National Research Foundation | iThemba LABS — Laboratory for Accelerator Based Sciences

Nuclear Research in South Africa and on the African Continent

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Note:

The presentation has a bias on South Africa: Apologies for any omissions – largely a function of lack of detailed knowledge of the continental landscape

SLIDE COURTESY

- ❖ Medical Physics : Dr. Dan Jones (iTL: ret)
- ❖ Nuclear Medicine : Prof. Ellman (Stellenbosch U.)
- ❖ PET-CT : Prof. M. Sathekge (U. Pretoria)
- ❖ Members of iTL Accelerator Department
- ❖ Prof W Rautenbach (CSIR: ret.)

- Rob Adam & R von Gogh (Necsa)
- J Sharpey-Schafer (ex director: iTL)

Outline of the Presentation

Part I

- **Overview of Nuclear Facilities in Africa**
- **Accelerators and Reactors in South Africa**

Research & Applications at iTL

- ✓ **Nuclear Physics Research**
- ✓ **Hadron Therapy & Radio-isotope production**
- ✓ **Radio -Active Isotope Beams**

Part II: SA- CERN Programme

Nuclear : From Fundamental to Applications

- **Nuclear Research came from quest to understand origin of different nuclei**
  - **Big bang: H, He and Li**
  - **Stars: elements up to Fe**
  - **Supernova: heavy elements**
- **We are all made of stardust**

- **Nuclear fission for energy generation.**
  - **No greenhouse gasses**
  - **Safety and storage of radioactive material.**
- **The Nuclear fusion dream**
  - **No safeguards issues**
  - **Less radioactive material.**

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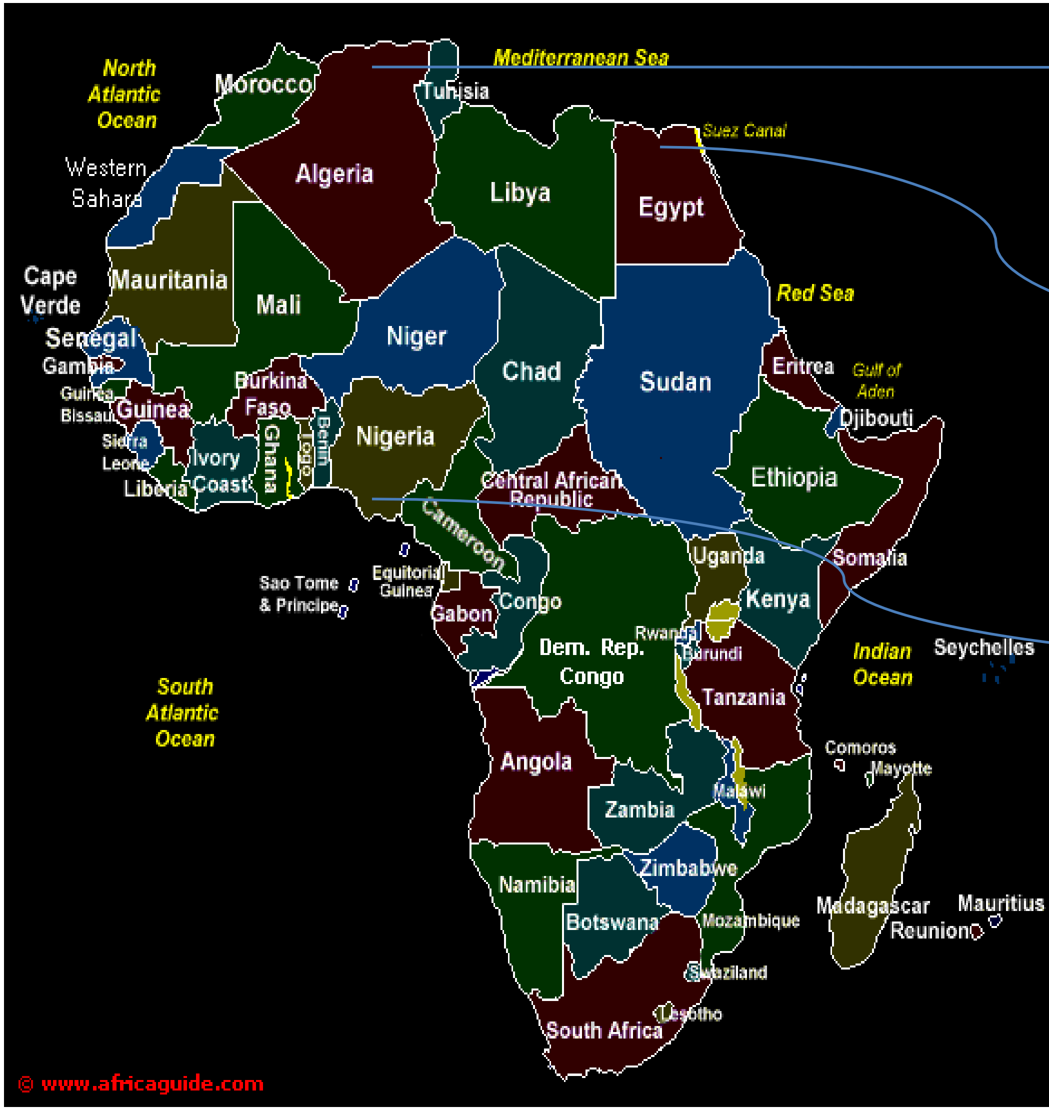
Applications

- Medical Applications
  - Radiotherapy for cancer
    - Kill cancer cells.
    - Used for 100 years but can be improved by better delivery and dosimetery
    - Heavy ion beams can give more localised energy deposition.
  - Medical Imaging
    - MRI (Nuclear magnetic resonance)
    - X-rays (better detectors ➔ lower doses)
    - PET
    - Tc99(m)
    - Many others….

- Other Applications
  - Radioactive Dating
    - C^{14}/C^{12} gives ages for dead plants/animals/people.
    - Rb/Sr gives age of earth as 4.5 Gyr.
    - O^{16}/O^{18} in H_2O in ice gives temperature
    - U^{238}/Th^{232} in stars gives ages of galaxies
  - Element analysis
    - Forensic (eg date As in hair).
    - Biology (eg elements in blood cells)
    - Archaeology (eg provenance via isotope ratios).

Nuclear Facilities in Africa



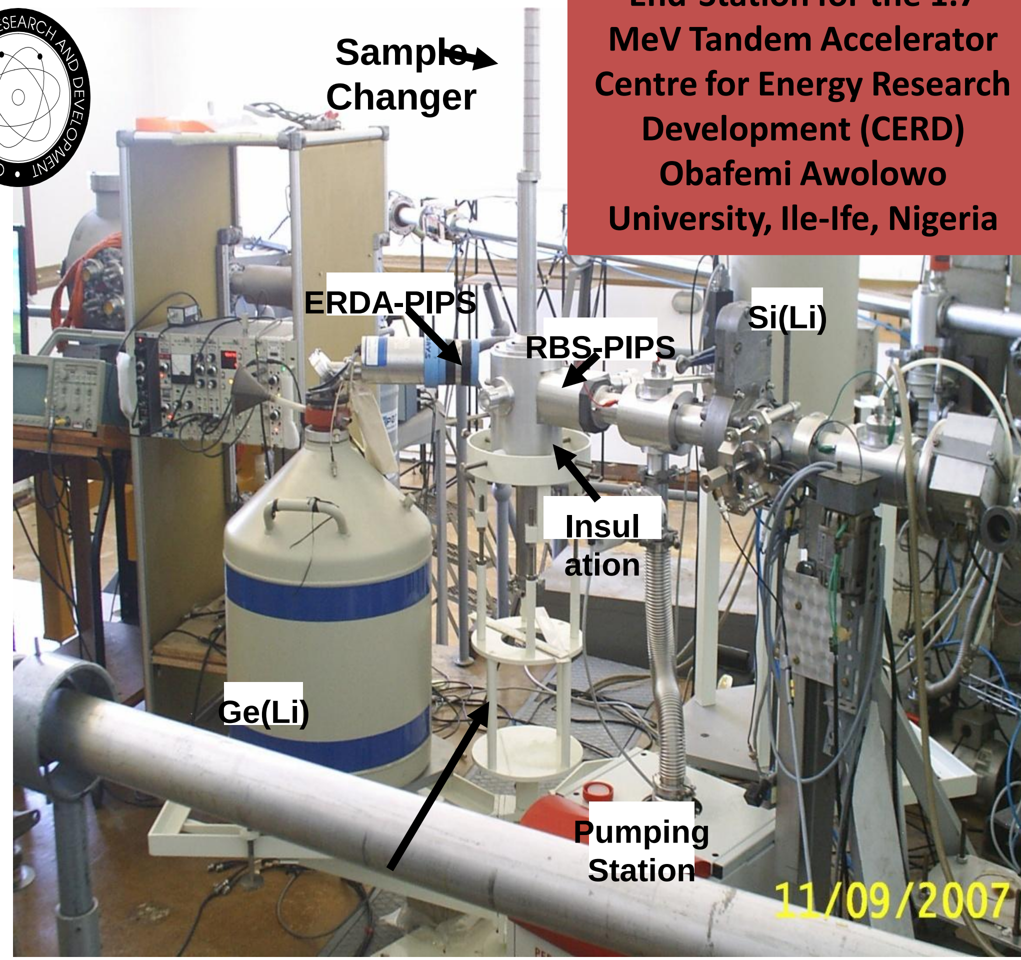
Comena, Algiers Centre national pour la Recherche Nucleiare: CRNA 3.75MV-VDG

Inshas Cyclotron Facility (ICF), Cairo; Russian type MGC-20 AVF cyclotron (20 MeV).

Centre for Energy Research development (CERD); Ife, Nigeria

Nigeria

Ion Beam Analysis (IBA) End-Station for the 1.7 MeV Tandem Accelerator Centre for Energy Research Development (CERD) Obafemi Awolowo University, Ile-Ife, Nigeria



Centre for Energy Research & Development Pelletron Tandem Accelerator Other Names: CERD 1.7 Pelletron
Location: CERD-Ife Ife (Osun State)
Subordinate to: Nigerian National Nuclear Commission
Size: 1.7MV
Status: Operational + work carried out

End station commissioned by the iThemba LABS team.

Beginning of Nuclear Research in SA

- 1948 – 1950: At CSIR, newly appointed head of the Nuclear Physics Division sent to the Nobel Institute in Stockholm to do Nuclear Physics research with a classical cyclotron.

- 1950: Decision to design and build a 16 MeV deuteron classical cyclotron at the Nuclear Physics Division, CSIR

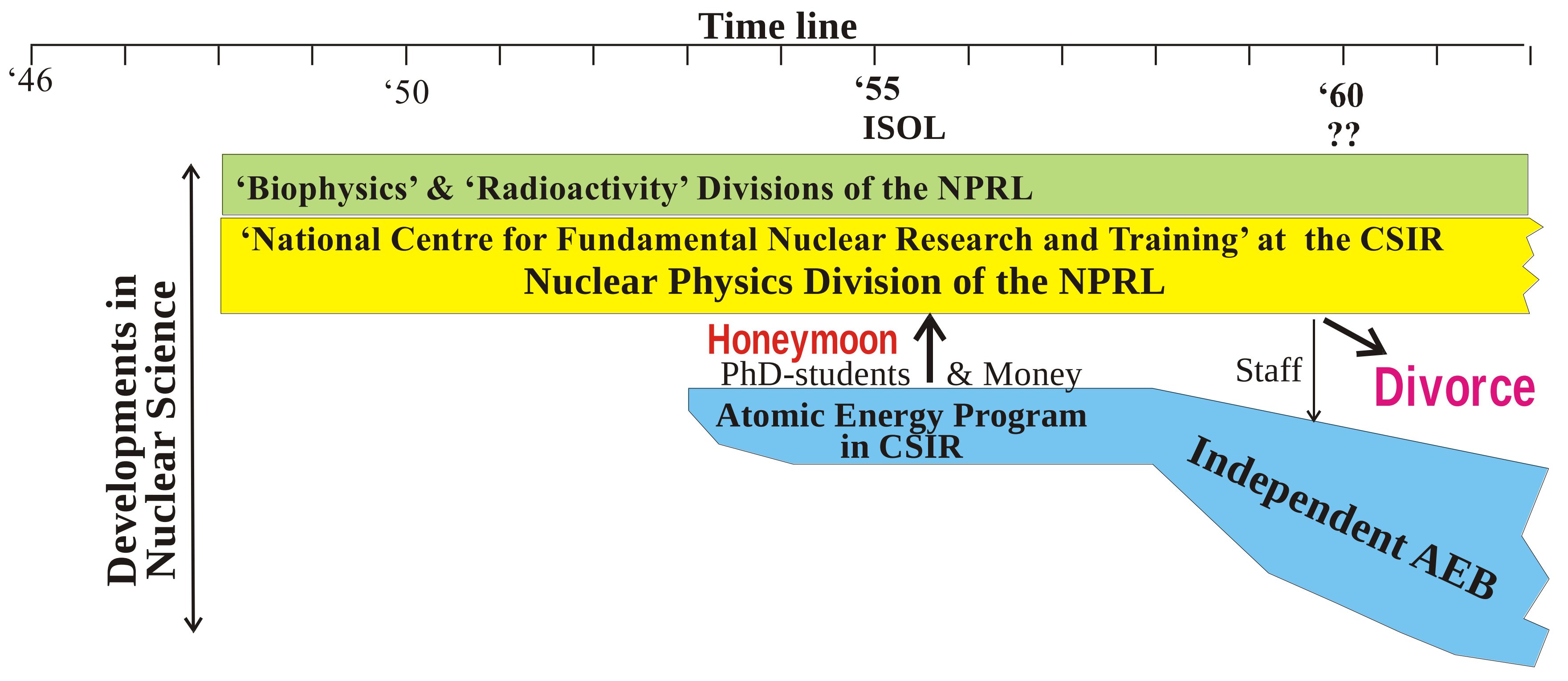
- Southern University Nuclear Institute (SUNI) established jointly by Universities of Stellenbosch & Cape Town [1964]

- Pioneering Neutrino experiments (led by F Riennes) in the mines of Johannesburg (*circa*: 1966)

- JPF Sellschop establishes a research accelerator at University of Witwatersrand, Johannesburg [1972]

CSIR: <u>C</u>ouncil for <u>S</u>cientific and <u>I</u>ndustrial <u>R</u>esearch

Organisational changes in nuclear sciences in SA: 1953 - 1960



Evolution of Nuclear Technology and Business at Atomic Energy Board

Research and Development Era – 1960 to mid 1970s

- SAFARI reactor operating at 20 MW and many other high level research and development programs
- Weapons Program [“Strategic” Era]

Strategic Era – mid 1970s to early 1990s

- PWR and SAFARI fuel Manufacture
- Isotope Production

Commercial Era – early 1990s (signing of the IAEA-NPT)

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Some Accelerators in South Africa				
Organisation	**Type**	**Date**	**Particle**	**Energy (MeV)**
CSIR	Cyclotron	1956/60	H_2^+	5.8 - 15.2
			$^2H^+$	11.5 - 17.3
			$^3He^{++}$	18 - 39
			$^4He^{++}$	23 - 34.6
SUNI / iThemba LABS	VdG	1964	p a.o.	6
NECSA	VdG	1962	p a.o.	4
Univerity of Potchestroom	VdG	1972	p a.o.	2
University Pretoria	VdG	1964	p a.o.	2.5
WITS	Tandem	Nov. 72	p a.o.	12 (6)
iThemba LABS	Cyclotron	1984	p a.o.	8
	Cyclotron	1986	p a.o.	11.5 - 227
			Xe	790
	Cyclotron	1994	p to Xe	8 (41.6)
De Beers	RFQ	1997	d	4 and 5
De Beers	RFQ	2003	d	4 and 5
Pretoria Private Hospital	Cyclotron	2006	p	PET isotopes
NECSA	Cyclotron	2007	p	PET isotopes

Research Facilities in South Africa

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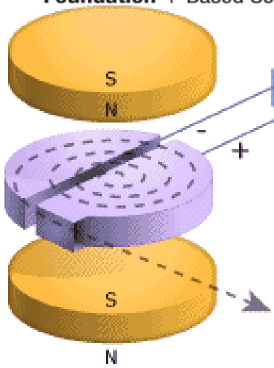
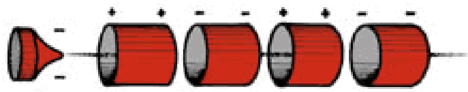
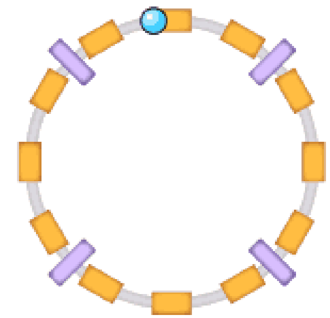
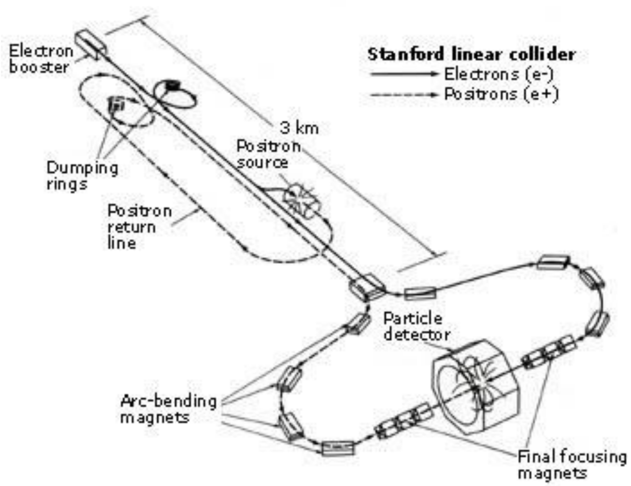
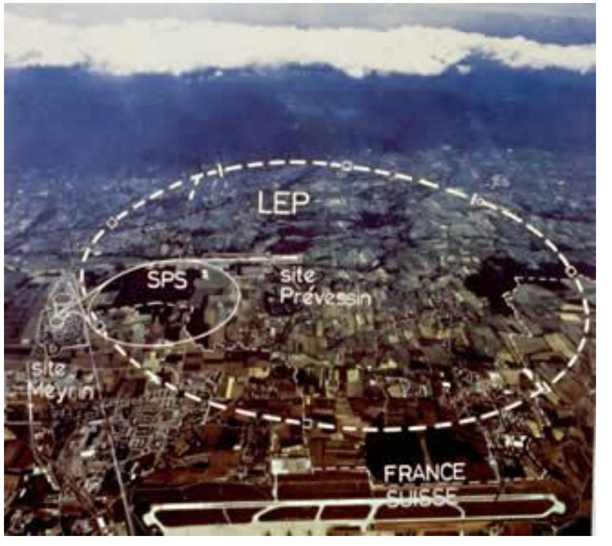
Accelerators







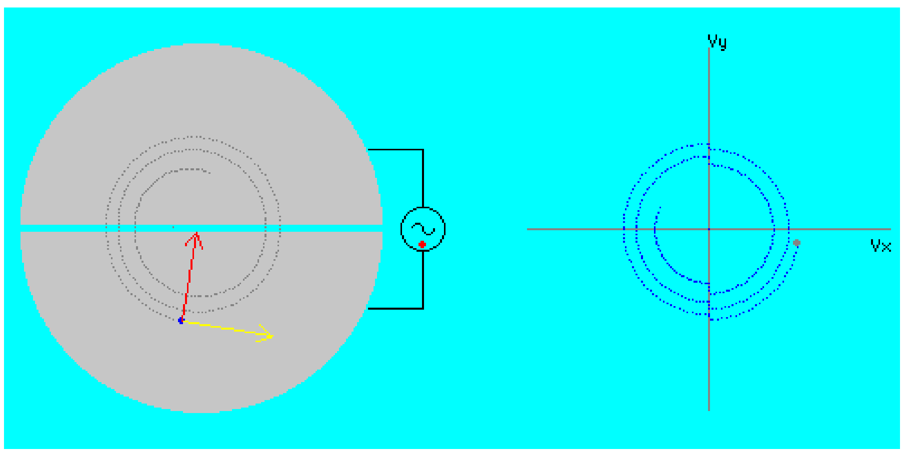




Cyclotron ***Linear Accelerator*** ***Synchrotron***

Cyclotrons

The earliest accelerators were cyclotrons. Cyclotron consists of two D-shaped objects (dees) with a potential difference between them. A stream of particles moved in a plane perpendicular to a uniform magnetic field, which bent the particle tracks so that they passed through an electric field in a gap between dees and were accelerated.



For non-relativistic particles the frequency of the machine was determined by the Lorentz force law, $F = e\,v\,B$, and the formula for centripetal acceleration, $v^2 / r = F / m = e\,v\,B / m$, so the angular frequency is given by: $\omega = e\,B / m$.

Operates a 200 MeV separate-sector cyclotron

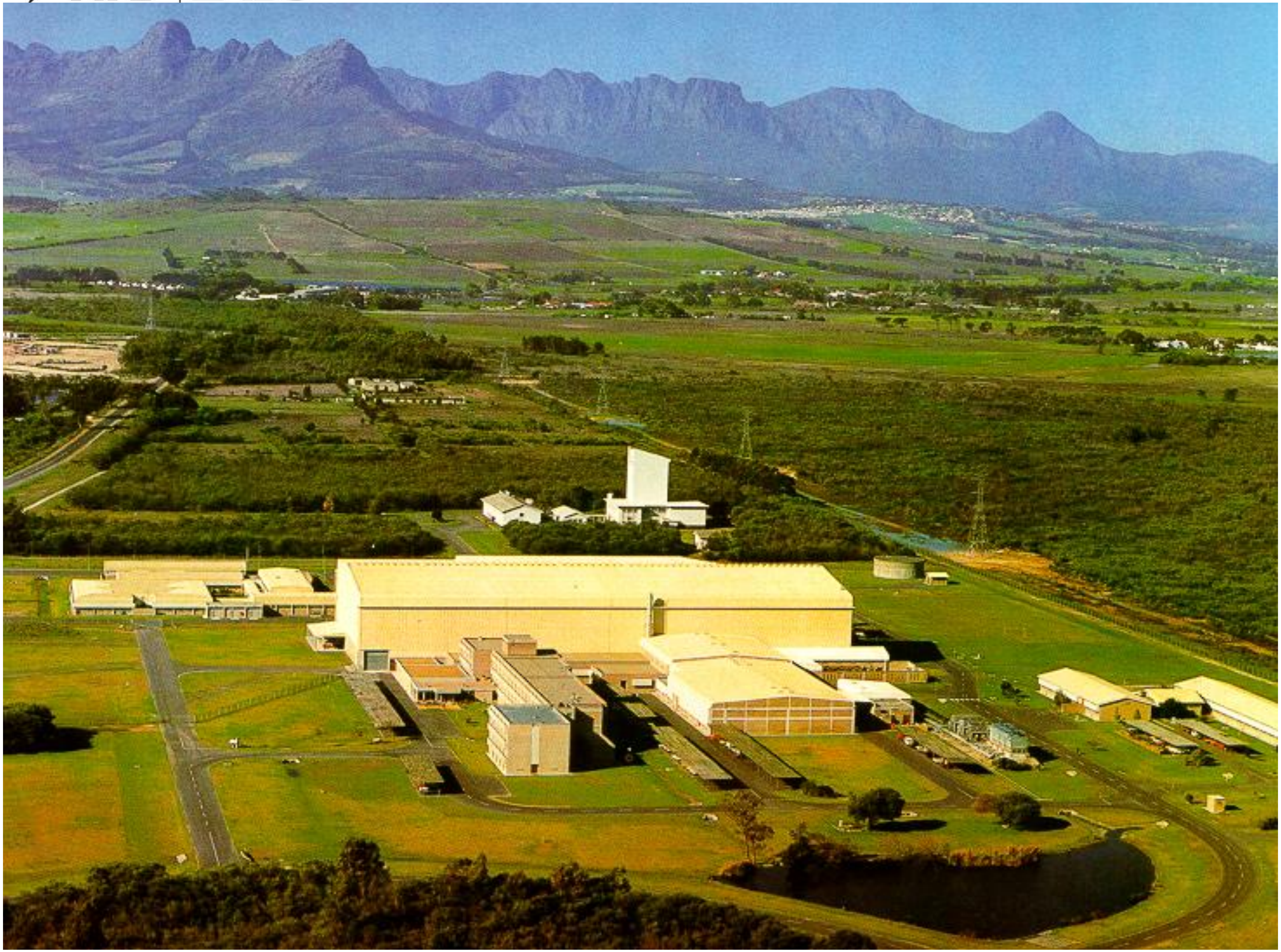
The dream of a multi-disciplinary medium energy national accelerator ~1964

Limited useful life of the cyclotron (and of all other nuclear accelerators in SA).

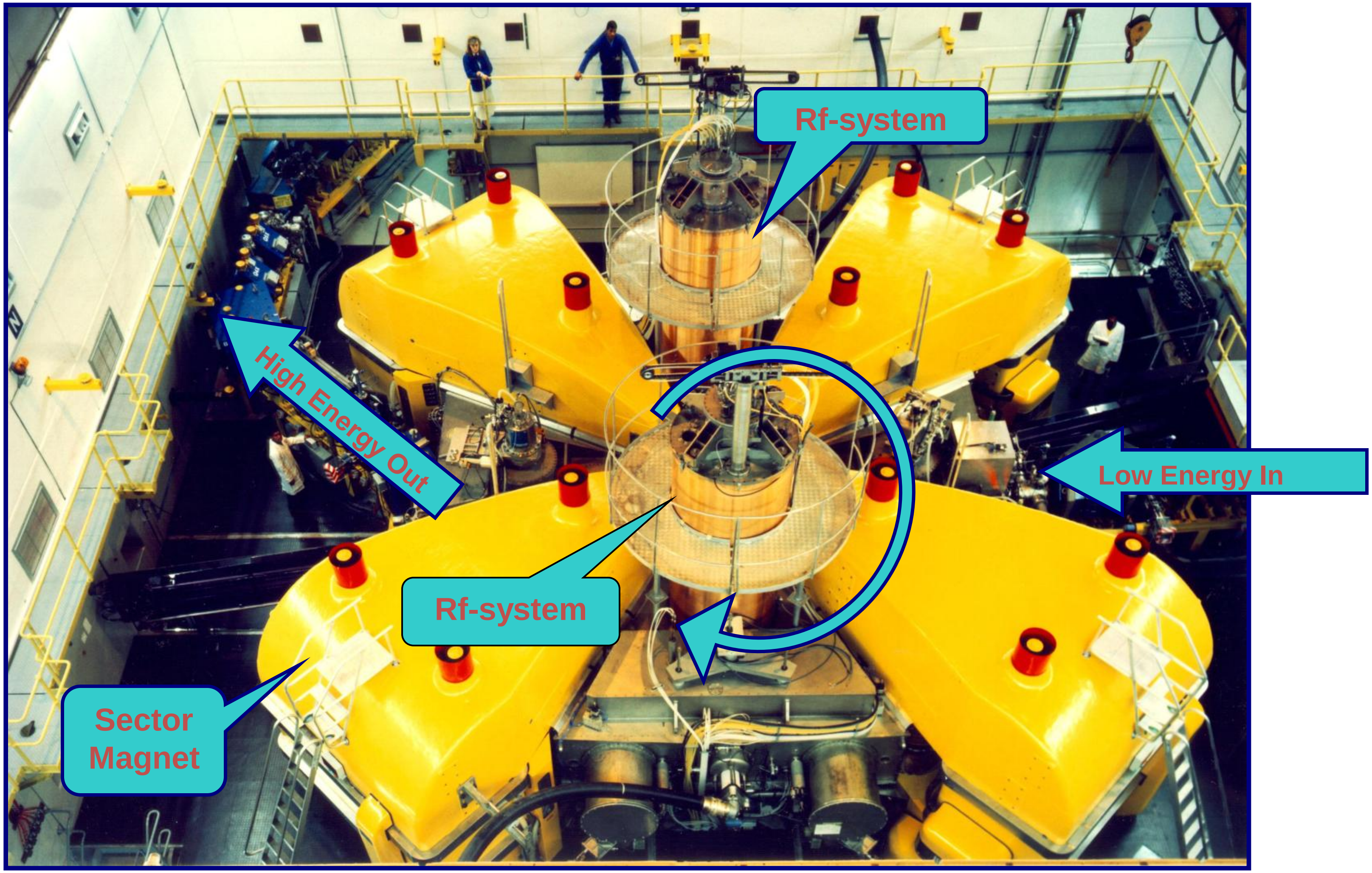
- **Started discussing the use of medium energy particle beams in nuclear physics;**
- **Investigated the use of high intensity medium energy beams in isotope production.**

Monitored the development of the open sector cyclotron concept, as a viable multi-disciplinary medium energy accelerator - started a low key theoretical study of it.

Aerial View of iThemba LABS



The iThemba LABS Cyclotron

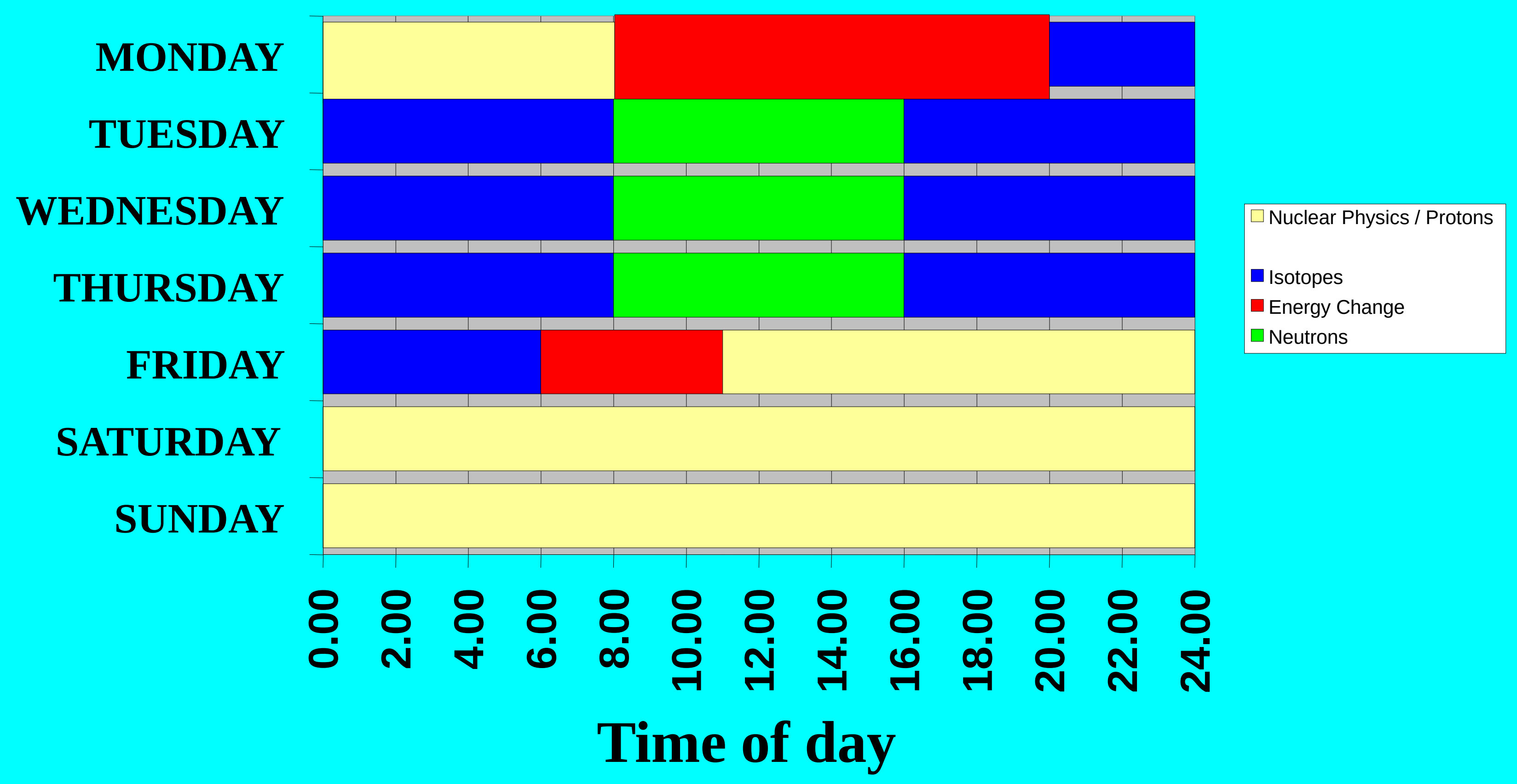


iThemba LABS

iThemba L(aboratory) for A(ccelerator)-B(ased) S(ciences) is a multi-disciplinary research centre, operated by the NRF (National Research Foundation). It provides accelerator and ancillary facilities for:

- **Research and training in the physical, biomedical and material sciences**
- **Treatment of cancer patients with energetic neutrons and protons and related research**
- **Production of radioisotopes and radiopharmaceuticals for use in nuclear medicine, research and industry and related research**

CYCLOTRON OPERATING SCHEDULE



Beams delivered at iThemba LABS

Some beams at iThemba LABS			
Element	Mass	Energy range MeV	
		from	to
H	1	11.5	227
He	4	25	200
B	11	55	60
C	12	58	400
C	13	75	82
N	14	140	400
O	16	73	400
O	18	70	110
Ne	20	110	125
Ne	22	125	125
Al	27	150	349
Si	28	141	141
Cl	37	205	250
Ar	40	280	280
Zn	64	165	280
Kr	84	450	530
Kr	86	396	462
I	127	730	730
Xe	129	750	790
Xe	136	750	750

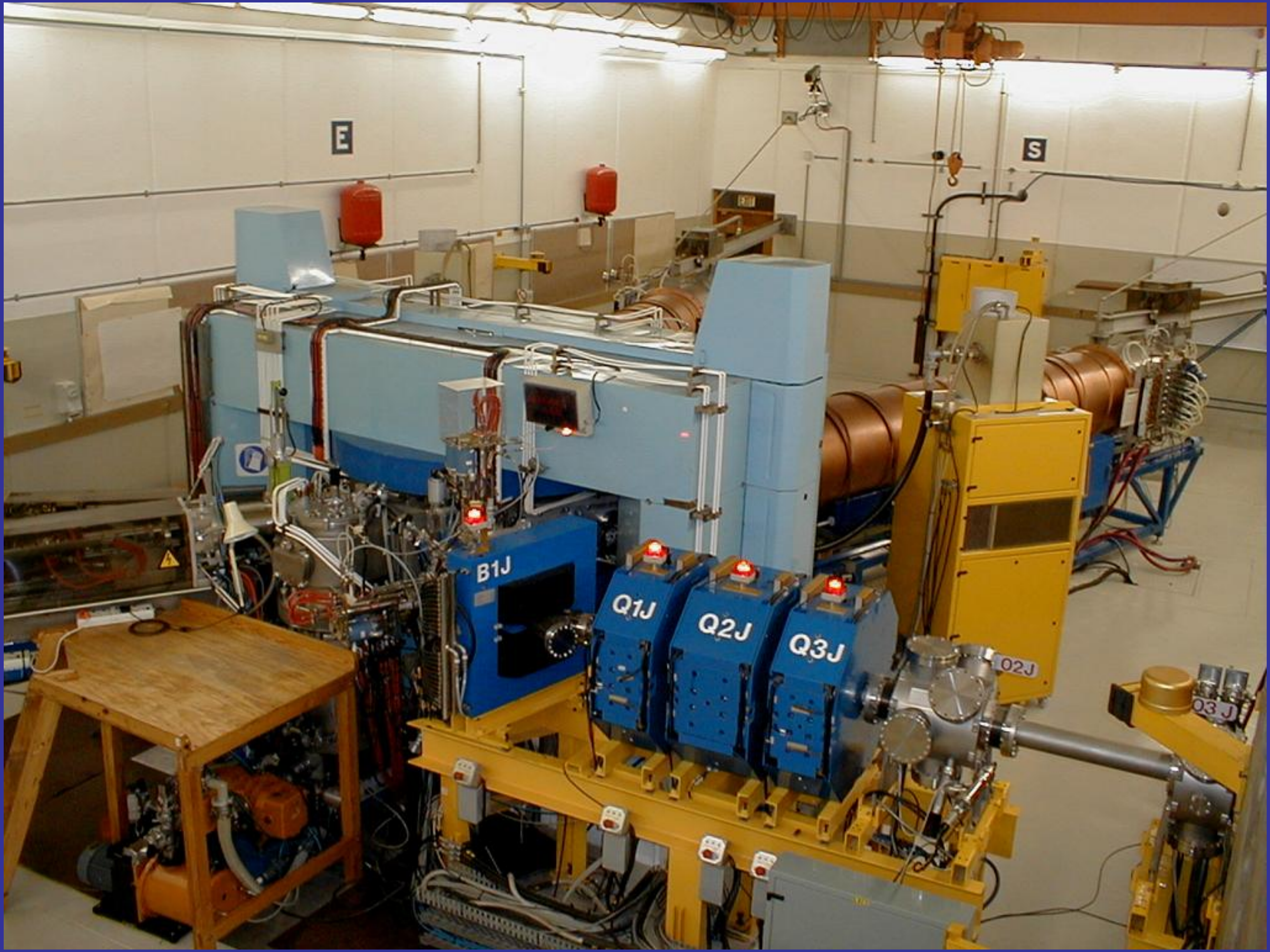
66 MeV Proton Beam

- **Beam current on target: 250 µA**
- **Transmission efficiency through the SSC:**

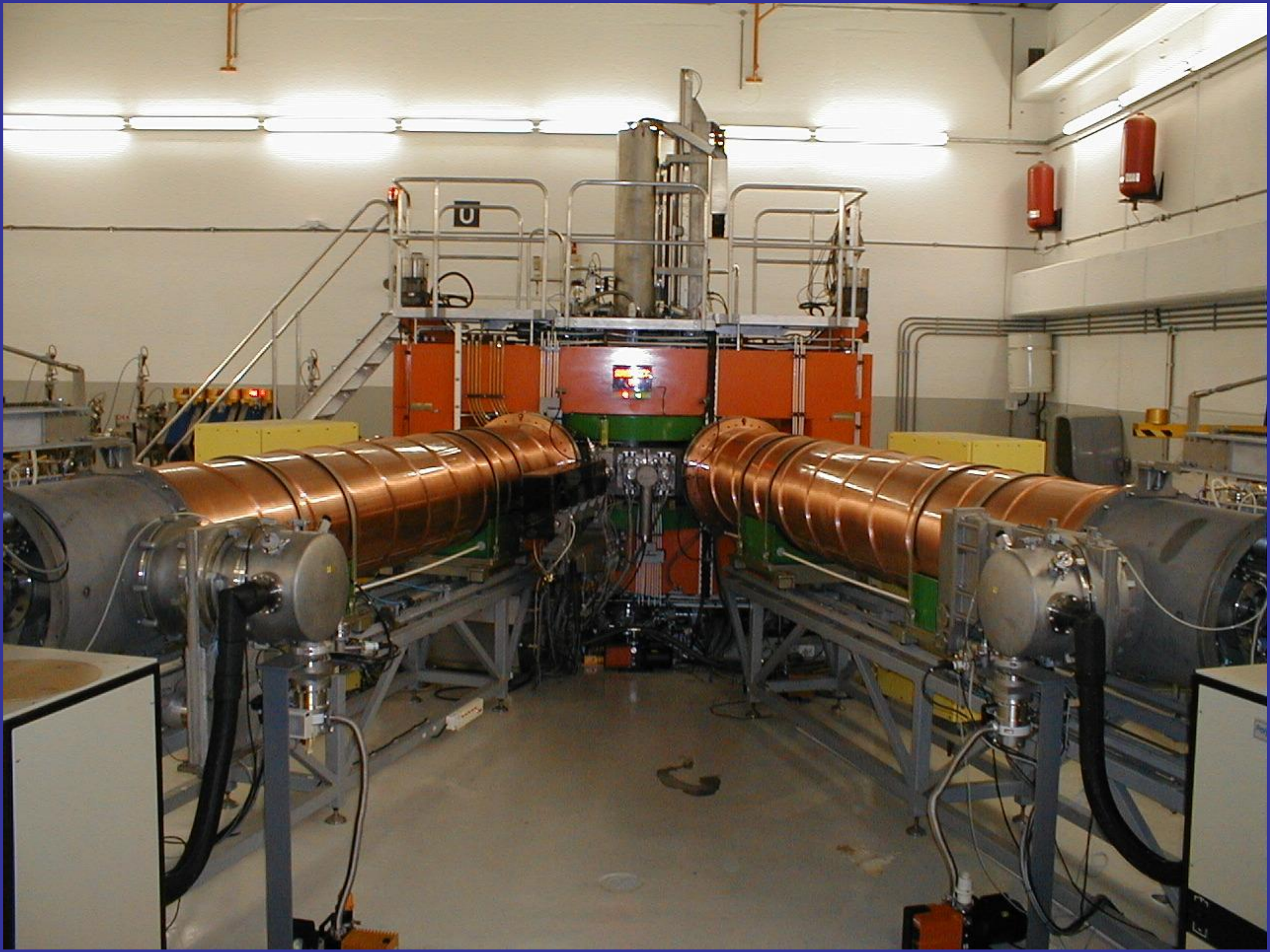
99.8%

UPS

Solid-pole injector cyclotron 1 (SPC1)

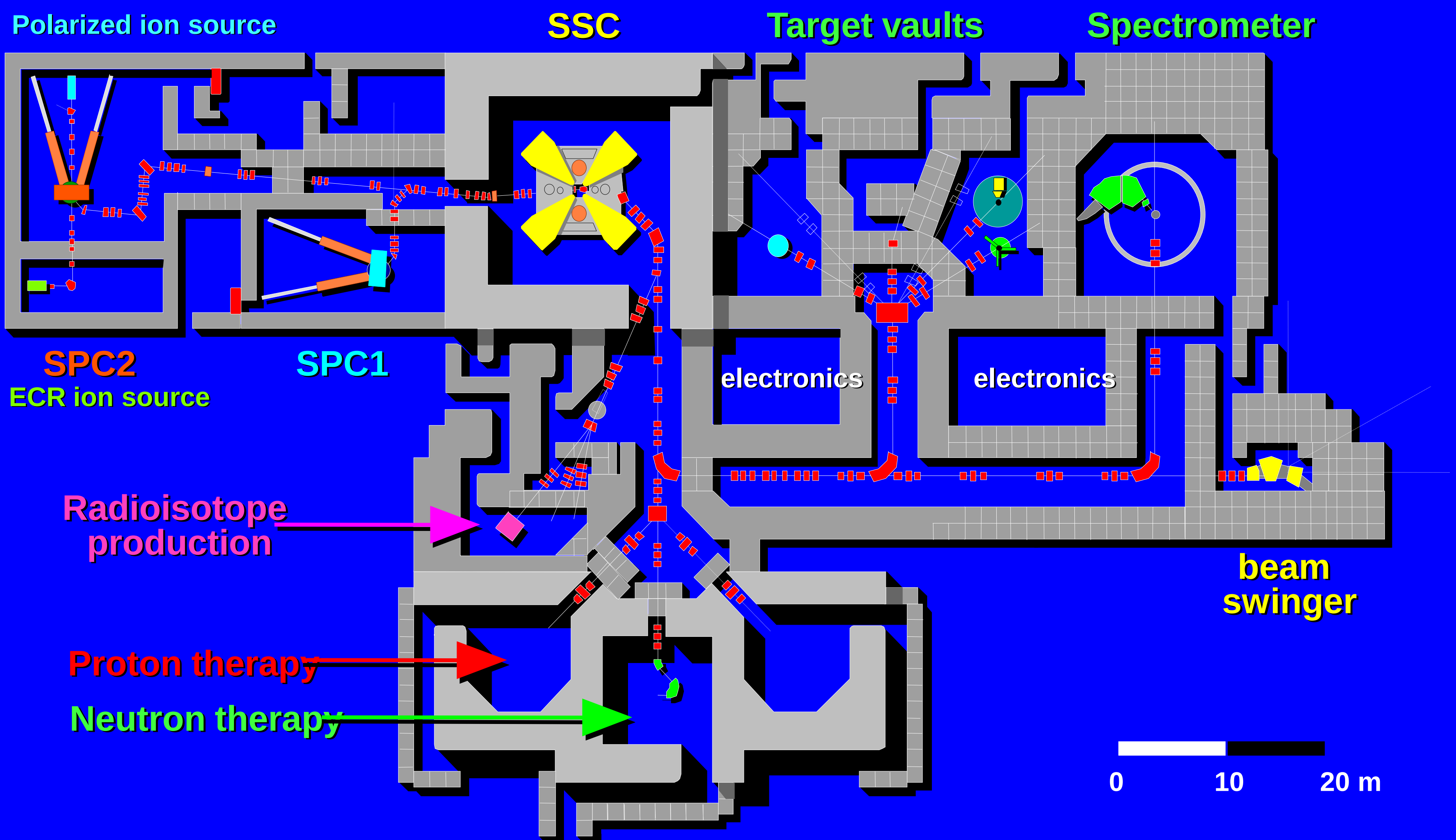


Solid-pole injector cyclotron 2 (SPC2)

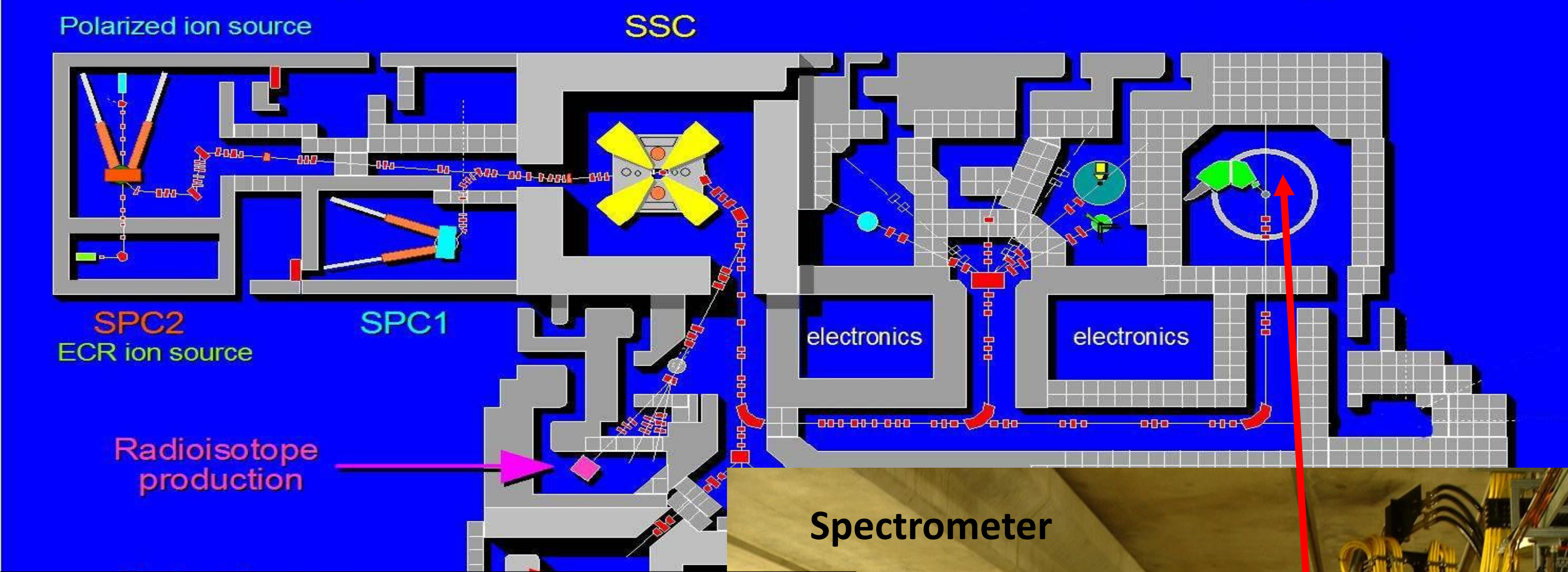


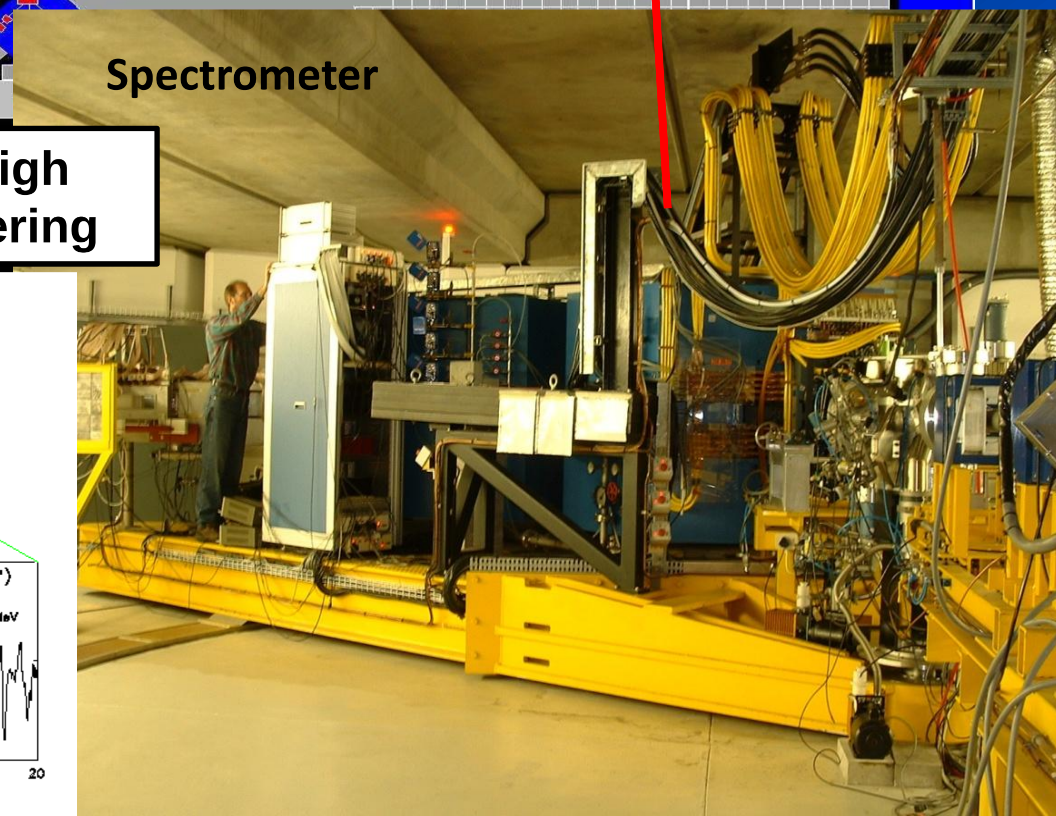
Separated-Sector Cyclotron Facility

National Research Foundation

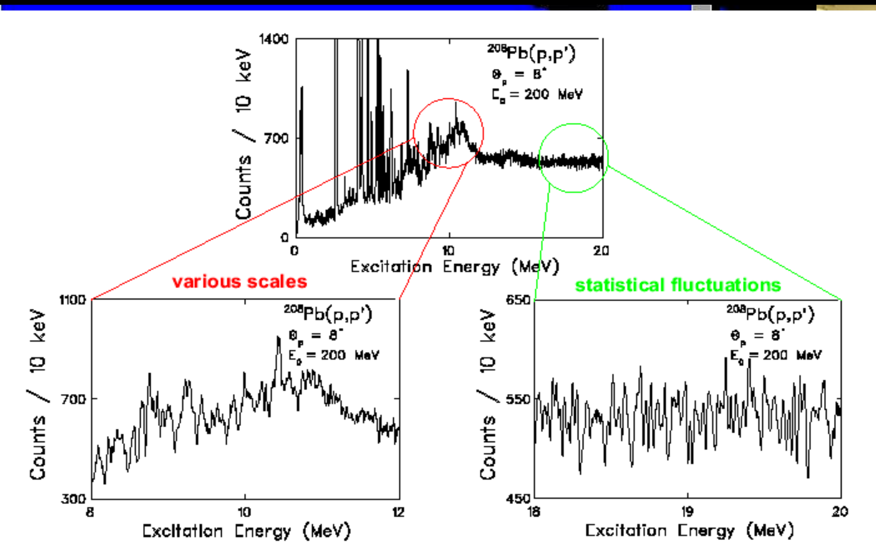


Separated-Sector Cyclotron Facility

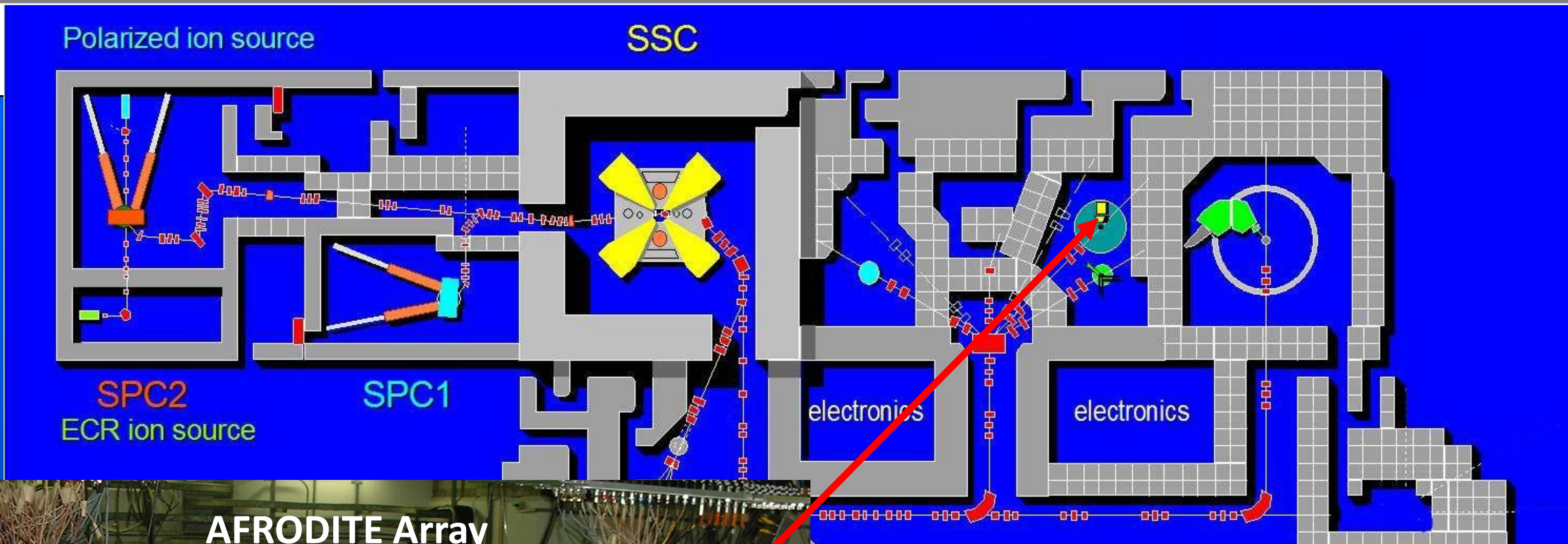


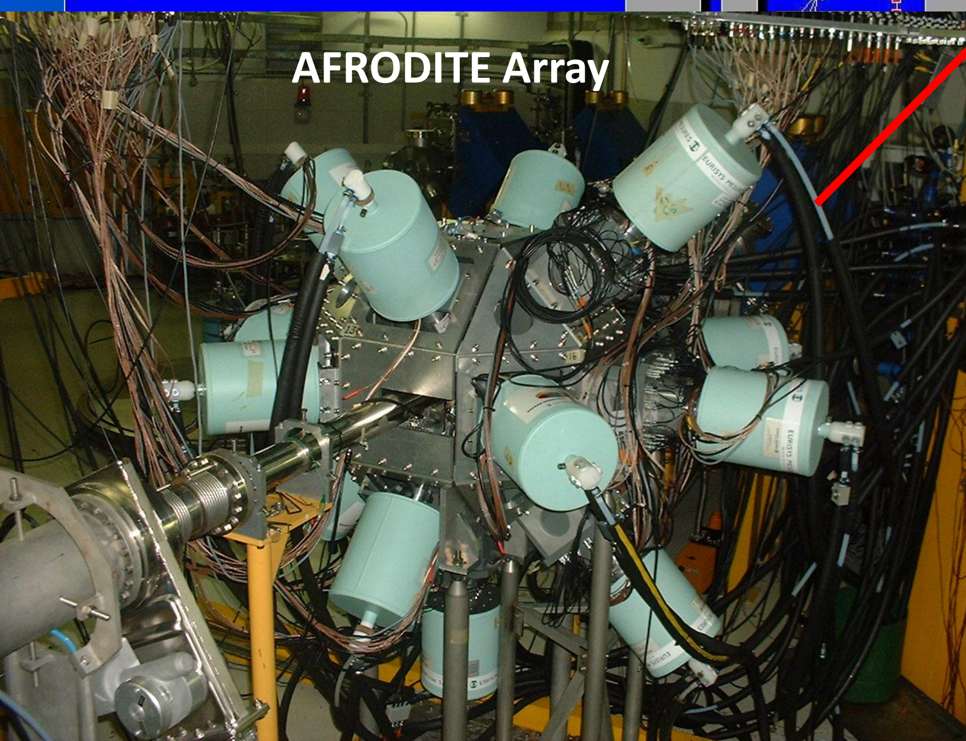


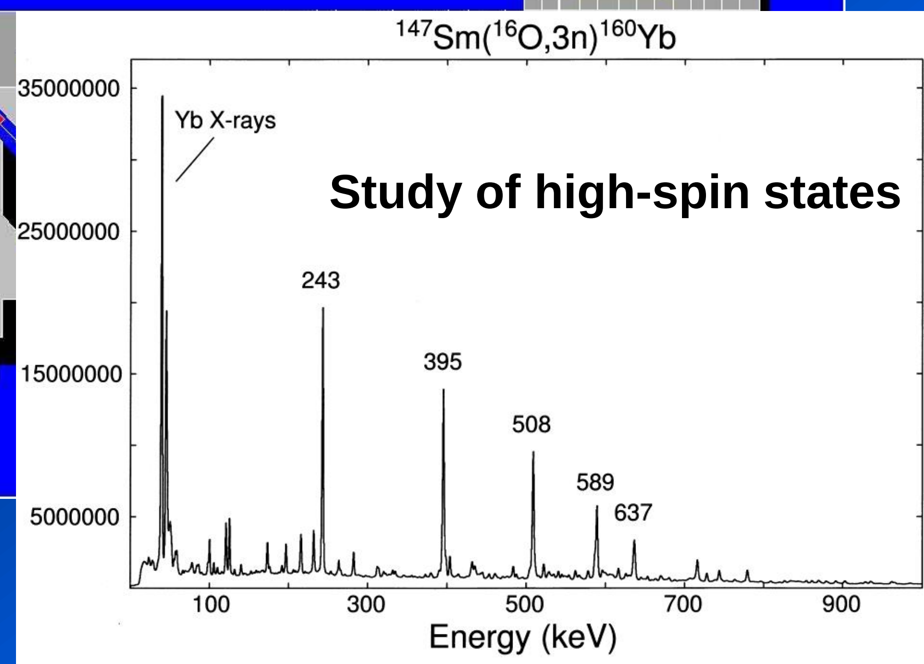
Fine Structure of ISGQR from high resolution proton inelastic scattering



The Separated Cyclotron Facility

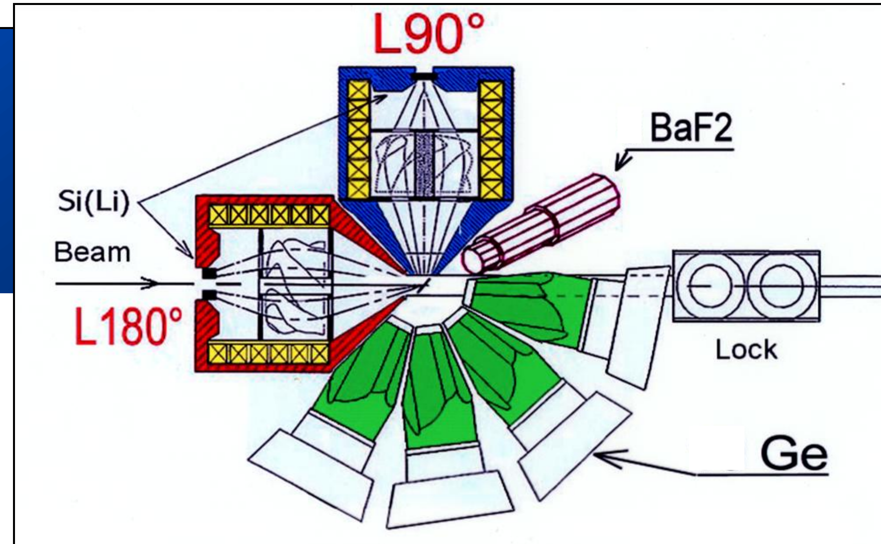






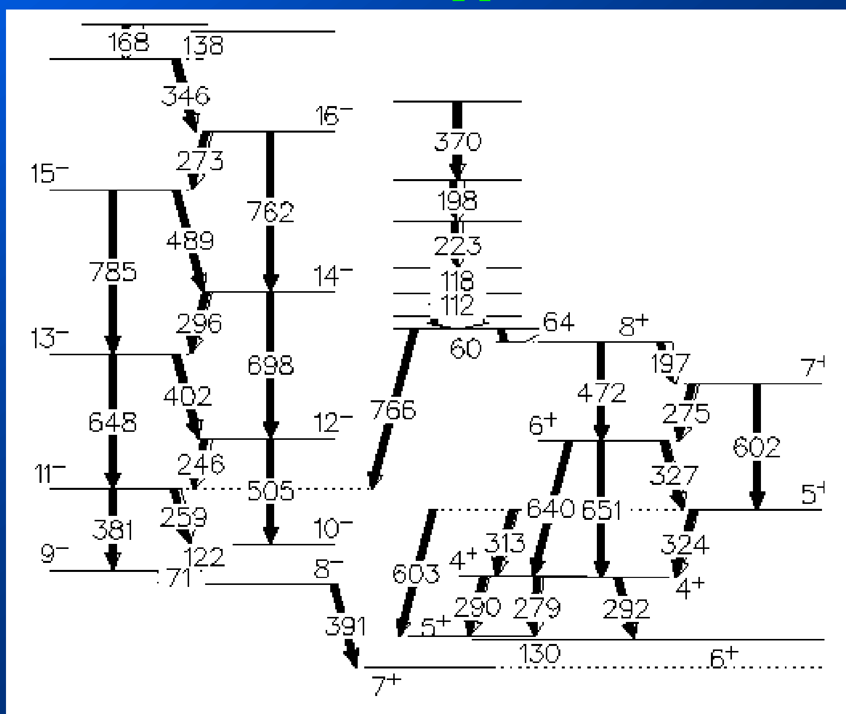
Electron-gamma studies

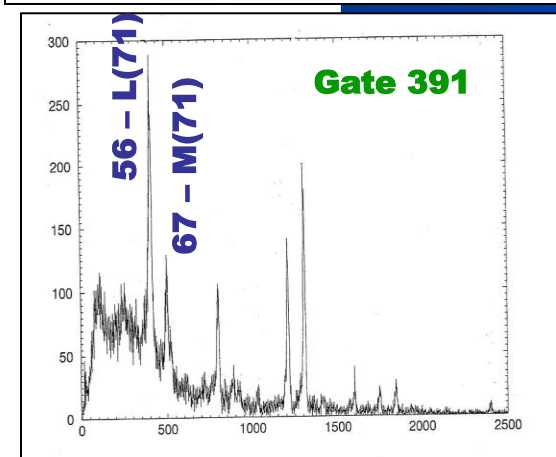
The Orsay electron spectrometers



Electron spectroscopy is very useful, particularly for discovering transitions with energies close to the energies of the X-rays

For instance: ^{198}Tl





The introduction of the 71 keV leads to discovering for the first time signature inversion in the Tl isotopes.

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Radio nuclides

- **Currently, iThemba LABS produces weekly the medical radionuclides ^{67}Ga, ^{123}I and ^{81}Rb.**

- **^{67}Ga and ^{123}I are used to prepare radiopharmaceuticals for the local users.**

- **^{81}Rb is used to manufacture the $^{81}Rb/^{81m}Kr$ generator.**

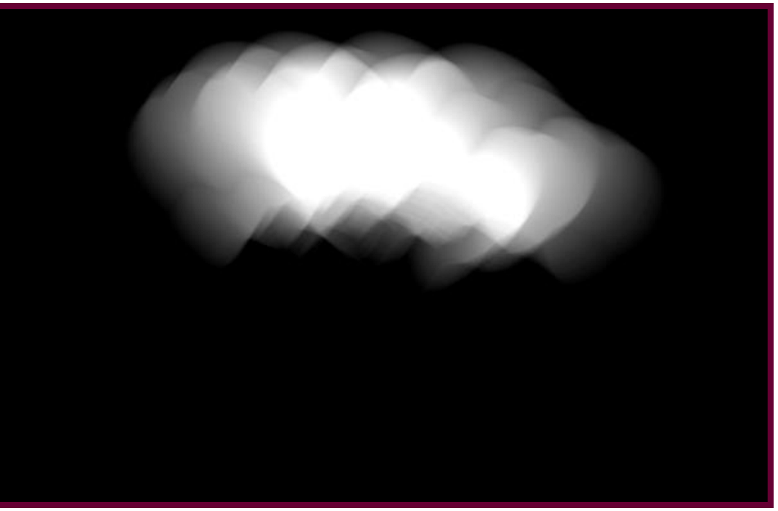
- **^{82}Sr is produced for use in medical generators to obtain the PET radionuclide ^{82}Rb.**

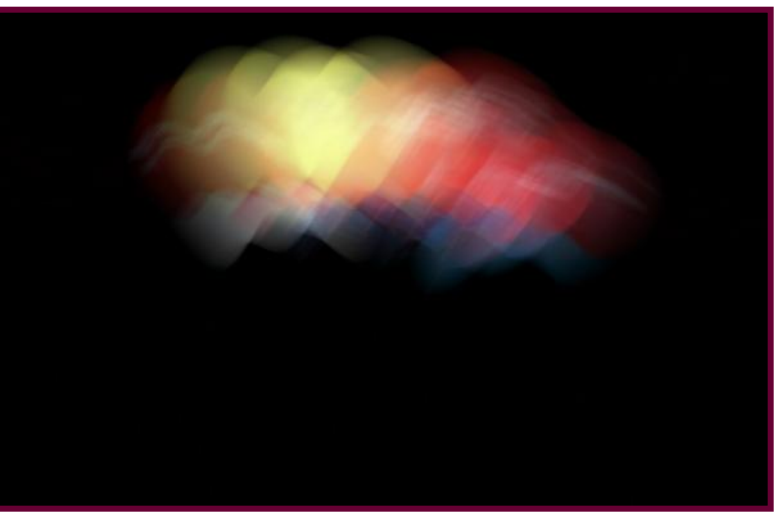
- **^{22}Na is produced to manufacture positron sources.**
  - Export to CERN (anti- H experiment)

- **Close to 60 local users in nuclear medicine**

Supply for Nuclear Medicine

NU-Clear Medicine: PET/CT





PET/CT Road Map to Personalized Molecular Medicine

NEUTRON AND PROTON THERAPY

Compared with conventional radiations (photons, electrons):

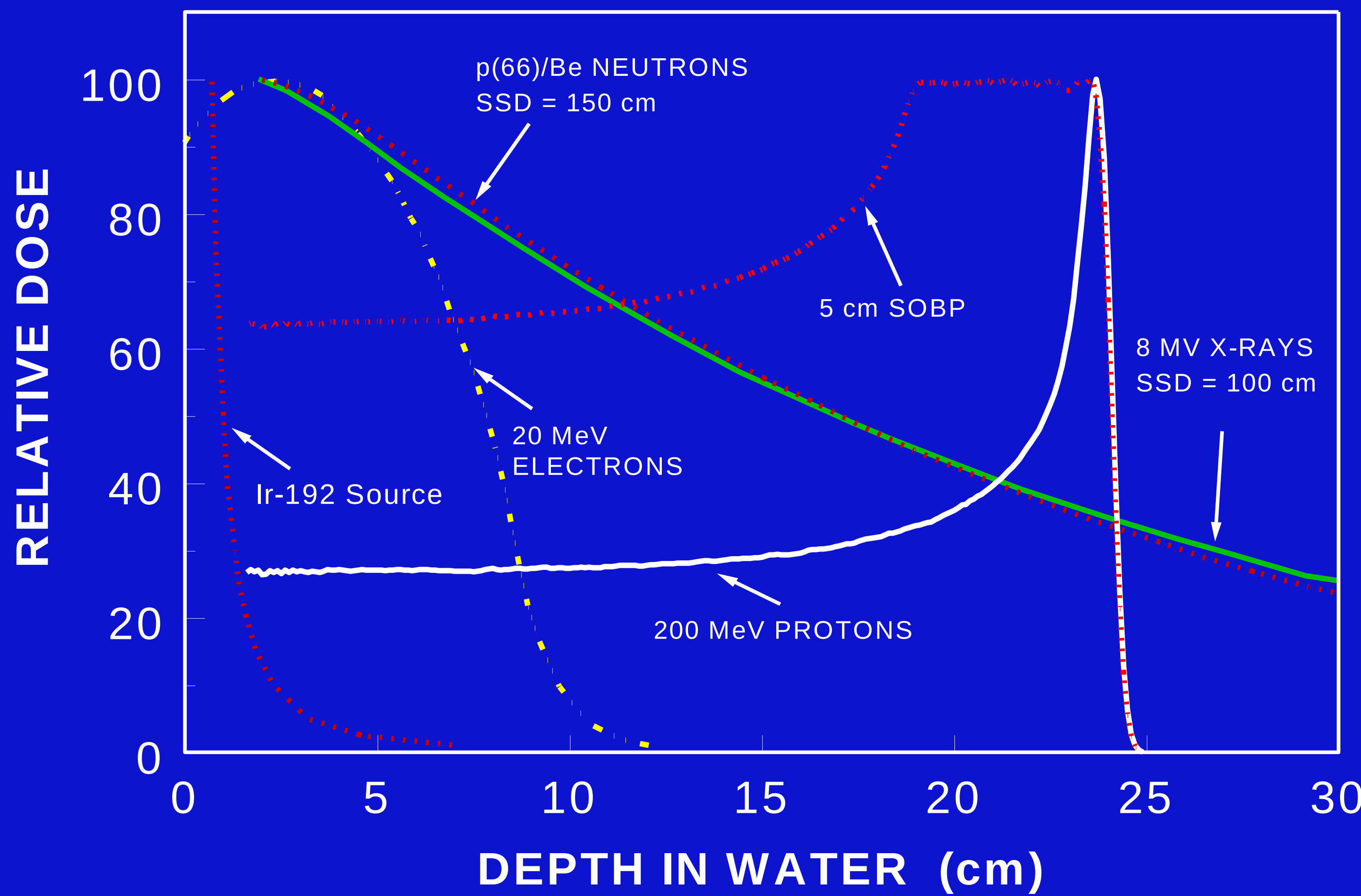
- **Neutrons have similar physical characteristics to x-rays and are more effective for treating radioresistant tumors, usually large and/or slow-growing, such as salivary gland tumours, advanced prostate cancer**

Neutrons are used because of their BIOLOGICAL EFFECTS

- **Protons have more favorable dose distributions (fixed range, little scattering) which can easily be controlled and are used to treat well-delineated lesions (benign and malignant) close to critical structures, which can easily be avoided, such as brain lesions, early prostate cancer**

Protons are used because of their PHYSICAL PROPERTIES

Depth dose curves for different treatment modalities



Particle Therapy Programme

- **Neutron Therapy at 66MeV (commenced: 1988)**
- **Proton Therapy at 200MeV (commenced: 1993)**
  - **Number of Patients Treated:**

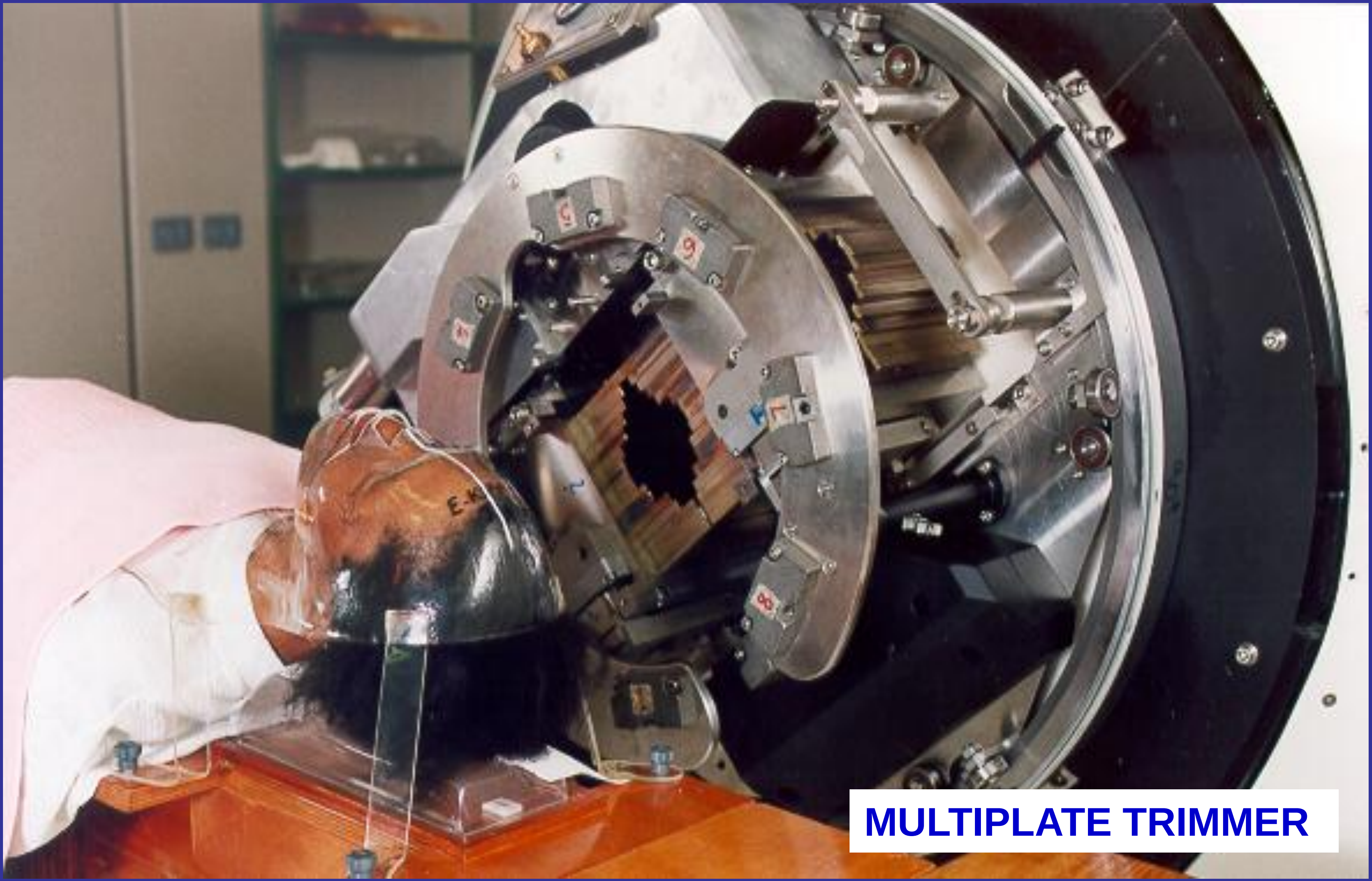
Neutrons:	**> 1 460**
Protons:	**> 500**

- **Various Types of Cancer Treated:**

Protons:	**Brain Tumours; Acoustic Neuroma; Pillsbury Adenoma; Eye Tumour.**
Neutrons:	**Breast; Salivary Glands Head, Neck Carcinomas; Malignant Melanomas.**

Neutron Therapy

Early Neutron patient



MULTIPLATE TRIMMER

Cancer Statistics in South Africa

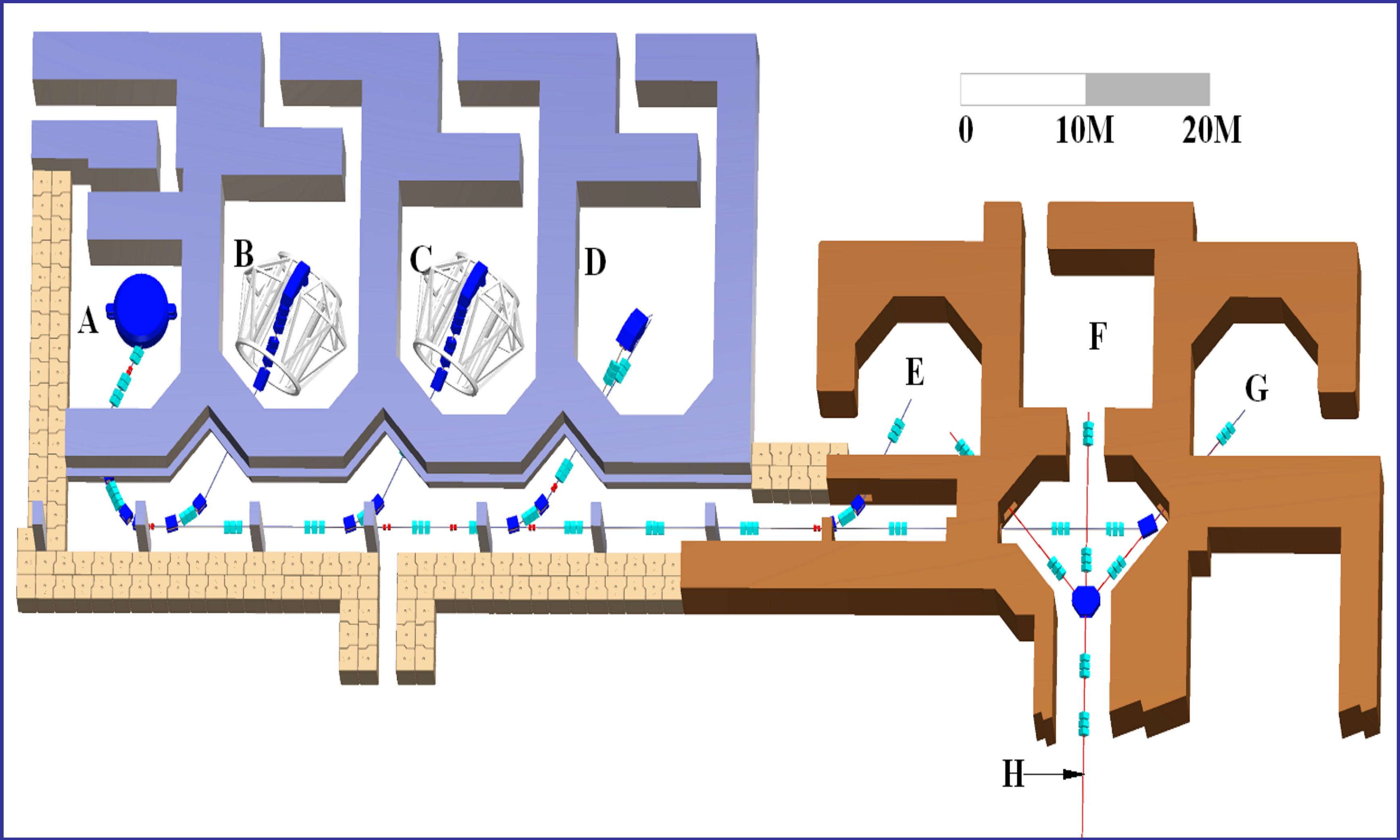
- Private Sector treats about 16000 new cases with 30 linear accelerators

- The State treats about 16 000 with 18 linear accelerators and 13 cobalt machines

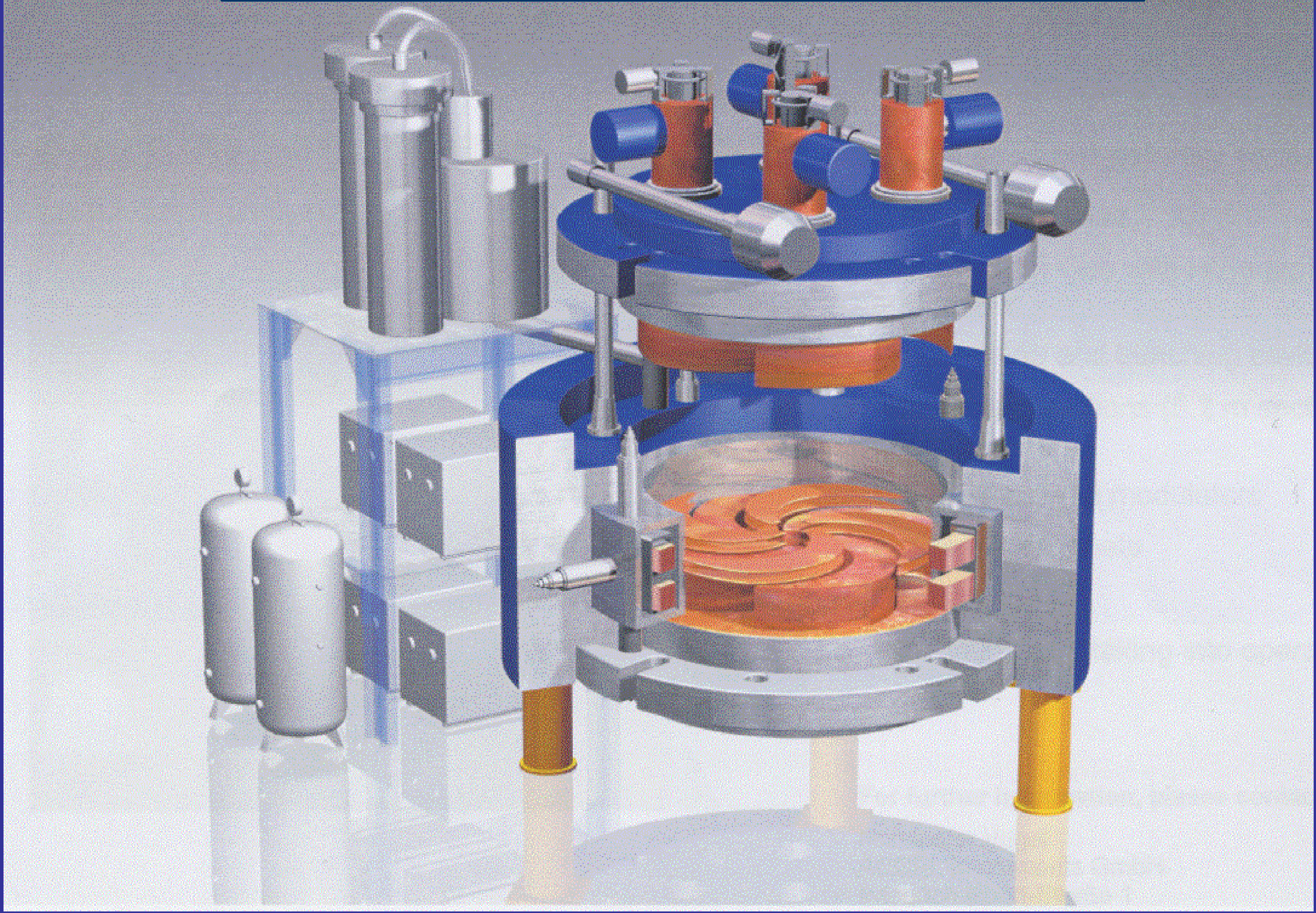
- By the end of 2008 there will be 10 linear accelerators capable of delivering stereotactic treatment

- Number of cases for proton therapy will be less than 200 from the State. The private sector will not refer patients for proton therapy

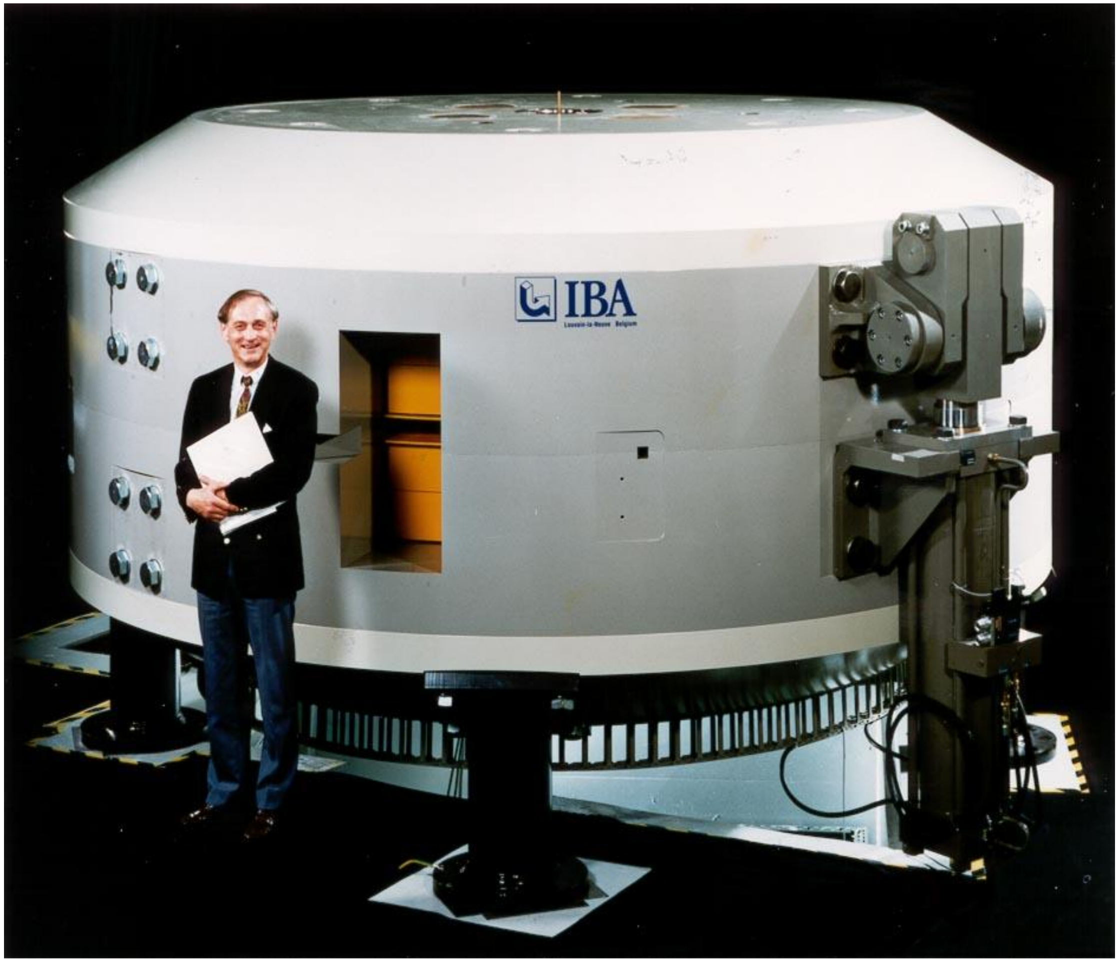
New dedicated facility for proton therapy



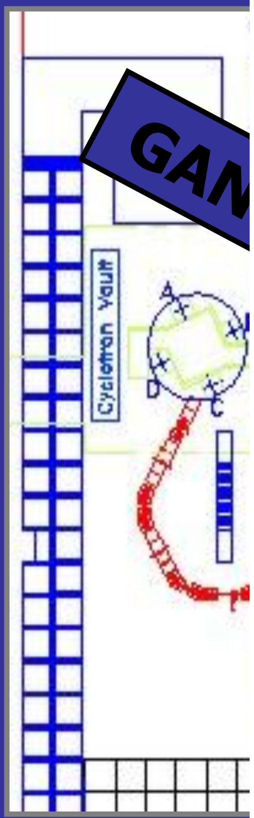
Superconducting 250 MeV cyclotron - ACCEL

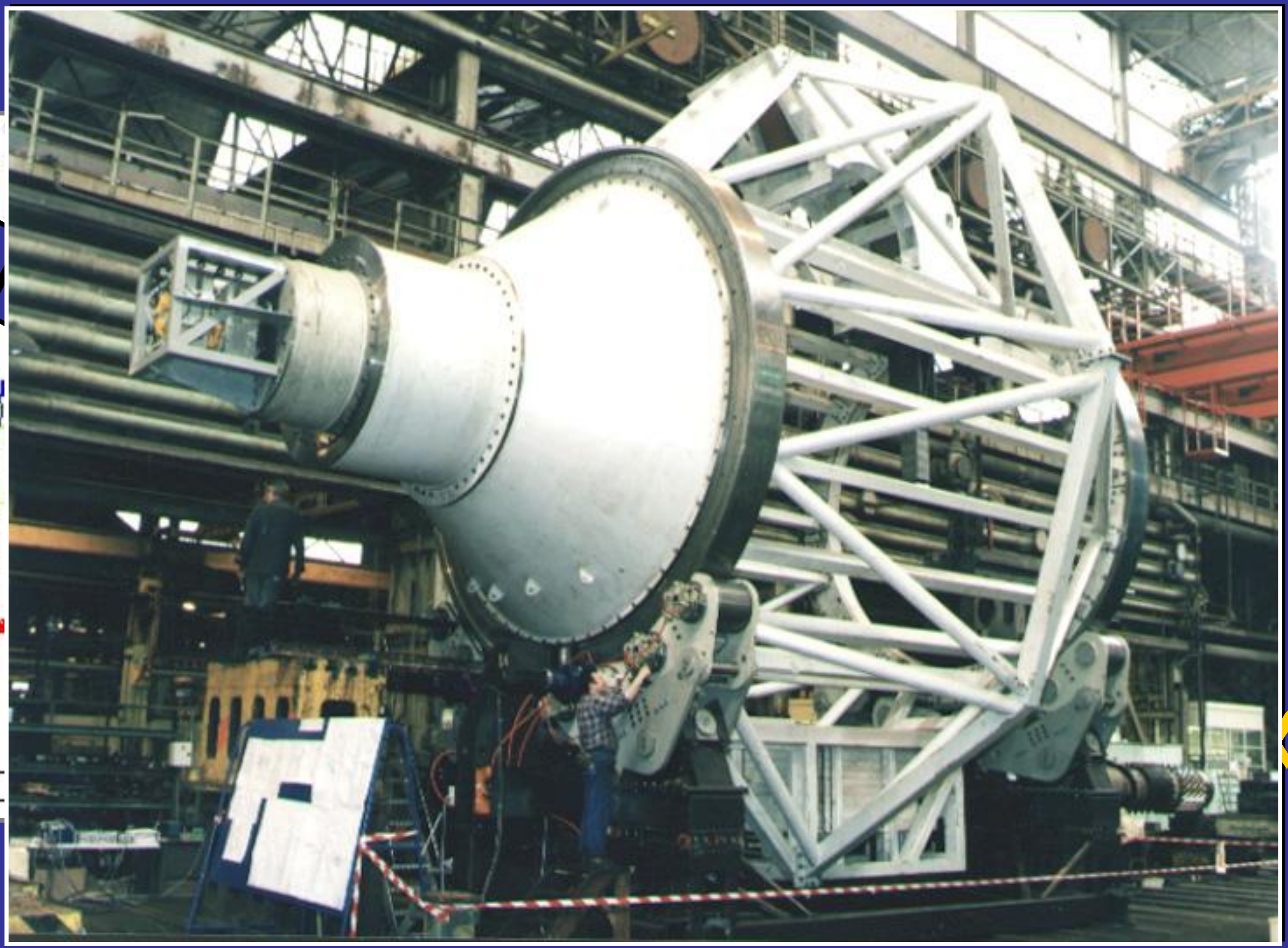


230 MeV room-temperature cyclotron from IBA



Isosentriese Gantry





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Current Plans

- **iThemba LABS : Key node in African network of Sub-Atomic Science & Technology**
  - ✓ **Staging post for SA-CERN, SA-JINR Dubna and other international Facilities**

- **Centre for Nanoscience; AMS facility**

- **iTPTC (iThemba Particle Therapy Centre)**

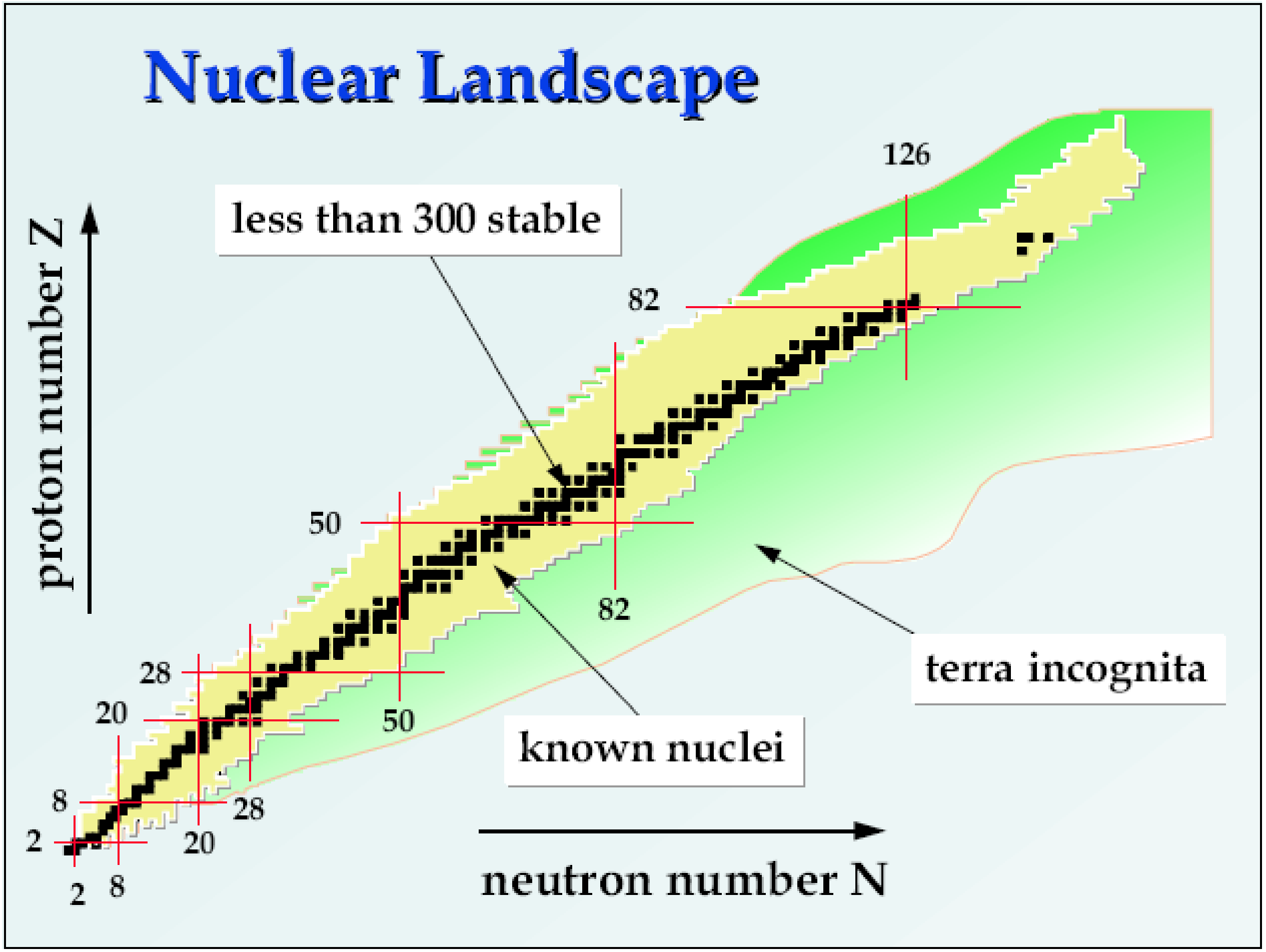
- **Radioactive Ion Beams : Nuclear Physics & Materials Science**

National Research Foundation
iThemba LABS
Laboratory for Accelerator Based Sciences

Radioactive Ion Beams : Proposed Flagship programme for Nuclear Physics at iTL

Why ?

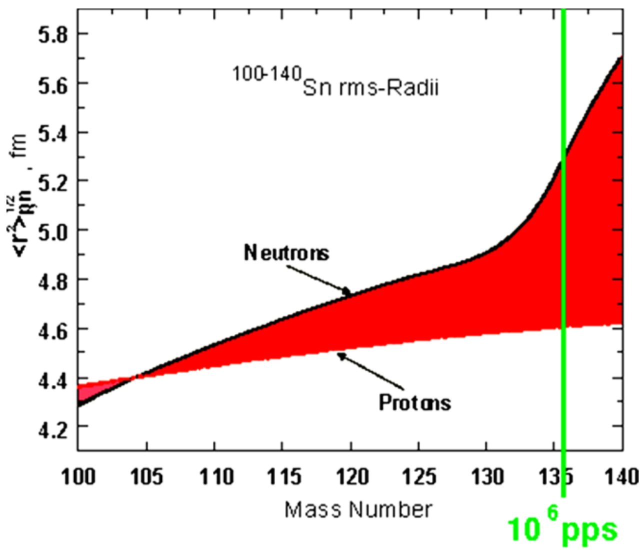
<u>*“TERRA INCOGNITA”*</u>



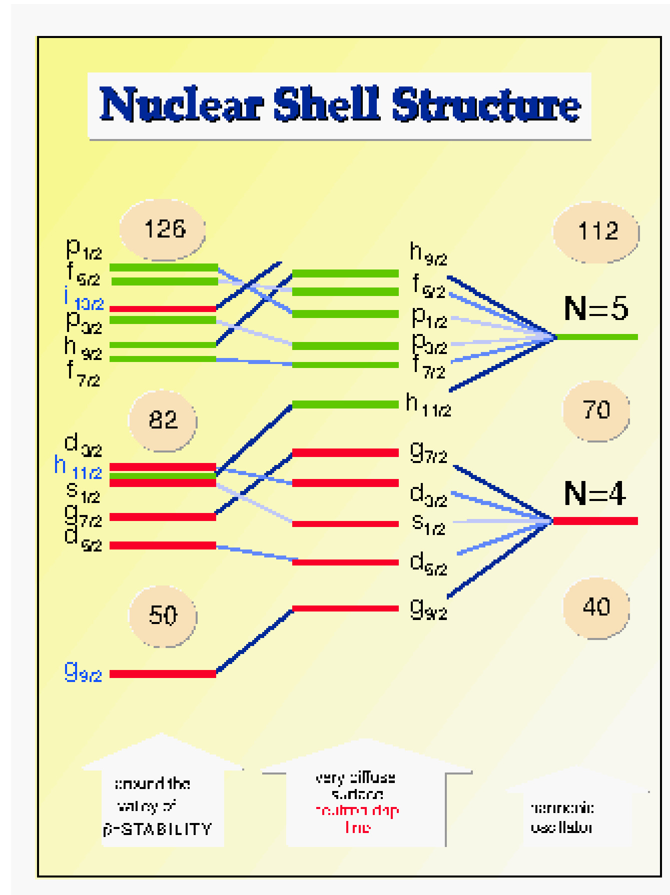
<u>*REQUIRES RADIOACTIVE BEAMS!*</u>

Neutron Skin!

Drastic Changes of Shell Structure far of stability!



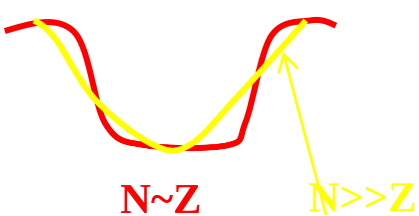
Estimated difference in neutron and proton root-mean-square radii of the Sn isotopes (H.Lenske).



Softening of the nuclear potential:

High-l pushed upward and

Spin-Orbit splitting reduced

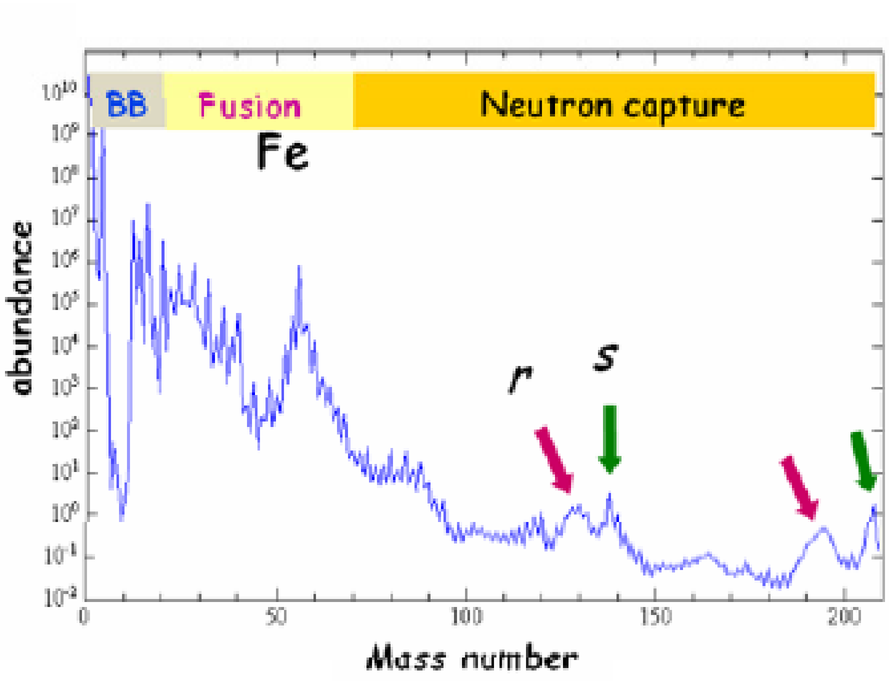


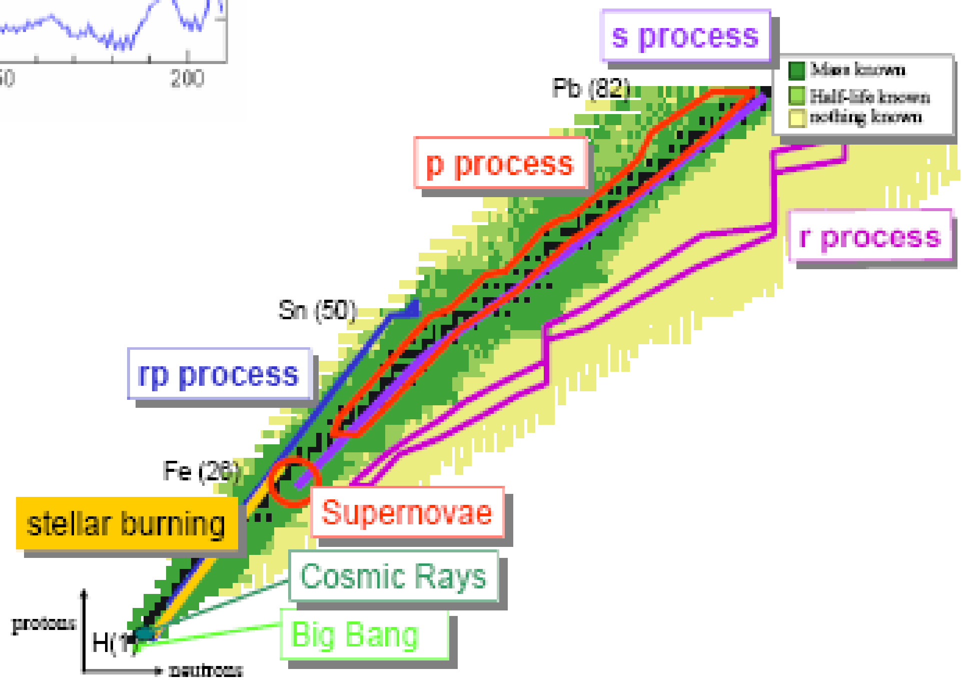
Shell quenching and reordering:

Transition from SO gaps (50,82,126)

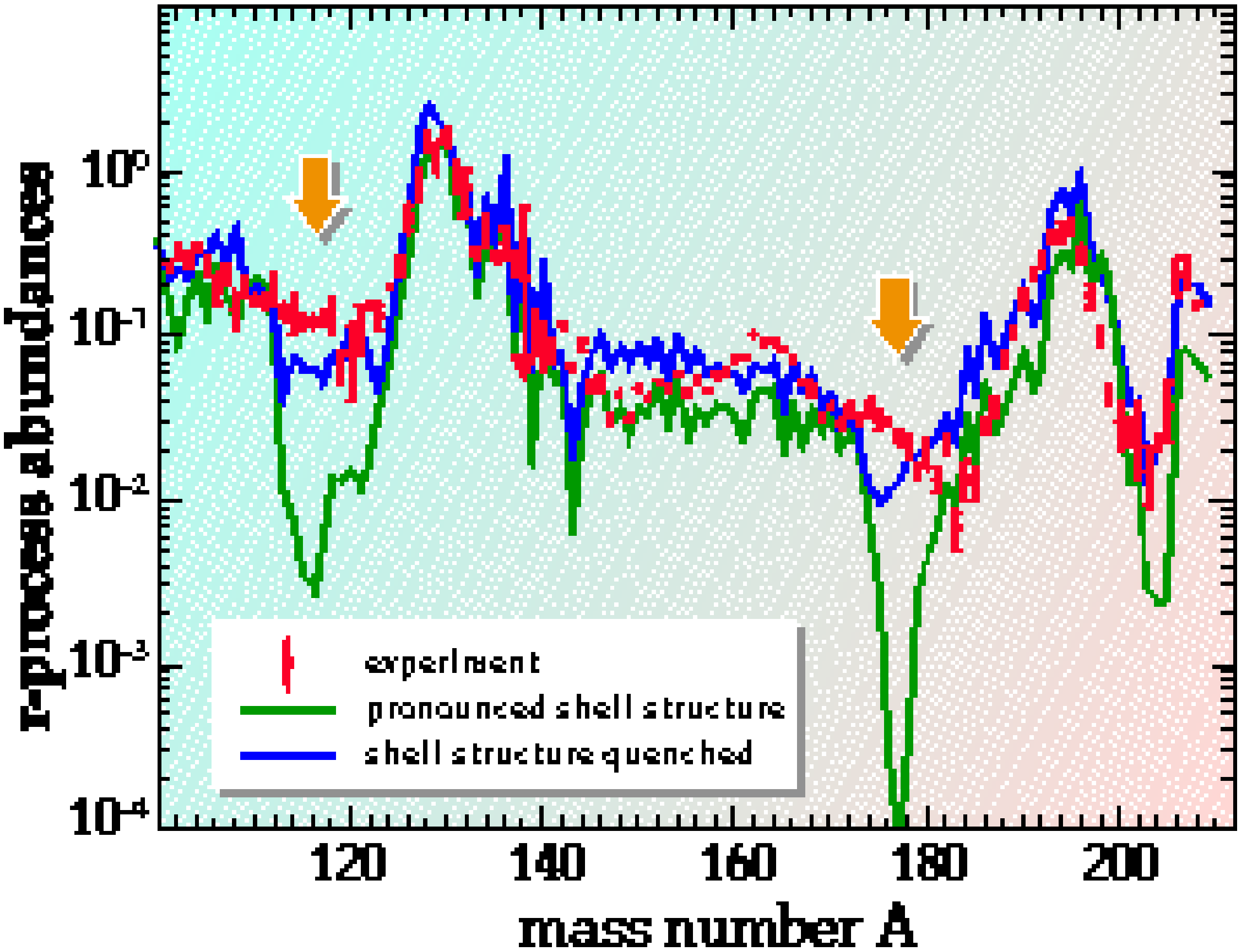
to HO gaps (40,70,112)

Origin of the elements: astrophysical r-process





r-process abundances: effect of quenching spin-orbit term



To Summarize:

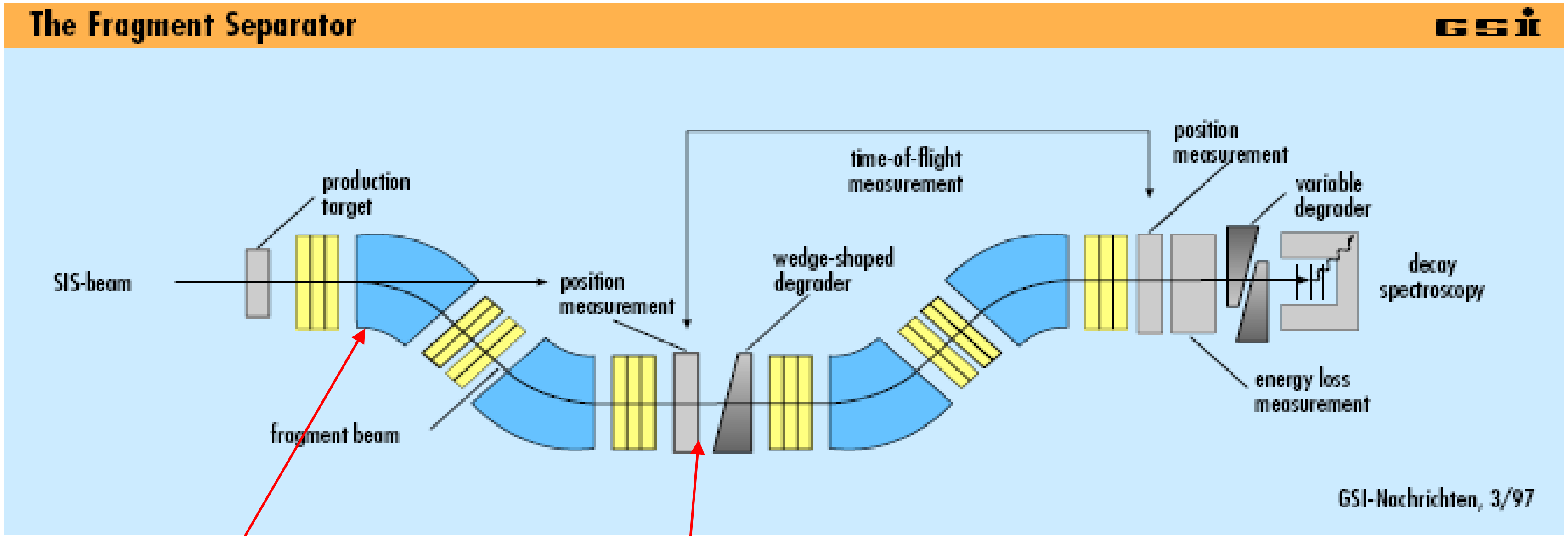
The Shell Model of the Text Books is wrong!

Radio-Active Beams will help us probe nuclear structure better

Producing Radioactive Beams:

(i) In-flight isotope separation

Relativistic Primary Beam: reaction products - “fragments”-
all fully stripped and traveling at nearly the original beam velocity (40 – 1000 MeV/u)

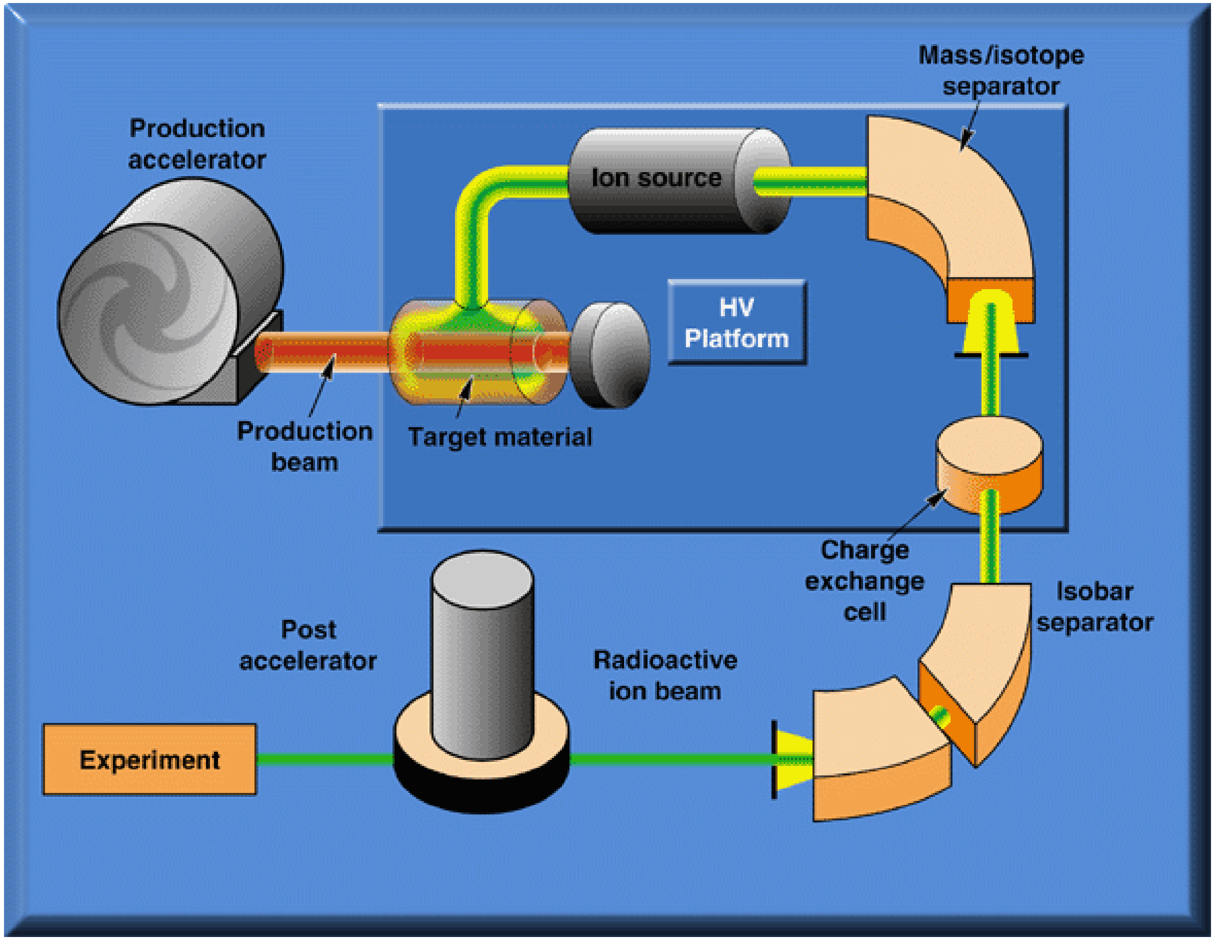


$$\frac{m}{q} \propto B\rho$$

$$Z^2 = q^2 \propto \frac{dE}{dx}$$

ii) Isotope Separation Online (ISOL)
ISOLDE (CERN)

From HRIBF, Oak Ridge



Rough figure of merit is the total power on Target.

i.e. Beam energy X Current

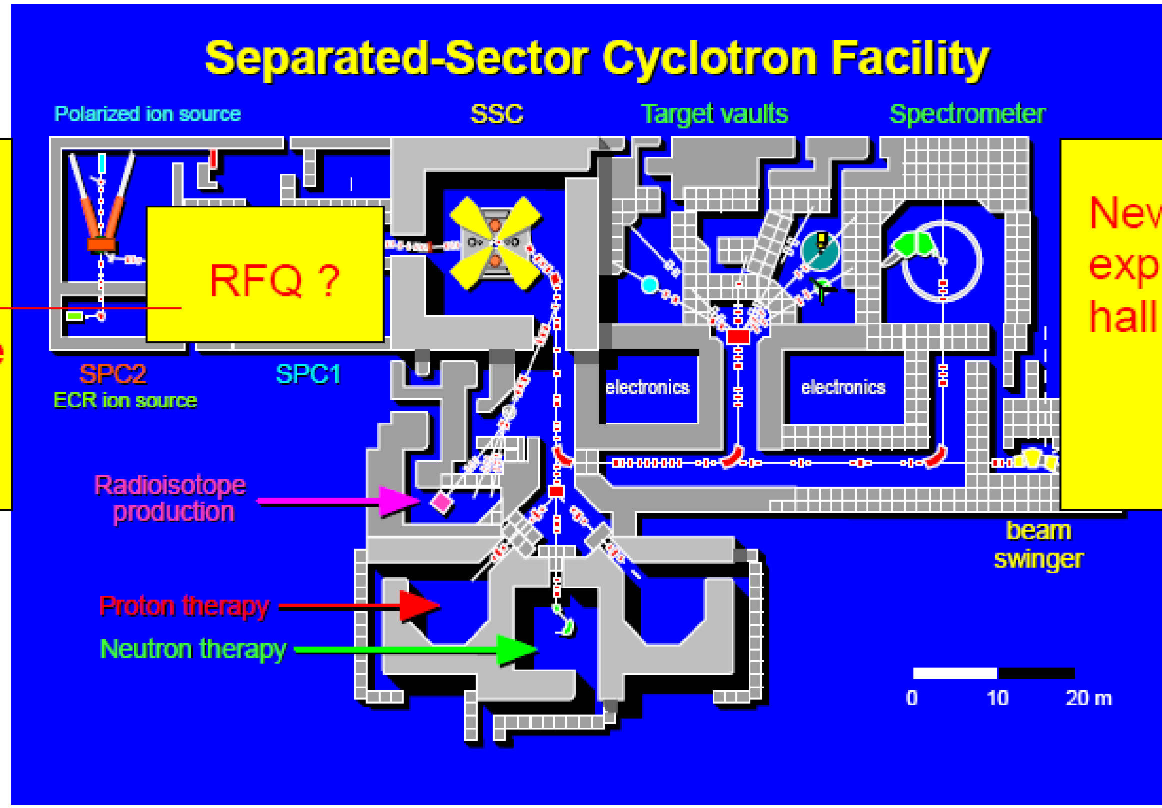
e.g. 1μA of 1 MeV beam =1 Watt

70 kW (1mA)
140 kW (2mA)

Fixed en.
K=70 PSI
Cyclotron
2mA

ISOL
tgt &
source

New
Isotope
Production



New
exp.
hall

Figure 8 ISOL Option 3: New primary accelerator, SSC as post-accelerator

(Like SPES at Legnaro € 43M 8kW(?))

Table 3.1

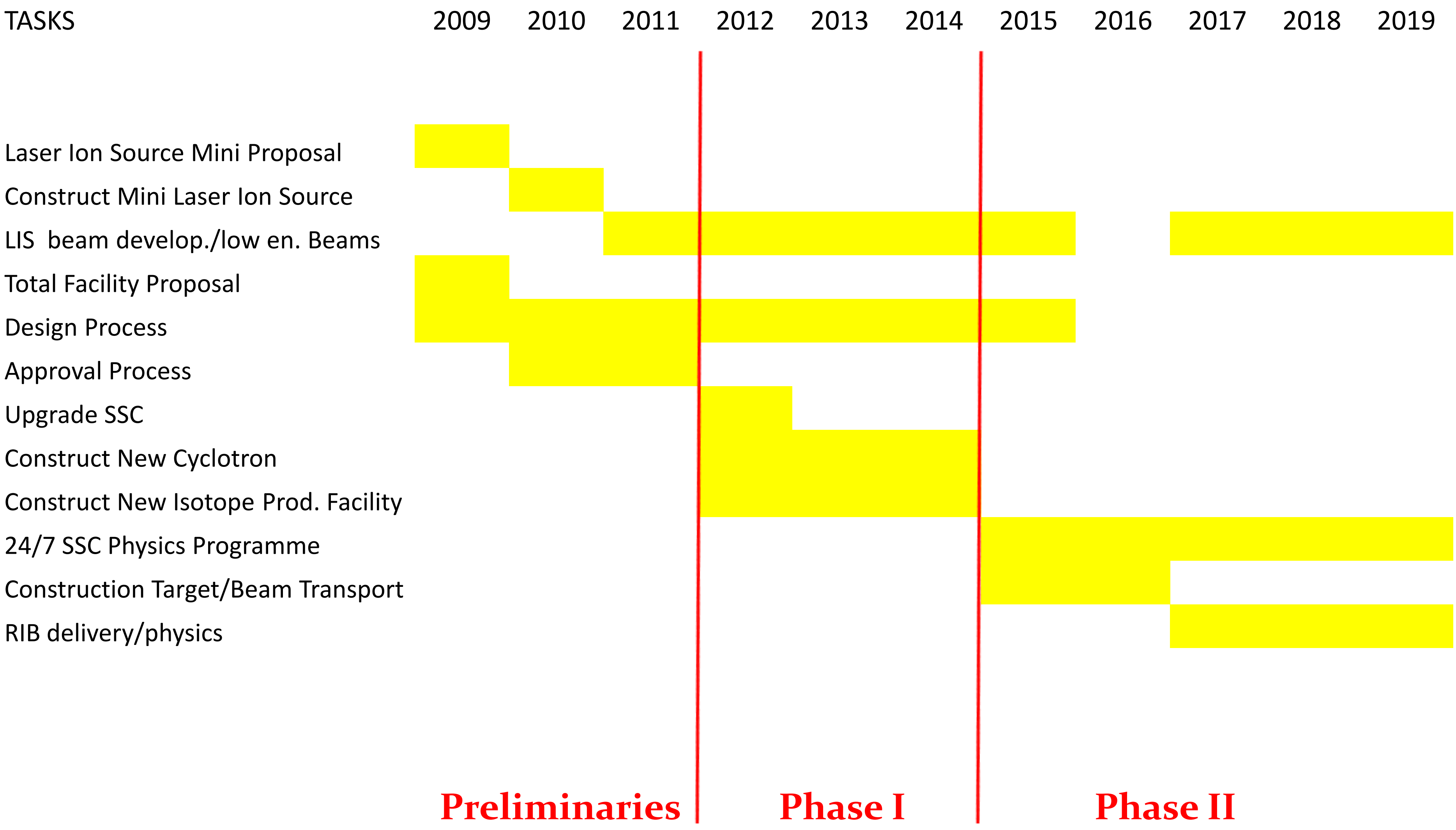
	Primary beam	Power on target	target	Fission s^{-1}	Reaccelerator	AMeV A=130 20+	^{132}Sn rate
ISOLDE	p 1-1.4 GeV 2 mA	0.4 kW	Direct&Conv	$4 \cdot 10^{12}$	Linac	3	10^7
HRIBF	p 40 MeV 10 μA	0.4 kW	Direct	$4 \cdot 10^{11}$	Tandem 25MV	4	$2 \cdot 10^5$
TRIAC	p 30 MeV 3 μA	0.9 kW	Direct	10^{11}	IH Linac	1	$3\ 10^5$
HIE ISOLDE upgrade			Direct&Conv	$4 \cdot 10^{12}$	SC Linac	5-10	$2 \cdot 10^8$
HRIBF up-grade	p 54 MeV 20 μA	1.8 kW	Direct	10^{12}	Tandem 25MV	4	$5 \cdot 10^5$
SPIRAL2	d 40 MeV 5mA	200 kW	Convert.	10^{14}	Cyclotron	6	$2 \cdot 10^9$
SPES	p 40 MeV 200 mA	8 kW	Direct	10^{13}	SC Linac	10	$3 \cdot 10^8$
SPIRAL	C-Kr 95 AMeV	6 kW	Direct		Cyclotron		
TRIUMF	p 450 MeV 70 mA	17 kW	Direct		SC Linac		
CRC UCL	p 30 MeV 300 mA	9 kW	Direct		Cyclotron		
EXCYT	13C 45 AMeV	0.5 kW	Direct		Tandem 15MV		

Costs

Table 14.2

	2008	2009	2010	2011	2012	2013	
							k€
infrastrutture	220	620	5000	8000	700	300	14840
target	1500	1300	1000	750	1050	300	5900
Beam Transfer	400	2350	2100	2000	650	150	7650
safetyRadioprot	250	110	750	2800	1800	290	6000
Cyclotron		2000	2000	2000	1000	1400	8400
Re-accelerator	900	2700	3000	300	100		7000
High Intensity Linac	300	200	1600	700	500	300	3600
Neutron Facility BNCT - LENOS	550	850	500	550	650	200	3300
	4120	10130	15950	17100	6450	2940	56690

iThemba Timeline – Phased Approach



TASK	sub task	iThemba	External
Development of Stakeholders	Creation & Support of Users	Directorate Physics MRG	
Commercial Case	Isotope Production	Isotope Production	NECSA
Political/Social Case	All	Directorate Physics	NECSA Univerities/Educational Instituitions PBMR ESKOM ……
Physics Case	Physics	Physics MRG	Universities
	HR Development	Physics MRG	Universities
Technical Case	RIB Development	Accelerator Group Physics Group Radiation Safety	Univerisities National Laser Centre NECSA?
	Detector Development	Accelerator Group Physics Group	Univerisities
	HR Development	Directorate Accelerator Group Physics Group MRG Isotope Production	Universities/Educational Institutions
	Finance	Directorate Accelerator Group Physics Group MRG Isotope Production Administration	

Educational Programs & Outreach

Science Awareness Programs:

G. Arendse

Interventions aimed at promoting an awareness and appreciation of science amongst learners (primary and secondary schools), teachers and the general public through interactive workshops, science shows, public lectures, and publications.

Training at iThemba LABS

	2005/06	2006/07	2007/08
1. Number of M.Sc and Ph.D. students currently using your Facility for their project work.	195	211	205
2 Number of M.sc. and Ph.D. students who used your facility that graduated during the last three years.	26	35	40
3. Number of publications in refereed journals in last three years	45	47	51
4. No. of international conference contributions in last three years.	72	81	56
5. No. of scientists from HEIs that used your facility in the last three years	225	282	278
6. No of scientists from Africa that were involved in research at your Facility in the last three years	45	63	53
7. No of international scientists from elsewhere who were involved in research at your Facility in the last thee years.	94	110	78

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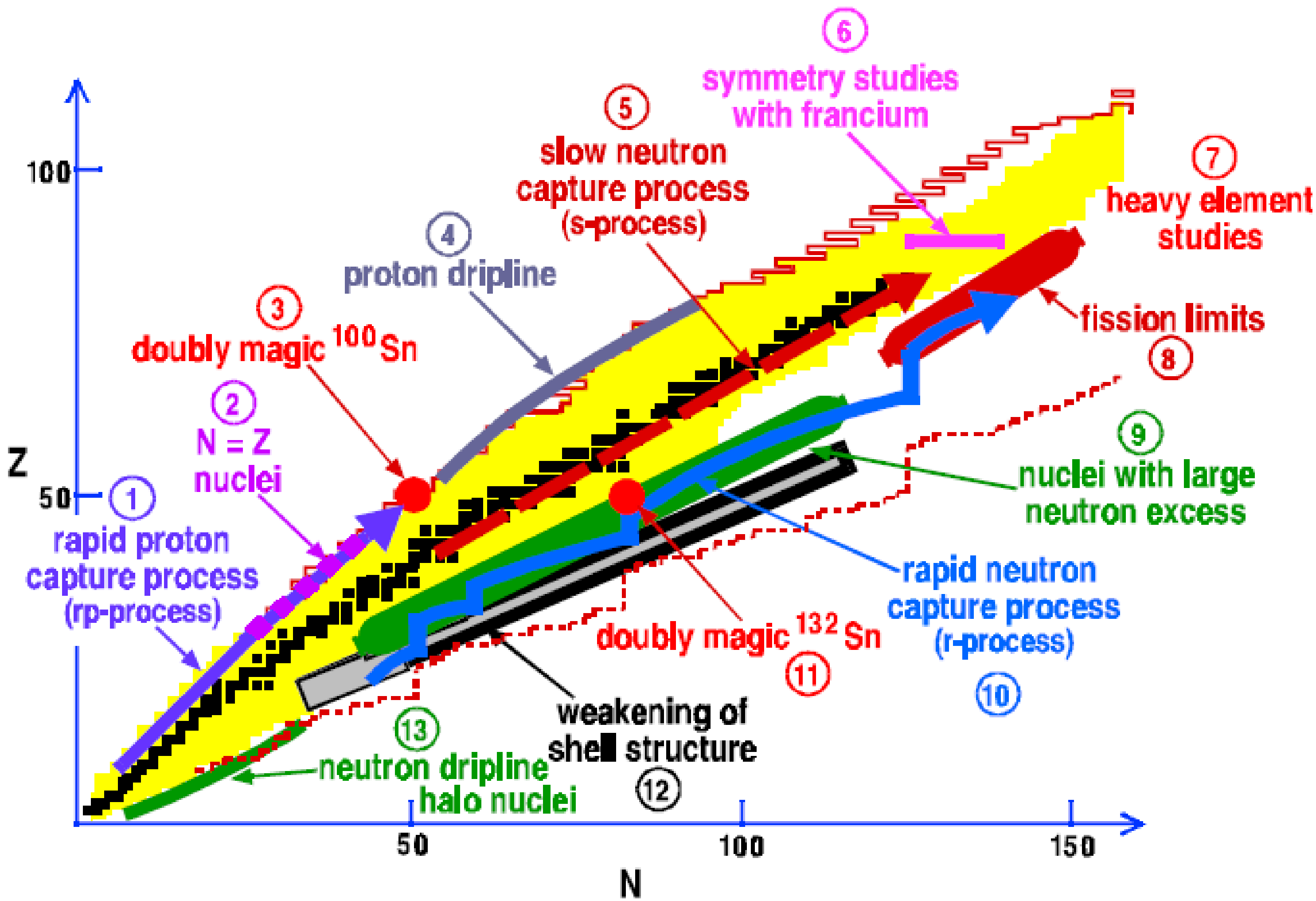
End of part I



6
symmetry studies
with francium
5
slow neutron
capture process
(s-process)
7
heavy element
studies
4
proton dripline
3
doubly magic 100 Sn
fission limits
8
2
N = Z
nuclei
9
nuclei with large
neutron excess
100
Z
50
1
rapid proton
capture process
(rp-process)
rapid neutron
capture process
(r-process)
doubly magic 132 Sn
11
10
weakening of
shell structure
13
neutron dripline
halo nuclei
12
50
100
150
N