

# *Accelerator Driven Nuclear Energy- The Thorium Option*

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Fermilab

- 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.
- Gave an Accelerator division seminar (03/07), followed by a talk to the Winchester Academy (Waupaca, WI), University of Chicago Colloquium, Argonne Colloquium, Argonne/UC/Fermilab and finally Fermilab colloquium.
- There is widespread consensus in many countries with nuclear energy experience that ADS (Accelerator Driven Sub-critical systems ) need to be developed.

# Format of talk

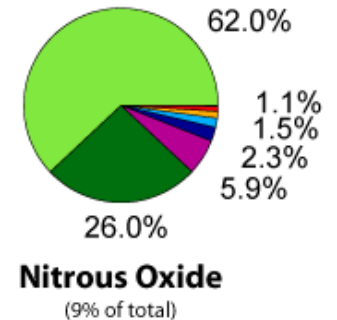
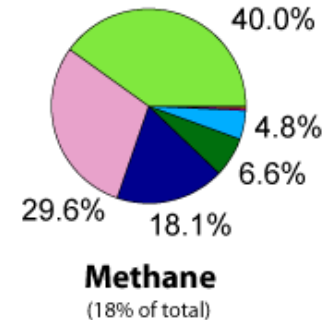
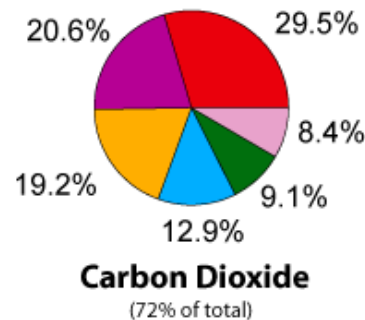
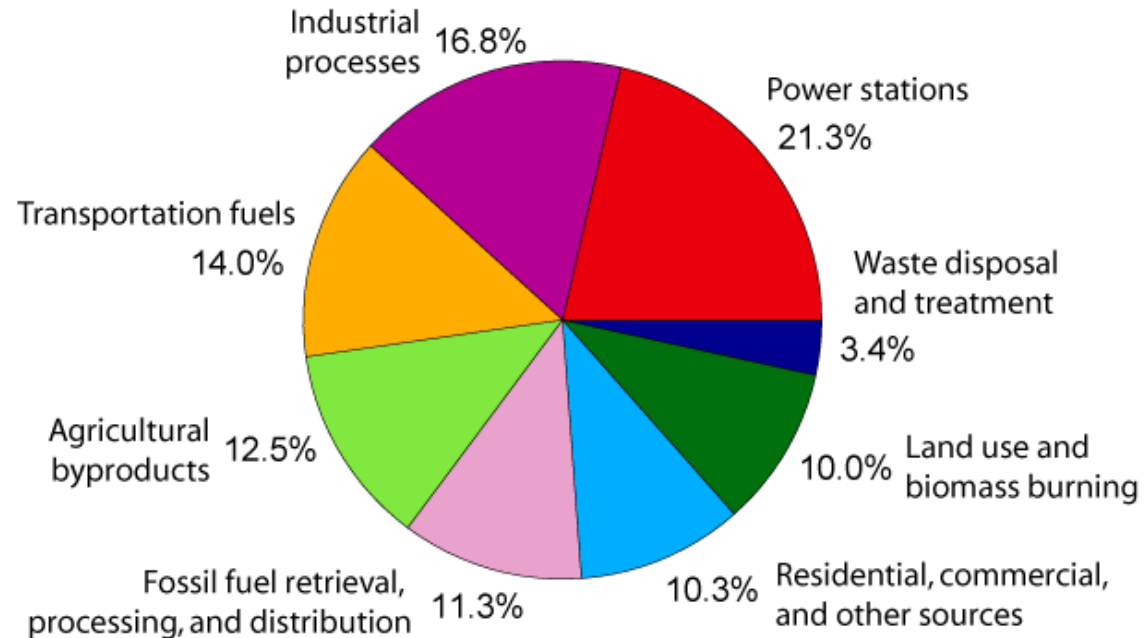
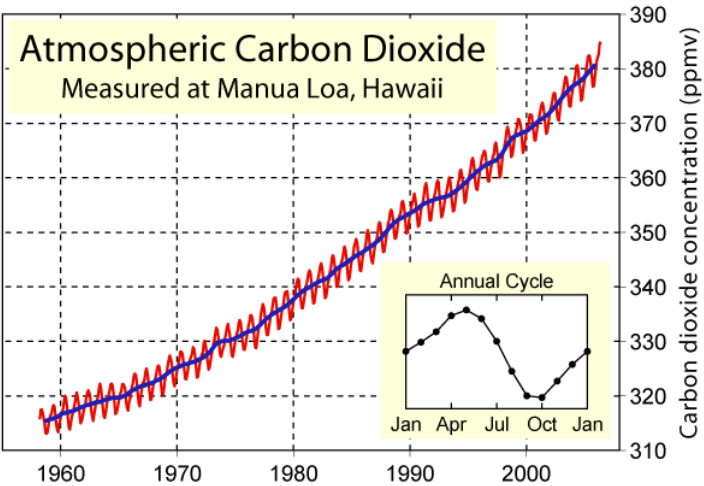
- Global warming- Inconvenient truth-Briefly review evidence—Drives the rest of the argument
- Will briefly review the world energy situation and projections
- Nuclear reactors -review various types
  - » Uranium 235 Fission reactors
    - Pressurised water reactors
    - CANDU Heavy water reactors
  - » 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).
- R.R. Wilson Fermilab note FN-298
- 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. Leads to a Muon Factory followed by a Neutrino factory.

# 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 ( $\text{CO}_2$ , 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

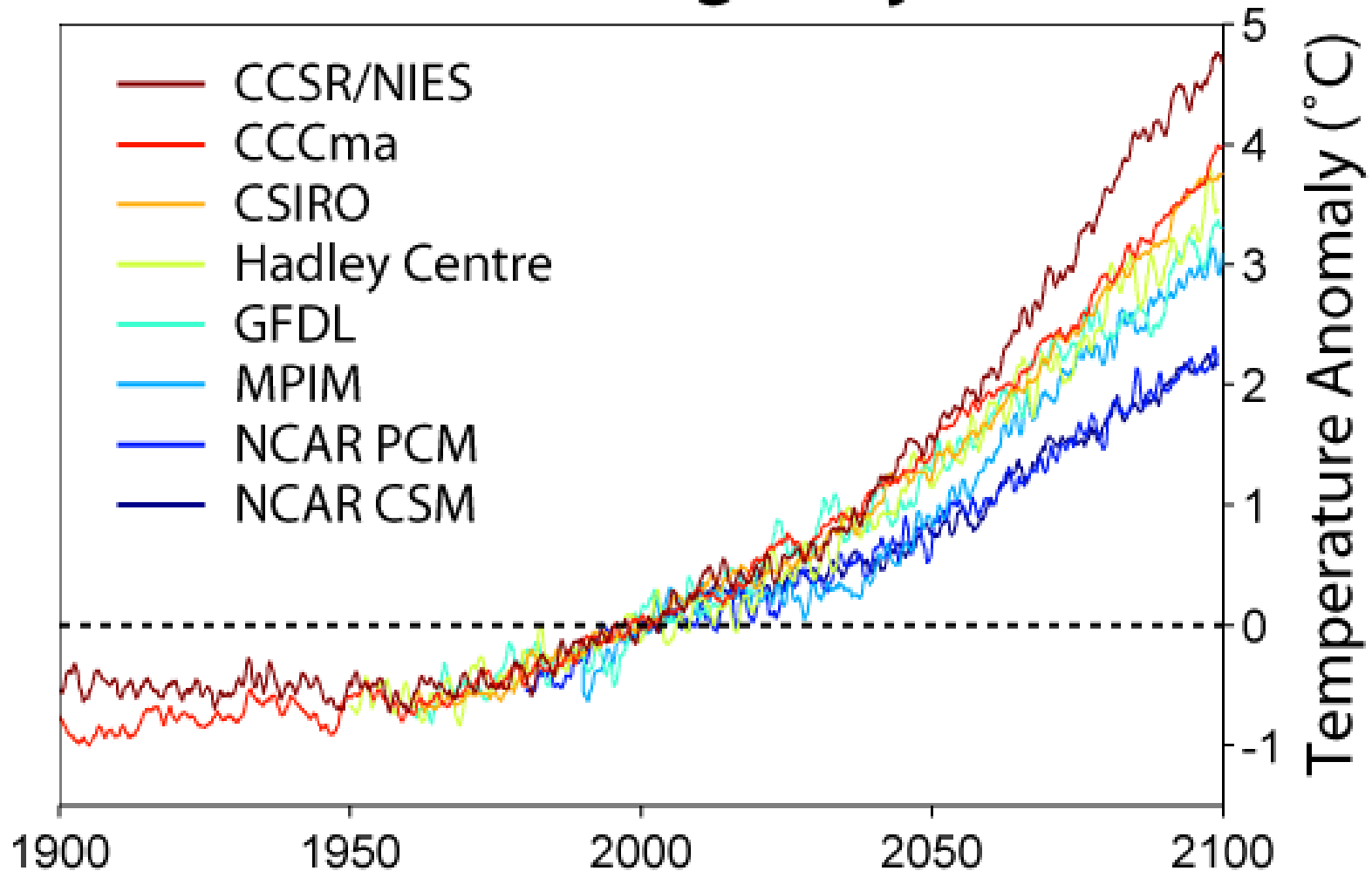
# Global Warming-GASES

## Annual Greenhouse Gas Emissions by Sector



# *Global Warming-model spread*

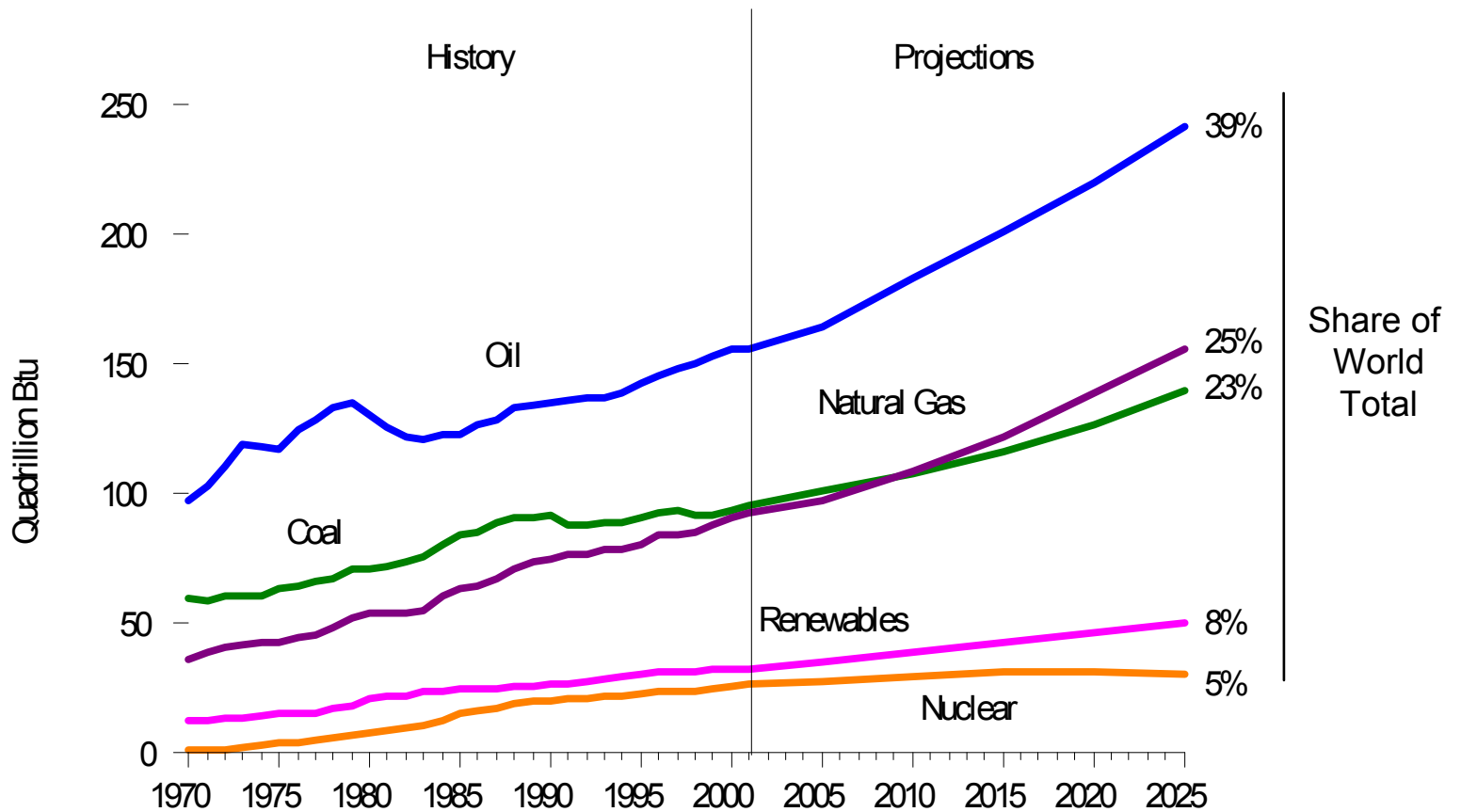
## Global Warming Projections



# *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?**

# World Primary Energy Consumption by Fuel Type, 1970-2025

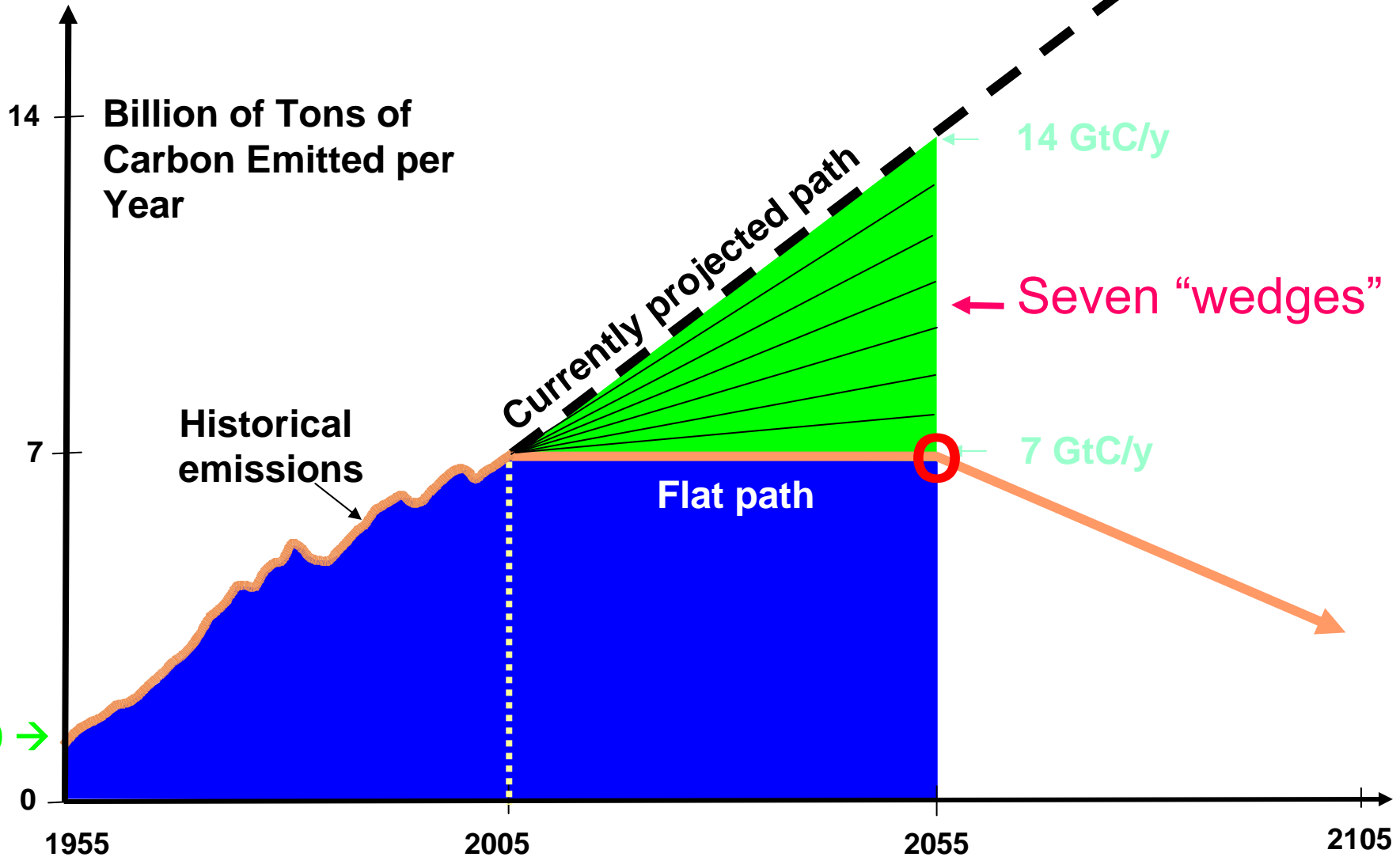


# *How do we combat global warming?*

- 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-
  - » Current sources of Uranium will run out in 50-100 years if conventional nuclear power is used.
  - » Nuclear Waste—long term storage, use only .7% of natural Uranium ( $^{235}\text{U}$ ). If more fuel needed, will have to breed.
  - » Fast breeder reactors are inherently critical. 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.

March 18, 2009

Rajendran Raja, Fermilab Colloquium



# *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. ADS is higher tech than conventional nuclear reactors.
- Ultimately, proliferation is a political issue.
- National security can also be compromised by lack of energy independence.

# Periodic Table of the Elements

1 IA New Original																	18 VIIIA	
1 H Hydrogen 1.00784	2 He Helium 4.002602											13 Al Aluminum 26.981536	14 Si Silicon 28.0855	15 P Phosphorus 30.973761	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948	
3 Li Lithium 6.941	4 Be Beryllium 9.012102											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797	
11 Na Sodium 22.989770	12 Mg Magnesium 24.3050	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIII	9 VIII	10 VIII	11 IB	12 IIB	13 Al Aluminum 26.981536	14 Si Silicon 28.0855	15 P Phosphorus 30.973761	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948	
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938049	26 Fe Iron 55.8457	27 Co Cobalt 58.933200	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.409	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798	
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293	
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57 to 71		72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98039	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89 to 103		104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (269)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (271)	111 Rg Roentgenium (272)	112 Uub Ununbium (285)	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (292)	117 Uus Ununseptium	118 Uuo Ununoctium

Atomic masses in parentheses are those of the most stable or common isotope.

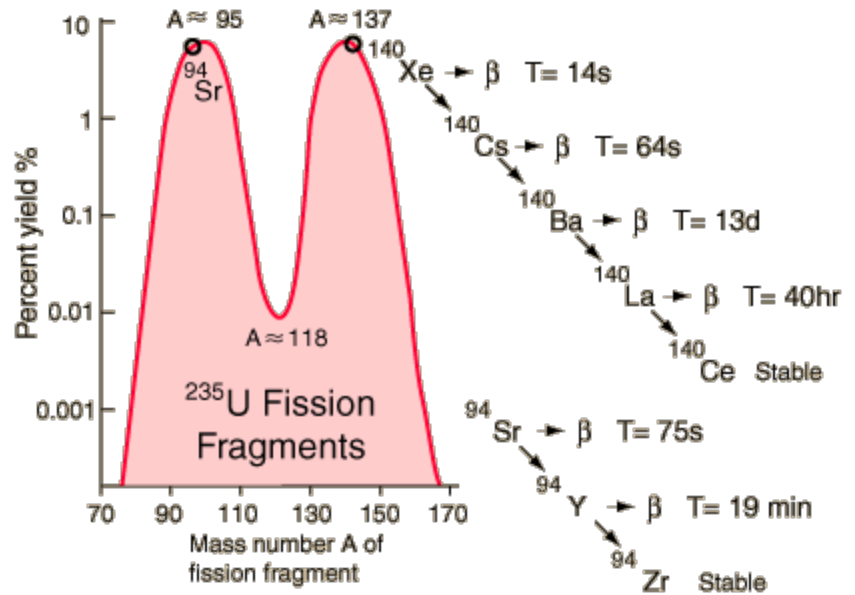
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Note: The subgroup numbers 1-18 were adopted in 1984 by the International Union of Pure and Applied Chemistry. The names of elements 112-118 are the Latin equivalents of those numbers.

57 La Lanthanum 138.9055	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
89 Ac Actinium (227)	90 Th Thorium 232.0381	91 Pa Protactinium 231.03688	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

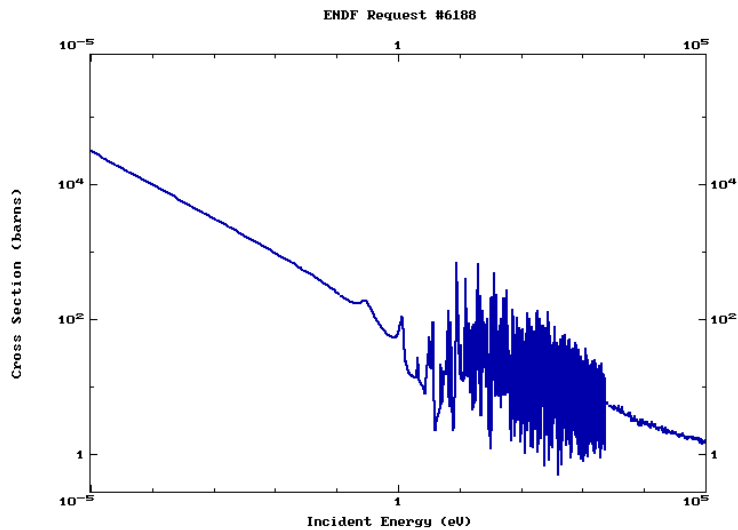
# Reactors 101--Fissile and Fertile Nuclei

- 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.

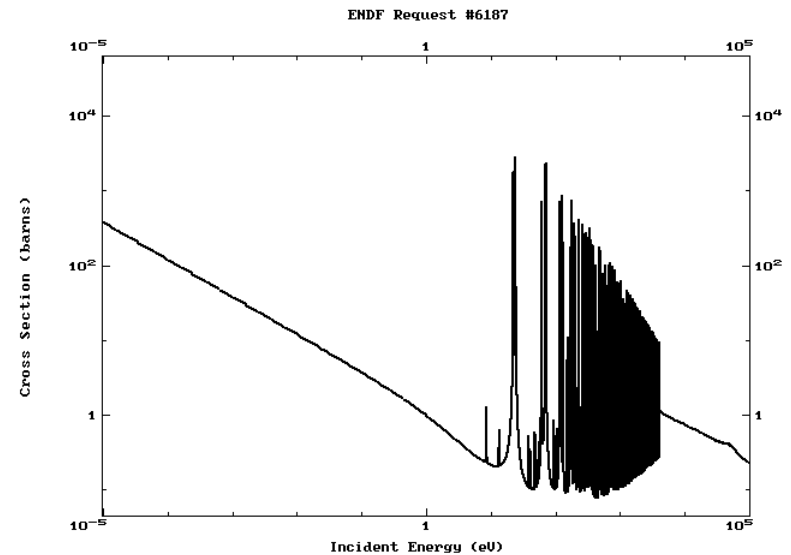


Mean energy released per fission  
~200 MeV

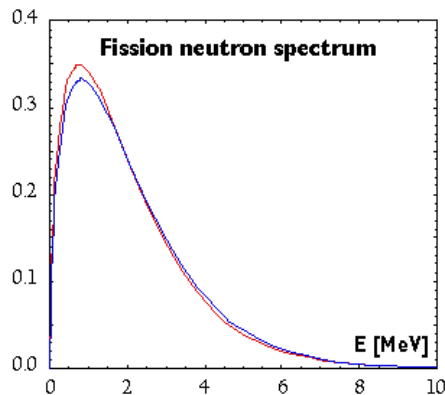
# *Fission and breeding cross sections.*



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

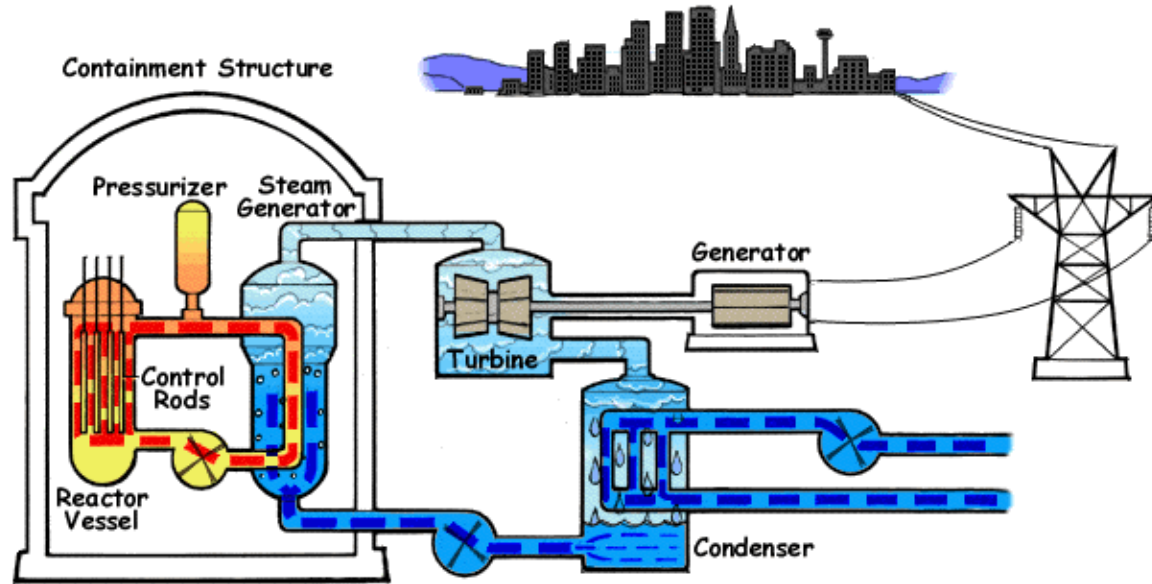


Cross section in barns for  $Th^{232} + n \rightarrow Th^{233} + \gamma$ . This is a breeding cross section. Another is

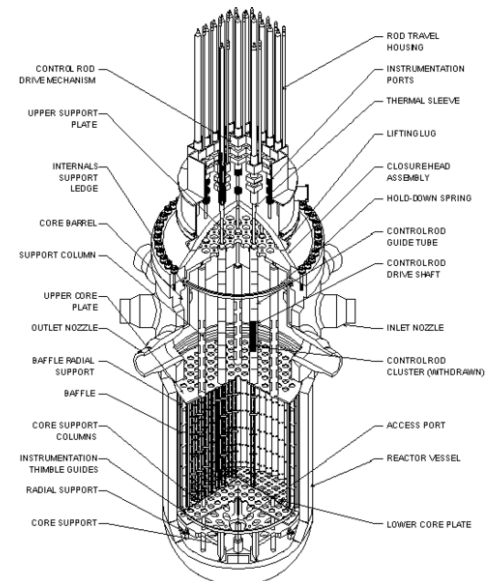


# Fission Reactors-Pressurised Water reactors (PWR)

- 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.

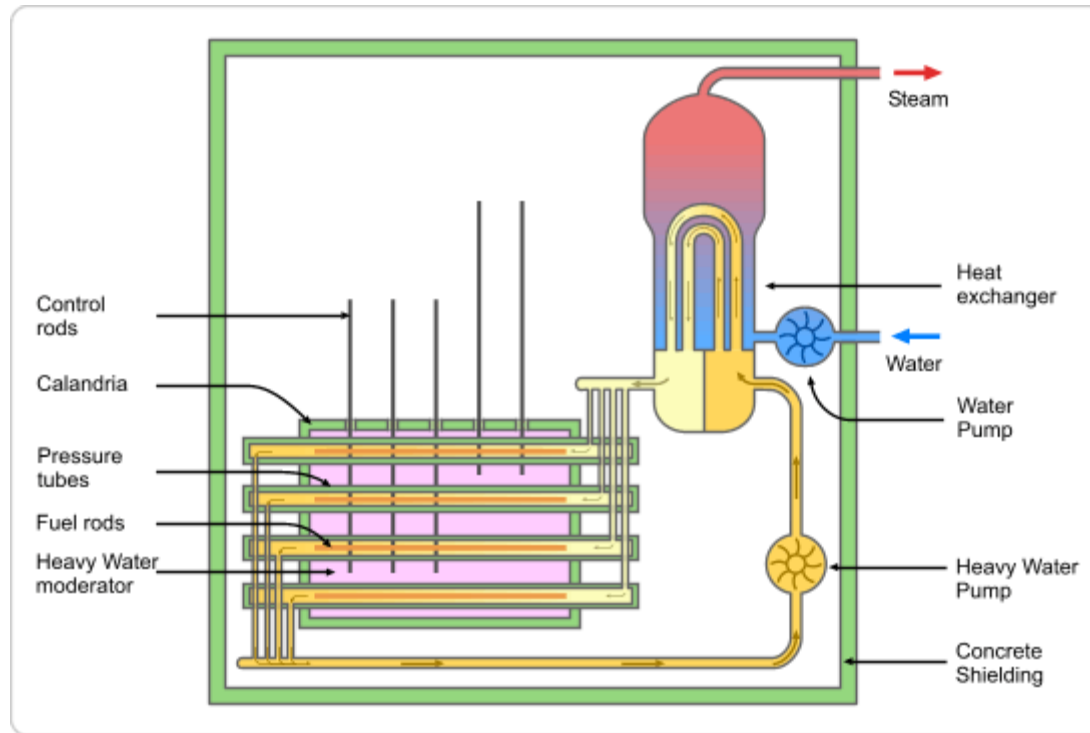


Control rods used for starting and stopping the reactor.



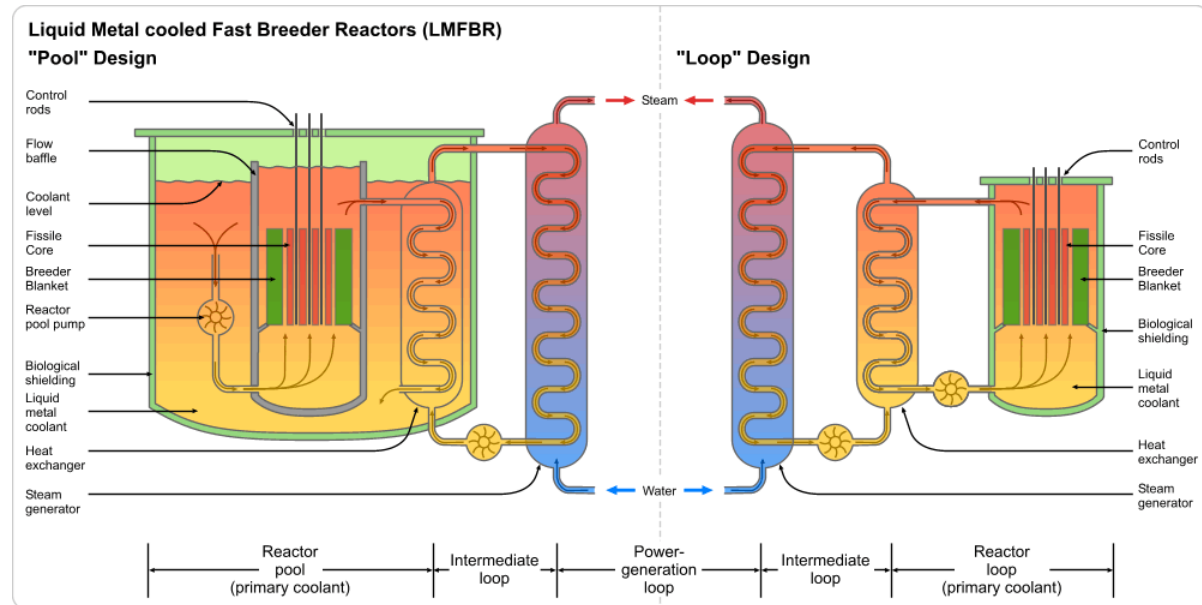
# *Fission Reactors-Pressurised Heavy Water reactors*

- 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 half-life). However, higher actinide waste products take  $\sim 10^5$  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  $\text{Pu}^{239}$  or  $\text{U}^{235}$  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

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

neutrons.

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

Criticality is a property of the pile.

# *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. ”

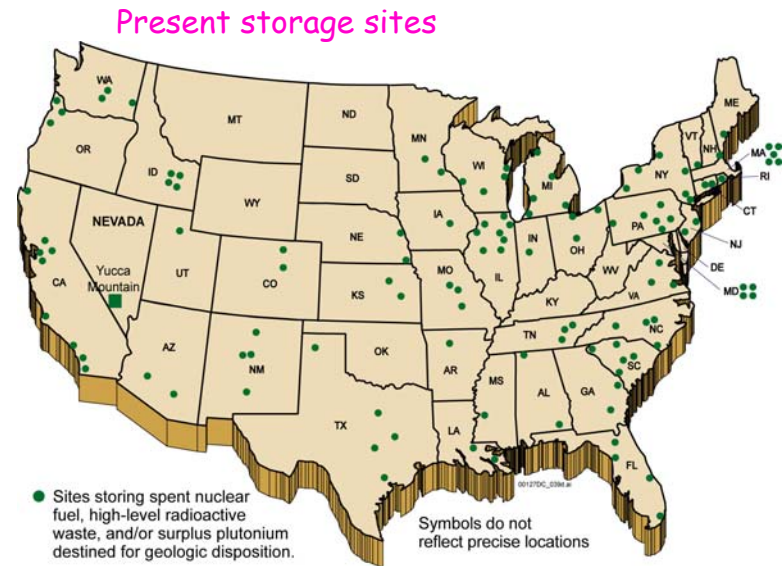
We **MUST** breed if we want to use nuclear energy long term.

# *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.- Colossal "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



# *Very Big Accelerators as Energy producers*

## *R.R. Wilson August 9, 1976-FN-298*

- “One Consequence of the application of superconductivity to accelerator construction is that the power consumption of accelerators will become much smaller. This raises the old possibility of using high energy protons to make neutrons which are then absorbed by fertile uranium or thorium to make fissionable material like plutonium that can be burned in a nuclear reactor [shades of E.O.Lawrence’s M.T.A, project in Canada].”
- Basic idea is to shoot 1 TeV protons into block of Uranium to produce Plutonium. Gets an energy amplification factor of 12.
- Wilson considers various targets and also talks about other energies for the proton machine that are more optimal.
- Wilson is amazingly prescient in this paper. {calculations by A. Van Ginneken)—subcriticality mentioned and high intensity neutrino sources foreseen.



# *Wilson and pushing the envelope*

- "You will not succeed unless you learn to work at the edge of failure"-R.R. Wilson
- Wilson continually pushed back the envelope of what was possible.
  - » Main ring energy 200 GeV/c to 400 GeV/c. made the discovery of the Upsilon possible in 1977.
  - » The Energy Doubler-World's first Superconducting accelerator (I have heard many a skeptical snicker when the Tevatron was being proposed)-Made the discovery of the top quark possible.—led to SSC, LHC
- Building the world's first 10 MegaWatt LINAC will have far reaching consequences not only for nuclear energy production /waste management, it will also make the Muon Factory possible leading to the neutrino factory and eventually the muon collider.



# Accelerator Driven Energy Amplifier

- Idea developed by 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. Spontaneous 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
<i>Europe</i>			
Finland		60	60
Greenland	54	32	86
Norway	132	132	264
Turkey	380	500	880
Europe Total	566	724	1290
<i>America</i>			
Argentina	1		1
Brazil	606	700	1306
Canada	45	128	173
Uruguay	1	2	3
USA	137	295	432
America total	790	1125	1915
<i>Africa</i>			
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
<i>Asia</i>			
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
<i>Total WOCA</i>	<i>1754</i>	<i>2188</i>	<i>4106</i>

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  $\text{Th}^{232}$  (predominant),  $\text{U}^{238}$  and Potassium 40.

$\text{Th}^{232}$  has halflife of 14 billion years,  $\text{U}^{238}$ (4.5 billion years) and  $\text{K}^{40}$  (1.3billion years).  $\text{Th}^{232}$  is roughly 4-5 times more abundant than  $\text{U}^{238}$ . May be enough Thorium to last  $2.2 \times 10^5$  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  $^{233}\text{U}$ , one needs to limit neutron fluxes to  $\sim 10^{14} \text{ cm}^{-2} \text{ sec}^{-1}$ . Provide this by an accelerator.



- Let  $\sigma_i$  be the capture cross section of neutrons and  $\sigma_f$  be the fission cross section.

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

- Where  $\Phi$  is the neutron flux and  $\tau_2$  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

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

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

- In stationary conditions

$$\frac{n_3}{n_1} = \frac{\sigma_i^1}{(\sigma_i^3 + \sigma_f^3)}$$

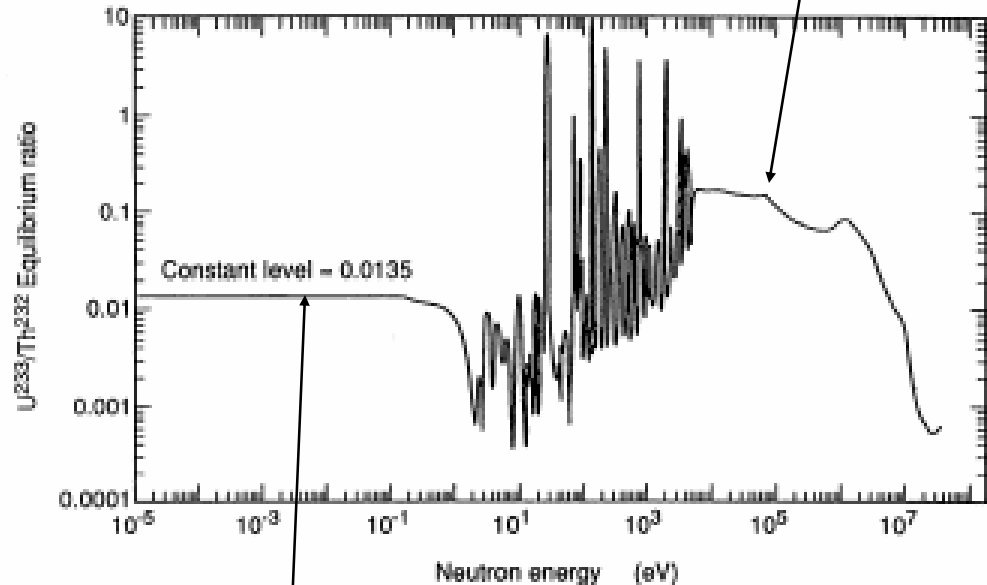
- Independent of neutron flux  $\Phi$
- Power of reactor is given by

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

# 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*

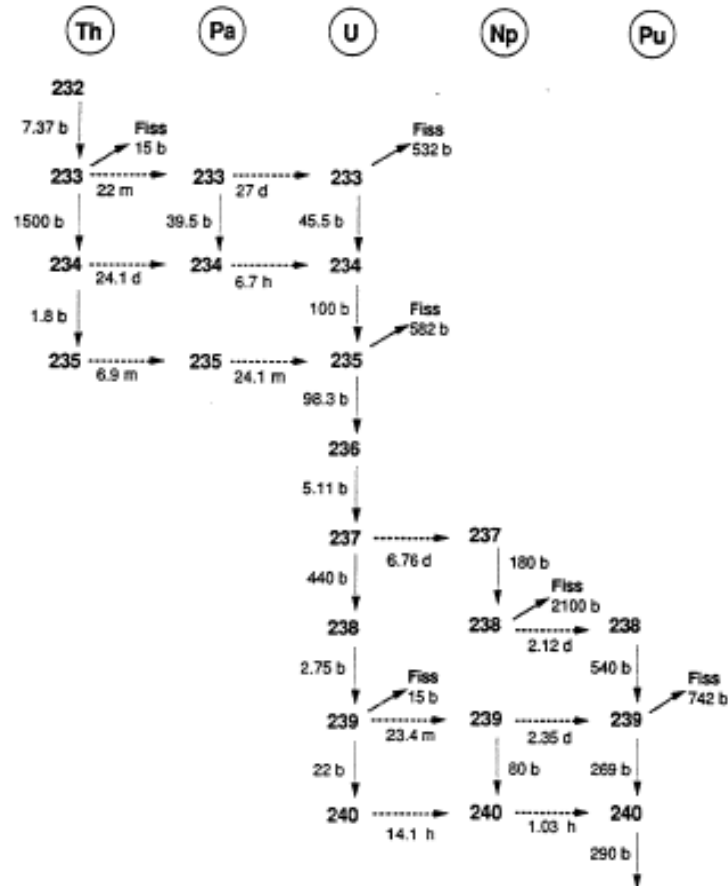


Figure 3

# *Pure thorium initial state.*

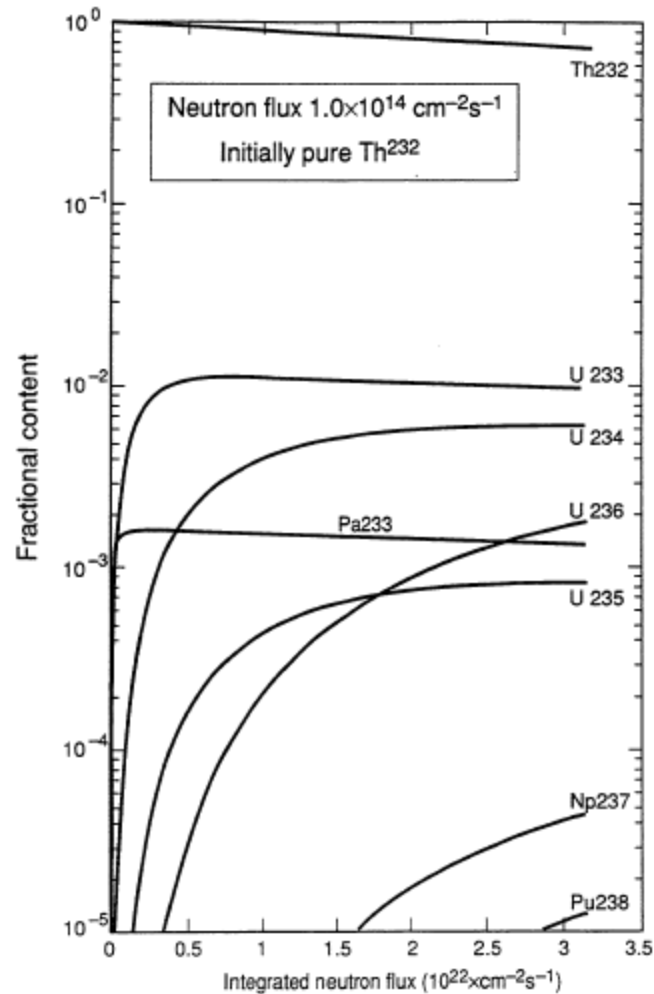


Figure 4



# Thorium with initial $^{233}\text{U}$ as fuel

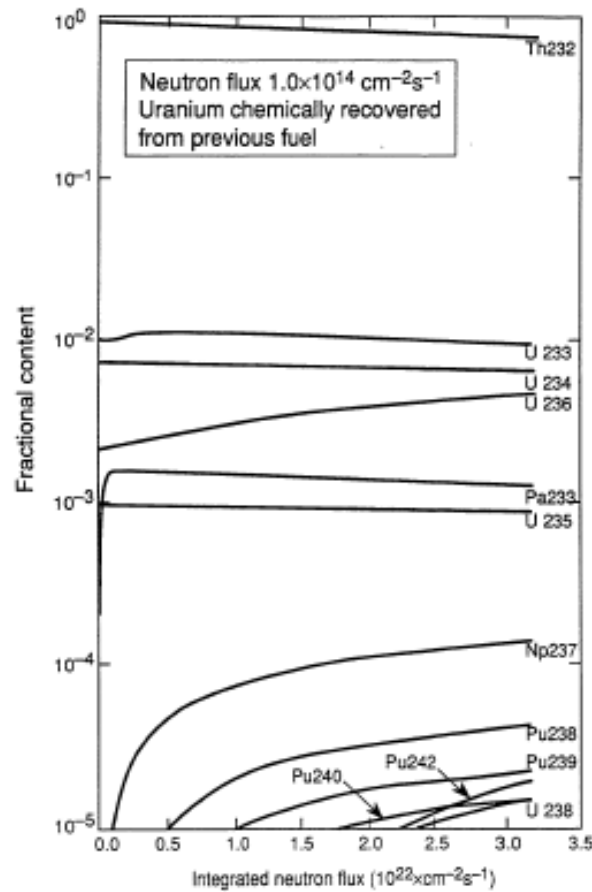


Figure 5

# *Natural Uranium 238 as fuel*

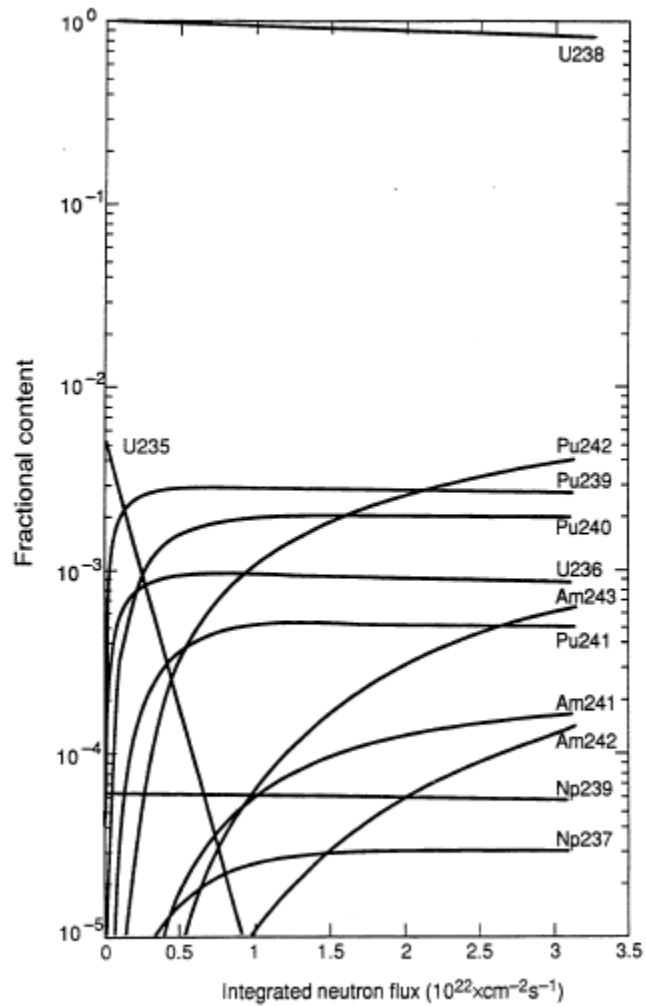
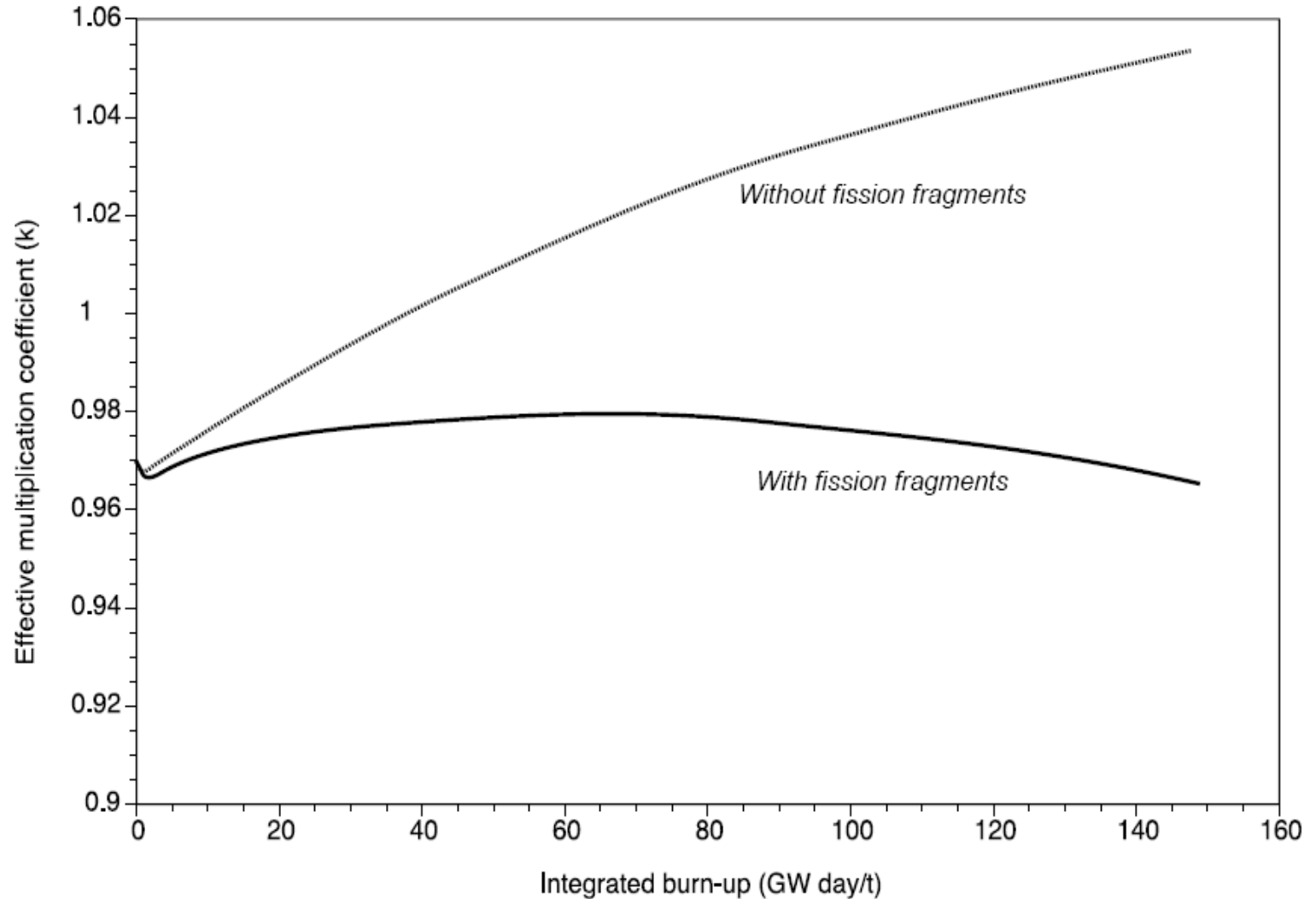


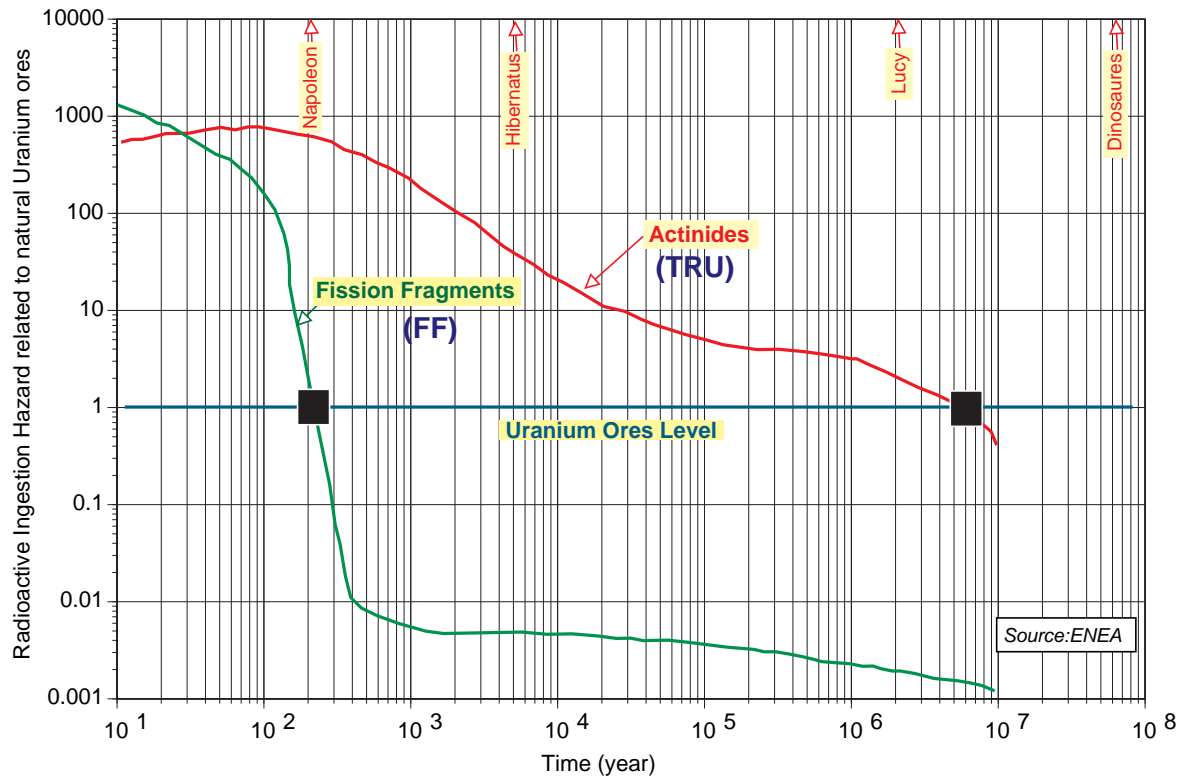
Figure 7

# Variation of $k$ with time for EA

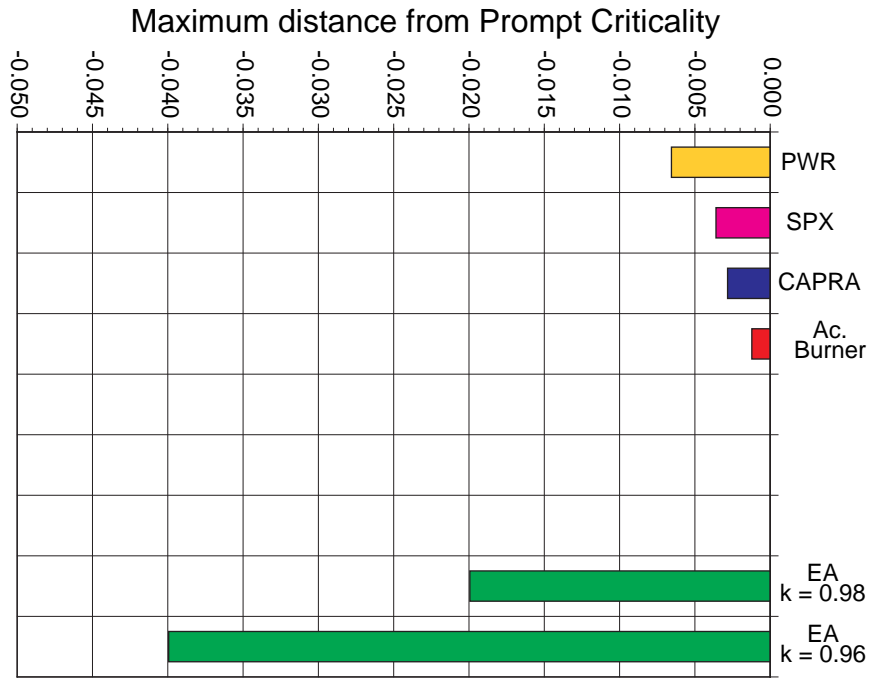


# *Waste problem a lot better than conventional reactors.*

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

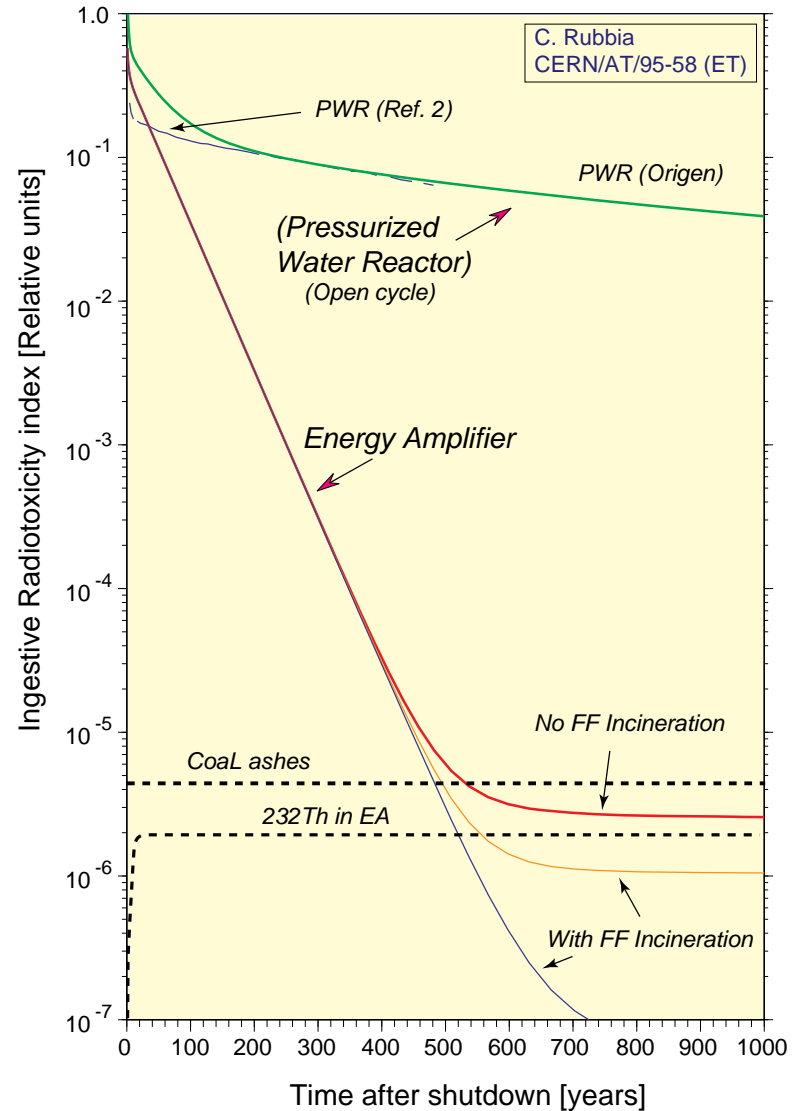


# Advantages of the EA:



Allowed Operational Safety Margin

*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

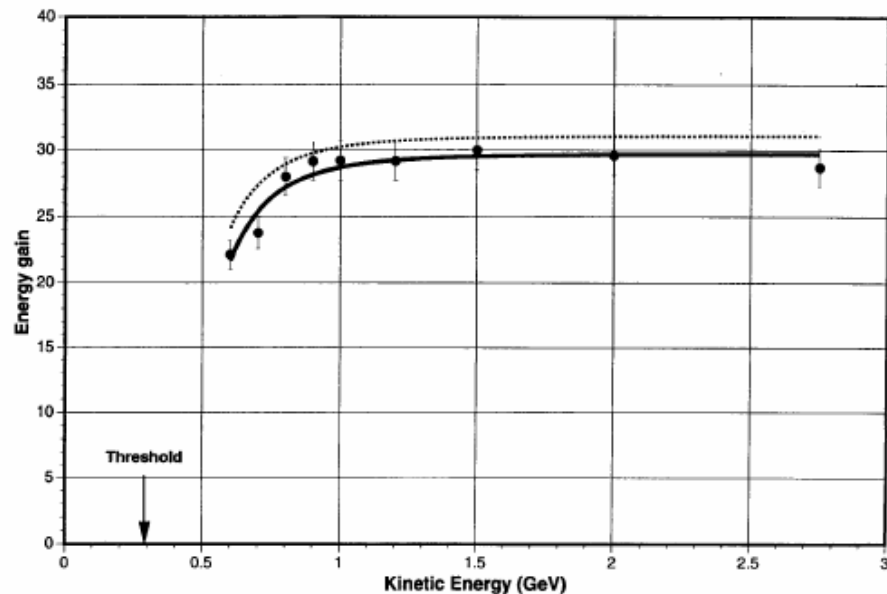
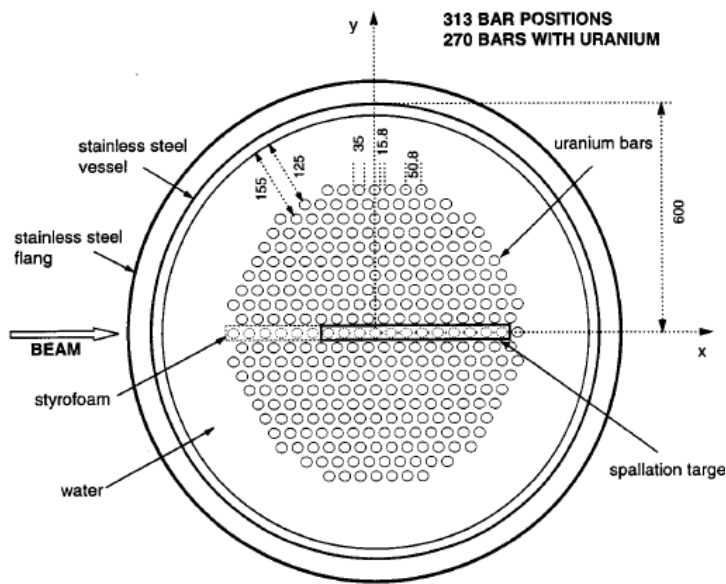
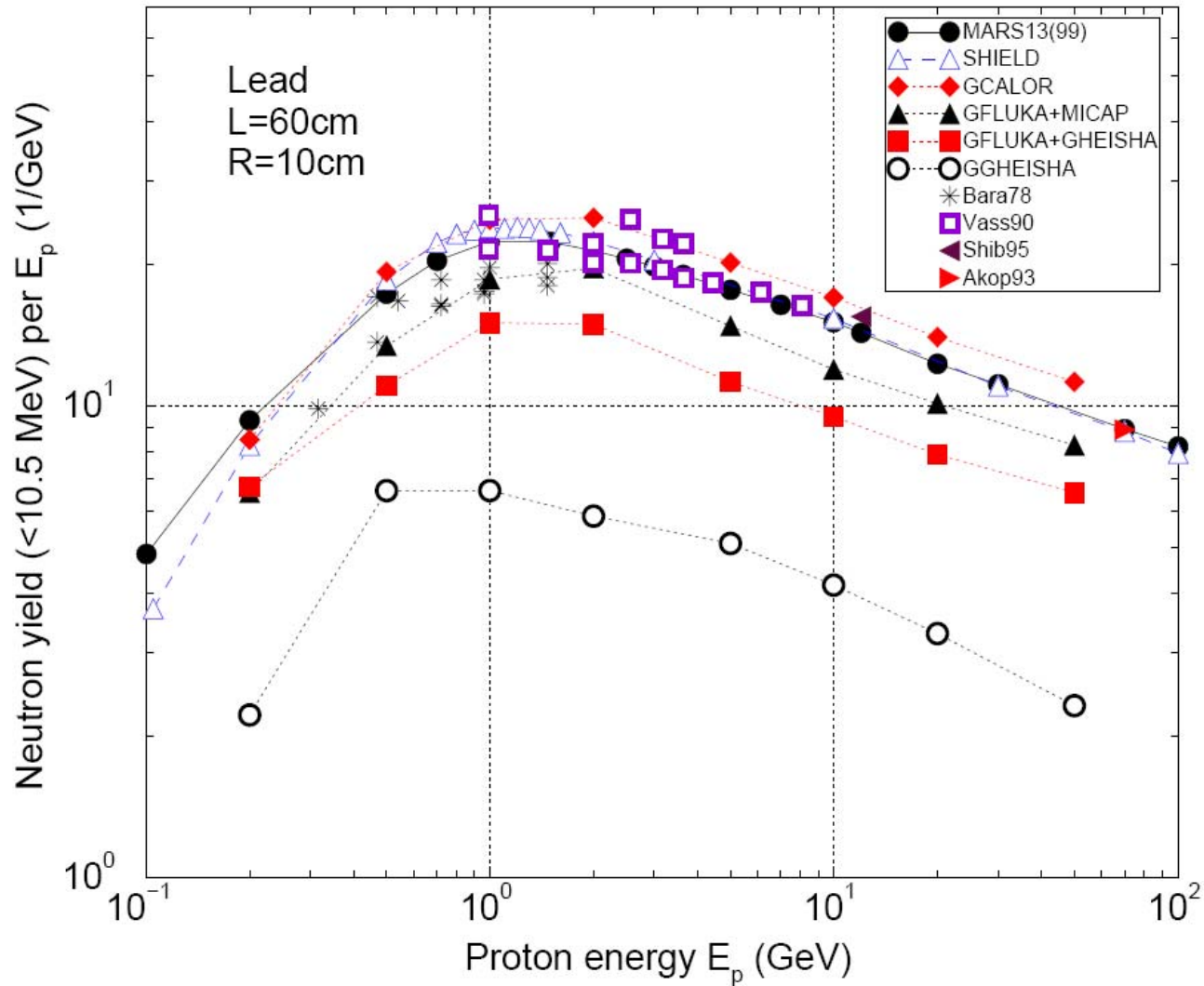


Figure 7

# Neutron Yield from Lead Absorber for $p$ , $d$ , $\alpha$ and $C$



# The Conceptual design

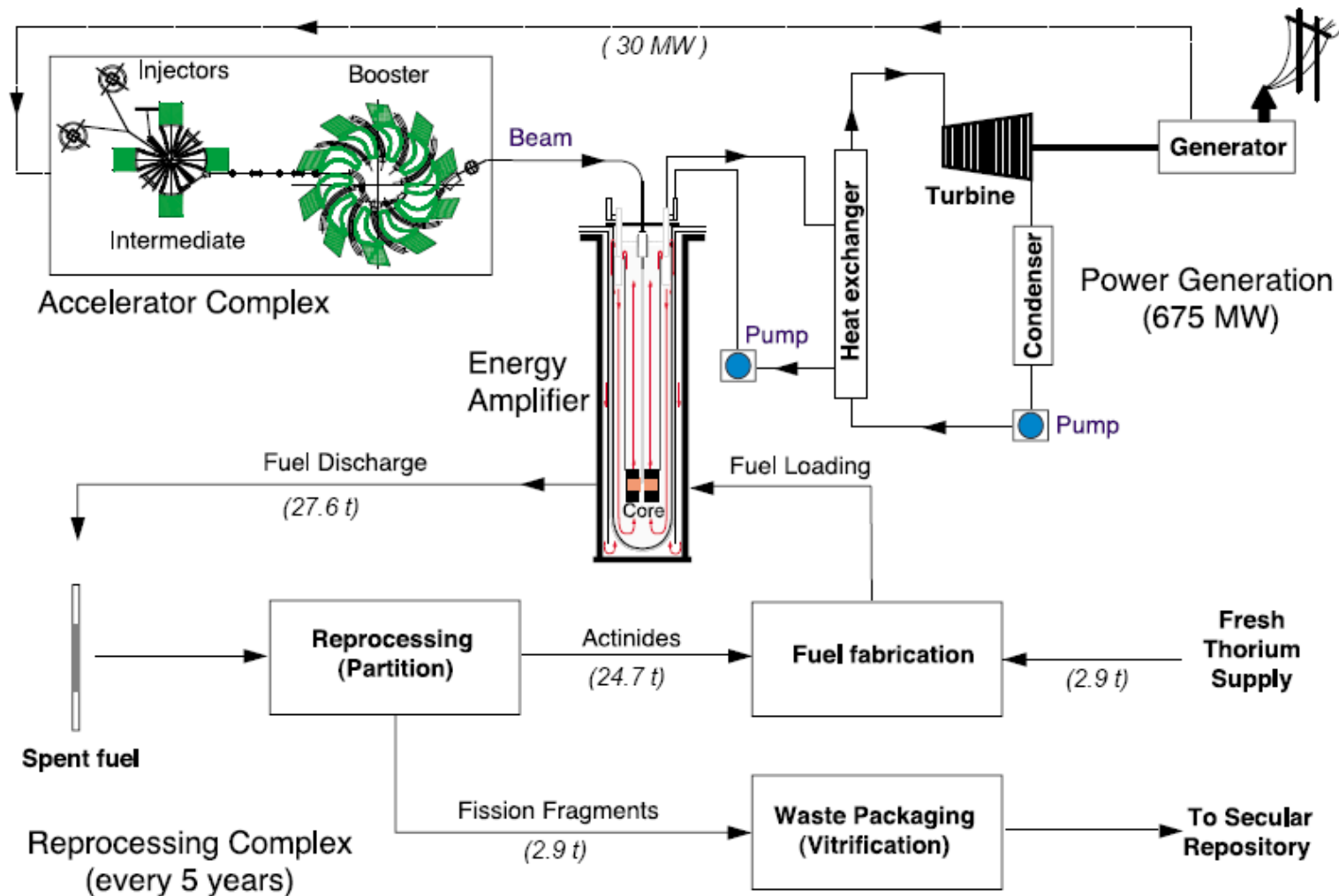


Figure 1.1



# EA reactor details

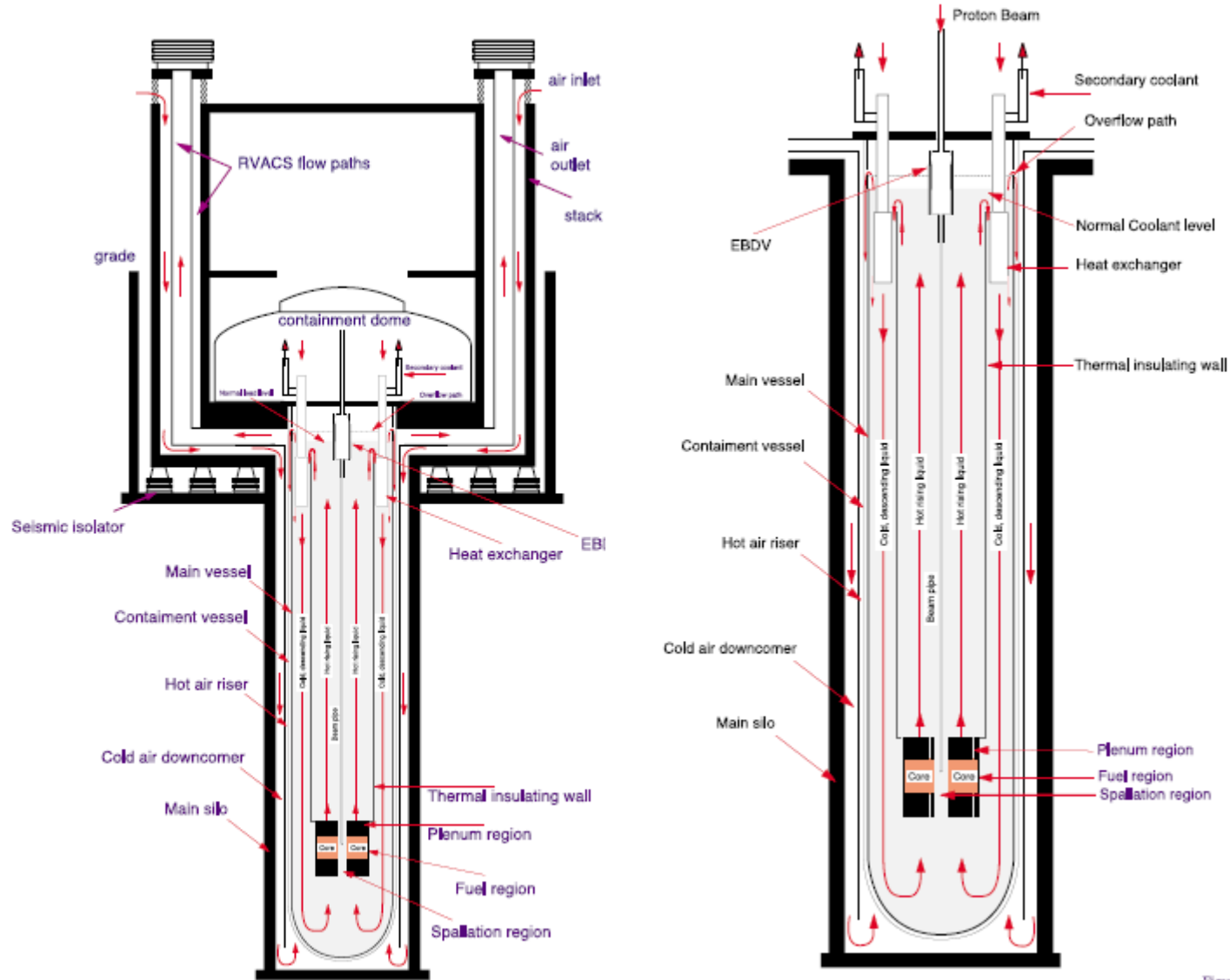
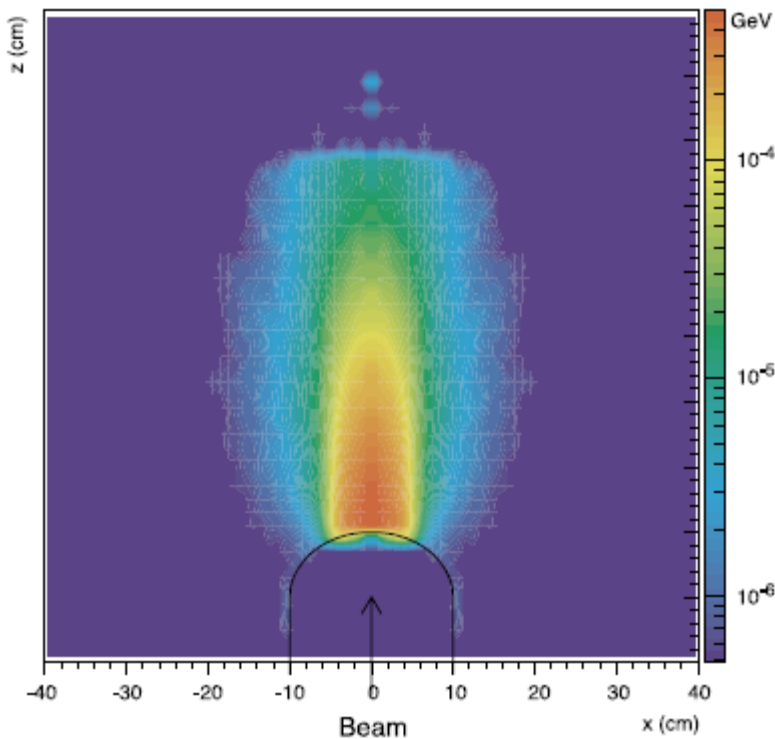


Figure 4.1a

Figur

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



- Each 10MW EA will produce  $\sim 700$  MW 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*

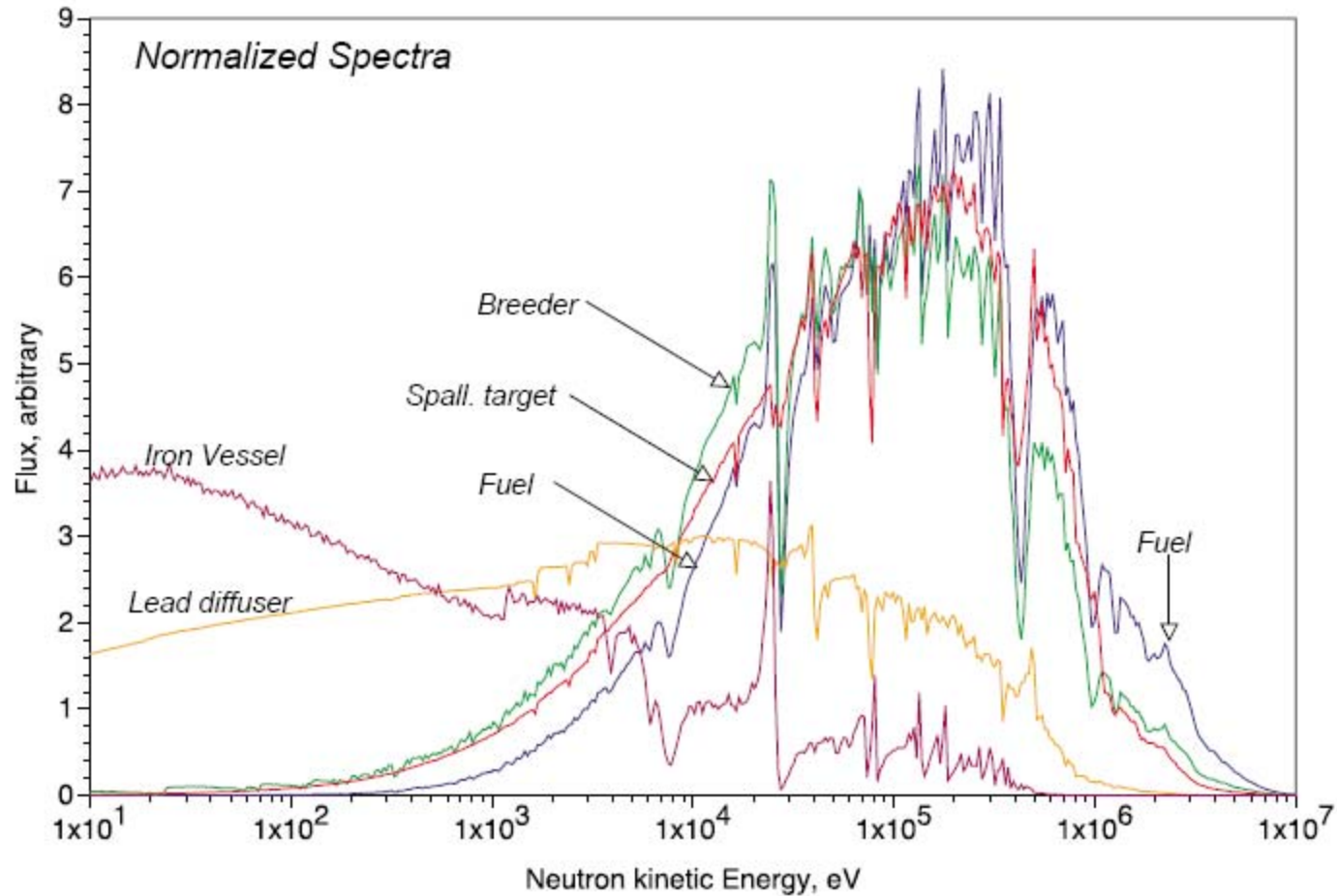
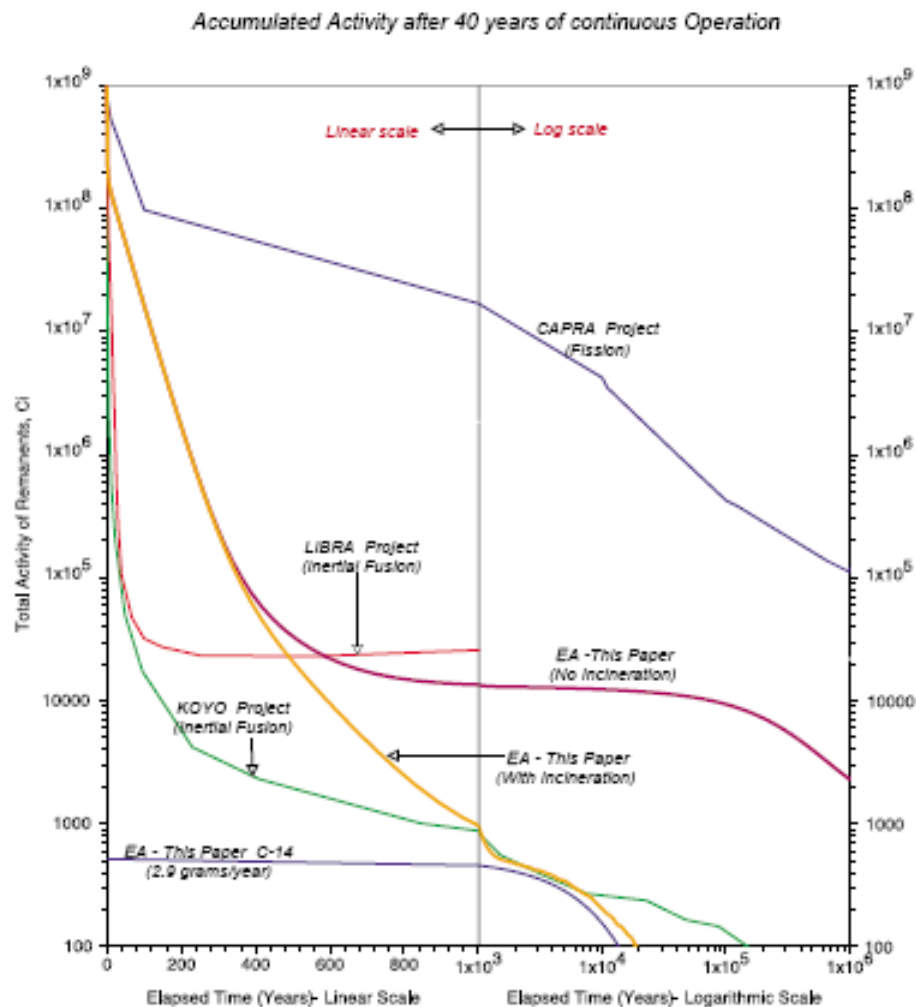


Figure 5.10

# 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.



# *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 says 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", 6<sup>th</sup> 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*

Nuclear data evaluation and experimental research of accelerator driven systems  
using a subcritical assembly driven by a neutron generator ..... 207  
*S. Chigrinov, I. Rakhmo, K. Rutkovskaya, A. Kievitskaia, A. Khilmanovich,  
B. Martynkevich, L. Salnikov, S. Mazanik, I. Seraftimovich, E. Sukhovitskij*

India, Japan,  
China actively  
interested in this  
approach.



INTERNATIONAL ATOMIC ENERGY AGENCY

IAEA

November 2002



# *Comparison of ADS and Fast Reactors (350 page study )by Nuclear Energy Agency (NEA) and Organization for Economic Co-operation and Development (OECD)*

Nuclear Development

**Accelerator-driven Systems (ADS)  
and Fast Reactors (FR) in  
Advanced Nuclear Fuel Cycles**

A Comparative Study

**ADS is better at burning waste than fast reactors.**

NUCLEAR ENERGY AGENCY  
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

# *Executive Summary*

- Fuel cycles with multiple recycling of the fuel and very low fuel losses are required to achieve the desired hundred-fold radiotoxicity reduction.
- All transmutation strategies with multiple recycling of the fuel can achieve similar radiotoxicity reductions, but the choice of the strategy strongly influences fuel cycle requirements.
- The ADS is particularly suited as a "dedicated" minor actinide burner in steady-state scenarios and provides flexibility in transient scenarios.
- The ADS-based evolutionary, and the FR-based innovative, approaches appear to be attractive transmutation strategies, from both technical and economic viewpoints.
- The full potential of a transmutation system can be exploited only if the system is utilised for a minimum time period of about a hundred years.
- A considerable amount of R&D on sub-critical reactors, advanced fuels, and materials would be needed before ADS-based transmutation technology could be deployed.

# Implementation 1995 style - 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.

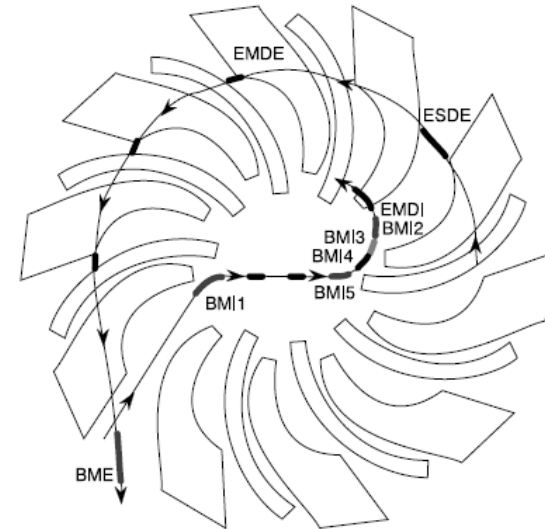
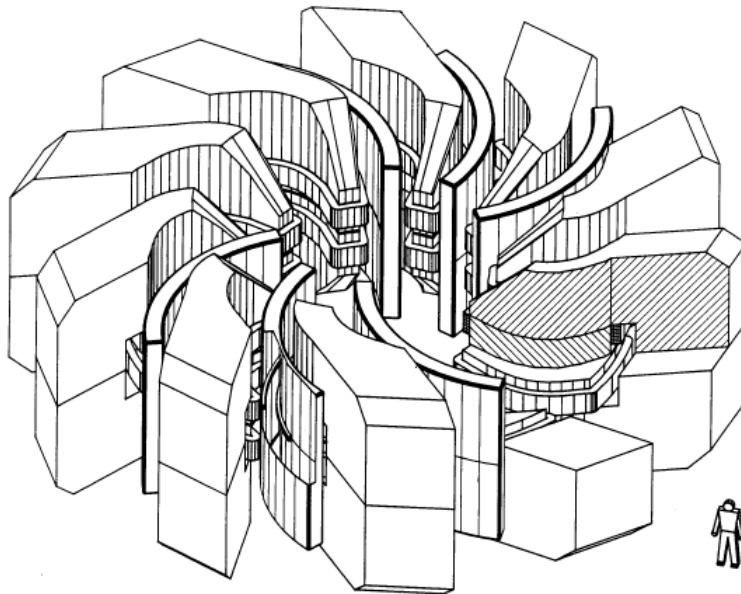


FIG. 3.9 Location of the injection and extraction channel elements of the booster ring cyclotron

Figure 3.7

# 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 application.

Keep smiling,

-Bill

On 3/9/07, Rajendran Raja <[raja@fnal.gov](mailto: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: [GW.Foster@gmail.com](mailto:GW.Foster@gmail.com)  
Web: <http://gwfoster.com>

	8 GeV Initial	8 GeV {Ultimate}	SNS (Spallation Neutron Source)	TESLA-500 (w/ FEL)	TESLA- 800
Energy	8 GeV	8 GeV	1 GeV	500 GeV	800 GeV
Particle Type	H <sup>+</sup> , e <sup>+</sup> , or e <sup>-</sup>	H <sup>+</sup> , e <sup>+</sup> , or e <sup>-</sup>	H <sup>+</sup>	e <sup>+</sup> , e <sup>-</sup>	e <sup>+</sup> , e <sup>-</sup>
Beam 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
Beam Pulse Width	3 msec	1 msec	1 msec	0.95 msec	0.86 msec
Beam Current (avg. in pulse)	8.6 mA	26 mA	26 mA	9.5 mA	12.7 mA
Repetition Rate	2.5 Hz	10 Hz	60 Hz	5(10) Hz	4 Hz
Number of Superconducting Cavities	384	384	81	21024	21852 / 2
Number of Cryomodules	48	48	23	1752	1821
Number of Klystrons	12	33	93	584	1240
Number of Cavities per Klystron (typ)	36	12	1	36	18
Maximum Surface Fields (max)	52 MV/m	52 MV/m	35 MV/m	46.8 MV/m	70 MV/m
Maximum Accelerating Gradient (max)	26 MV/m	26 MV/m	16 MV/m	23.4 MV/m	35 MV/m
Operating Frequency (MHz)	1300, 325	1300, 325	805, 402.5	1300	1300
Machine Active Length	614 m	614 m	258 m	22 km	22 km

Need to go from pulsed to CW linac.

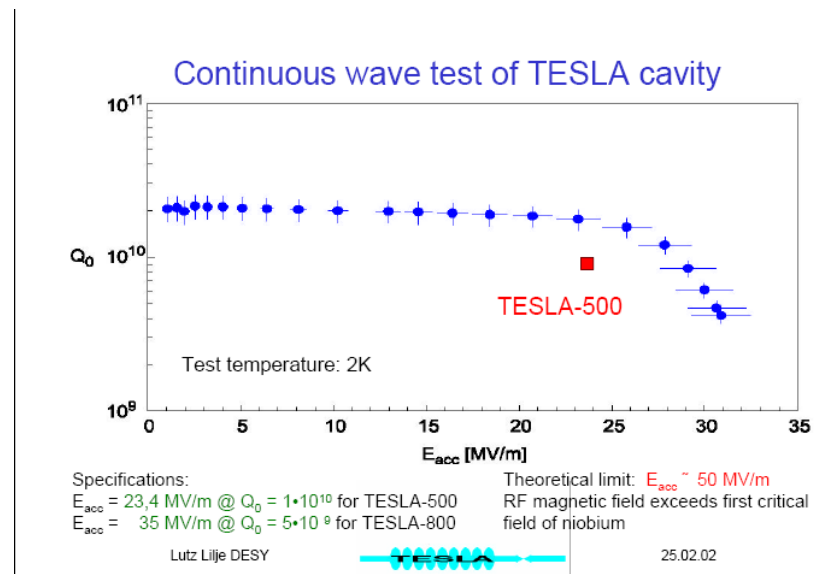
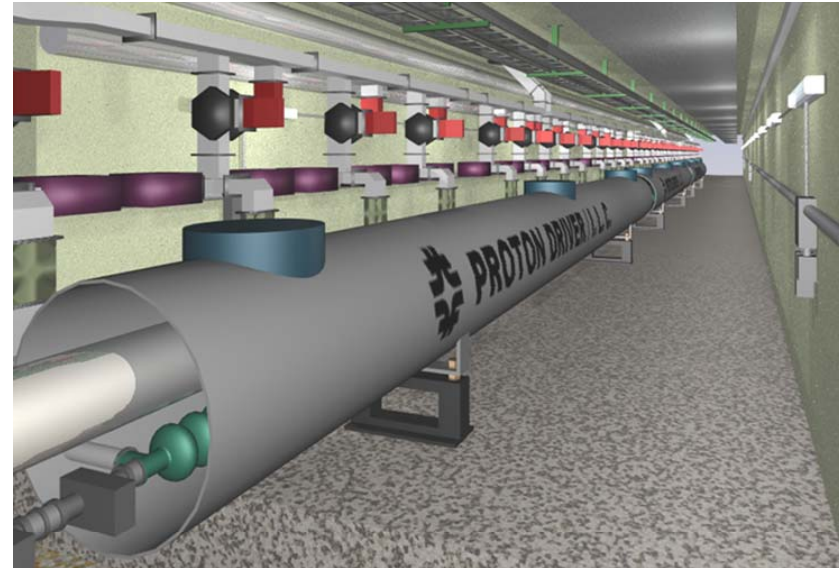
# SCRF Q factor vs normal rf Q factor

- Q factor of an oscillating system is defined as

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

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

- SCRF Q factors  $\sim 2.0E10$
- Normal rf Q factors are of order  $3E5, 5E5$ .
- So SCRF has an advantage of  $\sim 1E5$  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 ( $\beta=0.47, 0.61, 0.81$ ) 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
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
<b>LINAC ACTIVE LENGTH *</b>	<b>613.6 m</b>	<b>8000 MeV</b>		
Transfer Line to Ring	972.5 m	8000 MeV	47	half-cells (quads)
Tunnel to Front End Equipment Drop	20.0 m			TBD
<b>TUNNEL TOTAL LENGTH *</b>	<b>1606.0 m</b>			

Either 3-Spoke  
or Elliptical for  
110-400 MeV

# *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
- $\beta = 0.2$  Superconducting Single Spoke Cavities to  $\sim 30$  MeV
- $\beta = 0.4$  SC Single Spoke Cavities to  $\sim 125$  MeV
- $\beta = 0.6$  SC Triple Spoke Cavities to  $\sim 400$  MeV
- $\beta = 0.8$  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	<u>26 mA pulse</u> 62 $\mu$ A average	<u>9 mA pulse</u> <u>0.25 mA average</u>	100 mA	<u>10 mA</u>
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%	<u>1%</u> <u>1.3%</u>	CW CW	<u>CW</u> <u>CW</u>
1 GeV Beam Power	0.0625 MW	<u>0.25 MW</u>	100 MW	<u>10 MW</u>

Compare to FRIB capabilities as well



## 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	<i>Eff = 64 %</i>	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
		<b>TOTAL</b>	<b>25 MW</b>

# 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.

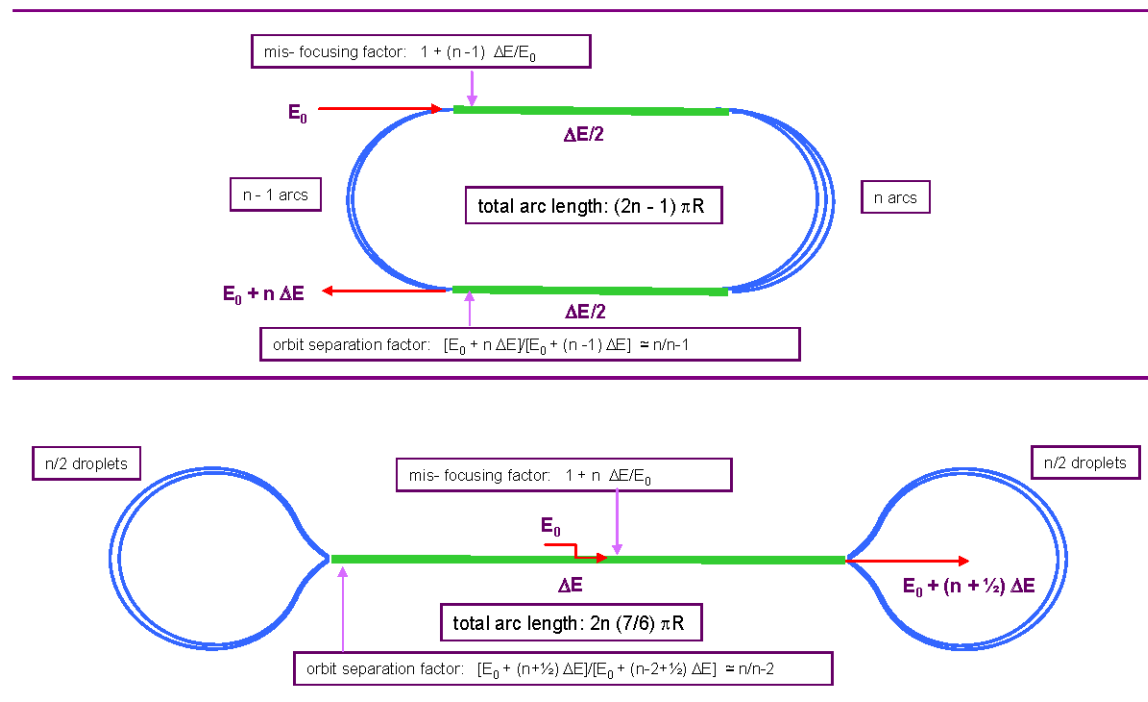


Figure 1. Performance merits of the 'Racetrack' and 'Dogbone' RLA configurations

# FFAG Designs

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

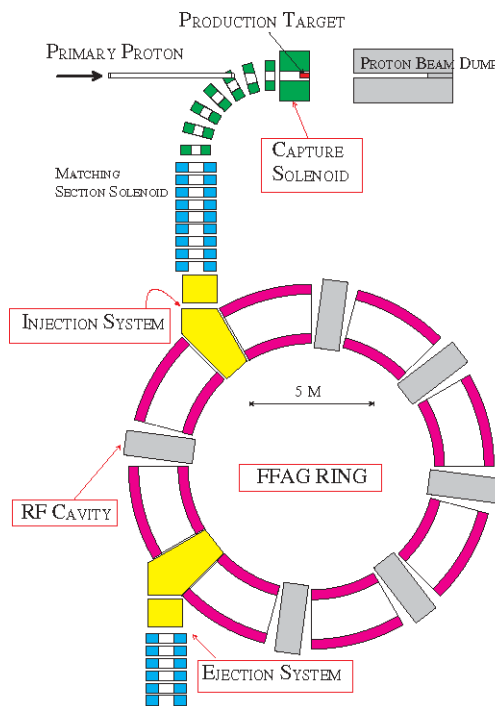


Figure 1: A schematic layout of PRISM

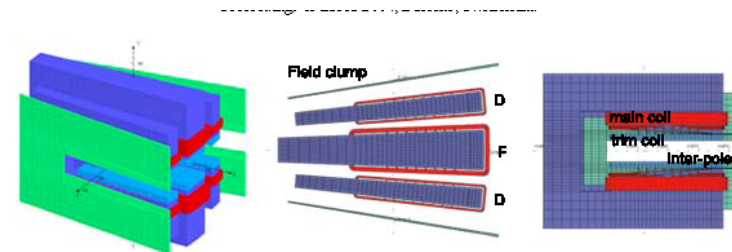


Figure 3: Schematic views of a PRISM-FFAG magnet. A bird's-eye view (left), a top view (center) and a side view (right).

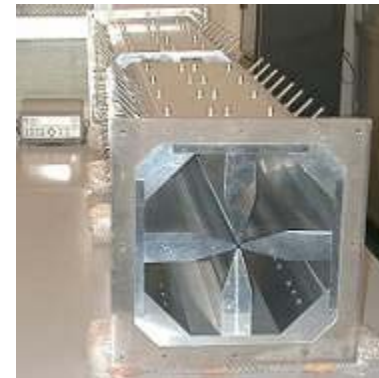
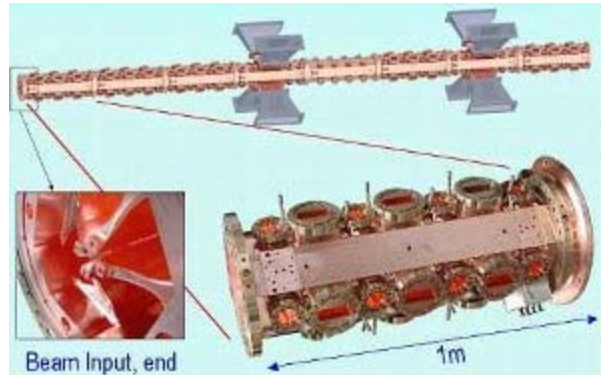
# *International Fusion Materials Irradiation Facility (IFMIF)- 125mA x2 14 MeV Deuterons*



Ion Source SACLAY+ LEBT + RFQ Saclay below

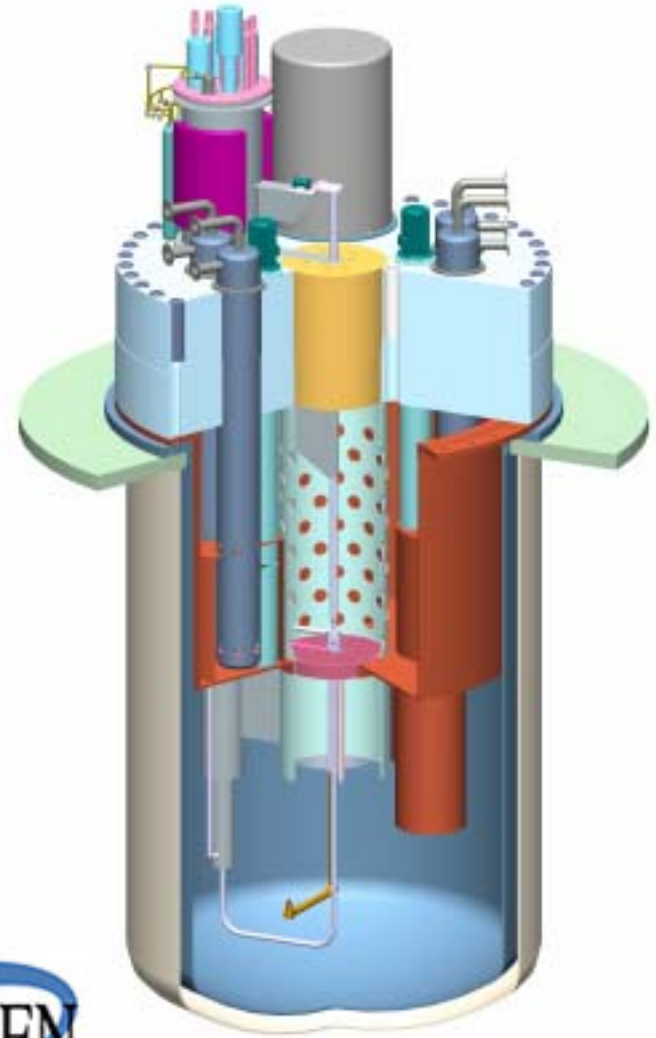


ECR ion source JAERI+ RFQ Jaeri below



# *MYRRHA (located in Belgium)*

- Chosen Linac technology to do transmutation.
- Expect to do this by 2020
- Experimental demonstration. Not intended for commercial energy production.
- Have chosen Lead/Bismuth Eutectic as spallation target/coolant





# *Scenarios and Possibilities*

- Adding a project of this type to the Fermilab program would require high level approval.
- It would need to be accompanied by a large and reliable source of funds tied to the national green energy needs.
- An immense amount of synergy exists between the neutrino factory needs and this effort.
- SCRF technology is needed by both
- High currents. Having achieved 10MW beam at 1 GeV, the Linac can be continued to 8 GeV, CW with 1.25mA current giving a 10MW source at 8 GeV.
- Targetry and material studies are in common. Los Alamos has done a significant amount of work in this regards with their previous efforts in APT. More needs to be done.
- Reliability of accelertors has to be improved greatly.
- Costs will come down in mass production. We need ~ 200 copies.
- Can think of waste burning centers.

# *Reactor Design and Fuel Recycling*

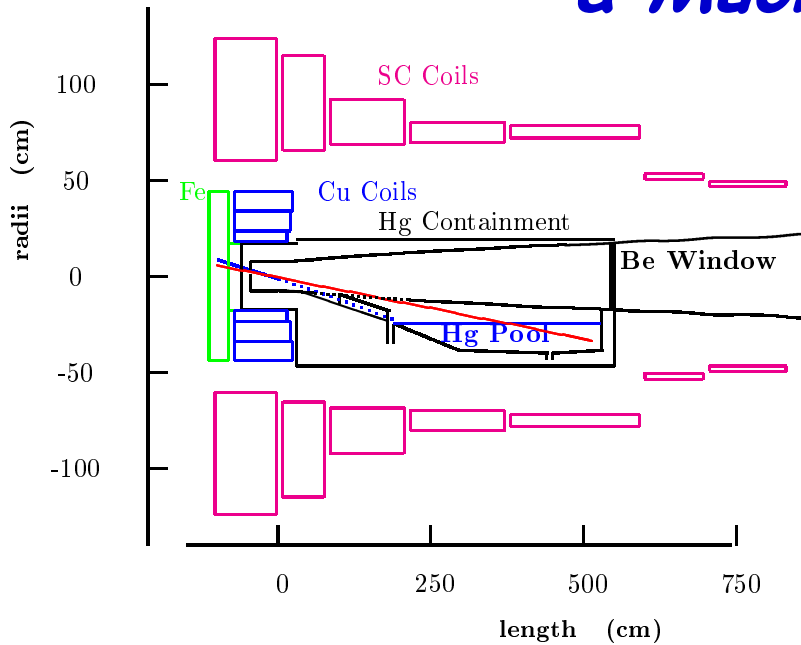
- Fermilab has no expertise in either. So this has to be done by other national or international labs.
- Fermilab, if it gets into this area should concentrate only on achieving the high power linac.
- Reactor Design (Argonne, BARC)
- Fuel Recycling (Argonne, LLNL, ORNL, BARC, European labs)
- Full ADS test could be elsewhere.
- So what does a high intensity source buy us physics wise?
- 10 MW 1 GeV front end can be extended to 8 GeV and run at 1.25MA CW to give a 10MW driver for a Muon factory.



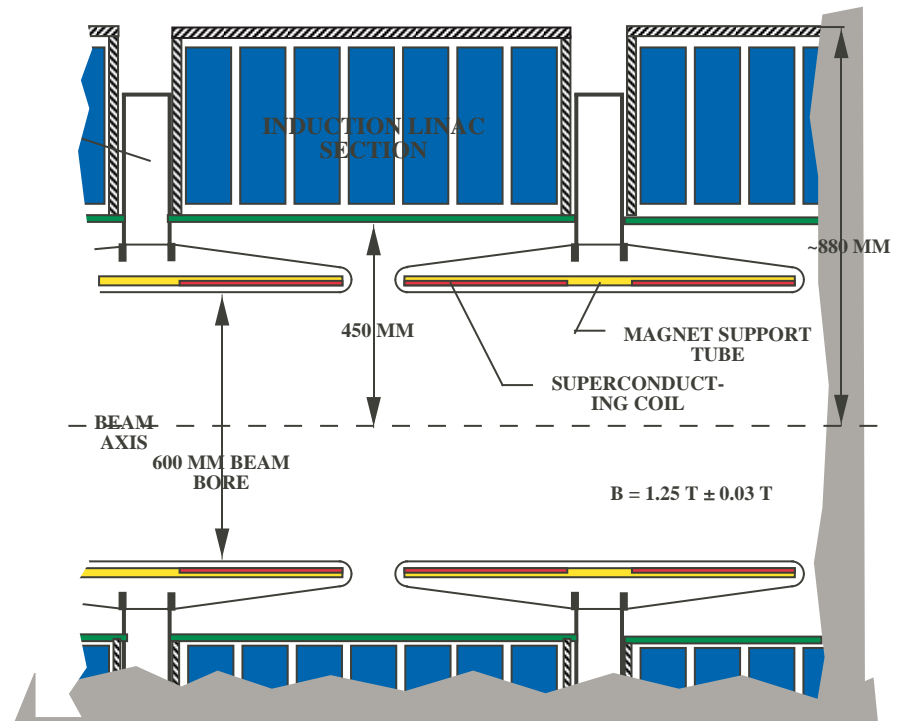
# Physics potential of an intense proton source

- 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. Gives a Muon Factory.



Big learning curve to do to achieve collection and 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%.  $4 \times 10^{20}$  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  $d_\mu$  measurement is still at the Letter of Intent stage and the reach of experiments is not yet entirely clear.)

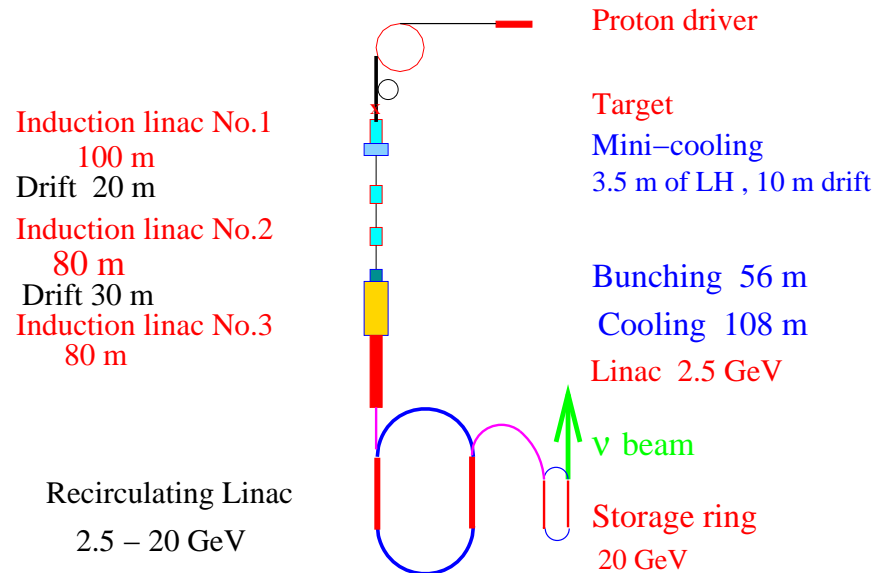
Test	Current bound	Current prospects	Future
$B(\mu^+ \rightarrow e^+\gamma)$	$< 1.2 \times 10^{-11}$	$\approx 5 \times 10^{-12}$	$\sim 10^{-14}$
$B(\mu^- \text{Ti} \rightarrow e^- \text{Ti})$	$< 4.3 \times 10^{-12}$	$\approx 2 \times 10^{-14}$	$< 10^{-16}$
$B(\mu^- \text{Pb} \rightarrow e^- \text{Pb})$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

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

New Physics	Limit
Heavy neutrino mixing	$ V_{\mu N}^* V_{eN} ^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	$\Lambda_c > 3,000 \text{ TeV}$

# Stage 3, Stage 4

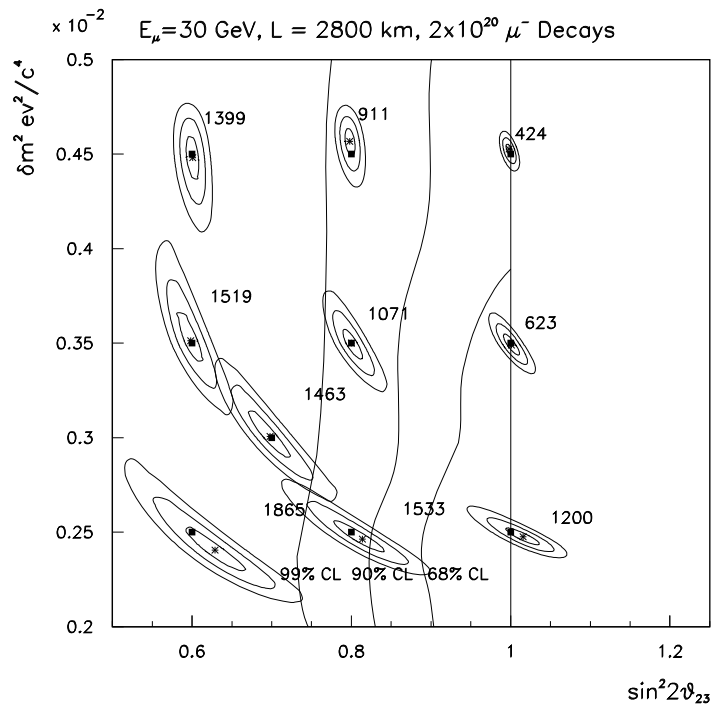
- Stage 3-Accelerate muons to 2.5GeV.
- $g-2$ , edm of muons can start. (needs 3.1 GeV magic momentum)
- Stage 4- Full neutrino factory



# *Neutrino Factory Physics Potential*

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

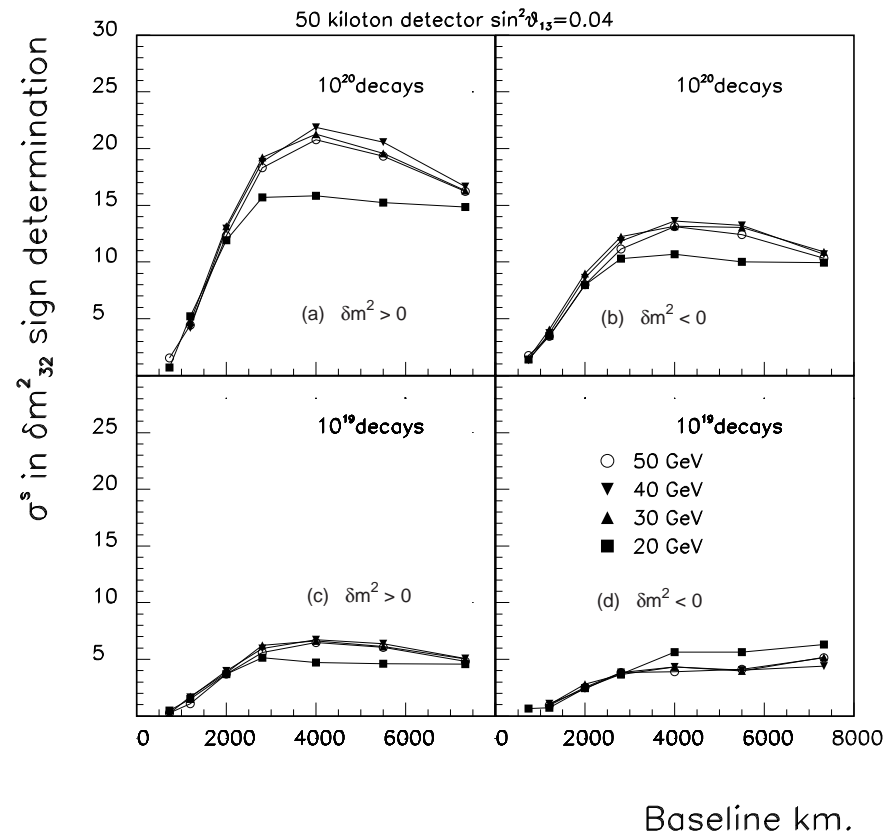
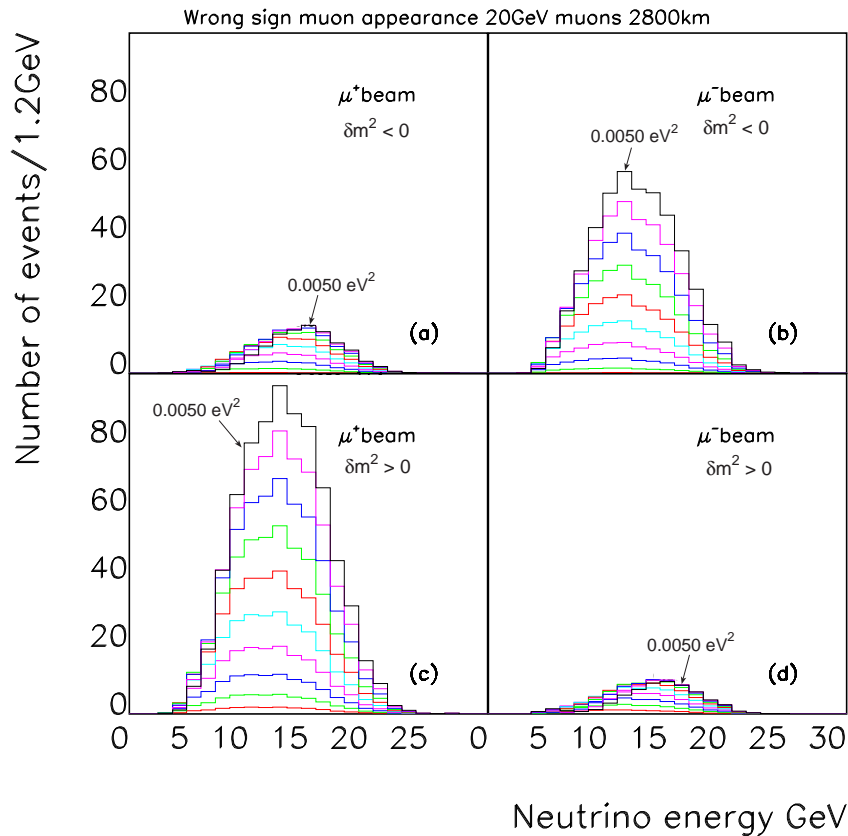
# Neutrino factory determination of oscillation parameters



V. Barger, S. Geer, R. Raja, K. Whisnant,  
Phys. REVD62, 013004 (2000)  
Predictions for 2800km baseline  
 $2 \times 10^{20}$  muon decays.

# Neutrino Factory Determination of $\delta m^2_{32}$ Sign

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



20GeV  $\mu$  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 50 GeV 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  $\alpha_s$  from sum rules and global fits reduced.
- Polarized parton densities measurable. Few percent 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  $\sim 2 \times 10^{-4}$
- 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

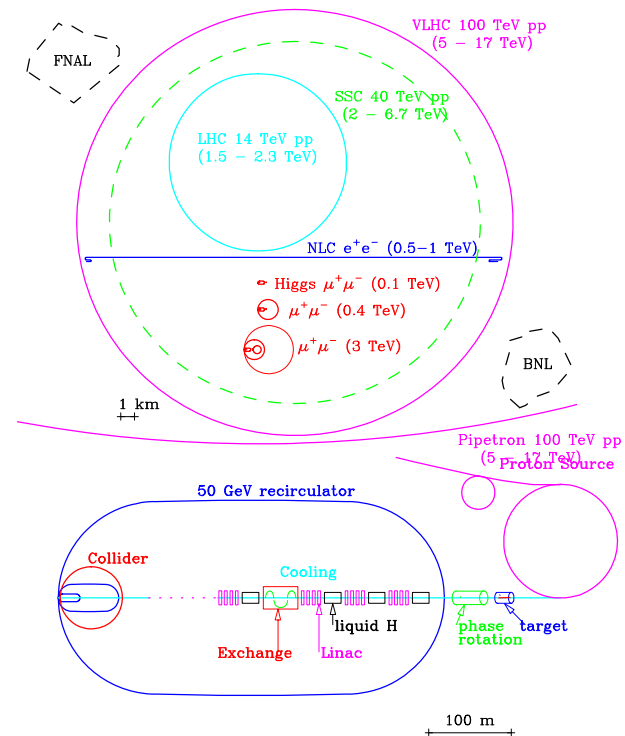
## Muon Colliders

- 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 115 GeV 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



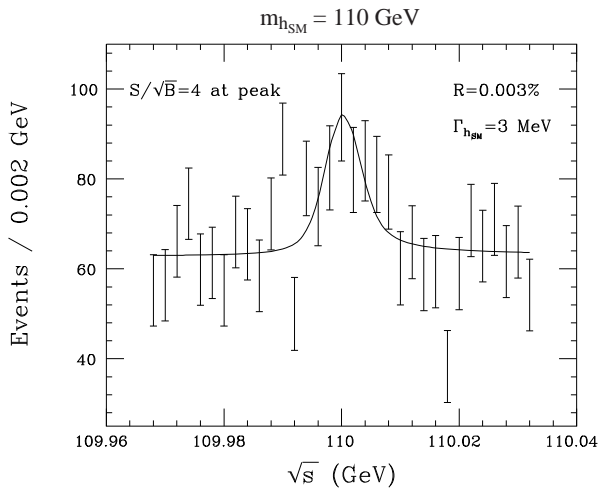
6/29/01

Andrew M Sessler, Snowmass 2001

# Higgs Factory/Muon Collider

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

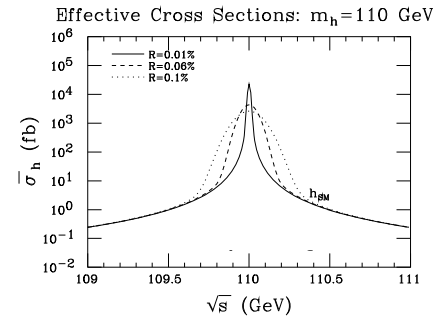
## Scanning the Higgs peak using the muon collider



## Light Higgs Resonance Profile

Convolve  $\sigma_h$  with Gaussian spread

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



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

## Light Higgs width

$$80 \lesssim m_h \lesssim 120 \text{ GeV}$$

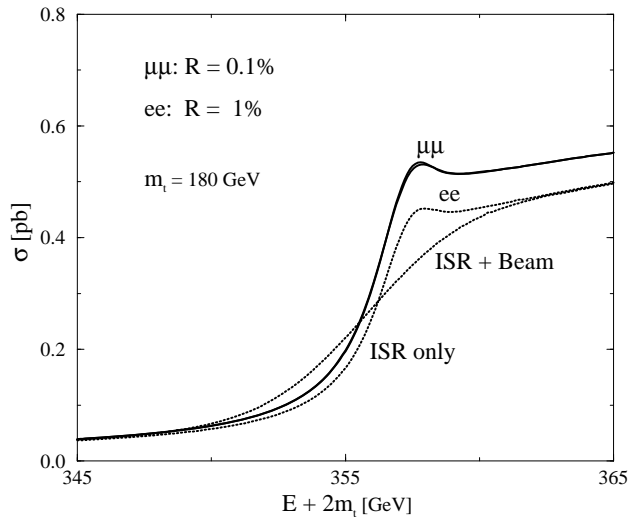
$$\Gamma_h \approx 2 \text{ to } 3 \text{ MeV} \quad \text{if } \tan\beta \sim 1.8$$

$$\Gamma_h \approx 2 \text{ to } 800 \text{ MeV} \quad \text{if } \tan\beta \sim 20$$

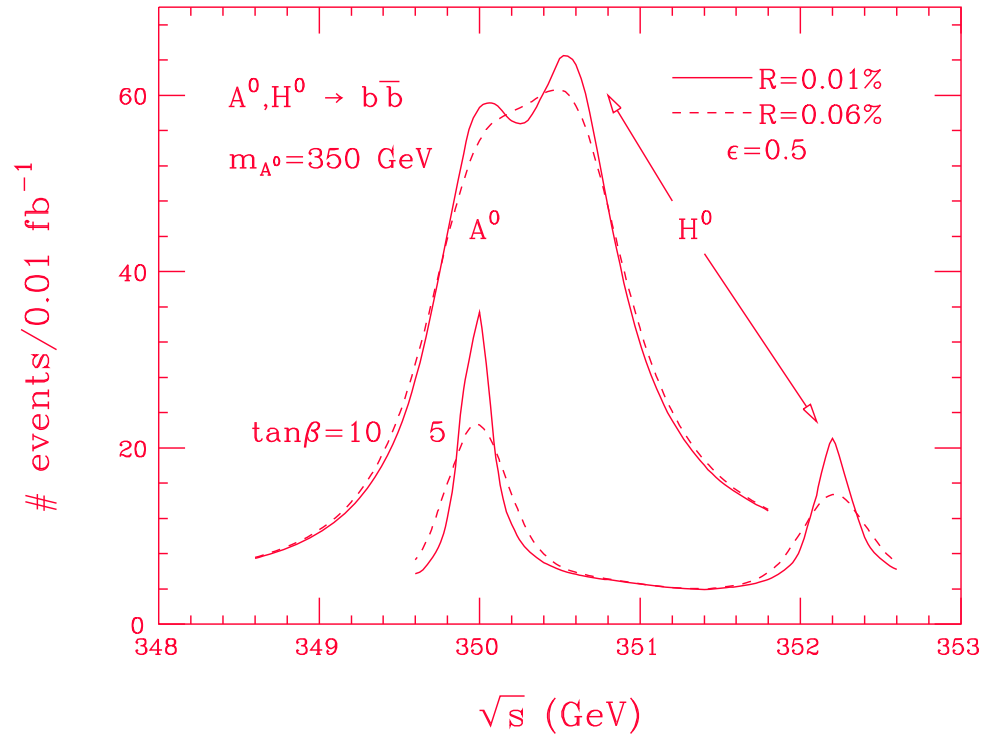
# Higher energy Muon Colliders

- 3TeV center of mass
- Will not cause neutrino Background problems.
- More exotic cooling,
- Exotic locations etc.

## Top quark threshold- ISR and beam effects



## Separation of $A^0$ & $H^0$ by Scanning



# 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 to 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 will 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.
- ADS is sub-critical and better at burning Minor Actinide Waste than fast reactors.
- In order to make further progress, a workshop that brings together all the interested parties may be worth pursuing.