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National Research Foundation
iThemba LABS
Laboratory for Accelerator Based Sciences

Nuclear structure studies at iThemba LABS relevant for neutrino physics

R Neveling[1], P Adsley[2], L Donaldson[1,3], P Papka[1,4],
L Pellegri[1,3], FD Smit[1], GF Steyn[1]

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[2] IPN Orsay
[3] University of the Witwatersrand
[4] Stellenbosch University

$0\nu\beta\beta$: Role of nuclear reaction studies

Observation of lifetime of $0\nu\beta\beta$ & knowledge of the **NME** will yield information on neutrino mass

Measure matrix elements

- heavy-ion double charge exchange reactions:
  NUMEN@LNS & RCNP
  - low cross-sections

OR

Constrain matrix elements

- constraining models by measuring numerous nuclear structure observables through single nucleon & pair transfer
- also requires magnetic spectrometer facilities, **BUT**
  "suitable magnetic spectrographs ... on the verge of extinction"
  "dwindling facilities ... RCNP Osaka, IPN Orsay, Munich Q3D..."

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"dwindling facilities ... RCNP Osaka, IPN Orsay, Munich Q3D..."

...soon also TUNL Split-pole & FSU Split-pole...

Add iThemba LABS to list of existing facilities

iThemba LABS in Cape Town, South Africa

Largest National Research Facility in SA and the largest accelerator facility in the southern hemisphere :

- more than 55% of the NRF budget for research facilities (~20M USD)
- approx 300 staff members

SEPARATED SECTOR CYCLOTRON
30 YEARS
1987 - 2017

- Fundamental studies of nuclear phenomena,
- Applications of ion beams, nanoscience research,
- Research and development of radionuclides for science & medicine
- Radiation biology and particle therapy
- AMS

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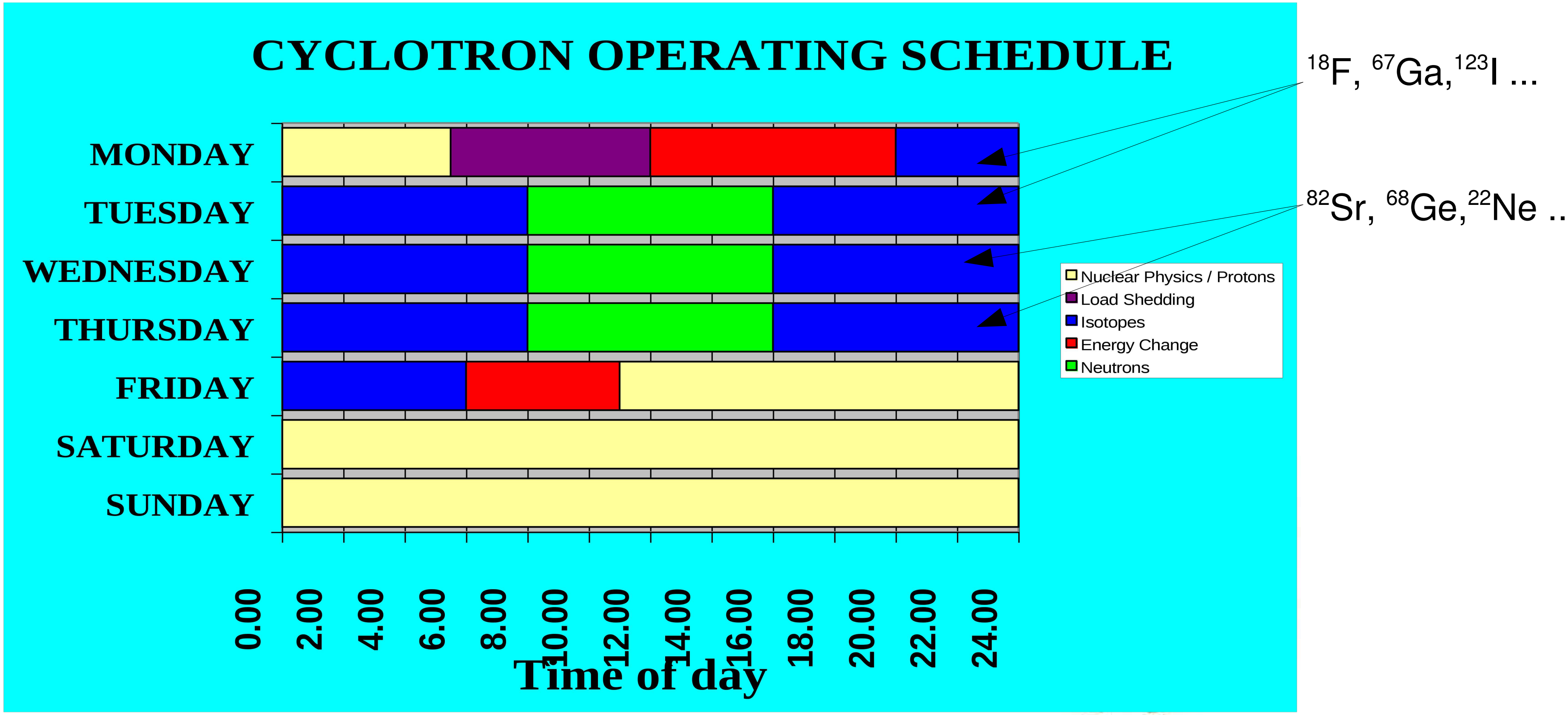
iThemba LABS: SSC facility

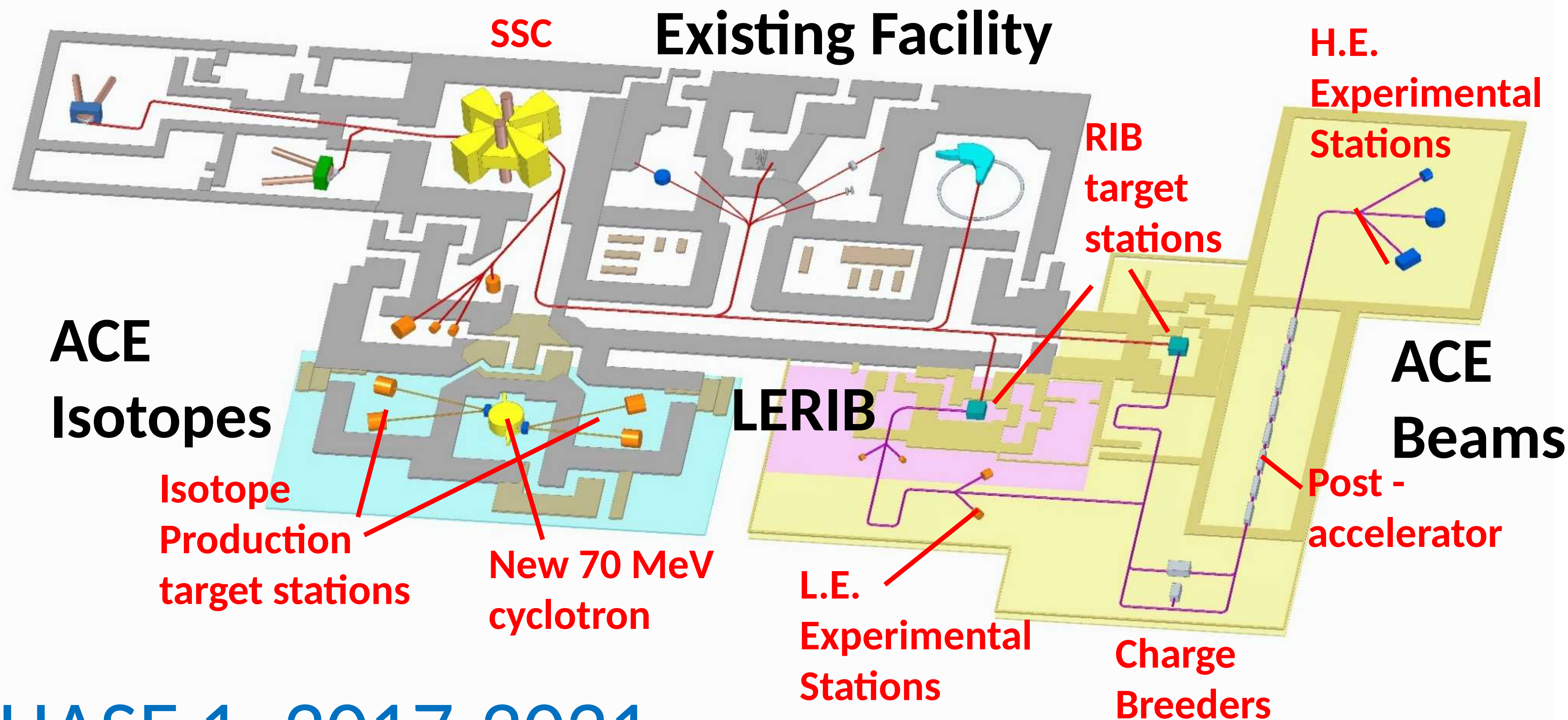
Big problem for overseas collaborators: fragmented beam schedule
e.g. 6 day experiment requires visit of 3 weeks



Changes in scheduling regiment:

- with immediate effect: Wed PM to Mon AM possible
- SAIF will make 24-7 running possible

South African Isotope Facility (SAIF)



PHASE 1: 2017-2021

- ACE-ISOTOPES, new 70 MeV cyclotron at iThemba LABS
- Isotope Production off SSC and onto new cyclotron
- Free SSC for research
- **More than doubles physics beam time (including stable light and heavy ions)**
- Production of low energy radioactive beams using the ISOL method

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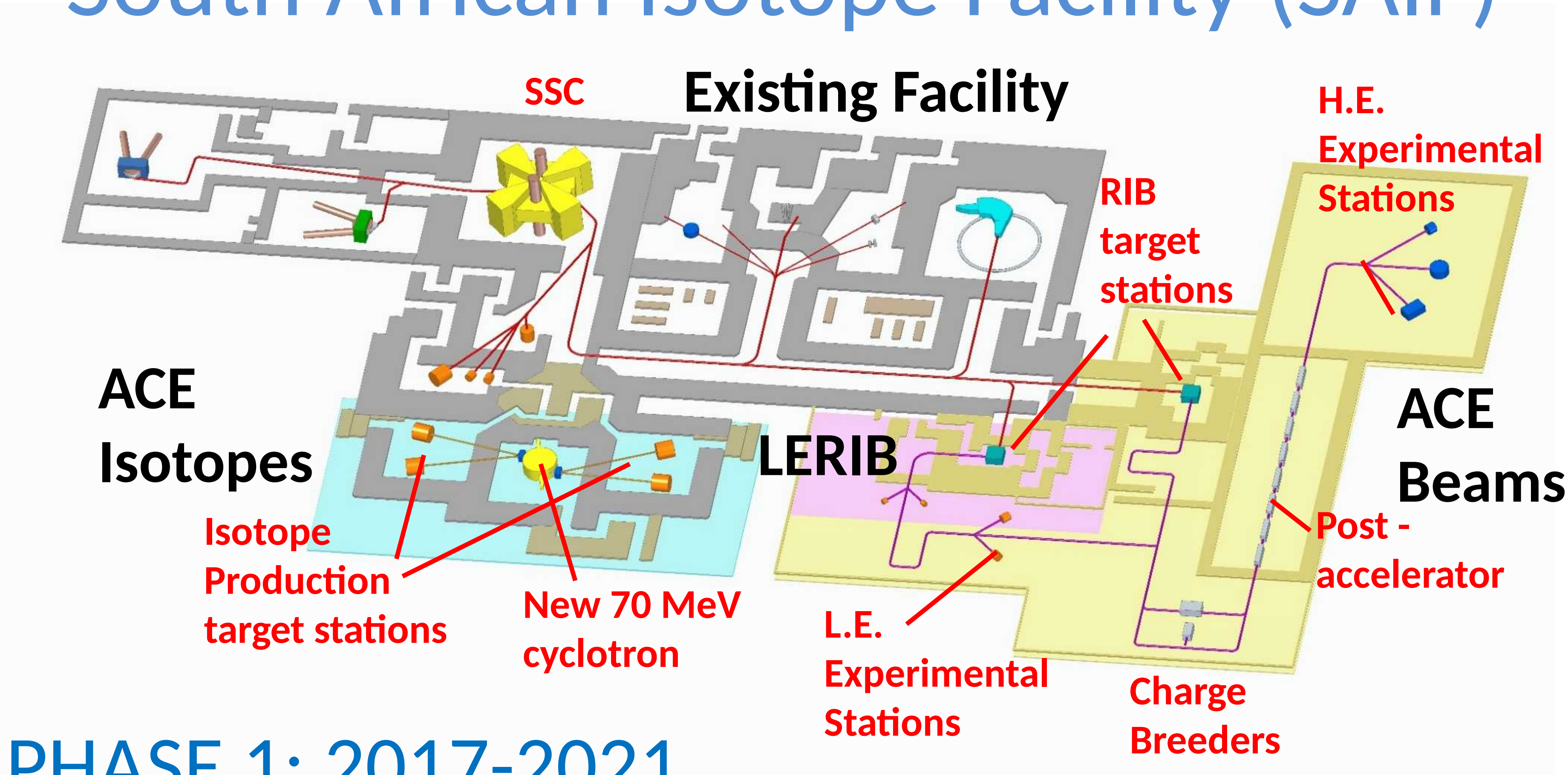


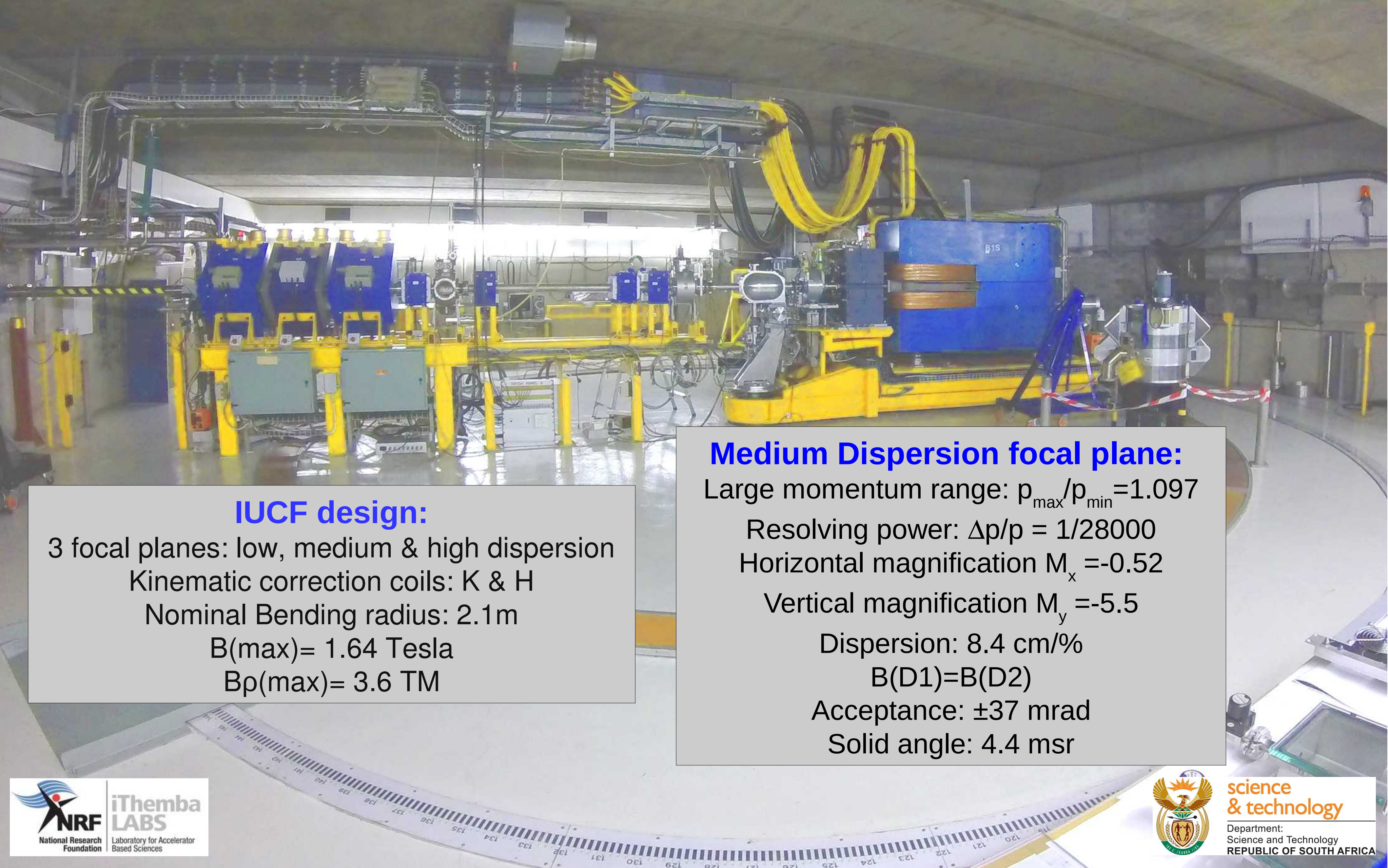
PHASE 1: 2017-2021

The budget speech of the minister of Science and Technology (16/05/2017)

"The NRF supports a transdisciplinary research agenda at the iThemba Laboratory for Accelerator-Based Sciences. This facility, which has developed a plan for the South African Isotope Facility, will support research in nuclear physics, materials sciences, radiobiology and the production of rare and exotic radio-isotopes for the medical industry."

0νββ: Role of nuclear reaction studies: The K600 at iTL

A kinematically corrected QDD magnetic spectrometer for light ions



IUCF design:

3 focal planes: low, medium & high dispersion
Kinematic correction coils: K & H
Nominal Bending radius: 2.1m
B(max)= 1.64 Tesla
Bρ(max)= 3.6 TM

Medium Dispersion focal plane:

Large momentum range: p_{max}/p_{min}=1.097
Resolving power: $\Delta p/p$ = 1/28000
Horizontal magnification M_x =-0.52
Vertical magnification M_y =-5.5
Dispersion: 8.4 cm/%
B(D1)=B(D2)
Acceptance: ±37 mrad
Solid angle: 4.4 msr

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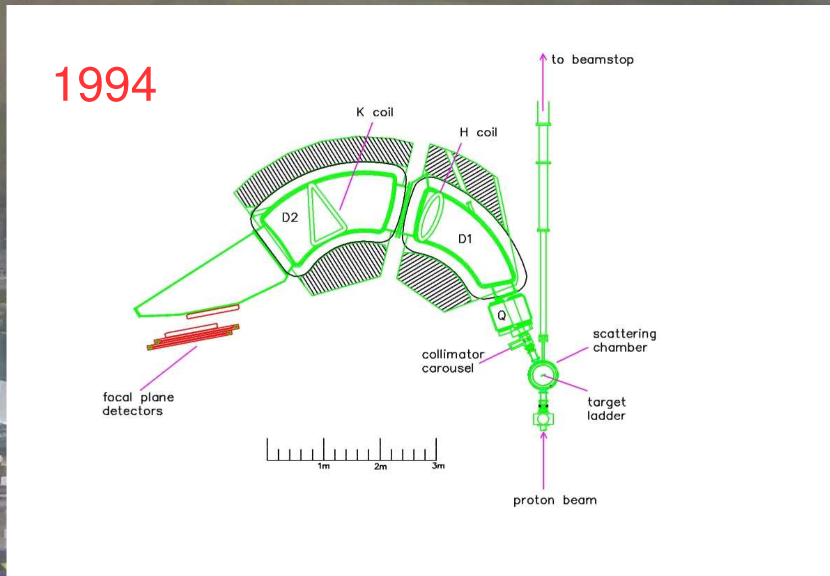
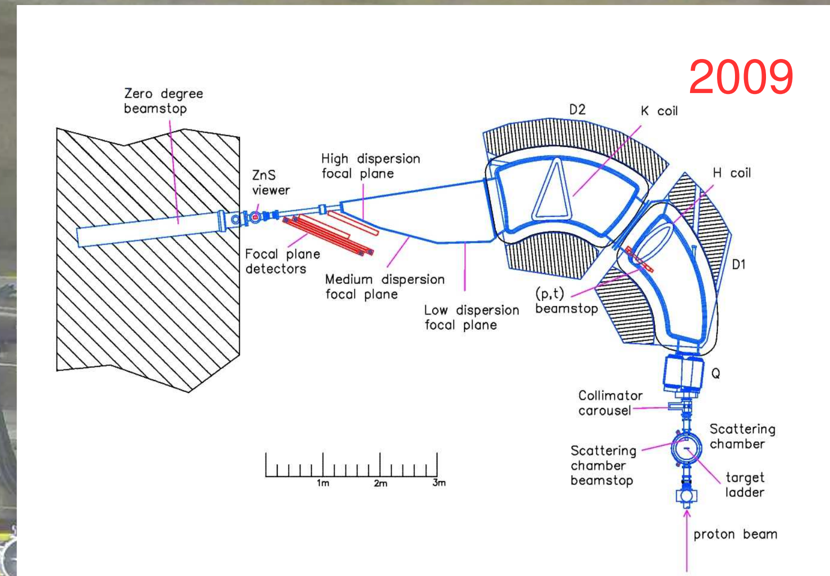
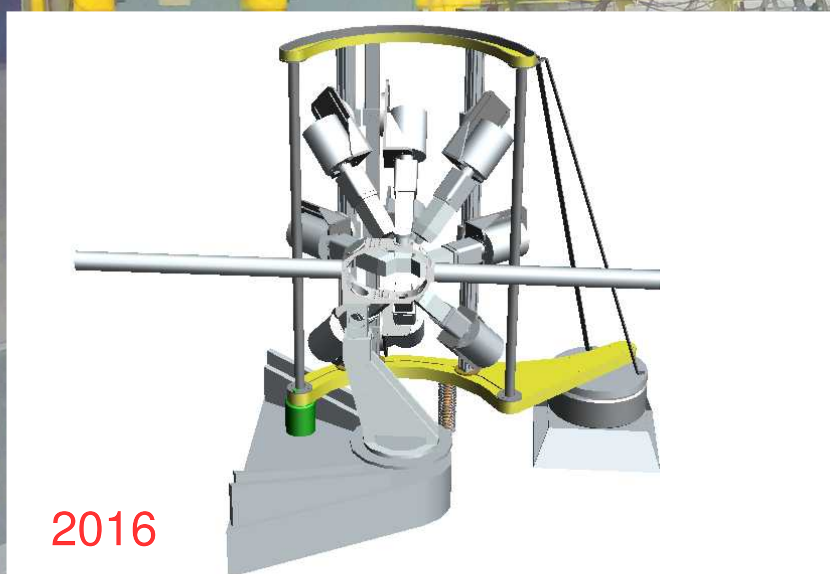
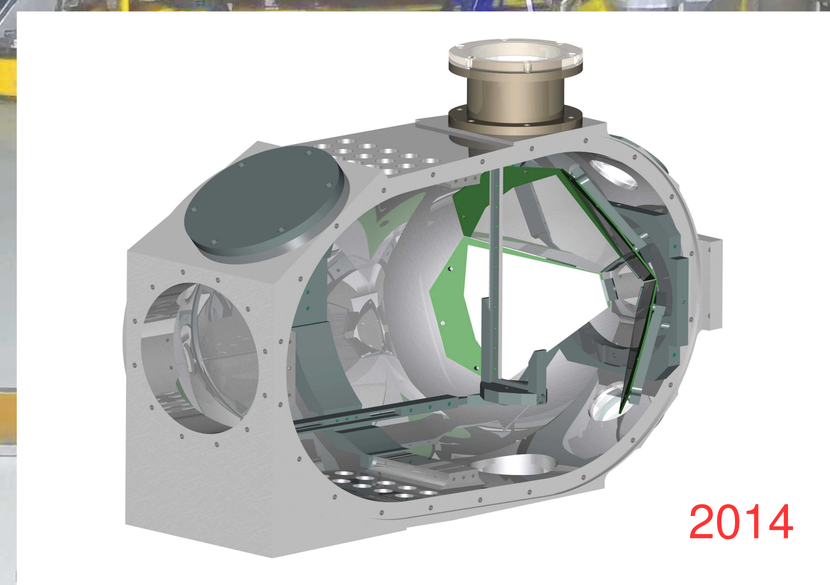
The K600 at iTL









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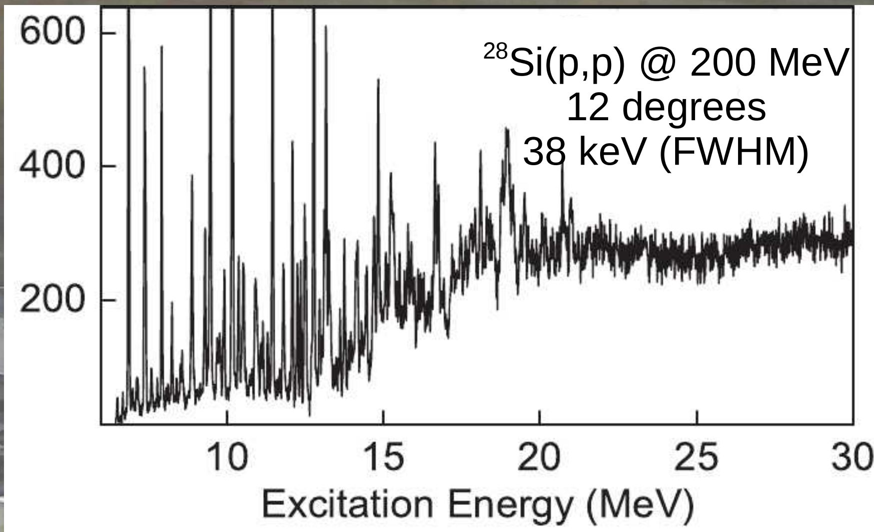

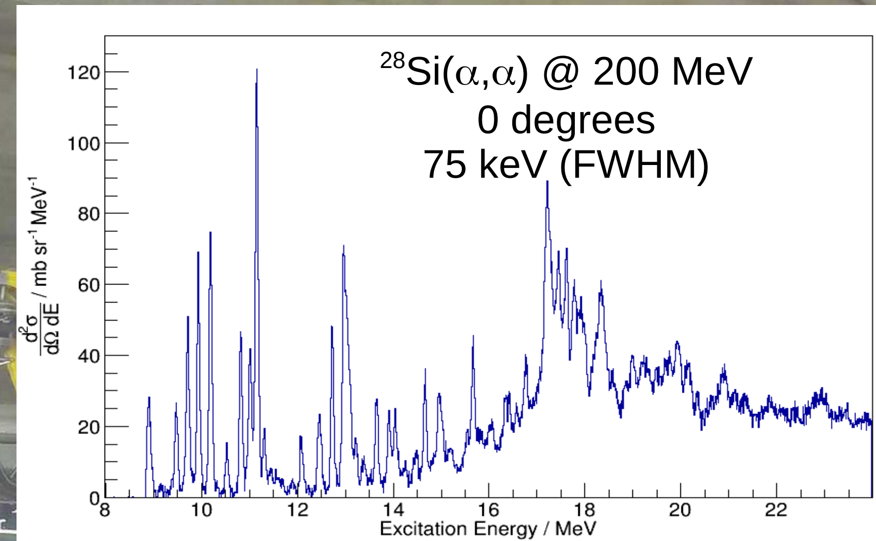

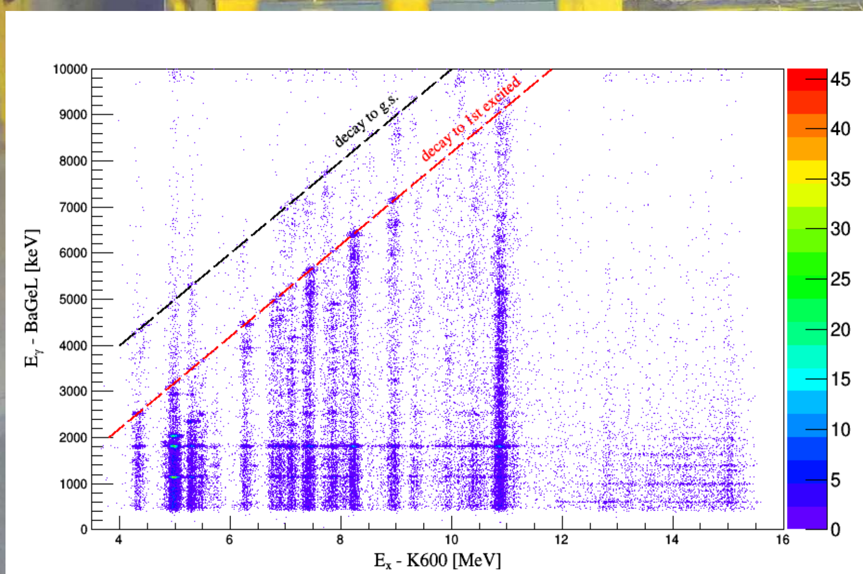

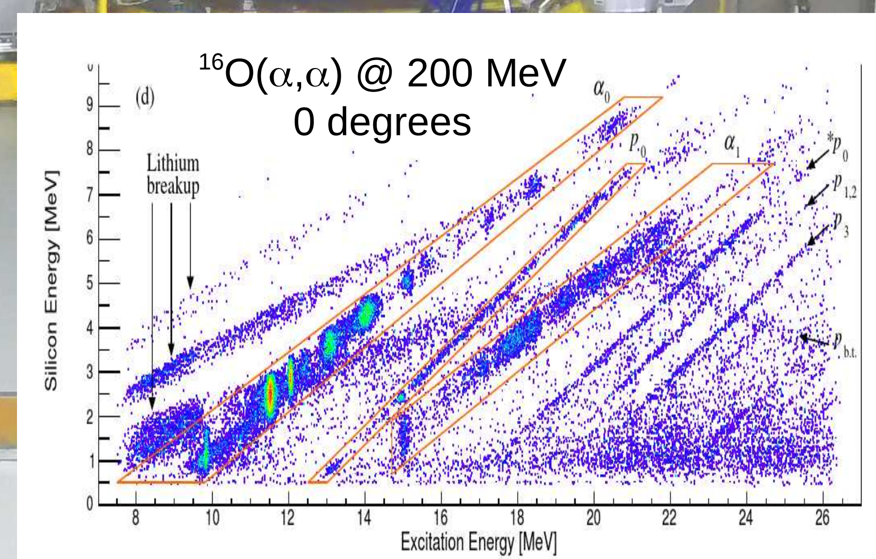

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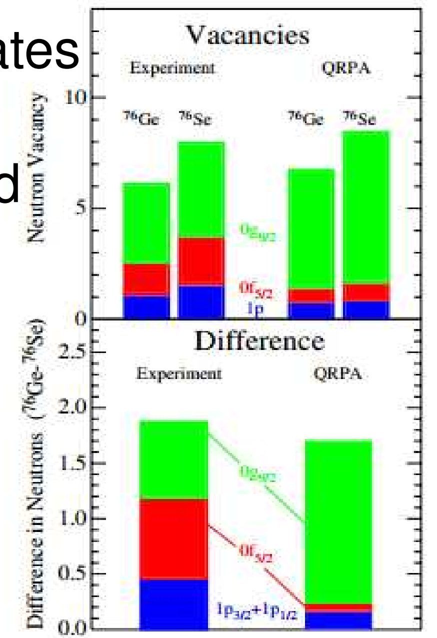
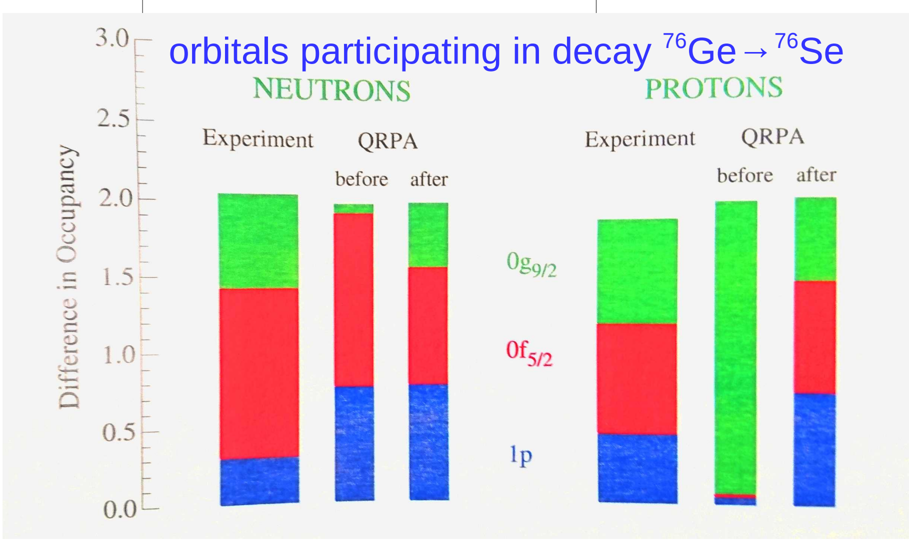
Single nucleon transfer reactions

Characterize **initial and final states in 0νββ nuclei**

- specific configuration of valence nucleons making up ground states
  Freeman & Schiffer, J.Phys.G: Part Phys 39 (2012) 124004
- big changes in configuration of nucleons mean decay is inhibited e.g. deformation
- consistent results can be obtained by measuring both nucleon adding and removal reactions on same target **



n adding:	(d,p) (α,^{3}He)	n vacancy
n removal:	(p,d) (^{3}He,α)	n occupancy
p adding:	(α,t) (^{3}He,d)	p vacancy
p removal:	(d,^{3}He)	p occupancy



** PRL108 (2012) 022501

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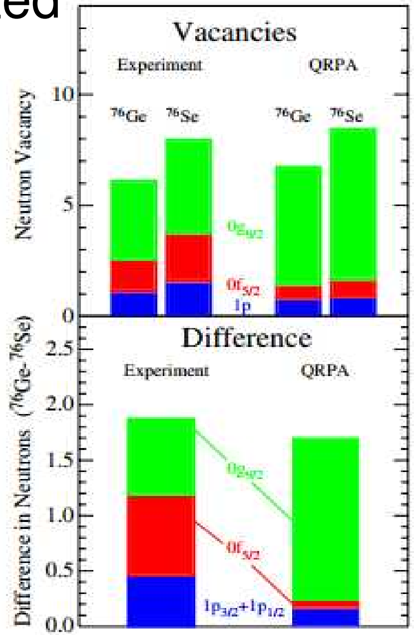
p removal:	$(d,{}^3He)$	p occupancy *need cyclotron*



"*dwindling facilities: RCNP Osaka, IPN Orsay, Munich Q3D, TUNL & FSU Split-pole*"

→ 4 tandems facilities, one cyclotron

** PRL108 (2012) 022501

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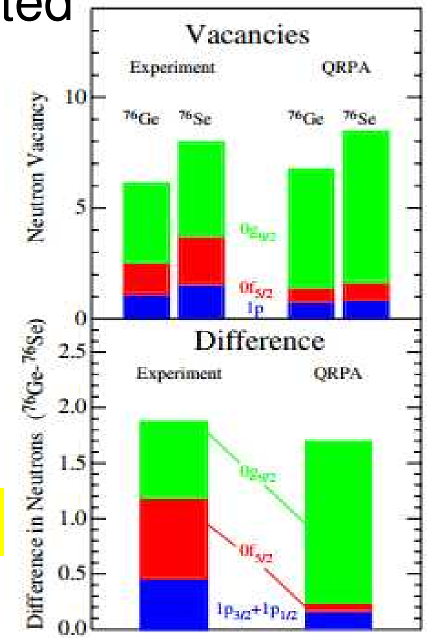

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p adding:	(α,t) (^{3}He,d)	p vacancy	
p removal:	(d,^{3}He)	p occupancy	*need cyclotron*

	RF "blind spot"	*good E*
p	20 - 30 MeV	mid 20's
d	35 - 46 MeV	mid 10's, above 80
α	-	around 40
^{3}He	-	mid 20's

** PRL108 (2012) 022501

Single nucleon transfer reactions

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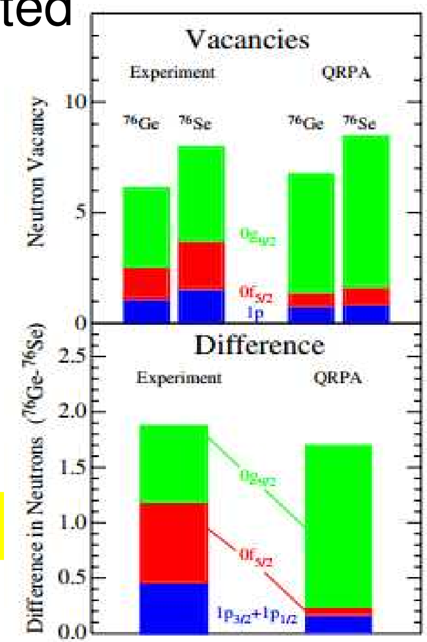

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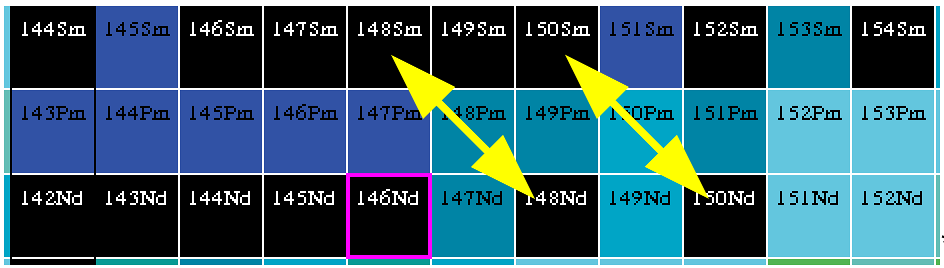
p adding:	(α,t) (^{3}He,d)	p vacancy	
p removal:	(d,^{3}He)	p occupancy	*need cyclotron*

Looking at systematic data
→ along isotopic chains - not just at 0νββ candidates



** PRL108 (2012) 022501

Pair transfer reactions

Probing pairing properties of double beta decay candidates

Test assumptions of BCS of GS of even-even nuclei

If BCS true, (p,t) should not populate 0^+ states

- Measure the energy spectrum of outgoing ions.
- Identify 0^+ states via forward peaked $\ell=0$ transitions.
- Measure cross sections accurately by minimizing systematic effects.
- Useful to make measurements on neighbouring isotopes for consistency.

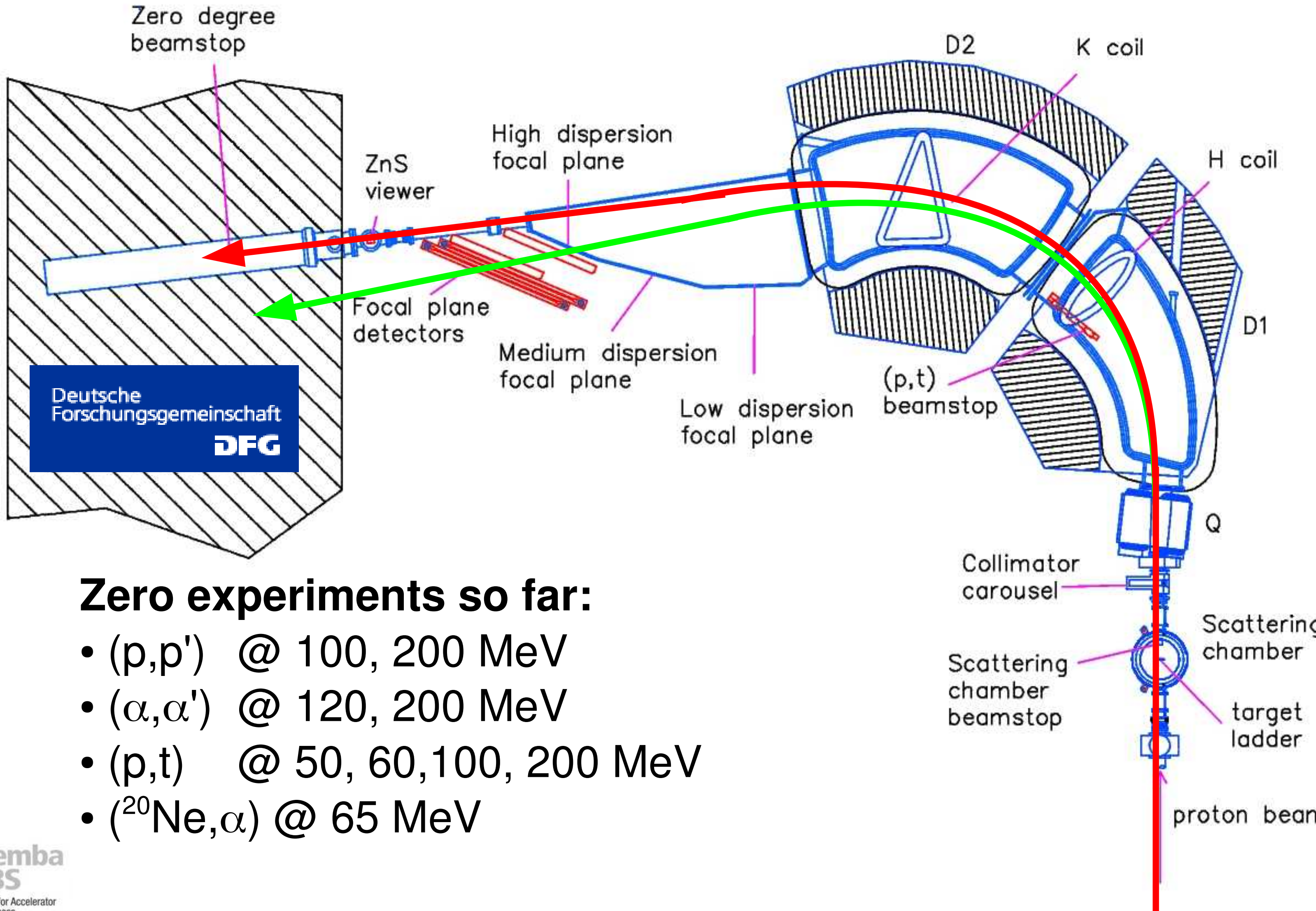
Sean Freeman:
TRIUMF workshop 2016

Looking at systematic data
(p,t) along isotopic chains - not just at $0\nu\beta\beta$ candidates

See talk of Bernadette Rebeiro

The K600 at 0°: since 2009

*Supported by the **South African NRF** and the **German DFG** under contracts SFB 634, NE 679/2-2*



Zero experiments so far:

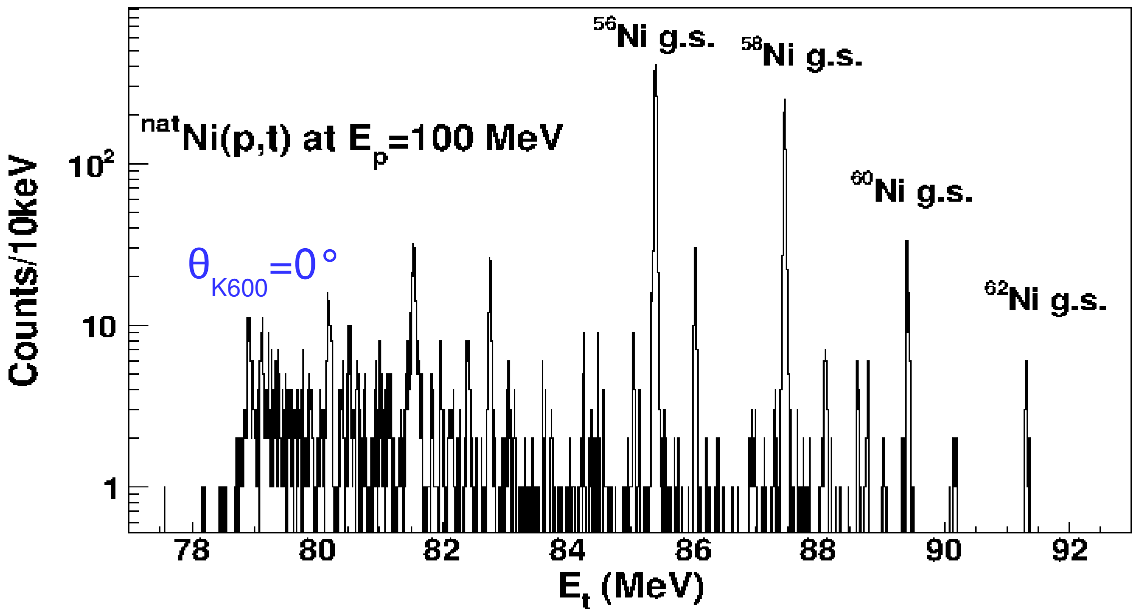
- (p,p')   @ 100, 200 MeV
- (α,α') @ 120, 200 MeV
- (p,t)   @ 50, 60,100, 200 MeV
- $(^{20}Ne,\alpha)$ @ 65 MeV

(p,p') setup: B(D1)/B(D2)=1.5

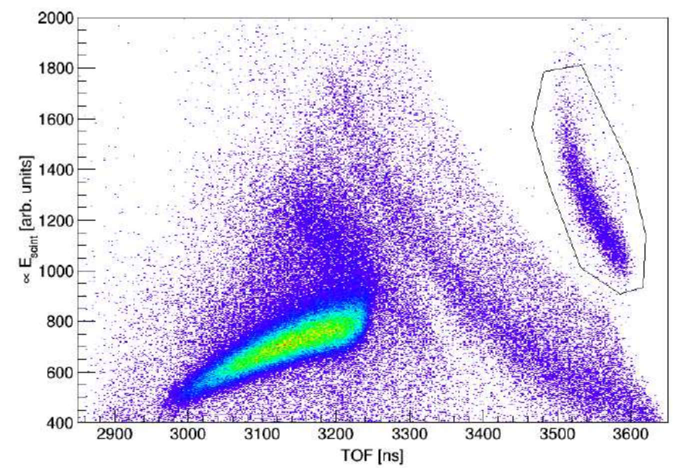
(p,t) setup: B(D1)/B(D2) = 1

The K600 at 0°: (p,t)

- 0-degree mode: enhanced sensitivity to 0^+ states
- Easier to confirm weak 0^+ states



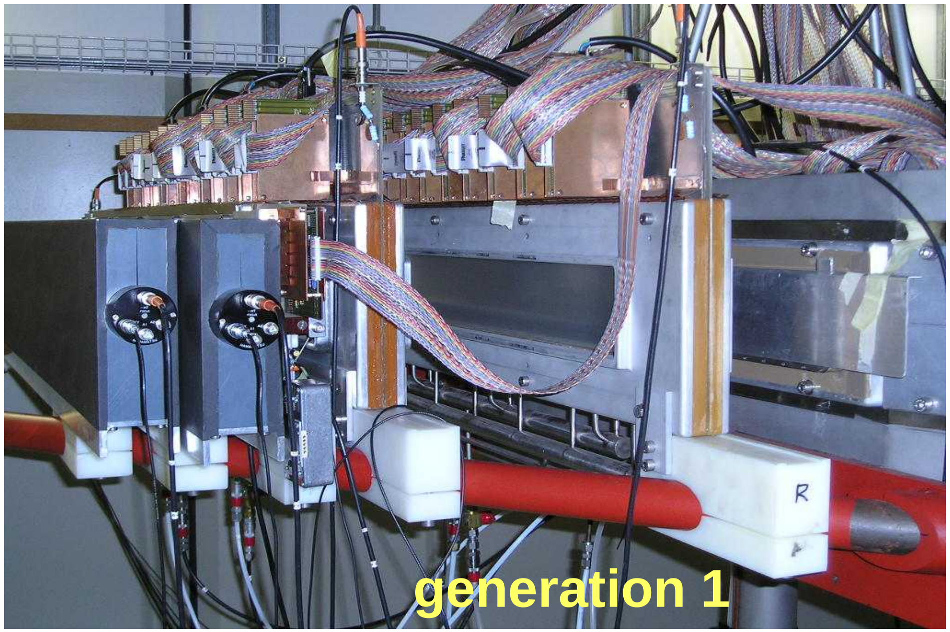
clean, good PID:



- Lowest proton beam of 30 MeV a problem?
- As you move neutron-deficient, Q-values become more negative
  →Need slightly higher beam energy to maintain good matching condition at all excitation energies
- E_t-byte of ~4 MeV @ E_t=22 MeV

Existing focal plane detectors

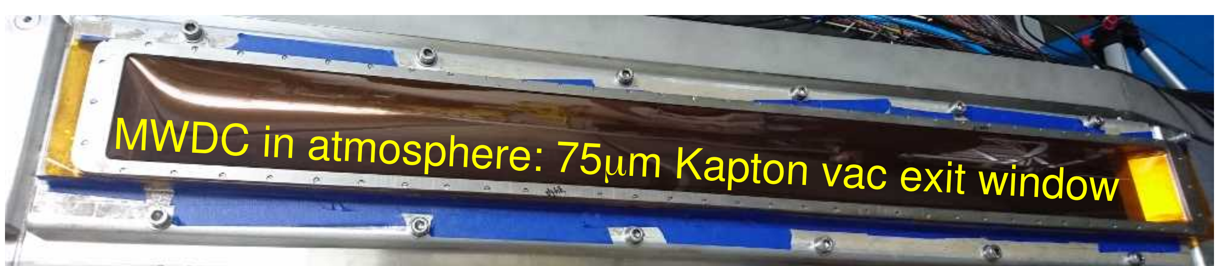
2 MWDC + 2 scintillators **(2 generations available)**



2nd generation:

- 2 wireplanes (vertical and 50°), sandwiched between 3 Al HV planes
- 198 (X) + 143 (U) active wires per detector, 682 signal wires in total
- 20 m diameter Au plated W wires
- 20 m thick aluminium HV planes (16 mm separation)
- 90% Ar 10% CO_2 gas mixture

PROUDLY SOUTH AFRICAN



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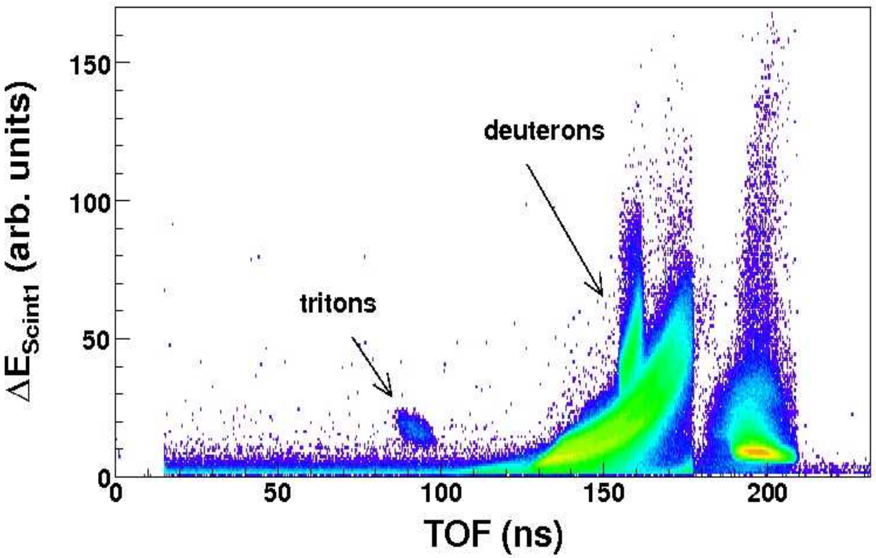
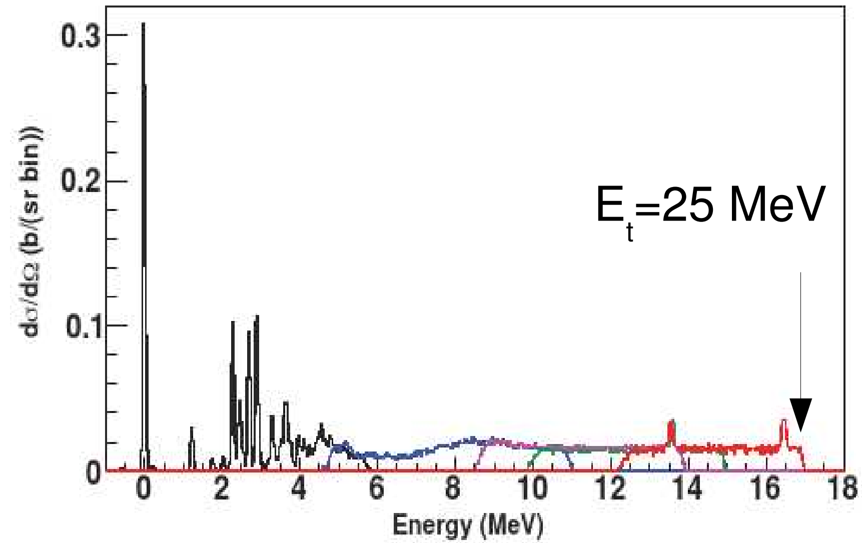
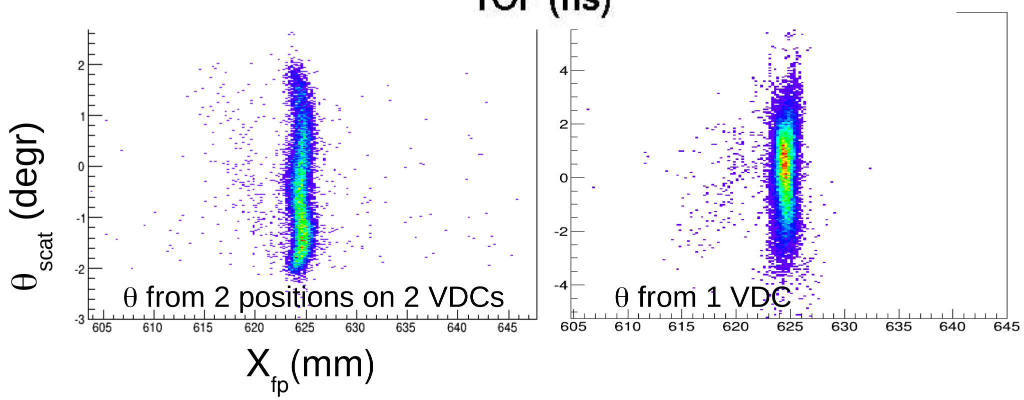
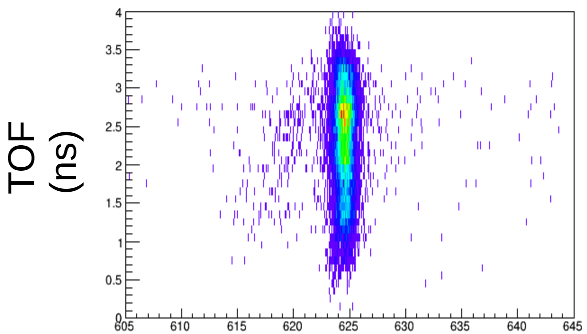
Focal plane detectors...

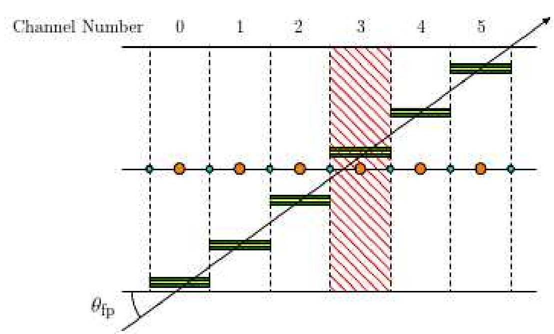
Lowest E measurement so far: $^{120}Sn(p,t)$ at 50 MeV at 0° ➔ GPV search

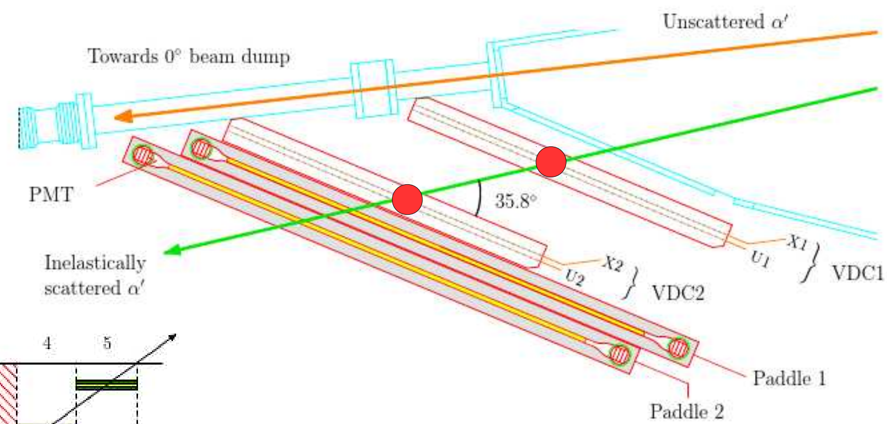




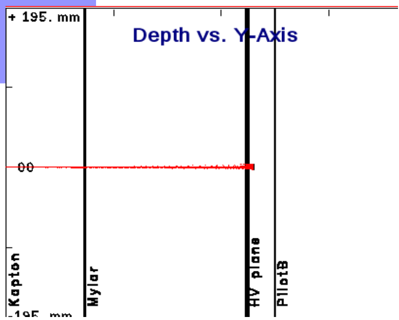






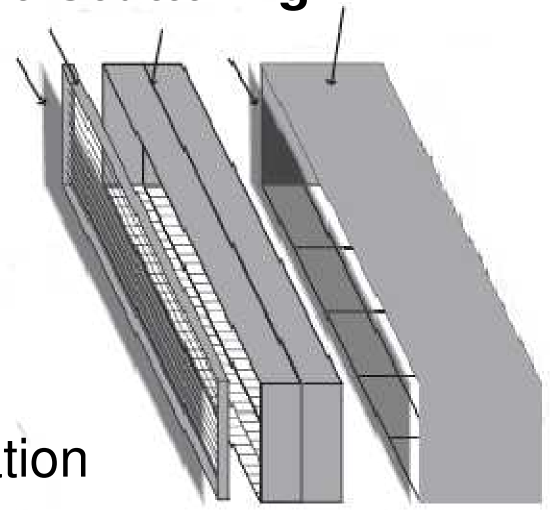


New focal plane detectors required



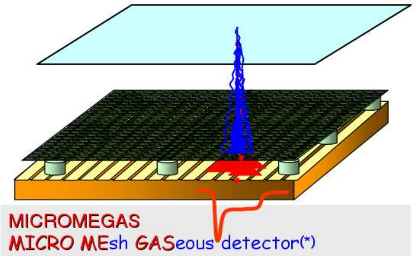
Problems:

- **No low energy detection capability** (e.g. ^{3}He,α at 10-20 MeV/u)
- No heavy ion detection capability
- Resolution in (α,α'): affected by target thickness and **multiple scattering from Kapton exit window**



New focal plane detector needed:

- low pressure, thin vacuum exit window
- Minimal or no wires
- TPC-like, proportional drift chamber, position and dE information from cathode pads at bottom
- Considering micromegas technology for signal amplification stage

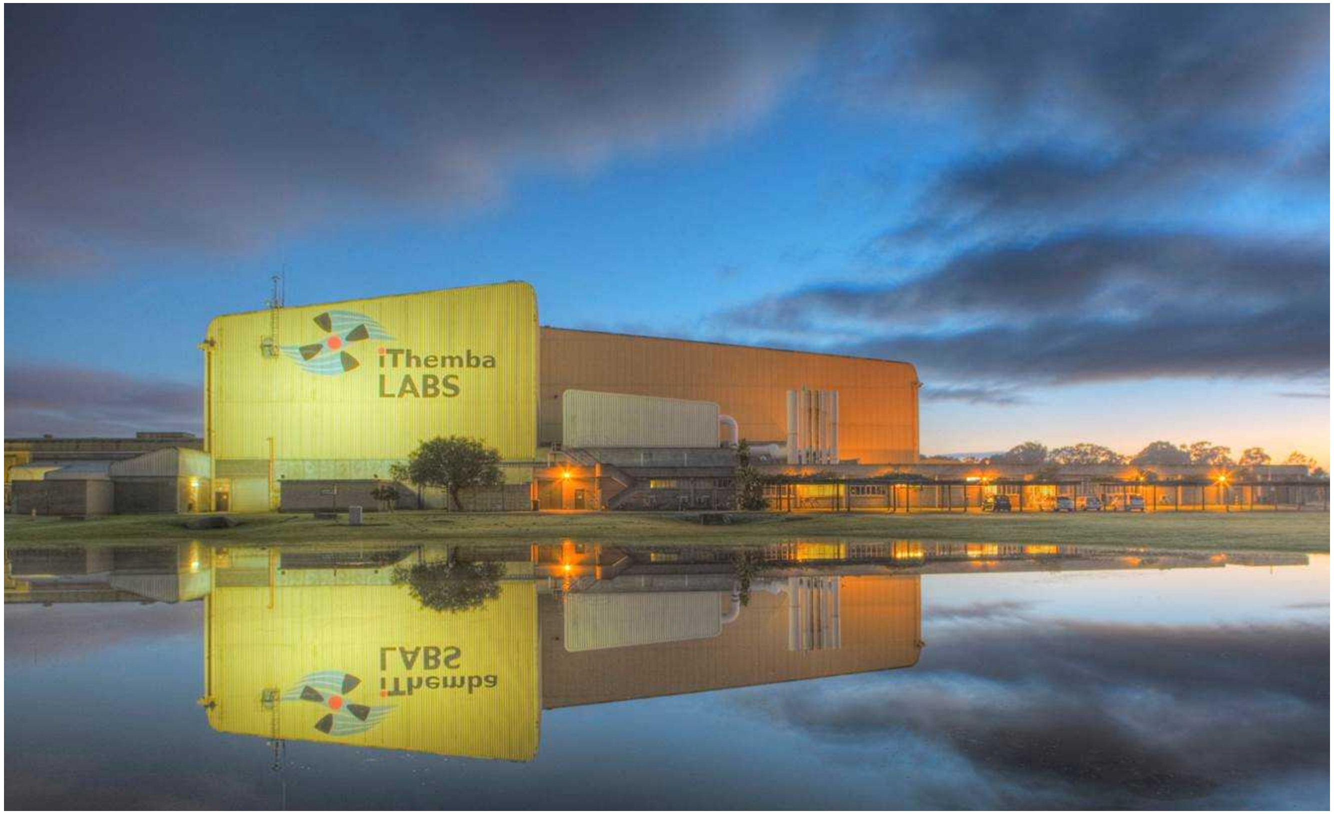


What happens next?

- Design process kickstarted: visit to CEA-Saclay
- LETTER OF INTENT submitted to Dec 2017 PAC
- Detailed design, source funding ...

Summary

- Combination of K200 SSC and K600 magnetic spectrometer
  with 0 degree capabilities
- New scheduling possibilities, more beamtime on horizen
- New focal plane detector system to be built to exploit transfer reactions



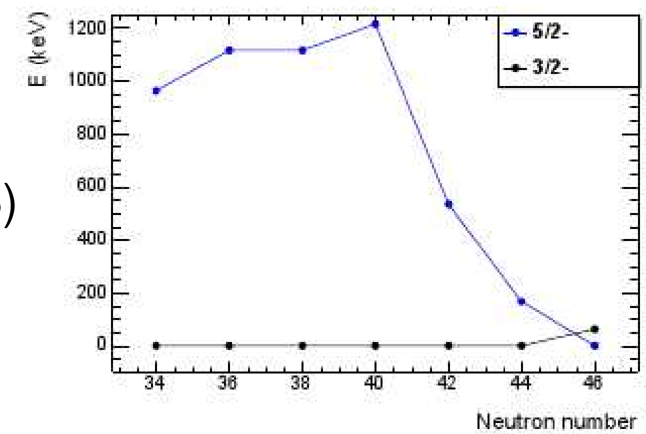
iThemba LABS:

new opportunities and an exciting future

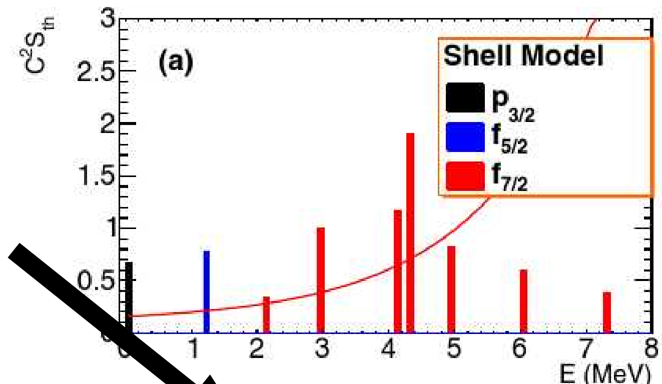
(d,^{3}He) example: shell structure

Probing the proton gap: behavior of πf7/2 orbital

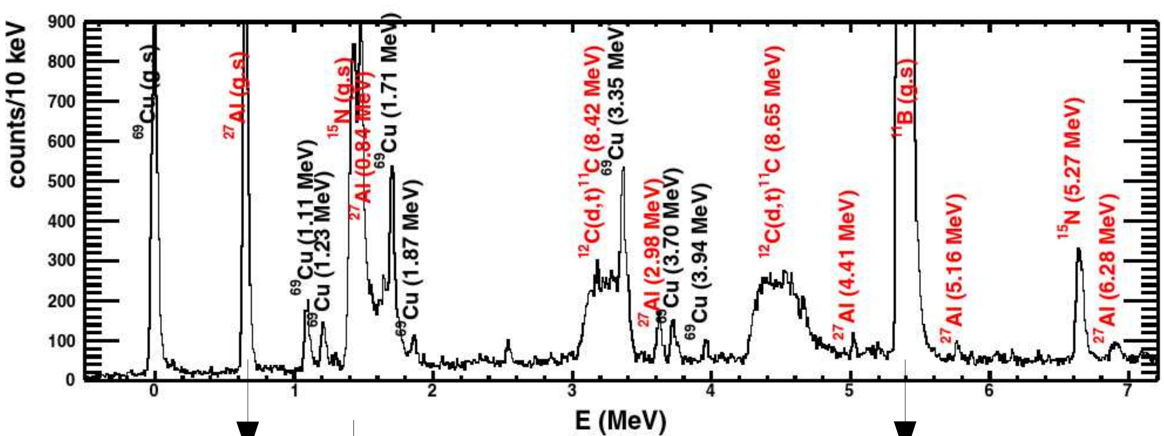
^{70}Zn(d,^{3}He)^{69}Cu - Pierre Morfouace et al. PRC **93** 064308 (2016)



Orsay Enge split pole at 6°,9°,12°,15, 18°,21°,24°
27 MeV deuteron beam
^{70}Zn target: 18.7μg/cm^2 on ^{12}C backing
42 keV (FWHM) resolution
triton contamination of Ex spectrum



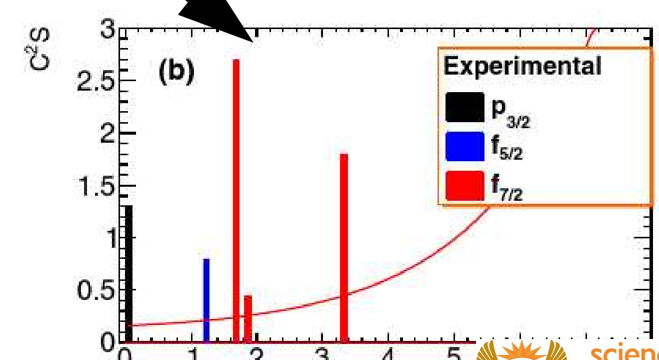
Missing strength, no proper momentum matching for L=3



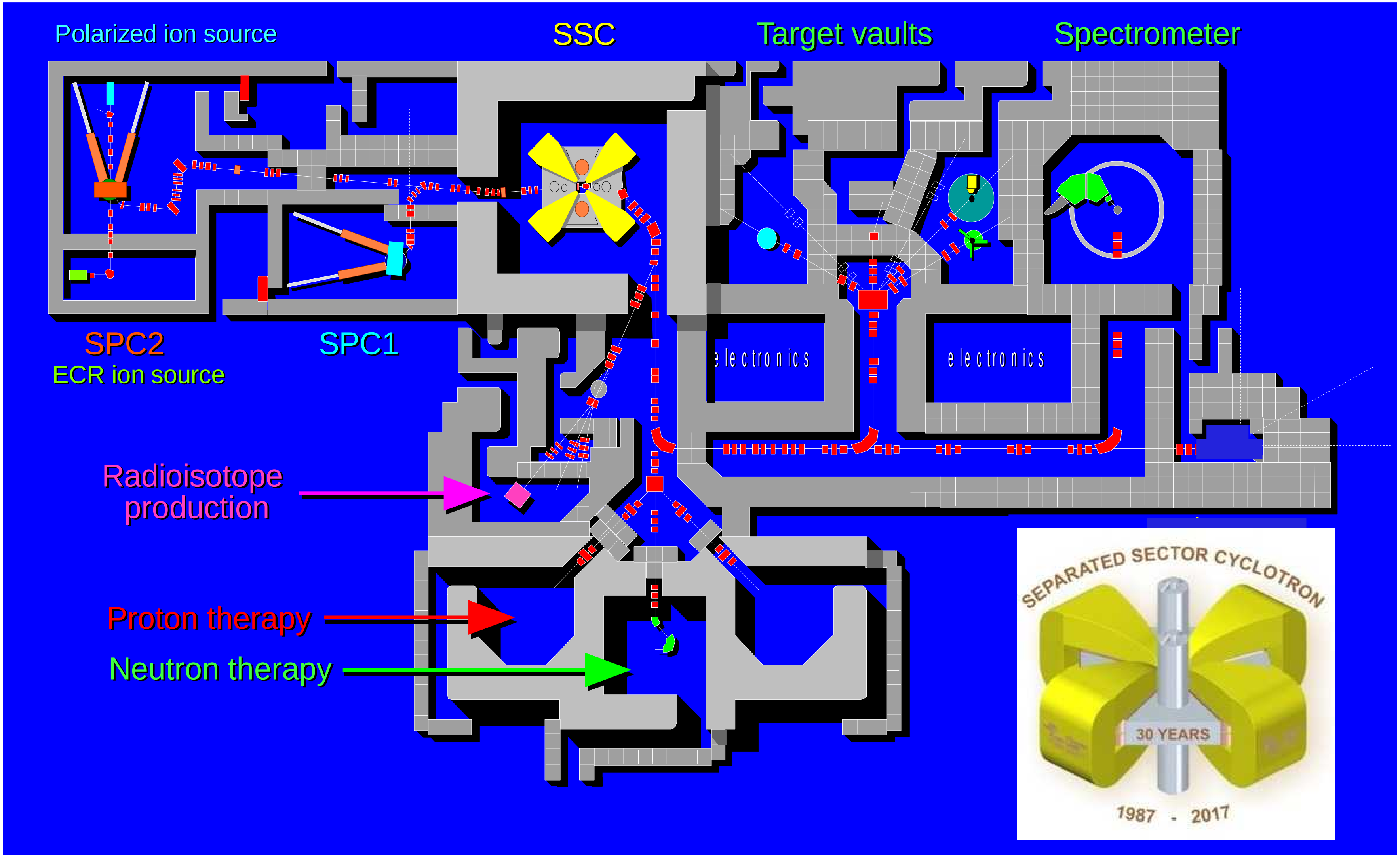
^{28}Si(d,^{3}He)

^{16}O(d,^{3}He)

^{12}C(d,^{3}He)



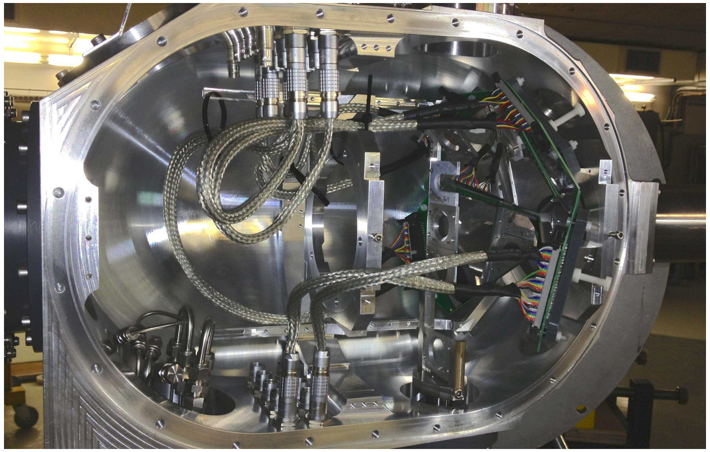
iThemba LABS: SSC facility



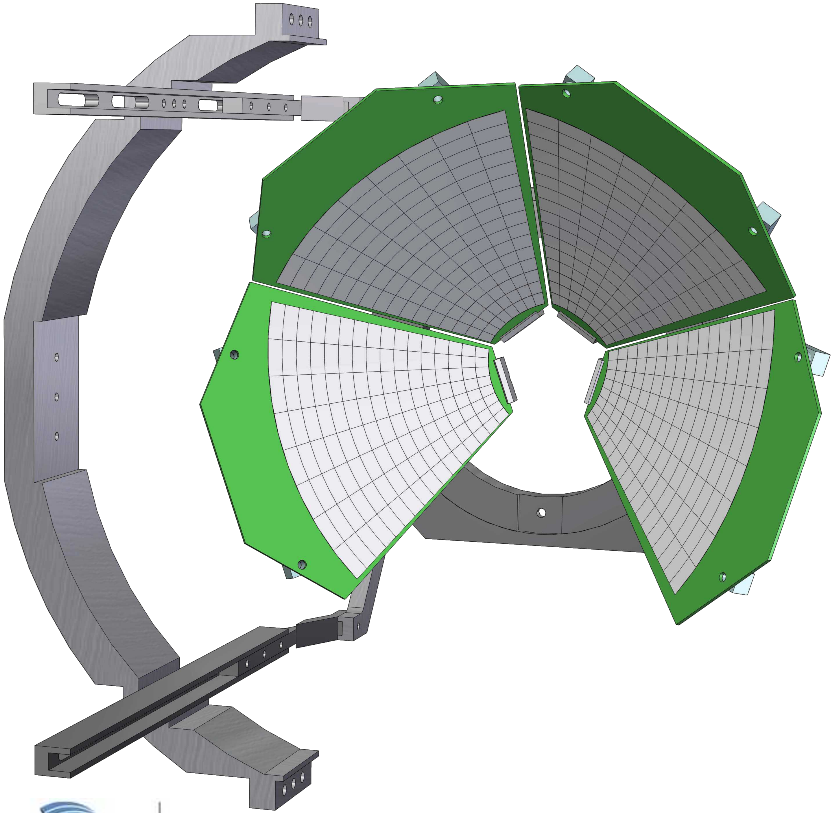
SSC: 30 years in operation !!

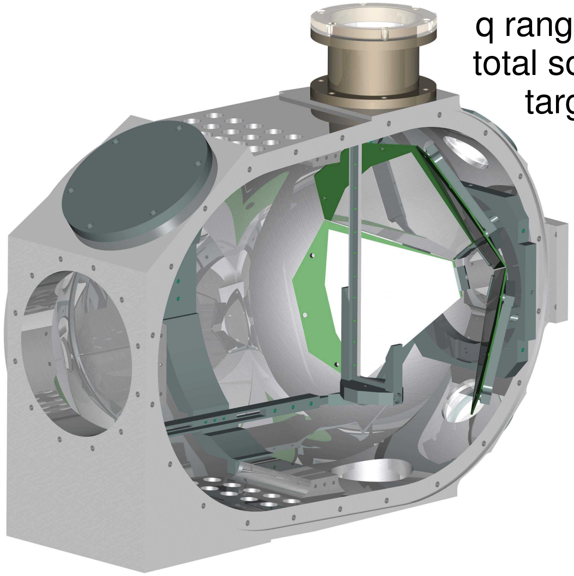
CAKE (Coincidence Array for K600 Experiments)

- Up to 5 MMM-type Double-Sided Silicon Strip Detectors
- 25% solid angle covered
- Energy resolution of 30-40 keV
- Target thickness dominates experimental resolution
- PID through time-of-flight relative to decay particle energy



5× MMM-400 Double Sided Silicon Strip Detectors
Lampshade configuration
400 mm thick (7 MeV p, 28 MeV a)
16 rings, 8 sectors ,
q range: 114° - 166° divided in 16 angle bins
total solid angle: 26% of 4p; 0.66 msr/DSSSD
target to detector separation: 100-110 mm

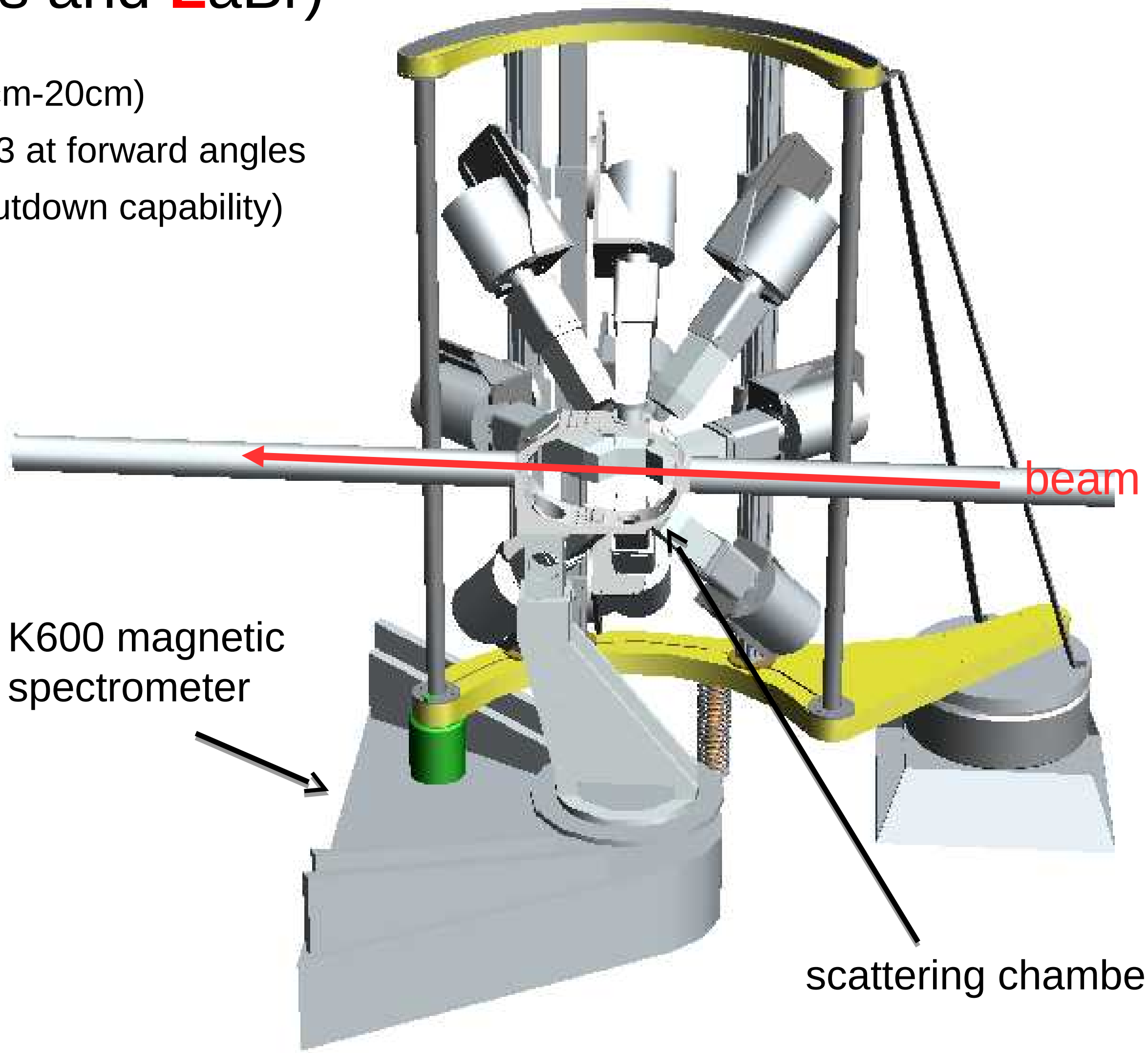




K600 magnetic spectrometer: Recent Developments

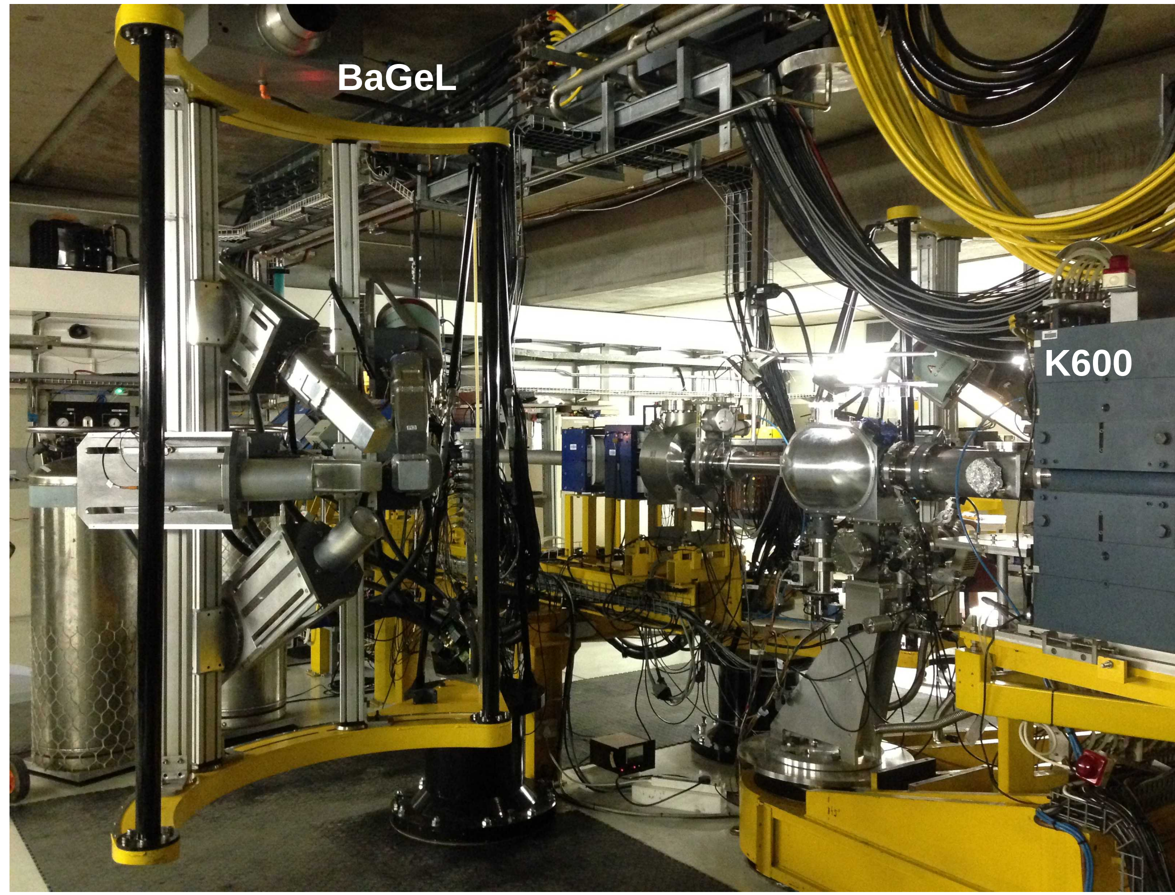
BaGeL (Ball Gemaniums and LaBr)

- Different distance from the target (10cm-20cm)
- 12 detectors at backward angles and 3 at forward angles
- Independent HV system (with bias shutdown capability) and a clover temperature monitoring
- Automated LN2 filling system
- For measurement at 0° or > 19°



BaGeL in action

First successful experiment on October 2016: PDR in deformed nuclei ^{154}Sm(α, α' γ)



BaGeL with 8 Clovers+2 $LaBr_3$:Ce @ 17cm from tgt
Eff 8 Clover = 0.6% @ 6 MeV, with addback
Eff 2 LaBr3:Ce = 0.4% @ 6 MeV

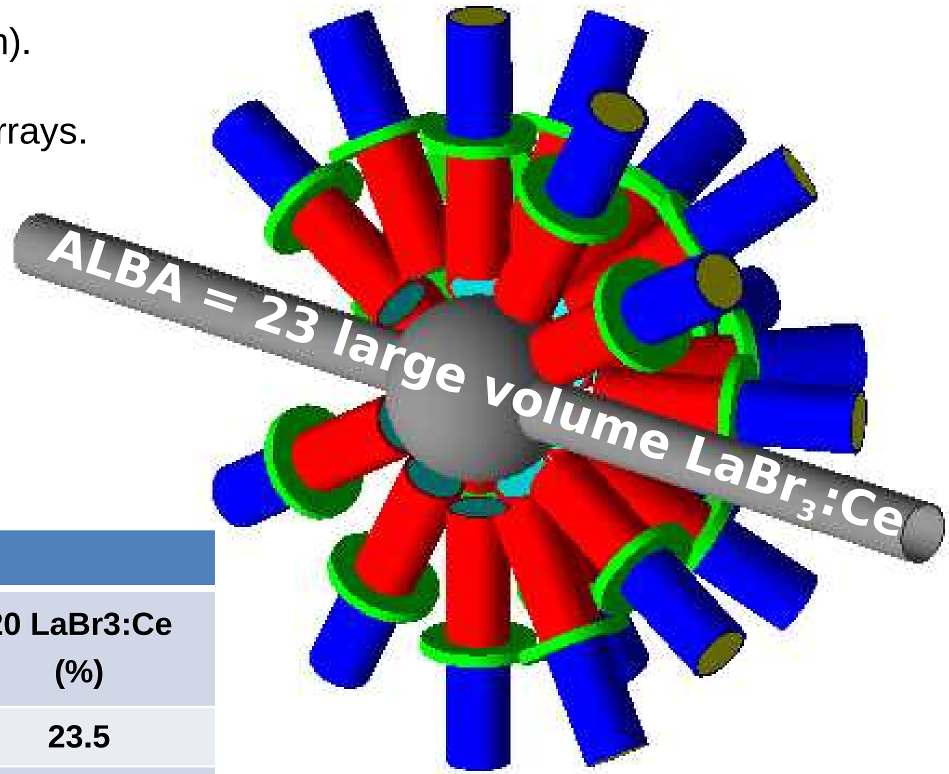
ALBA = African LaBr$_3$:Ce Array

- **African LaBr$_3$:Ce Array – ALBA**: 23 large-volume LaBr3:Ce. First four arrived September 2017
- Tapering of LaBr3:Ce detectors (allow to get to 11cm).
- Detectors mounted in flexible and interchangeable arrays.

High Efficiency

ALBA array

23 large volume LaBr$_3$:Ce



Efficency at 11cm from target			
γ-ray Energy (MeV)	1 LaBr3:Ce (%)	6 LaBr3:Ce (%)	**20 LaBr3:Ce (%)**
1	1.2	7.1	**23.5**
5	0.5	2.9	**9.8**
10	0.3	1.7	**5.6**

Low-statistics experiments now possible…

large-volume LaBr3:Ce radius 90mm, length 203mm

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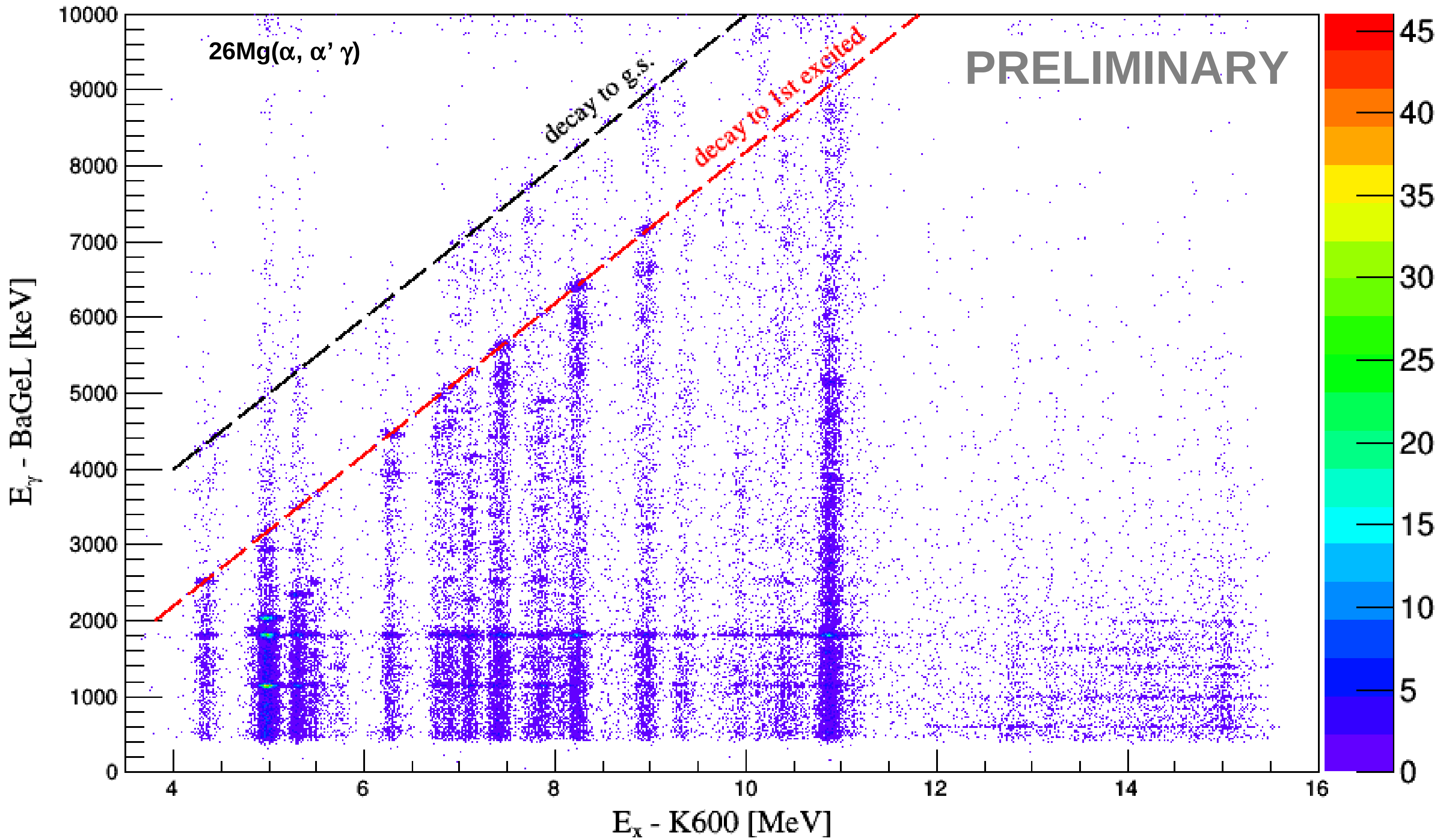
BaGeL in action

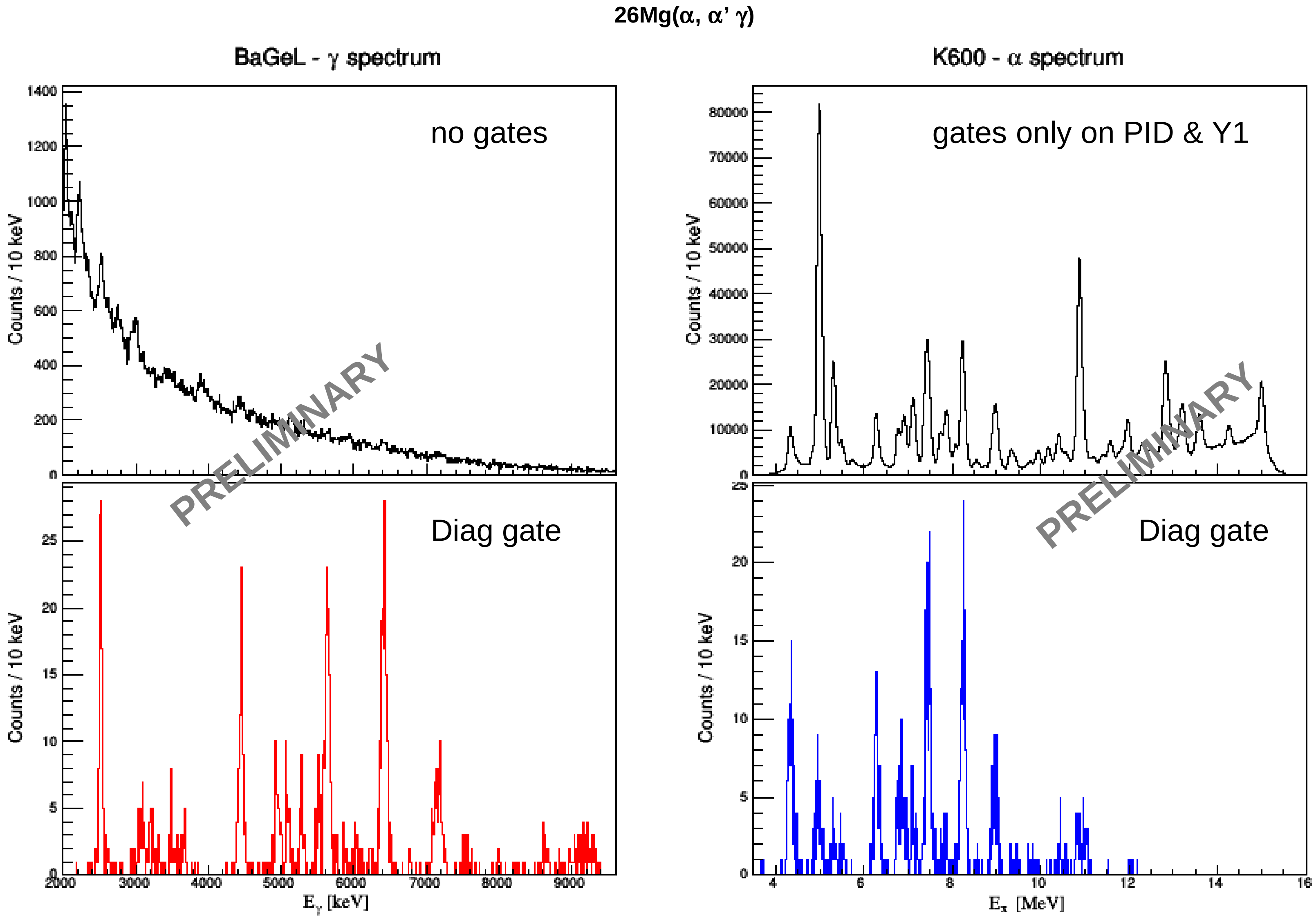
With only one LaBr3:Ce detector:

GATES: PID & Y1 plane & GammaTime



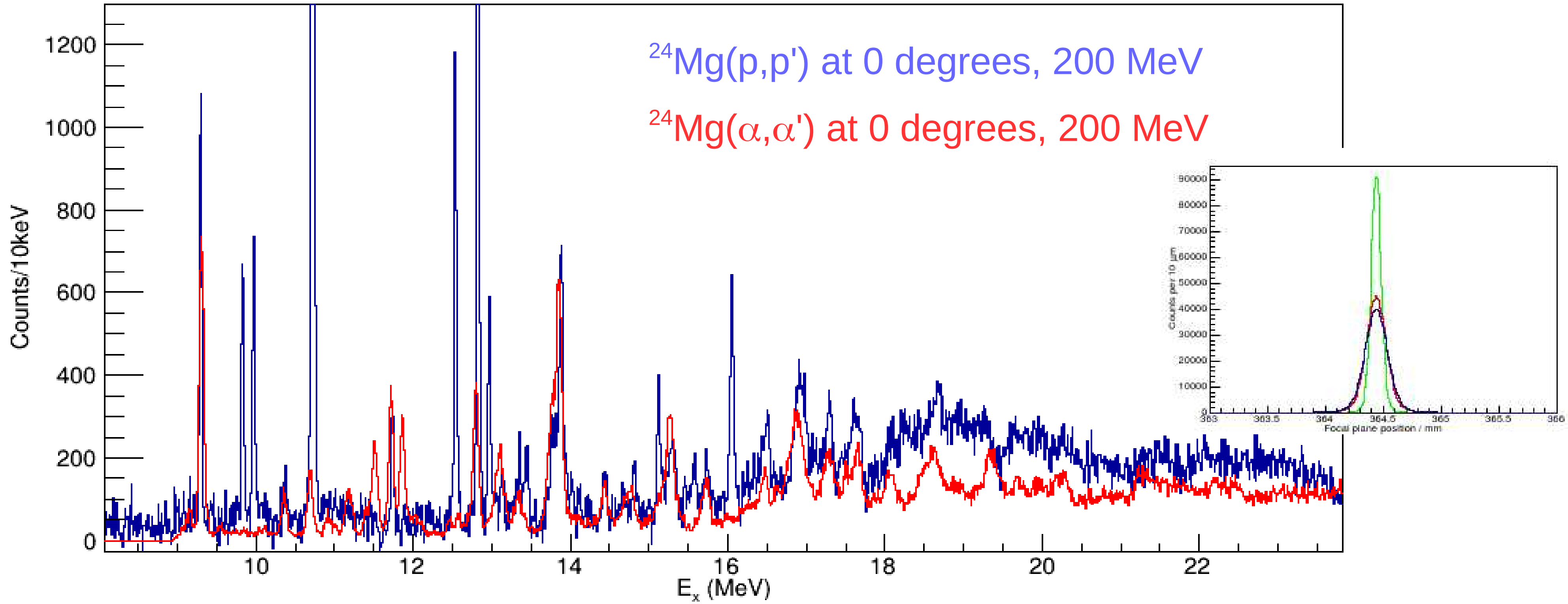
BaGeL in action

With only one LaBr3:Ce detector:



Only the peaks that decay to the 1st excited states are selected

New detector requirements



Resolution in (α,α'): affected by target thickness AND multiple scattering from Kapton exit window

Want to have low energy detection capability: e.g. investigate pair transfer through (p,t) reaction along isotopic chains @ E_{beam}=30 MeV