Applications of Research Reactors: Purpose and Future

Danas Ridikas

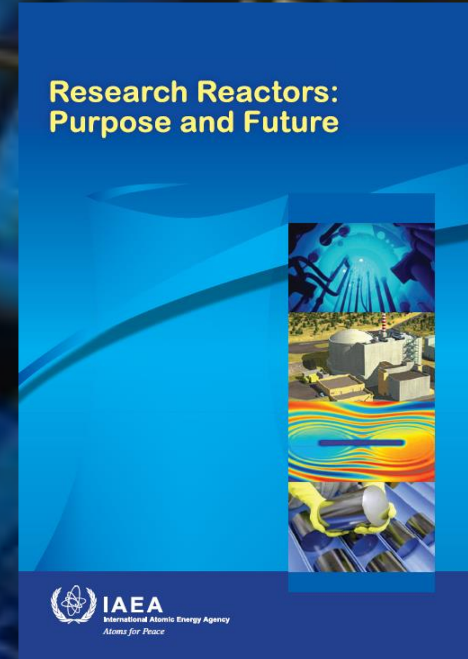
Research Reactor Officer, Physics Section
Division of Physical and Chemical Sciences (NAPC)
Department of Nuclear Applications and Sciences (NA)

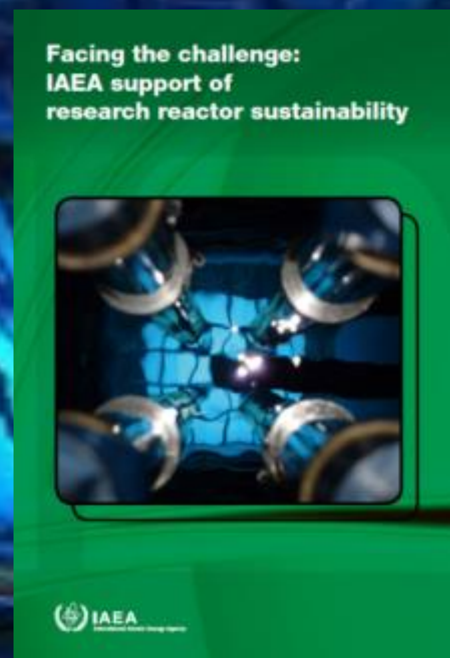
IAEA, Vienna, Austria

IAEA
International Atomic Energy Agency

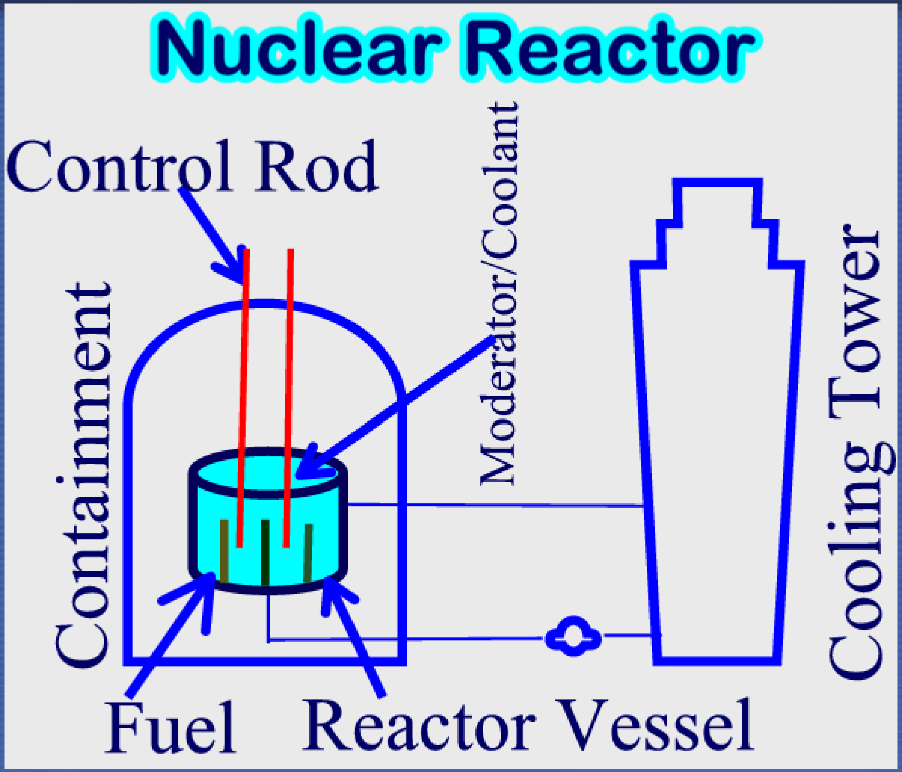
Outline

- Historical background
- Applications of Research Reactors
- Future perspectives
- List of references





Background



Main Components of Research Reactor

FUEL	Natural Uranium / Enriched Uranium
FORM	Metal, Alloy, Oxide, Silicide
CLAD	Aluminium, Zirconium, Stainless Steel
MODERATOR	H_2O, D_2O, Graphite, Beryllium
CONTROL	Boron, Cadmium, Nickel
COOLANT	Water, Gas, Sodium, PbBi
VESSEL	to contain all components

Basic Nuclear Physics

Interaction of neutrons with matter (fission, capture, scattering)
Criticality, role of delayed neutrons, radiocative decay
Basics of thermohydraulics

IAEA

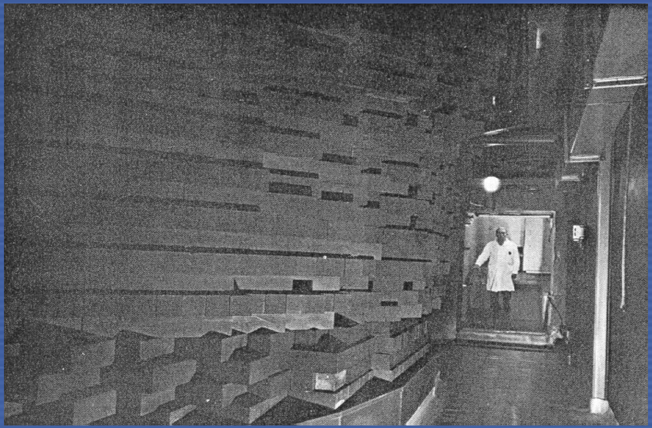
Contact: D.Ridikas@iaea.org

Background

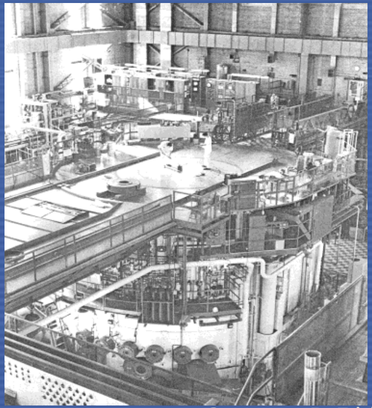
Some historical facts

- USA, Dec. 1942: Chicago Pile (CP1), E. Fermi
  - Objective: neutron source for Pu production

- Russia, Dec. 1946, F-1, I. Kurchatov
  - Objective: excess neutrons for Pu production



- Canada, Jul. 1947, Chalk River Laboratories
  - NRX – National Research Experiment
  - Reached 20MW(t) in 1949
  - Used for basic research
  - Contributed to nuclear x-section data



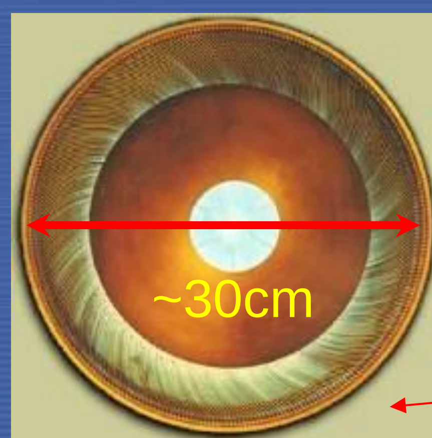
IAEA

Contact: D.Ridikas@iaea.org

Background

Other general information: features

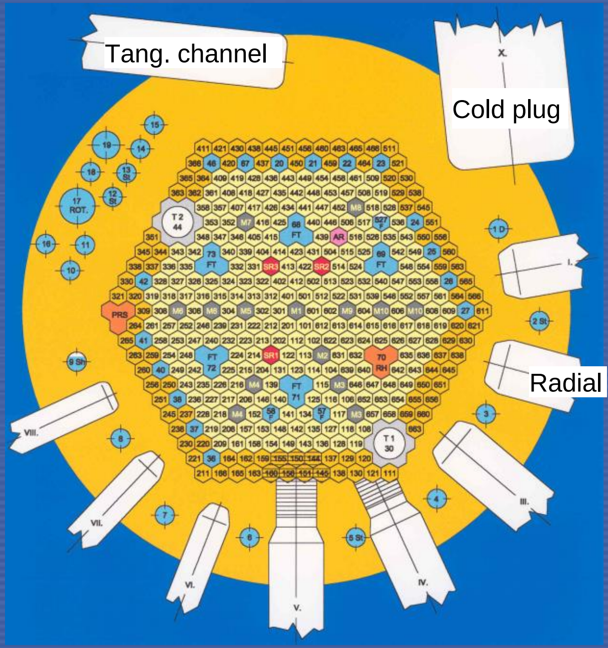
- Typically, RR cores have small volume
- Many have powers less than 5 MW(t)
- Higher enrichment than power reactors
- Natural and forced cooling
- Pulsing capability



Background

Other general information: purpose

- Produce and provide access to the neutrons
- Access can be provided:
  - inside core, along core boundary and from external beams
- Typical Power range 100kW to 10MW
- Typical Steady-State Neutron Flux → 10^{12} to 10^{14} n/(cm^2 s)



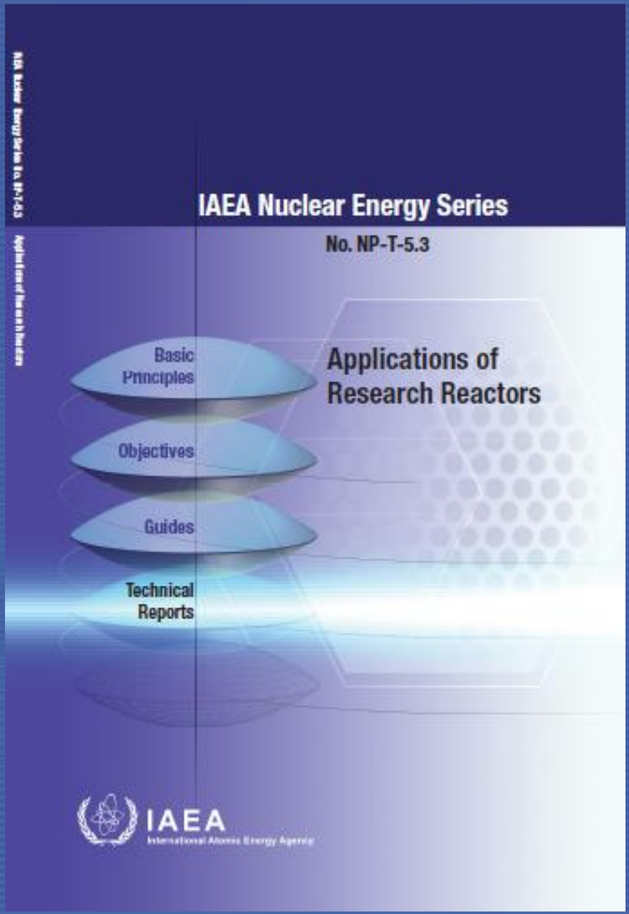
Contact: D.Ridikas@iaea.org

Applications of Research Reactors

Other general information: purpose (continued)

- Education & Training
- Neutron Activation Analysis
- Radioisotope Production
- Geochronology
- Neutron transmutation doping
- Neutron Radiography
- Neutron Scattering
- Positron source
- Neutron capture therapy
- Fuel/material testing and qualification
- Nuclear data measurements
- Computer code validation
- …

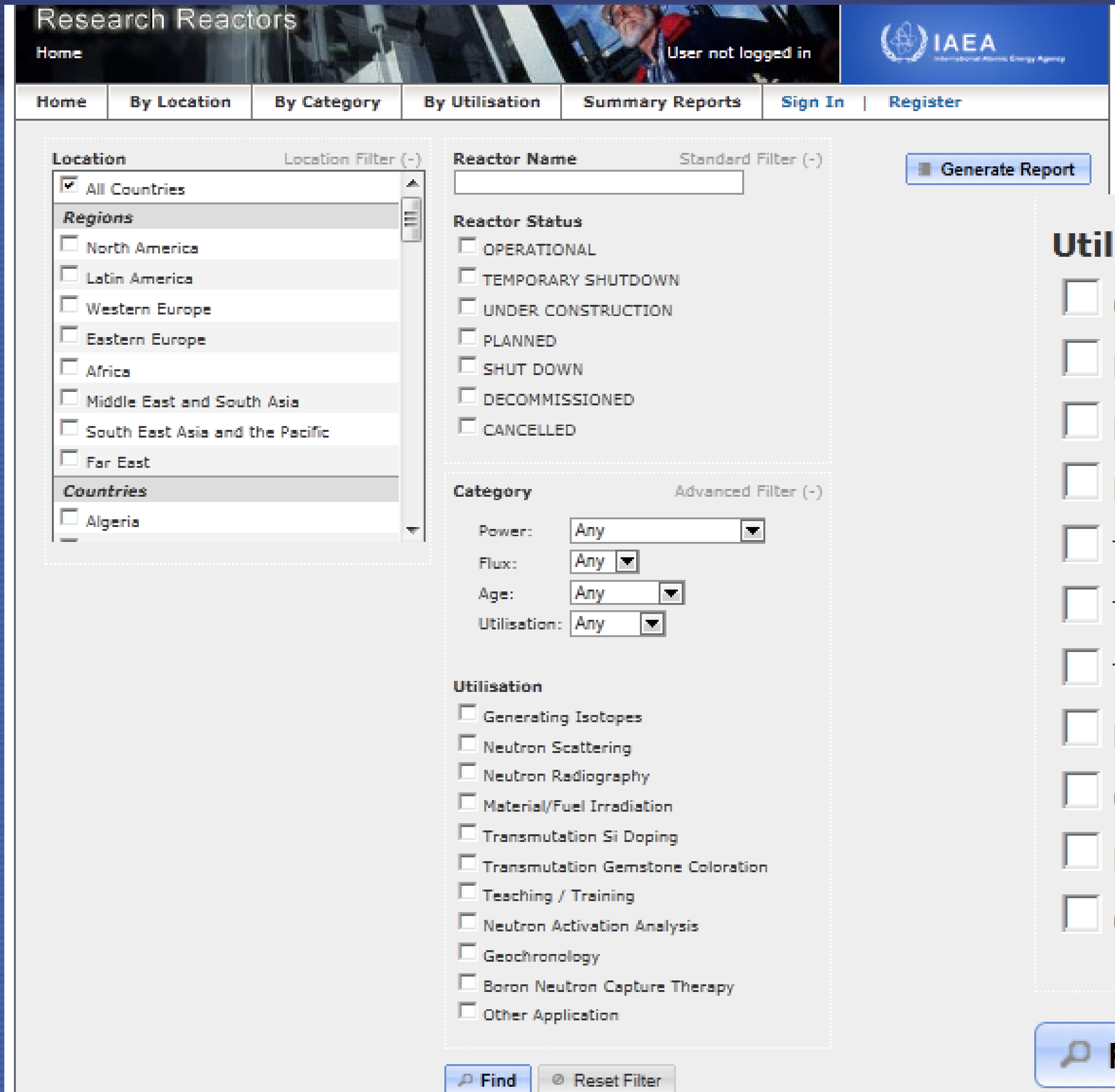
→ **For more information see**

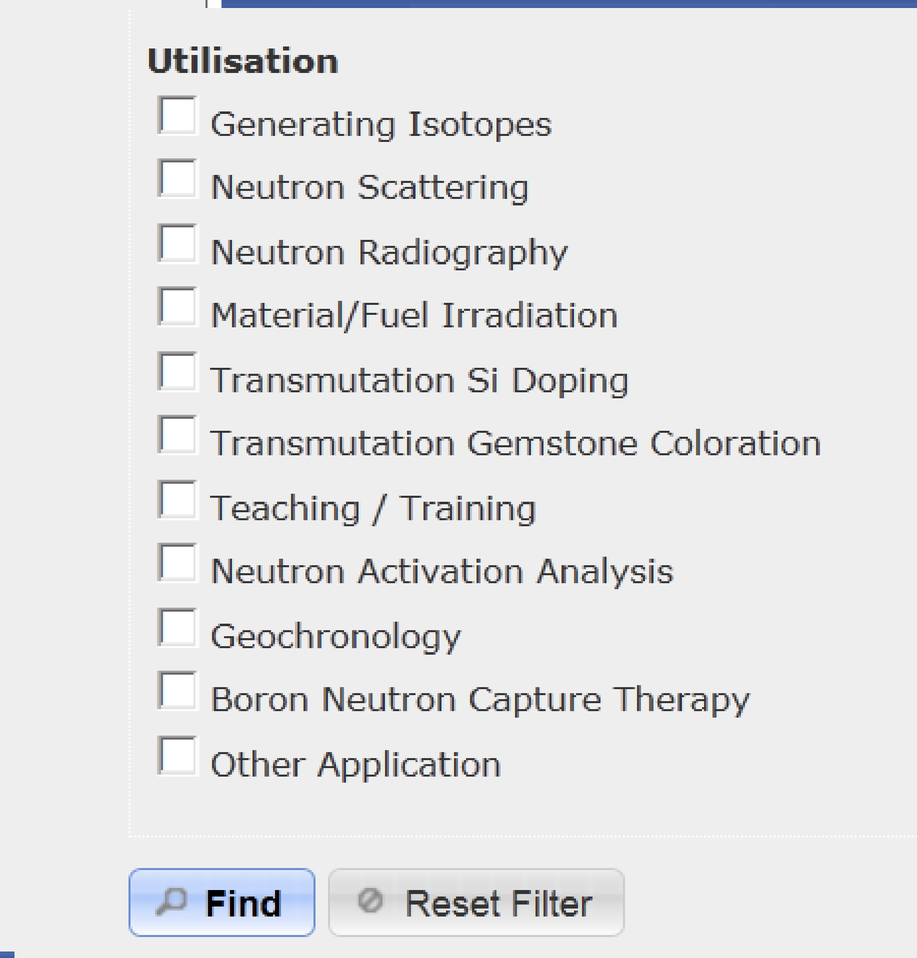


IAEA

Contact: D.Ridikas@iaea.org

Contents of the IAEA RRDB





IAEA

http://nucleus.iaea.org/RRDB/

Contact: D.Ridikas@iaea.org

RRs world-wide

Source: IAEA RRDB

TOTAL:	737
Operational	247
Temp. shutdown	20
Under construction	3
Planned	8
Shutdown/Decommissioned	454
Cancelled	6

Operational RRs are distributed over 56 countries

Russia	65
USA	42
China	15
France	10
Japan	8

Region	Operational RRs
Africa	7
Americas	65
Asia-Pacific	49
Europe (with Russia)	126

IAEA

Contact: D.Ridikas@iaea.org

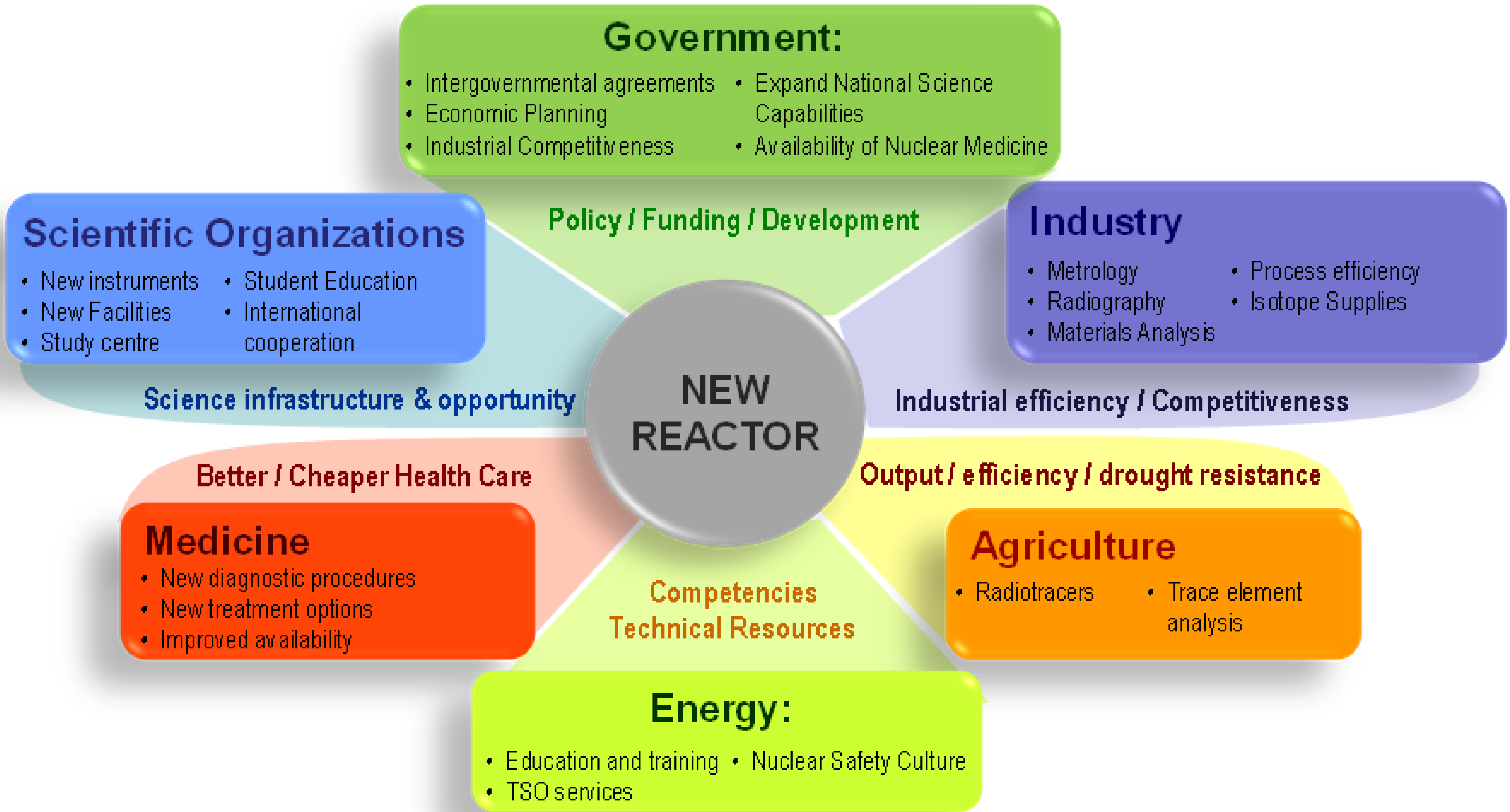
Involvement of 247 operational RRs

Application	Number of oper. RR involved	Involved / Operational, %
Education & Training	163	66
Neutron Activation Analysis	115	47
Radioisotope production	83	34
Neutron radiography	67	27
Material/fuel testing/irradiations	63	26
Neutron scattering	44	18
Nuclear Data Measurements	35	14
Si doping	25	10
Geochronology	24	10
Gem coloration	19	8
Neutron Therapy	16	6
Other	120	49

IAEA

Indispensable to define priorities & plan the IAEA activities!

RR stakeholders and users



IAEA

→ Education & training (1)

- **Public tours & visits**
- **Teaching physical and biological science students**
- **Teaching radiation protection & radiological engineering students**
- **Nuclear engineering students**
- **Nuclear power plant operator training**

→ Can be potential source of income

Contact: D.Ridikas@iaea.org

→ Education & training (2)

IAEA

Contact: D.Ridikas@iaea.org

Education & training (example)

Typical flow from Academics to Nuclear

Academic background → **Nuclear training required**

PhDs	**50+** Experts	**+ 12 to 24 months**
Engineers & Masters	**400+** Project + M&O staff	**+ 6 to 12 months**
Bachelors & Technicians	**800+** Construction & Operating staff	**+ 3 to 9 months**

Population need estimates for 2 NPPs

IAEA

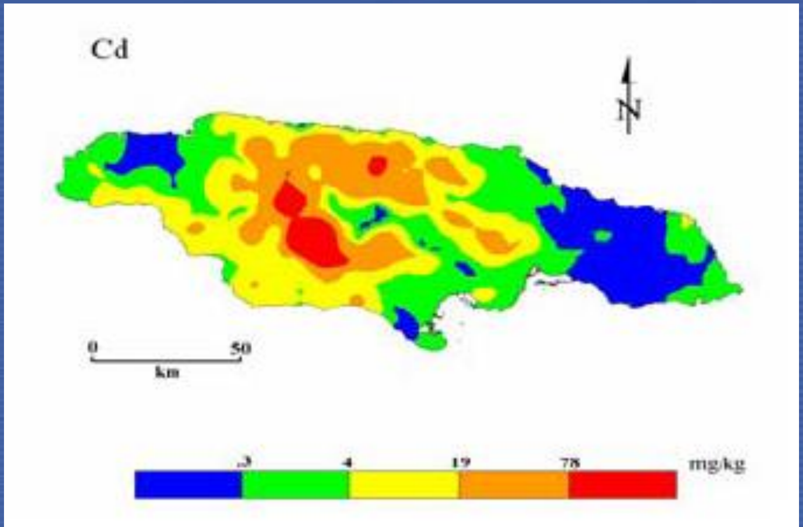
Courtesy: AREVA, France, 2009.

Contact: D.Ridikas@iaea.org

→ Neutron Activation Analysis (1)

Qualitative & **quantitative** analytical technique for the determination of **trace elements/impurities**

- Samples from mg to kg, detected concentration ~**ppb**
- Uses : Archaeology, Biomedicine, Environmental Science, Geology and geochemistry, Industrial products, Nutrition, Quality assurance of analysis & reference materials
    - Rocks, minerals, and soils
    - Atmospheric aerosols
    - Archaeological artifacts
    - Tree rings
    - Dust in ice cores
    - Hair, nails, skin, etc.
    - Plant and animal matter
    - Coal
- Can be a potential source of **income**



Soil mapping using NAA in Jamaica

IAEA

Contact: D.Ridikas@iaea.org

→ Neutron Activation Analysis (2)

Sampling

Pre-irradiation sample treatment

Radiochemical separation in P or DNAA

Irradiation

Radiochemical separation in RNAA

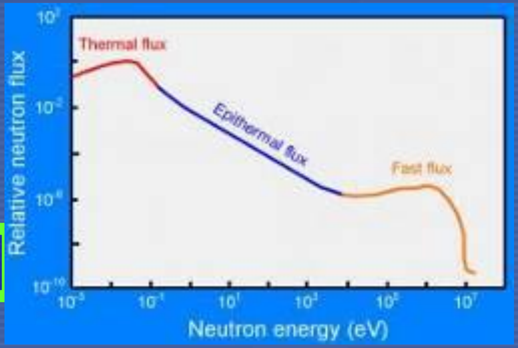
Cyclic NAA

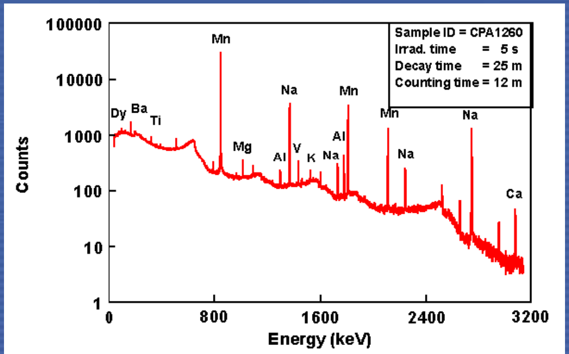
Prompt-ray counting in PGNAA

Radioactivity measurement

Elemental concentration calculation

Critical evaluation of results and preparation of the NAA report





IAEA

Contact: D.Ridikas@iaea.org

→ Radioisotope Production (1)

<u>Used in</u>

- Medicine (diagnostic and therapy), but also
- Industry, agriculture & research

- Most used :
  - in medicine Mo-99 (85% of all procedures), and
  - in industry Co-60

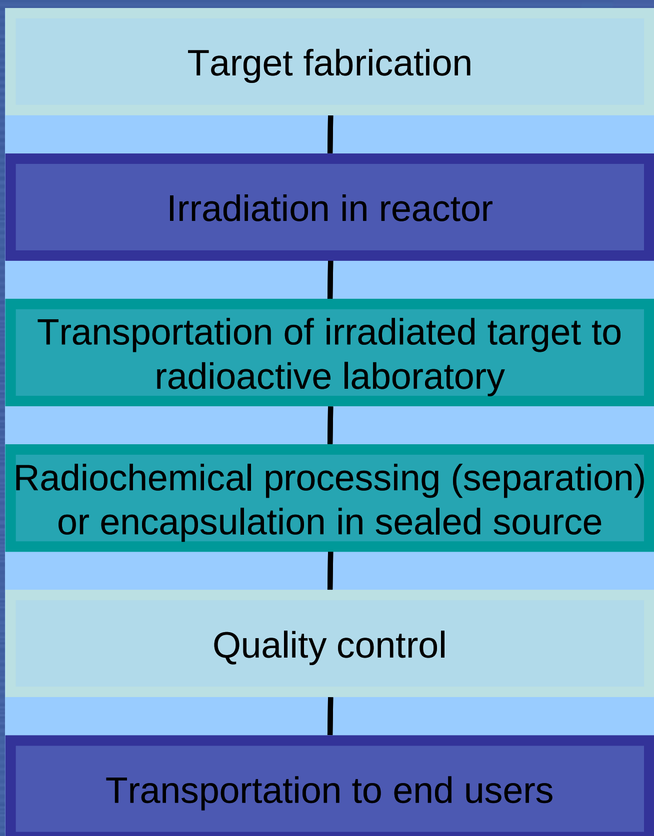
- Potential source of **income, big demand**

- Also produced in particle accelerators

Typical forms of isotopic radioactive sources

Contact: D.Ridikas@iaea.org

→ Radioisotope Production (2)



Fission :

- **Short lived fission products: ^{99}Mo, ^{131}I**
- **Long lived fission products: ^{137}Cs, ^{147}Pm**

Capture

- **(n,γ) :** $^{59}Co + n \rightarrow {}^{60}Co + \gamma$
- **(n,γ) → β- :** $^{130}Te + n \rightarrow {}^{131}Te^{*} + \gamma \rightarrow {}^{131}I + \beta^{-}$

Threshold reactions

- **(n,p) :** $^{32}S + n \rightarrow {}^{32}P + p$
- **(n,α) :** $6Li + n \rightarrow {}^{3}H + {}^{4}He$

Multistage reactions: $^{186}W\,(n,\gamma)$ & $^{187}W(n,\gamma) \rightarrow {}^{188}W$

Contact: D.Ridikas@iaea.org

→ Geochronology (1)

- **Dating method of small (mg) quantities of minerals**
  - **Actinide free**
  - **Including actinides**

Geologic studies on the origin and thermal histories of

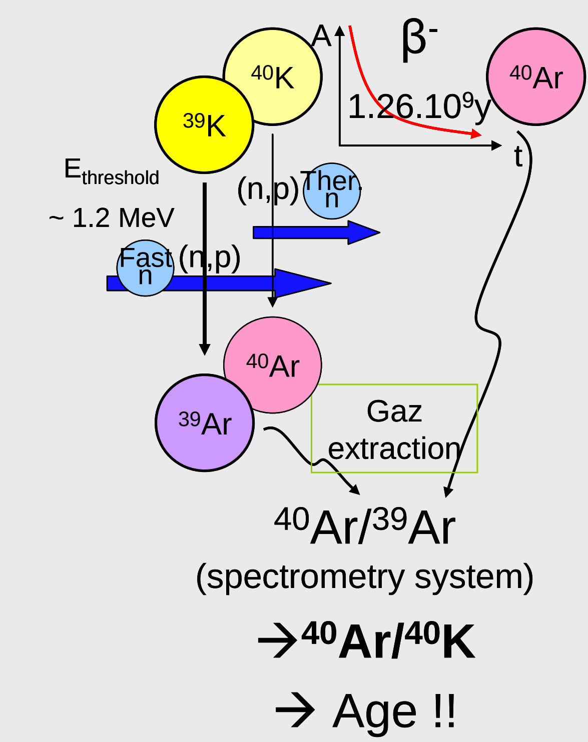
• mineral deposits, emplacement, cooling
• uplift history of plutonic rocks
• formation of metamorphic belts
• development of volcanic terraces
• formation and amalgamation of the Earth's crust
• age and development of the landscape
• timing of catastrophic events in earth history

Age range from 2000 years to 4,6 billion years

Scoria cone erupted on an ancient fluvial terrace of Rio Chico, Argentina

→ Geochronology (2)

- Dating method of small (mg) quantities of minerals
  - Actinide free
    Decay of natural potassium ^{40}K → ^{40}Ar
    Ratio $^{40}Ar/^{40}K$ from $^{40}Ar/^{39}Ar$ via $^{39}K(n,p)^{39}Ar$, E_{th}=1.2MeV
    Use of gas extraction spectrometry systems

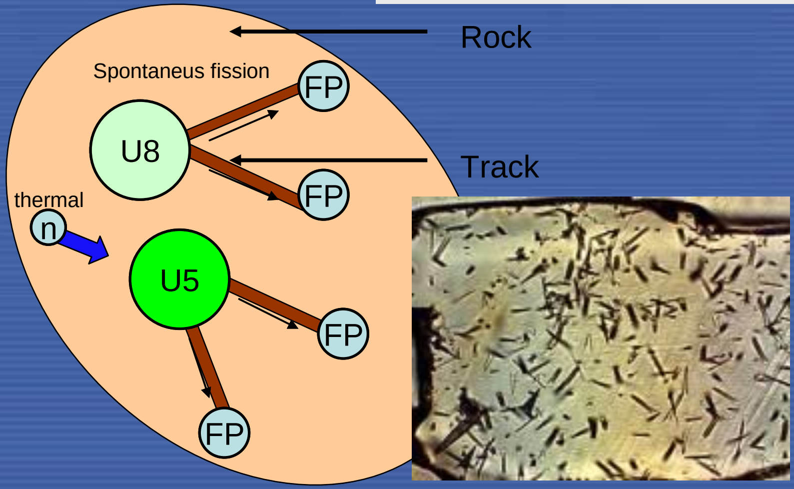


  - Including actinides (apatite, zircon)
    Use of fission track method
    The age is determined by

$$N_{fissionU5} = f(N_{U5})$$

$$N_{U5} \rightarrow N_{U8}(t=0)$$

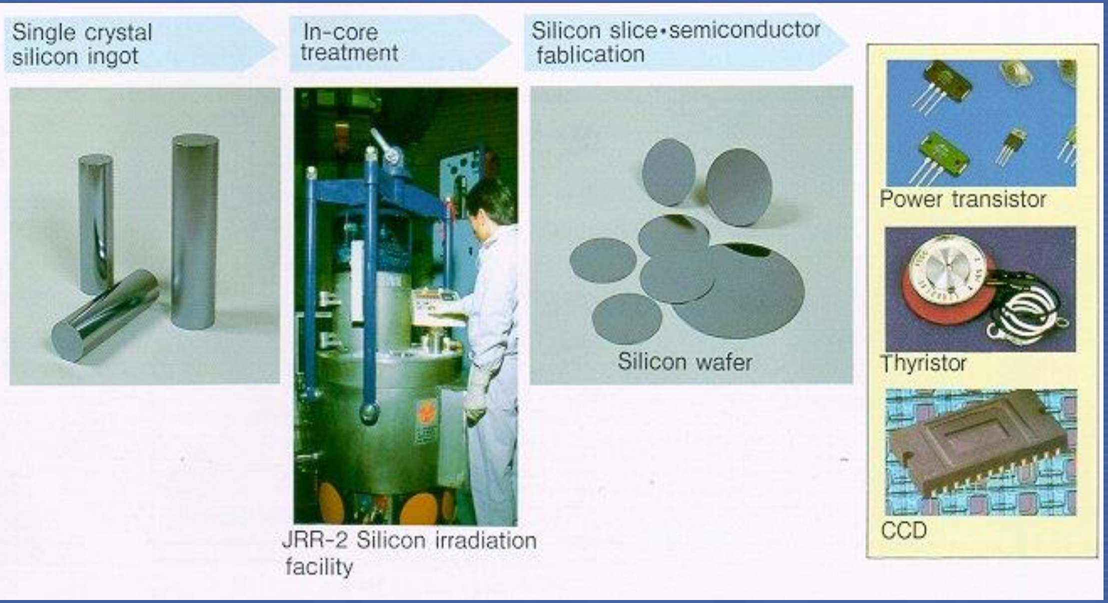
$$N_{fissionU8} = f(N_{U8}(t))$$



Contact: D.Ridikas@iaea.org

→ Transmutation effects (1)

- **Silicon transmutation doping**



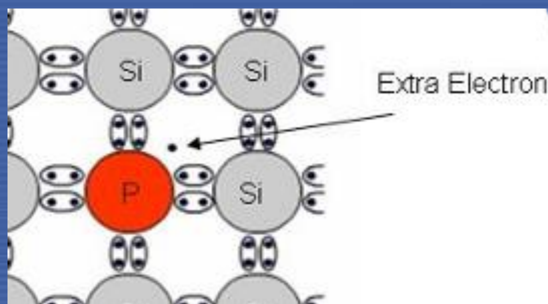
- **Gemstone coloration**

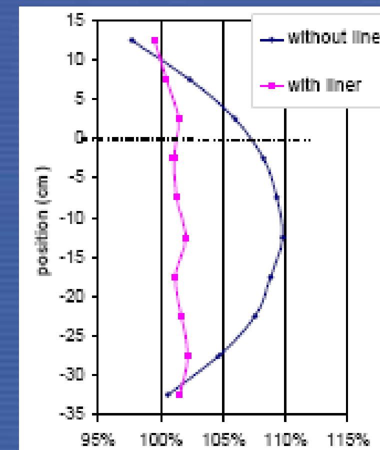

Colourless topaz (left) and blue topaz (right)

Contact: D.Ridikas@iaea.org

→ Transmutation effects (2)

- **Silicon transmutation doping**
  - $^{30}Si(n,\gamma)^{31}Si \rightarrow {}^{31}P$
  - Source of income





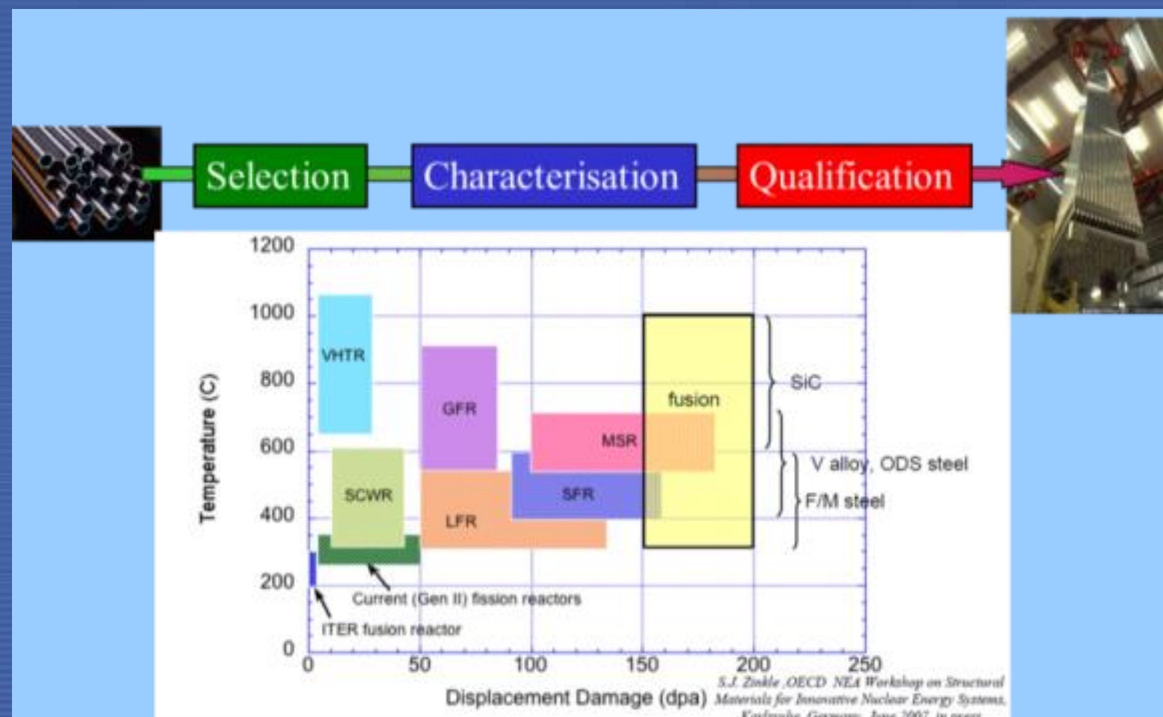
- **Gemstone coloration**
  - Improve gemstone properties (e.g. colour)
  - Source of income

IAEA

Contact: D.Ridikas@iaea.org

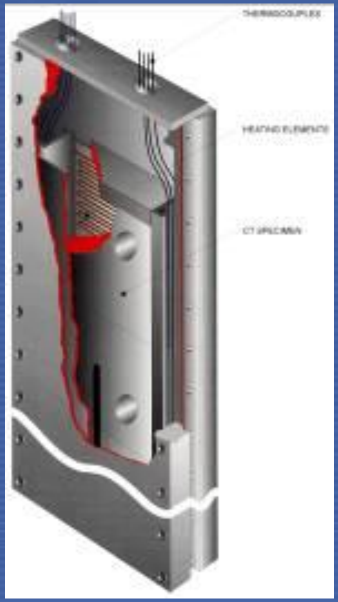
→Fuel/material/detector testing/qualification (1)

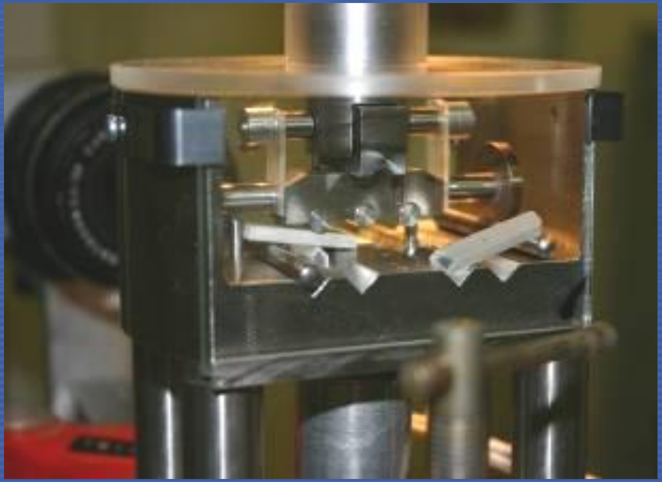
- Instrument development, testing, calibration, qualification
- Fuel/material testing (ageing, corrosion, irradiation)
- Fuel/material qualification (temperature, pressure, irradiation)
- Development of new fuels/materials (actinide fuels, high temperature reactors, fast reactors, fusion reactors, …)

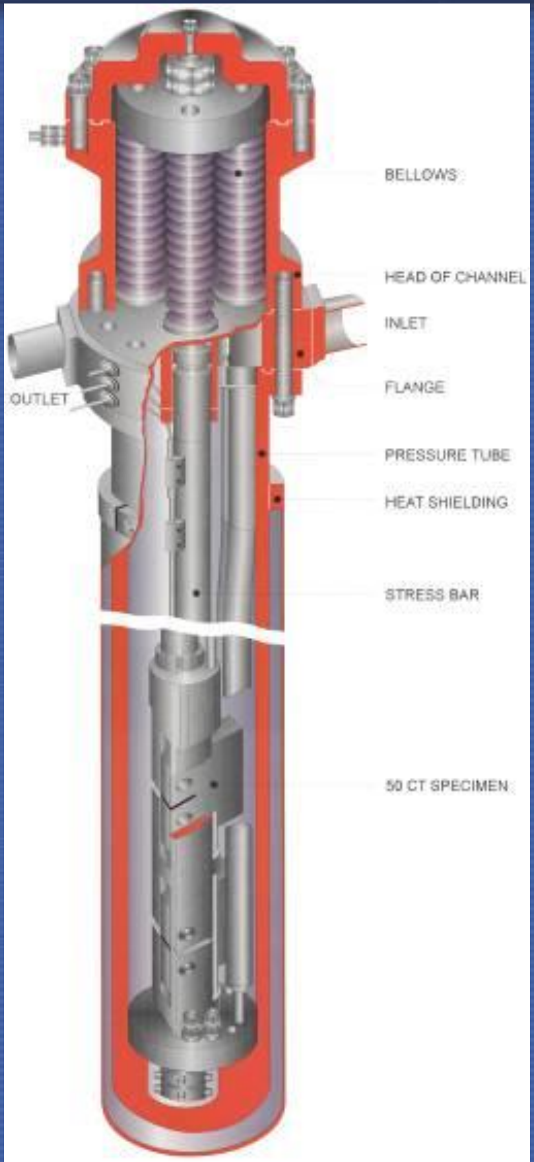


→Fuel/material testing/qualification (2)

- Equipped irradiation rigs
- Independent/controlled heating
- Thermocouples
- Neutron monitoring
- Irradiation loops (p, T, neutrons)
- Hot laboratories
- Mechanical tests
- Visual examination
- Radiochemistry





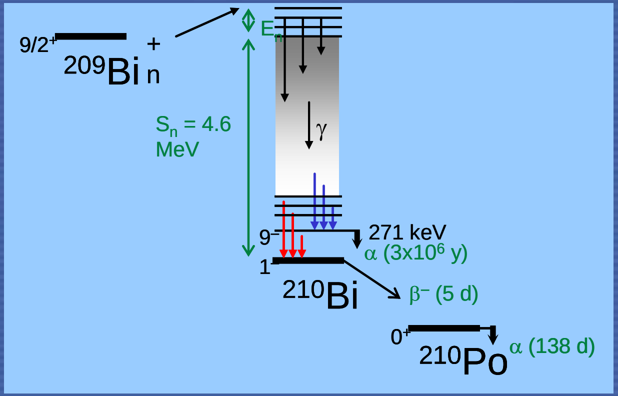


Contact: D.Ridikas@iaea.org

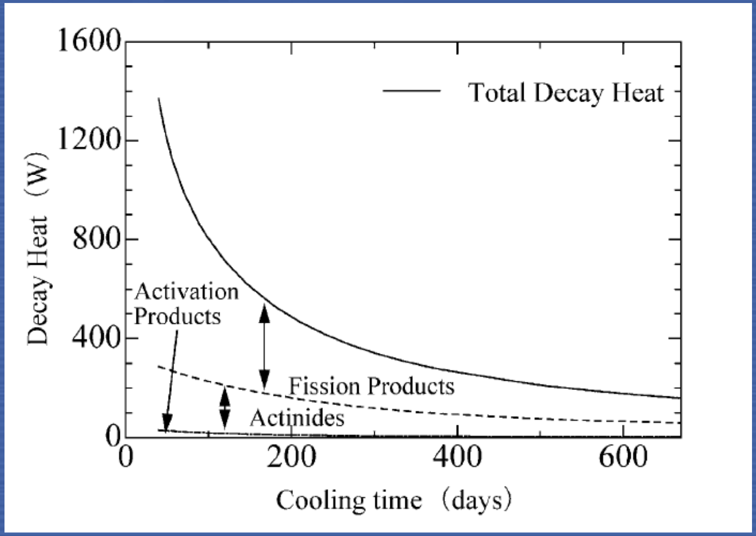
→ Provision of nuclear data (1)

- Fission & capture cross sections
- Branching ratios
- Neutron multiplicities
- Fission yields
- Decay data
  (half-lives, branching ratios, decay particles, heat)
- Delayed neutrons
- …

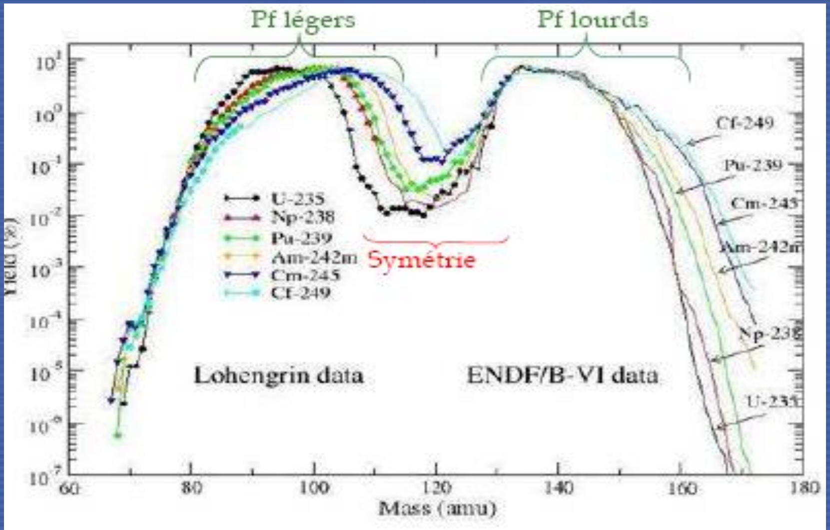
Measured (n,γ) x-section, leading to ^{210}Po



Decay type: α - 1 %, β - 52 %, γ - 47 %



Repartition of decay heat of spent MOX fuel

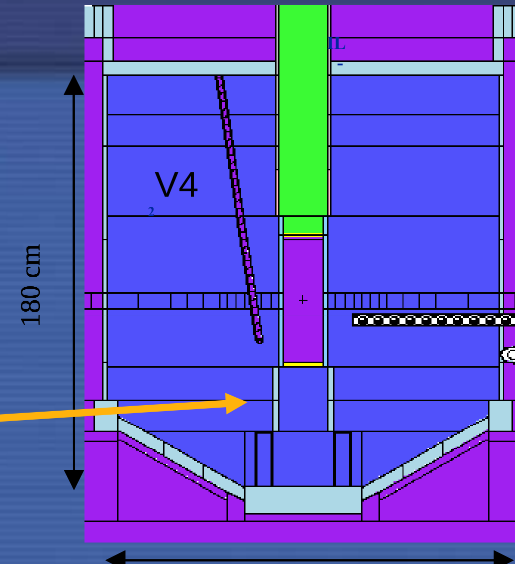


Measured FF mass distribtuion

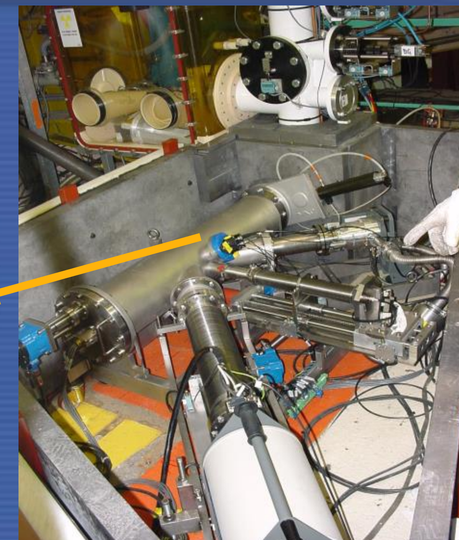
Contact: D.Ridikas@iaea.org

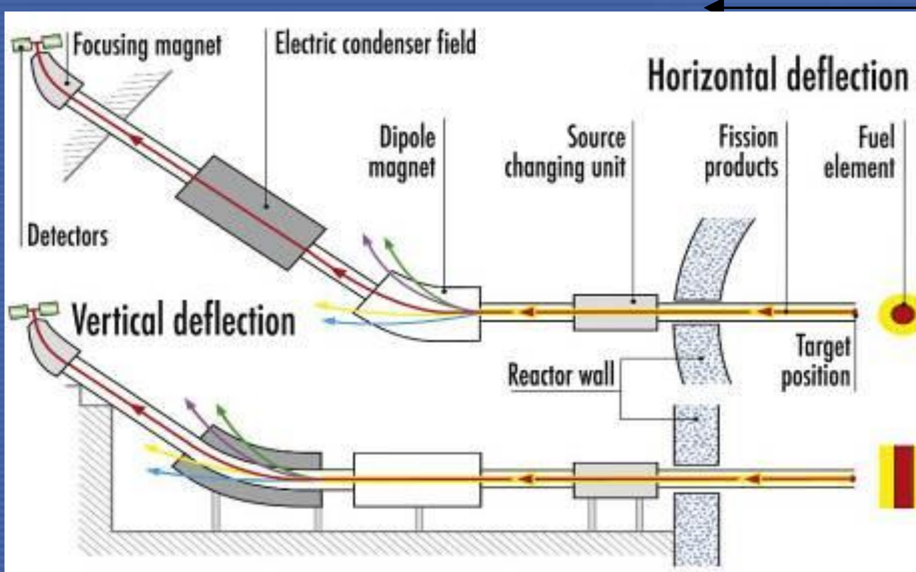
→ Provision of nuclear data (2)

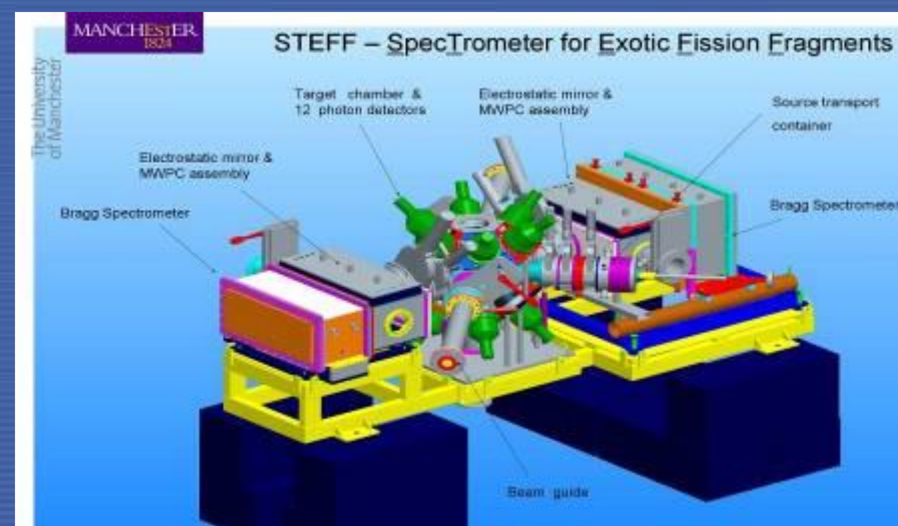
Fission μ-chamber



H9







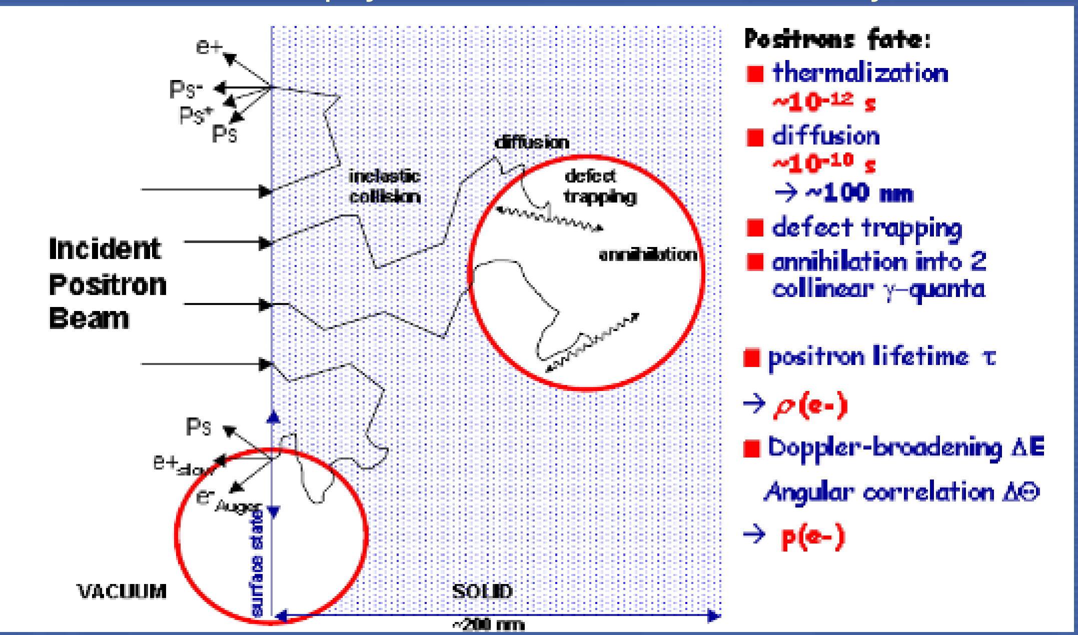
IAEA

Contact: D.Ridikas@iaea.org

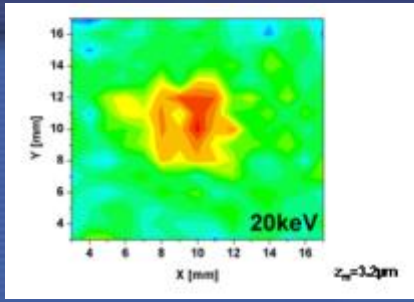
→ Positron source (1)

Use of positron sources:

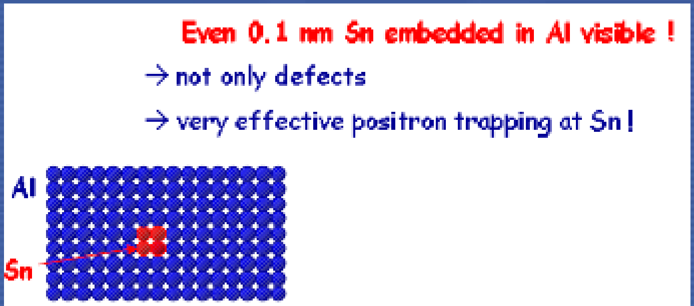
- as particle probe to detect defects in materials
- as particle probe to examine defects in lattices
- in solid state physics for surface sensitive analysis



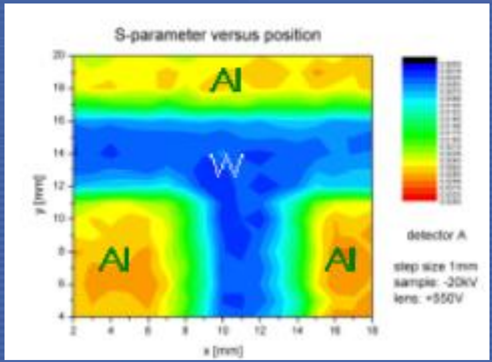
- 3D irradiation defect mapping

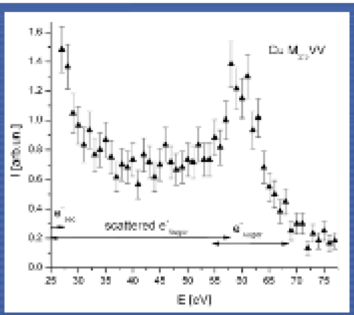


- Examination of lattice defects



- Elemental dependence





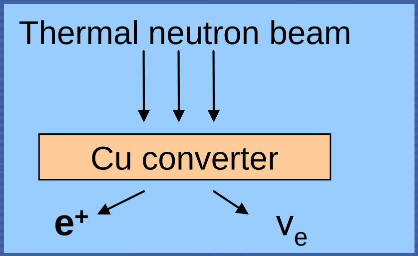
- Surface contamination

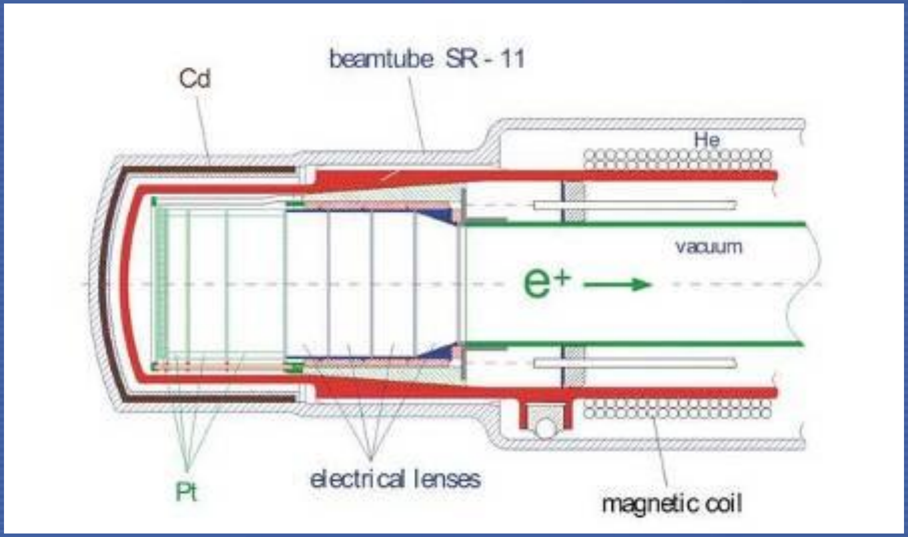
Contact: D.Ridikas@iaea.org

→ Positron source (2)

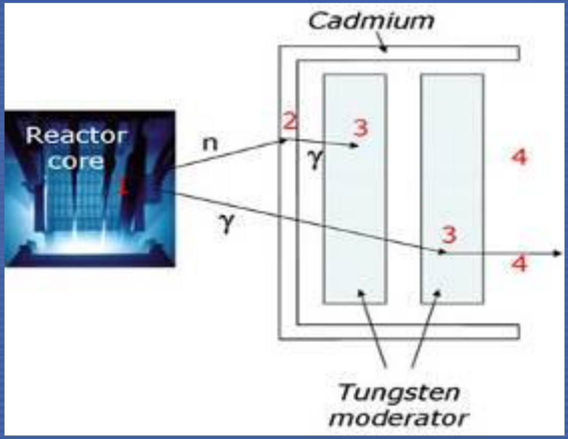
- Activation method

$^{63}Cu\ (n,\gamma)\ ^{64}Cu \rightarrow\ ^{64}Ni + e^{+} + \nu_e$ (12.8h)

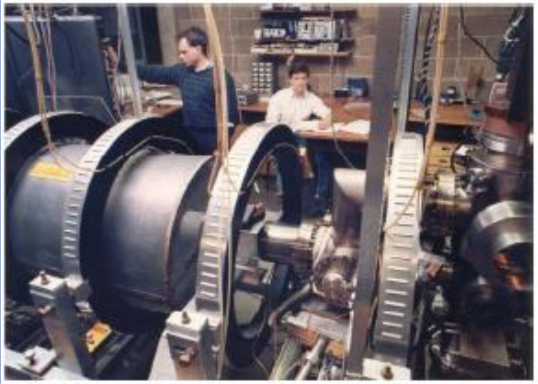




- Hard Gamma Ray Direct Converter Method



MAGNETIC-TRANSPORT POSITRON BEAM



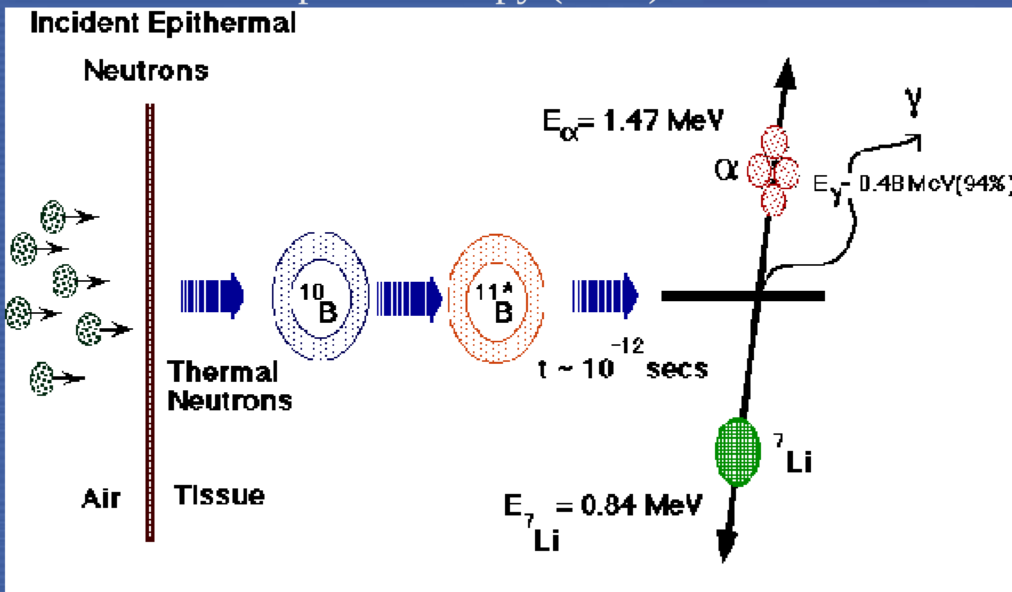
1. n & γ are emitted from reactor core
2. (n,γ) on Cd produce additional γ
3. Pair creation in W
4. Moderated positrons are emitted

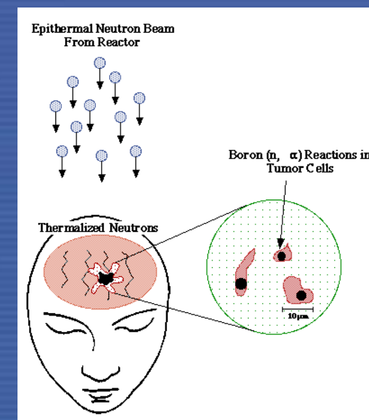
IAEA

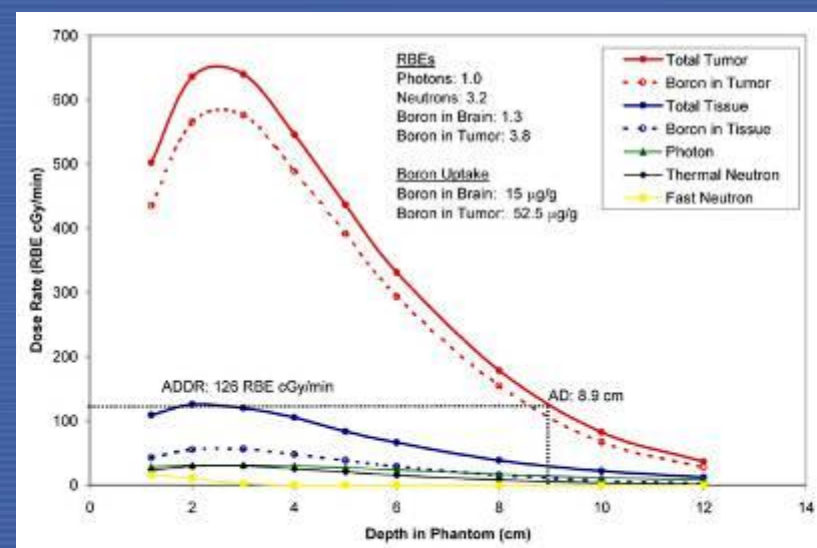
Contact: D.Ridikas@iaea.org

→ Neutron Capture Therapy (1)

Four years after the discovery of neutrons in 1932 by J. Chadwick of Cambridge University, a biophysicist, G.L. Locher of the Franklin Institute at Pennsylvania introduced the concept of Neutron Capture Therapy (NCT).







3 figures of merit in terms of advantage:

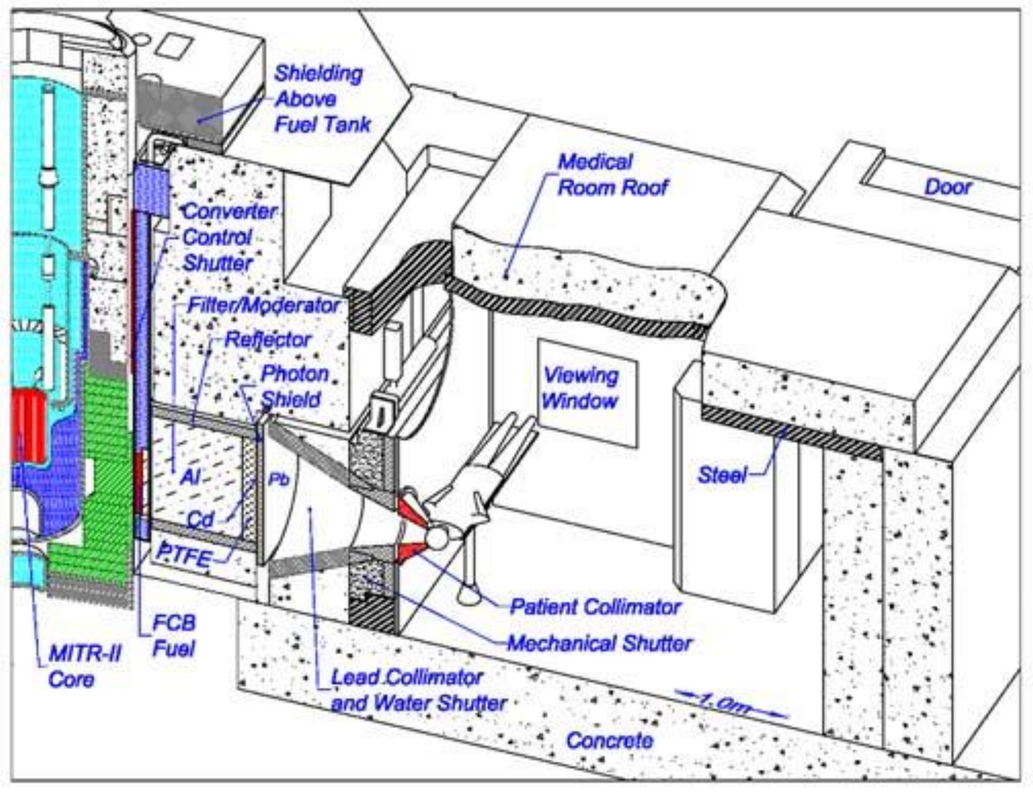
- depth
- dose ratio
- depth-dose rate

and… remaining questions! In total <1000 patients treated, mainly in Finland and Japan

IAEA

Contact: D.Ridikas@iaea.org

Neutron Capture Therapy (2)



Dose phantom

Clinical treatment: patient's position

Contact: D.Ridikas@iaea.org

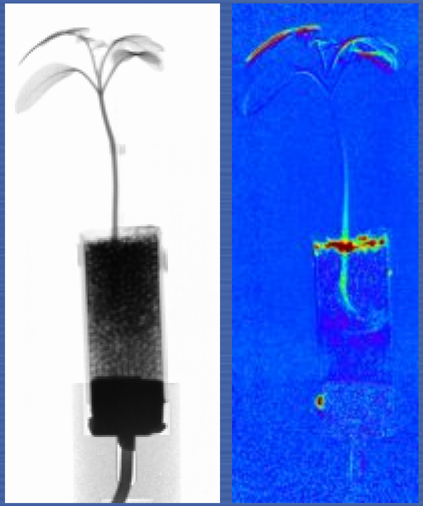
→ Neutron Radiography (1)

- Provide static or dynamic “picture” in 2D or 3D
- Non-destructive technique down to 10 μm level
- Various applications
  →Potential income

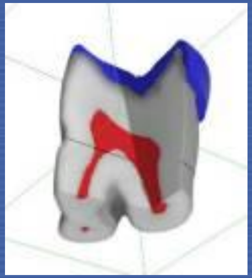
Mineral distribution in stones

Application to plants

Lubricates in engines

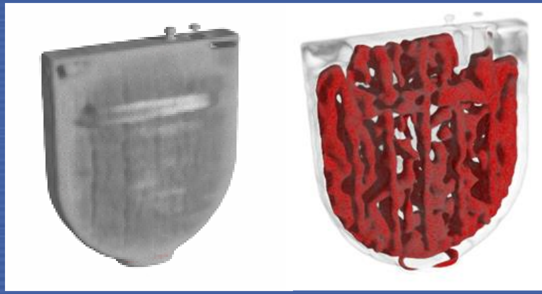


H_2O D_2O



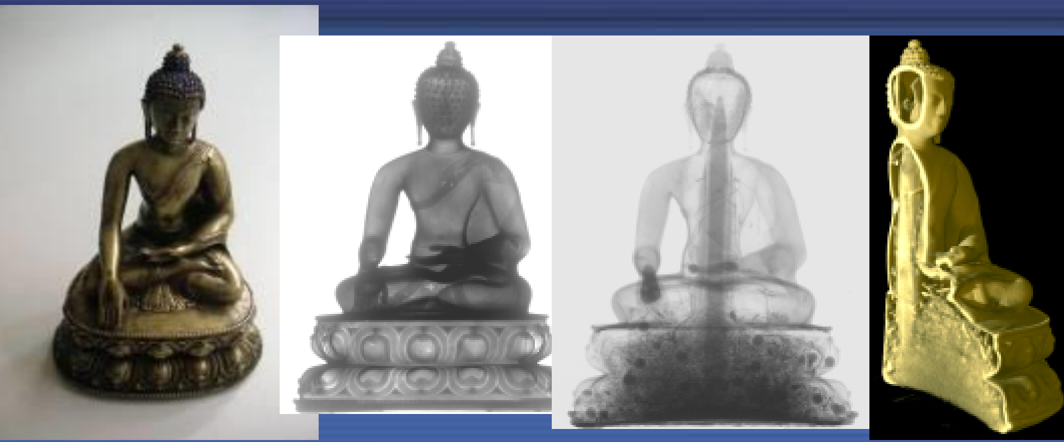
Medical applications

Voltage sources/cells



Contact: D.Ridikas@iaea.org

→ Neutron Radiography (1) continued

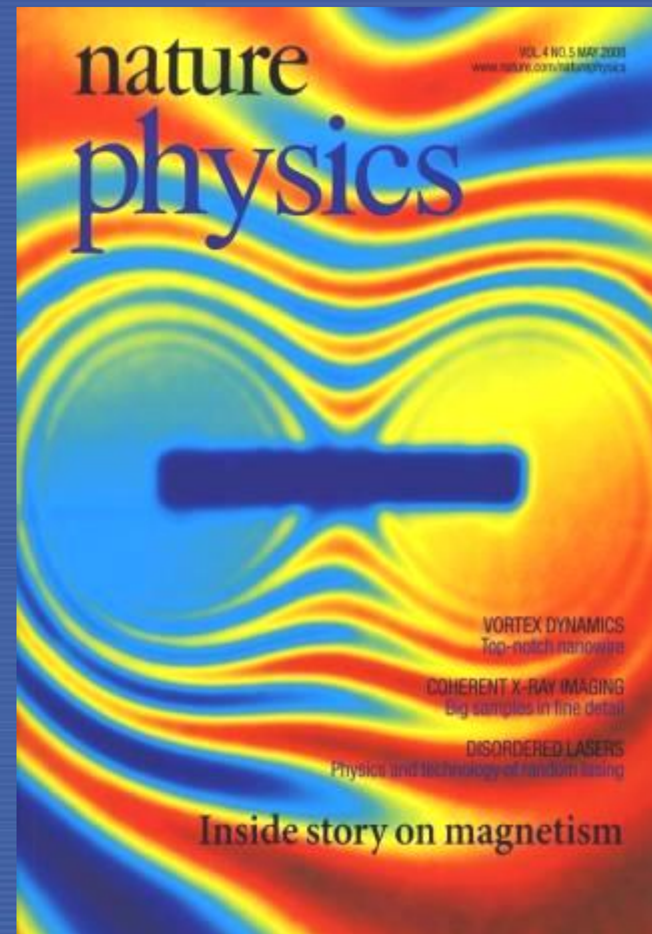


Cultural heritage:

Photo, x-ray, radiography, tomography

Brasing connections

- Polarised neutron tomography

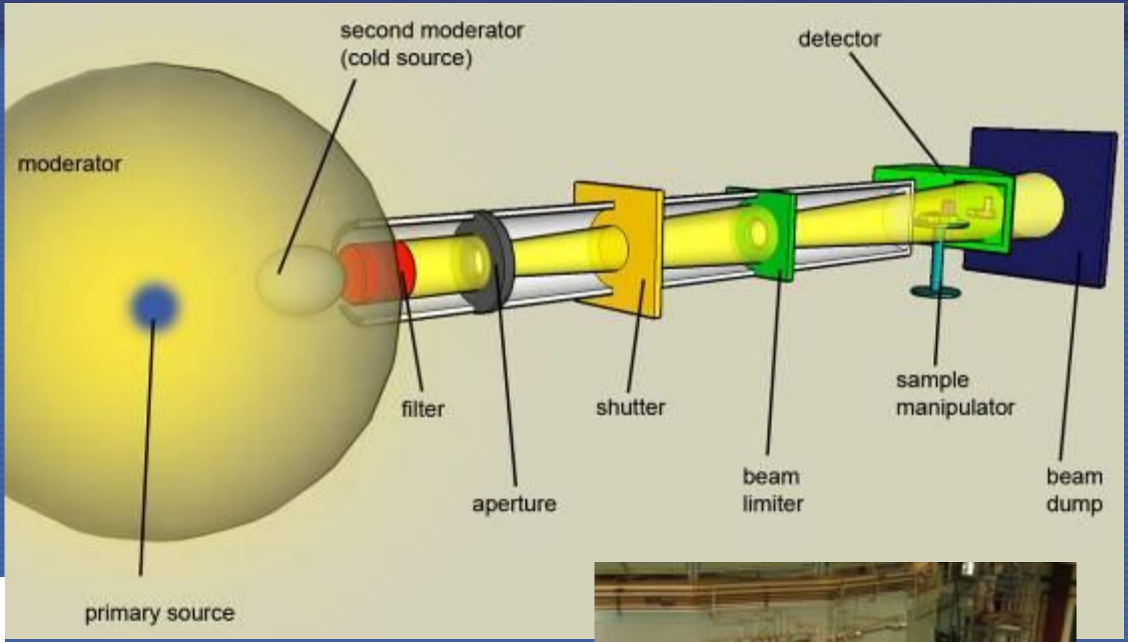


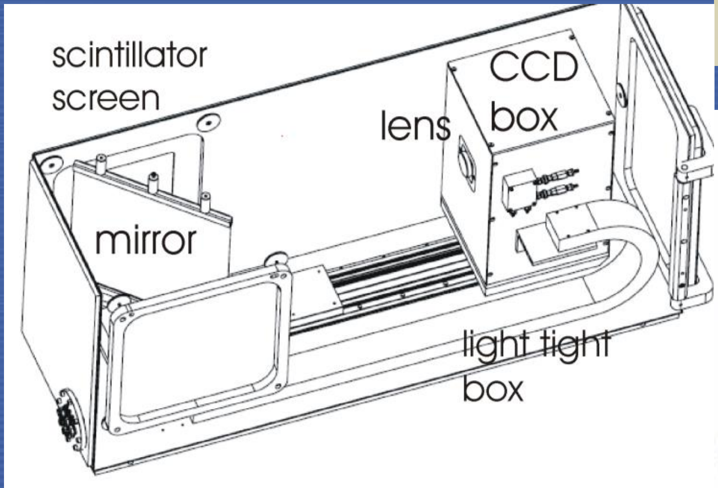
IAEA

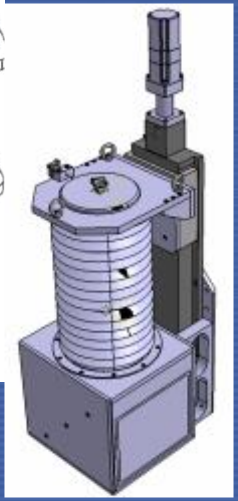
Contact: D.Ridikas@iaea.org

→ Neutron radiography (2)

- Neutron beam
- Detection system
- Manipulation system
- Computer system
- Image Reconstruction Software
- Image display
- Operator Interface





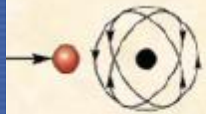


Contact: D.Ridikas@iaea.org

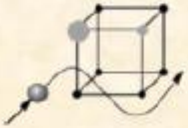
Basics on neutron scattering research

Why Neutrons?

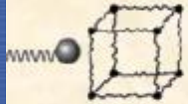
1. Neutrons have the right wavelength



2. Neutrons see the Nuclei



3. Neutrons see Light Atoms next to Heavy Ones



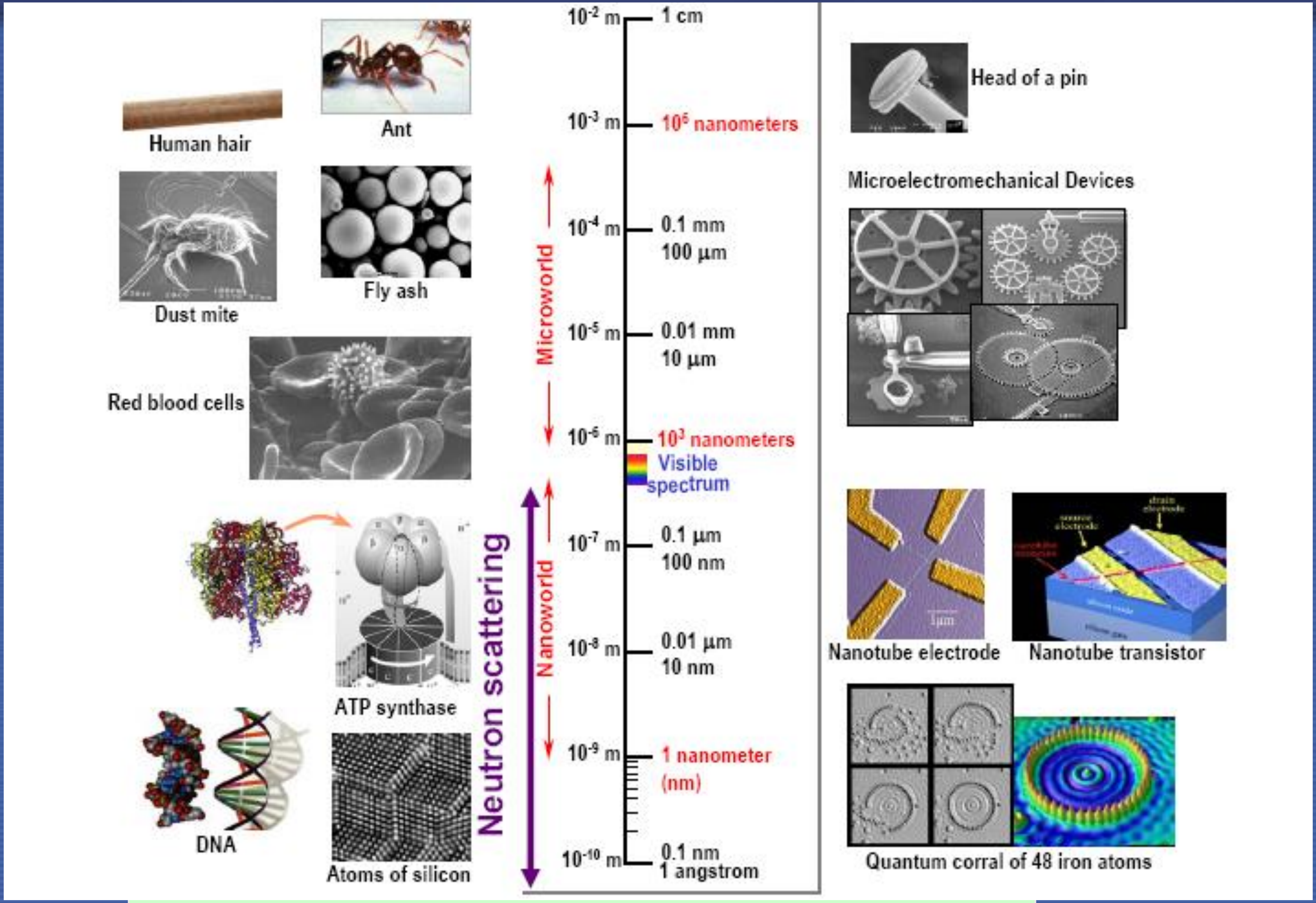
4. Neutrons measure the Velocity of Atoms

5. Neutrons penetrate deep into Matter

6. Neutrons see Elementary Magnets

Contact: D.Ridikas@iaea.org

→ Neutron scattering (1)



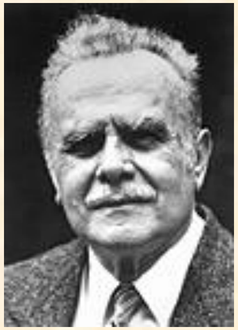
Neutrons: microns to angstroms!

IAEA

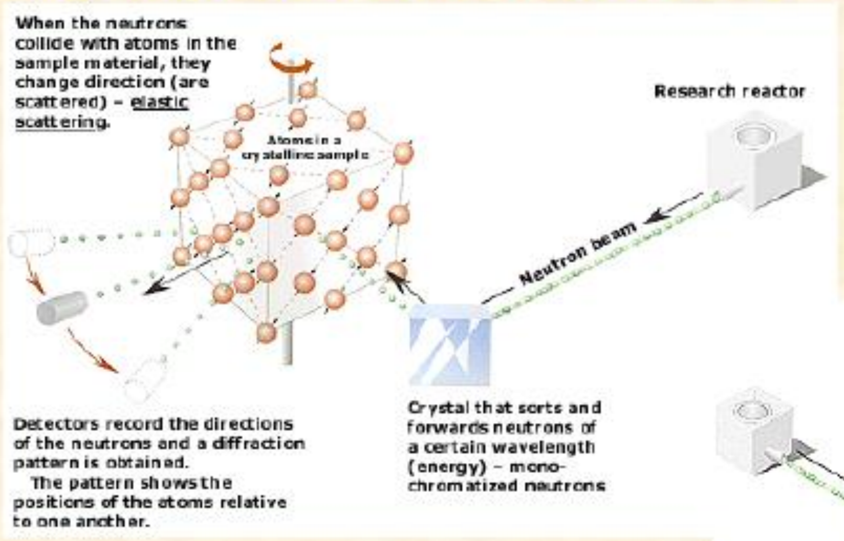
Contact: D.Ridikas@iaea.org

What do neutrons do?

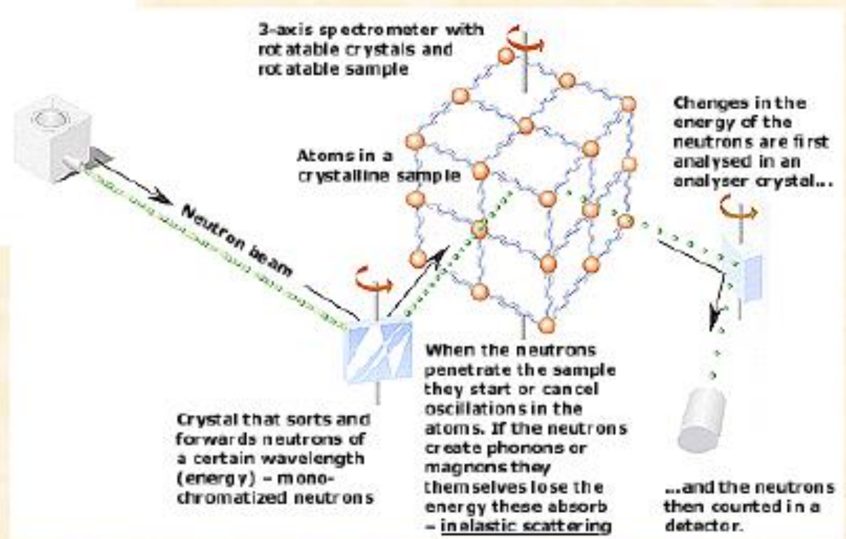
Nobel Prize in Physics 1994 - Shull and Brockhouse



Neutrons show where atoms are…..



… and what atoms do



Contact: D.Ridikas@iaea.org

→ Neutron scattering (2)

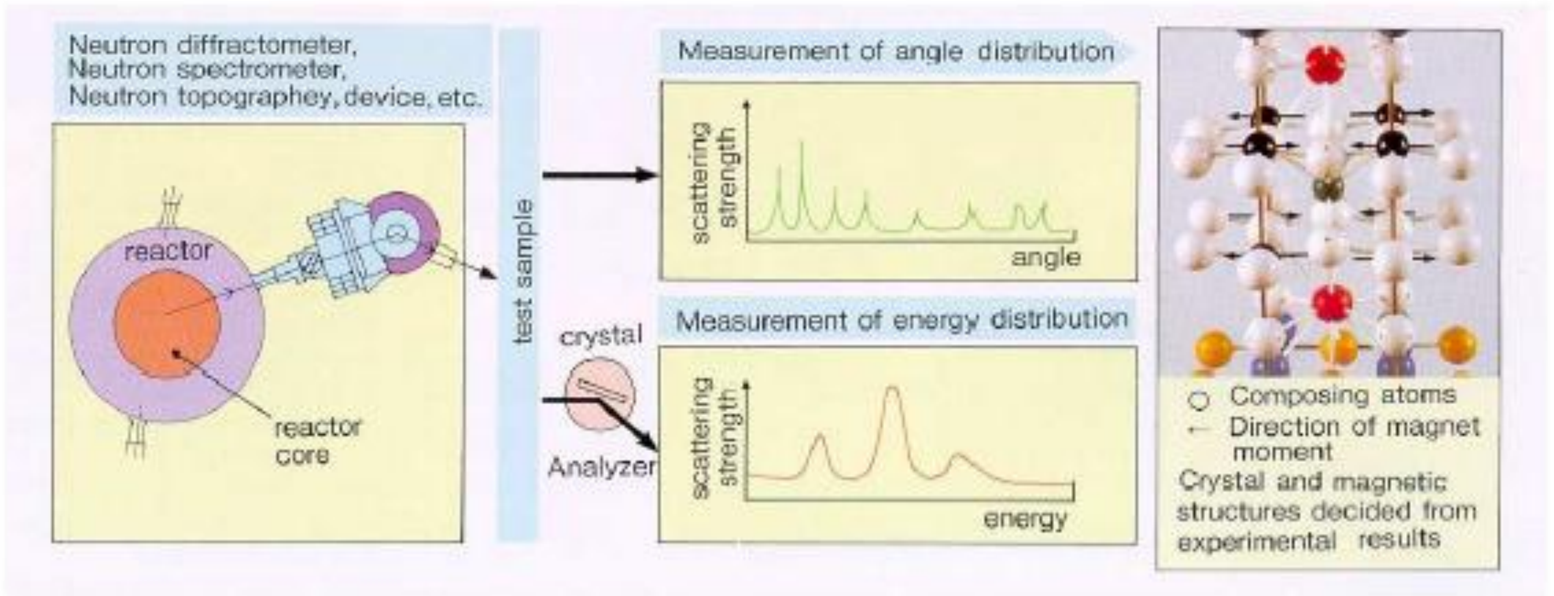


FIG. 10. The neutron scattering methodology.

- Cold, thermal, hot neutron sources
- Neutron beams, neutron guides, mirrors and ports
- Neutron scattering instruments

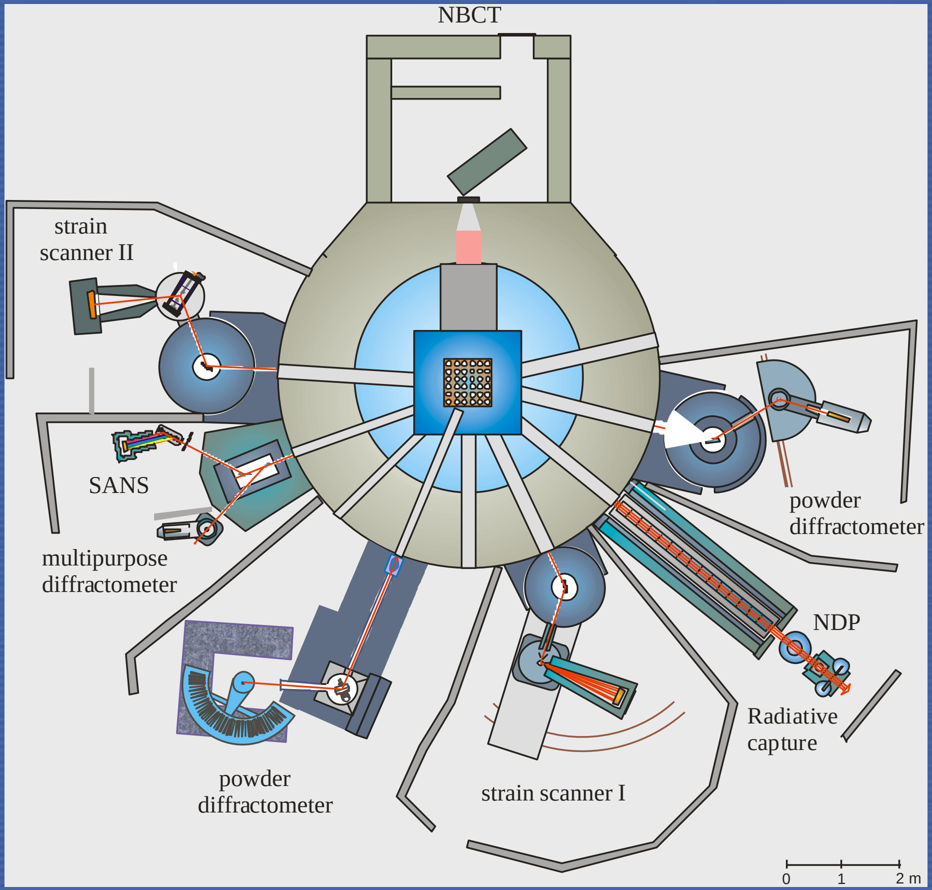
(diffractometer, spectrometer, interferometer, strain scanner,…)

- Data acquisition, analysis and interpretation systems

Contact: D.Ridikas@iaea.org

→ Neutron scattering (2)

Experimental facilities installed @ LVR-15

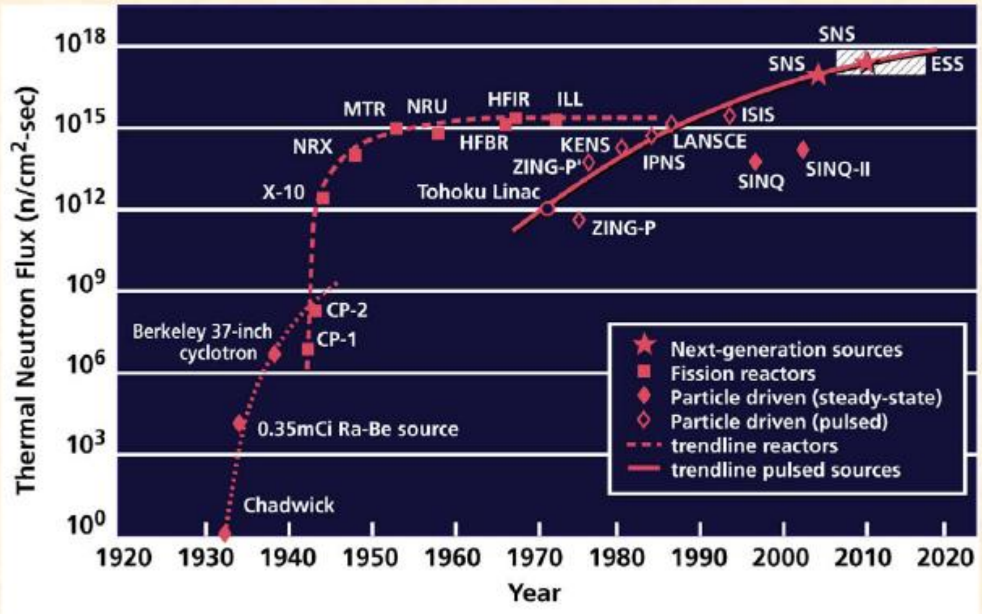


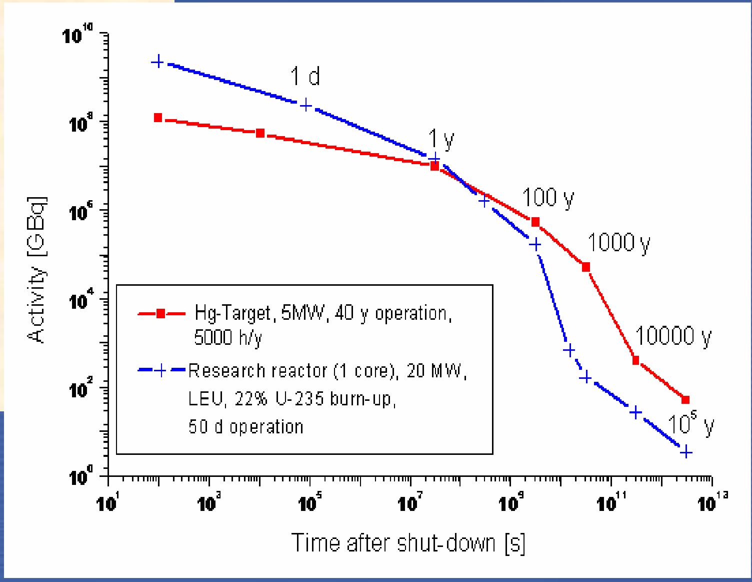
Guide hall II @ HZB

Contact: D.Ridikas@iaea.org

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

IAEA

Contact: D.Ridikas@iaea.org

How do we produce neutrons?

a) www.ill.fr

a. Fission Reactions

$n^1 + U^{235} \rightarrow$ 2 fission fragments + $2.5n^1$ + 200 MeV

thermal

1 neutron to maintain chain reaction

1 neutron escapes & is available for use

0.5 neutrons absorbed

1 neutron

2 to 3 neutrons

Example: 20 MW Research Reactor

No. of fissions/sec = $\frac{20 \times 10^6 \text{ watts}}{200 \text{ MeV/fission}}$ = 6×10^{17} fissions/second

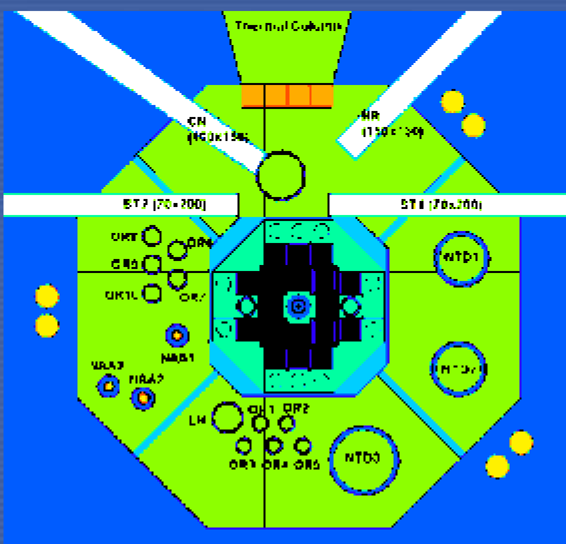
generates 1.5×10^{18} neutrons/sec in the whole reactor volume

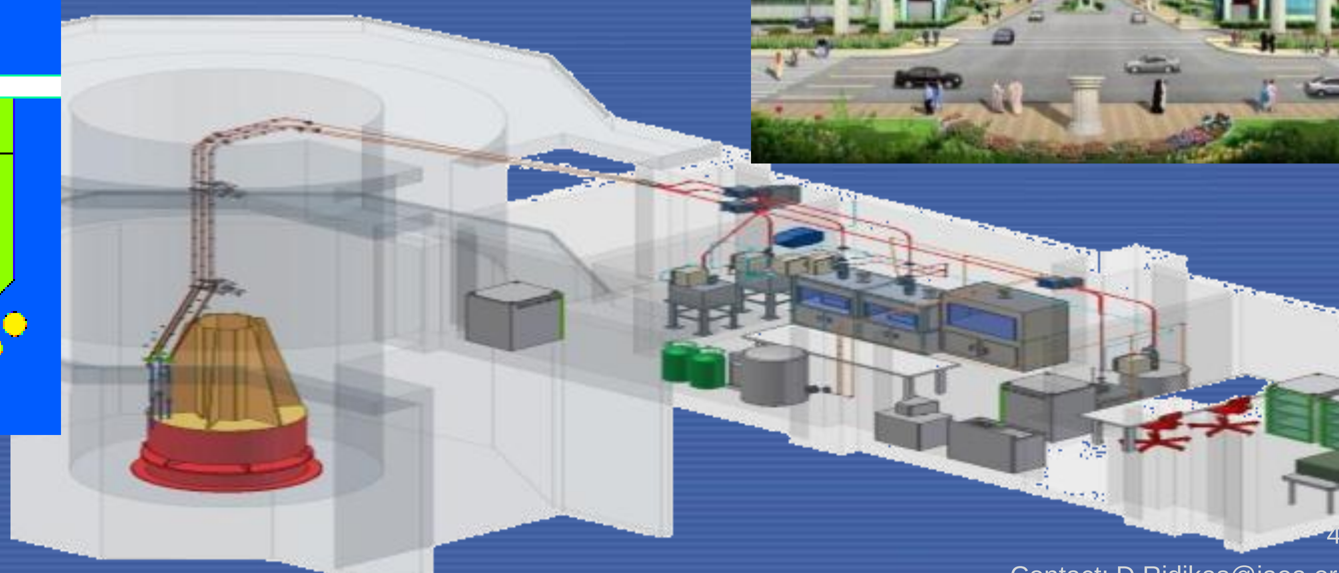
Contact: D.Ridikas@iaea.org

New RRs considered in many developing countries

Example: Jordan Research & Training Reactor (JRTR),
Under construction by KAERI-Daewoo Consortium, operation planned in June 2016

- **5 MW (upgradable to 10MW), neutron flux ~$1.5*10^{14}$ n/(s cm^2)**
- **Fuel: ~19.75 % U-235, U_3Si_2-Al, Coolant & Moderator: H_2O, Reflector: Be**
- **Multipurpose RR: radioisotope production, Si doping, neutron beams, NAA, E&T, etc.**
- **1st step to the national NPP programme**





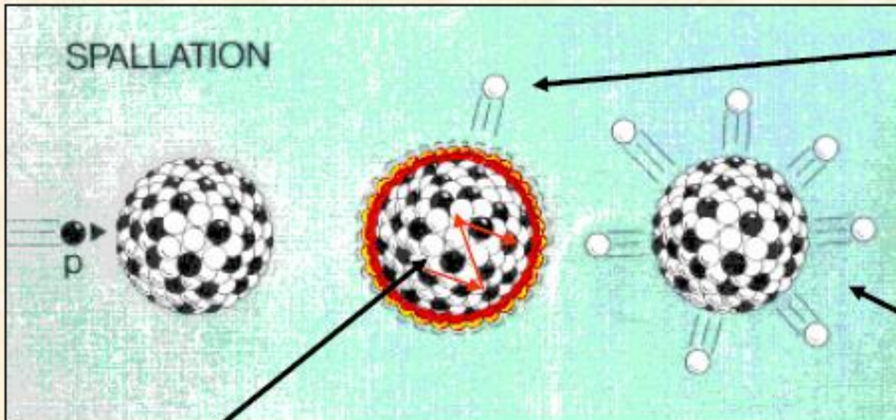
Contact: D.Ridikas@iaea.org

How do we produce neutrons?

b) www.sns.gov

b. Artificially accelerated particles

(iii) Spallation with Protons

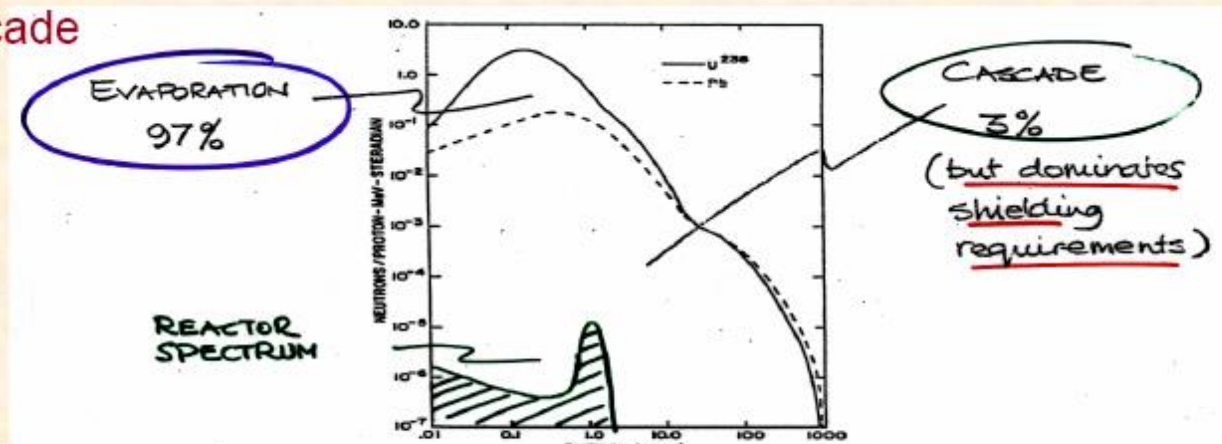


2. Inter Nuclear Cascade

Up to 40 neutrons per incident proton

3. Evaporation

1. Internal Cascade

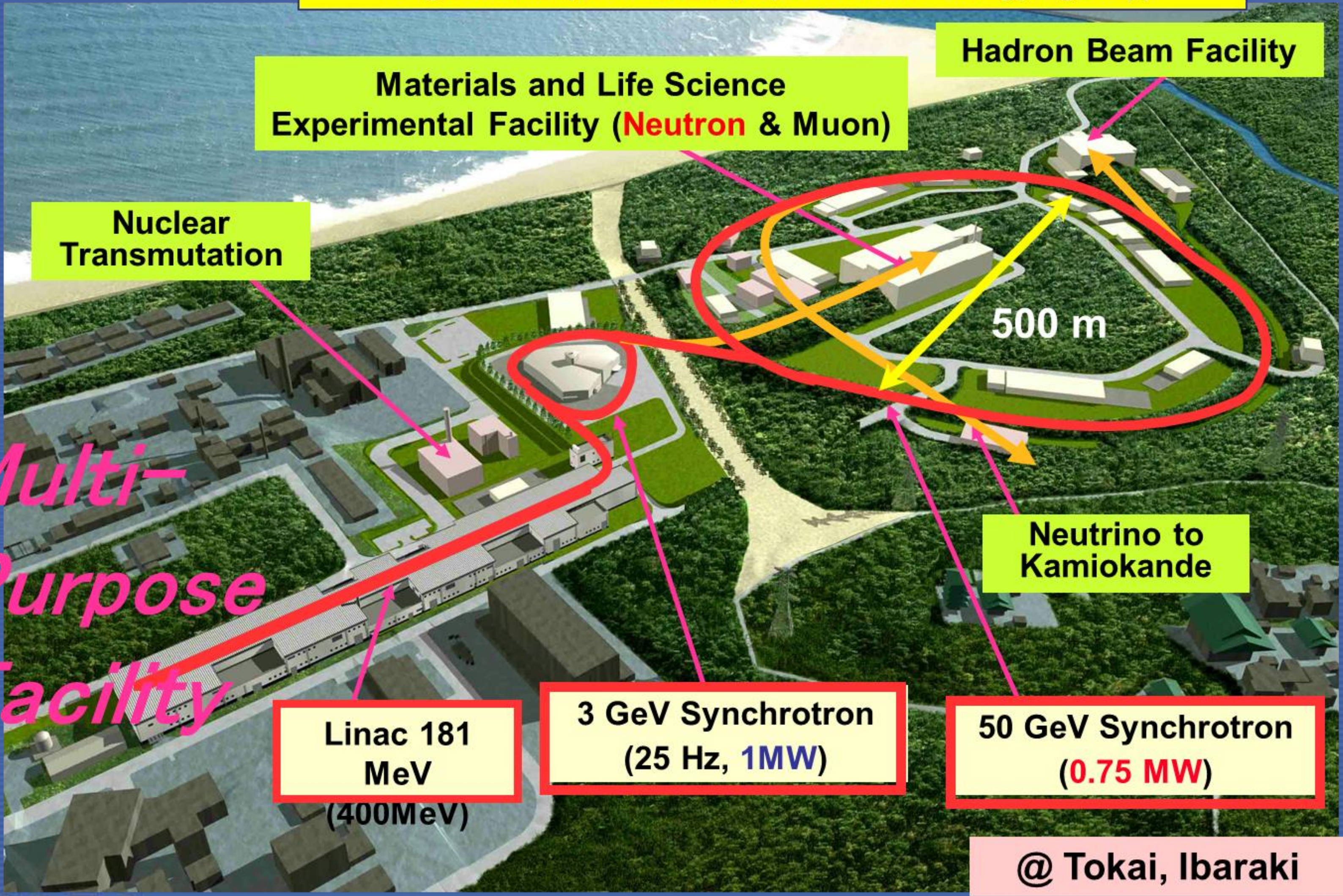


Contact: D.Ridikas@iaea.org

J-PARC

J-PARC = Japan Proton Accelerator Research Complex

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



Multi-Purpose Facility

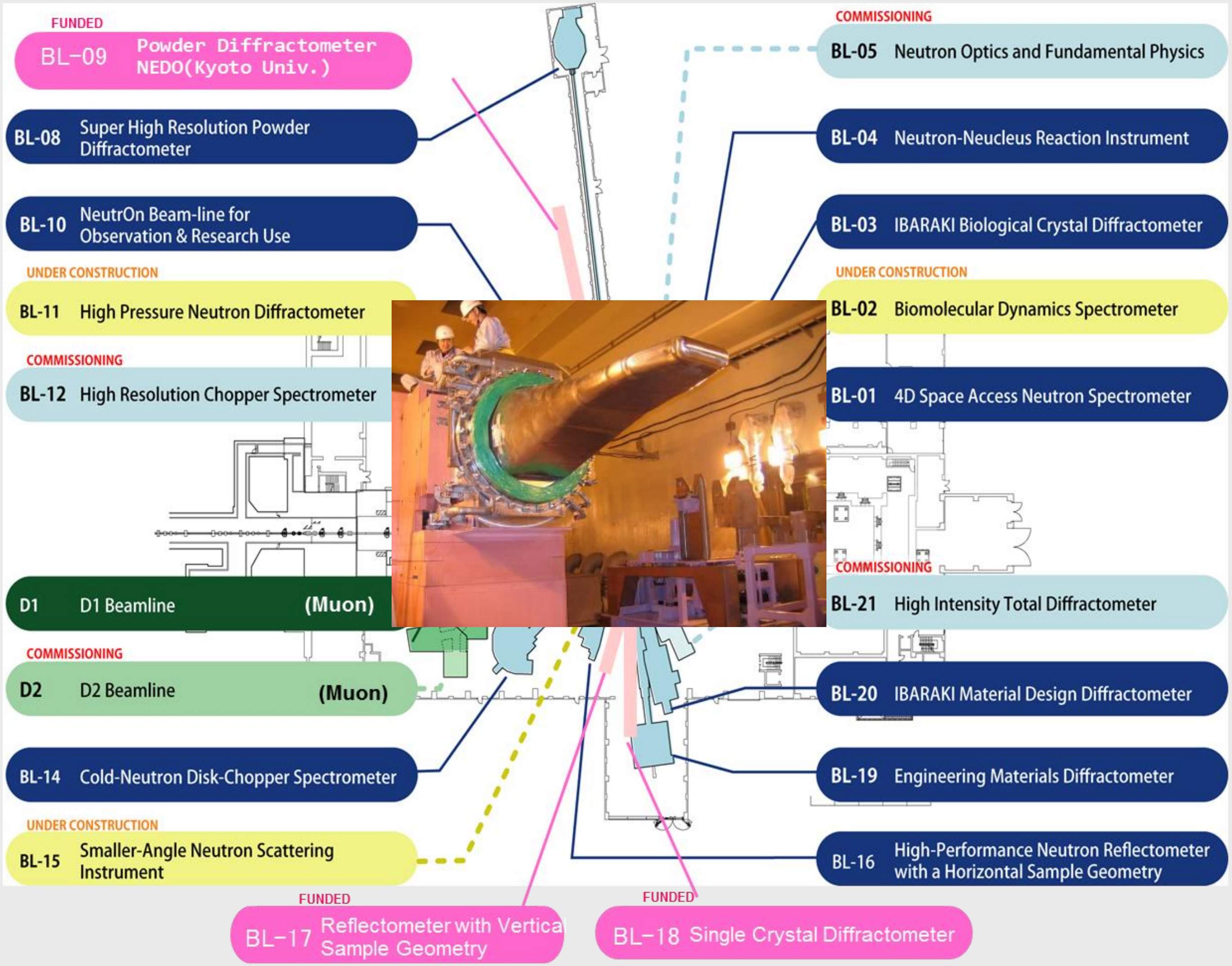
IAEA

Contact: D.Ridikas@iaea.org

Neutron Instruments (Beamlines)

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

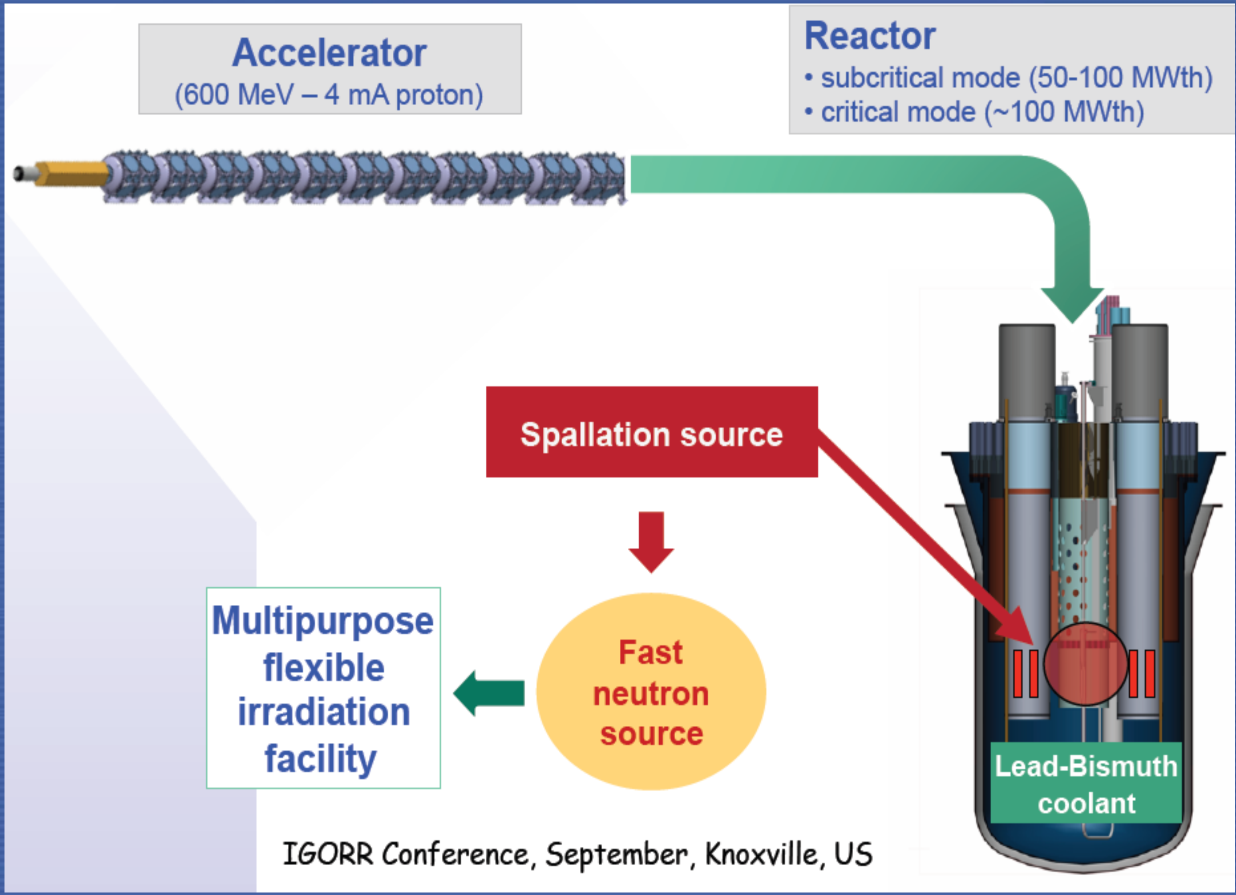
In operation:	9
On-beam commissioning:	3
Under construction:	3
Funded:	3



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
  - …

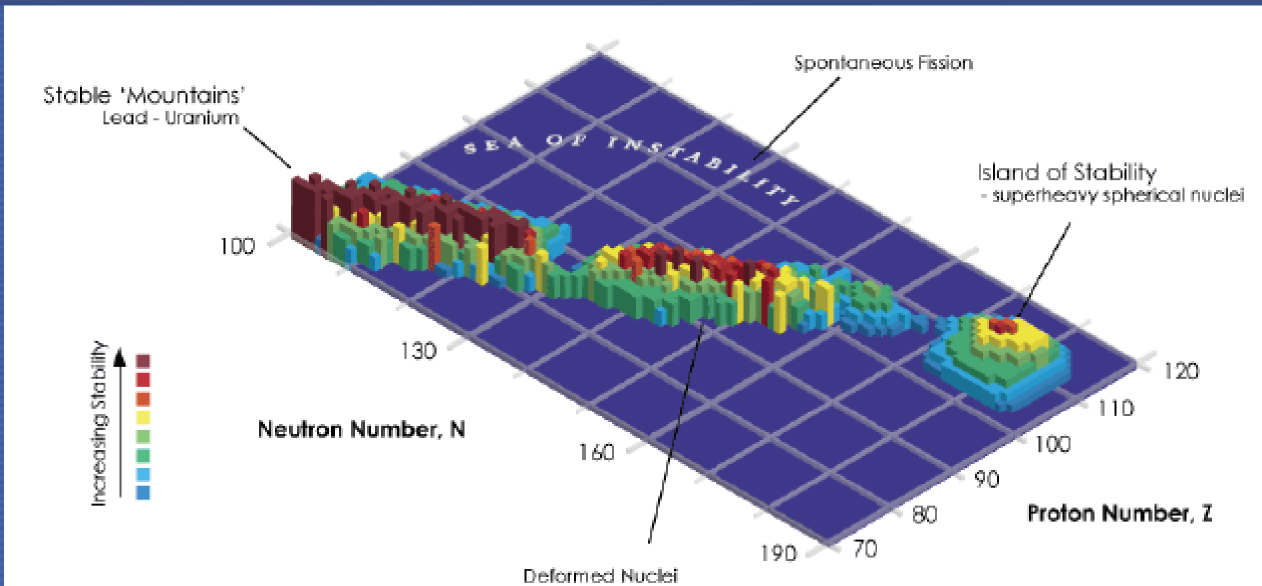


IAEA

Contact: D.Ridikas@iaea.org

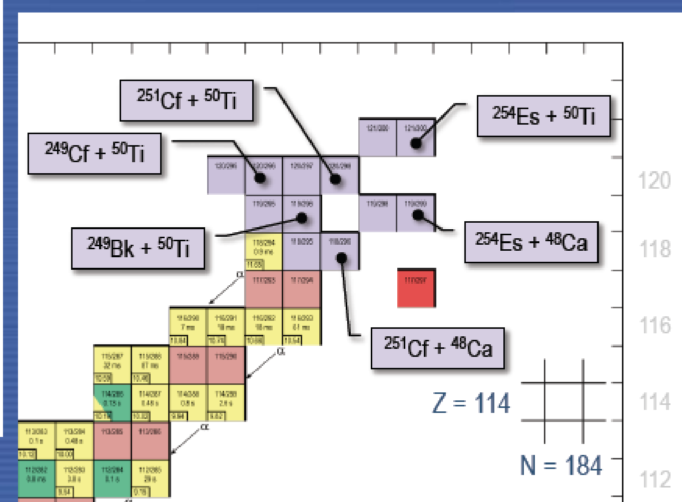
Combined applications of RRs and Accelerators:

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



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

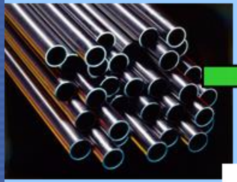
Gen I | Gen II | Gen III | Gen III+ | Gen IV

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

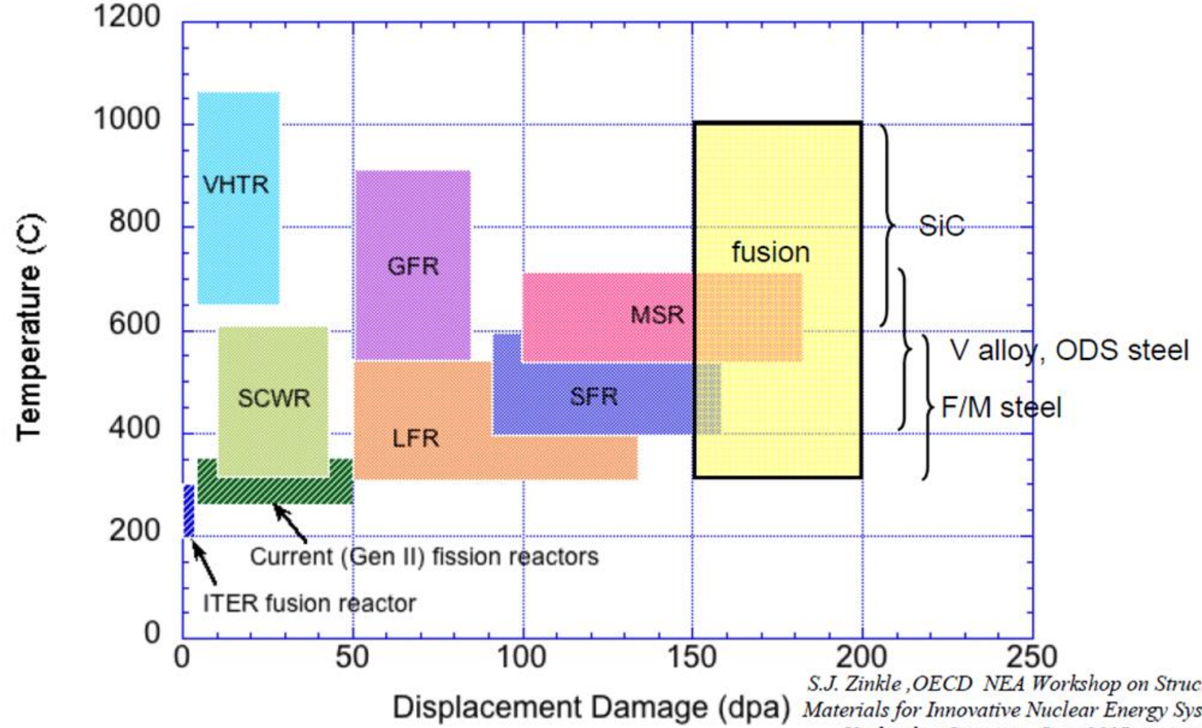
IAEA

Contact: D.Ridikas@iaea.org

Material development in nuclear industry

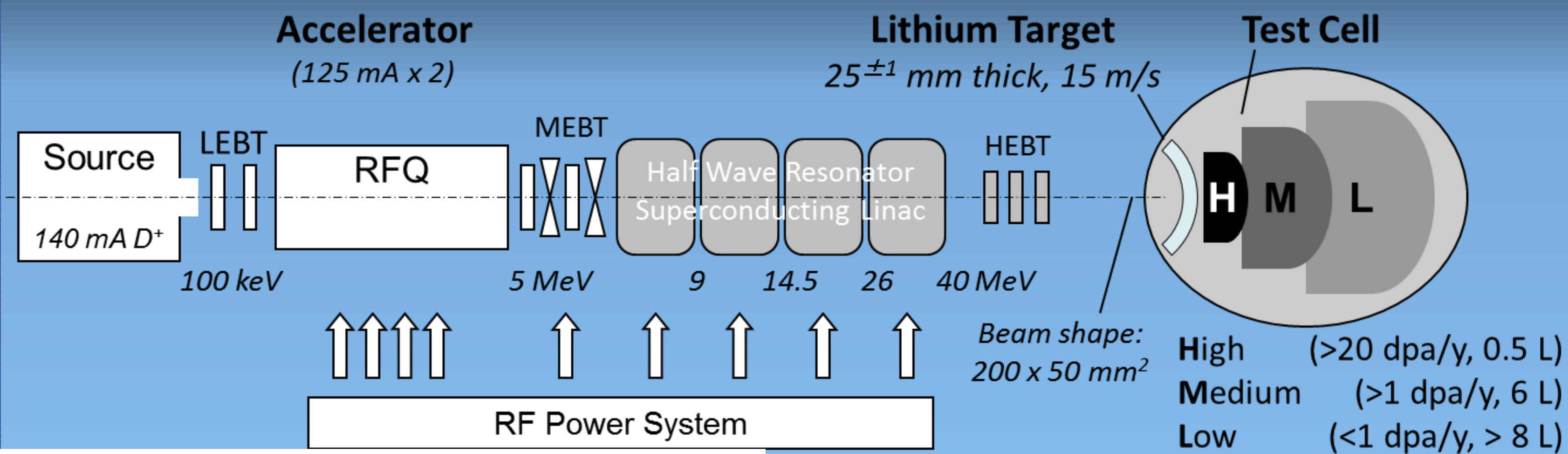


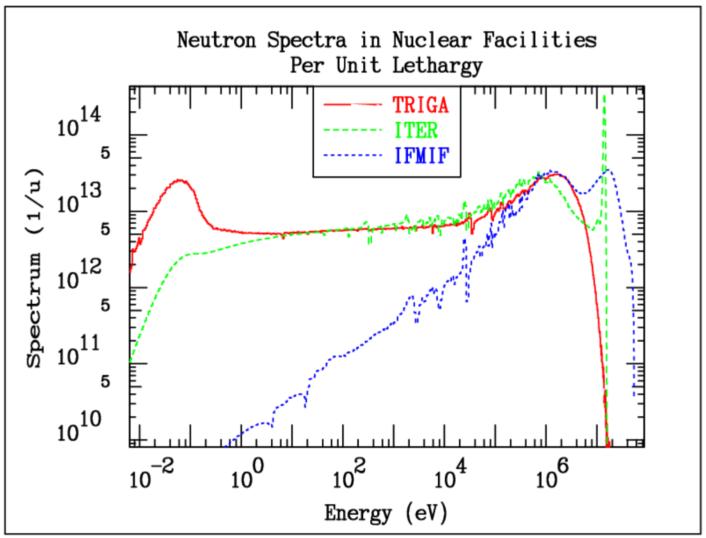
Selection → Characterisation → Qualification



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

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

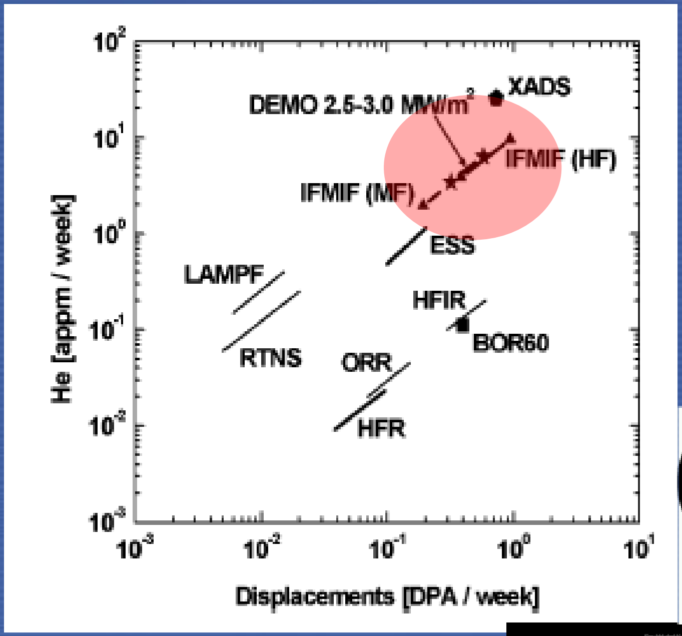
$^{6}Li(d,n)^{7}Be$

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

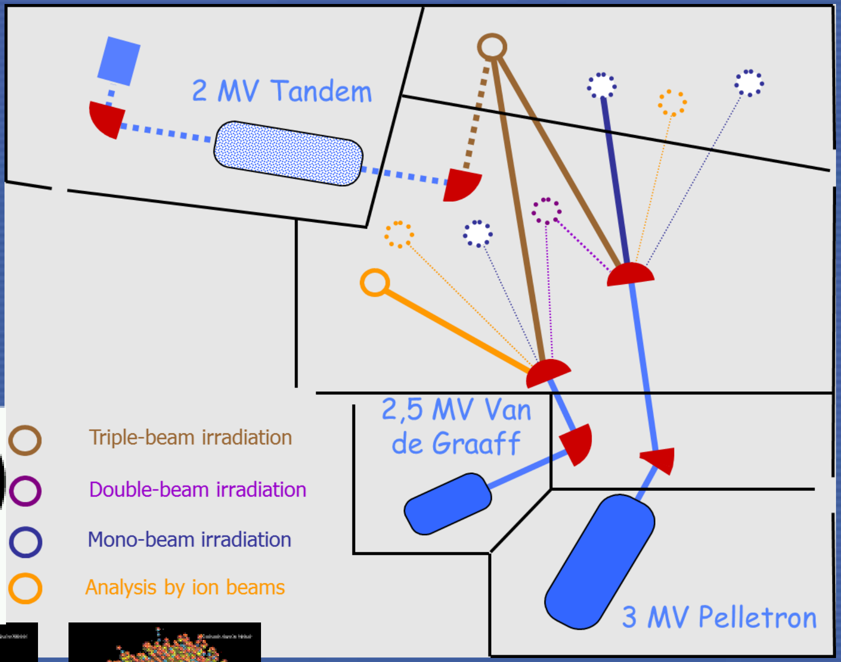
Contact: D.Ridikas@iaea.org

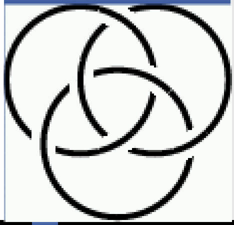
Combined/comprehensive multi-disciplinary approach

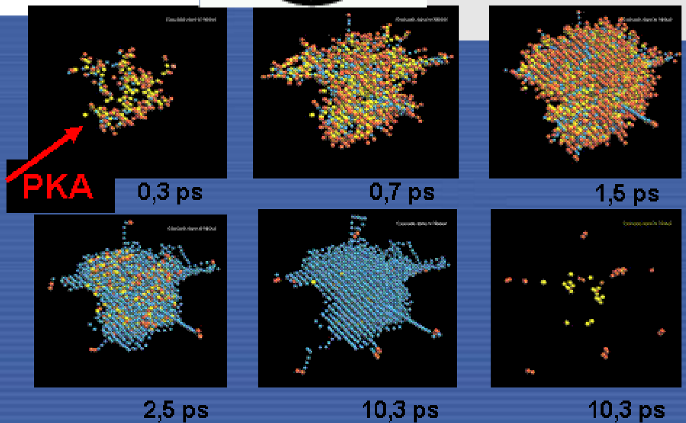
High Flux Fast RRs for dpa generation (e.g. BOR60 in Russia)



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







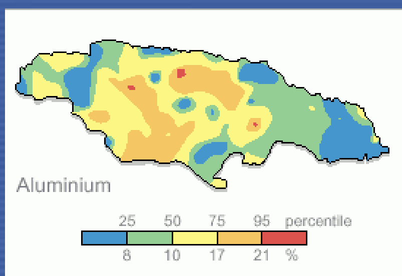
Use the best physics understanding through complex modelling of occurring phenomena

Contact: D.Ridikas@iaea.org

Research Reactors will remain indispensable training, research and technological tools

Radioisotopes for improved agricultural yields

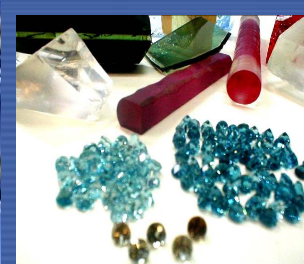
Radioisotopes for medical diagnosis & treatment



Neutron activation analysis for geological & environmental studies

Neutron imaging for studying objects of national heritage

Irradiation effects leading to added value of products



Education & training in nuclear science & technology

Neutron scattering for better materials & objects

IAEA

Contact: D.Ridikas@iaea.org

List of main references for RRs@IAEA

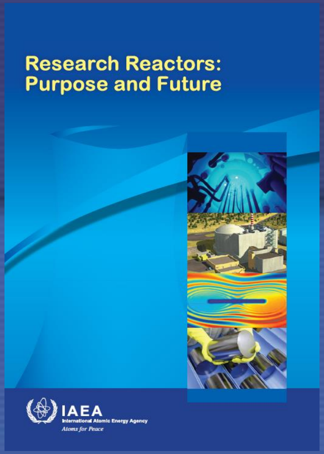
NA: http://www-naweb.iaea.org/napc/physics/research_reactors/

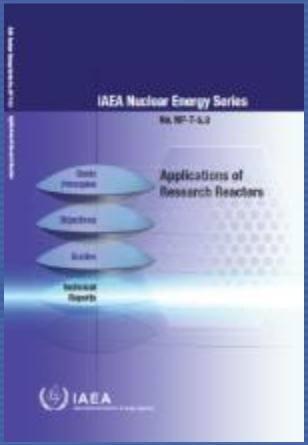
NE: http://www.iaea.org/OurWork/ST/NE/NEFW/Technical_Areas/RRS/home.html

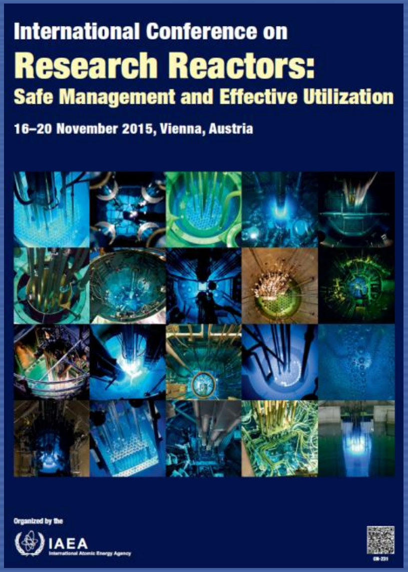
NS: http://www-ns.iaea.org/tech-areas/research-reactor-safety/

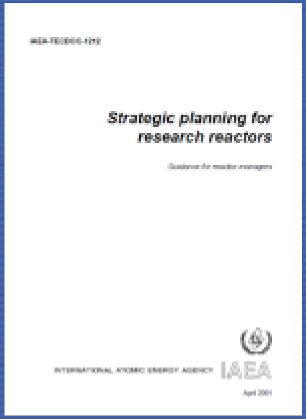
IAEA RRDB: http://nucleus.iaea.org/RRDB/

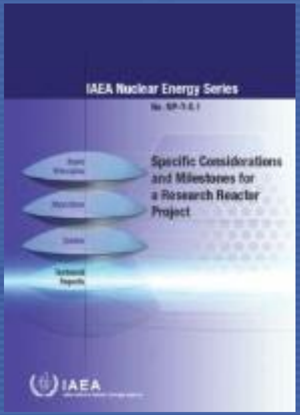
Bibliography:
http://www.iaea.org/OurWork/ST/NE/NEFW/Technical_Areas/RRS/bibliography.html











Contact: D.Ridikas@iaea.org