Alex C. MUELLER
Deputy Director

cnrs
dépasser les frontières

IN2P3
Institut national de **physique nucléaire**
et de **physique des particules**

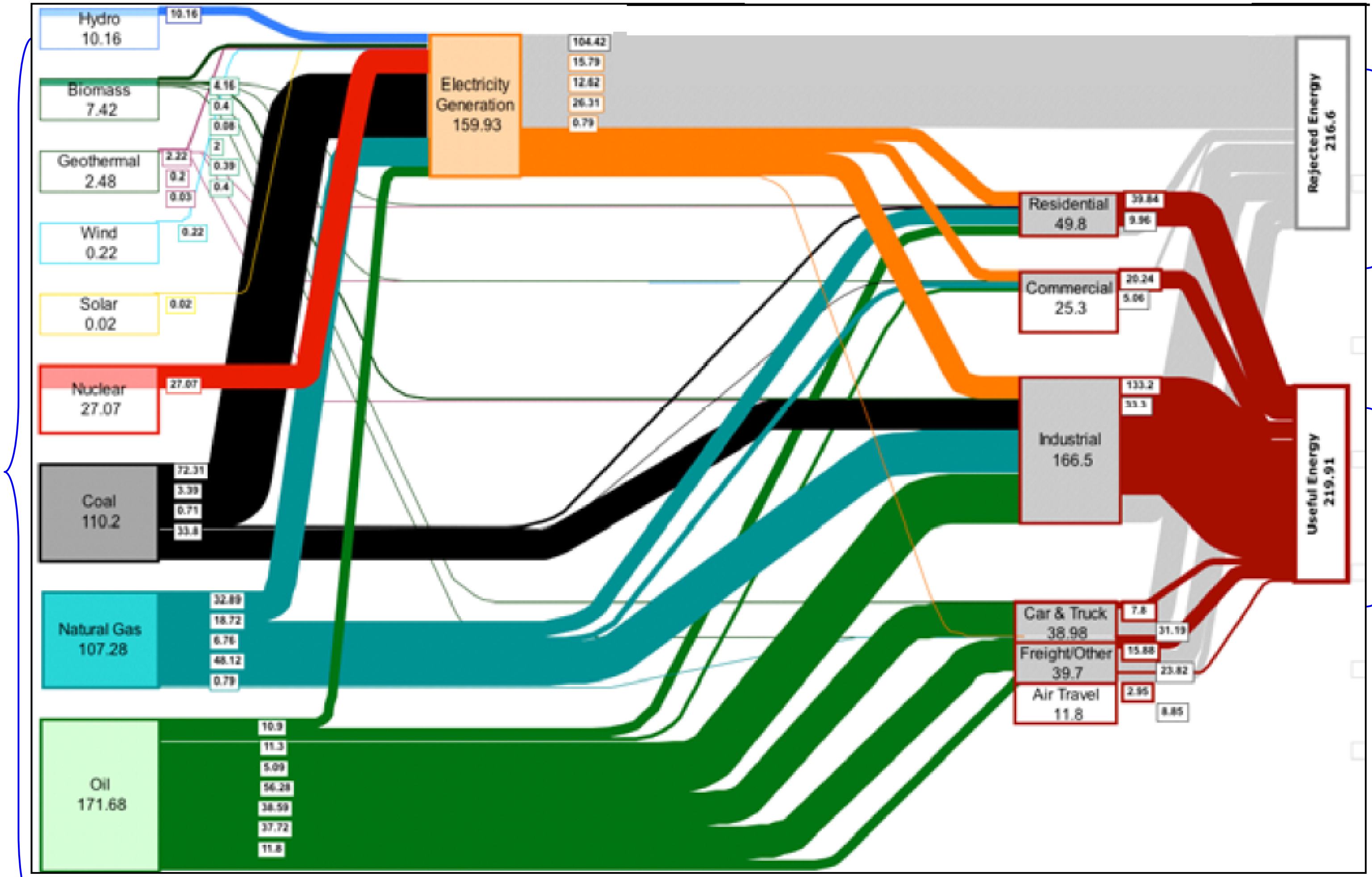
Transmutation von Atommüll

17 Juni 2011, Institut für Physik, Universität Heidelberg

Avant Propos

- Der Wissenschaftler muss Fakten sammeln, beschreiben, analysieren.
- Das ist per Definition ein nachvollziehbarer Vorgang.
- Der Bürger hat demokratisches Entscheidungsrecht nach freier Meinungsbildung.
- Diese Meinungsbildung sollte natürlich zunächst einmal auf (wissenschaftlichen) Fakten beruhen, nur dann ist auch das demokratische System als Solches "sustainable", es handelt sich also gewissermassen um eine demokratische Bürgerpflicht.
- Erst dann, in einem zweiten Schritt darf die Güterabwägung erfolgen, in der andere Kriterien (z.b. ethische) den Ausschlag geben können.
- Der heutige Vortrag soll Informationen zum ersten Schritt liefern, das Publikum möge aber dem Redner gestatten, auch seine Meinung gelegentlich durchblicken zu lassen.

2005 World Energy Flow Diagram



Primary Energy

461 EJ

Rejected Energy

229EJ

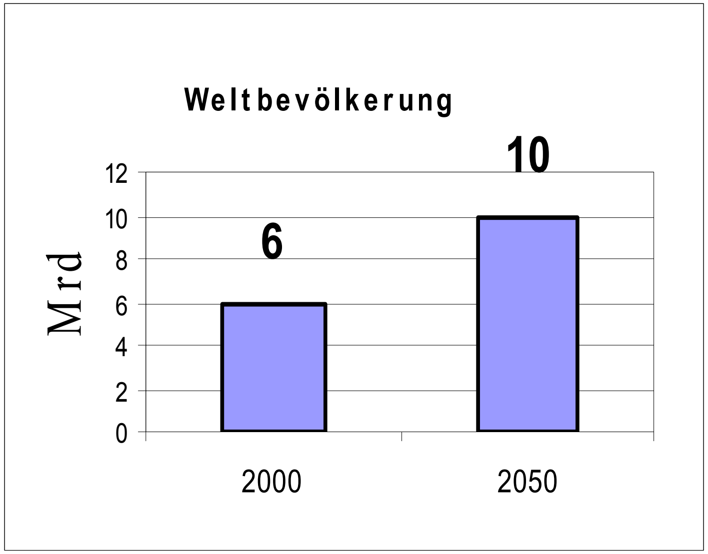
Useful Energy

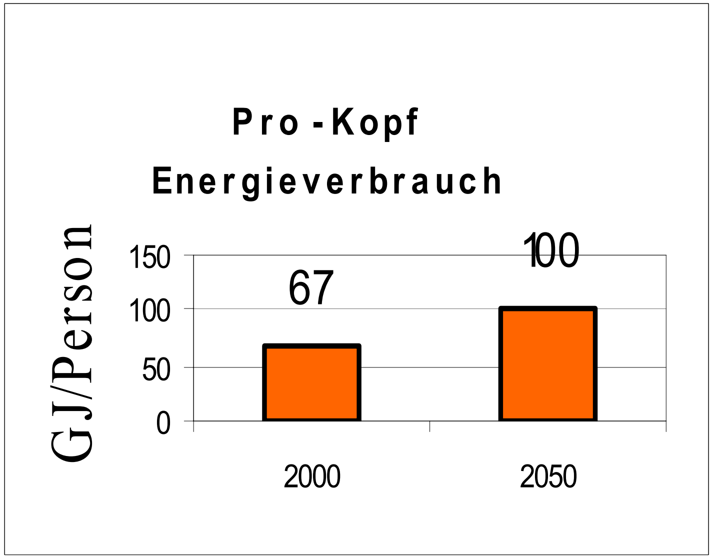
232EJ

Source: Lawrence Livermore National Laboratory
chart figures in quads – 1 quad=1.05 EJ

Zukünftiger Energiebedarf

These 1: "Die Weltbevölkerung wird wachsen"

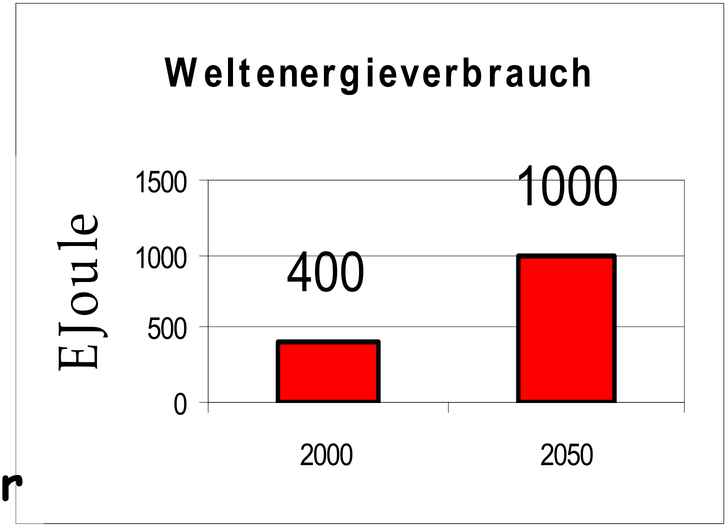




These 2: "Der pro Kopf Energieverbrauch wird steigen, auch wenn die Industrienationen massiv Energie einsparen."

Wieso?

Im Mittel verbraucht ein US-Amerikaner heute 15 Mal mehr Energie als ein Inder, ein Deutscher acht Mal mehr. Die Schwellenländer holen auf.



The dilemma of the future energy mix

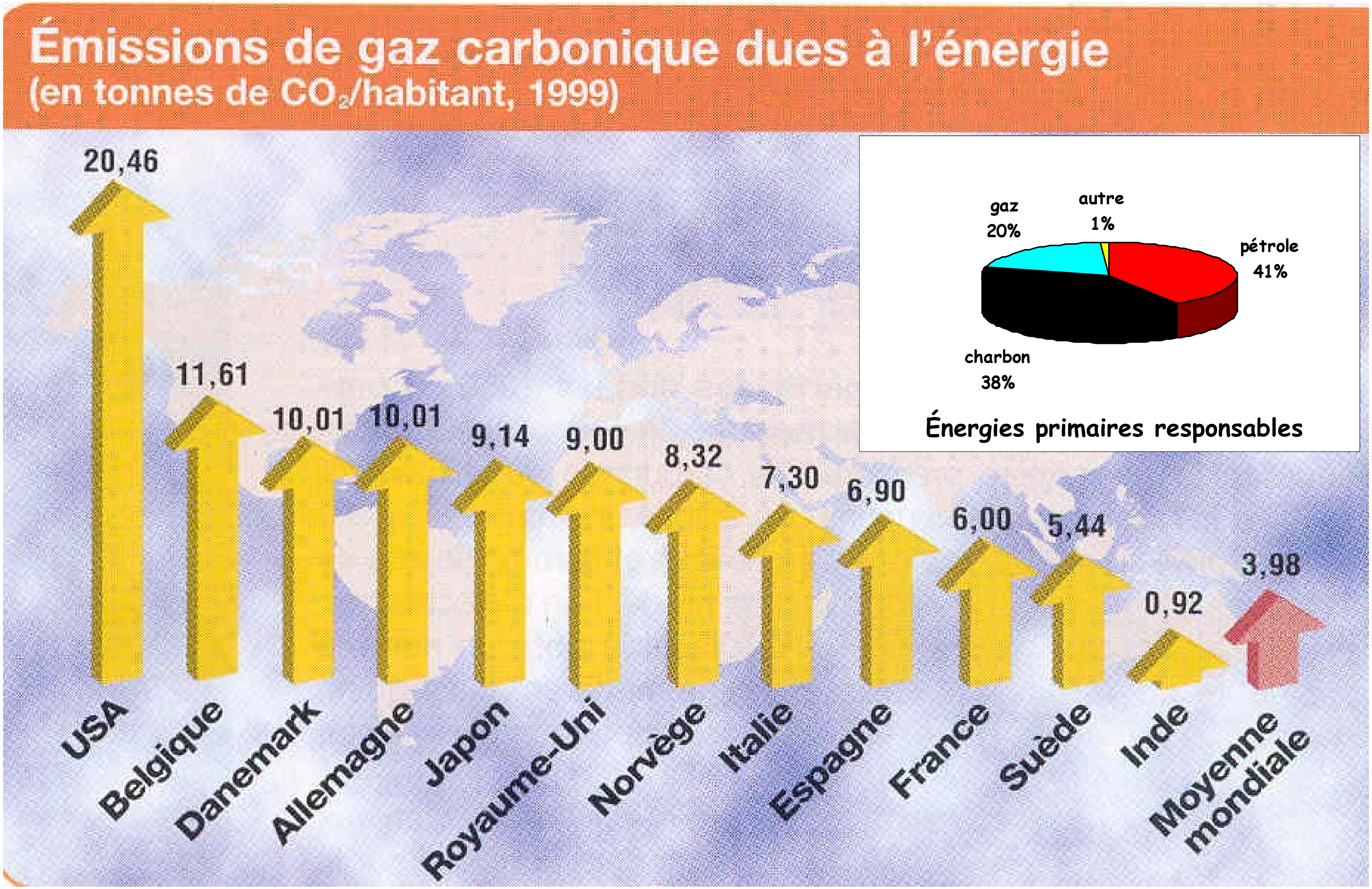
Hypothesis for 2050

- Energy consumption will only increase by a foctor of 2 (energy economies !!)
- CO_2 emissions will be reduced by a factor of 2

			2005			2050
Consommation	~10 Gtep		(% de 10 Gtep)		20 Gtep	(% de 20 Gtep)
Fossiles	7.9	→	78%	: 2	4.1	20%
Bio & Waste	1.0	→	10%	x 3	3.3	17%
Hydro	0.6	→	6%	x 2	1.2	6%
Other Renewables*	0.05	→	0.5%	x 100	5.4	27%
Nuclear	0.6	→	6%	x 10	6.0	30%

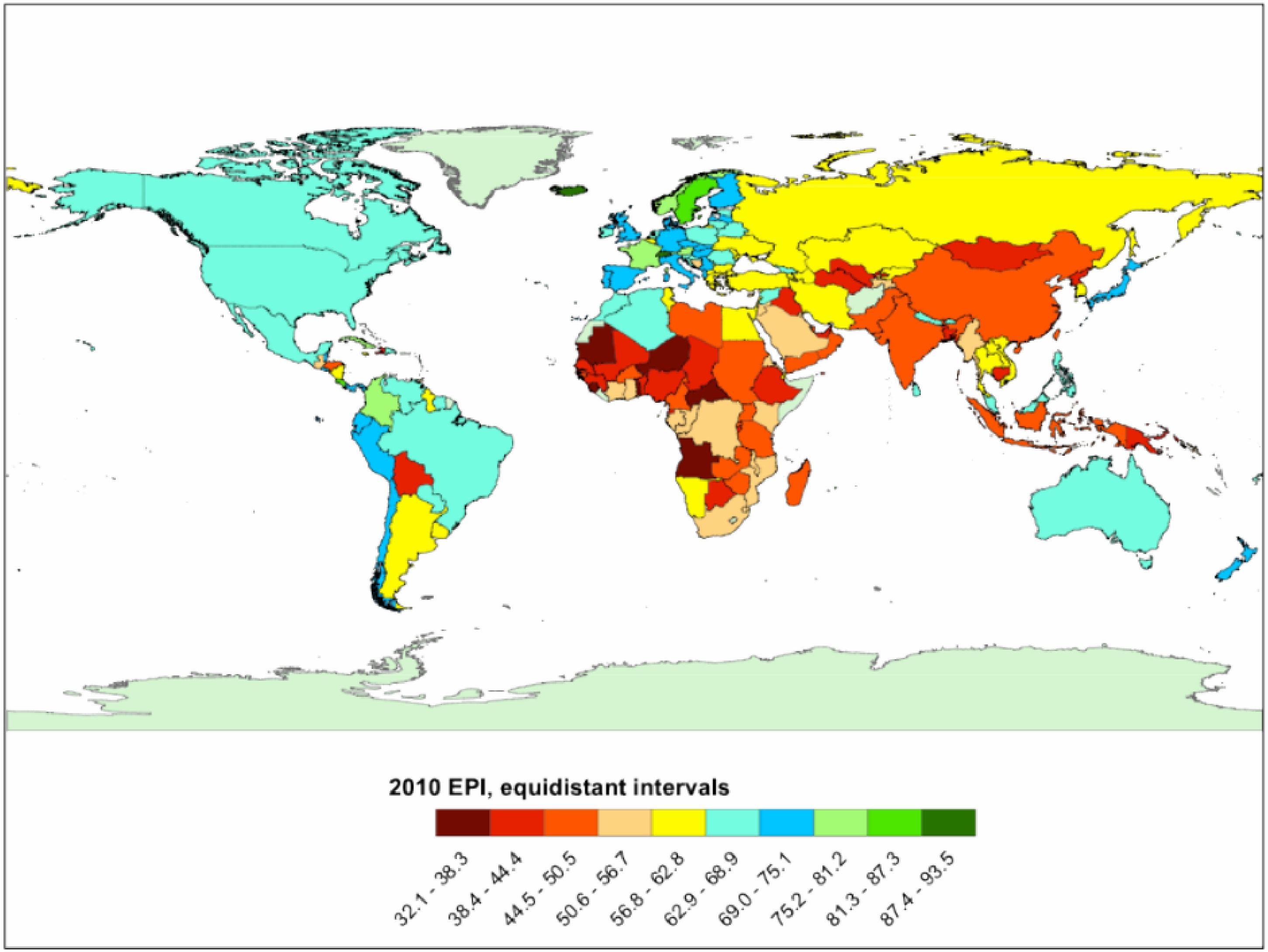
*Solar (thermal and photovoltaic, wind, geothermal, biomasse)

Total de CO_2 émis: 24 milliards de tonnes par an



The 2010 EPI*-index (U Yale et al.)

*Environmental Performance Index



Selected Rankings:

CH:	2
Swe:	4
Nor:	5
F:	7
Fin:	12
D:	17
DK:	32
US:	61
China:	121
India:	123

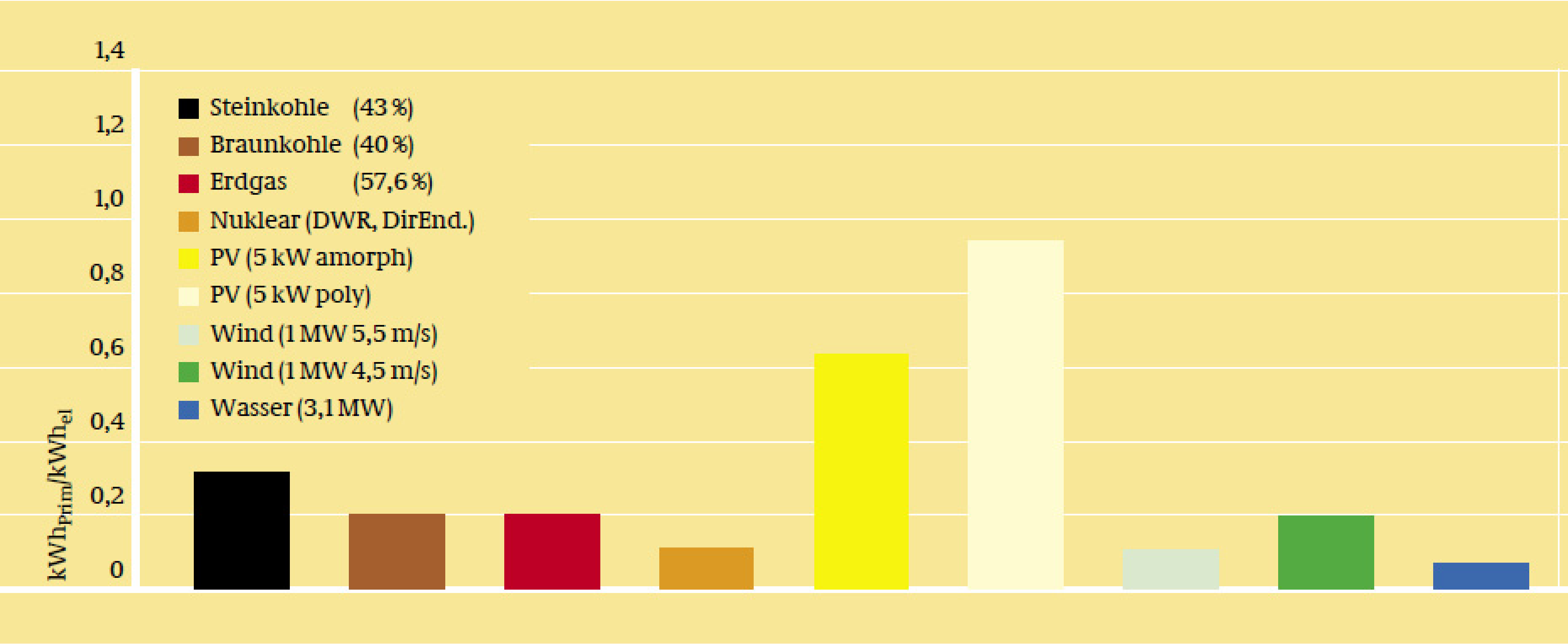
Wieso Elektrizitätsproduktion?

- Elektrizität ist "hochwertige" Energie. Man kann Heizen, Treibstoff synthetisieren, Fahrzeuge bewegen, Industrie versorgen usw.

- Für "einfache" Aufgaben (z.B. Heizen) ist es teilweise trotzdem sinnvoller direkt den Primärenergieträger zu verwenden, weil die Umwandlungsverluste wegfallen.

(Zitat J. Stadlmann, GSI)

Cumulated required Energy Needs



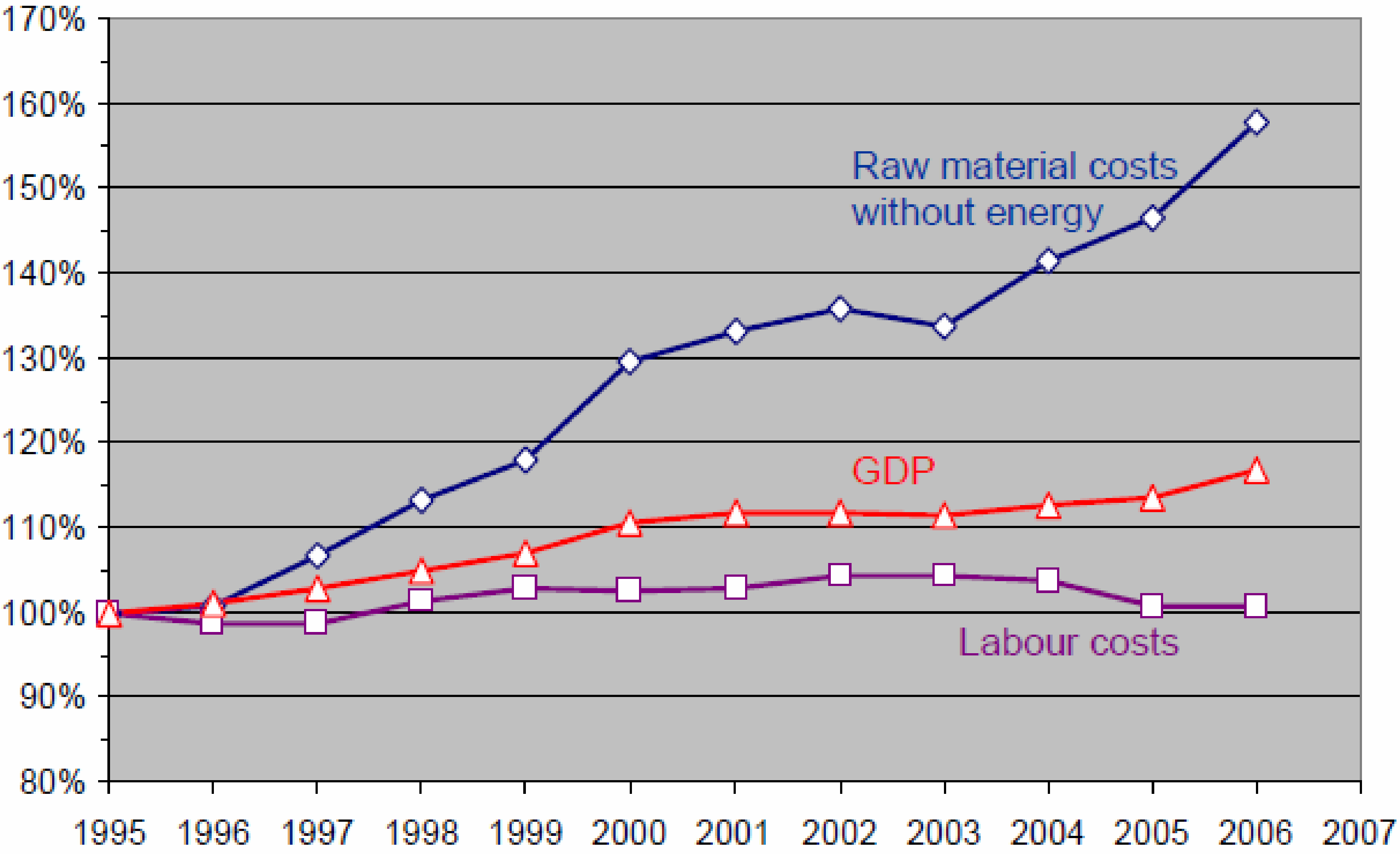
thesis T. Marheineke, Univ. Stuttgart

Total life cycle raw material requirements

	Iron [kg / GWh$_{el}$]	**Copper** [kg / GWh$_{el}$]	**Bauxite** [kg / GWh$_{el}$]
Coal (43 %)	2308	2	20
Lignite (40 %)	2104	8	19
Gas CC (57.6 %)	969	3	15
Nuclear (PWR, ult. waste dispo.)	445	6	27
PV poly	6708	251	2100
(5 kW) amorph	8153	338	2818
Wind 5.5 m/s	5405	66	54
(1 MW) 4.5 m/s	10659	141	110
Hydro (3.1 MW)	2430	5	10

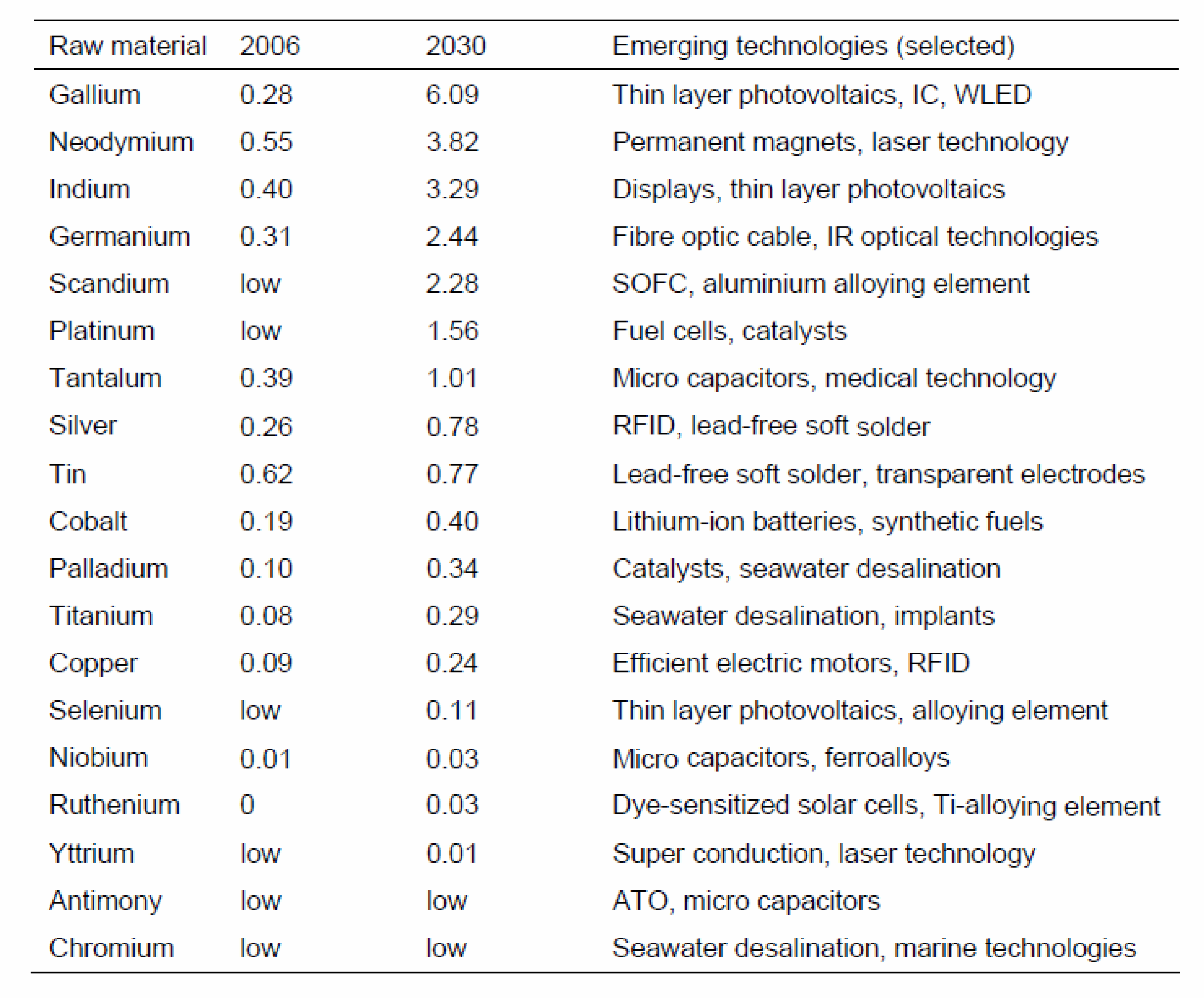
Source: Marheineke 2002

Development of costs in the German Manufacturing Industry
(from a 2009 Fraunhofer Study, in constant prices)



note: extreme market volatility for raw material prices, sharp drop during banking crisis

Future demand of (rare) raw materials
(from a 2009 Fraunhofer study)

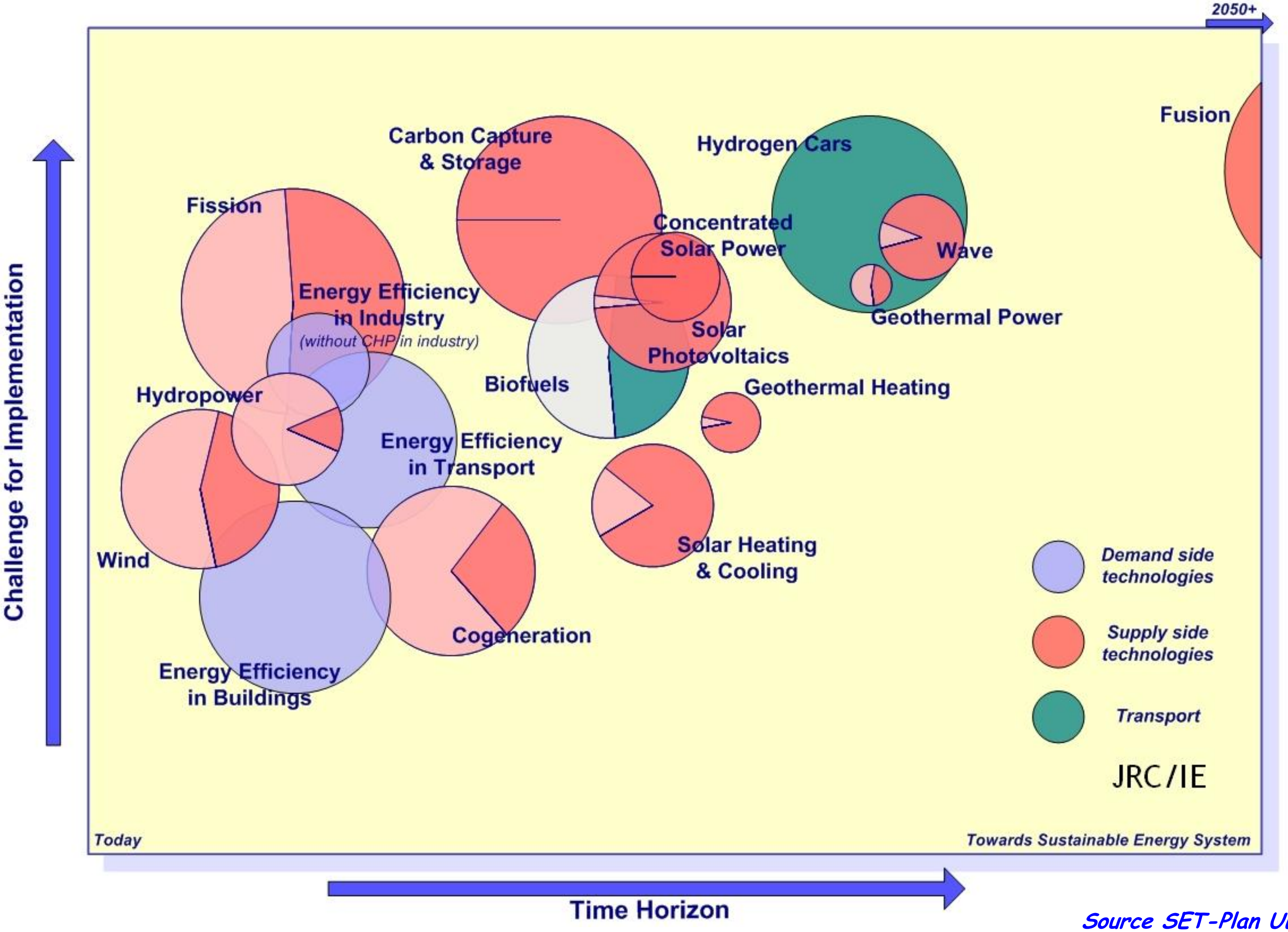


Raw material	2006	2030	Emerging technologies (selected)
Gallium	0.28	6.09	Thin layer photovoltaics, IC, WLED
Neodymium	0.55	3.82	Permanent magnets, laser technology
Indium	0.40	3.29	Displays, thin layer photovoltaics
Germanium	0.31	2.44	Fibre optic cable, IR optical technologies
Scandium	low	2.28	SOFC, aluminium alloying element
Platinum	low	1.56	Fuel cells, catalysts
Tantalum	0.39	1.01	Micro capacitors, medical technology
Silver	0.26	0.78	RFID, lead-free soft solder
Tin	0.62	0.77	Lead-free soft solder, transparent electrodes
Cobalt	0.19	0.40	Lithium-ion batteries, synthetic fuels
Palladium	0.10	0.34	Catalysts, seawater desalination
Titanium	0.08	0.29	Seawater desalination, implants
Copper	0.09	0.24	Efficient electric motors, RFID
Selenium	low	0.11	Thin layer photovoltaics, alloying element
Niobium	0.01	0.03	Micro capacitors, ferroalloys
Ruthenium	0	0.03	Dye-sensitized solar cells, Ti-alloying element
Yttrium	low	0.01	Super conduction, laser technology
Antimony	low	low	ATO, micro capacitors
Chromium	low	low	Seawater desalination, marine technologies

note:
1) authors recognize extreme difficulty of reliable predictions

2) only impact of selected emerging technologies analysed, "business-as-usual" underlying for current technologies.

Key technologies for a low carbon energy system



Source SET-Plan UE

Generations of nuclear power plants

adapted from van Heek
Groningen Energy Convention 2005

Generation I

Early prototype/
demo reactors
- Shippingport
- Dresden, Fermi I
- Magnox

- First demo of nuclear power on commercial scale
- Close relationship with DOD
- LWR dominates

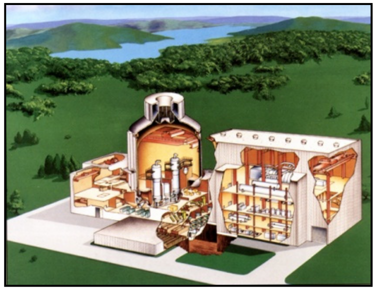
Generation II

- LWR-PWR, BWR
- CANDU
- HTGR/AGR
- VVER/RBMK

- Multiple vendors
- Custom designs
- Size, costs, licensing times driven up

Generation III

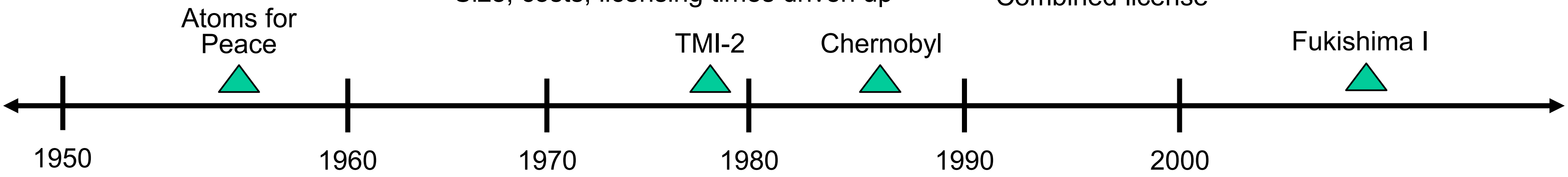
- ABWR, System 80+, AP600, EPR



- Passive safety features
- Standardized designs
- Combined license

Generation IV

- Highly economical
- Proliferation resistant
- Enhanced safety
- Minimize waste



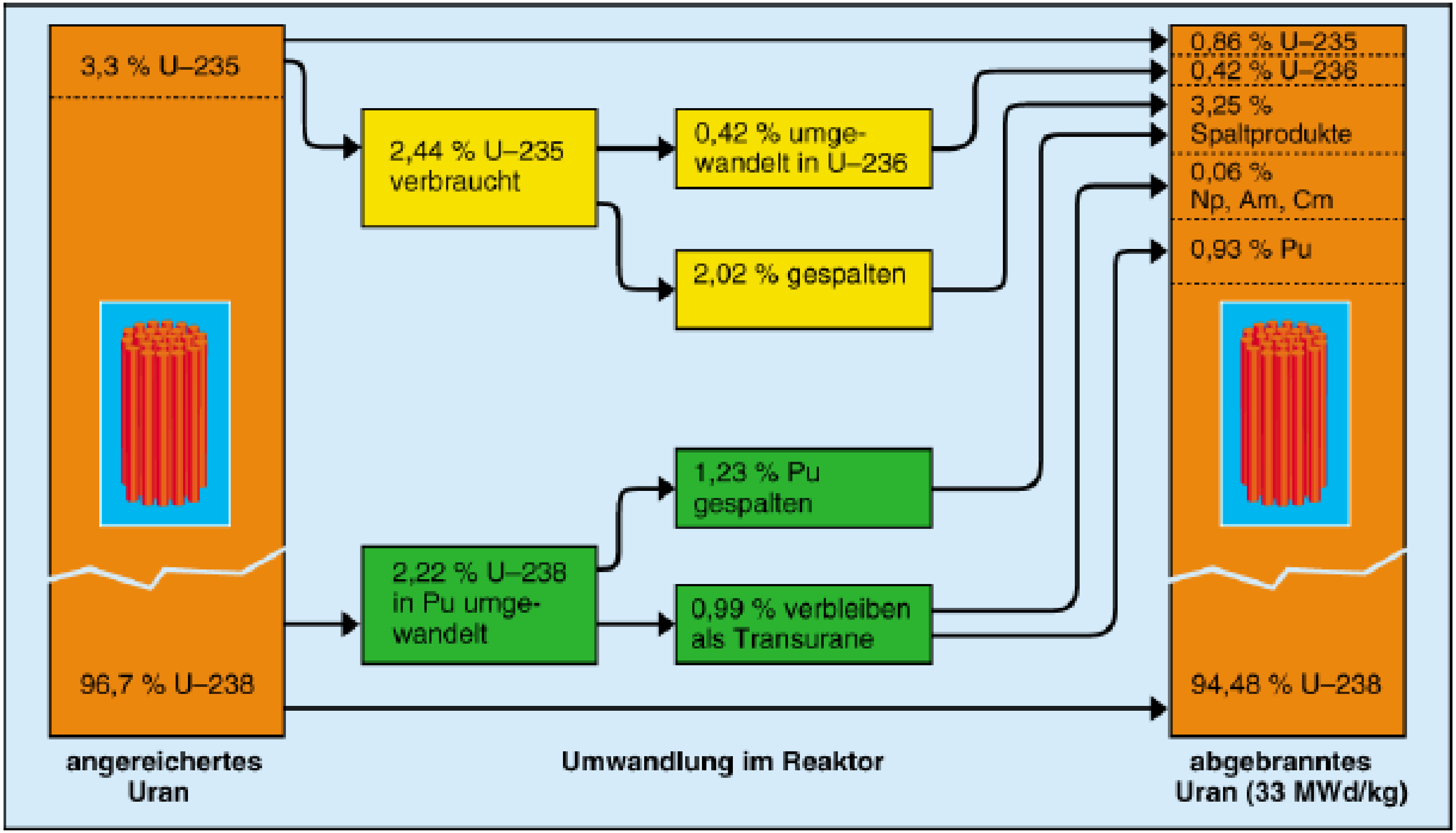
Present Gen-II Nuclear Power Plants in Europe

Kernkraftwerke in Europa, Stand 30.9.2009

Worldwide:
440 NPP on grid
560 planned
(170 sites)

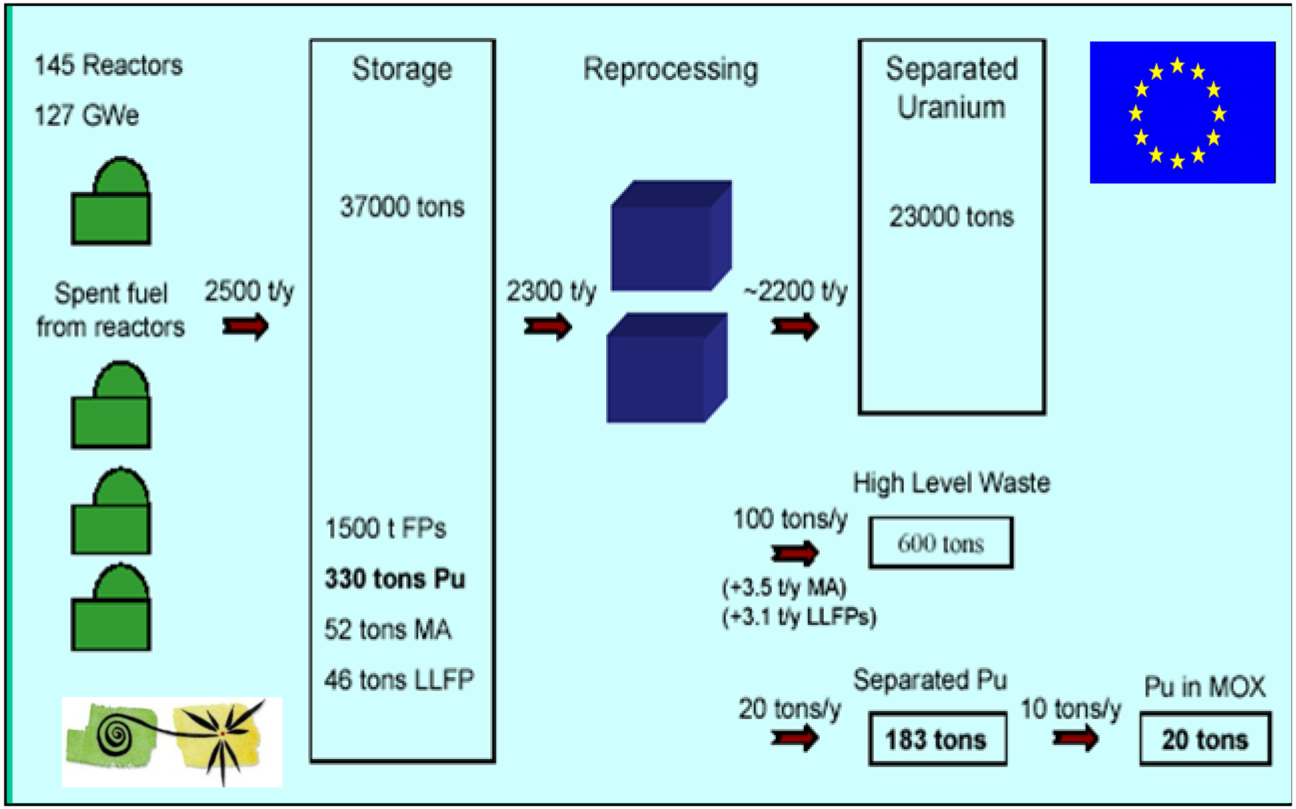
From fuel to waste in a (typical) present Gen-II reactor

aus dem « Karlsruher Lexikon »



Zusammensetzung des Kernbrennstoffs für Leichtwasserreaktoren vor und nach dem Reaktoreinsatz

Nuclear energy makes 880 TWh/y (35% of EU's electricity), but PWR produce important amounts of high level waste



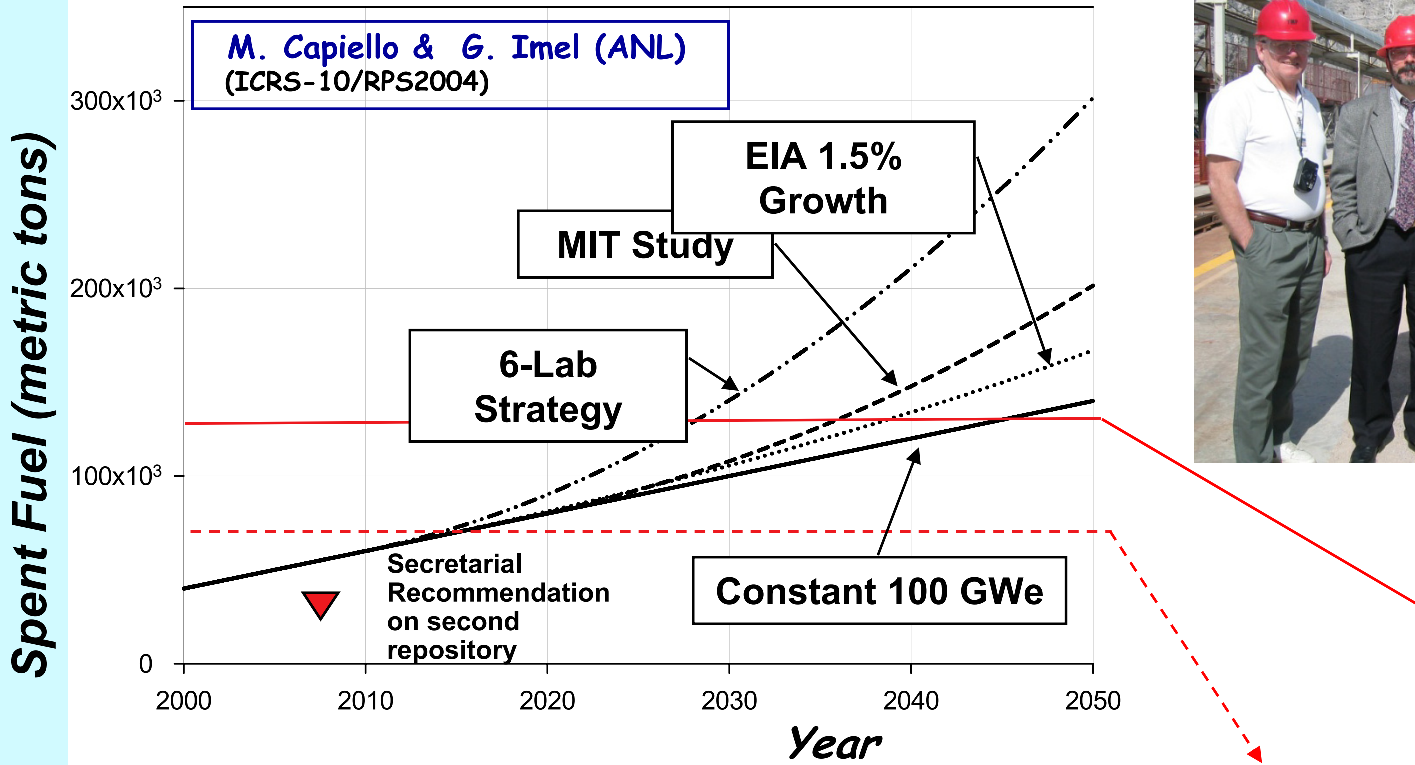
Nuclear Waste from present LWR's (Light Water Reactors)

- ➔ is highly radiotoxic (10^8 Sv/ton)
- ➔ at the end of present-type nuclear deployment about 0.3 Mtons, or 3×10^{13} Sv, compare to radiation workers limiting dose of 20mSv
- ➔ the initial radiotoxicity level of the mine is reached after more than 1 Mio years
- ➔ worldwide, at present 370 "1GW_{el} equiv. LWR" produce 16% of the net electricity

- **Geologic time storage of spent fuel is heavily debated**
  - ➔ leakage in the biosphère ?
  - ➔ expensive (1000 €/kg), sites? (Yucca mountain would hold 0.07 Mio tons!!)
  - ➔ public opposition

The Yucca Mountain Dilemma

- In the United States, the plan is/was to send all spent nuclear fuel to the Yucca Mountain Repository. The challenge they are faced with is that new repositories will be needed as nuclear energy continues or grows.

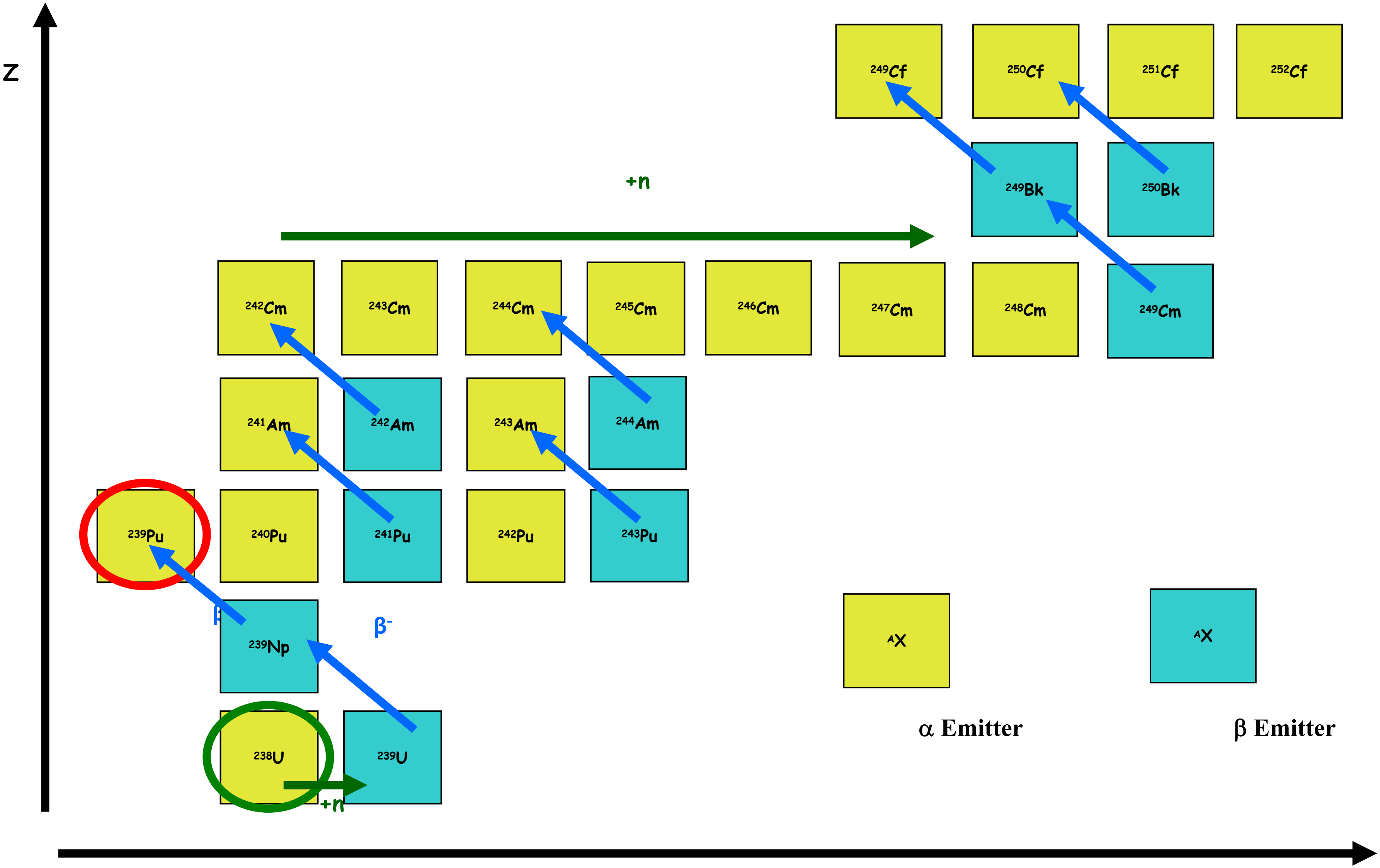


Legislated capacity

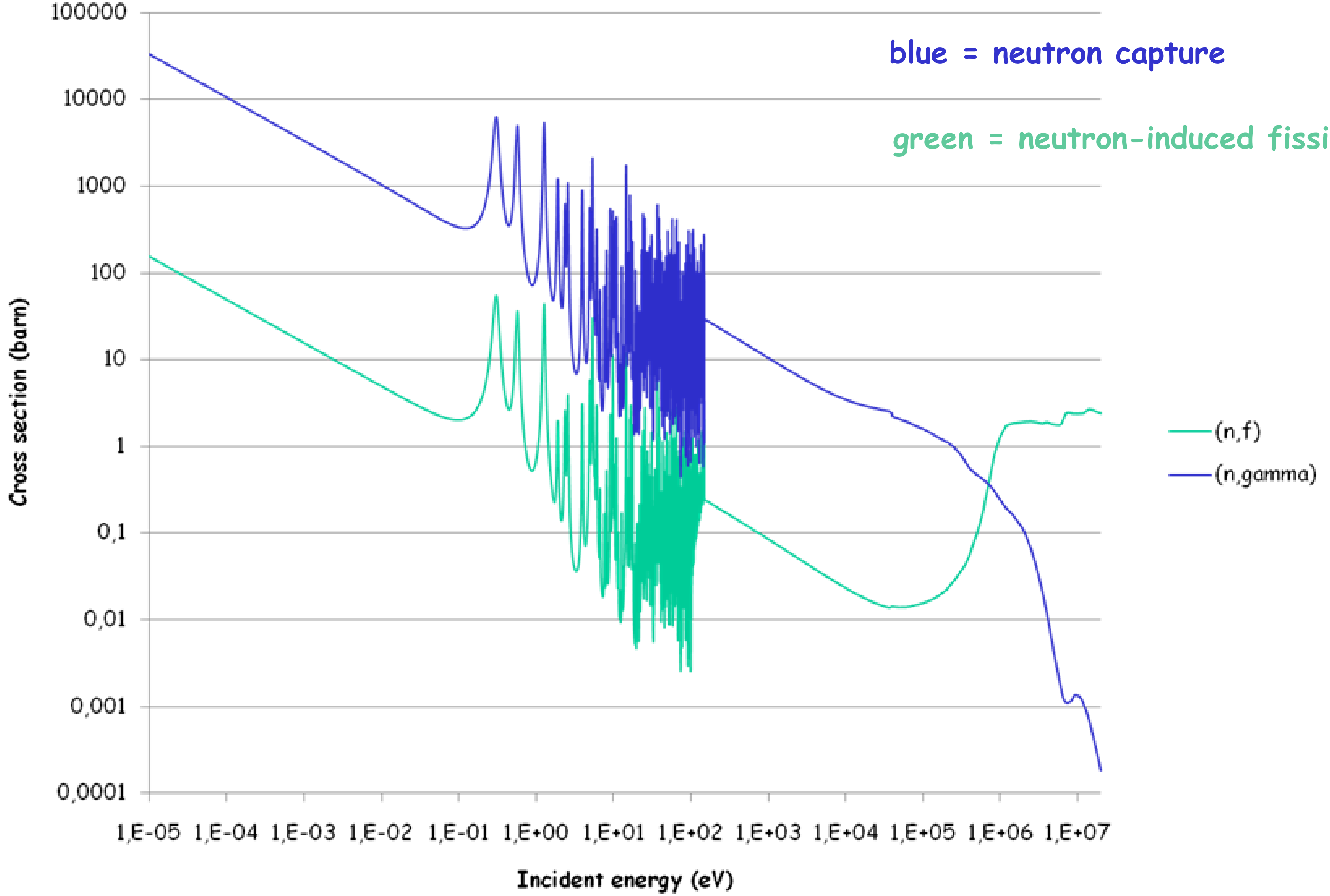
Capacity based on limited exploration

Speaker @ Yucca Mountain

Nuclear Reaction Flow in a PWR building up MA-waste



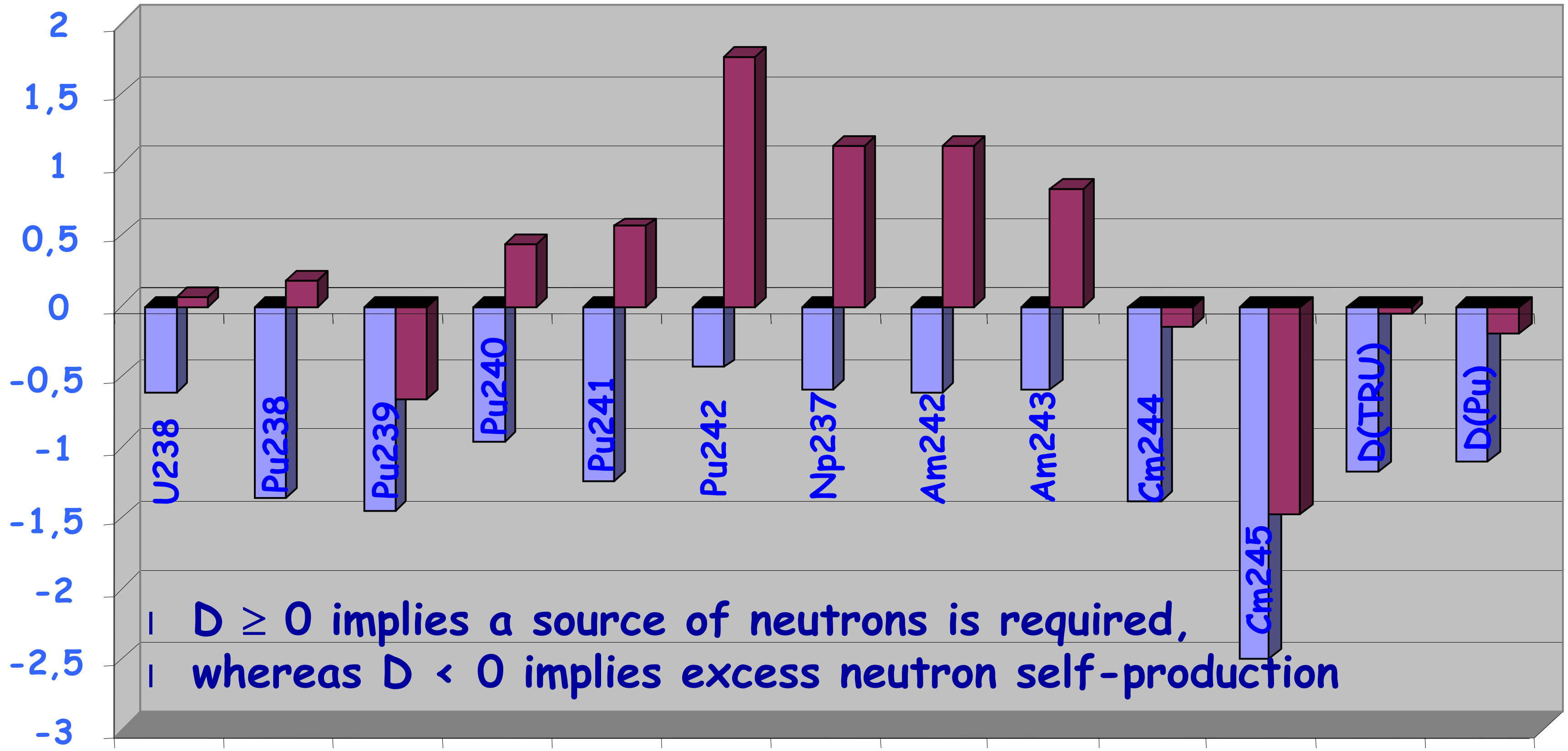
Am241 fission and capture cross sections



blue = neutron capture

green = neutron-induced fission

Neutron consumption per fission ("D-factor") for thermal (red) and fast (blue) neutron spectra



- D ≥ 0 implies a source of neutrons is required,
- whereas D < 0 implies excess neutron self-production

➡ thermal neutron "make nuclear waste" and do not use the resource optimally

➡ Sustainability = Fast Neutrons

Partitioning and Transmutation for GEN-II/III

Partitioning:

Separating out of spend fuel certain chemical elements

Transmutation:

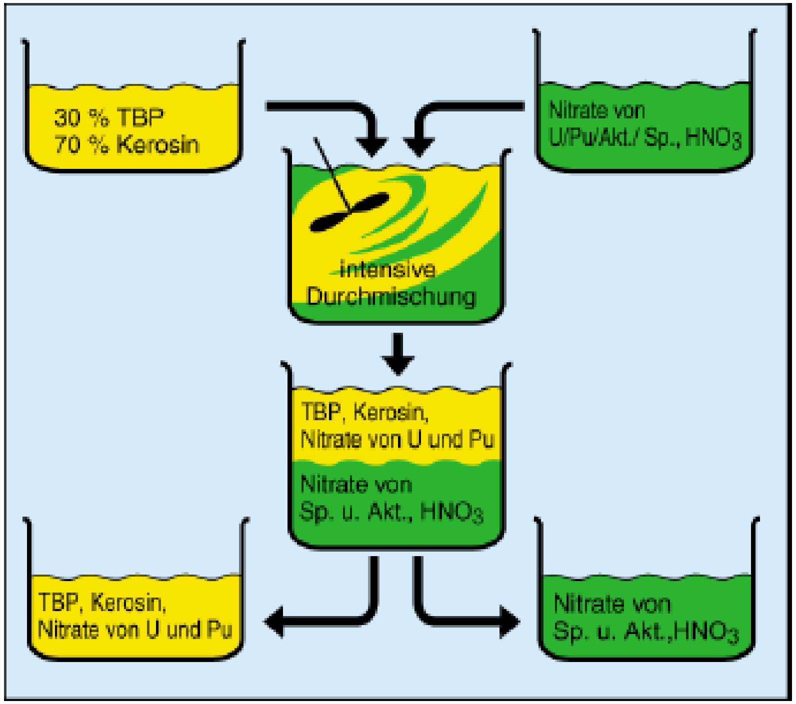
Transforming a chemical element into another

Advanced fuel cycles with P/T may greatly benefit to deep geological storage:

- Reduction of radiotoxicity.
- Reduction of the heat load

- ➢ larger amount of wastes can be stored in the same repository
- ➢ according to the PATEROS study a "one-order-of-magnitude" reduction in the needed repositories can be expected (a factor of 50 under optimum conditions)

Beispiel für Partitioning: PUREX



aus dem Karlsruher Lexikon

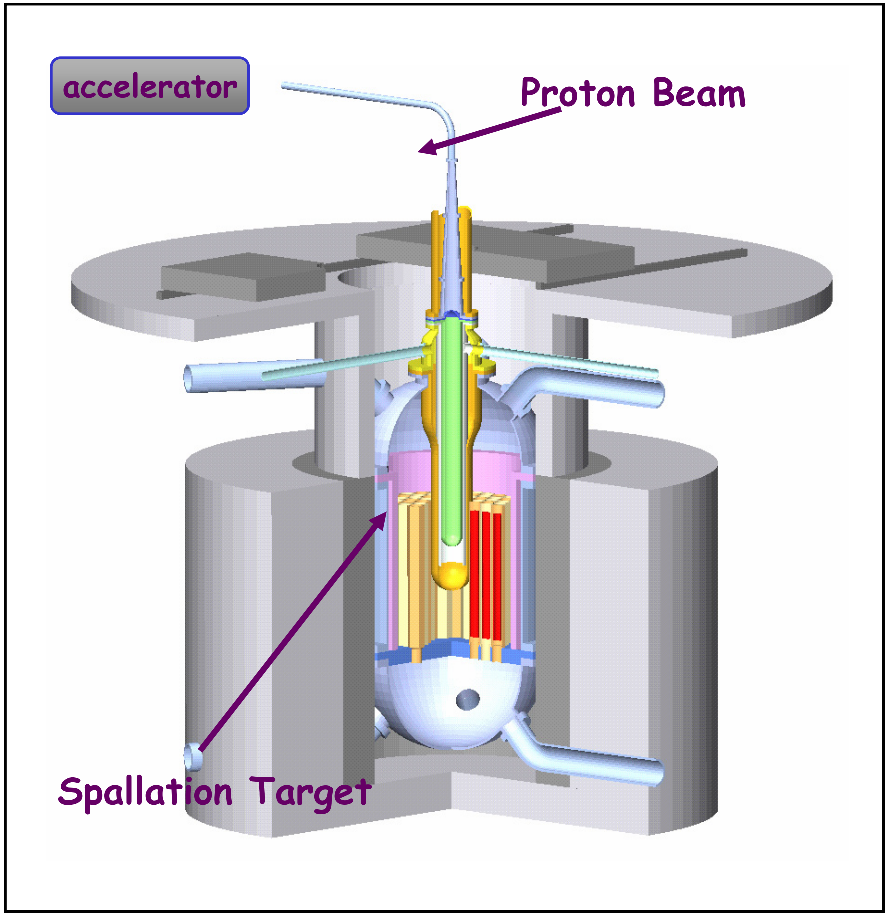
Nach Auflösen des bestrahlten Brennstoffes in Salpetersäure werden durch organische Lösungsmittelextraktion - als organisches Lösungsmittel dient 30-prozentiges Tributylphosphat (TBP) in Kerosin - Uran und Plutonium in der organischen Phase gehalten, während die Spaltprodukte in der wässrigen, salpetersauren Phase verbleiben. Weitere Verfahrensschritte erlauben anschließend das Trennen von Uran und Plutonium voneinander.

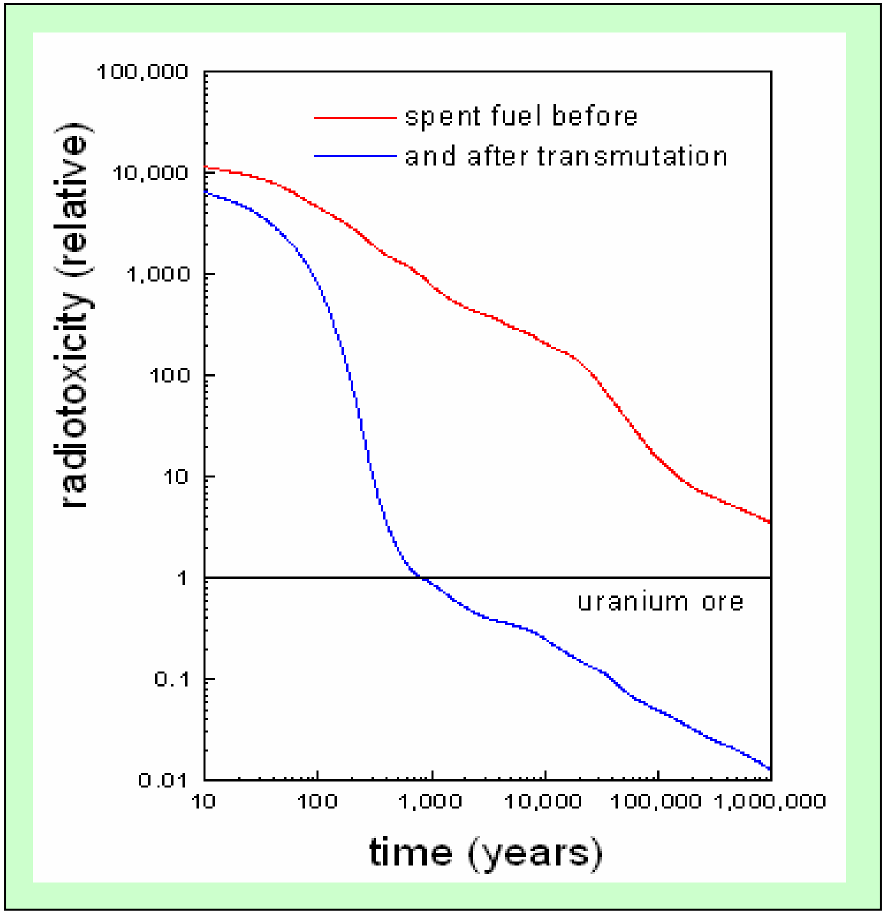
ADS: Accelerator Driven (subcritical) System for transmutation

Both critical (fast!!) reactors and sub-critical Accelerator Driven Systems (ADS) are potential candidates as dedicated transmutation systems.

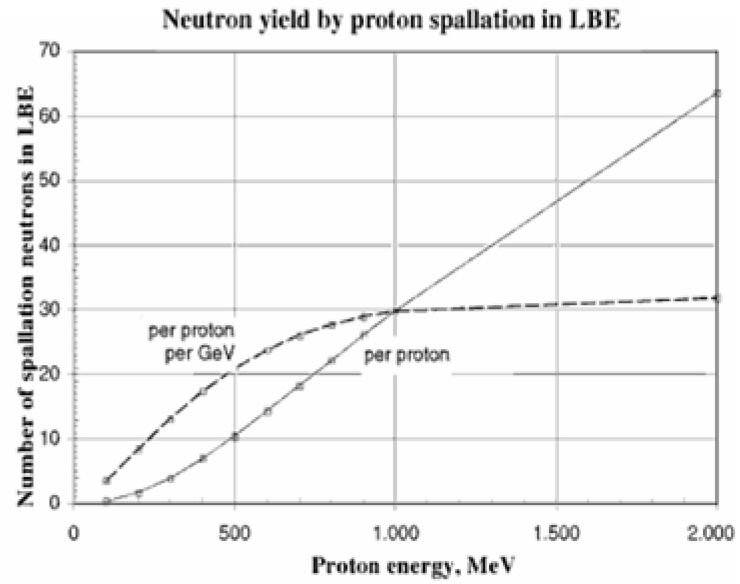
Critical reactors, however, loaded with fuel containing large amounts of MA pose safety problems caused by unfavourable reactivity coefficients and small delayed neutron fraction.

ADS operates flexible and safe at high transmutation rate (sub-criticality not virtue but necessity!)

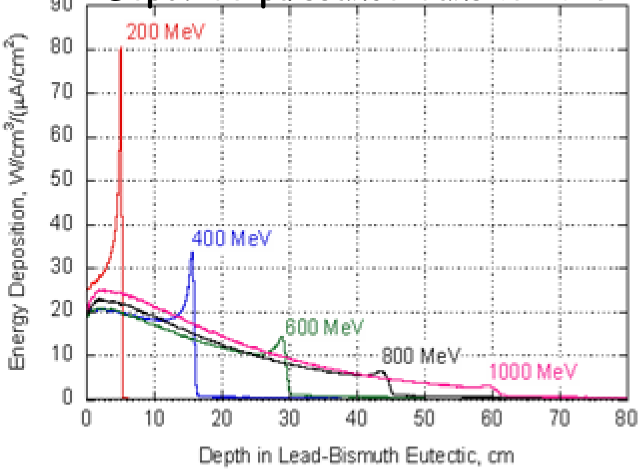




Faisceaux de protons requis



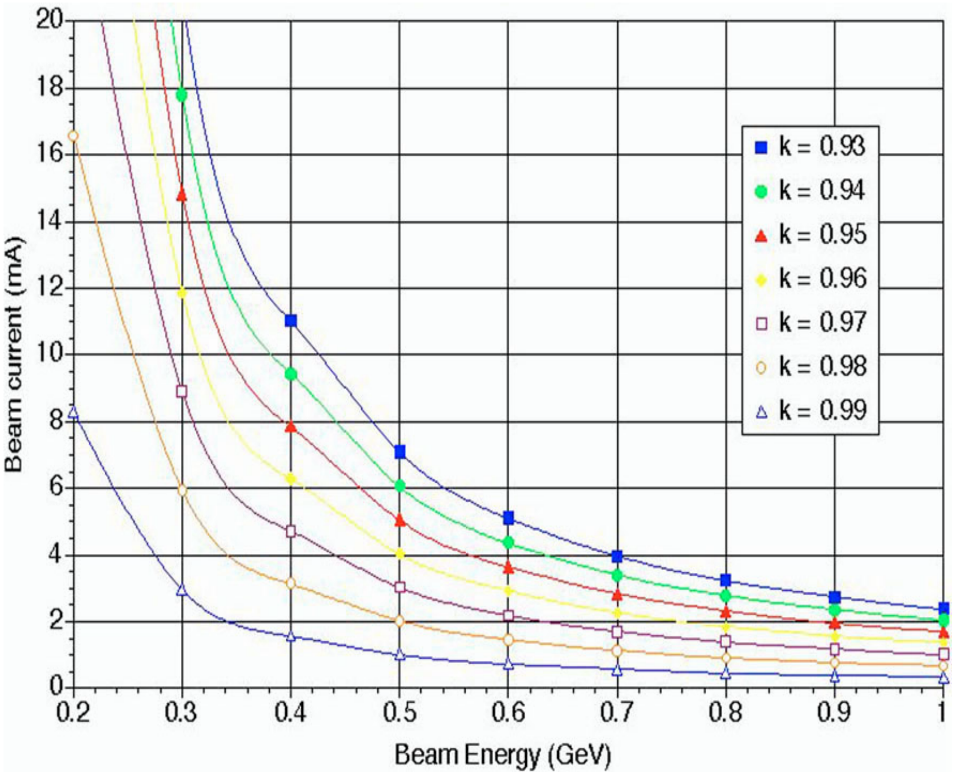
Dépôt de puissance dans le Pb-Bi



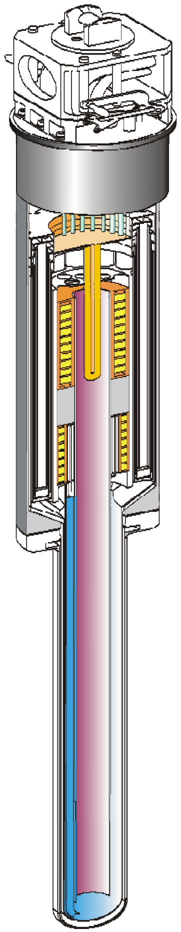
Abaques Courant/Energie/Sous-Criticité

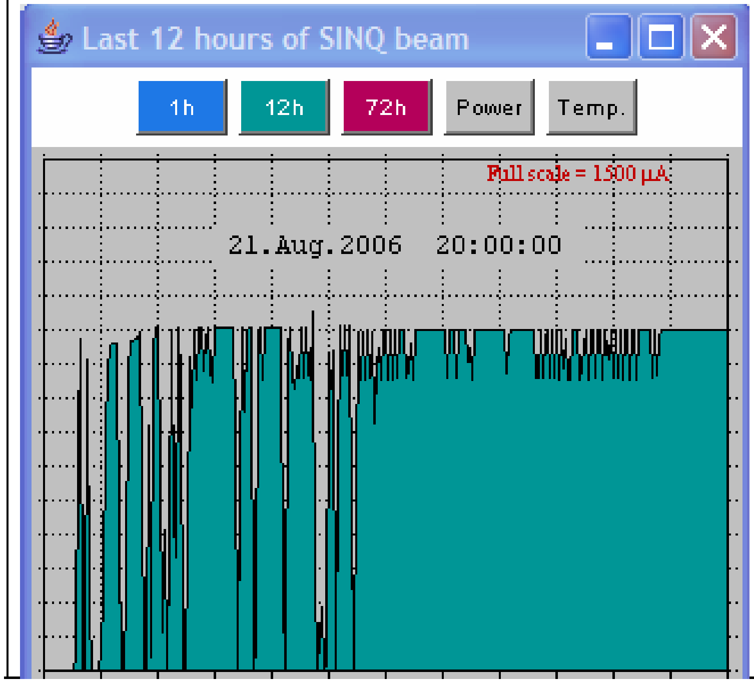
pour un démonstrateur de 80 MW$_{\text{therm}}$

(simulation par ANSALDO)



2006: Succes of the Megapie experiment at PSI



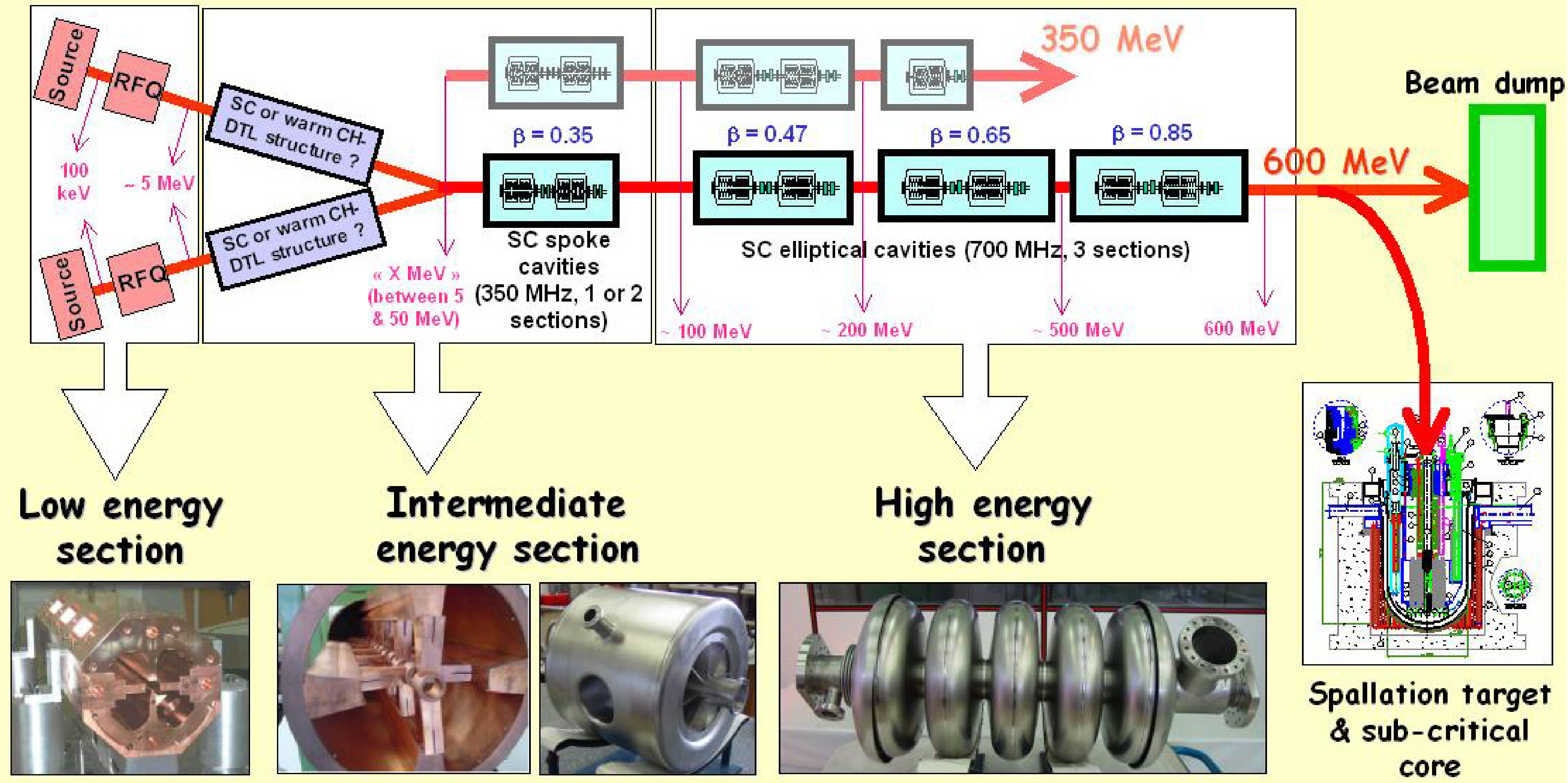


Start of Normal User operation.

Normal user operation was started on August 21st around 8:30 and is planned to continue until the normal annual winter shut-down starting on December 23rd 2006.

The first 12 hours of proton beam is seen to the left.

PDS-XADS Reference Accelerator Layout



Low energy section

Intermediate energy section

High energy section

Spallation target & sub-critical core

Strong R&D & construction programs for LINACs underway worldwide for many applications

(Spallation Sources for Neutron Science, Radioactive Ions & Neutrino Beam Facilities, Irradiation Facilities)

Accelerator main specifications

High-power proton CW beams

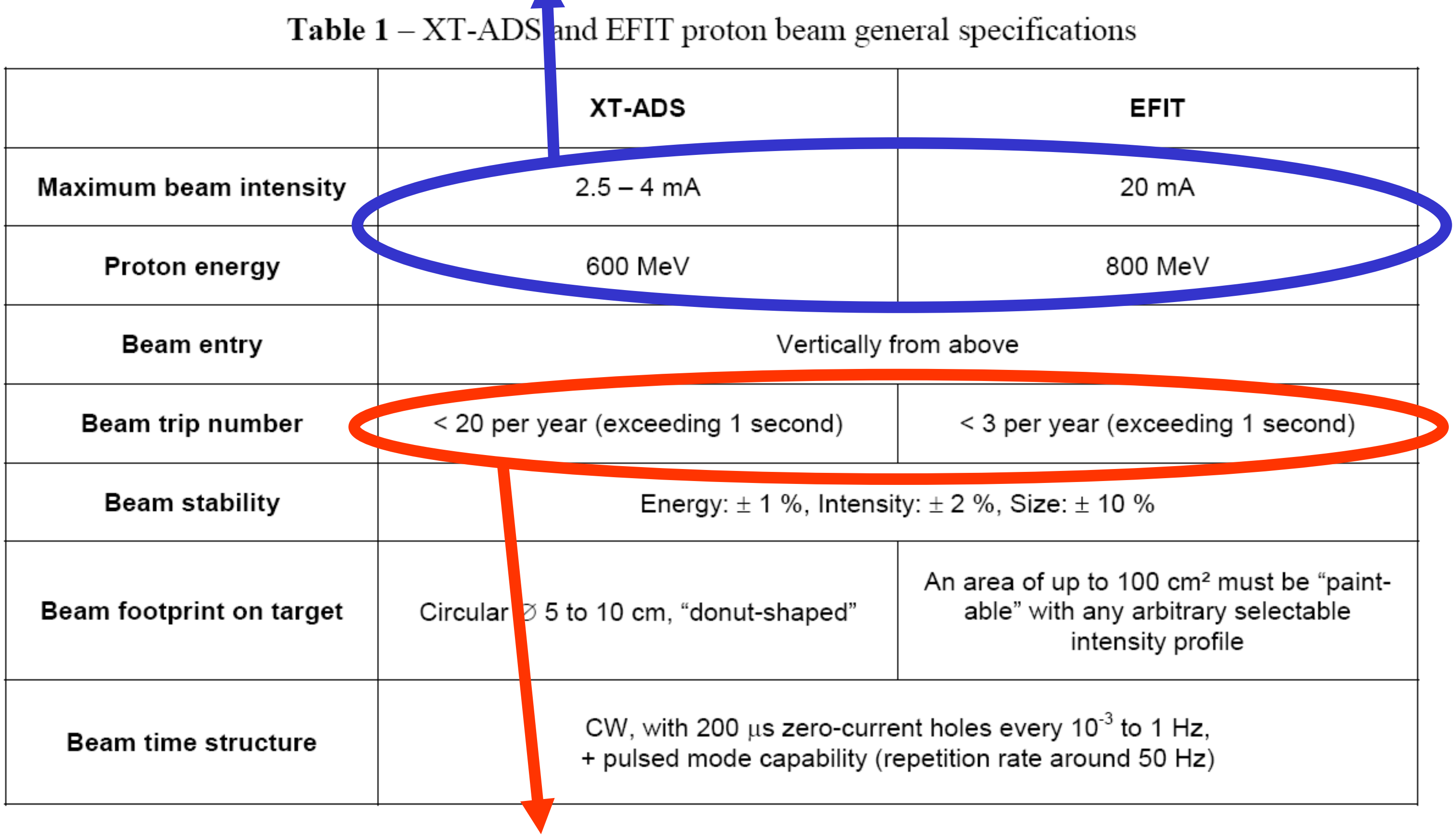


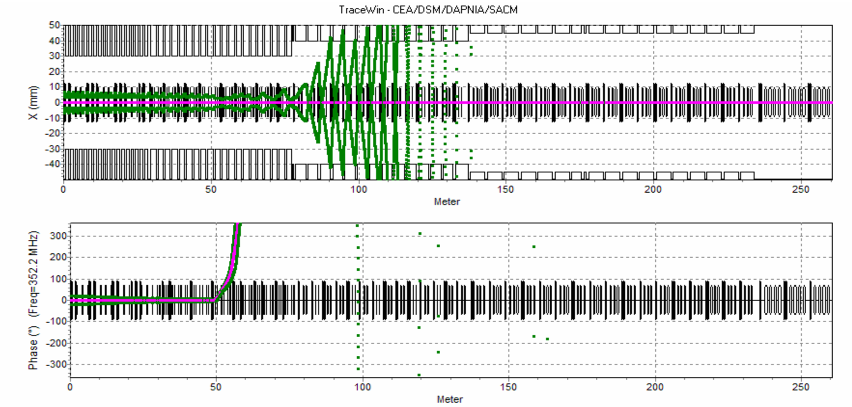
Table 1 – XT-ADS and EFIT proton beam general specifications

	XT-ADS	EFIT
Maximum beam intensity	2.5 – 4 mA	20 mA
Proton energy	600 MeV	800 MeV
Beam entry	Vertically from above	
Beam trip number	< 20 per year (exceeding 1 second)	< 3 per year (exceeding 1 second)
Beam stability	Energy: ± 1 %, Intensity: ± 2 %, Size: ± 10 %	
Beam footprint on target	Circular ∅ 5 to 10 cm, “donut-shaped”	An area of up to 100 cm² must be “paint-able” with any arbitrary selectable intensity profile
Beam time structure	CW, with 200 μs zero-current holes every 10^{-3} to 1 Hz, + pulsed mode capability (repetition rate around 50 Hz)	

Extrememely high reliability is required !!!

Fault Tolerance, a new concept uniquely applicable in a modular super conducting Linac

Fault tolerance in the independently phased SC sections is a crucial point because a few tens of RF systems failures are foreseen per year.



1. Consequences of the failure of a superconducting RF cavity

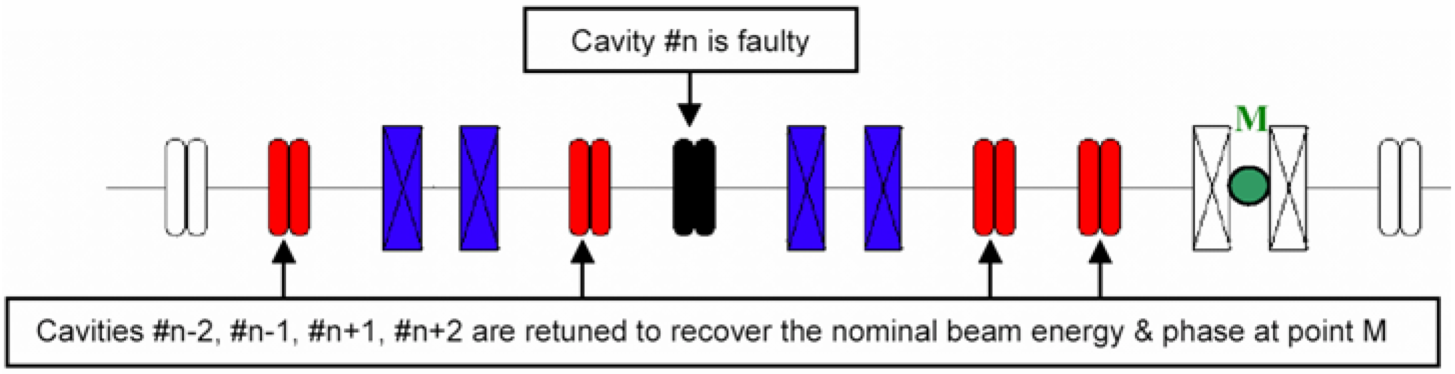
→An RF system failure induces phase slip (non relativistic beam)

→ If nothing is done, the beam is always LOST

2. Linac retuning after the failure of a RF cavity or of a quadrupole

→ Local compensation philosophy is used

→ In every case, the beam can be transported up to the high energy end without beam loss

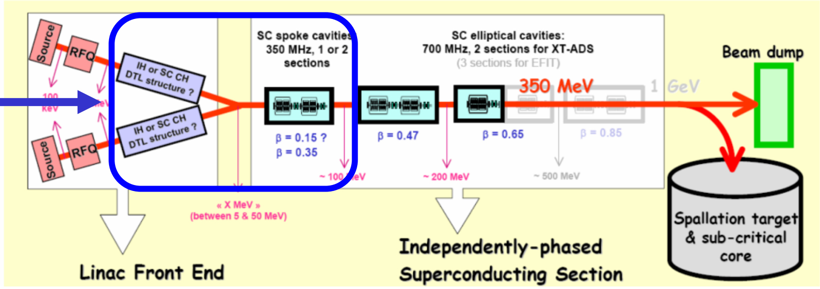


Cavity #n is faulty

Cavities #n-2, #n-1, #n+1, #n+2 are retuned to recover the nominal beam energy & phase at point M

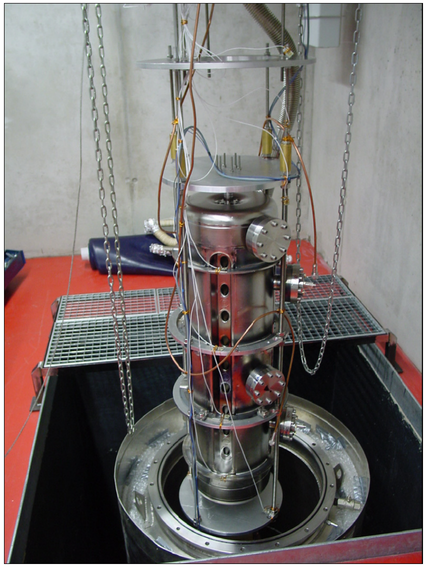
An example of R&D Intermediate-energy RF structure started in FP6 **EUROTRANS** and continued in FP7 **MAX**

Intermediate Energy Section
(3/5 MeV -> 100 MeV)



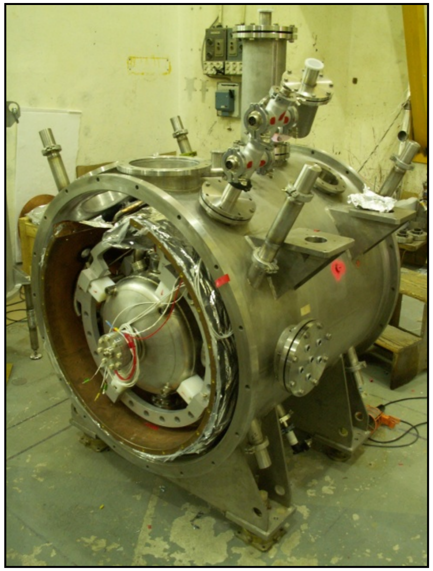
2 main types of structures are evaluated

- **Multi-gap H structures** (front end)
- **Superconducting spoke cavities** (independently-phased linac)



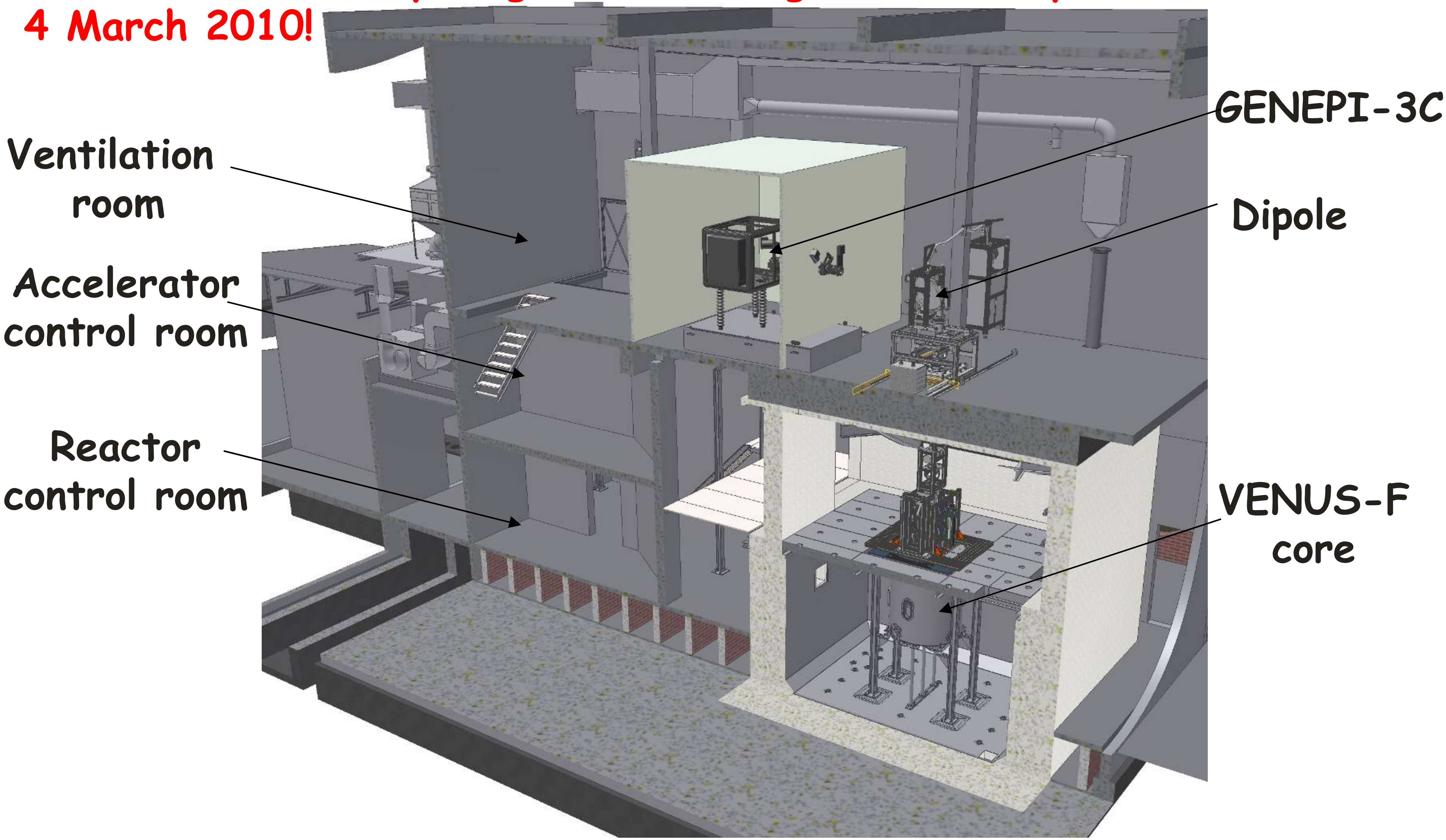
JOHANN WOLFGANG GOETHE
UNIVERSITÄT
FRANKFURT AM MAIN

CENTRE NATIONAL
DE LA RECHERCHE
SCIENTIFIQUE

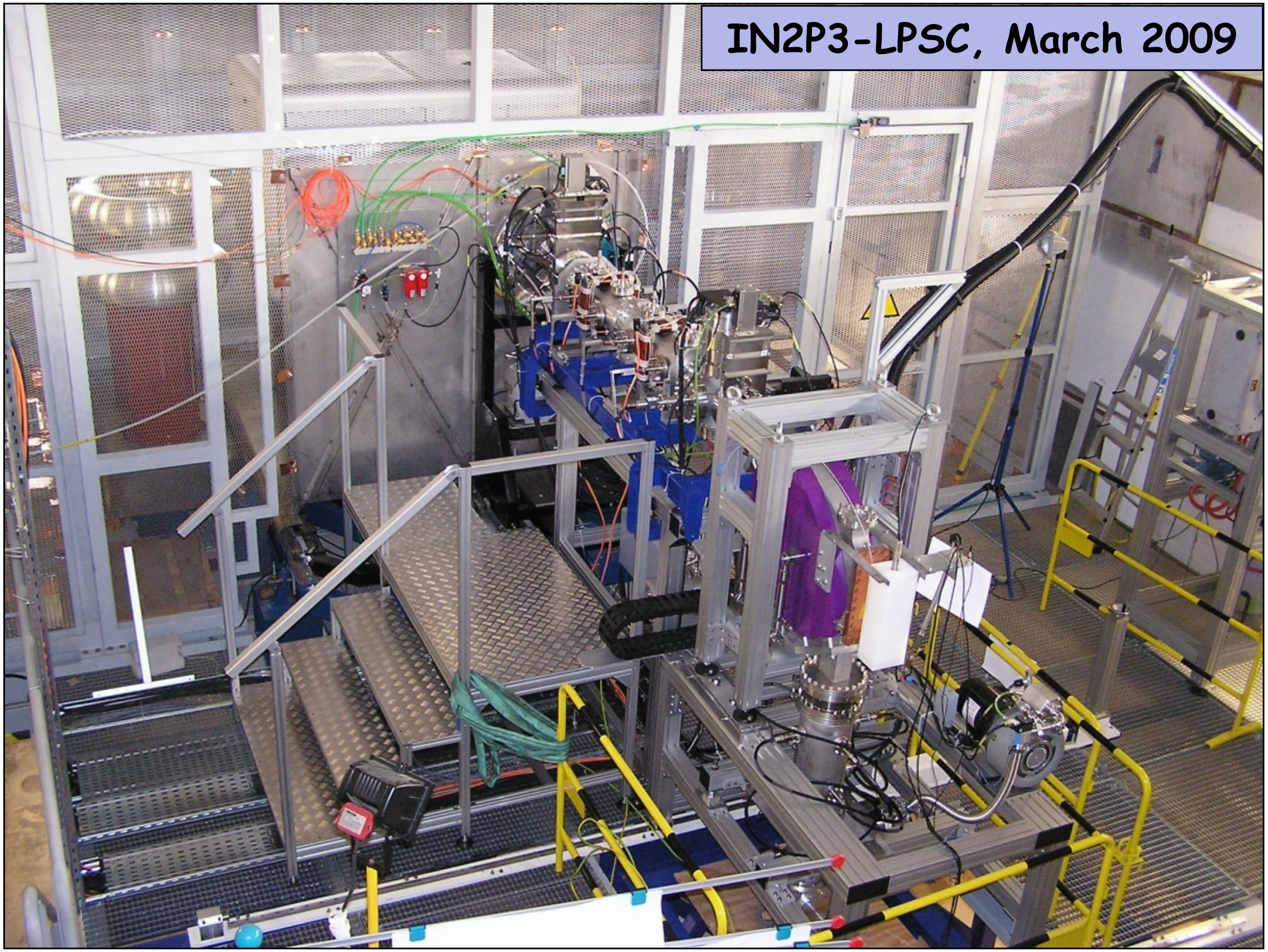


Testexperiment in Mol (B): GENEPI-3C coupled to VENUS-F

INAUGURATION By Belgian Gvt et High-level F Represetatives
4 March 2010!

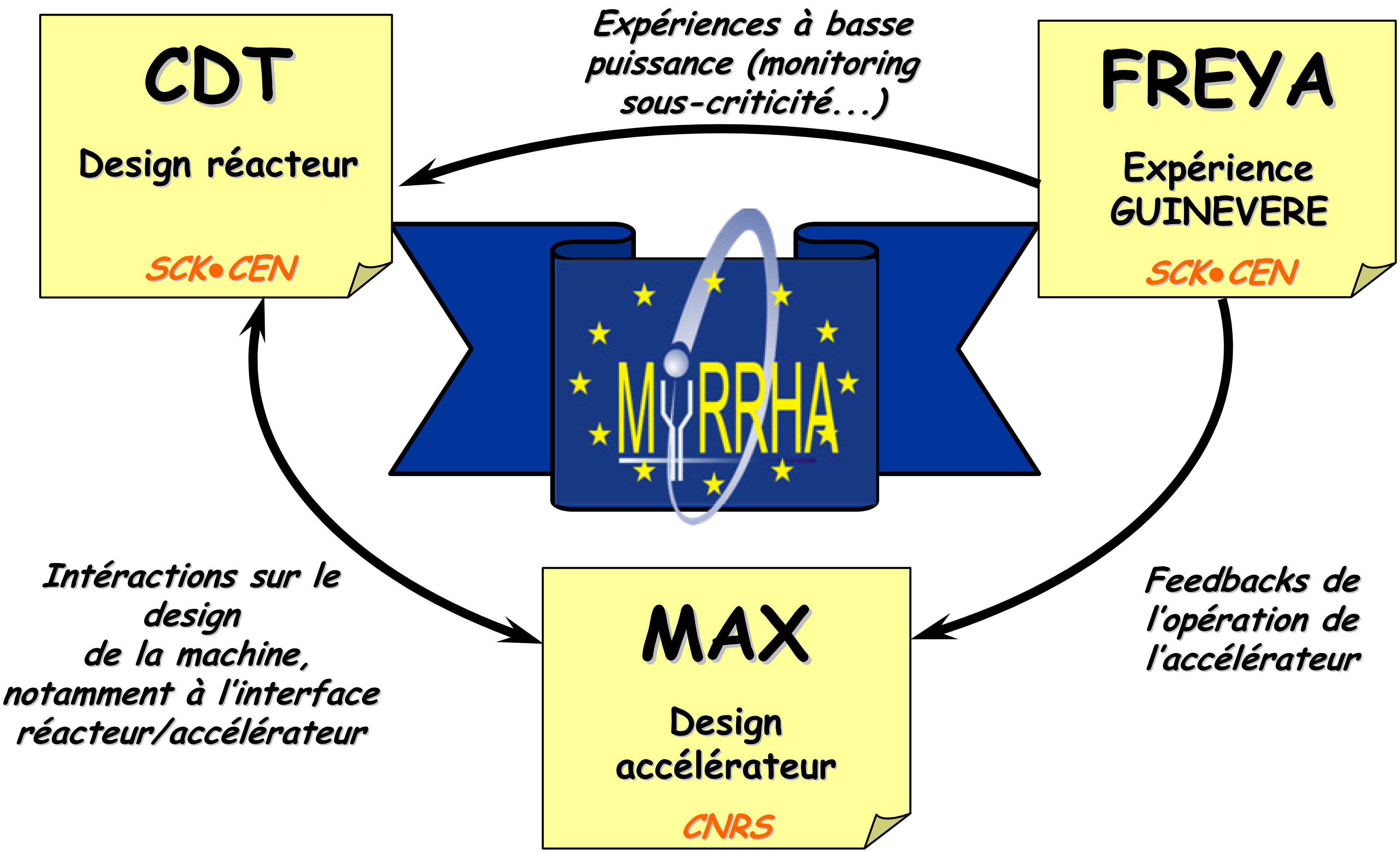


GENEPI 3C Acelerator



IN2P3-LPSC, March 2009

Present R&D for Myrrha within FP7



CDT

Design réacteur

SCK•CEN

Expériences à basse puissance (monitoring sous-criticité...)

FREYA

Expérience GUINEVERE

SCK•CEN

Intéractions sur le design de la machine, notamment à l'interface réacteur/accélérateur

MAX

Design accélérateur

CNRS

Feedbacks de l'opération de l'accélérateur

ADS Demonstrator = MYRRHA

Main features of the ADS demo

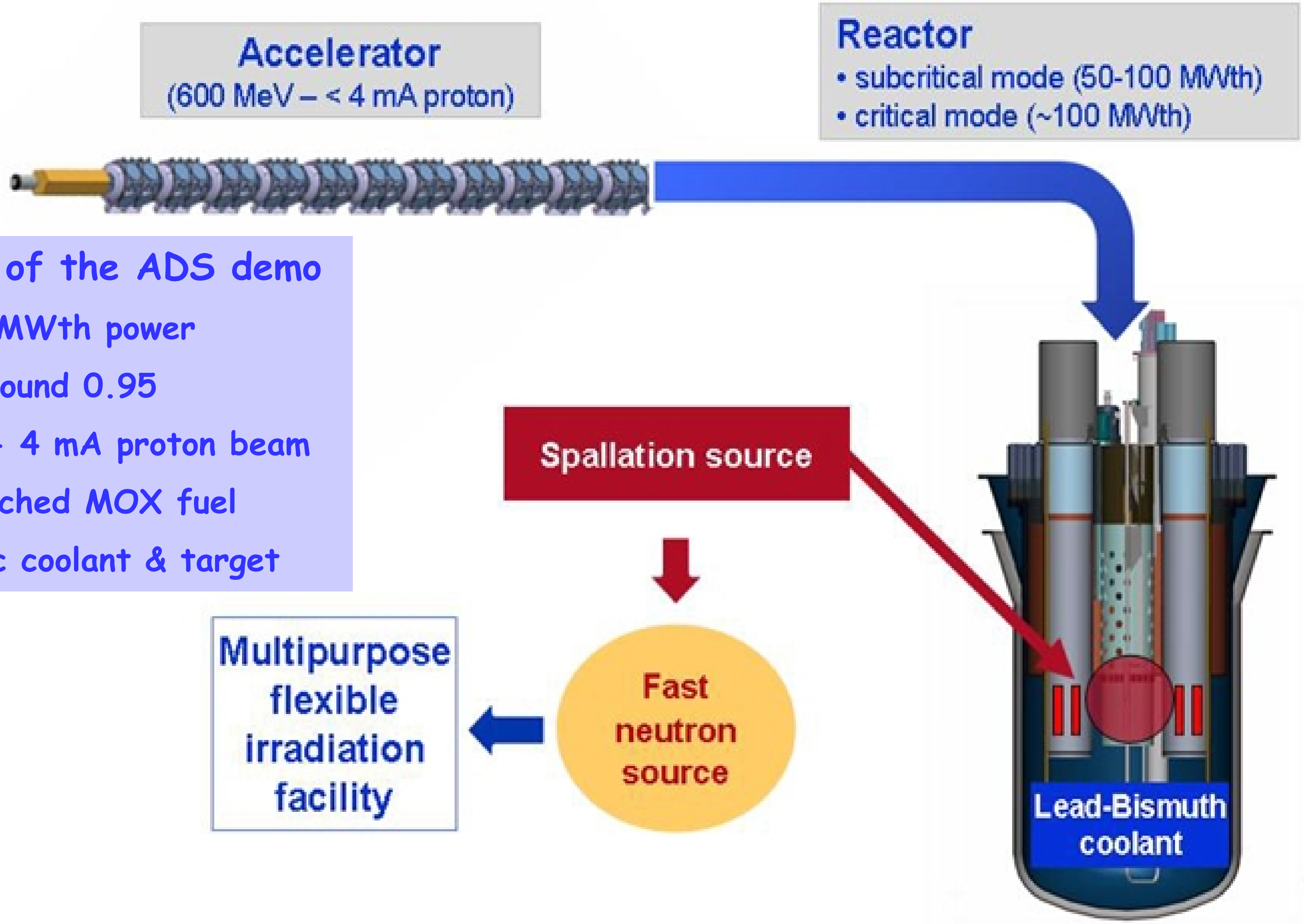
50-100 MWth power

k_{eff} around 0.95

600 MeV, 2.5 - 4 mA proton beam

Highly-enriched MOX fuel

Pb-Bi Eutectic coolant & target



Accelerator
(600 MeV – < 4 mA proton)

Reactor
- subcritical mode (50-100 MWth)
- critical mode (~100 MWth)

Spallation source

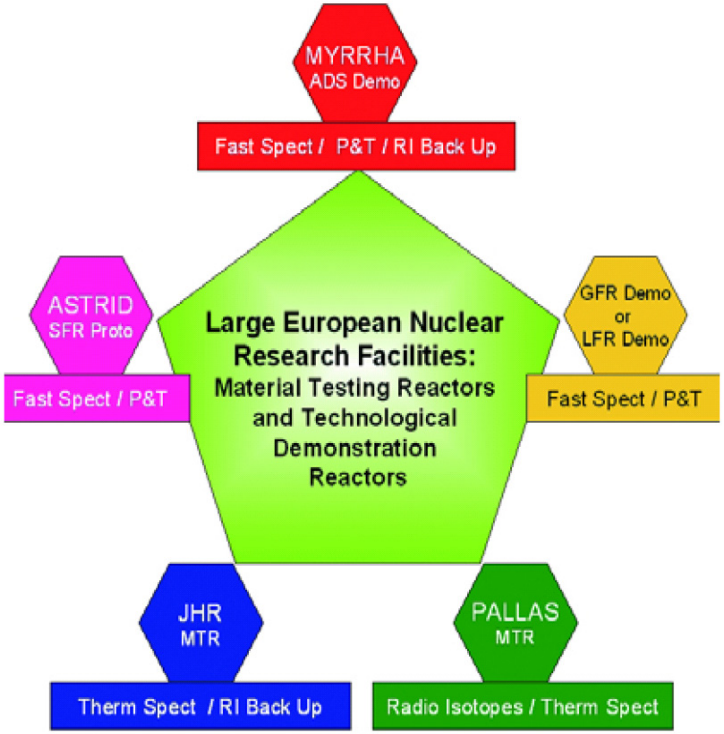
Fast neutron source

Multipurpose flexible irradiation facility

Lead-Bismuth coolant

MYRRHA and Gen-IV: a LFR demonstrator

Agenda européen pour le développement des démonstrateurs de réacteurs de 4ème génération



MYRRHA
ADS Demo
Fast Spect / P&T / RI Back Up

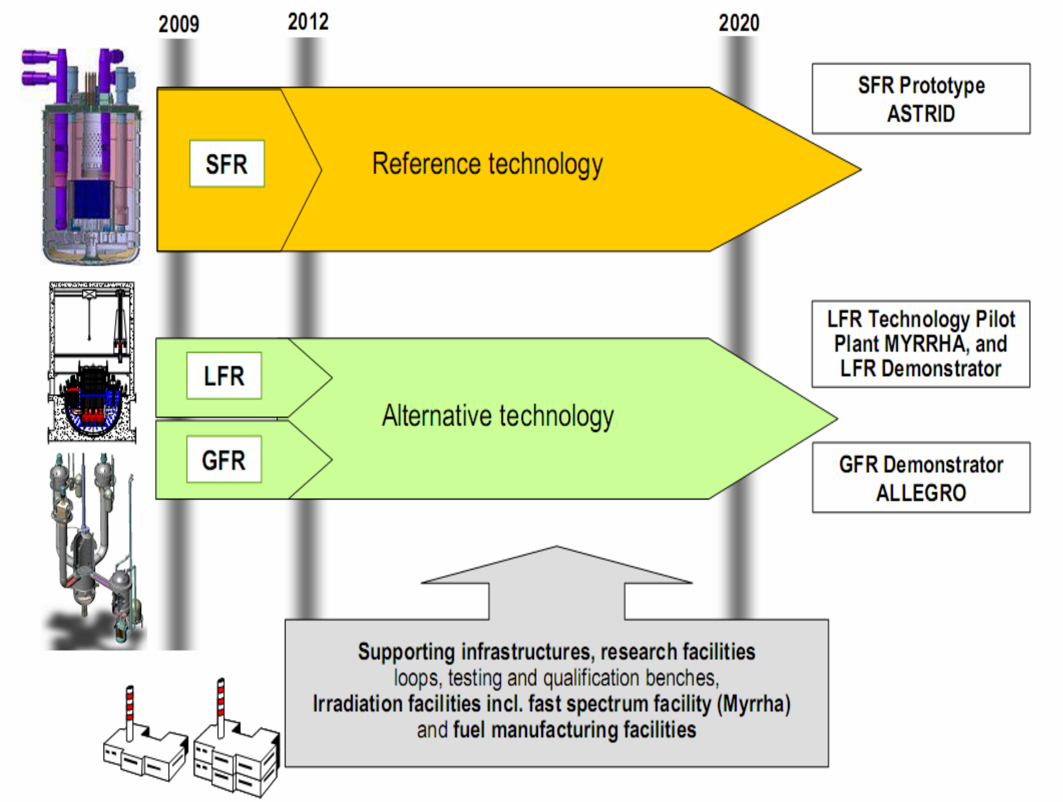
Large European Nuclear Research Facilities:
Material Testing Reactors and Technological Demonstration Reactors

ASTRID
SFR Proto
Fast Spect / P&T

GFR Demo or LFR Demo
Fast Spect / P&T

JHR
MTR
Therm Spect / RI Back Up

PALLAS
MTR
Radio Isotopes / Therm Spect



2009
2012
2020

SFR
Reference technology

SFR Prototype ASTRID

LFR
GFR
Alternative technology

LFR Technology Pilot Plant MYRRHA, and LFR Demonstrator

GFR Demonstrator ALLEGRO

Supporting infrastructures, research facilities loops, testing and qualification benches, Irradiation facilities incl. fast spectrum facility (Myrrha) and fuel manufacturing facilities

SNETP
Sustainable Nuclear Energy Technology Platform

The Roadmap for MYRRHA

On March 5, 2010 the Belgian government decided the funding of the MYRRHA at a level of 40% of the total cost of the project with a first budget release of 60 M€ for the period 2010-2014 aiming at:

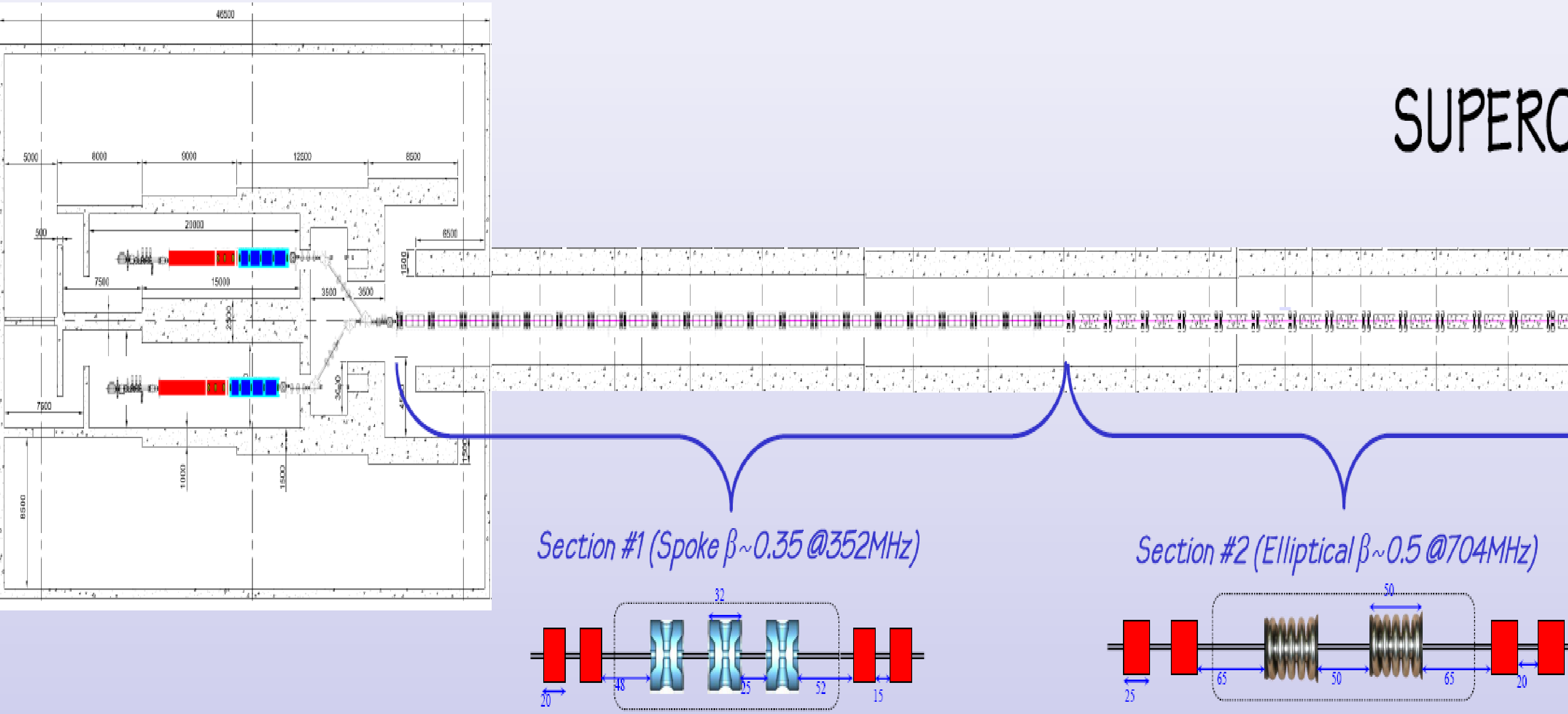
- completing the front-end engineering design (FEED) of the project,
- securing the licensing of the project
- obtaining the construction permit
- establishing the international consortium

The main next milestones of the project are as follows:

- 2010-2014 : Completion of Front End Engineering Design
- 2014 : Obtaining the construction permit
- 2014 : Consolidation of the international consortium
- 2015 : Tendering and contract awarding
- 2016-2018 : Construction of components and civil engineering
- 2019 : On-site assembly
- 2020-2022 : Commissioning
- 2023 : Progressive start-up
- 2024 : Full power operation

L'accélérateur linéaire de MYRRHA

INJECTOR BUILDING

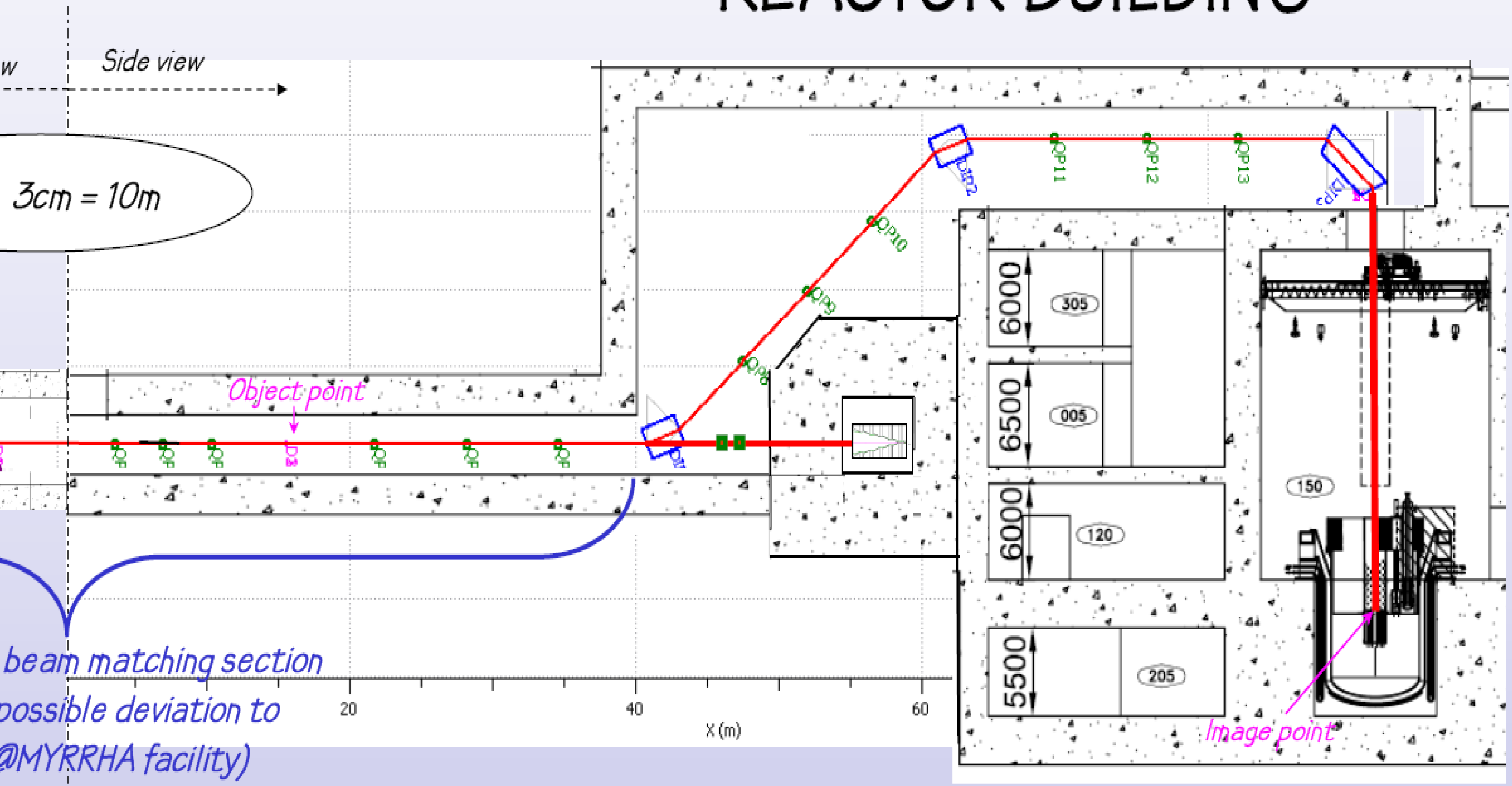


Section #1 (Spoke β~0.35 @352MHz)

Section #2 (Elliptical β~0.5 @704MHz)

L'accélérateur linéaire de MYRRHA

REACTOR BUILDING

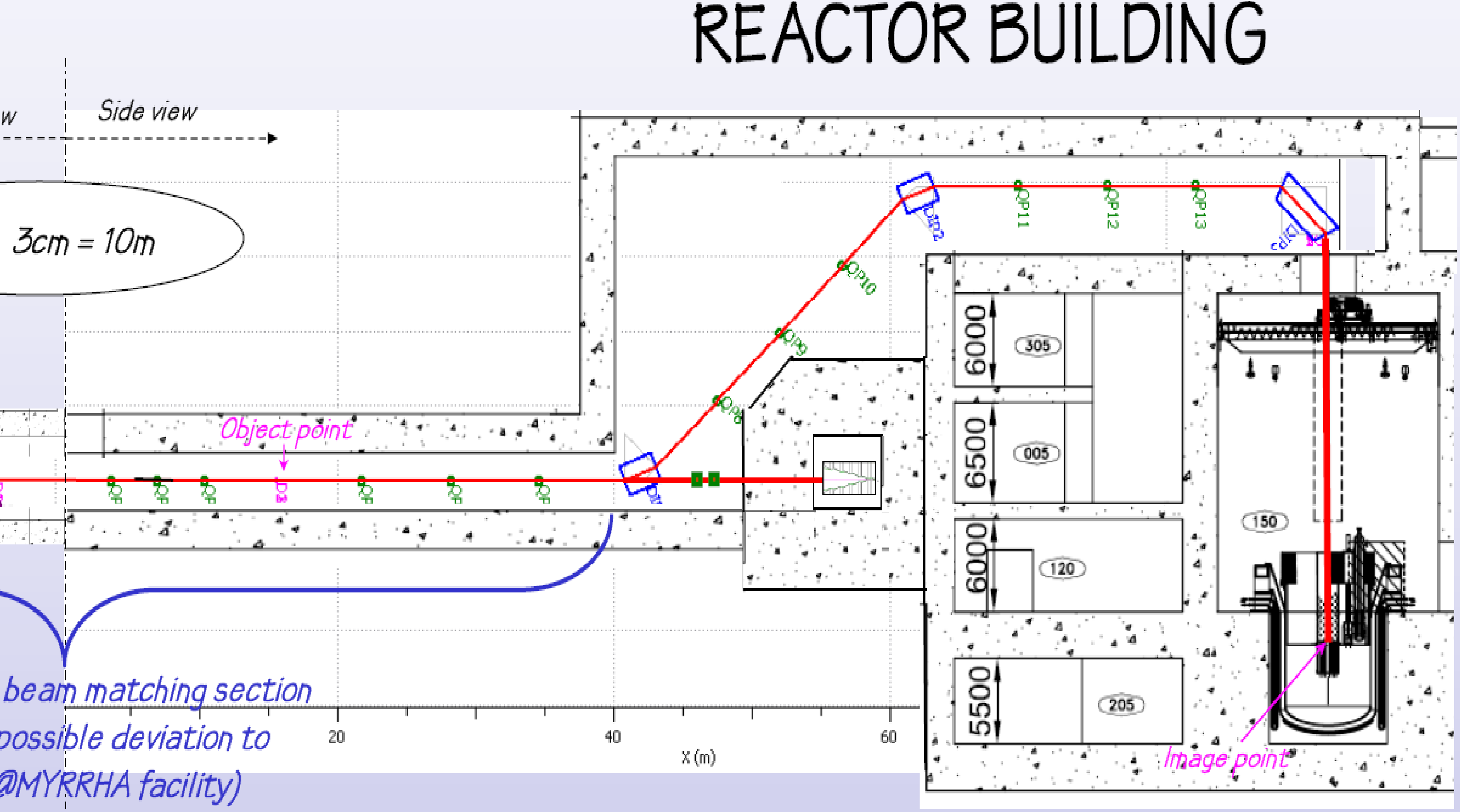


beam matching section

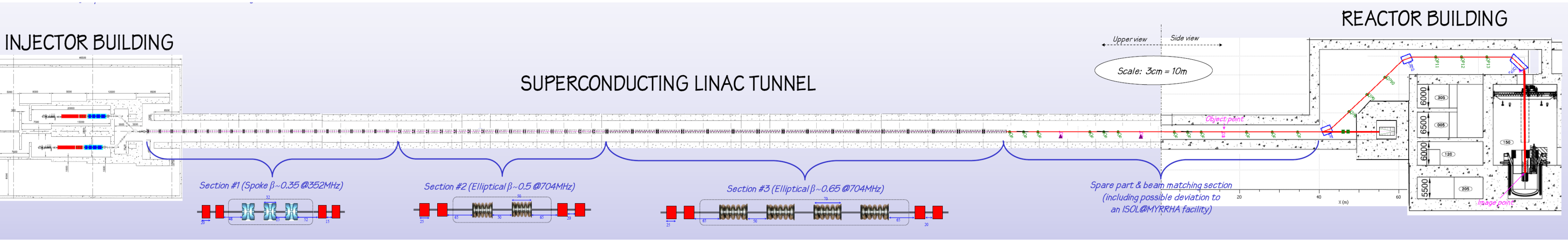
possible deviation to

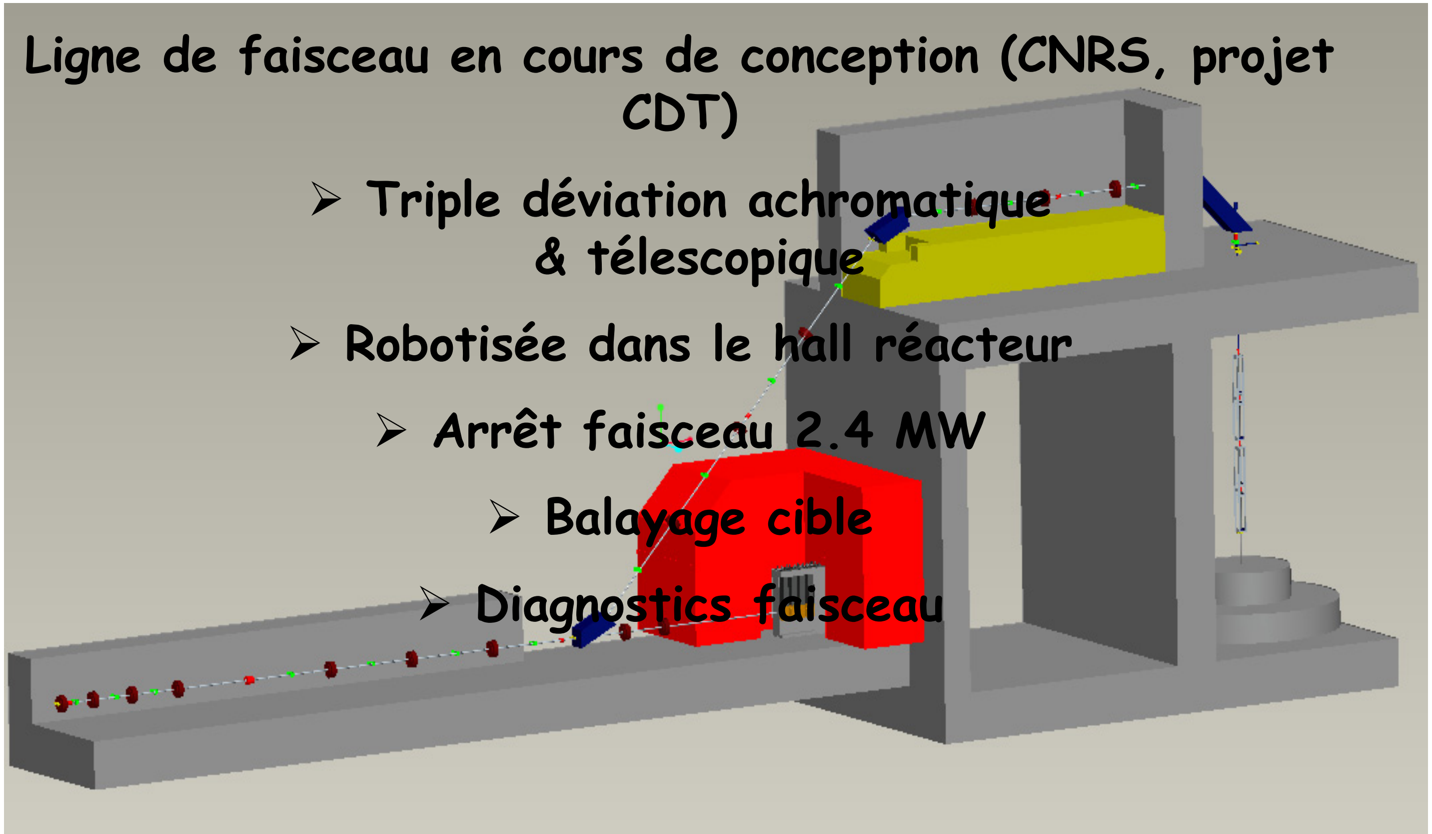
@MYRRHA facility)

L'accélérateur linéaire de MYRRHA



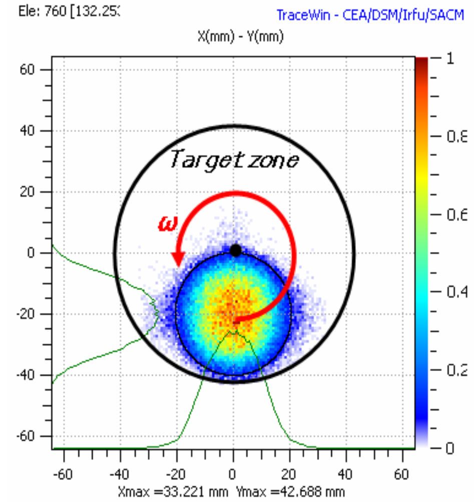
La ligne de faisceau finale



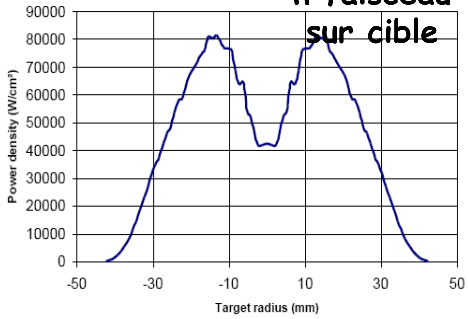


Ligne de faisceau en cours de conception (CNRS, projet CDT)

- **Triple déviation achromatique & télescopique**
- **Robotisée dans le hall réacteur**
- **Arrêt faisceau 2.4 MW**
- **Balayage cible**
- **Diagnostics faisceau**



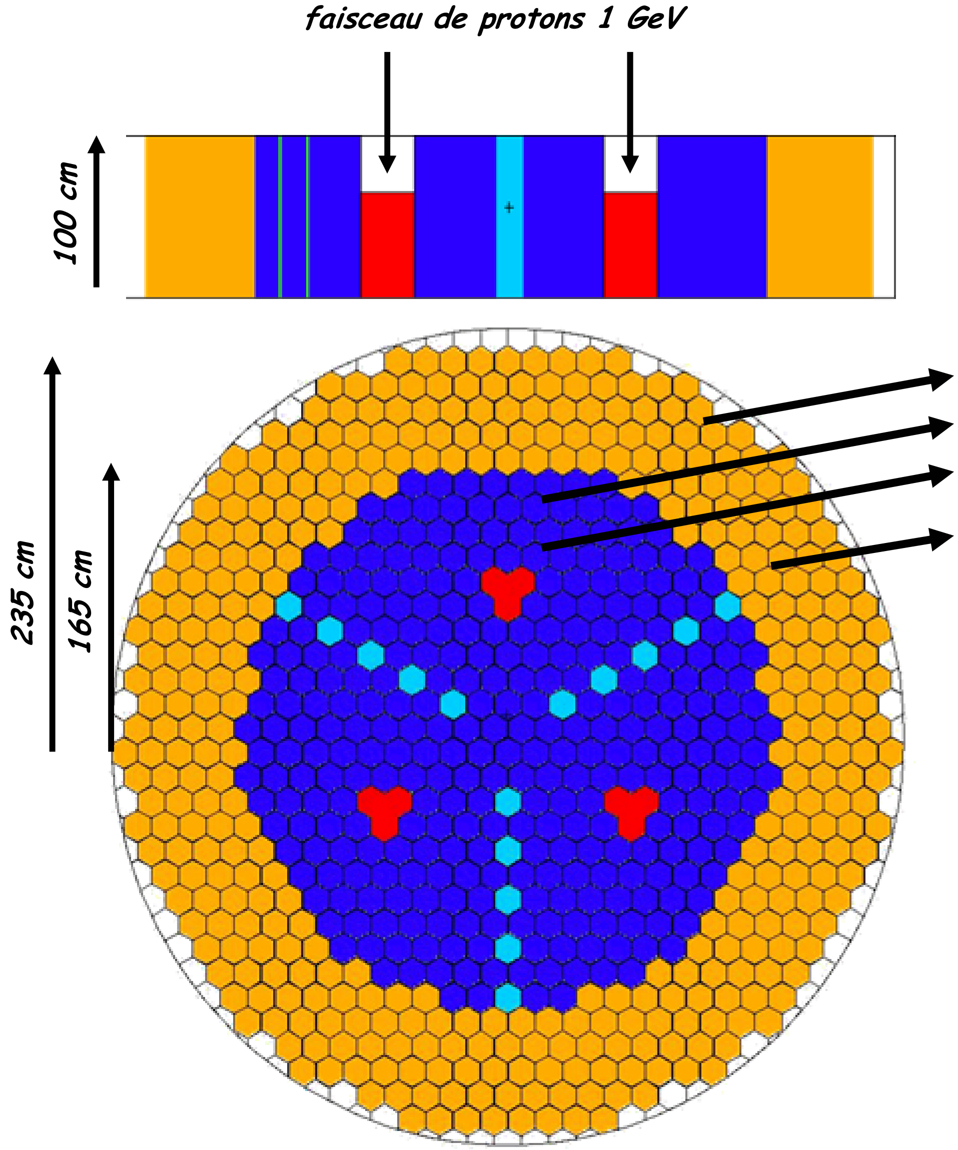
Distribution faisceau sur cible



From Tholière et al.:
MUST : MUltiple Spallation Target ADS

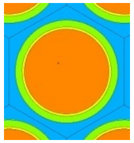
→ Trois cibles de spallation
→ $P = 3\ GW_{th}$
→ $I_{tot} \sim 100\ mA$
→ $K_{eff} \sim 0.98$

Barres de commandes à étudier

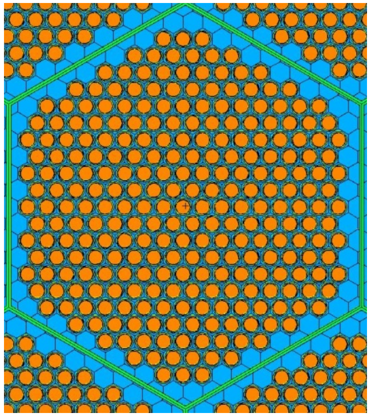


Réflecteur
Combustible
Cible de spallation
Assemblage commande

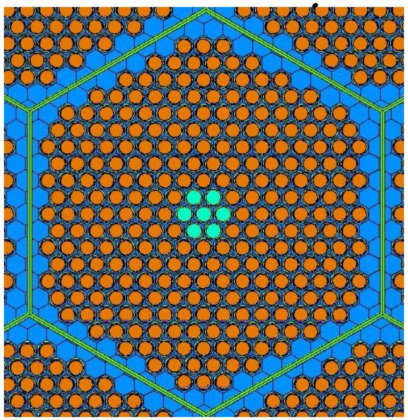
Crayon



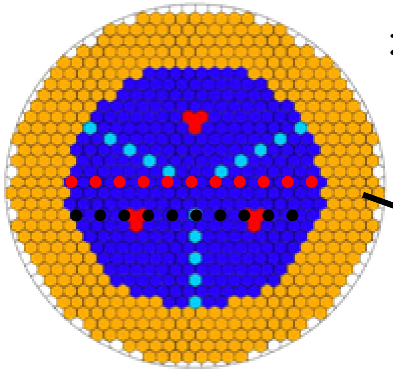
Assemblage



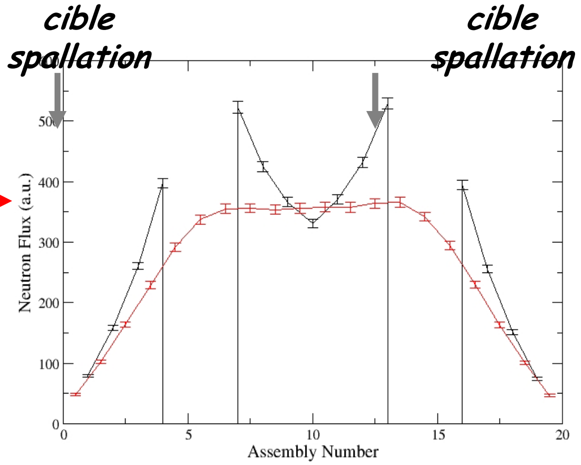
Assemblage



Flux radiaux avec 3 cibles (from Guertin et al.)



Neutron fllux (a.u.)

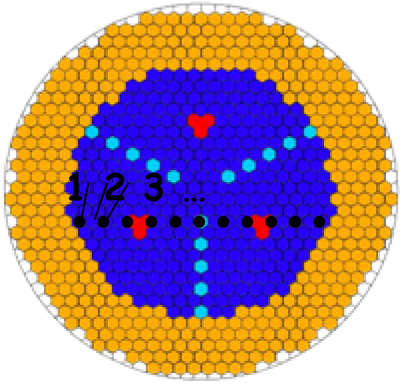


Assemblage

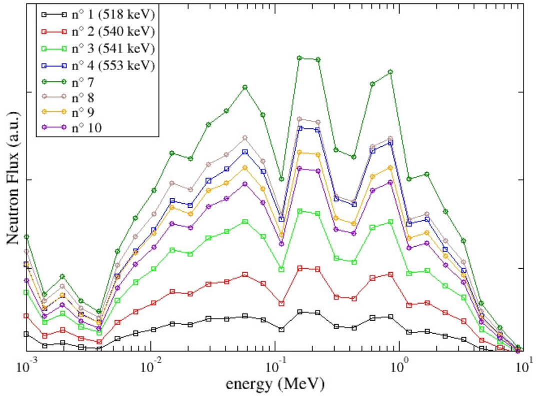
- Barres de commandes trop importantes

- Chute du flux au delà des cibles

- Nappe de puissance aplatie « dans » les cibles



Neutron fllux (a.u.)



Energie (MeV)

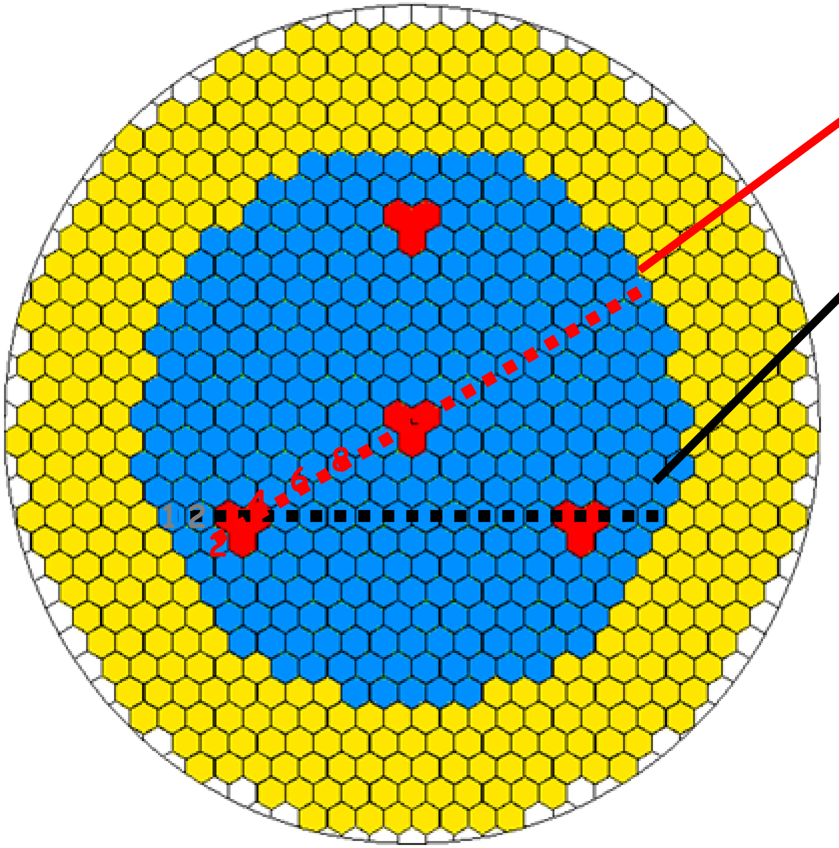
Energie moyenne : peu de différences…

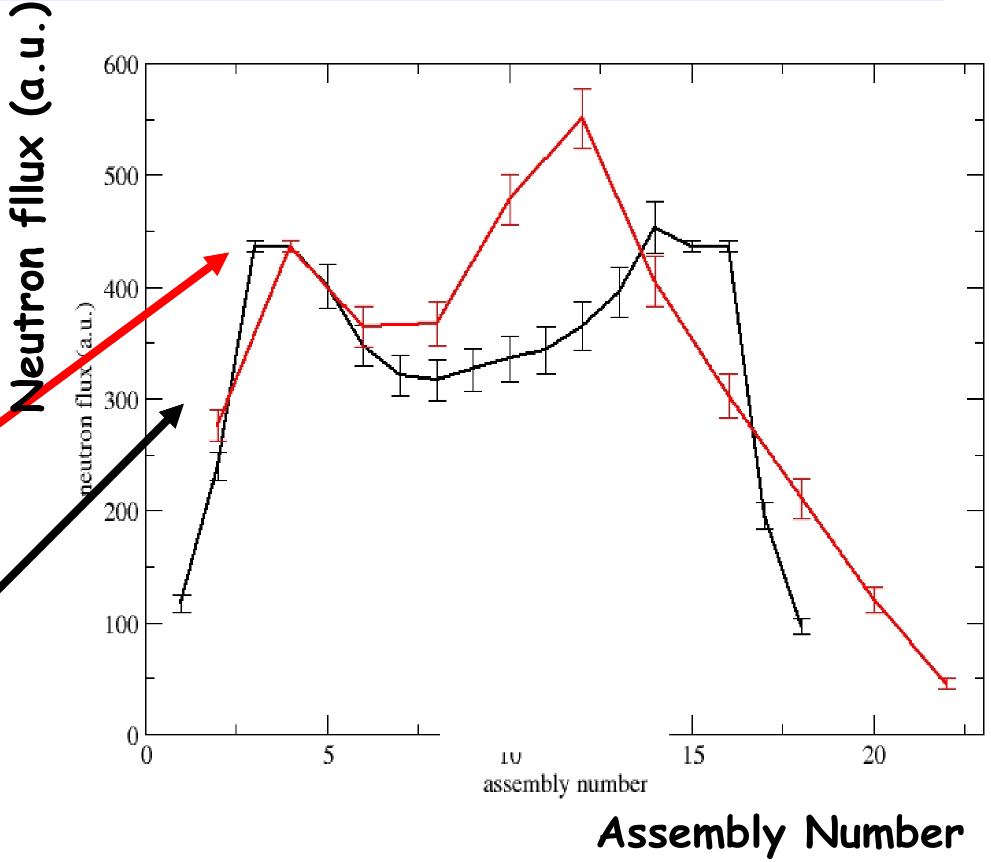
Exploitation du flux rapide ?

Concept MUST à 4 cibles

→ Quatre cibles de spallation
→ P = 3 GW_{th}
→ I_{tot} ~ 100 mA
→ K_{eff} ~ 0.98

Barres de commandes à inclure





Le flux de neutrons est distribué de façon plus homogène dans le cœur sous- critique

Ordres de grandeurs à l'équilibre

Application d'ACDC #1

- Durée de cycle = 7 ans
- Durée de refroidissement = 5 + 2 ans
- Composition initiale : A.M. sortie RNR/MOX

- Multi-recyclé : ^{237}Np, ^{241}Am, ^{243}Am, ^{242}Cm, ^{244}Cm

---

Strate électrogène RNR-MOX :

Puissance totale = 63.8 GW_e
Nombre d'unités = 44 réacteurs de 1.45 GW_e

M_{Np} = 4.6 kg/GWe.an
M_{Am} = 34.6 kg/GWe.an
M_{Cm} = 1.21 kg/GWe.an
→ $M_{A.M.}$ = 40.41 kg/GWe.an

Strate incinératrice ADS :

Puissance unitaire = 3 GW_{th}

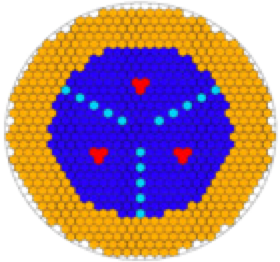
Atomes	Masse à t = 0 an	Masse à t final
Np	1.15 t	0.02 t
Am	8.51 t	0.97 t
Cm	1.57 t	1.01 t

Flux d'actinides mineurs :

→ 2578 kg/an

Taux de disparition d'actinides mineurs :

1319 kg/an



→ 2 ADS pour y parvenir

1kg d'AM : P = 2.5 MWth
→ 2.2 ADS

Ordres de grandeurs à l'équilibre

Application d'ACDC #2

- Durée de cycle = 7 ans
- Durée de refroidissement = 5 + 2 ans
- Composition initiale : A.M. sortie REP/UOX

- Multi-recyclé : ^{237}Np, ^{241}Am, $^{242*}Am$, ^{243}Am, ^{243}Cm, ^{244}Cm, ^{245}Cm, ^{246}Cm, ^{247}Cm

---

Strate électrogène REP-UOX :

Puissance totale = 63 GW_e
Nombre d'unités = 49 réacteurs de ~1.3 GW_e

M_{Np} = 1.83 kg/TWhé → 1008 kg/an
M_{Am} = 7.25 kg/TWhé → 4001 kg/an
M_{Cm} = 1.25 kg/TWhé → 690 kg/an

Flux d'actinides mineurs :

→ 5699 kg/an

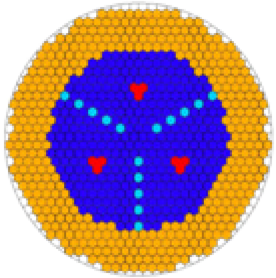
Strate incinératrice ADS :

Puissance unitaire = 3 GW_{th}

Atomes	Masse à t = 0 an	∆Masse à t final
Np	1.64 t	1.46 t
Am	6.82 t	5.93 t
Cm	2.86 t	1.33 t

Taux de disparition d'actinides mineurs :

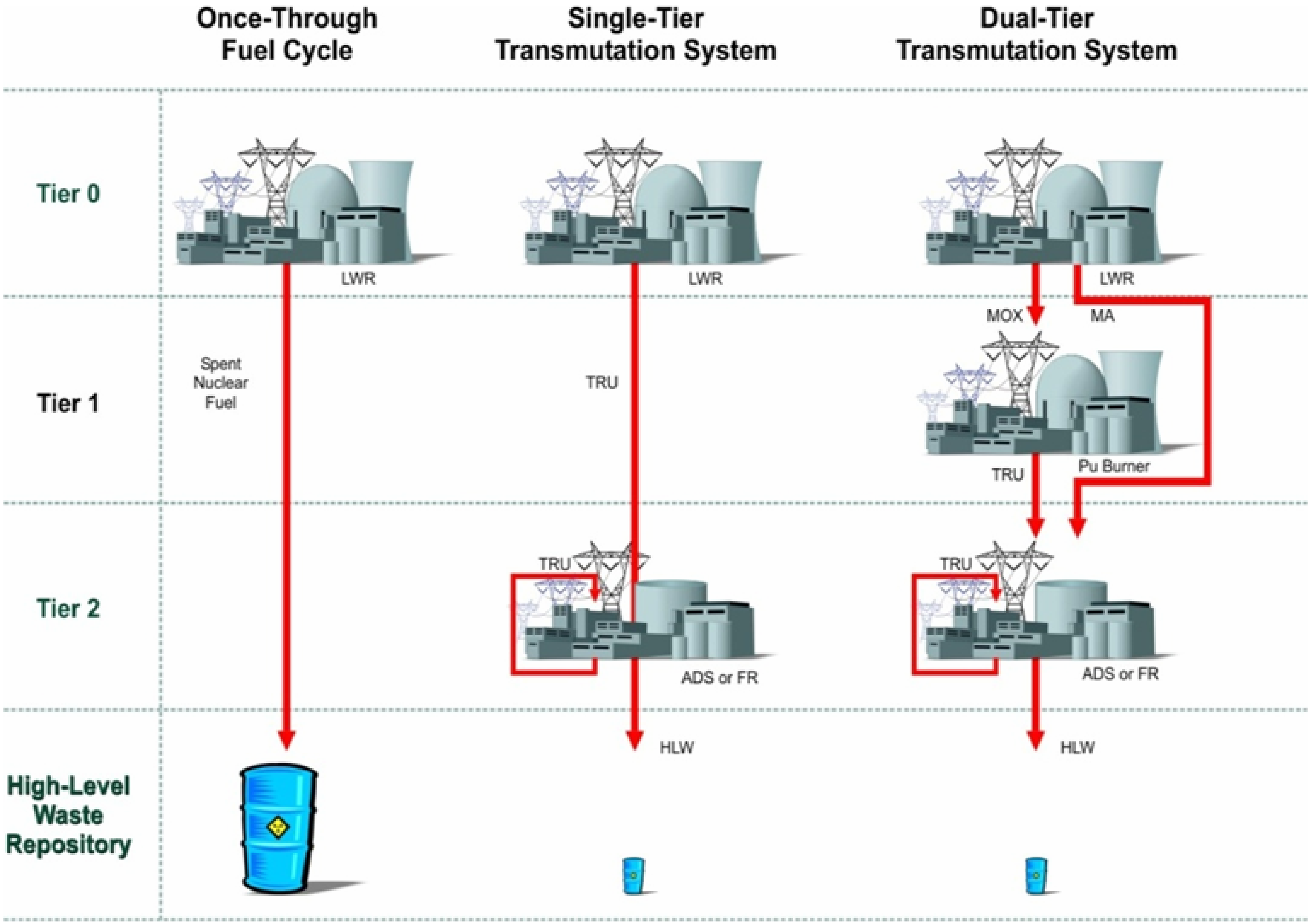
1246 kg/an



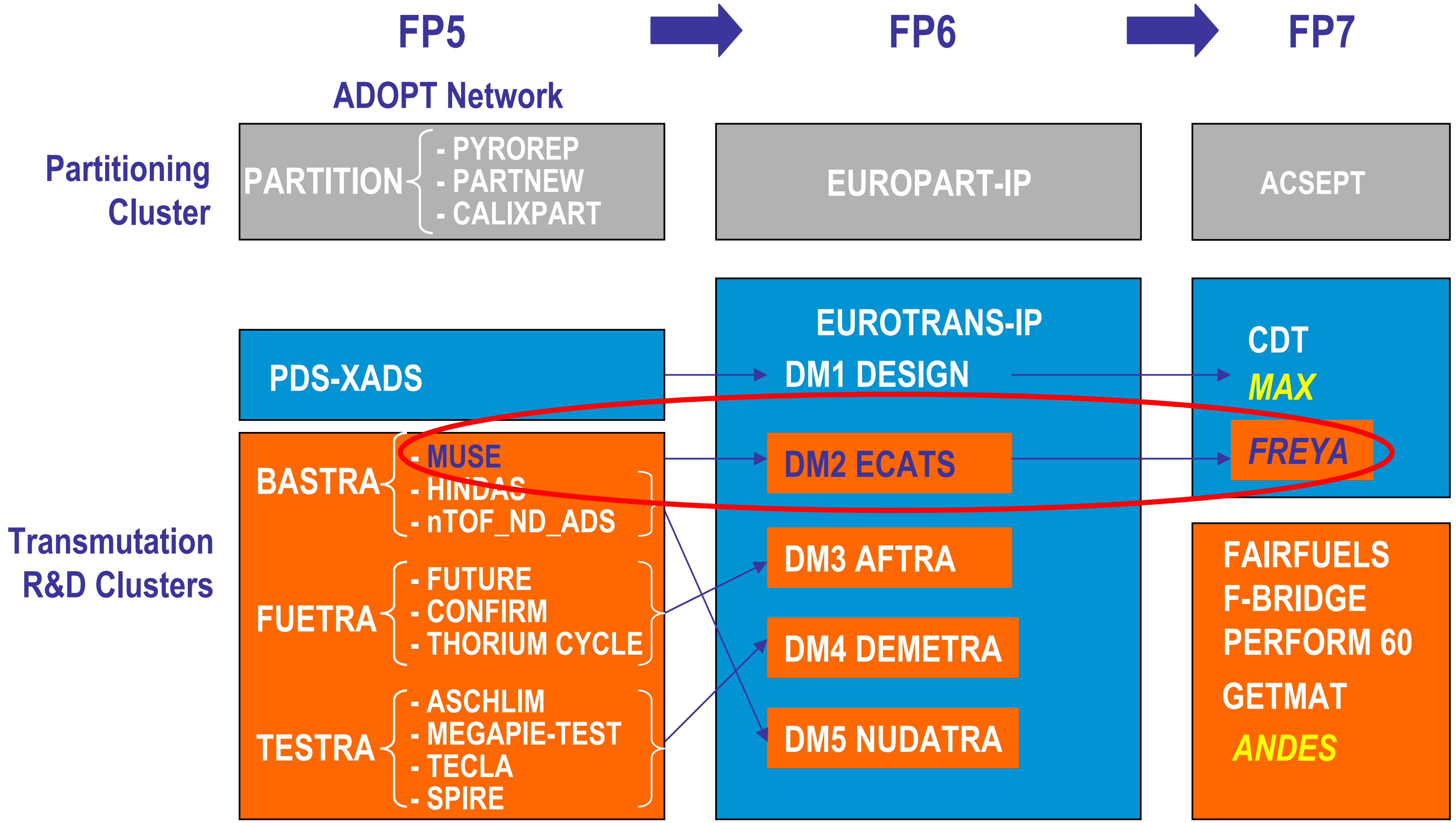
→ 4.6 ADS pour y parvenir

1kg d'AM : P = 2.5 MW_{th}
→ 4.7 ADS

Once-through vs.Transmutation



FP 5,6,7 R&D clusters on Partitioning and Transmutation



FP5 → FP6 → FP7

ADOPT Network

Partitioning Cluster

- FP5: PARTITION
  - PYROREP
  - PARTNEW
  - CALIXPART
- FP6: EUROPART-IP
- FP7: ACSEPT

Transmutation R&D Clusters

FP5:

- PDS-XADS
- BASTRA
  - MUSE
  - HINDAS
  - nTOF_ND_ADS
- FUETRA
  - FUTURE
  - CONFIRM
  - THORIUM CYCLE
- TESTRA
  - ASCHLIM
  - MEGAPIE-TEST
  - TECLA
  - SPIRE

FP6: EUROTRANS-IP

- DM1 DESIGN
- DM2 ECATS
- DM3 AFTRA
- DM4 DEMETRA
- DM5 NUDATRA

FP7:

- CDT
- *MAX*
- *FREYA*

- FAIRFUELS
- F-BRIDGE
- PERFORM 60
- GETMAT
- *ANDES*

Concluding Remarks

- Phasing out of fossile fuel needs to be done in a sustainable way
- Nuclear Power likely (?) to increase by factor 2-5 worldwide (possible influence from Japan Tsunami???)
- Waste from present (Gen-2), and now-installed (Gen-3) can be adressed by dedicated transmutation systems (ADS)
- (fast) Gen-4 concepts "self-incinerate" their waste.
- ADS for taking care of GEN-II/III legacy
- good progress for a european ADS demonstrator
- Gen-4 molten salt reactor with Thorium produces much less waste
- Conclusion after conclusion: some data on Fukushima

Sanitary Impact (Tchernobyl vs. Fukushima), some numbers

taken from assessment by R. Massé and IRSN publications

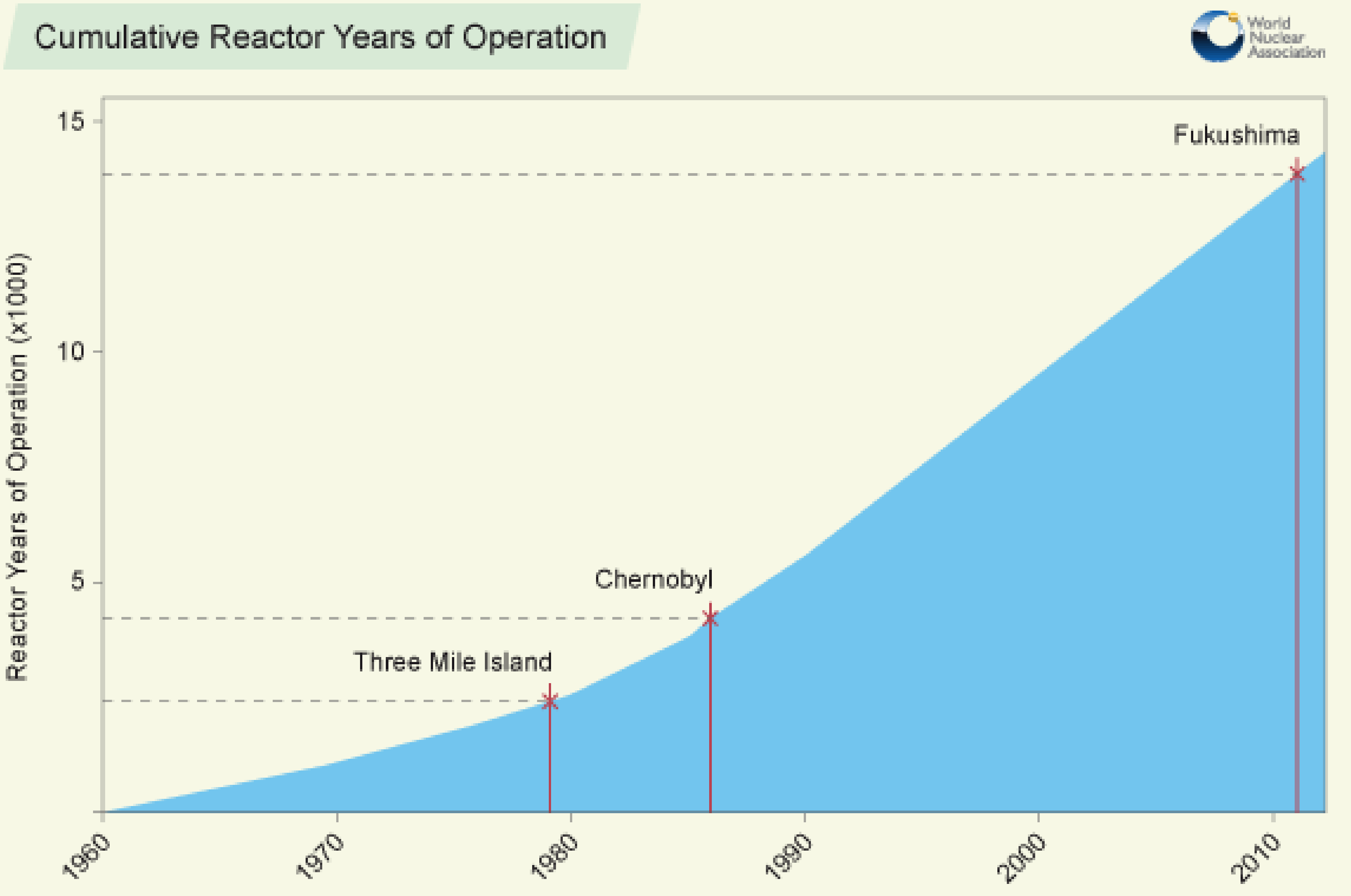
		Tchernobyl	Fukushima
• released radioactivity	^{131}I	1500 PBq	90 PBq
	^{137}Cs	90 PBq	10 PBq
	refractory elements	abundant in vincinity	traces
	Plutonium	"	difficult to distinguish from Nuclear Weapon tests
• doses to "liquidators" and death rate		average 117 mSv to 530000p 237p 1000 mSv to 16000mSv	600p total, all < 250 mSv 30p >100 , 3p > 170mSv
deaths for high-dose 237p		28p "immediately" 33p in 20y	none
other liquidators		4,6% cancer-rate equiv. to non affected population!	none
• general population		6400000p average 100 mSv to thyroid, no excess cancer rate except 7000 thyroid cancers (mainly young children), 15 deaths, likely to increase	none

- some general remarks

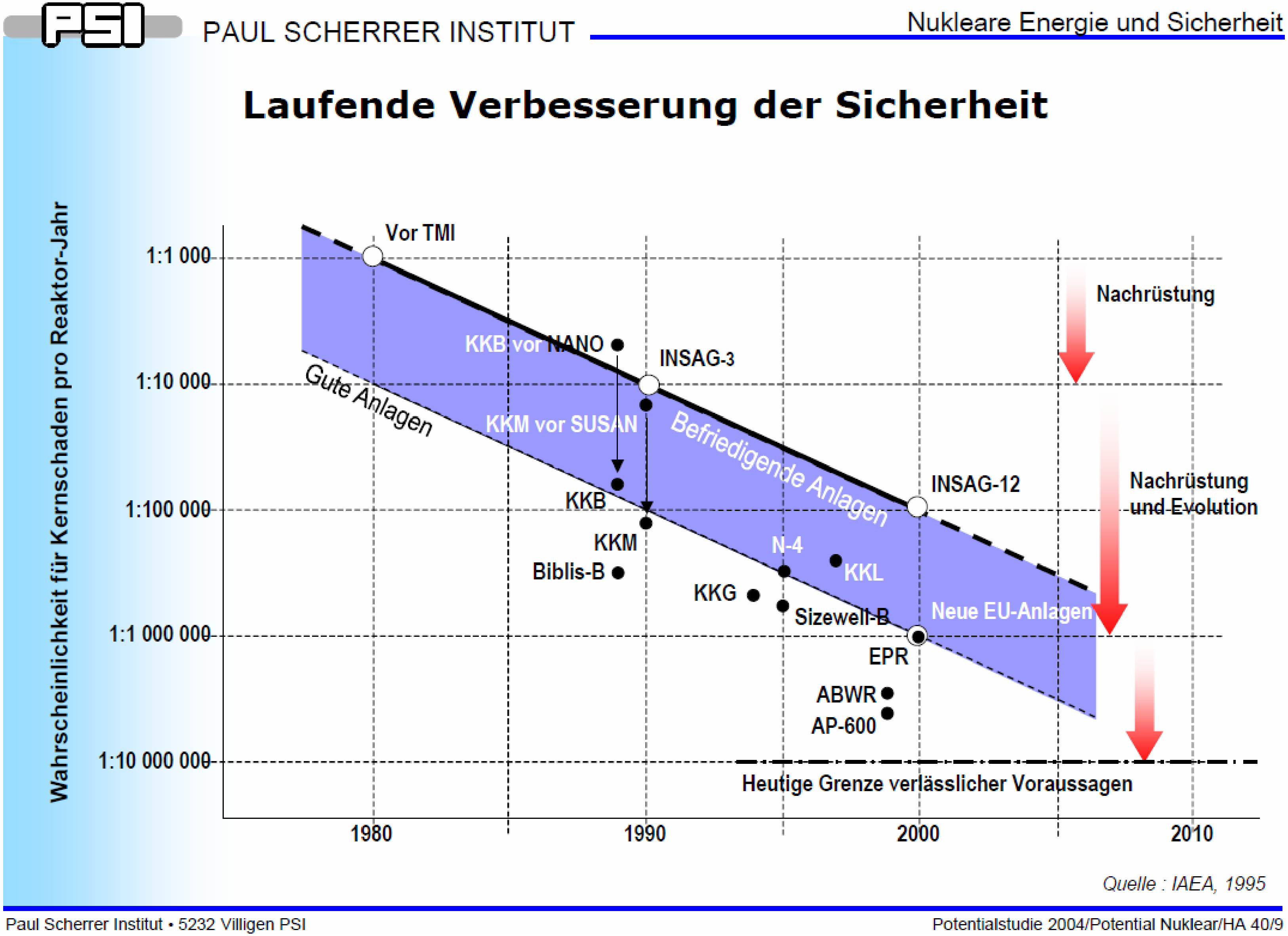
1) even if there are neither other excess cancers (nore excess congenital deformations!), there might be difficult-to-assess sanitary impacts (suicide, alcohol, tobacco....) because of generalised "misery of life"

2) Earthquake + Tsunami = 30000 deaths
"Feinstaub" = 250000 deaths/y in Europe, 1,6 Mio deaths from bio-mass in developing countries
..... and already 38 deaths from echericia coli contaminated german bio-food

Reaktor-Sicherheit 1



Reaktor-Sicherheit 2



PAUL SCHERRER INSTITUT

Nukleare Energie und Sicherheit

Laufende Verbesserung der Sicherheit

Quelle : IAEA, 1995

Paul Scherrer Institut • 5232 Villigen PSI

Potentialstudie 2004/Potential Nuklear/HA 40/9