Accelerator Driven Nuclear Energy- The Thorium Option-Issues and Ideas

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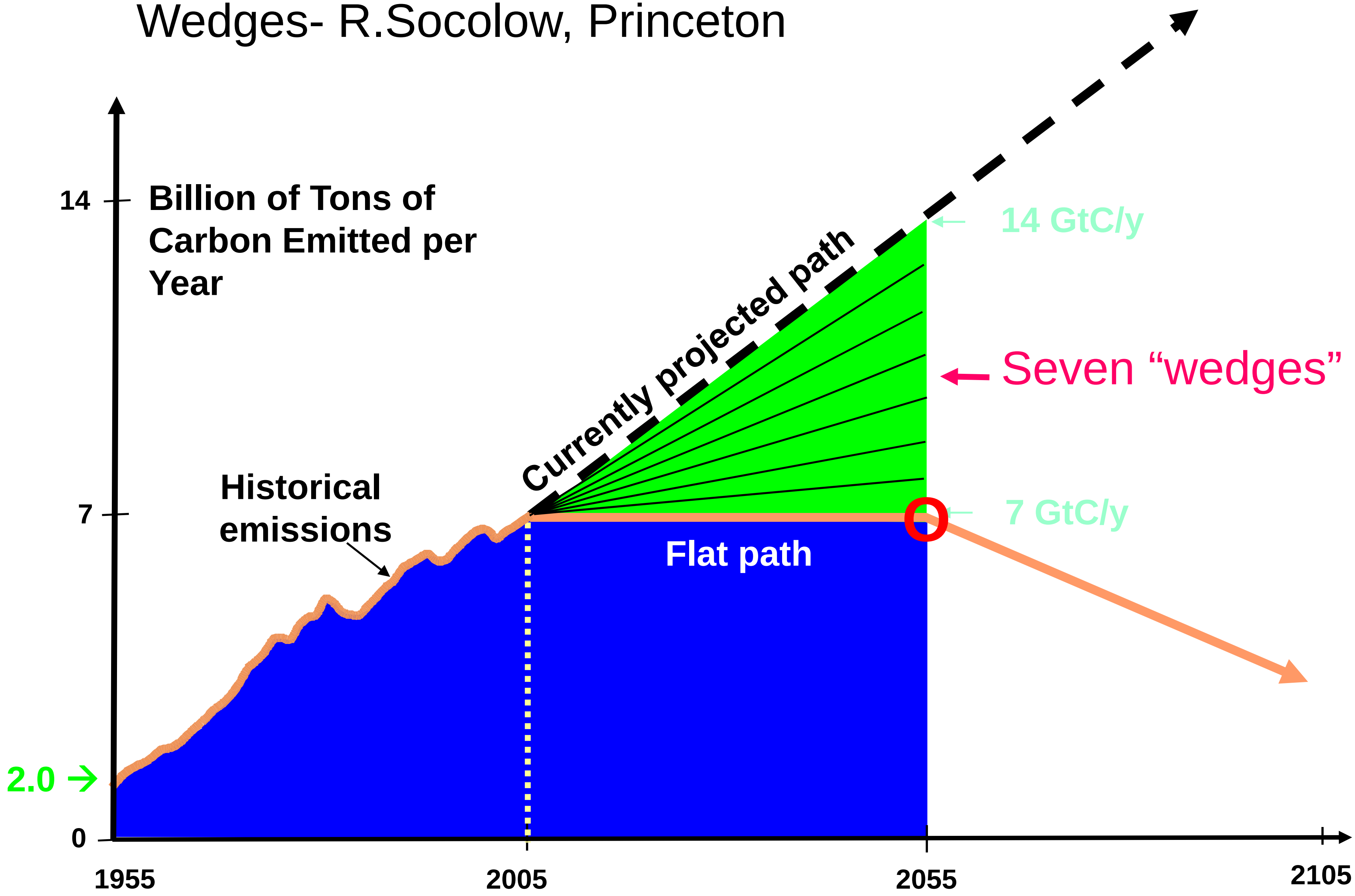
Fermilab

- I do not represent any institution, especially Fermilab management.
- Basic drive is to produce “green Energy” and solve the nuclear waste problem in a safe way. Produce more fuel.
- Needs a 10MegaWatt 1 GeV proton machine—doable using SCRF run in a CW mode. Does not exist yet. Needs R&D
- Reactor needs R&D. Liquid lead/Bismuth eutectic can be used as target producing spallation neutrons. Acts as coolant. Other targets need to be studied.
- Can use Thorium, Uranium 238 and existing nuclear waste as fuel.
- Sub-critical and hence more acceptable to public.
- Need to reprocess spent fuel.
- The resultant machine will open up new avenues in particle physics.
- This accelerator R&D project is a natural extension of Project X.
- Reactor design R&D will have to be done elsewhere.

Wedges- R.Socolow, Princeton



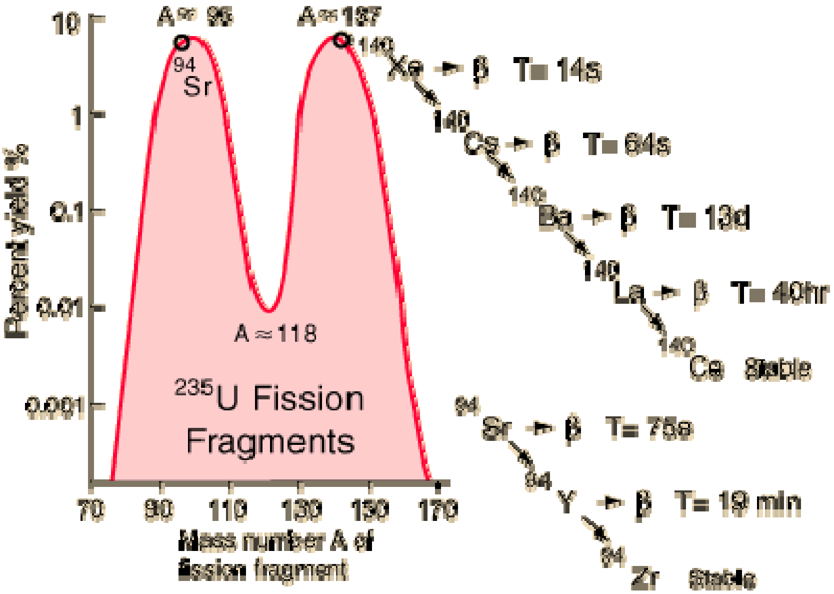
1 Wedge needs 700 GW (2 current capacity) from nuclear energy by 2055.

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).
  - » Fast reactors are inherently critical. Have not caught on.
  - » Try a new tack- supply fast neutrons using accelerators.

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 reactors" and also the "energy amplifier", the subject of this talk.
- Need to recycle fuel



Mean energy released per fission ~200 MeV

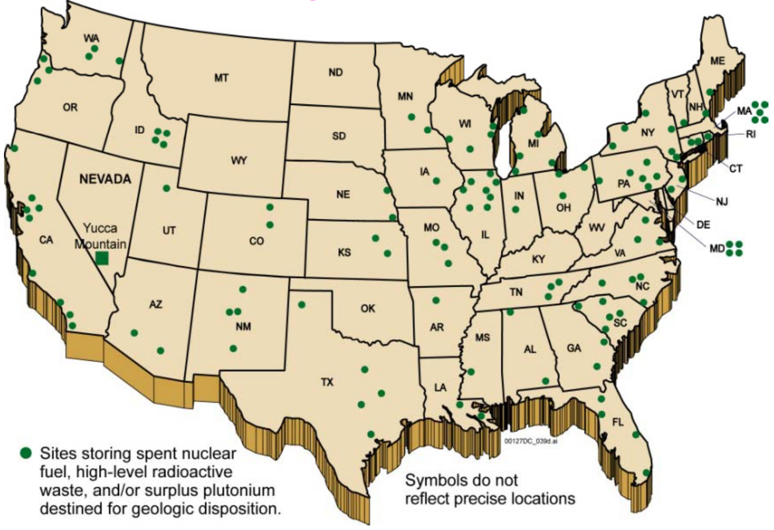
Recycling Strategies

- 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.
- Fast reactors or ADS is 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



● Sites storing spent nuclear fuel, high-level radioactive waste, and/or surplus plutonium destined for geologic disposition.

Symbols do not reflect precise locations

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”

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.

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

- 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

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

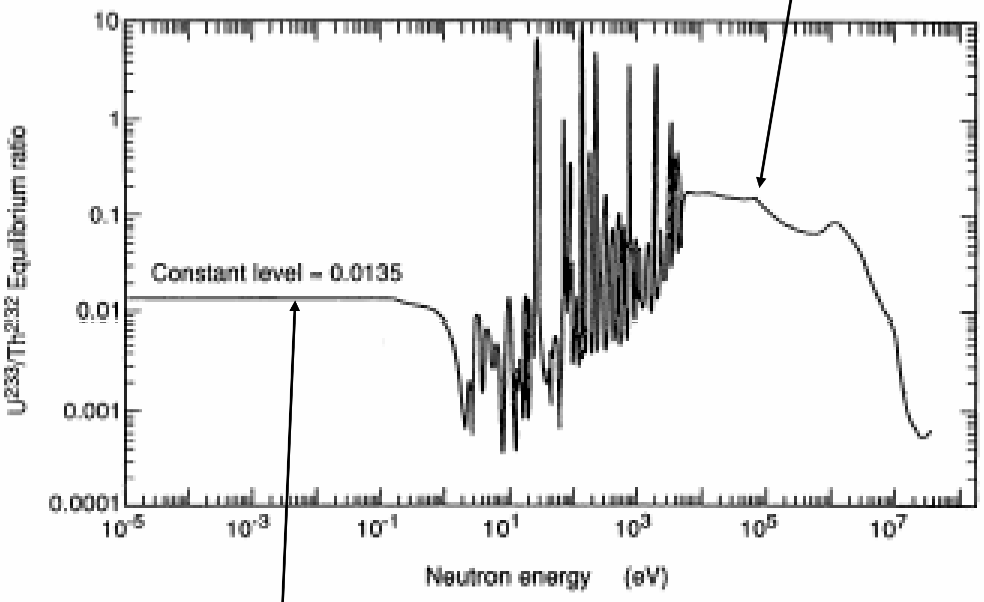
- Independent of neutron flux Φ
- Power of reactor is given by

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

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

Pure thorium initial state.

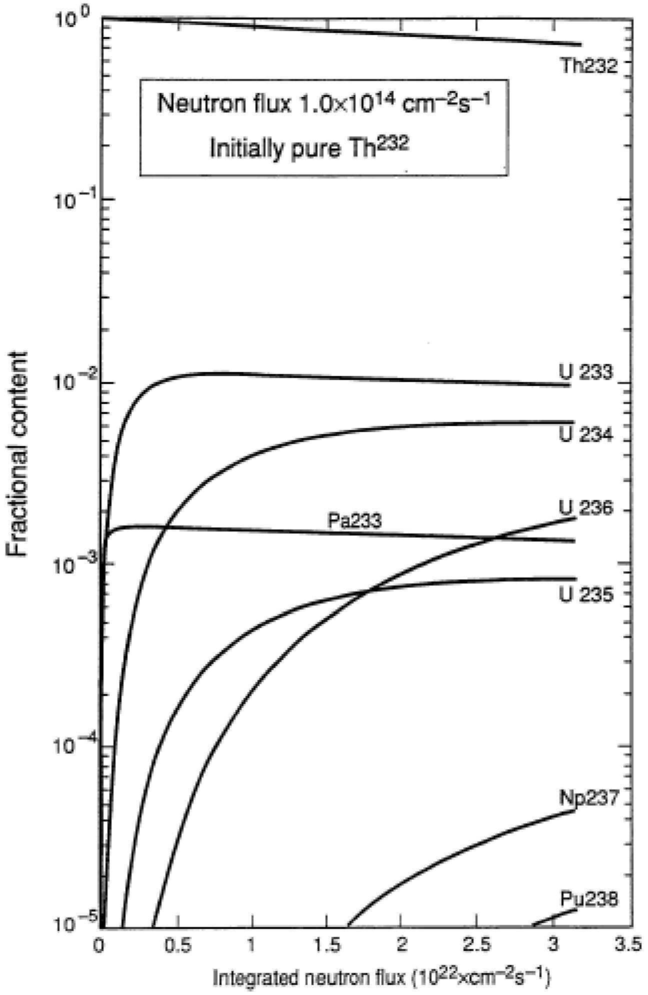


Figure 4

Natural Uranium 238 as fuel

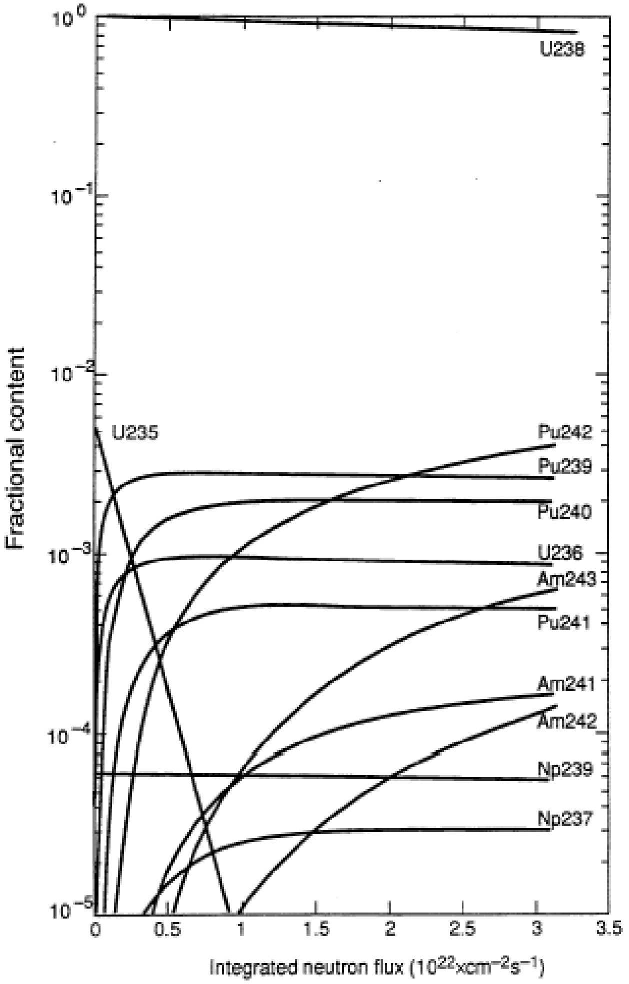
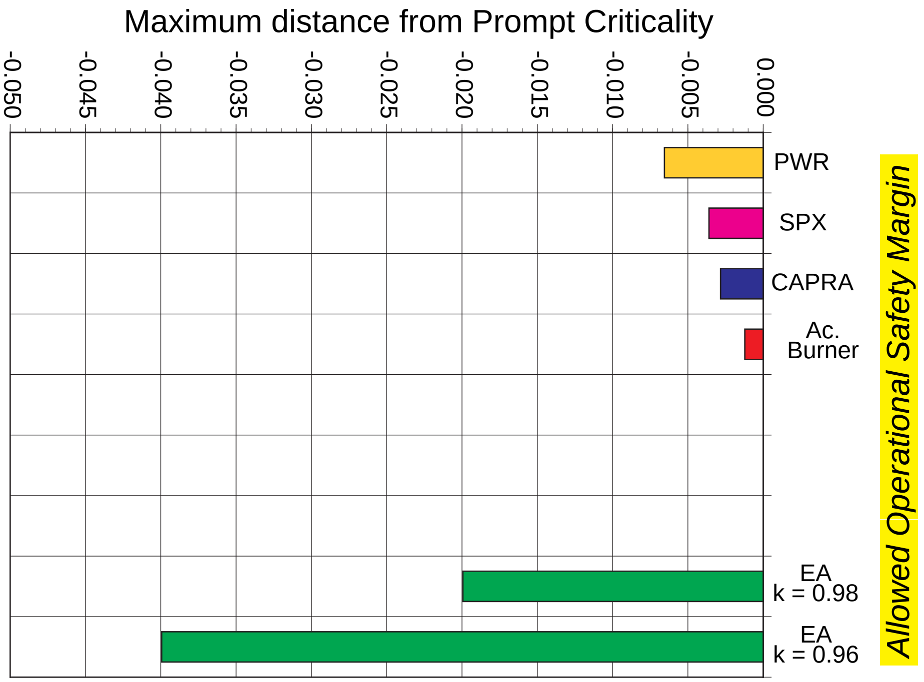
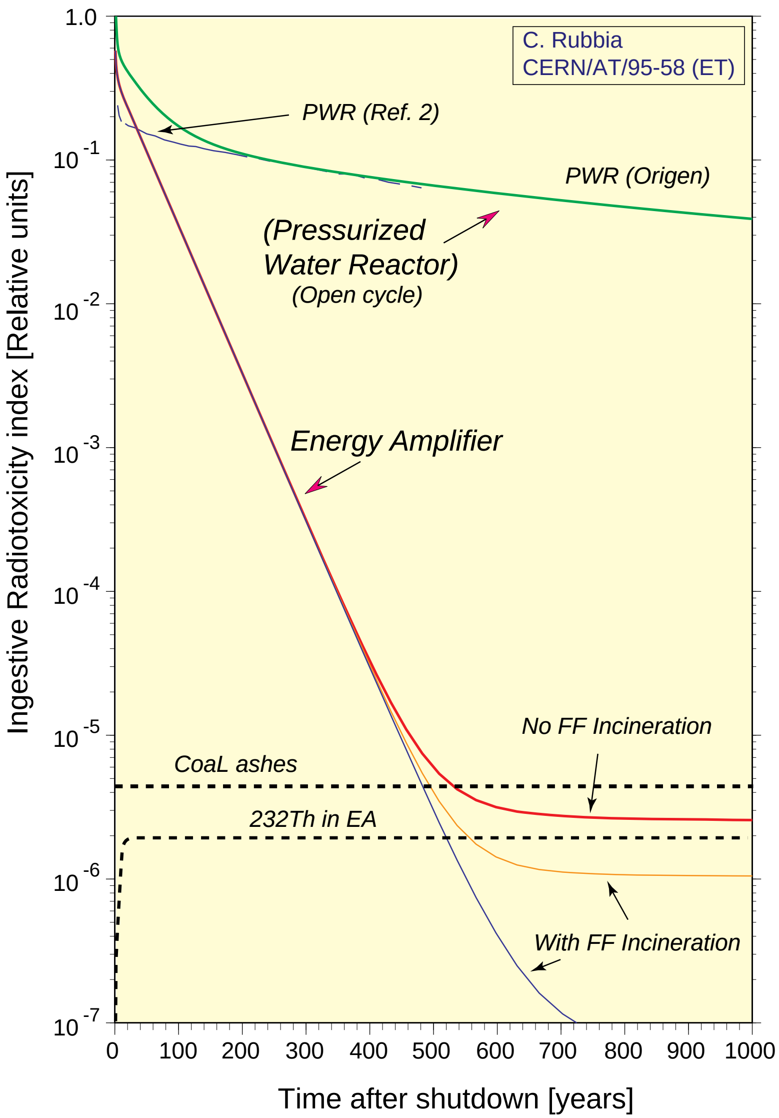


Figure 7

Advantages of the EA:



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



The Conceptual design

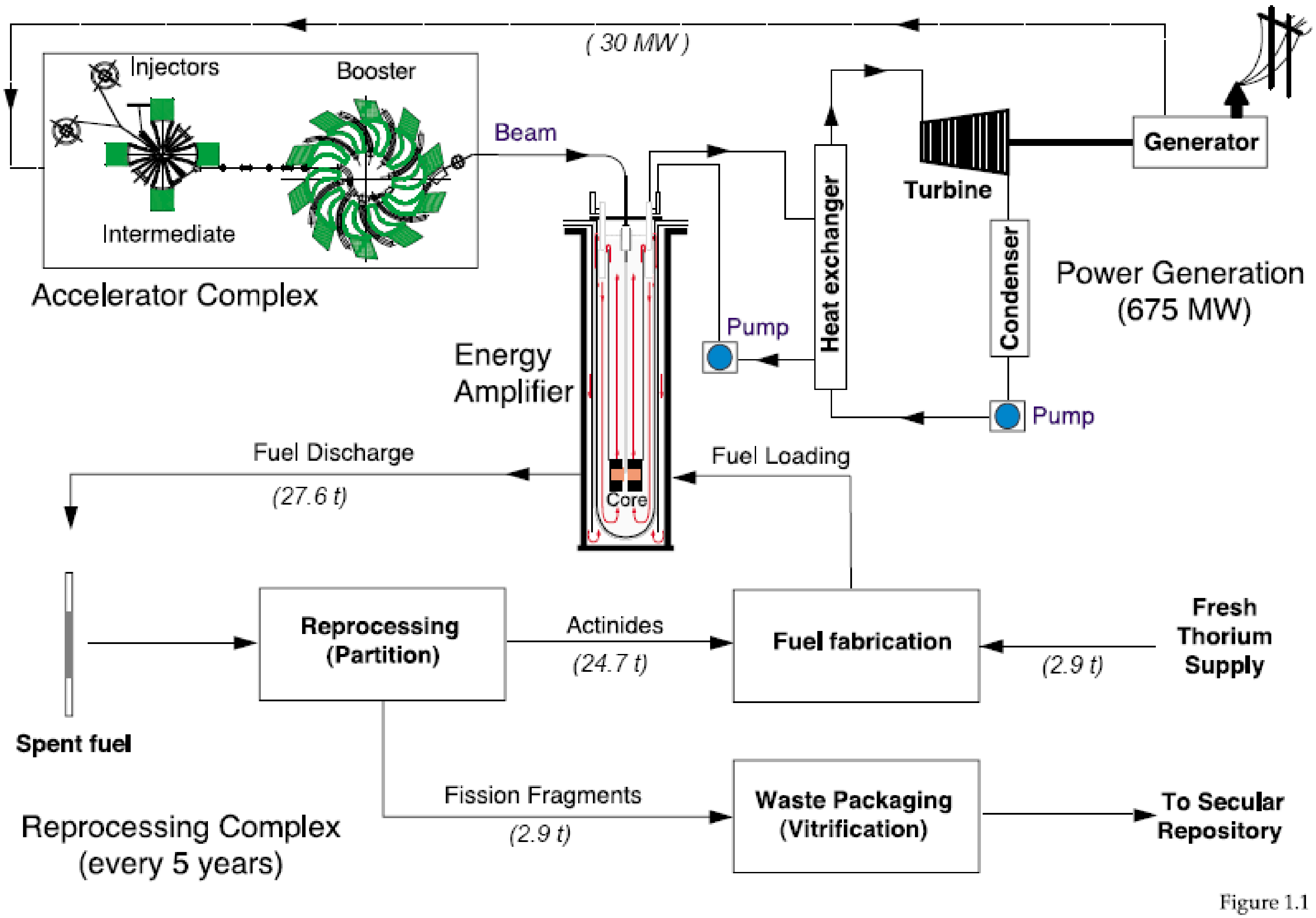


Figure 1.1

SCRF Q factor vs normal rf Q factor

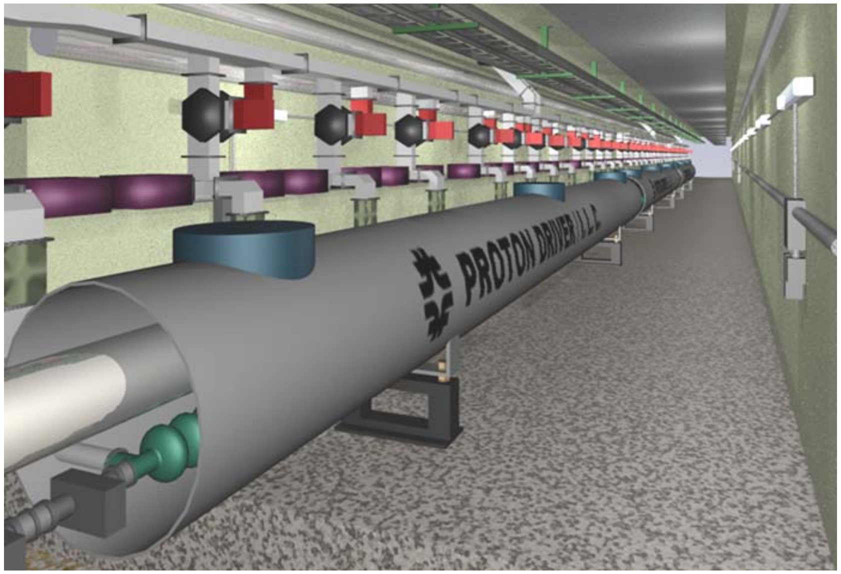
- Q factor of an oscillating system is defined as

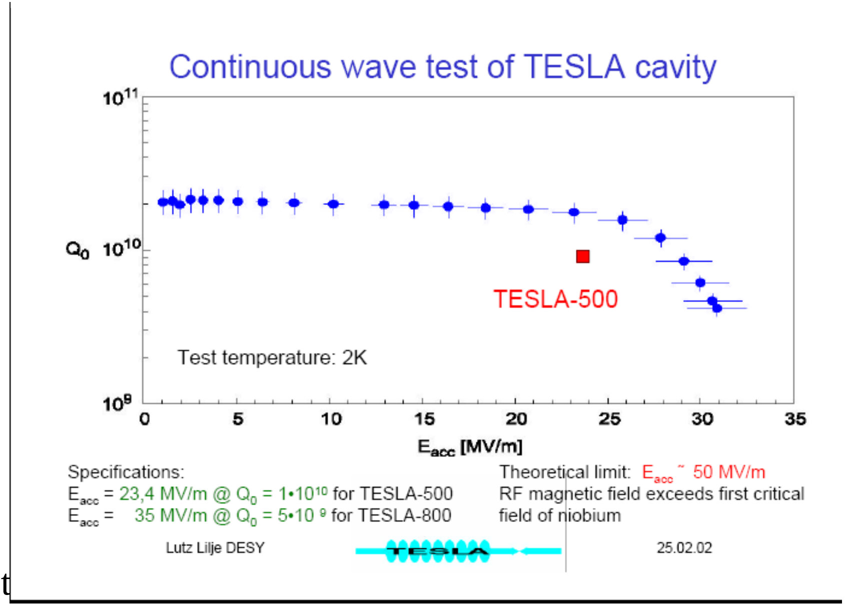
$$Q = \omega \frac{\text{Energy stored in cavity}}{\text{Power lost in cavity}}$$

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

- 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.




Continuous wave test of TESLA cavity

Specifications:
E_{acc} = 23,4 MV/m @ $Q_0 = 1 \cdot 10^{10}$ for TESLA-500
E_{acc} = 35 MV/m @ $Q_0 = 5 \cdot 10^{9}$ for TESLA-800

Theoretical limit: E_{acc} ˜ 50 MV/m
RF magnetic field exceeds first critical field of niobium

Lutz Lilje DESY

25.02.02

Scale Comparisons- B.Webber- Has produced a list of what works in the PD design for CW and what has to be modified.

	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

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

Major R&D areas

- Design 10 MW, 1 GeV Protons source
- Reactor Design, Safety systems
- Material studies
-
- Targetry, yields, radiation damage
- Fuel Reprocessing techniques
- Workshop on Applications of High Intensity Proton Accelerators at Fermilab Sep 21-24
- The first prototype proton driver can lead directly to a neutrino factory.

Workshop on Applications of High Intensity Proton Accelerators

Venue: - Fermilab
Date: September 21 - 24, 2009 (to be confirmed)

Recent advances in superconducting rf technology have made possible the construction of high intensity proton accelerators (10 Milliamp current or higher) at energies exceeding 1 GeV. Fermilab is developing a design of a High Intensity Proton Linac (Project-X) to support the future High Energy Physics Programs. The workshop proposes to bring together researchers working in areas as diverse as

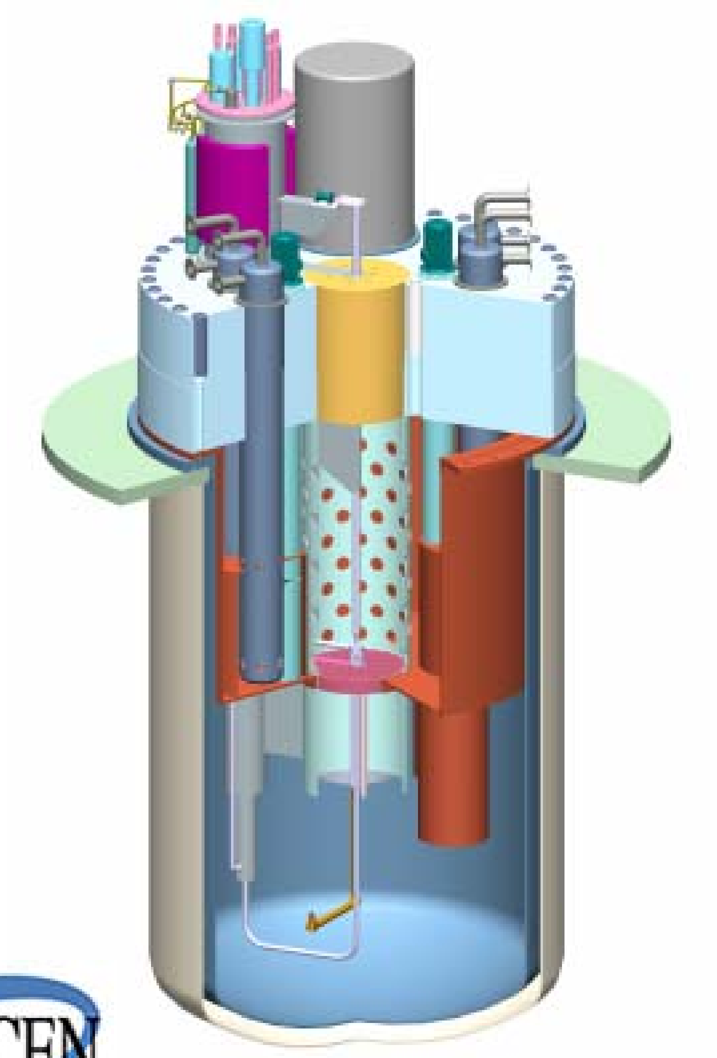
- Production of high intensity proton beam for Muon Factory and Neutrino Factory
- Accelerator based solutions to Nuclear Energy and Transmutation of waste including Accelerator Driven Subcritical Systems
- Material Irradiation and development studies

The present design of Project-X linac is to provide 1 MWatt of pulsed beam power at 8 GeV. The workshop will cover topics related to challenges in the design of High Power CW and pulsed linear accelerator, targetry as well as design of systems to collect pions to achieve muon beams leading to a neutrino factory. The workshop is timed to enable the design of Project-X and other projects (SPL,...) to give due consideration to these future upgrade possibilities.

Location: Fermilab

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



SCK•CEN

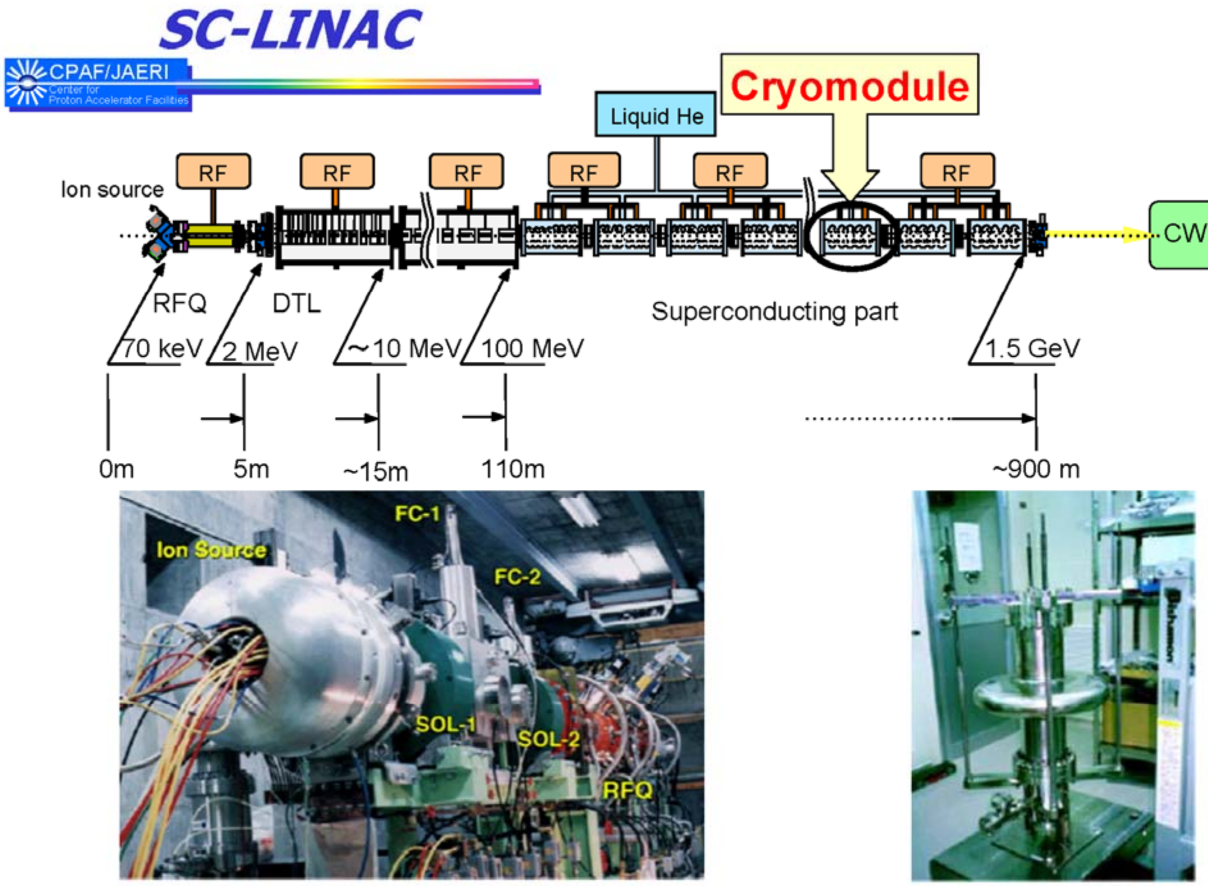
Japanese Experiment on ADS—J-PARC transmutation facility.

- Dear FFAG colleagues;

  I am pleased to inform you that the ADSR(Accelerator Driven Sub-critical Reactor) experiment using the FFAG proton accelerator and the nuclear reactor (KUCA) has started successfully on March 4 at KURRI (Kyoto University Research Reactor Institute). Protons accelerated up to 100MeV by the FFAG hit the tungsten target placed at the nuclear reactor to produce the spallation neutrons and changes of neutron multiplication have been observed for various criticality of the reactor. This would probably be the world first ADSR experiment combining high energy proton accelerator and nuclear reactor. The first stage of the ADSR experiment will continue by the end of March, 2009. We believes that FFAGs has opened another new window in their applications.

  Best regards,

  Yoshi



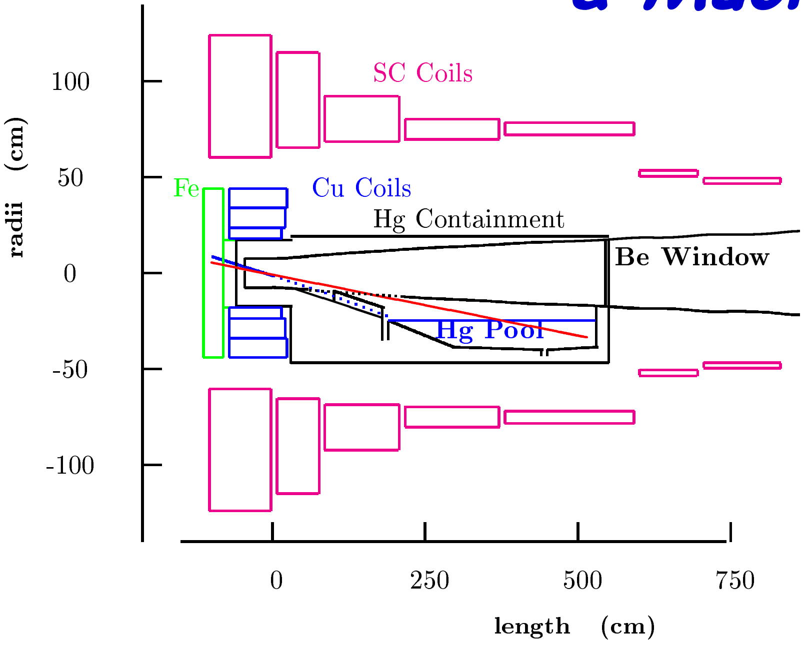
RFQ high current test : 70 mA

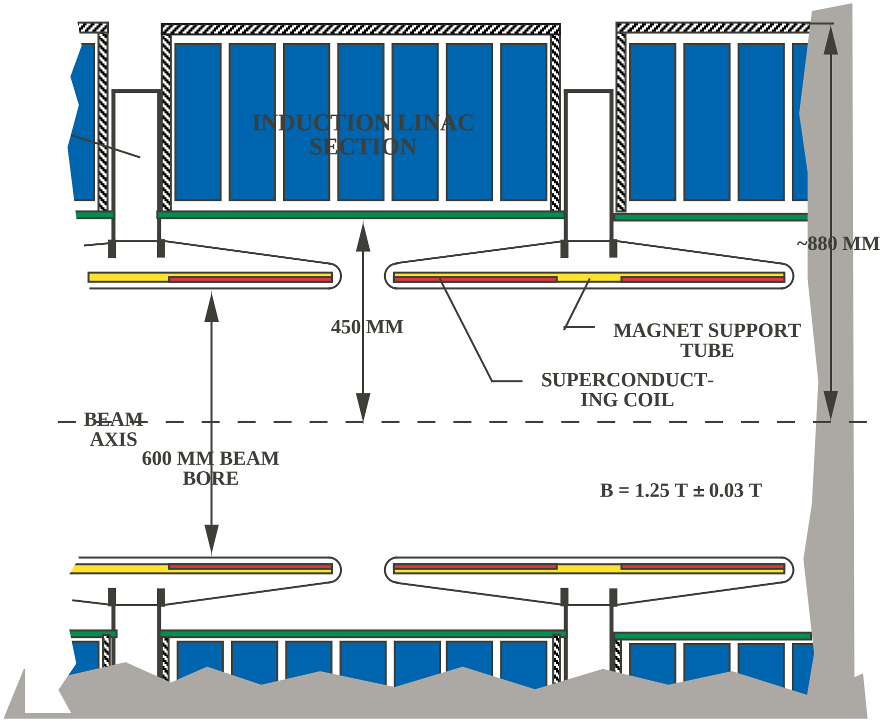
SC-cavity single cell test : 44 MV/m (2.1 K)

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 to give a 10MW driver for a Muon factory leading to a neutrino factory.

Stage 2 collection , phase rotation. Gives a Muon Factory.

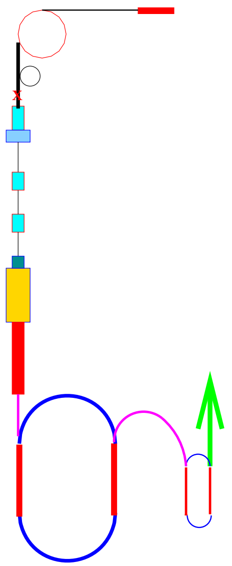




Big learning curve to do to achieve collection and phase rotation.

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



Induction linac No.1
100 m
Drift 20 m
Induction linac No.2
80 m
Drift 30 m
Induction linac No.3
80 m

Recirculating Linac
2.5 − 20 GeV

Proton driver

Target
Mini−cooling
3.5 m of LH , 10 m drift

Bunching 56 m
Cooling 108 m
Linac 2.5 GeV

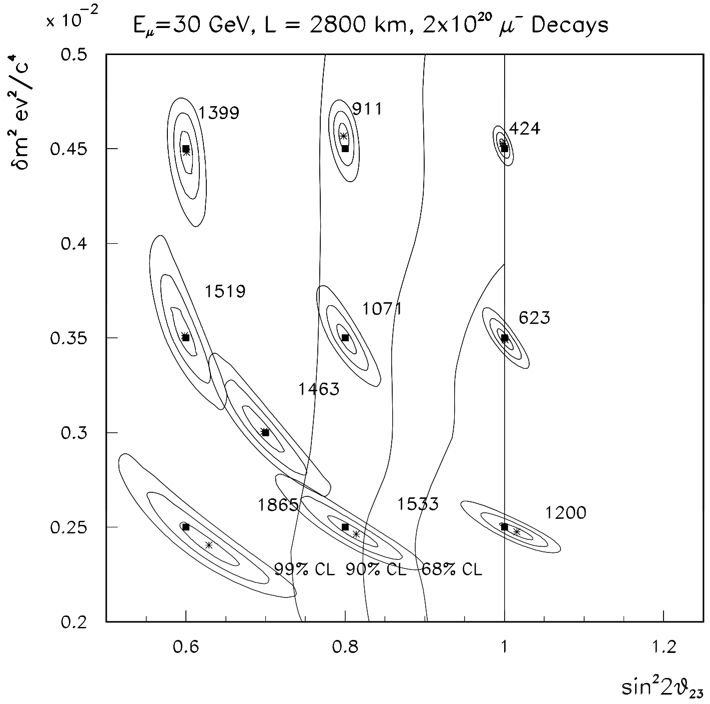
ν beam

Storage ring
20 GeV

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 $2x10^{20}$ muon decays.

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.

Scenarios

- Will stimulate Super Conducting RF and Accelerator R&D. Fermilab should be engaged in accelerator R&D on this as a direct offshoot of the Project X team—Extra funding
- Other labs (Argonne, BARC, LANL)have the expertise to study the reactor designs and targetry.
- Needs High Level DoE 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

- Needs (accelerator R&D only)
- Design of a CW version of 1 GeV 10 mA proton source
- Design of an extension to 8 GeV (CW or Pulsed?) as neutrino factory driver.
- Material studies on targeting 10MW of beam.
- Other physics (e.g. rare kaon decay that can be done with a 1 MW beam at say 2 GeV proton energy. Group at Fermilab investigating this).

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. More compact machine

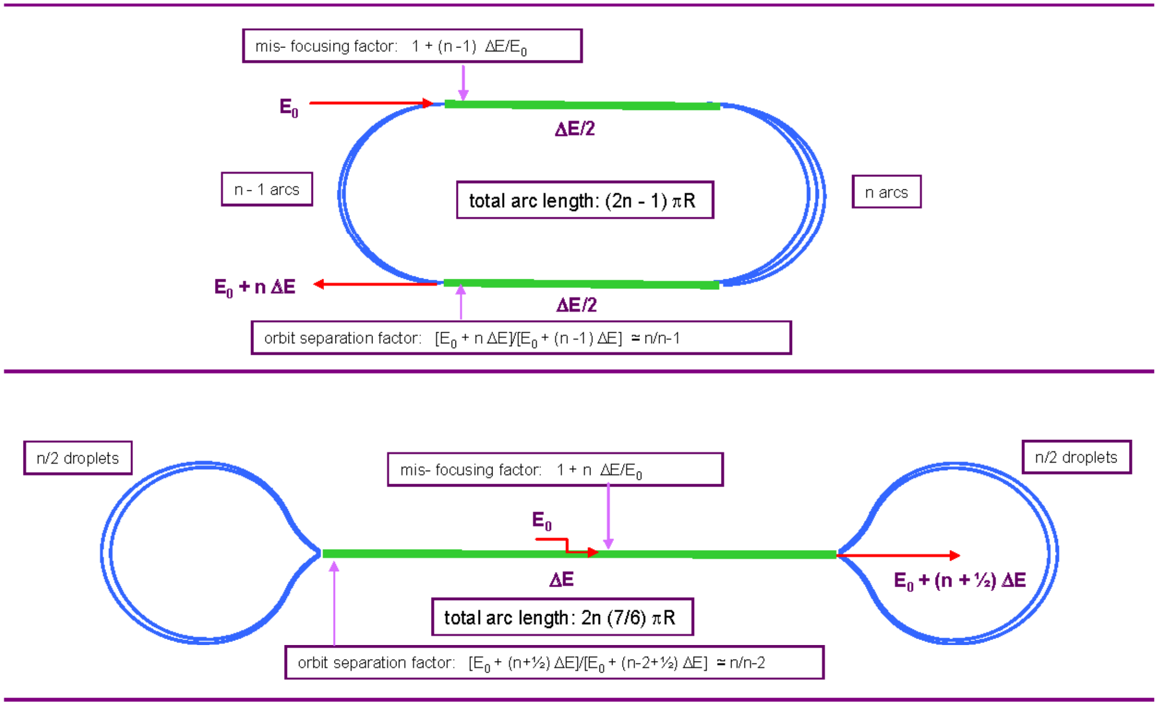


Figure 1. Performance merits of the 'Racetrack' and 'Dogbone' RLA configurations