The Abdus Salam International Centre for Theoretical Physics

2473-23

Joint ICTP-IAEA School on Nuclear Energy Management

15 July - 3 August, 2013

Nuclear Infrastructure for Research, Development and Applications II

D. Ridikas
IAEA, Vienna, Austria

Lecture 2

Nuclear Infrastructure for R&D and Applications: Accelerators

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IAEA
International Atomic Energy Agency

Outline

- Introduction
- Historical background
- Types of accelerators
- IAEA Data Base of Accelerators
- Selected applications of accelerators
- Examples of combined applications: RRs and Accelerators

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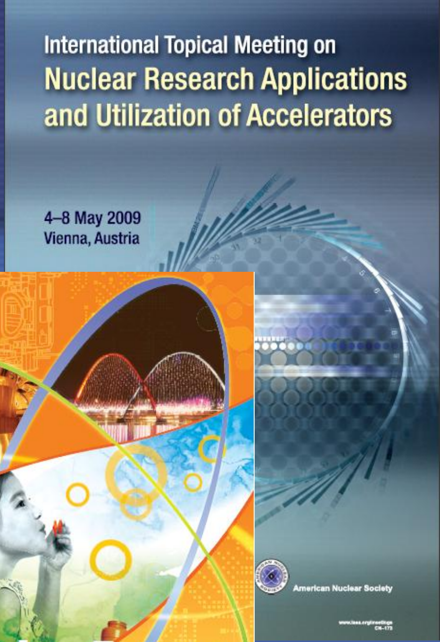
Major Activities within Physics Section

Assistance and support of Member States in the field of

1. **Accelerators**
2. **Research Reactors**
3. Controlled Fusion
4. Nuclear Instrumentation
5. Cross-cutting Material Research

Based on Member States needs, requests & recommendations

- Planning & implementation of P&B activities
- Proposal and implementation of CRPs
- Management of Data Bases
- Organization of Conferences, Technical & Consultancy Meetings
- Organization of ICTP workshops, training schools and courses
- Support of TC projects
- Promotion of Nuclear Sciences, Applications and Technologies



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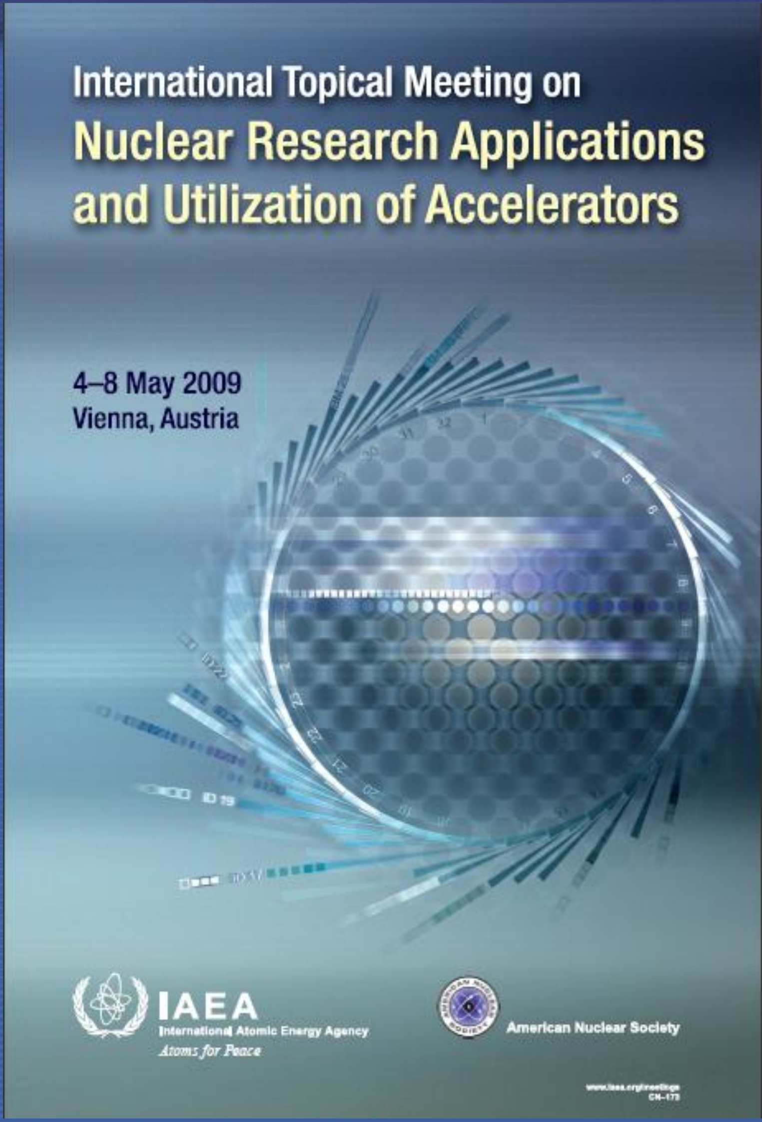
Topics addressed

- **Applications**
  - Simulation of radiation damage and testing of materials for nuclear systems;
  - Research and development of applications for advanced materials;
  - Different aspects of industrial accelerator applications;
  - Interdisciplinary endeavours.

- **Accelerator technology**
  - Operation, instrumentation and control;
  - New acceleration techniques;
  - Research and development

- **Accelerator Driven Systems (ADS)**
  - Innovative nuclear systems;
  - ADS experiments and test facilities;
  - Nuclear data.

- Topics dealing with purely radioisotope production or clinical applications were not intended to be covered!



http://www-pub.iaea.org/MTCD/publications/PDF/P1433_CD/datasets/foreword.html
http://accapp11.org/

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Historical background (>100 years!)

- In 1911 Rutherford used energetic α-particles from Ra and Th sources to investigate the inner structure of atoms. He demonstrated the existence of a positively-charged nucleus with a diameter of $<10^{-11}$ cm. Later in 1919, Rutherford also used α-particles to produce the first artificial nuclear reaction,

$$\alpha + N \rightarrow O + p$$

- The available intensity of the α-radiation from natural source was very weak and not collimated. But these two experiments were of extreme importance and demonstrated the demand for accelerators to supply high-intensity beams of charged particles with a well defined energy. In 1927 Rutherford called on physicists to build accelerators with sufficient energy to study nuclear reactions.

- In 1929, Robert Van de Graaff demonstrated a high voltage machine to accelerate particles. This accelerating machine was developed further for use in "atom-smashing" experiments.

It was quickly recognized that this accelerating machine had great potential for developing industrial and medical applications. Now, more than eight decades later, accelerators of many different designs have been developed.

Historical background evolution

The first accelerators were built to accelerate protons and electrons only.

Today, it is possible to accelerate ions from all elements of the periodic system and in many cases even as multi-charged ions. Furthermore, it is now possible to accelerate artificially produced positrons and antiprotons.

This impressive development has been possible only by repeated use of the following cycle:

New Idea → Improved Technology → Until Saturation

…and then again New Idea, etc. This pattern appears clearly from a modified Livingston diagram

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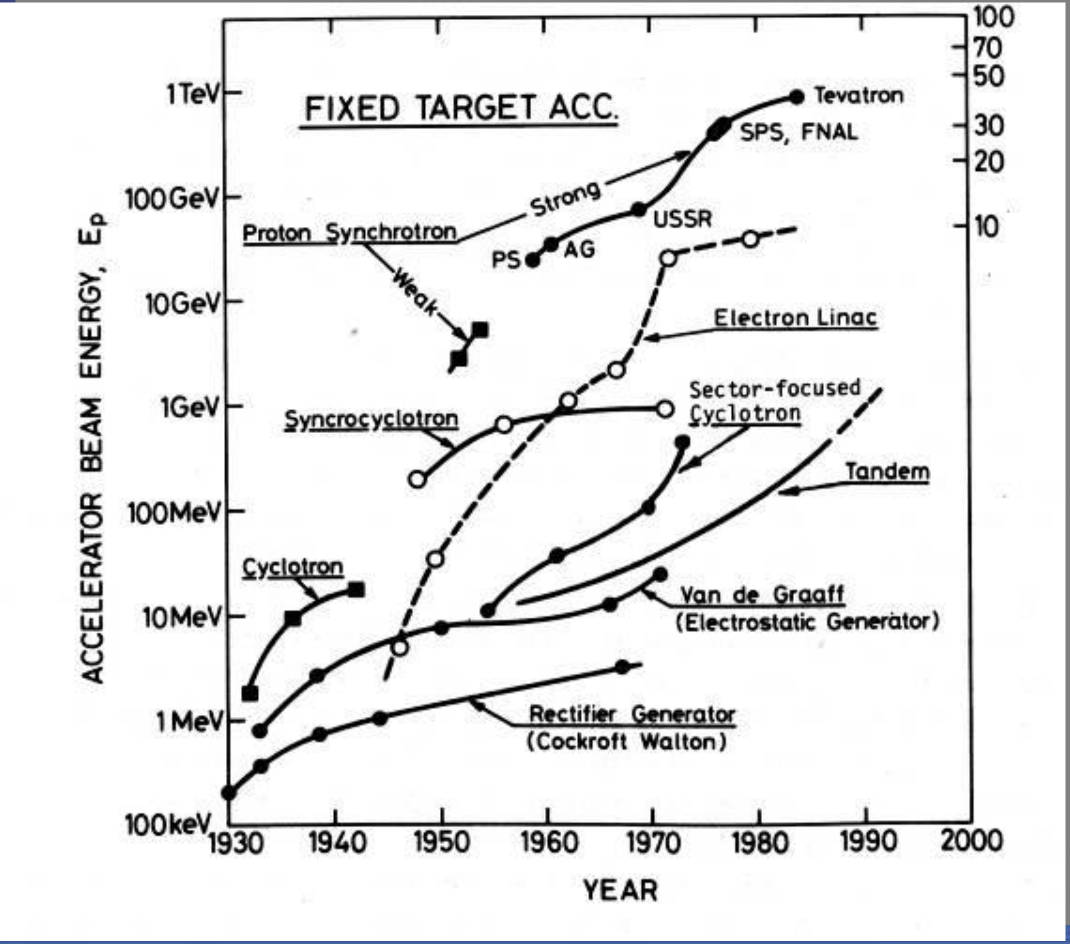
Historical background

A modified Livingston diagram



- Each point represents an accelerator & each line joins accelerators of a given type
- Each line represents a new accelerator technology
- At the beginning of each technology the chart shows a rapid increase in the achievable energy and then leveling off as that technology becomes fully exploited.
- Each technology is supplanted in turn by a new one having a similar historical profile.

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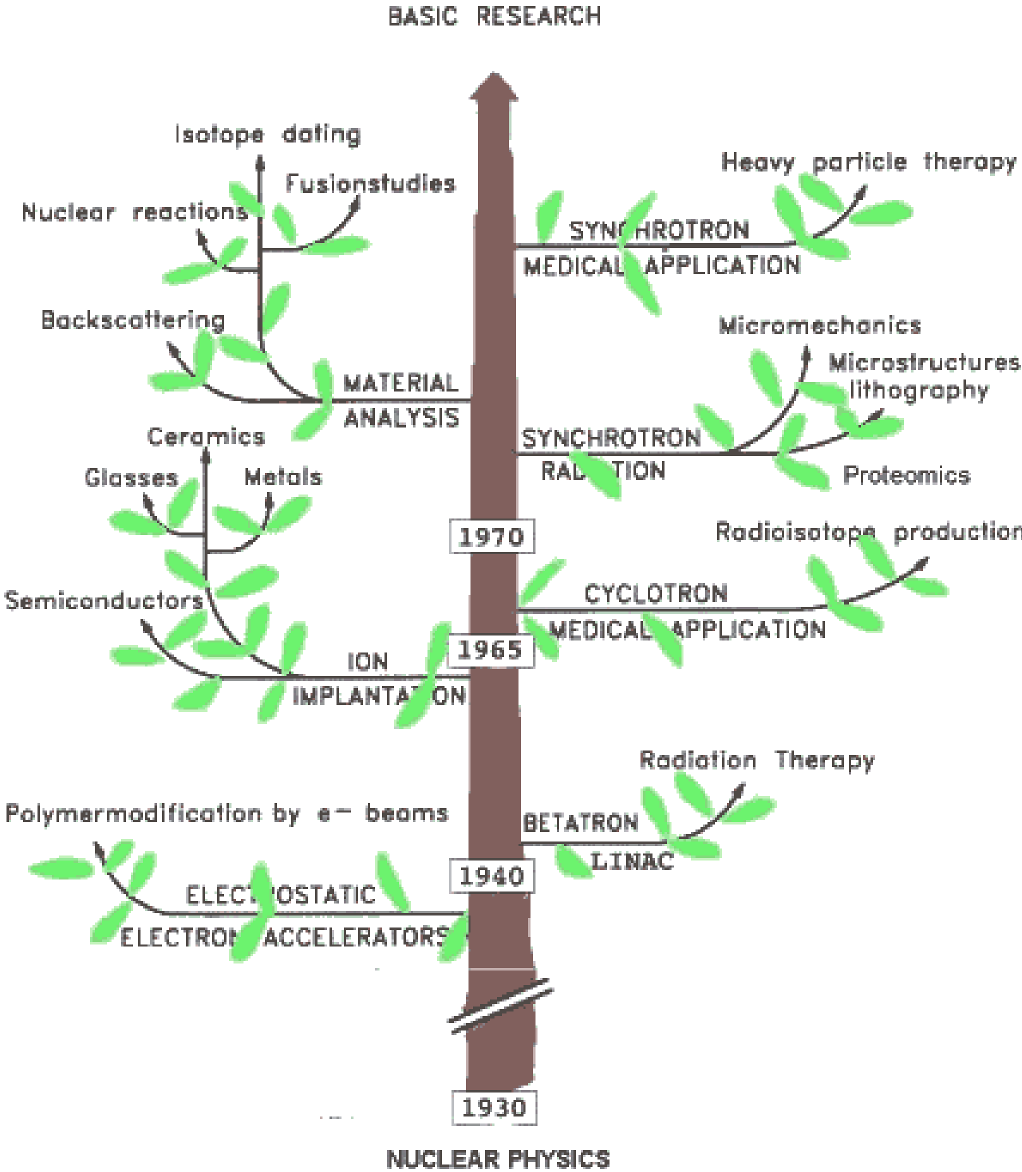
Accelerators: a tool for nuclear research



CATEGORY	NUMBER
Ion implanters and surface modification	~ 7,000
Radiotherapy	~ 5,000
Accelerators in industry	~ 1,500
Accelerators in non-nuclear research	~ 1,000
Medical isotopes production	~ 200
Research in nuclear sciences	~ 150
Synchrotron light sources	~ 70
Hadrontherapy	~ 20
TOTAL	**~ 15,000**

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Accelerators: types

1. In direct current accelerators particles are accelerated by applying a voltage difference, constant in time, with a value that determines the final energy of the particle.

2. In linear accelerator particles are successively accelerated in a large number of acceleration gaps between electrodes to which a high frequency voltage is applied. The energy gain in the gaps is a small fraction of the value of the final energy.

3. In cyclical accelerators magnets are used to return the particles again and again to the same acceleration gaps. Such accelerators are therefore in general more compact.

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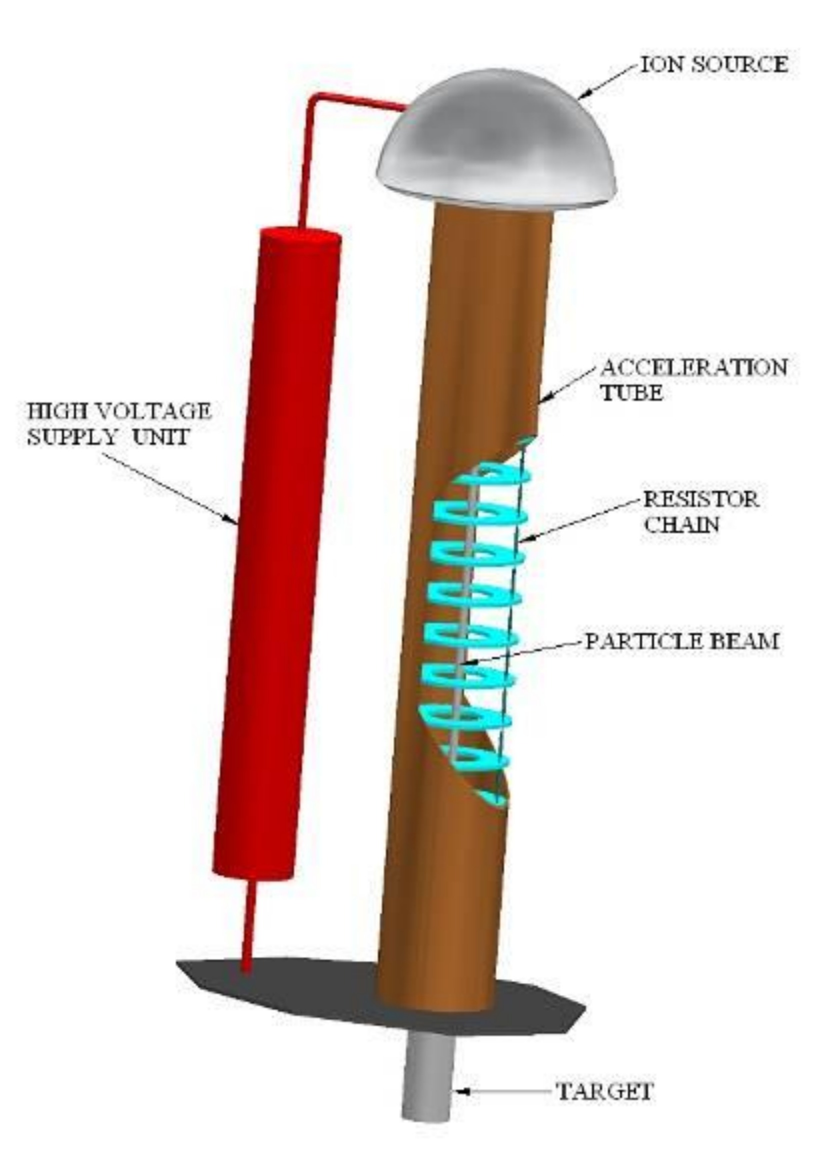
Direct-current Accelerators

The principle of a DC accelerator is shown in the figure. The voltage from a high voltage generator is connected to the accelerating tube, and the particles are accelerated in one step through the tube, which is constructed as a long drift tube with a number of electrodes along the axis giving a more or less uniform field distribution for acceleration



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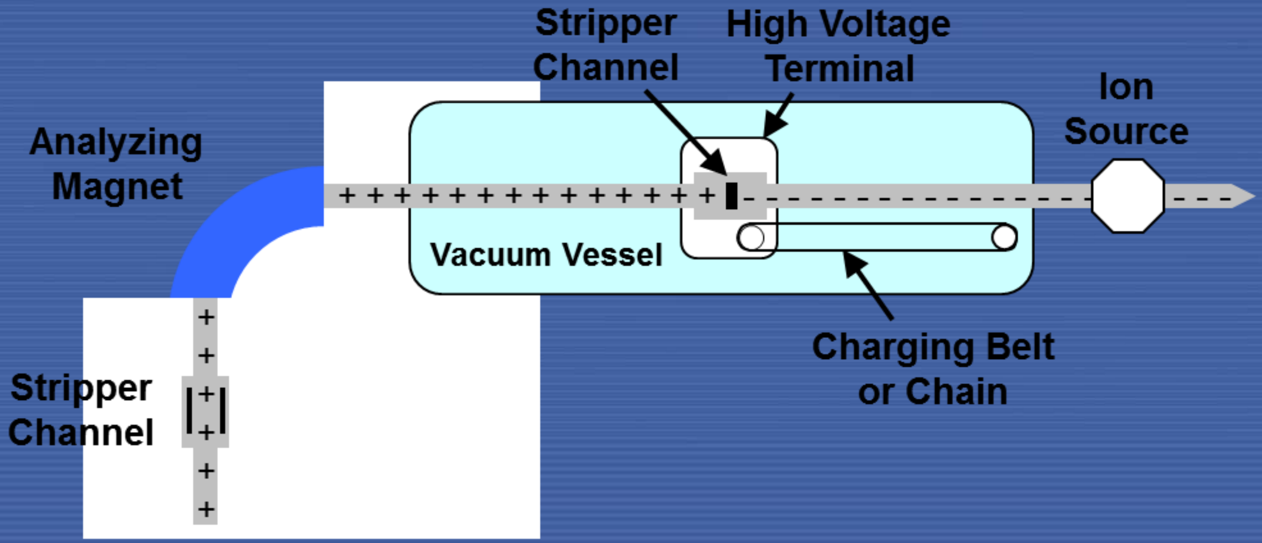
The Tandem Accelerator

A tandem Van de Graaff machine accelerates negatively charged particles towards a positively charged terminal. As the particle passes through the terminal, electrons are removed from the particle with a stripper. This causes the particle to become positively charged and is therefore accelerated away from the positively charged terminal. The high voltage terminal is therefore used to accelerate the ions twice (tandem).



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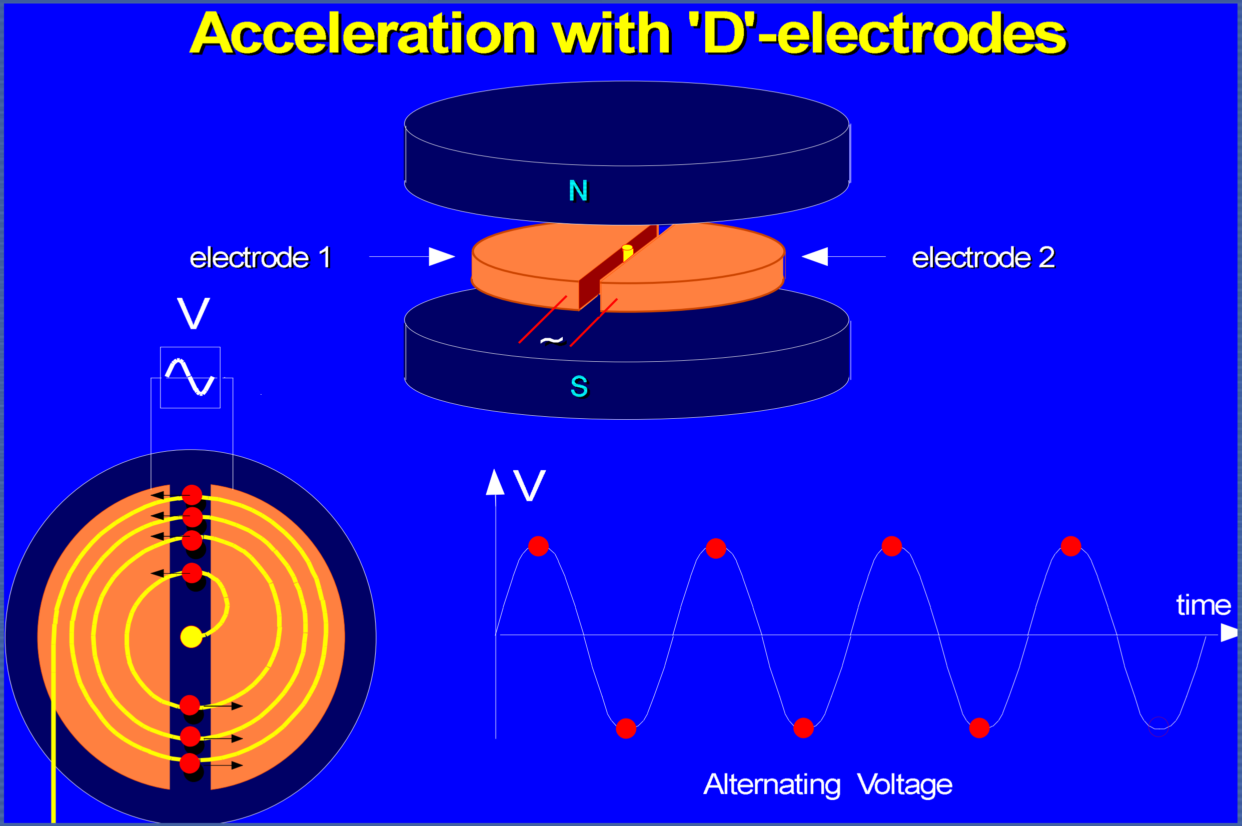
The Cyclotron Principle

An alternating voltage with a frequency equal to the orbital frequency of the particles is applied between the dees



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Multipurpose cyclotron accelerator from IBA

ion	extraction	E_{min}	E_{max}	I_{max}
		MeV	MeV	μA
H^-	stripping	30	70	750
D^-	stripping	15	35	50
H_2^+	ESD	-	35	50
α	ESD	-	70	50

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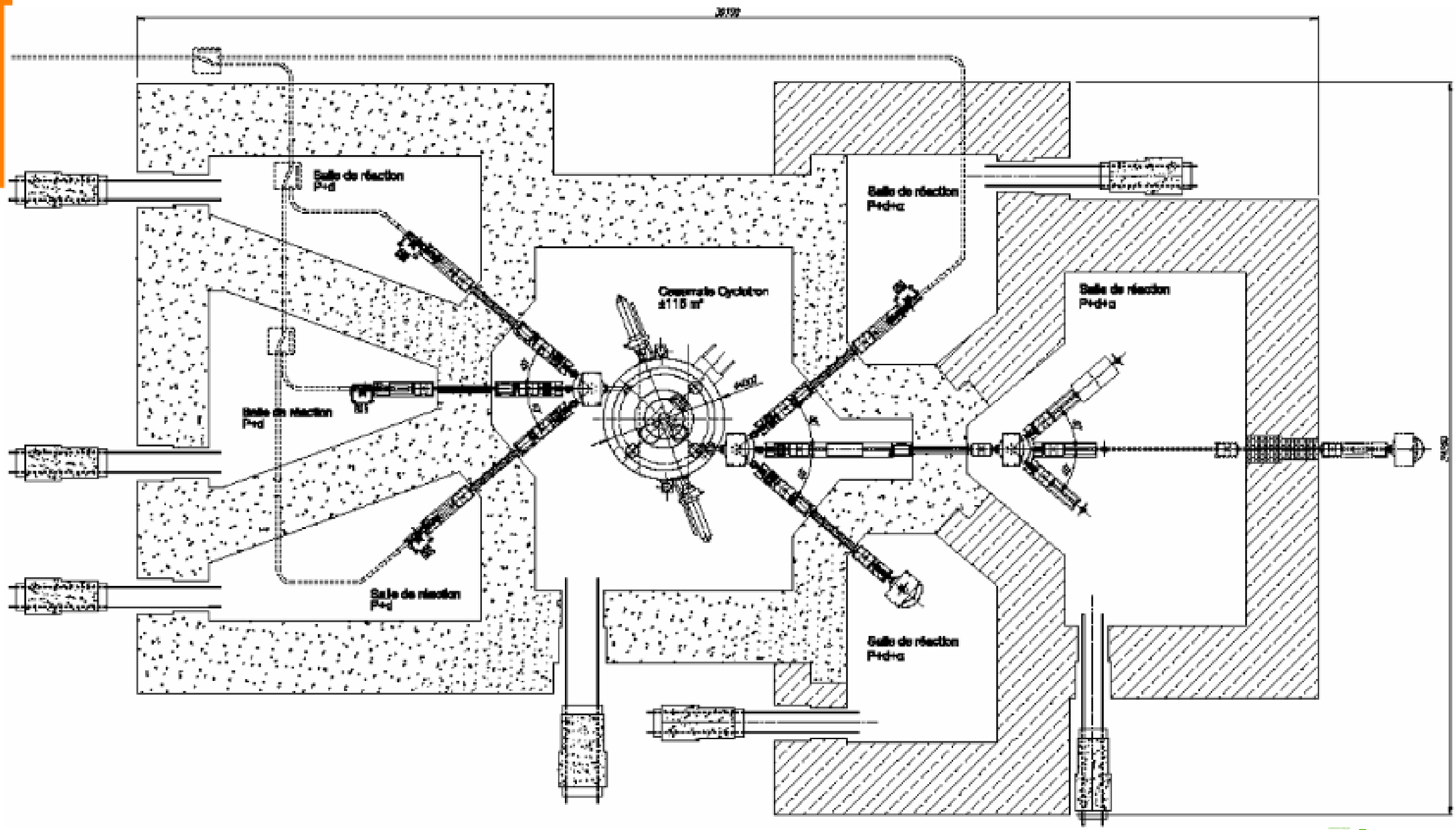
Beam Transport Lines



IBA Molecular

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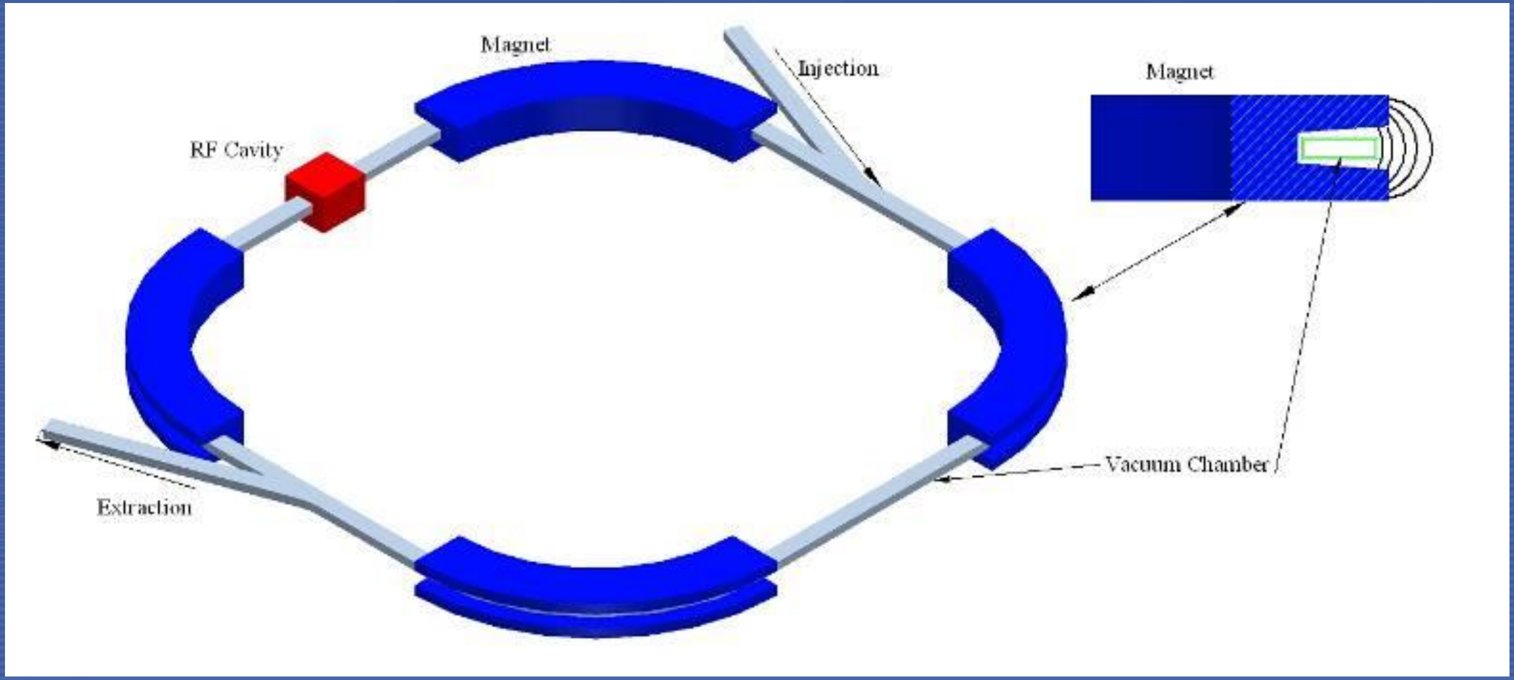
The Synchrotron principle

A linac can be used as an injector, and the massive magnet is replaced by a ring of magnets. An RF system is used for acceleration, and the magnetic field increases with energy in such a way that the radius is kept constant during acceleration. Since the magnetic field increases the frequency of the RF systems has to be increased simultaneously.



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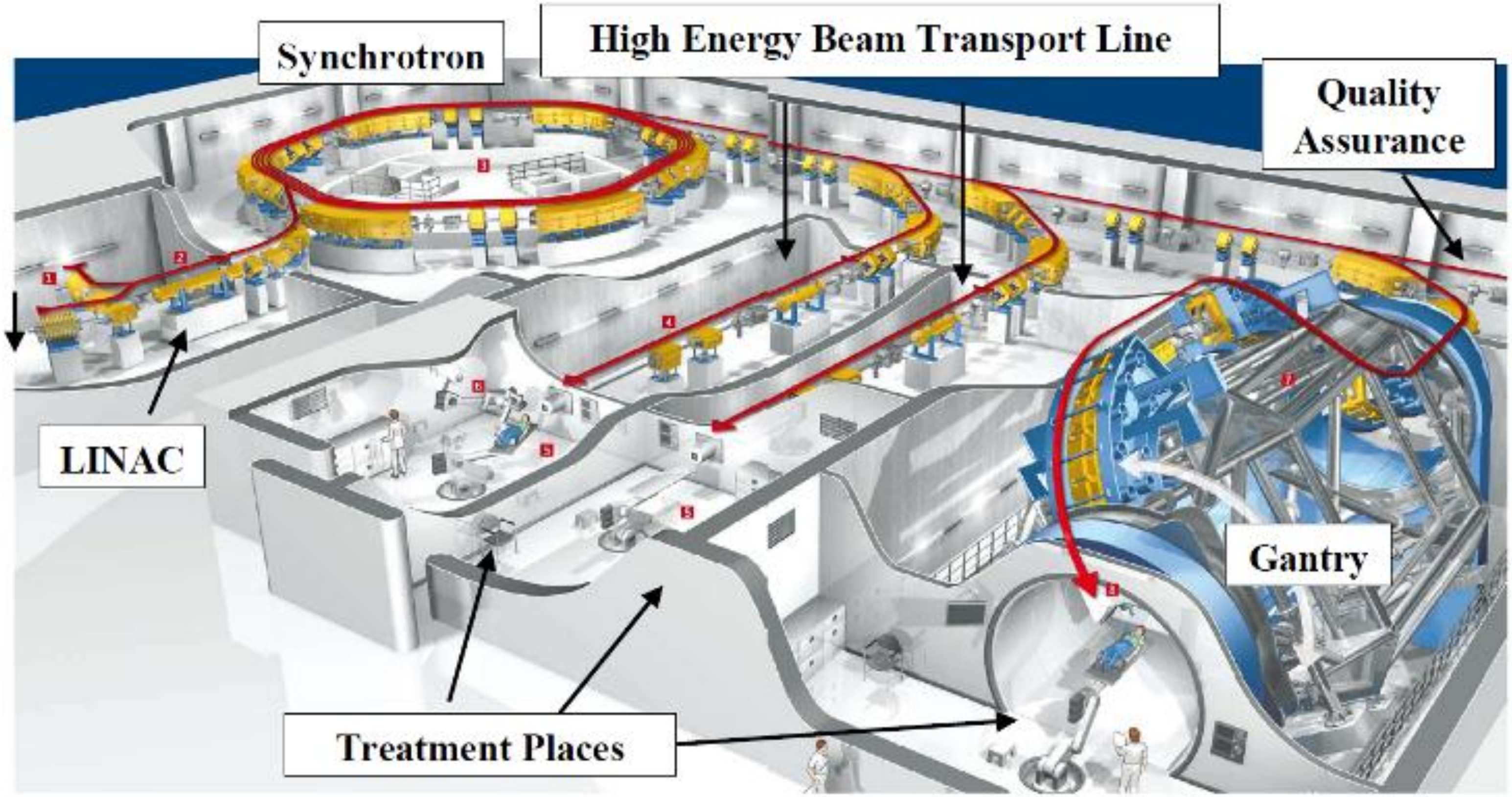
HIT HEIDELBERG



GSI accelerator design **First turn in the synchrotron Febr. 2007**
Commissioning of the facility in progress

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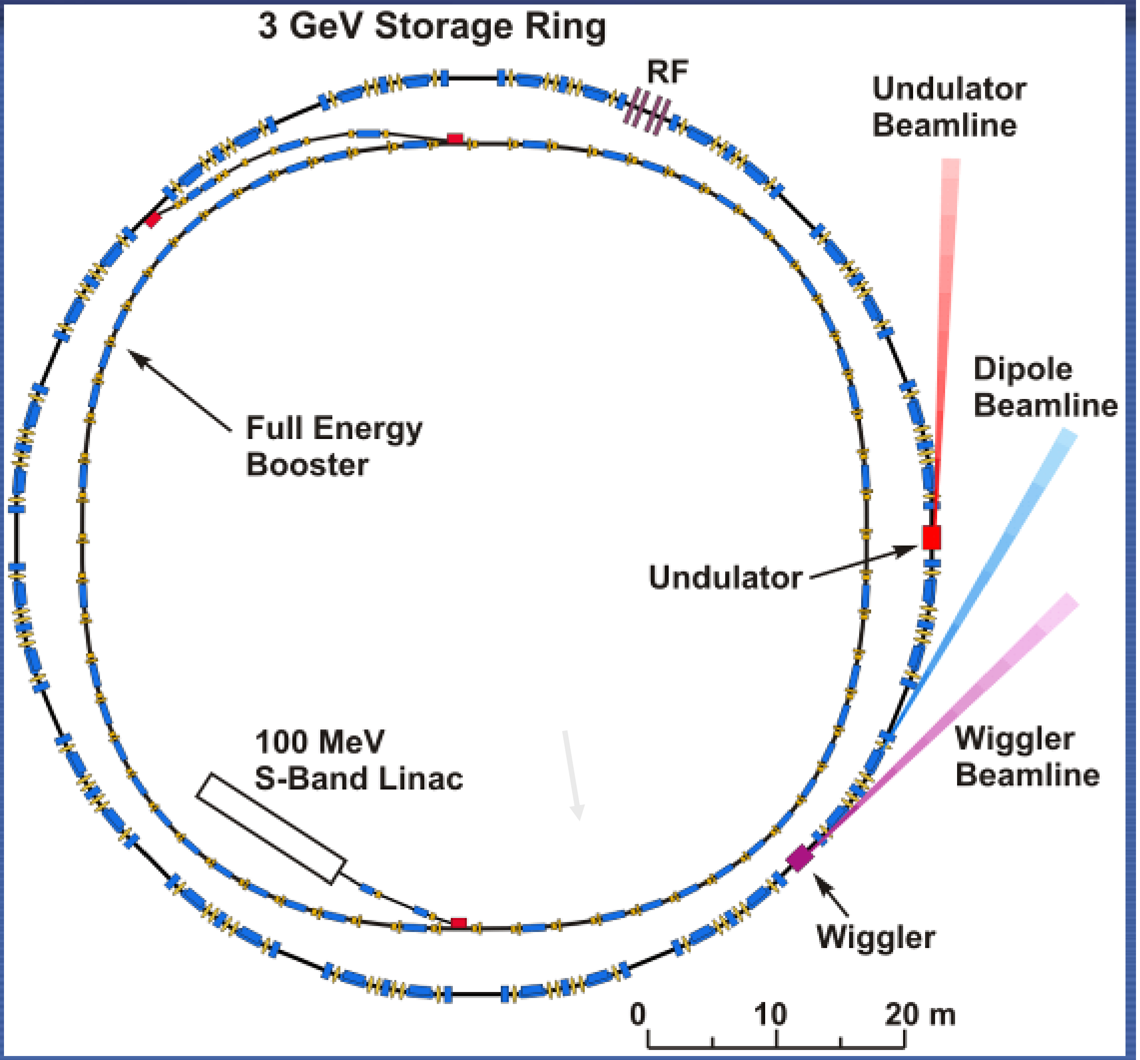
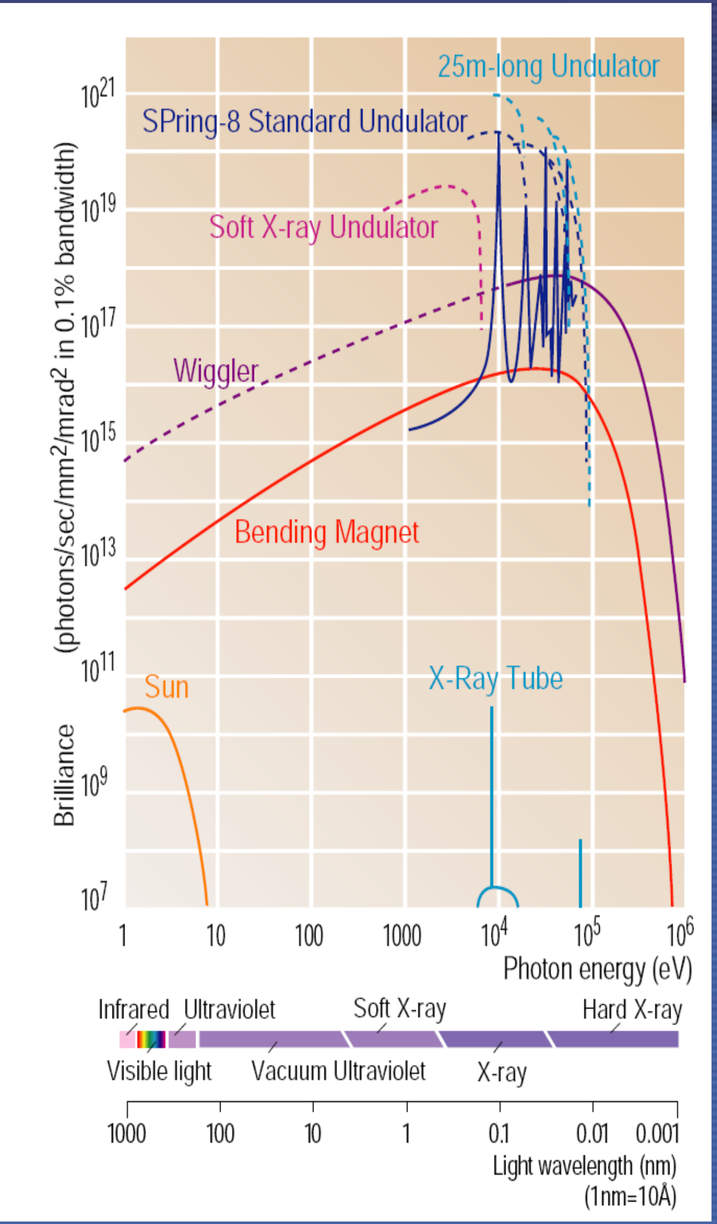
Synchrotron Light Source





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IAEA Accelerator Data Base

- Physics Section Database
- Foreword (Home)
- Accelerators
- Spallation Neutron Sources
- Synchrotron Light Sources
- Editorial Note

Home | Accelerators | Spallation Neutron Sources | Synchrotron Light Sources

Database of Ion Beam, Spallation Neutron and Synchrotron Light Sources in the World

Foreword

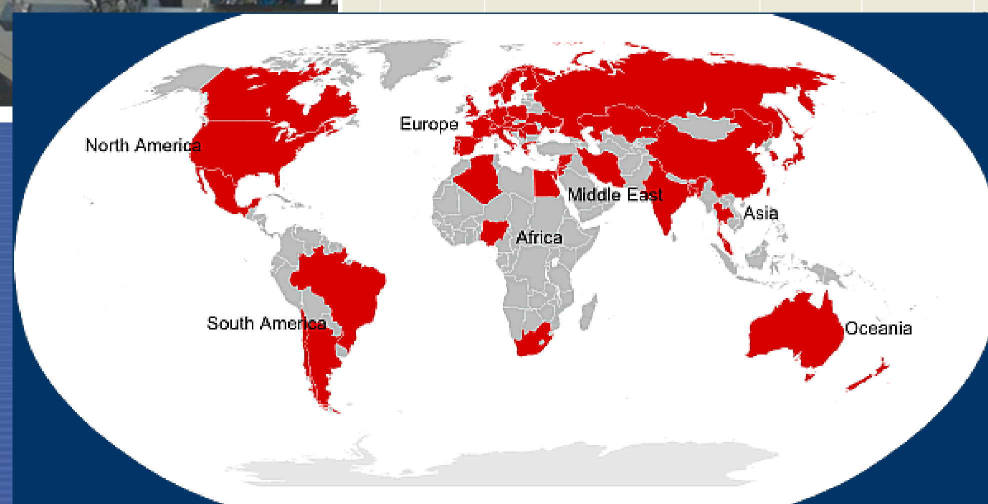
The Database of Ion Beam, Spallation Neutron Sources and Synchrotron Light Sources in the World contains technical information on accelerator-based radiation facilities used for applied research and analytical services in IAEA Member States. The database is compiled using information publicly available from IAEA databases, research institutes in Member States and accelerator manufacturers. The IAEA makes no warranties, either express or implied, concerning the accuracy, completeness, reliability, or suitability of the information.

The database organises the accelerator-based radiation facilities into three categories: low-energy electrostatic (ion beam) accelerators, spallation neutron sources and synchrotron light sources. Included are geographical maps of the global distribution of these facilities and as well as individual entries in Member States.

Home | Accelerators | Spallation Neutron Sources | Synchrotron Light Sources

All Accelerators

No.	Country	Organisation	City	Accelerator Type	Description	Voltage
1	Algeria	Centre de Recherche Nucleaire d'Alger	Algiers	Single-ended	Van de Graaff	3.75 MV
2	Argentina	Comisión Nacional de Energía Atómica	Buenos Aires	EN-FN-MP-UD	20UD	20 MV
3	Australia	University of Melbourne	Melbourne	Single-ended	5U	5 MV
4	Australia	Australian National University	Canberra	EN-FN-MP-UD	14UD	14 MV
5	Australia	Australian National University	Canberra	Pelletron	5SDH-4	1.7 MV
6	Australia	Australian Nuclear Science and Technology Organisation	Sydney	EN-FN-MP-UD	FN	8 MV
7	Australia	Australian Nuclear Science and Technology Organisation	Sydney	Tandetron		2 MV
8	Australia	Australian National University	Canberra	Pelletron	5SDH	1.7 MV
9	Austria	VERA - Vienna Environmental Research Accelerator	Vienna	Pelletron	9SDH-2	3 MV
					Insulated IS	400kV
					n de Graaff	3 MV
					DH-2	1.7 MV
						2 MV
					D	8 MV



Accelerators: 163

Spallation n-sources: 9

Light synchrotrons: 38

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http://www-naweb.iaea.org/napc/physics/accelerators/database/datasets/foreword_home.html

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Industrial applications of accelerators (1)

- **Industrial processes using electrons**

Industries	Processes	Products
Chemical	Cross-linking	Polyethylene
Petrochemical	Depolymerization Grafting Polymerization	Polypropylene Co-polymers Lubricants
Electrical	Cross-linking Heat shrink memory Semiconductor modification	Building Instruments Telephone wires, power cables, insulating tapes, shielded cable splices, Zener diodes, ICs, SCRs
Coatings adhesives	Curing Grafting Polymerization	Adhesive tapes Coated paper products Wood/plastic composites, veneered panels, thermal barriers
Plastics	Cross-linking	Food shrink wrap
Polymers	Foaming Heat shrink memory	Plastic tubing and pipes Moulded packaging forms
Rubber	Vulcanization Green strength Graded cure	Tyre components Battery separators Roofing membrane

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Industrial applications of accelerators (2)

- **Sterilization & disinfection**

Radiation effect	Dose requirements
Radiography (film)	1.0–10.0 mGy (0.1–1.0 rad)
Human lethal dose (LD_{50})	0.4–0.5 Gy (400–500 rad)
Sprout inhibition (potatoes, onions)	100–200 Gy (10–20 krad)
Potable water cleanup	250–500 Gy (25–50 krad)
Insect control (grains, fruits)	250–500 Gy (25–50 krad)
Waste water disinfecting	0.5–1 kGy (50–100 krad)
Fungi and mould control	1–3 kGy (100–300 krad)
Food spoilage bacteria	1–3 kGy (100–300 krad)
Municipal sludge disinfecting	3–10 kGy (300–100 krad)
Bacterial spore sterilization	10–30 kGy (1–3 Mrad)
Virus particle sterilization	1–30 kGy (1–3 Mrad)
Smoke scrubbing (SO_2 and NO_x)	10–30 kGy (1–3 Mrad)
Ageing of rayon pulp	10–30 kGy (1–3 Mrad)
Polymerization of monomers	10–50 kGy (1–5 Mrad)
Modification of polymers	50–250 kGy (5–25 Mrad)
Degradation of cellulose materials	100–500 kGy (10–50 Mrad)
Degradation of scrap Teflon®	0.5–1.5 MGy (50–150 Mrad)

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Industrial applications of accelerators (3)

- Radiation damage studies (materials + electronics)
- Ion implantation in semiconductor manufacture
- Surface hardening with ions
- Precision machining and membrane manufacture
- Positron Emission Tomography
- …

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Research applications of accelerators

- High energy physics
- Nuclear physics
- Astrophysics
- Material analysis with particle beams
    - Rutherford Backscattering
    - Particle Induced X-Ray Emission (PIXE)
    - Nuclear Reaction Analysis
    - Elastic recoil detection
    - Charged particle activation analysis
    - Accelerator Mass Spectrometry
    - Extended X-ray absorption of fine structure
    - …

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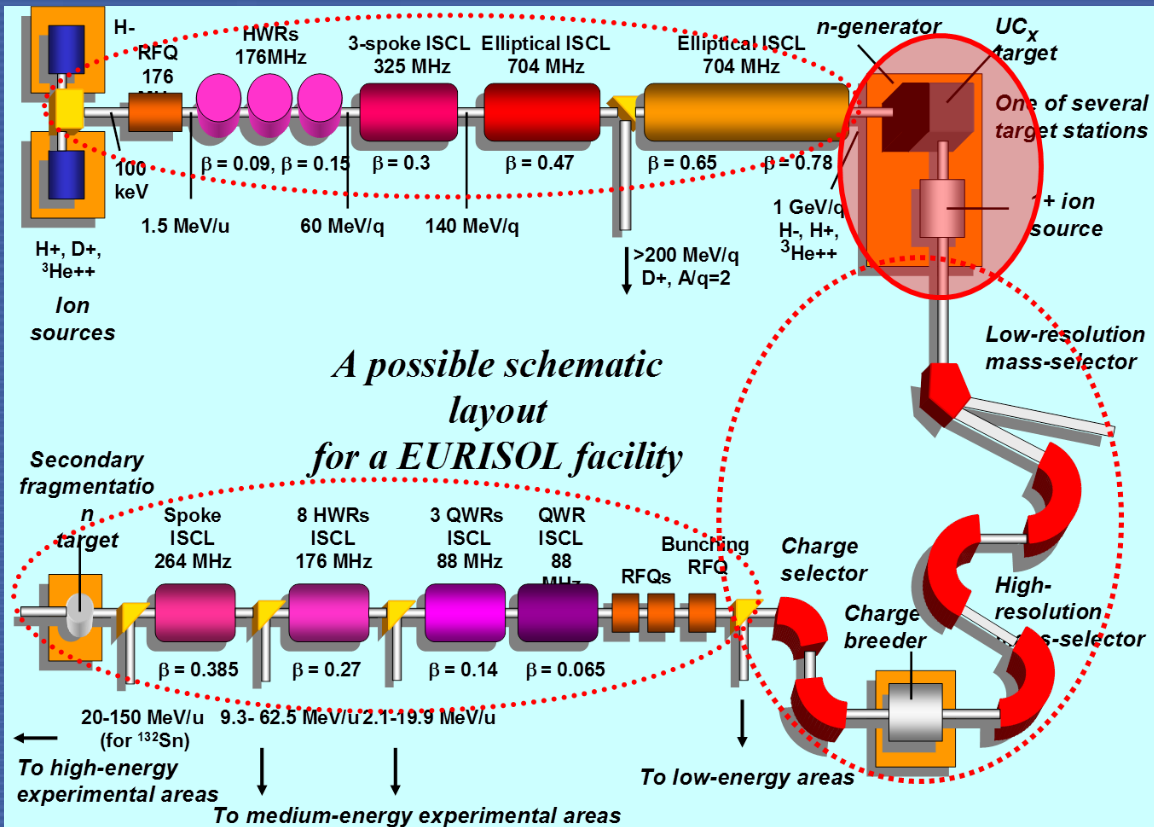
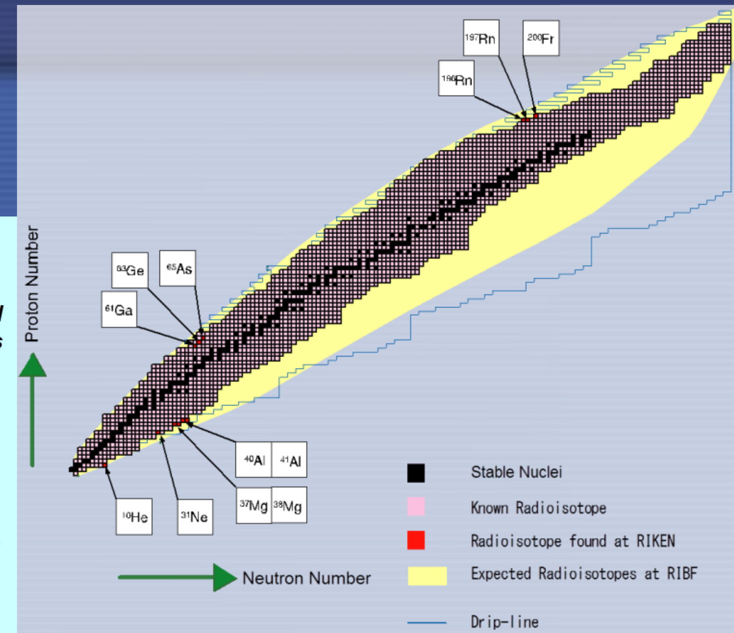
Radioactive Ion Beam (RIB) production





- Nuclear structure
- Astrophysics
- Nuclear drip-line, skins and halos
- Superheavy elements
- …

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Example: iThemba LABS & the NRF

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:

1. **Production of radioisotopes and radiopharmaceuticals** for use in nuclear medicine, research and industry and related research

2. **Treatment of cancer patients** with energetic neutrons and protons, including related research

3. **Research and training** in the physical, biomedical and material sciences

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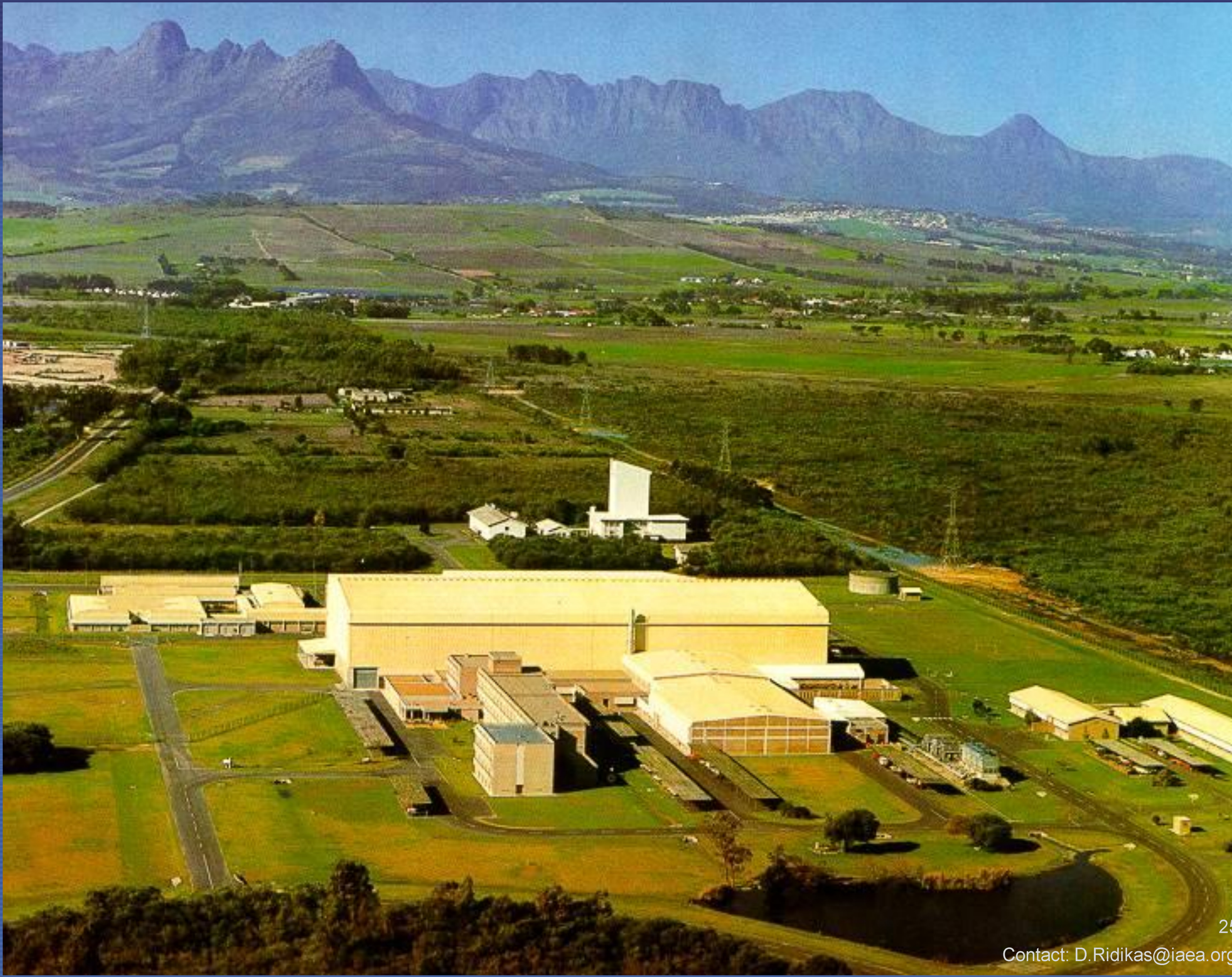

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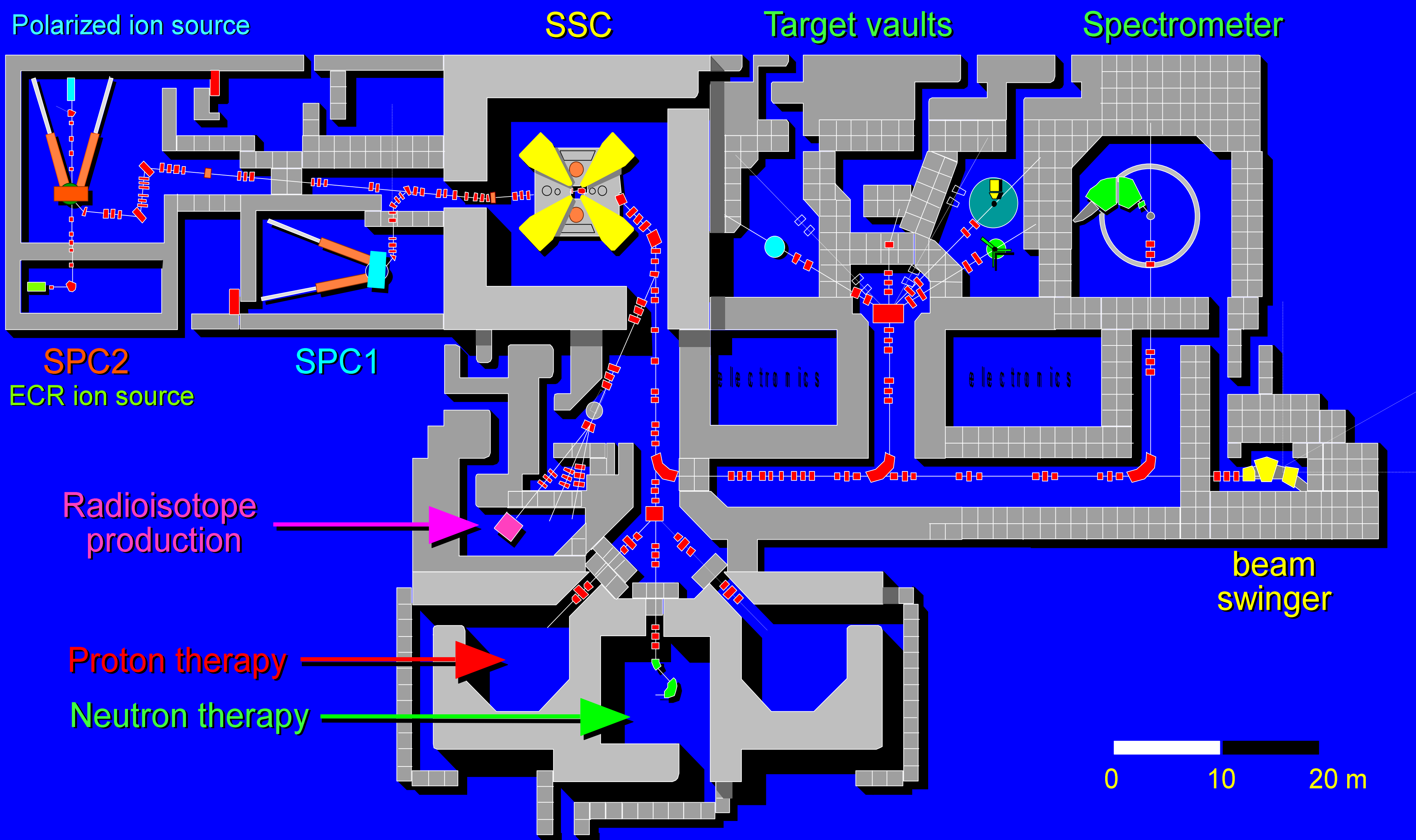
Separated-Sector Cyclotron Facility



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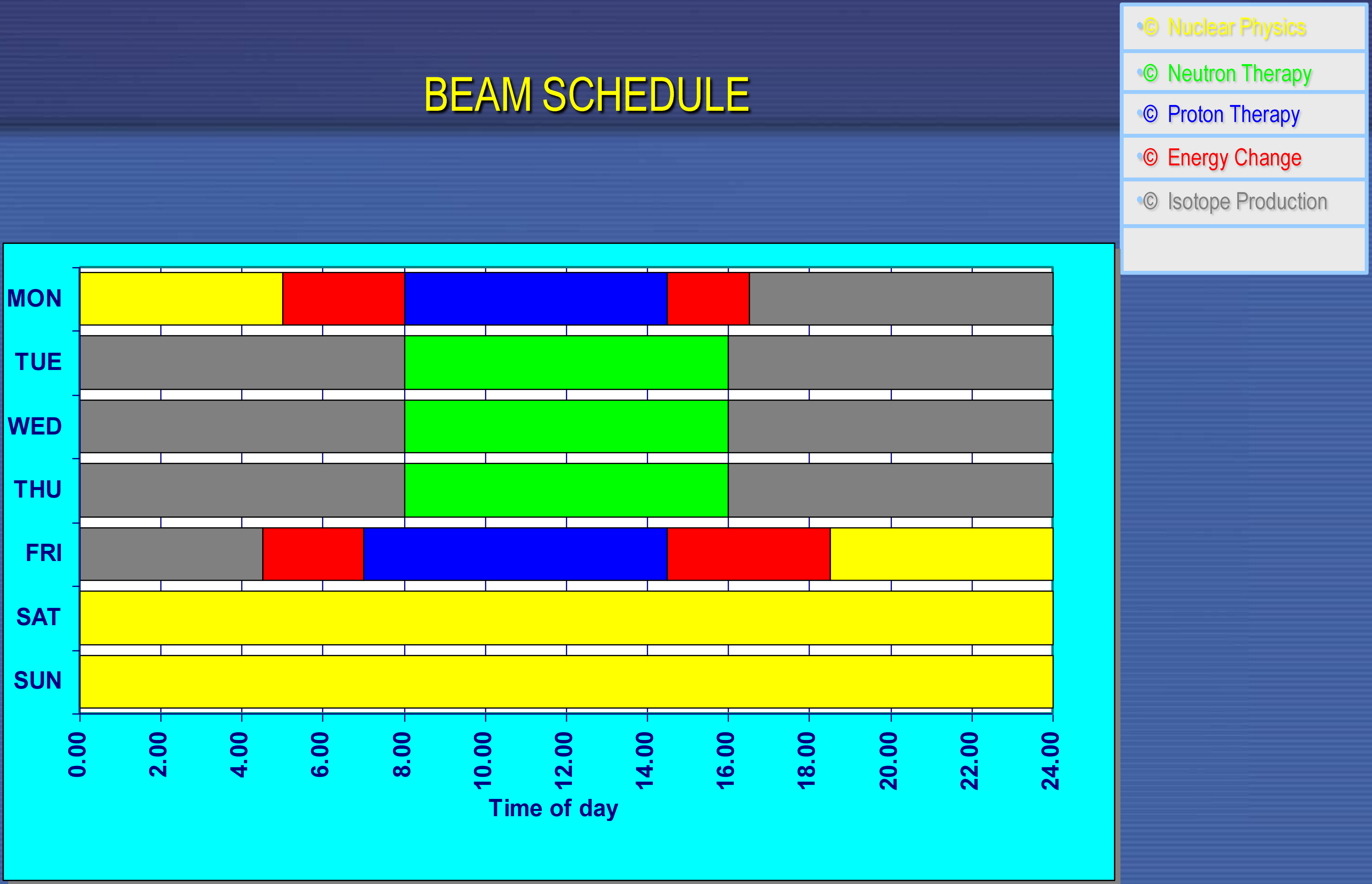
BEAM SCHEDULE



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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

Example:

66 MeV Proton Beam

Beam current on target: 250 µA

Transmission efficiency through the SSC: 99.8%

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Radioisotope production station & auxiliary facilities

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Radiopharmaceuticals currently in routine production

Radionuclide	Half-Life (hours)	Nuclear Reaction	Radiopharmaceutical Product	Main Use
^{18}F	1.83	$^{15}O(p,n)^{18}F$	^{18}F-FDG	Glucose metabolic studies
^{67}Ga	78.3	$Zn(p,xn)^{67}Ga$ $Ge(p,x)^{67}Ga$	^{67}Ga-citrate	Localization of certain tumours and inflammatory regions
$^{81}Rb/^{81m}Kr$	4.58	$Kr(p,xn)^{81}Rb$	$^{81}Rb/^{81m}Kr$ generator	Lung ventilation studies
^{123}I	13.2	$^{127}I(p,5n)^{123}Xe \rightarrow {}^{123}I$	^{123}I-sodium iodide ^{123}I-mIBG	Thyroid studies Localization of certain tumours such as neuroblastoma, pheochromocytoma

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Radiopharmaceuticals currently in routine production

Radionuclide	Half-Life (days/years)	Nuclear Reaction	Product	Main Use
^{82}Sr	25 days	$Rb(p,xn)^{82}Sr$	Produced as a radionuclide	Used to manufacture $^{82}Sr/^{82}Rb$ generators
^{68}Ge	271 days	$Ga(p,xn)^{68}Ge$	Produced as a radionuclide	Used to manufacture $^{68}Ge/^{68}Ga$ generators or used for calibration of gamma camera's or PET CT scanners
^{88}Y	106.6 days	$Sr(p,xn)^{88}Y$	Produced as a radionuclide	Non –medical application
^{109}Cd	453 days	$Ag(p,xn)^{109}Cd$	Produced as a radionuclide	Non-medical application
^{22}Na	2.602 years	$Mg(p,n)^{22}Na$	Produced as a radionuclide	Positron Annihilation Studies

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Neutron or proton therapy

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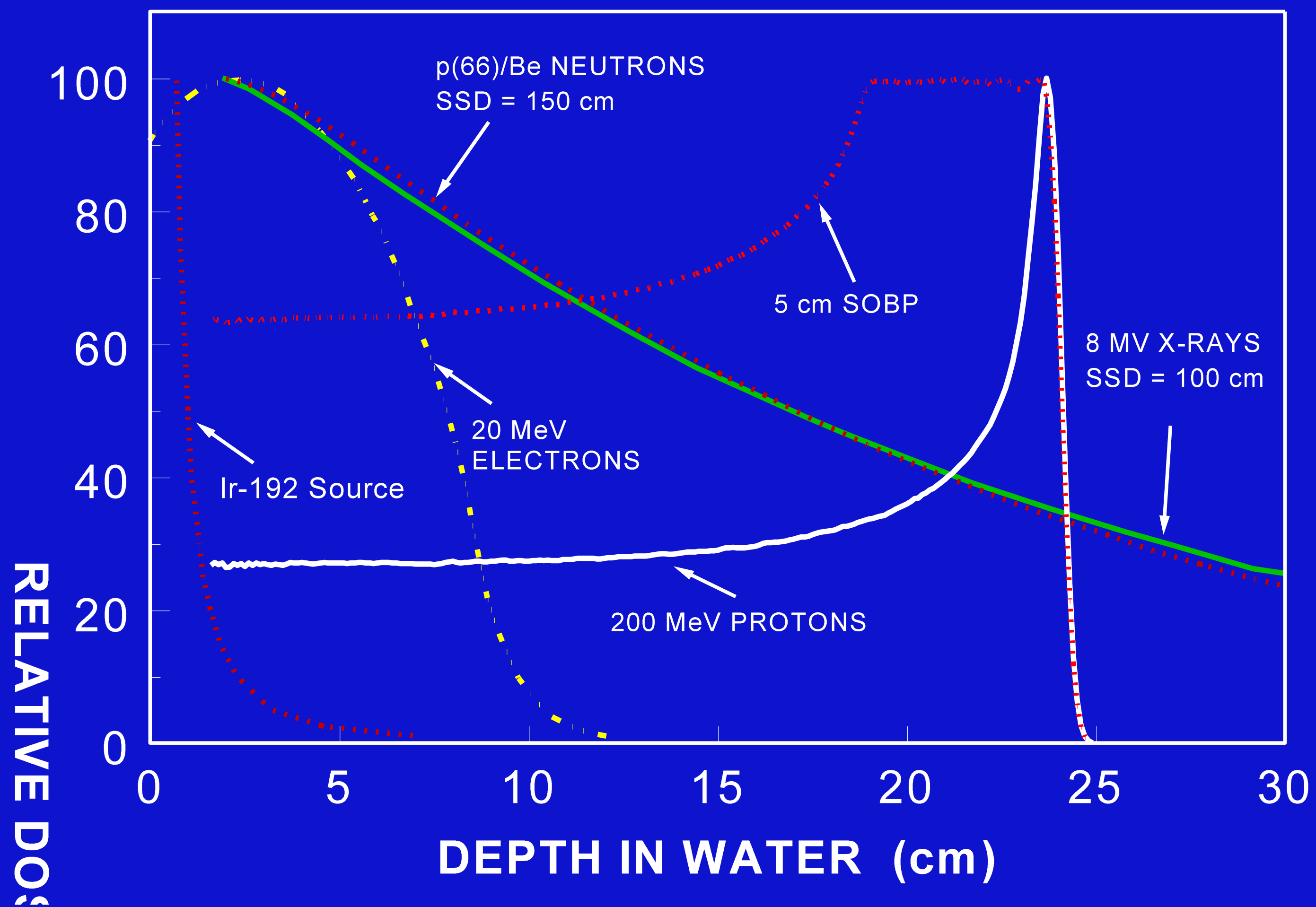
Depth dose curves for different treatment modalities



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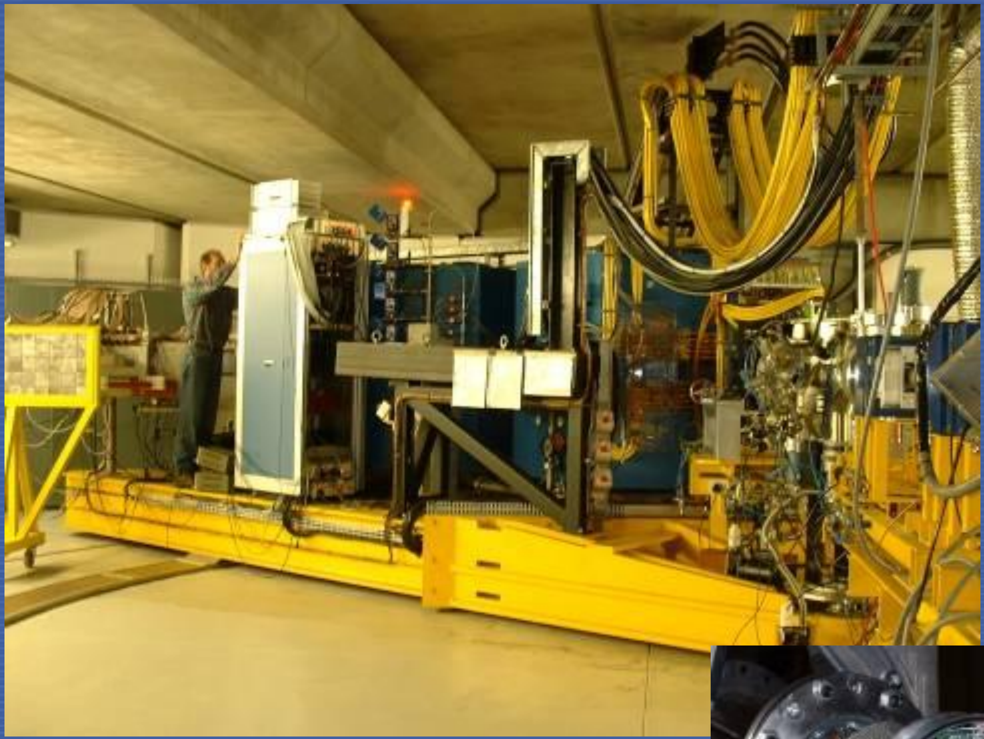
Basic Research and Development

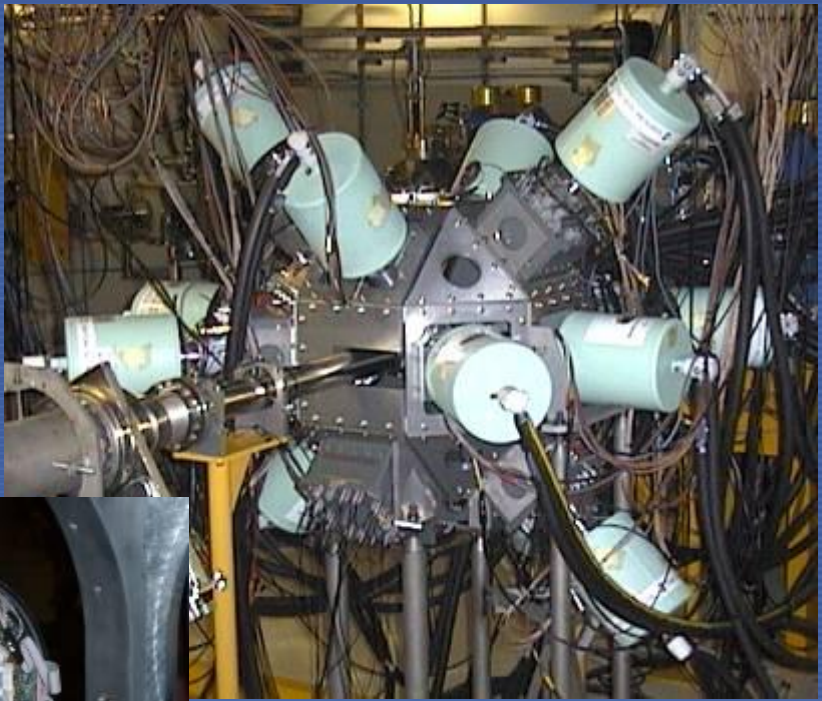
The k=600 Magnetic Spectrometer and

Si+NaI detectors for charged particles



Gamma ray spectrometers

for decay or prompt gammas



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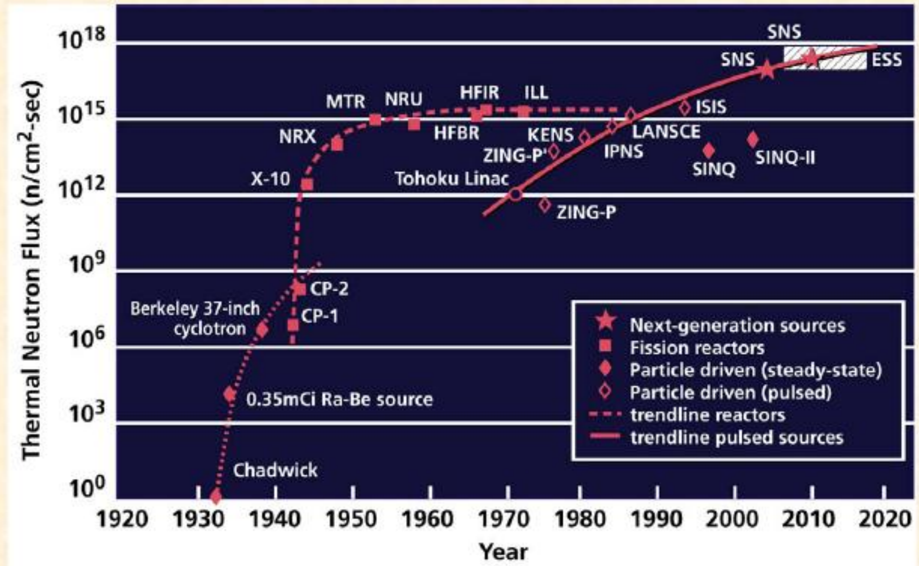
Neutron production: RRs or Accelerators?

Reactors have reached the limit at which heat can be removed from the core
Pulsed sources have not yet reached that limit and hold out the promise of higher intensities



Research Reactor of 1MW:

~3x10^{16}fissions/s ~0.8x10^{17}n/s

Spallation Neutron Source of 1MW:

(1GeV;1mA;protons)~25n/p * 6.25x10^{15}p/s ~1.6x10^{17}n/s

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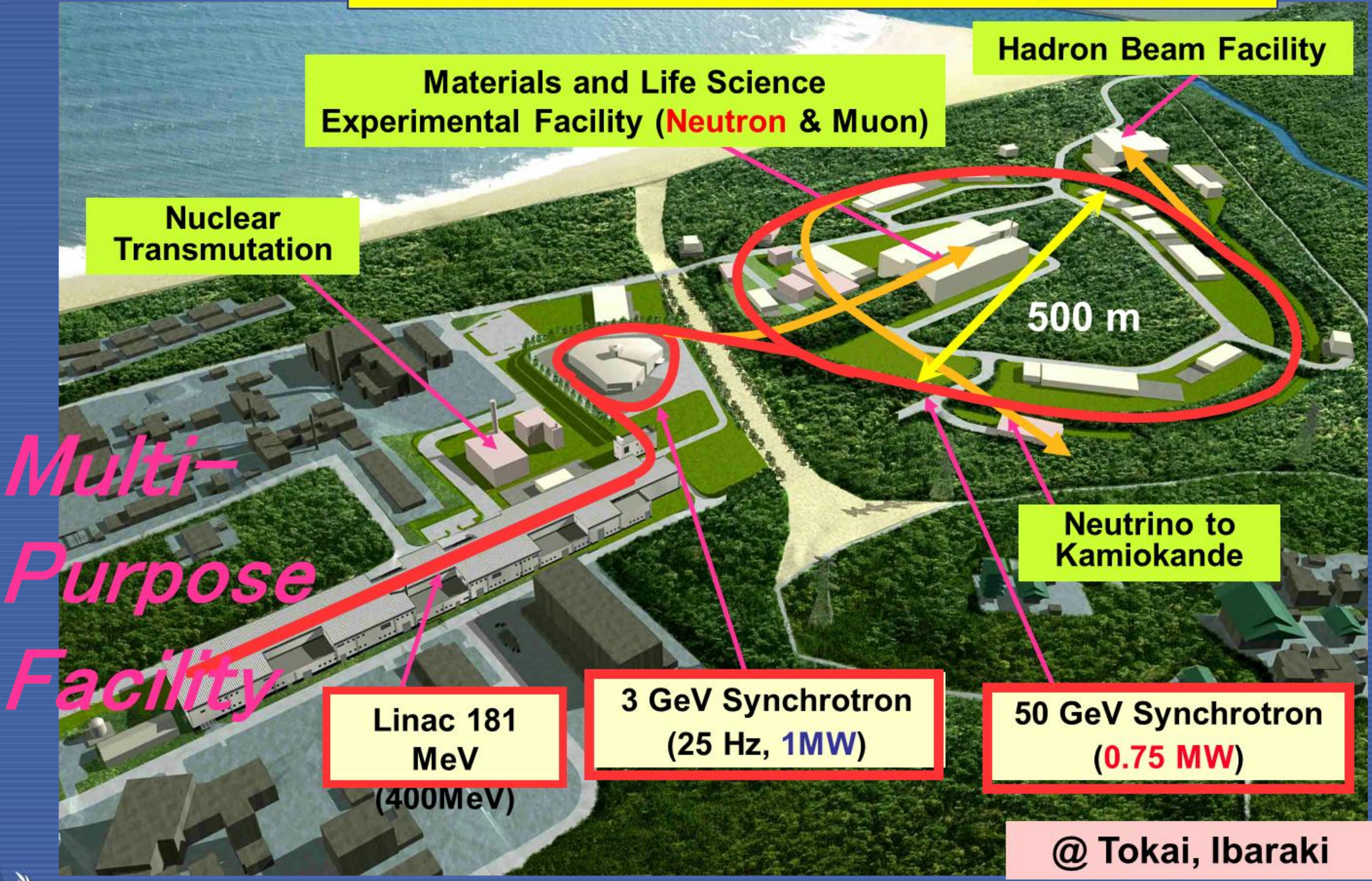
J-PARC = Japan Proton Accelerator Research Complex

Joint Project of KEK (High Energy Accelerator Research Organization) and JAEA (Japan Atomic Energy Agency)



@ Tokai, Ibaraki

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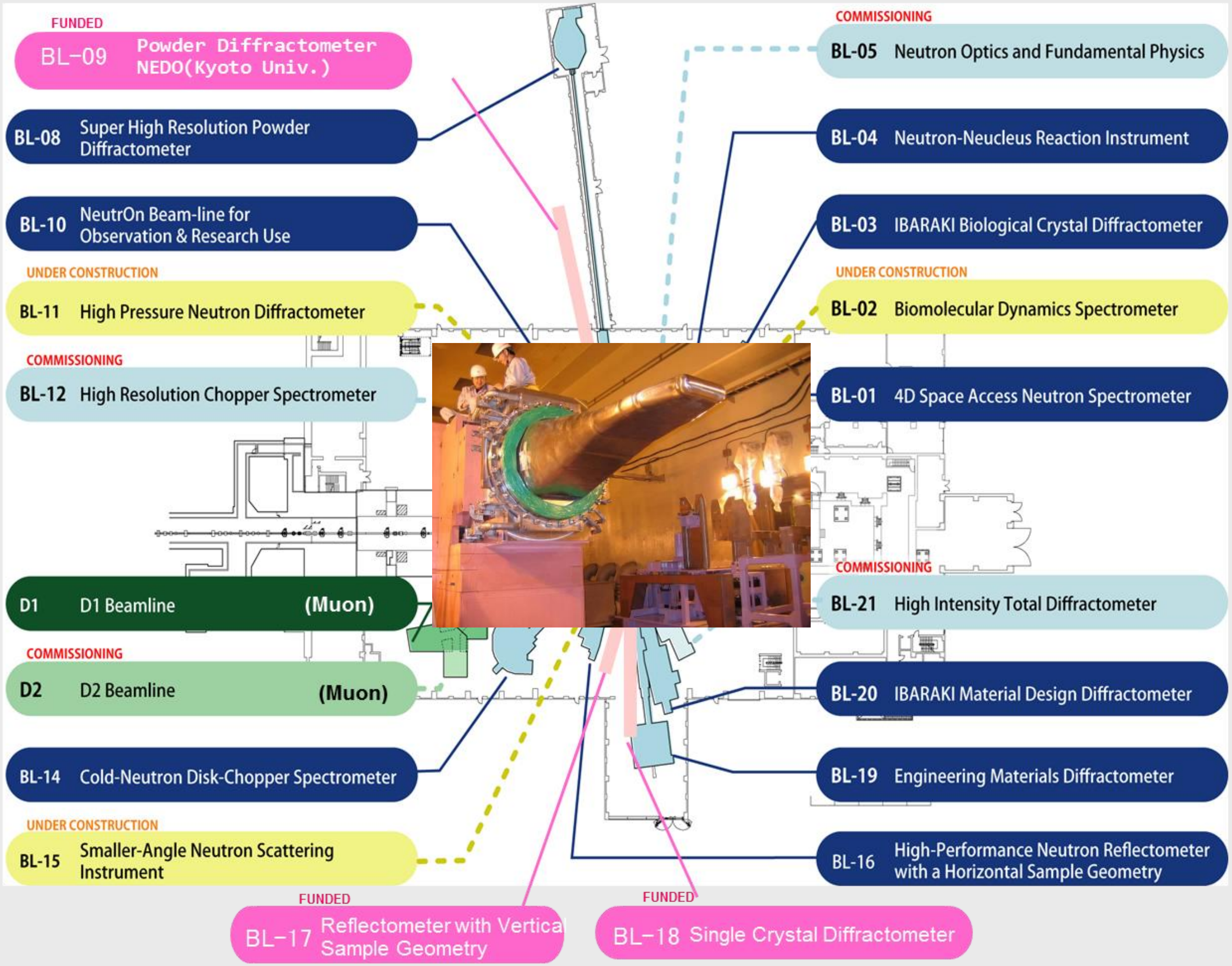
Neutron Instruments (Beamlines)

18 bemlines have been working or budgeted, of the 23 available ports

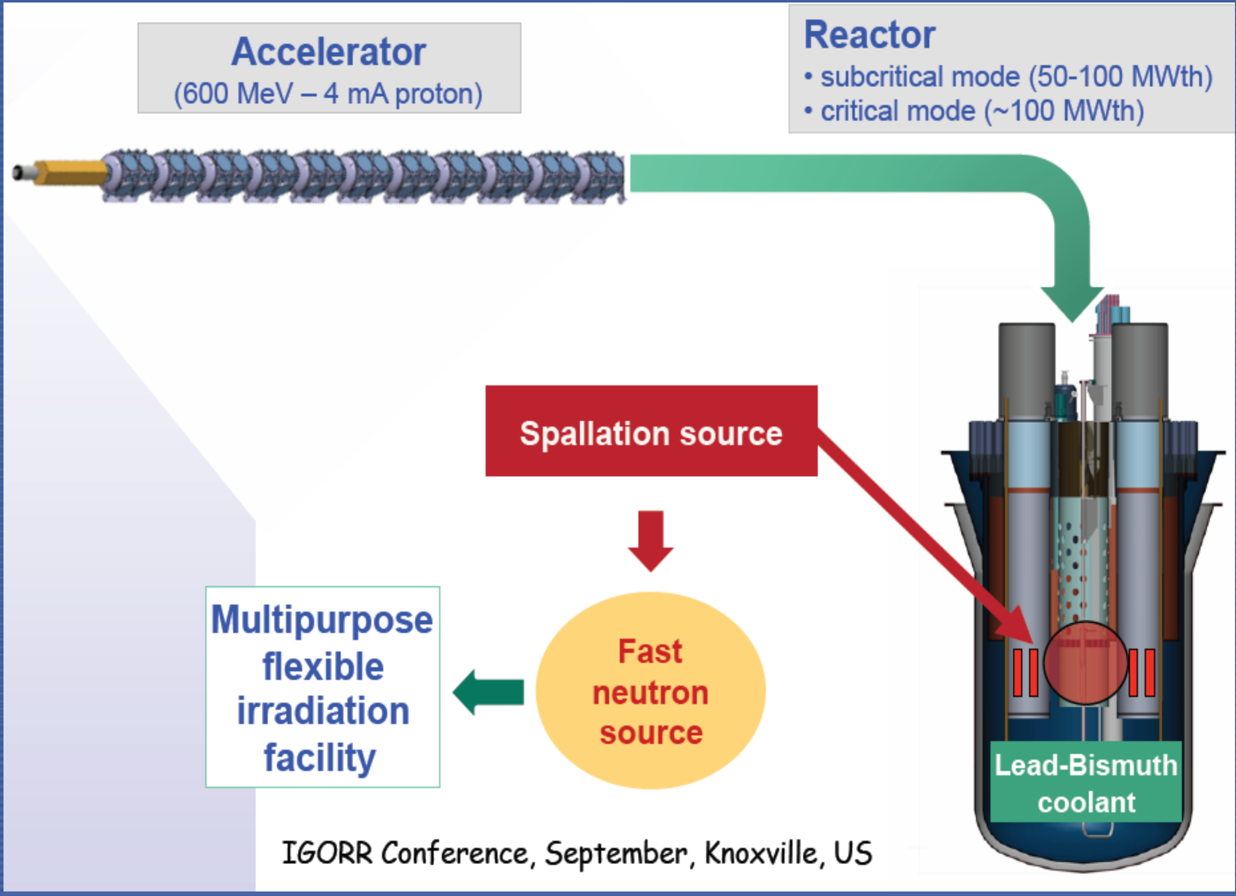
In operation:	**9**
On-beam commissioning:	**3**
Under construction:	**3**
Funded:	**3**



Combined applications of RRs and Accelerators:
ADS MYRRHA project in Belgium

Purpose:

- Prototype fast neutron ADS
- Demo for nuclear waste transmutation
- Fast & intense neutron source for
  - RI production
  - Si doping
  - Materials/fuel studies
  - Gen IV studies
  - R&D
  - E&T
  - …



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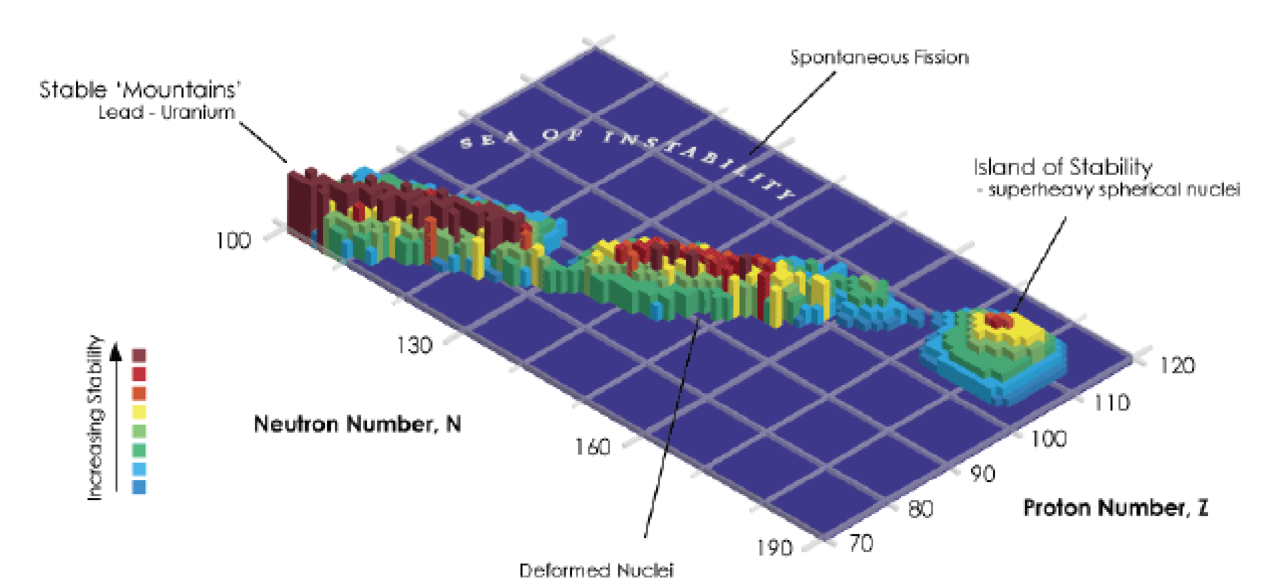
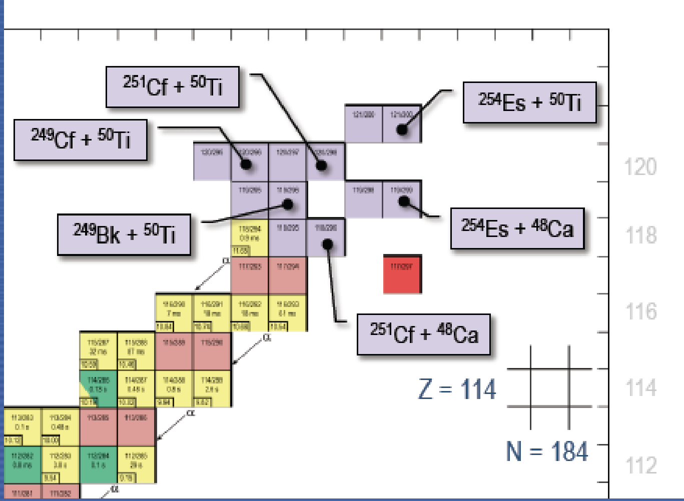
Combined applications of RRs and Accelerators:
Production of Super Heavy Elements



Fuel change-out at the
High Flux Isotope Reactor (ORNL)

Year	Element	Laboratory	Reaction	Number of atoms synthesized to date
2000	114	JINR, Russia[1]	$^{48}Ca \rightarrow {}^{244}Pu$ (ORNL)	50 atoms
2004	113	JINR, Russia[1]	Decay product of element 115	8 atoms
2004	115	JINR, Russia[1]	$^{48}Ca \rightarrow {}^{243}Am$ (ORNL)	30 atoms
2005	116	JINR, Russia[1]	$^{48}Ca \rightarrow {}^{248}Cm$ (RIAR/ORNL)	30 atoms
2006	118	JINR, Russia[1]	$^{48}Ca \rightarrow {}^{249}Cf$ (ORNL)	3 – 4 atoms
2010	117	JINR, Russia[2]	$^{48}Ca \rightarrow {}^{249}Bk$ (ORNL)	6 atoms



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Source: ORNL (USA)

Generations of Nuclear Reactors

Generation I

Early Prototypes

- Shippingport
- Dresden
- Magnox

Generation II

Commercial Power

- PWRs
- BWRs
- CANDU

Generation III

Advanced LWRs

- CANDU 6
- System 80+
- AP600

Generation III+

Evolutionary Designs

- ABWR
- ACR1000
- AP1000
- APWR
- EPR
- ESBWR

Generation IV

Revolutionary Designs

- Safe
- Sustainable
- Economical
- Proliferation Resistant and Physically Secure

1950	1960	1970	1980	1990	2000	2010	2020	2030

Gen I	Gen II	Gen III	Gen III+	Gen IV

http://www.gen-4.org/Technology/evolution.htm

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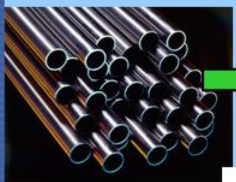
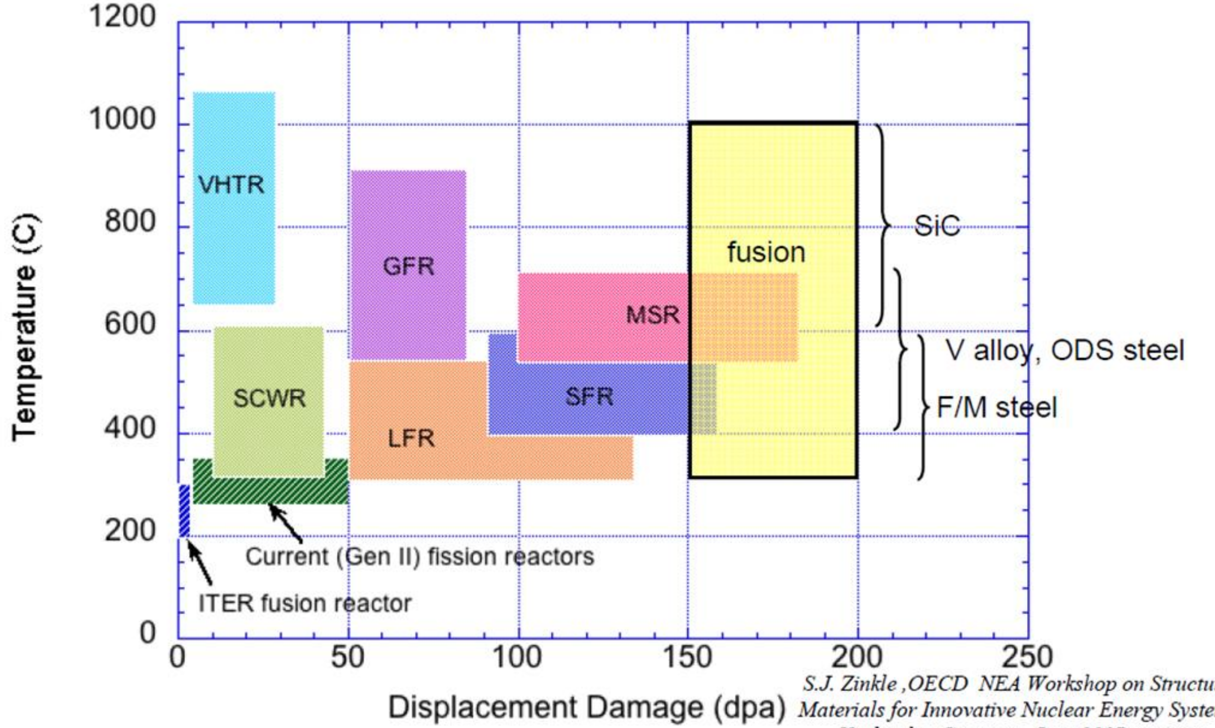
Material development in nuclear industry

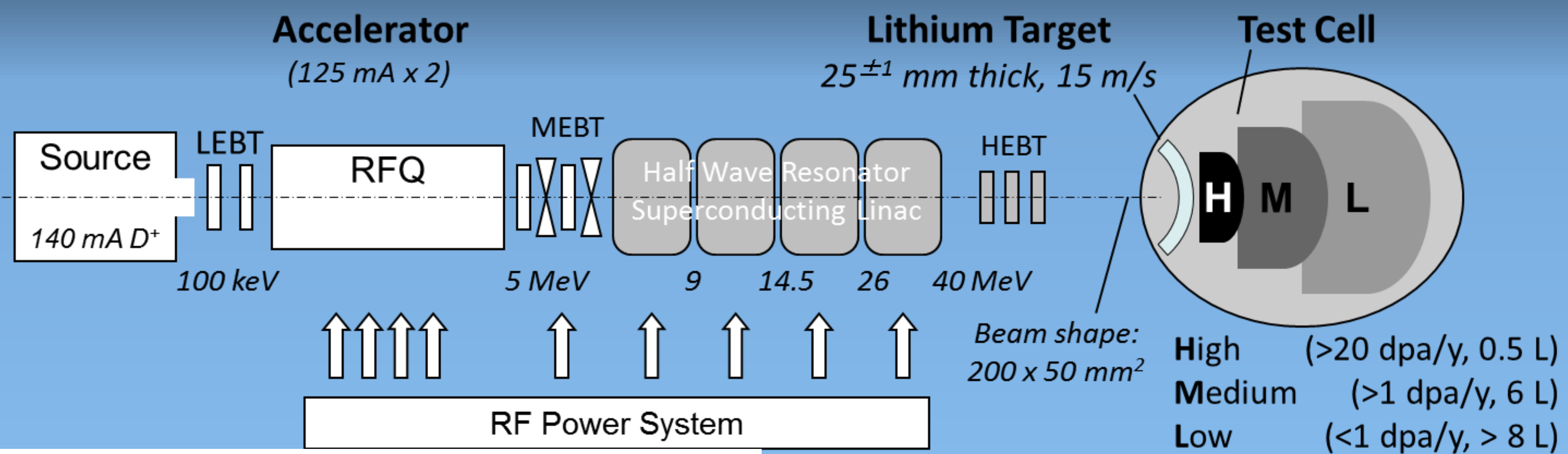


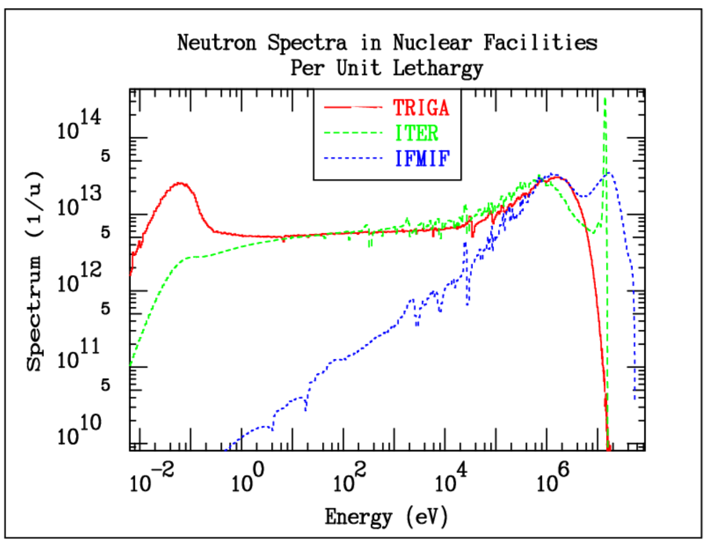
Selection → Characterisation → Qualification



S.J. Zinkle ,OECD NEA Workshop on Structural Materials for Innovative Nuclear Energy Systems, Karlsruhe, Germany, June 2007, in press

International Fusion Material Irradiation Facility (IFMIF)





Typical reactions

$^{7}Li(d,2n)^{7}Be$

$^{6}Li(d,n)^{7}Be$

$^{6}Li(n,T)^{4}He$

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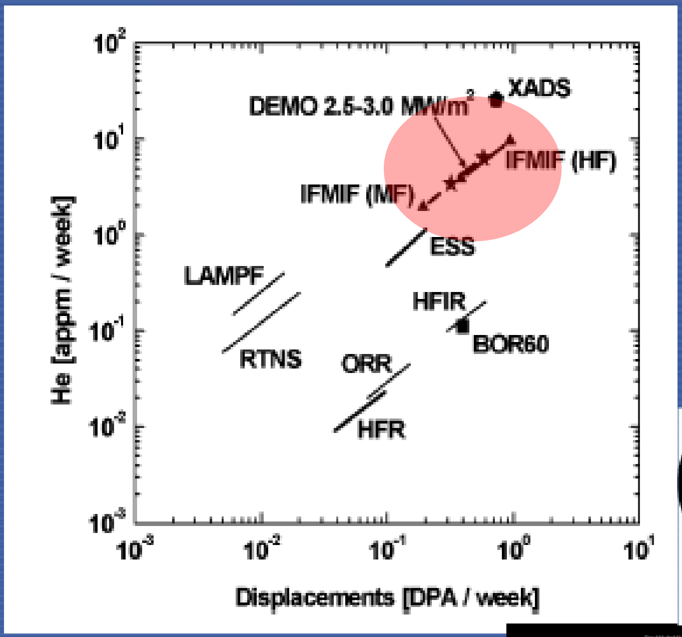
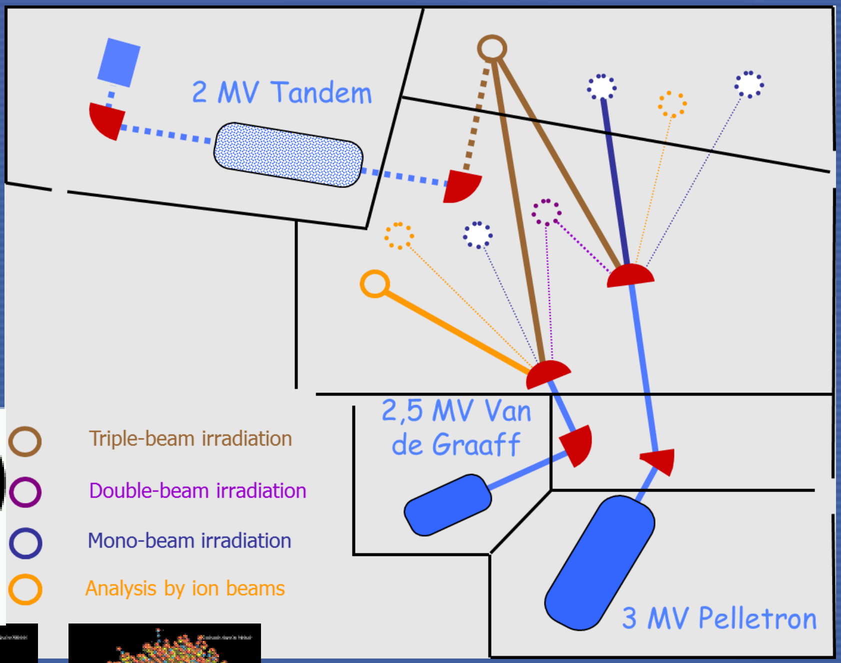
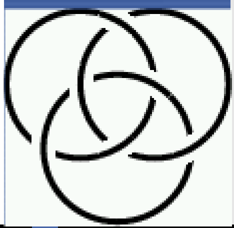
Combined/comprehensive multi-disciplinary approach

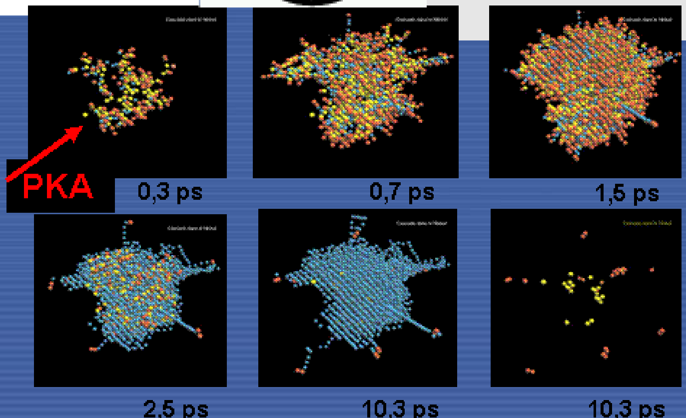
High Flux Fast RRs for dpa generation (e.g. BOR60 in Russia)



Multi-ion beams for H, He and FF generation (e.g. JANNUS facility in France)







Use the best physics understanding through complex modelling of occurring phenomena

Thanks for your attention and...

...I wish you a successful continuation!

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