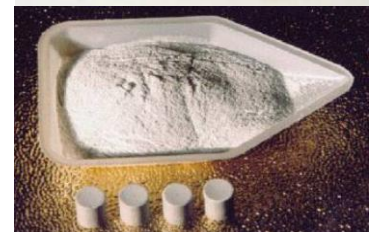


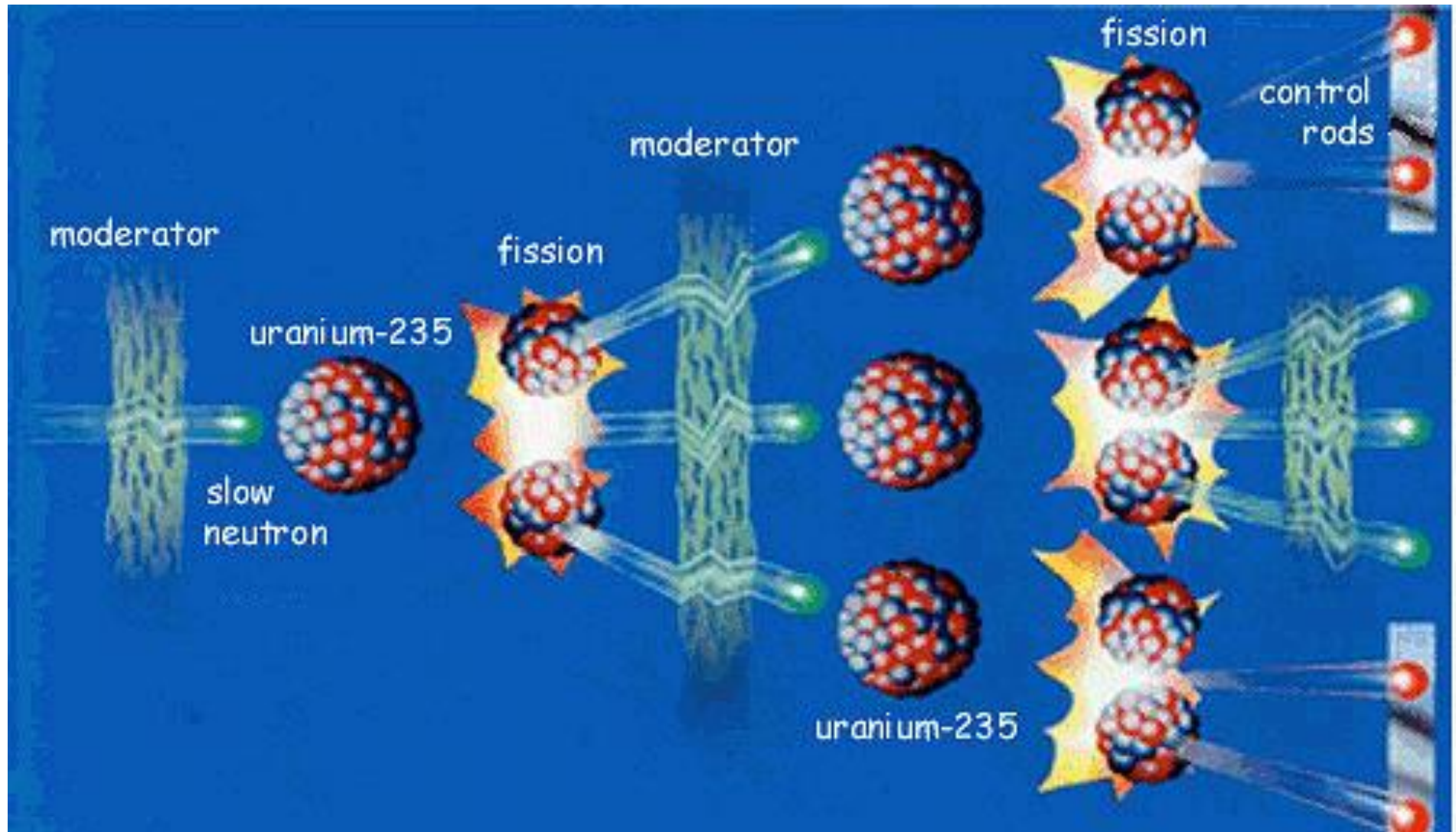
Accelerator Driven Subcritical Reactors

- Introduction:
 - ◆ Fission.
 - ◆ Conventional reactor.
 - ◆ Fast breeder reactor.
- The Energy Amplifier or ADSR.
- Waste from ADSR.
- Conventional accelerators.
- Fixed Field Alternating Gradient accelerators.
- Acceleration using electromagnetic induction?
- Summary.

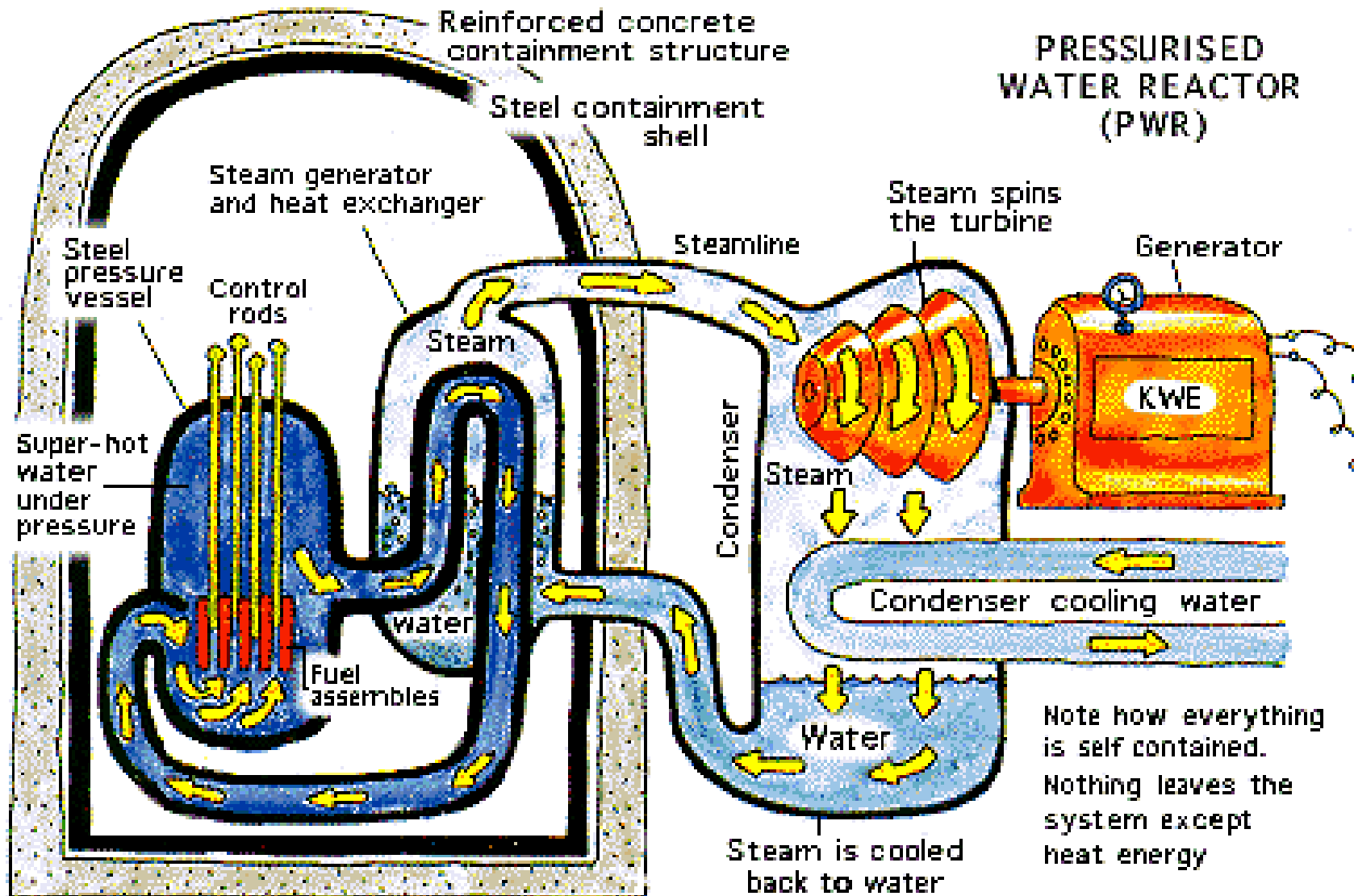
- Equivalent are:
 - 5×10^9 tonnes coal
 - 27×10^9 barrels of oil.
 - 2.5×10^{12} m³ of natural gas.
 - 65×10^3 tonnes of uranium (2.5 g/tonne).
 - 5×10^3 tonnes of thorium (10 g/tonne).



Nuclear fission



Conventional fission reactor

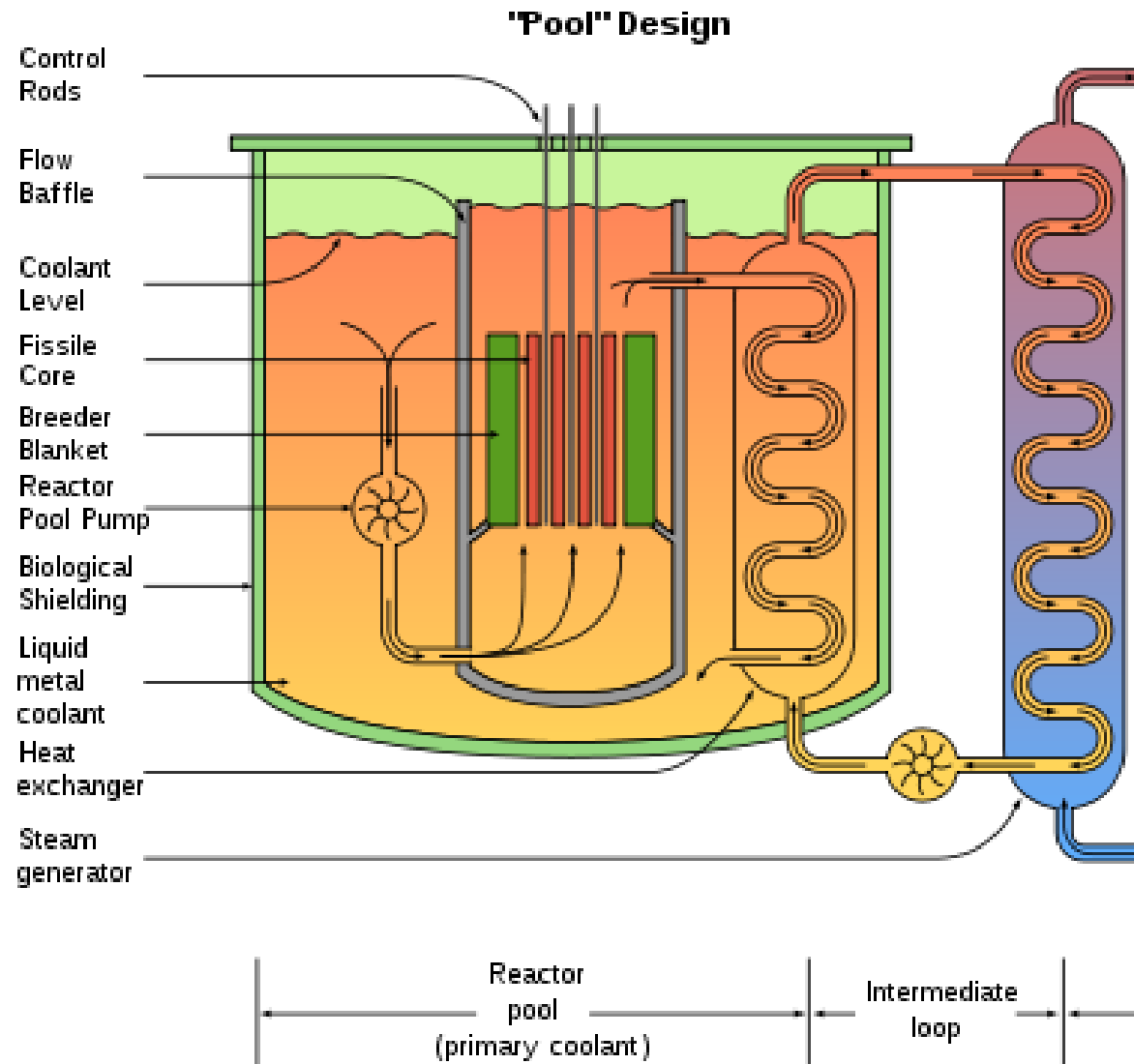


Features of conventional fission reactor

- Each fission:
 - ◆ Caused by absorption of 1 neutron.
 - ◆ Produces ~ 2.5 neutrons.
 - ◆ Some neutrons lost, leaving k to produce k new fission reactions.
- Conventional reactor:
 - ◆ Require $k = 1$.
 - ◆ If $k < 1$ stops working.
 - ◆ If $k > 1$ explodes.
- (Perceived) problems:
 - Safety:
 - ◆ Chernobyl.
 - ◆ Three Mile Island.
 - Waste:
 - ◆ Actinides with half lives of kyears to 100s of kyears.
 - Proliferation.
 - Uranium reserves uncertain.
 - ◆ Extract from oceans?
 - ◆ Use fast breeder reactors?

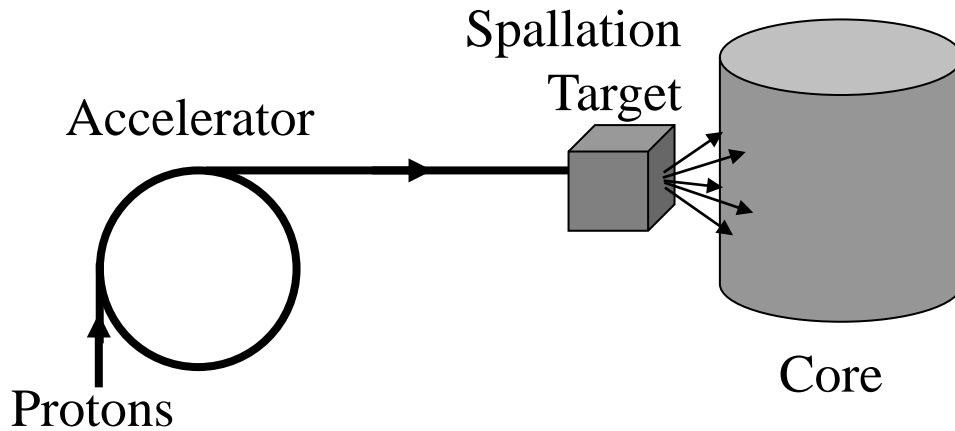
Fast Breeder Reactor

- Generally uses ^{239}Pu as fissile material.
- Produced by fast neutrons bombarding ^{238}U jacket surrounding reactor core.
- ^{239}Pu fission sustained by fast neutrons, so cannot use water as coolant (works as moderator).
- Liquid metals (or heavy water) used instead.
- India has plans to use thorium in its Advanced Heavy Water Reactors, in these ^{232}Th is converted to fissile ^{233}U .



Energy Amplifier or ADSR

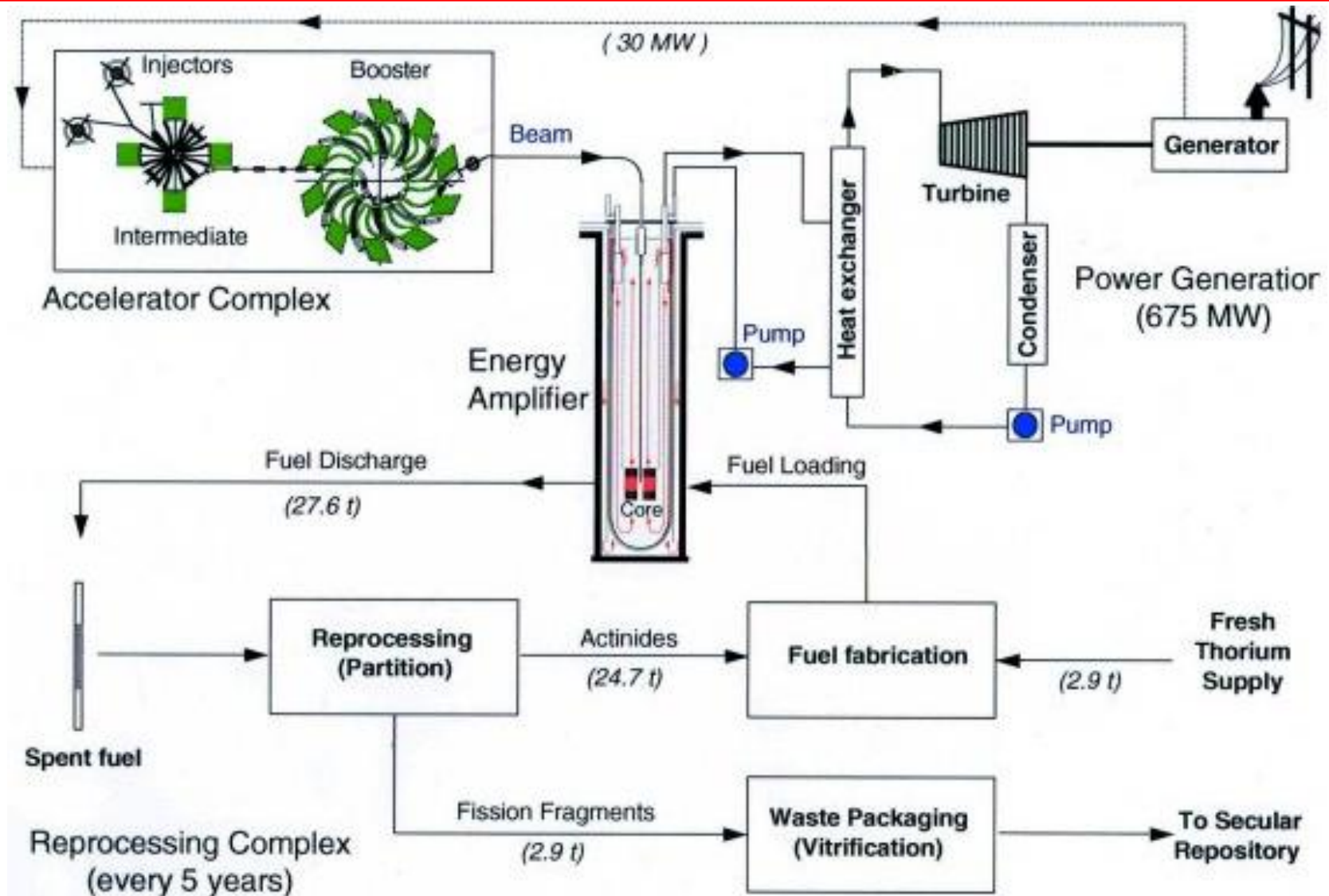
- Accelerator Driven Subcritical Reactor is intrinsically safe.
- Principal:



- Run with $k < 1$ and use accelerator plus spallation target to supply extra neutrons.

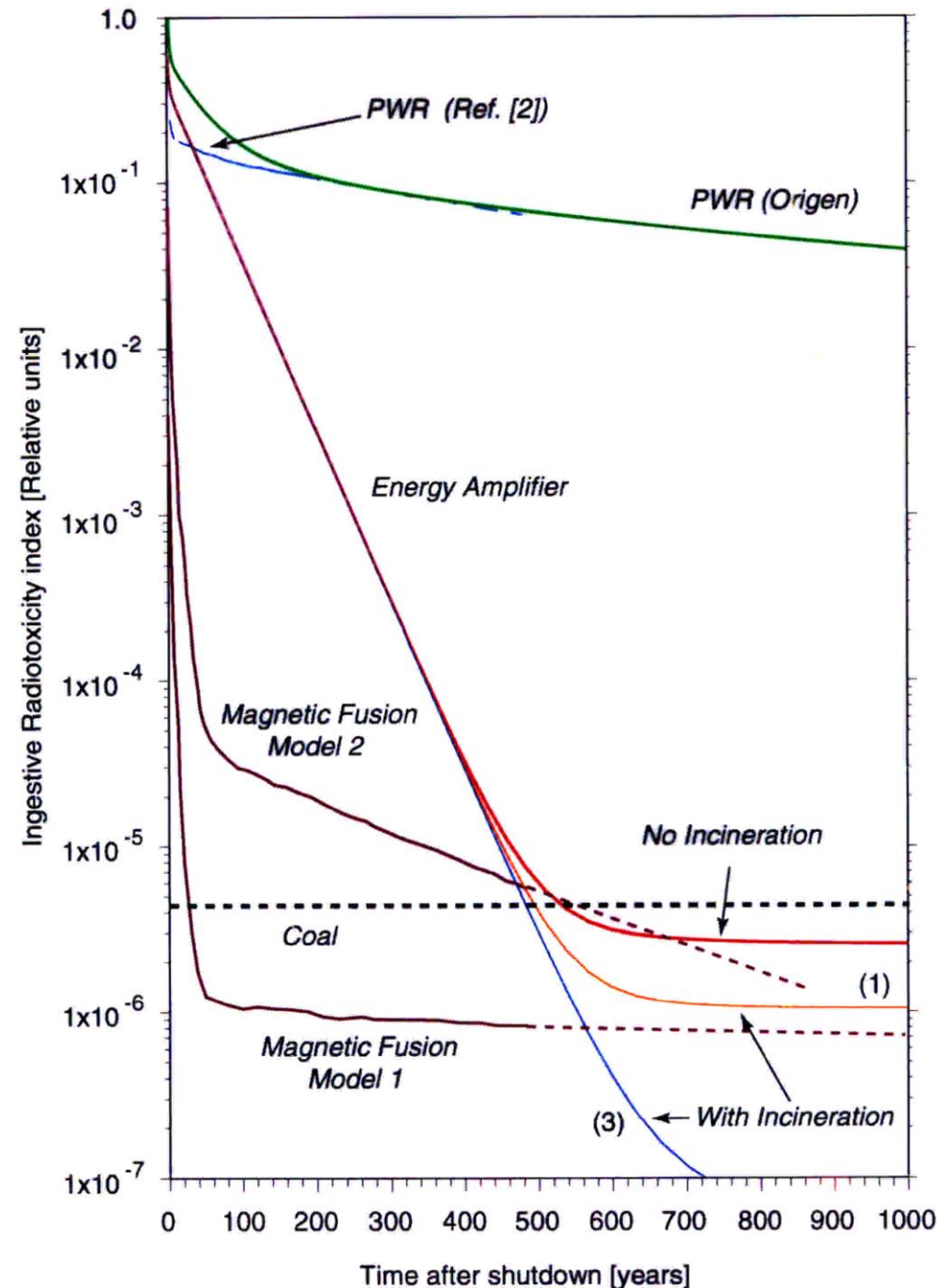
- Switch off accelerator and reaction stops.
- Need $\sim 10\%$ of power for accelerator.
- Can use thorium as fuel.
- $^{232}\text{Th} + n \rightarrow ^{233}\text{U}$.
- Proliferation “resistant”:
 - No ^{235}U equivalent.
 - Fissile ^{233}U contaminated by “too hot to handle” ^{232}U .
- There is lots of thorium (enough for several hundred years)...
- ...and it is not all concentrated in one country!

Energy Amplifier or ADSR



Waste from ADSR

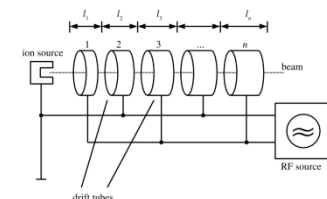
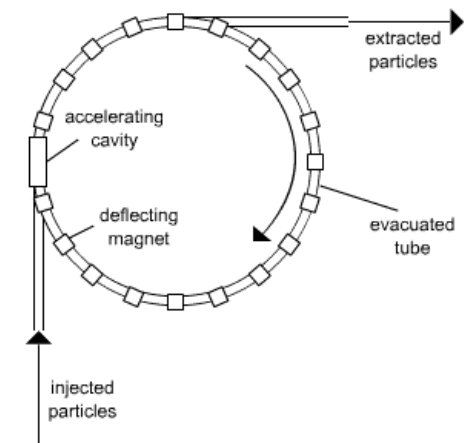
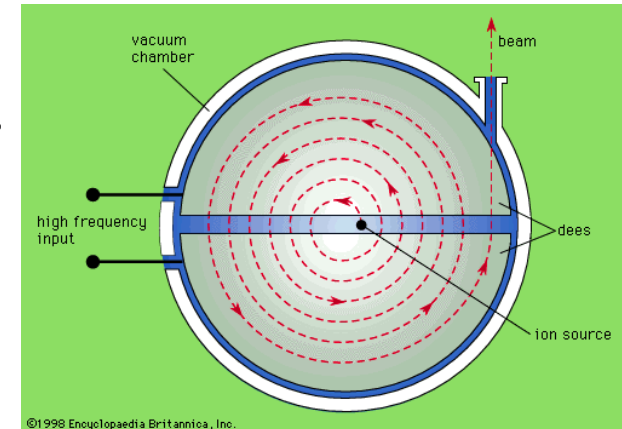
- Actinides produced in fission reactions are “burnt up” in the reactor.
- Remaining waste has half life of a few hundred rather than many thousands of years.
- Can use ADSR to burn existing high activity waste so reducing problems associated with storage of waste from conventional fission reactors.
- So why haven't these devices already been built?



Accelerator

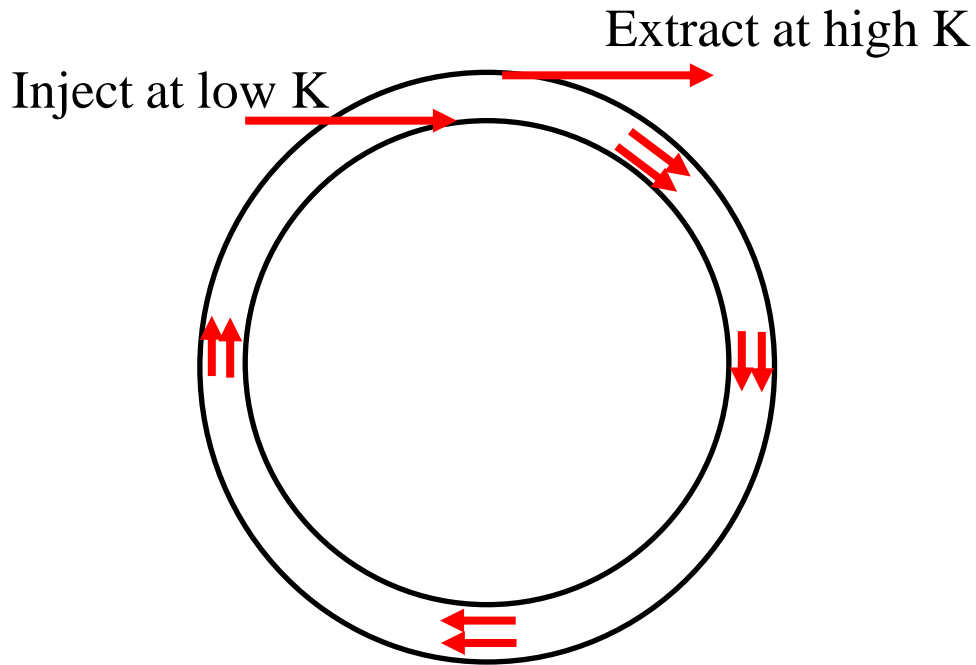
- Challenge for ADSRs is accelerator.
- Required proton energy ~ 1 GeV.
- For 1 GW thermal power need current of 5 mA, power of 5 MW.
- Need high reliability as spallation target runs hot.
- If beam stops, target cools, stresses and cracks: max. 3 trips per year.
- Compare with current accelerators:
 - ◆ PSI cyclotron: 590 MeV, 2 mA, 1 MW.
 - ◆ ISIS synchrotron: 800 MeV, 0.2 mA, 0.1 MW.
 - ◆ Many trips per day!

- Cyclotron, fixed B field, radius increases: energy needed too high!
- Synchrotron, constant radius, B field ramped: current too high!
- Linac: perfect, but too costly?



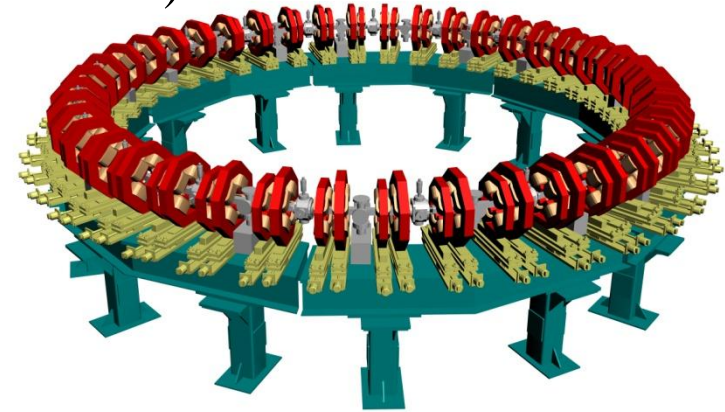
Fixed Field Alternating Gradient Accelerator

- FFAG, radius of orbit increases slightly with energy: protons move from low field to high field region.

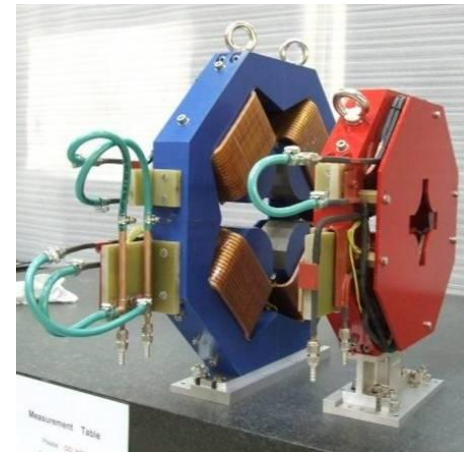


- Simplicity of operation hopefully ensures the necessary reliability.

- nsFFAG designed at Daresbury (EMMA):

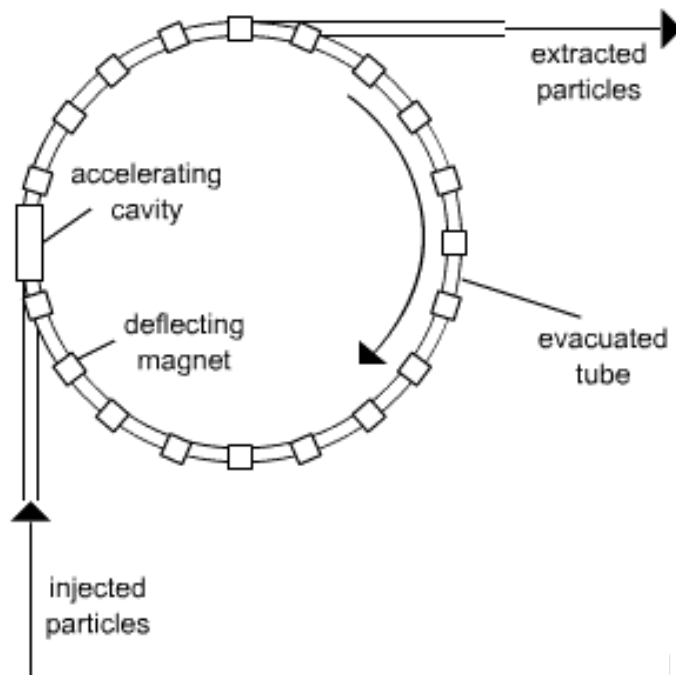


- Construction underway.



FFAG and acceleration

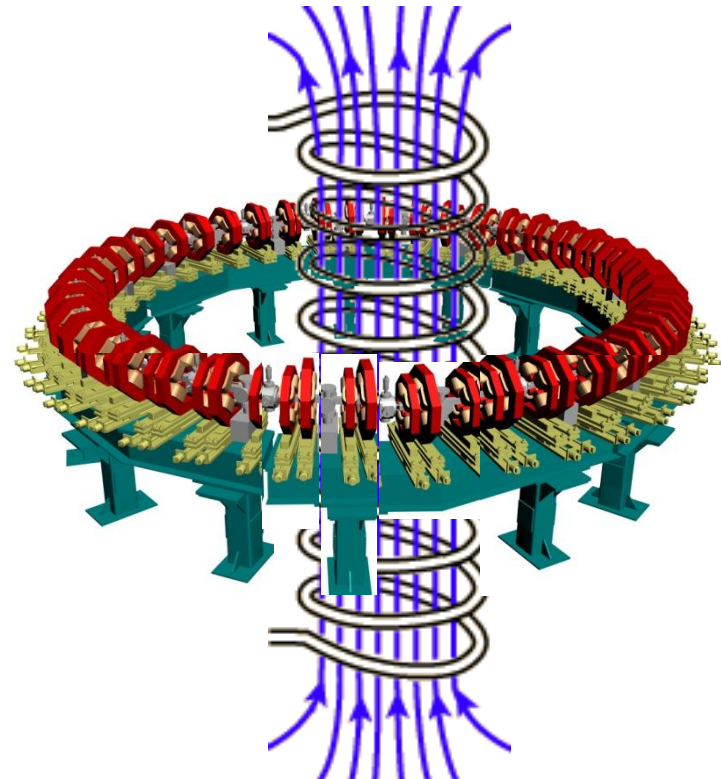
- RF cavities conventionally used to accelerate charged particles.



- A problem with FFAG is synchronisation of RF with particle orbits over large energy range.

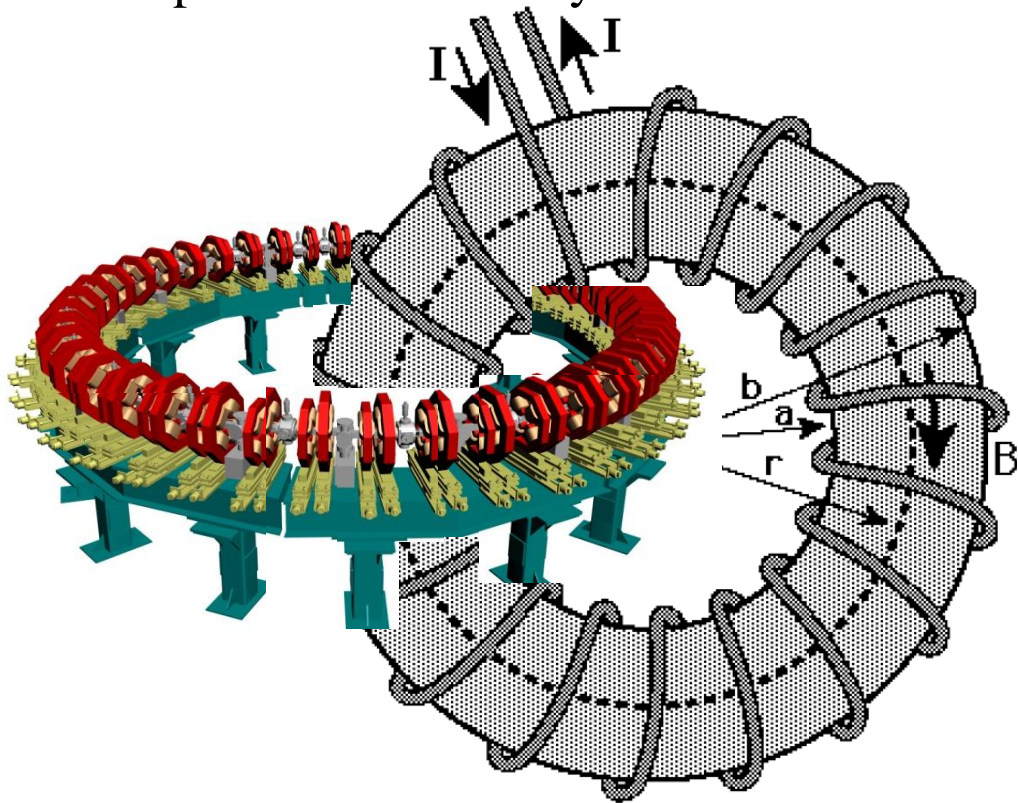
- Alternative: inductive acceleration?

- Use Faraday's Law: $\mathcal{E} = \oint_{2\pi r_A} \vec{E} \cdot d\vec{s} = -\frac{d\Phi}{dt}$



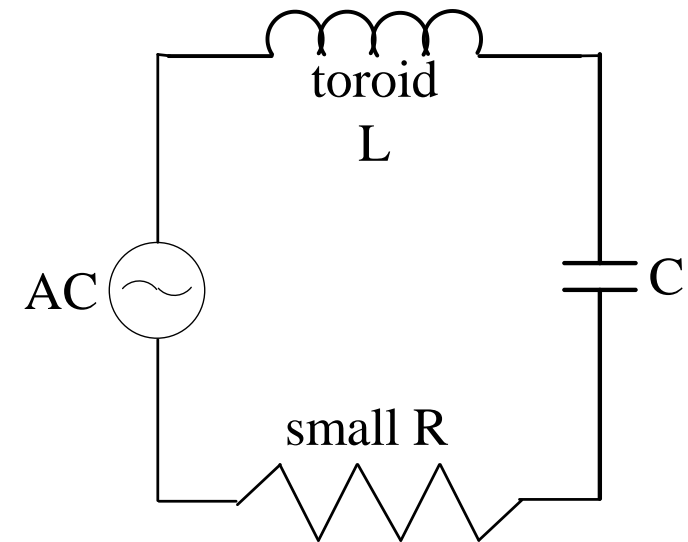
FFAG betatron

- Make solenoid into toroid so no problems with stray fields:



- Perhaps use one toroid for two FFAGs?

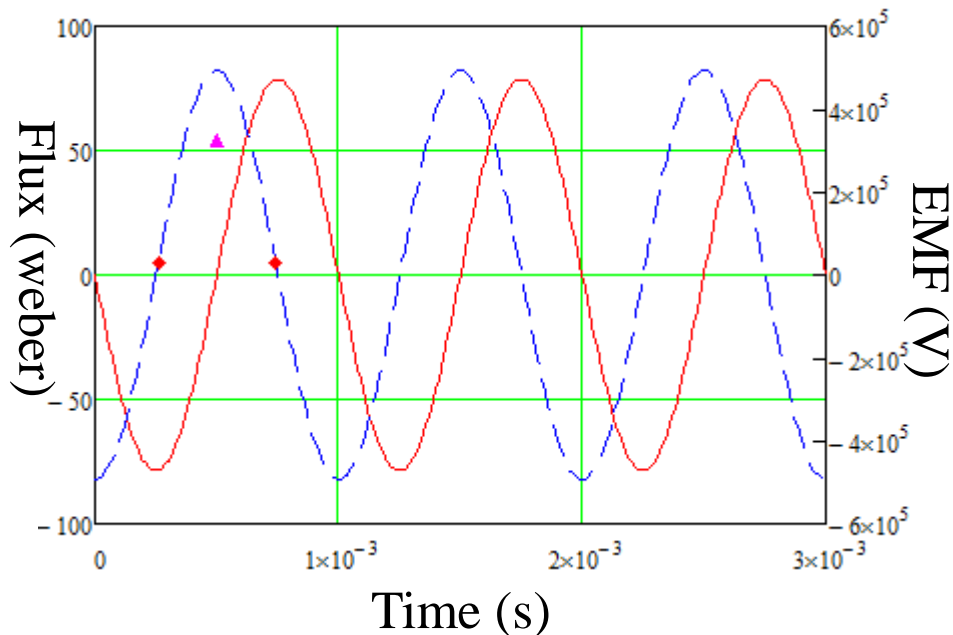
- Make toroid part of LCR circuit.



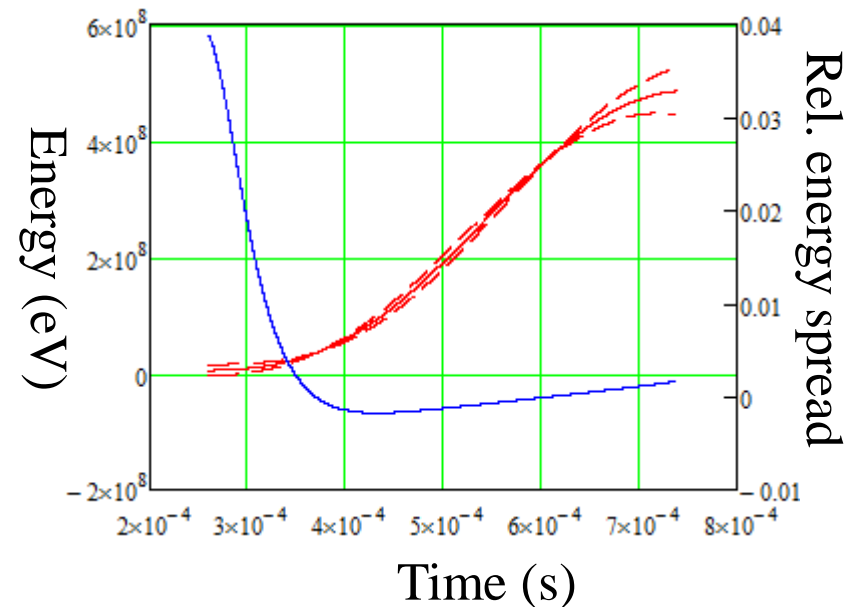
- Choose capacitance so resonance at required frequency.
- E.g. here:
 - ◆ $f_B = 1 \text{ kHz}$.
 - ◆ $T_B = 1/f_B = 1 \times 10^{-3} \text{ s}$.

FFAG Betatron

- Choose also:
 - ◆ Field in toroid $B = 1$ T.
 - ◆ (Small) toroid radius $r_T = 5$ m.
- Inject protons with $K_i = 5$ MeV.
- Integrate over $0.26T_B < t < 0.74T_B$.



- Look at acceleration of particle with central energy and of particles with energy $K_i \pm 0.001 \times K_i$.
- Differences for latter amplified by factor 100 in plot:



- Accel. to 500 MeV in $< 5 \times 10^{-4}$ s.

Summary

- New approaches to power generation through nuclear fission worth considering.
- Energy Amplifier or Accelerator Driven Subcritical Reactor interesting:
 - ◆ Safe.
 - ◆ Produces waste with short half-life.
 - ◆ Can use thorium.
- Major challenge is requirement for 5 MW, 5 mA, 1 GeV, extremely reliable proton accelerator.
- Fixed Field Alternating Gradient accelerators operate with constant magnetic fields, allowing extremely rapid acceleration.
- Can problems of synchronising RF with orbiting particles be circumvented by using electromagnetic induction to drive acceleration?
- Preliminary studies suggest concept is interesting enough to justify further work.
- Tests using EMMA at Daresbury possible?