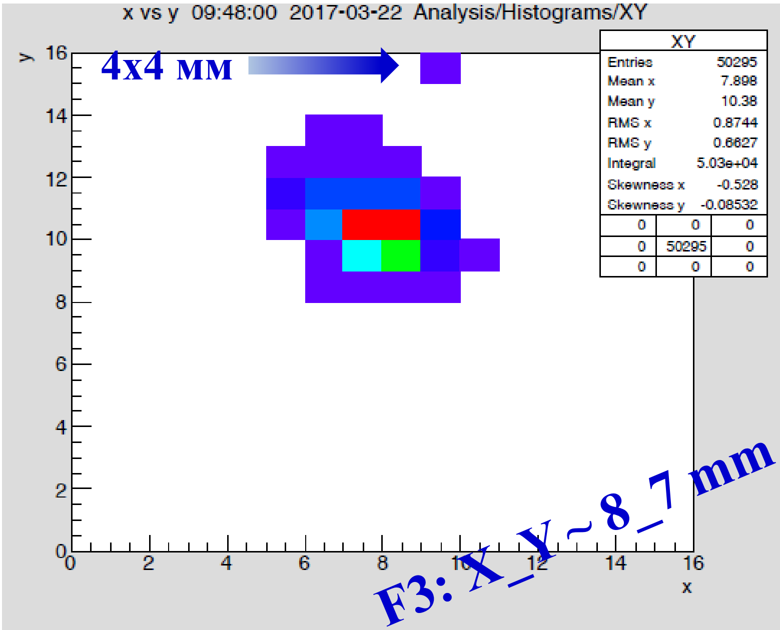
Goals of the test in March 2017:

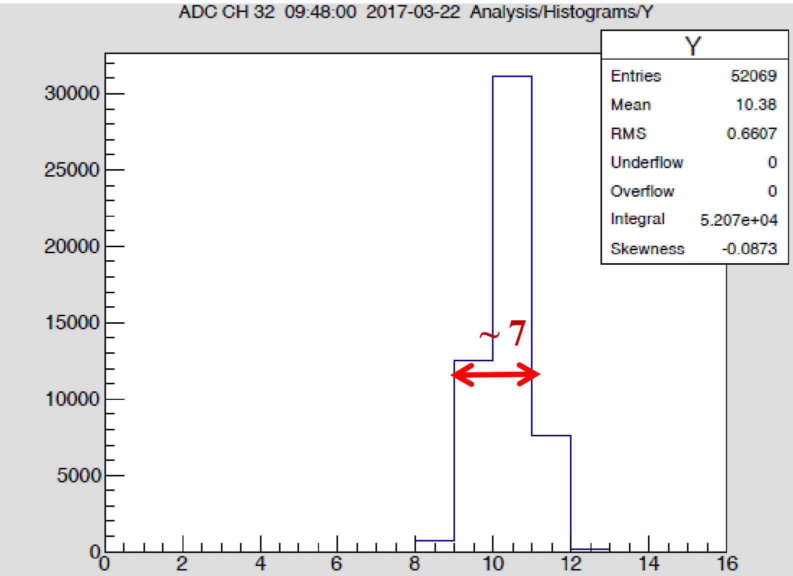
- ^{15}N profile at F3 depending on F1 diaph. (∅ 25, 12, 7 mm)
-- main parameters (I, P, X_Y) of some RIBs at F3, F4, F5

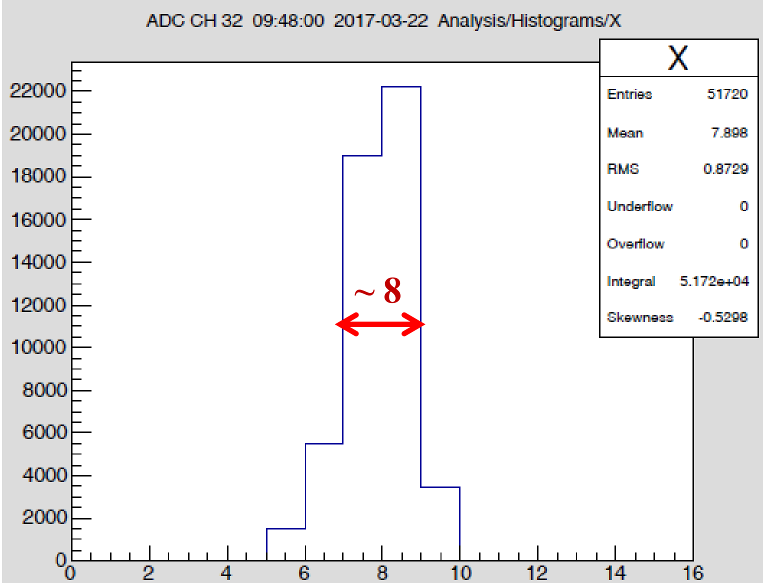


RIB's profile estimation in ^{15}N (49.7 AMeV) + Be (2 mm) reaction
(X_1 _Y_1 = 2_8 mm, ε = 35 mrad, Δp/p = 2.5%, W = 1 mm)

Beam profile of ^{15}N at F3 with ∅7 mm diaphragm at F1



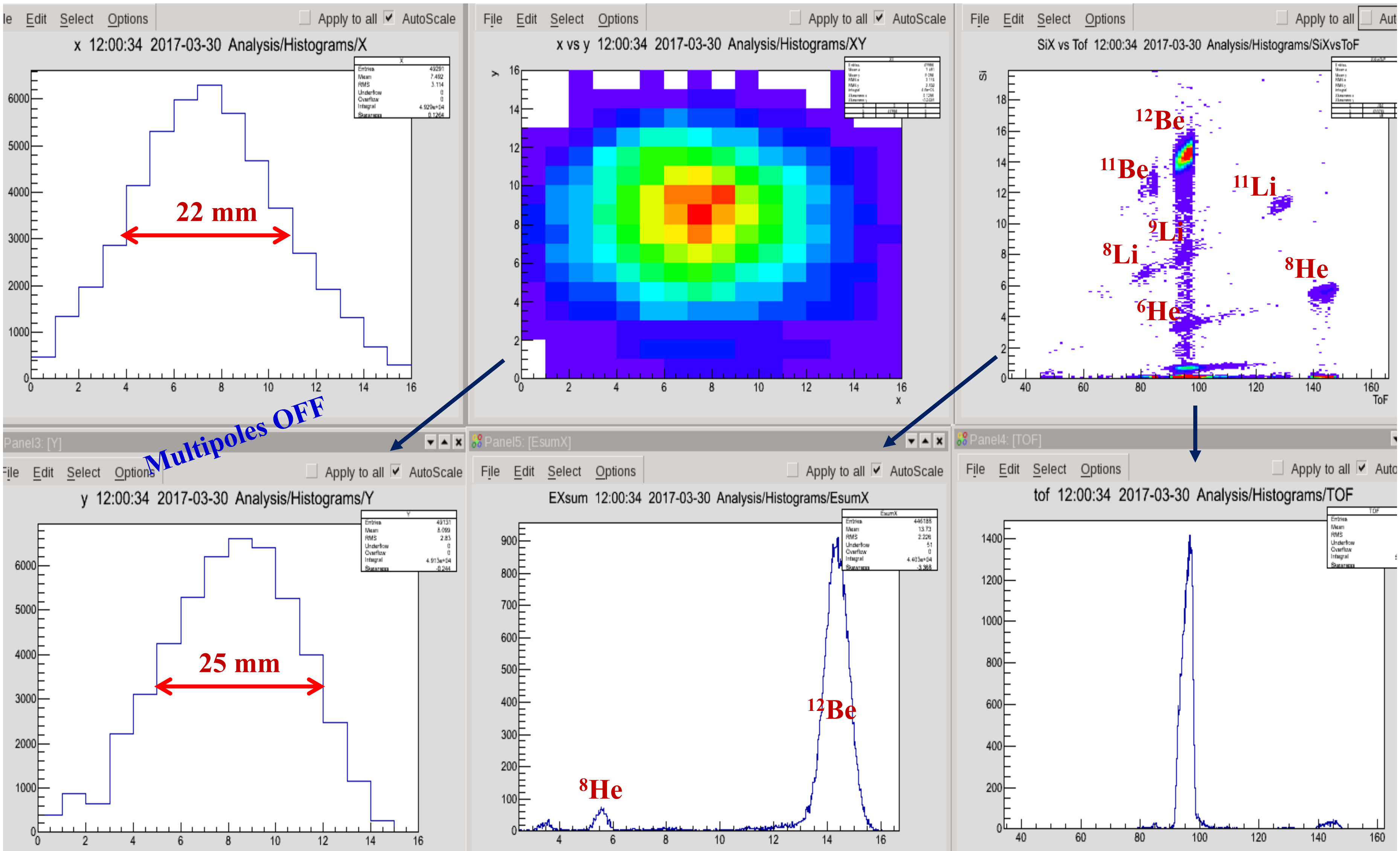




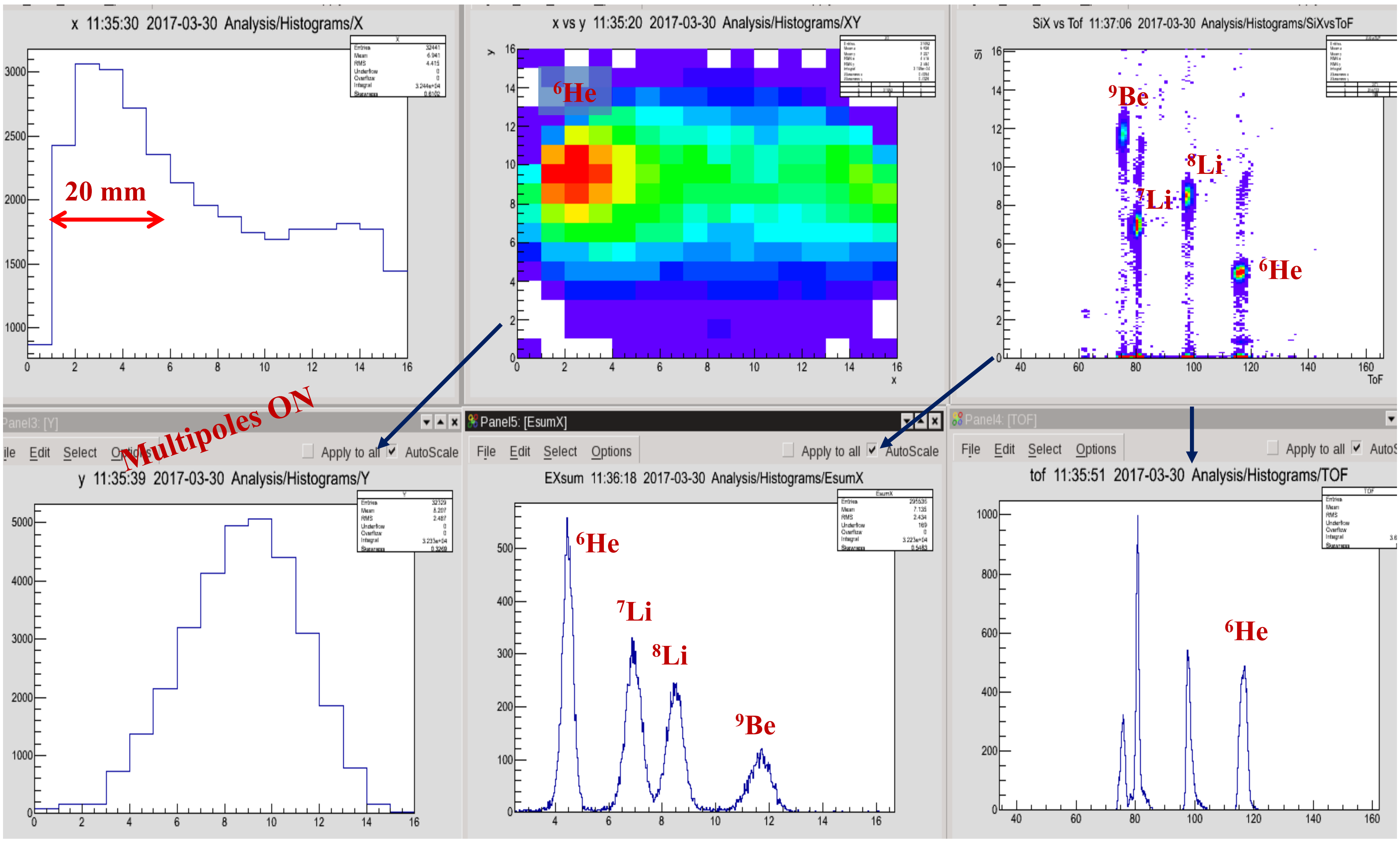
* Ion optics working well !

** RIB production could be started

^{12}Be from ^{15}N(49.7 AMeV) + Be(2 mm):
I = 190 1/s @ 1 pnA; Δp/p = 4%; P ~ 92%; E = 39.4 AMeV; X_5_Y_5 = 22_25 mm
Good agreement with calculation & Factor ~ 25 (I_Acc2 / I_Acc1)



^{6}He from ^{15}N(49.7 AMeV) + Be(2 mm):
I = 2700 1/s @ 1 pnA; $\Delta p/p$ = 2%; E = 31.5 AMeV;
X_5_Y_5 = 20_20 mm; P ~ 53% @ F3: ±11 mm



Good agrement with estimations

RIBs production rates in ^{15}N(49.7 AMeV) + Be(2 mm) reaction
F1: I(^{15}N) = 1 pnA @ 7 mm; F2: $\Delta p/p$ = 2%, Wedge_Be = 1 mm

RIB	Energy, MeV/nucl.	Intensity, 1/s
^{14}B	37,7	120
^{12}Be	39,4	150
^{11}Li	37,0	4
^{9}Li	33,1	1100
^{8}He	35,8	25
^{6}He	31,5	2700

Experiments in 2017

Main parameters (I, P, X_Y) are agree well with estimations

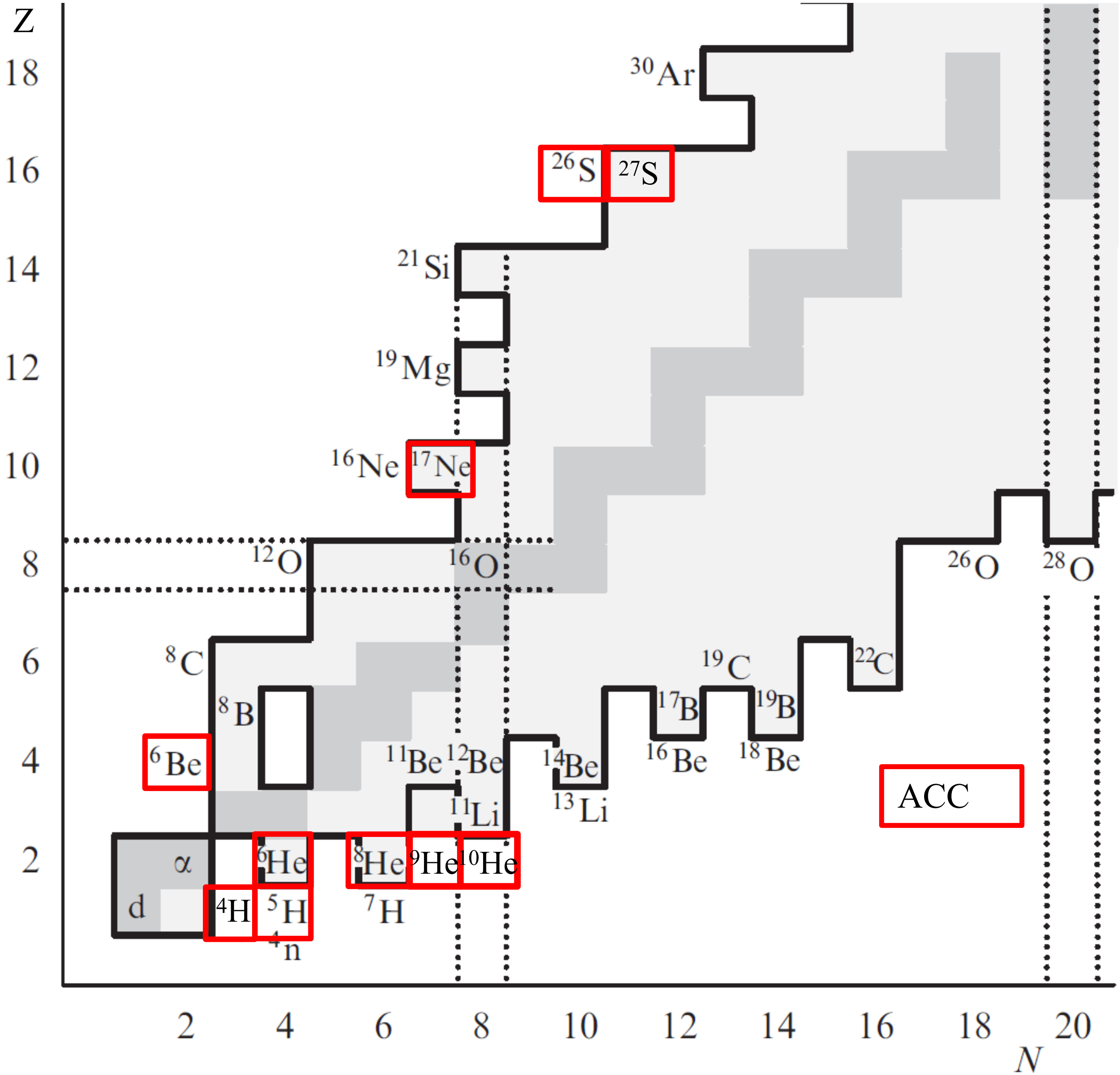
First experiments with RIBs could be started in 2017 (I < 0.1 pμA)

Experiments with intense primary beam (~ 1 pμA) will be able since 2018

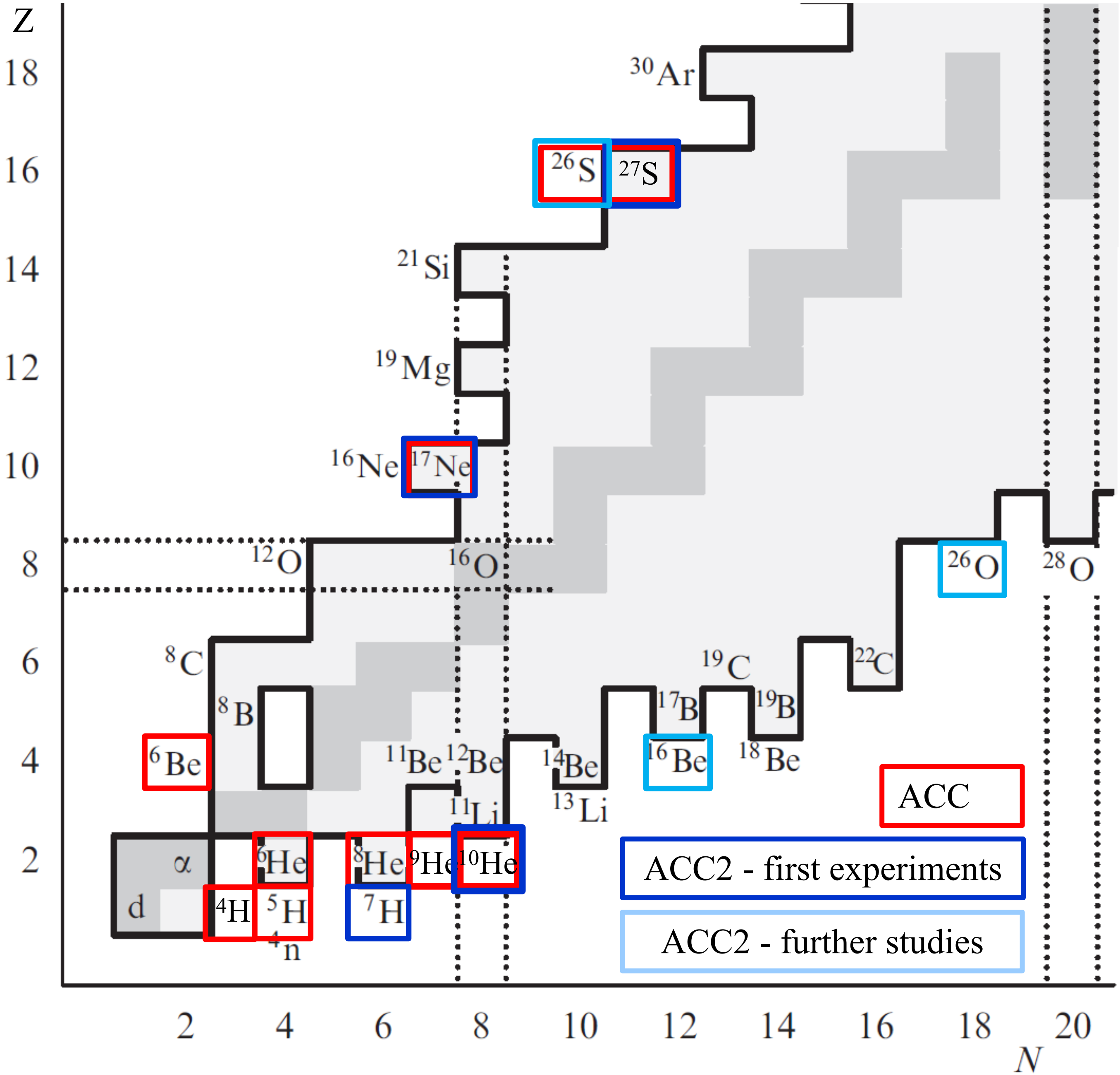
^{12}Be + d → ^{6}Li + ^{8}He (alpha transfer cross section)
^{6}He + d → ^{3}He + ^{5}H (proton transfer cross section)
Dovember 2017

Moving ahead to ^{7}H via ^{11}Li or ^{8}He
2018 - flagship exp.

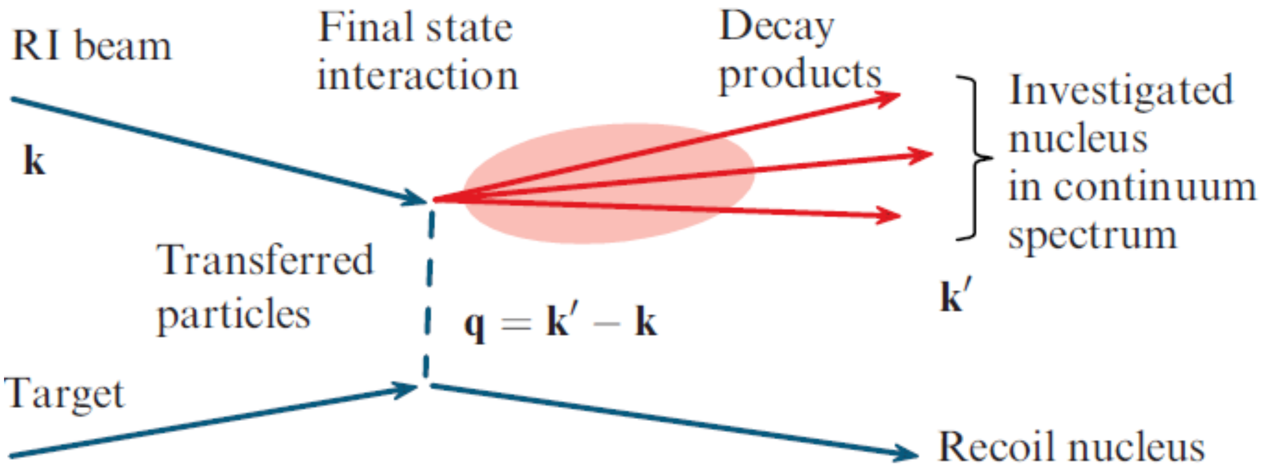
Scope of activity of ACCULINNA



Scope of activity for ACCULINNA-2

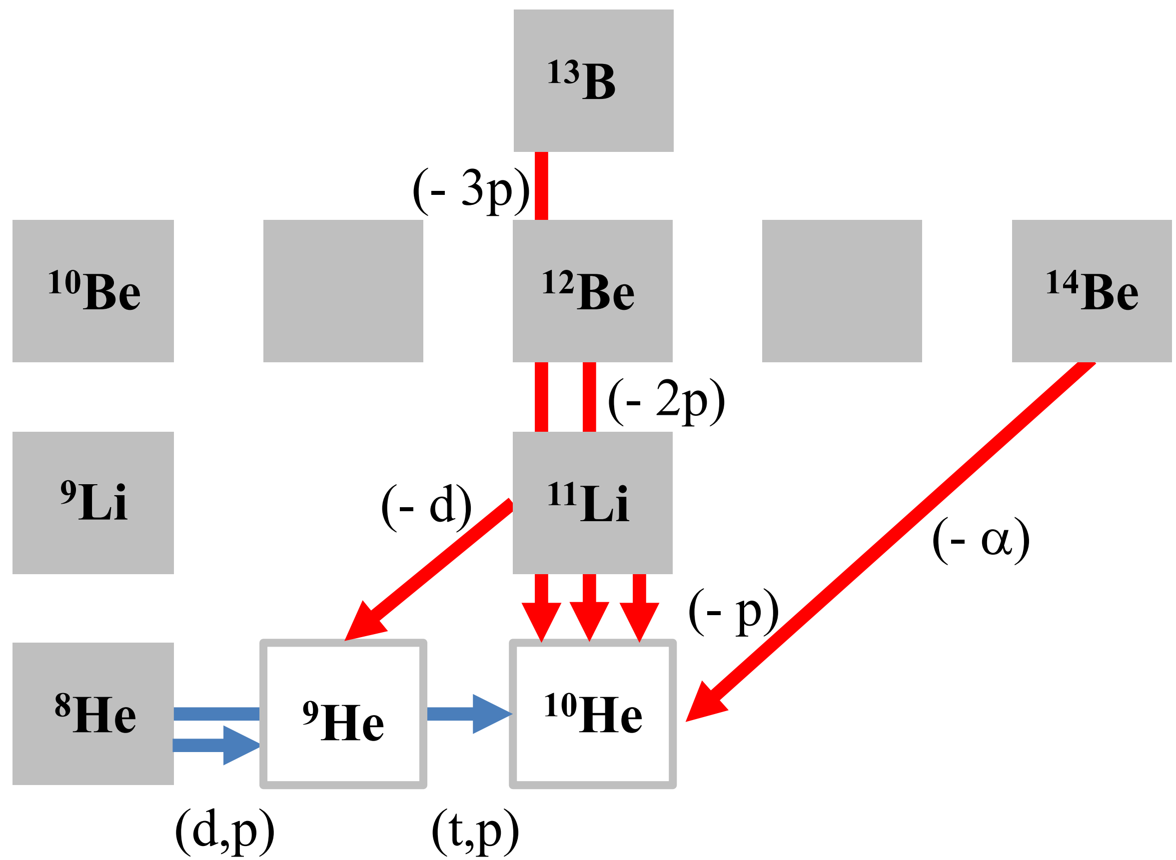


ACCULINNA-2 - reactions

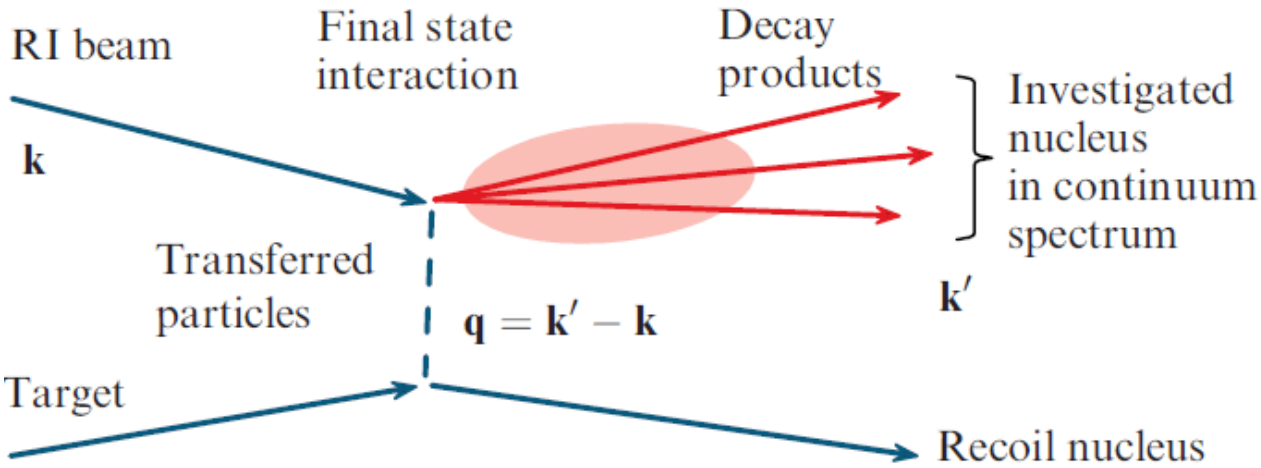


Pole mechanism inherent to the direct reactions

Reactions leading to the formation of heavy helium isotopes

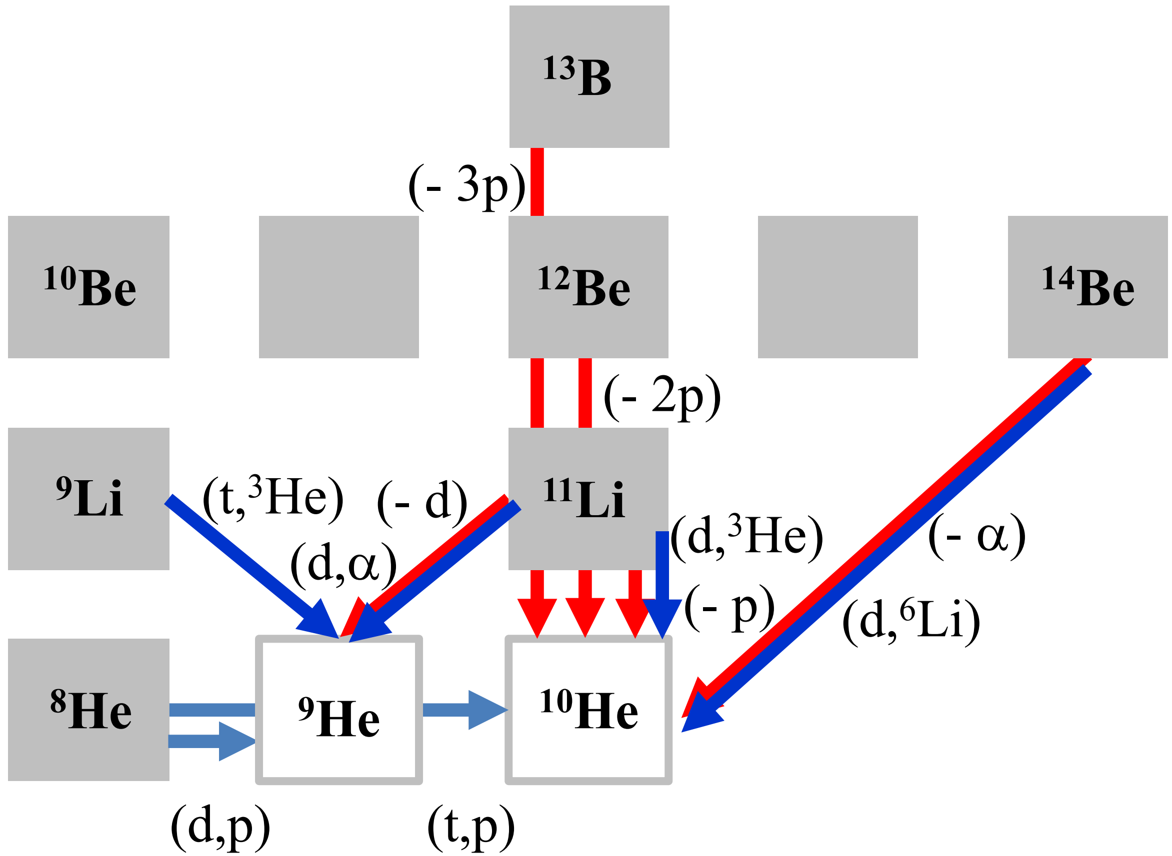


ACCULINNA-2 - reactions



Pole mechanism inherent to the direct reactions

Reactions leading to the formation of heavy helium isotopes



Plan for the year 2018:

^{6}He+d elastic and inelastic scattering at **θ_{lab} ~ 5-80 deg (~20-170 CMdeg)**

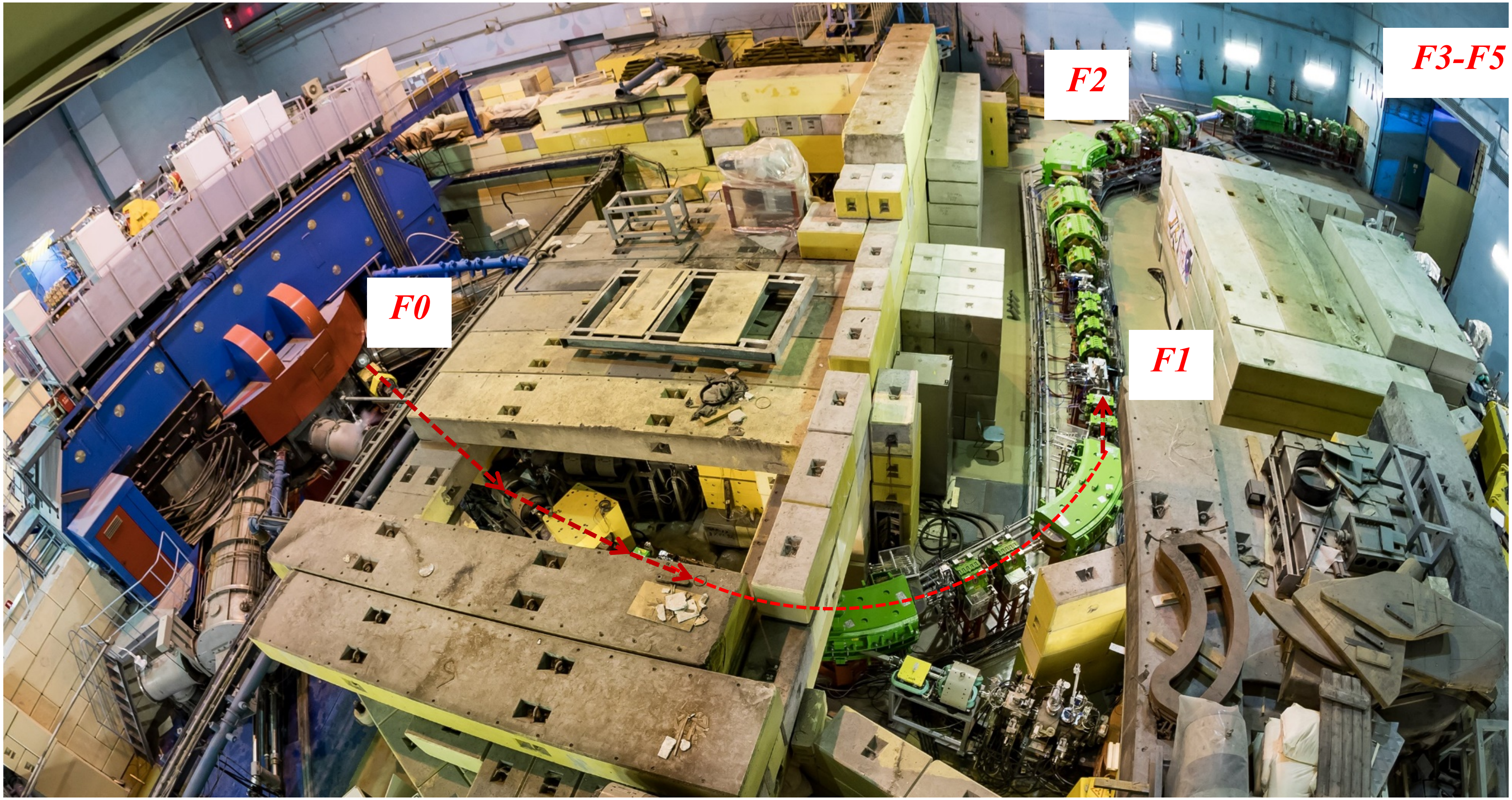
Beta-delayed alpha decay of ^{11}Be: ***re-investigation with the use optical-TPC***

***d*(^{6}He,^{3}He)^{5}H *invariant mass measurement* and *first attempt for d*(^{8}He,^{3}He)^{7}H**

	08.12.2017	*JANUARY*	*FEBRUARY*	*MARCH*	*APRIL*	*MAY*
1	КОМБАС, 10.01.18 – 29.01.18					
2	Ревизия, 29.02.18-04.02.18					
3	ACC-2, WU 04.02.18-23.02.18					
4	ACC-1, ЛРБ 25.02.18-27.02.18					
5	РОСКОСМОС, 01.03.18-15.03.18					
6	ACC-2, сект. 6, 17.03.18-15.04.18					
7	Переход на НЭ 15.04.18-29.04.18					

1. КОМБАС, 10 января – 29 января 2018, 11B 36A MeV, 1 eμA.
2. Ревизия каналов. 29 января – 04 февраля 2018.
3. ACCULINNA-1(?), эксперимент (Варшавский ун-т), 4 февраля – 23 февраля 2018, 11B, 32S(?), 36A MeV.
4. ACCULINNA-1, эксперимент (ЛРБ), 25 февраля – 27 февраля 2018, 32S?,11B.
5. РОСКОСМОС, 01 марта – 15 марта 2018.
6. ACCULINNA-2, эксперимент (сектор 6 ЛЯР), 17 марта – 15 апреля 2018, 11B, 36A MeV.
7. Переход на низкие энергии. 15 апреля – 29 апреля 2018.

Moving ahead to the flagship experiment ^{7}H

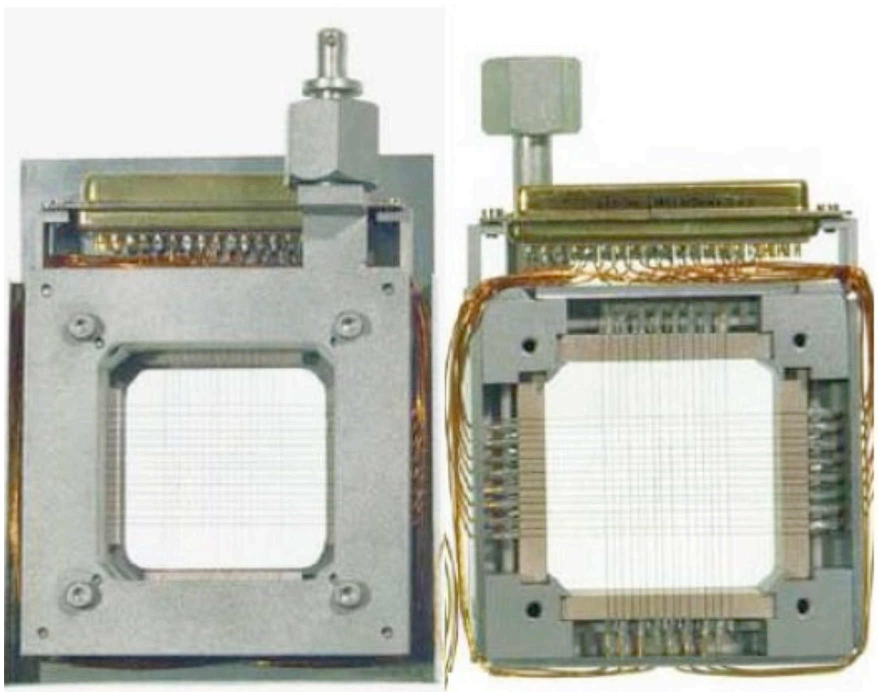


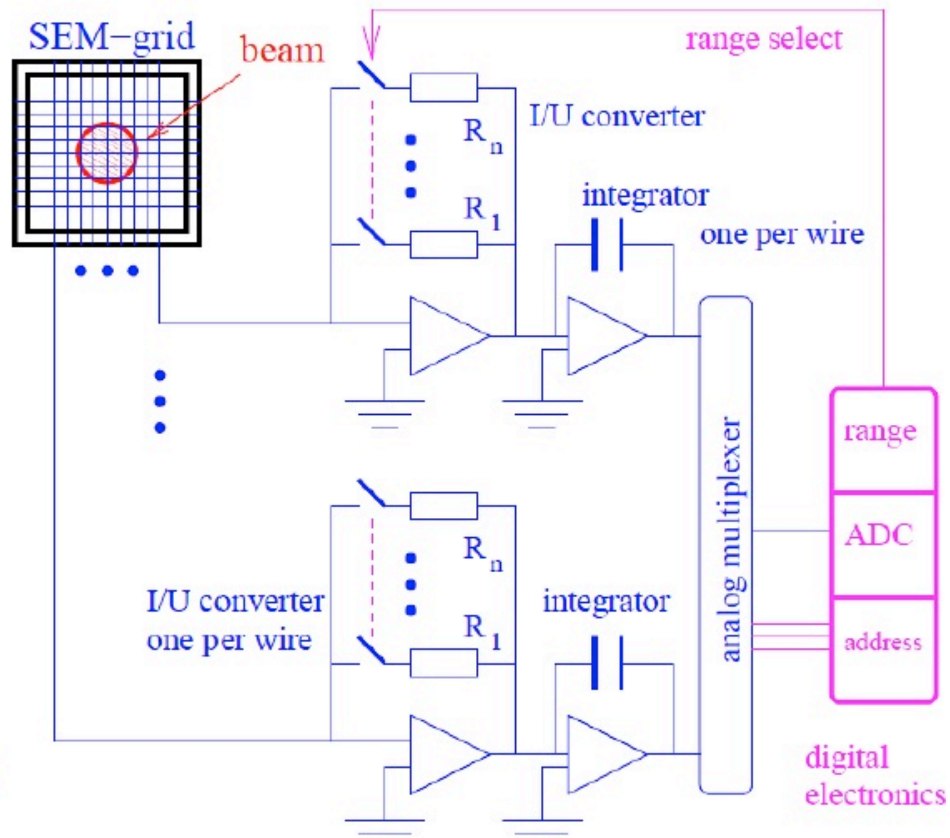
1. *Primary beam diagnostics along the line F0-F1 has been partly completed.*
2. *Radiation shell near movable gate at F3 was done; at F1-F2 area – 2018.*
3. *All communications at F3-F5 (electricity, water, air condition, reaction chamber etc.) were fully completed.*

Primary beam diagnostics along the line F0-F1: Faraday Cups & Al_2O_3

Secondary Electron Emission Crids with POLAND electronics (since 2018)

Example: 15 wire spaced by 1.5 mm:



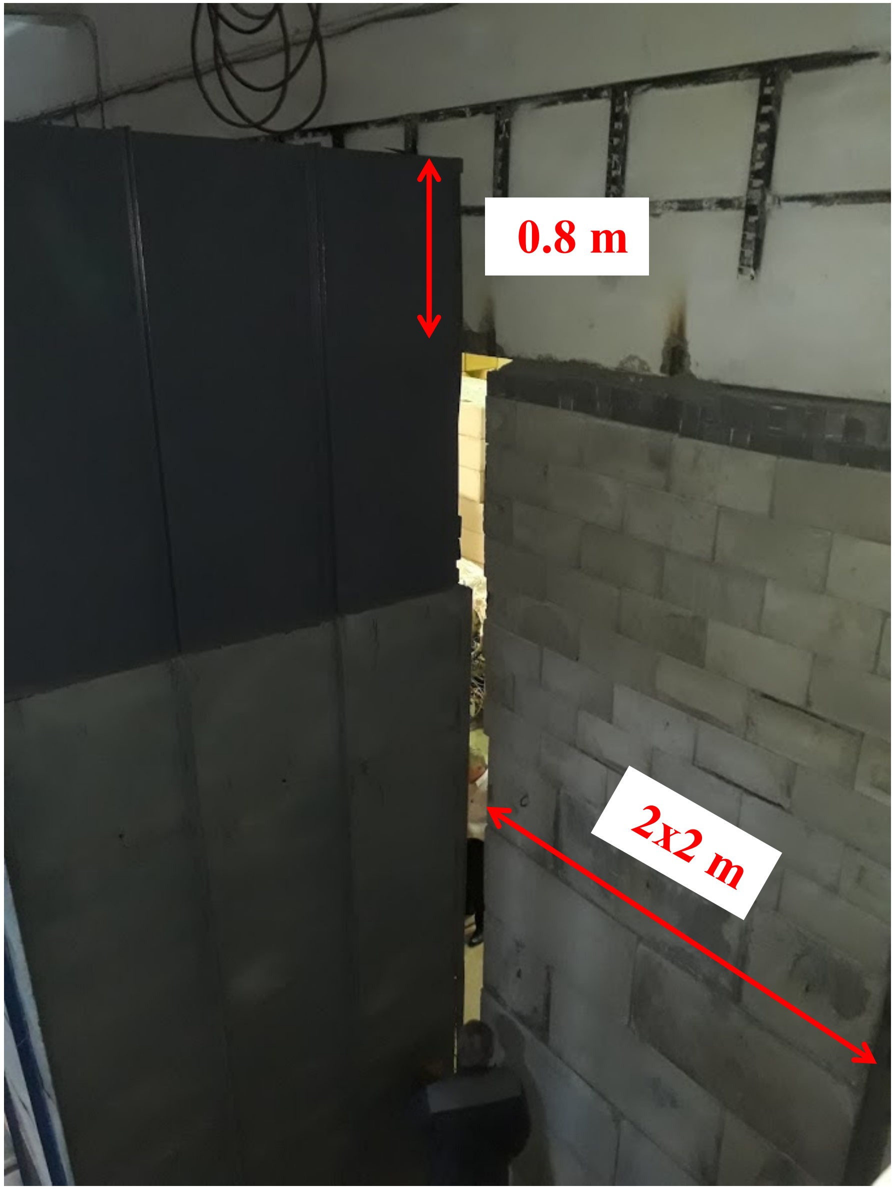


Each wire is equipped with one I/U converter different ranges settings by R_i

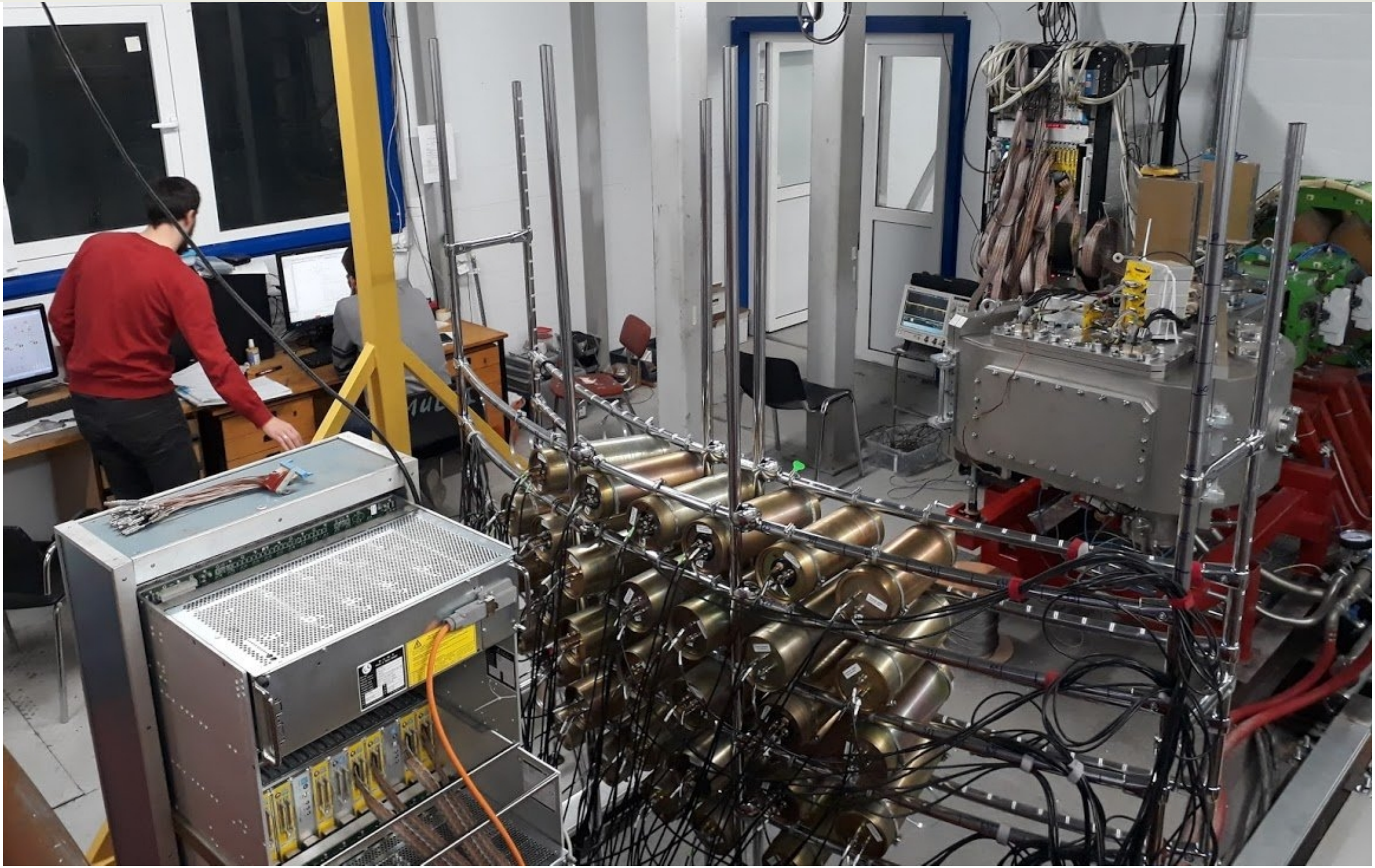
$\Rightarrow$ very large dynamic range up to 10^6.

I ~ $10^6 \div 10^{12}$ ions/wire,
permanent data,
~ 0.5 mm accuracy

Radiation shell in the area of movable gate was significantly reinforced:
a) column 2x2 m; b) top of the gate ++> overlap with a wall (August 2017)



F3-F5 area was fully completed by communications, equipment and electronics

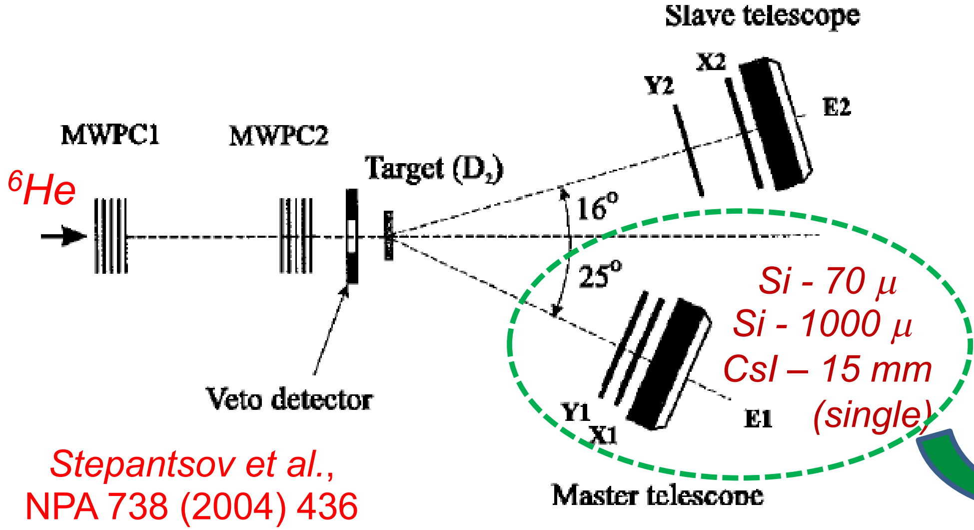


First experiment at ACCULINNA-2 was performed in December 2017 with ^{15}N primary beam (E~49 AMeV & I~0.1 pμA on the production target, Be 2 mm)

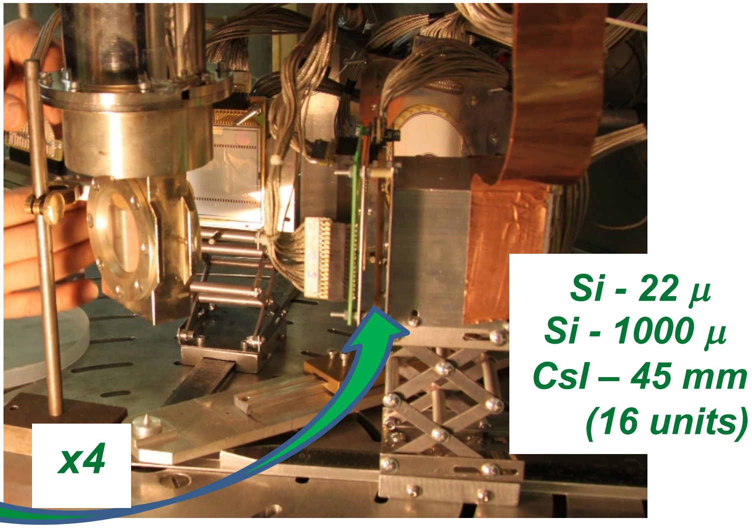
Plan on 2017: $d(^6He,^3He)^5H$ as a tool for the main run $d(^8He,^3He)^7H$

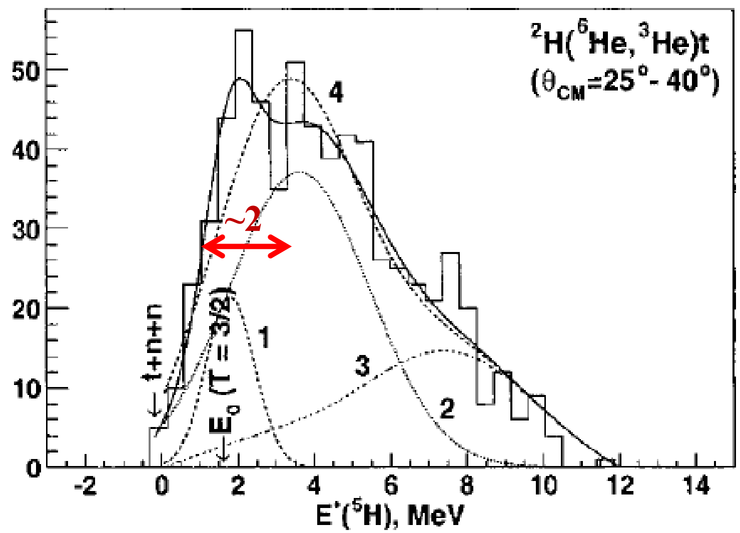
* cross section values for the *1p* and *1n* transfer reactions in a wide θ_{CM}

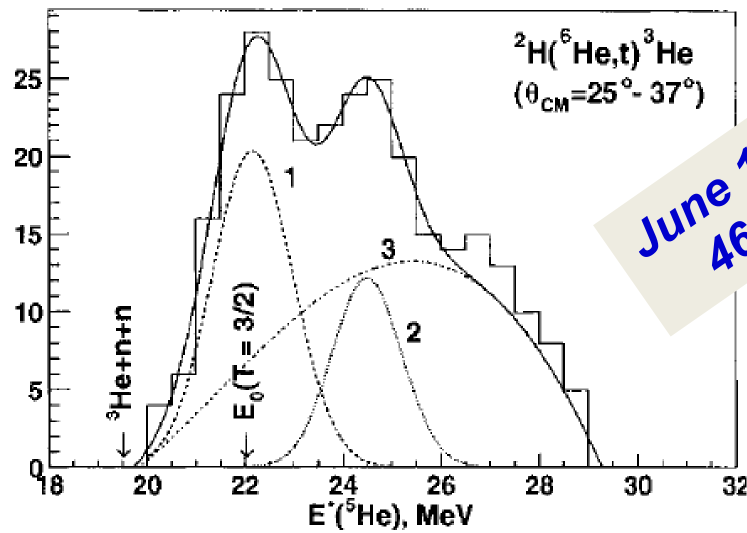
** improvement in missing mass measurements via novel telescopes



Stepantsov et al., NPA 738 (2004) 436







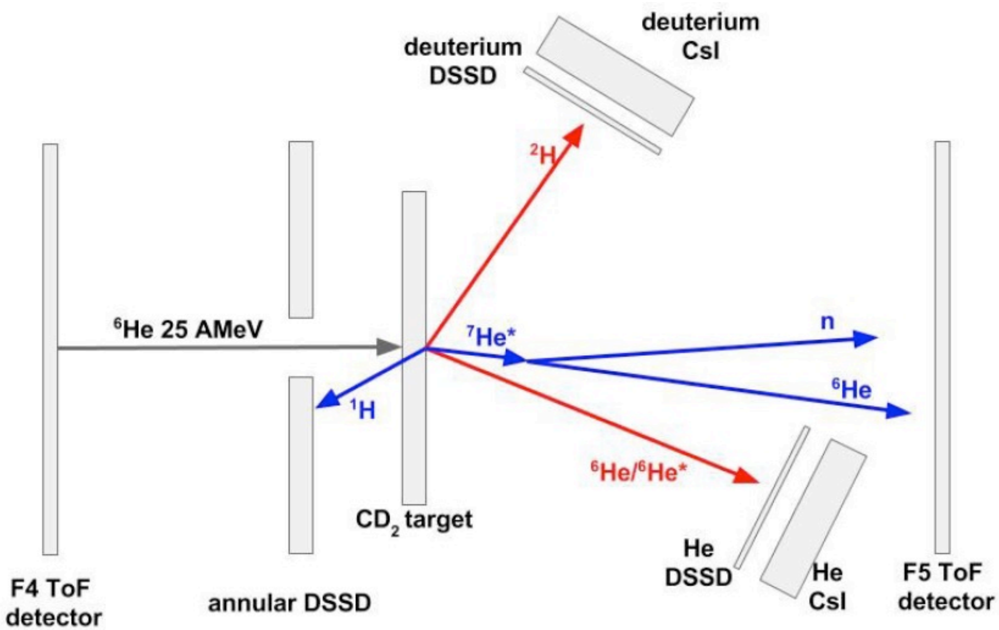
June 14, 2017
46th PAC

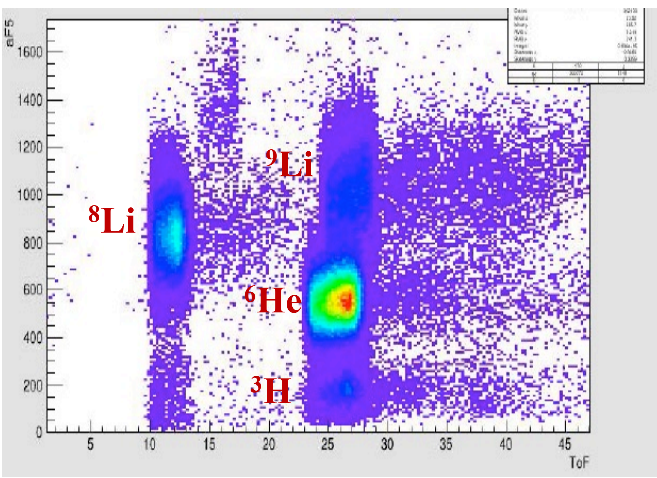
^5H (left) and ^5He (right) energy spectra depending on ^3He-t coincidences

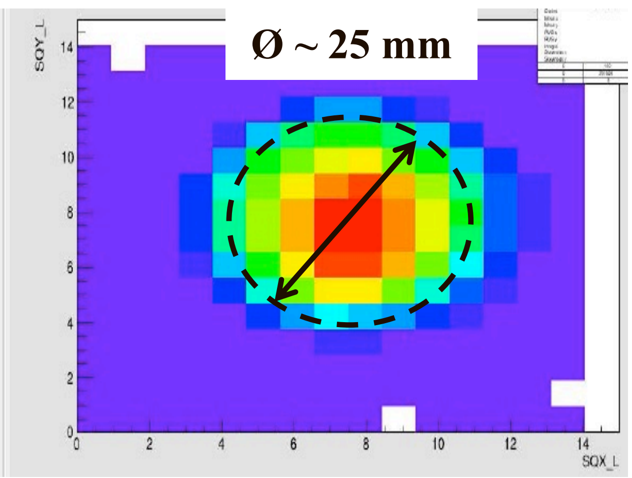
Experimental program in 2017 was a little bit modified:

^{6}He+*d* (elastic and inelastic scattering in a wide θ_{CM}) instead of *d*(^{6}He,^{3}He)^{5}H

Motivation: *pure information about OP, more simple run, short expositions*





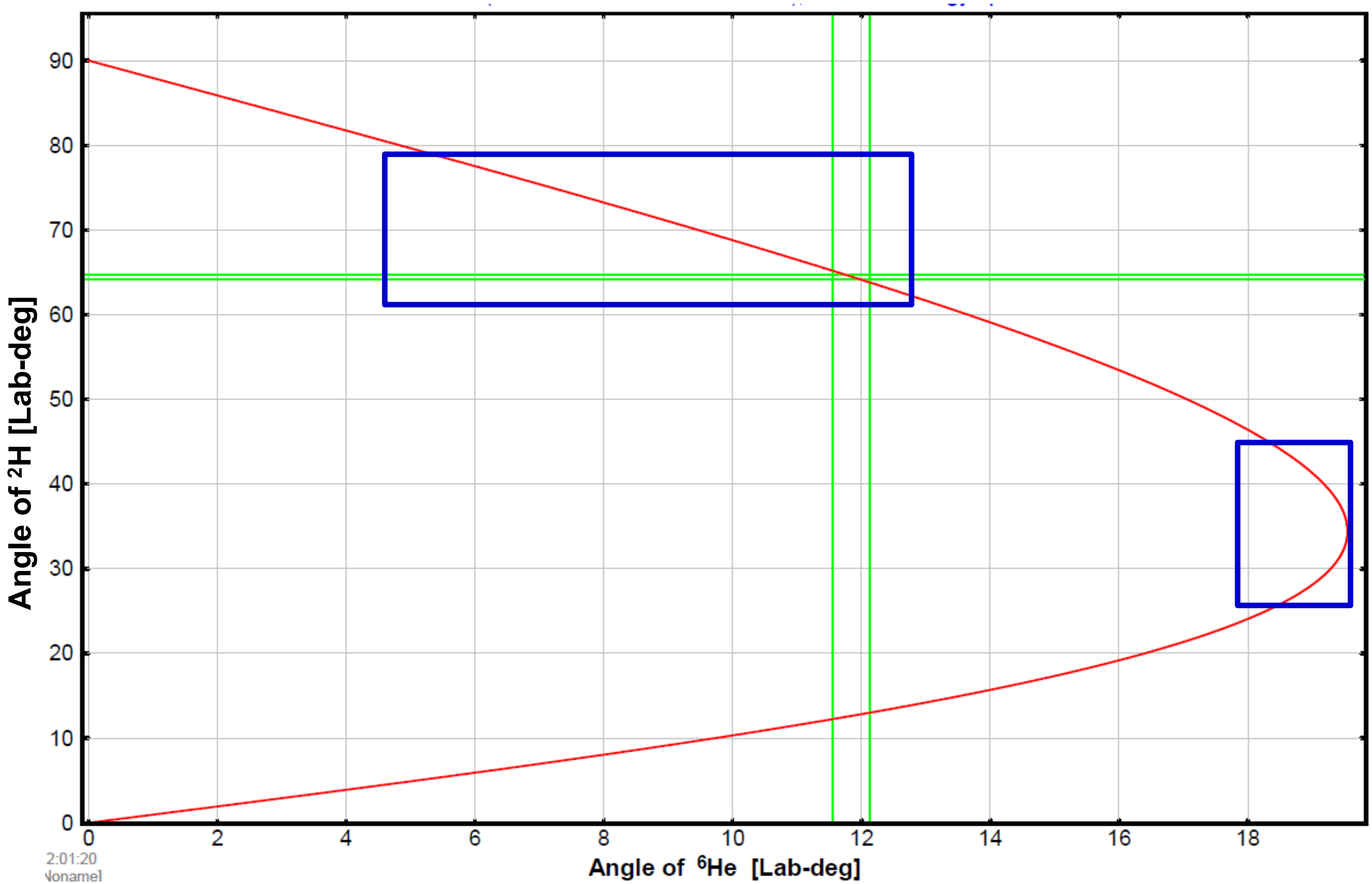


2x10^{5} ^{6}He/s @ 0.1 pμA
Δp/p = 3%
P ~ 75 %
E ~ 38 AMeV

Preliminary results of the first exposition in December 2017.

d-^{6}He coincidences were measured in the following two ranges:

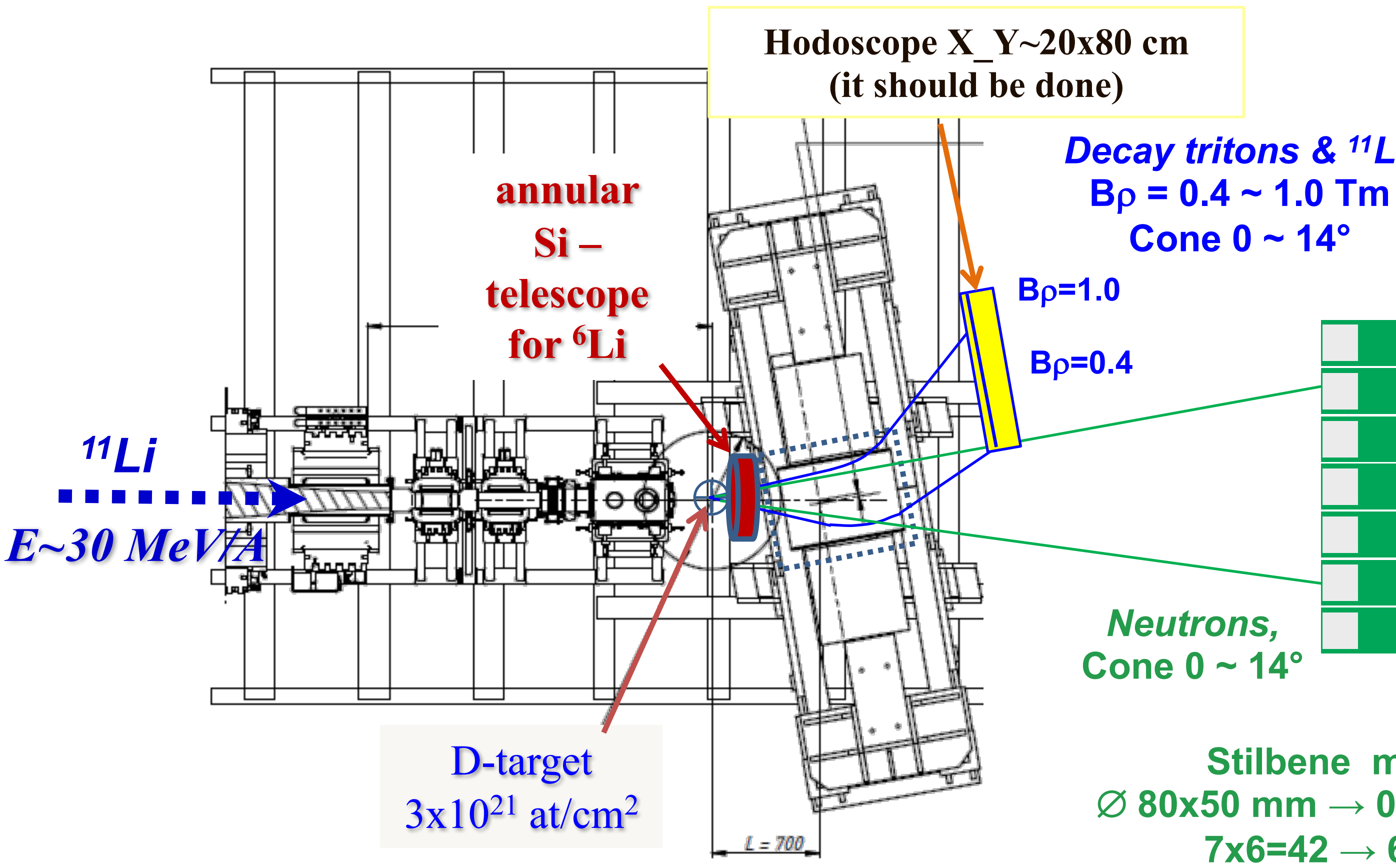
25-45 LABdeg (~130-90 CMdeg) and 60-80 LABdeg (~20-60 CMdeg)

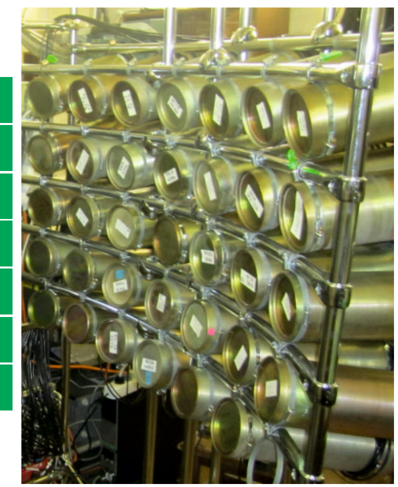


Plan: 5-80 LABdeg (20-170 CMdeg) for both elastic and inelastic process

Hunt for ^{7}H and search for the *4n* radioactivity in the *d*(^{11}Li,^{6}Li)^{7}H reaction

Plan on 2018





Stilbene modules
∅ 80x50 mm → 0.25° accuracy
7x6=42 → 64 units

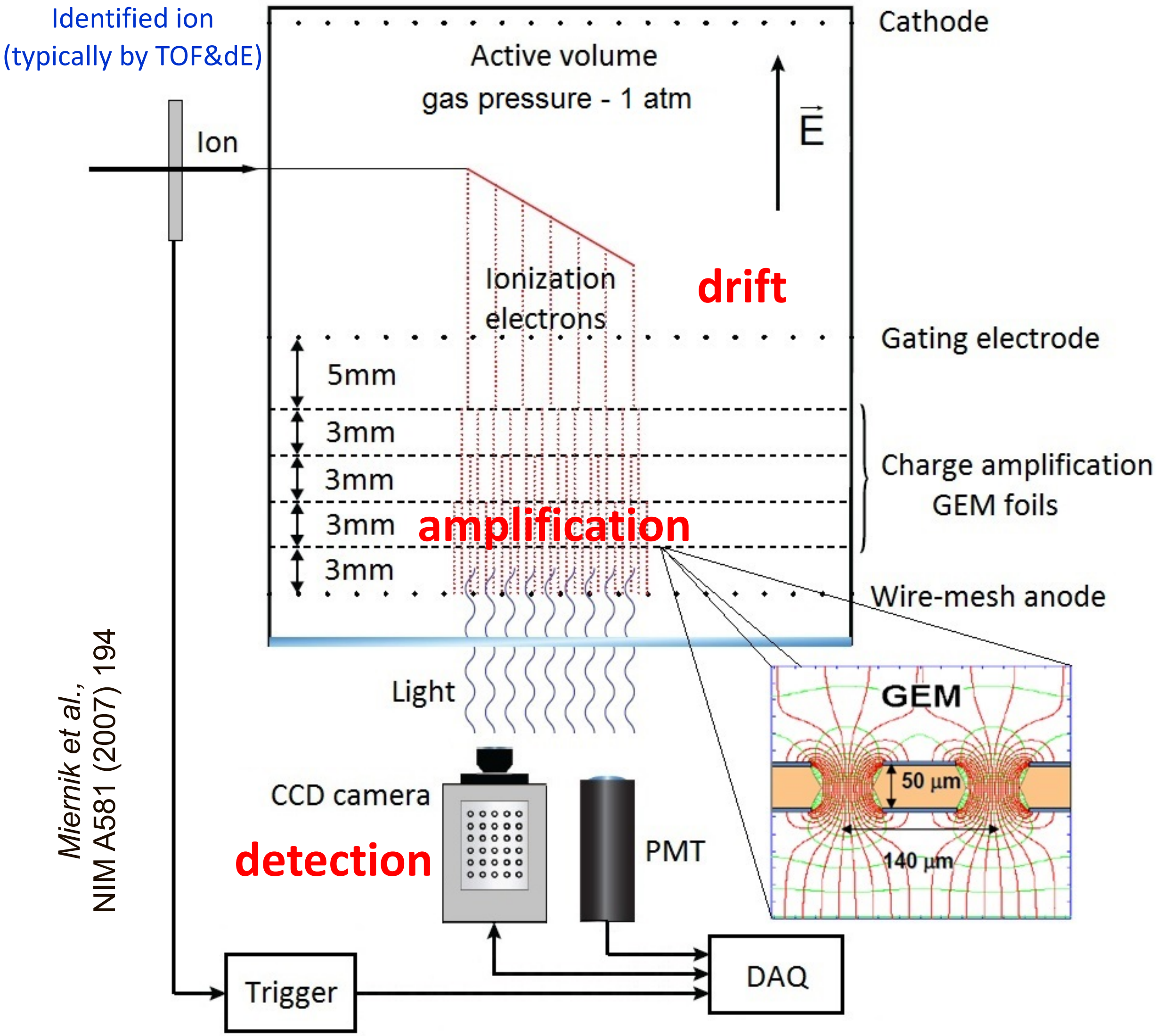
* *I(^{11}Li @ 30 AMeV) ~ 2x10^{4} pps ==>* ~ 100 ^{7}H events/day (*missing mass*)

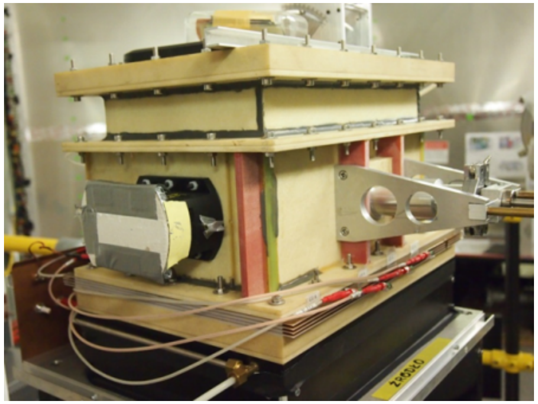
** Decay energy will be measured with around 100 keV resolution,

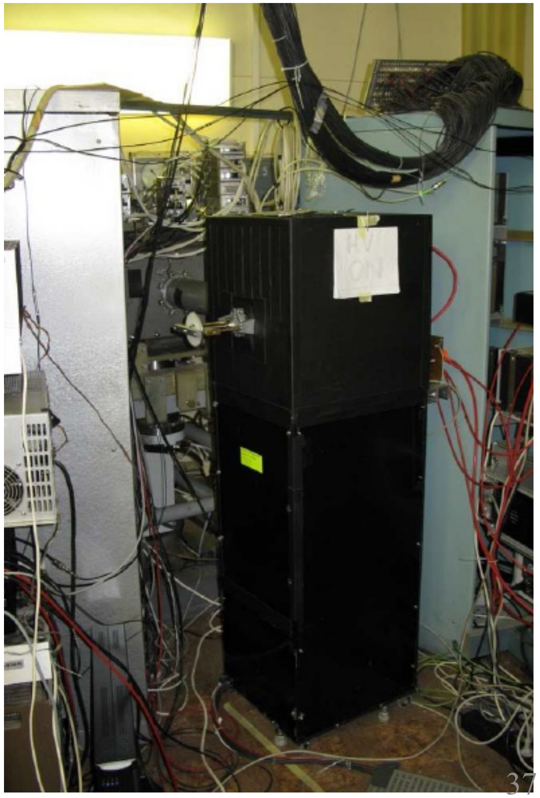
~ 3 events/day (*^{6}Li-t-n coincidences*)

Experimental tool - Optical Time Projection Chamber

Optical Time Projection Chamber (OTPC) - A new type of modern ionization chamber with an optical readout. Invented at the University of Warsaw by W. Dominik

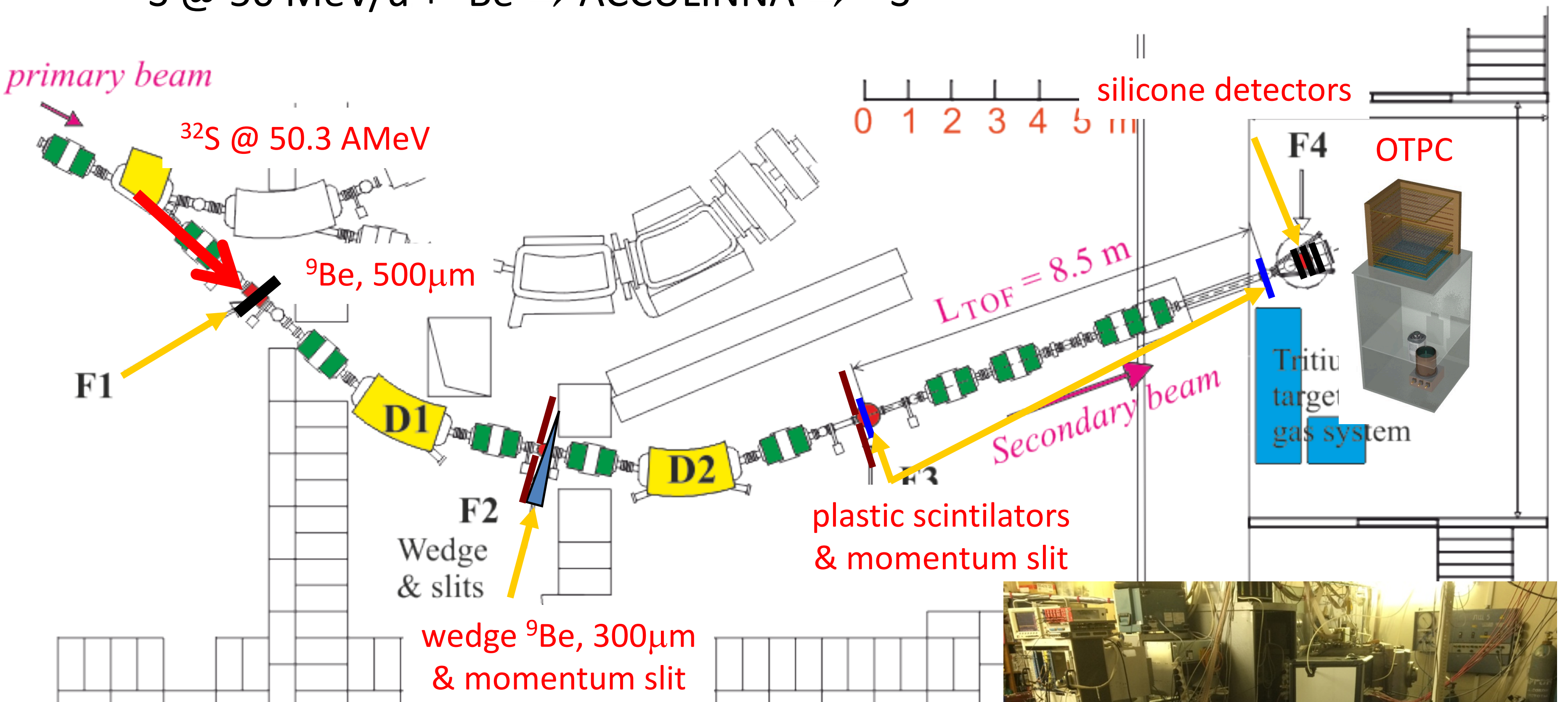


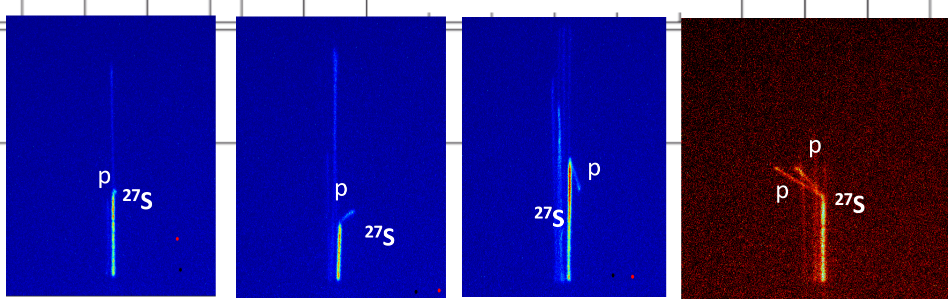


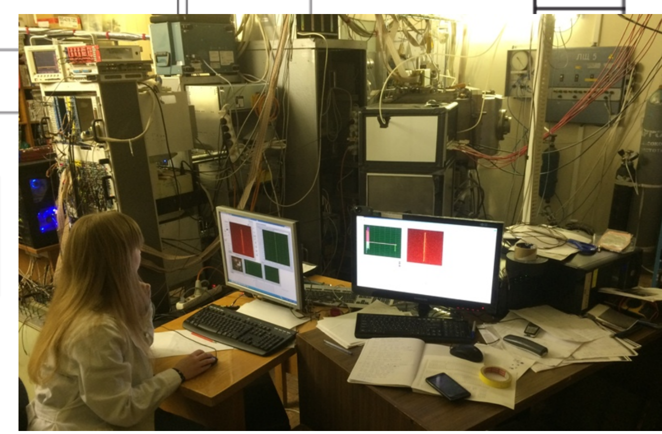


Study of β-delayed charged particle emission from ^{27}S and ^{26}P

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



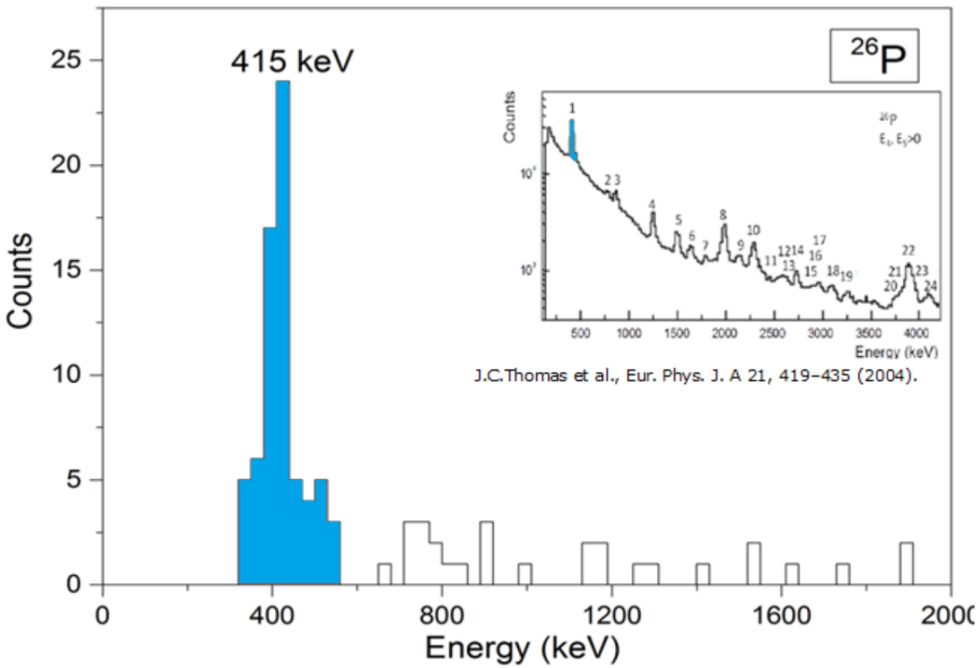


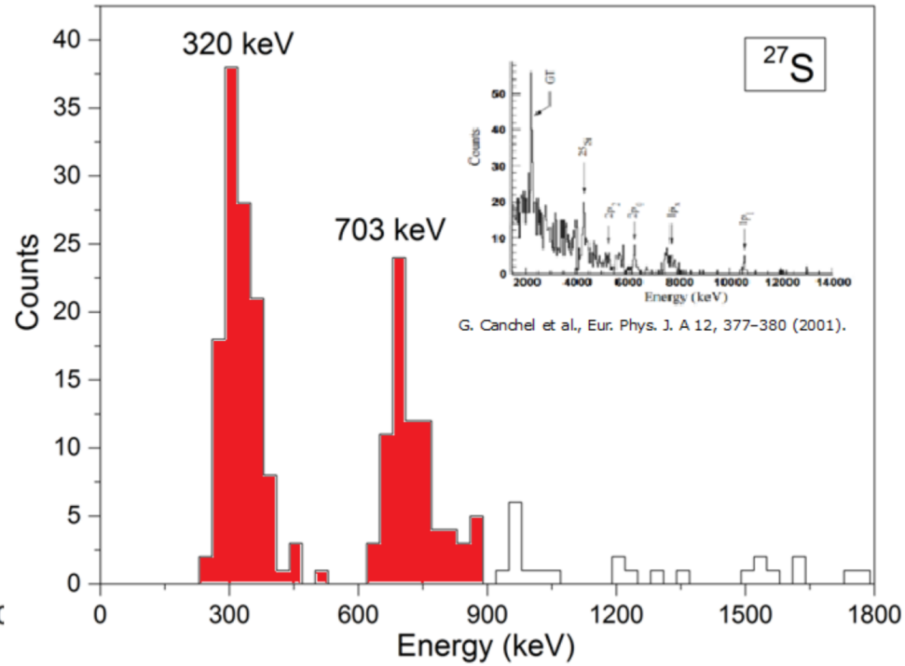


Data acquisition

L. Janiak, N Sokolowska et al., **PRC 95 (2017) 034315**

Study of β-delayed charged particle emission from ^{27}S and ^{26}P





^{26}P				^{27}S			
$P_{\beta p}$ 415 кэВ	$P_{\beta p}$ ~800 кэВ	$P_{\beta 2p}$	P_{tot}	$P_{\beta p}$ 320 кэВ	$P_{\beta p}$ 710 кэВ	$P_{\beta 2p}$	P_{tot}
10.4(9)% ÷ 13.8(10)%	1.1(3)%	1.5(4)%	35(2)%	24(3)% ÷ 28(2)%	> 6.7(8)%	3.0(6)%	64(3)%
17.96(90)%	2.5(3)%	2.2(3)%	39(2)%	2.3±0.9%		1.1±0.5%	~ 4%

Thomas et al., EPJ A21 (2004) 419

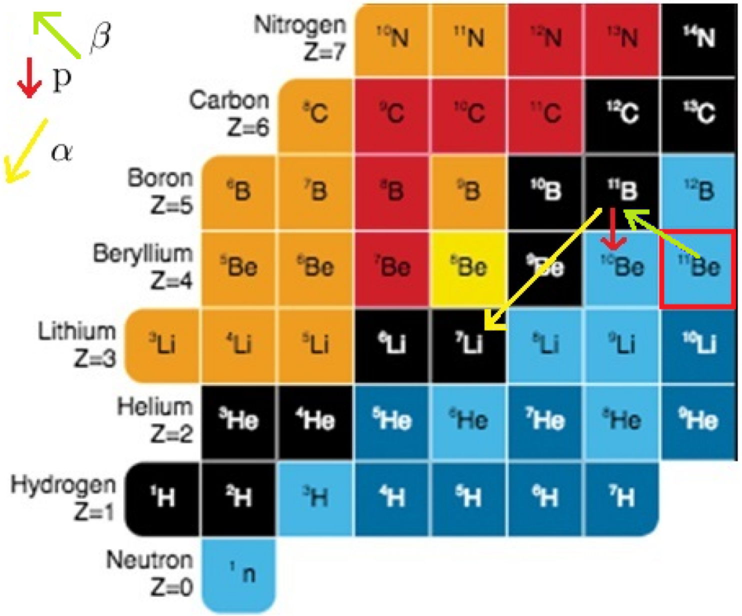
Canchel et al., EPJ A12 (2001) 377 $P_{\beta 3p} < 0.08\%$

***L. Janiak, N Sokolowska et al.*, PRC 95 (2017) 034315, *N Sokołowska* Master Thesis, AGH, Krakow 2016**

In 2018/2019 new measurments of *β*- delayed particle emission from ^{27}S @ **ACCULINNA-2** are planned → much better statistic of two orders of magnitude is expected (we plane tu purify the beam with RF-kicker)

Study of β-delayed particle emission from ^{11}Be

One of the approaches of study of ^{11}Be by means of the OTPC at ACCULINNA-2
Accurate determination of the branching ratio of β-delayed α emission decay



- 1n halo nucleus
- $T_{1/2} = 13.76(7)$ s
- decay modes:
  - β^-, BR = 100%
  - $\beta^-\alpha$, BR = 3.1(4)% [1]
  - β^-p, BR:
    - * theoretical predictions $\sim 10^{-8}$
    - * experimental indirect measurement $\sim 10^{-6}$ [2]
    - * NO DIRECT observation so far

[1] - D. Millener et al., Phys. Rev. C26 (1982) 1167-1185
[2] - K. Riisager et al., Phys. Lett. B 732, 305 (2014).

OTPC collaboration

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

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

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

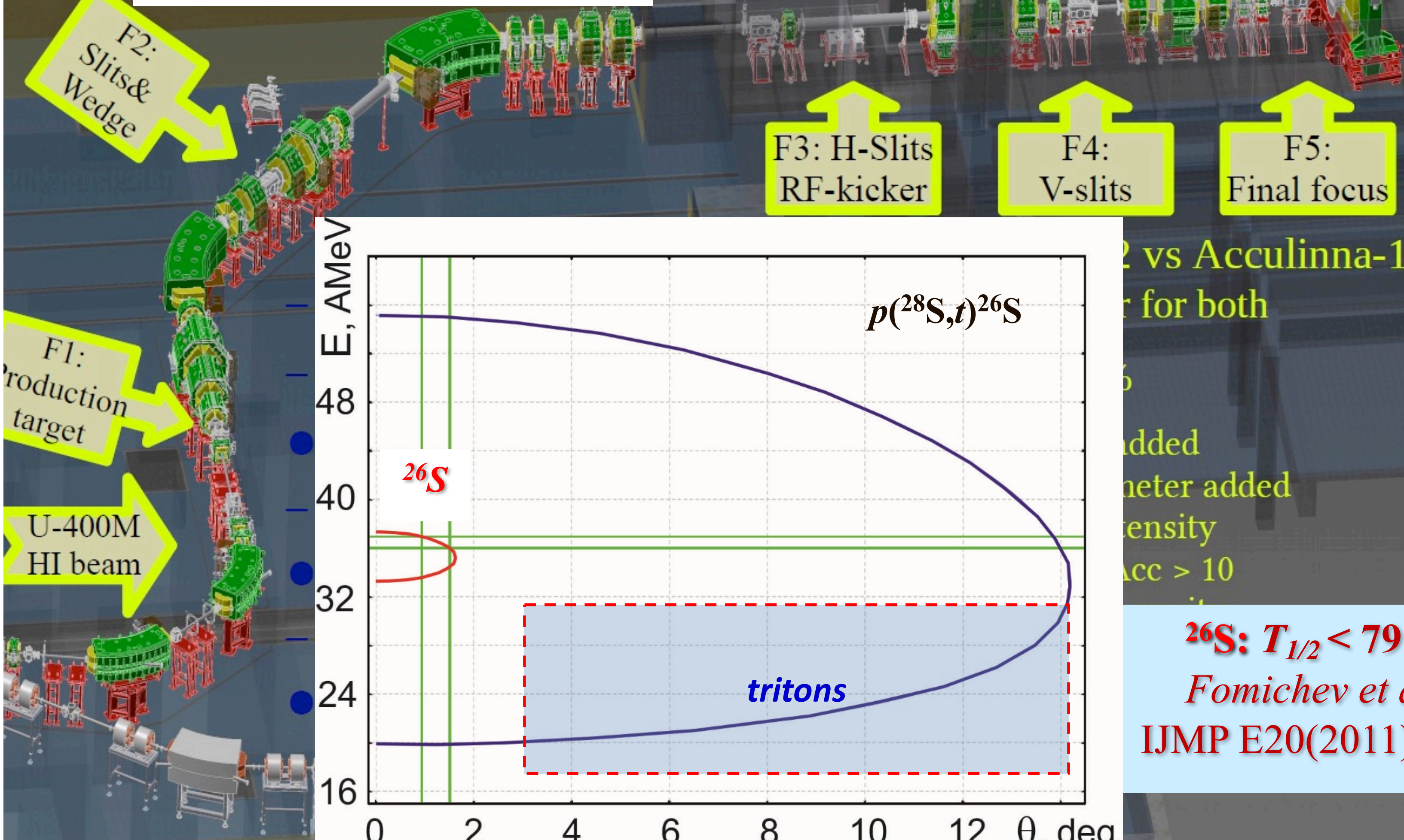
CERN - ISOLDE
- M. Kowalska
- M. Borge

Plan on 2019:

^{26}S in the reaction $p(^{28}S,t)^{26}S$: *I(^{28}S)~10^{3} pps, P~25%, E~38 MeV/A,*

1 mm liquid H_2, σ~200 μb/sr ==> ~ 10 events ^{26}S per week

Requests: ***RF-kicker*** **&**
zero angle spectrometer



^{26}S: $T_{1/2}$ < 79 ns
Fomichev et al.,
IJMP E20(2011)1491

Summary and outlook

- ACCULINNA-2 fragment separator commissioned in 2017 is now ready for first-day experiments.
- The intensities obtained in the fragmentation reaction ^{15}N (49.7 AMeV) + ^{9}Be for the RIBs of ^{14}B, ^{12}Be, $^{9,11}Li$, $^{6,8}He$ were on average 25 times higher in comparison with the values for old facility.
- The first-priority experimental program with RIBs is focused on ^{6}He+d scattering, beta-delayed exotic decays of ^{11}Be and $^{5,7}H$ study.
- Further experiments (with RF-kicker and zero angle spectrometer) will be aimed on ^{26}S observation in (p,t) reaction with ^{28}S.
- We are open for collaboration

Thank you for attention