IAEA Projects on Radiation Effects Modelling and Experiments for Fission and Fusion Power Plants

Joint ICTP-IAEA Workshop on the
Training in Basic Radiation Materials Science and its
Applications to Radiation Effects Studies and
Development of Advanced Radiation-Resistant Materials

G. Mank

IAEA, Physics Section

IAEA
International Atomic Energy Agency

21 November 2008, ICTP, Trieste

Outline

1. Introduction

2. Materials Research
    1. Research Reactors
    2. Fusion
    3. Accelerators

3. IAEA activities on Materials Research (Physics Section)

IAEA

The Demand

- New fuel for the next generation of NPP
- Simulation and modelling of radiation effects (using accelerators and research reactors)
- Synergies related to fission and future fusion power plants

IAEA

The Challenge

- Materials Research at Research Reactors (overbooking – under-utilization)

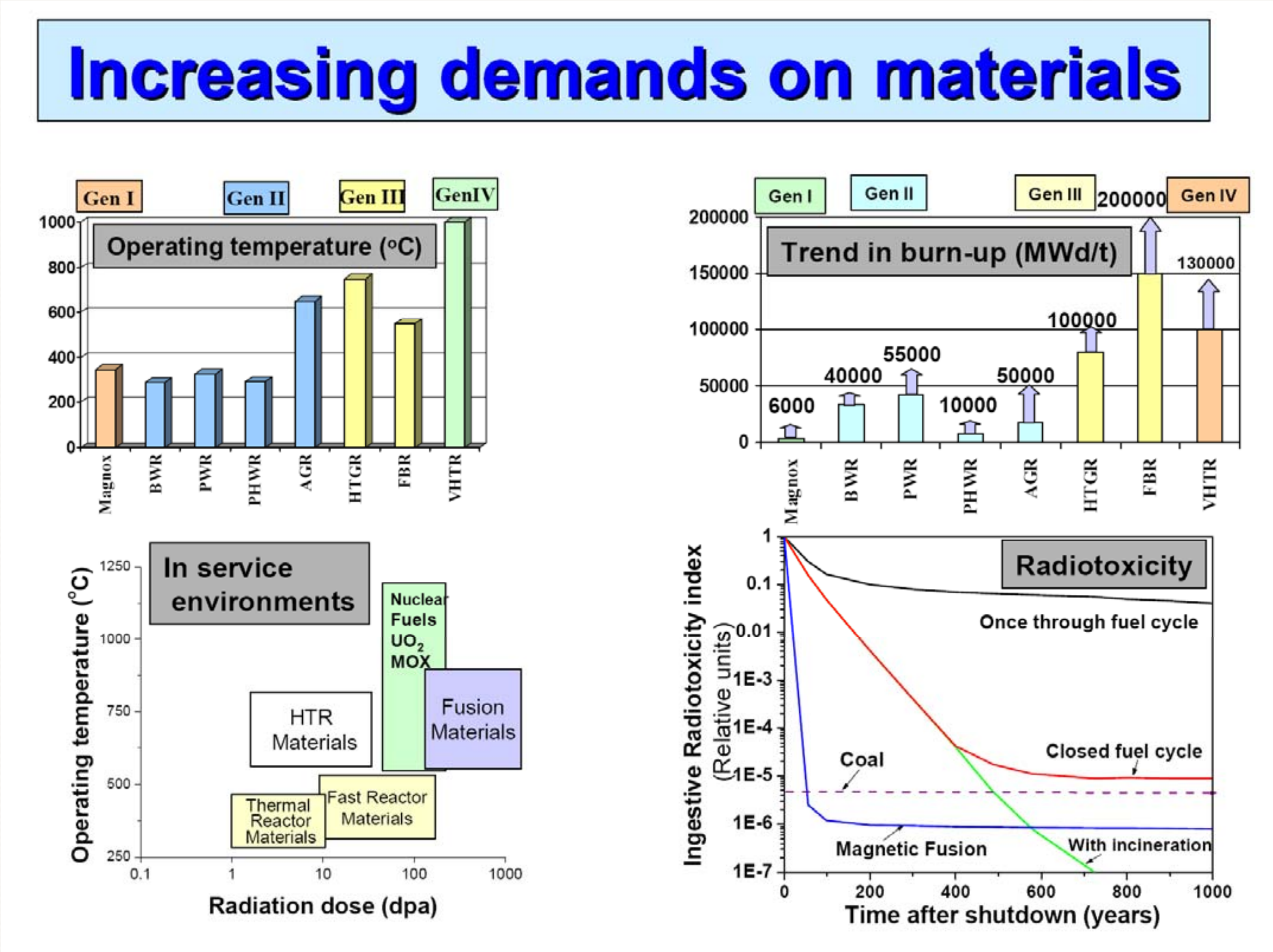
- Accelerators (tool for materials research)

- ITER and the fusion demo reactor

- Next Generation Power Plants

IAEA

The Challenge - Fission



IAEA

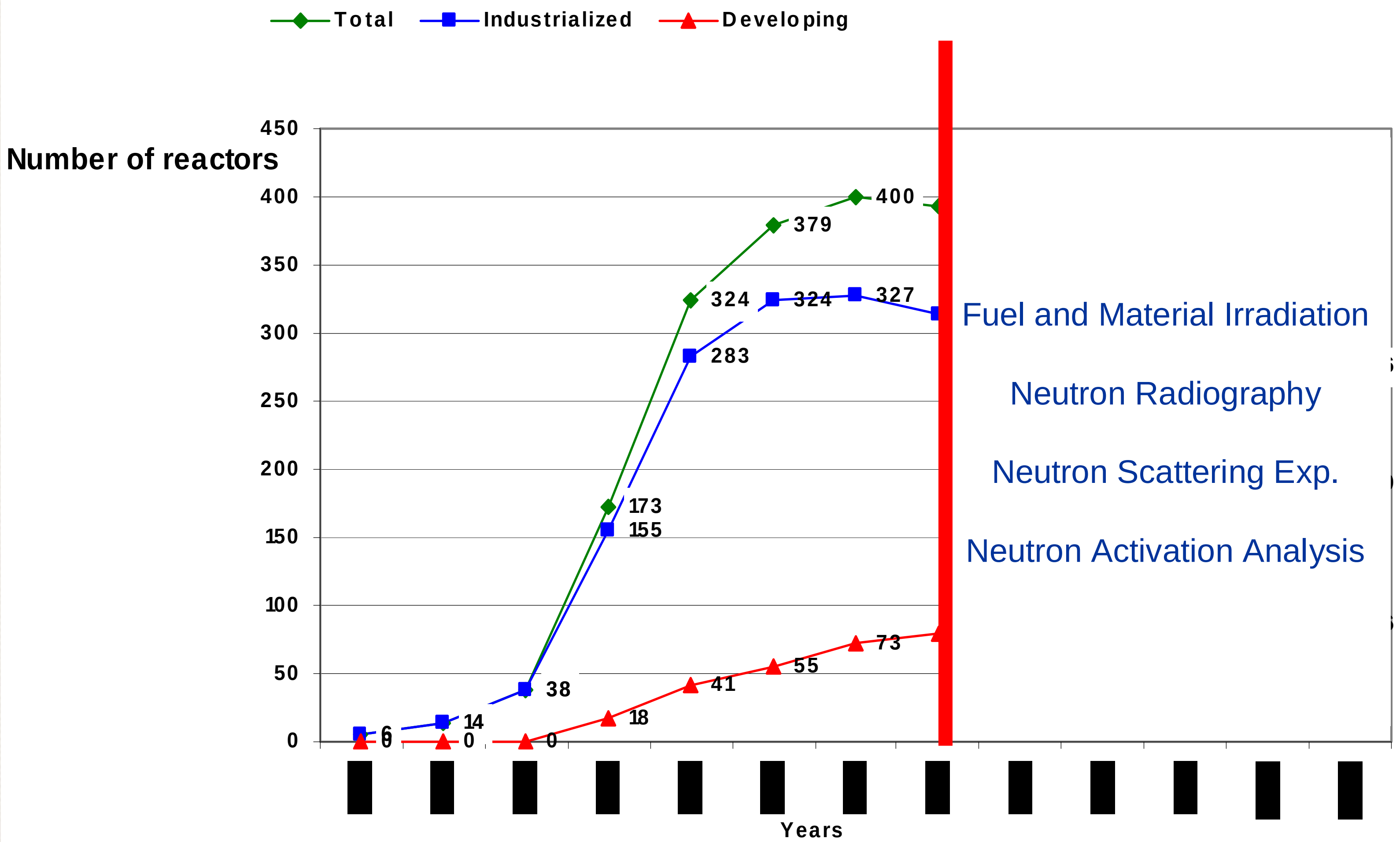
IAEA Scientific Forum 2005,
http://www-pub.iaea.org/MTCD/Meetings/Announcements.asp?ConfID=138

The Challenge - Fission

This workshop

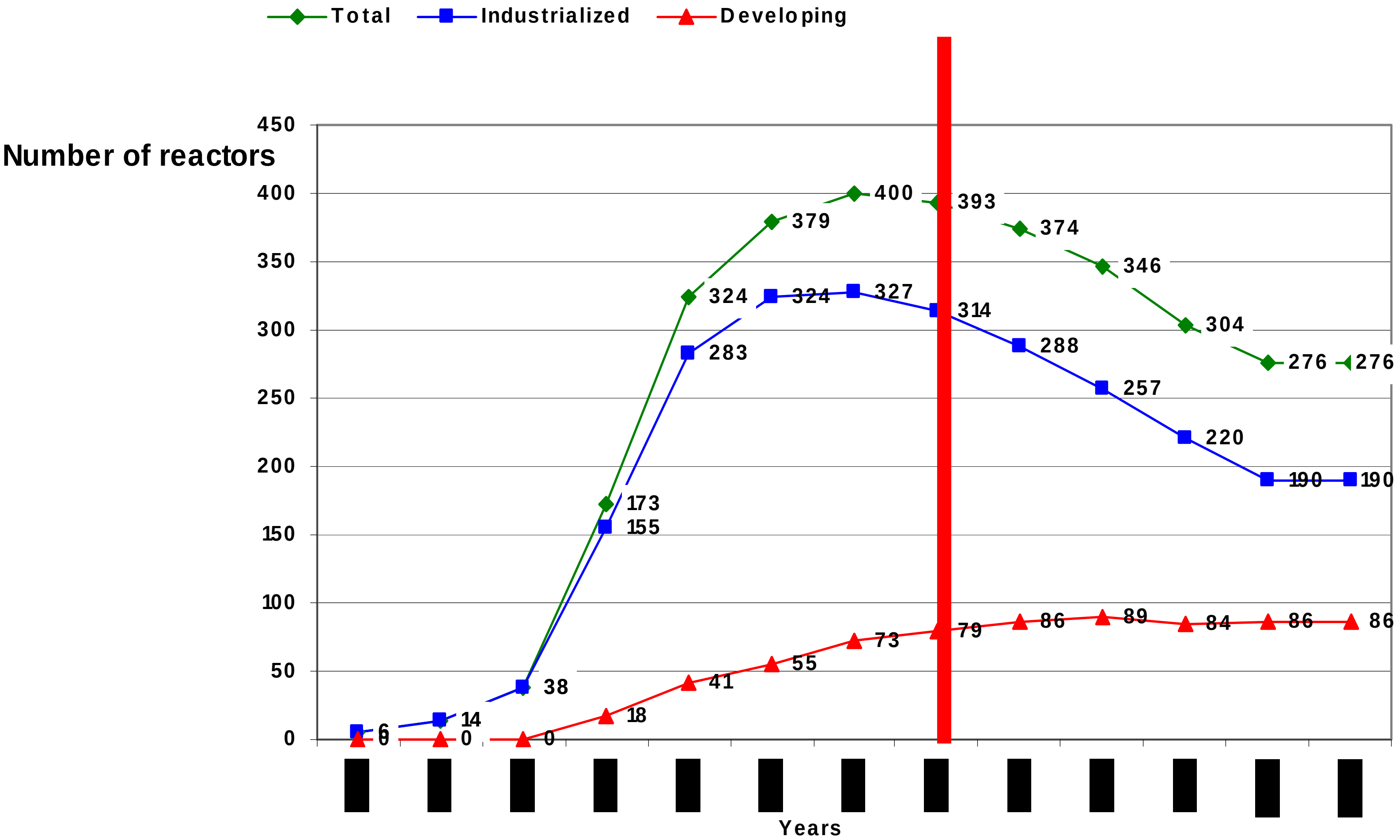
IAEA

Number of Research Reactors



Number of research reactors in industrialized and developing countries

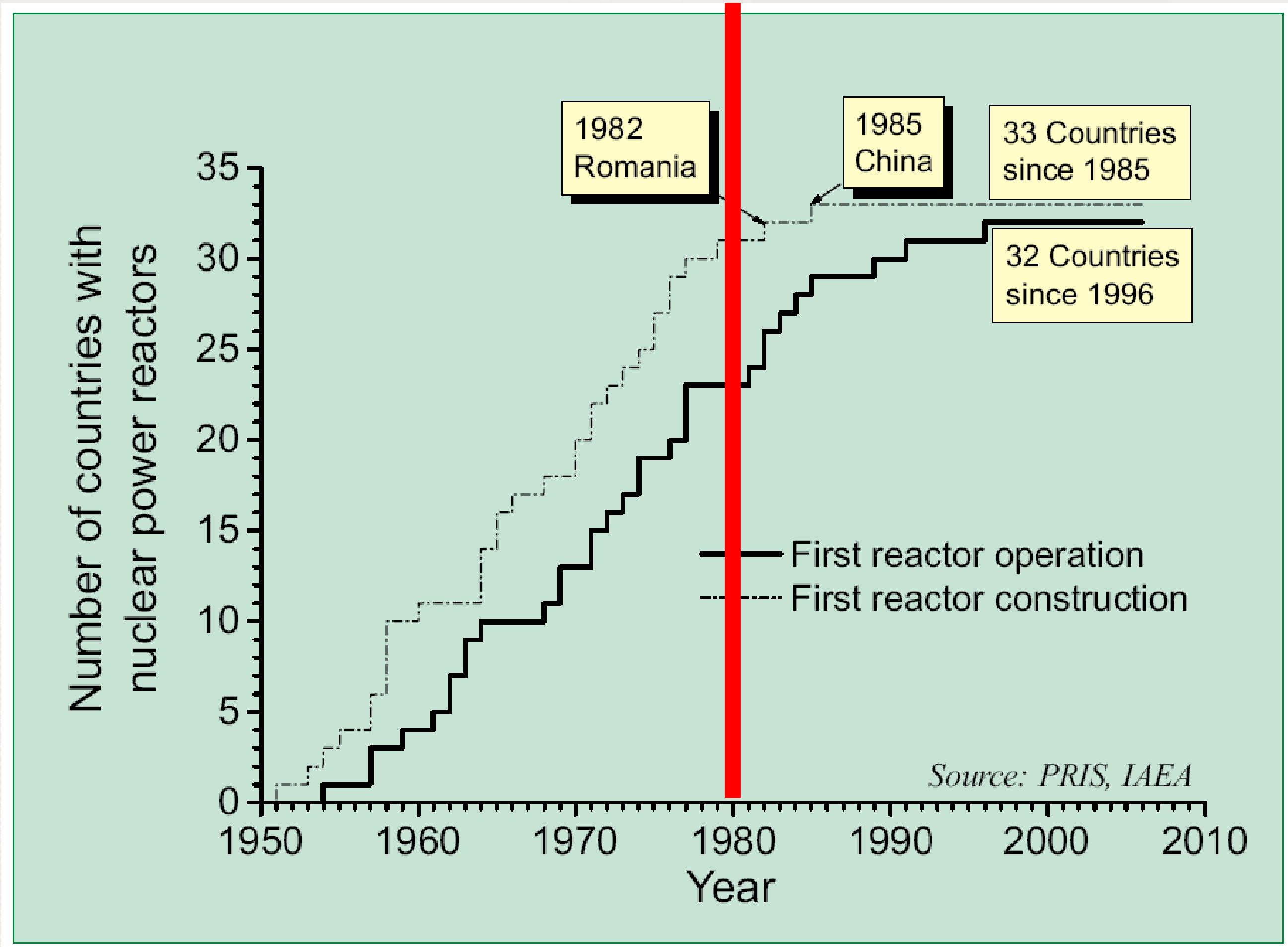
Number of Research Reactors



Number of research reactors in industrialized and developing countries

IAEA

Nuclear Power Reactors Worldwide



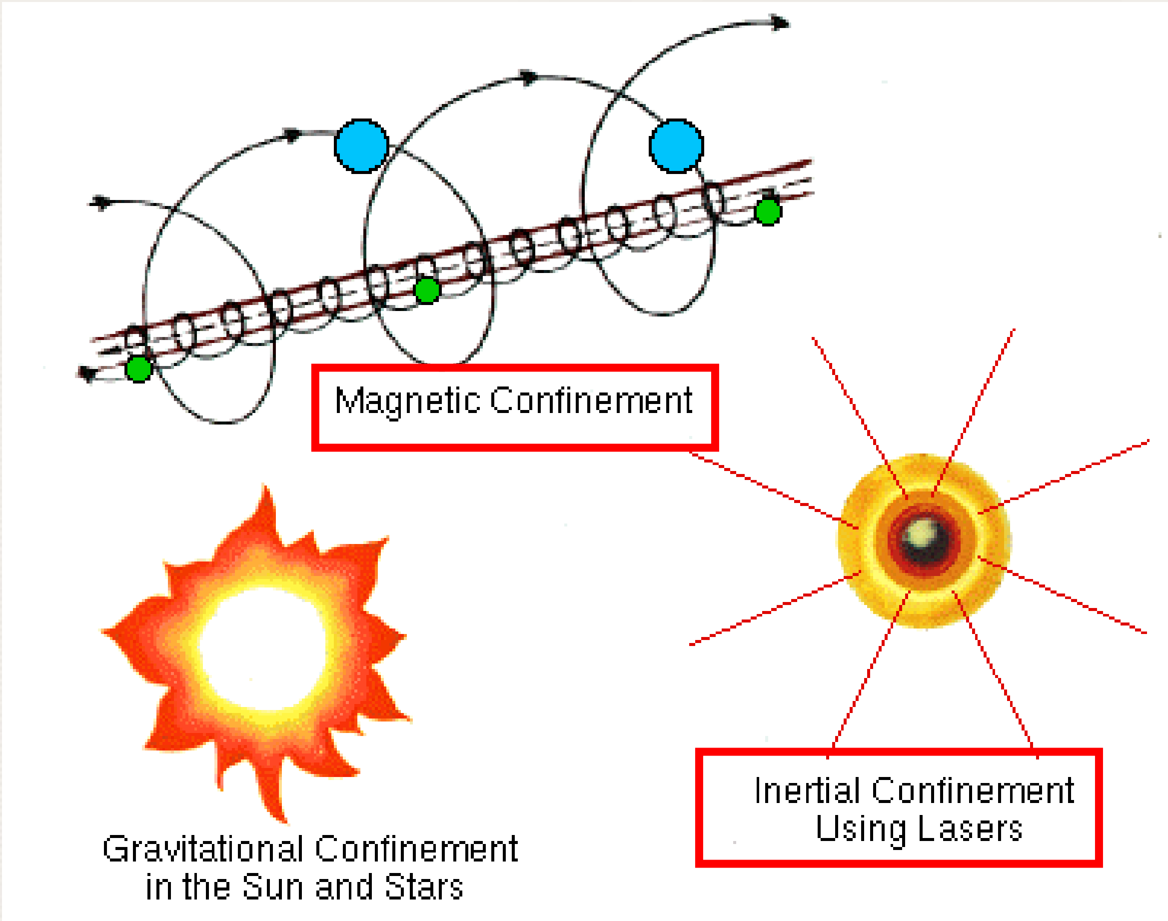
IAEA

The Challenge - Fusion

Specific aspects of status of fusion research and materials needs

See also ➔ Talk by Dudarev

Confinement

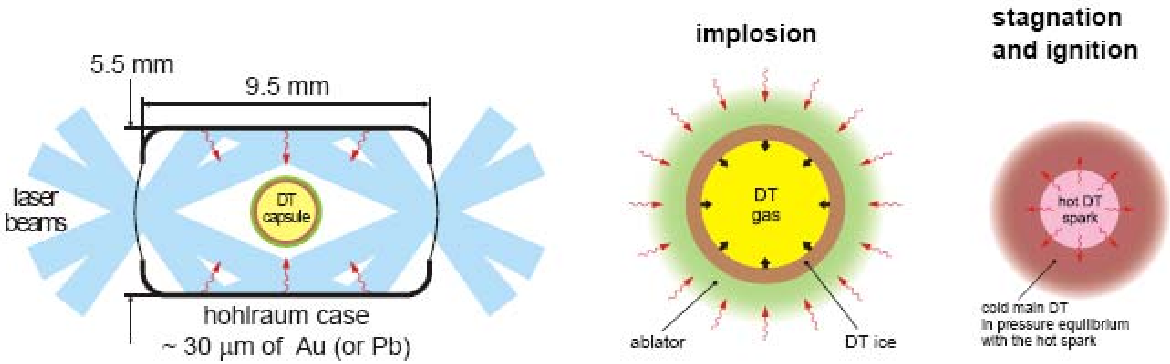


General Atomics

Inertial Confinement - Indirect drive

Main route to ignition: indirect laser drive with central hot-spot ignition

Baseline target and driver designs for NIF have been worked out more than 10 years ago.



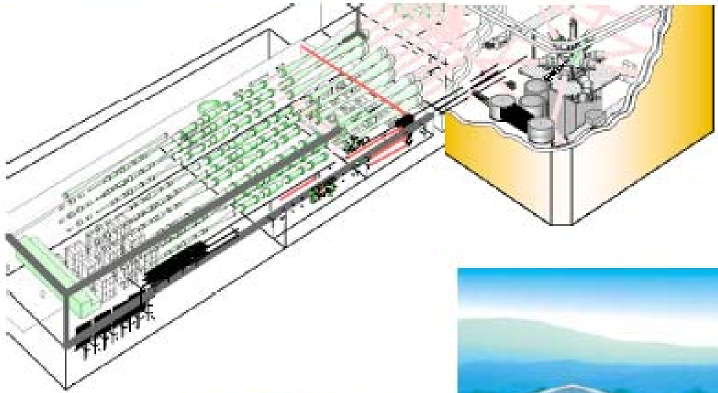
- Laser light creates a "bath" of thermal X-rays in a cylindrical hohlraum, which then drive spherical implosion of a DT capsule.
- The compressed DT is ignited from a central hot spot, which is naturally formed in the process of implosion provided that the implosion velocity $\geq (2\text{–}3)\times 10^7$ cm/s.

What have been the latest new developments?

IAEA

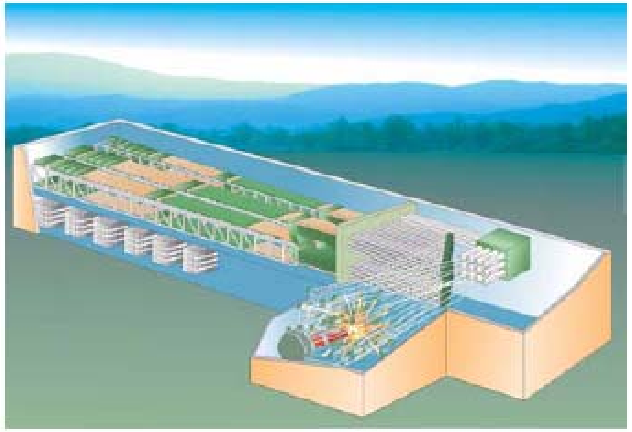
FireX

Fast Ignition Realization Experiment (FIREX) Project

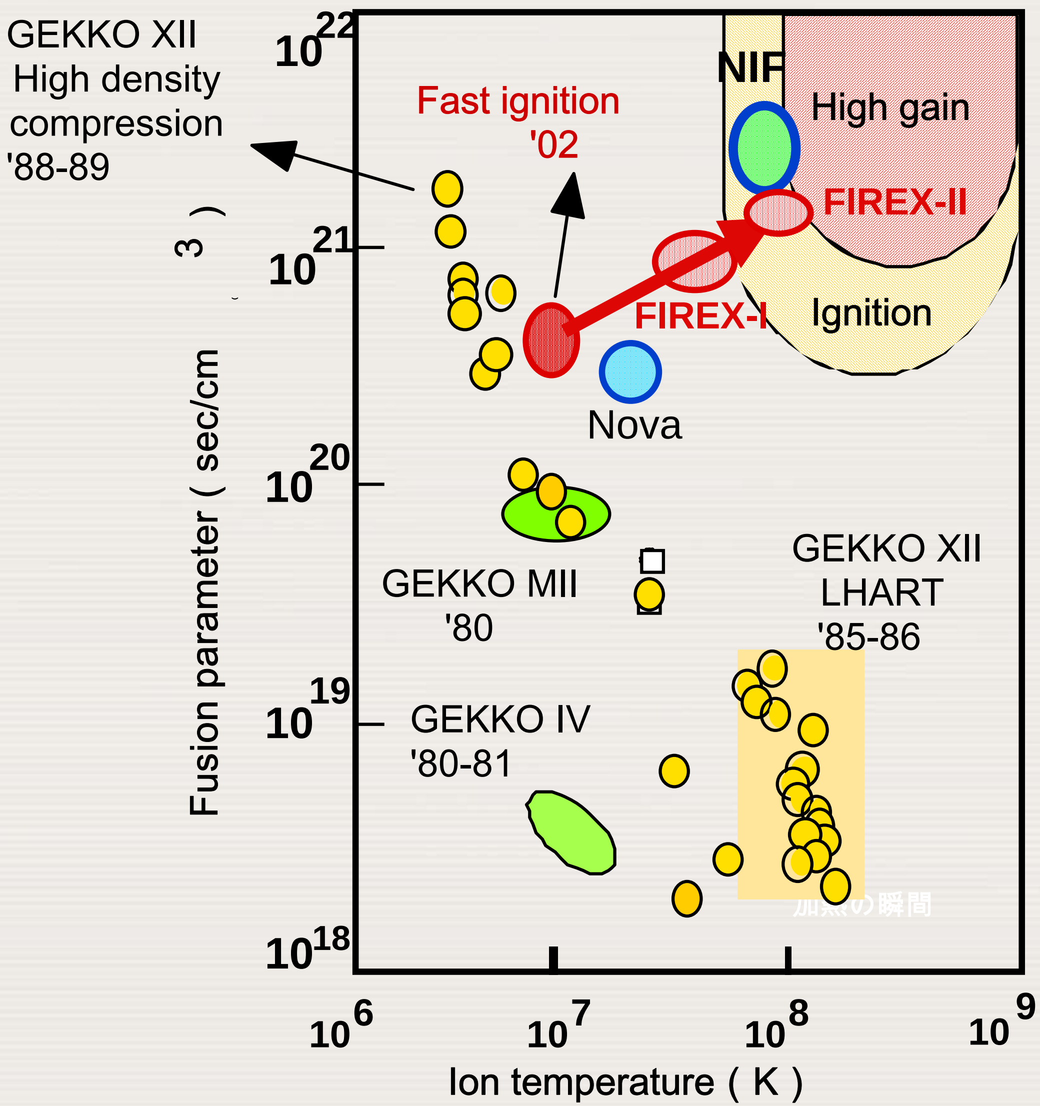


FIREX I & II

Principle of Fast Ignition will be Proved with the FIREX Project

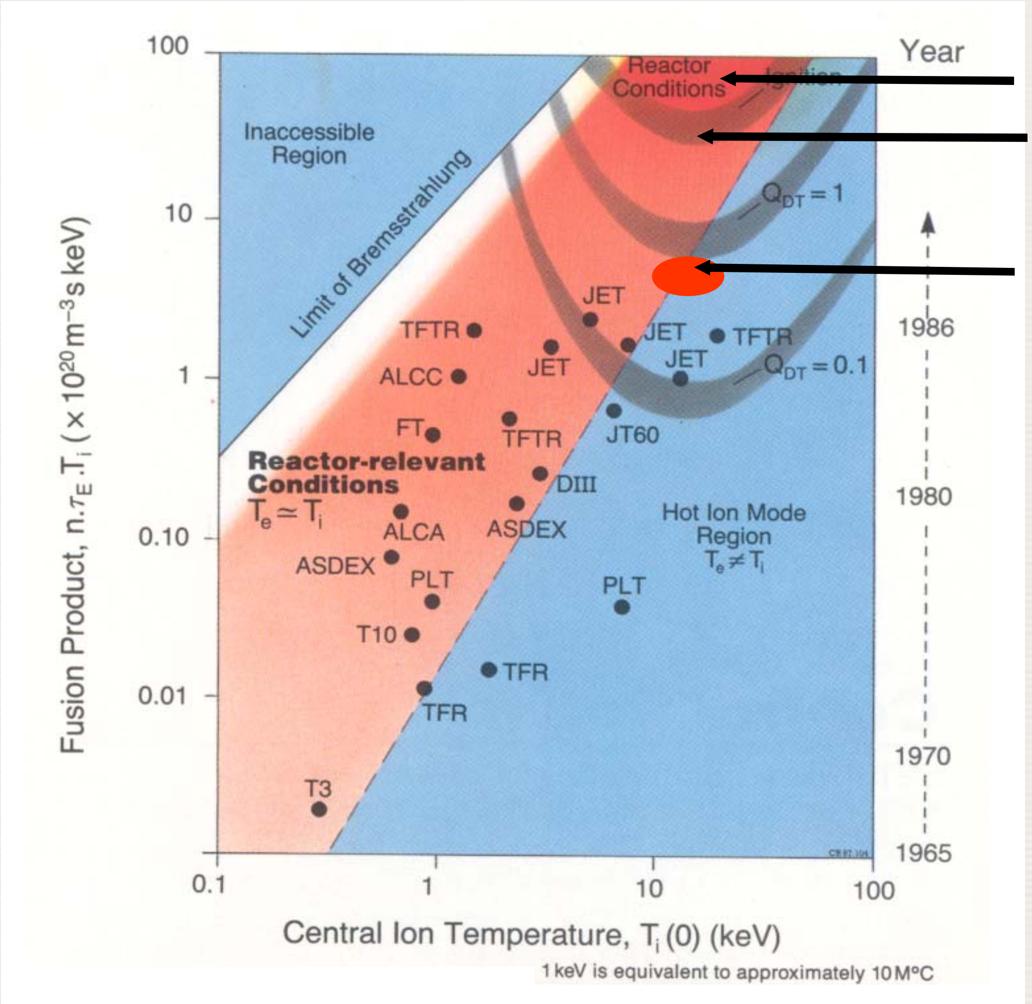


Progress in IFE



IAEA

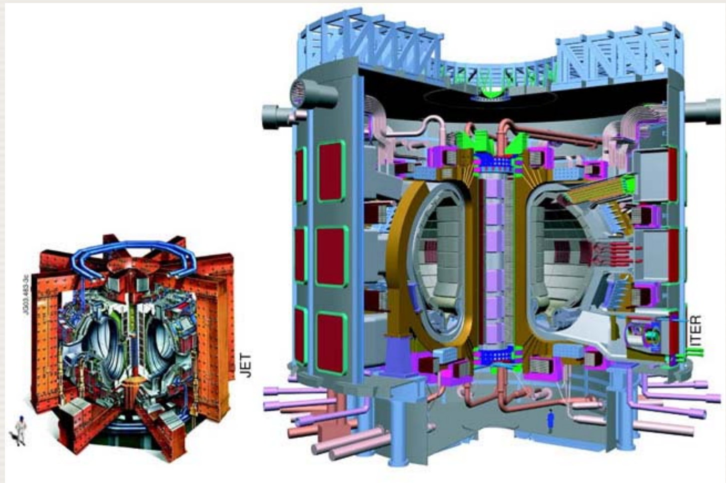
Magnetic Fusion is most advanced



Fusion Reactor

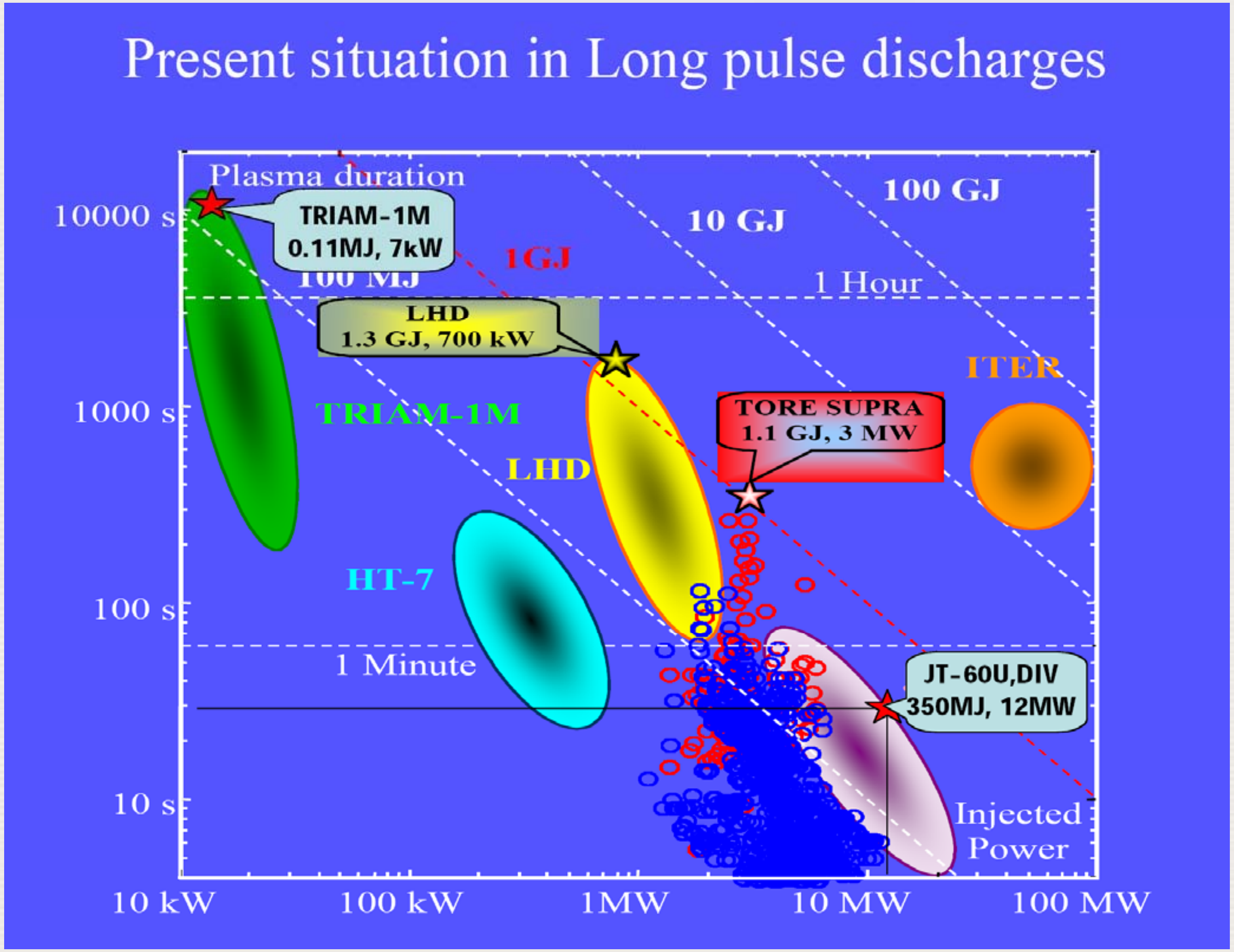
ITER

Today: JET, JT60-U

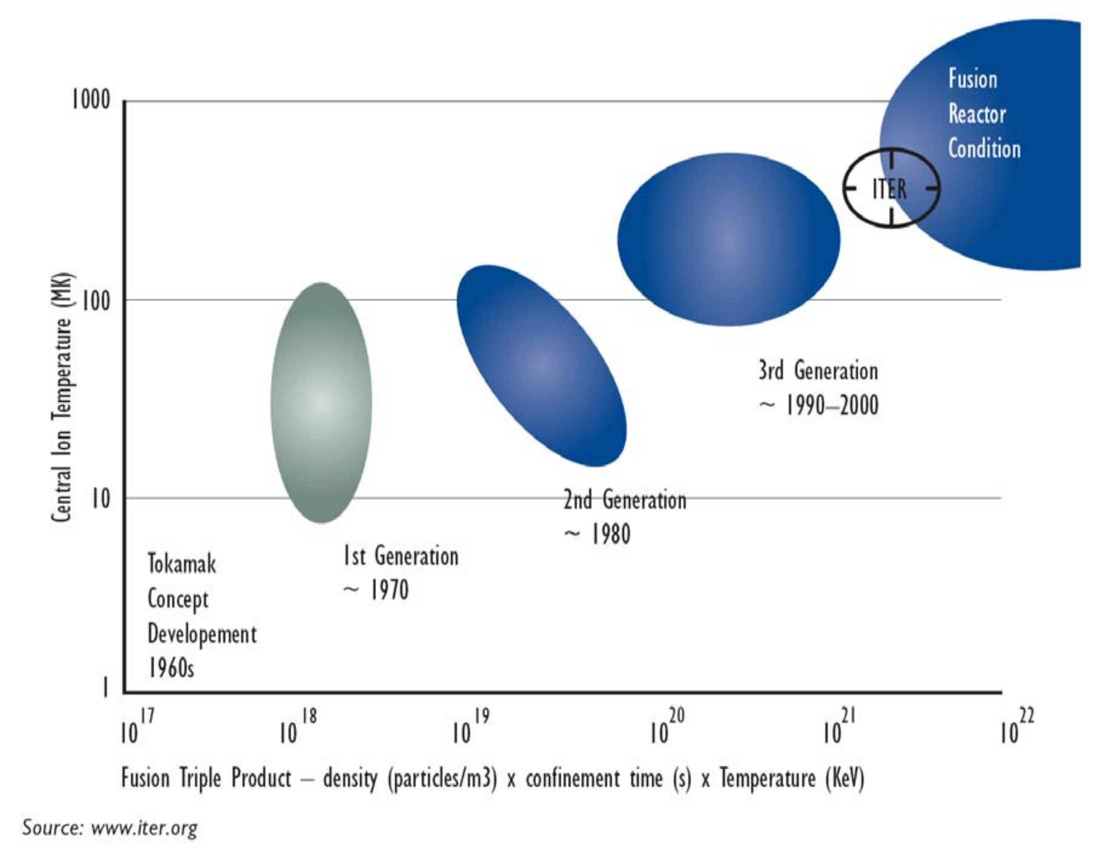


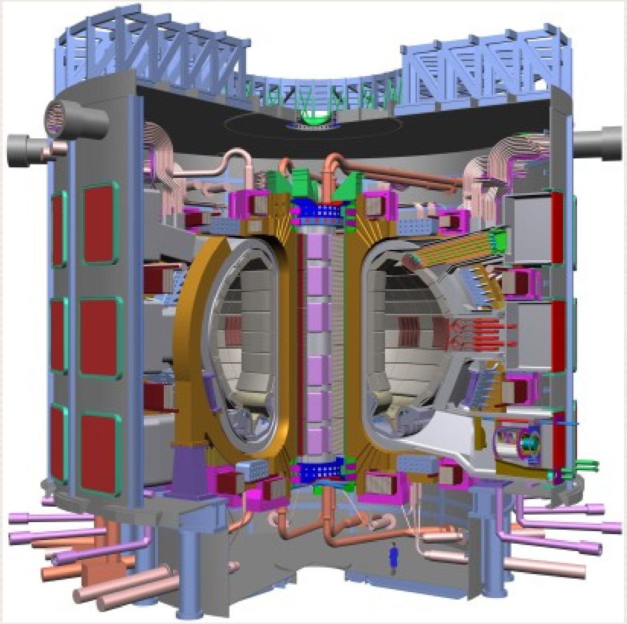
IAEA

Heat load – long pulses



Achievements and Fusion Needs

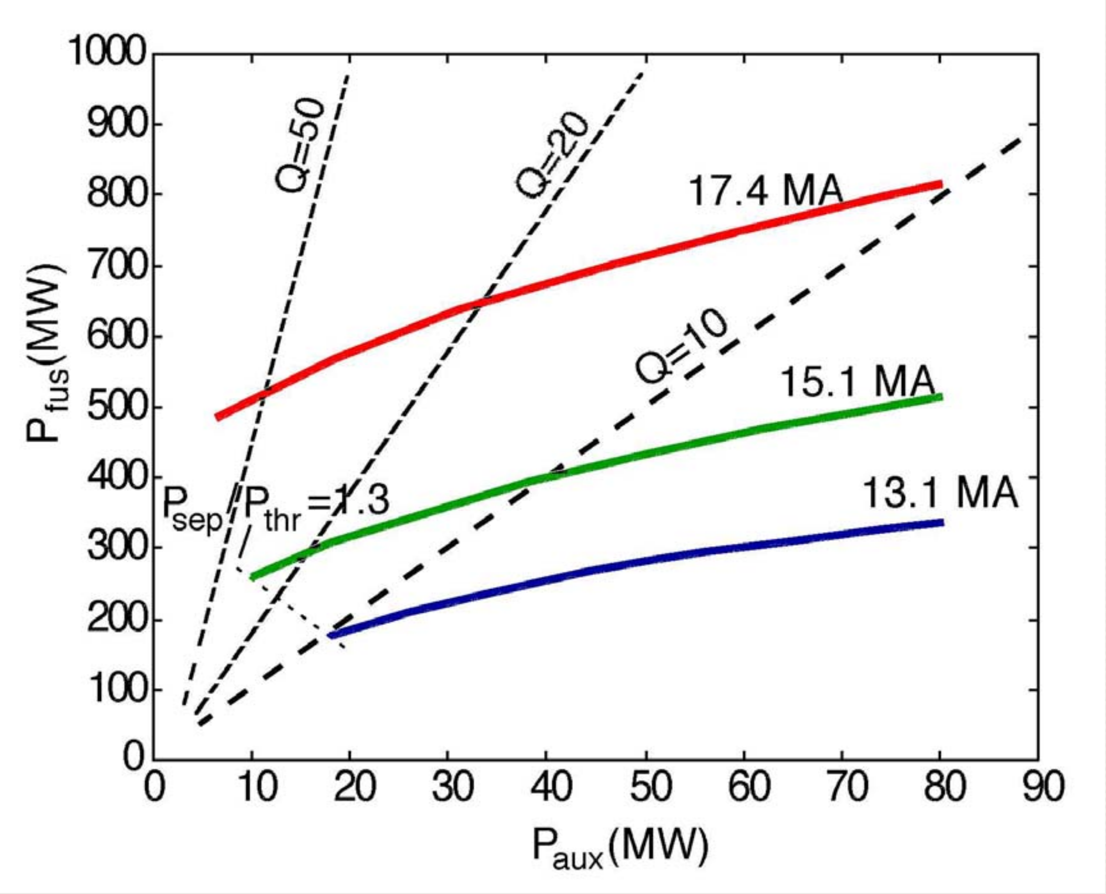




Progress in controlled magnetic fusion since the first research at the beginning of the 1960s. Fusion reactor conditions will be touched by the new international ITER device.

IAEA

ITER Performance, pulse length up to 1000 s



B. Spears, FPA 2003, Washington

Fusion Needs: Long Pulse Operation

Objective: The specific requirements associated with the theory, construction and steady state operation of new machines are addressed. These meetings bring experts from the fields of steady state operation, energetic particles, transport and data acquisition together to present their results and discuss physical and technological aspects of new long-pulse machines.

- Technical Meetings on Steady State Operation, Energetic Particles, H-mode Physics and Transport Barriers, Fusion Power Plants and Data Acquisition

IAEA

Dust and Irradiation

1. Tritium (total site inventory)
2. Tokamak dust (Beryllium, Carbon, Tungsten)
3. Activated Corrosion Products
4. Activated Wall and Blanket

Principle: Safety ALARA

Problem: Radioactive Waste

Power Source	Total Waste (cubic meters)	High-Level RAD Waste
Coal	10,000 (ashes)	0
Fission	440	120
Fusion:		
Today's Materials	2000	30
Advanced Materials	2000	0

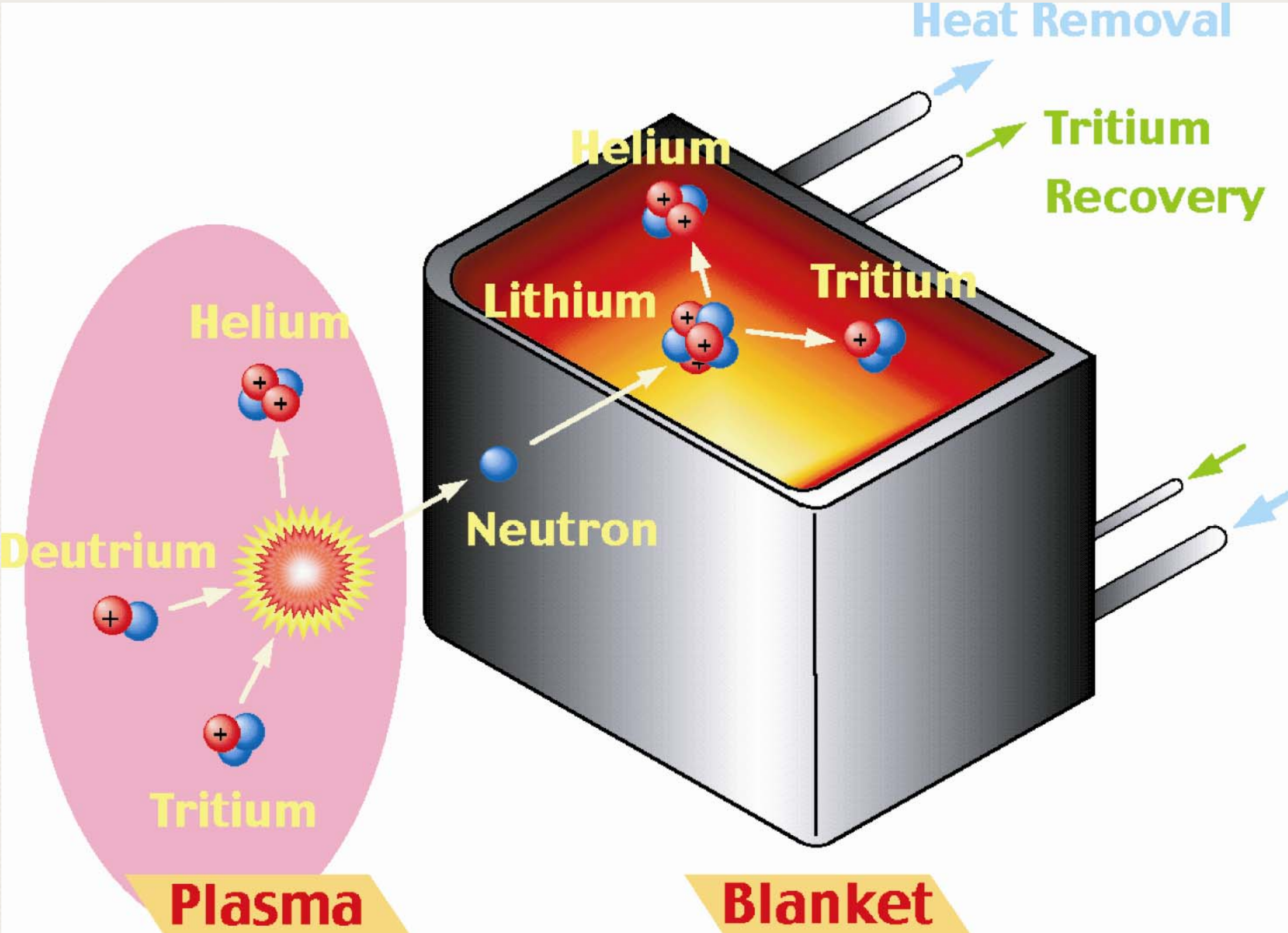
1000 MW(e) Power Plant - 30 year Lifetime

General Atomics

ITER: 6100 t remaining after 100 years

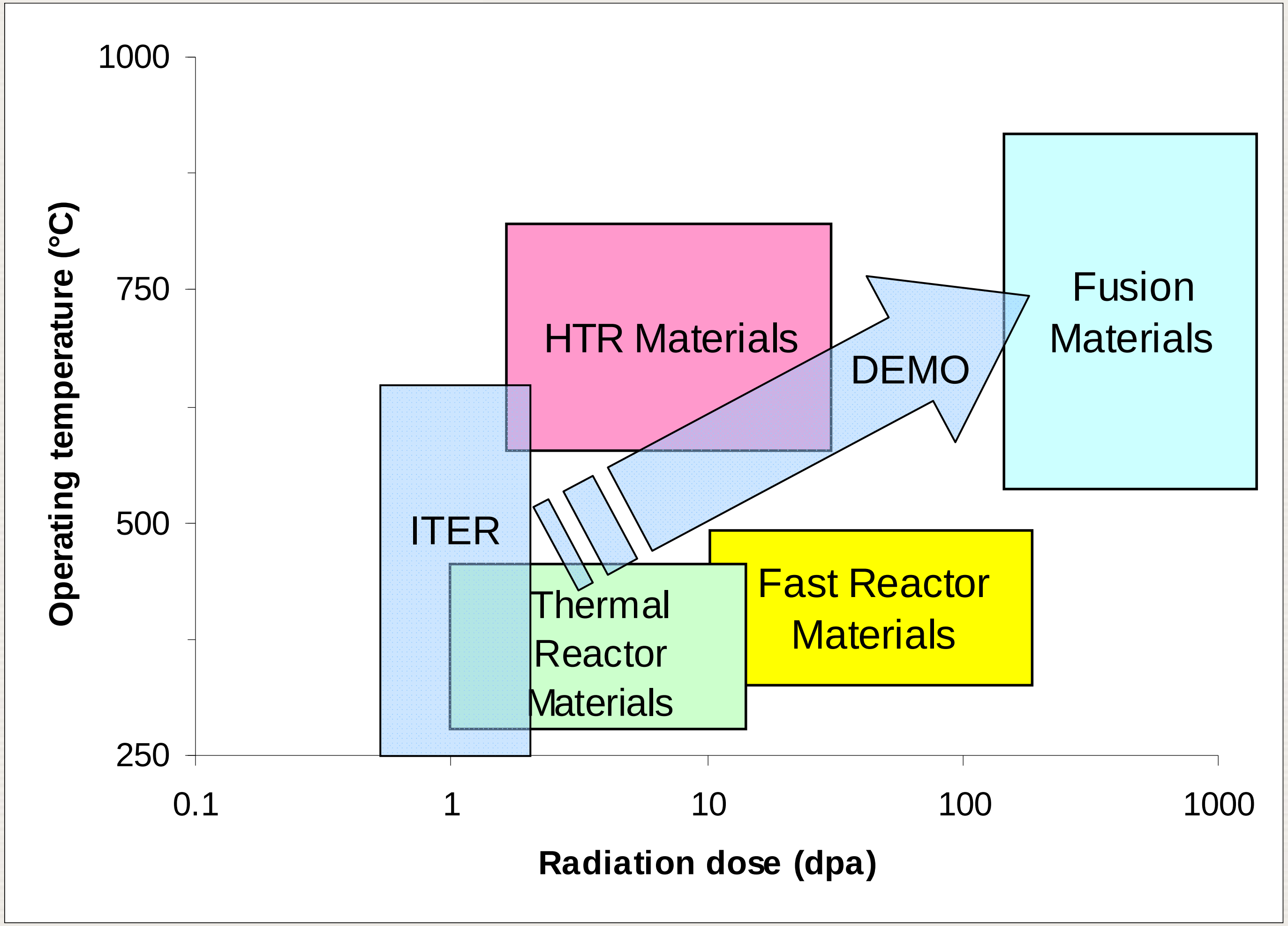
IAEA

Schematic Reactor – Tritium breading



IAEA

The Way to a Fusion Power Plant

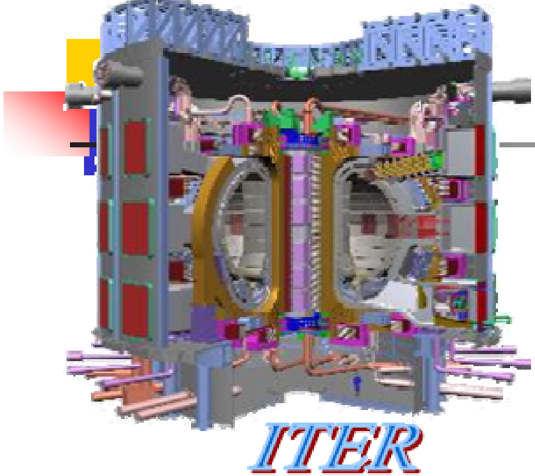


IAEA

New Materials for Fusion

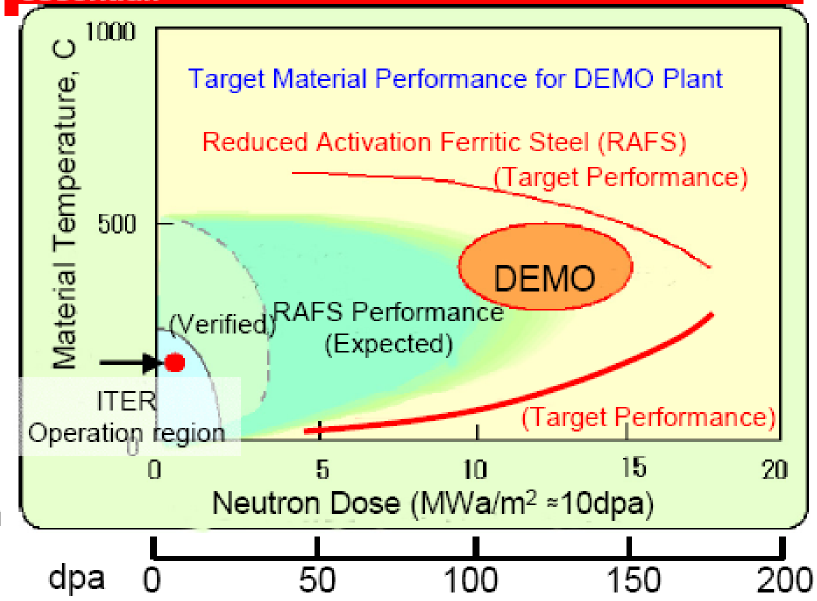
Necessity of Blanket & Material Development for Fusion Power Generation

IFMIF



Blanket & Material development is the major technology task not covered by ITER

In addition to TBM tests in ITER, material development and its database construction is essential.



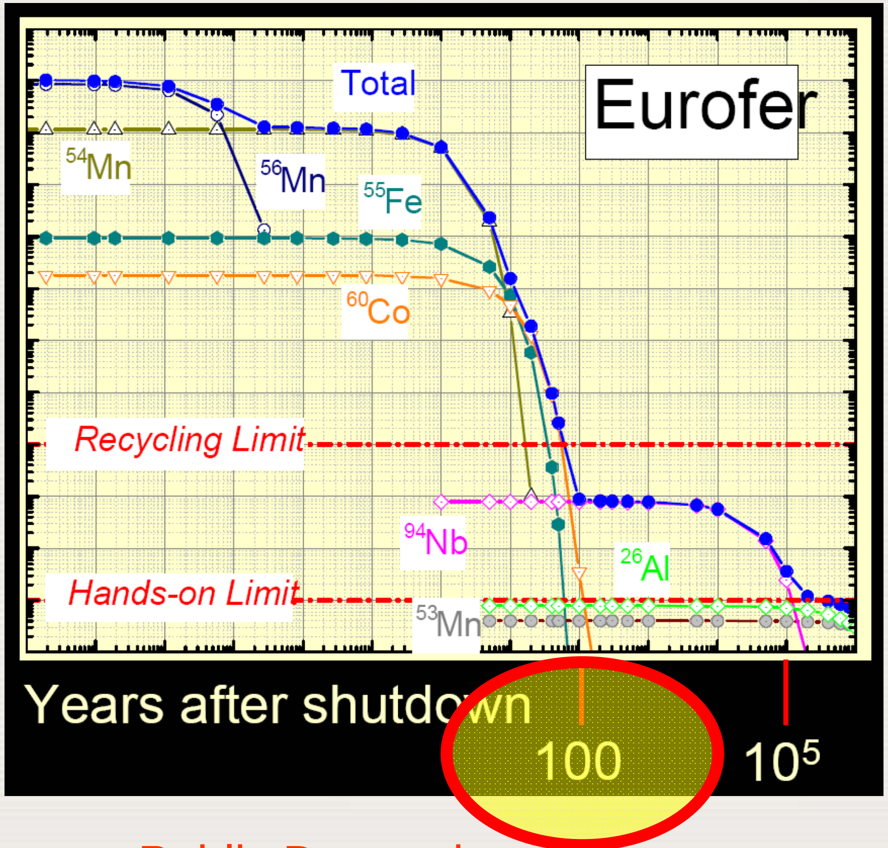
- **Core plasma technology:**
  High plasma fusion power gain (Q = 10), extended DT burn - steady state (Q = 5) ultimate goal.
- **Fusion Technology:**
  Fabrication of SC coil, plasma facing components, shielding, heating and current drive, tritium handling, remote handling, establish technology integration

IAEA

Matsui, IEA Paris, 2005

Structural Material: Activation of a RAFM Steel

- <u>EUROFER 97:</u>
- Recycling dose rate level of 10 mSv/h is achieved after 50-100 years
- Hands-on dose rate level of 10 µSv/h is achieved after 10^5 years



Public Demand:

- <u>Assumptions:</u>
- HCLL PPCS reactor model B
- Fusion power: 3.3 GW
- First wall made of EUROFER 97
- Neutron flux: 1.53×10^{15} $cm^{-2}.s^{-1}$
- 5 full power year irradiation

Fusion Material

Plasma Facing Components

Function	First wall	Breeding blanket	Divertor
Armour material	W-base alloy, W-coated ODS steel, flowing liquid metal: Li	-	W-base alloy, W-coated SiC/SiC, flowing liquid metal: Li, Ga, Sn, SnLi
Coolant	-	-	-

Functional Material

Function	First wall	Breeding blanket	Divertor
Neutron multiplier material	-	Be, $Be_{12}Ti$, $Be_{12}V$, Pb	-
Tritium breeding material	-	Li, eutectic Pb-Li, Li-base ceramic materials	-
Coolant	-	Water, helium, eutectic Pb-Li, Li	Water, helium

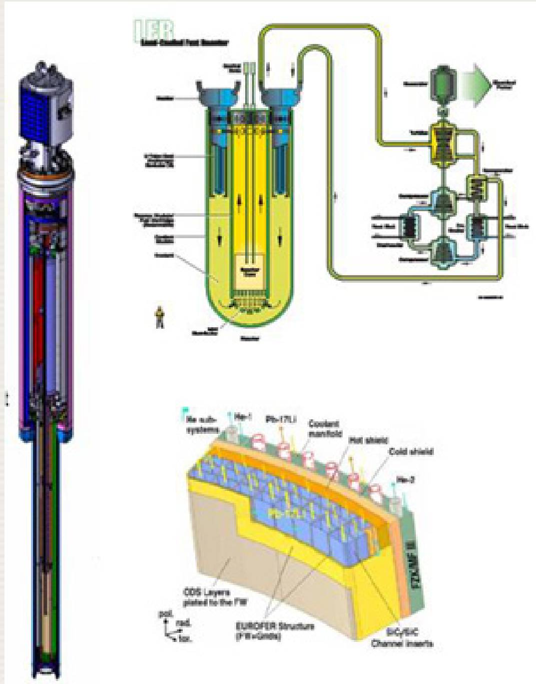
Structural Material

Function	First wall	Breeding blanket	Divertor
Structural material	RAFM steel, ODS steel, V-base alloy, SiC/SiC	RAFM steel, ODS steel, V-base alloy, SiC/SiC	ODS steel, W-base alloy
Coolant	-	Water, helium, eutectic Pb-Li, Li	Water, helium

IAEA

N. Baluc et al. , Fusion Energy Conf. 2006, China

The Test Blanket Module



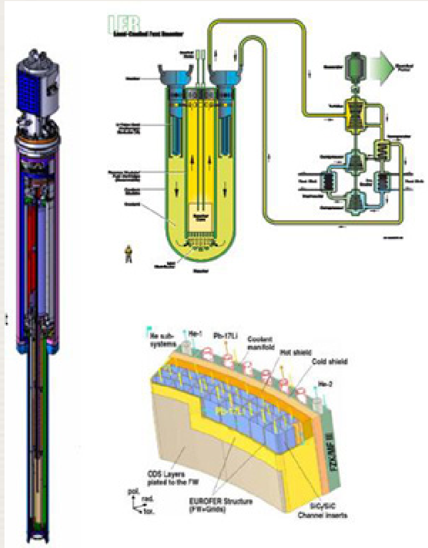
Functional Material

Function	First wall	Breeding blanket	Divertor
Neutron multiplier material	-	Be, $Be_{12}Ti$, $Be_{12}V$, Pb	-
Tritium breeding material	-	Li, eutectic Pb-Li, Li-base ceramic materials	-
Coolant	-	Water, helium, eutectic Pb-Li, Li	Water, helium

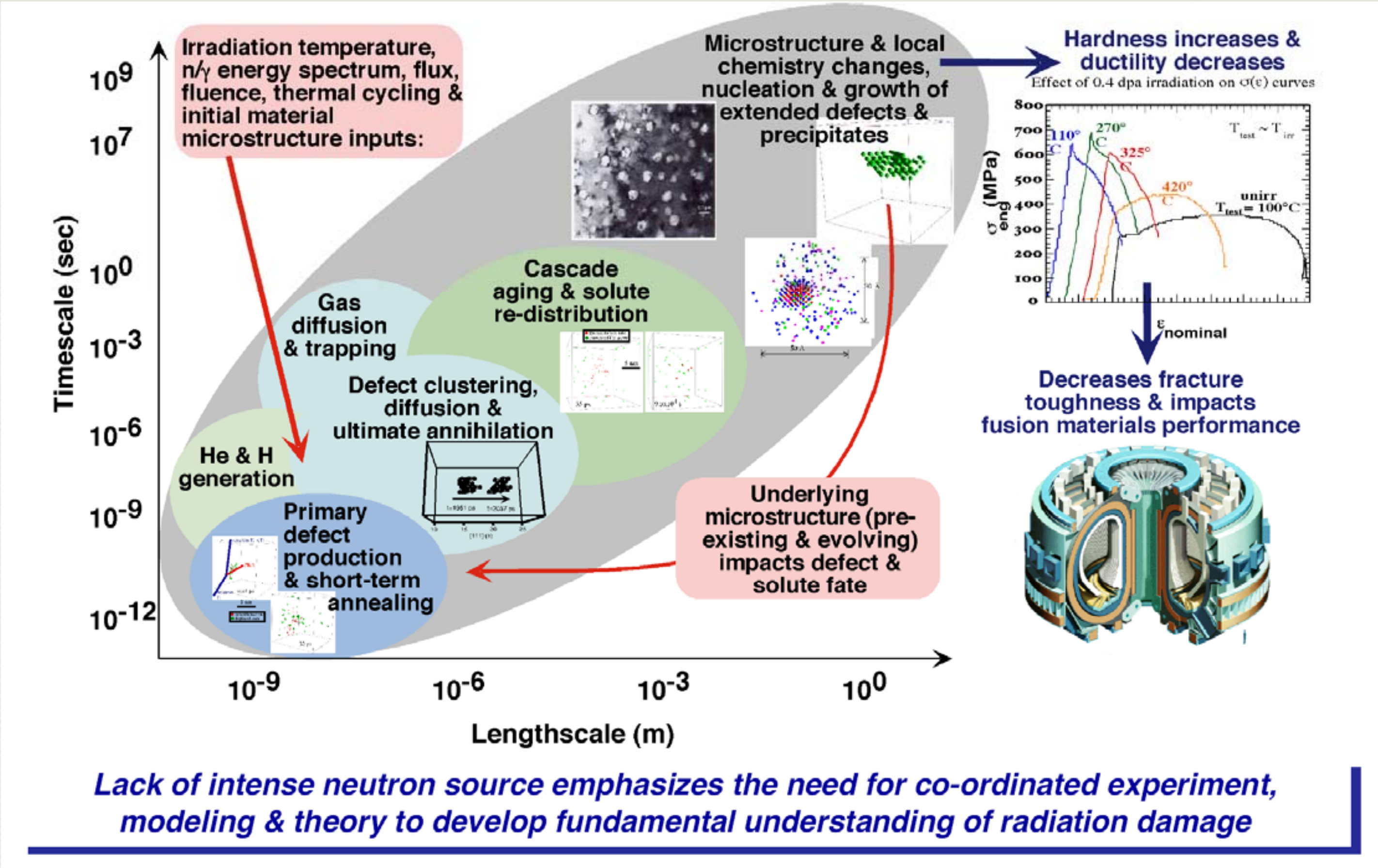
N. Baluc et al. , Fusion Energy Conf. 2006, China

IAEA

HLM Reactors - ADS - ITER

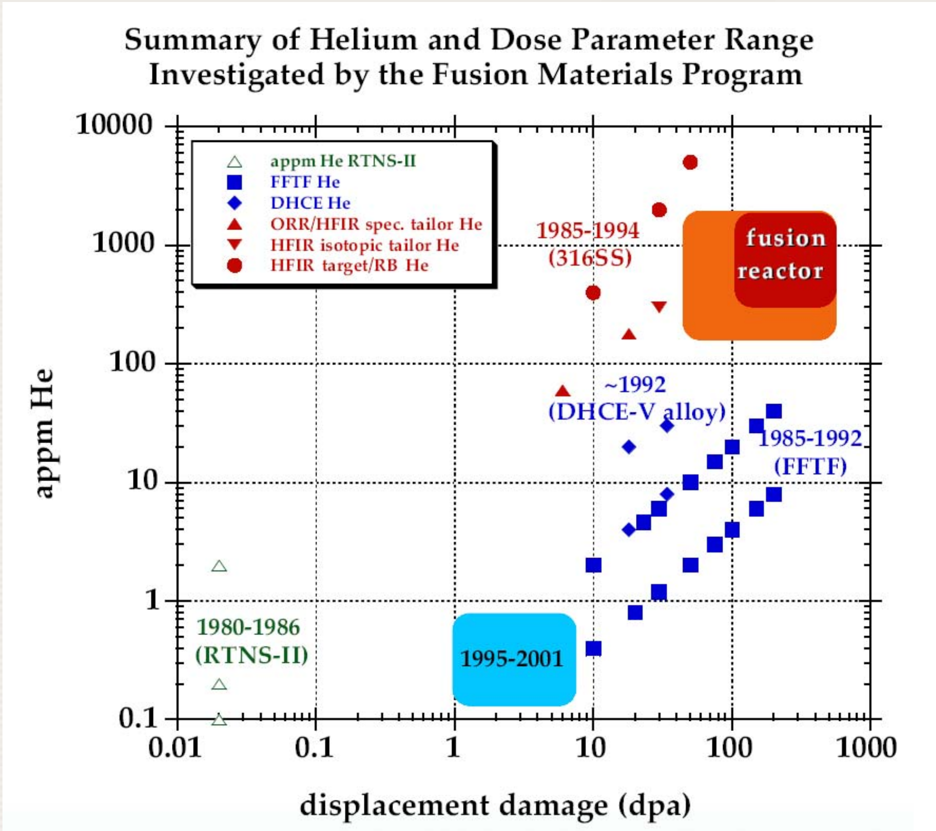


- A wide use of pure lead, as well as its alloys (such as lead-bismuth, lead-lithium), is foreseen in several nuclear-related fields: it is studied as coolant in critical and sub-critical nuclear reactors, as spallation target for neutron generation in several applications and for tritium generation in fusion systems.
- Nowadays, the possibility to use Heavy Liquid Metals (HLM) both as spallation target and coolant of the sub-critical part of the Accelerator Driven Systems (ADS) seems very attractive, the ADS being proposed as a viable solution to burn nuclear waste.
- The use of lead as coolant appears as an appealing choice also for critical reactors. In the generation IV nuclear reactors technology evaluation, in fact, lead fast reactors (LFR) appear as a promising technology, top ranked both in sustainability because of the closed fuel cycle and in proliferation resistance and physical protection due to the long life core.
- Slowly flowing lead lithium alloy in eutectic composition (Li 15.7%at) is the tritium breeder and neutron multiplier for one of the two EU blanket concepts to be tested in ITER.



Multiscale Modeling of Radiation Damage in Fusion Reactor Materials Brian D. Wirth et al presented at DOE, March 12, 2002

IAEA



Multiscale Modeling of Radiation Damage in Fusion Reactor Materials Brian D. Wirth et al presented at DOE, March 12, 2002

Spallation Source for Fusion Research: IFMIF

Issue	Today's expts	ITER	IFMIF	DEMO Phase 1	DEMO Phase 2	Power Plant
Disruption avoidance	2	3		3	R	R
Steady-state operation	1	3		3	r	r
Divertor performance	2	3		r	R	R
Burning plasma Q>10		3		R	R	R
Power plant plasma performance	1	3		3	R	R
T self-sufficiency		1		3	R	R
Materials characterisation			3	R	R	R
Plasma-facing surface lifetime	1	1		2	3	R
FW/blanket materials lifetime		1	2	2	3	R
FW/blanket components lifetime		1		1	3	R
Divertor materials lifetime		1	2	2	3	R
NB/RF heating systems performance	1	3		R	R	R
Electricity generation at high availability				1	3	R
Superconducting machine	1	3		R	R	R
Tritium issues	1	3		R	R	R

Key:

1	Will help to resolve the issue
2	May resolve the issue
3	Should resolve the issue
r	Solution is desirable
R	Solution is essential

IAEA

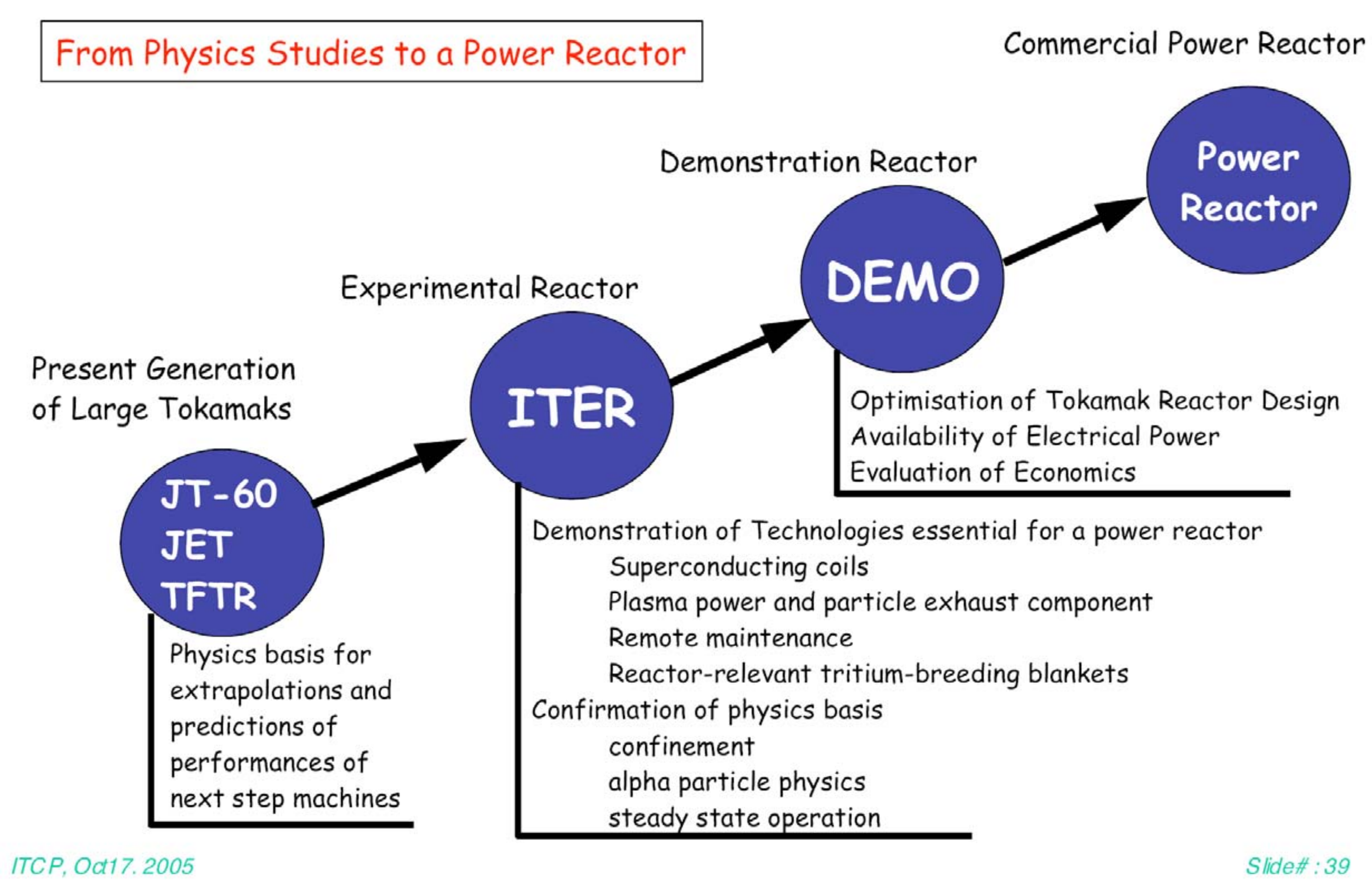
Fusion Needs: Materials and Wall

Objective: The choice of wall and blanket is crucial for the success of magnetic and inertial fusion. Data analysis as well as dedicated experiments are supported.

- Technical Meetings on Fusion Power Plants, Atomic and Molecular data and on codes as well as 4 Coordinated Research Projects e.g. on molecular processes, spectral features, tritium inventory and wall studies in small tokamaks are supported. A school on pulsed neutrons: enhancing the capacity for materials science will discuss materials research under very high neutron peak fluxes.

IAEA

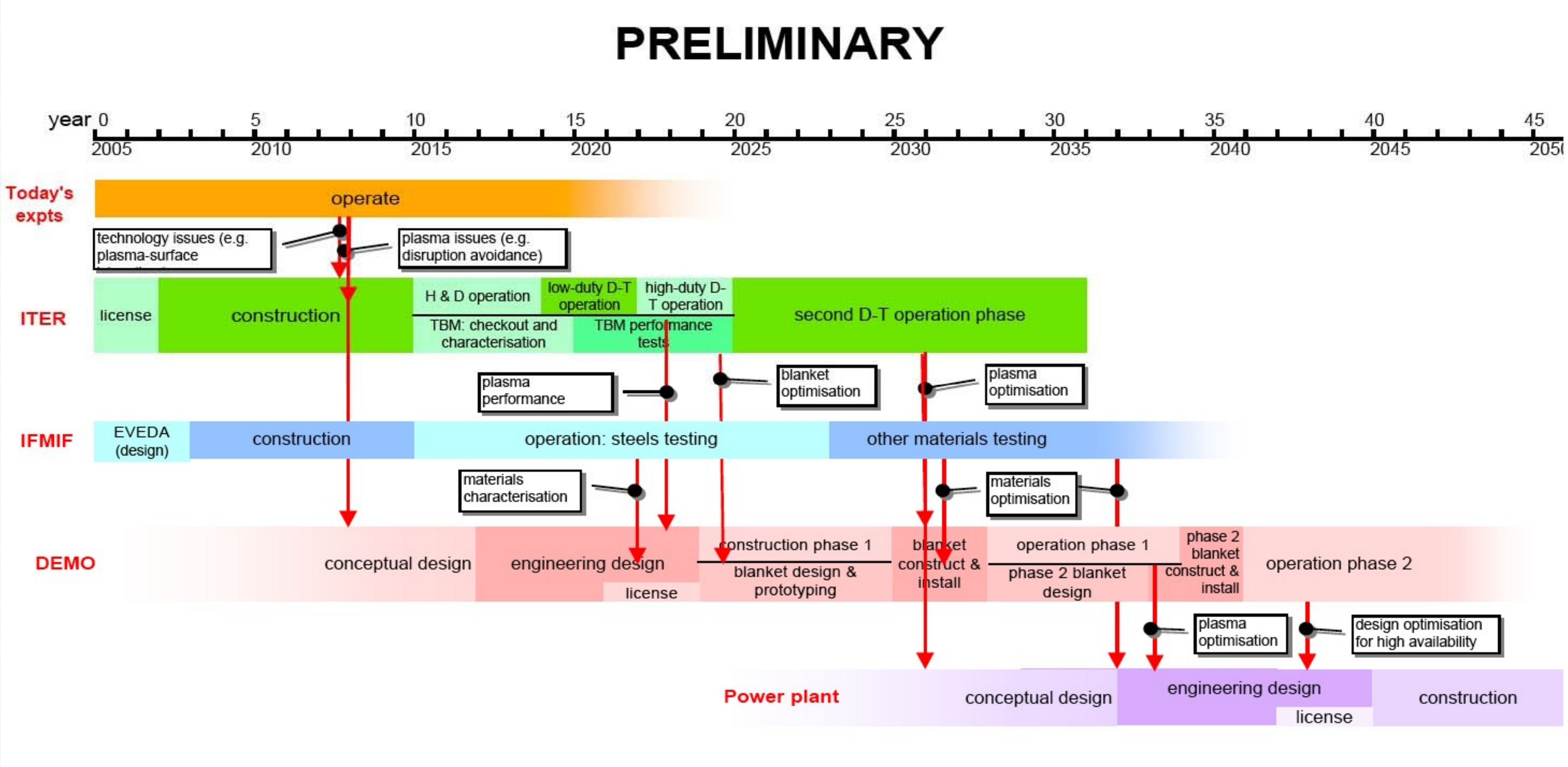
Next Steps in Fusion Research



C. Rubbia

IAEA

Time frame magnetic fusion



IAEA

Overview of Demands

Reactor Type	Inlet Temp (°C)	Outlet Temp (°C)	Maximun Dose (dpa)	Pressure (MPa)	Coolant	Structural Material
PWR	**290**	**320**	**100**	**16**	**Water**	**FM Steel, SS**
SCWR*	**290**	**500**	**15-67**	**25**	**Water**	**FM steel, SS**
VHTR*	**600**	**1000**	**1-10**	**7**	**Helium**	**Ni alloys, Graphite, ceramics**
SFR*	**370**	**550**	**200**	**0.1**	**Sodium**	**(ODS) FM steel, SS**
LFR*	**600**	**800**	**200**	**0.1**	**Lead**	**(ODS) FM steel, SS**
GFR*	**600**	**850**	**80**	**7**	**Helium SC CO_2**	**(ODS) FM steel, SS, Ni alloys, ceramics**
Fusion DEMO EU, Model C	**480**	**700**	**150**	**8**	**Helium**	**(ODS) FM steel, ceramics, refract.**
Spallation MYRRHA, XT-ADS	**300**	**400**	**~60**	**0.1**	**Pb-Bi**	**FM-steel, SS**

* Gen IV Rod Map 2002

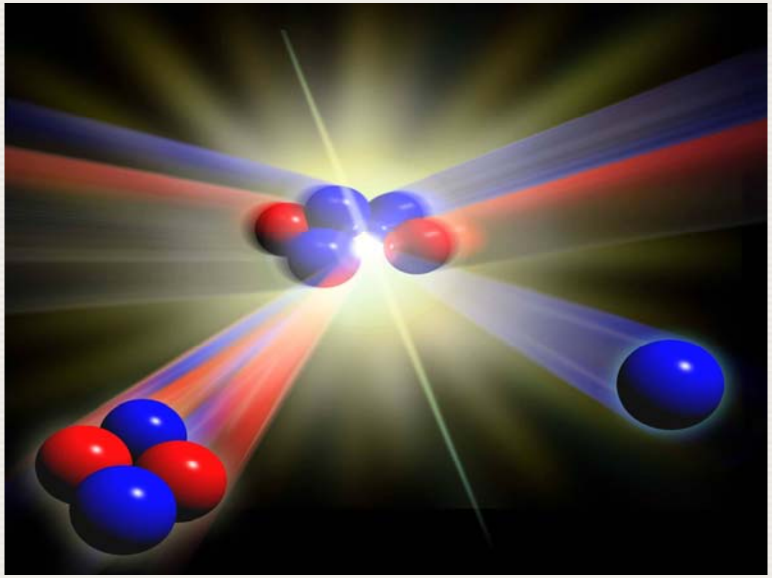
Th. Walter Tromm OECD/NEA SMINS- Workshop 04-06/06/2007

IAEA

Main Emphasis

Drivers of fusion future programme:

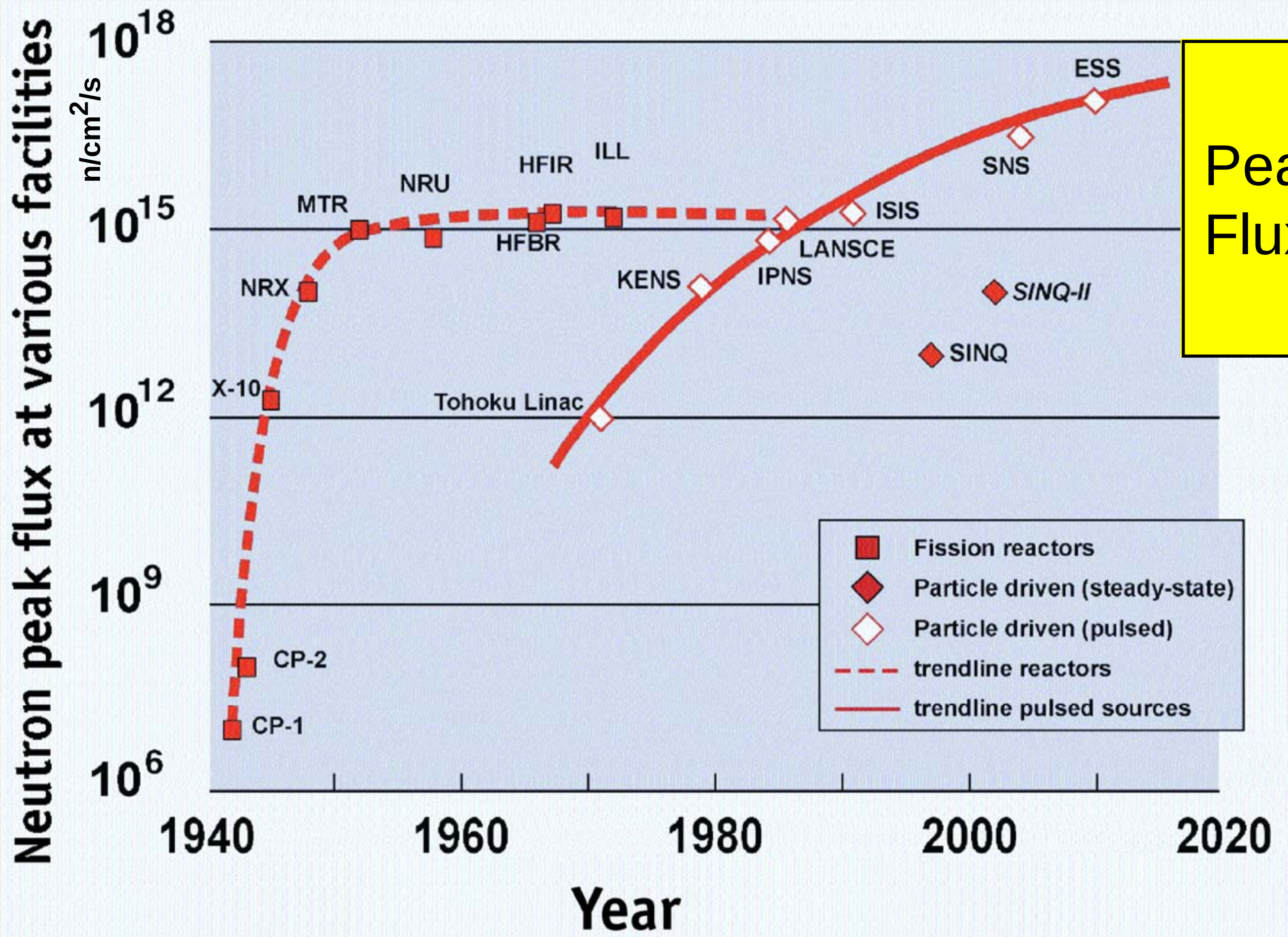
- Support Member States on the move towards a fusion power plant
- Materials research for nuclear power plants (fission and fusion)



IAEA

Materials Research at / for Accelerators

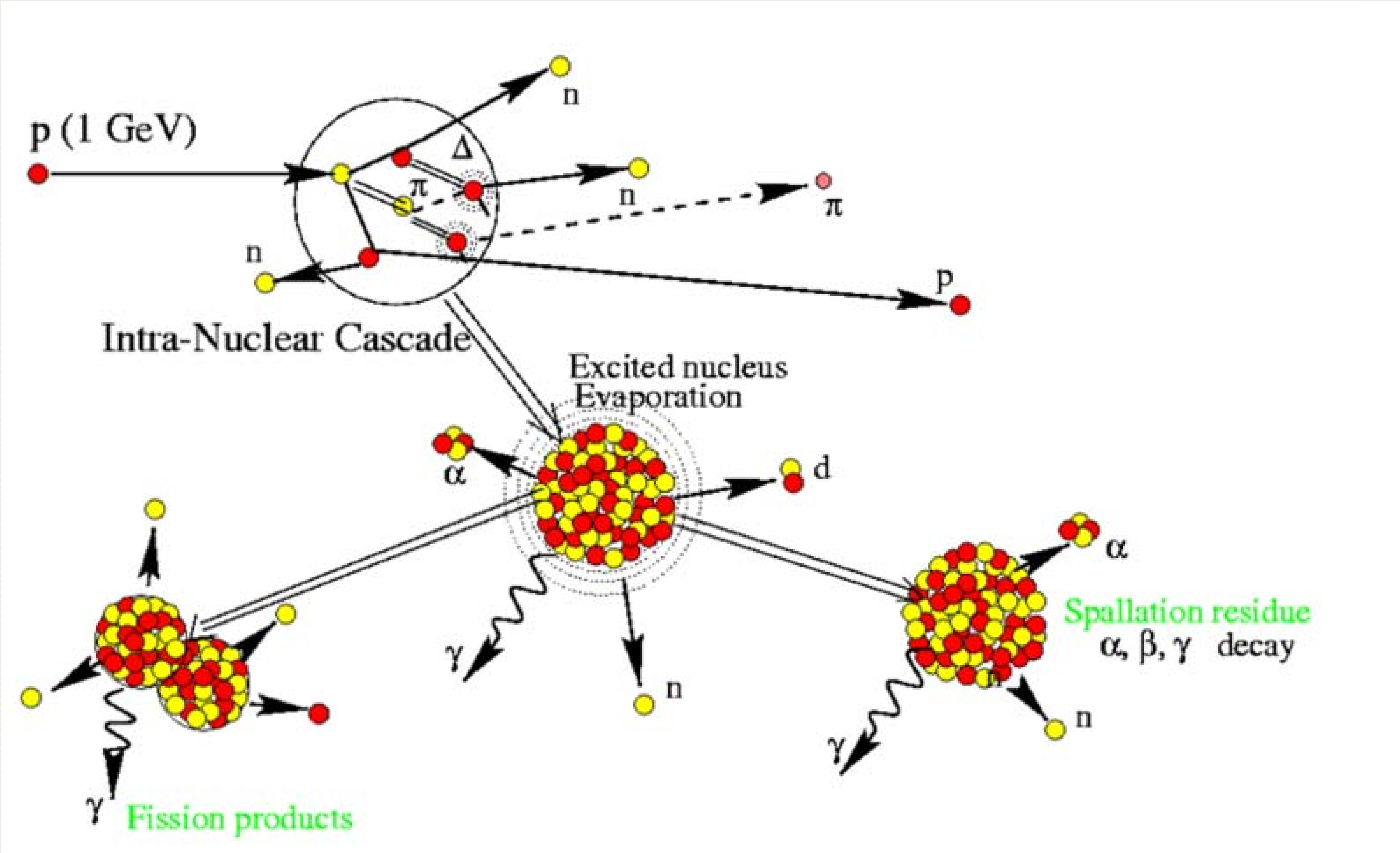
Neutron Production:



Peak Neutron Flux Limited

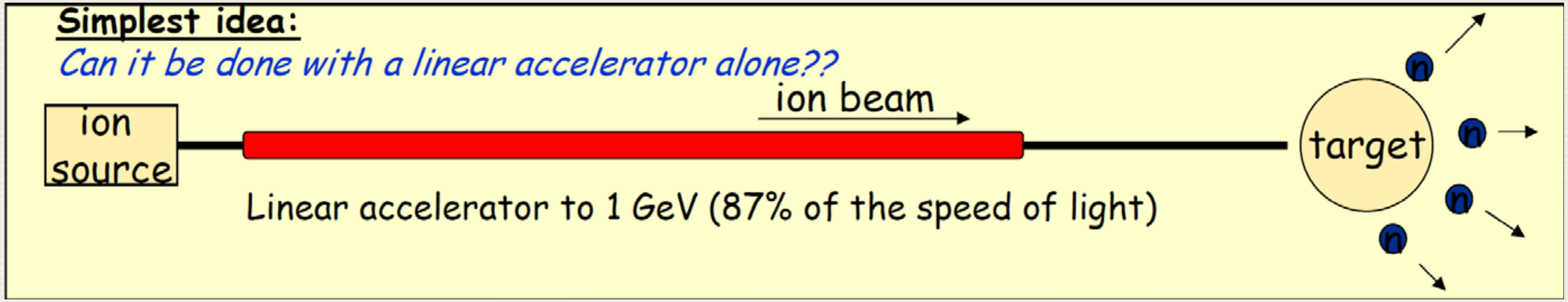
IAEA

Neutron Production using Spallation:



IAEA

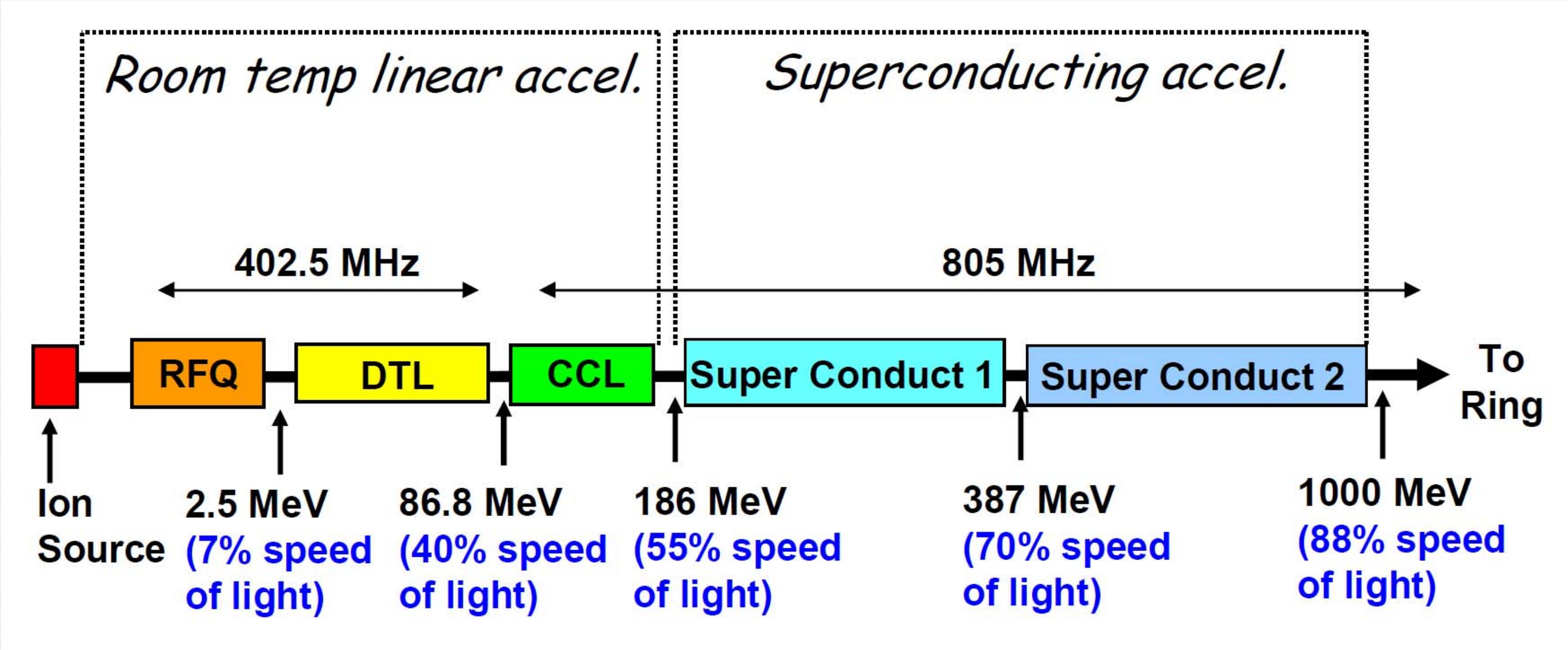
Spallation Accelerator:



(courtesy: K. Herwig, SNS)

IAEA

Spallation Accelerator (SNS):

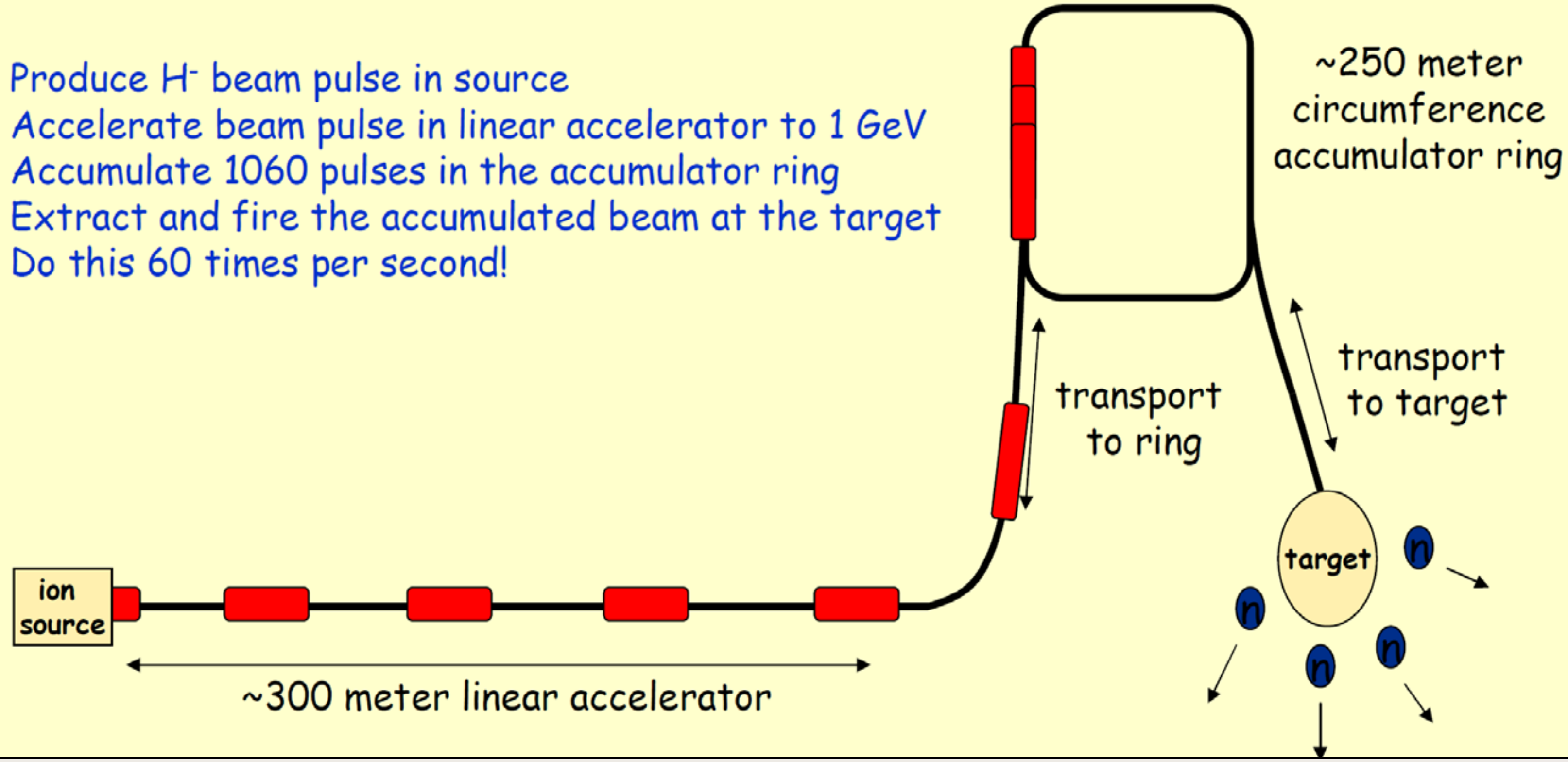


(courtesy: K. Herwig, SNS)

Spallation Neutron Source (SNS):

Final Design

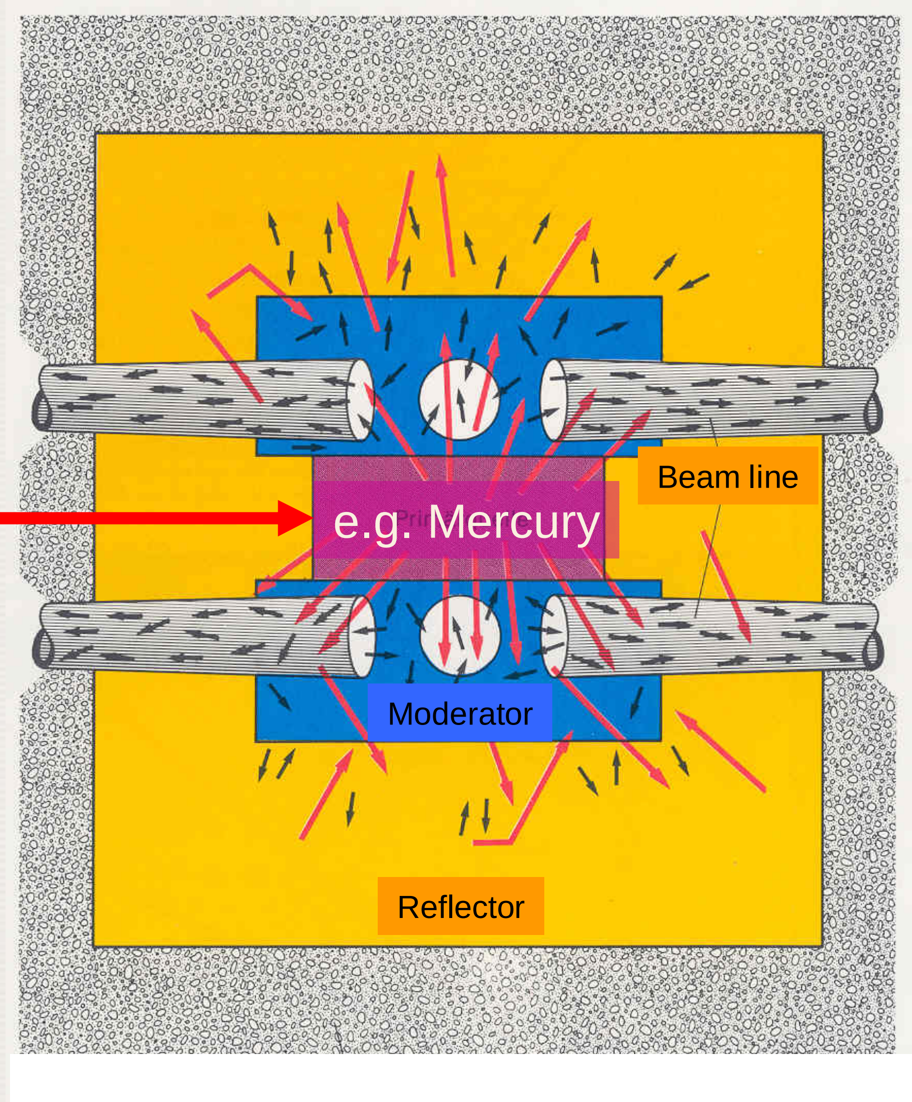
1) Produce H⁻ beam pulse in source
2) Accelerate beam pulse in linear accelerator to 1 GeV
3) Accumulate 1060 pulses in the accumulator ring
4) Extract and fire the accumulated beam at the target
5) Do this 60 times per second!



(courtesy: K. Herwig, SNS)

Spallation target:

Protonbeam



IAEA

Spallation Neutron Sources worldwide:

	Primary Acceleration	Pulse Rate (Hz)	Final Energy (MeV)	Power (kW)*
PSI	Cyclotron	CW	800	1100
ISIS	RCS	50	800	160
PSR (Lujan)	Linac	20	800	100
IPNS	RCS	30	450	7.5
SNS (Achieved)	Linac	30	880	180
SNS (Design	Linac	60	1000	1400
J-PARC (Design)	RCS	25	3000	1000 **

* Operational level during neutron production

** After linac upgrade

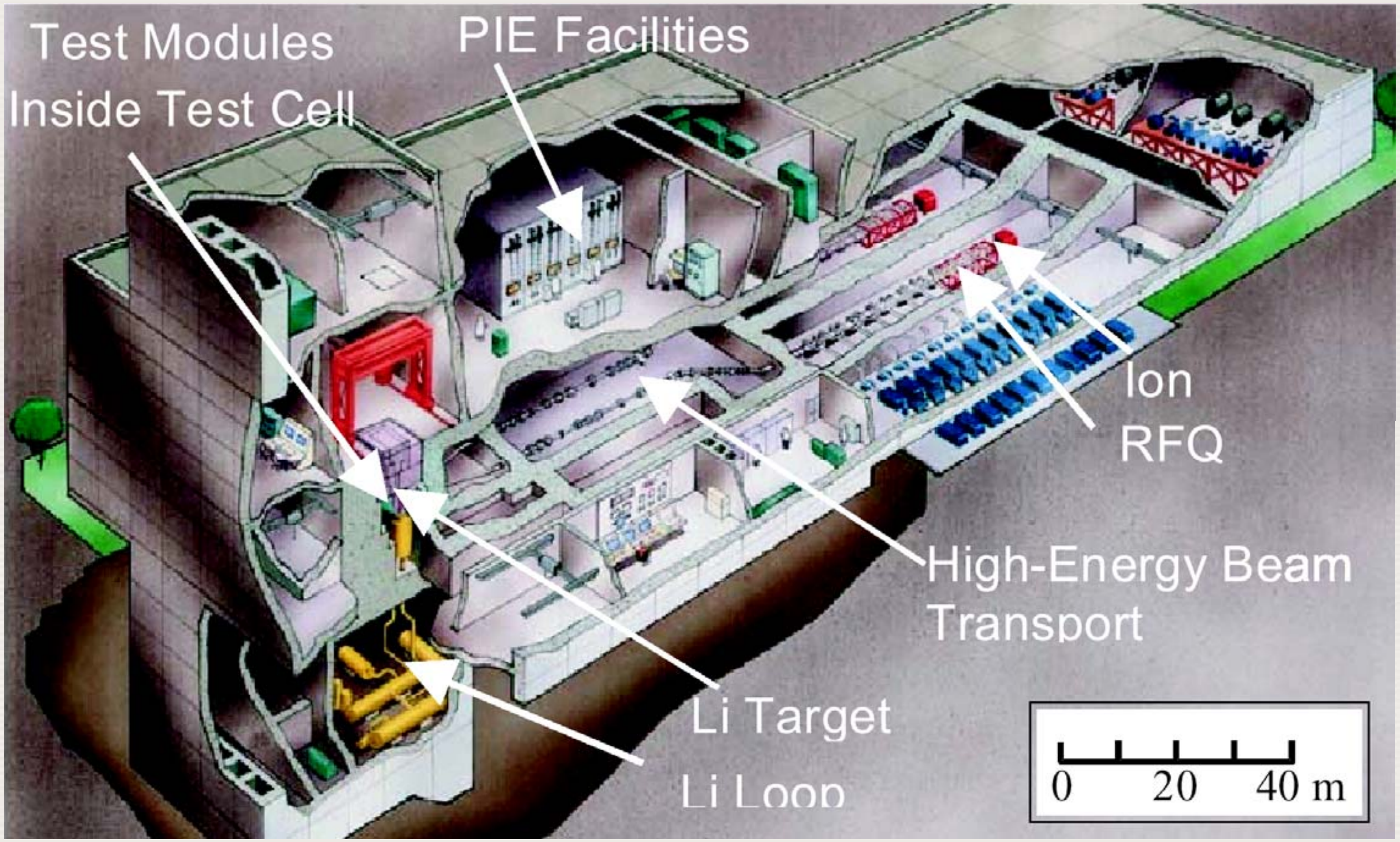
Neutron Sciences HFIR SNS SPALLATION NEUTRON SOURCE

OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

UT-BATTELLE

IAEA

Spallation Source for Fusion Research: IFMIF



Source: IEA

IAEA

Spallation Source for Fusion Research: IFMIF

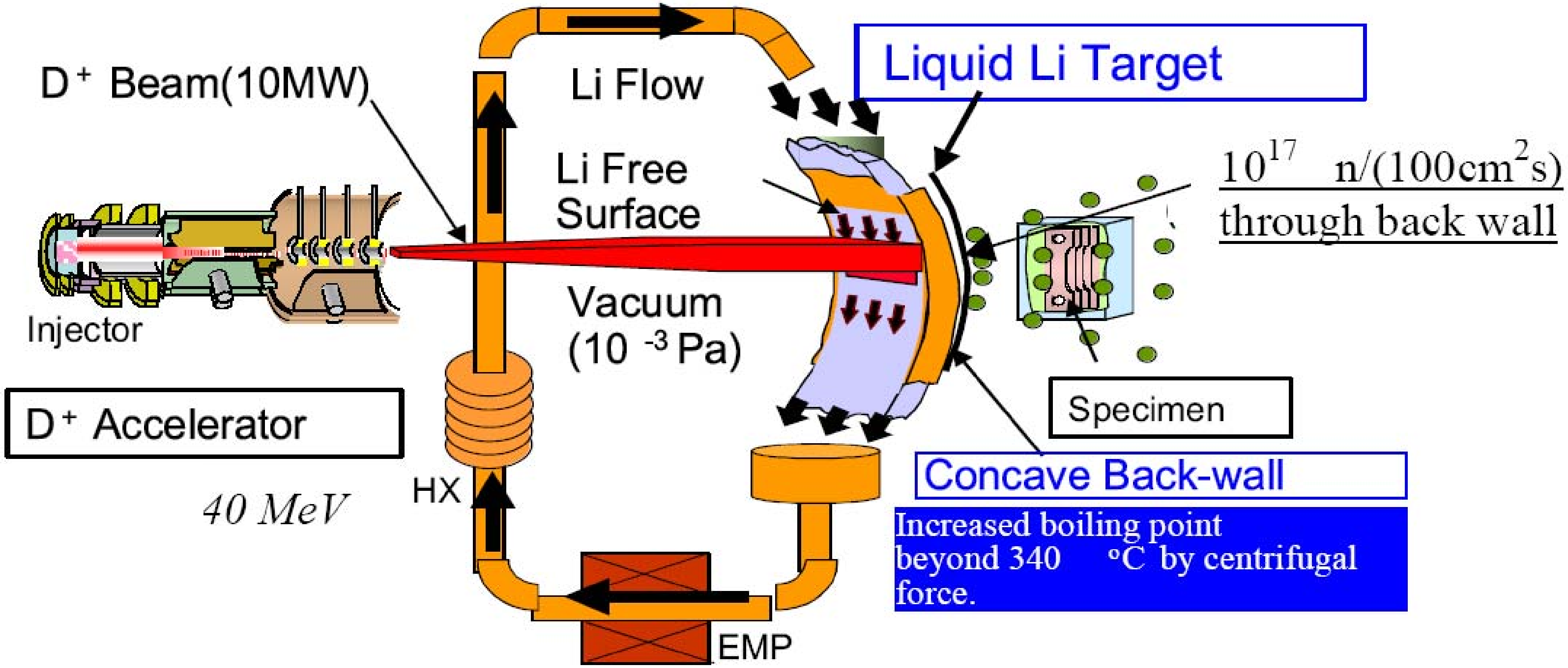


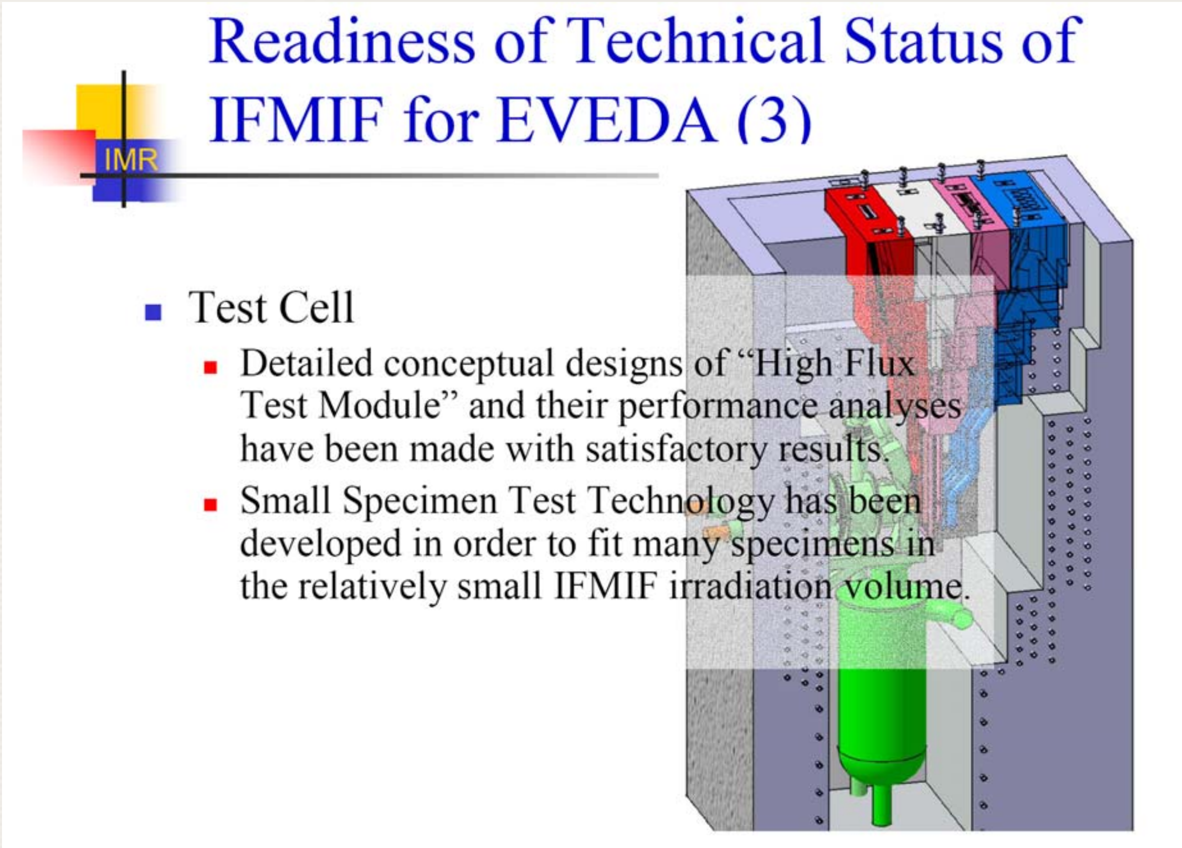
Figure 8. The IFMIF design concept

IAEA

IFMIF: Neutron Data

Data for neutron cross sections (> 20 MeV) needed:

Nuclear Data Section has been asked to support



The IAEA's action

1. **Fission**

2. **Fusion**

3. **Accelerators and Materials**

The IAEA's action

International Conferences
(as supported by Physics Section):

Research Reactor Conference (next 2011)

Fusion Energy Conference (next 2010)

Accelerator Conference (next 2009)

Workshop on Structural Materials for Innovative Nuclear Systems SMINS (together with NEA. next 2009)

IAEA

The IAEA's action

Coordinated Research Projects (CRP)
Fission: FUMEX I – III (NE-Department)

Objective I:
The major objective of the CRP was to improve the predictive capabilities of codes used in fuel behaviour modelling for extended burn-up. The focus was on the topics:
- **Thermal performance**
- **Fission gas release**
- **Pellet to clad interaction (PCI) at extended burn-up above 50 MWd/kg.**

Objective II:
In addition, the CRP addressed the performance of codes used for transient analysis such as RIA and LOCA at extended burn-up.

IAEA

The IAEA's action

Fission: FUMEX (I – III)

Significant improvements in the capability to model fuel temperature, fission gas release and dimensional change have been achieved, and with the recently completed FUMEX-2, the range of fuel burnup that is capable of being analysed accurately has increased to around 60,000 MWd/tU in support of the extended burnups in modern LWR fuel cycles.

Objective III:
FUMEX-3 will address concerns with high burnup transient behaviour, consequences of the rim effect observed at high burnup and will also consider fuel behaviour in advanced PHWR fuel cycles with high ratings and extended burnup.

➔ **Killeen, Inomzentsev**

IAEA

The IAEA’s action

Fission: Simulation and Modelling of Radiation Effects, SMoRE (2008-2011)

Extend understanding of the basic physics of accelerator irradiation under operational conditions in fission reactors, and through synergy with other nuclear concepts such as fusion and spallation systems.

That goal will bridge from micro- to macroscopic behaviour of materials through modelling validated by specific detailed experiments.

IAEA

The IAEA's action

Fission: SMoRE (2008-2011)

The CRP will give a special emphasis to following phenomena:

- Primary damage, cascade and sub-cascade formation
- Irradiation activated kinetic processes
- Void and gaseous swelling, including He + H synergisms
- Phase stability and self-organization under irradiation
- Irradiation effects on mechanical properties
- Corrosion processes under irradiation
- Role of impurities (e.g. transmutation, fabrication)

Following alloys/steels will be considered primarily for further studies of above-mentioned phenomena, in particular,

- Zr alloys
- Austenitic and ferritic-martensitic steels
- ODS materials

Structural materials related to other nuclear systems which contribute to the specific research objectives can be considered too.

IAEA

The IAEA's action

Fission: Technical Meetings

The overall objective of a Technical Meeting is to provide a forum to exchange ideas and information through scientific presentations and brainstorming discussions, it is anticipated that this meeting will achieve overall objectives.

IAEA

The IAEA's action

Fission:

Technical Meeting on "Accelerator Simulation and Theoretical Modelling of Radiation Effect" June 2008

To demonstrate how experimental accelerator simulation methods and theoretical modelling tools could be applied for investigation of irradiation phenomena, which degrade physical and mechanical properties and induce dimensional changes.

IAEA

The IAEA’s action

Fission:

Technical Meeting on “Accelerator Simulation and Theoretical Modelling of Radiation Effect” June 2008

To demonstrate how experimental accelerator simulation methods and theoretical modelling tools could be applied for investigation of irradiation phenomena, which degrade physical and mechanical properties and induce dimensional changes.

Schemes of triple beam accelerators

movie

The IAEA's action

Fission:

Technical Meeting on "Research Reactor Applications for Materials under High Neutron Fluence" November 2008

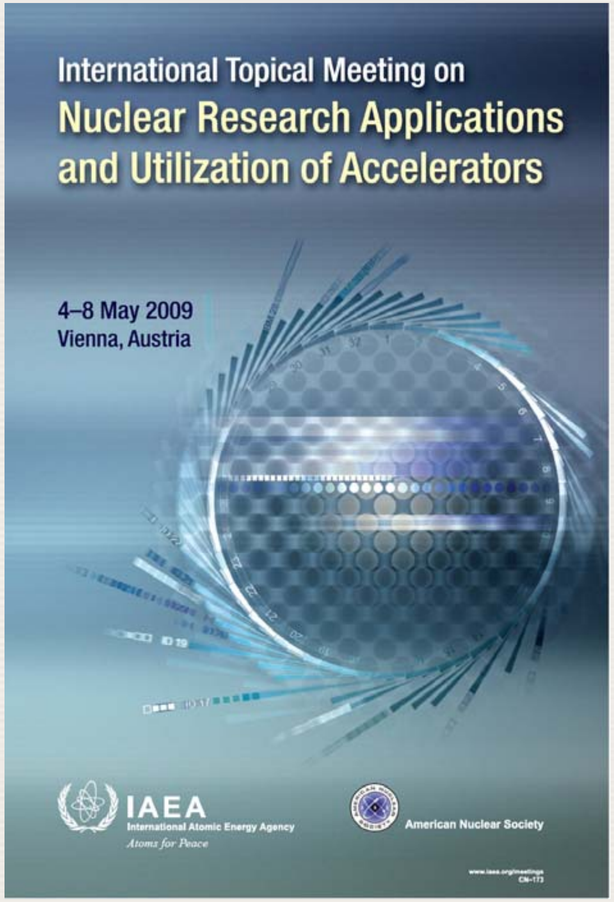
Specific objectives:

- Available irradiation facilities and recent development of Irradiation devices
- New material irradiation programmes and their implementation
- Radiation damage at high doses
- Effective and optimal operation procedures
- Information exchange

Accelerator Conference AccApp

Topics to be addressed at the conference:

- 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.



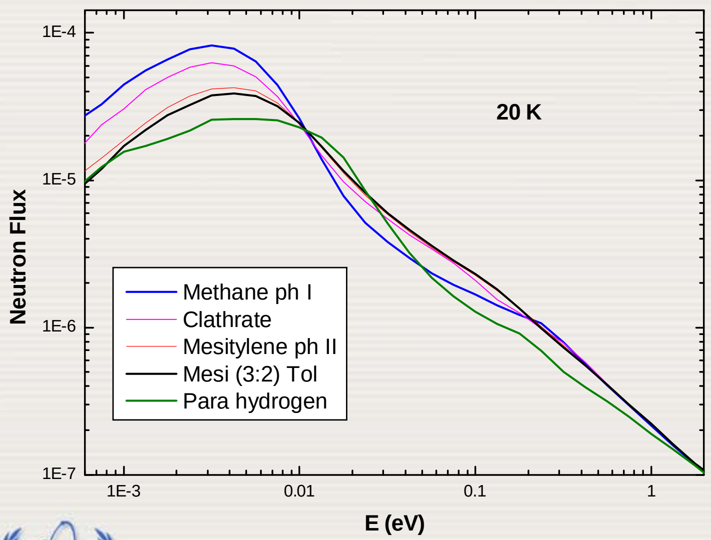
IAEA http://www-pub.iaea.org/MTCD/Meetings/Announcements.asp?ConfID=173

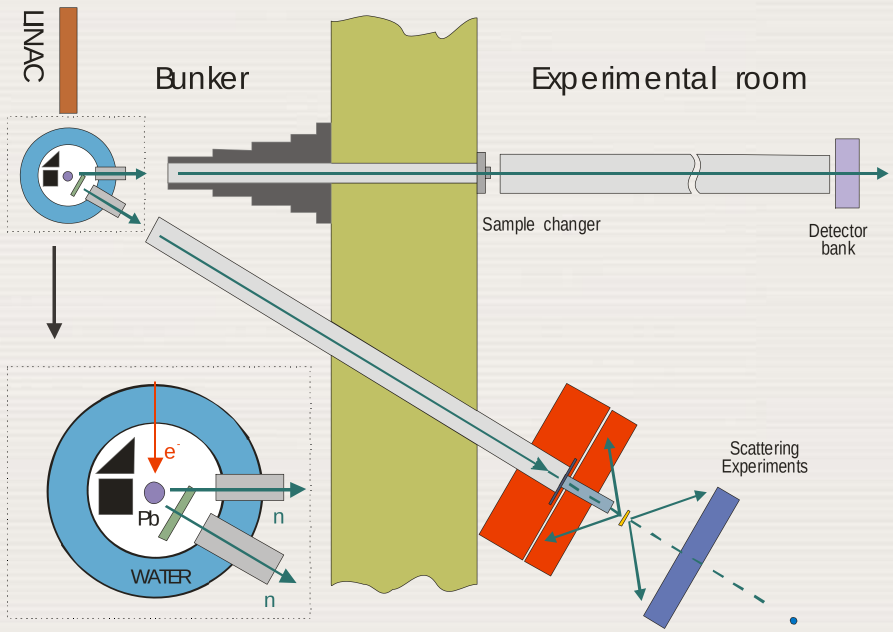
CRP, low – medium energy spallation neutron sources

Improved Production and Utilization of Short Pulsed, Cold Neutrons at Low-Medium Energy Spallation Neutron Sources

- Improvement of spallation source by development of cryogenic moderators
- Increase of potential usage of beam lines by contributing to improve micro-focusing small angle neutron scattering
- Enhance capability for strain determination by improving data extraction and evaluation from high resolution transmission measurements

25 MeV e LINAC, CENTRO ATOMICO BARILOCHE - ARGENTINA





IAEA

Spallation Modelling Benchmarking

IAEA
International Atomic Energy Agency

INDC(NDS)-0530
Distr. SC

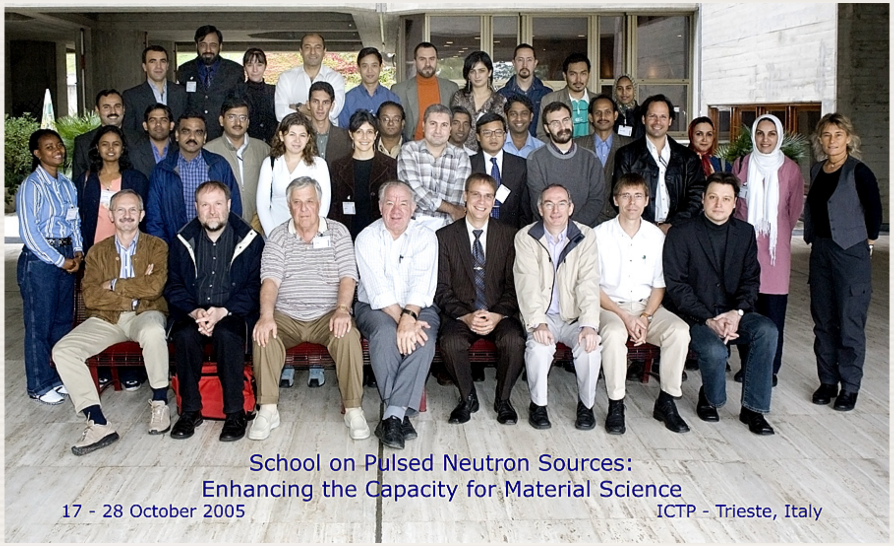
INDC International Nuclear Data Committee

Joint ICTP-IAEA Advanced Workshop on Model Codes for Spallation Reactions

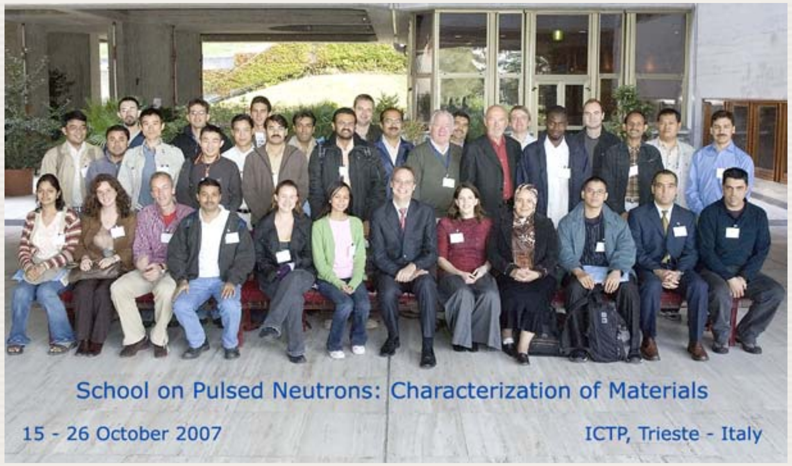
MEETING PROCEEDINGS

IAEA

Schools on Accelerators:



School on Ion Beam Analysis and Accelerator Applications,
13-24 March 2005, ICTP, Trieste, Italy



IAEA

Accelerators and Materials:

Joint ICTP/IAEA Workshop on Advanced Simulation and Modelling for Ion Beam Analysis

23 - 27 February 2009

Miramare - Trieste, Italy

Joint ICTP/IAEA School on
NOVEL SYNCHROTRON RADIATION APPLICATIONS

16-20 March 2009

ICTP, Miramare - Trieste, Italy

Joint ICTP/IAEA Advanced Workshop on Development of Radiation Resistant Materials

20 – 24 April 2009

(Miramare – Trieste, Italy)

Joint ICTP/IAEA School on Physics and Technology of Fast Reactors **Systems**

9 November - 20 November 2009

IAEA

The IAEA's action

Fusion:

Technical Meetings

Physics and Technology of Inertial Fusion Energy Targets and Chambers (2009)
Steady State Operation of Magnetic Fusion Devices (2009)
First Generation of Fusion power Plants: Design and Technology (2009)

The IAEA's action

Fusion:

Coordinated Research Projects:

Integrated approach to dense plasma applications in nuclear fusion technology

Pathways to Energy from Inertial Fusion – An integrated approach

Investigations on Materials under High Repetition Intense Fusion Pulses (2011)

Dense Plasmas technology and applications for main steam fusion research (2010)

IAEA

Summary I

Material Research at research reactors, neutron sources and accelerators is important for future projects on:

NPP, Gen IV reactors, *transmutation*

Fusion (magnetic and inertial)

Material Research has to be complementary using:

New neutron sources and their capabilities

Including different investigation technologies

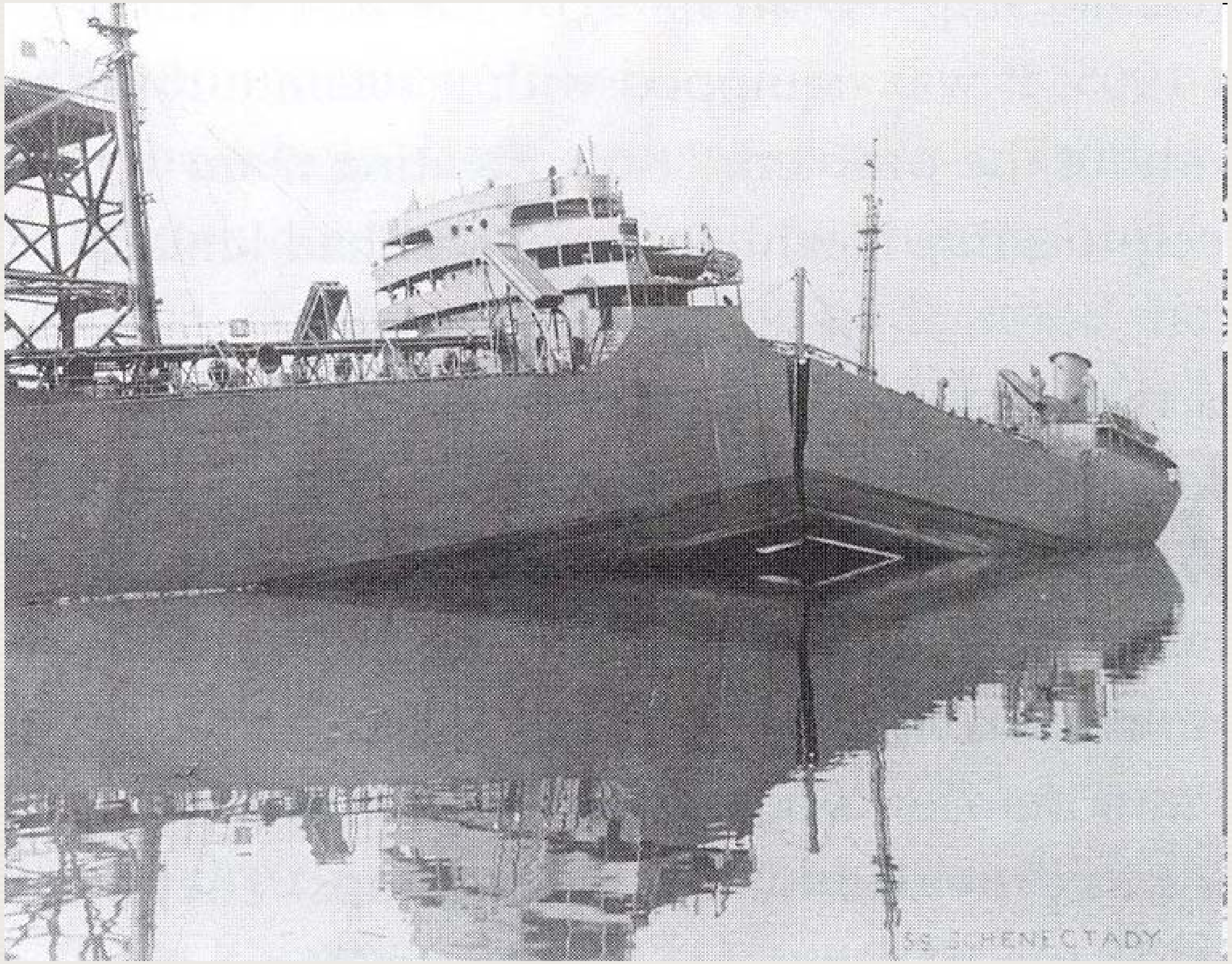
IAEA

Summary II

The IAEA takes action on urgent issues related to materials for energy.

The new programme and budget 2010/11 includes many new activities on materials research, which need support from the Physics Section, the Fuel Section, and the Research Reactor Cross-coordination.

Take care of materials!



In 1943 the T2 tanker Schenectady broke in two due to brittle metal and bad welding. Finally sold to Trieste. (from Wikipedia).