Accelerator Driven Nuclear Energy- The Thorium Option

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- Global warming- Inconvenient truth-Briefly review evidence—Drives the rest of the argument
- Will briefly review the world energy situation and projections
- Nuclear reactors –review various types
  - » Uranium 235 Fission reactors
    - Pressurised water reactors
    - CANDU Heavy water reactors
  - » Fast Breeder Reactors
  - » Problems-
    - Fuel enrichment
    - Nuclear Waste Storage
- Accelerator supplying neutrons is an old idea. 1948 fear of uranium shortage- MTA accelerator project started to produce fissile material from U238 (0.25Amps of deuterons).
- Accelerator Driven Breeder reactors (C.Rubbia et al-1993-1997)
  - » Thorium option
  - » Uranium 238 Option
  - » Advantages in fuel availability, efficiency and waste storage
- Needs a 1 GeV 10-20 MegaWatt accelerator
  - » May be doable with SCRF.
  - » Challenging accelerator R&D.
- Discuss physics that can be done with such a machine.

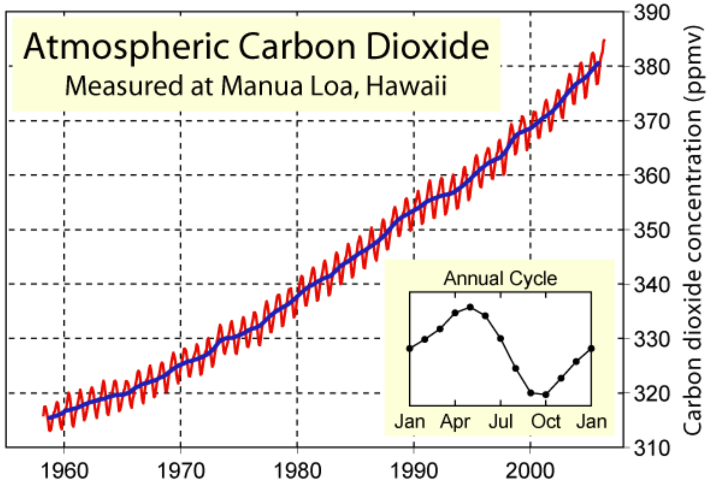
Disclaimer

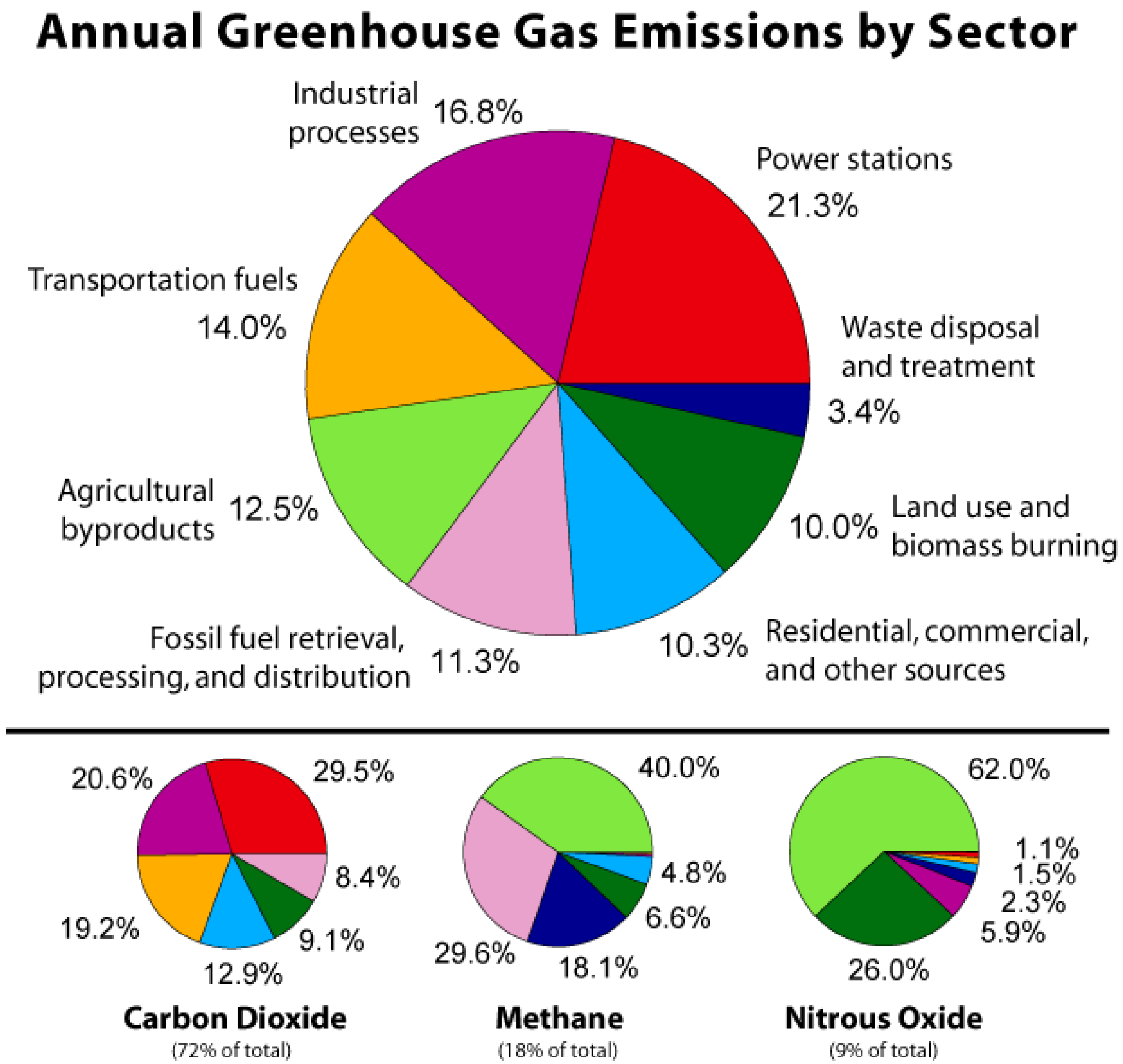
- I do not represent the views of any institution, especially Fermilab in what follows.
- I became interested in this topic when the global warming problem became undeniable, a few years ago.
- I do not claim to be a reactor expert. Have some experience with accelerators.
- Two of us, Chris Hill and myself are planning a book called "The Good Reactor" to explain these ideas to the general public.

Global Warming

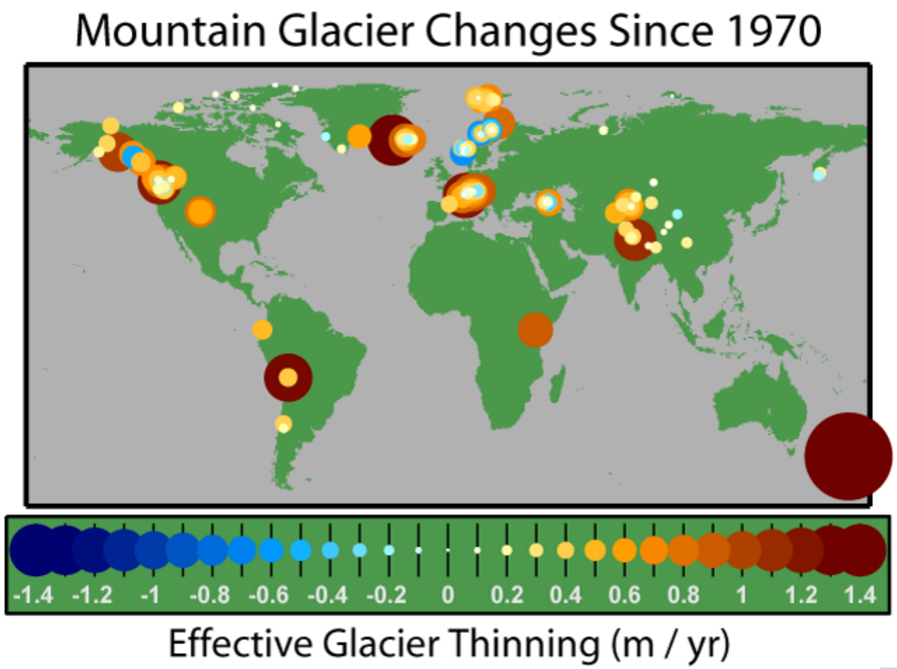
- It is being taken very seriously. We will take it as established.
- An Inconvenient Truth (Gore's Movie) winning two oscars has brought a significant amount of public attention to this problem
- After this, Great Britain announced cut in Greenhouse gases (CO_2, Methane, Nitrous oxide)
- European Union followed suit
- U.S will need to comply as well sooner or later. U.S. Supreme court ruled EPA responsible for controlling greenhouse gases. MoveOn.org organized ~1000 demonstrations across nation
- How will we meet our energy needs?
- I will argue that Nuclear energy will need to make a comeback
- Accelerator driven Thorium option represents an attractive method
  - » No greenhouse gases
  - » Plenty of fuel
  - » Sub-critical

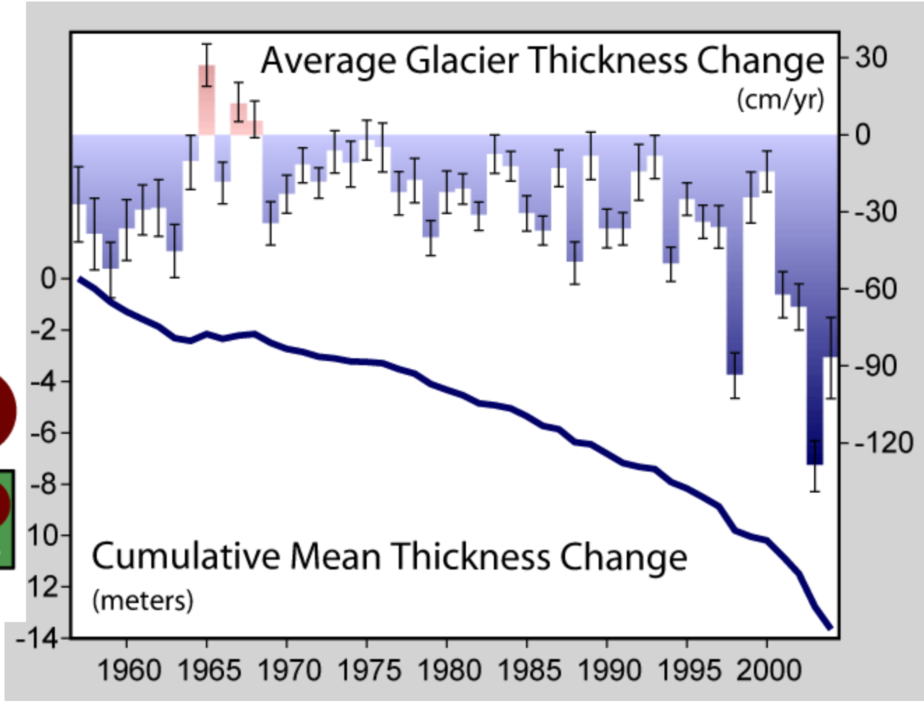
Global Warming-GASES



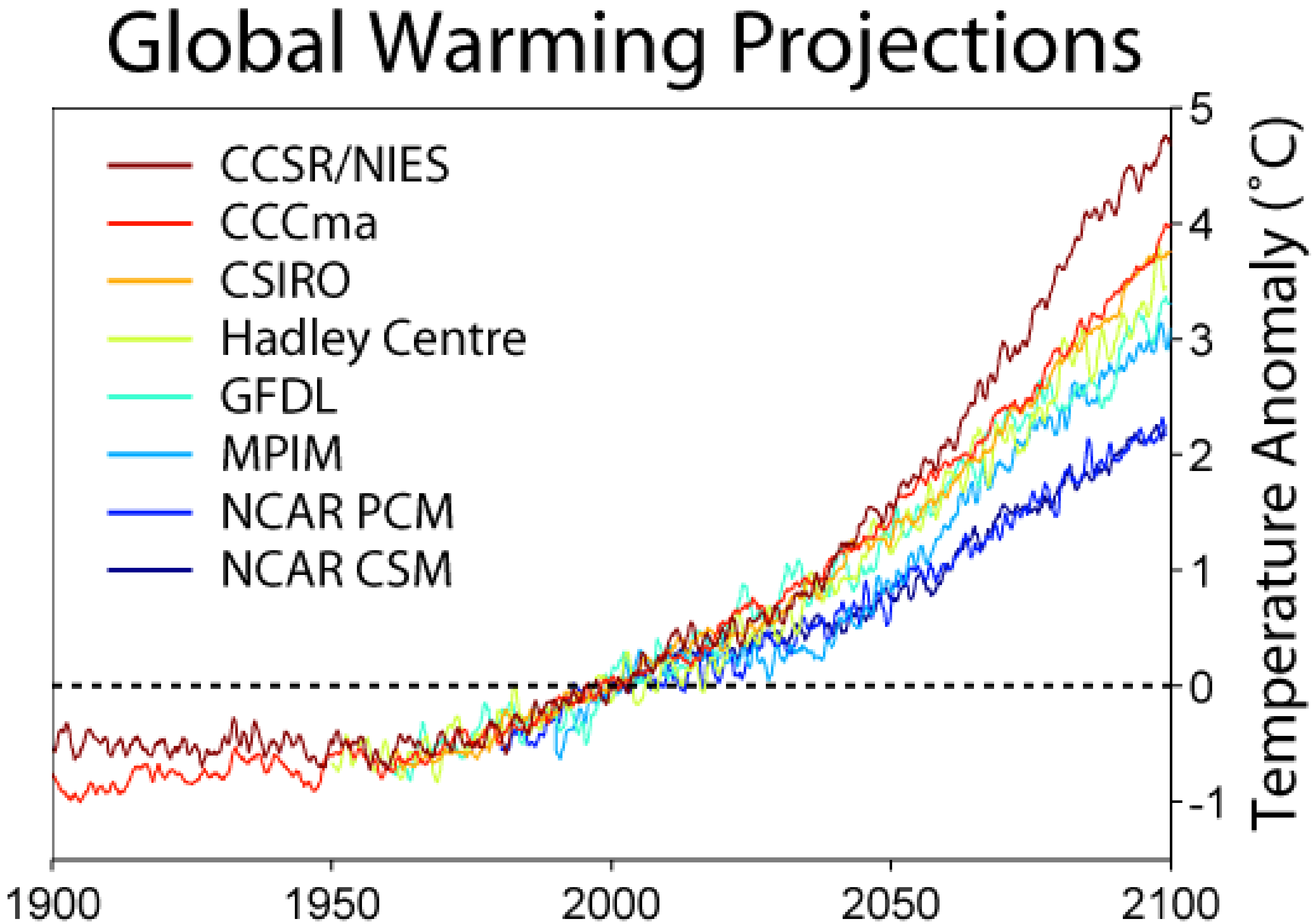


Global Warming-Glaciers

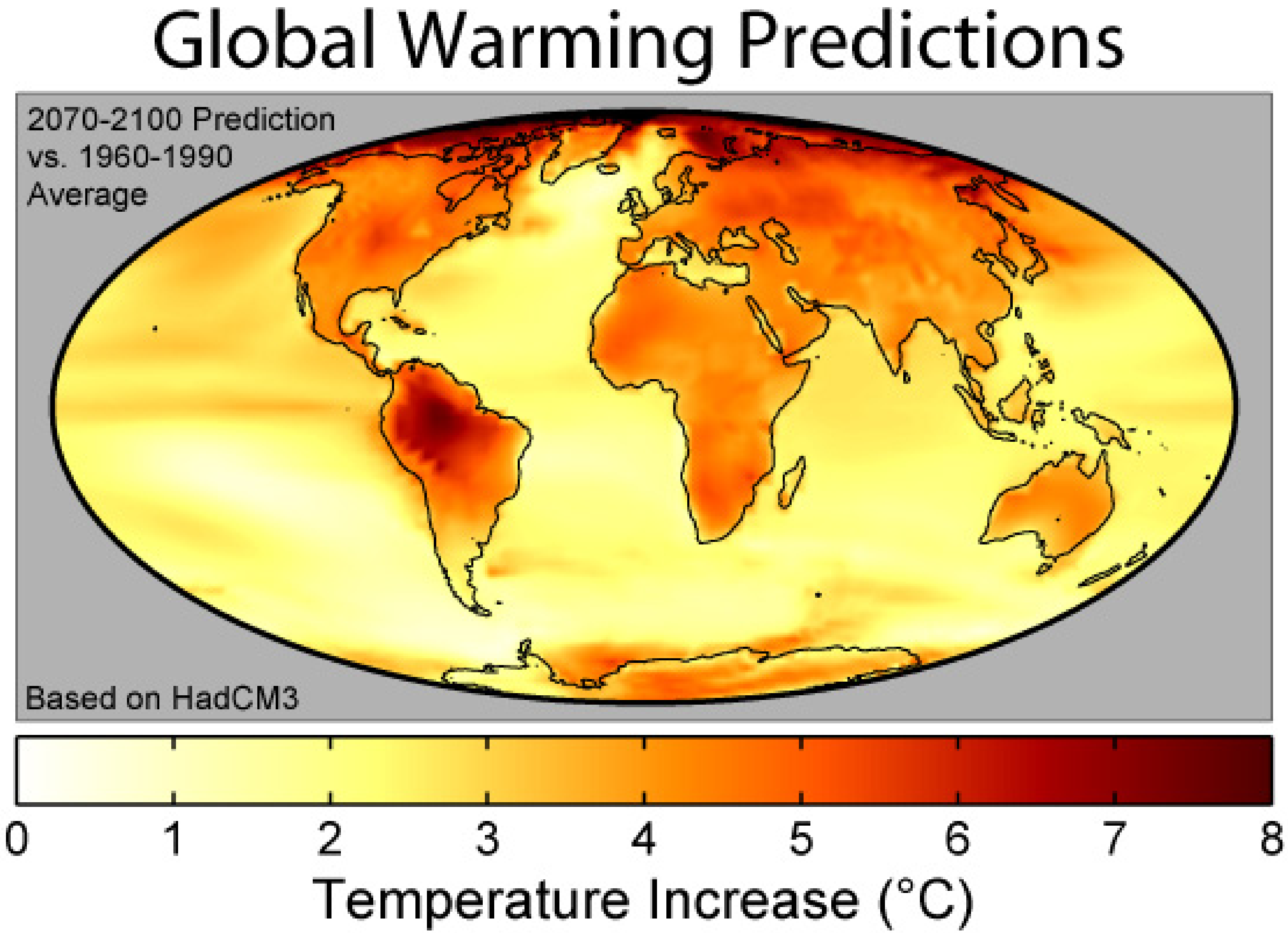




Global Warming-model spread



Calculations from Hadley Centre HADCM3 Climate model- If nothing is done by 2100

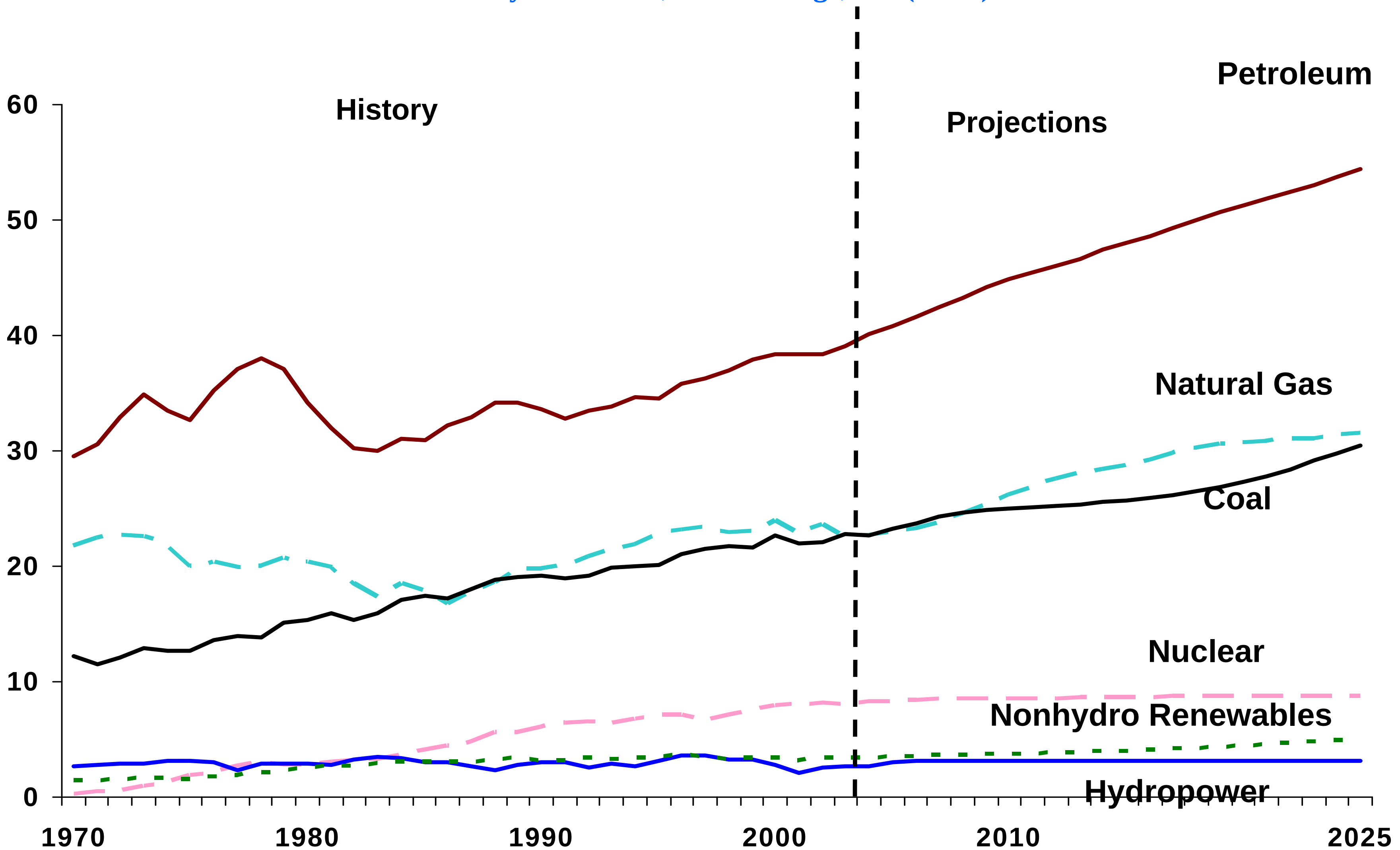


Predicted effects of global warming

- **Top Scientists Warn of Water Shortages and Disease Linked to Global Warming**
-
-
- By THE ASSOCIATED PRESS
- Published: March 12, 2007
- WASHINGTON, March 11 (AP) — The harmful effects of global warming on daily life are already showing up, and within a couple of decades hundreds of millions of people will not have enough water, top scientists are likely to say next month at a meeting in Belgium.
- At the same time, tens of millions of others will be flooded out of their homes each year as the earth reels from rising temperatures and sea levels, according to portions of a draft of an international scientific report by the authoritative Intergovernmental Panel on Climate Change.
- Tropical diseases like malaria will spread, the draft says. By 2050, polar bears will mostly be found in zoos, their habitats gone. Pests like fire ants will thrive.
- For a time, food will be plentiful because of the longer growing season in northern regions. But by 2080, hundreds of millions of people could face starvation, according to the report, which is still being revised.
- Loss of coastal cities in 100 years?

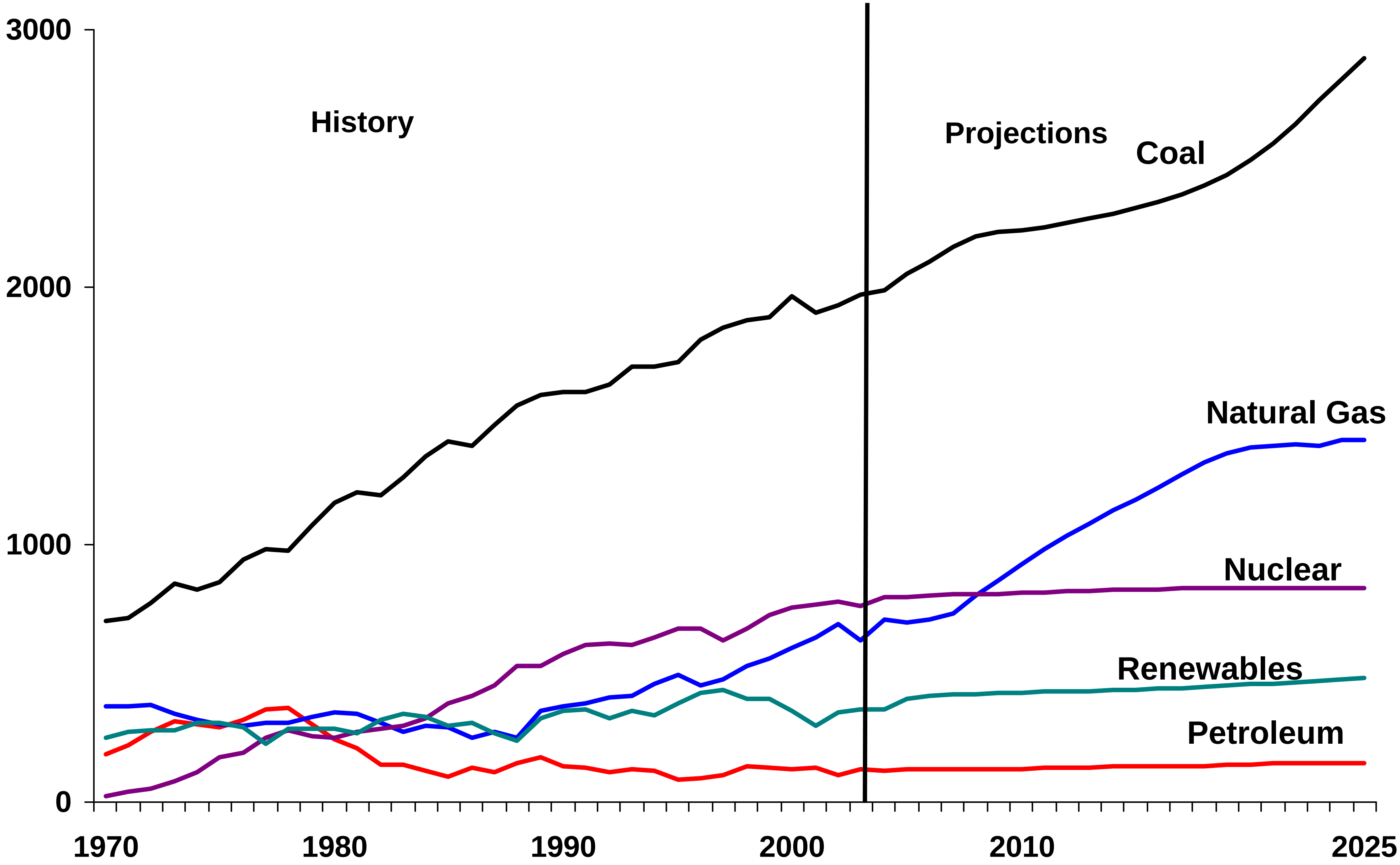
U.S. Energy Consumption by Fuel, 1970-2025
(quadrillion Btu)

Source-Talk given by Guy Caruso, Administrator, Energy Information Administration, Center for Energy Studies Industry Associates, Baton Rouge, LA (2005.)



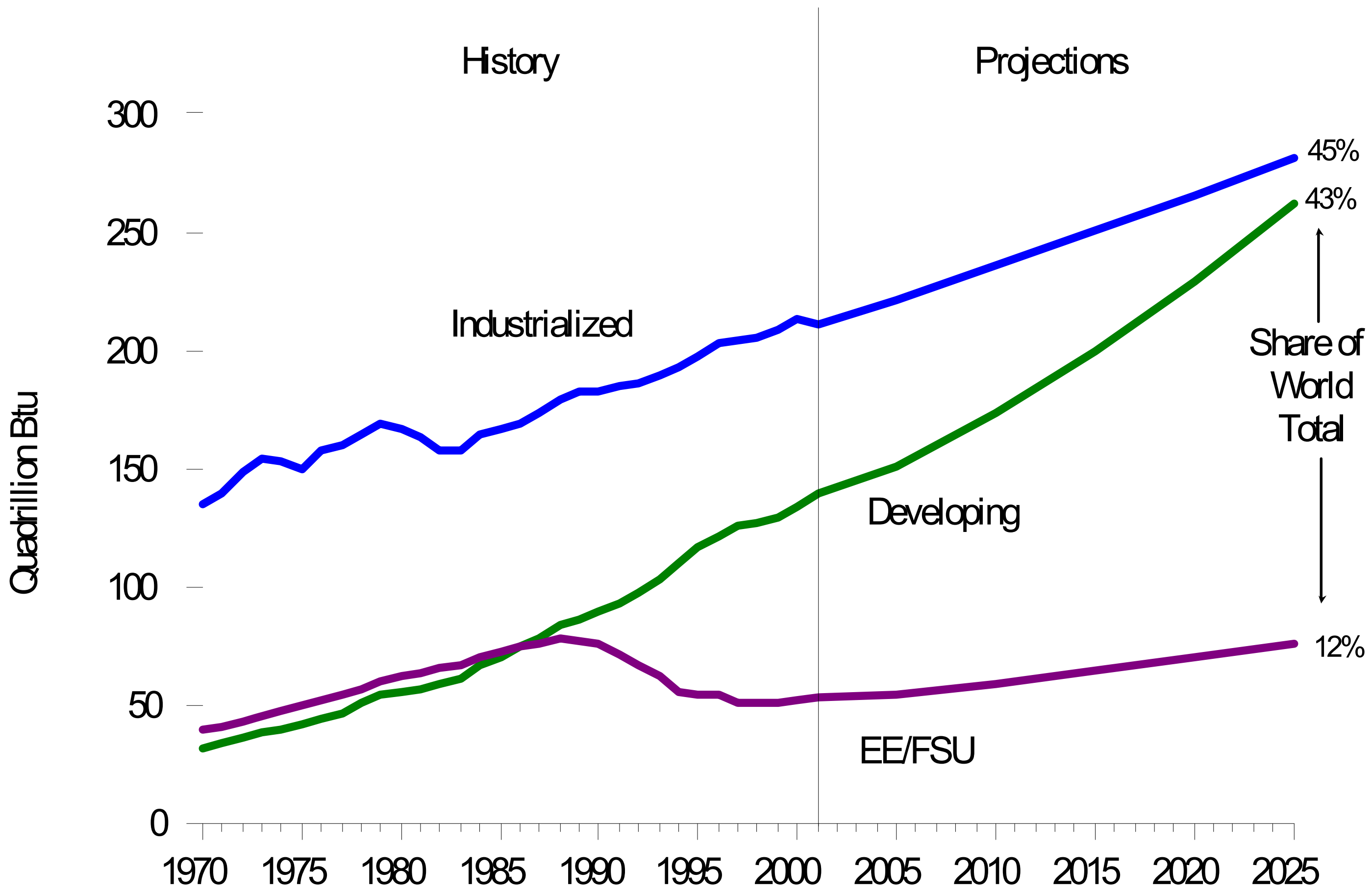
Annual Energy Outlook 2005

U.S. Electricity Generation by Fuel, 1970-2025
(billion kilowatthours per year)



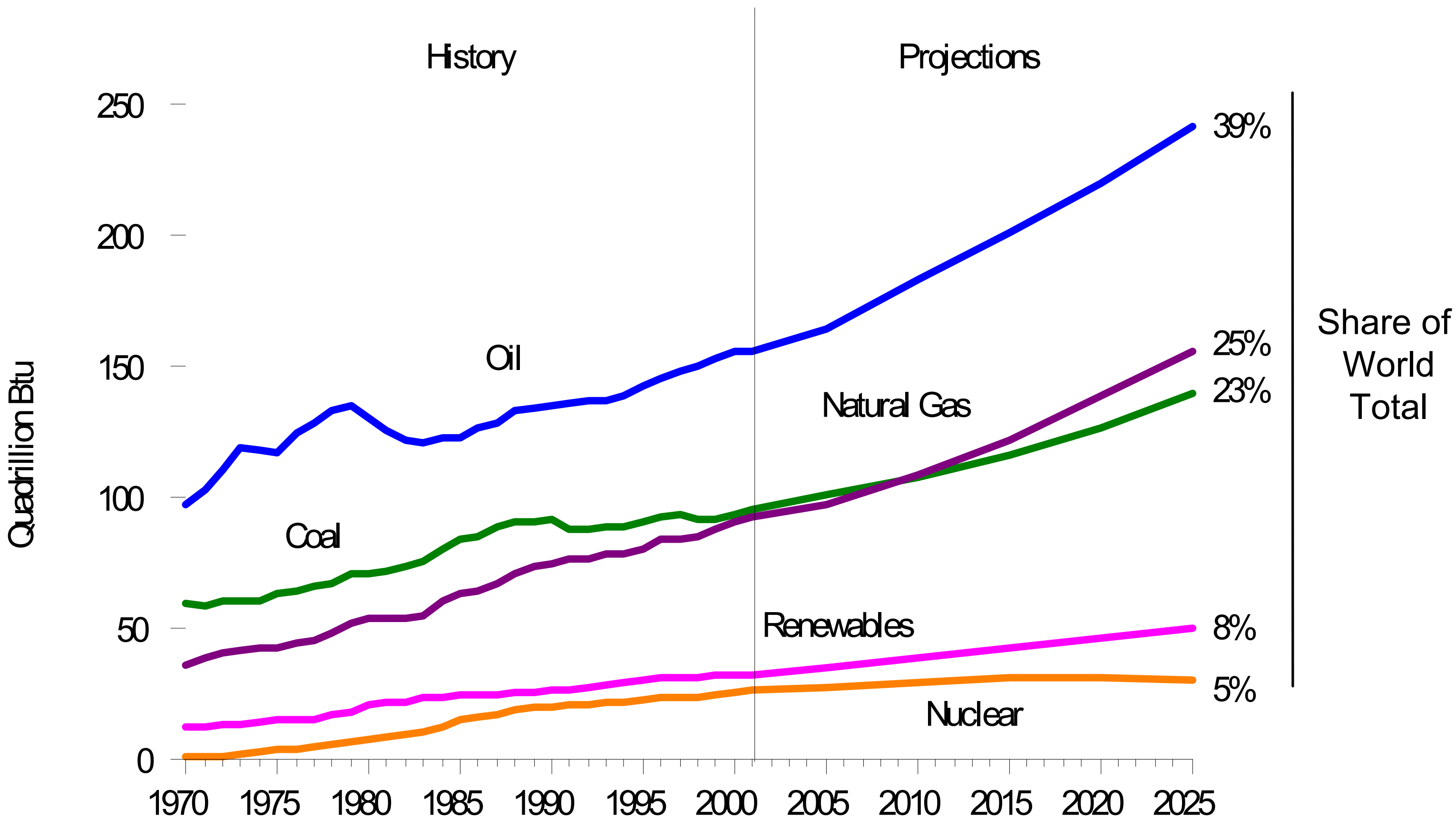
Annual Energy Outlook 2005

World Marketed Energy Consumption by Region, 1970-2025



Interr

World Primary Energy Consumption by Fuel Type, 1970-2025



International Energy Outlook 2004

KEY Findings of DoE's Energy Information Administration

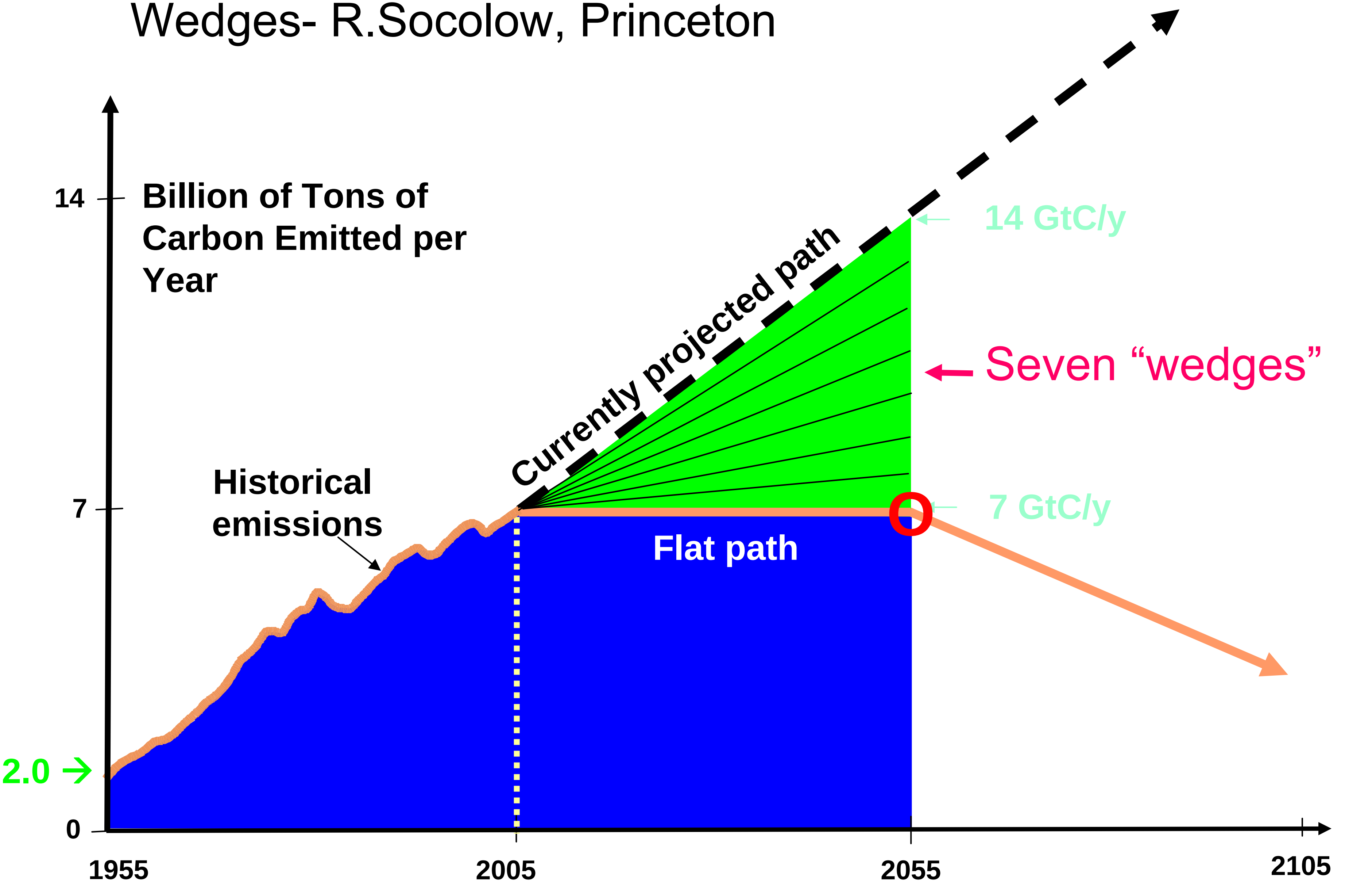
Source-Talk given by Guy Caruso, Administrator, Energy Information Administration, Center for Energy Studies Industry Associates, Baton Rouge, LA (2005.)

- In the short-term, tight markets and political tensions keep world oil prices high.
- Through 2025, oil remains the dominant source of worldwide energy use with 39 percent of total energy demand.
- Both domestically and internationally, natural gas demand will expand rapidly.
- The United States and developing Asia, including China, account for 60 percent of the growth in world oil demand in the mid-term.
- Transportation will account for much of the growth in oil use in the industrialized world; in the developing world, oil demand grows in all end-use sectors.
- The United States will rely on imports for 68 percent of its oil requirements in 2025.
- U.S. dependence on Persian Gulf OPEC will increase, but other OPEC and non-OPEC producers will remain important U.S. suppliers.

How do we combat global warming?

- Conservation
- Cleaner burning of coal, oil, natural gas
- More solar, wind, geothermal—Need Scale up by factor of 10—Unforeseen problems. Transmission grid, storage of power could be such issues.
- Nuclear energy---Fission, Fusion
- Which one shall we choose?
- Answer all of the above.
- Nuclear energy currently has problems-
  - » Nuclear Waste—long term storage, use only .7% of natural Uranium (^{235}U). If more fuel needed, will have to breed.
  - » Fast breeder reactors are inherently critical. Need to react in ~ 1 second to insert control rods.- Need plutonium core-not economically competitive with Light Water Reactors (LWR) at present
  - » Try a new tack– breed using accelerators.

Wedges- R.Socolow, Princeton



1 Wedge needs 700 GW (2 current capacity) from nuclear energy by 2055.

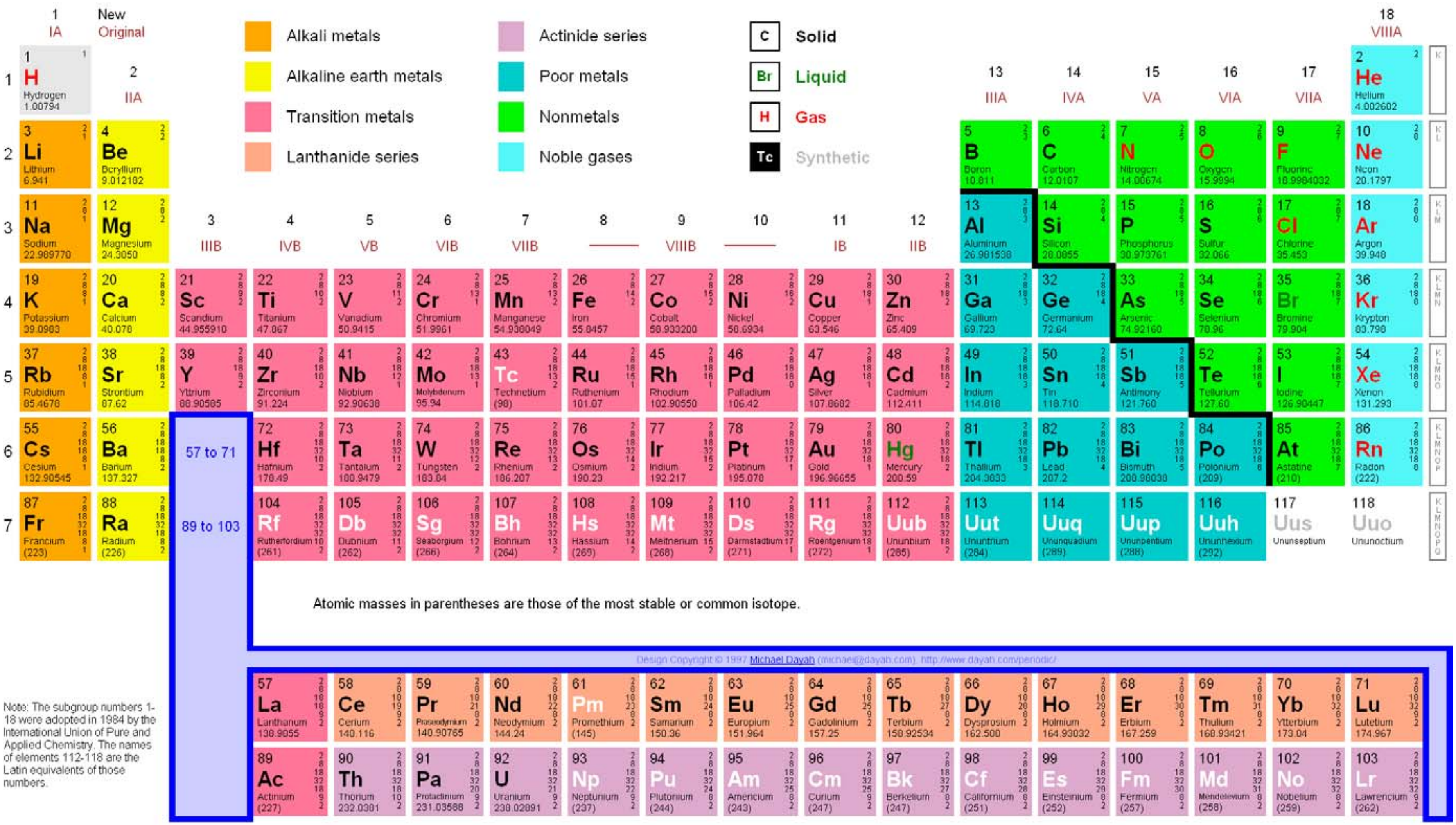
Proliferation Issues

- Talked to one of the scientific advisors to the Obama Campaign—He stated "Proliferation can be achieved through much lower technology than nuclear reactors—eg Centrifuges."
- The higher the tech, the more proliferation resistant the scheme is. AADS is higher tech than conventional nuclear reactors.
- Ultimately, proliferation is a political issue.
- National security can also be compromised by lack of energy independence.

Nuclear Reactors by Country

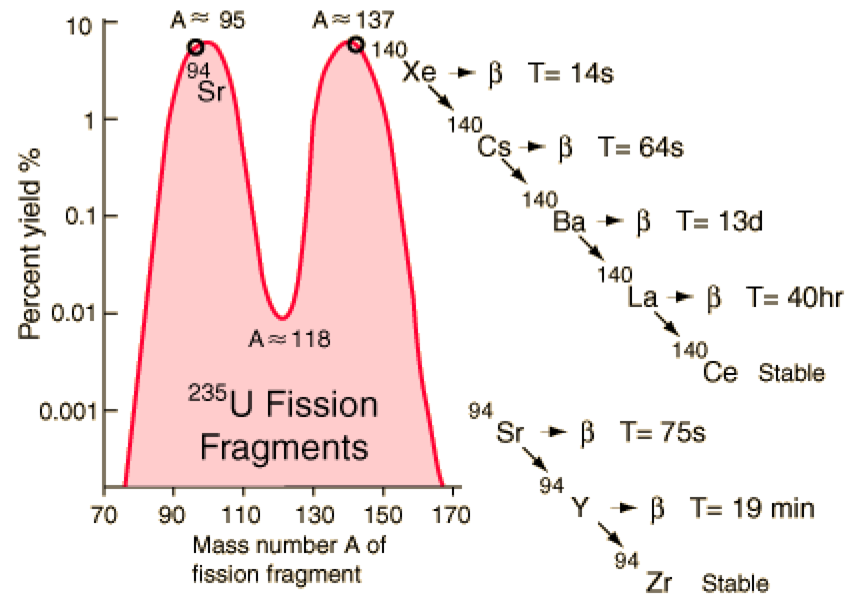
			Nuclear Reactors by Country			
Country	Number of reactors	Power MW	Constructing	Planned or ordered	Proposed	
World	**442**	**370721**	**28**	**62**	**160**	
EU	147	130267	2		7	
USA	104	99209	1		13	
France	59	63363	1		1	
Japan	55	47593	1	1		
Russia	31	21743	4	1	8	
UK	23	11852				
S.Korea	20	16810		8		
Canada	18	12599		2		
Germany	17	20339				
India	16	3557	7	4	20	
Ukraine	15	13107		2		
Sweden	10	8910				
China	10	7572	5	5	19	
Spain	8	7446				

Periodic Table of the Elements



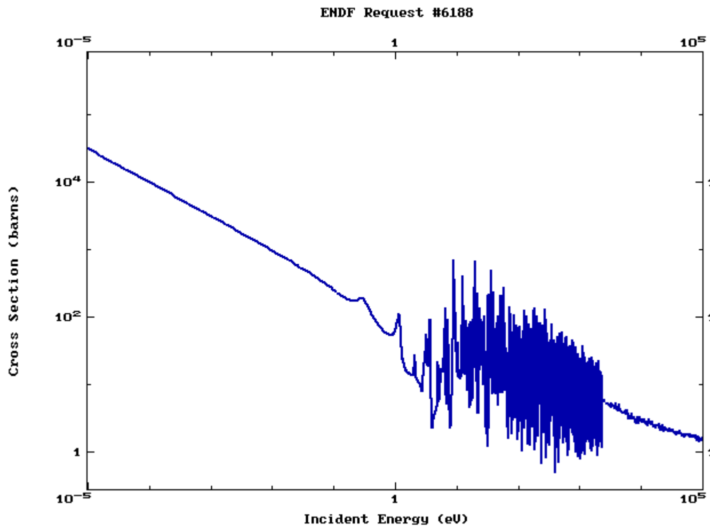
Reactors 101--Fissile and Fertile Nuclei

- In the actinides, nuclei with odd Atomic Weight (U^{235}, U^{233}, Pu^{239}) are fissile nuclei. They absorb slow thermal neutrons and undergo fission with the release of more neutrons and energy.
- Those with even Atomic Weight (Th^{232}, U^{238} etc) are Fertile nuclei. They can absorb "Fast neutrons" and will produce fissile nuclei. This is the basis of "fast breeders" and also the "energy amplifier", the subject of this talk.

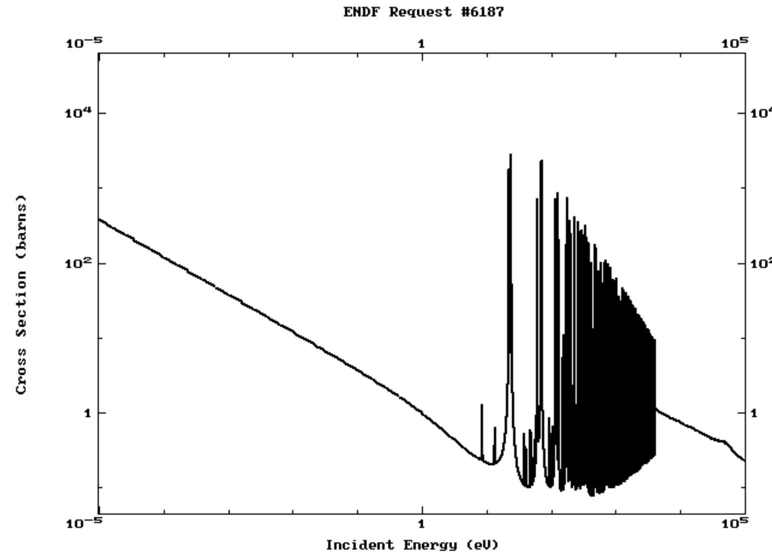


Mean energy released per fission ~200 MeV

Fission and breeding cross sections.

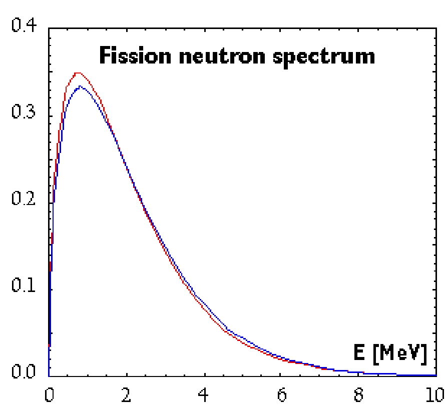


Cross section in barns for $U^{235}+n \rightarrow$Fission vs incident neutron energy (eV).



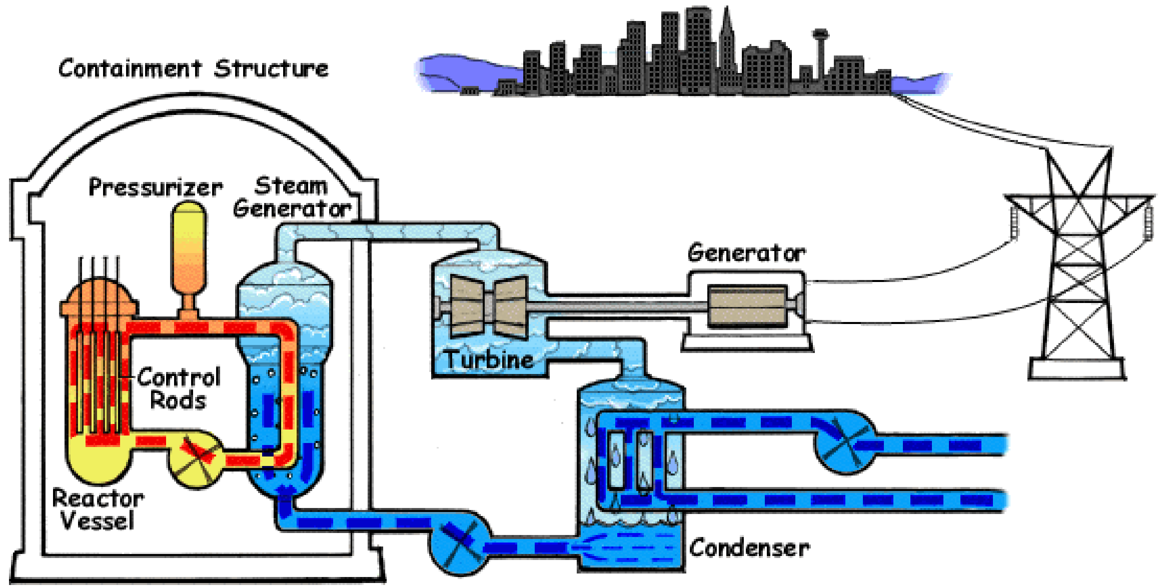
Cross section in barns for $Th^{232}+n \rightarrow Th^{233}+\gamma$. This is a breeding cross section. Another is

$$U^{238}+n \rightarrow U^{239}+\gamma$$
$$U^{239} \rightarrow Np^{239}+\beta^{-}\ (23.4\text{m})$$
$$Np^{239} \rightarrow Pu^{239}+\beta^{-}\ (2.35\text{d})$$

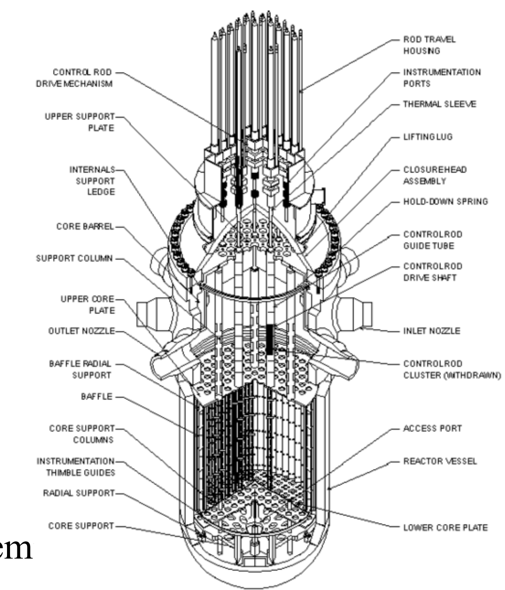


Fission Reactors-Pressurised Water reactors (PWR)

- Moderation using boric acid in pressurised water (150atm). Too much heat will produce steam, will reduce moderation. Safety feedback loop
- Uranium is enriched to ~4% U^{235}, Natural 0.7%
- Delayed neutrons from decay of isotopes make the reactor just critical.

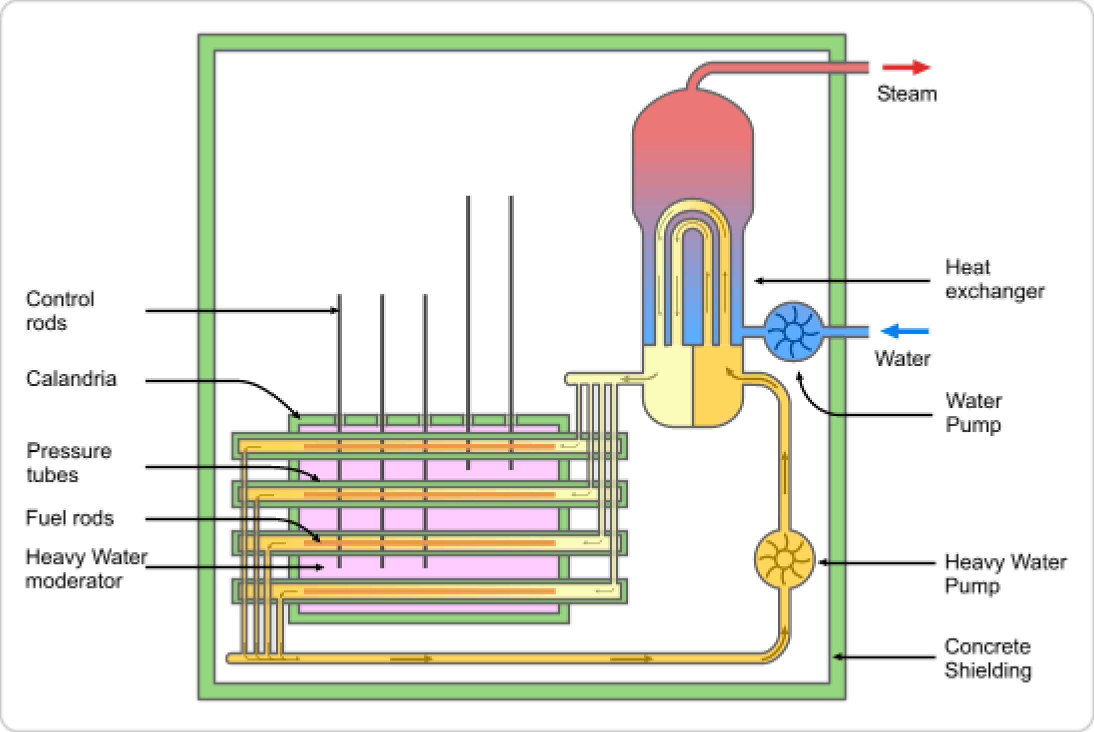


Control rods used for starting and stopping the reactor.



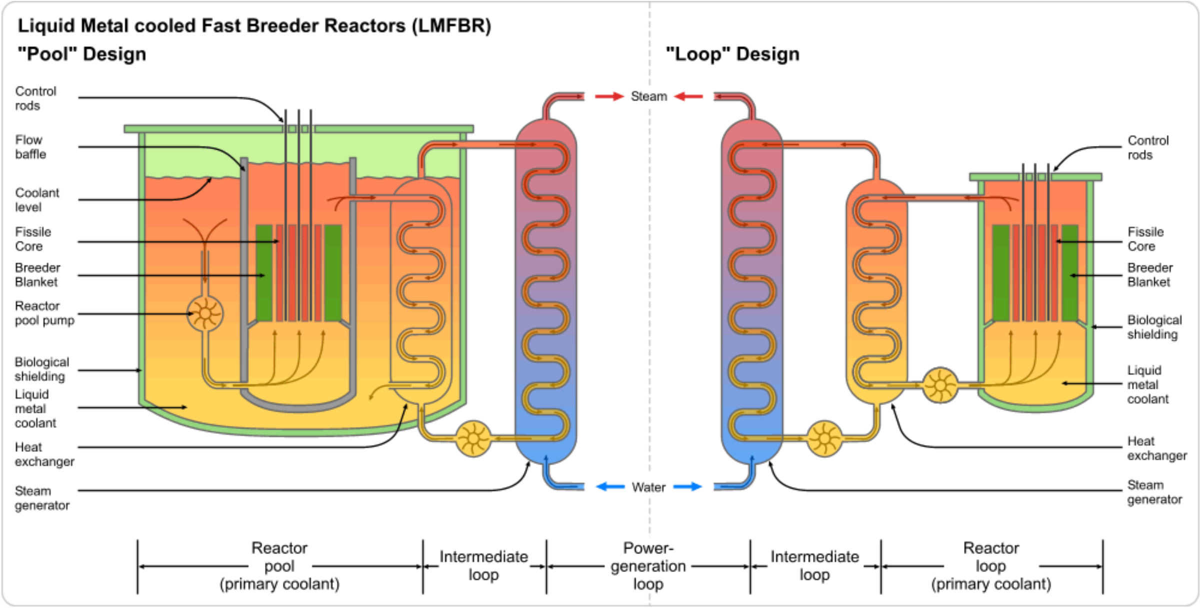
Fission Reactors-Pressurised Heavy Water reactors

- Heavy Water reactors- CANDU type. Moderated using D_2O- Permits operation with natural Uranium, since more neutrons survive being slowed down by the heavy water. Heavy water is a considerable expense.



Fast Breeder Reactors

- Neutrons not moderated.
- Use the neutrons to breed fissile material using fertile nuclei (U^{238}, Th ^{232}).
- Coolant is usually liquid sodium. Cannot use Water!
- Fissile core eg ($20\%PuO_2+80\%UO_2$)
- Breeds more fuel in the blanket and also in the fissile fuel.
- Control is more complicated than conventional reactors.



Two common designs shown= Pool type and loop type.

Drawbacks of Fission reactors

- Enrichment needed for both PWR and FBR.
  - Proliferation worries
- Waste storage is a worry for PWR's and PHWR's.
  - Fission products are highly toxic, but are shortlived (Max ~30yrs halflife). However, higher actinide waste products take ~10^5 years storage to get rid of.
- All reactors operate at criticality. So are potentially unsafe.
- Economics of pre-processing fuel and post-processing the waste must be taken into account in costing the reactor kiloWatt hour.
- Uranium 235 is not that plentiful.
- Fast reactors need enriched Pu^{239} or U^{235} and do not compete economically (currently) with conventional fission reactors. French reactor Superphenix (1.2 GWe Commissioned 1984) was shut down in 1997 due to political and other problems.
- Fast Breeders have not caught on. At present BN-600 (Russia), Monju (Japan) FBTR (India) comprise most of the list.

Criticality factor k

- Let number of neutron at the first step of spallation $=N_1$. After these interact in the fuel once, they produce kN_1 neutrons. After the second level of interactions, this will produce N_1k^2 neutrons and so on. So in total there will be

$$N_{tot} = N_1(1+k+k^2+k^3...) = \frac{N_1}{1-k}$$

neutrons.

k has to be less than 1 or we have a runaway situation.

Criticality issues

- In both conventional and fast reactors, criticality is achieved by carefully balancing the neutron budget.
- Delayed neutrons from decay of unstable nuclei have time constants of up to 30 secs and ameliorate the job of controlling the reactor.
- Indeed Fermi declared that " without delayed neutrons we could not have a nuclear power program".
- In a critical reactor, any random increase in power generation must be controlled by a rapid feedback mechanism through mechanical control of neutron absorbing rods. In an ADS, this is done by control of accelerator power. Neutrons from Plutonium cannot be switched off!
- Richard Wilson adds to this " without delayed neutrons, we would have to have an accelerator driven sub-critical assembly".
- Both fast and conventional reactors rely on delayed neutrons for control. In conventional reactors, there is the additional mechanism of "doppler control". If the temperature rises, the fission cross section by thermal neutrons drops.

Uranium supply and demand

- Currently, Uranium supplies are expected to last 50- 100 years due to the projected use by existing and future planned conventional nuclear reactors.
- DoE Energy Information Administration Report #:DOE/EIA-0484(2008) states that

"Uranium Supplies Are Sufficient To Power Reactors Worldwide Through 2030 "

It further states

"Also, the uranium supply can be extended further by worldwide recycling of spent fuel and the use of breeder reactors. "

We MUST breed if we want to use nuclear energy long term.

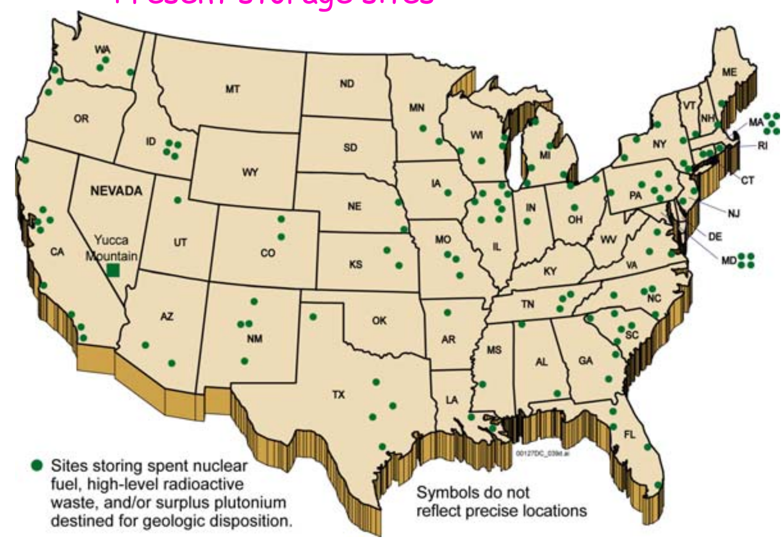
Recycling Strategies

- After years of usage, fission fragments rise in the reactor core. These absorb ("poison") thermal neutrons and the reactor can no longer operate at criticality.
- U.S currently stores away the "nuclear waste" after a single such pass.- Collossal "waste" of energy, since the spent fuel contains actinides.
- France and other European nations, recycle the fuel by removing the fission fragments. There is some small amount of breeding in conventional reactors.
- Breeder reactors are needed to address the fuel supply problem.

Waste Management-Yucca Mountain Repository

- $10Billion spent- Should have been ready by 1998
- Storing nuclear waste after single pass is wasting energy.
- ADS approach makes this unnecessary

Present storage sites



Accelerator Driven Energy Amplifier

- Idea due to C.Rubbia et al (*An Energy Amplifier for cleaner and inexhaustible Nuclear energy production driven by a particle beam accelerator, F.Carminati et al, CERN/AT/93-47(ET).).* Waste transmutation using accelerator driven systems goes back even further.(*C.Bowman et al, Nucl. Inst. Methods A320,336 (1992))*
- *Conceptual Design Report of a Fast Neutron Operated High Power Energy amplifier (C.Rubbia et al, CERN/AT/95-44(ET)).*
- *Experimental Determination of the Energy Generated in Nuclear Cascaded by a High Energy beam (S.Andriamonje et al) CERN/AT/94-45(ET)*
- *A Physicist's view of the energy problem, lecture given at Energy and Electrical Systems Institute,J-P Revol,Yverdon-les-bains, Switzerland,2002*
- *Advantages-*
  - » *Sub-Critical*
  - » *Use Thorium- More plentiful than U^{238}*
  - » *Breed more fuel*
  - » *Can burn waste*
- *Disadvantages-*
  - » *Needs 10 MW proton accelerator- Does not exist as yet*

Rubbia Energy Amplifier (EA)

- EA operates indefinitely in a closed cycle
  - » Discharge fission fragments
  - » Replace spent fuel by adding natural Thorium
- After many cycles, equilibrium is reached for all the component actinides of the fuel.
- Fuel is used much more efficiently
  - » 780 kg of Thorium is equivalent to 200 Tons of native Uranium in a PWR
  - » Rubbia et al estimate that there is enough Thorium to last ~ 10,000 years.
- Probability of a critical accident is suppressed because the device operates in a sub-critical regime. Spontanous convective cooling by surrounding air makes a "melt-down" leak impossible.
- Delivered power is controlled by the power of the accelerator.
- After ~ 70 years, the radio-toxicity left is ~ 20,000 times smaller than one of a PWR of the same output. Toxicity can be further reduced by "incineration"

Worldwide distribution of Thorium

Table 1.1 - Thorium resources (in units of 1000 tons) in WOCA (World Outside Centrally Planned Activities) [21]

	Reasonably Assured	Additional Resources	Total
Europe			
Finland		60	60
Greenland	54	32	86
Norway	132	132	264
Turkey	380	500	880
Europe Total	566	724	1290
America			
Argentina	1		1
Brazil	606	700	1306
Canada	45	128	173
Uruguay	1	2	3
USA	137	295	432
America total	790	1125	1915
Africa			
Egypt	15	280	295
Kenya	no estimates	no estimates	8
Liberia	1		1
Madagascar	2	20	22
Malawi		9	9
Nigeria	no estimates	no estimates	29
South Africa	18	no estimates	115
Africa total	36	309	479
Asia			
India	319		319
Iran		30	30
Korea	6	no estimates	22
Malaysia	18		18
Sri Lanka	no estimates	no estimates	4
Thailand	no estimates	no estimates	10
Asia total	343	30	403
Australia	19		19
Total WOCA	*1754*	*2188*	*4106*

This compilation does not take into account USSR, China and Eastern Europe. Out of 23 listed countries, six (Brazil, USA, India, Egypt, Turkey and Norway) accumulate 80% of resources. Brazil has the largest share followed by Turkey and the United States.

Geothermal energy is 38 Terawatts. Due to mostly decay of Th^{232} (predominant), U^{238} and Potassium 40.

Th^{232} has halflife of 14 billion years, U^{238}(4.5 billion years) and K^{40} (1.3billion years). Th^{232} is roughly 4-5 times more abundant than U^{238}. May be enough Thorium to last $2.2x10^5$ years using the energy amplifier method.

The basic idea of the Energy Amplifier

- In order to keep the protactinium (It can capture neutrons as well) around for beta decay to ^{233}U, one needs to limit neutron fluxes to ~10^{14} cm^{-2} sec^{-1}. Provide this by an accelerator.

$$^{232}Th + n \Rightarrow {}^{233}Th + \gamma \xrightarrow{(22m)} {}^{233}Pa + \beta^- \xrightarrow{(27d)} {}^{233}U + \beta^-$$

- Let σ_i be the capture cross section of neutrons and σ_f be the fission cross section.

$$\frac{^{232}Th}{(1)} \Rightarrow \frac{^{233}Pa}{(2)} \Rightarrow \frac{^{233}U}{(3)} \qquad \frac{dn_1}{dt} = -\lambda_1 n_1(t)\,; \frac{dn_2}{dt} = \lambda_1 n_1(t) - \lambda_2 n_2(t)\,; \frac{dn_3}{dt} = \lambda_2 n_2(t) - \lambda_3 n_3(t)$$

- Where Φ is the neutron flux and τ_2 is the lifetime of Pa

$$\lambda_1 = \sigma_i^{\,1}\Phi;\ \lambda_2 = \frac{1}{\tau_2};\ \lambda_3 = (\sigma_i^{\,3} + \sigma_f^{\,3})\Phi$$

Thin slab of Thorium solution

- In the limit $\lambda_1 \ll \lambda_2$ and $\lambda_1 \ll \lambda_3$, one finds

$$n_1(t) = n_1(0)e^{-\lambda_1 t};\; n_2(t) = n_1(t)\frac{\lambda_1}{\lambda_2}(1 - e^{-\lambda_2 t})$$

$$n_3(t) = n_1(t)\frac{\lambda_1}{\lambda_3}\left(1 - \frac{1}{\lambda_3 - \lambda_2}(\lambda_3 e^{-\lambda_2 t} - \lambda_2 e^{-\lambda_3 t})\right)$$

- In stationary conditions

$$\frac{n_3}{n_1} = \frac{\sigma^1{}_i}{(\sigma^3{}_i + \sigma^3{}_f)}$$

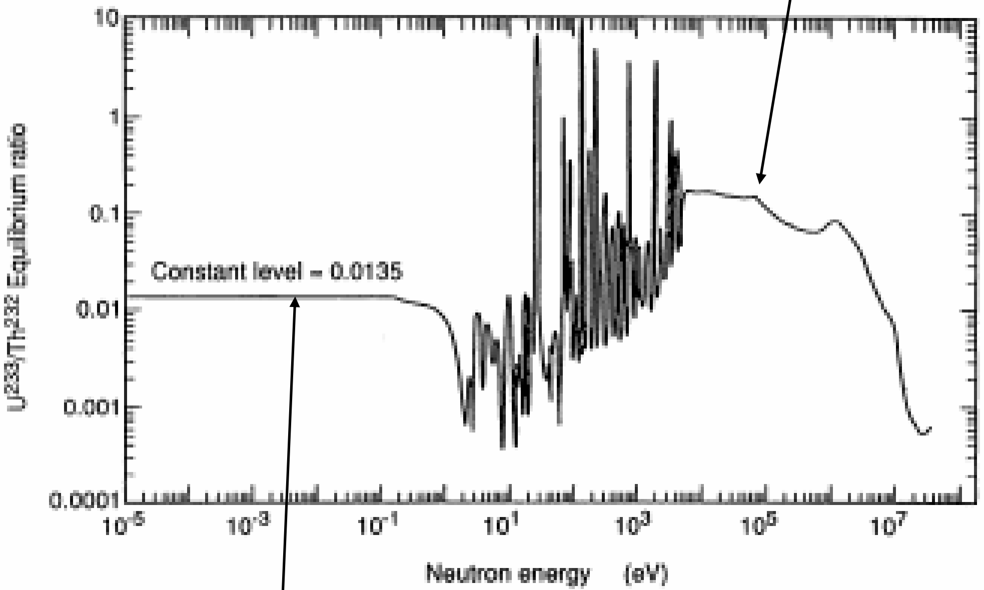
- Independent of neutron flux Φ
- Power of reactor is given by

$$P = 55.3\left(\frac{M}{1\,\mathrm{Ton}}\right)\left(\frac{\Phi_{ave}}{10^{14}\,cm^{-2}s^{-1}}\right)\left(\frac{300^o K}{T^o K}\right)^{1/2} \mathrm{MWatt}$$

Thin Slab solution

- Operate above the resonance region where n_3/n_1=0.1 a factor 7 larger than thermal neutron regime.

Operate with fast neutrons here



Thermal neutron regime

Situation more complicated. Do full MC

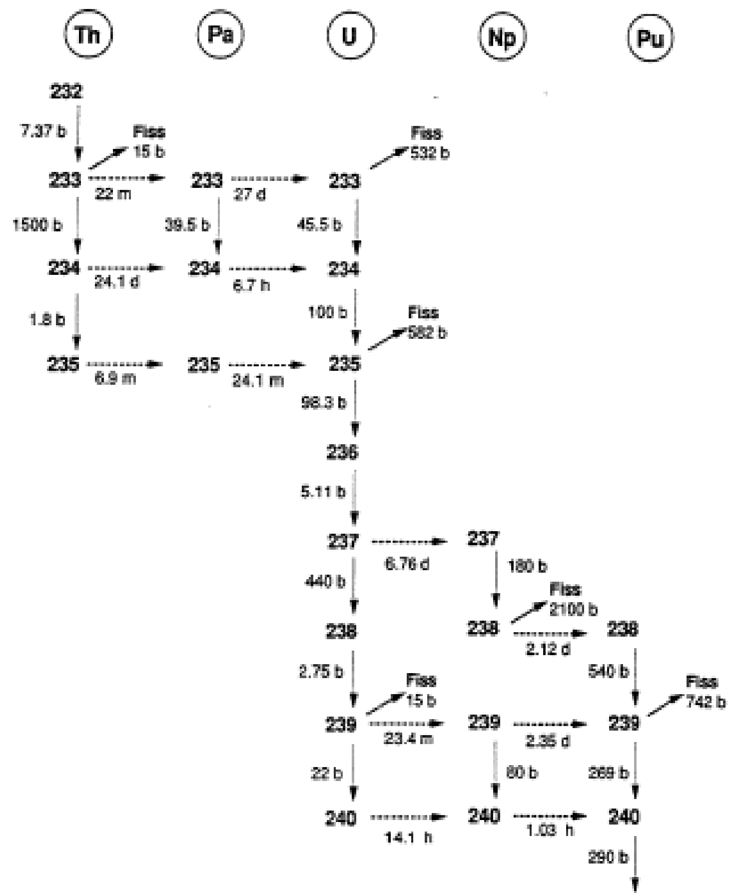


Figure 3

Pure thorium initial state.

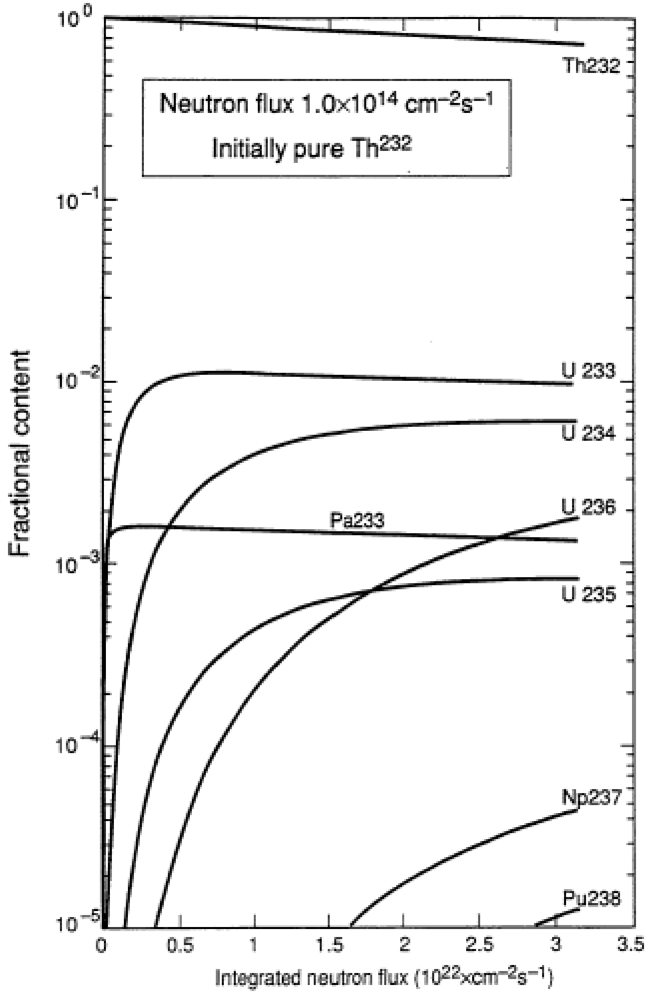


Figure 4

Thorium with initial ^{233}U as fuel

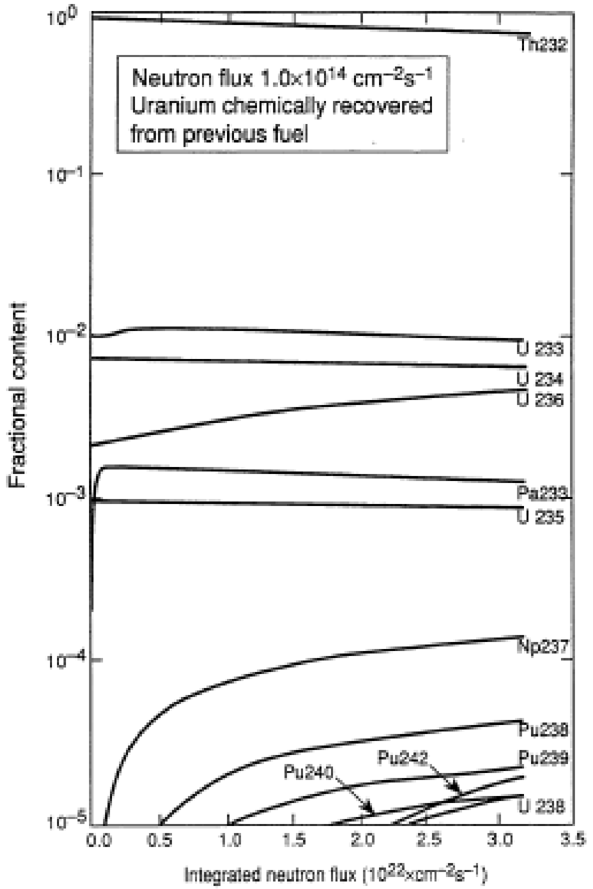


Figure 5

Natural Uranium 238 as fuel

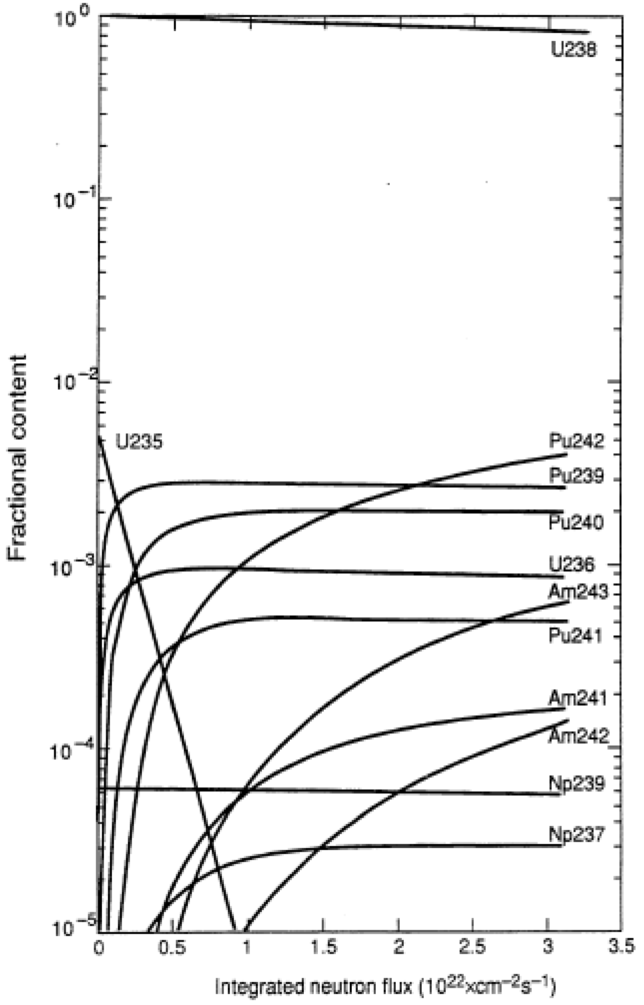
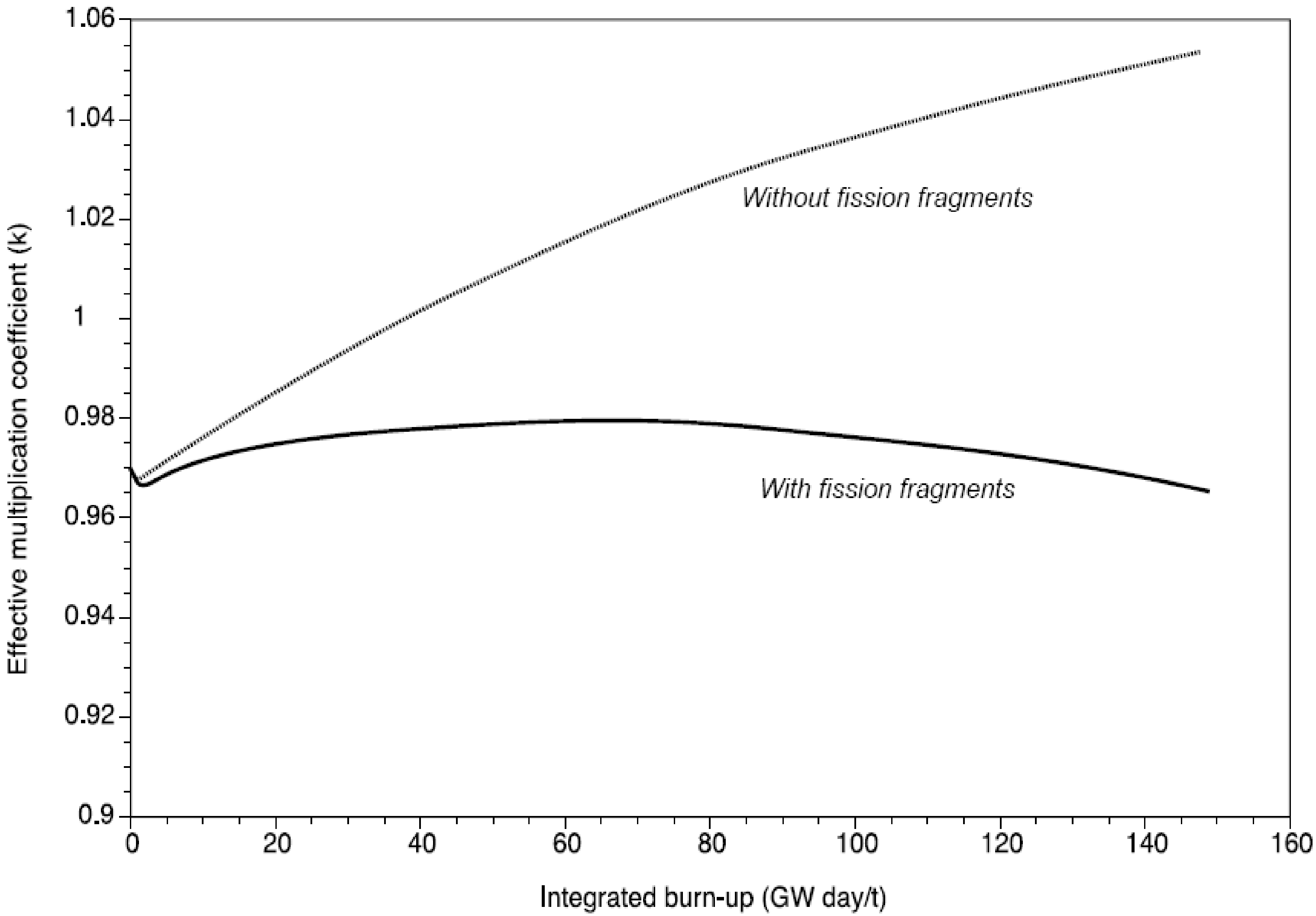


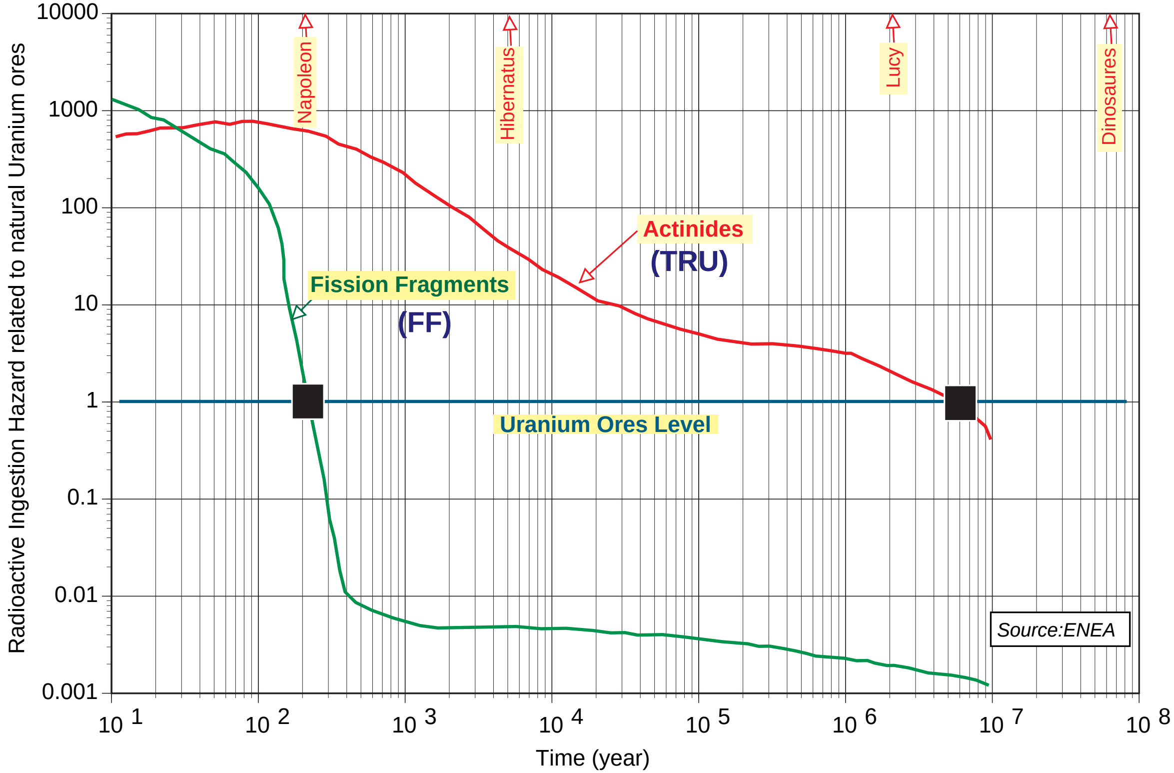
Figure 7

Variation of k with time for EA

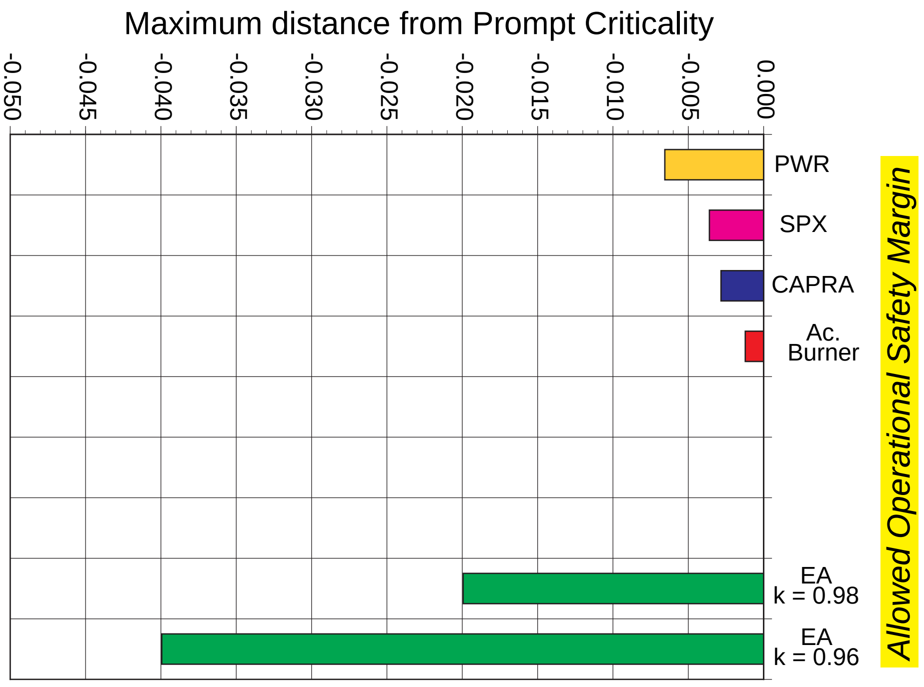


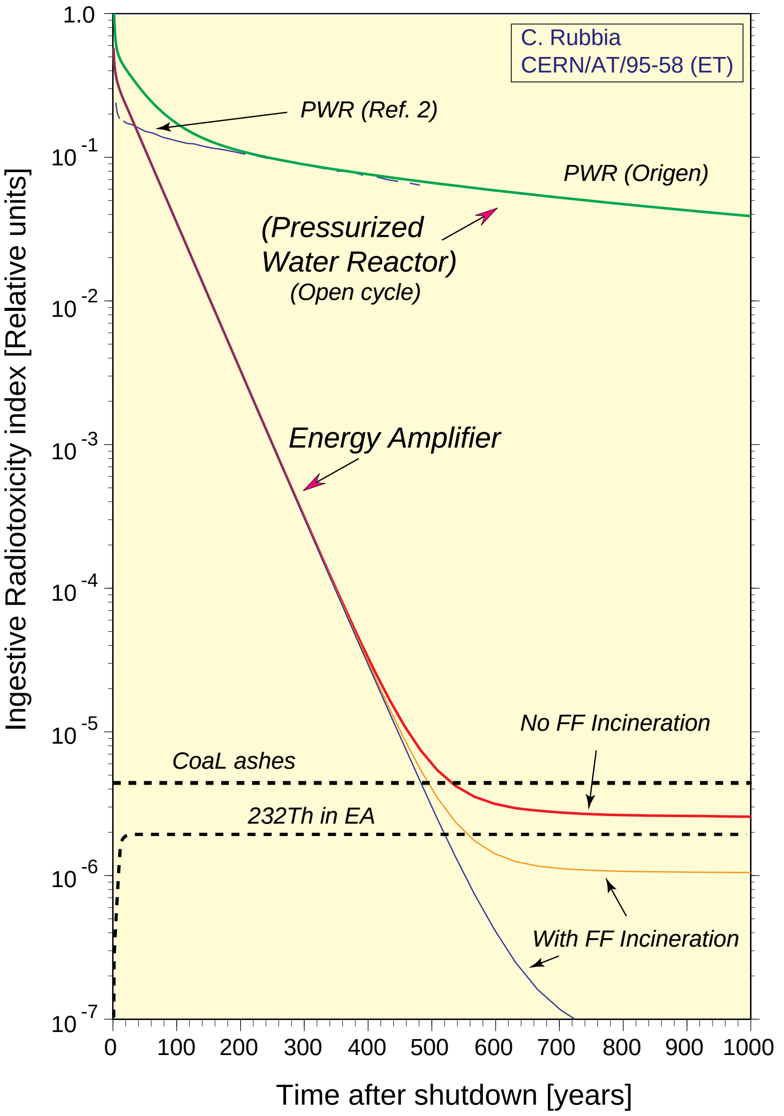
Waste problem a lot better than conventional reactors.

- Trends in radiotoxicity (degree of risk following ingestion) over the course of time for the two components of nuclear wastes from spent PWR fuel.



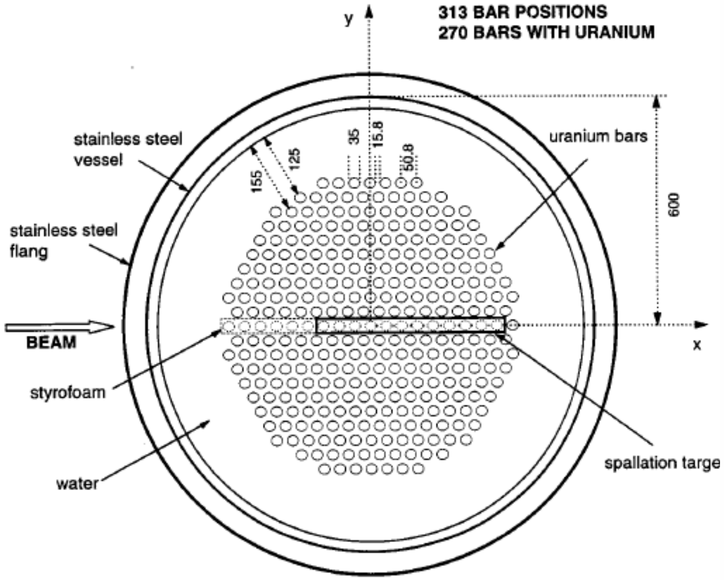
Advantages of the EA:





Safety margin with different systems
(fraction of delayed neutrons)
as compared with that of an Energy Amplifier

Experimental Verification-S.Andriamonje et al CERN/AT/94-95(ET) Phys.Lett.B348:697-709,1995



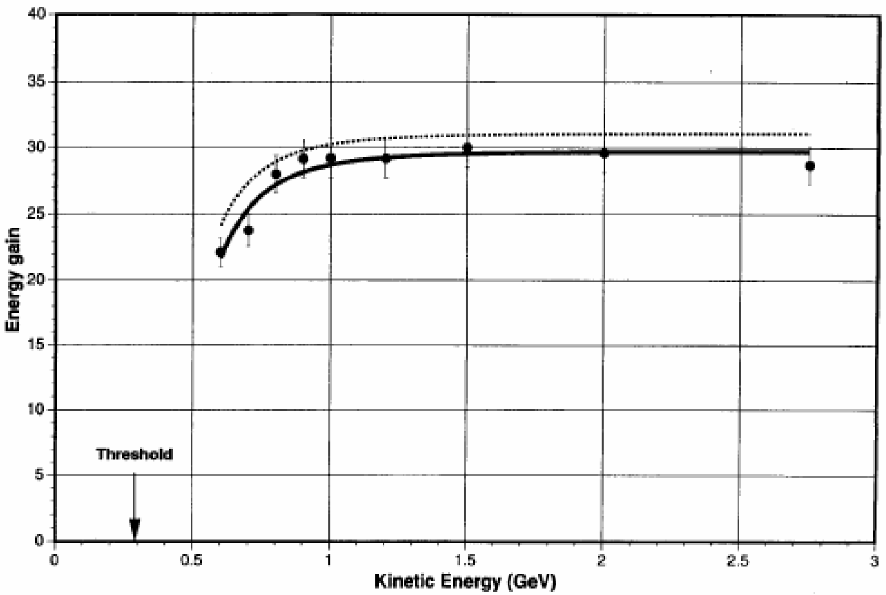


Figure 7

The Conceptual design

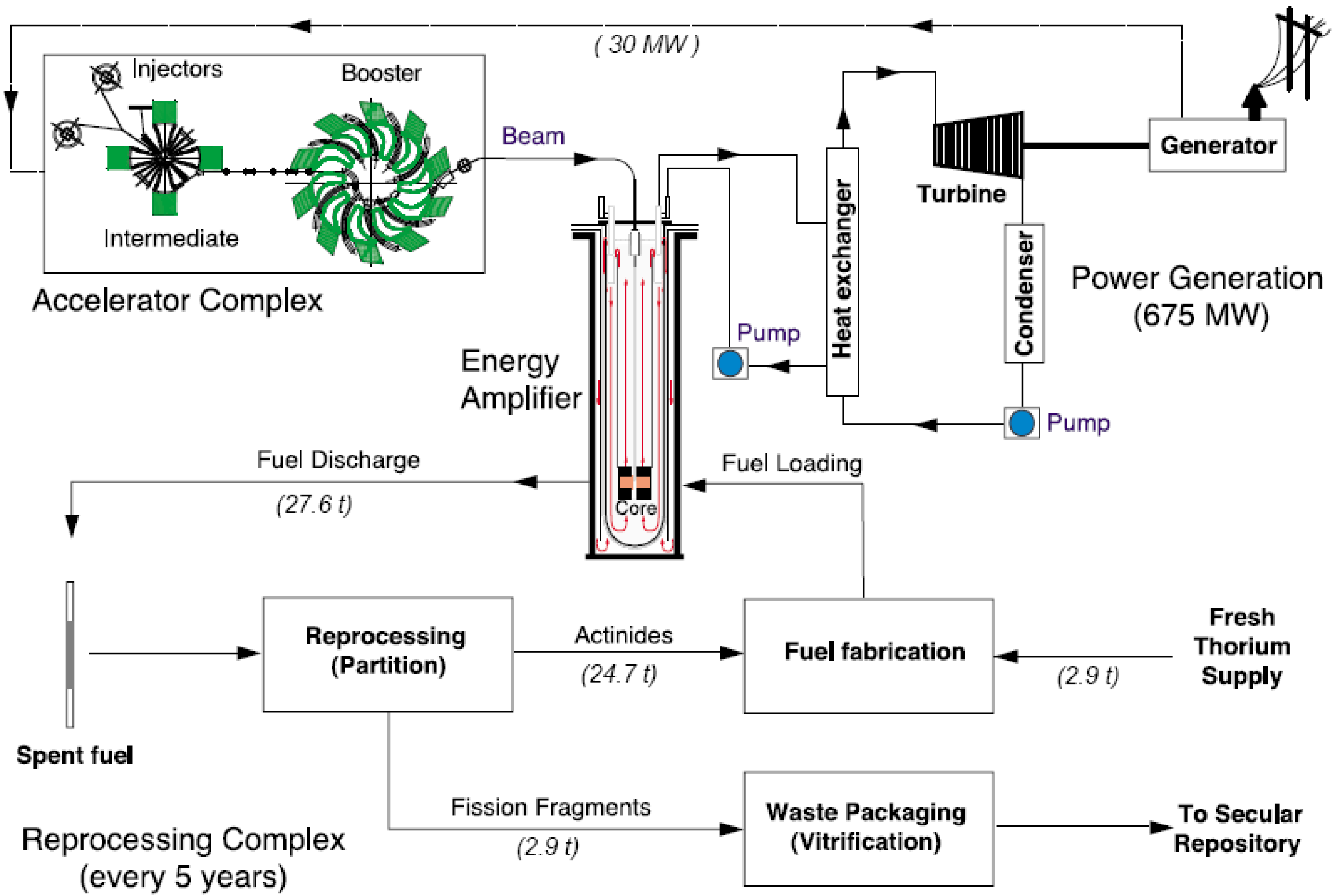


Figure 1.1

EA reactor details

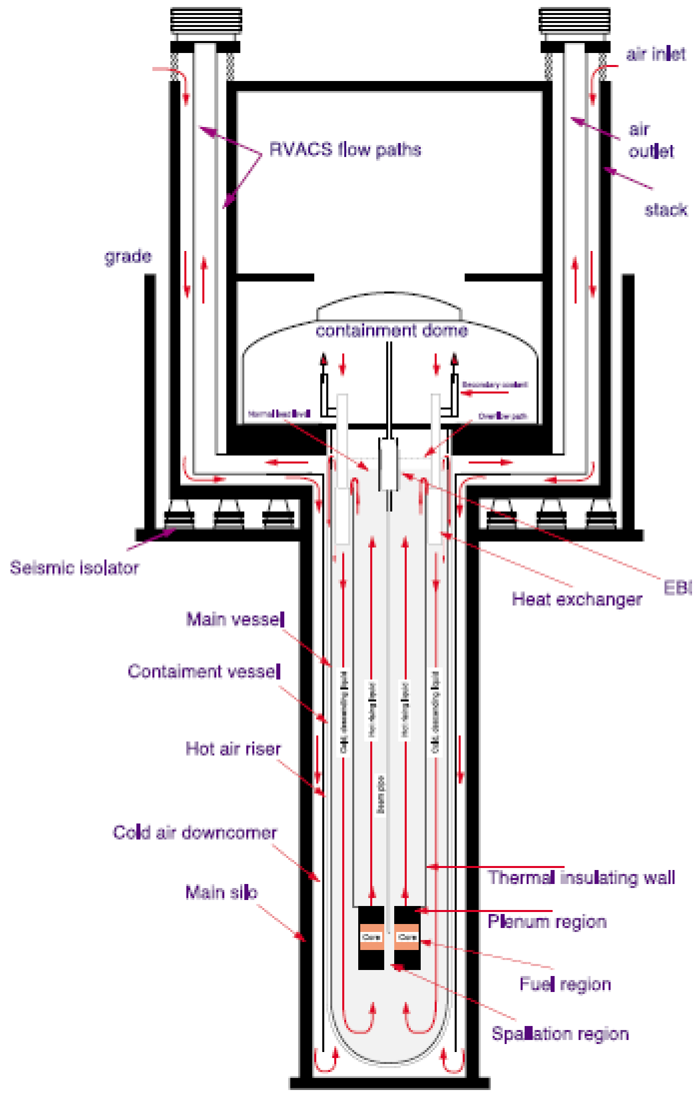
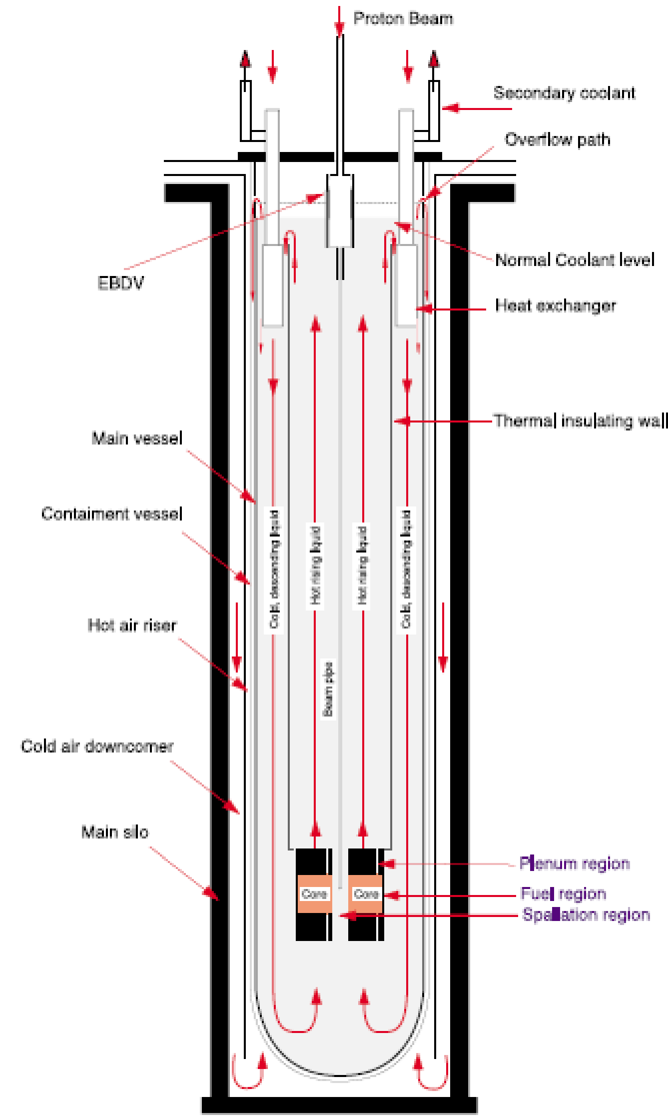
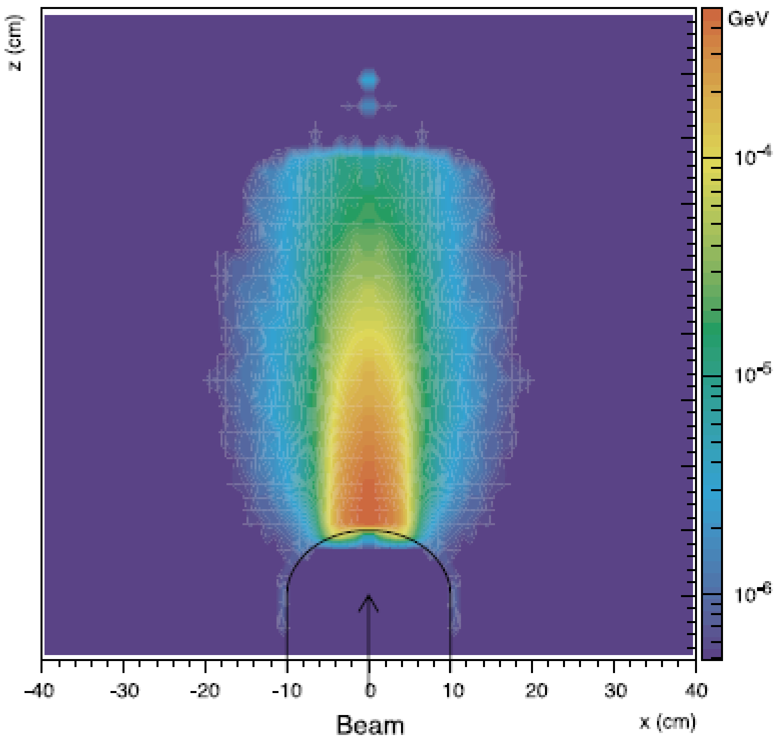


Figure 4.1a



Figure

Map of the energy deposit of a 1 GeV proton into the FEA target



- Each 10MW EA will produce ~700MW of electricity. A complex of 2 GWe will have three such reactors and machines. Mass production of machines and industrialization of EA systems will be needed.
- Also, each reactor may need to have more than one beam entry point to make the neutron flux more uniform. Window design easier.
- Much R&D needed here.

Spectrum of neutrons in various parts of EA– single beam

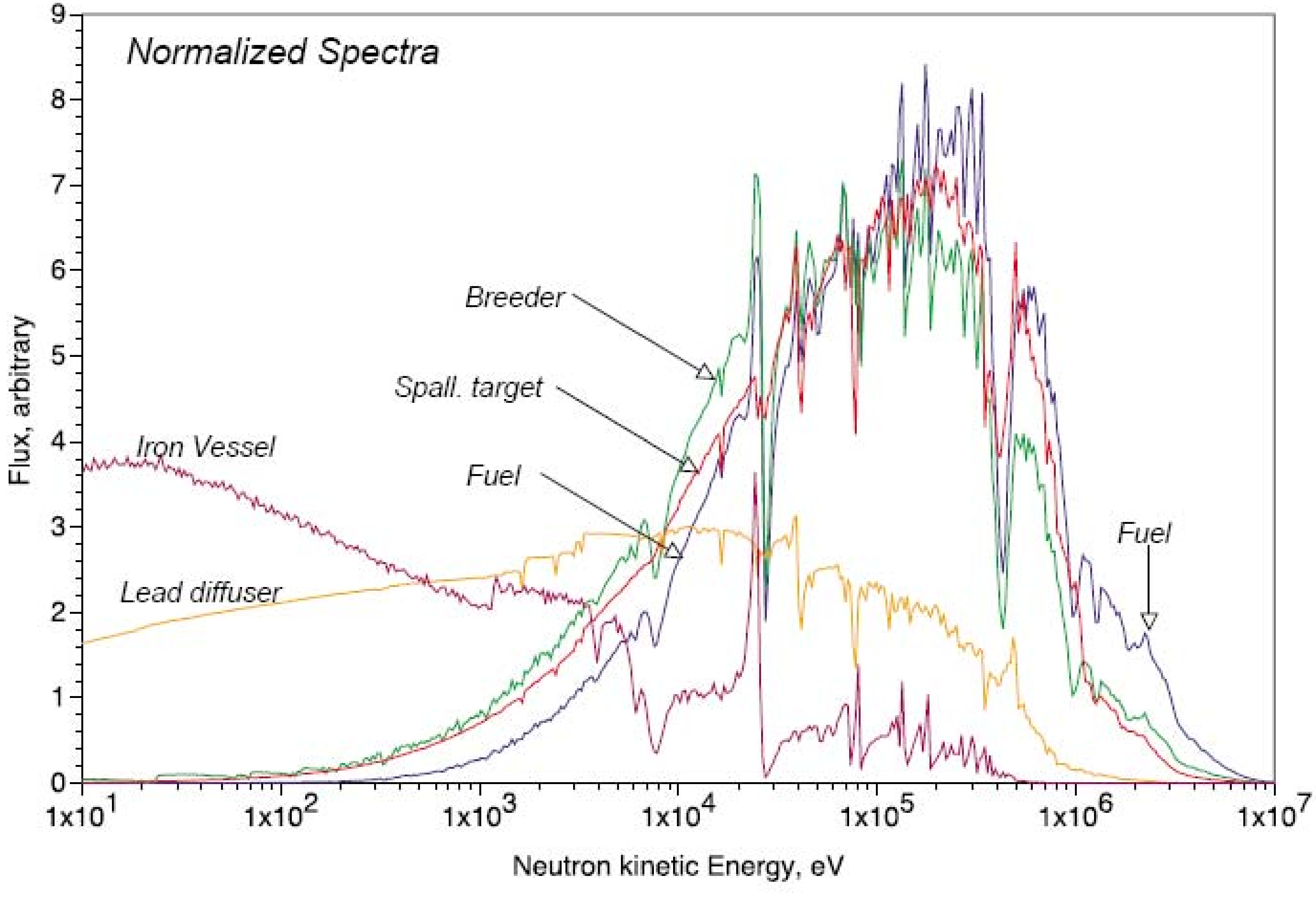
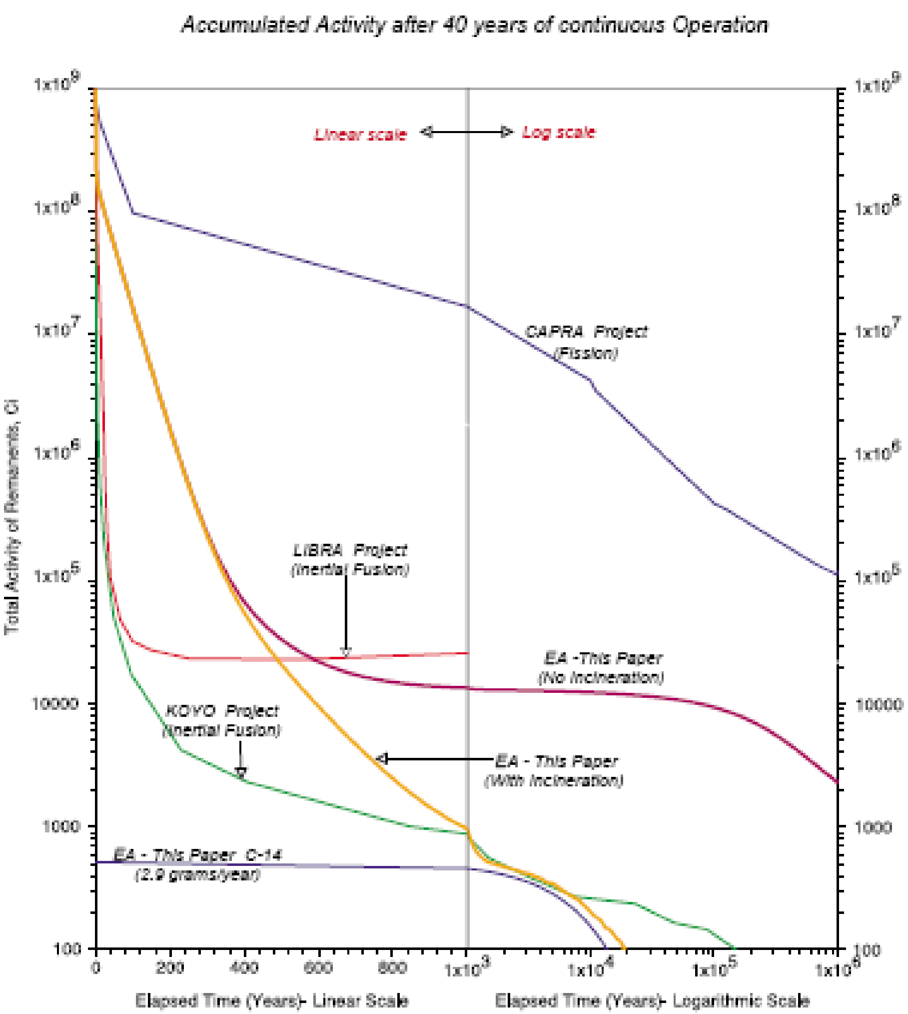


Figure 5.10

Waste Storage Times

- Fission Products are shorter lived (~30 years half life) than actinides(~10^5 years). So actinide wastes need storage for geological periods of time – Yucca mountain solution. EA produces less actinide waste so the storage time is reduced.



A preliminary Estimate of the Economic Impact of the Energy Amplifier-CERN/LH/96-01(EET)

Table 30. *Cost estimate of kWh*[7]*, cost ratios and limits.*

Energy source	*Costs in ¢/kWh* Best estimate	Lower limit	Upper Limit	*Ratio to EA* Best estimate	Lower limit	Upper Limit
Net disc. rate 5%						
Nuclear	4.3	4.0	4.6	2.1	1.6	2.9
Coal	5.2	4.9	5.5	2.6	2.0	3.4
Gas	5.3	5.0	5.6	2.6	2.0	3.5
EA	2.0	1.7	2.3	—	—	—
Net disc. rate 10%						
Nuclear	6.3	6.0	6.6	2.0	1.6	2.6
Coal	6.6	6.9	6.3	2.1	1.7	2.8
Gas	5.8	5.5	6.1	1.9	1.4	2.5
EA	3.1	2.6	3.6	—	—	—

Nay Sayers

Accelerator Driven Subcritical Assemblies

Report to :

Energy Environment and Economy Committee
U.S. Global Strategy Council

Richard Wilson
Harvard University

June 20th 1998

Abstract

Recently three groups in Gatchina, Russia, Los Alamos Scientific Laboratory USA, and CERN, Switzerland have proposed to use accelerator driven subcritical assemblies as sources of electricity as an alternate to nuclear fission reactors. By this means the proposers hope to avoid some of the problems that presently plague these reactors and prevent universal acceptance and expansion of the technology. These proposals are discussed and it is shown that there is no appreciable improvement in any real safety parameter, and although there may be an improvement in public acceptance this is very uncertain. An alternate proposal, to use these assemblies to transmute long lived transuranic actinides into other material is also discussed. It is pointed out that such transmutation may well be unnecessary. Nonetheless a modest research program along these lines may well be advisable.

2008– I spoke with RW at length- He is much more enthusiastic about the idea and days we should do vigorous R&D on the concept. He emphasized the issues in targetry as well as the accelerator.

The future of Nuclear power-Deutsch Moniz Study-2003

The U.S. Department of Energy should focus its R&D program on the once-through fuel cycle;

The U.S. Department of Energy should establish a Nuclear System Modeling project to carryout the analysis, research, simulation, and collection of engineering data needed to evaluate all fuel cycles from the viewpoint of cost, safety, waste management, and proliferation resistance;

The U.S. Department of Energy should undertake an international uranium resource evaluation program;

The U.S. Department of Energy should broaden its waste management R&D program;

The U.S. Department of Energy should support R&D that reduces Light Water Reactor (LWR) costs and for development of the HTGR for electricity application.

HTGR = High Temperature gas Cooled Reactor

Deutsch Moniz Study- Page 45

NOTES

1. See, for example, OECD Nuclear Energy Agency, Trends in the Nuclear Fuel Cycle ISBN 92-64-19664-1 (2001) and Nuclear Science Committee "Summary of the workshop on advanced reactors with innovative fuel," October 1998, NEA/NSC/DOC(99)2.
2. Several nations have explored breeder reactors, notably the U.S., France, Russia, Japan, and India.
3. Minor actinides are Americium (Am), Neptunium (Np), and Curium (Cm).
4. There are still other options, such as using an accelerator to produce neutrons in a sub-critical assembly.
5. The three surviving developmental breeder reactors are Phenix in France, Monju in Japan, and BN600 in Russia.
6. The MOX fueled plants are currently operating with only about a third of their core loaded as MOX fuel; the balance is UOX fuel. Hence only about 9 GWe are being generated in these reactors from the MOX fuel
7. Single pass recycle means that a discharged fuel batch is reprocessed once only.
8. TRU here refers to the U.S. definition: low-level waste contaminated with transuranic elements.
9. Due to process holding time, the actual amount of separated Pu inventory could be several or more years' worth of separations.
10. For additional details, see Appendix 5-E and Marvin Miller, *Uranium resources and the future of nuclear power,* Lecture notes, MIT, Spring 2001; for copies contact marvmiller@mit.edu.
11. Uranium resources, production, and demand ("The Red Book"), OECD Nuclear Energy Agency and International Atomic Energy Agency, 2001.
12. Such resources are also known as measured resources and reserves.
13. Uranium Information Center, "Nuclear Electricity", 6th edition, Chapter 3 (2000). Available on the web at http:www.uic.com.au/ne3.htm.
14. For example, recent research in Japan indicates that uranium in seawater — present in concentration of 3.3 ppb — might be recovered at costs in the range of $300–$500/kg.

Prof. Mujid Kazimi(MIT) in a talk (2008) at IIT stated that the DoE has moved away from this and is more amenable to breeder reactors.

IAEA Proceedings

IAEA-TECDOC-1319

Many articles on ADS and Thorium—eg

Too many to mention all

Thorium fuel utilization:
Options and trends

Proceedings of three IAEA meetings held in Vienna in 1997, 1998 and 1999

India, Japan, China actively interested in this approach.

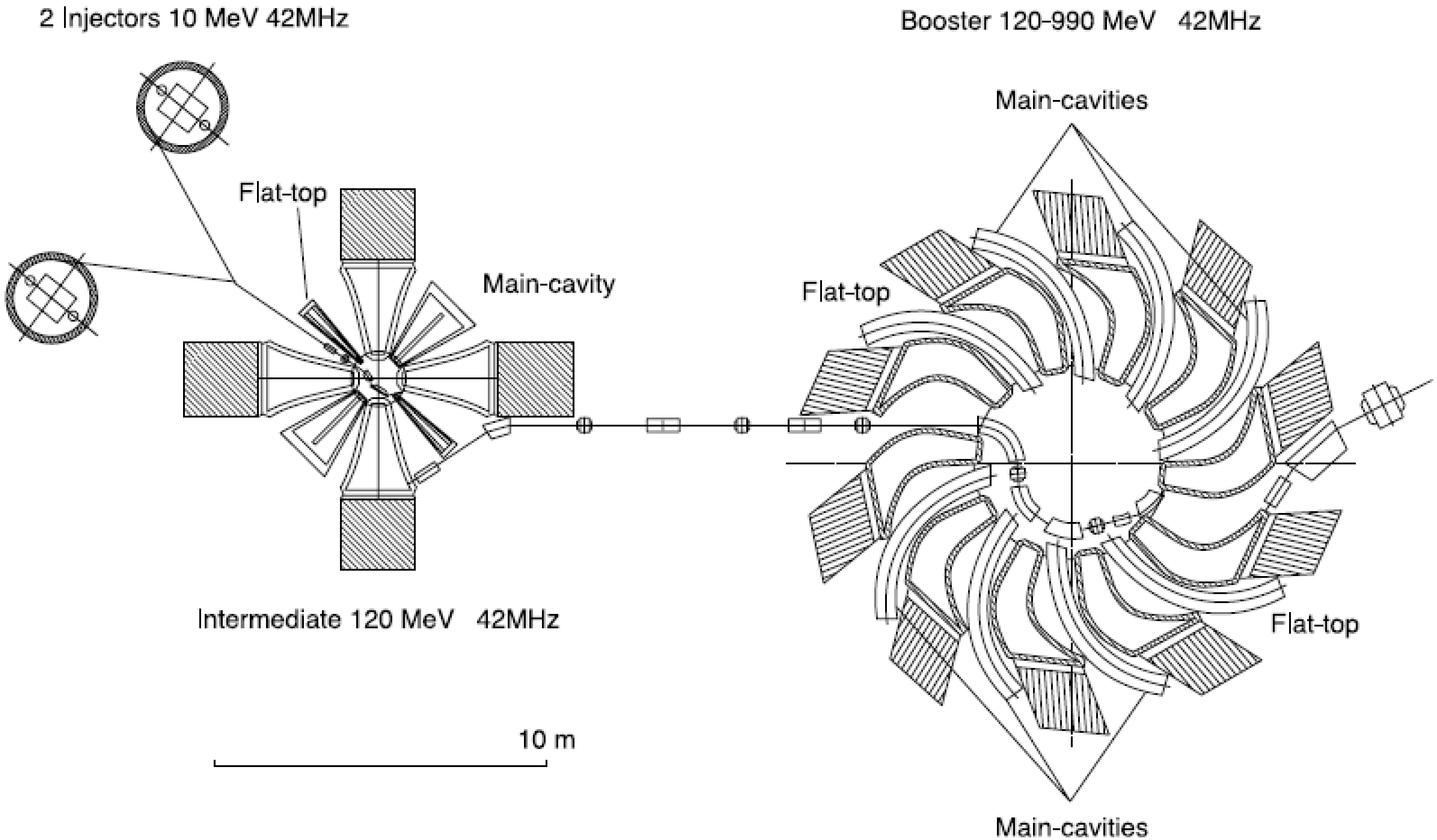
INTERNATIONAL ATOMIC ENERGY AGENCY IAEA

November 2002

Scenarios and Possibilities

- We will now attempt to show that superconducting rf technology may be a candidate used to make the 10-20 MWatt proton source for the project.

EA accelerator design- PSI type solution-1995 vintage-PSI has just started incineration studies with 1 MW beam in liquid target- Cern Courier



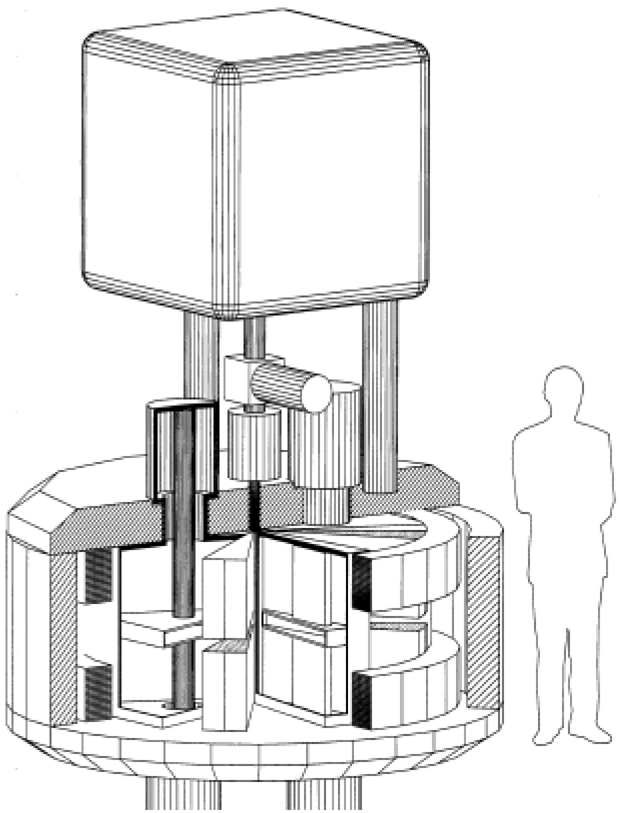
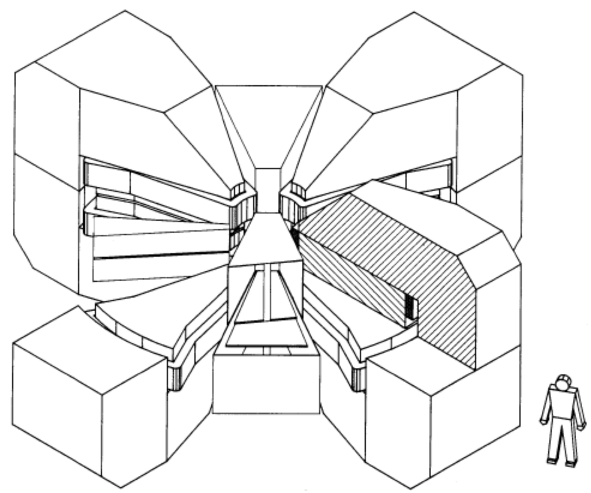
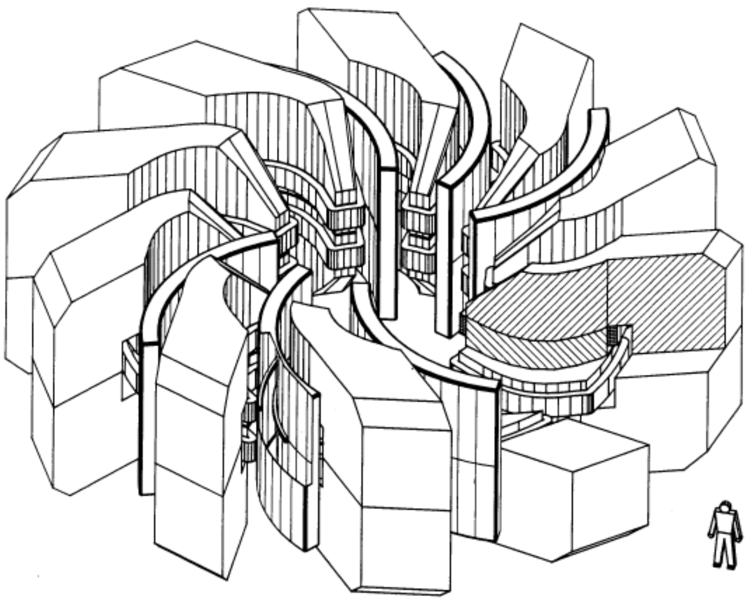


FIG. 3.2 General view of the injector cyclotron



Two stage Cyclotron solution

- 30 MW in and 10 MW out. Efficiency achievable (so claimed) because lot of the power costs are "overheads" and do not scale with beam intensity. So higher the beam power, the greater the efficiency. Can we pump 10 MW into the rf cavities? No one has done this to date. This is the greatest challenge for the EA and one that calls for accelerator R&D.



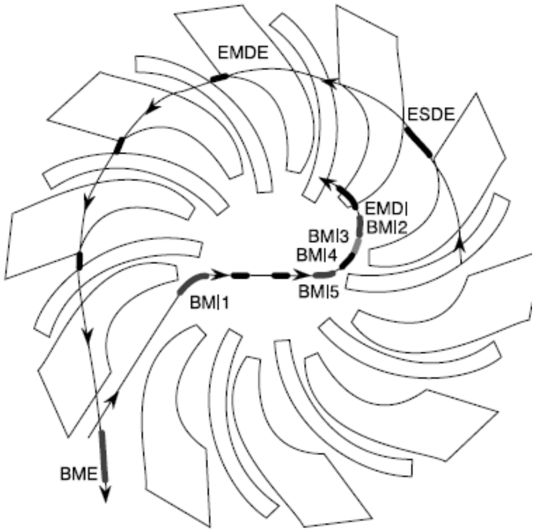


FIG. 3.9 Location of the injection and extraction channel elements of the booster ring cyclotron

Figure 3.7

Accelerator Design-1995 vintage

Tables and Figures relevant to Section 3.

Table 3.1 - Main parameters of the two ring cyclotrons

Accelerator	ISSC	BSSC
External diameter	10.5 m	16 m
Magnet iron weight	1000 tons	3170 tons
Magnet power	0.6 MW	2.7 MW
RF power	1.54 MW	12.5 MW

Table 3.2 - Main parameters for the 42 MHz design

Accelerator type	Injector	Intermediate	Booster
Injection	100 KeV	10 MeV	120 MeV
Extraction	10 MeV	120 MeV	990 MeV
Frequency	42 MHz	42 MHz	42 MHz
Harmonic	4	6	6
Magnet gap	6 cm	5 cm	5 cm
Nb. sectors	4	4	10
Sector angle (inj/ext)	15 /34 deg	26/31 deg	10/20 deg
Sector spiral extraction	0 deg	0 deg	12 deg
Nb. cavities	2	2	6
Type of cavity	delta	delta	single gap
Gap Peak Voltage injec.	110 KVolt	170 KVolt	550 KVolt
Gap Peak Voltage extrac.	110 KVolt	340 KVolt	1100 KVolt
Radial gain per turn ext.	16 mm	12 mm	10 mm

Table 3.3 - Main parameters of the injector cyclotrons

Injection energy	100 keV
Extraction energy	10 MeV
Number of sectors	4
Pole radius	0.75 m
Total yoke height	1.2 m
Maximal field in the sectors	1.5 T
Number of main RF cavities	2
RF frequency	42 MHz
Harmonic number	4
Peak Voltage	113 kV
Losses per cavity	17 kW
Number of flat-top cavities	2
RF frequency of flat-top cavities	126 MHz
Peak Voltage of flat-top cavities	13 kV
Axial Deflector field	15 kV/cm

Table 3.4 - Main characteristics of the ISSC cyclotron RF cavities

	Main cavities	Flat-top cavities
Number of cavities	2	2
Type of cavity	$\lambda/2$, double-gap, tapered walls	$\lambda/2$, double-gap, tapered walls
Frequency	42.0 MHz	126.0 MHz (h=3)
Cavity height	2.6 m	1.0 m
Cavity length	2.6 m	2.45m
Voltage at injection	2×170 kV	2×20 kV
Voltage at extraction	2×340 kV	2×40 kV
Quality factor	13000	11000
Losses/cavity	220 kW	9 kW
Beam power/cavity	550 kW	-65 kW
Total power/cavity	770 kW	-56 kW
Total electric power/cavity (70% efficiency)	1.1 MW	13 kW

Can the 8GeV PD be modified to do 10MW?

- It is straightforward.
- The design would be more comparable to the RIA driver linac, which was CW and could put out something like 0.5MW for 800 MeV protons if I recall correctly.
- The FFAG machine is also very attractive for this kind of applicaion.
- keep smiling,
- -Bill
- On 3/9/07, Rajendran Raja <raja@fnal.gov> wrote: Hi Bill,

  Good to see you at Fermilab the other day. I am looking into the possibility of using SCRF to produce a 10 Megawatt 1 GeV Linac. That is 10mA of beam, CW.

  The design of your 8 GeV proton driver, delivers 10mA but at 15Hz yielding 2 MWatts. How difficult do you think it would be to get 10mA CW at 1GeV?

  The idea is to investigate the feasibility of an Energy Amplifier using Thorium.

  regards
  Raja

--
G. William (Bill) Foster
Cell: (630) 853-1749
Home: (202) 216-0691
Email: GWFoster@gmail.com
Web: http://gwfoster.com

	8 GeV Initial	8 GeV {Ultimate}	SNS (Spallation Neutron Source)	TESLA-500 (w/ FEL)	TESLA-800
c Energy	8 GeV	8 GeV	1 GeV	500 GeV	800 GeV
cle Type	H^-, e+, or e^-	H^-, e+, or e^-	H^-	e+, e^-	e+, e^-
n Power	0.5 MW	2 MW	1.56 MW	22.6 MW	34 MW
Power (incl. warm FE)	5.5 MW	13 MW	~15 MW	97 MW	150 MW
n Pulse Width	3 msec	1 msec	1 msec	0.95 msec	0.86 msec
n Current(avg. in pulse)	8.6 mA	26 mA	26 mA	9.5 mA	12.7 mA
e Rate	2.5 Hz	10 Hz	60 Hz	5(10) Hz	4 Hz
perconducting Cavities	384	384	81	21024	21852 / 2
yomodules	48	48	23	1752	1821
ystrons	12	33	93	584	1240
vities per Klystron(typ)	36	12	1	36	18
ty Surface Fields (max)	52 MV/m	52 MV/m	35 MV/m	46.8 MV/m	70 MV/m
lerating Gradient(max)	26 MV/m	26 MV/m	16 MV/m	23.4 MV/m	35 MV/m
ating Frequency (MHz)	1300, 325	1300, 325	805, 402.5	1300	1300
c Active Length	614 m	614 m	258 m	22 km	22 km

Need to go from pulsed to CW linac.

SCRF Q factor vs normal rf Q factor

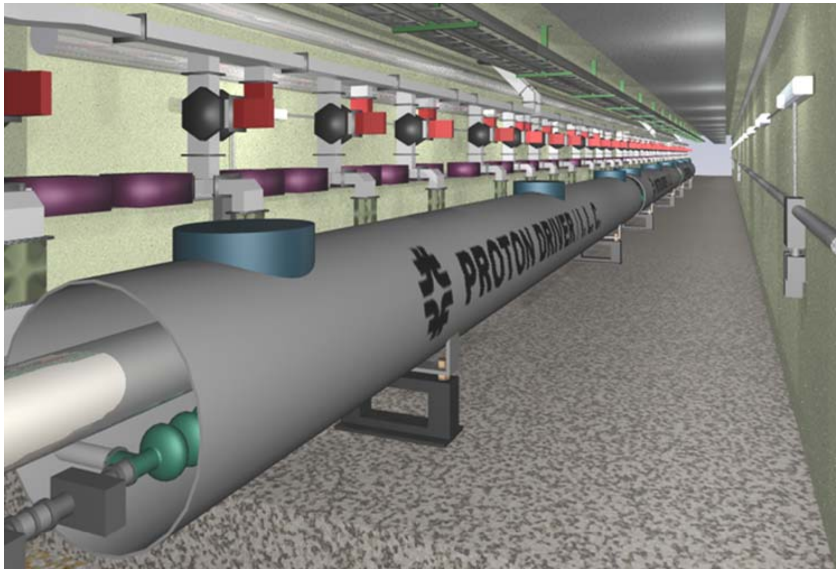
- Q factor of an oscillating system is defined as

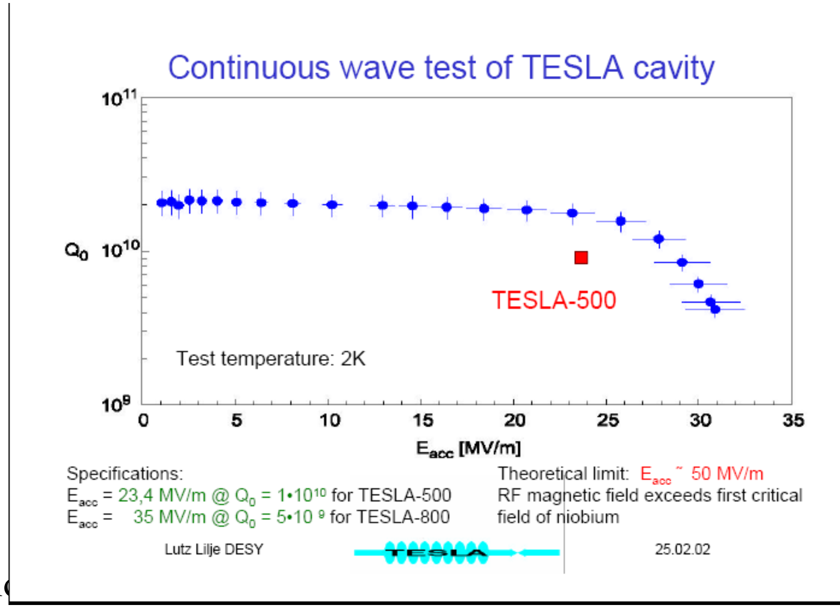
$$Q = \omega \frac{\text{Energy stored in cavity}}{\text{Power lost in cavity}}$$

$$\text{eg } Q = \frac{1}{R}\sqrt{\frac{L}{C}} \text{ for a resonant tuned circuit}$$

- SCRF Q factors ~2.0E10
- Normal rf Q factors are of order 3E5, 5E5.

- So SCRF has an advantage of ~1E5 in terms of energy dissipated in the rf itself. However, one needs to factor in cryogenics, klystron losses etc.





8 GeV PD parameters

- Present proton Driver design takes ~250m to get to 1 GeV and use three different flavors of SCRF β=0.47,0.61,0.81) to do so.

LINAC SEGMENT LENGTHS	8 GeV Linac				
	Length	Eout	# Modules		
Ion Source (H- and P)	~0.1 m	0.065 MeV			
Low-Energy Beam Transport (LEBT)	~0.1 m	0.065 MeV			
Radio-Frequency Quad (RFQ)	~4.0 m	3.0 MeV	TBD	RFQ modules	
Medium-Energy Beam Transport (MEBT)	3.6 m	3.0 MeV	4	Rebuncher Cavities	
Room Temperature Front End (RT-TSR)	10.4 m	15.8 MeV	21	Room Temp 3-Spoke Resonators	
SCRF Single-Spoke Resonator (SSR)	12.5 m	33 MeV	1	Cryomodules	
SCRF Double-Spoke Resonator (DSR)	17.2 m	110 MeV	2	Cryomodules	
SCRF Triple-Spoke Resonator(TSR Baseline)	64.0 m	400 MeV	6	Cryomodules	Either 3-Spoke or Elliptical for 110-400 MeV
Beta=0.47 SCRF (Low Beta Elliptical option)	18.8 m	175 MeV	2	Cryomodules	
Beta=0.61 SCRF (Medium Beta Elliptical Opt.)	38.5 m	400 MeV	4	Cryomodules	
Beta=0.81 SCRF (High Beta Elliptical)	70.1 m	1203 MeV	6	Cryomodules	
Beta=1 SCRF (1300 MHz "ILC" Main Linac)	438.3 m	8000 MeV	36	Cryomodules	
LINAC ACTIVE LENGTH *	**613.6 m**	**8000 MeV**			
Transfer Line to Ring	972.5 m	8000 MeV	47	half-cells (quads)	
Tunnel to Front End Equipment Drop	20.0 m			TBD	
TUNNEL TOTAL LENGTH *	**1606.0 m**				

What needs to change to get to 10MW at 1GeV/c?

- Courtesy Bob Webber
- 50 keV ion source
- RFQ to 2.5 MeV
- Copper Spoke Cavities to 10 MeV
- β = 0.2 Superconducting Single Spoke Cavities to ~ 30 MeV
- β = 0.4 SC Single Spoke Cavities to ~ 125 MeV
- β = 0.6 SC Triple Spoke Cavities to ~ 400 MeV
- β = 0.8 SC "Squeezed" ILC Cavities to > 1 GeV

All structures except 1300 MHz "squeezed" ILC cavities are 325 MHz

Scale Comparisons- B. Webber

	Proton Driver Phase 1	Proton Driver Phase 2	APT Linac (LANL Tritium)	Energy Amplifier Linac
Beam Current	26 mA pulse 62 μA average	9 mA pulse 0.25 mA average	100 mA	10 mA
Pulse Length	3 msec	1 msec	CW	CW
Repetition Rate	2.5 Hz	10 Hz	CW	CW
Beam Duty Factor RF Duty Factor	0.75% 1%	1% 1.3%	CW CW	CW CW
1 GeV Beam Power	0.0625 MW	0.25 MW	100 MW	10 MW

Compare to FRIB capabilities as well

What of Proton Driver Design Works- B.Webber

- Peak energy is not an issue
- Peak beam current capabilities are adequate
- Low emittance design of PD should satisfy beam loss control requirements of EA Linac

What of PD Design Does Not Work- B.Webber

- Ion Source - not designed for CW operation
  - » (LEDA proof-of-principle) (LEDA—Low Energy Demonstration Accelerator)
- RFQ - not designed for CW operation
  - » (LEDA proof-of-principle)
- Room Temp. Cavities (2-10 MeV) - not designed for CW operation
- Superconducting Cavity Power Couplers - not designed for CW
- Entire RF power system - not designed for CW operation
  - » Pulsed modulator → DC power supplies (LEDA proof-of-principle)
  - » Klystrons (LEDA partial proof-of-principle)
  - » RF Distribution System
  - » Fast Phase Shifters??
- Cryogenics System - not sized for CW RF operation
- Power and cooling water utilities infrastructure is inadequate
- Controls and Machine Protection System
- Radiation Shielding?

AC Power requirements for a Superconducting 1 GeV 10 MW Linac/Al Moretti– Preliminary

There are 87 Superconducting cavities at 4 K and 18 cavities at room temperature plus Rt. RFQ at 325 MHz and 50 ILC superconducting cavities at 1.8 K to reach 1 GeV. I have used data from reports of the PD, XFEL and Cryo group to derive this AC Power Table below. All Cavities and RFQ are made superconducting in this case.

klystron	*Eff = 64 %*	Power to Beam 10 MW	Mains Power 15.6 MW
Water tower cooling	Eff=80 %	15.6 MW/.80	7 MW
4 Deg Load	6100 W	*AC Power ratio 200/1*	1.2 MW
2 K Load	1250	*AC Power ratio 800/1*	1 MW
70 K load	5580	*AC Power ratio 20/1*	0.1 MW
HOM 2 K load	116	*AC Power ratio 800/1*	0.1 MW
		TOTAL	25 MW

Muon Acceleration topologies may be applied to EA proton source as well

- Slide from A. Bogacz.
- Multiple beam pipes and cavities all in one linear section. Multiple arcs. Shortened linear section. Shared cryogenics.

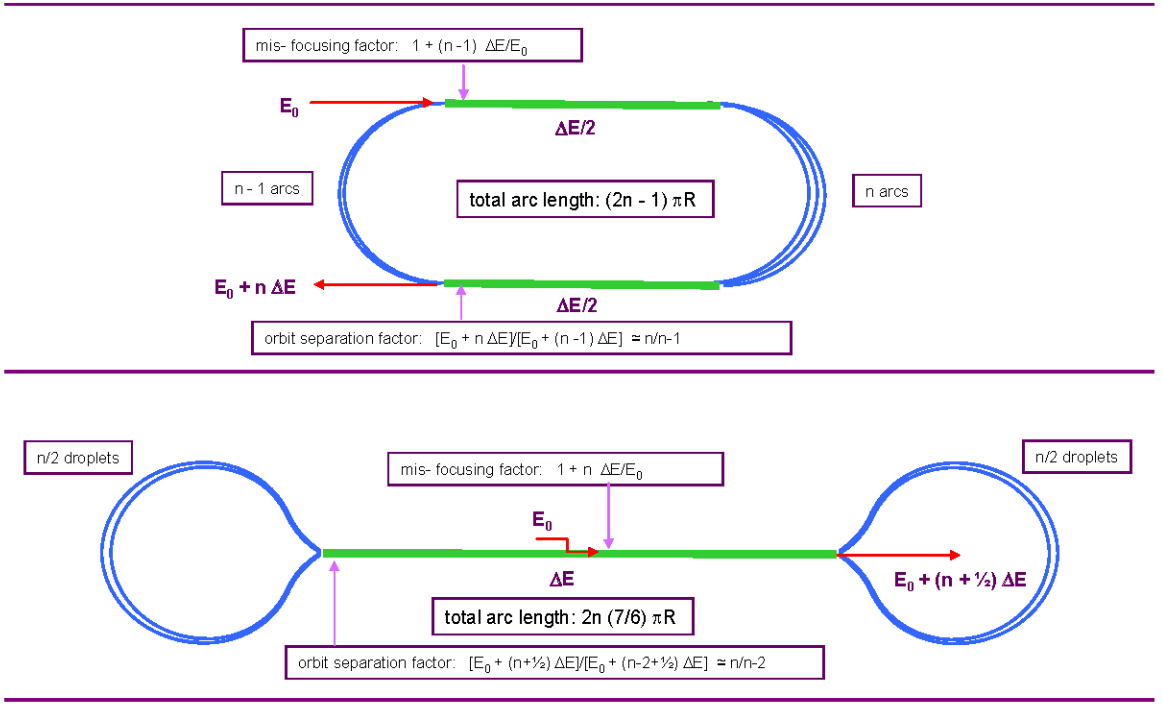


Figure 1. Performance merits of the 'Racetrack' and 'Dogbone' RLA configurations

FFAG Designs

- Scaling and Non- scaling FFAG (Fixed Field Alternating Gradient) accelerator. Large momentum acceptance. Sato et al, EPAC04 conference.

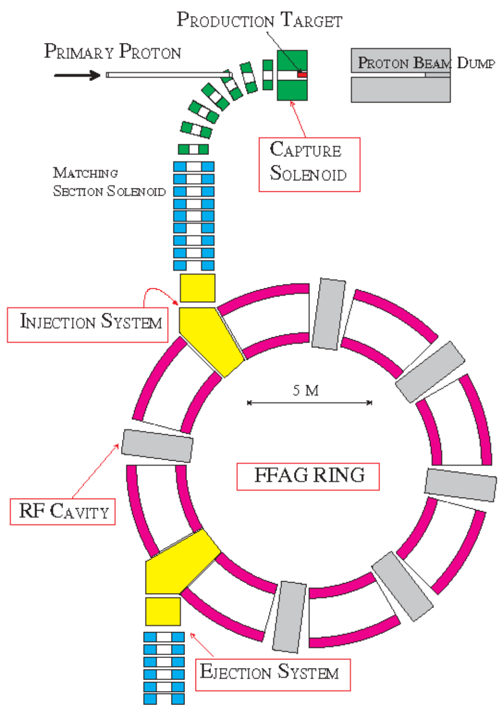


Figure 1: A schematic layout of PRISM

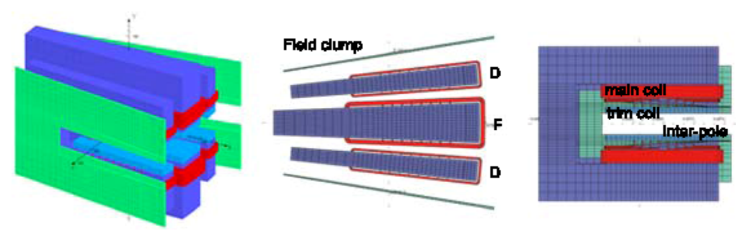
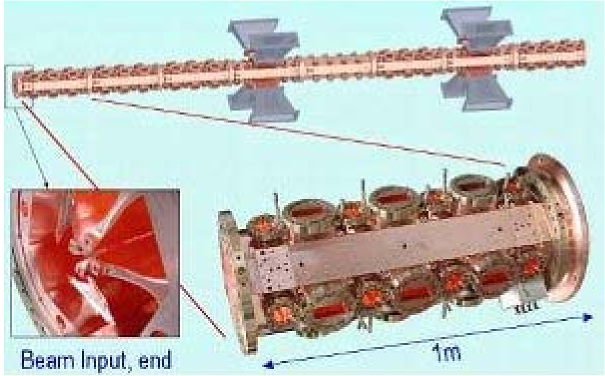


Figure 3: Schematic views of a PRISM-FFAG magnet. A bird's-eye view (left), a top view (center) and a side view (right).

International Fusion Materials Irradiation Facility (IFMIF)- 125mA x2 14 MeV Deuterons

Ion Source SACLAY+ LEBT + RFQ Saclay below

ECR ion source JAERI+ RFQ Jaeri below



Physics potential of an intense proton source

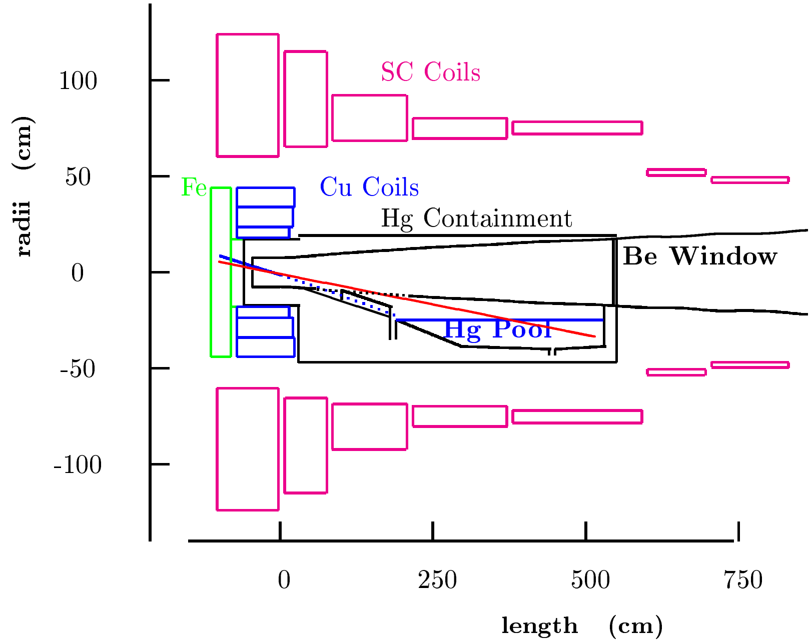
- 1) **Recent progress in neutrino factory and muon collider research within the Muon collaboration.**
  By Muon Collider/Neutrino Factory Collaboration (Mohammad M. Alsharoa *et al.*). FERMILAB-PUB-02-149-E, JLAB-ACT-03-07, 2002. 103pp.
  Published in **Phys.Rev.ST Accel.Beams 6:081001,2003**.
  e-Print: **hep-ex/0207031**
  TOPCITE = 100+
  References | LaTeX(US) | LaTeX(EU) | Harvmac | BibTeX | Keywords | Cited 120 times

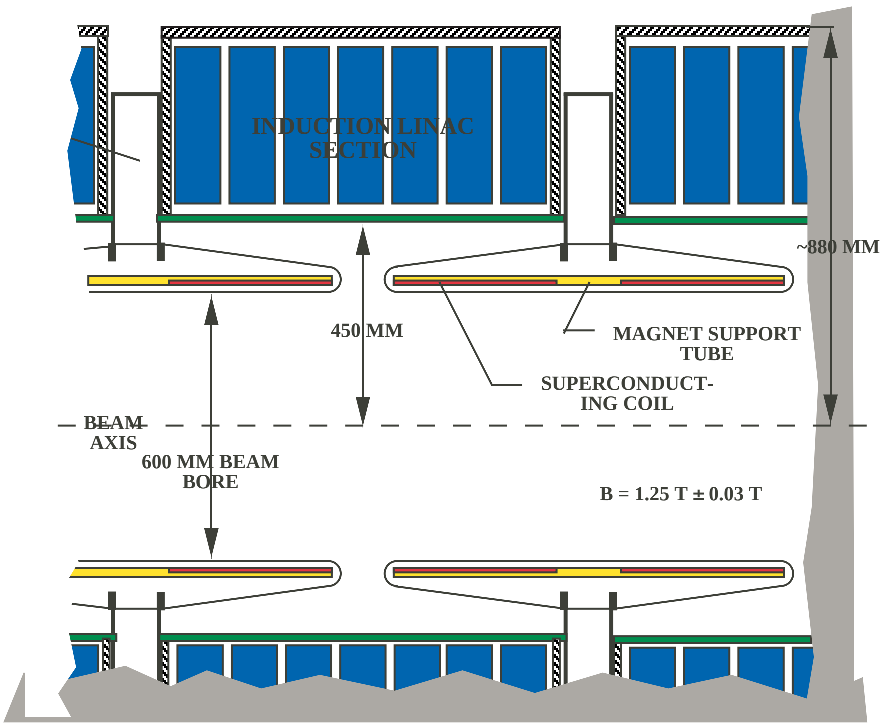
- 2) **The Program in muon and neutrino physics: Super beams, cold muon beams, neutrino factory and the muon collider.**
  Rajendran Raja *et al.* FERMILAB-CONF-01-226-E, Aug 2001. 130pp.
  Contributed to APS / DPF / DPB Summer Study on the Future of Particle Physics (Snowmass 2001), Snowmass, Colorado, 30 Jun - 21 Jul 2001.
  e-Print: **hep-ex/0108041** References | LaTeX(US) | LaTeX(EU) | Harvmac | BibTeX | Keywords | Cited 18 times

- 3) **Status of muon collider research and development and future plans.**
  Charles M. Ankenbrandt *et al.* BNL-65623, FERMILAB-PUB-98-179, LBNL-41935, LBL-41935, Aug 1999. 95pp.
  Published in **Phys.Rev.ST Accel.Beams 2:081001,1999**.
  e-Print: **physics/9901022**
  TOPCITE = 250+ References | LaTeX(US) | LaTeX(EU) | Harvmac | BibTeX | Keywords | Cited 322 times

- Physics Possibilities
  - » Staged Physics
  - » First Stage-Cold Muons
  - » Second Stage-Neutrino Factory
  - » Third Stage-Muon Collider
    - Higgs factory
    - >3TeV CMS Muon Collider—Energy frontier

Stage 2 collection , phase rotation





Stage 2

- Muon beam is phase rotated and transversely cooled. Central momentum 220MeV/c, transverse normalized emittance of 2.7 mm-rad and an rms energy spread of ~4.5%. 4x 10^{20} muons per year.
- Cold muon physics can start.

Table 3.2: Some current and future tests for new physics with low-energy muons (from [73], [80], and [81]). Note that the "Current prospects" column refers to anticipated sensitivity of experiments currently approved or proposed; "Future" gives estimated sensitivity with Neutrino Factory front end. (The d_μ measurement is still at the Letter of Intent stage and the reach of experiments is not yet entirely clear.)

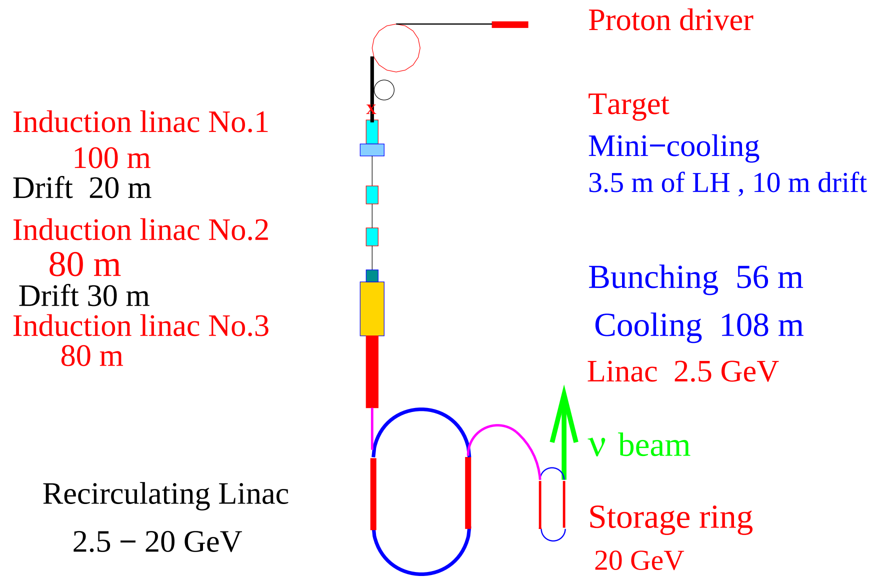
Test	Current bound	Current prospects	Future
$B(\mu^+ \to e^+\gamma)$	$< 1.2 \times 10^{-11}$	$\approx 5 \times 10^{-12}$	$\sim 10^{-14}$
$B(\mu^-\mathrm{Ti} \to e^-\mathrm{Ti})$	$< 4.3 \times 10^{-12}$	$\approx 2 \times 10^{-14}$	$< 10^{-16}$
$B(\mu^-\mathrm{Pb} \to e^-\mathrm{Pb})$	$< 4.6 \times 10^{-11}$		
$B(\mu^-\mathrm{Ti} \to e^+\mathrm{Ca})$	$< 1.7 \times 10^{-12}$		
$B(\mu^+ \to e^+e^-e^+)$	$< 1 \times 10^{-12}$		
d_μ	$(3.7 \pm 3.4) \times 10^{-19}\, e{\cdot}\mathrm{cm}$	$10^{-24}\, e{\cdot}\mathrm{cm}$?	?

Table 3.3: Some examples of new physics probed by the nonobservation of $\mu \to e$ conversion at the 10^{-16} level (from [73]).

New Physics	Limit
Heavy neutrino mixing	$\lvert V^*_{\mu N} V_{eN}\rvert^2 < 10^{-12}$
Induced $Z\mu e$ coupling	$g_{Z_{\mu e}} < 10^{-8}$
Induced $H\mu e$ coupling	$g_{H_{\mu e}} < 4 \times 10^{-8}$
Compositeness	$\Lambda_c > 3,000\,\mathrm{TeV}$

Stage 3, Stage 4

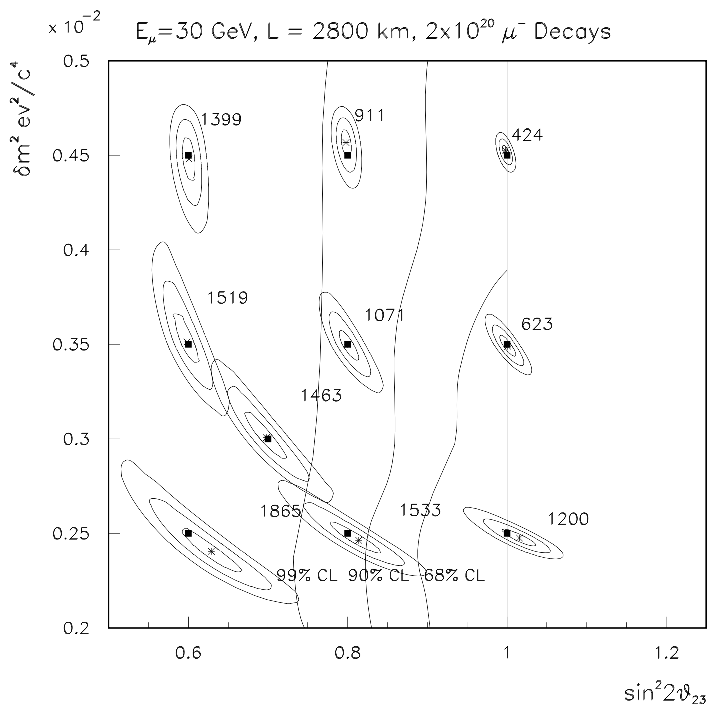
- Stage 3-Accelerate muons to 2.5GeV.
- g-2, edm of muons can start. (needs 3.1 GeV magic momentum)
- Stage 4- Full neutrino factory



Neutrino Factory Physics Potential

- Determination of δm^2_{32} $\sin^2 2\theta_{23}$ with high accuracy
- Matter effects and sign of δm^2_{32}
- Observation of CP violation in the lepton sector. Measurement of the phase δ. Importance of CP violation in the lepton sector to baryon asymmetry in the early universe.
- Non-oscillation physics.

Neutrino factory determination of oscillation parameters

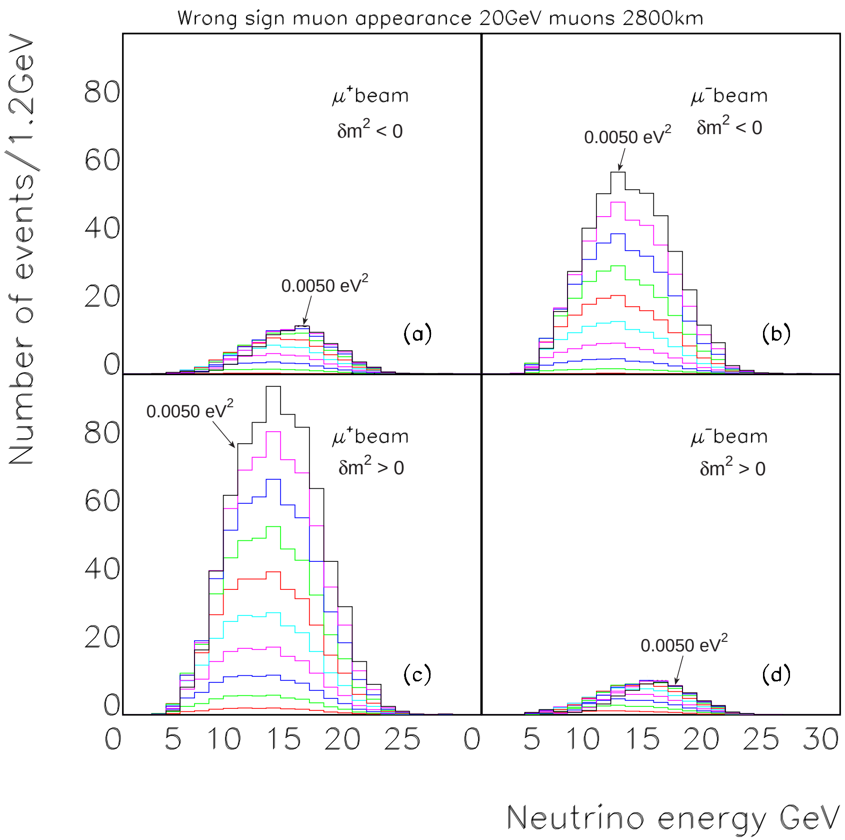


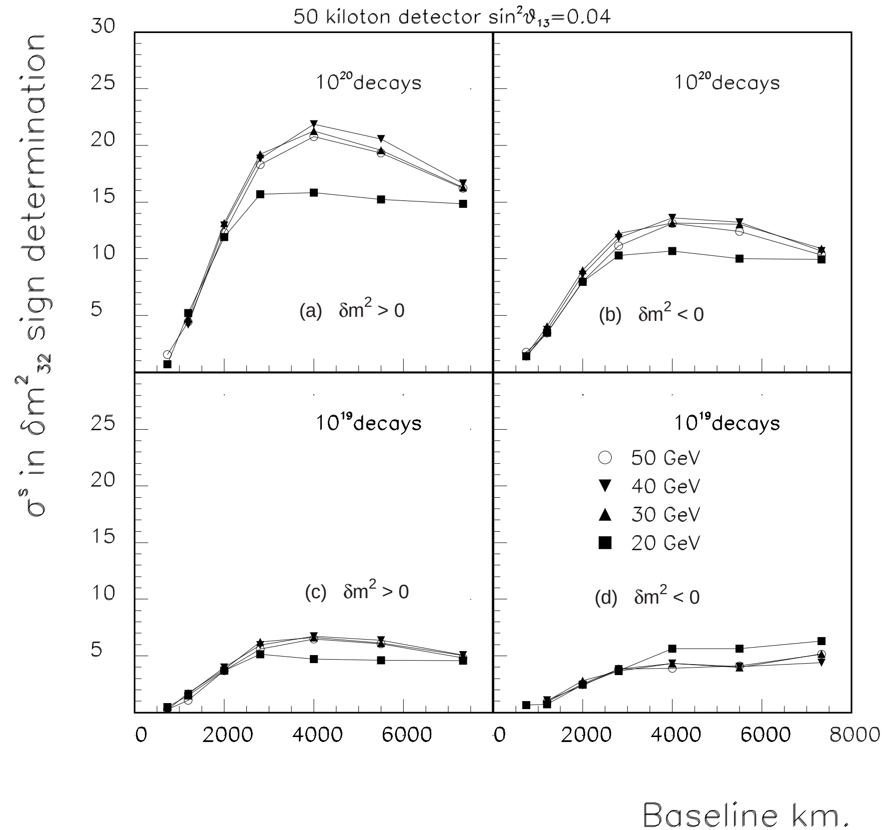
V.Barger,S.Geer,R.Raja,K.Whisnant, Phys.REVD62,013004(2000)

Predictions for 2800km baseline 2×10^{20} muon decays.

Neutrino Factory Determination of δm^2_{32} Sign

- V,Barger,S.Geer,R.Raja,K.Whisnant, Phys.Lett.B485(2000)379





20GeV μ 2800km 10^{20} decays

50k-ton detector

Non-oscillation Physics

- M.L.Mangano et al CERN-TH/2001-131,hep-ph/0105155
- Parton densities x>0.1, best accessible with 50GeV muon beams. Knowledge would improve by more than one order of magnitude. Individual quark and gluon components are measured with relative accuracies of 1-10% 0.1<x<0.6. Higher twist corrections accurately determined. Theoretical systematics in extracting α_s from sum rules and global fits reduced.
- Polarized parton densities measurable. Few percentge accuracy for up and down. Requires a-priori knowledge of polarized gluon density. Polarized DIS experiments at CERN and DESY and RHIC will provide this.
- $\sin^2\theta_W$ at the neutrino factory can be determined with error ~ 2×10^{-4}
- Permits usage of hydrogen targets. Nuclear effects can be bypassed.
- Rare lepton flavor violating decays of muons can be tagged with the appearance of wrong sign electrons and muons or of prompt taus.

Physics with Higgs factory/Muon Collider

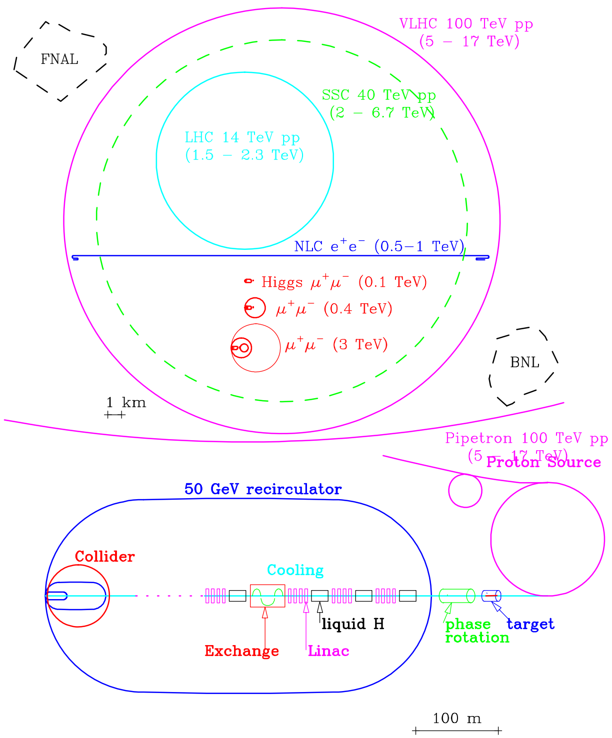
Muon Colliders

- Muon colliders are attractive because they are compact. Muon is 200 times heavier than electron, so Higgs like objects will have 40,000 more cross section in s-channel
- First Muon Collider/Higgs Factory can be used to scan a narrow Higgs of mass 115GeV and width 2-3 MeV. This is possible since we can measure the energy of the muon bunches to 1 part per million using g-2 spin precession as described in

  R.Raja and A. Tollestrup, Phys. Rev.D58(1998)013005
- Emittances need to be cooled by 10^6 for FMC to be a reality. However, if this is done (Emittance Exchange is a must), then higher energy colliders become feasible.
- W and top thresholds can be scanned and W mass and top quark mass measured very well.
- H^0/A^0 Higgs of the MSSM can be resolved in the s-channel using an MC if they are degenerate as in the 'decoupling limit' of the theory.
- Muon Colliders of 3-4 TeV can fit on existing lab sites.
- Backgrounds can be brought under control in detector regions using clever shielding ideas.

6/29/01 Andrew M Sessler, Snowmass 2001

Schematic of Muon Collider



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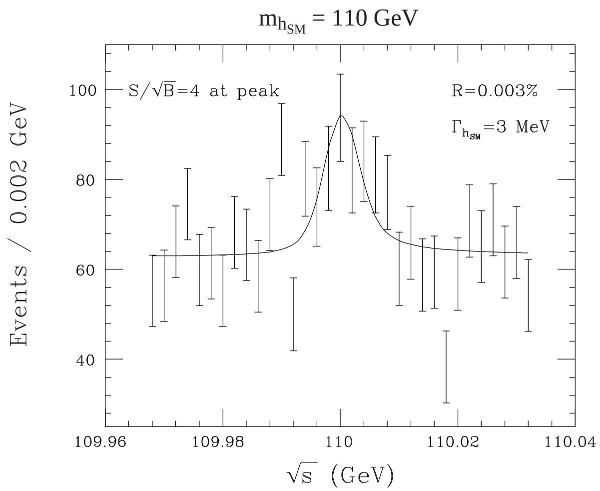
Higgs Factory/Muon Collider

Energy scale of muon ring measurable to 1E-6, (g-2) expt R. Raja, A. Tollestrup, PRD58,013005,1998

Scanning the Higgs peak using the muon collider

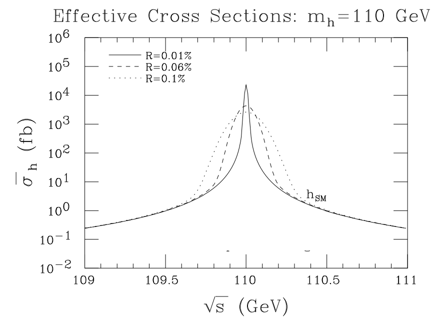


12

Light Higgs Resonance Profile

Convolve σ_h with Gaussian spread

$$\bar{\sigma}_h\left(\sqrt{s}\right) = \int \sigma_h\left(\sqrt{\hat{s}}\right) \frac{\exp\left[-\left(\sqrt{\hat{s}}-\sqrt{s}\right)^2\right] d\sqrt{\hat{s}}}{\sqrt{2\pi}\,\sigma_{\sqrt{s}}}$$



Need resolution $\sigma_{\sqrt{s}} \sim \Gamma_h$ to be sensitive to the Higgs width

Light Higgs width

$80 \lesssim m_h \lesssim 120$ GeV

$\Gamma_h \approx 2$ to 3 MeV if $\tan\beta \sim 1.8$

$\Gamma_h \approx 2$ to 800 MeV if $\tan\beta \sim 20$

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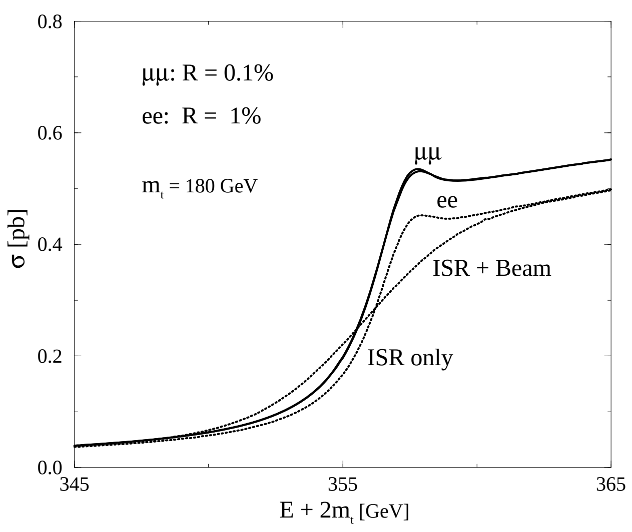
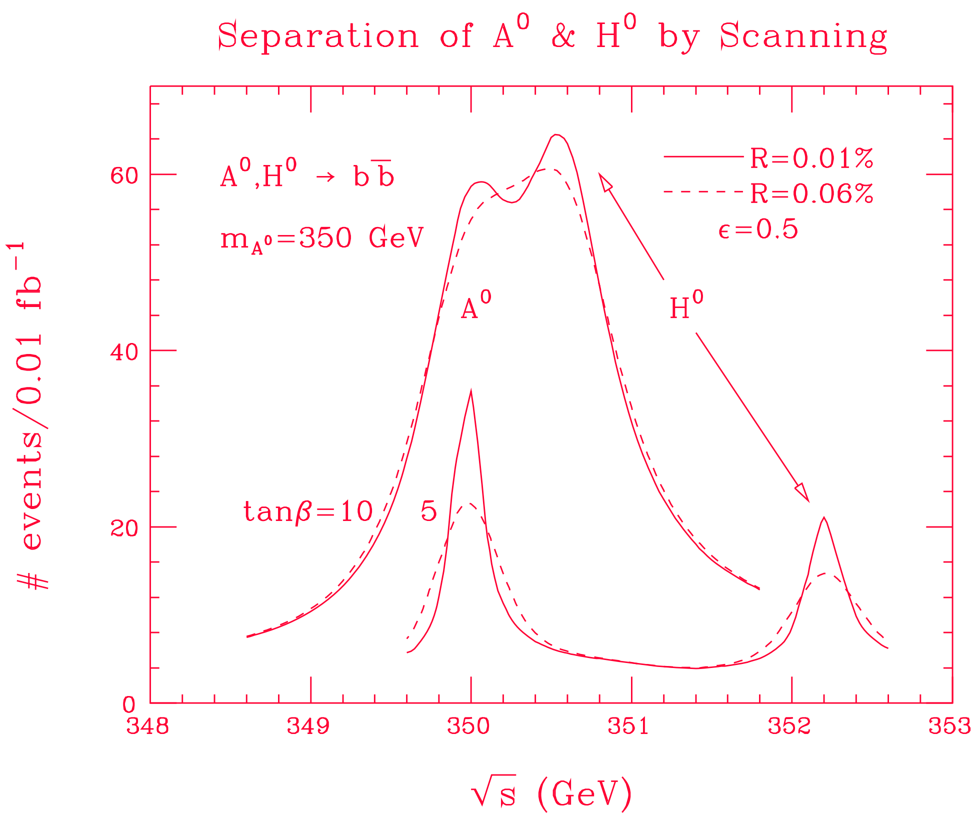
Higher energy Muon Colliders

- 3TeV center of mass

Will not cause neutrino
Background problems.
More exotic cooling,
Exotic locations etc.

Top quark threshold- ISR and beam effects





Scenarios

- Will stimulate Super Conducting RF and Accelerator R&D.
- For instance, Argonne has the expertise to study the reactor designs and targetry.
- Fermilab and Argonne both have the expertise toc develop the 10MW Accelerator(10 SNS!). Both problems are challenging.
- Needs Presidential initiative
- The machine and the accelerator can be put together in a third site (far from population) to produce the first prototype.
- Once successful, need to replicate the system ~500 times! Bring down costs.
- Can consider centralized breeding sites that then run conventional fission reactors using U233 bred from such sites.

Conclusions

- SCRF technology may help produce a high power proton source that can add to the mix of nuclear technologies. Sub-criticality is an advantage. Challenging accelerator R&D.
- In order to make further progress, a workshop that brings together all the interested parties may be worth pursuing.