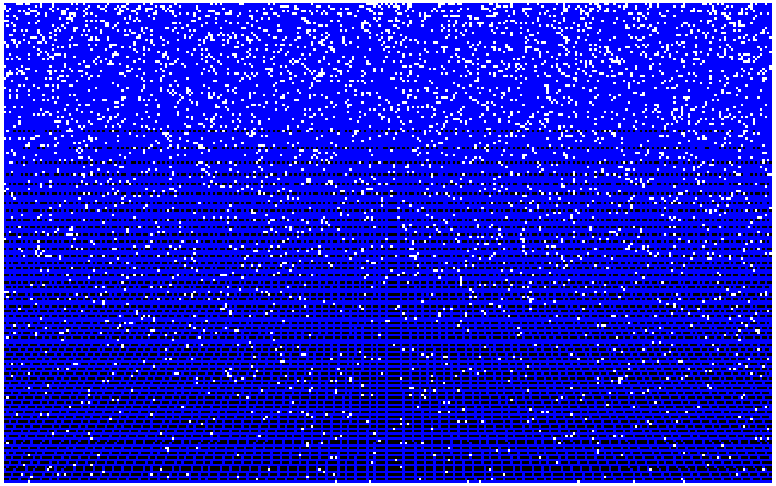
Kernenergie

HOVO cursus



Jo van den Brand en Gideon Koekoek

www.nikhef.nl/~jo/energie

15 november 2011

Inhoud

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- **Gideon Koekoek**
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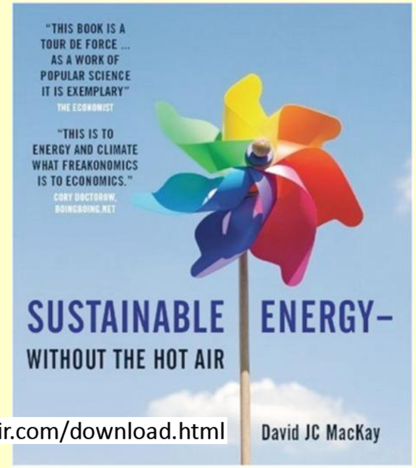
- **Dictaat**
  - **Werk in uitvoering**
- **Boeken**
  - **Energy Science, John Andrews & Nick Jelley**
  - **Sustainable Energy – without the hot air, David JC MacKay**
  - **Elmer E. Lewis, Fundamentals of Nuclear Reactor Physics**



http://www.withouthotair.com/download.html

Gratis te downloaden

- **Inhoud van de cursus**
  - Week 1 Motivatie, exponentiële groei, CO2 toename, broeikasteffect, klimaat
  - Week 2 Energieverbruik: transport, verwarming, koeling, verlichting, landbouw, veeteelt, fabricage
  - Week 3 Energie, thermodynamica
  - Week 4 Entropie, enthalpie, Carnot, Otto, Rankine processen, informatie
  - Week 5 Kernenergie: kernfysica, splijting
  - Week 6 Kernenergie: reactorfysica I
  - Week 7 Kernenergie: reactorfysica II
  - Week 8 Kernenergie: maatschappelijke discussie (risico's, afval), kernfusie
  - Week 9 Energiebronnen: fossiele brandstoffen (olie, gas, kolen), wind, zon (PV, thermisch, biomassa), waterkracht, geothermisch
  - Week 10 Energie: scenario's voor Nederland, wereld, fysieke mogelijkheden, politiek, ethische vragen, economische aspecten

With thanks to dr. Stefan Hild, University of Glasgow

Kernreactor

Stabiel bedrijf vereist *multiplicatiefactor k = 1:* per reactie moet gemiddeld 1 neutron weer een nieuwe kernsplijting induceren

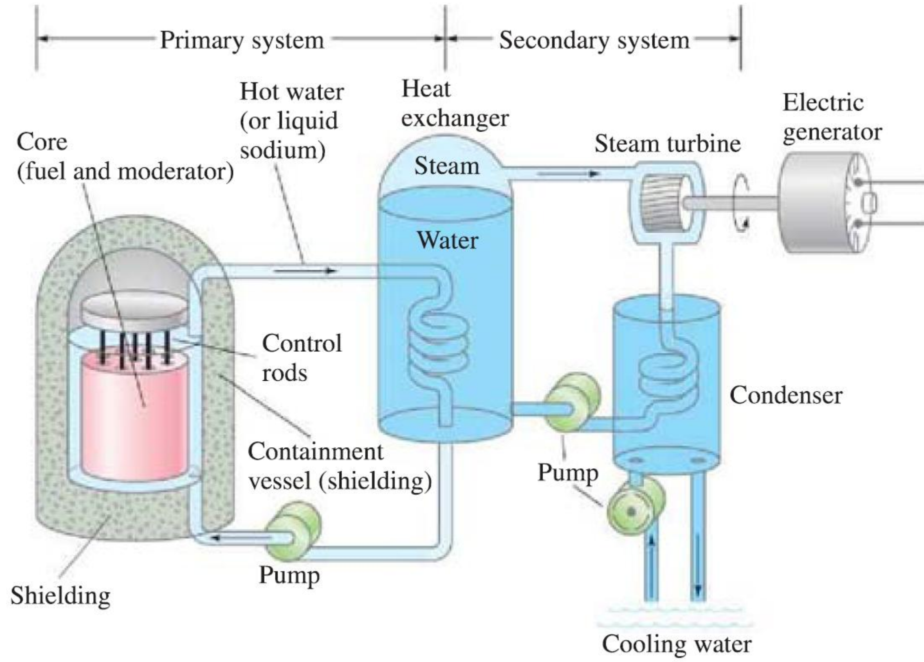
Subkritisch (superkritisch): *k < 1 (k > 1)*

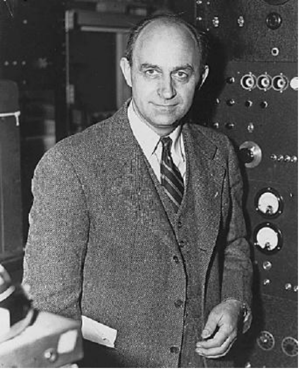
Regelstaven van cadmium (of boron) absorberen neutronen en zorgen dat de reactor precies kritisch (*k* = *1*) blijft

Regeling is enkel mogelijk dankzij een kleine fractie (1%) vertraagde neutronen afkomstig van kernverval met levensduur van enkele seconden

Reactor voor onderzoek: neutronenbron voor productie van isotopen

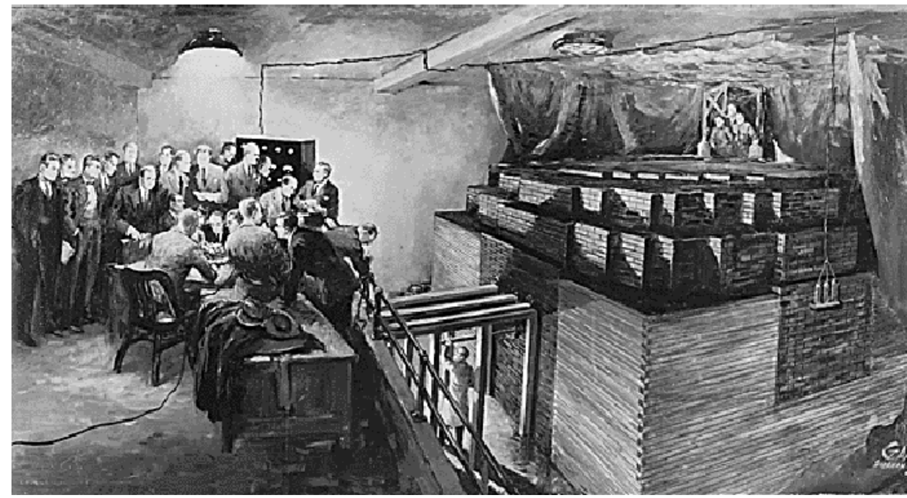
Reactor voor productie van energie
Verrijkt uranium van 2 – 4%
Water of vloeibaar zout onder hoge druk

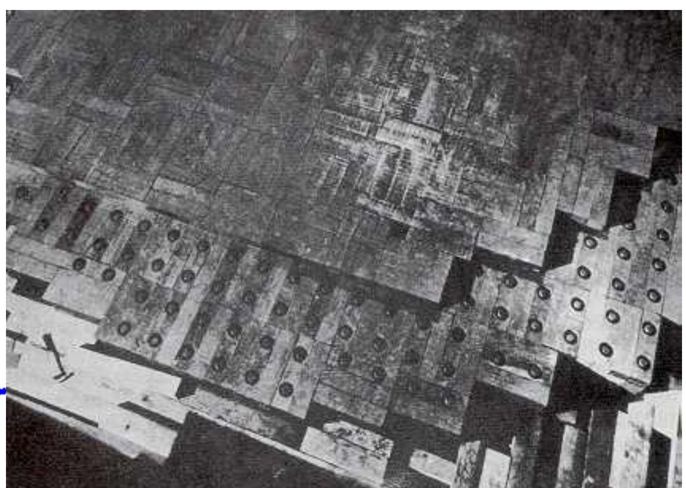


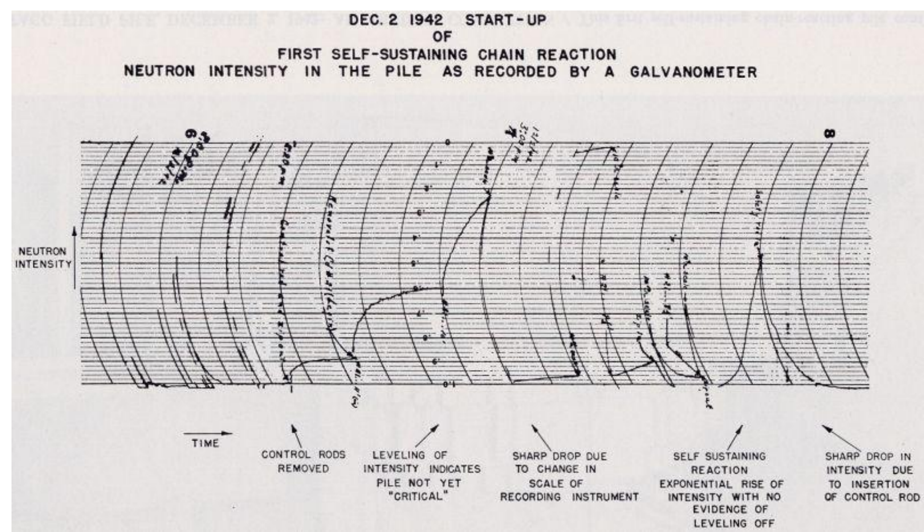


Het begin

- Enrico Fermi
- Chicago, Dec. 2, 1942
- Criticality reached

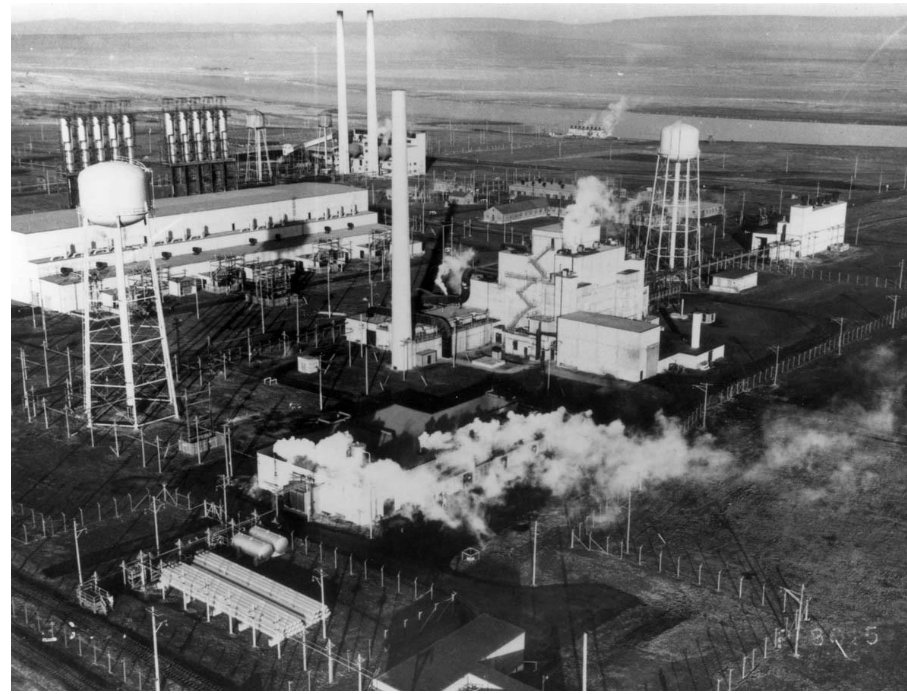


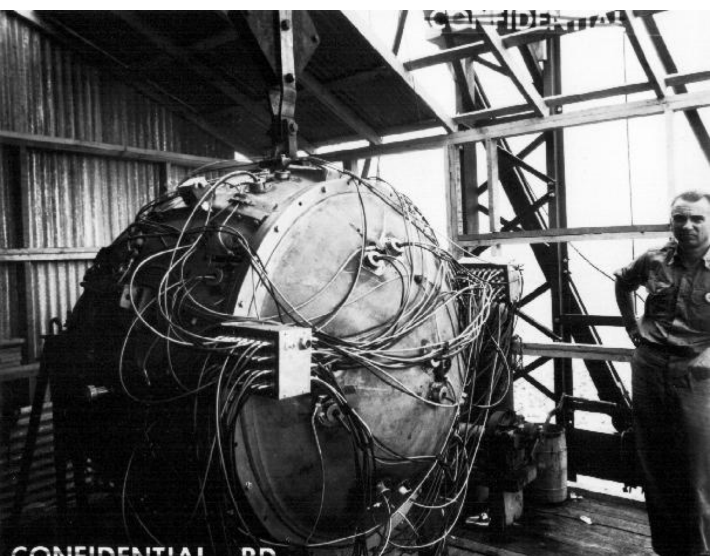


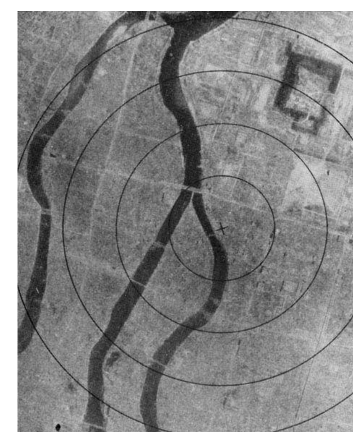


Het begin

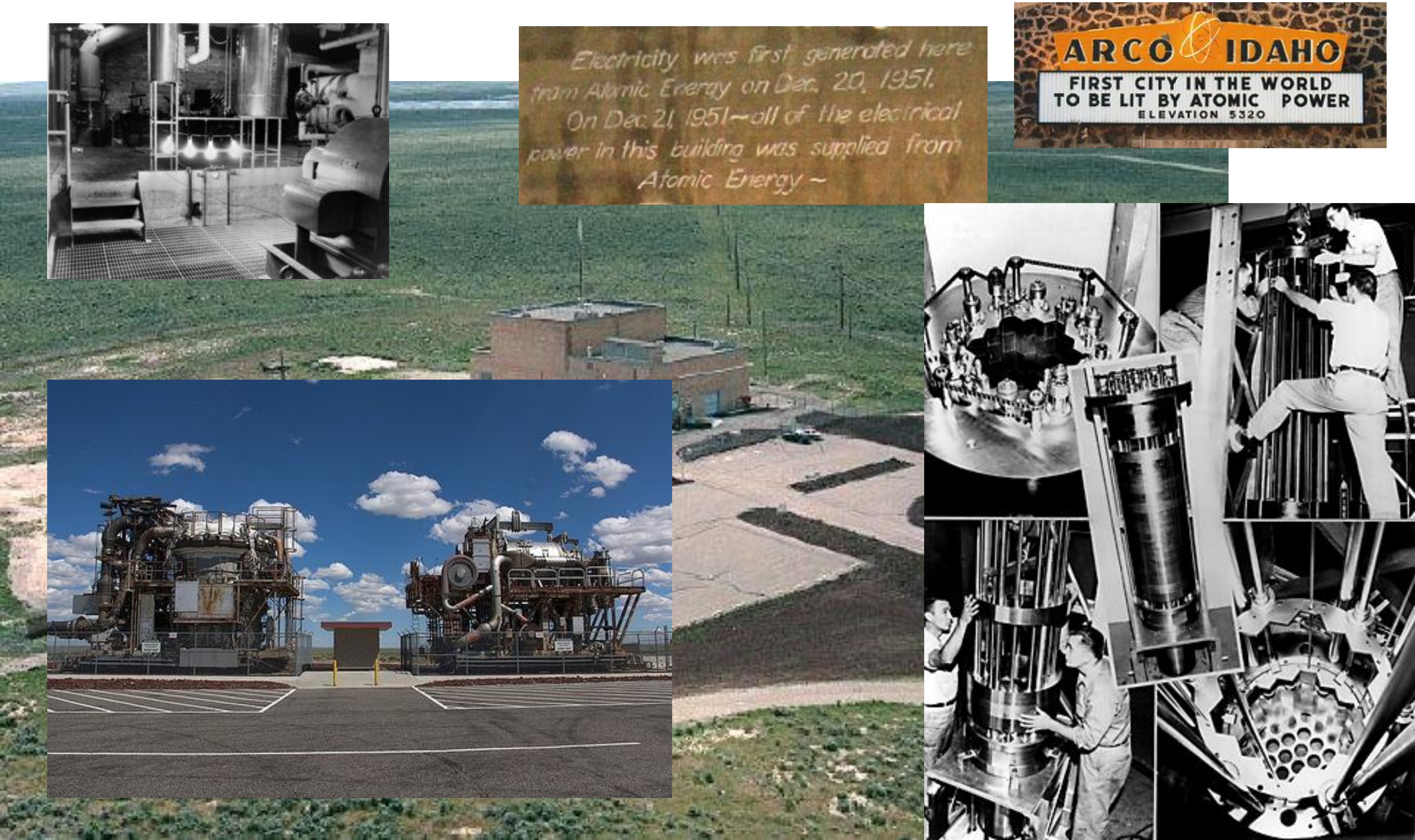
- Manhattan project
- Plutonium productie
- Reactor B in Hanford
- Trinity: the gadget
- Nagasaki bom



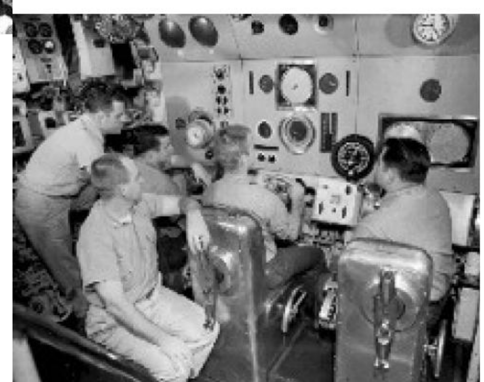


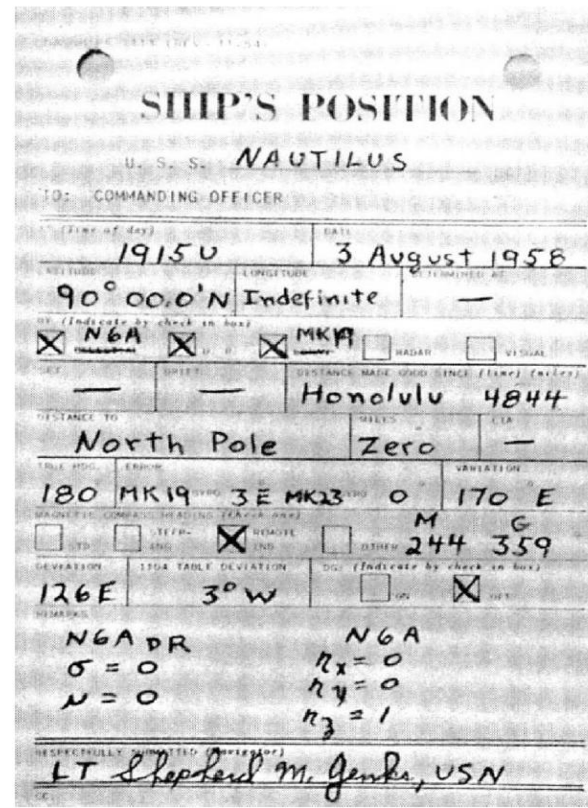


EBR – 1 in Idaho (1951)



Nautilus (1954)




SHIP'S POSITION

U. S. S. NAUTILUS

TO: COMMANDING OFFICER

(Time of day)	DATE	
1915 U	3 August 1958	
LATITUDE	LONGITUDE	DETERMINED AT
90° 00.0'N	Indefinite	—

BY (Indicate by check in box): ☒ N6A ☒ … ☒ MK19 ☐ RADAR ☐ VISUAL

SET	DRIFT	DISTANCE MADE GOOD SINCE (time) (miles)
—	—	Honolulu 4844

DISTANCE TO	MILES	ETA
North Pole	Zero	—

TRUE HDG.	ERROR		VARIATION
180	MK19 GYRO 3E	MK23 GYRO 0	170 E

MAGNETIC COMPASS HEADING (Check one): ☐ STD ☐ STEER-ING ☒ REMOTE IND ☐ OTHER M 244 G 359

DEVIATION	TABLE DEVIATION	DG: (Indicate by check in box)
126E	3° W	☐ ON ☒ OFF

REMARKS

N6A DR
σ = 0
ν = 0

N6A
$n_x = 0$
$n_y = 0$
$n_z = 1$

RESPECTFULLY SUBMITTED (Navigator)
LT Shepherd M. Jenks, USN

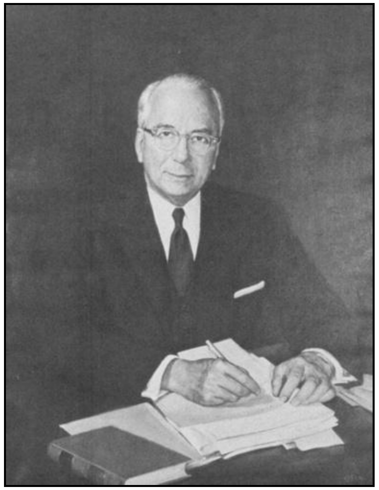
vrije Universiteit amsterdam

Kernenergie

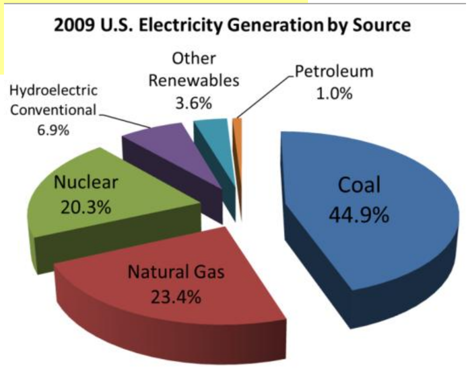
Kernenergie vandaag:

- Levert 16% van de elektriciteit in de wereld
  - 20% in USA
  - 77% in Frankrijk
  - 54% Belgie
  - 26% Duitsland
  - 46% Zweden
  - 4% Nederland
- 69% van de non-carbon elektriciteit in USA
- Ongeveer 441reactoren in de wereld
  - 147 in EU (200+ in Europe)
  - 104 in USA
    - ❑ Geen gebouwd in USA na 1970s
    - ❑ Kleine budgetten voor R&D

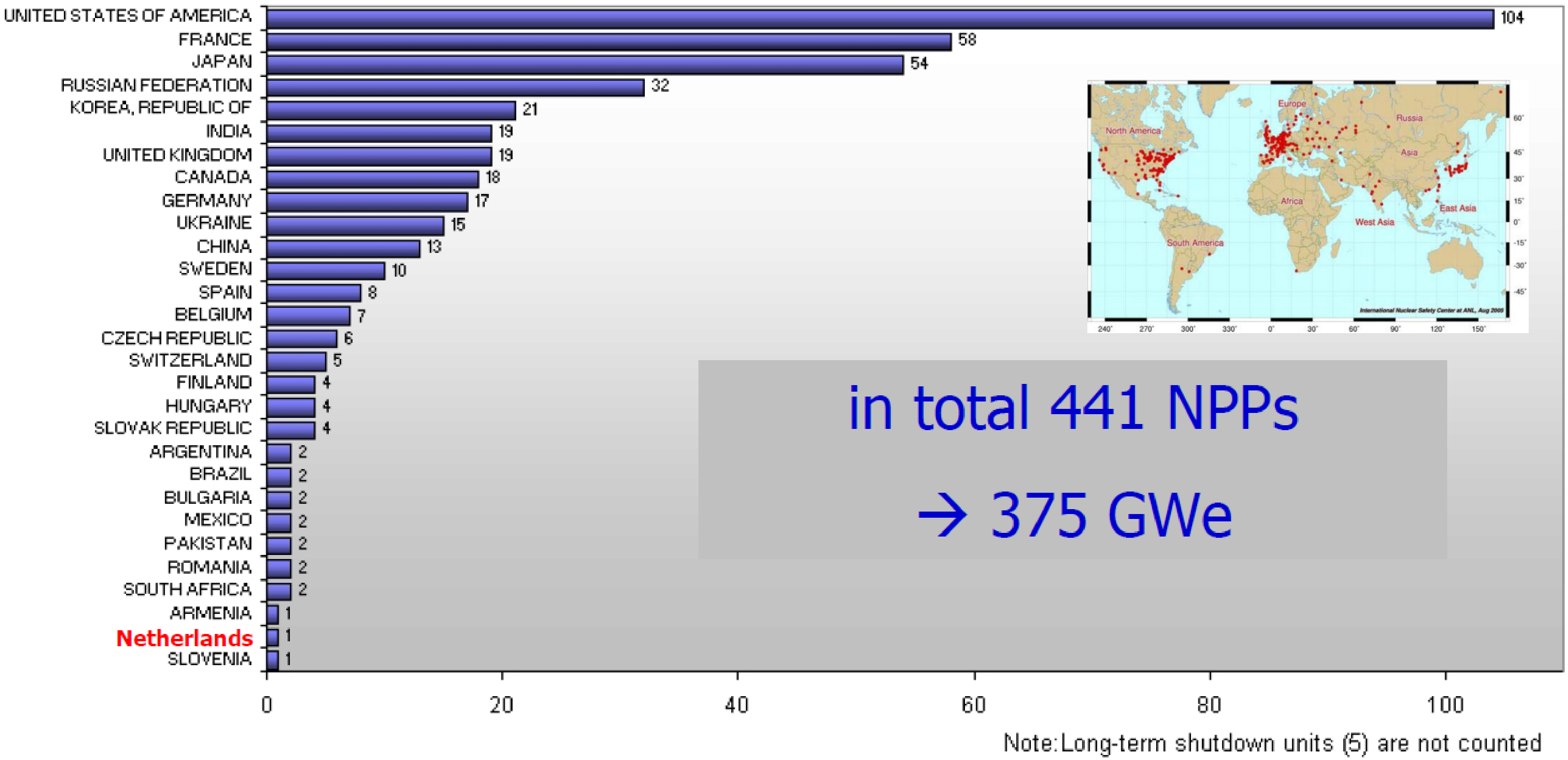
Lewis Strauss, Chairman of the U.S. Atomic Energy Commission (1954



"It is not too much to expect that our children will enjoy in their homes [nuclear generated] electrical energy too cheap to meter."



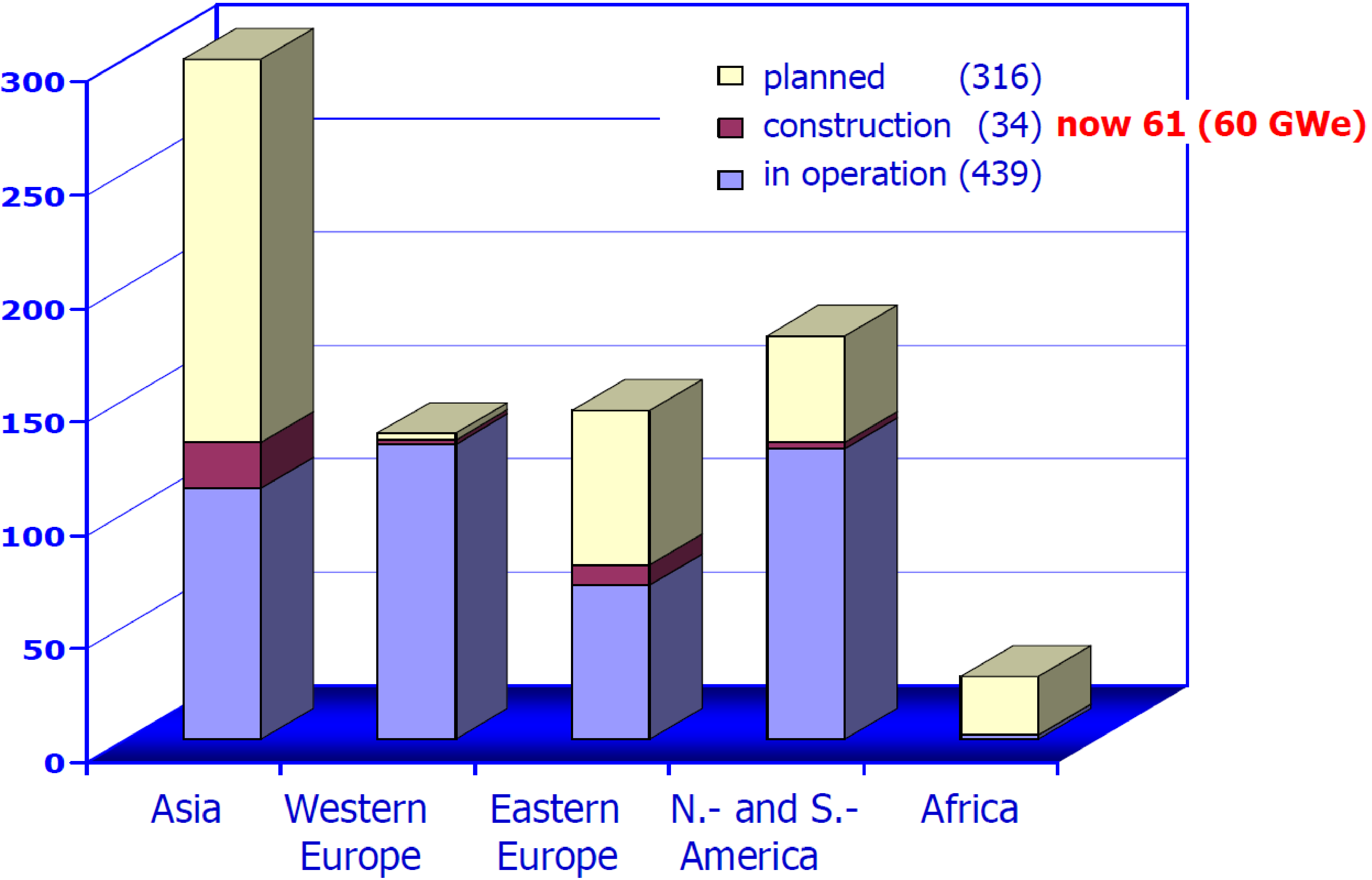
Nuclear Power Plants in operation



Alle reactoren in de USA zijn gebouwd in ongeveer 25 jaar

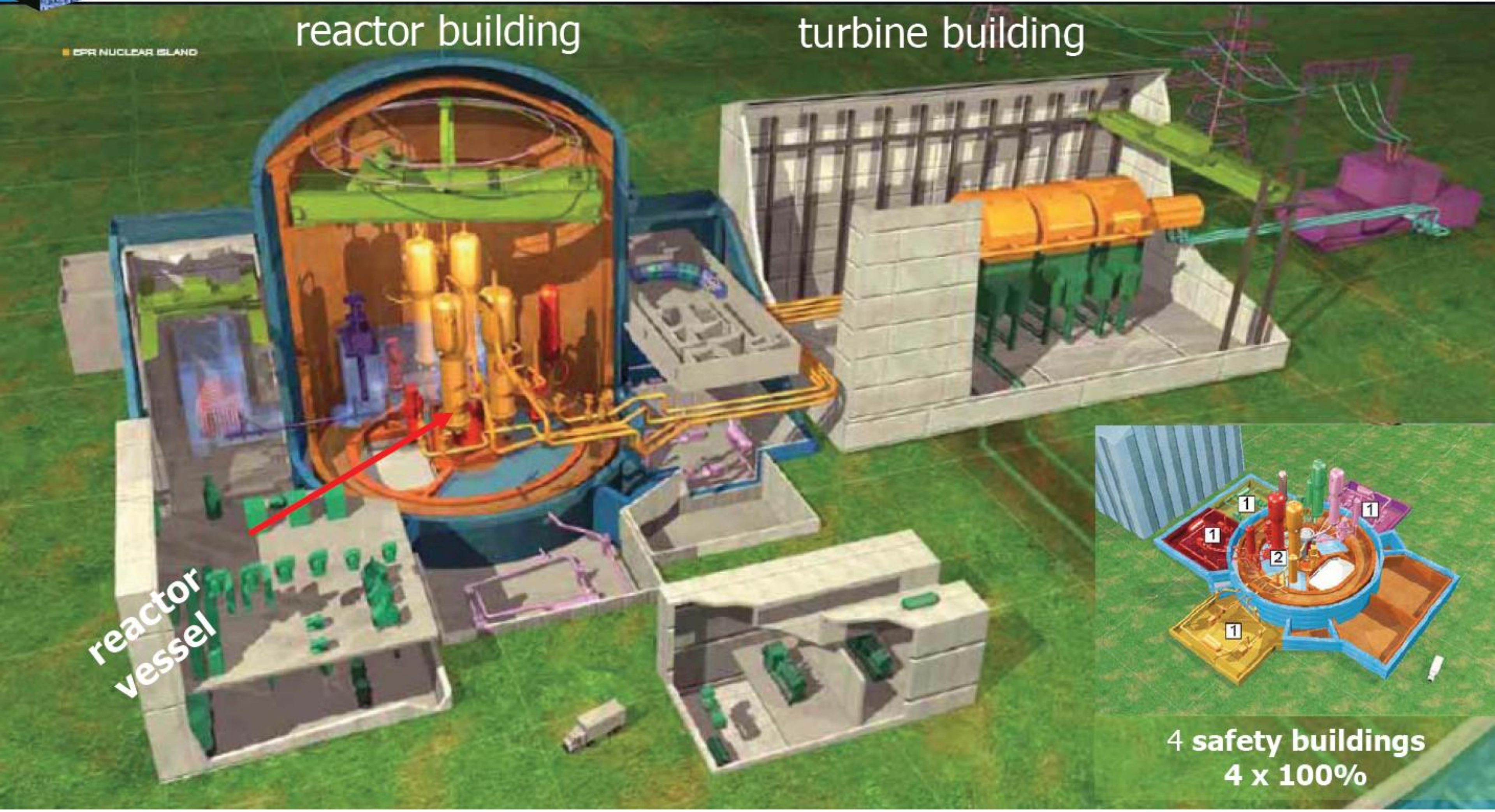
Status nuclear power plans

January 2008

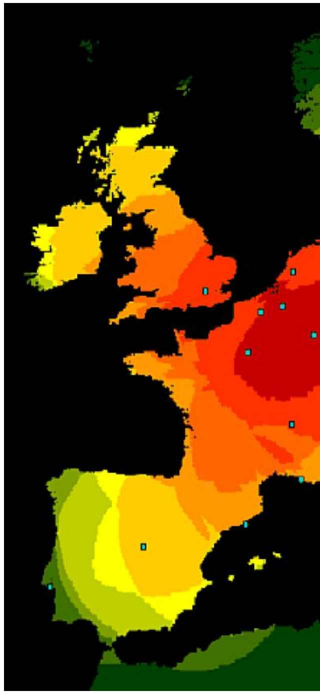


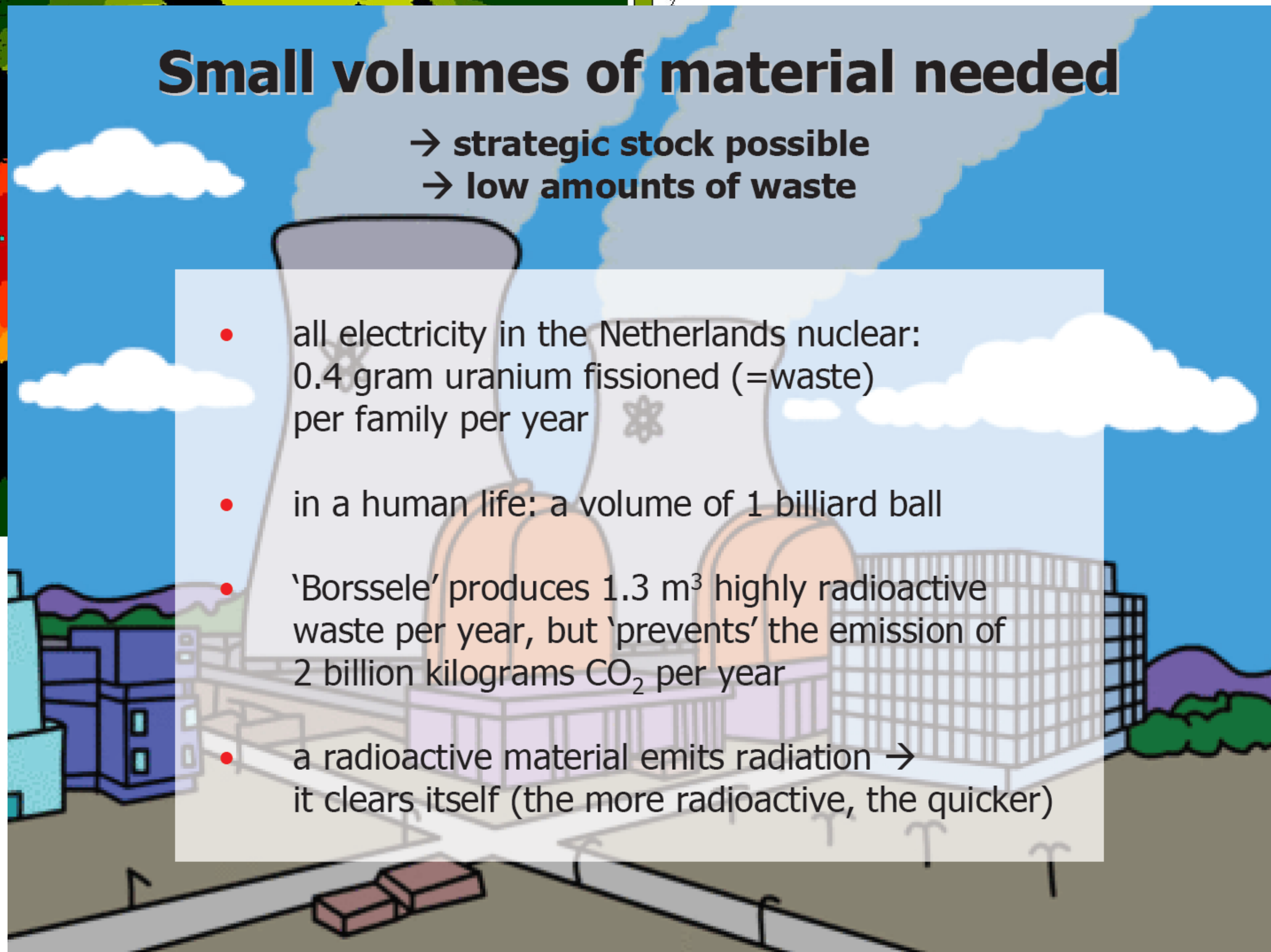
European Pressurized Water Reactor

4500 MWth



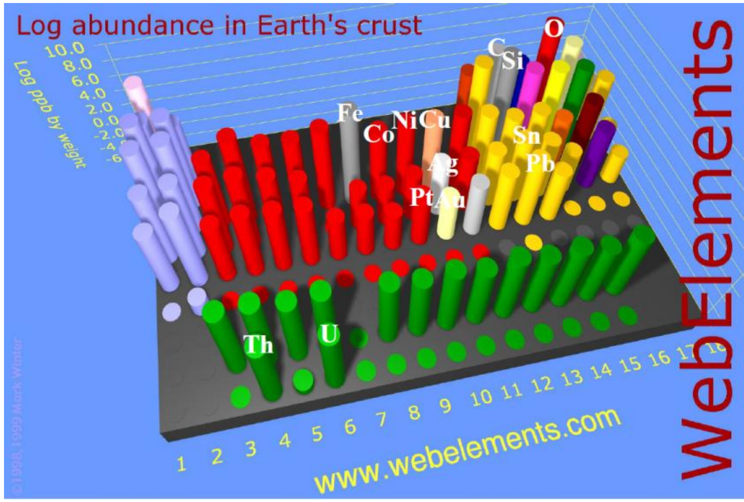
Kernenergie en Nederland



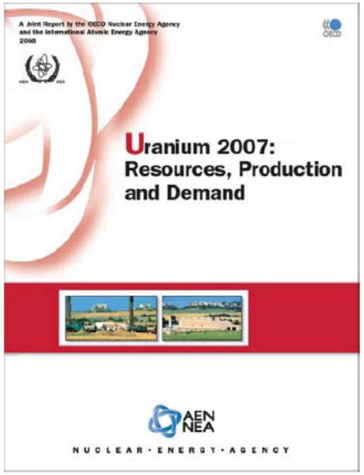


Beschikbaarheid uranium

Uranium resources:



- The earth's crust contains 40 x as much uranium as silver; as much uranium as tin
- Cheap uranium (up to 130$ per kg): 5.5 million tons; enough for 80 years (0.1 ct/kWh)
- For the double price:
  10 times as much; enough for 800 years
  using fast reactors: 80,000 years
- Uranium as byproduct from phosphate deposits (22 Mt recoverable)
- Uranium from seawater (450$ per kg): 4 billion tons; enough for 6,000,000 years



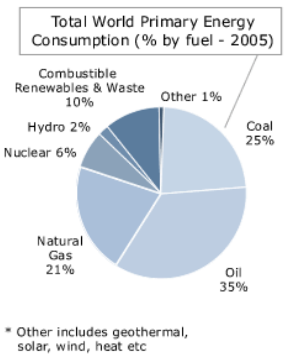
Source: OECD NEA & IAEA, "Uranium 2007: Resources, Production and Demand" ("Red Book").

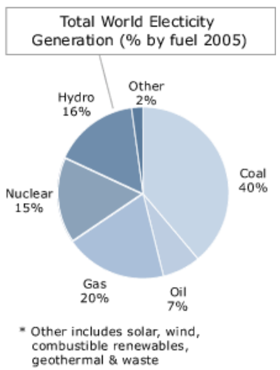
NIKHEF

Mining accidents

Fatalities and injuries for mining in USA

Year	Average Annual Deaths	Average Annual Injuries
1936-1940	1,546	81,342
1941-1945	1,592	82,825
1946-1950	1,054	63,367
1951-1955	690	38,510
1956-1960	550	28,805
1961-1965	449	23,204
1966-1970	426	22,435
1971-1975	322	33,963
1976-1980	254	41,220
1981-1985	174	24,290
1986-1990	122	27,524
1991-1995	99	24,201
1996-2000	86	17,500
2001-2005	62	12,952
2006-2007	69	11,800





PR China	2482Mt	Russia	233Mt
USA	990Mt	Indonesia	169Mt
India	427Mt	Poland	95Mt
Australia	309Mt	Kazakhstan	92Mt
South Africa	244Mt	Colombia	64Mt

deadliest year in U.S. coal mining history was 1907, with 3,242 deaths

Benxihu (Honkeiko) Colliery (本溪湖媒礦), located at Benxi, Liaoning, China. On April 26, 1942, a gas and coal-dust explosion in the mine killed 1,549, 34% of the miners working that day.

Source: State Administration of Work Safety

Coal mining accidents: USA and China

As of 10/29/2008

COAL FATALITIES BY STATE
(CALENDAR YEAR)

STATE	2008	2007	2006	2005	2004	2003	2002	2001	2000	1999	1998	1997	1996	TOTAL
ALABAMA	2	3	2	4	2	1	1	14		2	1	1	2	35
ALASKA														0
ARIZONA			1									1	1	3
ARKANSAS								1						1
CALIFORNIA														0
COLORADO		1							1	1	2		1	6
CONNECTICUT														0
DELAWARE														0
FLORIDA														0
GEORGIA														0
HAWAII														0
IDAHO														0
ILLINOIS	1					3		1	2	1		1	2	11
INDIANA	1	3			1	1	1	2	1	1		1		12
IOWA														0
KANSAS														0
KENTUCKY	5	2	16	8	6	9	9	5	13	9	12	5	12	111
LOUISIANA														0
MAINE														0
MARYLAND		2	1	1						1				5
MASSACHUSETTS														0
MICHIGAN														0
MINNESOTA														0
MISSISSIPPI														0
MISSOURI														0
MONTANA			1											1
NEBRASKA														0
NEVADA														0
NEW HAMPSHIRE														0
NEW JERSEY														0
NEW MEXICO		1					1							2
NEW YORK														0
NORTH CAROLINA														0
NORTH DAKOTA												1		1
OHIO				1				2		2	1			6
OKLAHOMA		1		1										2
OREGON														0
PENN (ANTH)	1		1	1	1		3	1	2	2			1	13
PENN (BITUM)	4	1		3		1					1	4	2	16
PUERTO RICO														0
RHODE ISLAND														0
SOUTH CAROLINA														0
SOUTH DAKOTA														0
TENNESSEE					1							1		2
TEXAS	1	1						1		1				4
UTAH		10	1		2		1		4			3	2	24
VERMONT														0
VIRGINIA	2		1		3	3	4	2	4	5	5	5	2	36
WASHINGTON														0
WEST VIRGINIA	8	9	23	3	12	10	6	13	9	9	7	7	12	128
WISCONSIN														0
WYOMING	1			1		2	1		2	1			1	9
TOTAL	26	34	47	23	28	30	27	42	38	35	29	30	38	427

中国劳工通讯 China Labour Bulletin

Year	Total number of coal mine accidents	Total number of deaths
2000	2,863	5,798
2001	3,082	5,670
2002	4,344	6,995
2003	4,143	6,434
2004	3,639	6,027
2005	3,341	5,986

In 2004: China official statistics: 6,027 deaths
USA reported 28 deaths in the same year

Coal production in China is twice that of the USA, while the number of coal miners is around 50 times that of the USA

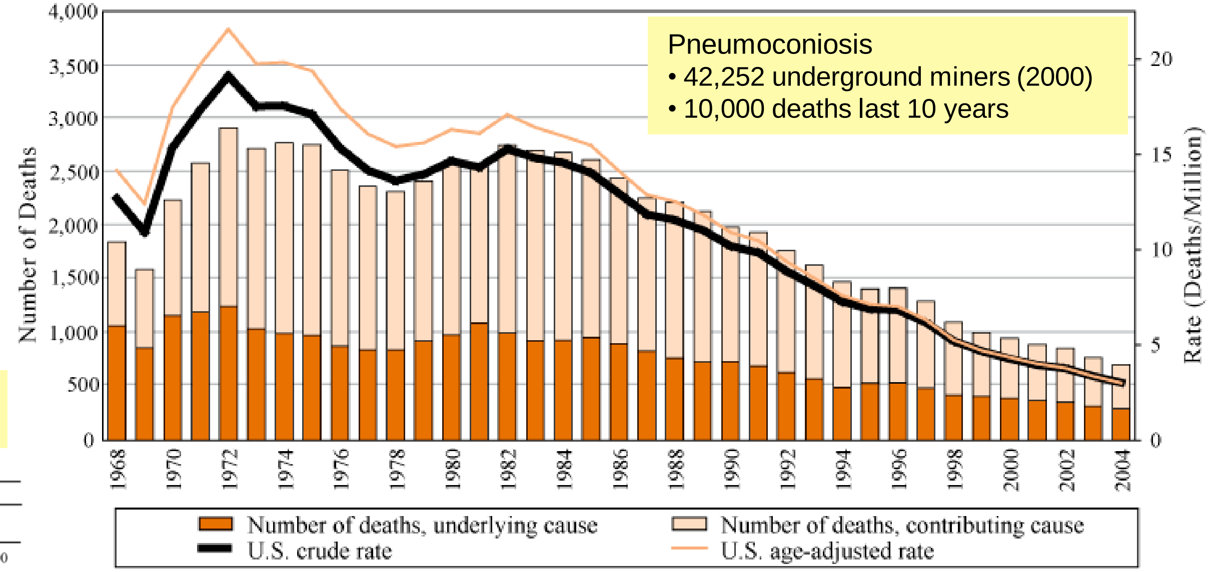
Thus, deaths in coal mines in China are
4 times as common per worker
108 times as common per unit output
as in the USA.

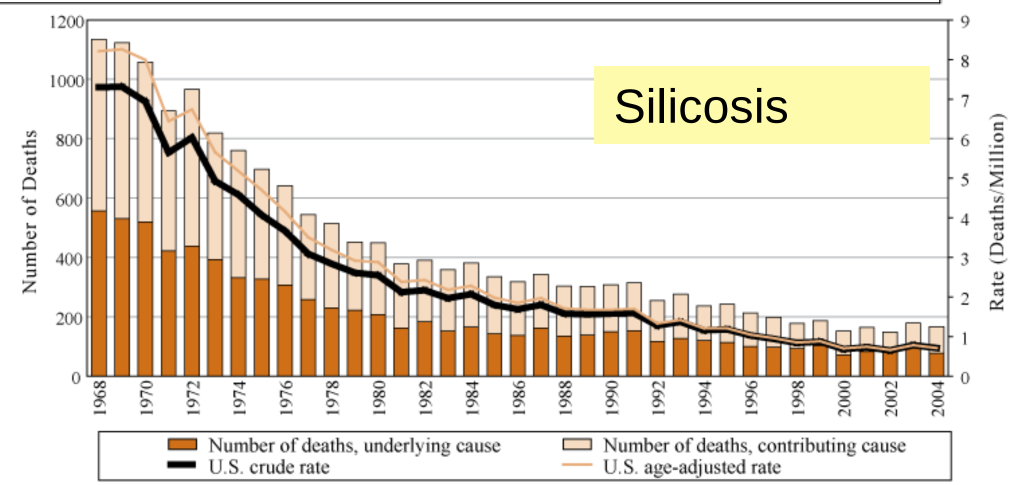
Work-Related Lung Disease (WoRLD) Surveillance System

CENTERS FOR DISEASE CONTROL AND PREVENTION

http://www.cdc.gov/

US residents, age 15 and over, 1968 - 2004





Federal Black Lung Program:

	Social Security Administration (SSA)		Department of Labor (DOL)		All	
Year	Beneficiaries	Amount (dollars)	Beneficiaries	Amount (dollars)	Beneficiaries	Amount (dollars)
1980	399,477	1,032,000,000	139,073	813,205,000	538,550	1,845,205,000
1981	376,505	1,081,300,000	163,401	805,627,000	539,906	1,886,927,000
1982	354,569	1,076,000,000	173,972	784,085,000	528,541	1,860,085,000
1983	333,358	1,055,800,000	166,043	858,854,000	499,401	1,914,654,000
1984	313,822	1,038,000,000	163,166	873,932,000	476,988	1,911,932,000
1985	294,846	1,025,000,000	160,441	905,517,000	455,287	1,930,517,000
1986	275,783	971,000,000	156,892	629,075,000	432,675	1,600,075,000
1987	258,988	940,000,000	153,769	655,290,000	412,757	1,595,290,000
1988	241,626	904,000,000	150,123	656,689,000	391,749	1,560,689,000
1989	225,764	882,000,000	145,289	650,123,000	371,053	1,532,123,000
1990	210,678	863,400,000	139,854	626,521,000	350,532	1,489,921,000
1991	196,419	844,400,000	134,205	942,428,000	330,624	1,786,828,000
1992	182,396	822,500,000	128,761	973,636,000	311,157	1,796,136,000
1993	168,365	794,300,000	123,213	984,666,000	291,578	1,778,966,000
1994	155,122	751,900,000	117,569	994,655,000	272,691	1,746,555,000
1995	143,011	696,700,000	111,769	995,722,000	254,780	1,692,422,000
1996	131,143	654,600,000	105,923	992,128,000	237,066	1,646,728,000
1997	119,233	614,888,000	100,352	1,004,672,000	219,585	1,619,560,000
1998	109,271	576,389,000	94,488	999,822,000	203,759	1,576,211,000
1999	98,977	541,200,000	88,716	1,005,246,000	187,693	1,546,446,000
2000	91,596	522,147,000	82,910	422,656,000	174,506	944,803,000
2001	79,518	487,420,000	70,530	396,928,000	150,048	884,348,000
2002	73,593	453,862,000	65,747	384,234,000	139,340	838,096,000
2003	65,638	416,971,000	61,162	370,389,000	126,800	787,360,000
2004	58,598	379,829,000	56,719	346,864,000	115,317	726,693,000
2005	51,972	345,476,000	52,531	329,863,000	104,503	675,339,000

Federal Black Lung Program:
- 4000 new cases of black lung every year in the USA (4% of workers annually)
- 10 000 new cases every year reported in China (0.2% of workers).

Black lung disease in China

Black lung disease claims 140,000 lives in China

The black lung disease has claimed 140,000 lives in the Chinese mainland since the occupational disease report system was founded in 1950s, revealed vice Health Minister Jiang Zuojun at a televised conference for prevention and treatment of occupational diseases held in Beijing March 17, 2005.

A total of 580,000 black lung cases have been reported in China so far, and there are 440,000 people suffering from black lung disease at present. The number of black lung case is increasing roughly 10,000 annually. In addition, China reports nearly 30,000 poison cases relating to occupation and use of pesticide in production. About 1,500 people die from poison.

Jiang acknowledged the occupational disease has grown so rampant in some areas that "black lung village" and "poison village" have emerged. Many laborers have become impoverished due to the disease. Moreover inappropriate settlement of disputes over occupational diseases has led to incidents that influence social harmony and stability, including blockade of road, strike, demonstration, and group appeal to higher authority for help. Occupational disease has become a grave problem that harms public health and social stability.

To strengthen prevention and treatment of occupational diseases, the Chinese government has adopted occupational health review system for construction projects; imposed strict approval for aptitude of service departments for occupational health; rectified diagnosis and appraisal for occupational disease.

The Health Ministry has decided to launch a publicity week with feature "Safeguard laborer's health by prevention of occupational diseases", in which consultation regarding prevention and treatment of occupational disease will be offered to laborers free of charge.

By People's Daily Online

Radiation exposure of coal

Americans living near coal-fired power plants are exposed to higher radiation doses than those living near nuclear power plants that meet government regulations

The population effective dose equivalent from coal plants is 100 times that from nuclear plants

The extremely high standards of the nuclear industry result in a regimen of care and containment

NCRP Report No. 95, *Radiation Exposure of the U.S. Population from Consumer Products and Miscellaneous Sources*
NCRP Report No. 95 is another of the assessment series of reports. This Report recognizes that there are many consumer products available which emit ionizing radiation, in some cases as an essential element of the proper performance of the device and in other cases as incidental or extraneous to the purpose for which the product was designed. The Report evaluates the exposures from all of these types of products. Treated are electronic products such as television receivers and airport luggage inspection systems; radioactive materials such as radioluminous products, building materials, glass and ceramics; and miscellaneous exposure sources such as high voltage vacuum electronic units. Also covered are exposures resulting from disposal of radioactive surplus items and transport of radioactive materials. Recommendations for dose reduction are also provided in the Report

Science 8 December 1978: Vol. 202. no. 4372, pp. 1045 – 1050 DOI: 10.1126/science.202.4372.1045

Articles
Radiological Impact of Airborne Effluents of Coal and Nuclear Plants

J. P. McBride [1], R. E. Moore [2], J. P. Witherspoon [2], and R. E. Blanco [3] [1] Research staff member of the Chemical Technology Division, Oak Ridge, Tennessee 37830
[2] Research staff members of the Health and Safety Research Division, Oak Ridge, Tennessee 37830
[3] Manager of Radioactive Waste Management Research and Development Programs at Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

Radiation doses from airborne effluents of model coal-fired and nuclear power plants (1000 megawatts electric) are compared. Assuming a 1 percent ash release to the atmosphere (Environmental Protection Agency regulation) and 1 part per million of uranium and 2 parts per million of thorium in the coal (approximately the U.S. average), population doses from the coal plant are typically higher than those from pressurized-water or boiling-water reactors that meet government regulations. Higher radionuclide contents and ash releases are common and would result in increased doses from the coal plant. The study does not assess the impact of non-radiological pollutants or the total radiological impacts of a coal versus a nuclear economy.

The amount of uranium-235 alone dispersed by coal combustion is the equivalent of dozens of nuclear reactor fuel loadings

The energy content of nuclear fuel released in coal combustion is greater than that of the coal consumed

Unclean Fuels Kill 1.5 Million People Per Year - UN

GENEVA - Half the world's population burns wood, coal, dung and other solid fuels to cook food and heat their homes, exposing them to dangerous smoke that kills 1.5 million people a year, the UN health agency said on Thursday.

The World Health Organisation (WHO) said women and children in Africa and Asia were especially vulnerable to indoor air pollution from open fires and poorly ventilated stoves.

Children make up 800,000 of the 1.5 million people who die each year from polluting household fuels, women account for 500,000 deaths and the remaining 200,000 are men.

"Day in day out, and for hours at a time, women and their small children breathe in amounts of smoke equivalent to consuming two packs of cigarettes per day," the WHO said.

Yet in a report entitled "Fuel For Life: Household Energy and Health," the Geneva-based agency said it could cost as little as US$6 per family to install better-insulated and fuel efficient stoves in developing countries.

"Making cleaner fuels and improved stoves available to millions of poor people in developing countries will reduce child mortality and improve women's health," WHO Director General Lee Jong-wook said.

Inhaling indoor smoke doubles a child's risk of pneumonia and makes adults three times as likely to suffer chronic pulmonary disease than those who cook with electricity, gas and other clean-burning fuels, it said.

Halving the 3 billion people worldwide cooking with solid fuels by 2015 would cost between US$13 billion to US$43 billion a year depending on the new energy source used, WHO said. Using liquefied petroleum gas would be cheaper than ethanol.

But it would save up to US$91 billion a year over 10 years due to health care savings, less illness, fewer deaths, and higher productivity due to less time-intensive fuel collection and cooking.

"With more time available, children would do better at school, while their mothers could engage in child care, agriculture or other income-generating activities," it said.

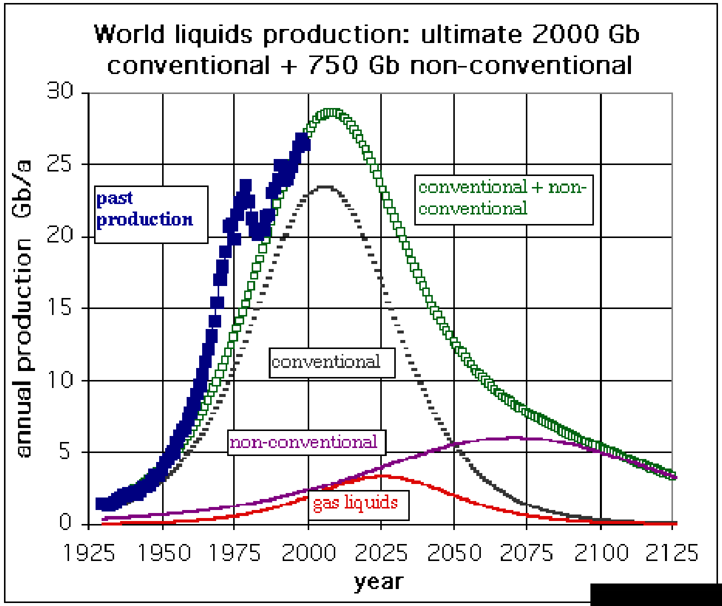
Making better-ventilated stoves available to half of those currently using inefficient cookers could save US$34 billion in fuel expenditure each year, it said.

Story Date: 5/5/2006

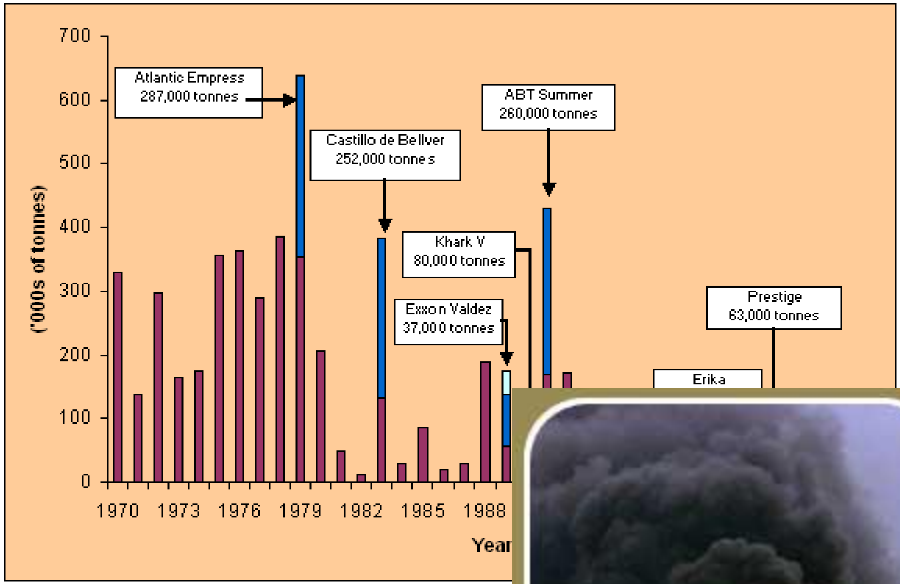
REUTERS
KNOW. NOW.

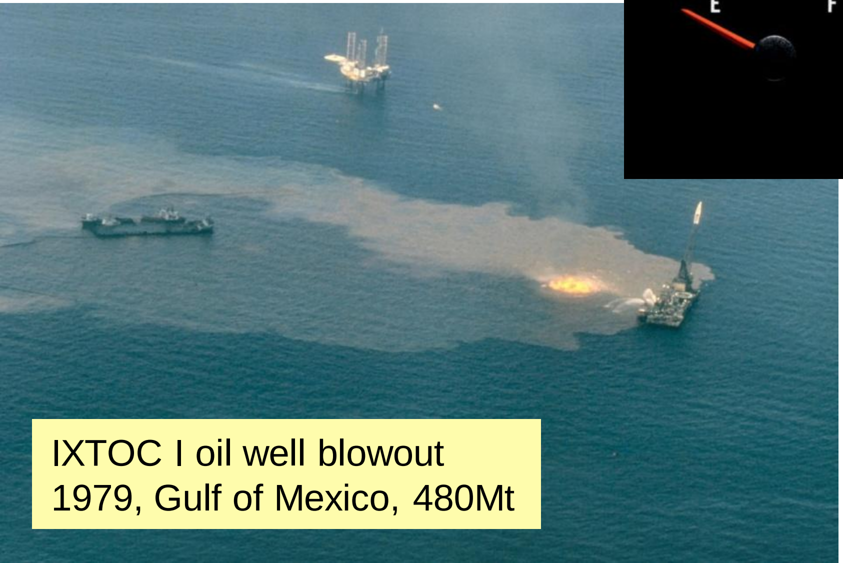
Oil spills

THE HUBBERT CURVE



THE INTERNATIONAL TANKER OWNERS POLLUTION FEDERATION LIMITED





IXTOC I oil well blowout
1979, Gulf of Mexico, 480Mt

Gulf war oil spill,
1991, 0.8 - 1.5Gt

Oil: pipeline ruptures, platform accidents

Nigeria
1998: At Jesse, Nigeria in the Niger Delta in Nigeria, a petroleum pipeline exploded killing about 1200 villagers, some of whom were scavenging gasoline. The worst of several similar incidents in this country
2000: Another pipeline explosion near the town of Jesse killed about 250 villagers
2000: At least 100 villagers died when a ruptured pipeline exploded in Warri
2000: A leaking pipeline caught fire near the fishing village of Ebute near Lagos, killing at least 60 people
2003: A pipeline punctured by thieves exploded and killed 125 villagers near Umuahia, Abia State
2004: A pipeline punctured by thieves exploded and killed dozens of people in Lagos State
2006: An oil pipeline punctured by thieves exploded and killed 150 people at the Atlas Creek Island in Lagos State.
2006: A vandalized oil pipeline exploded in Lagos. Up to 500 people may have been killed.
2008: 2008 Ijegun pipeline explosion

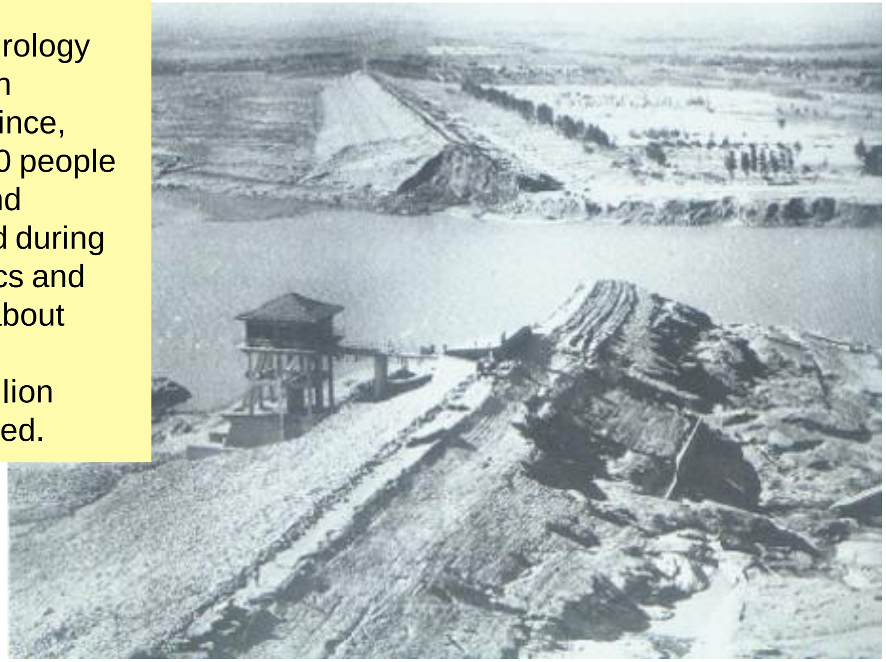
Russia
1989: Sparks from two passing trains detonated gas leaking from an LPG pipeline near Ufa. Up to 645 people were reported killed

Piper Alpha was a North Sea oil production platform operated by Occidental Petroleum (Caledonia) Ltd. The platform began production in 1976, first as an oil platform and then later converted to gas production. An explosion and resulting fire destroyed it on July 6, 1988, killing 167 men. Total insured loss was about US$ 3.4 billion.

Dam disasters

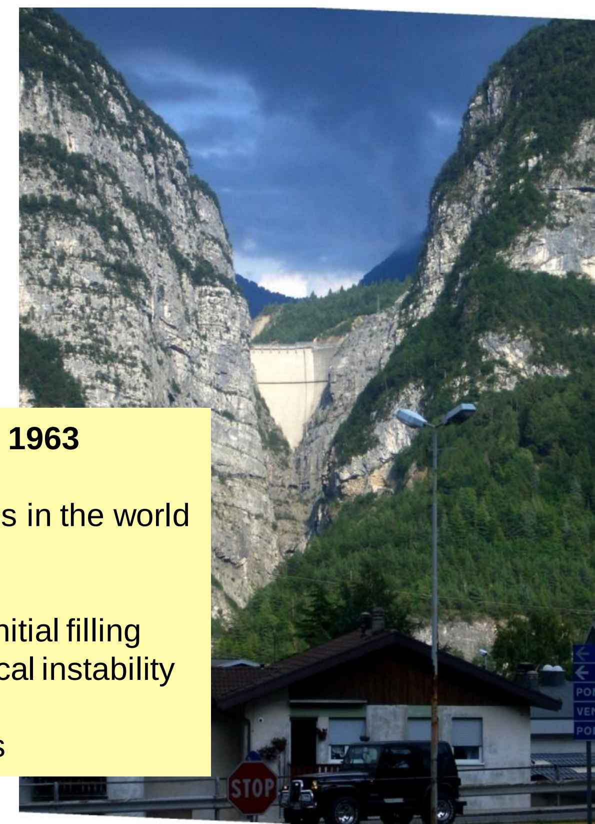
Banqiao dam failure – 1975

According to the Hydrology Department of Henan Province, in the province, approximately 86,000 people died from flooding and another 145,000 died during subsequent epidemics and famine. In addition, about 5,960,000 buildings collapsed, and 11 million residents were affected.



Val di Stava dam disaster – 1985

268 deaths



Vajont dam disaster – 1963

One of the highest dams in the world measuring 262 metres

Its 1963 failure during initial filling was caused by geological instability

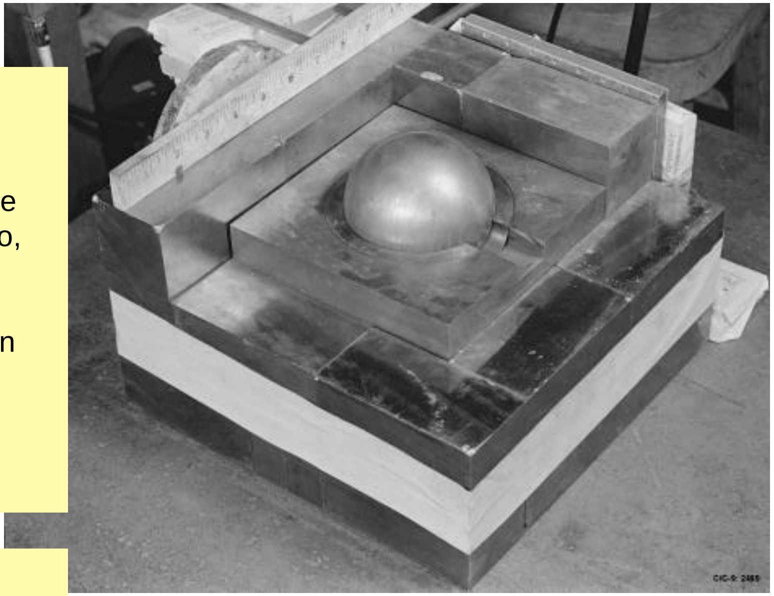
Total of 1910 casualties

International Nuclear Event Scale

International Atomic Energy Agency

Level 7: Major accident	Chernobyl	Large off-site impact
Level 6: Serious accident	Mayak	Significant off-site release
Level 5: Accident with wider consequences	Windskale, Three mile island	Severe reactor damage, limited off-site release
Level 4: Accident with local consequences	Sellafield, Saint-Laurent, Tokaimura	Public exposure (near limits), fatal exposure
Level 3: Serious incident	Thorp Sellafield, Paks	Public exposure (below limits), near accident
Level 2: Incident	Asco, Forsmark	No off-site impact, overexposure of worker
Level 1: Anomaly	Tricastin	Anomaly (water leak, contamination)

First nuclear accidents



Harry K. Daghlian, Jr., (1921 – September 15, 1945)

Physicist of Armenian descent with the Manhattan Project who accidentally irradiated himself on August 21, 1945 during a critical mass experiment at the remote Omega Site facility at Los Alamos National Laboratory in New Mexico, resulting in his death 21 days later.

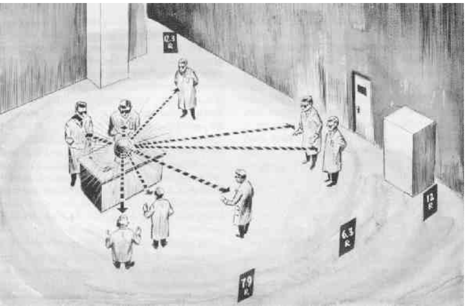
Daghlian was irradiated as a result of a criticality accident that occurred when he accidentally dropped a small tungsten carbide brick onto a 6.2 kg delta phase plutonium bomb core.

This core was later nicknamed the "Demon core”

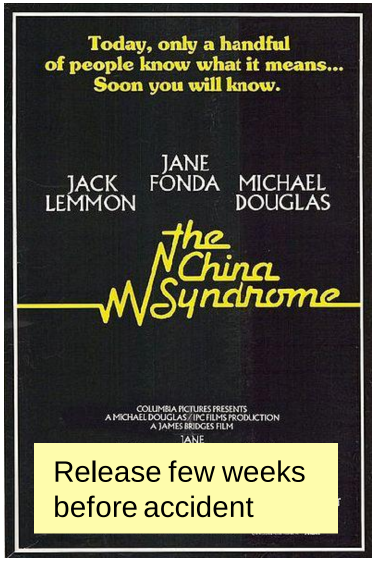
Louis Alexander Slotin (December 1, 1910 – May 30, 1946)

Canadian physicist and chemist who took part in the Manhattan Project. Performed experiments with uranium and plutonium cores to determine their critical mass values. After World War II, Slotin continued his research at Los Alamos National Laboratory.

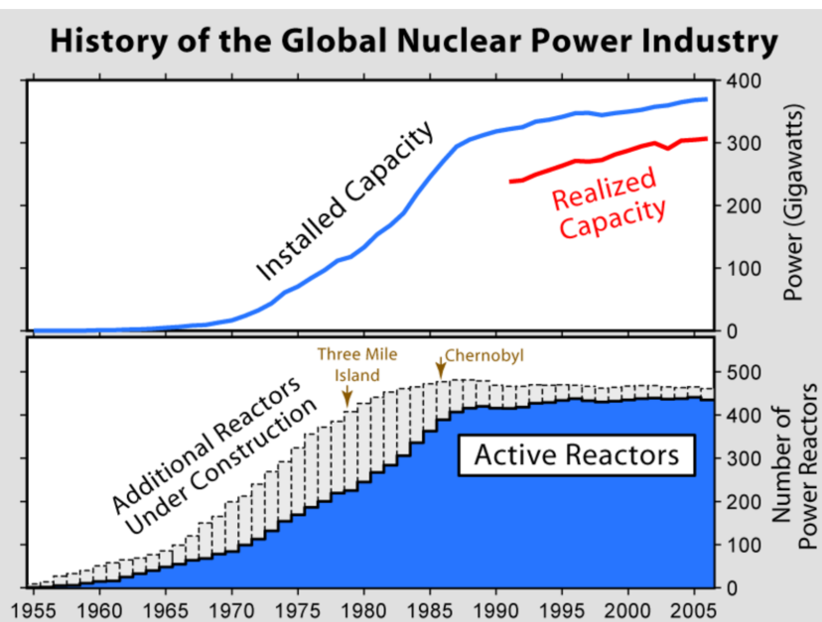
On May 21, 1946, Slotin accidentally began a fission reaction, which released a burst of hard radiation. He was rushed to hospital, and died nine days later.



Three Mile Island – TMI-2



Release few weeks before accident



TMI-2: PWR (Babcock & Wilcox)

March 28, 1979. Biggest nuclear accident in USA. Pump of secondary non-nuclear cooling fails. Turbine and reactor are shutdown (normal procedure).

Temperature and pressure in reactor rise (normal). Relief valve of pressurizer (PORV) opens.

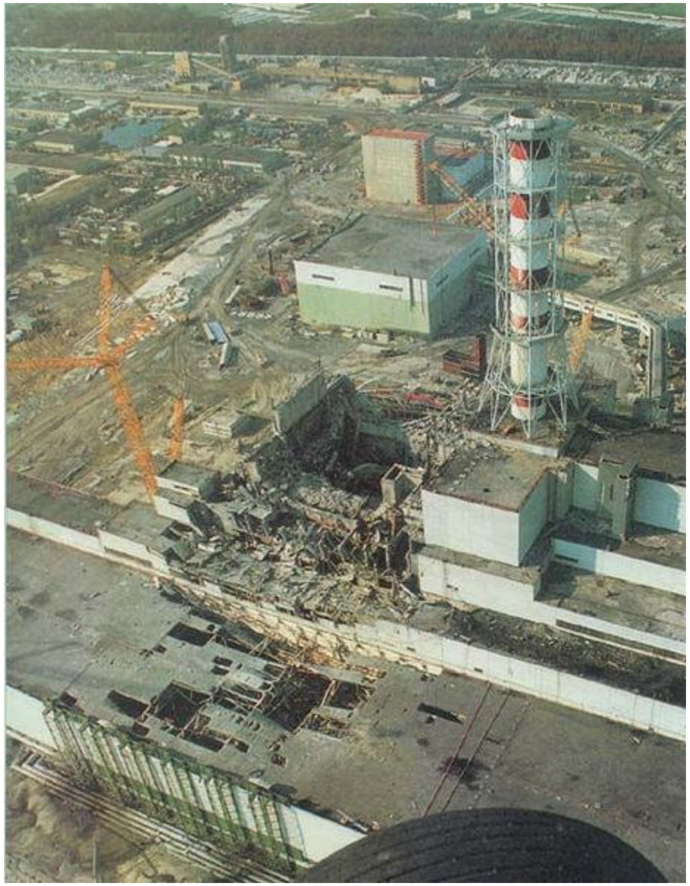
PORV should close, but fails to do so (not noticed by operators). Pressure keeps dropping, cooling water pours out of PORV. Reactor core overheats.

Backup system failed since after tests prior to accident people forgot to open valves (human error). Half of the core melted. All contained. Radioactive noble gases (~43 kCi krypton) were vented (<20 Ci of I-131).

Average dose to people within ten miles was 8 mrem. Nobody received more than 100 mrem (power plant workers norm: < 5 rem per year. Estimate of additional cancers <~ 1.

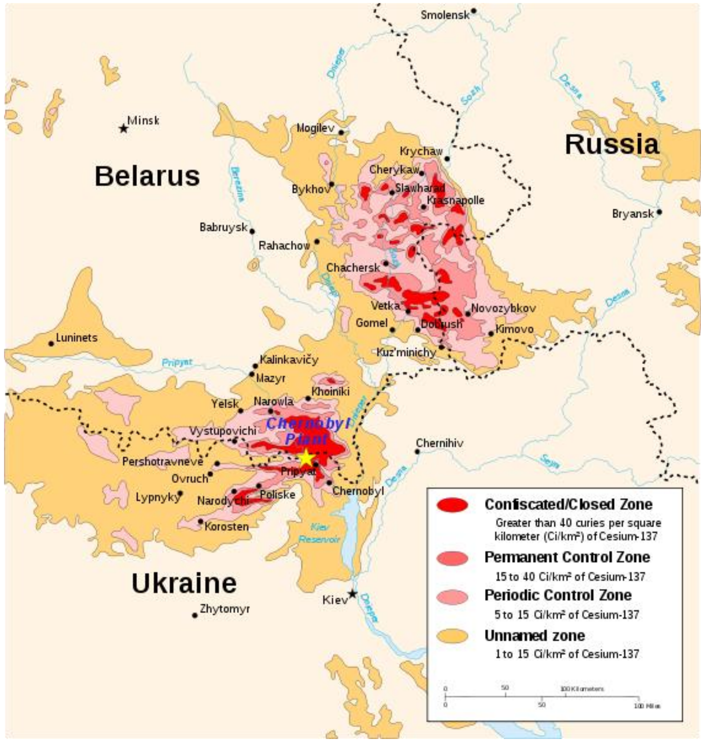
Tsjernobyl

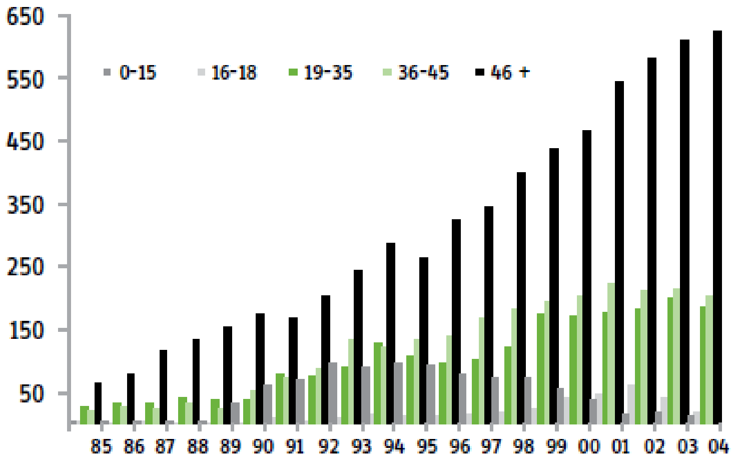
- Grootste kernramp in de geschiedenis
  - 26 april 1986
  - Level 7 op International Nuclear Event Scale
- De ramp
  - Test met kernreactor nummer 4
  - Schakel generator uit en kijk of er voldoende vermogen is om de koelinstallatie 60 seconde te laten werken totdat de noodaggregaten aanslaan
  - Reactorvermogen onbedoeld naar 30 MW
  - Hierdoor Xenon vergiftiging
  - Alle regelstaven uit en vermogen naar 200 MW
  - Voor de test was minimaal 600 MW nodig
  - Test toch voortgezet: waterpompen ingeschakeld
  - Door extra n-absorptie zakte vermogen verder
  - 20 van de 26 handbediende veiligheidsstaven uit
  - Turbine uit: vermogen steeg exponentieel
  - Noodstop uitgevoerd, maar dat duurt 19 seconden
  - Brandstofstaven braken, controlestaven klem
  - Reactor bereikt 30 GW, staven smelten
  - Stoomontploffing: 2000 ton dak van reactor
  - Grafiet moderator vat vlam



Tsjernobyl

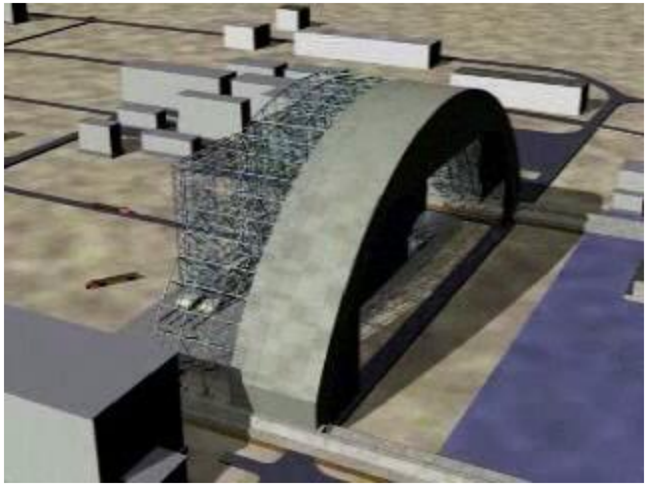
- Consequenties
  - 42 werkers gedood door straling binnen weken
  - 600.000 burgers en militaire `liquidators' blootgesteld aan hoge stralingsniveaus: decontaminatie reactor, site, straten en constructie sarcofaag
  - Radioactieve besmetting van 3000 km2 oppervlak door cesium-37 (halfwaardetijd gamma-emitter 30 jaar)
  - Groeiende epidemie van schildklierkanker door besmetting met jodium
  - Andere kankersoorten worden verwacht, maar zijn niet detecteerbaar vanwege de hoge achtergrond van kanker door andere oorzaken. Een theoretische studie stelt op basis van Hiroshima en Nagasaki overlevenden dat 4000 extra kankerdoden voor de 600.000 liquidators, 5000 voor de 6 miljoen mensen die in besmette gebieden (> 37 kBq/m2 voor cesium-137), en ongeveer 7000 voor de 500 miljoen Europeanen. Totaal 16.000 (6700 – 38.000 voor 95% confidence level)
- Gemiddeld
  - Eind 2008: 10.000 GWe-jaar kernreactor ervaring
  - Dus minder dan 2 doden per GWe-jaar; dat is minder dan bij fossiele brandstoffen
  - Trauma groot: 200.000 mensen verplicht verhuisd

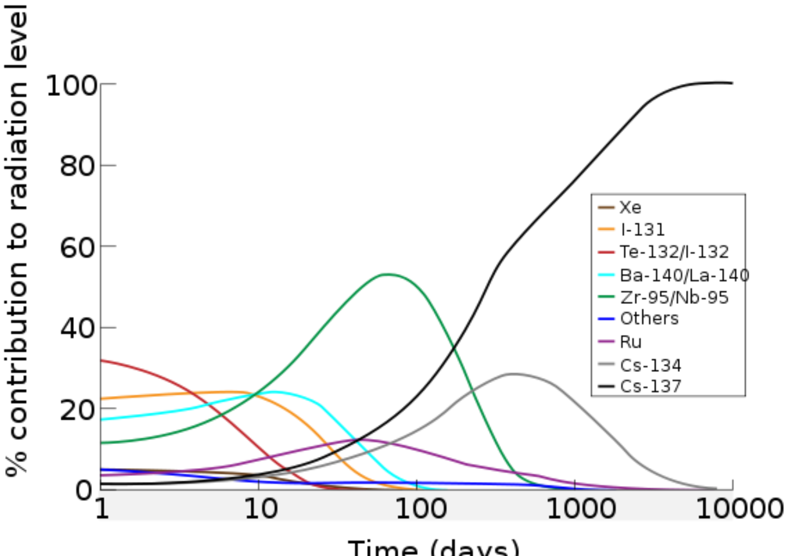




Tsjernobyl

- Economische aspecten
  - Schattingen varieren van $ 6.7 miljard tot $235 en $148 door overheden van Belarus en Ukraine
  - Sociale uitkeringen (Tsjernobyl gerelateerd) aan 7 miljoen mensen in 3 landen)
  - Verplaatsing populatie
  - Verlies van assets: 784.320 hectare landbouwgrond en 694.200 hectare bos. Merendeel is nu weer in gebruik
  - Belarus: 20% nationaal budget in 1992, 5% in 2001
  - Betaald door 18% extra belasting voor non-agricultural firms in 1994
  - Chernobyl Shelter Fund: $1.2 miljard voor de grootste bewegende structuur die ooit gebouwd is (span 270 m, hoogte 100 m en lengte 150 m; 2024 ton massa)
  - Potentiele kosten van een brand in spent-fuel pools in de USA worden op honderden miljarden geschat





The world total annual energy consumptions amount to 14 billion coal equivalent.

Nuclear power – October 2008

Reactor type	In operation		Under construction	
	Number	net capacity MWe	Number	net capacity MWe
PWR	265	243,295	27	24,195
BWR	94	85.287	3	3,925
AGR, GGR	18	9,034	-	-
CANDU/D_2O-PWR	44	22,390	4	1,298
RBMK	16	11,404	1	925
SNR	2	690	2	1.220
total	**439**	**372,100**	**34**	**31,563**

Energy reserves – 2006

european nuclear society

largest nuclear society for science and industry

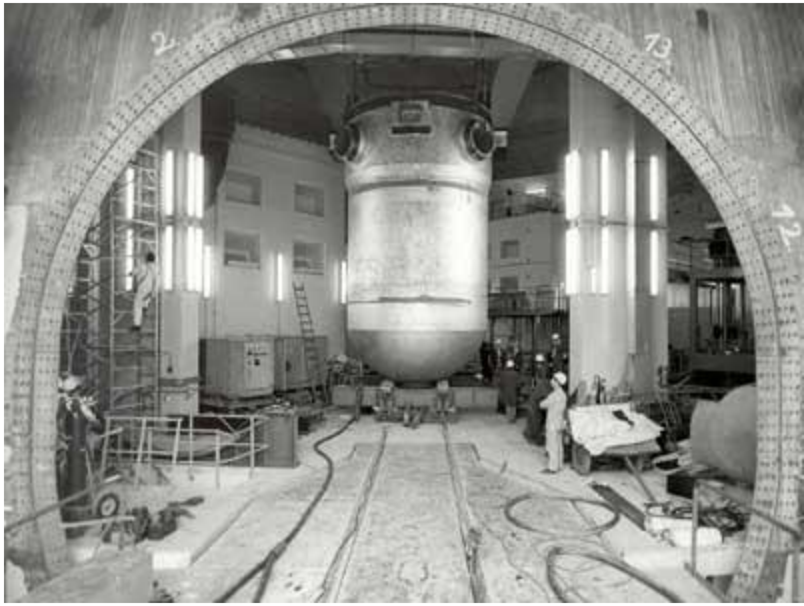
• Natural gas	235 billion t coal equivalent
• Mineral oil/shales/liquid gas	232 billion t coal equivalent
• Natural uranium	27 billion t coal equivalent
• Coal (all forms)	726 billion t coal equivalent.

The world total annual energy consumptions amount to 14 billion coal equivalent.

Nuclear installations in The Netherlands

Borssele PWR

- 1969 PZEM bestelt reactor bij Siemens/KWU
- 25 Oktober 1973 levering
  - Na succesvolle eerste testen
  - Overheid geeft permanente bedrijfsvergunning
- 1979 – 1984 Upgrade veiligheid
  - Reserve koelwatersysteem
  - Na Harrisburg, Maart 1979
- 1990 EPZ wordt eigenaar
- 11 Juli 1994 EZ stekt dat bedrijf wordt verlengd tot 2007
  - Upgrade project `Modifications’
  - 450 miljoen gulden
  - Er dient voldoende terugverdiendtijd te zijn
- Mei - Juni 2003 Balkenende-2
  - Sluiting uiterlijk in 2013
- 16 Juni 2006 Borssele Covenant
  - Bedrijf mogelijk tot 2034
  - Nuclear Energy Act Licence: elke 10 jaar safety check
  - Essent en Delta investeren 250 miljoen €duurzaam
  - Overheid idem dito



Borssele PWR

- PWR met 485 MWe
- Brandstof
  - MOX
  - Uranium van Kazakhstan
- Kernafval
  - Borssele produceert 12 ton per jaar
  - Areva NC doet reprocessing
  - Restafval moet teruggenomen worden en wordt opgeslagen door COVRA
  - Voldoende opslagcapaciteit voor 100 jaar
  - Transporten naar La Hague
  - Eerste in Juni 2011; 10 in 2012 – 2015
  - Reprocessed uranium wordt verrijkt in Rusland met uranium van duikboten; 25% blijft in Rusland
- 2009 Delta memorandum voor 2e centrale
  - Kosten 4 – 5 miljard euro
  - Verzoek tot vergunning in 2012
  - Start constructie in 2013, bedrijf in 2018

Kernsplijting

Opslag van radioactief materiaal staat ter discussie
Ongelukken hebben grote gevolgen (Chernobyl, Fukushima)
Decommissioning moet beschouwd worden
Snelle broedreactoren: genereren hun eigen brandstof (plutonium)
Proliferatie, diefstal van plutonium moet voorkomen worden

Manhattan project in WOII
Uranium en plutonium bommen (1945)
Nuclear weapons test ban treaty (1963) verbiedt testen van kernwapens in atmosfeer (fall-out is gevaarlijk in verband met consumptie)

Oppenheimer & Groves

Nagasaki

Kernfusie

Kernfusie

Energie komt vrij bij de fusie van kernen

Proton – proton cyclus in de Zon levert 26.7 MeV

$$ {}^1_1H + {}^1_1H \rightarrow {}^2_1H + e^+ + \nu \qquad (0.44\ \mathrm{MeV}) $$

$$ {}^1_1H + {}^2_1H \rightarrow {}^3_2He + \gamma \qquad (5.48\ \mathrm{MeV}) $$

$$ {}^3_2He + {}^3_2He \rightarrow {}^4_2He + {}^1_1H + {}^1_1H \qquad (12.86\ \mathrm{MeV}) $$

$$ 4\,{}^1_1H \rightarrow {}^4_2He + 2e^+ + 2\nu + 2\gamma $$

CNO cyclus (hete sterren)

$$ {}^{12}_6C + {}^1_1H \rightarrow {}^{13}_7N + \gamma $$

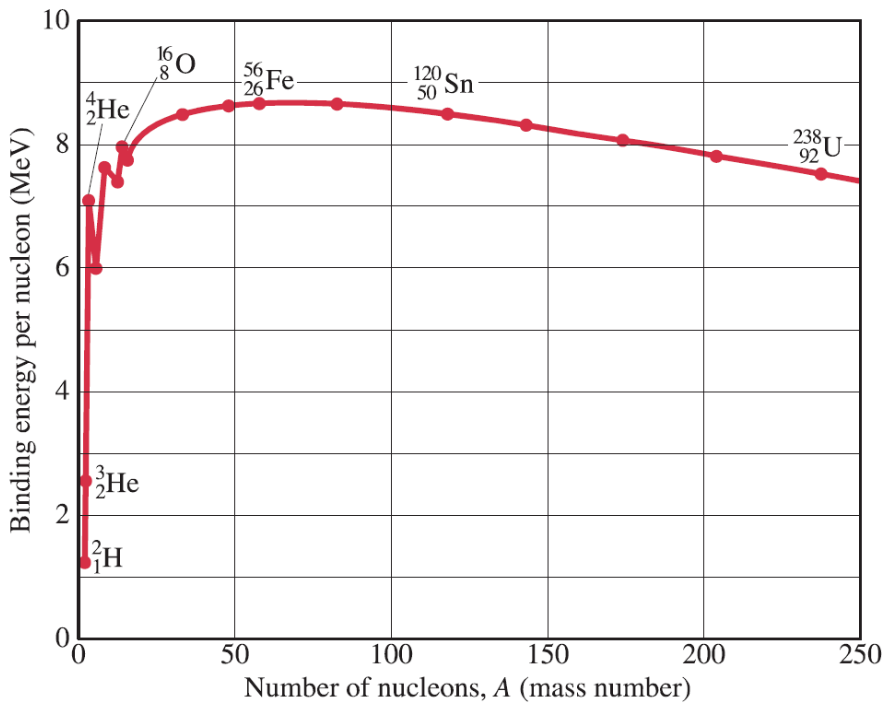
$$ {}^{13}_7N \rightarrow {}^{13}_6C + e^+ + \nu $$

$$ {}^{13}_6C + {}^1_1H \rightarrow {}^{14}_7N + \gamma $$

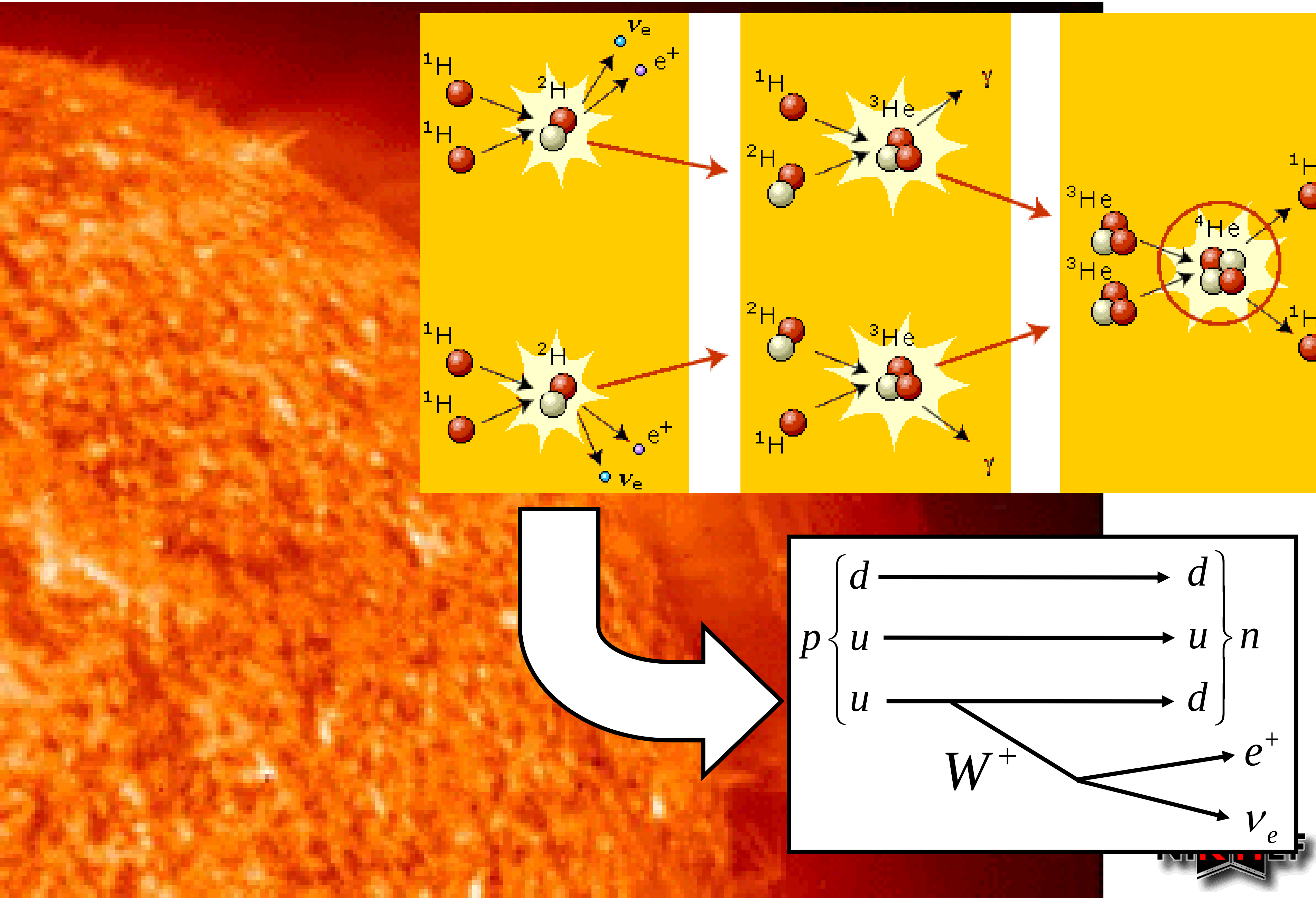
$$ {}^{14}_7N + {}^1_1H \rightarrow {}^{15}_8O + \gamma $$

$$ {}^{15}_8O \rightarrow {}^{15}_7N + e^+ + \nu $$

$$ {}^{15}_7N + {}^1_1H \rightarrow {}^{12}_6C + {}^4_2He. $$

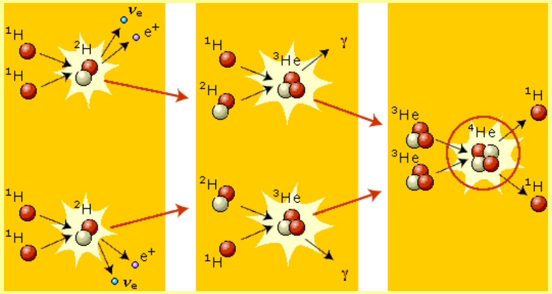


"Zwakke" wisselwerking



Fusie

- Mechanisme van energie productie in sterren
- Elke seconde wordt er ongeveer 600 miljoen ton waterstof omgezet door de *zwakke* wisselwerking



- Power dichtheid in de Zon is slechts 0.3 W/m^3

Temperatuur en kinetische energie

Temperatuur wordt altijd gebruikt om gemiddelde energie te geven. De eenheid is weer eV, i.e.

$$T = kT_k/e \ (\mathrm{eV}) = 8.617 \cdot 10^{-5} T_k \ (\mathrm{eV})$$

met T de temperatuur en T_k de temperatuur in Kelvin.

Merk op $1\ \mathrm{eV} = 11605\ \mathrm{K}$ $\quad 17.56\ \mathrm{MeV} = 2\ 10^{11}\ \mathrm{K}$

- De energie komt vrij in de vorm van kinetische energie
- De kinetische energie is niet gelijk verdeeld over de eindtoestanden, omdat zowel energie als impuls behouden moeten zijn

$$\frac{1}{2} m_{\mathrm{A}} v_{\mathrm{A}}^2 + \frac{1}{2} m_{\mathrm{B}} v_{\mathrm{B}}^2 = E_{fus}$$

$$m_{\mathrm{A}} v_{\mathrm{A}} + m_{\mathrm{B}} v_{\mathrm{B}} = 0$$

- Dez vergelijkingen kunnen opgelost worden en geven

$$E_A = \frac{1}{2} m_{\mathrm{A}} v_{\mathrm{A}}^2 = \frac{m_B}{m_A + m_B} E_{\mathrm{fus}} \qquad E_B = \frac{1}{2} m_{\mathrm{B}} v_{\mathrm{B}}^2 = \frac{m_A}{m_A + m_B} E_{\mathrm{fus}}$$

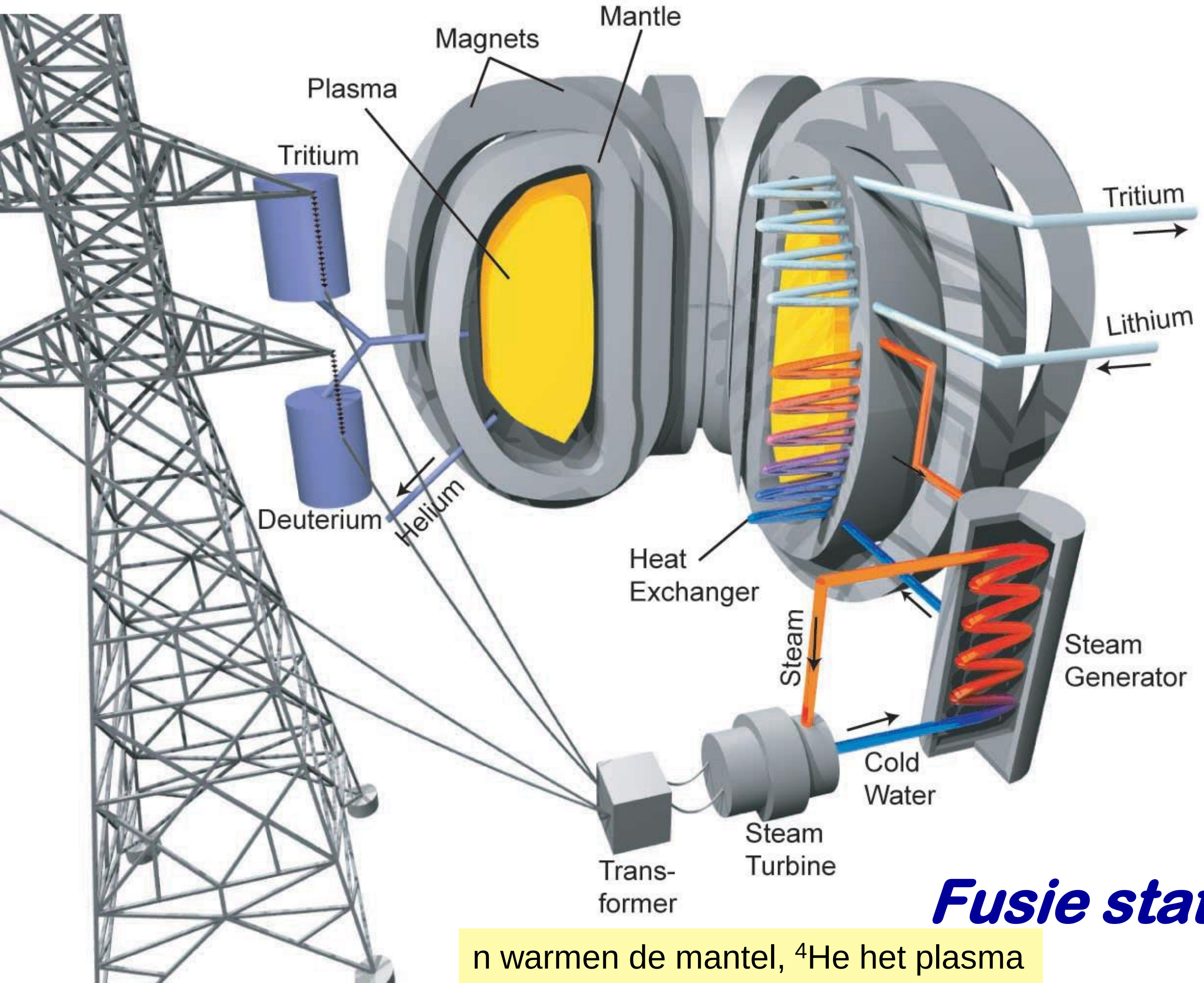
Lichtste deeltje heeft de meeste kinetische energie

- Neem de beroemde reactie

$$^2_1\mathrm{D} + {}^3_1\mathrm{T} \rightarrow {}^4_2\mathrm{He} + {}^1_0\mathrm{n}$$

- Helium kernen zijn ongeveer 4 keer zwaarden dan het neutron en krijgen dus 20% van de energie (3.5 MeV) terwijl het neutron 80% (14.1 MeV) krijgt

vrije Universiteit amsterdam



Fusie station

n warmen de mantel, ^{4}He het plasma

Kernfusie reactoren

Gebruik isotopen van waterstof

$$ {}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{1}H + {}^{1}_{1}H \qquad (4.00\,\text{MeV}) $$

$$ {}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{2}He + n \qquad (3.23\,\text{MeV}) $$

$$ {}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + n. \qquad (17.57\,\text{MeV}) $$

Abondantie van deuterium is 1 gram per 80 liter water

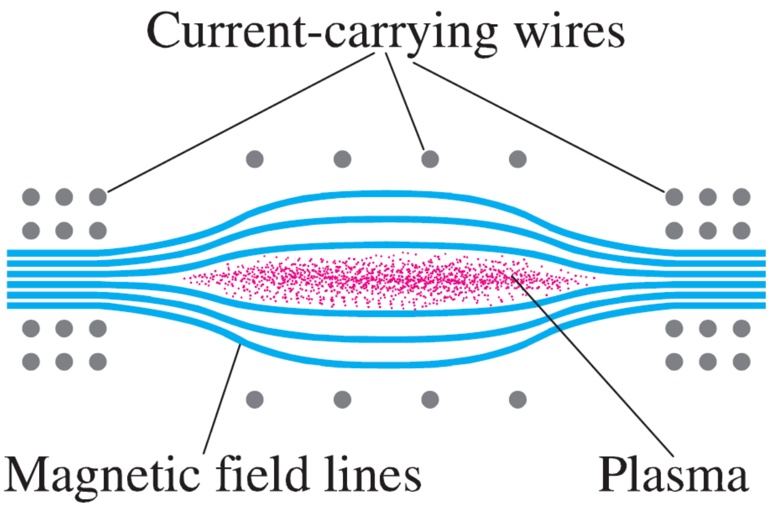
Praktisch probleem is het overwinnen van de Coulomb afstoting

Hoge temperatuur nodig in fusie reactor (paar honderd miljoen K)

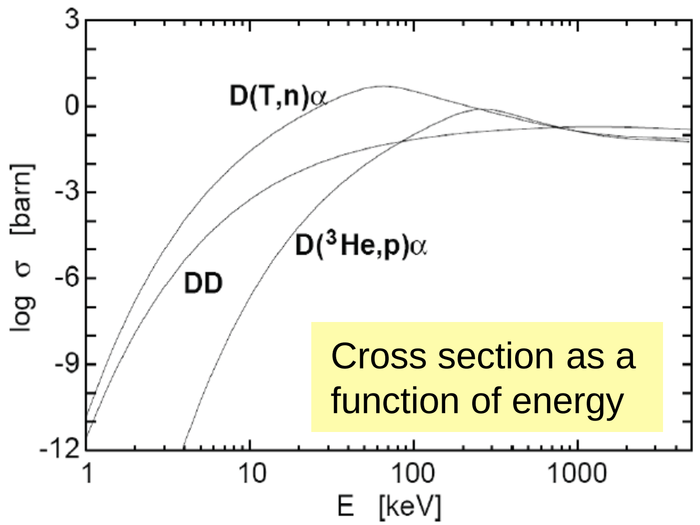
Opsluiting van het plasma is een uitdaging

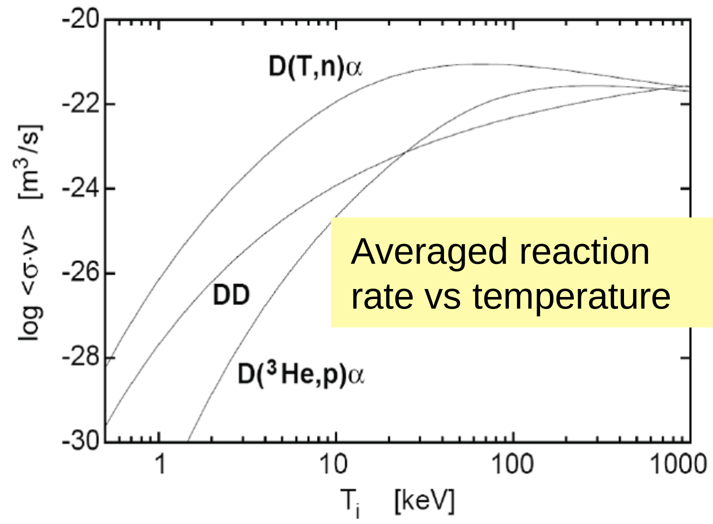
Magnetisch opsluiting in een magnetisch fles

Plasma lekt weg aan de uiteinden



Werkzame doorsneden

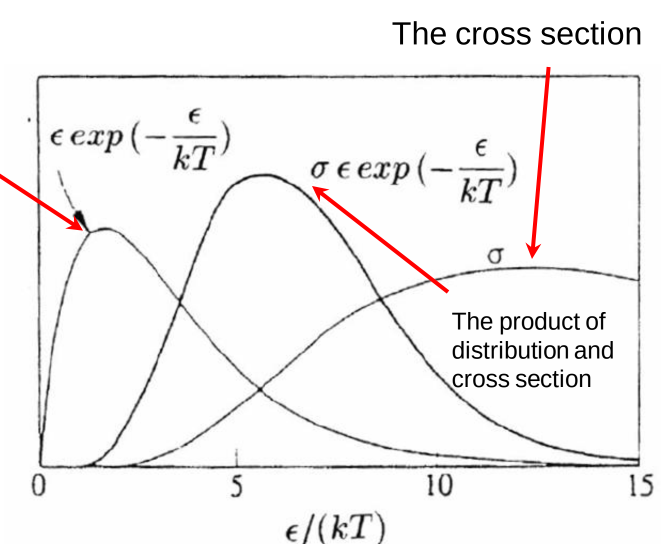




The averaged reaction rate does not fall of as strongly when going to lower energies

Even for temperatures below the energy at which the cross section reaches its maximum, there is a sufficient amount of fusion reactions due to the number of particles in the tail of the Maxwell distribution

The Maxwell (multiplied with the velocity)



Schematic picture of the calculation of the averaged reaction rate (Integrand as a function of energy)

Tokamak

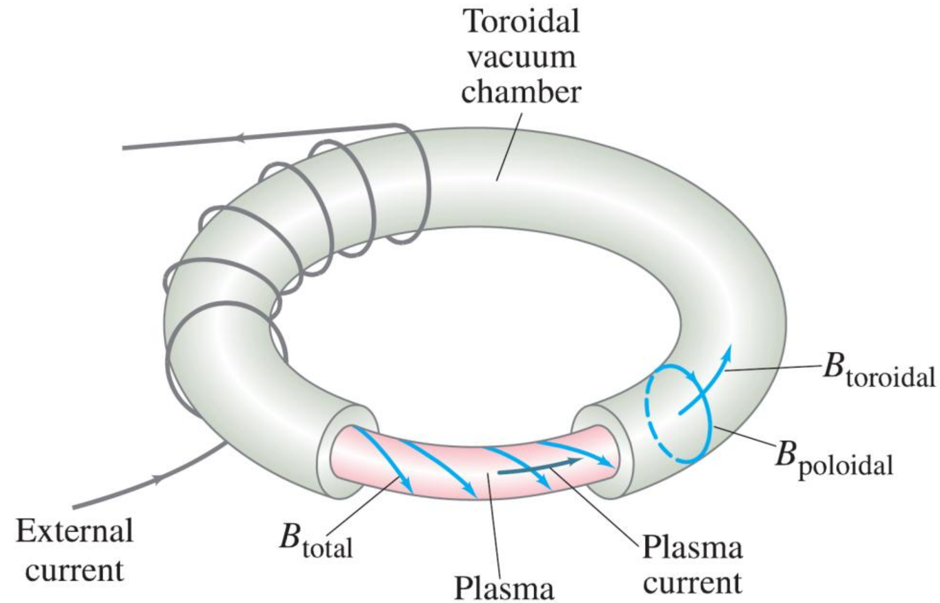
Magnetisch opsluiting met toroidaal veld (langs de as van de toroide)
Elektrische stromen in het plasma produceren poloidaal magneetveld
Superpositie levert een helisch veld en dat sluit het plasma op

Lawson criterium voor ontsteking van het plasma
Typisch τ = *1 – 3* seconde

$$n\tau \gtrsim 3 \times 10^{20}\ \mathrm{s/m^3}$$

Break-even wordt al een factor 10 lager bereikt (TFTR in Princeton, 1990)

ITER is het fusieproject van de toekomst (2016)



Gyro motion

Lorentz force leads to a gyration of the particles around the magnetic field

$$x - x_0 = \rho sin \omega_c t$$

$$y - y_0 = \rho cos \omega_c t$$

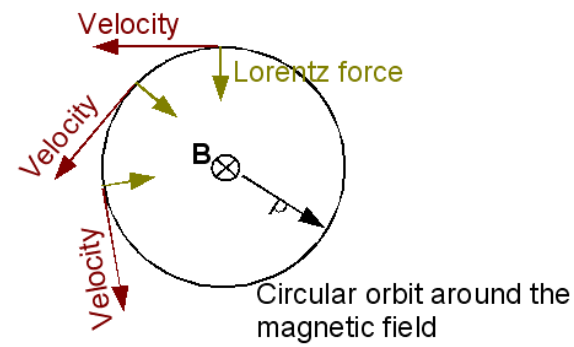
$$\rho = \frac{m v_\perp}{|q| B} \qquad \omega_c = \frac{|q| B}{m}$$

We will write the motion as

$$\mathbf{v} = v_{||} \mathbf{b} + \mathbf{v}_g$$

Parallel and rapid gyro-motion

$$m \frac{d\mathbf{v}}{dt} = q\mathbf{v} \times \mathbf{B}$$



For 10 keV and B = 5T:

- Larmor radius of deuterons ~4 mm
- electrons ~0.07 mm
- alpha particles (3.5 MeV) ~5.4 cm

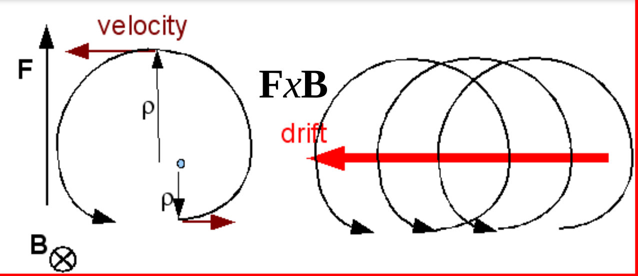
Cyclotron frequency:

- 80 MHz for hydrogen
- 130 GHz for electrons

Finite additional force *F (=qE)* leads to drift

Physics picture behind the drift velocity

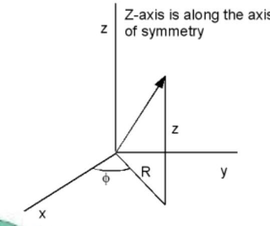
$$\rho = \frac{m v_\perp}{|q| B}$$



$$\mathbf{v} = v_{||}\mathbf{b} + \mathbf{v}_g + \frac{\mathbf{E} \times \mathbf{B}}{B^2} + \frac{m}{qB^2} \frac{\mathrm{d}\mathbf{E}_\perp}{\mathrm{d}t} + \frac{m v_{||}^2 + m v_\perp^2/2}{qB} \frac{\mathbf{B} \times \nabla B}{B^2}$$

Parallel motion Gyration ExB drift Polarization drift Grad-B and curvature drift

Tokamak



Bend the theta pinch into a donut shape

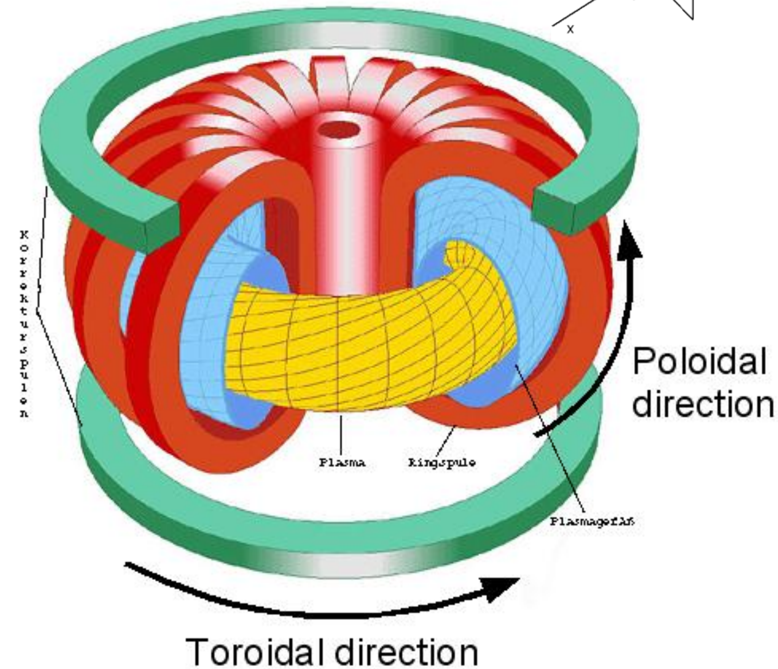
No end losses because the field lines go around and close on themselves

The magnetic field follows form

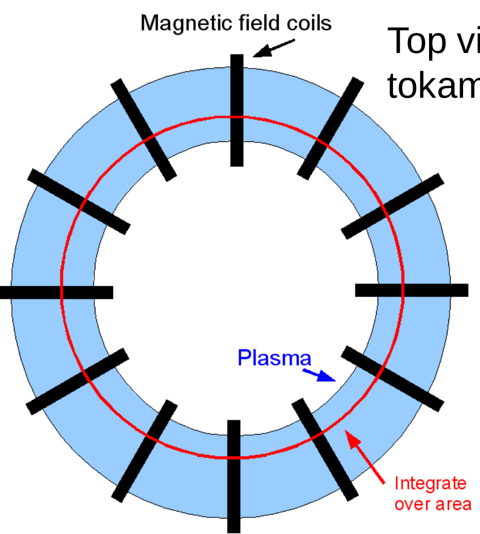
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$$

$$2\pi R B_\phi = \mu_0 I$$

And therefore varies with major radius *R* as $B_\phi = \frac{C}{R}$



Schematic picture of the tokamak



Top view of tokamak

Toroidal curvature has its price

The toroidal magnetic field has a gradient

$$B_\phi = \frac{C}{R} \longrightarrow \nabla B = \nabla\left(\frac{C}{R}\right) = -\frac{C}{R^2}\mathbf{e}_R = -\frac{B}{R}\mathbf{e}_R$$

Which leads to a drift in the vertical direction

$$\frac{\mathbf{B}\times\nabla B}{B^2} = \frac{1}{R}\mathbf{e}_z \qquad \mathbf{v}_d = \frac{mv_\parallel^2 + mv_\perp^2/2}{qBR}\mathbf{e}_z$$

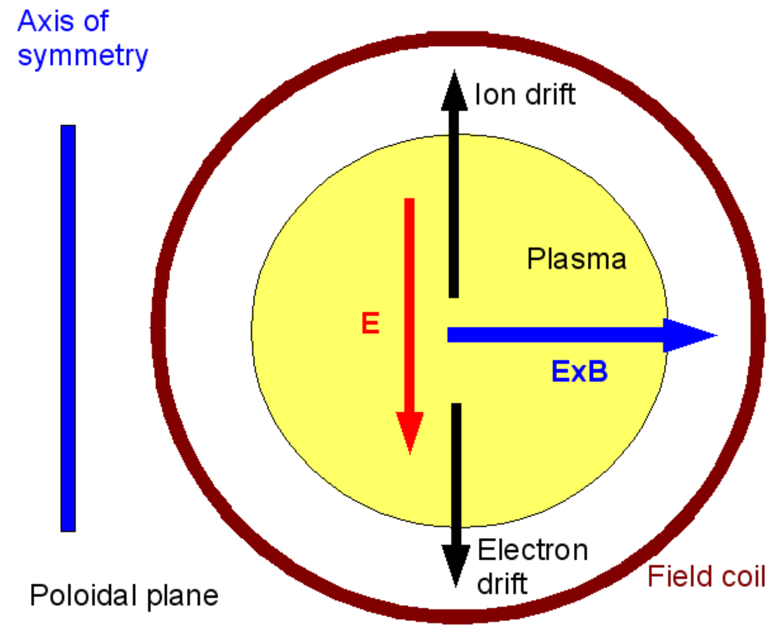
Note that the sign of the drift depends on the sign of the charge q

The drift $\mathbf{v}_d = \frac{mv_\parallel^2 + mv_\perp^2/2}{qBR}\mathbf{e}_z$

leads to charge separation

Build up of an electric field

and then to an ExB velocity



Poloidal cut of the tokamak.

The ExB velocity

$$\mathbf{v}_E = \frac{\mathbf{E}\times\mathbf{B}}{B^2} = -\frac{E_z}{B}\mathbf{e}_R$$

Is directed outward and will move the plasma on the wall in a short timescale

This effect is no surprise since $F = -\mu\nabla B$ ← $B_\phi = \frac{C}{R}$

Remedy: a toroidal plasma current will generate a poloidal field

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The toroidal electric field

Plasma is the second winding of a transformer

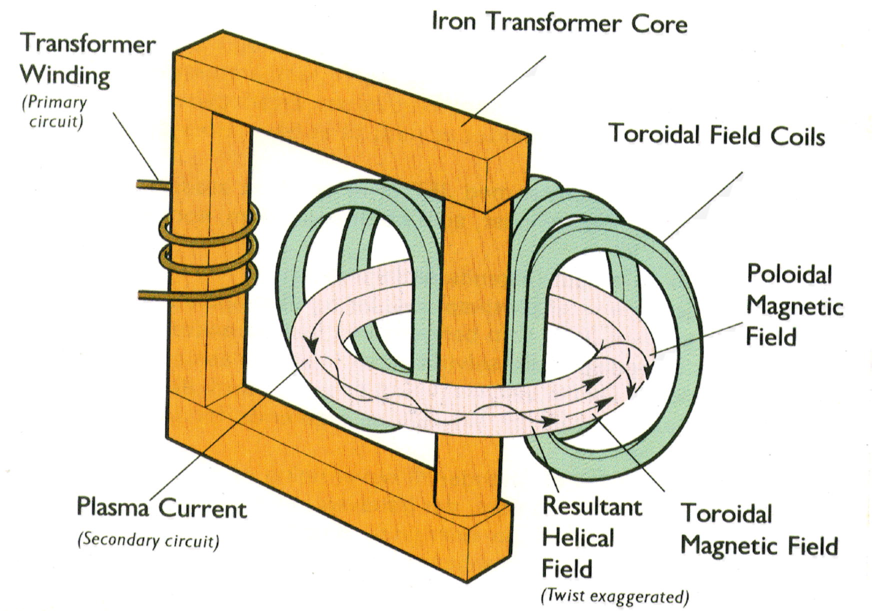
Flux in the iron core cannot be increased forever.
The tokamak is necessarily a pulsed machine

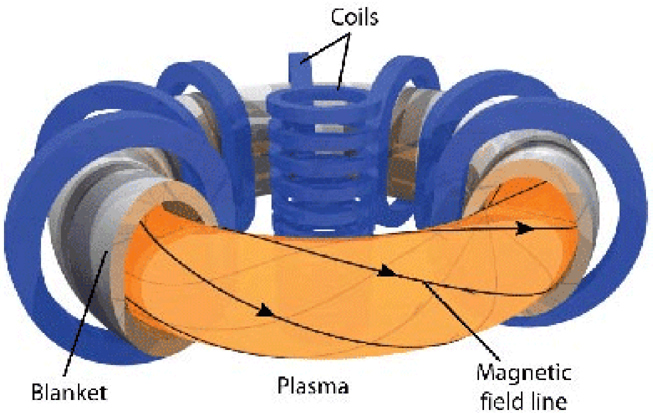
That is not good for energy production

Also thermal stresses are associated with the pulsed character

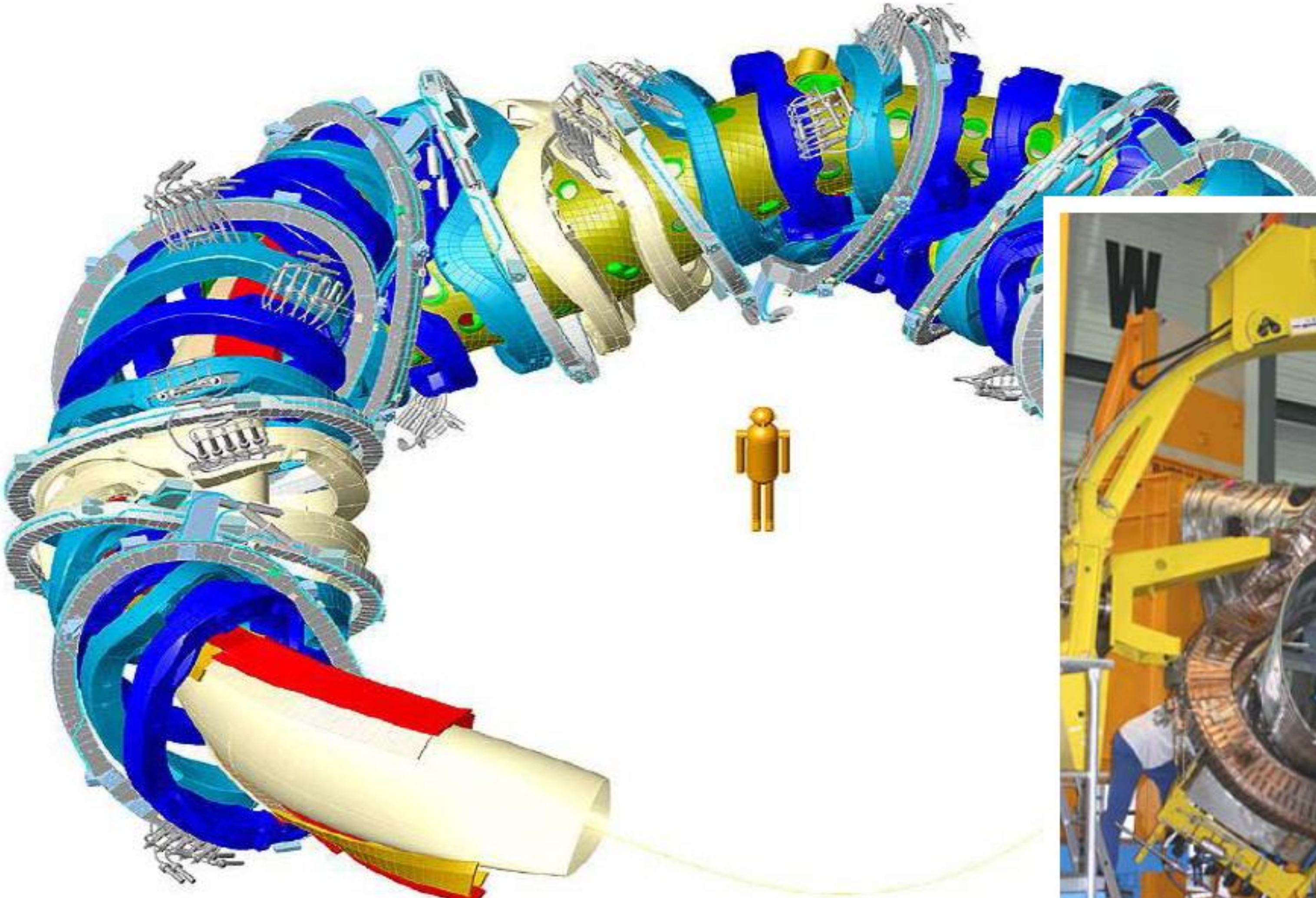
One can either: live with it / drive current another way / use a different concept

Because of the plasma current the field lines wind around helically

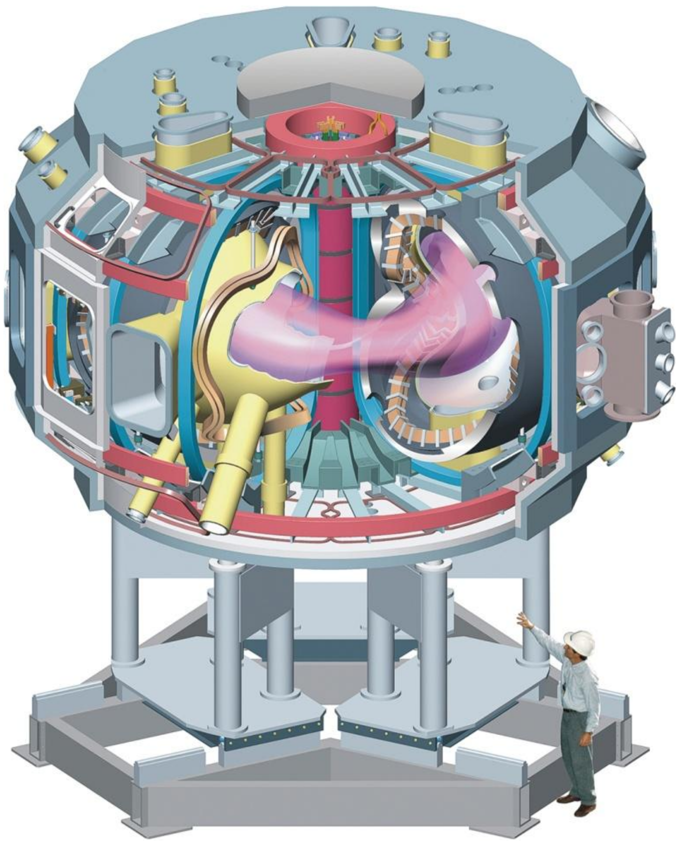




Tokamak niet enige oplossing: W7X

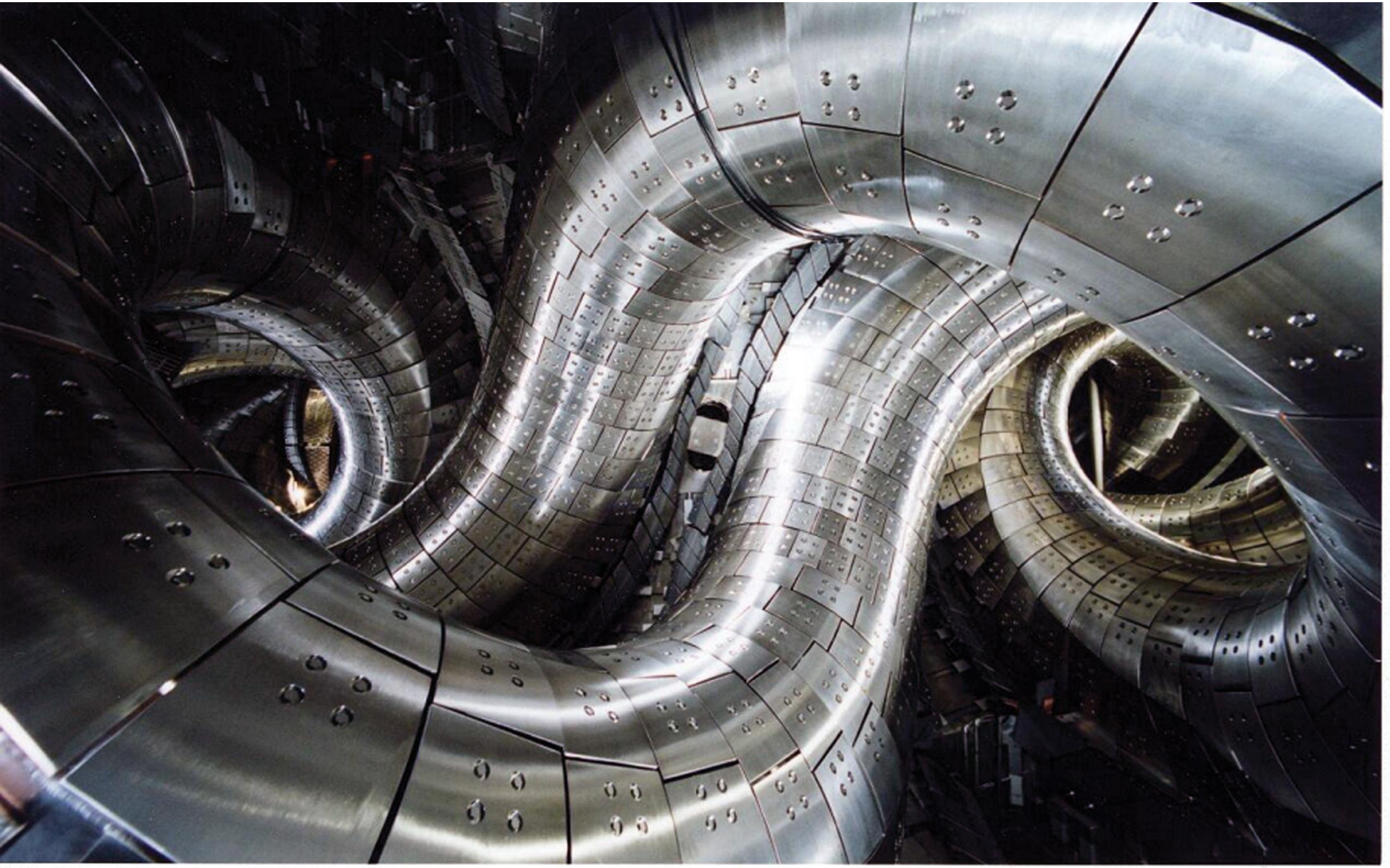


Compact stellarator NCSX princeton



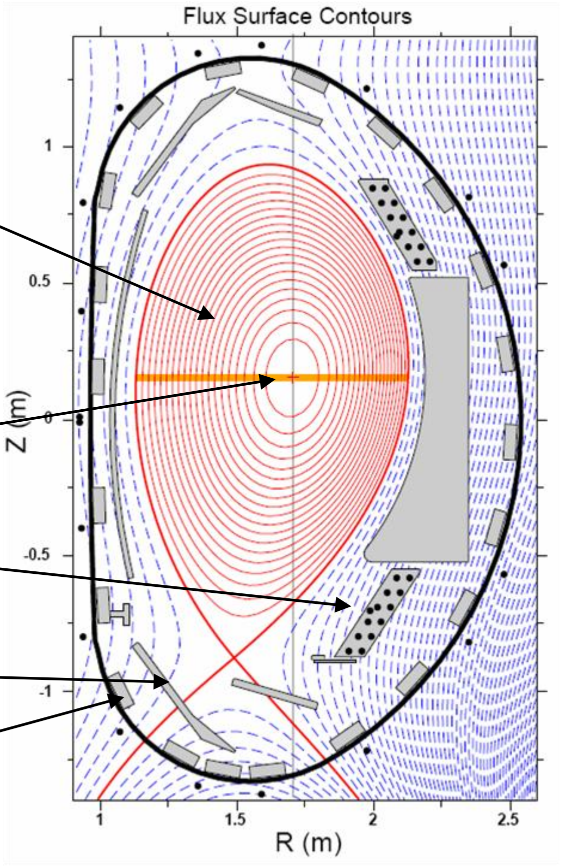
Compact stellarators are a challenge. The plasma current in this device is not driven by a transformer.

Stellarator – LHD in JAPAN



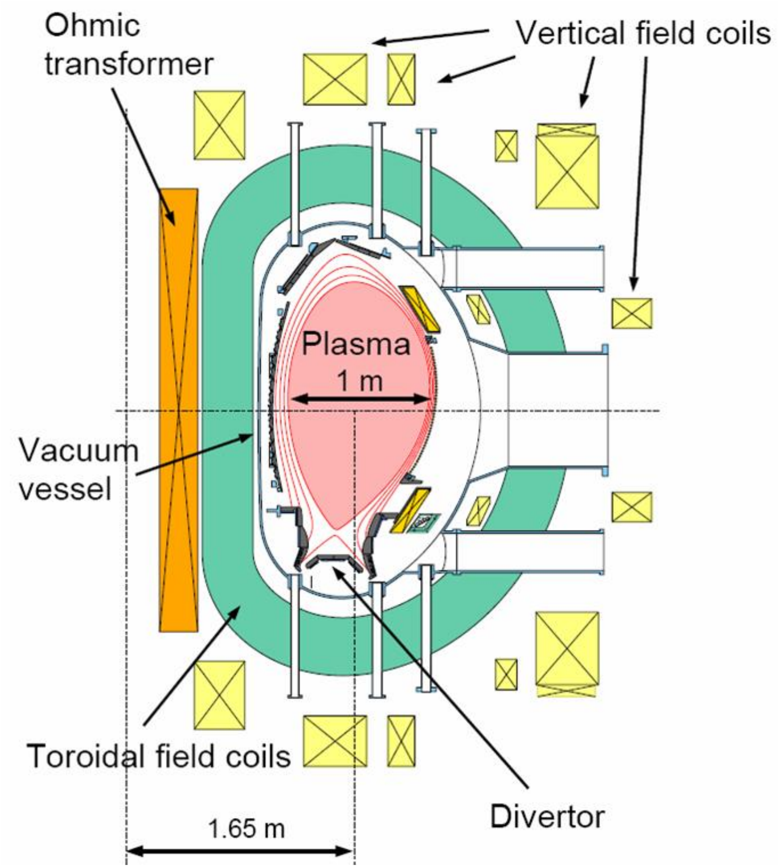
A tokamak

- Magnetic surfaces are the surfaces traced out by the magnetic field
- They are nested (best confinement)
- Centre is shifted outward
- Large passive coils
- Magnetic field ends on a set of plates
- Large set of small coils for diagnostic purposes



Plasma manipulation

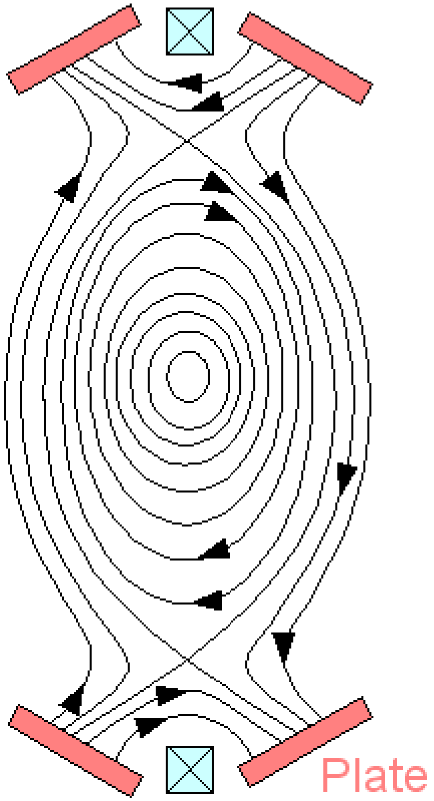
- Several coils around the plasma
- The vertical coils can shape the plasma and control its position
- Dominant shaping is the vertical elongation of the plasma



Schematic Drawing of the poloidal cross section of the ASDEX Upgrade tokamak

Plasma elongation

- Plasma can be diverted onto a set of plates
- Close to the coils the field of the coils dominates
- In between the field is zero resulting in a purely toroidal field line
- This shows up as an X-point in the figure of the magnetic surfaces
- Surfaces outside the one with the X-point are not close with the field ending on the plates



Preventing impurities – divertor

Given a fixed electron density, impurities dilute the fuel

$$n_e = n_D + n_T + Z n_I$$

Density of the impurity with charge *Z*

Acceleration of electrons by the ions in the plasma lead to radiation losses known as ‘Bremstrahlung’

The radiation scales with the average charge. High Z impurities enhance the radiation
High Z-impurities also lead to energy los

Plasma facing components have to be chosen carefully

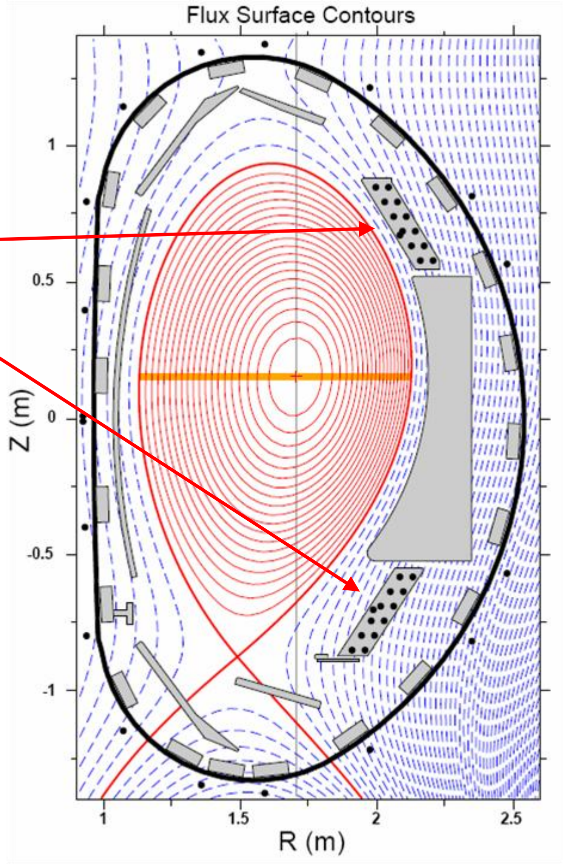
Carbon / Beryllium have a low Z

Carbon does not melt but has the proble
that it binds well with Tritium (contamina
of the machine)

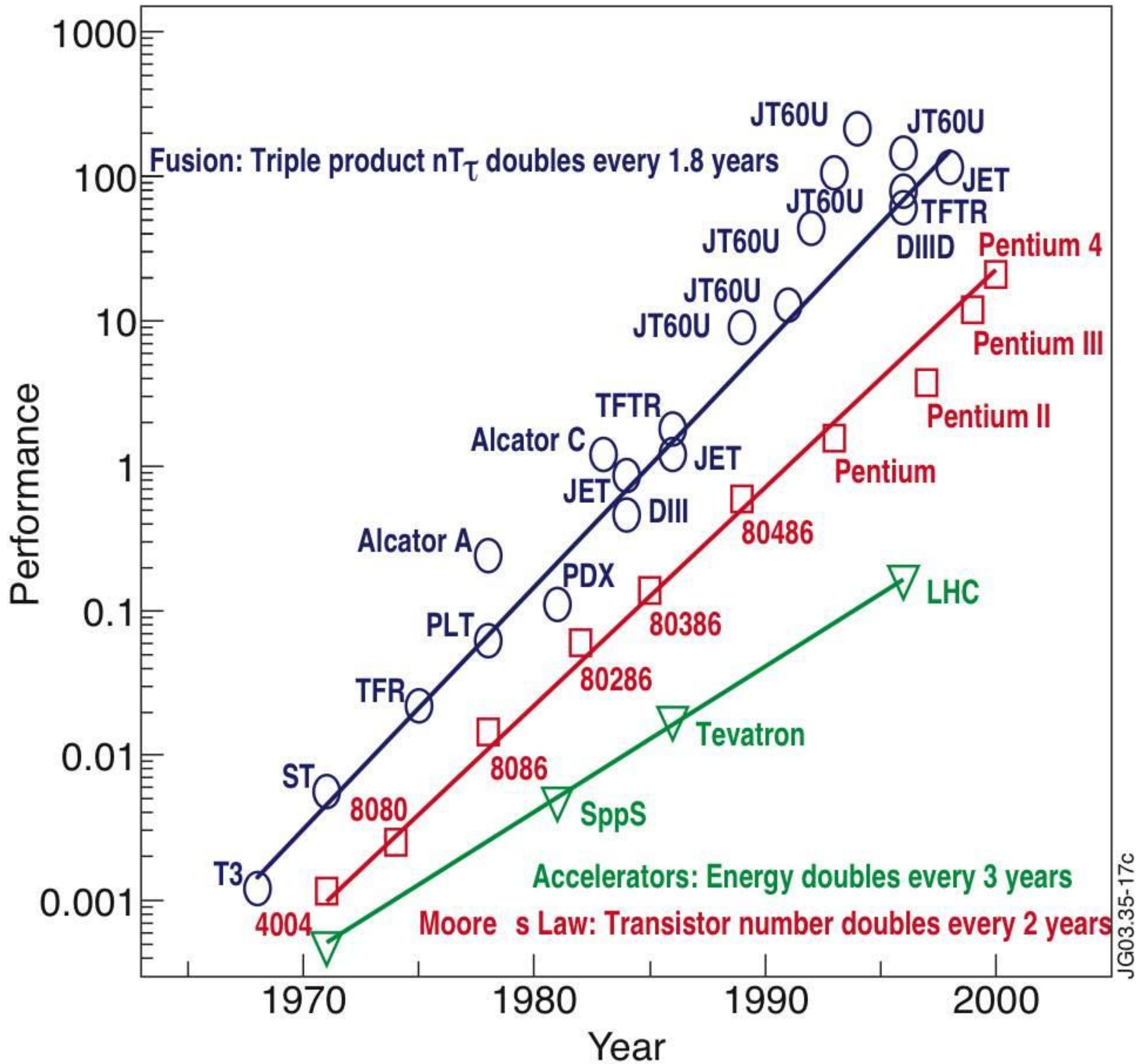
Tungsten has very high Z, but takes the
heat loads very well

Plasma instabilities

- Plasma vertical instability with growth rates of the order 10^6 s^{-1}
- For this reason the passive coils have been placed in the plasma
- When the plasma moves it changes the flux through the coils which generates a current that pushes the plasma back
- Growth rate is reduced to the decay time of the current in the coils (ms)



Voortgang in fusie onderzoek



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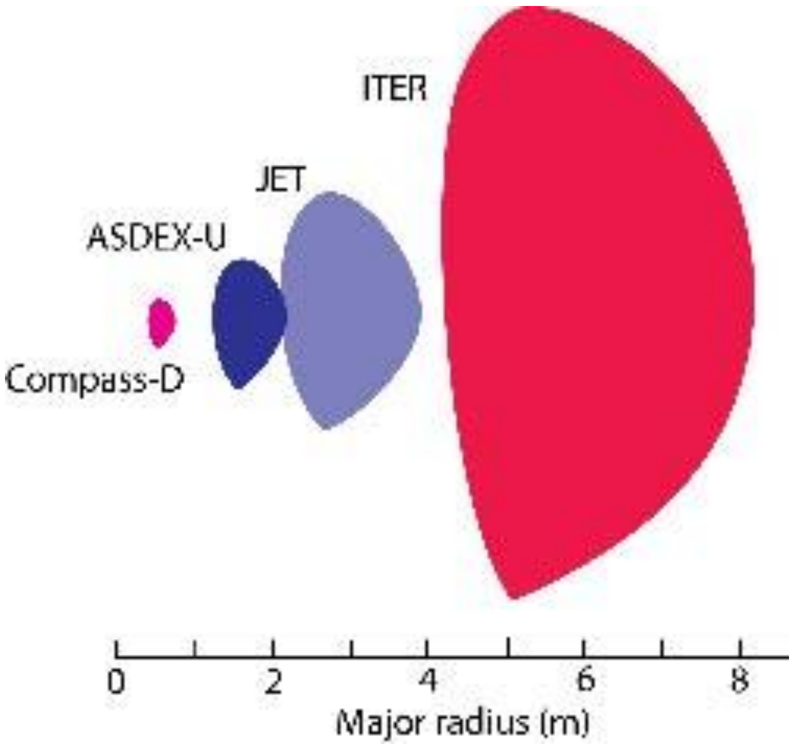
ITER

Wat is ITER?

- ITER = (International Tokamak Experimental Reactor) is de volgende stap in tokamak research.
- Grootste tokamak in de wereld
- Project is gestart in Cadarache, France
- Samenwerking tussen Europa, China, Japan, Korea, Rusland (en de US).



Doorsnede van het plasmavolume

Meer over ITER

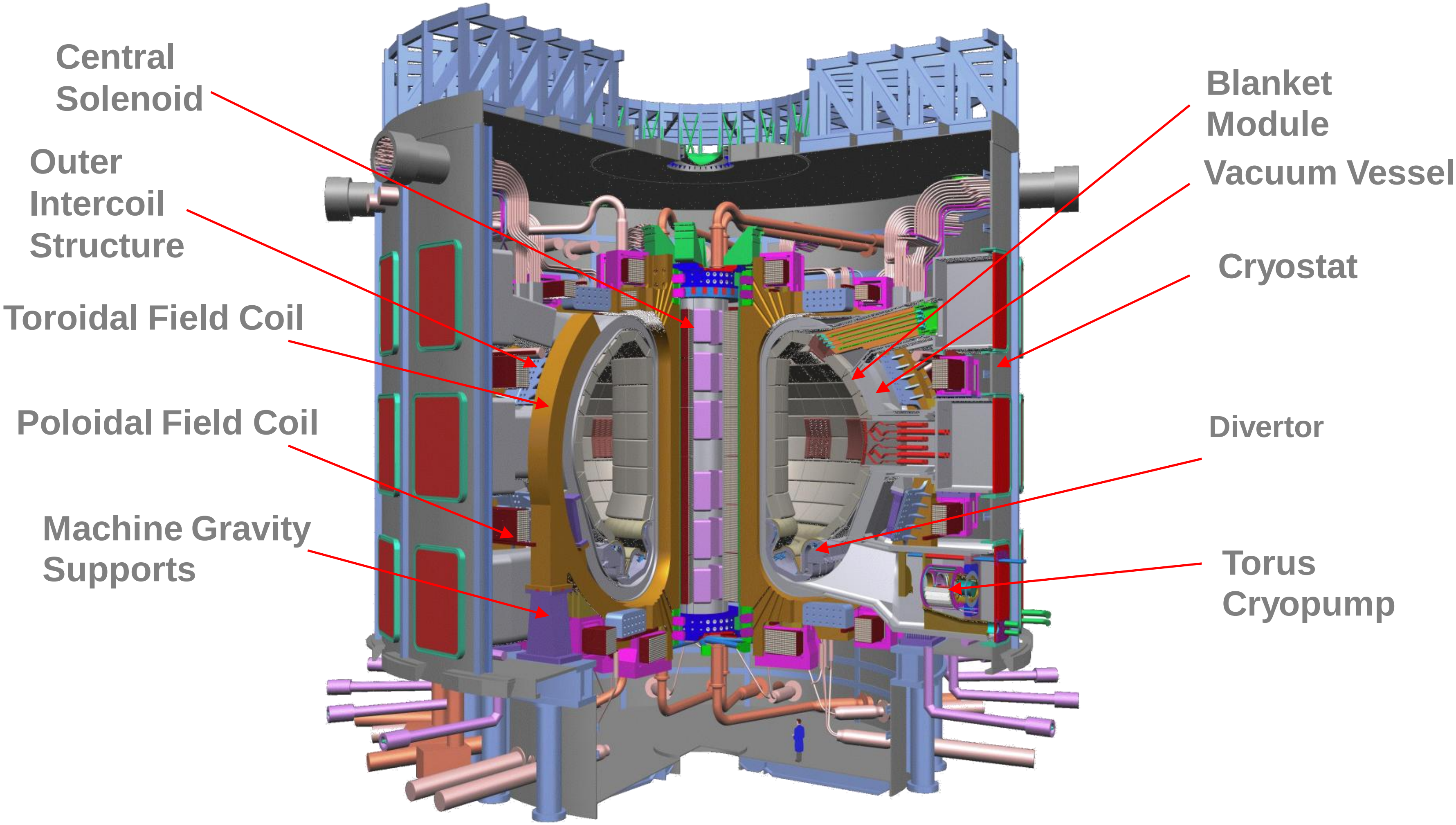
Belangrijkste missie

- Demonstreer dat het mogelijk is een fusiereactor te bedrijven. Dit omvat het genereren van een plasma dat door fusie reacties verwarmd wordt, maar ook dat aan de technische eisen voldaan kan worden.

Project

- Kosten 5 miljard Euro constructie + 5 miljard Euro voor bedrijf (het duurste experiment op Aarde)
- Constructie van het gebouw is begonnen in 2008 / Assemblade begint in 2012
- Assemblage gaat ongeveer 7 jaar duren
- 20 jaar bedrijf is geplanned

Ontwerp – belangrijkste eigenschappen



ITER parameters

• Total fusion power	500 MW
• Q = fusion power/auxiliary heating power (inductive)	≥10
• Average neutron wall loading	0.57 MW/m^2
• Plasma inductive burn time	≥ 300 s
• Plasma major radius	6.2 m
• Plasma minor radius	2.0 m
• Plasma current	15 MA
• Vertical elongation @95% flux surface/separatrix	1.70/1.85
• Triangularity @95% flux surface/separatrix	0.33/0.49
• Safety factor @95% flux surface	3.0
• Toroidal field @ 6.2 m radius	5.3 T
• Plasma volume	837 m^3
• Plasma surface	678 m^2
• Installed auxiliary heating/current drive power	73 MW (100 MW)

Availability of the fuel

- The natural abundance of Deuterium is one in 6700. There is enough water in the ocean to provide energy for 3×10^{11} years at the current rate of energy consumption (larger than the age of the universe)
- Deuterium is also very cheaply obtainable. Calculating the price of electricity solely on the basis of the cost of Deuterium, would lead to a drop of 10^3 in your electricity bill
- Tritium is unstable with a half age of 12.3 years. There is virtually no natural available resource of Tritium

- Tritium however can be bred from Lithium

$$^6_3\mathrm{Li} + ^1_0n \rightarrow ^4_2\mathrm{He} + ^3_1\mathrm{T} + 4.8\ \mathrm{MeV}$$

$$^7_3\mathrm{Li} + ^1_0n \rightarrow ^4_2\mathrm{He} + ^3_1\mathrm{T} + ^1_0n - 2.5\ \mathrm{MeV}$$

- Note that the neutron released in the fusion reaction can be used for this purpose
- The availability of Lithium on land is sufficient for at least 1000 if not 30000 years, and the cost per kWh would be even smaller than that of Deuterium.
- If the oceans are included it is estimated that there is enough fuel for 3×10^7 years.

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NIKHEF

Theta pinch

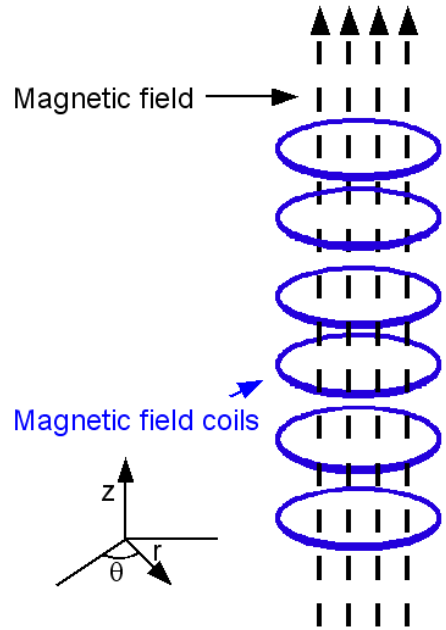
Straight magnetic field no tension

$$\nabla\left(p+\frac{B^2}{2\mu_0}\right)-\frac{\mathbf{B}\cdot\nabla\mathbf{B}}{\mu_0}=0$$

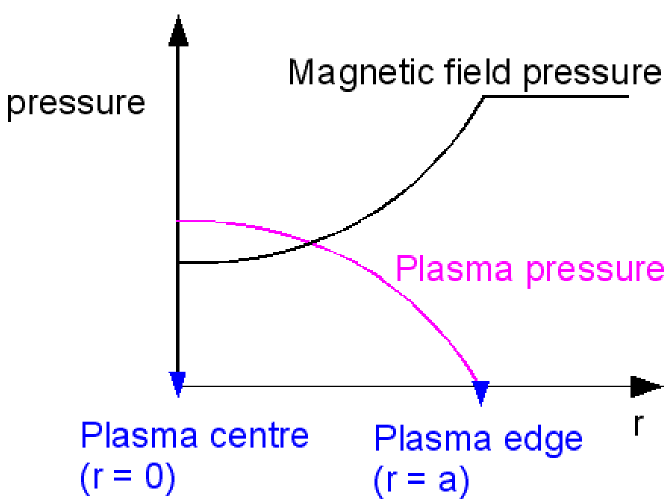
Equation gives constant total pressure

$$B_z\frac{\partial B_z}{\partial z}=0$$

Magnetic field is reduced inside the plasma
i.e. the plasma is diamagnetic



Plasma escapes at the ends; go toroidal …

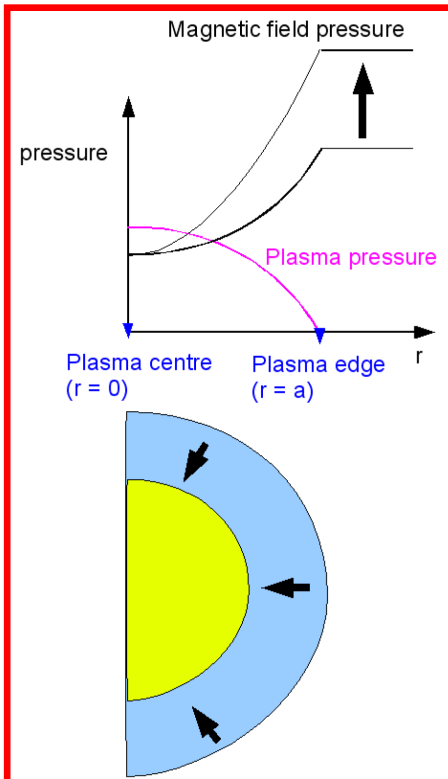


Ramp up the magnetic field by ramping the current in the coils

The magnetic field pressure will increase and is no longer balanced by the plasma pressure

The plasma is compressed

Compression leads to work against the pressure gradient force which will heat the plasma



Z-pinch

A strong current is generated in the z-direction

This current generates a magnetic field in the θ direction

JxB force is then fully determined

Pressure gradient must balance the JxB force and is then also fully determined by the current

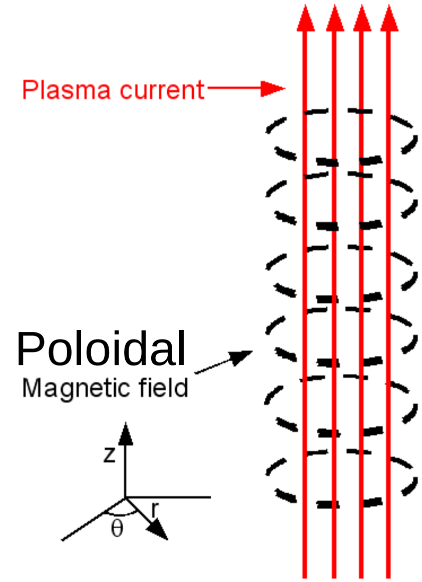
Current is the source of the magnetic field

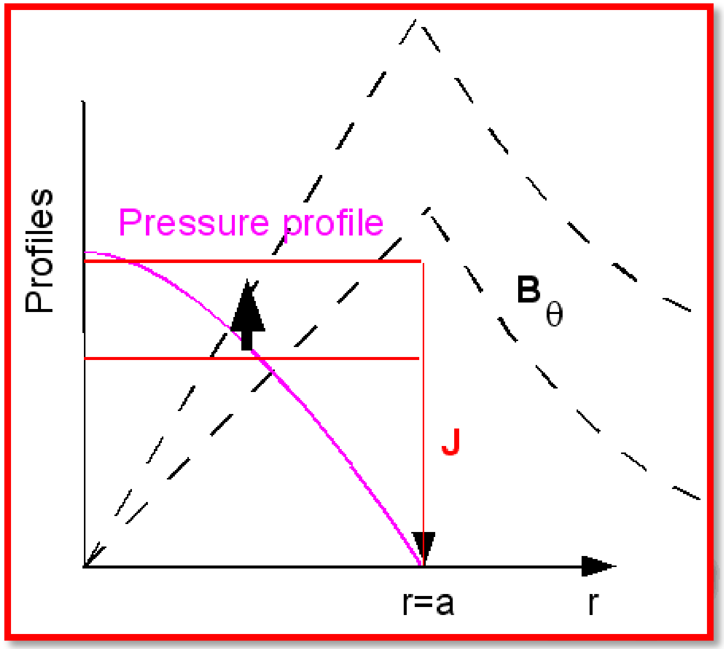
$$\oint \vec{B}\cdot d\vec{l} = \mu_0 I_{enc} \Rightarrow 2\pi r B_\theta = \mu_0 \pi r^2 J$$

Magnetic pressure $p_B \approx \frac{F_B}{A} = \frac{IBL}{2\pi RL} = \mu_0 I^2 L / \{(2\pi R)^2 L\} = B^2 / \mu_0$

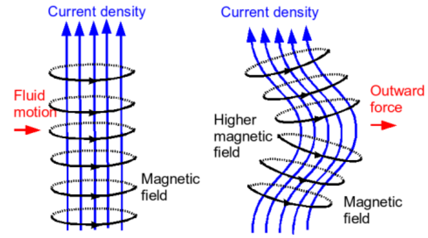
Ramping of the current will increase the magnetic field which will compress the plasma

Besides the heating due to compression, the current will also dissipate heat when the plasma resistivity is finite

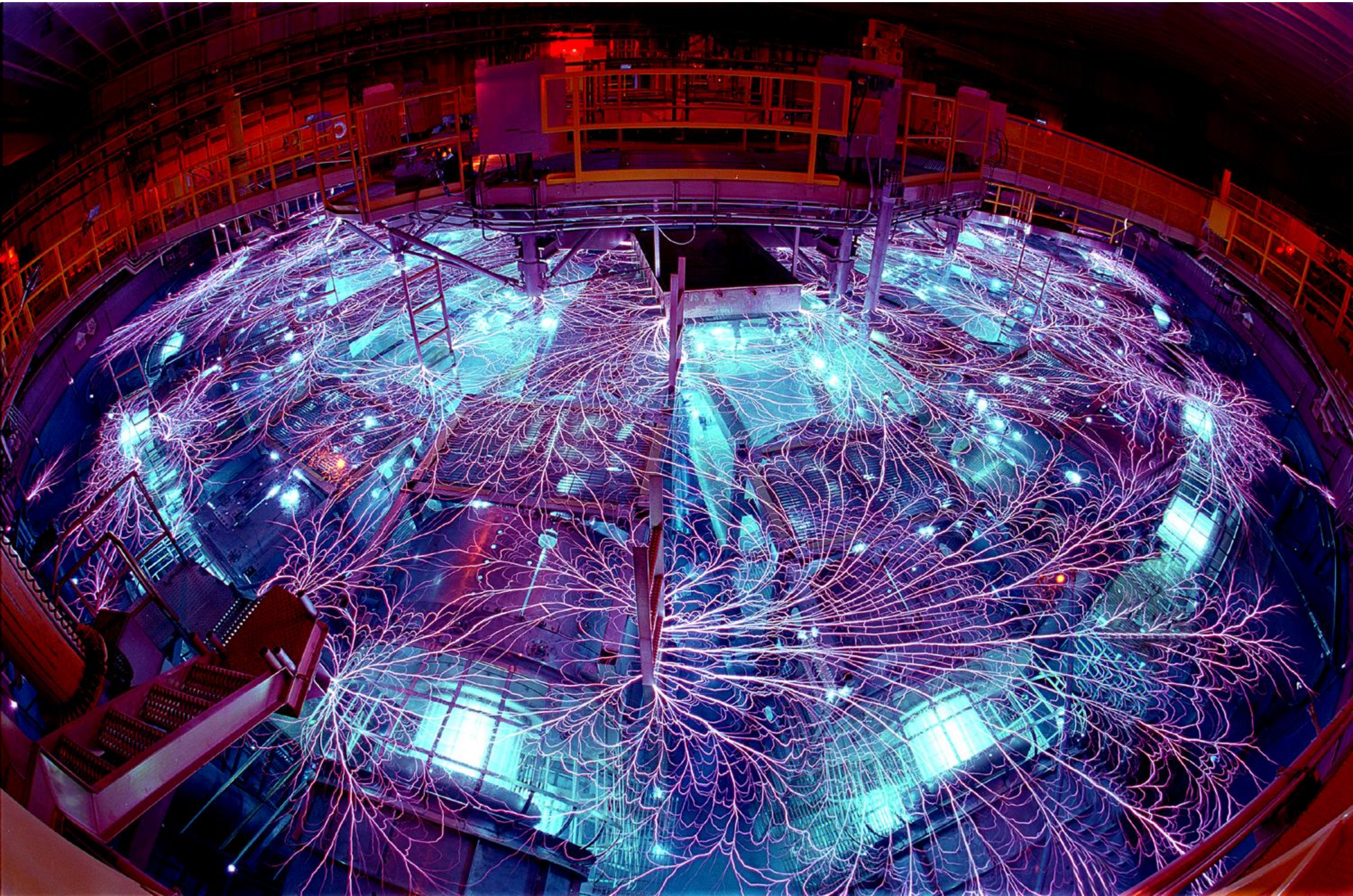




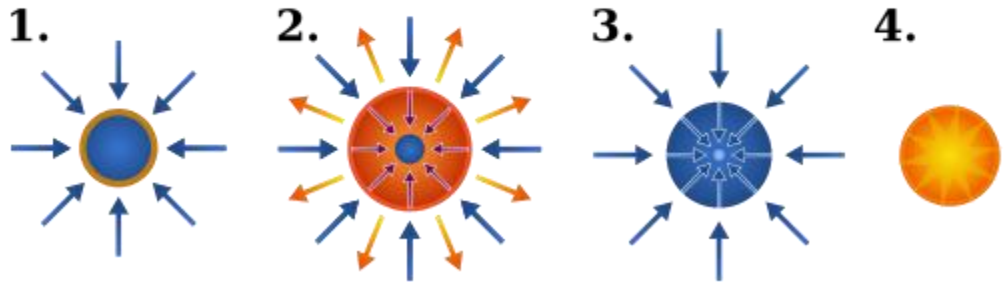
The Z-pinch is unstable. Most relevant instability is the kink



Sandia labs – Z pinch: 290 TW X-rays

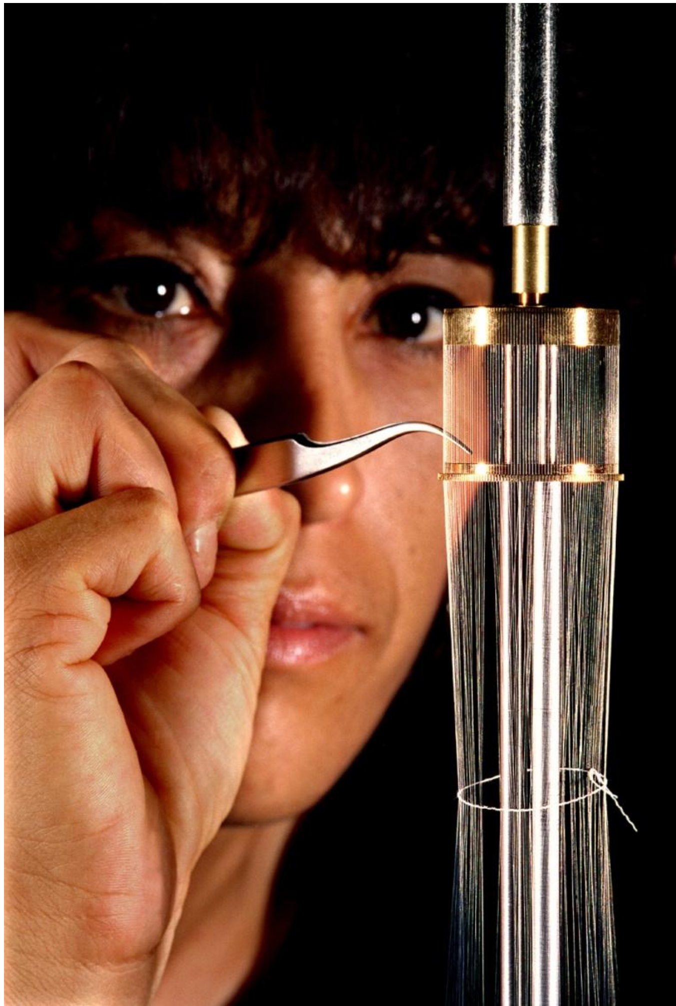


Sandia labs – Z pinch IFE

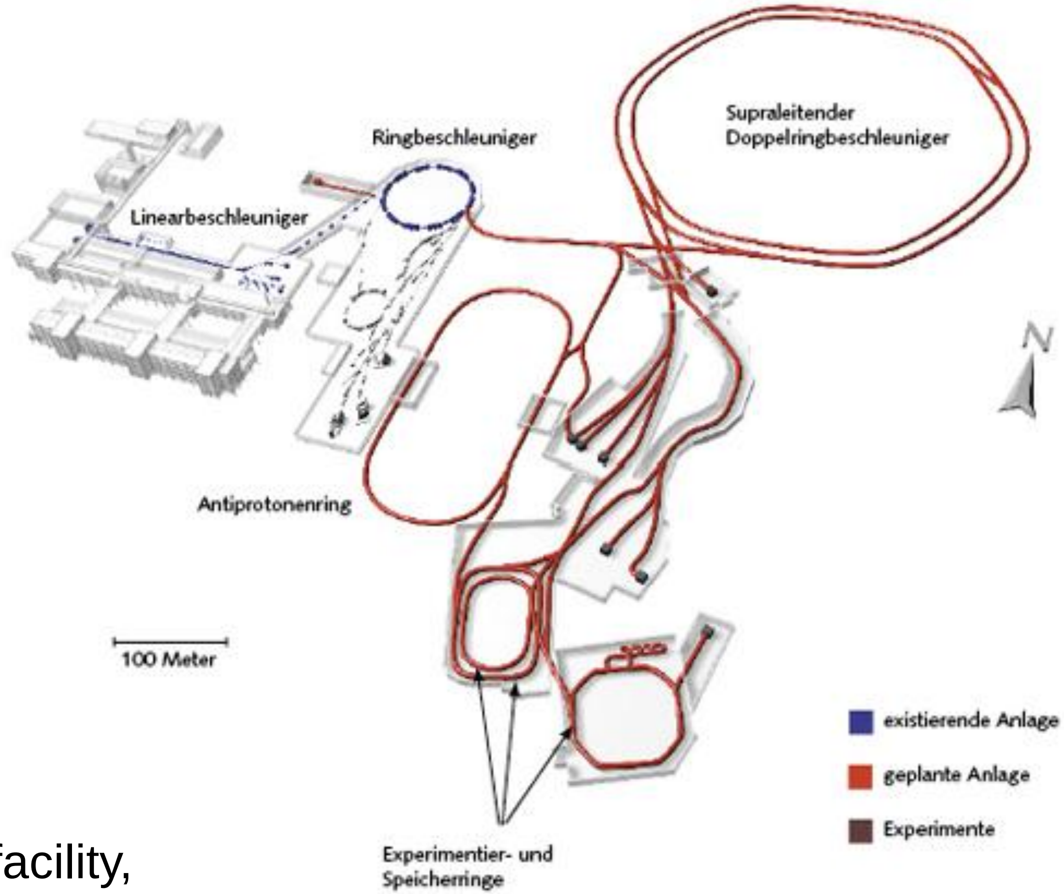


Laser of X-ray straling
Materiaal verdampt
Back-reaction comprimeert sample
Kernfusie treedt op

Sandia Z pinch
- 27 miljoen ampere
- 95 nanoseconde
- 350 Terawatt (80x wereld)
- 2.7 MJ X-ray energie
- 3.7 GK temperatuur bereikt
- deuterium fusie gerealiseerd in 2006
- metalen platen versneld tot 34 km/s
- ZN (Z neutron fusie machine: p – 7Li)



Possible drivers: ion beams



FAIR facility, Darmstadt, Germany

10 to 20 rings needed for fusion power plant!

Advantages:

- Excellent conversion from electric power to beam energy
- Large targets

Disadvantages:

- Concept was never tested
- Beam intensity is still too low

Possible drivers: lasers (best shot)

National Ignition Facility (NIF), Livermore, USA

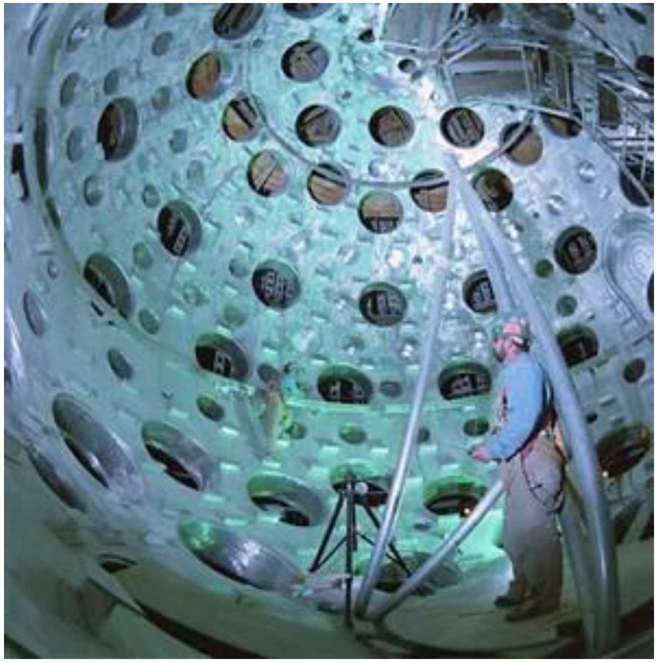
Advantages:

- Well advanced technology
- Good control of energy release

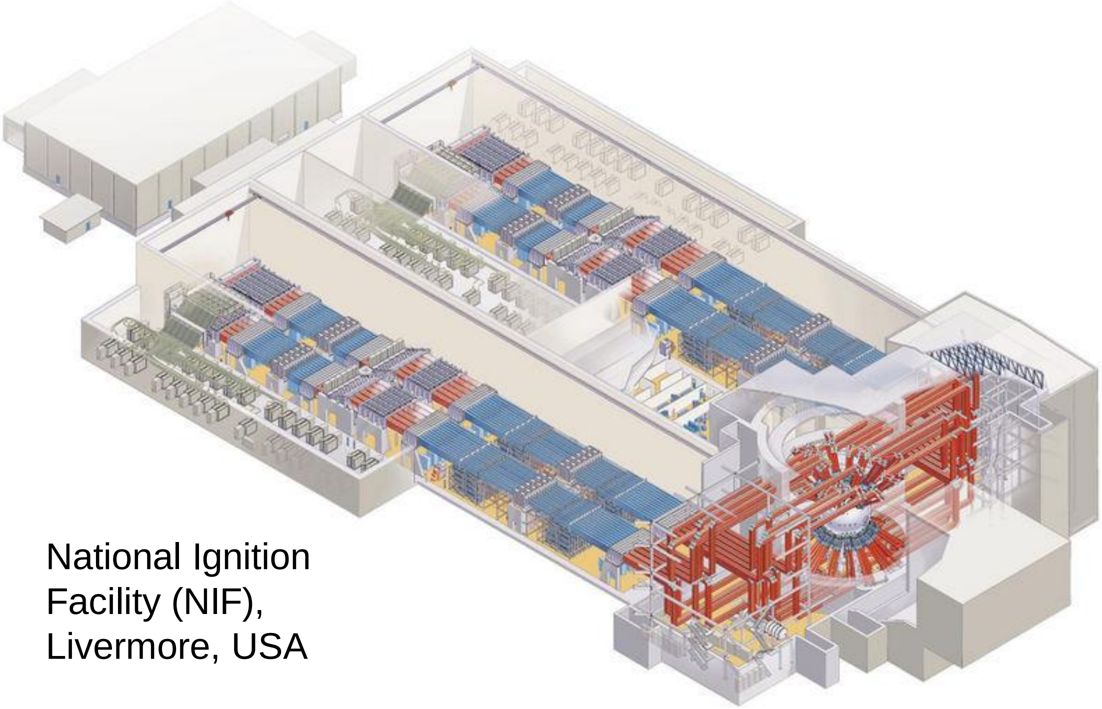
Disadvantages:

- Bad energy conversion
- Very expensive to build

Possible drivers: lasers



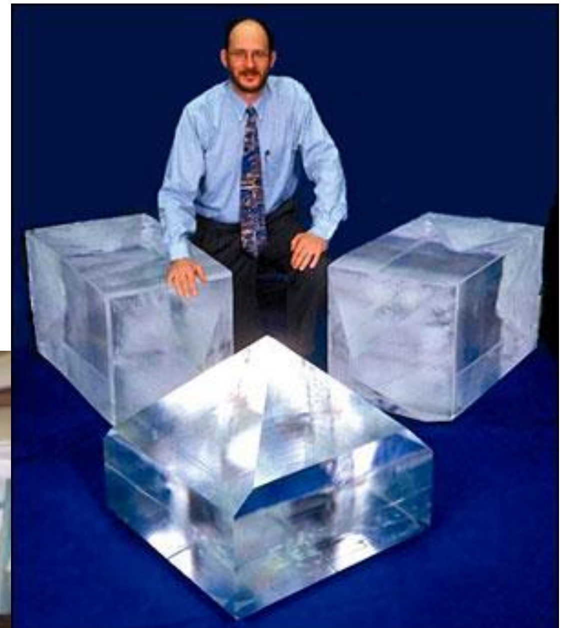
Target chamber, NIF with 192 laser beams



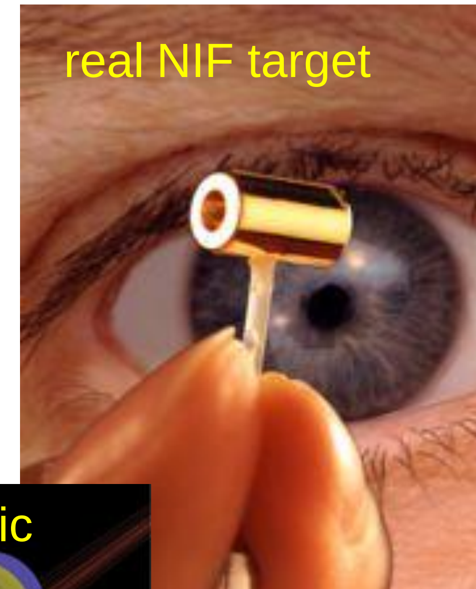
National Ignition Facility (NIF), Livermore, USA

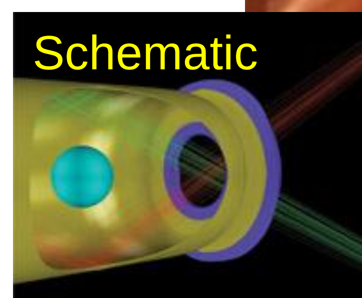
Possible drivers: lasers

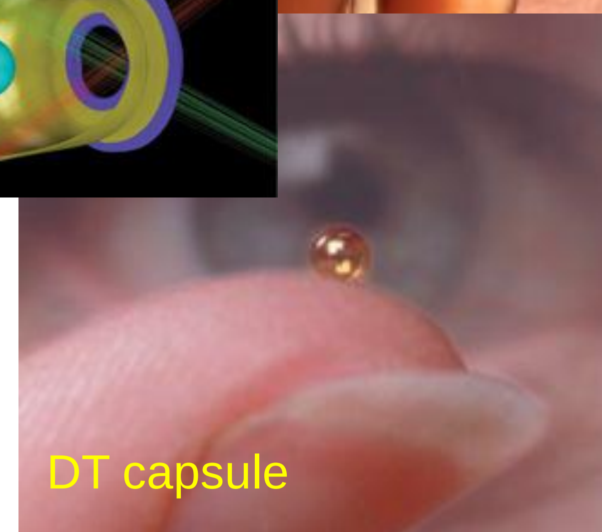
~1000 large Optics:



192 beam lines:







Engineering challenges at NIF

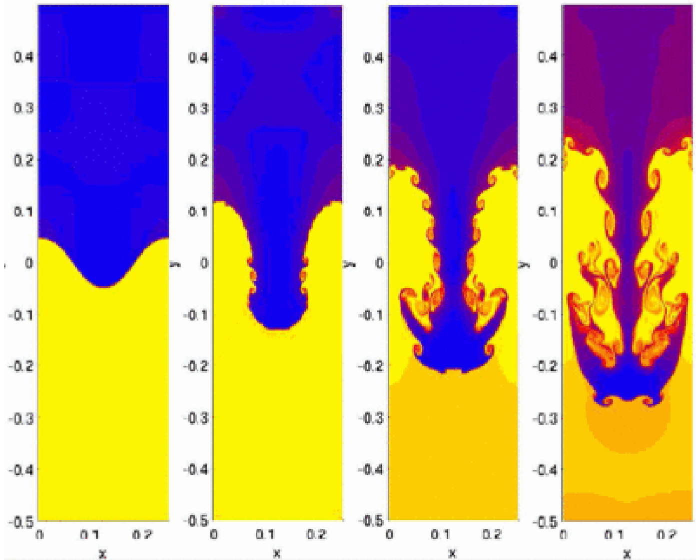
Problems blocking fusion energy

Technical and engineering problems

- High energy drivers are expensive and untested
- Energy conversion is too low (gain of >100 needed now)
- Repetition rate of drivers are too low (3-10 Hz needed)

Physics Problems

- Instabilities and Mixing
  - ► Rayleigh-Taylor unstable compression
  - ► Break of symmetry destroys confinement
- How to improve energy coupling into target
- What is the best material for the first wall?



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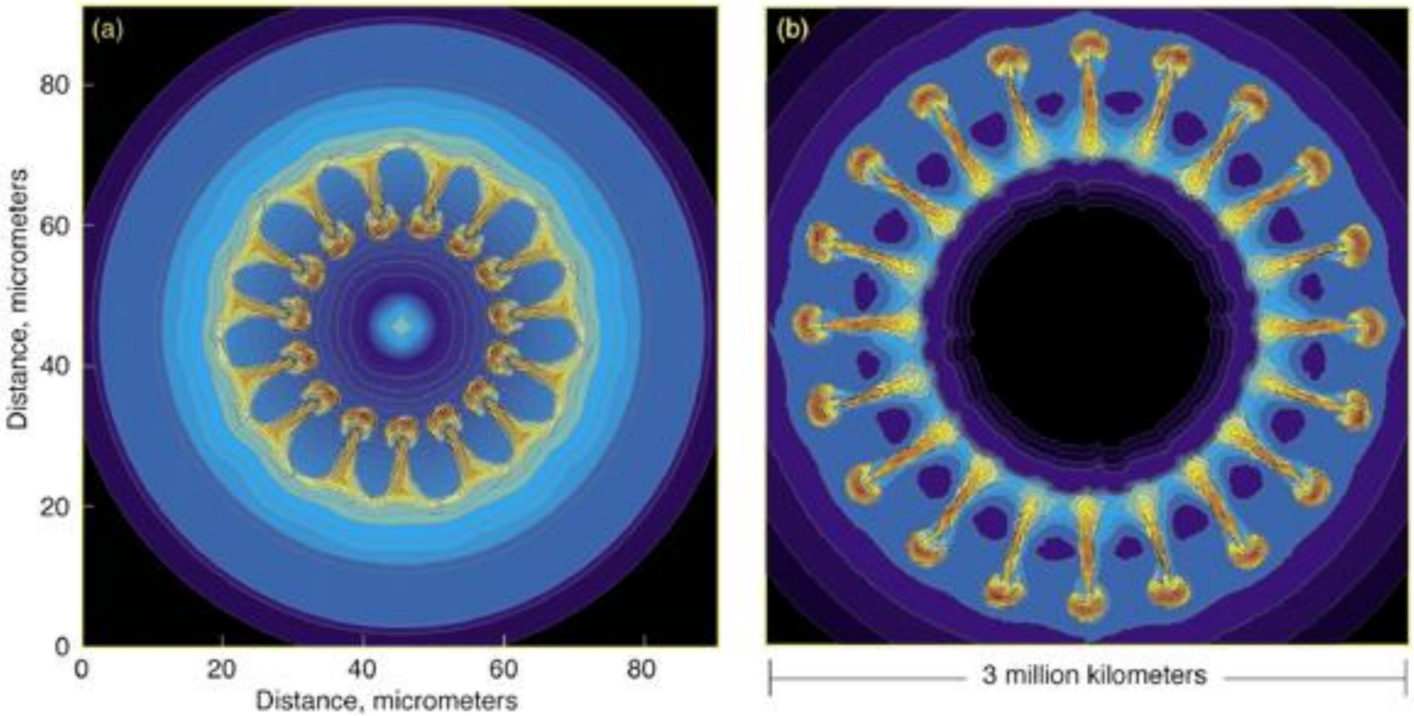
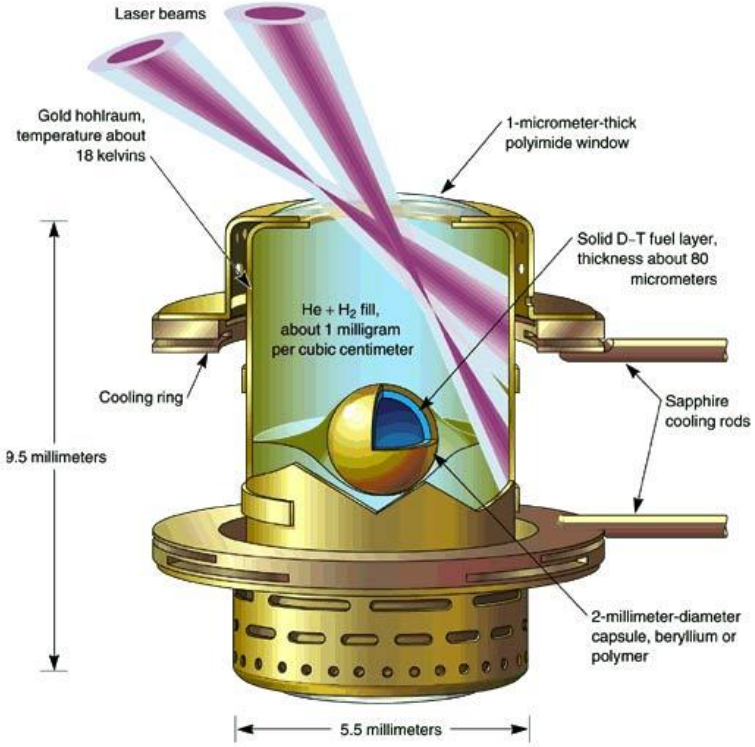
Rayleigh-Taylor Instability – spherical implosions / explosions



Striking similarities exist between hydrodynamic instabilities in (a) inertial confinement fusion capsule implosions and (b) core-collapse supernova explosions. [Image (a) is from Sakagami and Nishihara, *Physics of Fluids B* **2**, 2715 (1990); image (b) is from Hachisu et al., *Astrophysical Journal* **368**, L27 (1991).]

➢**Energy must be delivered as sysmmetric as possible!**

Relaxing the symmetry conditions – indirect drive

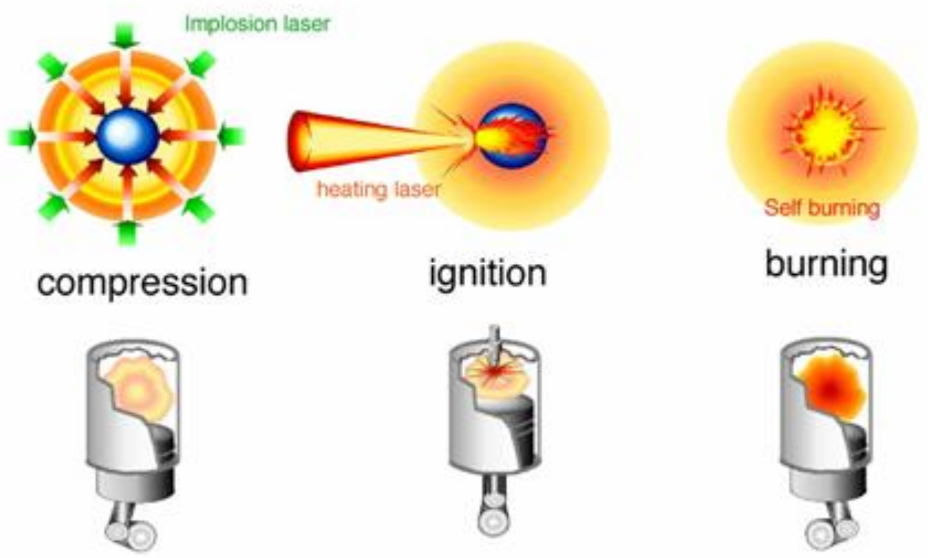


NIF design (laser)

Hohlraum for the Z-machine

- Laser beams heat walls
- Walls emit thermally (X-rays)
- X-rays compress and heat the fusion capsule
- X-rays highly symmetric!

Relaxing the symmetry conditions – fast ignition

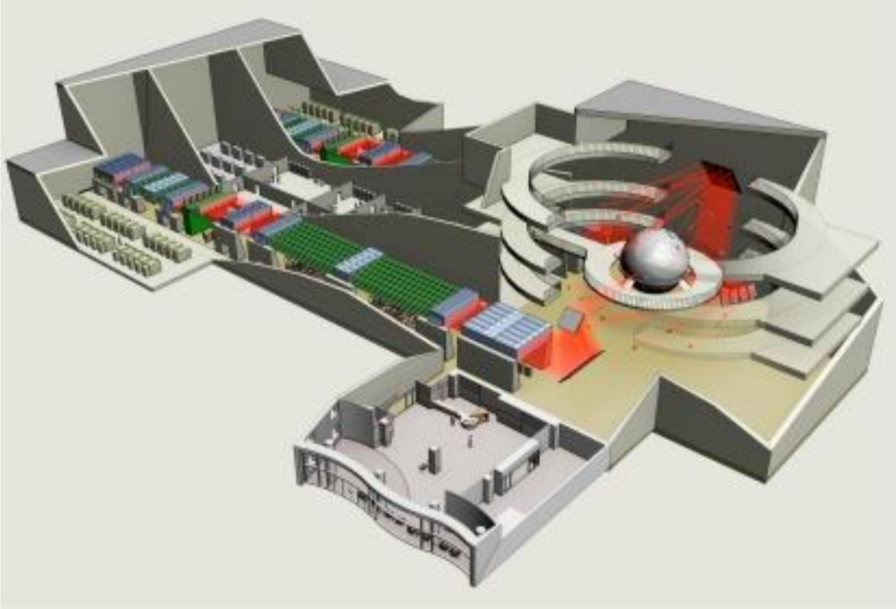


Fast ignition scheme
with many facets

- Idea: separate compression and ignition with two pulses
- ➢ Less compression, cooler targets, lower densities
- Problem: How can energy be transferred to hot spot?

Interesting experiments to come

- National Ignition Facility (NIF, Livermore, USA)
  - ► More than 90% completed, first tests done
  - ► First full scale experiments this year; ignition in 2010?
- Laser Mega-Joule (LMJ, France)
  - ► Commissioning (full scale) in 2011
- FIREX I and FIREX II (ILE, Osaka, Japan)
  - ► Fast ignition experiments showed prove-of-principle
  - ► Fully integrated experiments in 2010 / 2011
- HiPER project (Europe)
  - ► Fast ignition proposal
  - ► Full funding pending
- ITER



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Stralingsschade

Stralingsschade

Geladen deeltjes (alfa en beta stralen, protonen, ionen) ioniseren het medium waar ze doorheen gaan

Fotonen: foto-elektrisch effect, Compton effect en paarvorming

Neutronen: kernreacties

Materialen worden bros

Biologische schade: ionisatie in cellen, DNA schade

Bron activiteit in curie of becquerel (SI)

$$1\ \mathrm{Ci} = 3.70 \times 10^{10}\ \text{decays per second}$$
$$1\ \mathrm{Bq} = 1\ \mathrm{decay/s}$$

Activiteit neemt af in de tijd $\left|\frac{dN}{dt}\right| = \lambda N = \frac{0.693}{T_{\frac{1}{2}}} N$

Geabsorbeerde dosis [gray] (energie per kg materiaal)

$$1\ \mathrm{Gy} = 1\ \mathrm{J/kg} = 100\ \mathrm{rad}$$

Relative biological effectiveness (RBE), ook wel QF

Effectieve dosis in rem of sievert (SI)

$$\text{effective dose (Sv)} = \text{dose (Gy)} \times \text{QF}$$

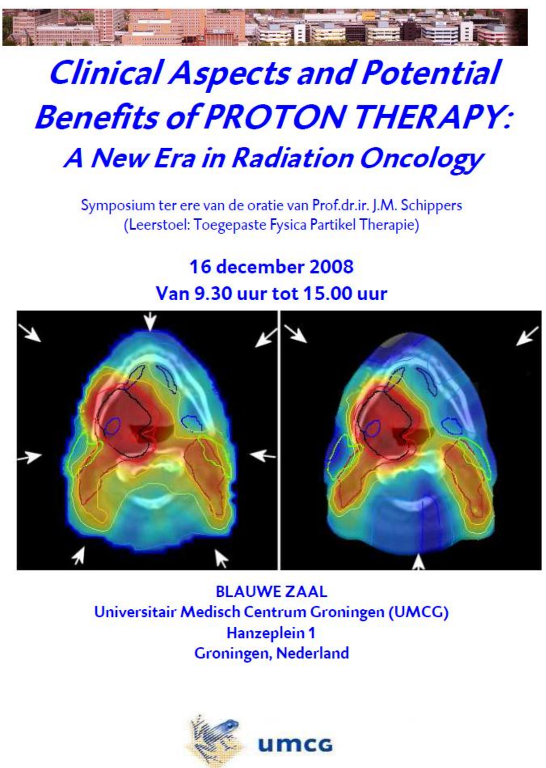
Natuurlijke achtergrond ongeveer 3 mSv
X-rays, scans ongeveer 0.6 mSv (limiet 1.0 mSv)
Fatale dosis: 4 Sv in korte tijd (50% fataal)

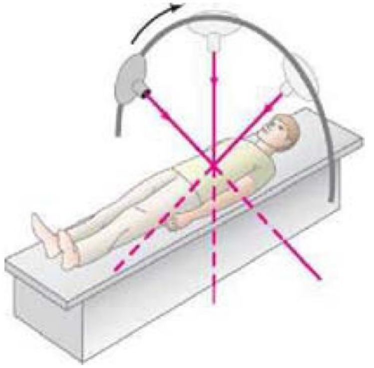
TABLE 42–1 Quality Factor (QF) of Different Kinds of Radiation

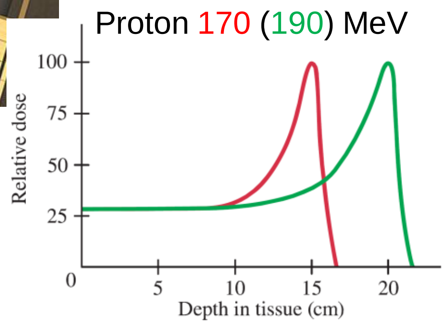
Type	QF
X- and γ rays	1
β (electrons)	≈ 1
Fast protons	1
Slow neutrons	≈ 3
Fast neutrons	Up to 10
α particles and heavy ions	Up to 20

Stralingstherapie

Gebruik van straling om mensen met kanker te behandelen
Relatief grote dosis nodig voor effectieve bestrijding
Kleine bundel γ straling voor behandeling goed gelokaliseerde tumoren
Roteer bron om schade aan gezond weefsel te minimaliseren
Bron: ${}^{60}_{27}\mathrm{Co}$ of een X-ray machine voor 200 keV tot 5 MeV
Actueel: proton en (koolstof) ionen therapie







Tracers

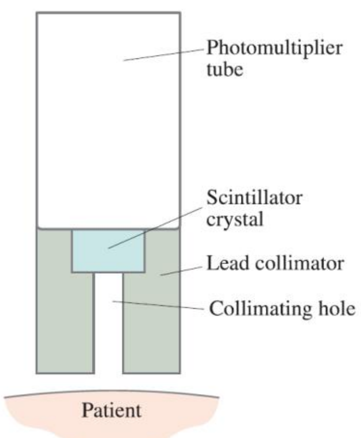
Radioactieve isotopen zoals ${}^{14}_{6}C$ of ${}^{3}_{1}H$

Autoradiografie met planten in een CO_2 omgeving

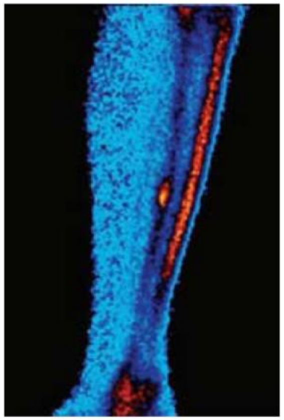
Medische diagnose met technetium-99 met levensduur van 6 uur ${}^{99m}_{43}Tc$

Technetium-99 kan in diverse verbindingen gebruikt worden, die specifiek zijn voor verschillende organen

Gamma camera's maken dynamische studies mogelijk



(a)



(b)

(a)

(b)

Tomografie: CT en PET

Conventionele X-ray (een soort schaduw-opname)

CT: computed (axiaal) tomografie (beeld slices af)

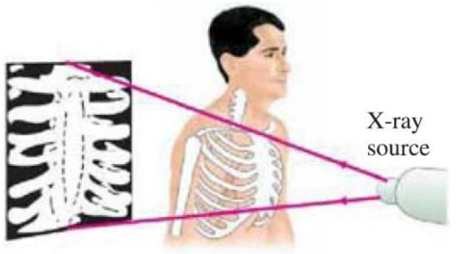
Een smalle bundel gaat door het lichaam

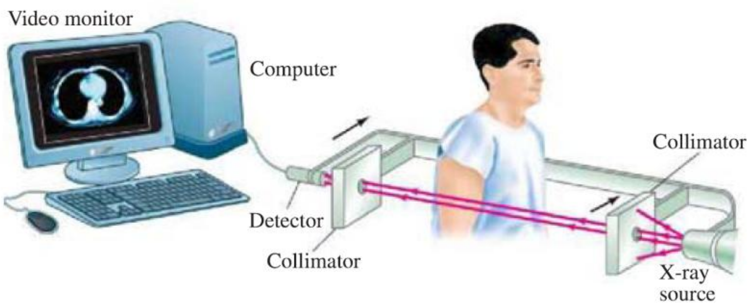
Bron en detector maken slices

Roteer apparaat met 1^{o} en maak slice

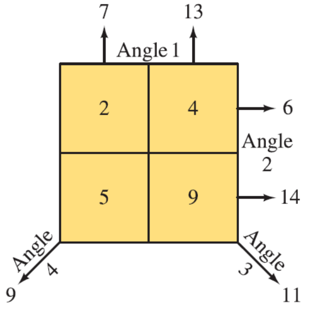
Fan-beam scanner

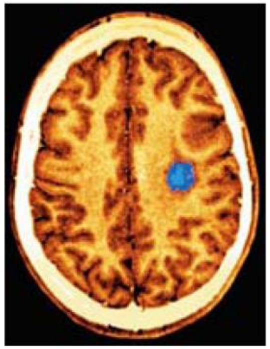
Beeldverwerking: pixels



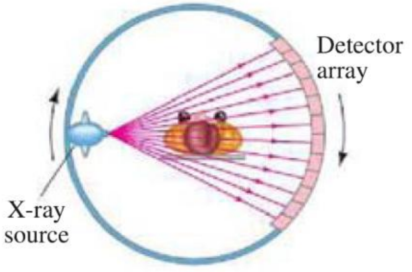


(a)

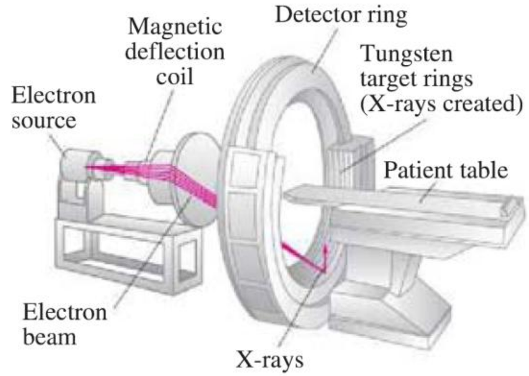




(b)



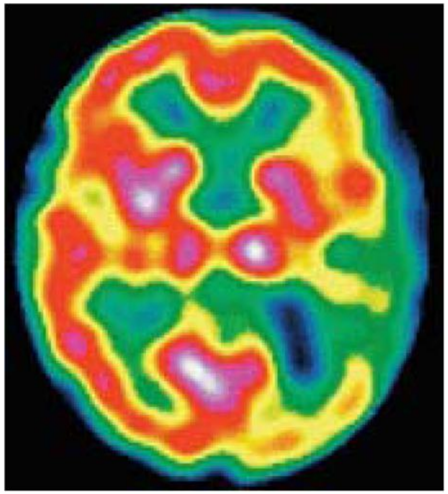
(a)



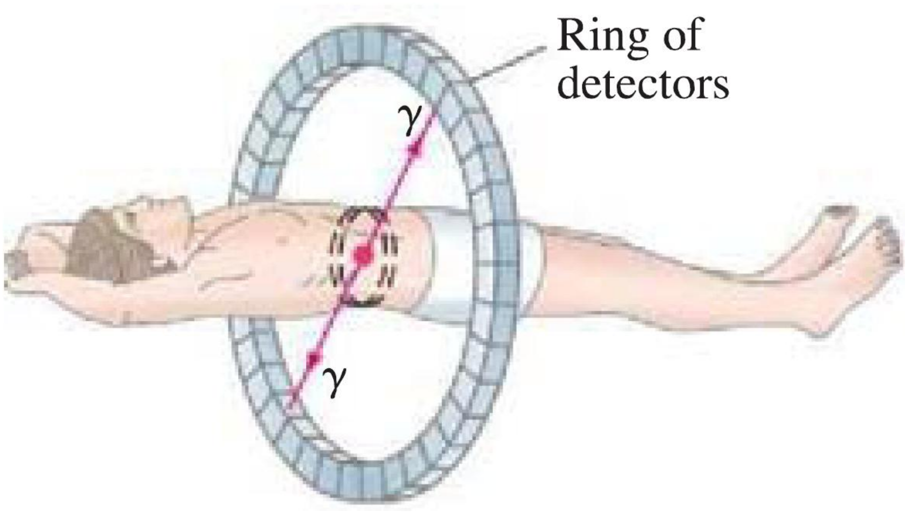
(b)

Emissie tomografie

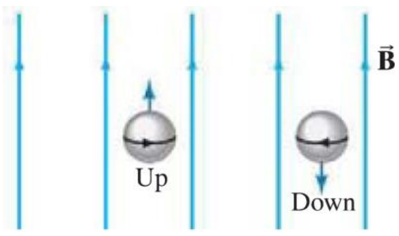
Single photon emission (computed) tomografie: SPET of SPECT
Meet X-rays van een tracer en doe CT



Positron emission tomografie (PET)
Gebruik positron emitters: ${}^{11}_{6}C$, ${}^{13}_{7}N$, ${}^{15}_{8}O$, and ${}^{18}_{9}F$
Positron annihileert met elektron
Er worden 2 fotonen geproduceerd
Gebruik een ring van foton detectoren



Kernspin resonantie (NMR)

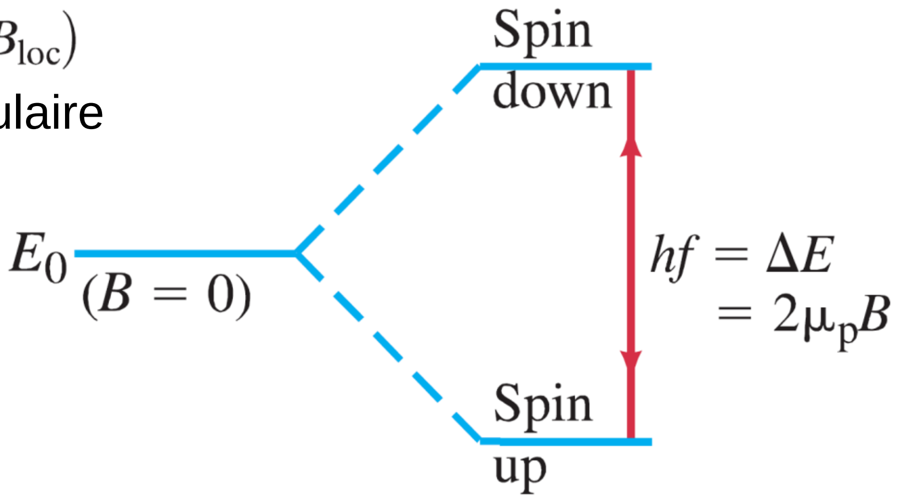


Kern in magneetveld heeft energie $\vec{\mu} \cdot \vec{B}$
Proton spin kan twee instellingen hebben (up, down)
Dit leidt tot twee energieniveaus
Er geldt $\Delta E = 2\,\mu_p B_T$

In NMR opstelling plaatsen we een sample in een statisch veld *B*
Vervolgens geven we een RF pulse met frequentie *f*, zodat $hf = \Delta E = 2\mu_p B_T$
Op deze wijze induceren we overgangen tussen beide niveaus
Voor een proton hebben we 42.48 MHz voor een 1.0 T veld
Voor een gebonden proton geldt

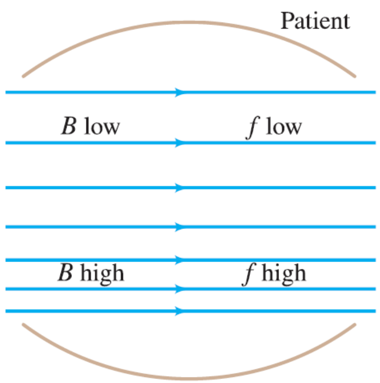
$$hf = 2\mu_p(B_{ext} + B_{loc})$$

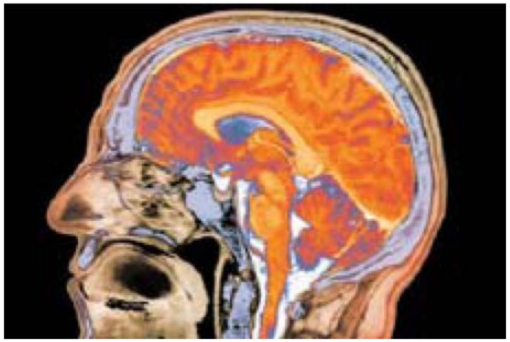
De frequentieverandering t.g.v. de moleculaire binding noemen we *chemical shift*

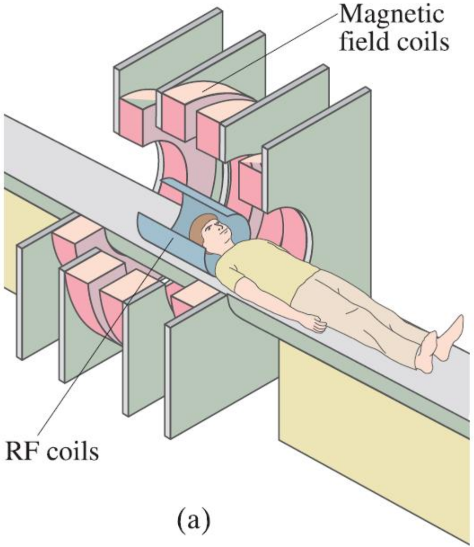


Magnetic Resonance Imaging (MRI)

MRI maakt beelden op basis van de proton spin (NMR principe)
CT technieken worden gebruikt in de 2D of 3D beeldproductie
Statisch magneetveld heeft een gradient
Hierdoor is resonantie beperkt tot slechts 1 plaats (voor 1 frequentie)
De plaats van resonantie wordt gevarieerd (door gradienten of frequentie)







(a)

(b)

Samenvatting

Voordelen

- Grote hoeveelheden brandston (lage prijs).
- Fusie is CO_2 neutraal.
- Kleine hoeveelheid radioactief afval.
- Geen risico van snelle energie afgifte.
- Brandstof is overal op Aarde beschikbaar.
  - Fusie is dus van belang voor iedereen die geen natuurlijke energiebronnen heeft.
  - Geo-politiek belang.
- Geef proliferatie van materiaal voor wapens

Nadelen

- Nog niet gedemonstreerd. Het bedrijf wordt gehinderd door allerlei, op zichzelf interessante natuurkundig fenomenenen.
- Het kostenplaatje is onduidelijk. Met name de kosten van de reactor.

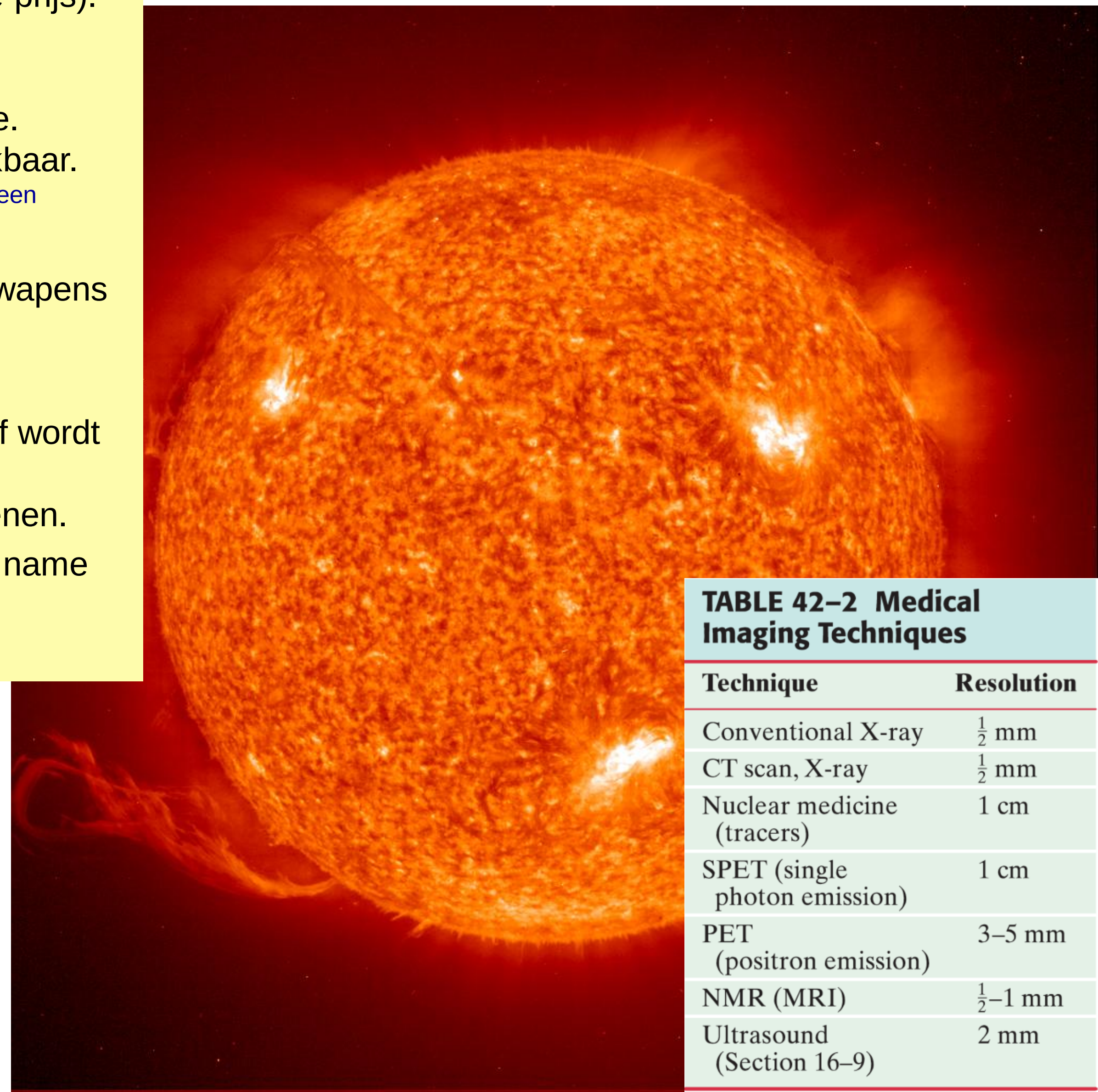


TABLE 42–2 Medical Imaging Techniques

Technique	Resolution
Conventional X-ray	$\frac{1}{2}$ mm
CT scan, X-ray	$\frac{1}{2}$ mm
Nuclear medicine (tracers)	1 cm
SPET (single photon emission)	1 cm
PET (positron emission)	3–5 mm
NMR (MRI)	$\frac{1}{2}$–1 mm
Ultrasound (Section 16–9)	2 mm

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