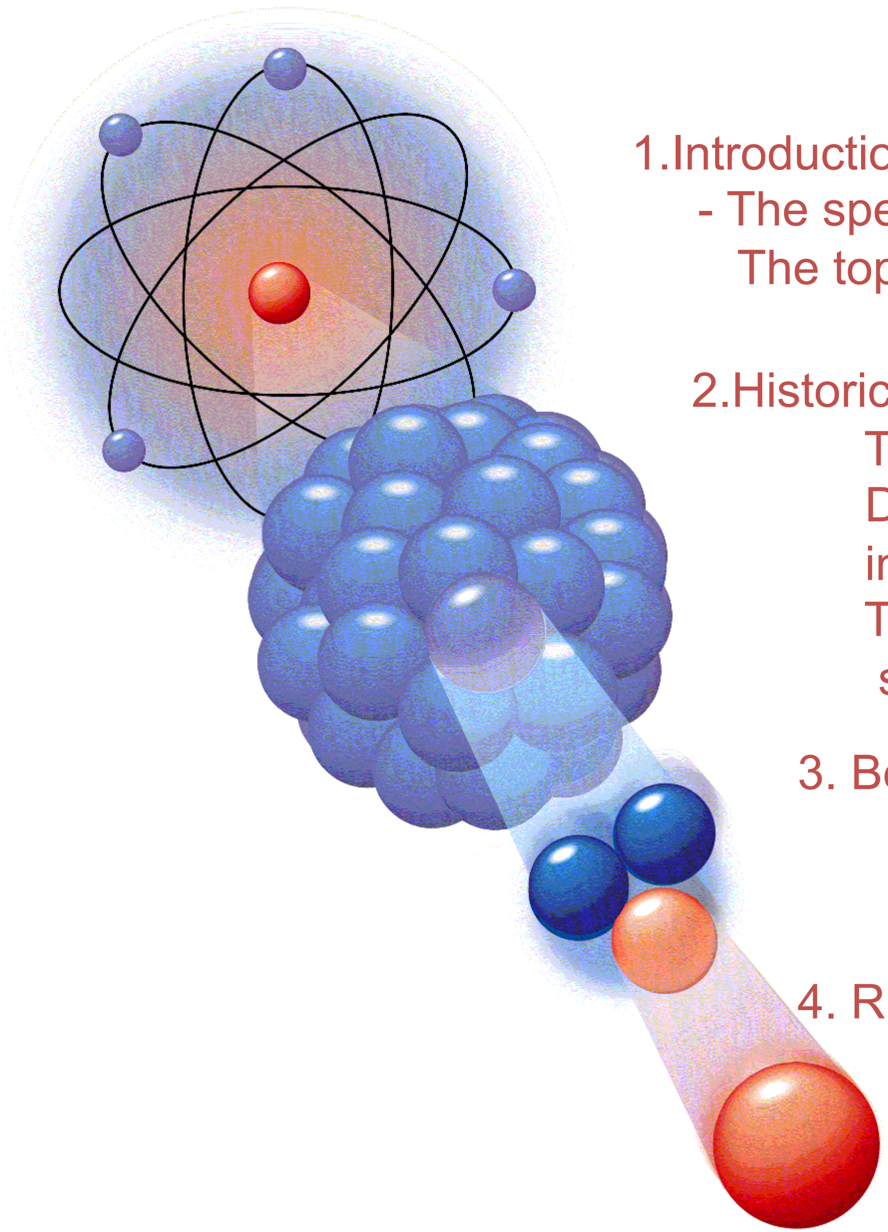
Advances in Nuclear physics driven by new experimental methods

W.Gelletly

UNIVERSITY OF SURREY

CENTRE FOR NUCLEAR & RADIATION PHYSICS

Physics Department,University of Surrey



Outline

1.Introduction
- The speaker
  The topic – themes and sub-themes
  -issues of importance

2.Historic examples
- The Wilson Cloud Chamber
- Discovery of reactions
- introduction of accelerators
- The beginnings and development of γ-ray spectroscopy

3. Beginnings of radioactive beam physics
   - On-line isotope separation
   - Isol-based accelerator facilities
   - In-flight facilities
4. RNB facilities World-wide
   - Isol facilities
   - In-flight facilities
   - Niche facilities
   - Traps, storage rings, gas catchers
5. summary + conclusions.

Today's themes

Our main focus here is on how experimental advances drive Nuclear Physics forward- on how they create a new paradigm.

EXPERIMENTAL METHODS

But before discussing experimental results, it is desirable to say something about experimental methods for accelerating protons and deuterons to high speeds. There is a natural tendency to relegate to the background the experimental methods and techniques and to regard the results brought to light in nuclear investigations as of first importance. It is so easy to forget that the nuclear investigations are made possible by the development of experimental methods and techniques. How greatly was nuclear physics enriched by the cloud chamber of C. T. R. Wilson!

E.O.Lawrence, Ohio journal of Physics 35,Issue 5, 388(1935)

We should not forget that these leaps forward are also often the basis for new applications and nuclear physics has been a particularly rewarding activity in this regard.

There may result also many important biological applications. I hesitate to express views in this direction, but some of my medical colleagues think it quite possible that the discovery of artificial radioactivity will ultimately be of great importance to medicine. Opinions of this sort, of course, are highly speculative, and I leave it to you to estimate the advantages for radiation therapy and biological research, of radioactive substances having practically any desired chemical and physical properties.

E.O.Lawrence, Ohio journal of Physics 35,Issue 5, 388(1935)

Ferid Haddad
Radioisotope Production
From nuclear physics to nuclear medicine

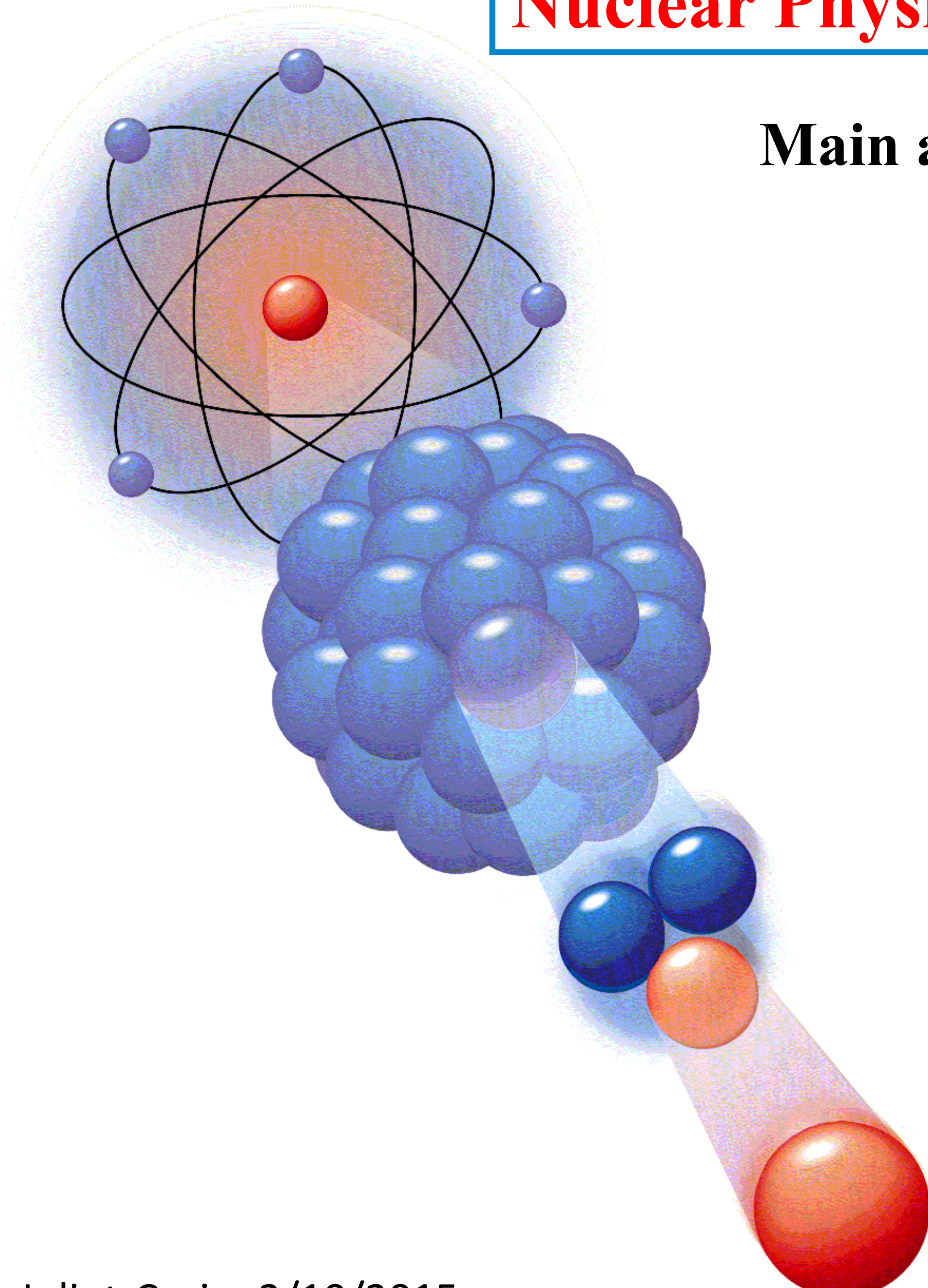
Today's sub-themes

1. Descriptions of developments in nuclear Physics (and science generally) in textbooks, literature and the web often provide a plausible story rather than reality

2. No doubt you often rely on databases and papers for information. Be sceptical - look at the sources of the information and decide if it is reliable or not!!

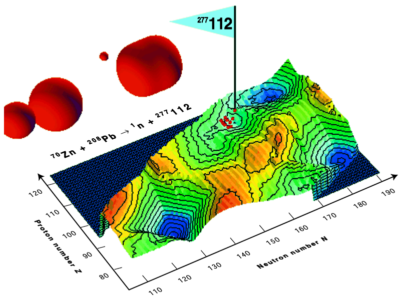
* "Surely you're joking Mr Feynman"

Nuclear Physics Research – very diverse



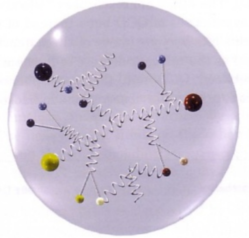
Main areas of activity

Nuclear structure



Nuclear Astrophysics

Hadron Physics



Phases of strongly interacting matter

Applications:
Medical, security, environmental.....

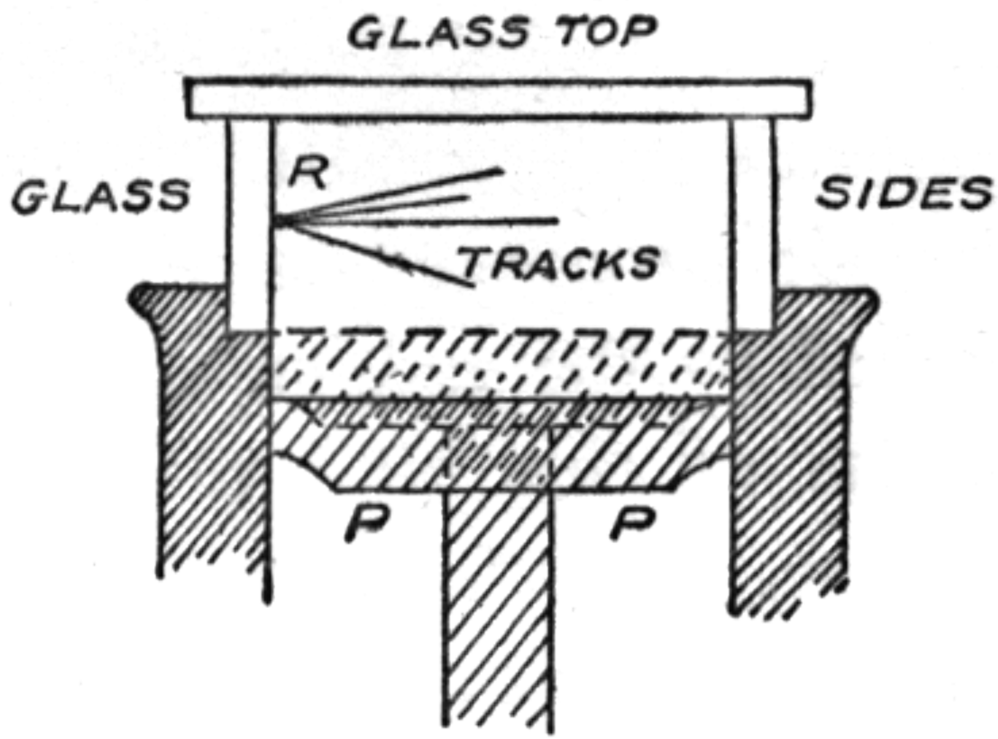


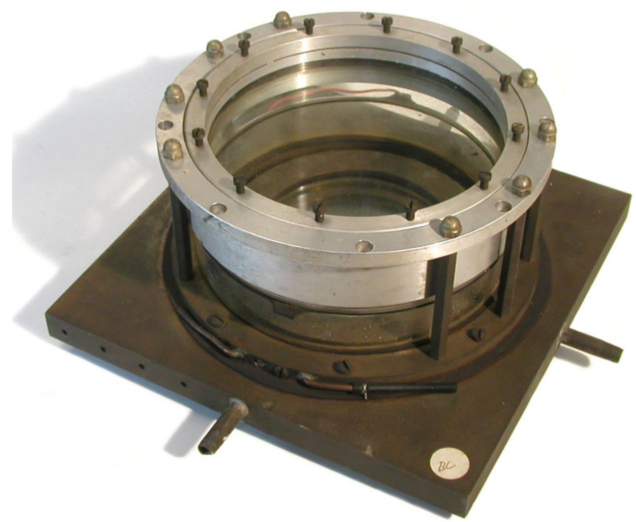
FIG. 2.—Section of the expansion chamber in Mr. C. T. R. Wilson's apparatus for measuring the track of helium atoms (see also Plate II).

The piston *PP* is dropped suddenly from the position indicated by the dotted lines to the position indicated by the full lines: so that the air in the chamber is suddenly chilled by expansion and fog settles on the tracks of the helium atoms shot out by the radium at *R*.

The Wilson Cloud Chamber

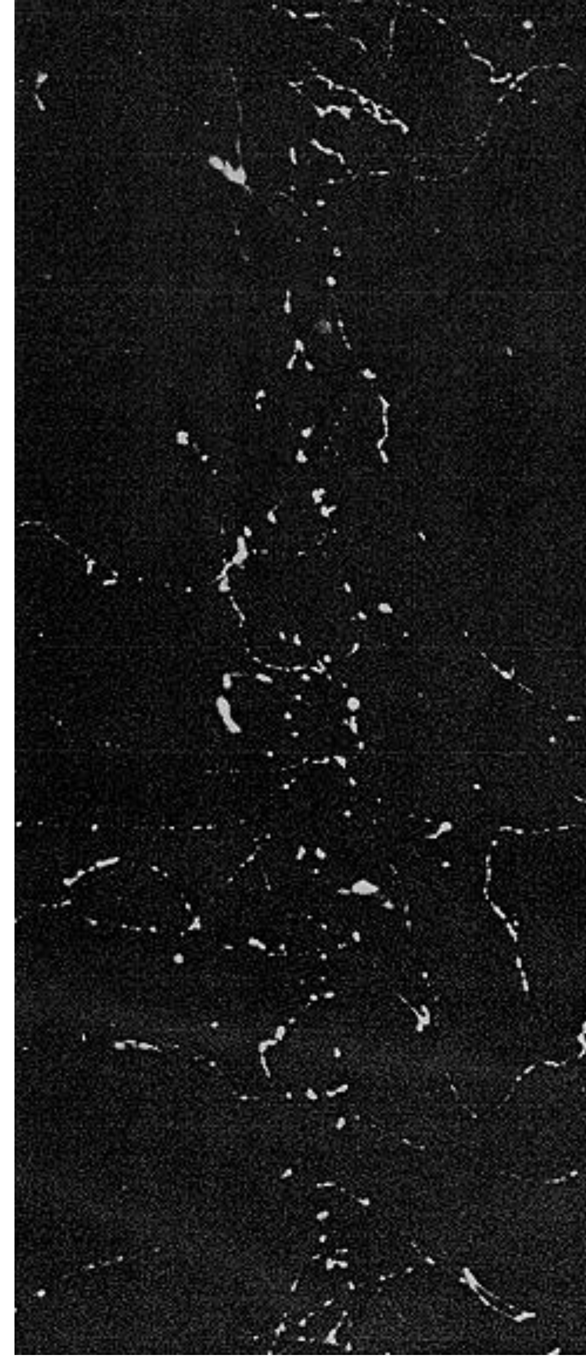
Remember E.O.Lawrence's

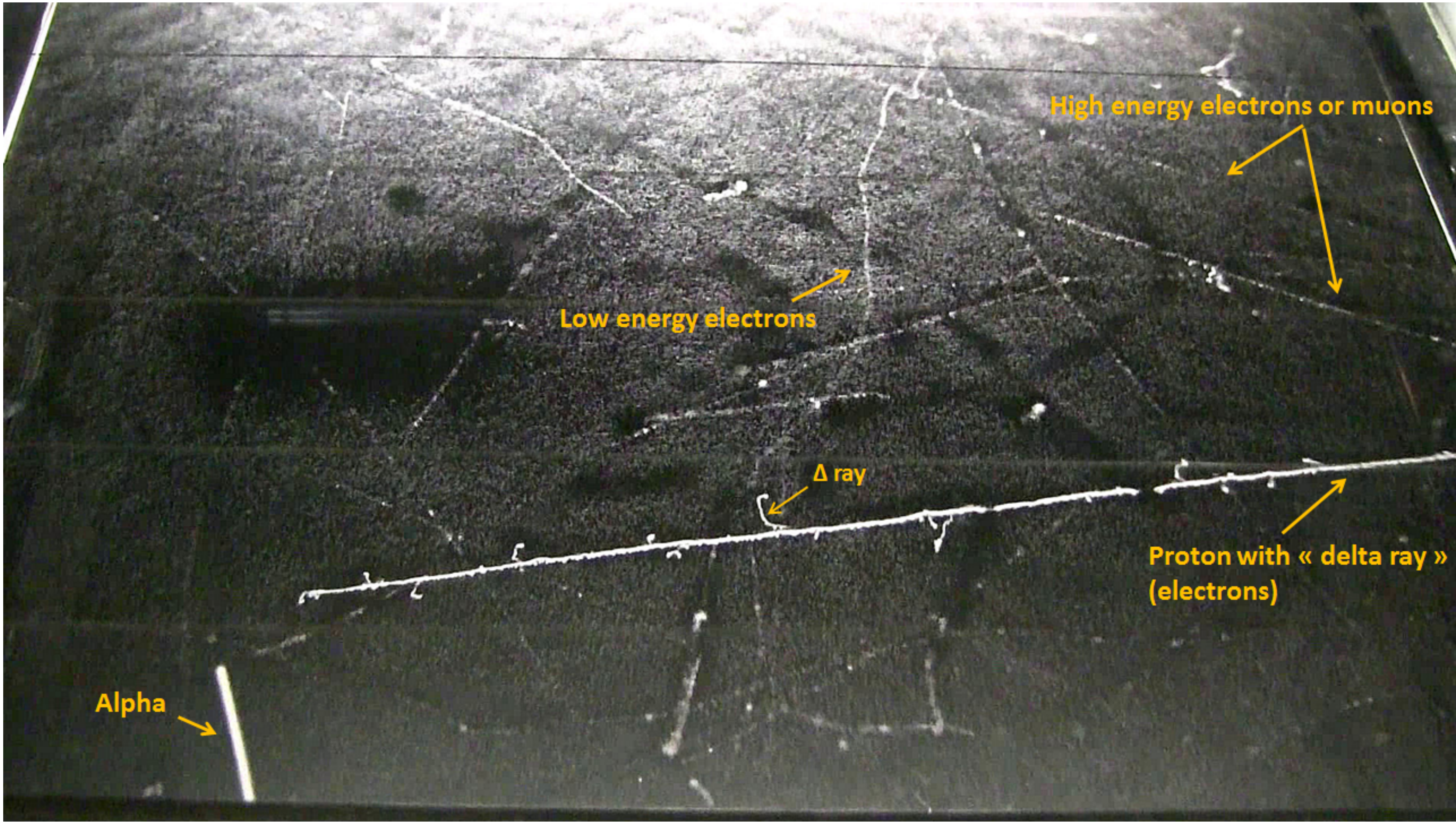
"How greatly was nuclear physics enriched by the Cloud Chamber of C.T.R. Wilson!"



Beta Particles

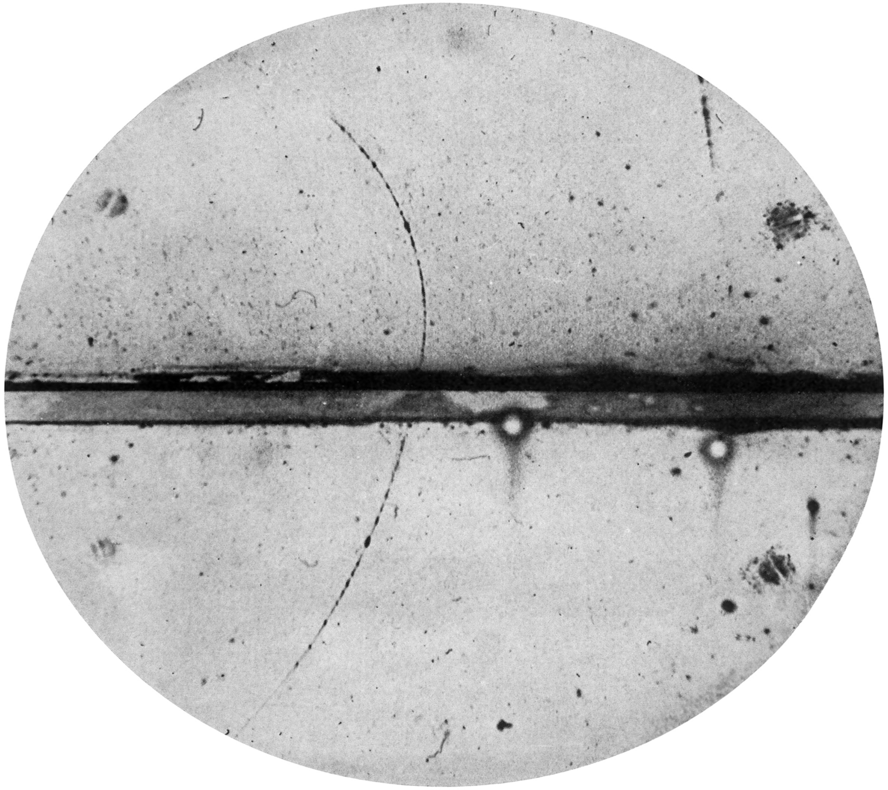
Electrons produced by Gamma rays




High energy electrons or muons
Low energy electrons
Δ ray
Proton with « delta ray »
(electrons)
Alpha

Discovery of the positron

• C.D.Anderson:- Science 76 (1932) 238



• C.D.Anderson:- American Journal of Physics 29 (1961) 825
"—played no part whatsoever in the discovery of the positron"

The counter controlled Cloud Chamber

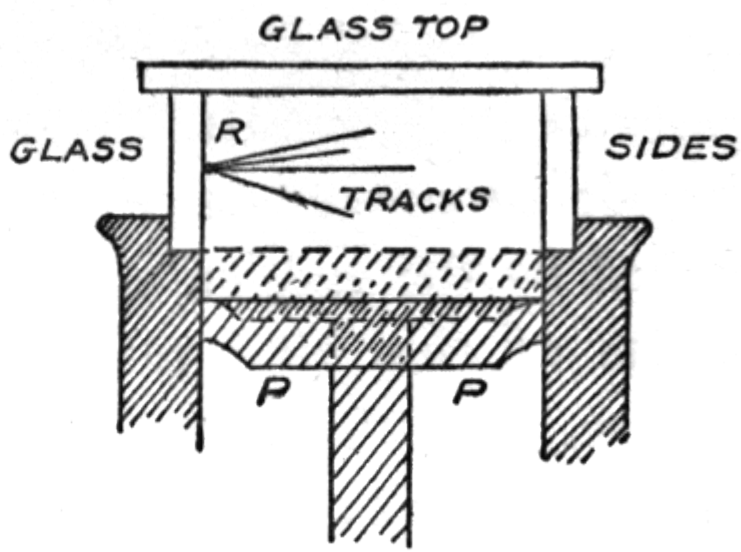


FIG. 2.—Section of the expansion chamber in Mr. C. T. R. Wilson's apparatus for measuring the track of helium atoms (see also Plate II).

The piston *PP* is dropped suddenly from the position indicated by the dotted lines to the position indicated by the full lines: so that the air in the chamber is suddenly chilled by expansion and fog settles on the tracks of the helium atoms shot out by the radium at *R*.

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On the Technique of the Counter Controlled Cloud Chamber

By P. M. S. BLACKETT, F.R.S.

(Received May 18, 1934)

[PLATES 2 and 3]

1—*General Considerations*

The method by which very fast atomic particles are made to take their own cloud photographs has proved very useful for the investigation of cosmic rays. A short account of the method and a detailed account of the results obtained by its use have already been given by Blackett and Occhialini.*

Recently Locher† and also Anderson, Millikan, Neddermeyer, and Pickering‡ have used the same method and have obtained some beautiful results.

The method consists in using two or more tube counters to detect the passage of a high energy particle through a cloud chamber. The electrical response of the counters is then made to actuate the cloud chamber by means of relays. In order that the cloud tracks so formed should be fairly fine, it is necessary that supersaturation of the vapour should be attained very quickly after the passage of the ray.

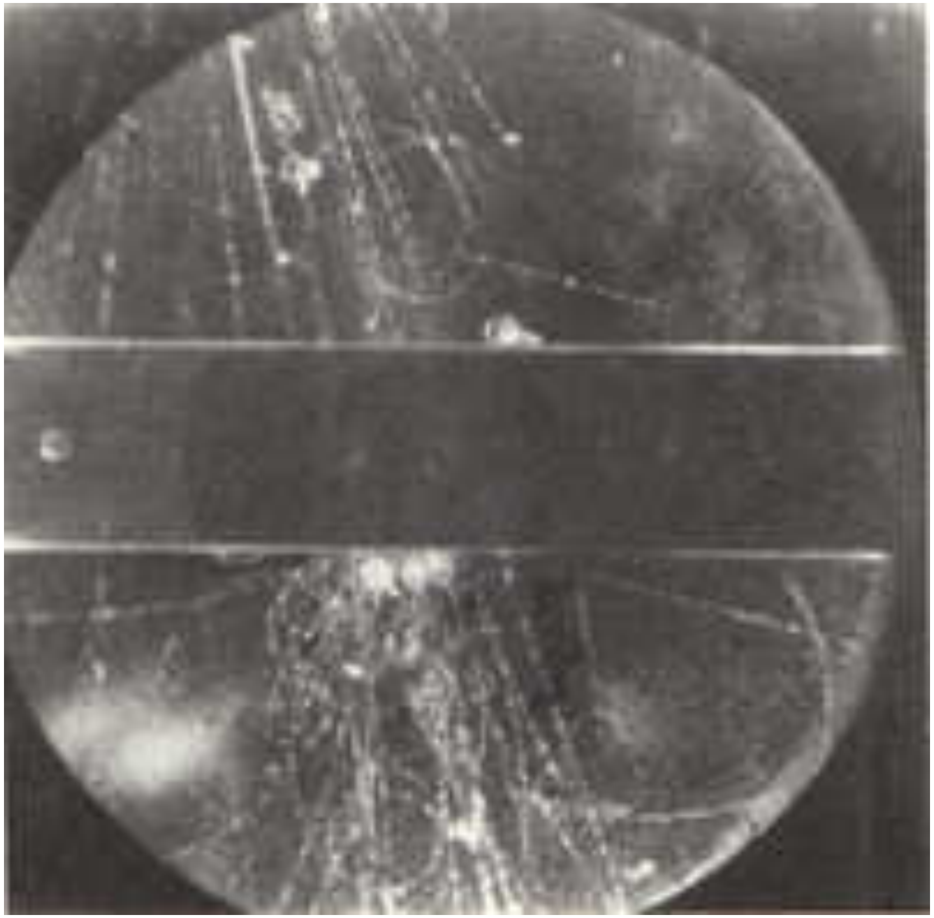
Now when a fast particle traverses a gas, it produces an equal number of positive and negative ions within a narrow cylindrical column. Neglecting, at present, recombination and the effect of the electric field, these ions will diffuse away from their starting-point according to the diffusion equation, so that after a time τ their distribution will be given by§

$$n = \frac{N_0}{4\pi D\tau} e^{-\frac{r^2}{4D\tau}}, \qquad (1)$$

where N_0 is the total number of ions of both signs per cm of track and D is the diffusion coefficient of the ions. If at a time τ after the passage of the ray the supersaturation of the vapour reaches the critical value for condensation on the ions, the mobility of the ions will then be suddenly reduced nearly to zero. So a photograph of such a track, taken a short time after the attainment

* 'Nature,' vol. 130, p. 363 (1932); 'Proc. Roy. Soc.,' A, vol. 139, p. 699 (1933).
† 'Phys. Rev.,' vol. 44, p. 779 (1933); 'Phys. Rev.,' vol. 45, p. 979 (1932).
‡ 'Phys. Rev.,' vol. 45, p. 357 (1934).
§ Jaffé, 'Ann. Physik,' vol. 42, p. 303 (1913).

- P.M.S.Blackett and G.Occhialini, Proc.Roy.Soc.A139 (1933) 699



How can we study the properties of Atomic Nuclei?

Nuclear Reactions

E. Rutherford, Philos. Mag., **ser. 6, v. 37,** 581 **1919**

Radioac

Collision of a Particle with Light Atoms. IV. An Annomalous Effect in Nitrogen.

n, 2n, d etc

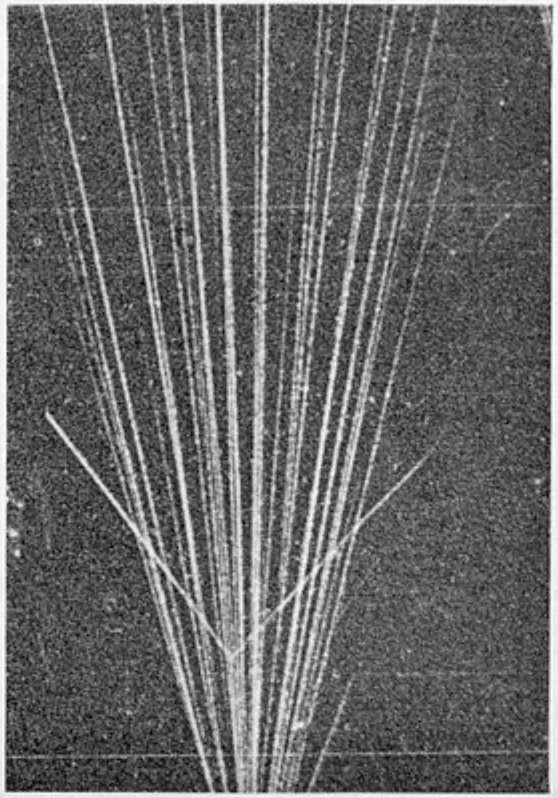
by Professor Sir E. Rutherford, F.R.S.,
University of Cambridge.

(Received 1919)

^{14}N (^{4}He,p) ^{17}O

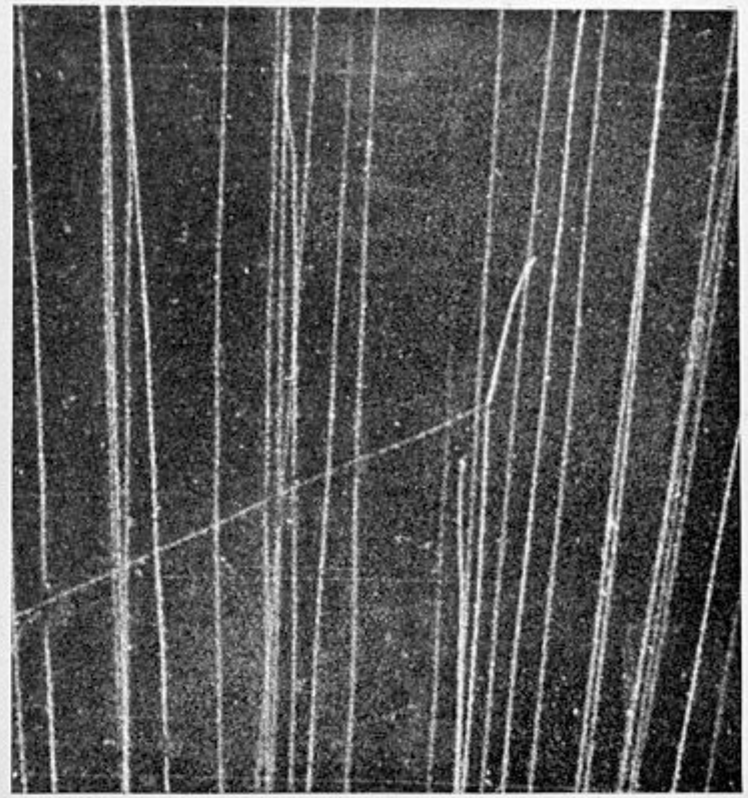
Discussion of results

From the results so far obtained it is difficult to avoid the conclusion that the long-range atoms arising from collision of α particles with nitrogen are not nitrogen atoms but probably atoms of hydrogen , or atoms of mass 2. If this be the case, we must conclude that the nitrogen atom is disintegrated under the intense forces developed in a close collision with a swift α particle, and that the hydrogen atom which is liberated formed a constituent part of the nitrogen nucleus. We have drawn attention in paper III to the rather



Alpha particle strikes helium nucleus and they part at right angles (Blackett)

See p. 293



Alpha particle enters nitrogen which ejects proton and becomes oxygen (Blackett)

See p. 306

Measurement of the g Factor of the 1+ 583-keV State in Na^{22} Using the $F^{19}(Po^{210}\alpha, n)Na^{22*}$ Reaction*

A. W. SUNYAR AND P. THIEBERGER
Brookhaven National Laboratory, Upton, New York
(Received 8 July 1966)

The $F^{19}(\alpha,n)Na^{22*}$ reaction which takes place in a source of Po^{210} dissolved in HF was used to prepare Na^{22*} in the 0.66-MeV 0+ excited state. The subsequent $0+ \rightarrow 1+ \rightarrow 3+$ γ-γ angular correlation was magnetically perturbed in order to measure the g factor of the 0.58-MeV first excited state. A value $g = +0.535 \pm 0.010$ was obtained. The energy and half-life of the 1+ state were remeasured as 583.0 ± 0.5 keV and $(243 \pm 2) \times 10^{-9}$ sec, respectively.

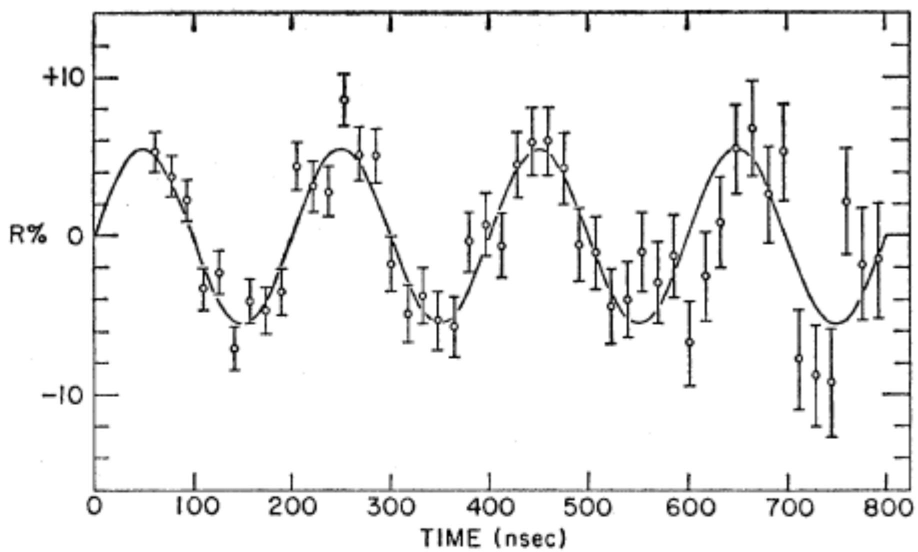


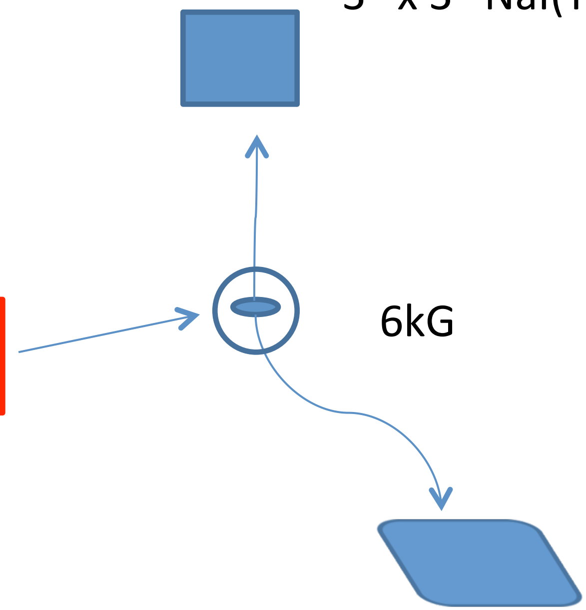
FIG. 1. $R(t) \equiv 2[N_1(t) - N_2(t)]/[N_1(t) + N_2(t)]$, where $N_1(t)$ and $N_2(t)$ are the normalized coincidence counting rates for opposite directions of the 6111 ± 30-G magnetic field, is shown plotted as a function of delay time t.

A.W.Sunyar and P.Thieberger, Phys.Rev.151 (1966)

- ^{19}F(5.3MeV α,n)$^{22}Na^*$ reaction

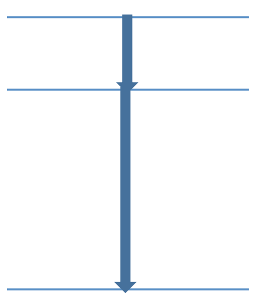
3" x 3" NaI(Tl)

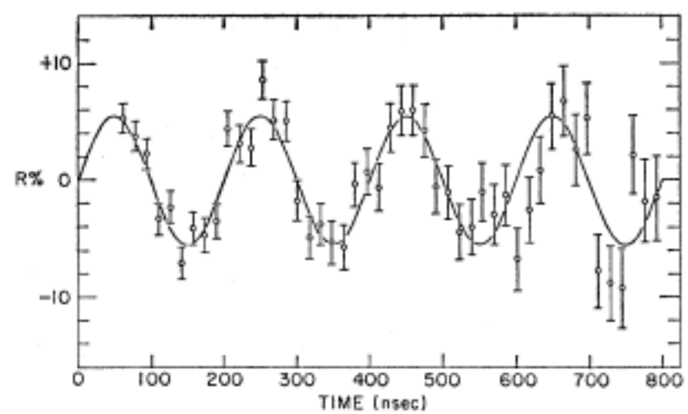
300 mCi ^{210}Po in Hf
teflon holder



6kG

3" x 3" NaI(Tl)





To go further required higher energy particles

Lawrence classified the possible methods as follows:

A. The "High Voltage" method-the ions fall through a potential difference in a vacuum tube.

-the Cockcroft –Walton and van de Graaff accelerators

B. The "surf board" method – the ions travel along in the field of a travelling wave.

- the Linear accelerator

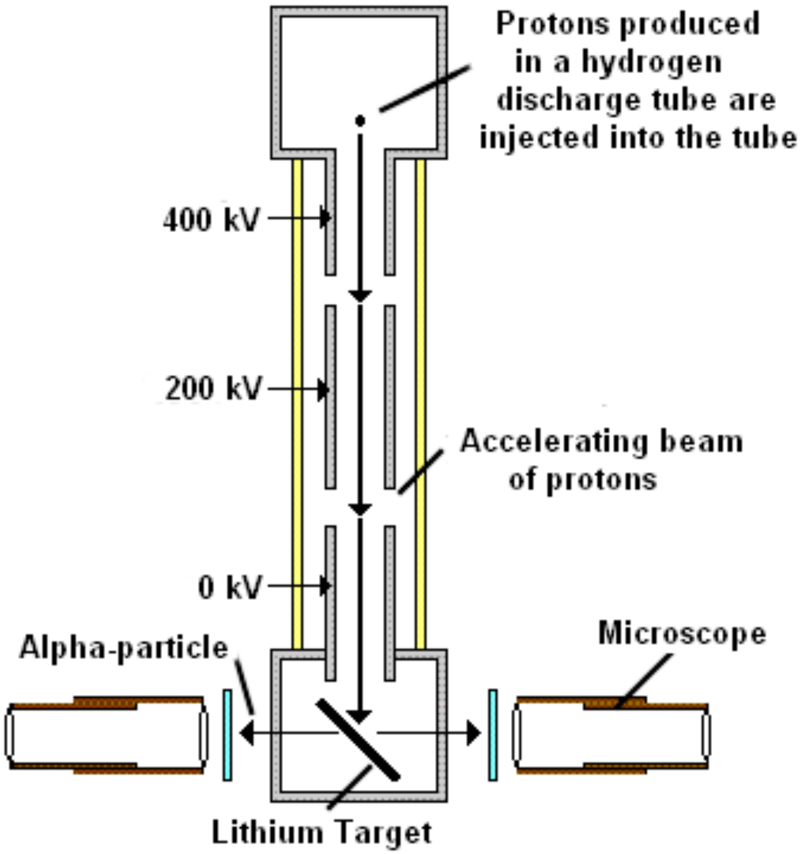
C. The "resonance" methods- or methods involving multiple acceleration

- the Cyclotron and Synchrotron

D. The laser Wakefield method – Tajima and Dawson PRL43 (1979)267

E.O.Lawrence, Ohio journal of Physics 35,Issue 5, 388(1935)

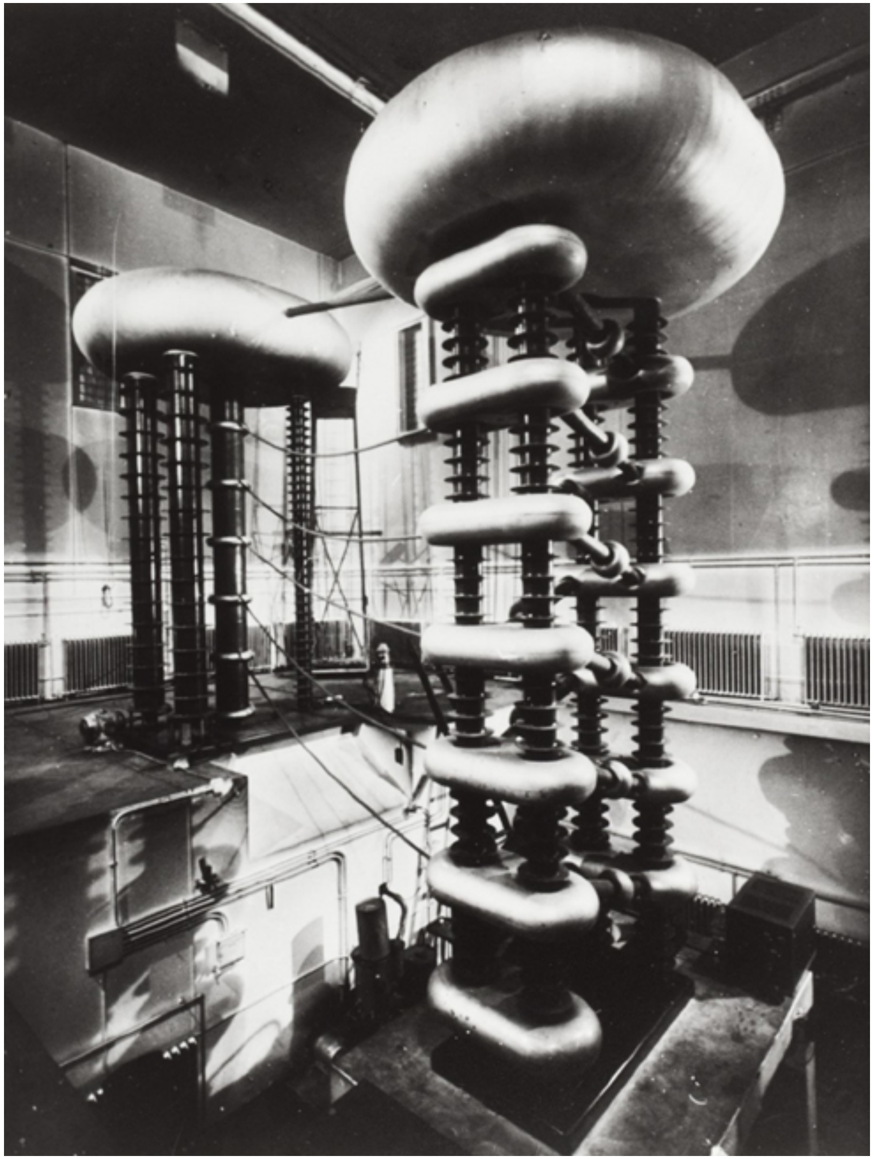
The Cockcroft-Walton Accelerator

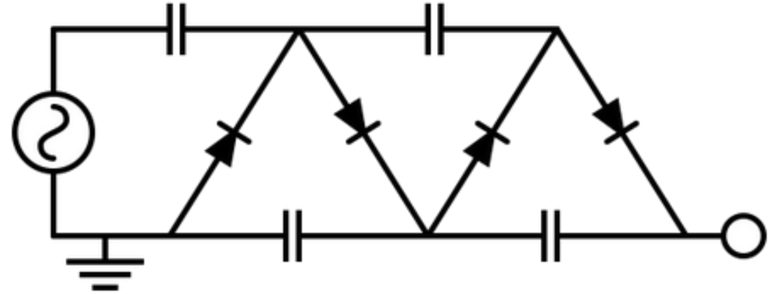


Disintegration of Lithium by swift ions
J.D.Cockcroft and E.T.S.Walton
Nature 129 (1932)649

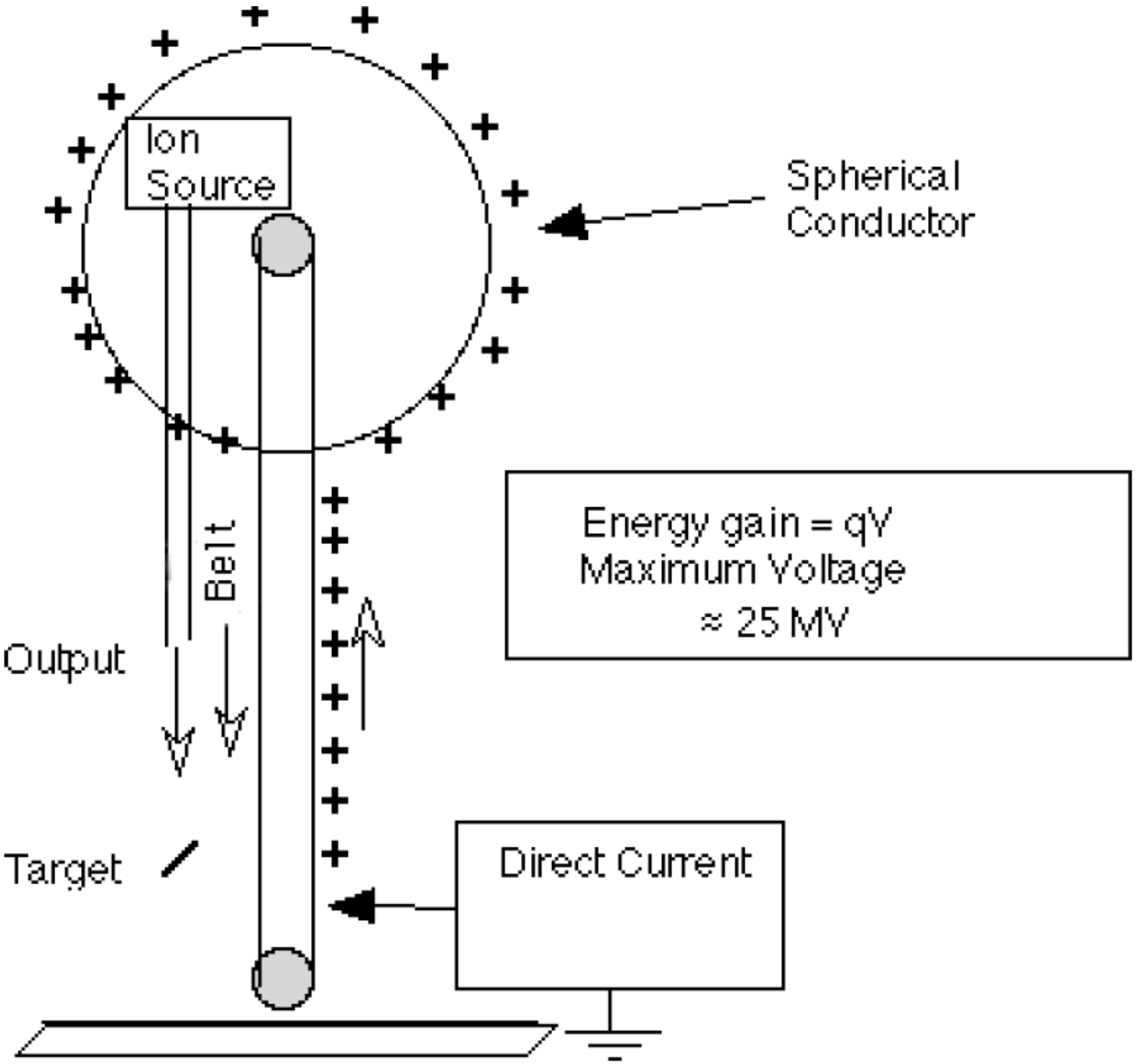
7Li + 1H → 4He +4He + MeV

Cockcroft-Walton Generator

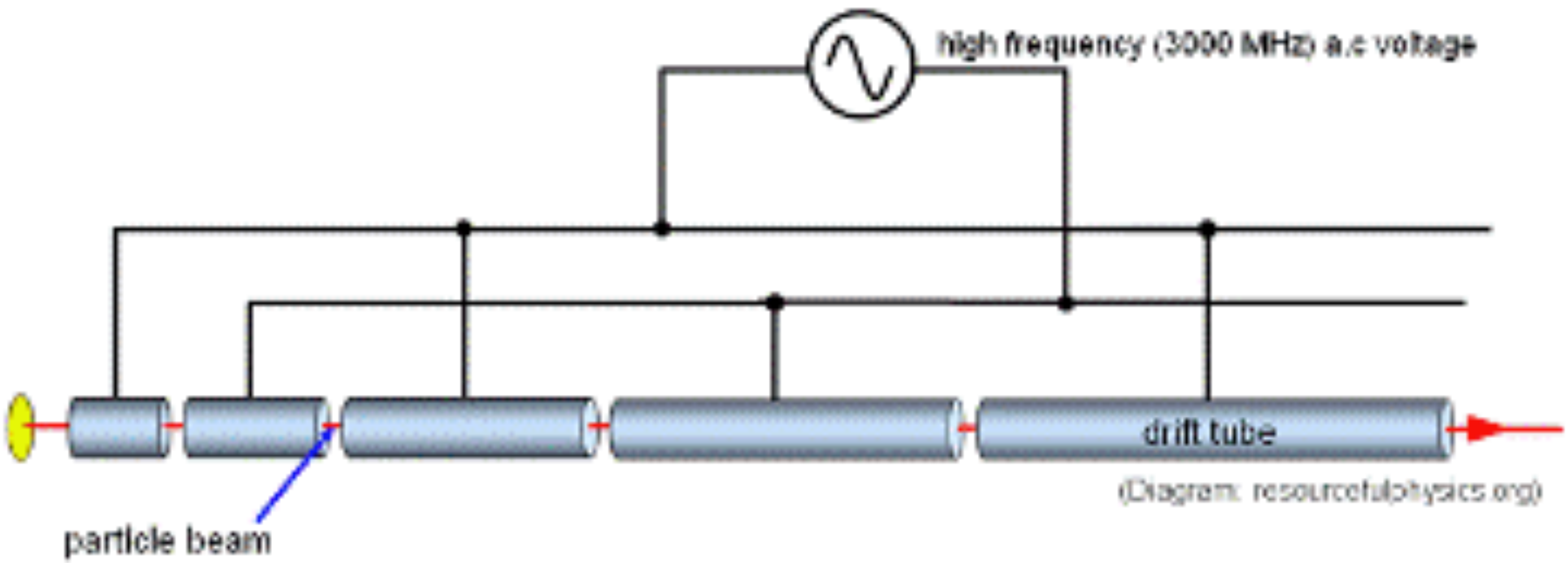




Van de Graaff Accelerator



Linear Accelerator



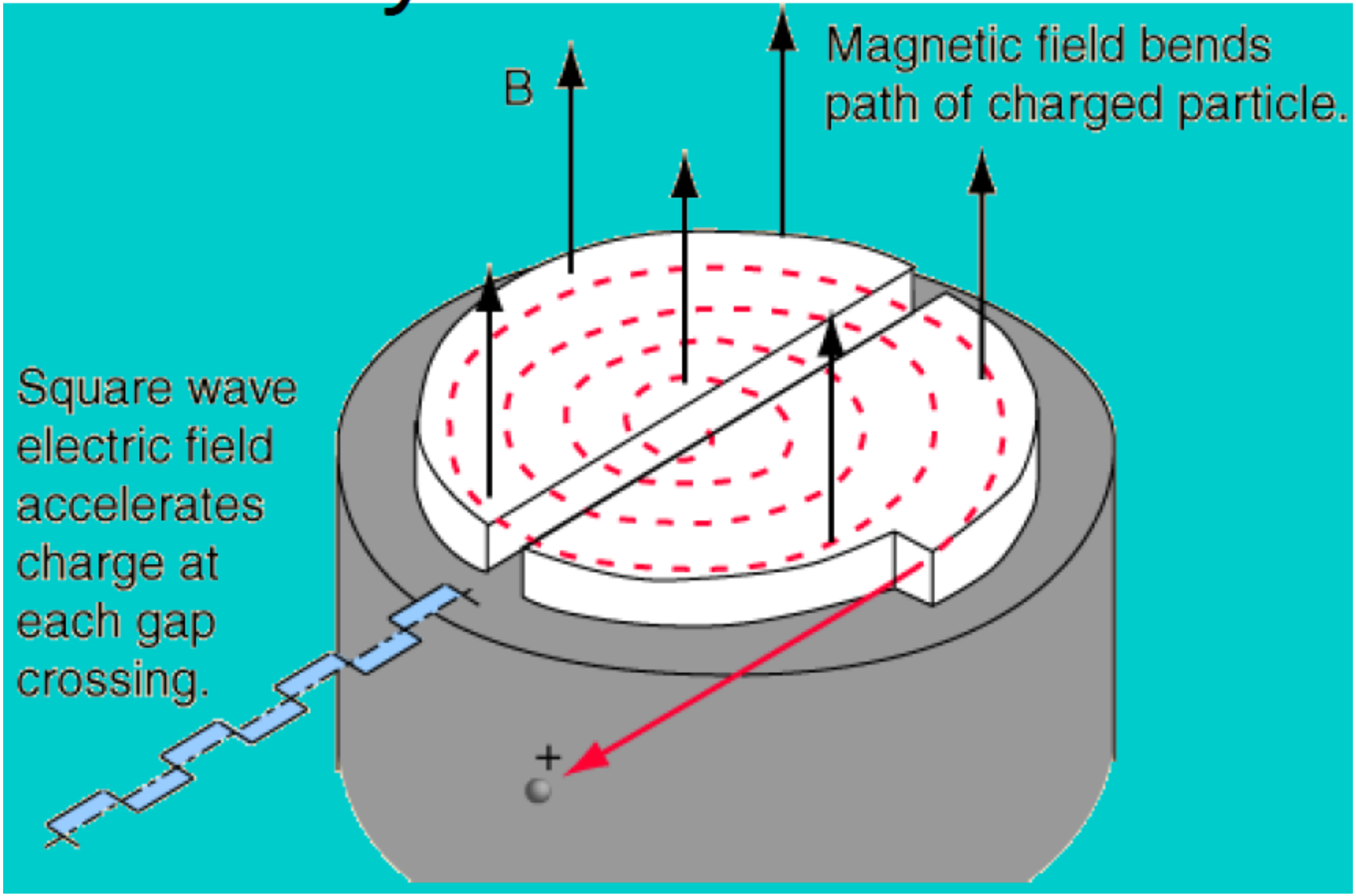
- Drift tubes-no acceleration since tubes act as Faraday cages

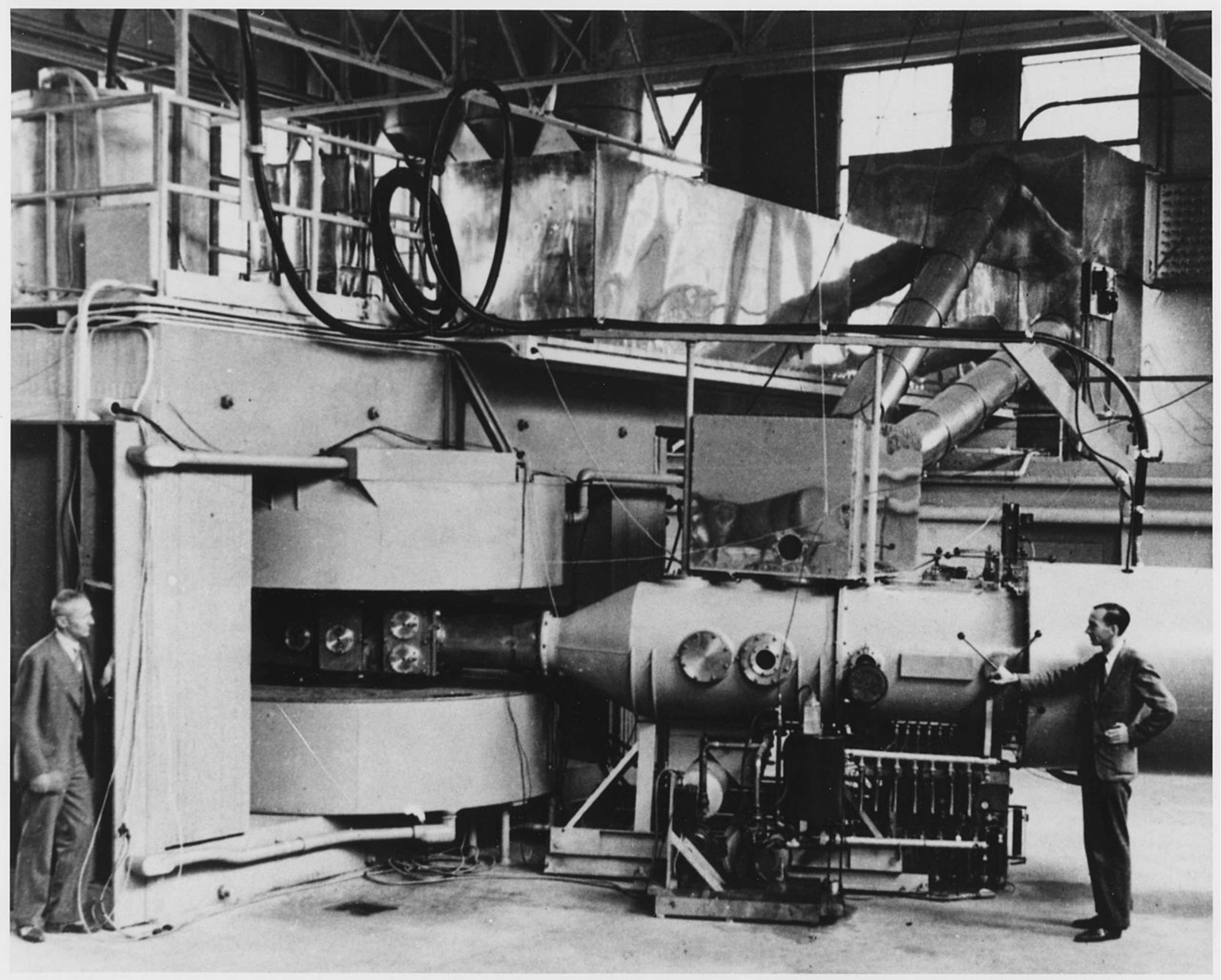
- Frequency of driving signal and gap spacings designed to give maximum acceleration as the particles cross the gap.

- Lenses (magnetic or electrostatic) to manipulate beam.

Drift tubes in TEVATRON Linac

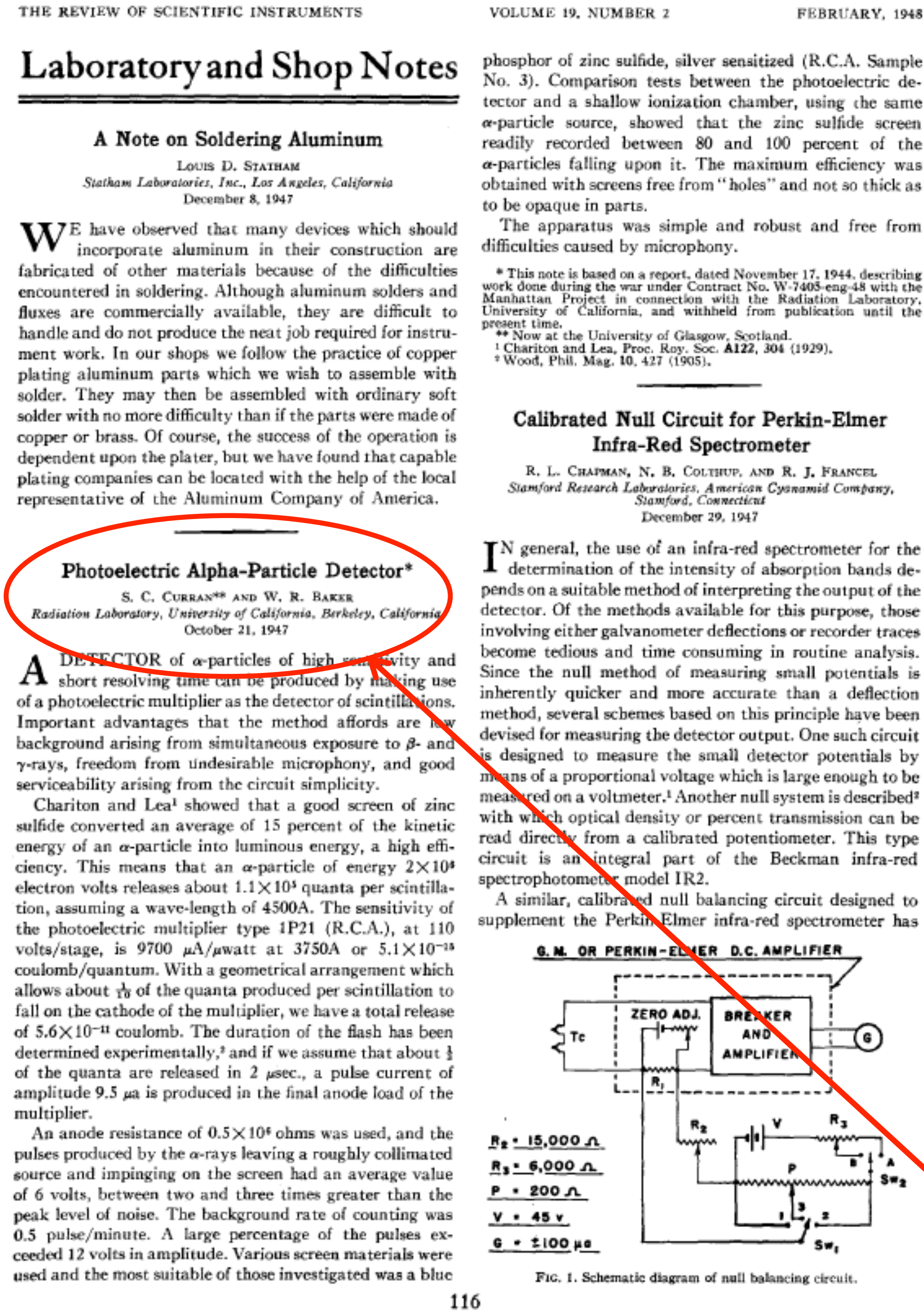
Cyclotron


B
Magnetic field bends path of charged particle.
Square wave electric field accelerates charge at each gap crossing.
+



Gamma-ray Spectroscopy – A big step forward

- Many of the Early studies in Nuclear Physics used the Spinthariscope



Laboratory and Shop Notes

A Note on Soldering Aluminum

LOUIS D. STATHAM
Statham Laboratories, Inc., Los Angeles, California
December 8, 1947

WE have observed that many devices which should incorporate aluminum in their construction are fabricated of other materials because of the difficulties encountered in soldering. Although aluminum solders and fluxes are commercially available, they are difficult to handle and do not produce the neat job required for instrument work. In our shops we follow the practice of copper plating aluminum parts which we wish to assemble with solder. They may then be assembled with ordinary soft solder with no more difficulty than if the parts were made of copper or brass. Of course, the success of the operation is dependent upon the plater, but we have found that capable plating companies can be located with the help of the local representative of the Aluminum Company of America.

Photoelectric Alpha-Particle Detector*

S. C. CURRAN** AND W. R. BAKER
Radiation Laboratory, University of California, Berkeley, California
October 21, 1947

A DETECTOR of α-particles of high sensitivity and short resolving time can be produced by making use of a photoelectric multiplier as the detector of scintillations. Important advantages that the method affords are low background arising from simultaneous exposure to β- and γ-rays, freedom from undesirable microphony, and good serviceability arising from the circuit simplicity.

Chariton and Lea[1] showed that a good screen of zinc sulfide converted an average of 15 percent of the kinetic energy of an α-particle into luminous energy, a high efficiency. This means that an α-particle of energy 2×10^6 electron volts releases about 1.1×10^5 quanta per scintillation, assuming a wave-length of 4500A. The sensitivity of the photoelectric multiplier type 1P21 (R.C.A.), at 110 volts/stage, is 9700 μA/μwatt at 3750A or 5.1×10^{-15} coulomb/quantum. With a geometrical arrangement which allows about $\frac{1}{10}$ of the quanta produced per scintillation to fall on the cathode of the multiplier, we have a total release of 5.6×10^{-11} coulomb. The duration of the flash has been determined experimentally,[2] and if we assume that about $\frac{1}{3}$ of the quanta are released in 2 μsec., a pulse current of amplitude 9.5 μa is produced in the final anode load of the multiplier.

An anode resistance of 0.5×10^6 ohms was used, and the pulses produced by the α-rays leaving a roughly collimated source and impinging on the screen had an average value of 6 volts, between two and three times greater than the peak level of noise. The background rate of counting was 0.5 pulse/minute. A large percentage of the pulses exceeded 12 volts in amplitude. Various screen materials were used and the most suitable of those investigated was a blue phosphor of zinc sulfide, silver sensitized (R.C.A. Sample No. 3). Comparison tests between the photoelectric detector and a shallow ionization chamber, using the same α-particle source, showed that the zinc sulfide screen readily recorded between 80 and 100 percent of the α-particles falling upon it. The maximum efficiency was obtained with screens free from "holes" and not so thick as to be opaque in parts.

The apparatus was simple and robust and free from difficulties caused by microphony.

* This note is based on a report, dated November 17, 1944, describing work done during the war under Contract No. W-7405-eng-48 with the Manhattan Project in connection with the Radiation Laboratory, University of California, and withheld from publication until the present time.
** Now at the University of Glasgow, Scotland.
[1] Chariton and Lea, Proc. Roy. Soc. A122, 304 (1929).
[2] Wood, Phil. Mag. 10, 427 (1905).

Calibrated Null Circuit for Perkin-Elmer Infra-Red Spectrometer

R. L. CHAPMAN, N. B. COLTHUP, AND R. J. FRANCEL
Stamford Research Laboratories, American Cyanamid Company, Stamford, Connecticut
December 29, 1947

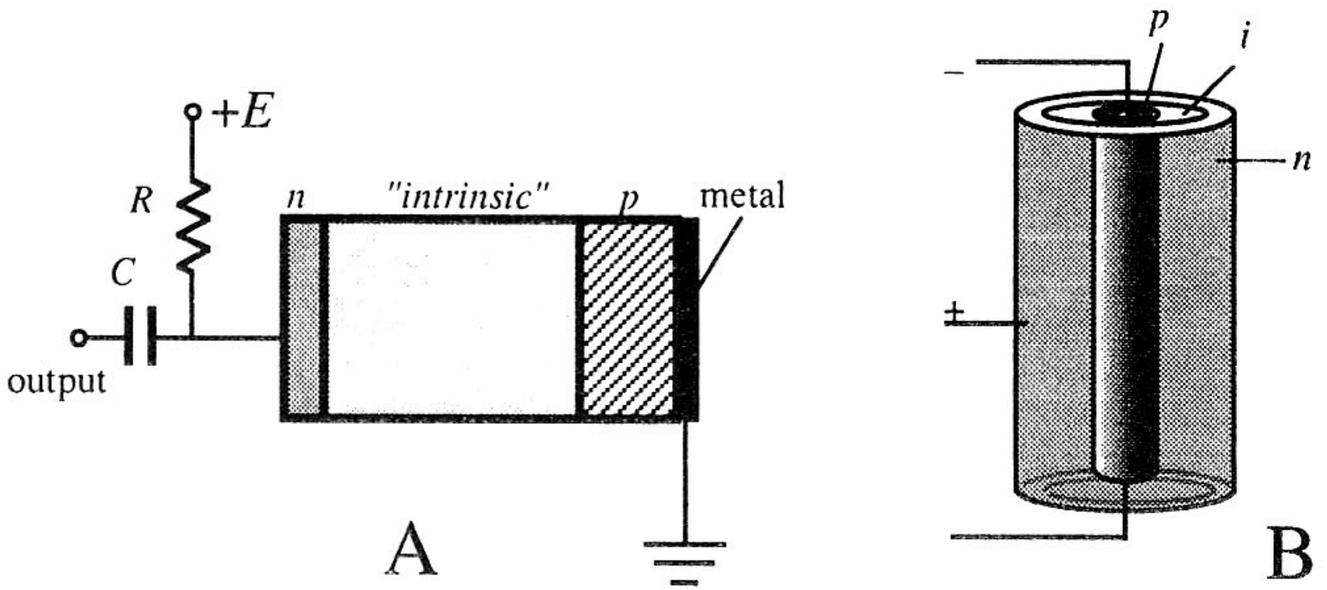
IN general, the use of an infra-red spectrometer for the determination of the intensity of absorption bands depends on a suitable method of interpreting the output of the detector. Of the methods available for this purpose, those involving either galvanometer deflections or recorder traces become tedious and time consuming in routine analysis. Since the null method of measuring small potentials is inherently quicker and more accurate than a deflection method, several schemes based on this principle have been devised for measuring the detector output. One such circuit is designed to measure the small detector potentials by means of a proportional voltage which is large enough to be measured on a voltmeter.[1] Another null system is described[2] with which optical density or percent transmission can be read directly from a calibrated potentiometer. This type circuit is an integral part of the Beckman infra-red spectrophotometer model IR2.

A similar, calibrated null balancing circuit designed to supplement the Perkin-Elmer infra-red spectrometer has

FIG. 1. Schematic diagram of null balancing circuit.

Curran and Baker, Rev.Sci.Inst 19 (1948)116

The Lithium-drifted Ge detector –Ge(Li)



Lithium-drifted *pin*-junction detector. A: Structure of the detector; B: coaxial configuration of the detector.

- **Li-drifted Si – E.M.Pell, J.Appl. Physics31 (1960)291**
- **First Ge(Li) - D.V.Freck and J.Wakefield, <u>Nature 193 (1960) 669</u>**

First gamma-ray spectrum with a Ge(Li) in print

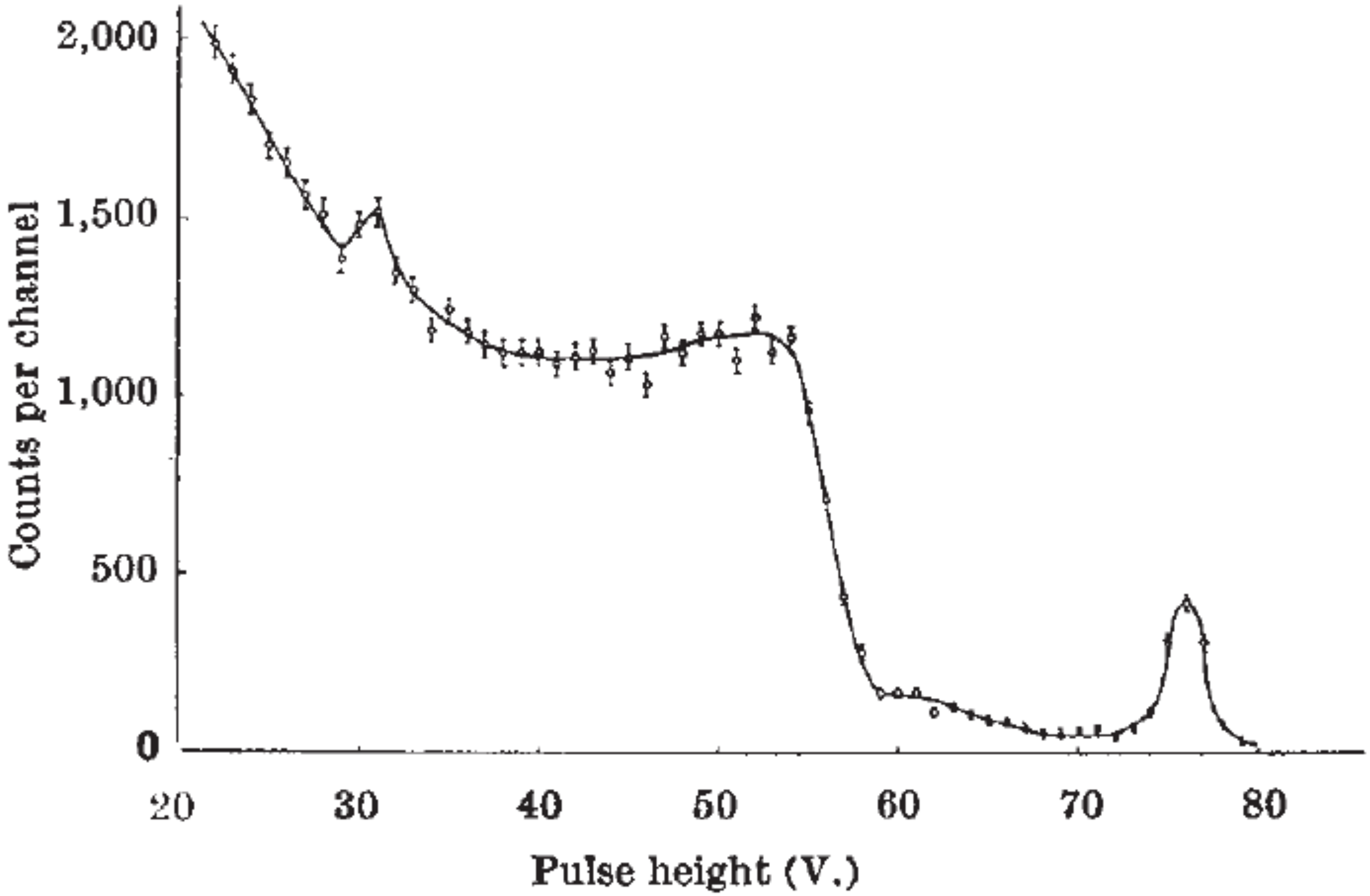
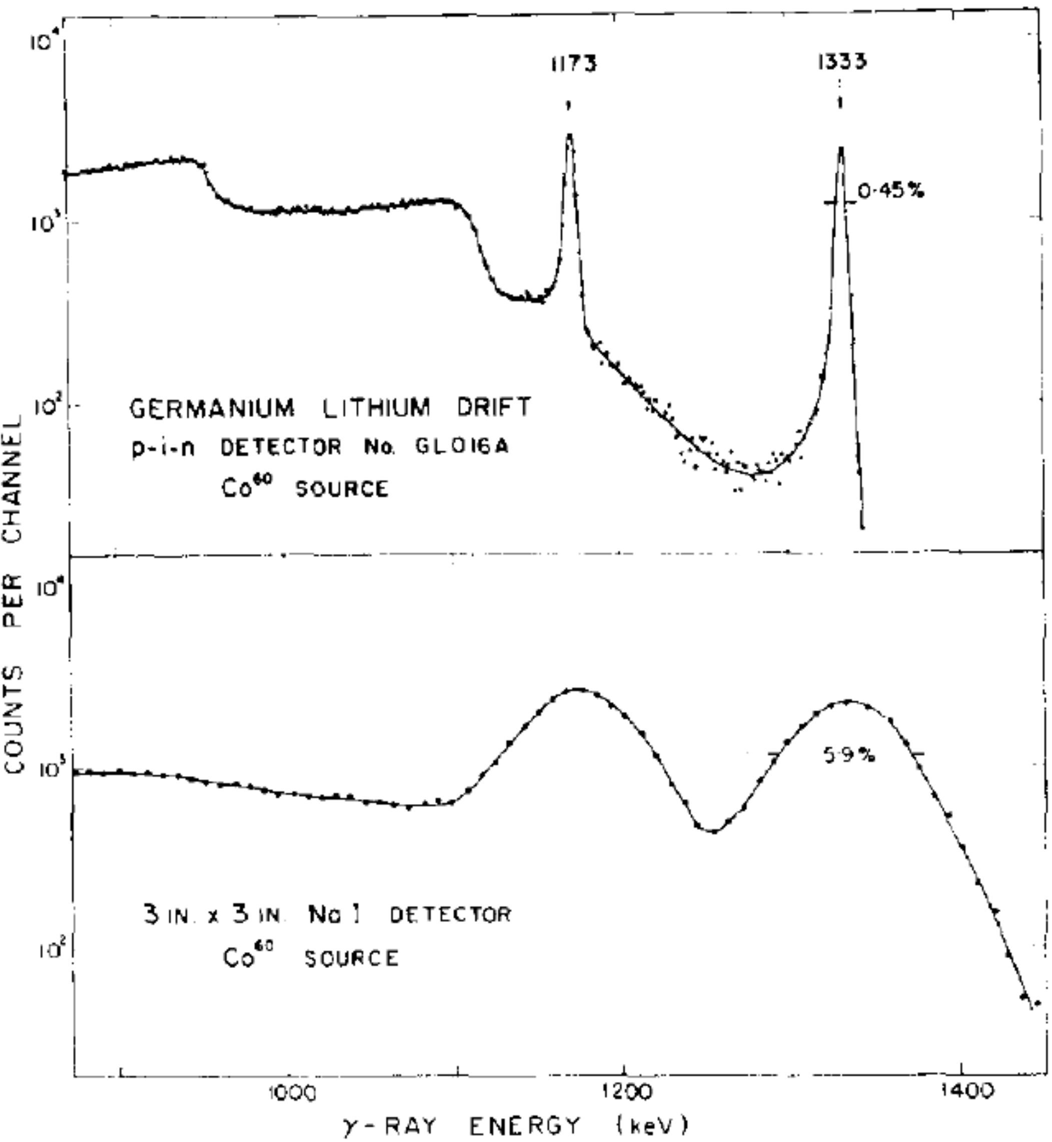


Fig. 1. Pulse-height spectrum from a *p-i-n* junction in germanium due to 663 keV. γ-rays from cæsium-137

Spectrum taken with a single channel pulse height analyser and scaler

D.V.Freck and J.Wakefield, Nature 193 (1960) 669

First Spectroscopy Quality Ge(Li)



- Many attempts to produce bigger and better Ge(Li) detectors
- 1963 Tavendale at Chalk River produced detectors of sufficient quality to allow real spectroscopy.
- He and George Ewan started to look at all the things one could do with such detectors.
- Here we see an example of the spectrum from ^{60}Co taken with one of their detectors compared to the spectrum in a 3" x 3" NaI(Tl)

A.J.Tavendale and G.T.Ewan, NIM 25 (1963) 185

Gamma-rays from fusion-evaporation reactions

H.Morinaga and P.C.Gugelot, Nuc.Phys.46 (1963)210

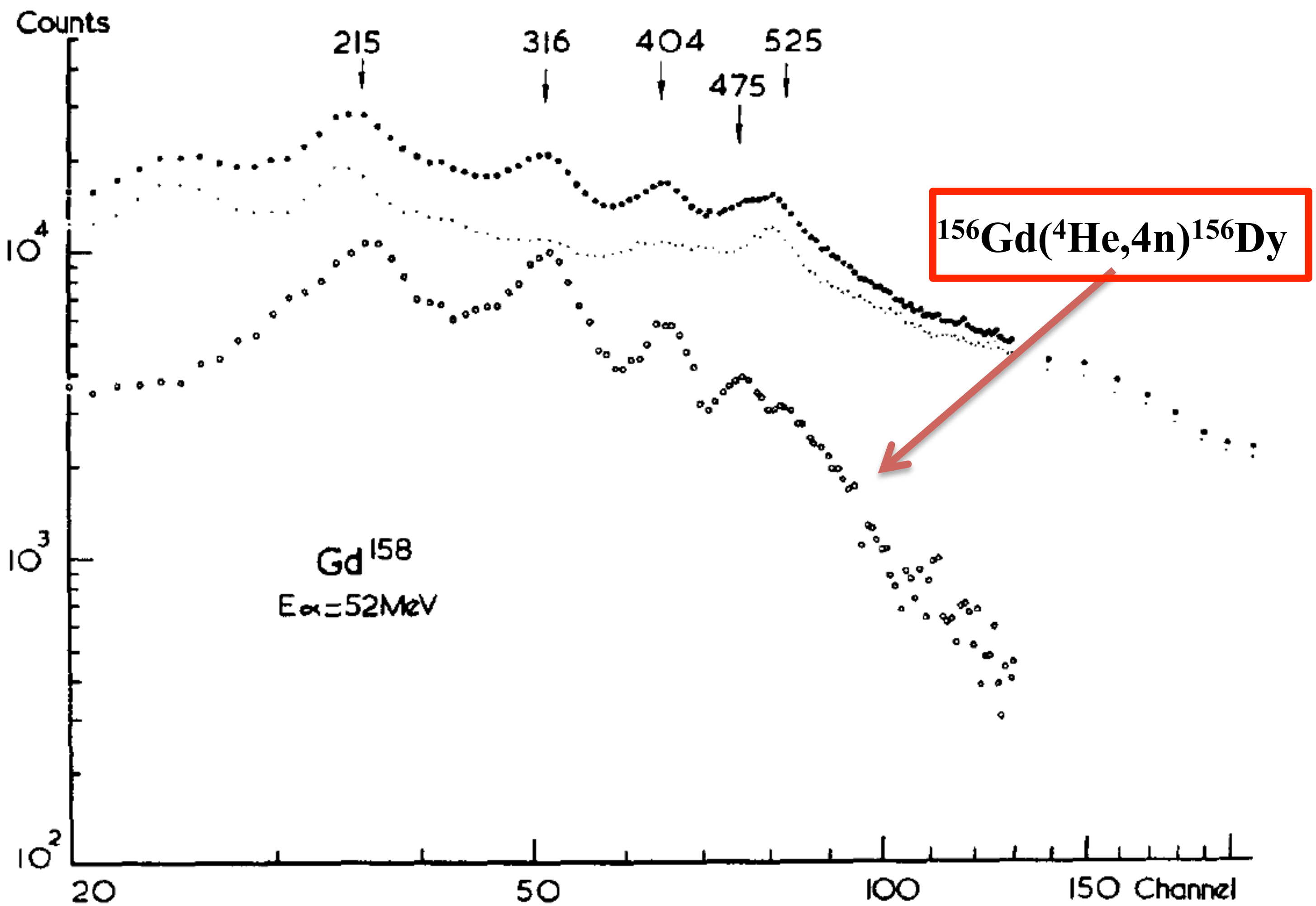


Fig. 5. The pulse-height spectrum as observed for a $^{158}Gd_2O_3$ target bombarded by 52 MeV alpha particles. Curves 1(•), 2(·) and 3(○) represent, respectively, runs with 1.5 mm lead absorber between target and counter, with 10 mm lead absorber in place and the difference between curve 1 and curve 2.

First Evidence of backbending

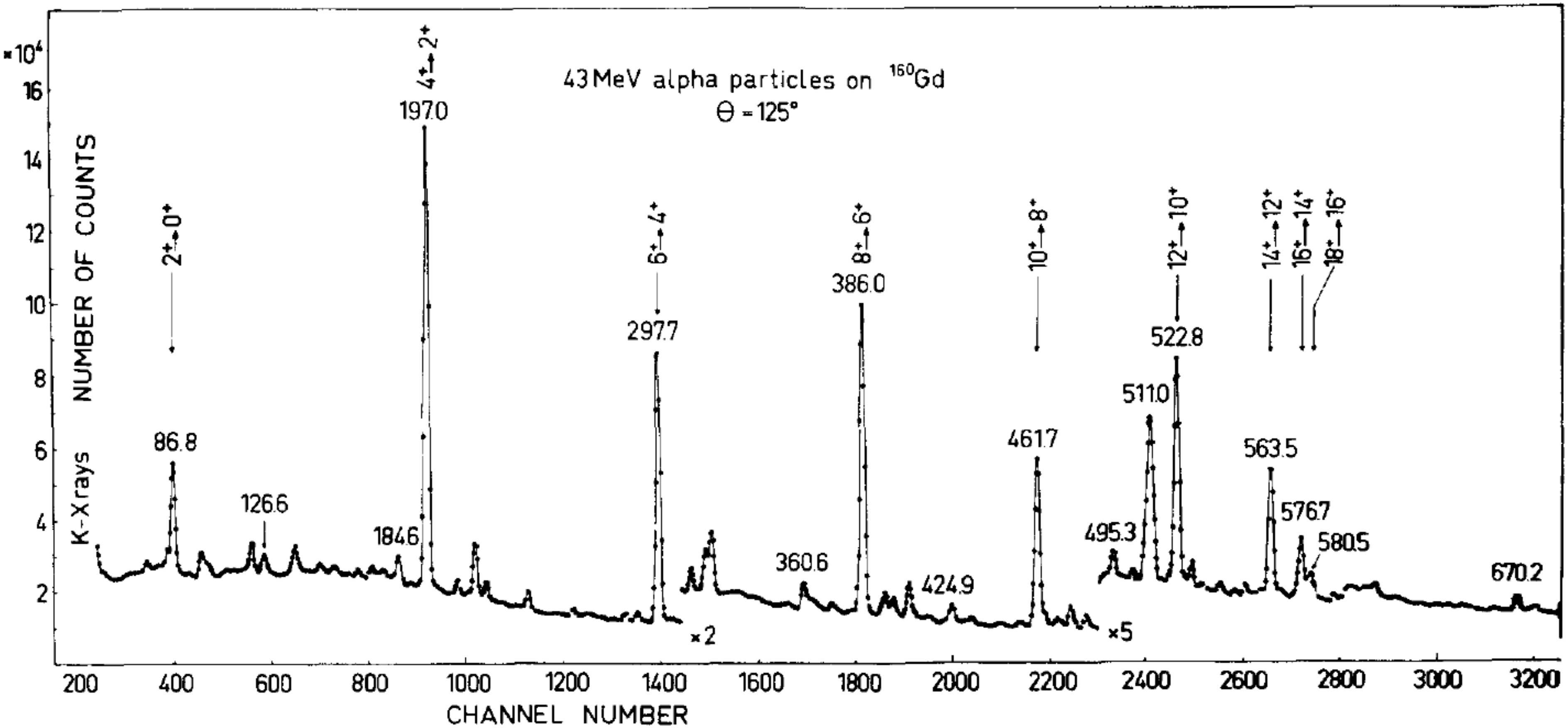


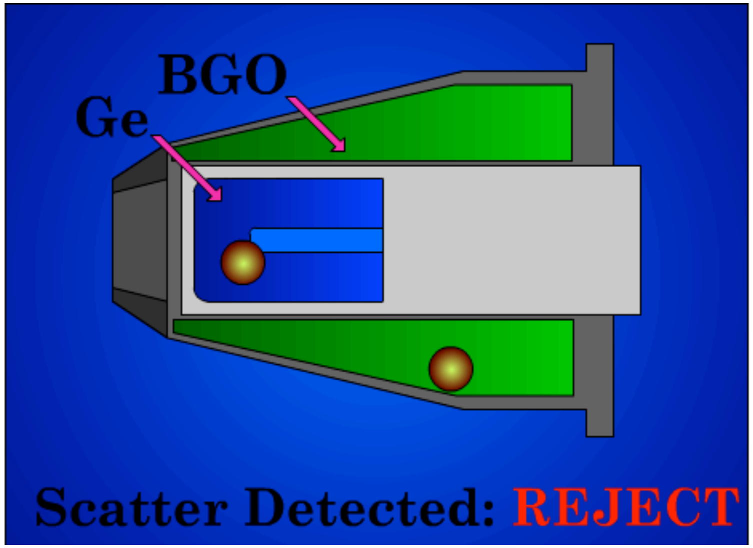
Fig. 1. The singles spectrum recorded at 125° relative to the beam. The indicated peaks are assigned to the (α, 4n) reaction.

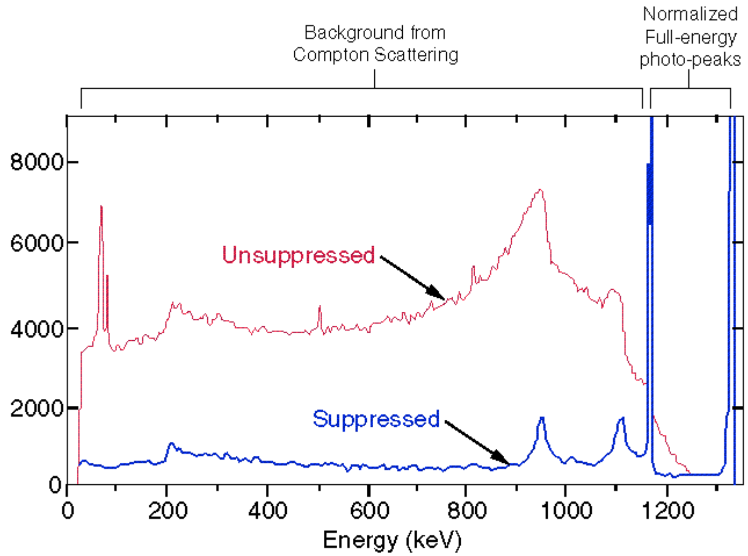
A.Johnson, H.Ryde and J.Sztarkier, Phys. Letters 34B (1971) 605

High resolution gamma spectroscopy

Germanium detectors are the best

The scattering problem…

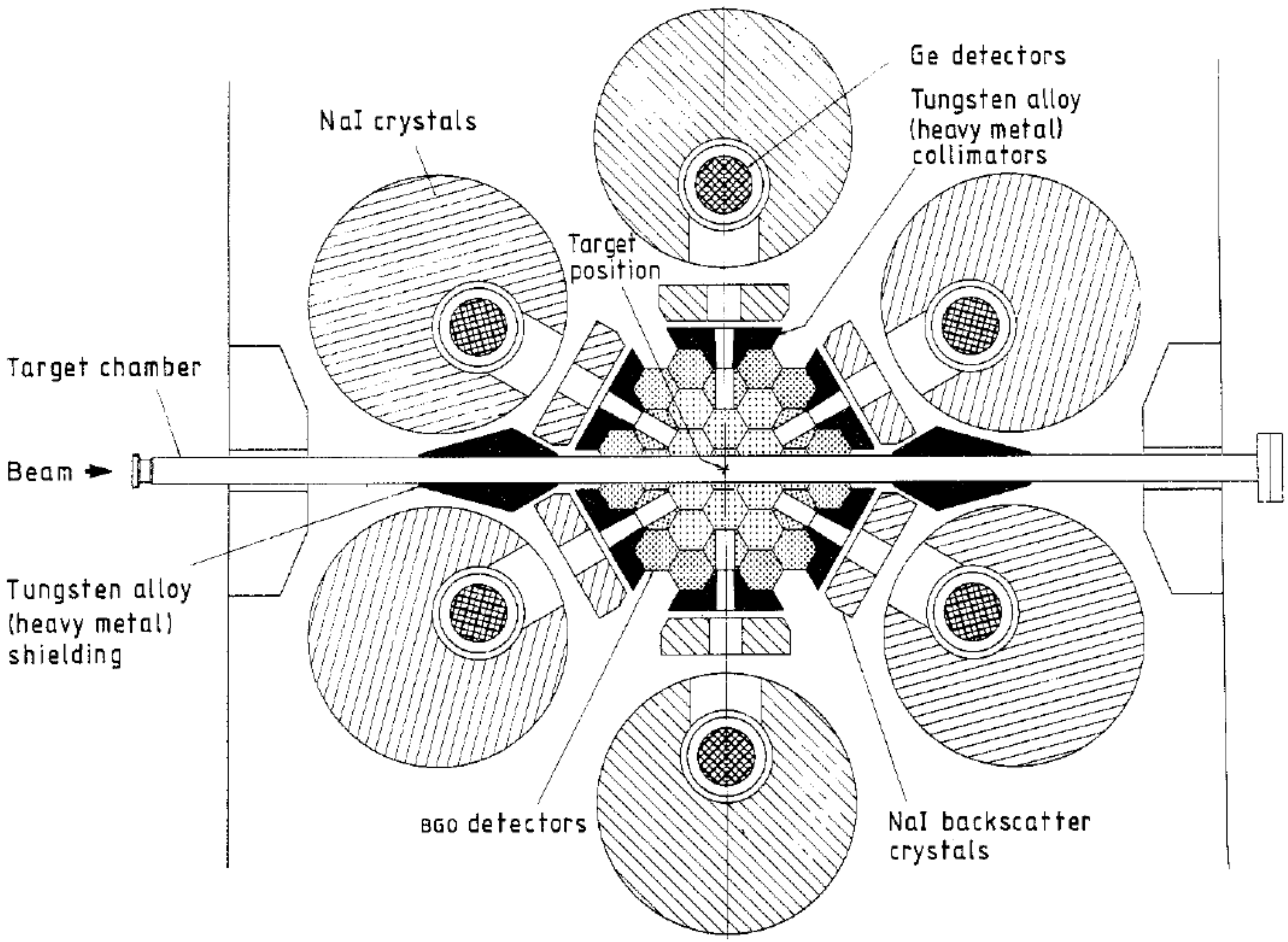




High background hence suppression shields

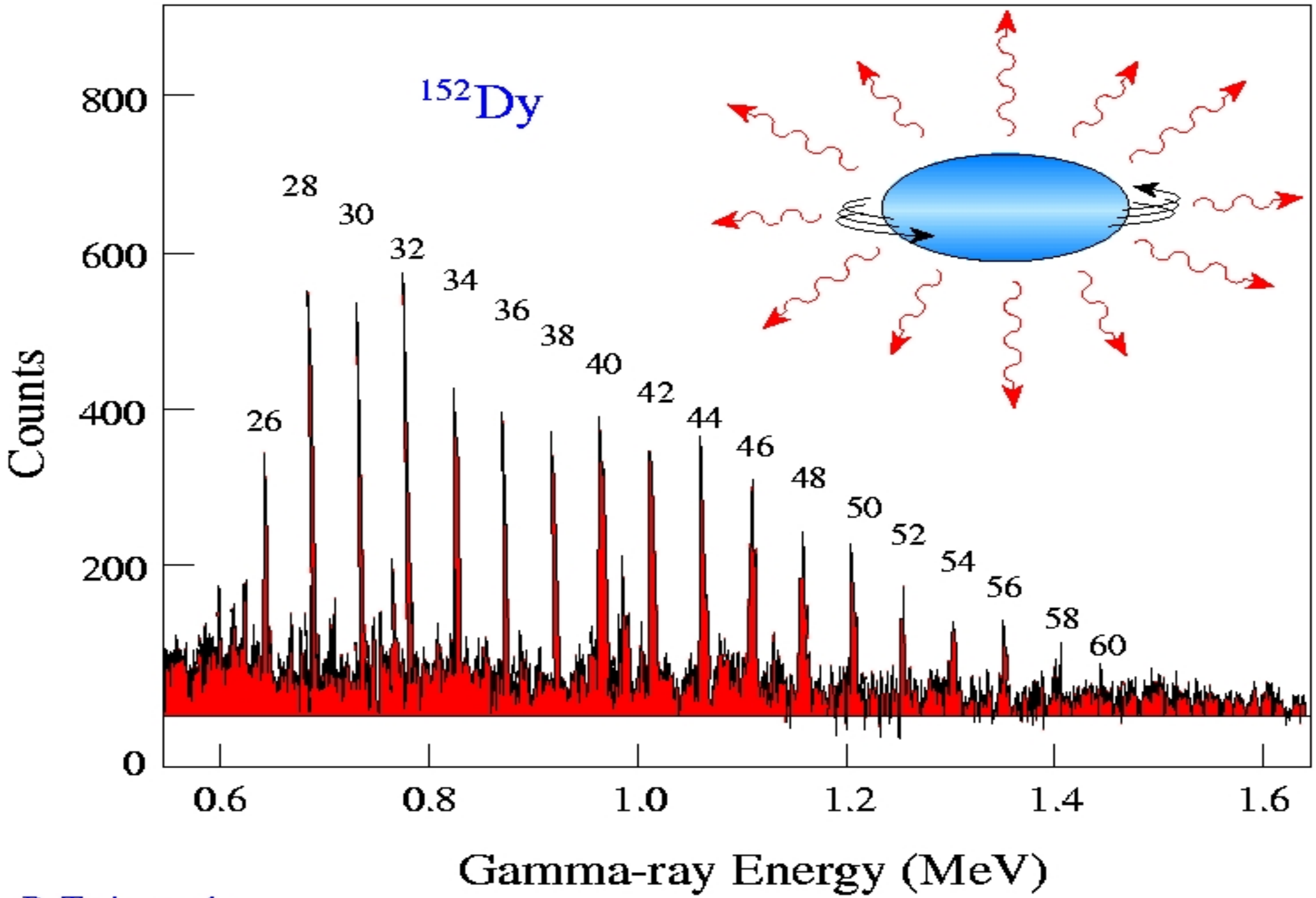
High efficiency hence arrays of ESS

The first Gamma-ray arrays

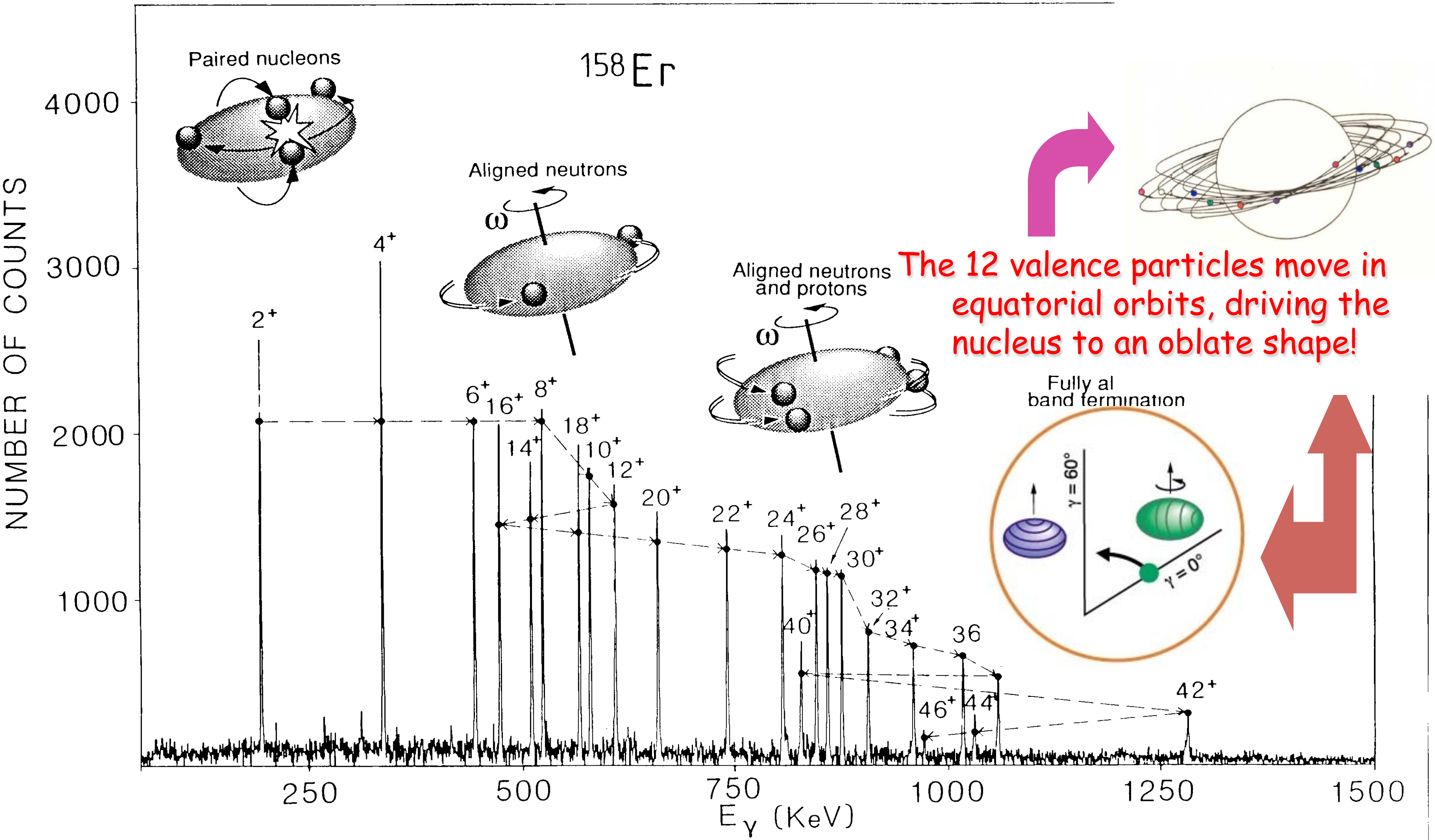


P.J.Twin et al., Nucl.Phys. A409 (1983) 343c

The first case of a high spin superdeformed band



P. Twin et. al
Phys. Rev. Lett. 57 (1986)



The 12 valence particles move in equatorial orbits, driving the nucleus to an oblate shape!

Simpson et al., Phys. Rev. Lett. (1984) – prolate-oblate shape change
P.O.Tjom et al., PRL 55 (1985) 2405 –lifetime measurements
T.Bengtsson and I. Ragnarsson, Physica Scripta T5 (1983) 165
J. Dudek, W. Nazarewicz Phys. Rev C32 (1985) 298
Ragnarsson, Xing, Bengtsson and Riley, Phys. Scripta 34 (1986) 651

Steps on the way to Modern γ-ray Spectroscopy with Ge Detectors.

- 1960:- First Ge(Li) detector - Freck and Wakefield
- 1963:- First Ge(Li) detectors of spectroscopic quality – Tavendale
- late 1970s:- HPGe detectors take over from Ge(Li)
- 1981:-first TESSA array with NaI(Tl) suppression shields
- 1985:- BGO suppression shields introduced
- 1994:- Cluster detector
- 1996:- Clover detector
- 2003:- MINIBALL with Digital processing of preamplifier signals
- XXXX:- Gamma ray tracking –AGATA and GRETA

See;- J.Eberth and J.Simpson, Prog. In Part.and Nucl. Physics 60(2008)283

Why do we need more efficiency?

Radioactive beams

FAIR
SPIRAL2
SPES
HIE-ISOLDE
FRIB
RIBF,RIKEN
etc.

- Low intensity
- High background
- Large Doppler broadening
- High counting rates
- High gamma-ray multiplicities

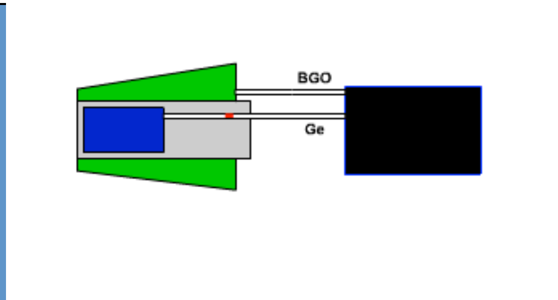
Harsh conditions
Need instrumentation with

High efficiency
High sensitivity
High throughput
Ancillary detectors

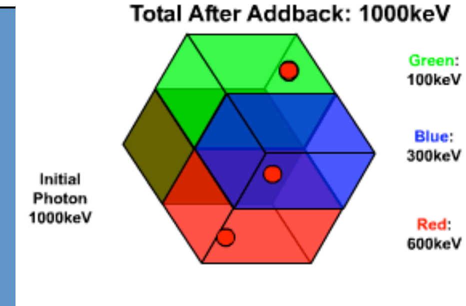
Conventional arrays will not suffice!

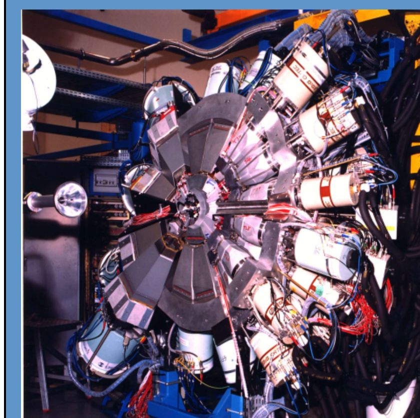
Idea of γ-ray tracking

Large Gamma Arrays based on
Compton Suppressed Spectrometers

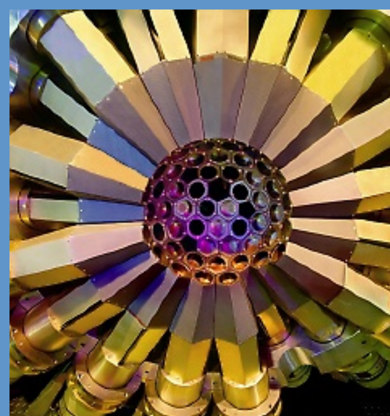


Tracking Arrays based on
Position Sensitive Ge Detectors

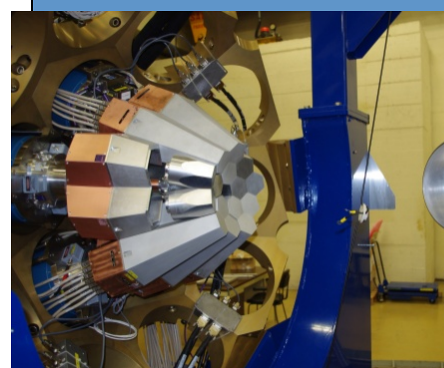




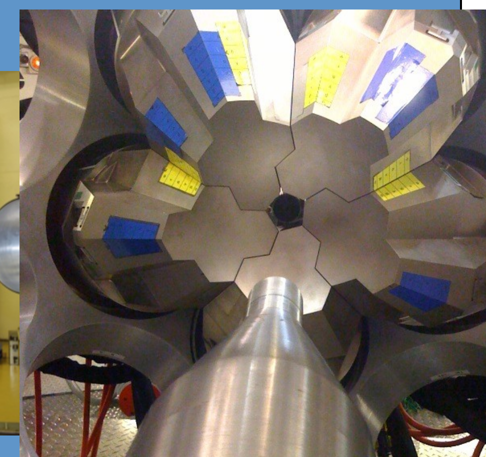
EUROBALL



GAMMASPHERE



AGATA



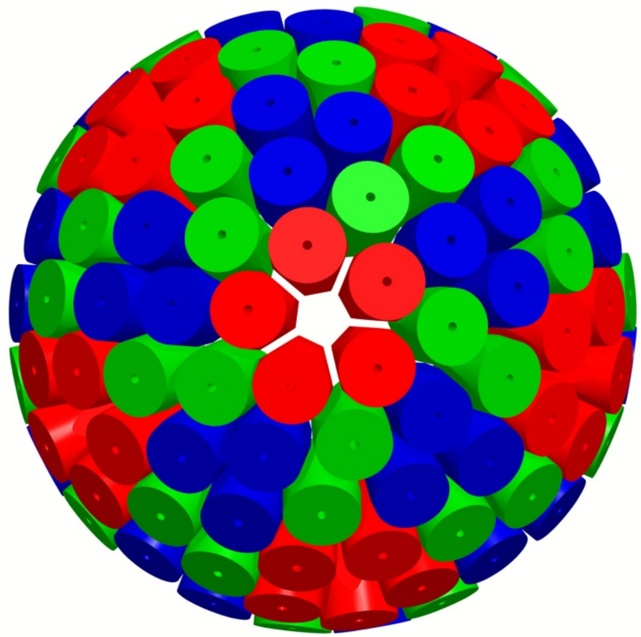
GRETINA/GRETA

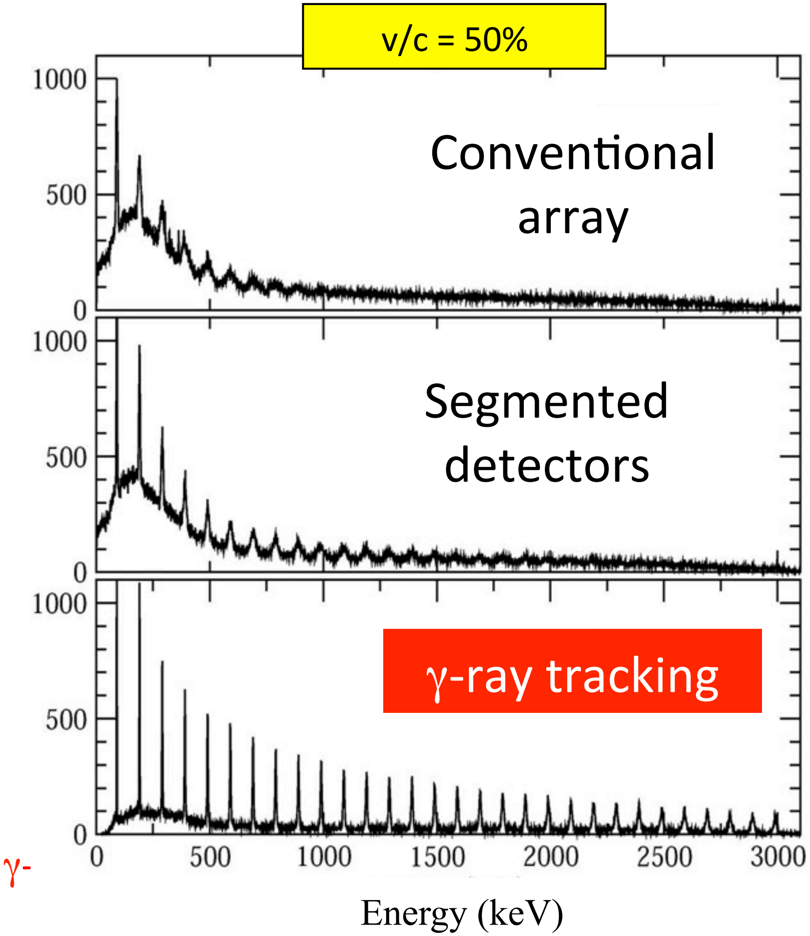
$\varepsilon \sim 10$ — 5 %
(M_γ=1 — M_γ=30)

$\varepsilon \sim 40$ — 20 %
(M_γ=1 — M_γ=30)

Huge increase in sensitivity

AGATA





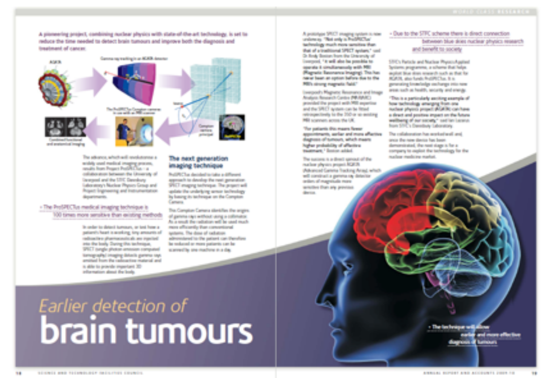
180 large volume 36-fold segmented Ge crystals

The innovative use of detectors (pulse shape analysis, γ-ray tracking, digital DAQ) will result in high efficiency (~40%) and excellent energy resolution, making AGATA the ideal instrument for spectroscopic studies of weak channels.

The effective energy resolution is maintained also at "extreme" v/c values

AGATA and KE

Direct application in medical and security areas as evidenced by funding from:
CLASP/PNPAS, EPSRC/TSB, MRC, NHS, NNL (NDA), AWE

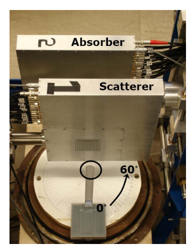


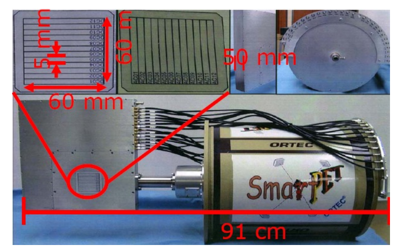
SMARTPET

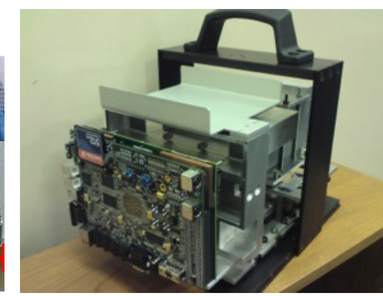
- Novel Small Animal PET system

PORGAMRAYS / PGRIS

- Hand-held radiation identification and location device







PROSPECTUS

- Novel SPECT imaging system.

All projects are collaborations (University of Liverpool) some with industrial partners.

Gamma Ray Detectors

Dino Bazzacco

INFN Sezione di Padova

The beginnings of Science with radioactive beams.

Short-Lived Krypton Isotopes and Their Daughter Substances

O. Kofoed-Hansen and K. O. Nielsen
Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark
(Received February 9, 1951)

The isotopes Kr^{89}, Kr^{90}, Kr^{91}, and their daughter substances have been investigated. Krypton formed in fission of uranium was pumped through a 10-m long tube directly from the cyclotron into the ion source of the isotope separator. The cyclotron and the isotope separator were operated simultaneously, and the counting could begin immediately after the interruption of the separation. The rubidium and strontium daughter substances were separated chemically; strontium was precipitated as carbonate. Half-lives were measured and an absorption analysis of the radiations was carried out. The results are given in Table I.

Table I. Observed radiations.

Isotope	Half-life	Radiation	E_{β}^{max}	Spectrum
Kr^{89}	3.18 min (2.6)	β^-, γ	4.0 Mev	Complex
Kr^{90}	33 sec (33)	β^-, γ	3.2 Mev	Complex
Rb^{90}	2.74 min	β^-, γ	5.7 Mev	Complex
Kr^{91}	10 sec (9.8)	β^-, γ probable	~3.6 Mev	Complex
Rb^{91}	100 sec	β^-, γ	4.6 Mev	Complex
Rb^{91}	14 min	β^-, γ	3.0 Mev	Complex

Previous data (see N.B.S. Circular 499: Nuclear Data) are given in parentheses.

It was found that at least 35 percent of the decays of Kr^{89} lead to an excited state of Rb^{89} which lies ~2 Mev above the ground state. This result is of importance for the interpretation of the β-recoil experiments with this krypton isotope.[1]

- O.Kofoed-Hansen and K.O.Nielsen, Phys.Rev.82 (1951) 96

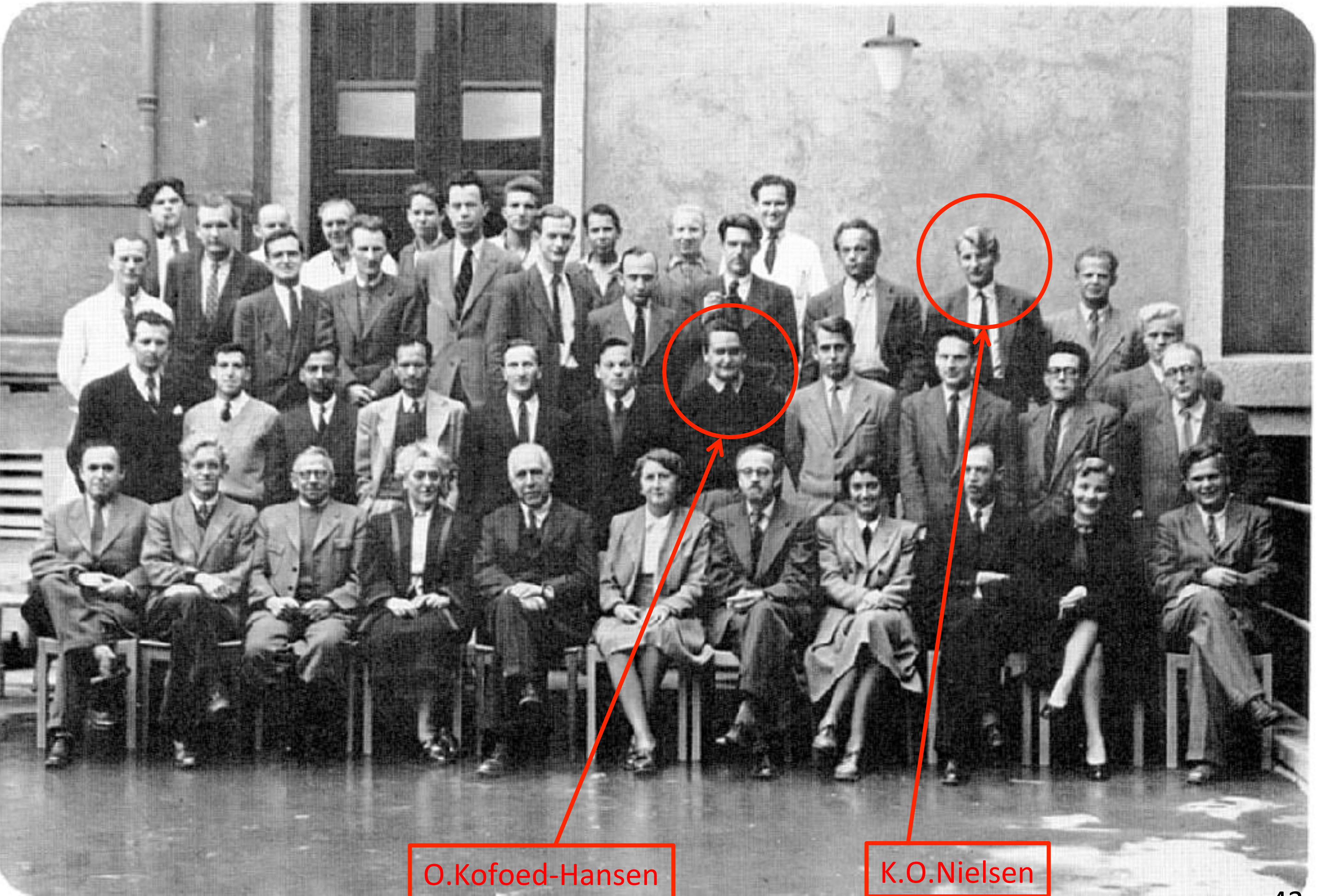
- Fission of uranium by deuterons

- Kr isotopes pumped into the ion source

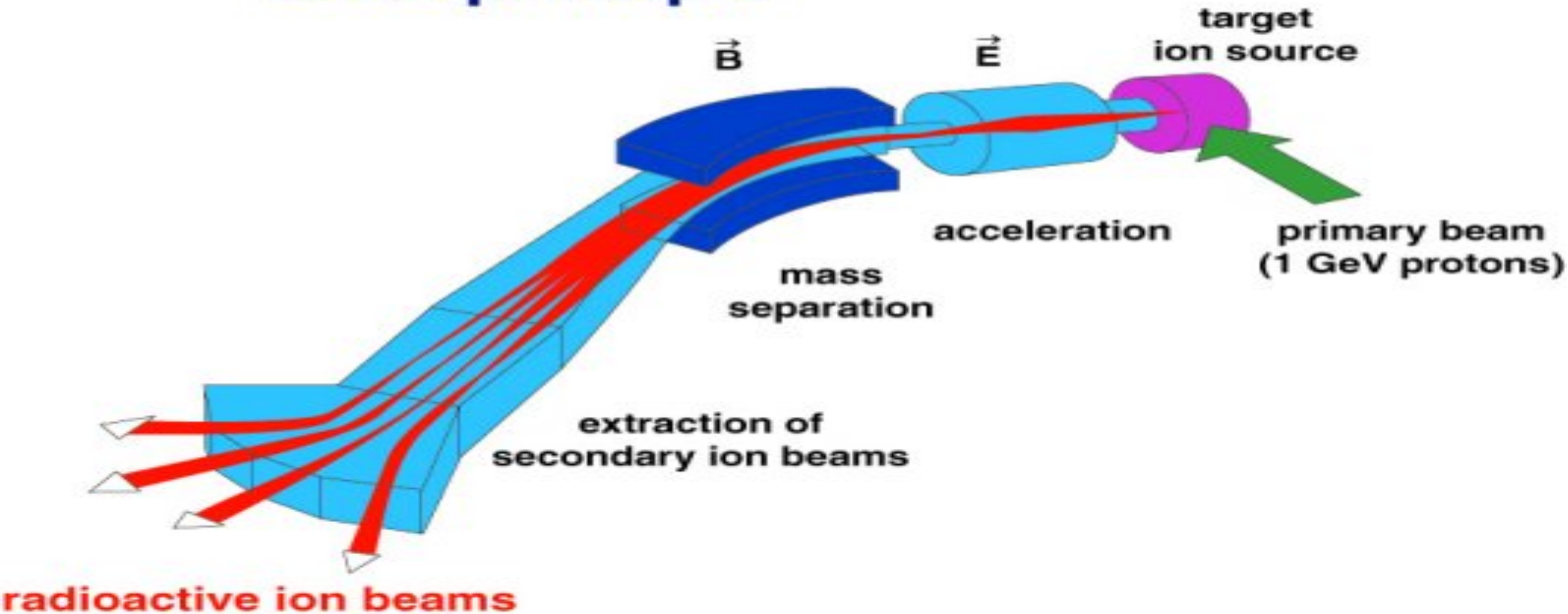
- Definition of On-line isotope separation

Cyclotron and Separator run simultaneously

Full Paper
O.Kofoed-Hansen and K.O.Nielsen, Kongl.Danske.Selsk.Mat-fys.Medd 26 (1951) 7

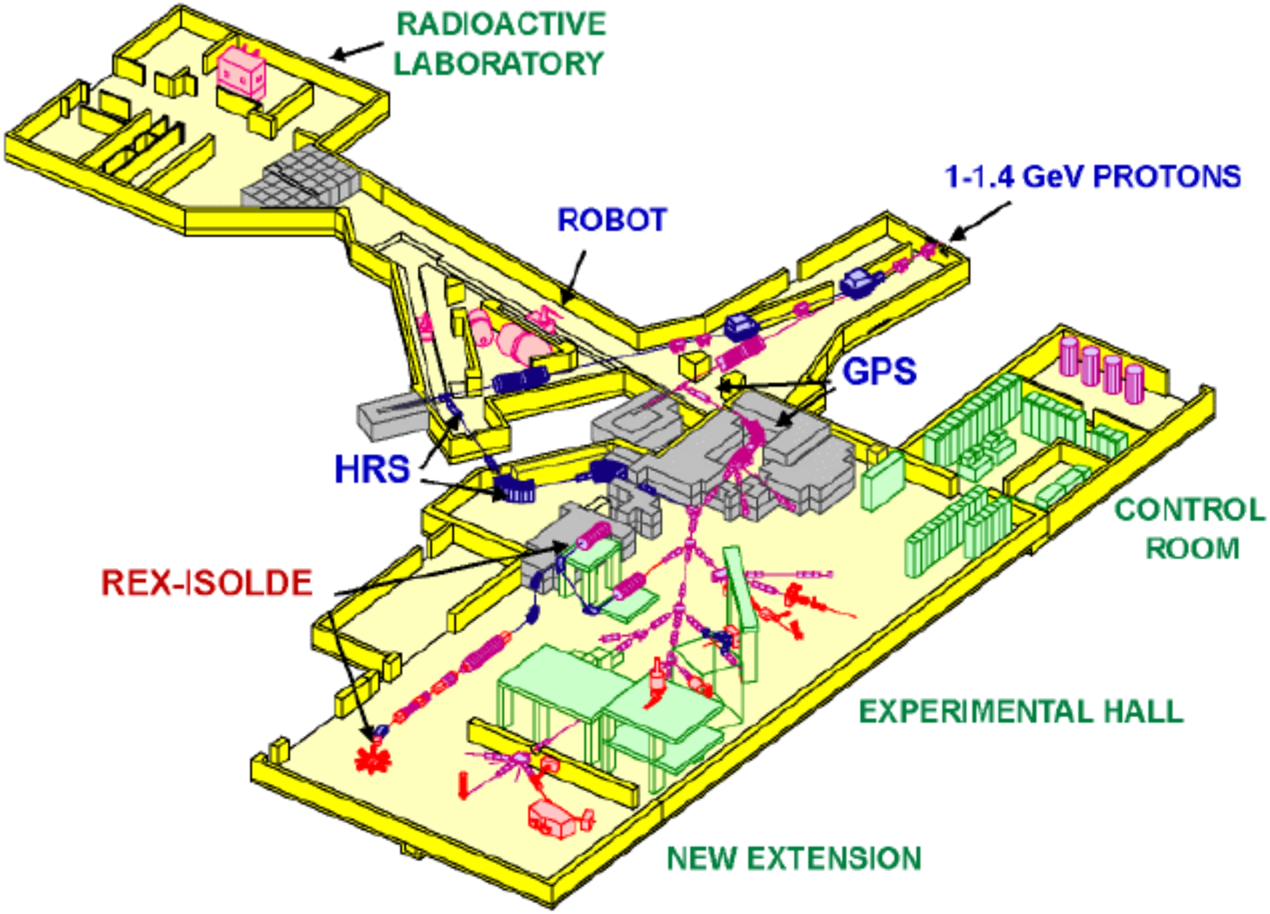

O.Kofoed-Hansen
K.O.Nielsen

ISOL-principle



Radioactive species are created in nuclear reactions
in a target-ion source maintained at high T.
They diffuse/effuse from the target into an ion source where are ionised
and then extracted by an electric field of ~ 60 keV.
Following mass separation they can be used at 60 keV or injected into a
post-accelerator to take them to the Coulomb Barrier or beyond.

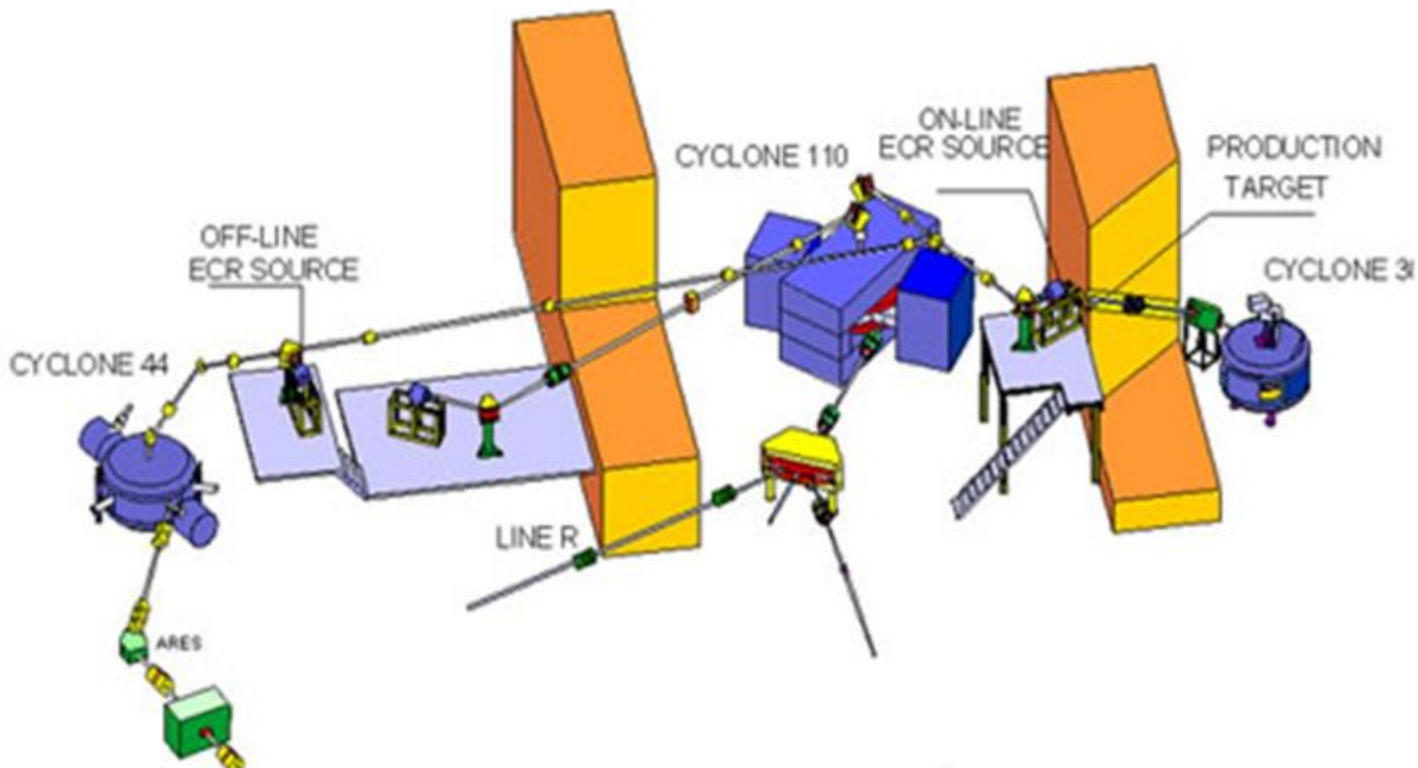
ISOLDE at CERN –the Archetypal ISOL Facility



1964 – Start of ISOLDE at CERN. This is by far the most successful of all on-line Isotope separators.

Louvain-la-neuve –the first ISOL-based RNB facility

- two cyclotrons
- primary beam: protons at 30 MeV
  - intensity: 0.5 mA (15 kW at target!)
- production reaction: $^{7}Li(p,2p)^{6}He$

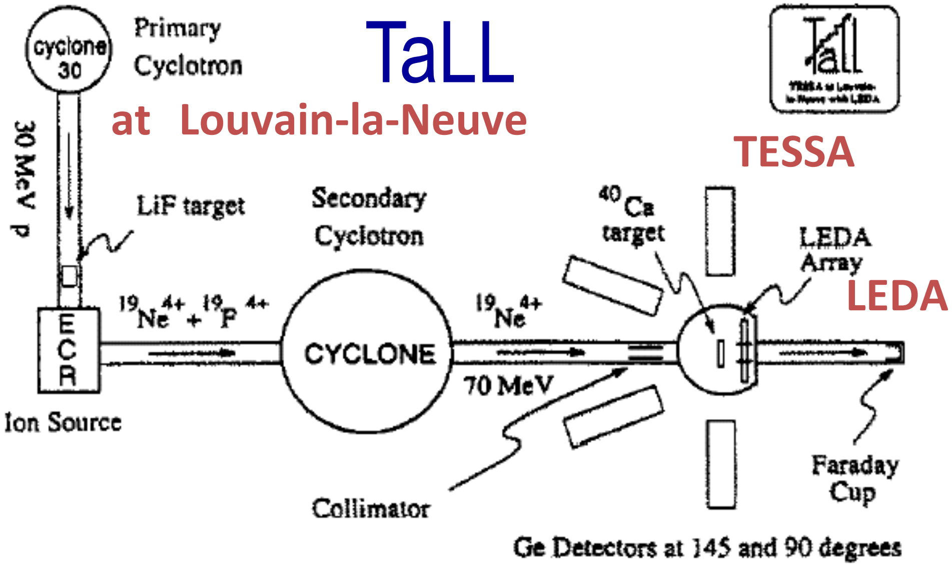


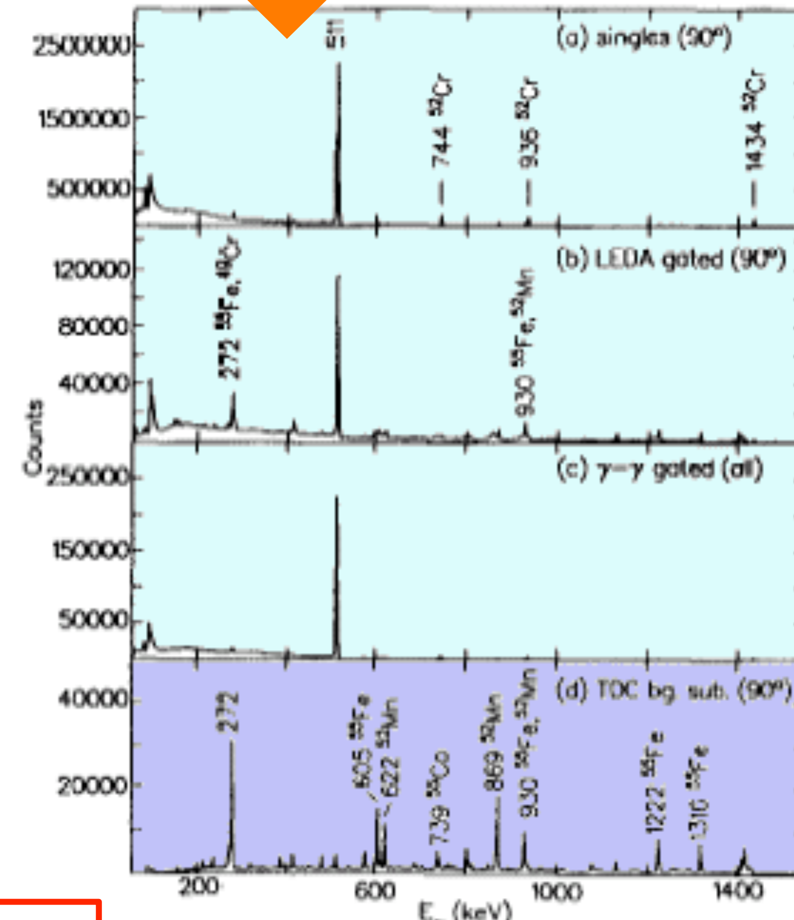
TaLL at Louvain-la-Neuve

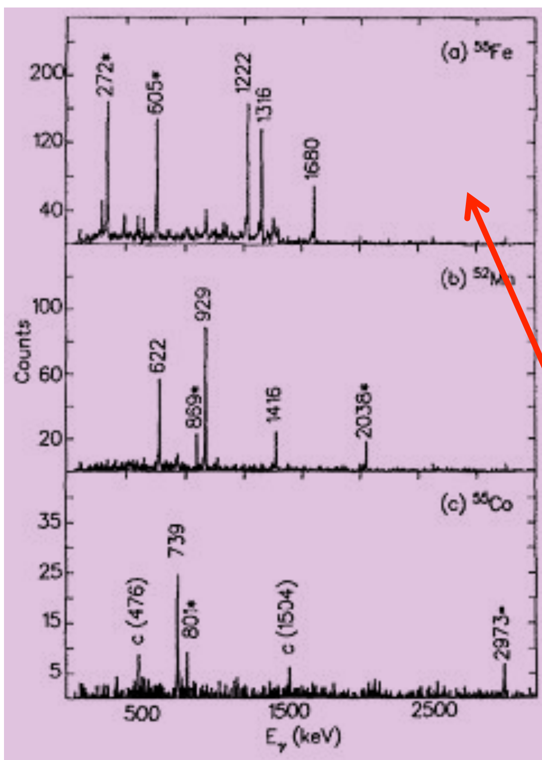
W.N. Catford *et al.*, NIM A371 (1996) 449
Nucl Phys A616 (1997) 303
J Phys G24 (1998) 1377

TESSA

LEDA



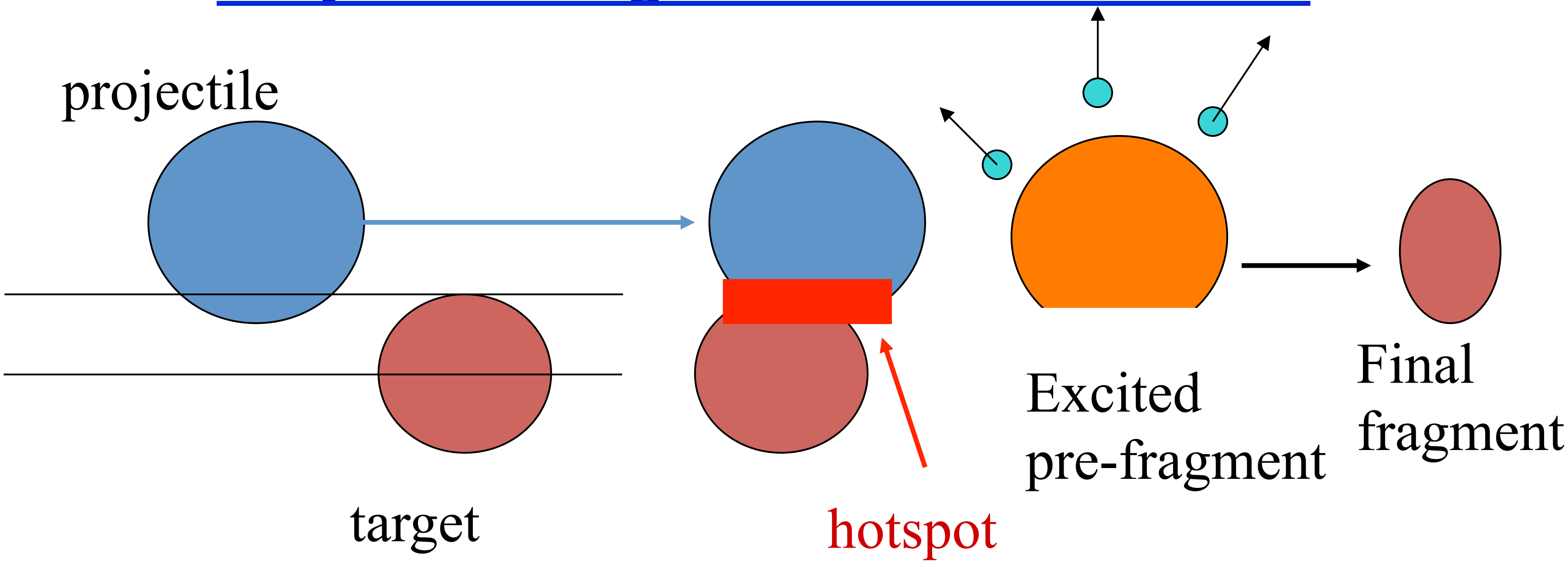




$^{19}Ne(^{40}Ca,3pn\gamma)^{55}Fe$

First fusion-evaporation study with RNB

Projectile Fragmentation Reactions

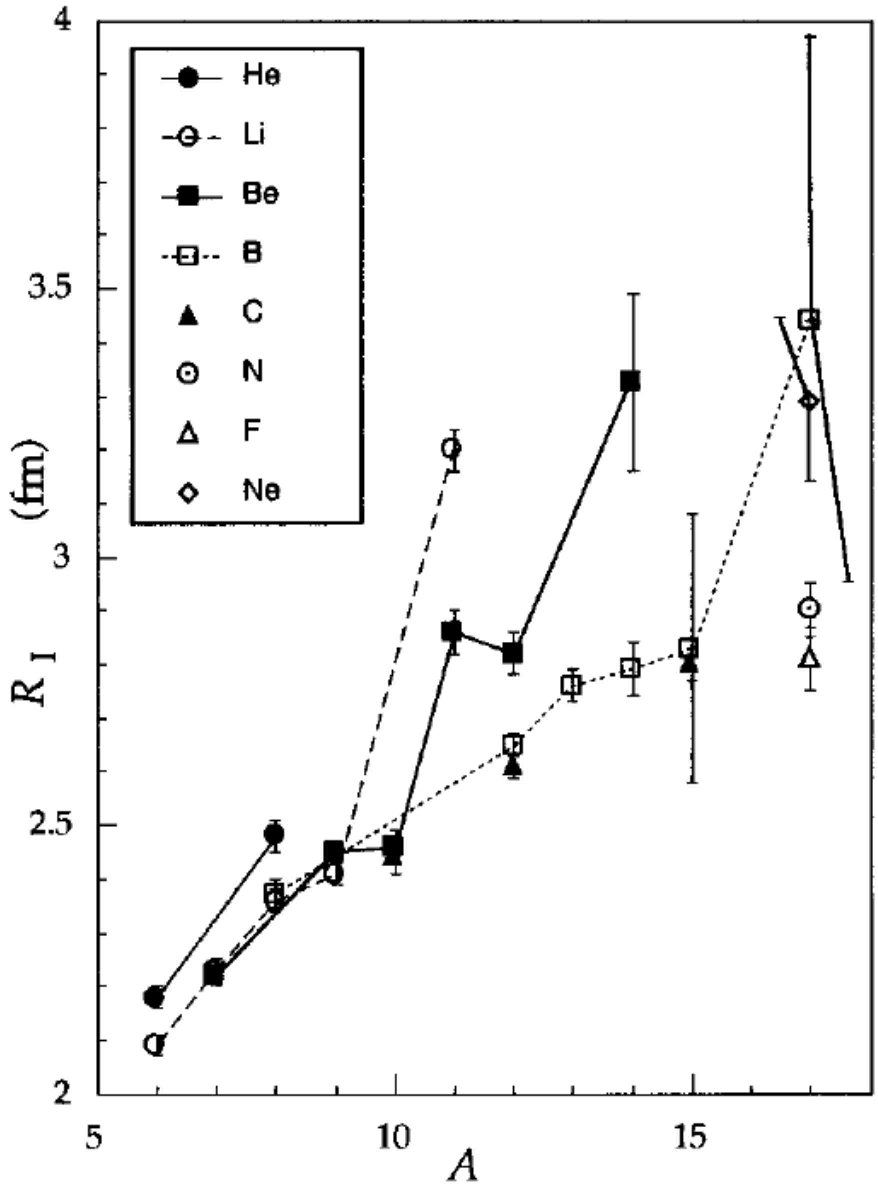


Early 1970s:- BEVALAC created – aimed at EOS of nuclear matter

T.M.Symons, Phys.Rev.letts 42 (1979)40 – realised a wide range of nuclear species produced in fragmentation reactions.

Energy (velocity) of beam > Fermi velocity inside nucleus ~30 MeV/u
Can 'shear off' different combinations of protons and neutrons.
Large variety of exotic nuclear species created, all at forward angles
with ~beam velocity.
Main Difficulty – beam is a cocktail of many species. Requires a sophisticated spectrometer.

Neutron haloes – I.Tanihata et al., Physics Letters B160 (1985) 380



- BEVALAC
- ^{11}B at 800 MeV/u → He beams
- $\sigma_I\ (p,t) = \pi[R_I(p) + R_I(t)]^2$

The interaction radius for ^{11}Li turned out to be much larger than one would expect from the well known

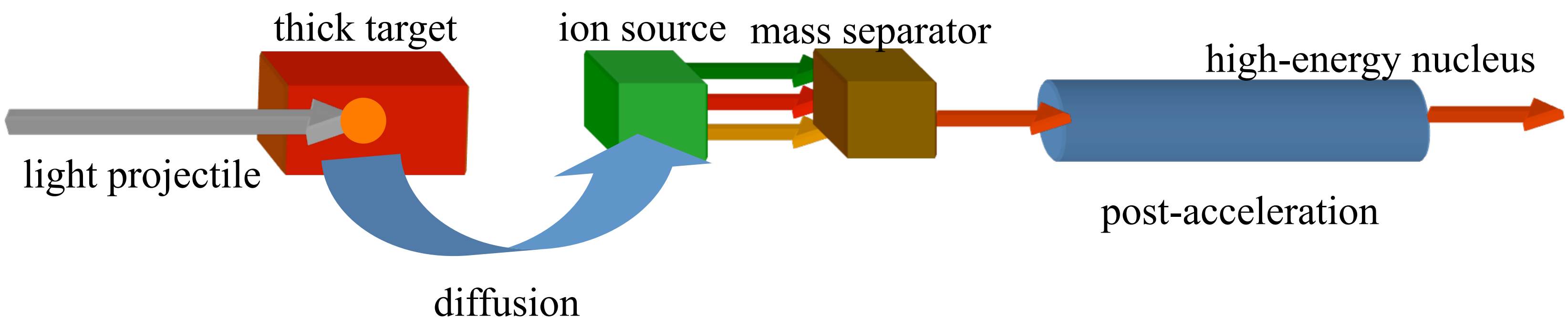
$$R = R_0.A^{1/3}$$

formula where R_0 = 1.2F

Interpretation:-P.G.Hansen and B.Jonson, Europhysics Letters 4(1987) 409

Production techniques

- Isotopic separation on-line (ISOL)

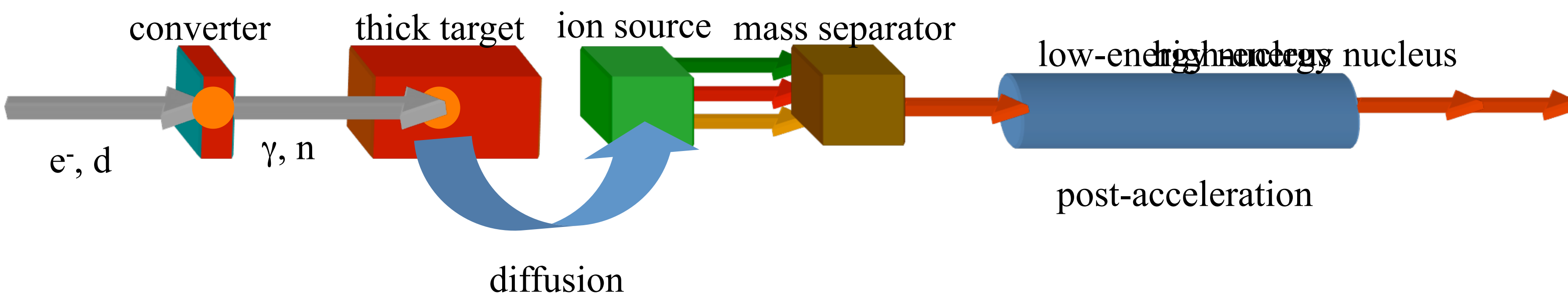


- ✓ light projectile into a heavy target nucleus (target spallation)
- ✓ charged and neutral projectiles (n,γ)
- ✓ thick target (100% of range) and high beam current (10^{16} p/s)
- ✓ high quality beams

- ✓ long extraction and ionization time (ms)
- ✓ chemistry dependent
- ✓ target heat load
- ✓ activation

Production techniques

➢ Gamma/neutron converters



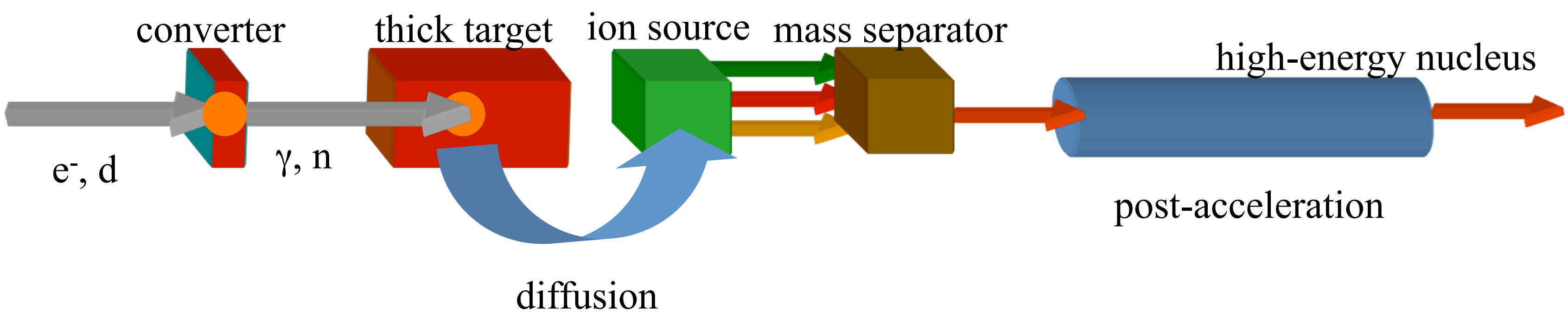
- This is the basis of SPIRAL II
  - one of the precursors of EURISOL, based on deuteron breakup

- The emphasis here is on the production of neutron-rich species in the fission of Uranium induced by photons or neutrons.

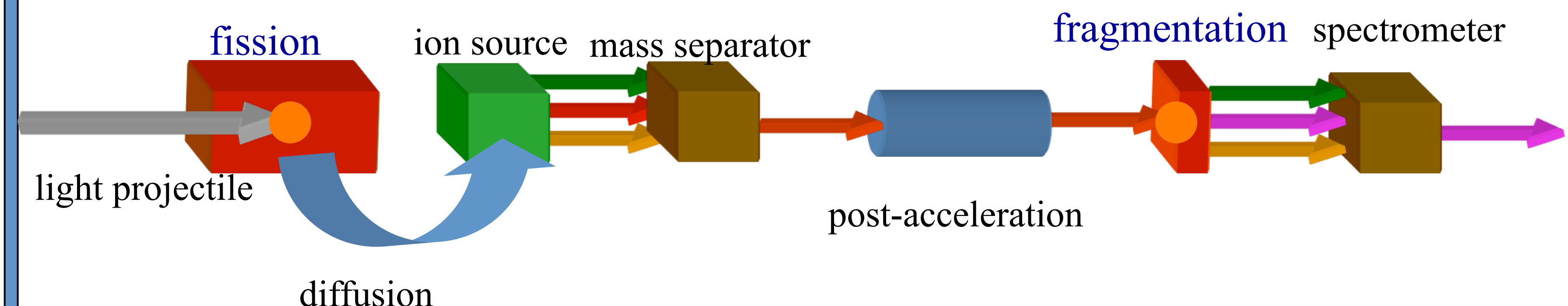
- The advantage of this technique is that it separates power dissipation and isotope production.

Production techniques

- Gamma/neutron converters(A variant of ISOL scheme)

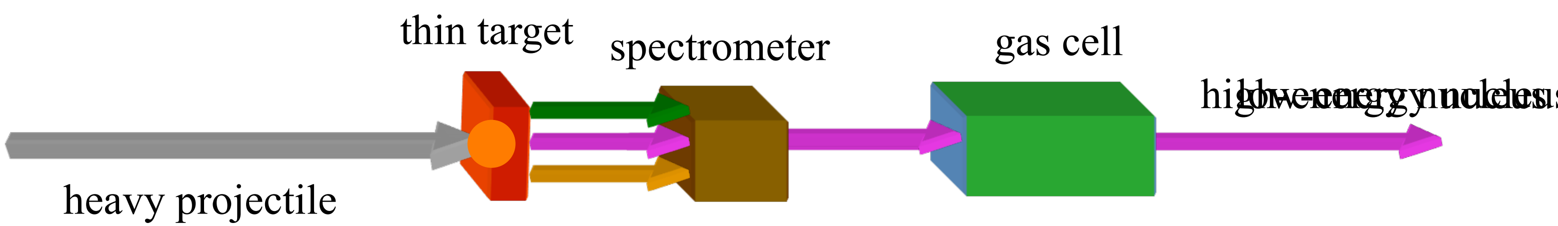


- Two-step reaction scheme(ISOL + Fragmentation)



Production techniques

➢ In-flight fragmentation



- ✓ heavy projectile into a light target nucleus (projectile fragmentation)
- ✓ short separation+identification time (100 ns)
- ✓ limited power deposition
- ✓ Independent of Chemistry

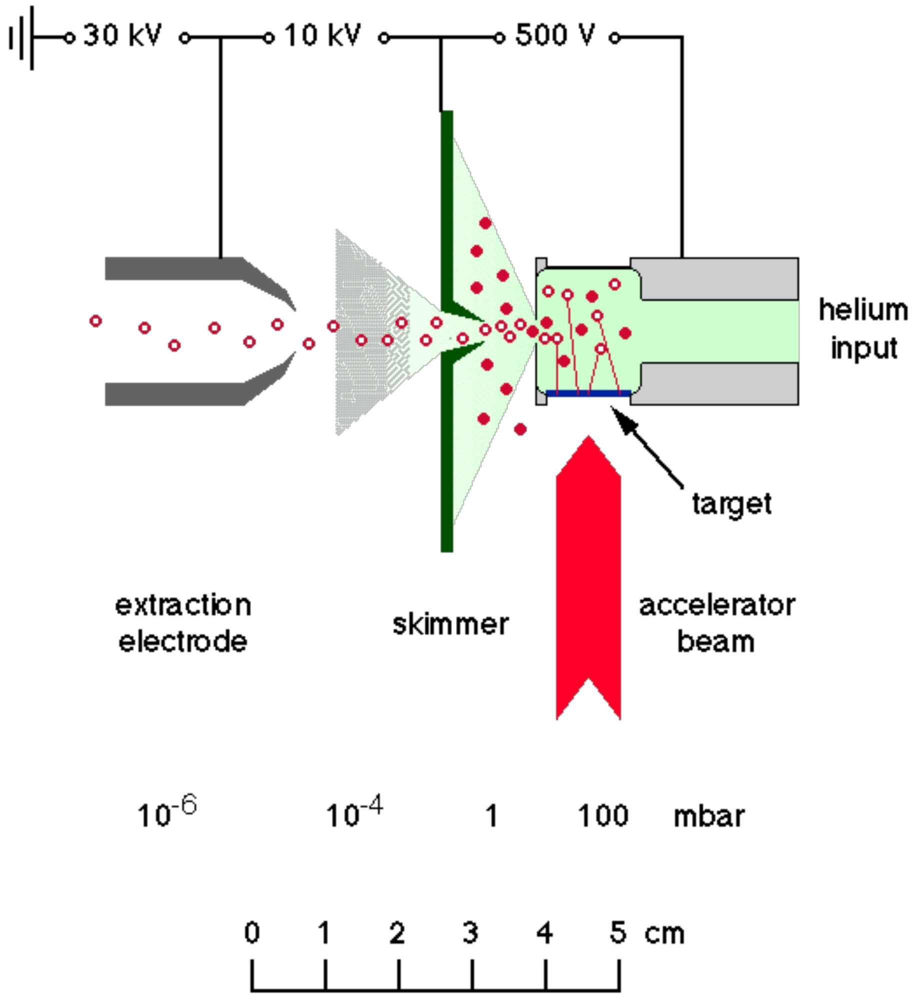
- ✓ thinner targets (10% of range) and lower beam currents (10^{12} ions/s)
- ✓ beam is a cocktail of different nuclear species

Key features of New facilities

• low production cross-sections	⟺	• beam-target combinations optimised highest possible beam intensity targets must cope with power
• very short half-lives of interest	⟺	• Minimise losses due to delays
• Unwanted nuclear species usually predominate	⟺	• selection and/or identification must be effective. Any manipulation must be efficient

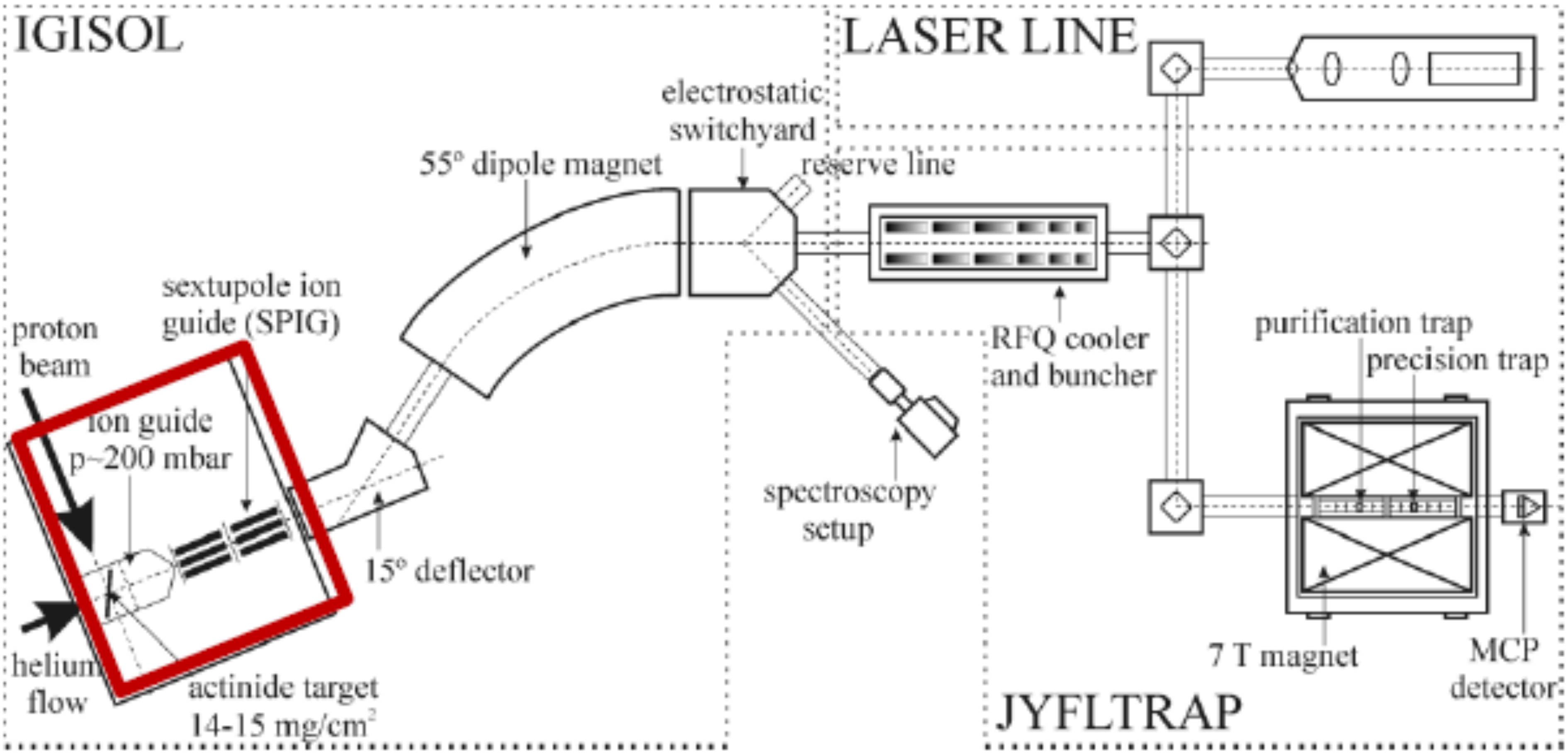
Main prerequisites- high efficiency, selectivity, sensitivity, short delay times.

Basis of IGISOL System at Jyvaskyla

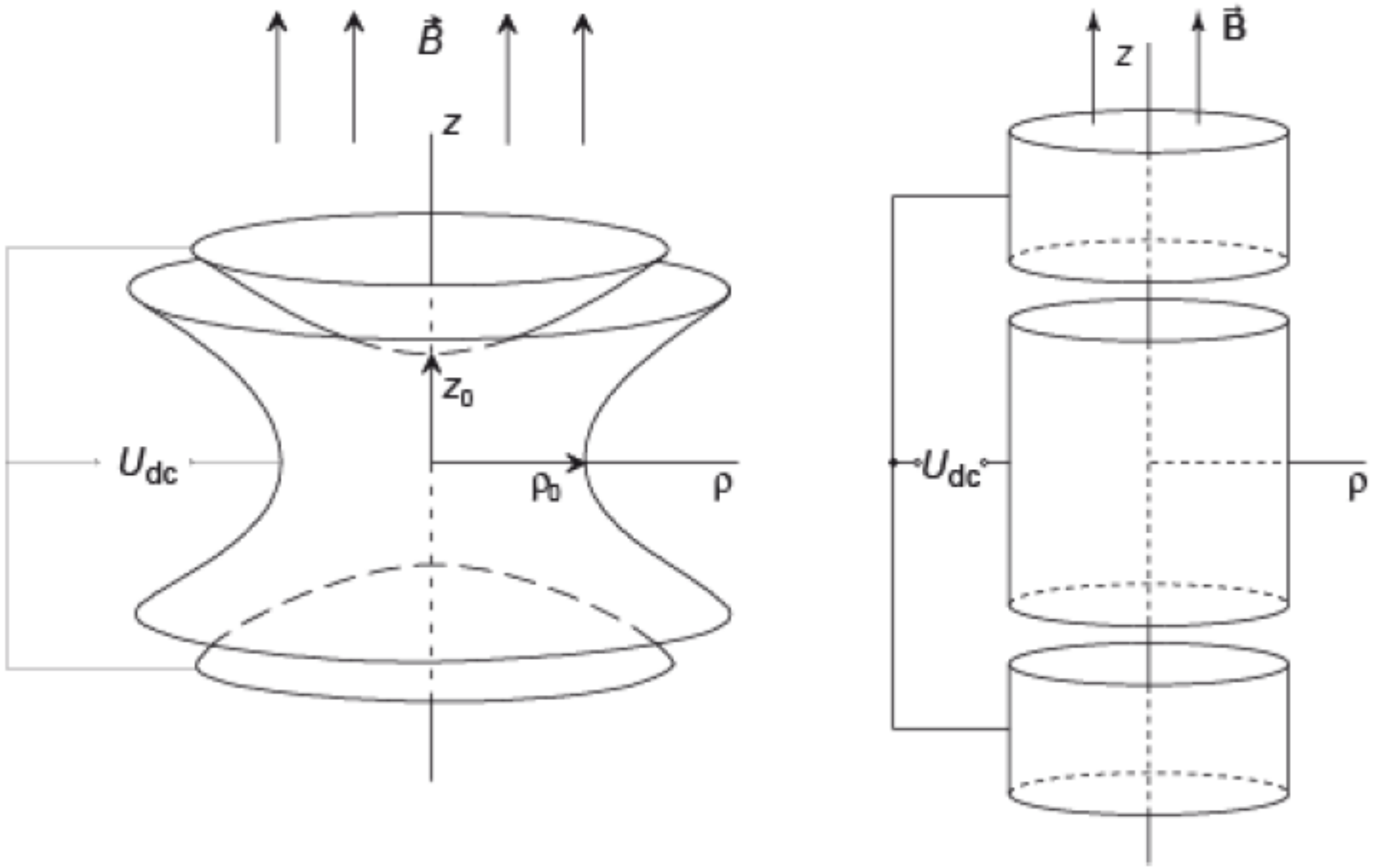


- Many smaller scale niche facilities
- IGISOL at Jyvaskyla –excellent example of a very productive small facility
- primary beam from K30 or K130 cyclotrons
- Thin target of ^{238}U or ^{232}Th
- Primary ions survive in He buffer gas
- They are extracted quickly (ms timescale)
- Independent of Chemistry

Overall View of the IGISOL Facility at Jyvaskyla



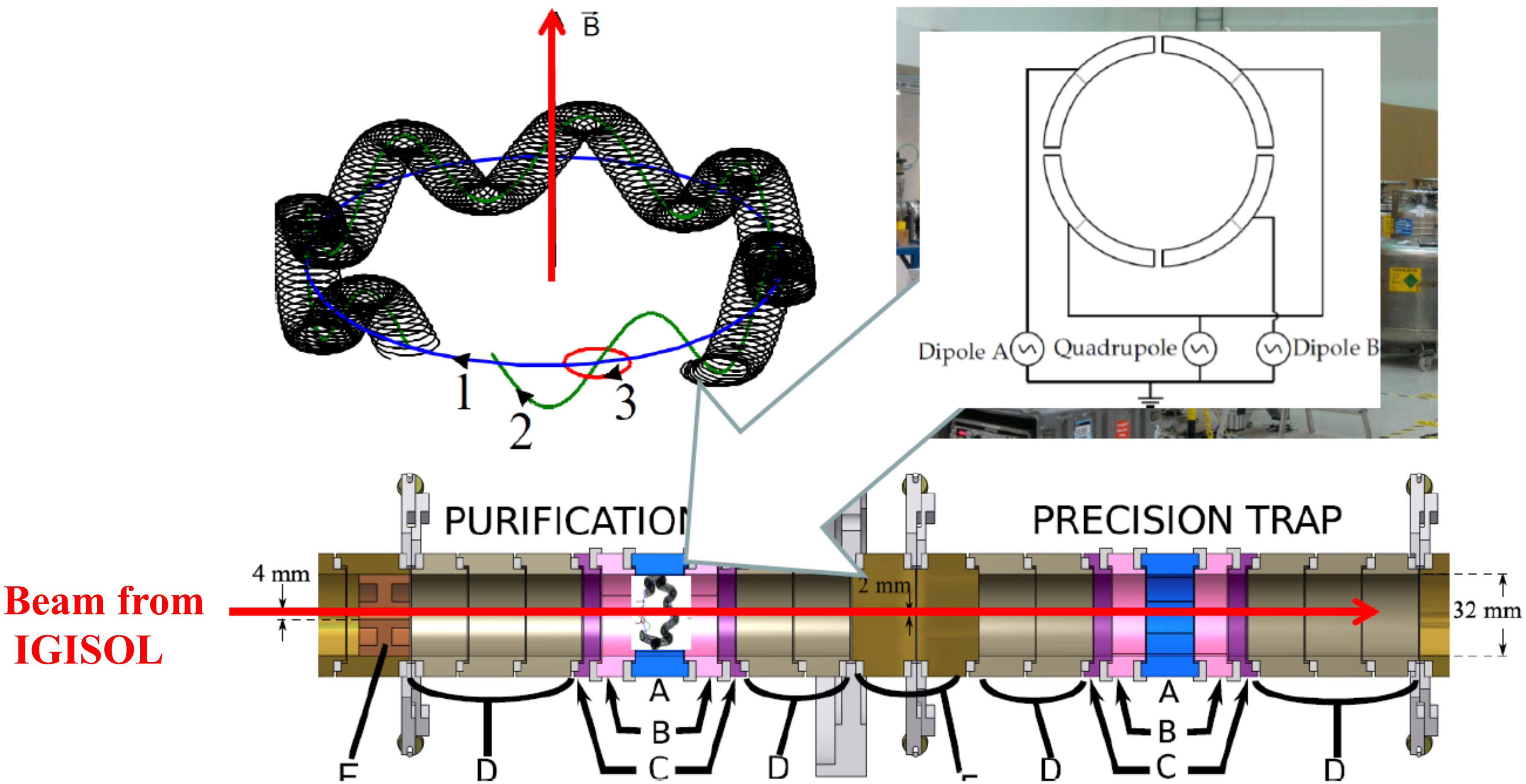
Penning Trap



Penning trap = Strong homogeneous magnetic field + weak, electrostatic quadrupole field. This gives radial and axial confinement

Double Penning Trap - JYFLTRAP

Isotopic purification with JYFLTRAP



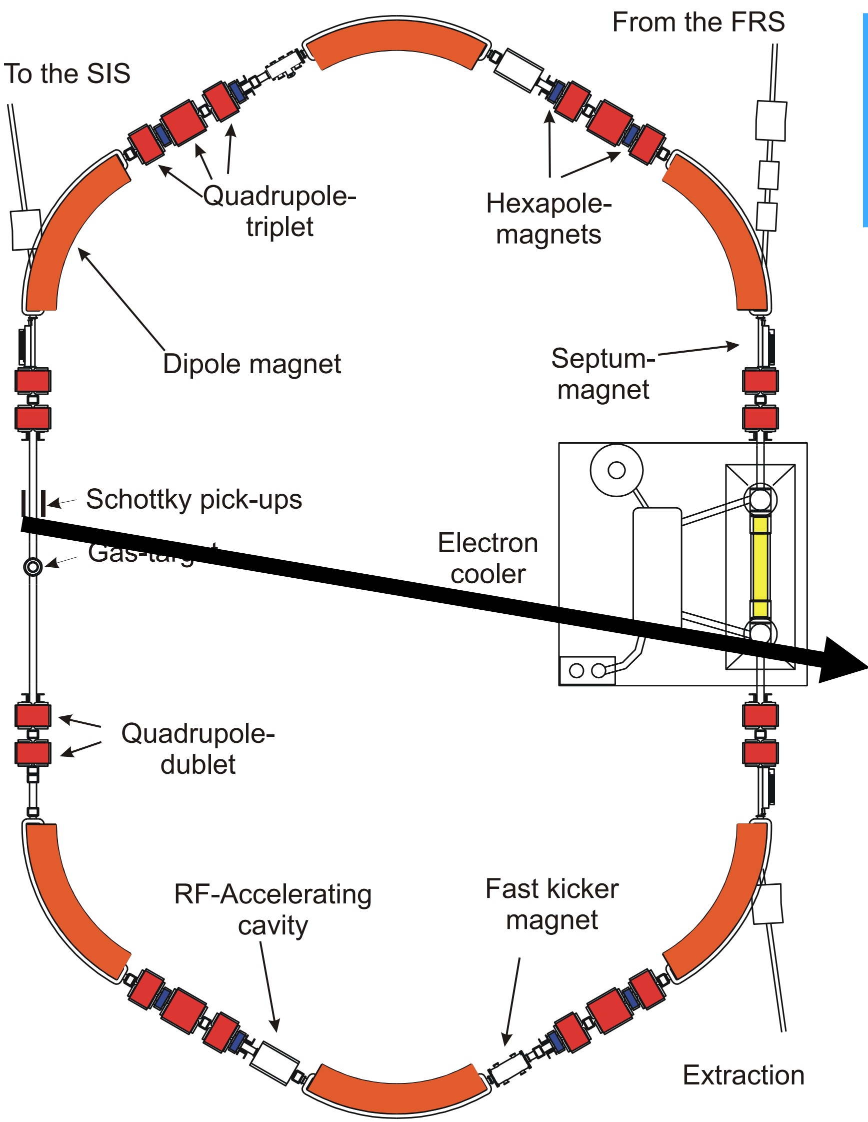
34th Joliot Curie School

Experimental techniques in Modern Nuclear Physics

The use of Traps in Modern Nuclear Physics

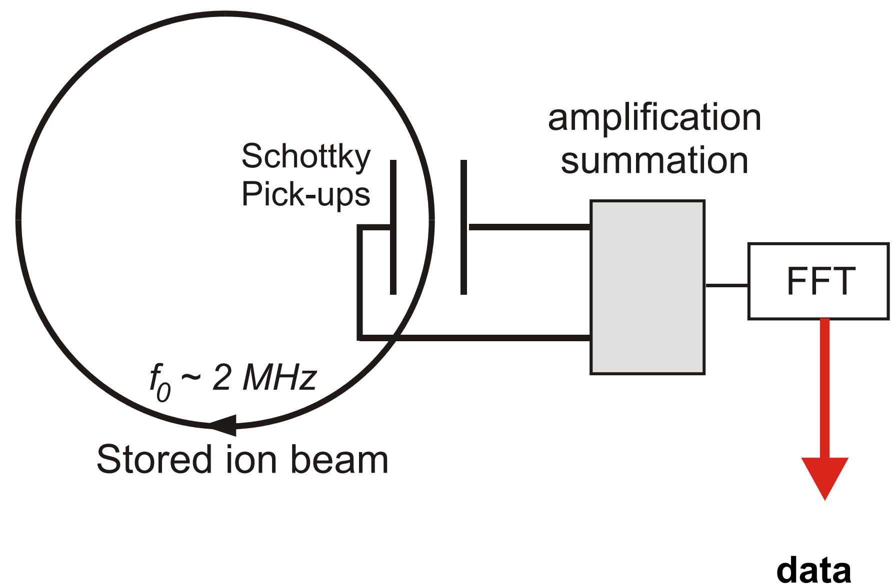
Stéphane Grévy – CENBG

Mass measurement: Schottky Mass Spectrometry for ground states and isomeric states



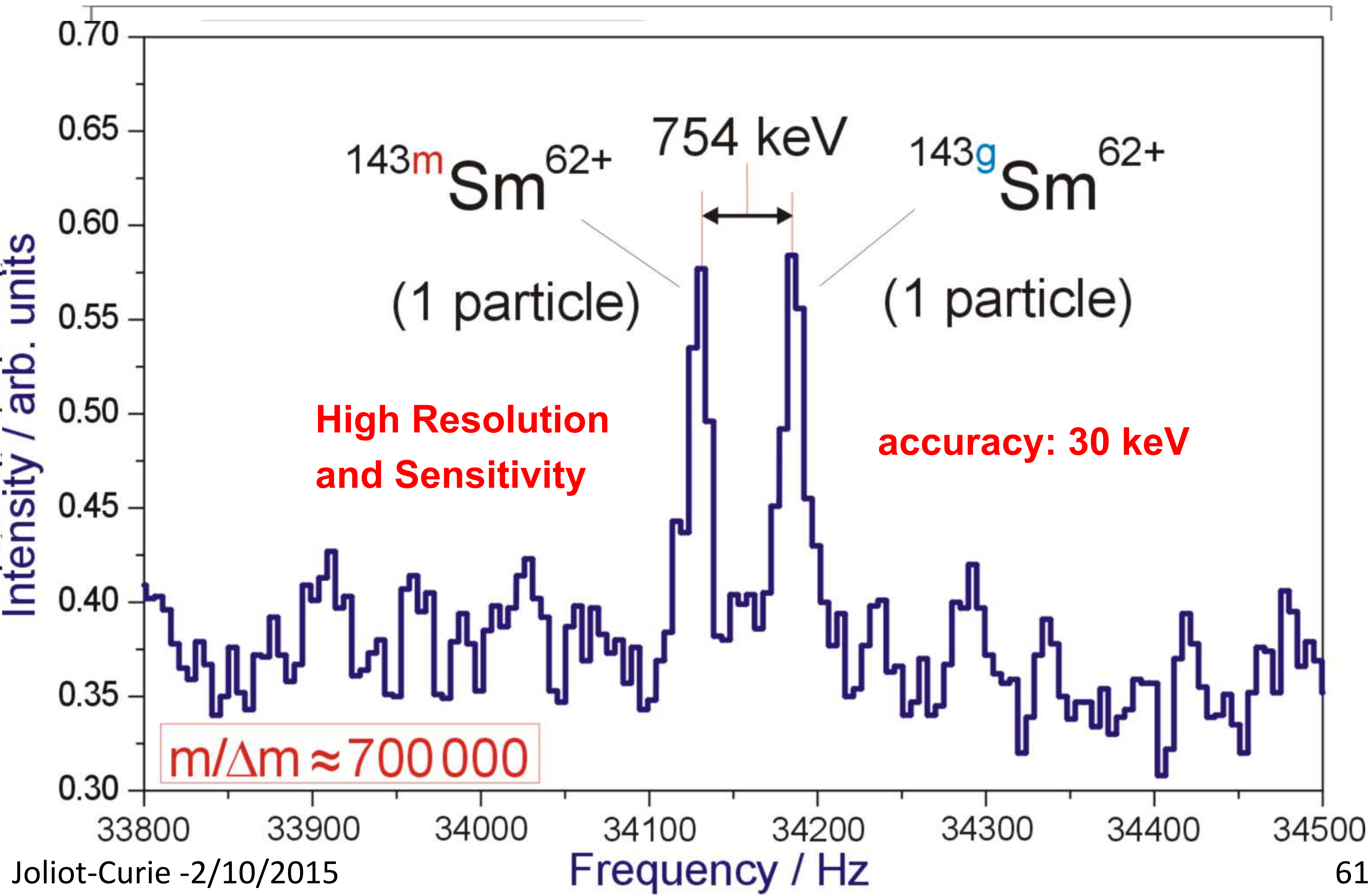
$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \cancel{\frac{\Delta v}{v}}\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

$$\frac{\Delta v}{v} \rightarrow 0$$



Zs.Podolyak

Schottky Mass Spectrometry



RIB Physics with Heavy-Ion Storage Rings

Yu. A. Litvinov[1]

[1] *GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany*

Main Current In-flight facilities

Facility	Accelerators	Energy	Typical Beam	Spectrometer
• GANIL	2 sep.sect.cyclotrons	$\leq$ 100 $MeVu^{-1}$	^{36}S 10^{13} pps	LISE
• GSI	Linac + synchrotron	$\leq$ 2 $GeVu^{-1}$	10^{10} pps per spill	FRS
• NSCL	2 sup.cond cyclotrons	$\leq$ 200 $MeVu^{-1}$	^{40}Ar 5x 10^{11} pps	A1900
• RIKEN	Ring cyclotron	$\leq$ 100 $MeVu^{-1}$	^{40}Ar 5x 10^{11} pps	RIPS

All four have major upgrades planned or, in the case of RIKEN completed.

RIBF, RIKEN is the only "next generation" facility in operation

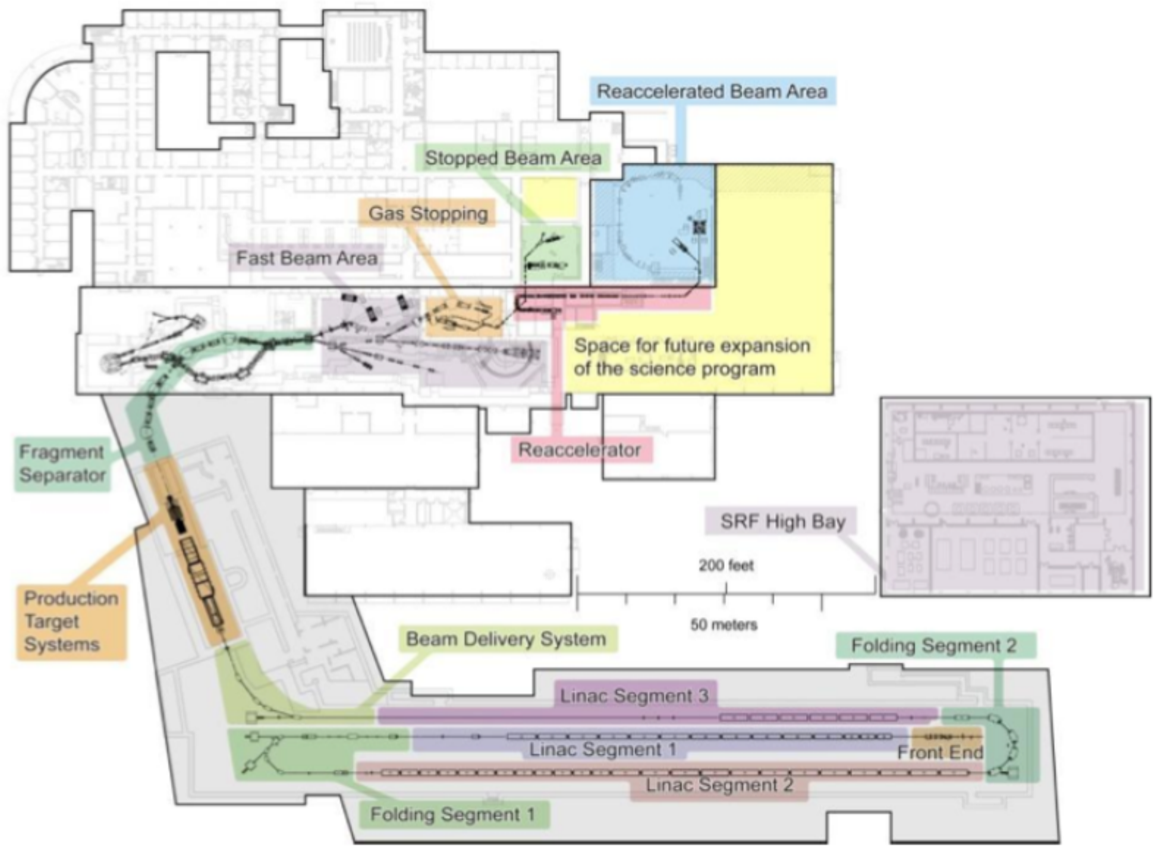
Main Current Isol facilities

Facility	Driver	Accelerator	Beam Energy	Beams
•REX-ISOLDE	PSBooster 1.4 GeV p	REX LINAC	0.3-3.0AMeV	Large variety
•SPIRAL	GANIL cyclotrons	CIME cyclotron	2.7-25AMeV	He,Ne,Ar,Kr,N,O,F
•TRIUMF	Cyclotron 500MeV p	ISAC1+ISAC2 RFQ + LINAC	0.2-11AMeV	Variety

All three laboratories have major upgrades planned

FRIB - Facility for Rare Isotope Beams

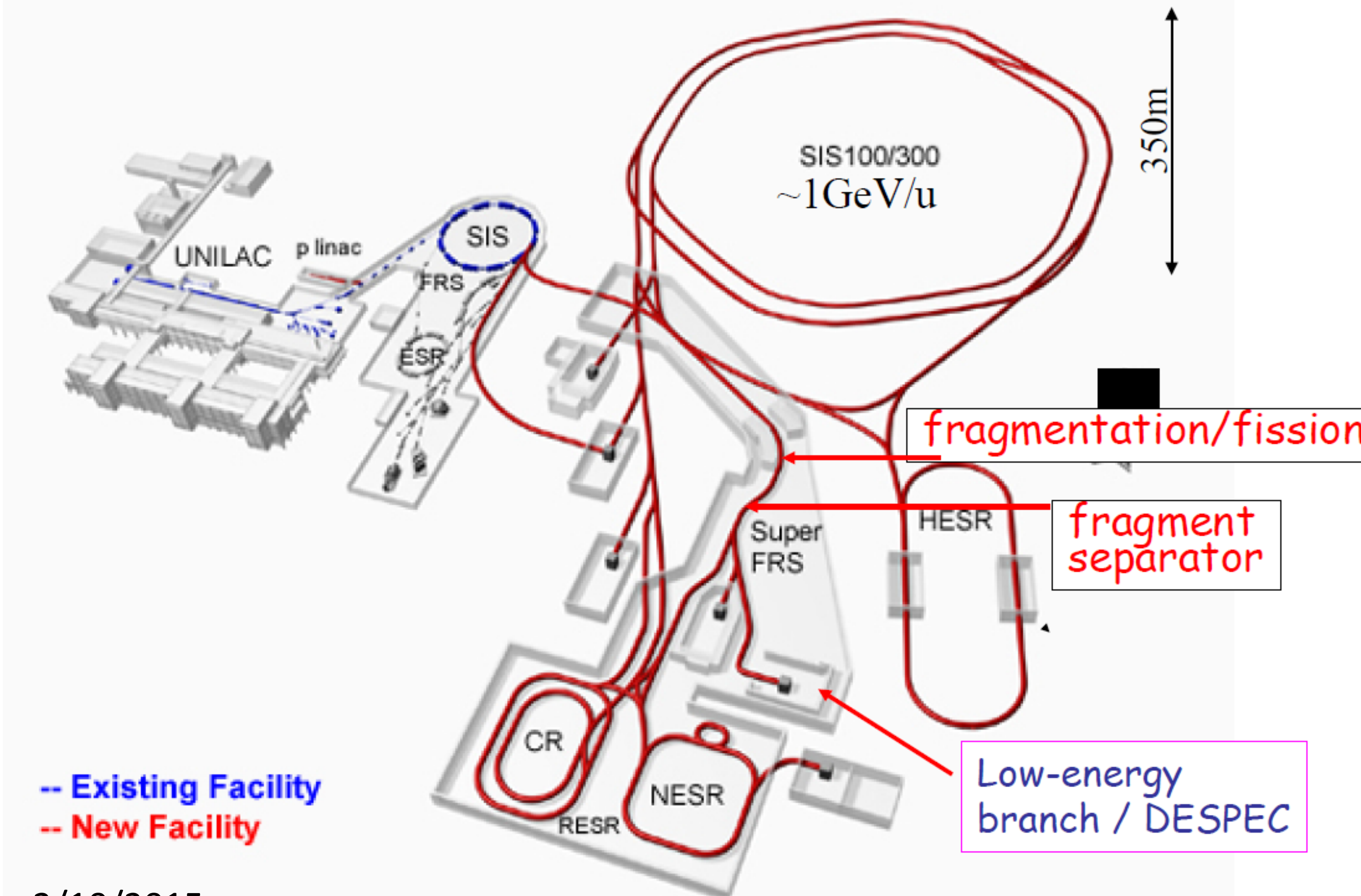
- Rare isotope production via in-flight technique with primary beams up to 400 kW, 200 MeV/u uranium
- Fast, stopped and reaccelerated beam capability
- Upgrade options
  - Energy 400 MeV/u for uranium
  - ISOL production – Multi-user capability



World-leading next-generation rare isotope beam facility

Facility for Antiproton and Ion Research (FAIR)

NUSTAR: SuperFRS and experiments on three (energy) branches…. > 800 collaborators

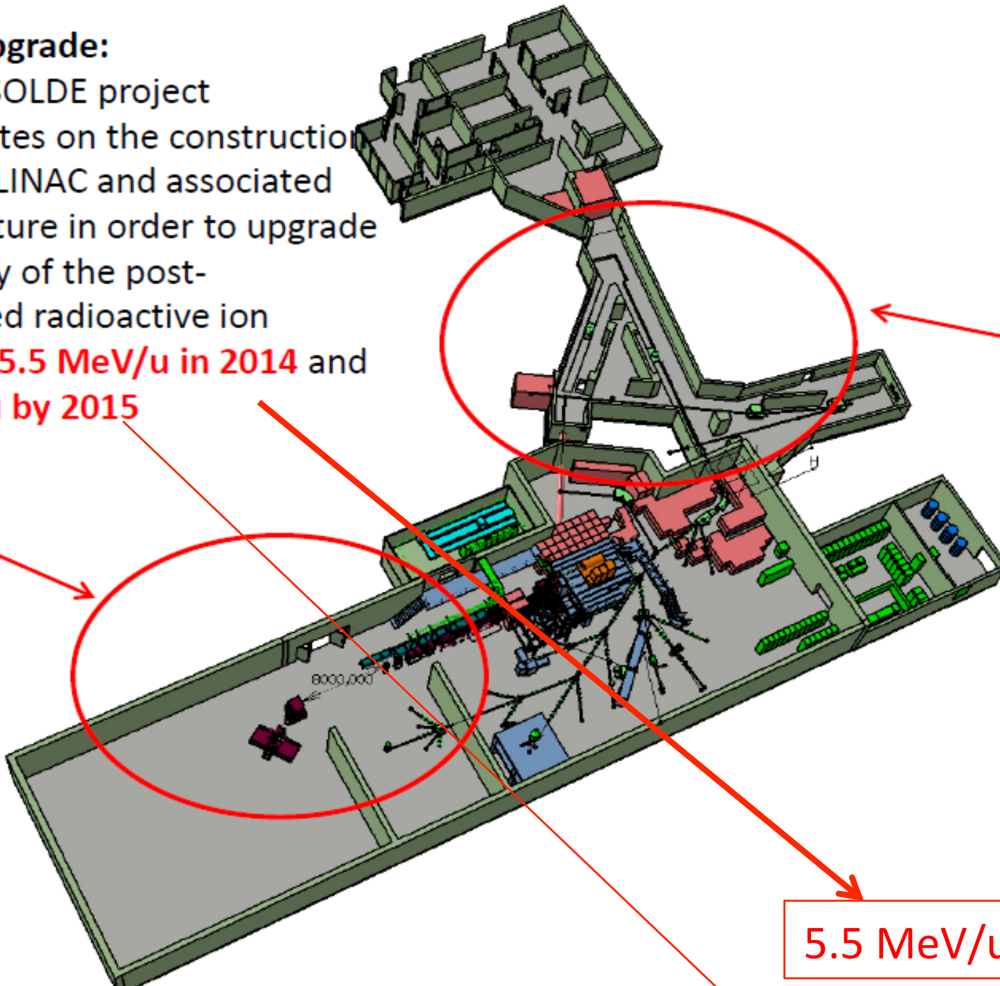


FAIR under construction at GSI.

Picture from 5. Apr 2013 (http://www.fair-center.de)

Scope of HIE-ISOLDE

Energy Upgrade:
The HIE-ISOLDE project concentrates on the construction of the SC LINAC and associated infrastructure in order to upgrade the energy of the post-accelerated radioactive ion beams to **5.5 MeV/u in 2014** and **10 MeV/u by 2015**

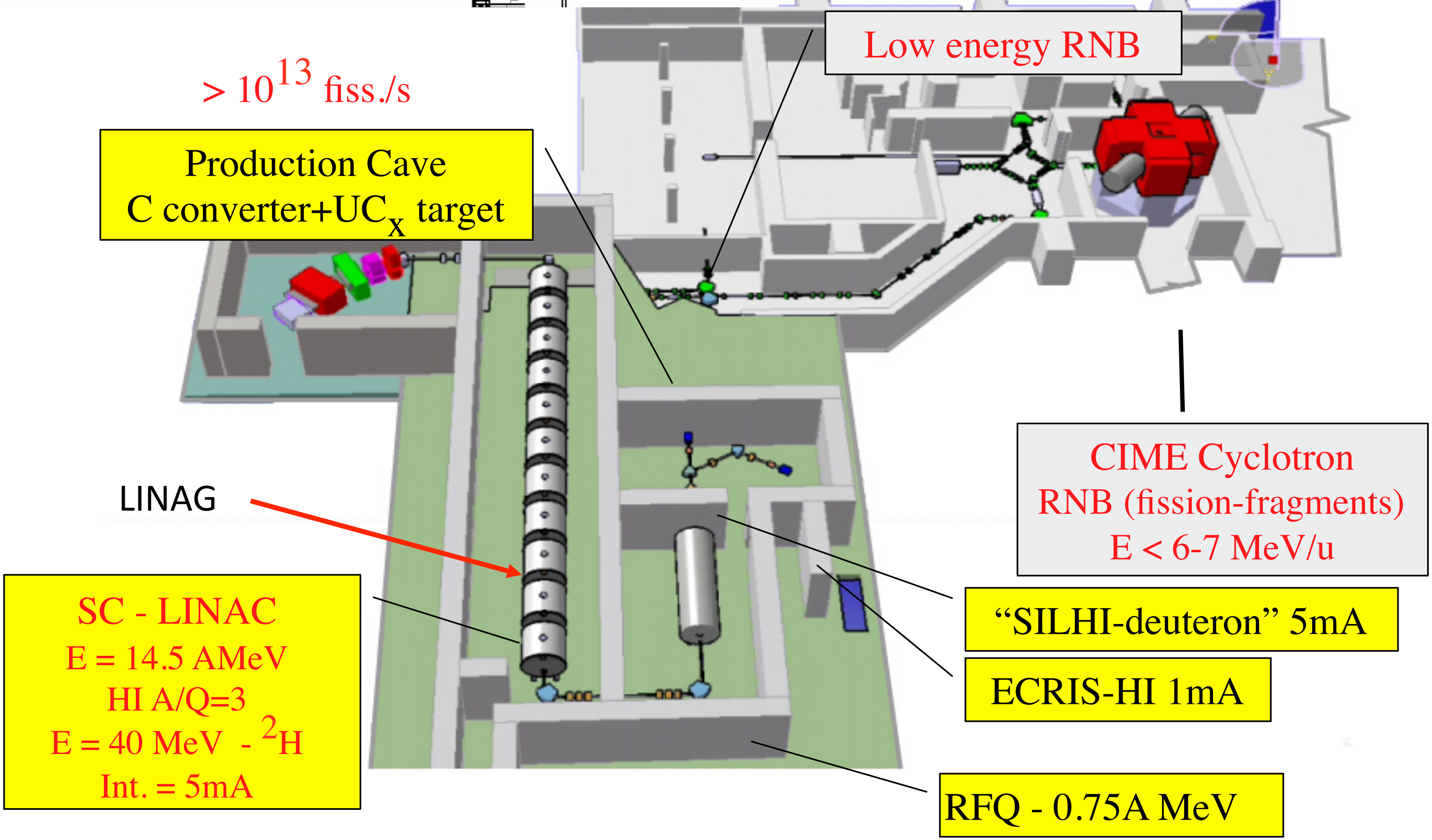


Intensity Upgrade:
The design study for the intensity upgrade, also part of HIE-ISOLDE, **starts in 2011**, and addresses the technical feasibility and cost estimate for operating the facility at **10 kW** once LINAC4 and PS Booster are online. **The 30 kW option (SPL beam) will be studied at a later stage**

5.5 MeV/u by end of 2015

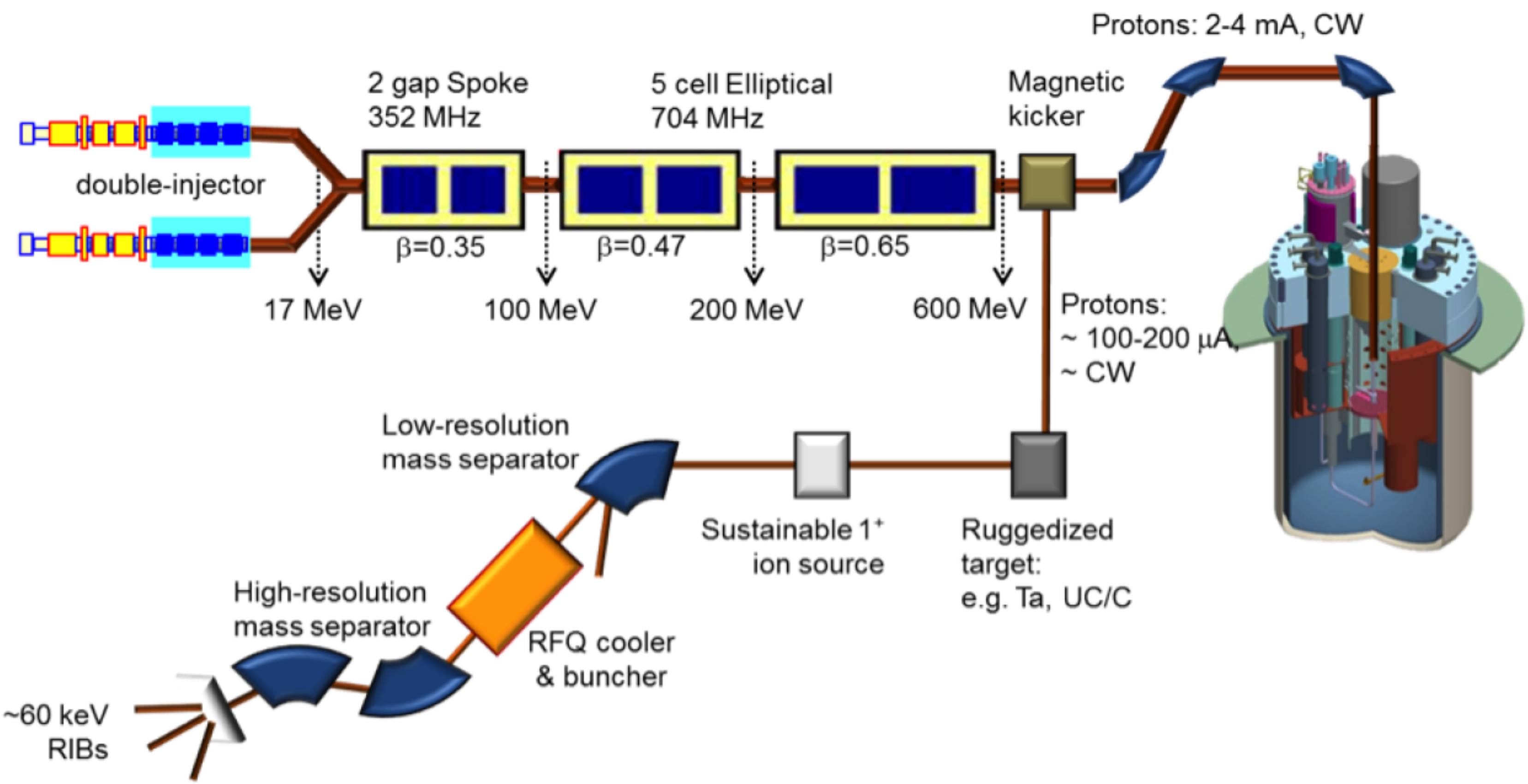
10MeV/u by 2017

• What is SPIRAL2 ?



Note:- LINAG will be a major new accelerator in its own right because of high intensity.
System will also produce intense fluxes of fast neutrons. [Parallel operation]

Myrrha and ISOL@MYRRHA



MYRRHA is designed to demonstrate that ADS technology works.

ISOL@MYRRHA uses 200µA of the beam

It will be used for experiments that require very long beamtimes.

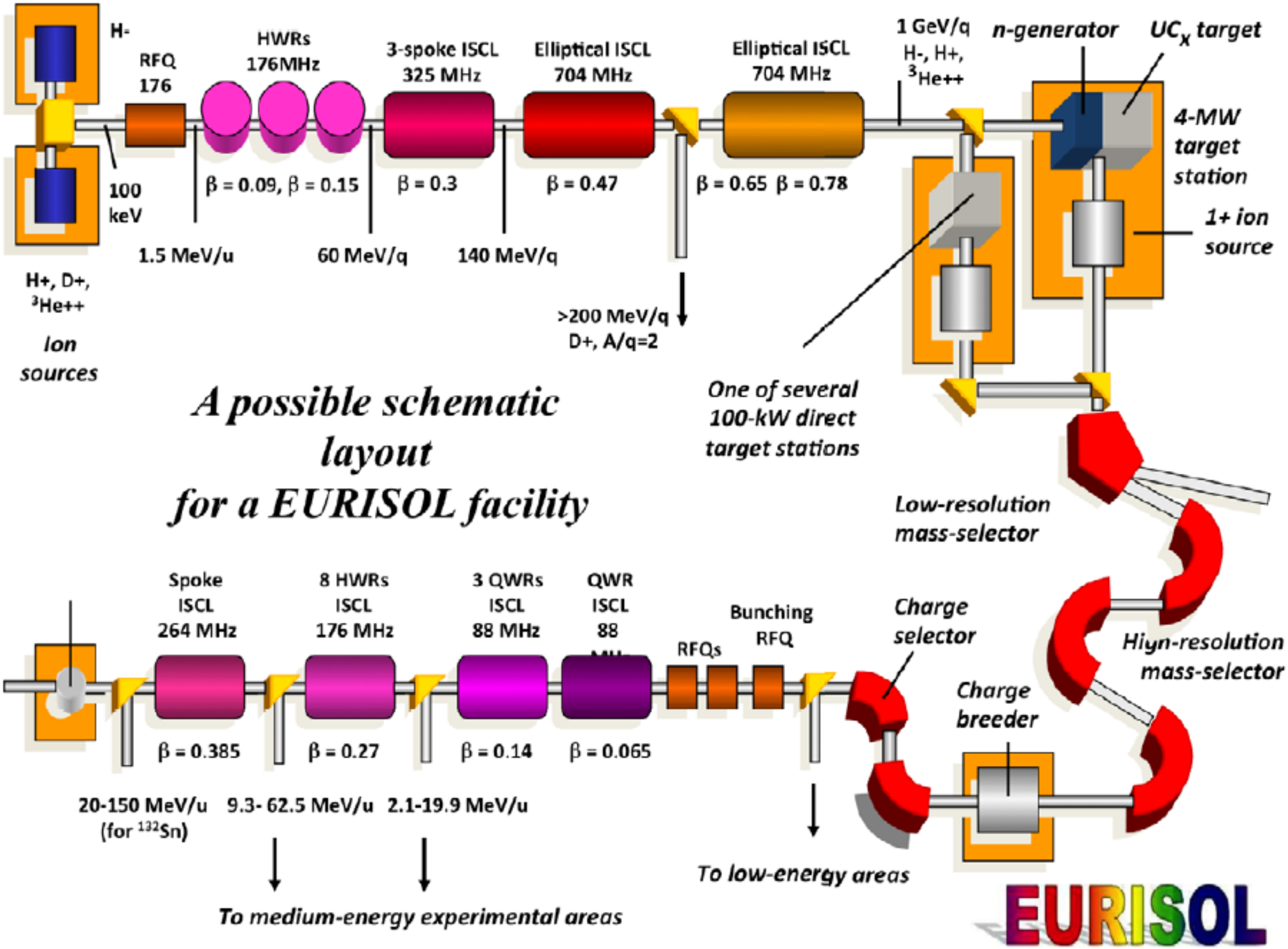
Beams could be ~ 100 x Isolde intensities

Radioisotope production

From nuclear physics to nuclear medicine

Ferid Haddad

ARRONAX, Nantes, France


H-
RFQ
176
HWRs
176MHz
3-spoke ISCL
325 MHz
Elliptical ISCL
704 MHz
Elliptical ISCL
704 MHz
1 GeV/q
H-, H+,
^{3}He++
n-generator
UC_x target
4-MW
target
station
1+ ion
source
100
keV
β = 0.09, β = 0.15
β = 0.3
β = 0.47
β = 0.65 β = 0.78
1.5 MeV/u
60 MeV/q
140 MeV/q
H+, D+,
^{3}He++
Ion
sources
>200 MeV/q
D+, A/q=2
One of several
100-kW direct
target stations
A possible schematic
layout
for a EURISOL facility
Low-resolution
mass-selector
Spoke
ISCL
264 MHz
8 HWRs
ISCL
176 MHz
3 QWRs
ISCL
88 MHz
QWR
ISCL
88
Bunching
RFQ
RFQs
Charge
selector
High-resolution
mass-selector
Charge
breeder
β = 0.385
β = 0.27
β = 0.14
β = 0.065
20-150 MeV/u
(for ^{132}Sn)
9.3- 62.5 MeV/u
2.1-19.9 MeV/u
To low-energy areas
To medium-energy experimental areas
EURISOL

Lasers

Laser-assisted modern nuclear physics

T.E. Cocolios
STFC Ernest Rutherford Fellow
School of Physics and Astronomy, The University of Manchester

Detectors

Charged-particle detection devices in present and forthcoming nuclear physics experiments

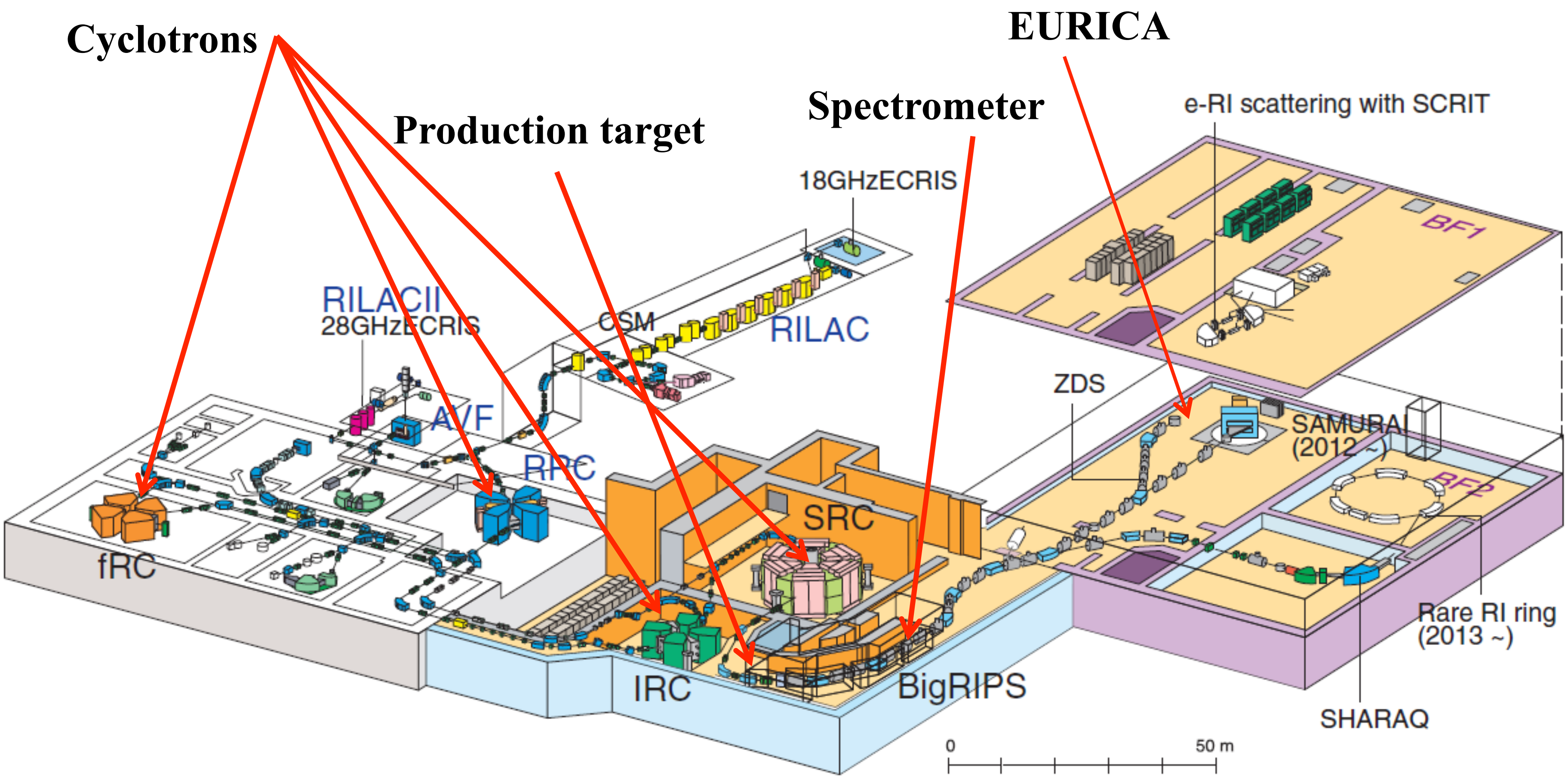
Riccardo Raabe - KU Leuven

Spectrometers

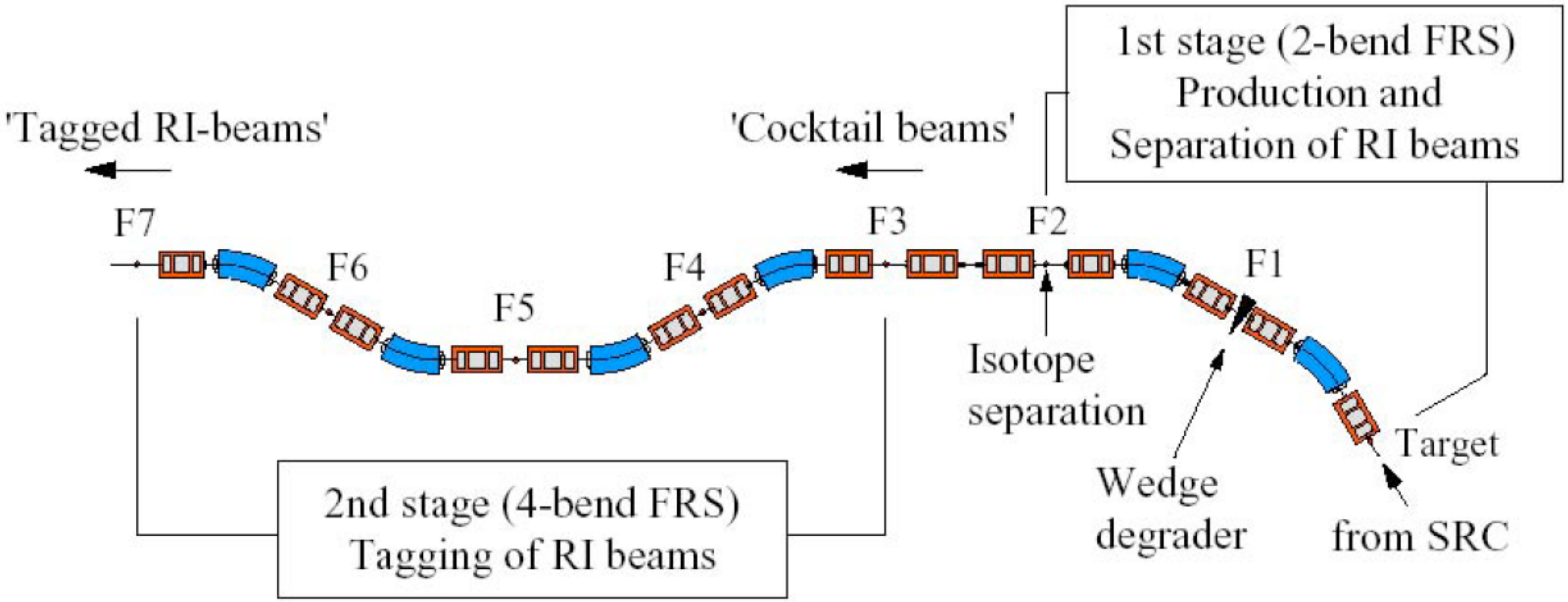
SPECTROMETRES ET SEPARATEURS EN PHYSIQUE NUCLEAIRE ET DIAGNOSTICS ASSOCIES

BERTRAND JACQUOT
GANIL, Bd Becquerel
14000 CAEN

Schematic View of RIBF, RIKEN

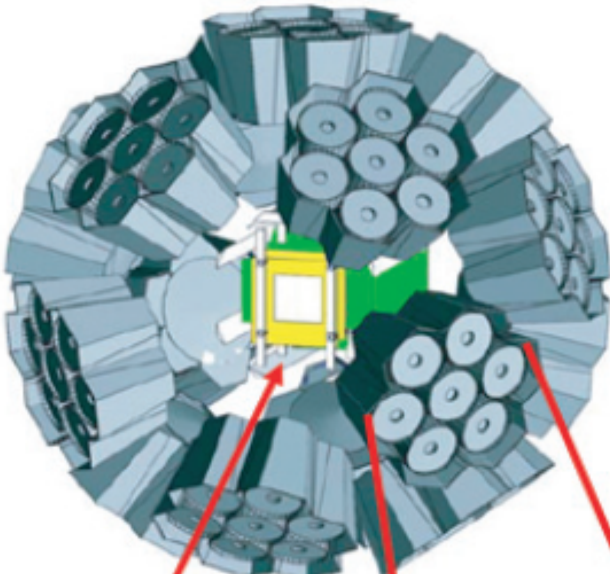


BIGRIPS: A tandem two stage separator

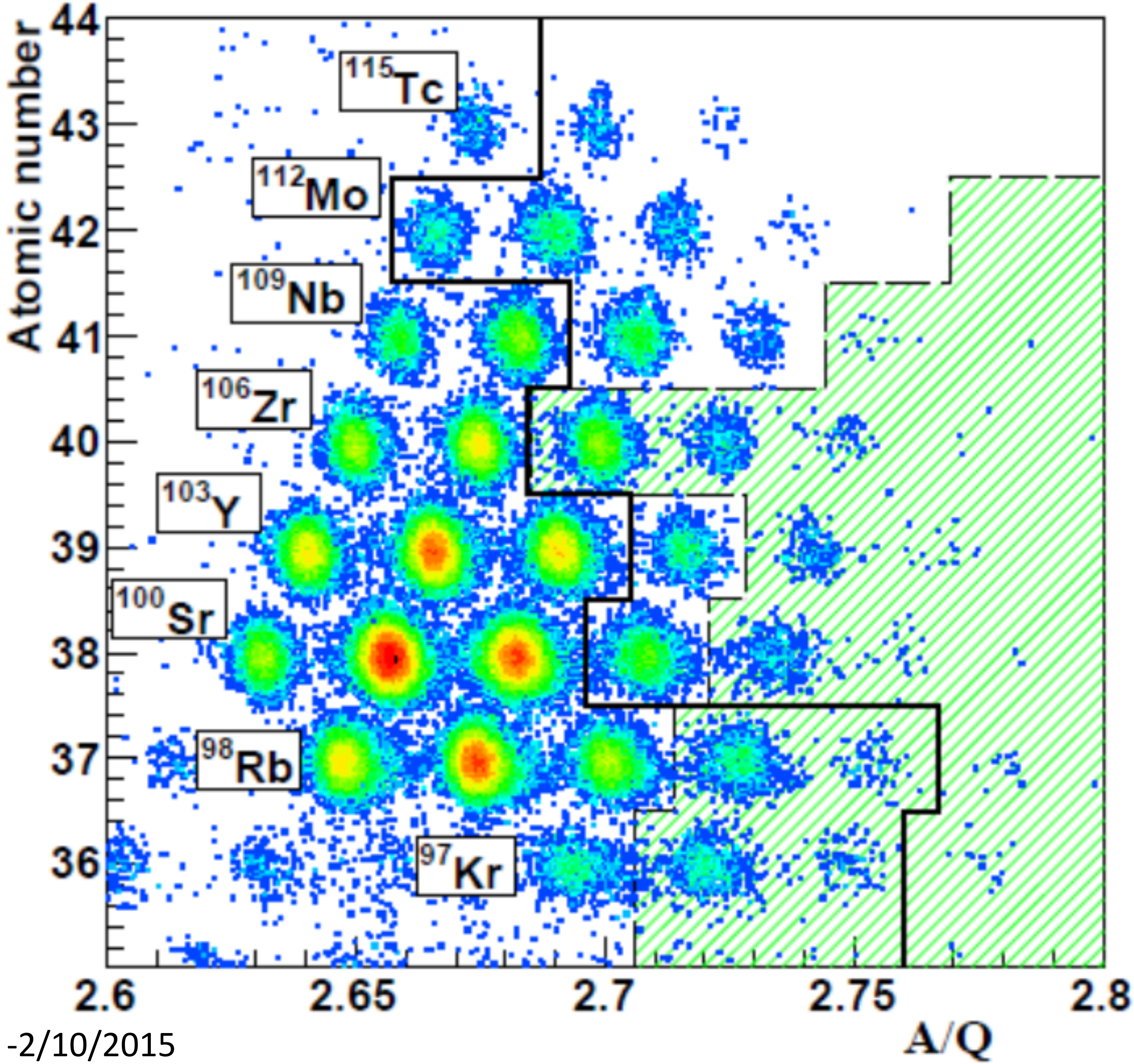


TOF, Bρ, ΔE → Z, A/Q (A, Q), P

Picture of EURICA



寿命測定装置



Atomic number
44
43
42
41
40
39
38
37
36
115Tc
112Mo
109Nb
106Zr
103Y
100Sr
98Rb
97Kr
2.6
2.65
2.7
2.75
2.8
A/Q

What have we learned?

1. Nuclear physics is indeed driven by advances in experimental methods and techniques

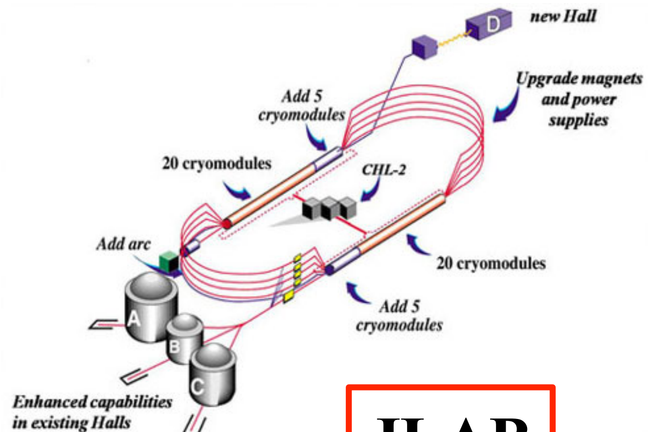
2. Typically there is an initial advance followed by successive improvements and developments

3. We see this very clearly in the case of γ – ray spectroscopy
see Dino Bazzacco

4. Be sceptical! It is always best to go back to the primary sources

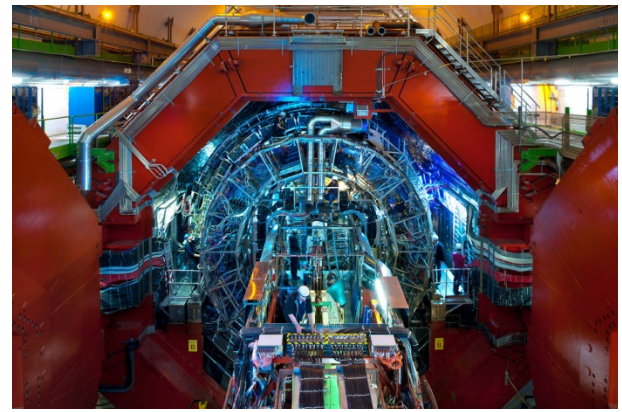
What have we learned?

We are lucky!! These are exciting times for nuclear physics



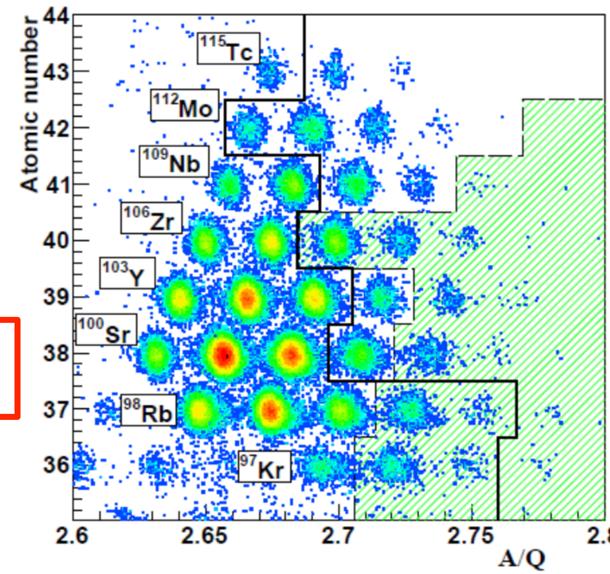
JLAB

ALICE



LUNA

RIKEN




JULY