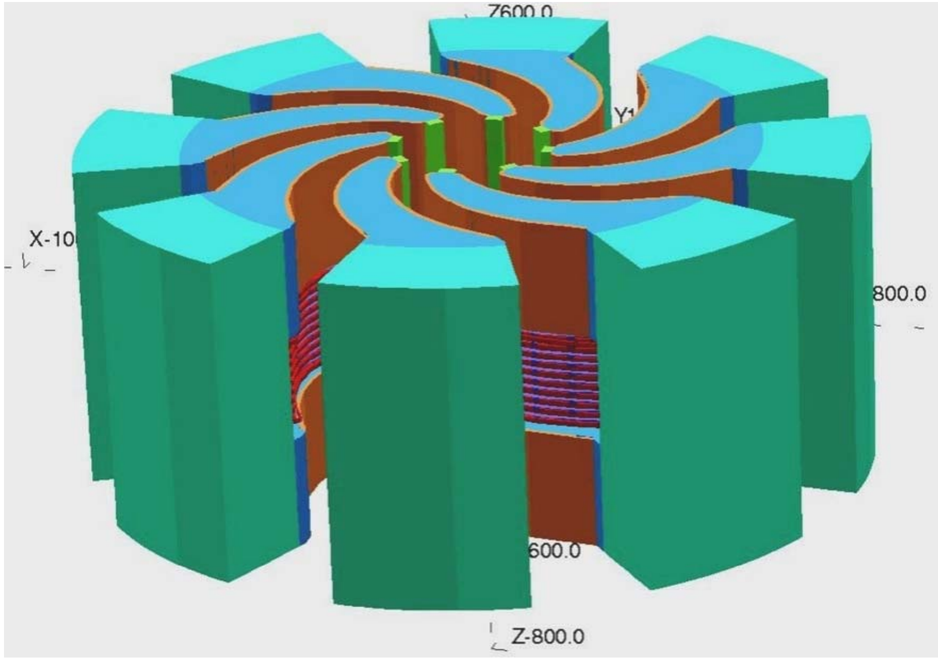
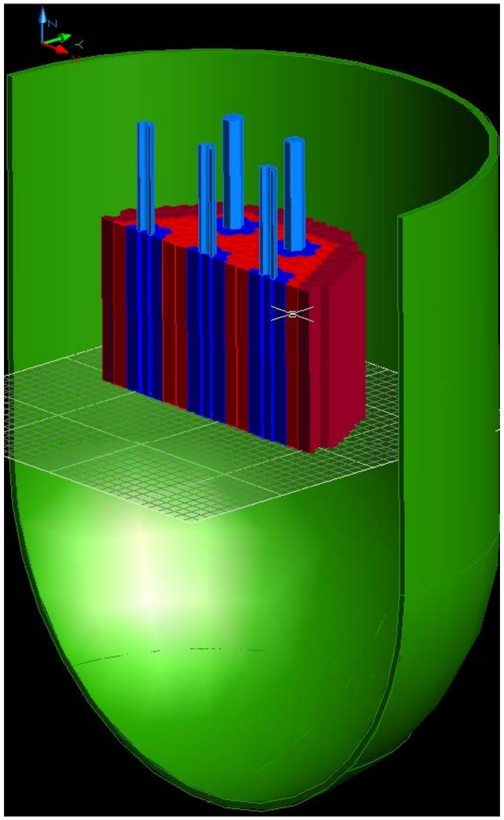
Thorium-Cycle Fission for Green Nuclear Power



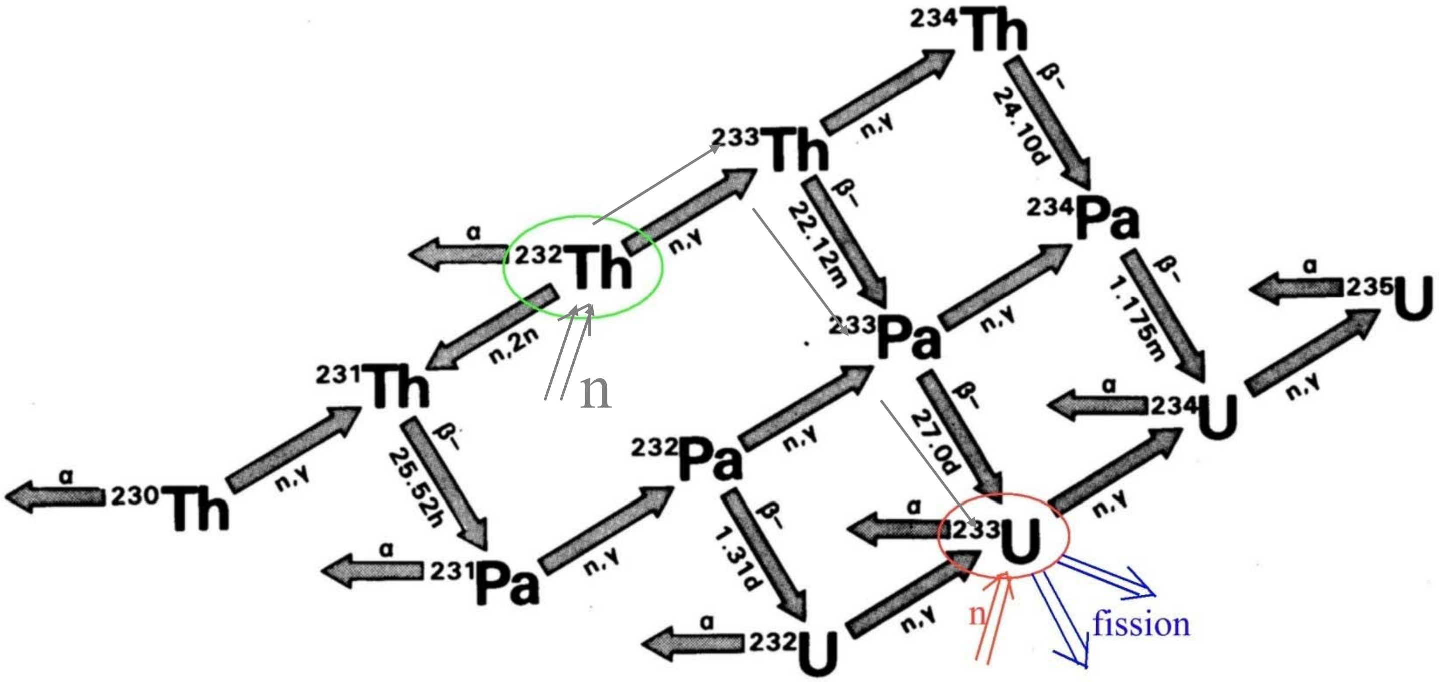


Peter McIntyre
Texas A&M University

Thorium fission for nuclear power

- Electrobreeding (transmutation of ^{232}Th →^{233}U) operates far from criticality (k ~ 0.98).
- The molten lead moderator provides natural convective cooling, huge thermal mass – can't melt down.
- The fast neutron flux used for electrobreeding - the reactor eats its own long-lived waste.
- A sealed GW core runs 7 years without access
- There are enough known reserves of thorium to power the Earth's energy economy for 1000 yrs.

The electrobreeding concept: 1 GeV protons→fast neutrons



- First proposed by E.O. Lawrence (1948),
  later by C. Rubbia (1995).

Fatal flaws: accelerator power, neutronics, reliability

Input & Output for Thorium Cycle

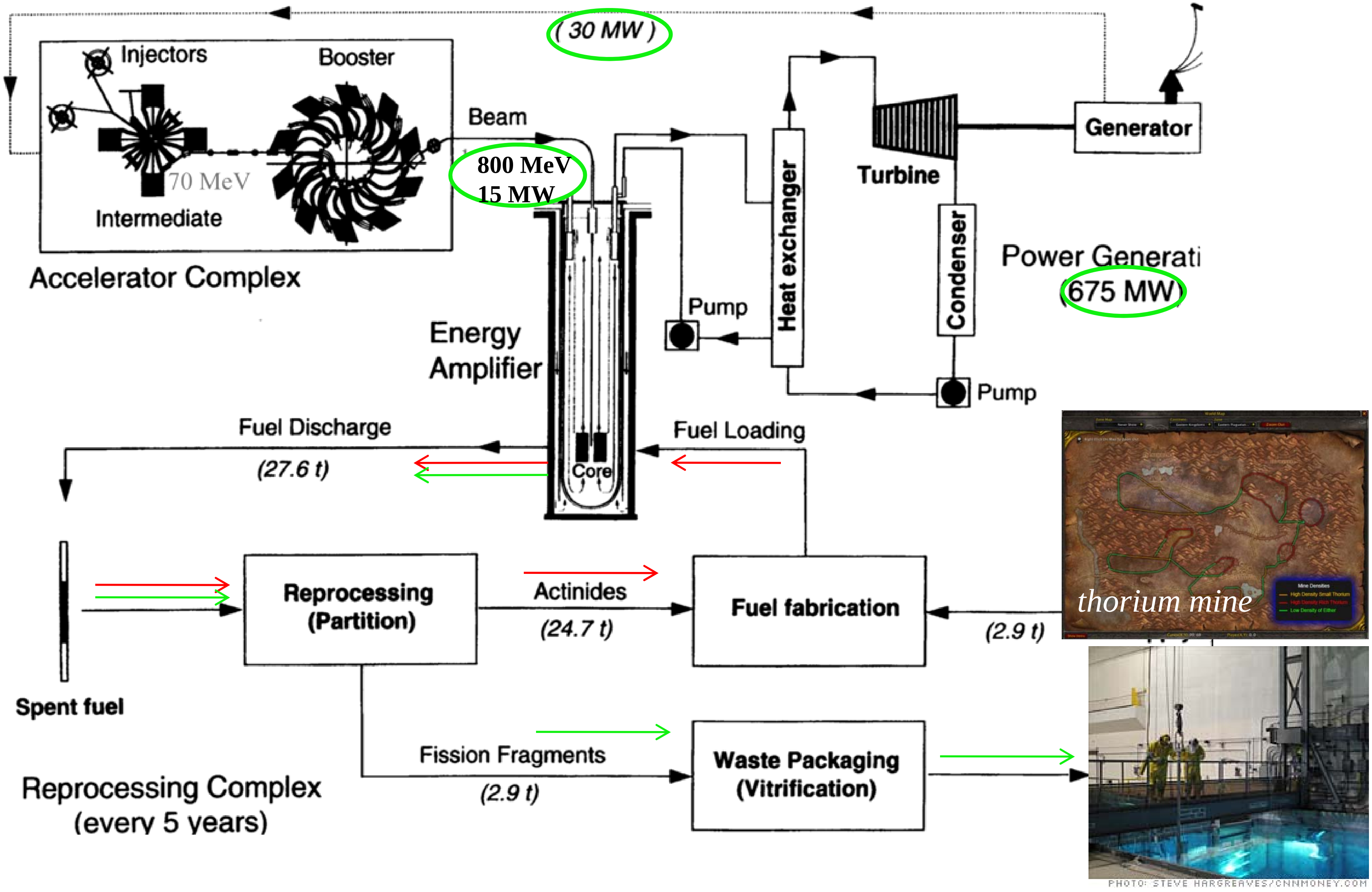
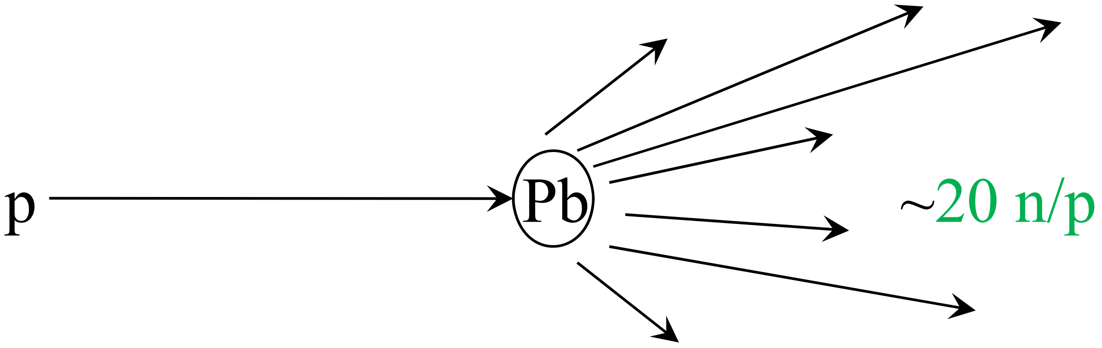


PHOTO: STEVE HARGREAVES/CNNMONEY.COM

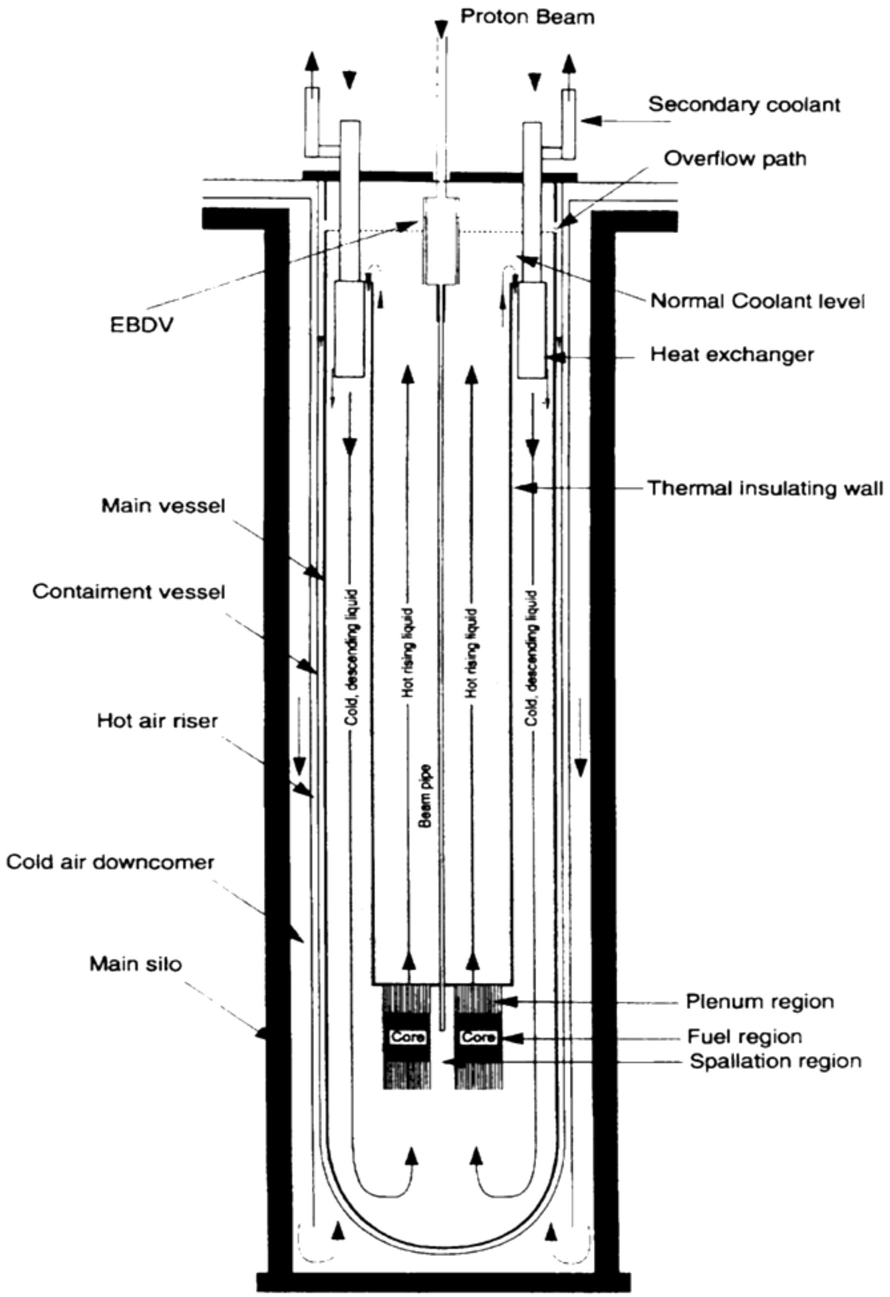
Fast neutrons are produced by spallation of ~1 GeV protons on Pb

- Produces fast neutrons.
- Neutrons degrade in very small energy steps in succeeding collisions with Pb nuclei.
- Molten lead serves as spallation target, moderator, and medium for convective heat exchange.



Reactor Vessel

- Height 30 m
- Diameter 6 m
- Vessel material: HT-9
- Wall thickness: 70 mm
- Coolant: molten lead
- Mass: 2,000 T
- Beam power: 15 MW
- Thermal power: 1,500 MW
- Electric power: 625 MW
- Accelerator power: 30 MW



Problem: ***We need a proton driver capable of ~800 GeV energy, 15 MW power, ~50% efficiency!***

- That is a very difficult design challenge for either isochronous cyclotrons or linacs – space charge limits in injectors and acceleration.
- Most difficult – the accelerator must be a *simple, reliable system that can be operated by a modest crew with long MTBF!*

Solution: Design a conservative accelerator, and replicate it:

- Three-stage accelerator system (2.5 mA)

0.1 → 5 MeV	RF quadrupole,
5 → 150 MeV	sector cyclotron,
150 → 800 MeV	isochronous cyclotron (IC)

- Assemble a stack of seven flux-coupled ICs

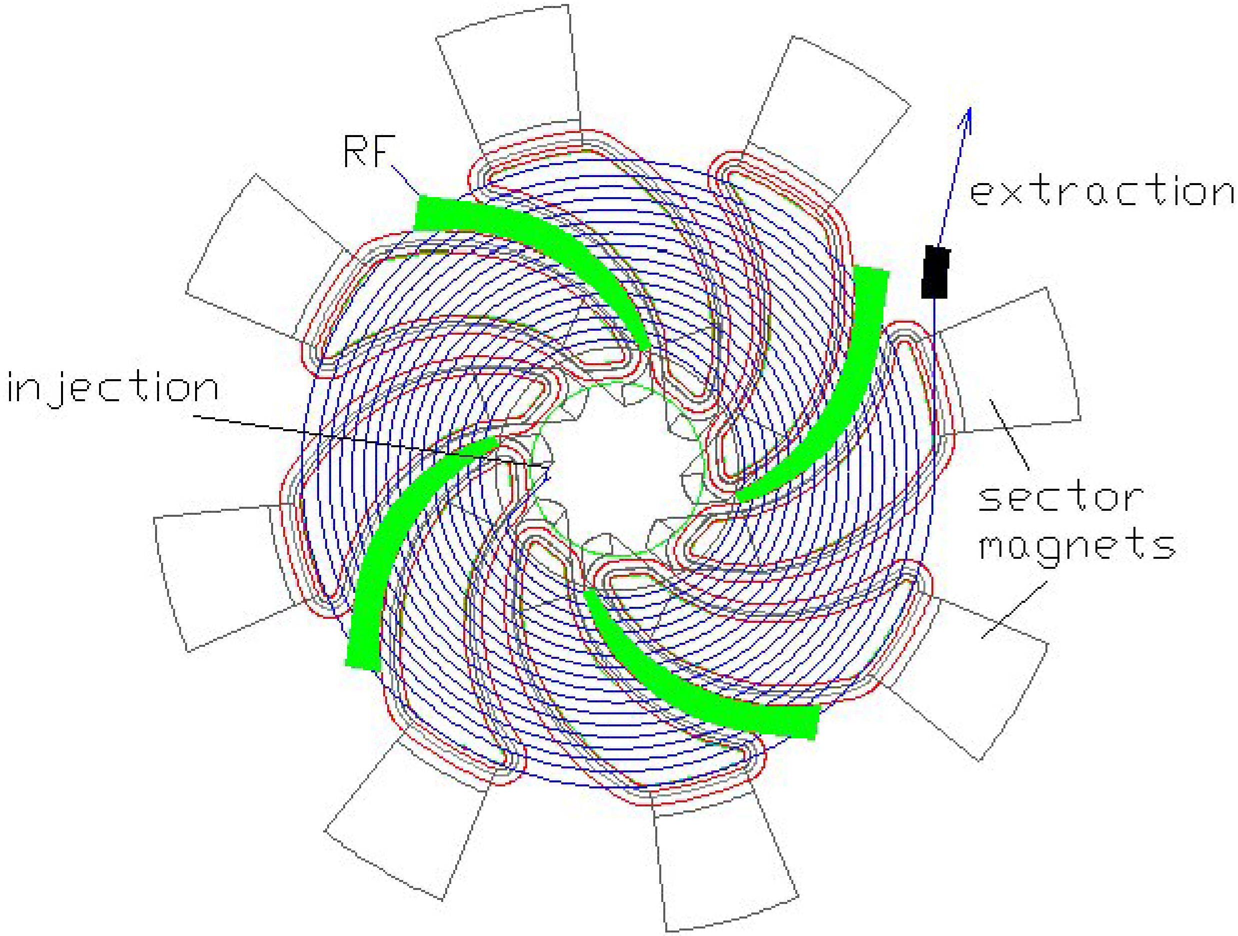
  Flux linkage

  Independent RF, injection, extraction, vacuum, transport

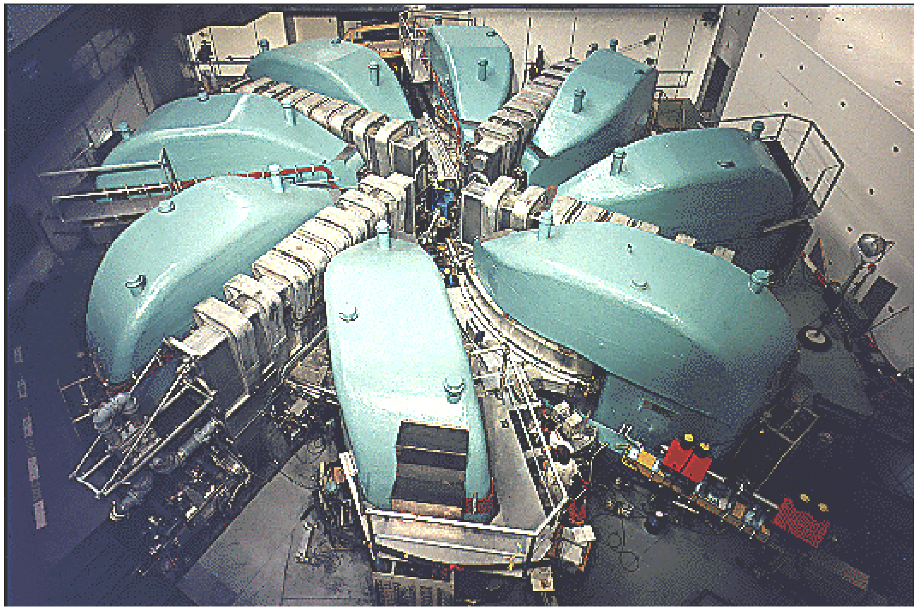
- *Reliability through redundancy*

  if one beam goes down, the reactor still operates.

An isochronous cyclotron uses sector magnets with poles shaped so that revolution frequency is constant from injection (70 MeV) to extraction (800 MeV)

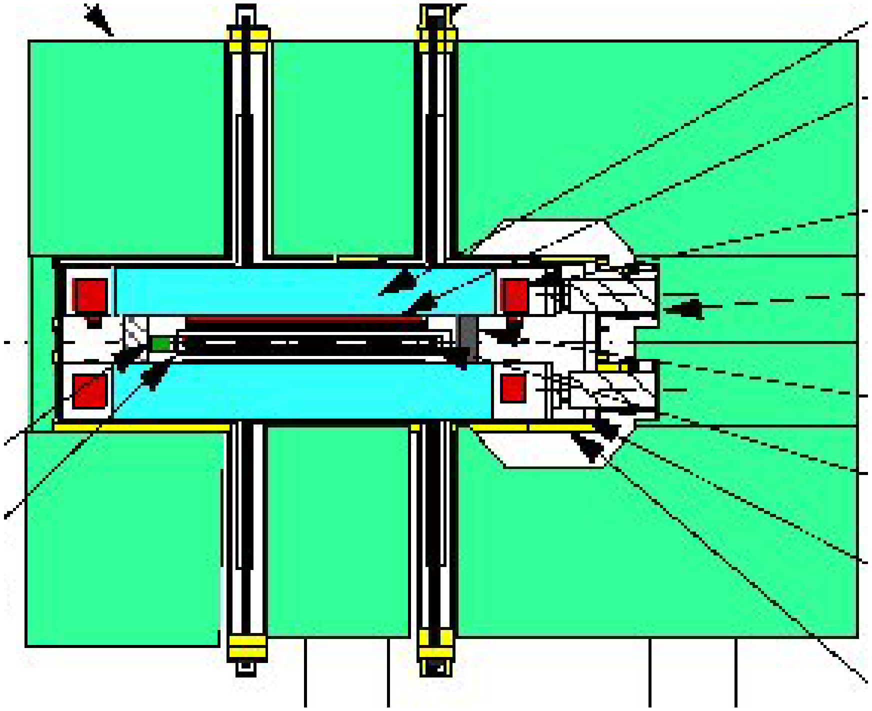


Combine the high-energy isochronous cyclotron of PSI:



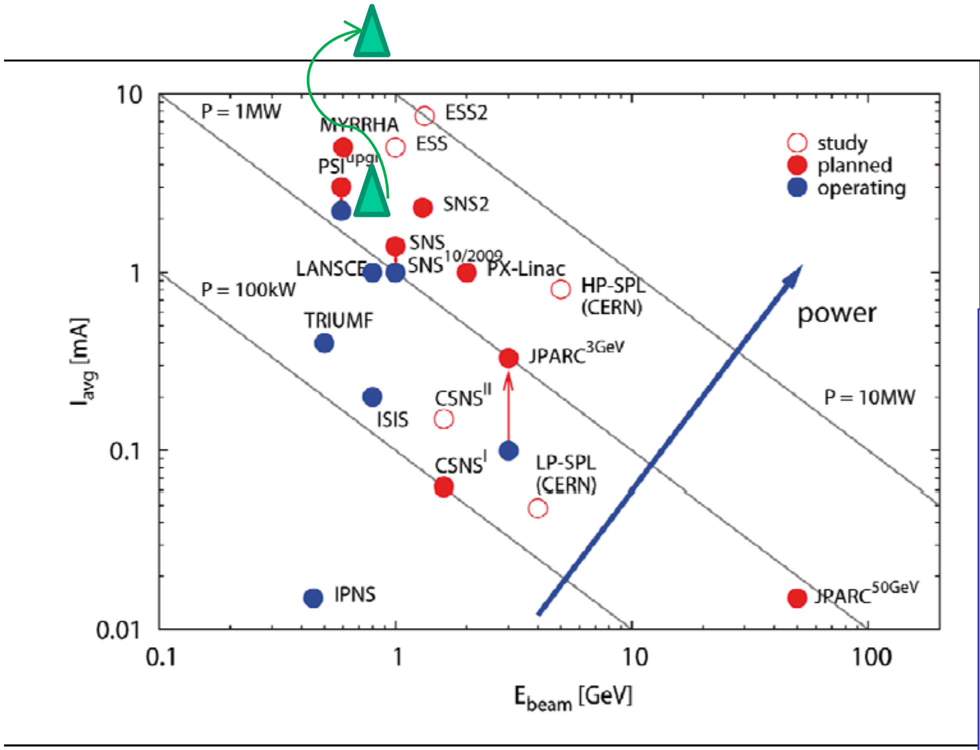
590 MeV, 2 mA

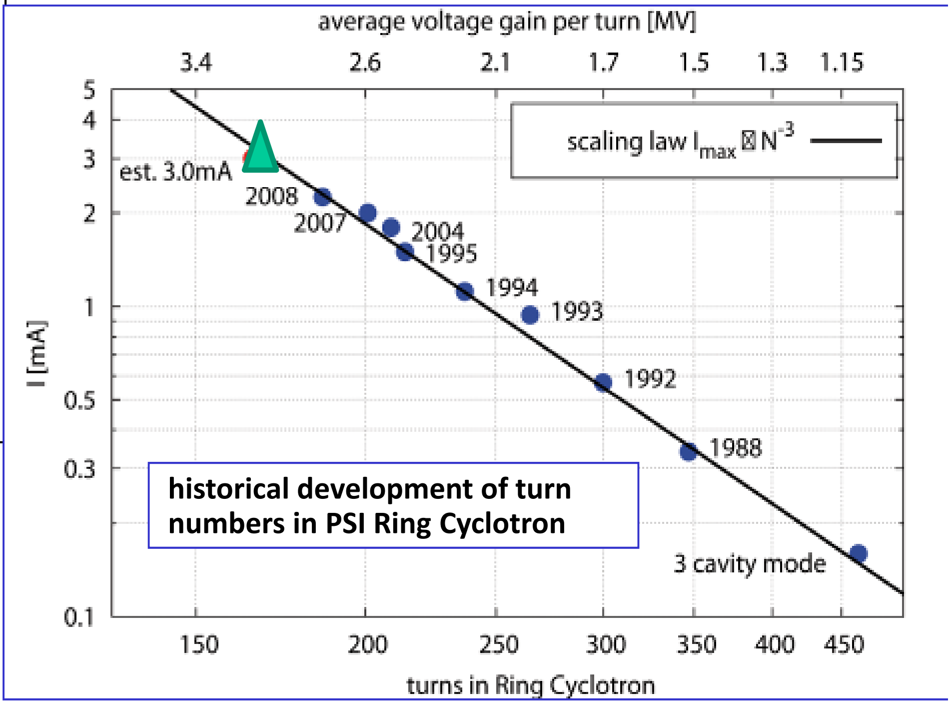
and the superconducting magnet design of Riken:



Superconducting coil, cold iron flux plate, warm iron flux return

Need low field, high RF to make efficient injection/extraction @ high power

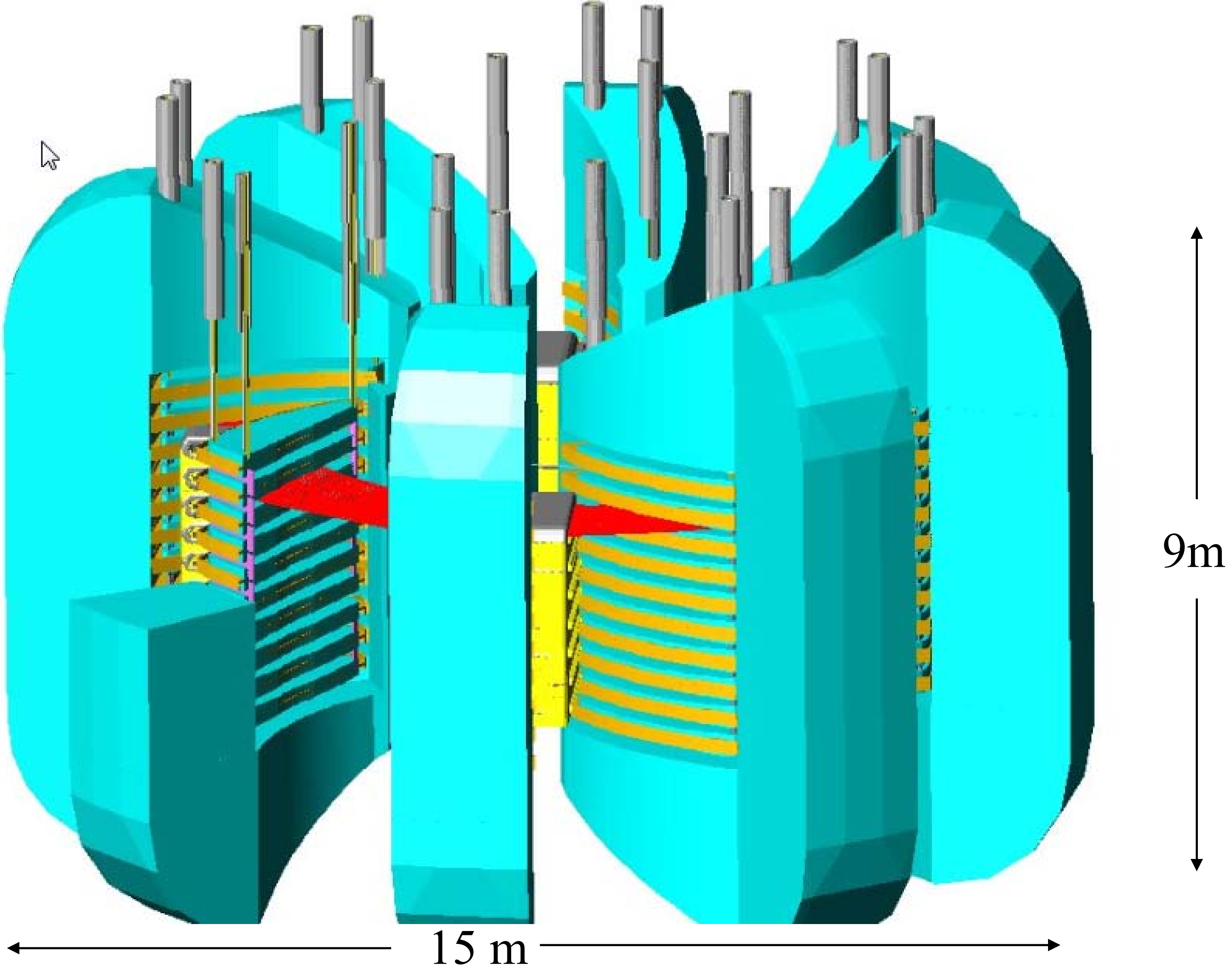




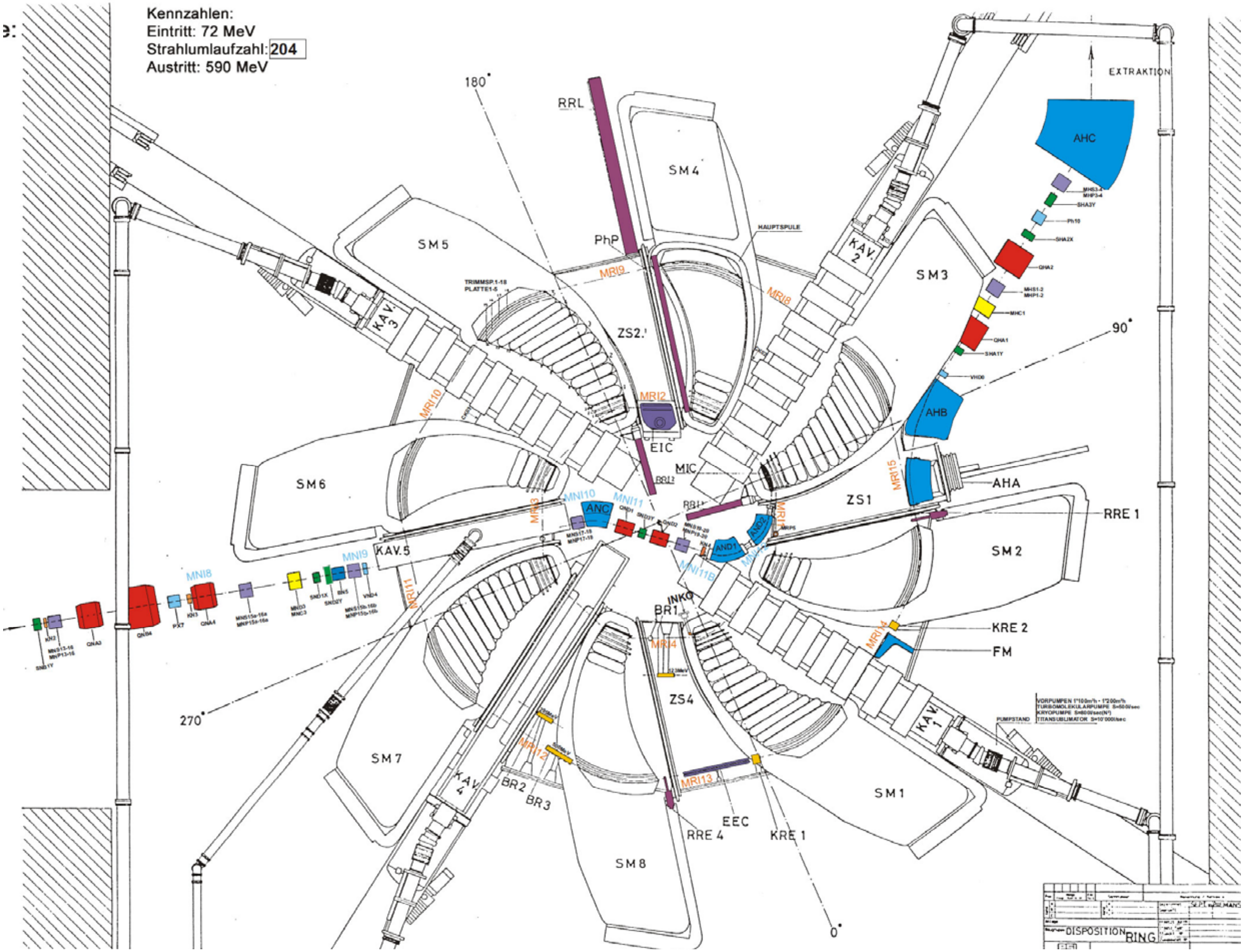
B = 1.7 T in sectors
RF = 3.5 MV/turn
200 → 800 MeV
170 turns

Seidel, TC ADS 2010

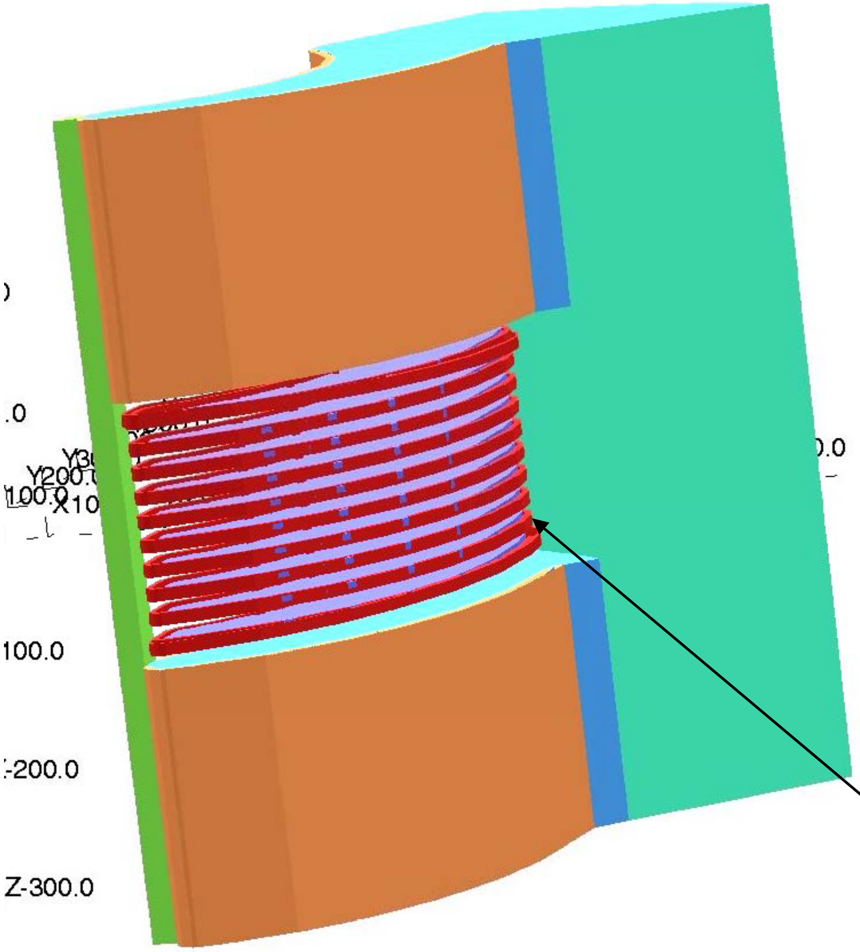
7-stack isochronous cyclotron

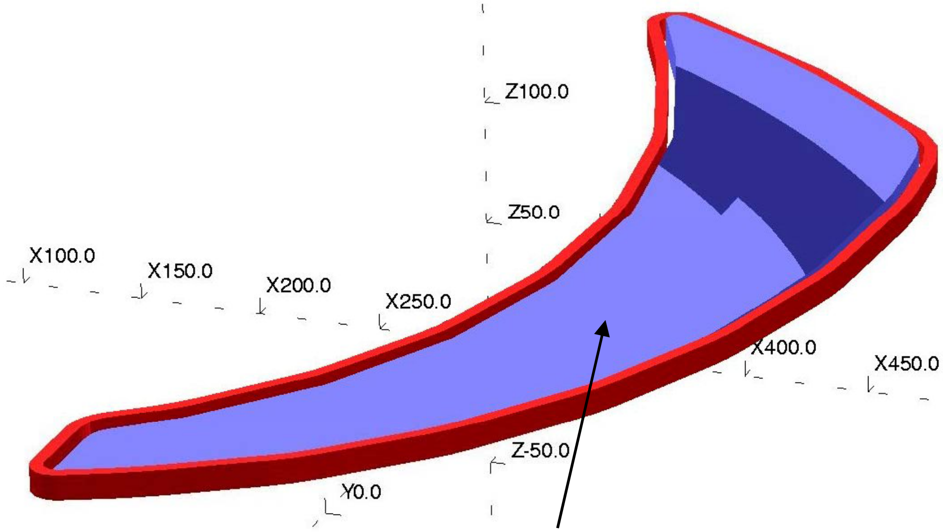


Layout injection, extraction similar to PSI



Each pole has 7 apertures, trims for isochronism and mid-plane symmetry



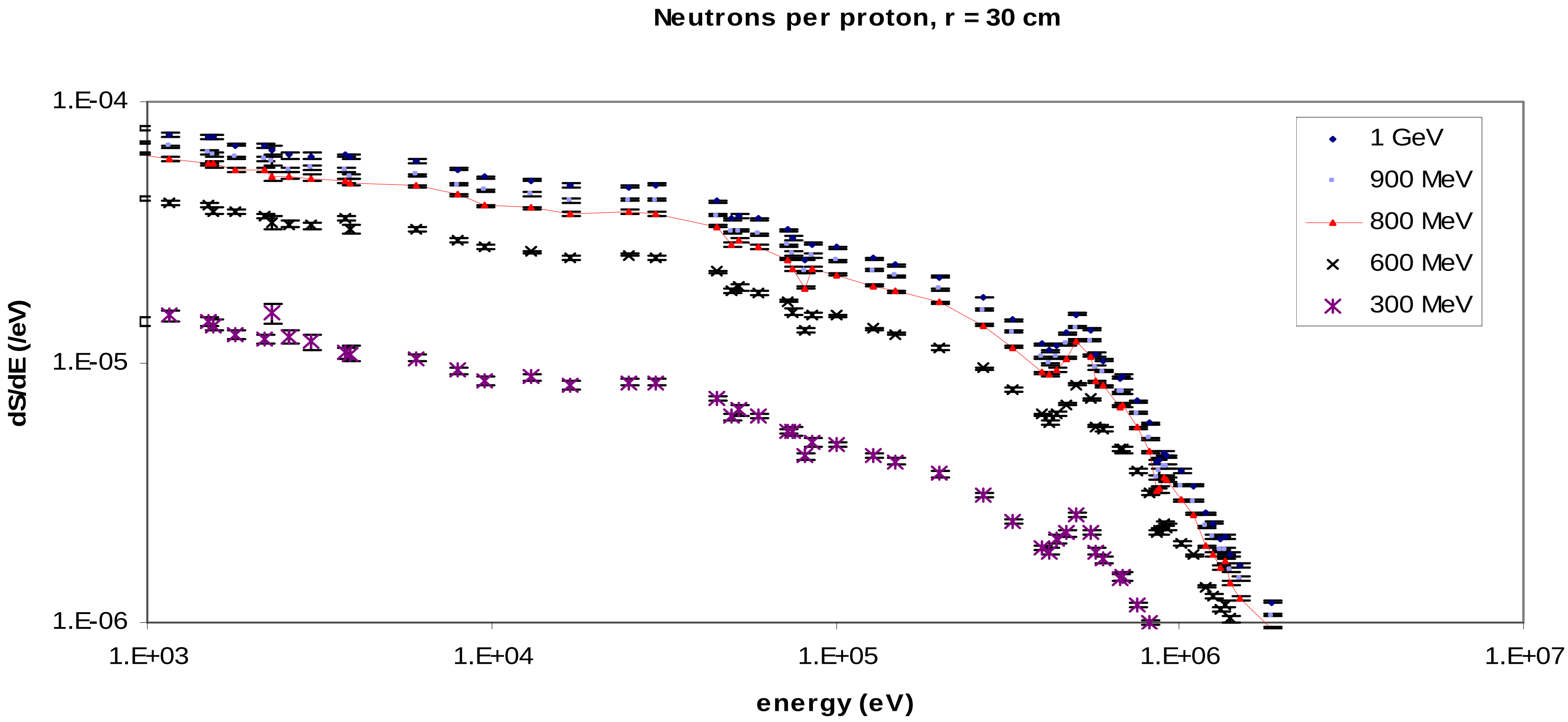


Flux plate = NbTi superconducting coil, contoured steel plate

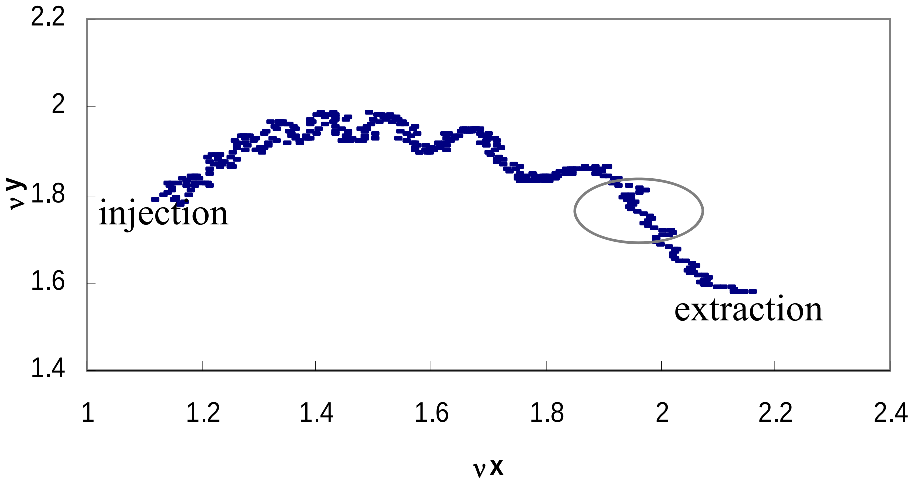
10 flux plates,
Top/bottom sacrificial gaps

R = 2 → 5 m, 10 cm aperture – cold bore vacuum

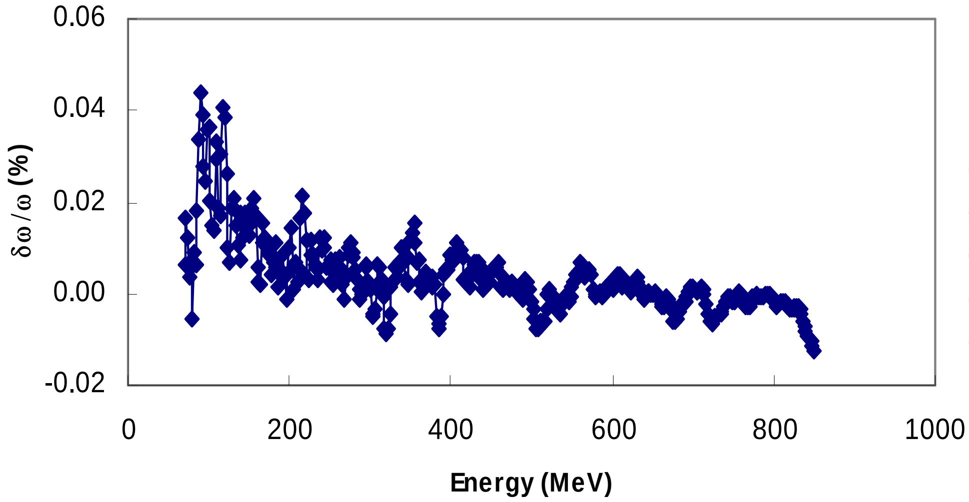
Best choice of proton energy ~800 MeV



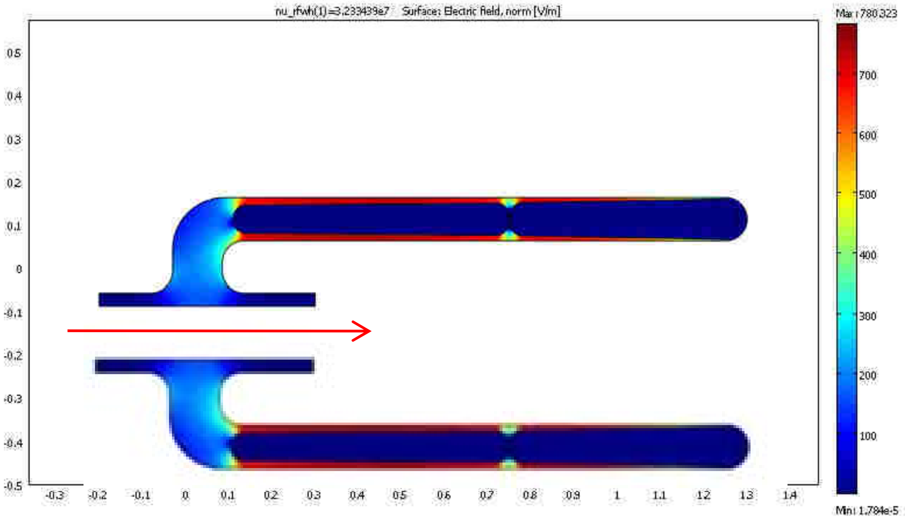
Control horizontal, vertical betatron tunes:



Trim magnet B(r) so that orbit frequency is constant (isochronous).

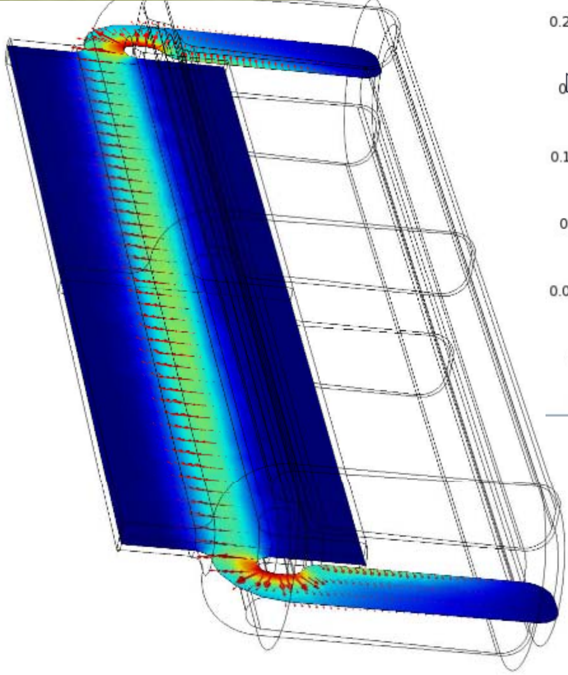


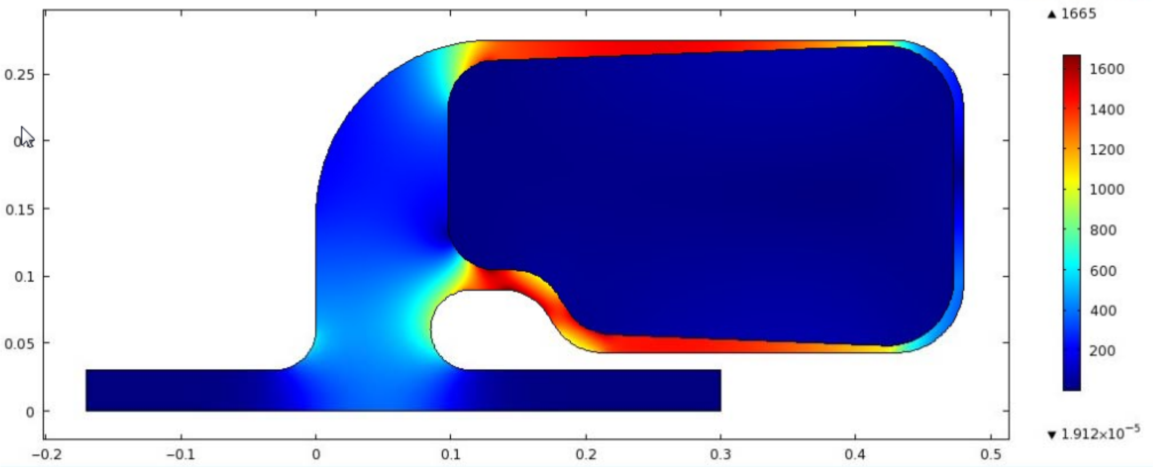
32 MHz dielectric-loaded superconducting cavity fits in the space between IC layers:



RF is a particular challenge

- Need ~700 kV/gap, 4 gaps for good turn/turn separation at injection, extraction
- Need compact structure: 50 cm IC separation
- Dielectric-loaded superconducting stubline



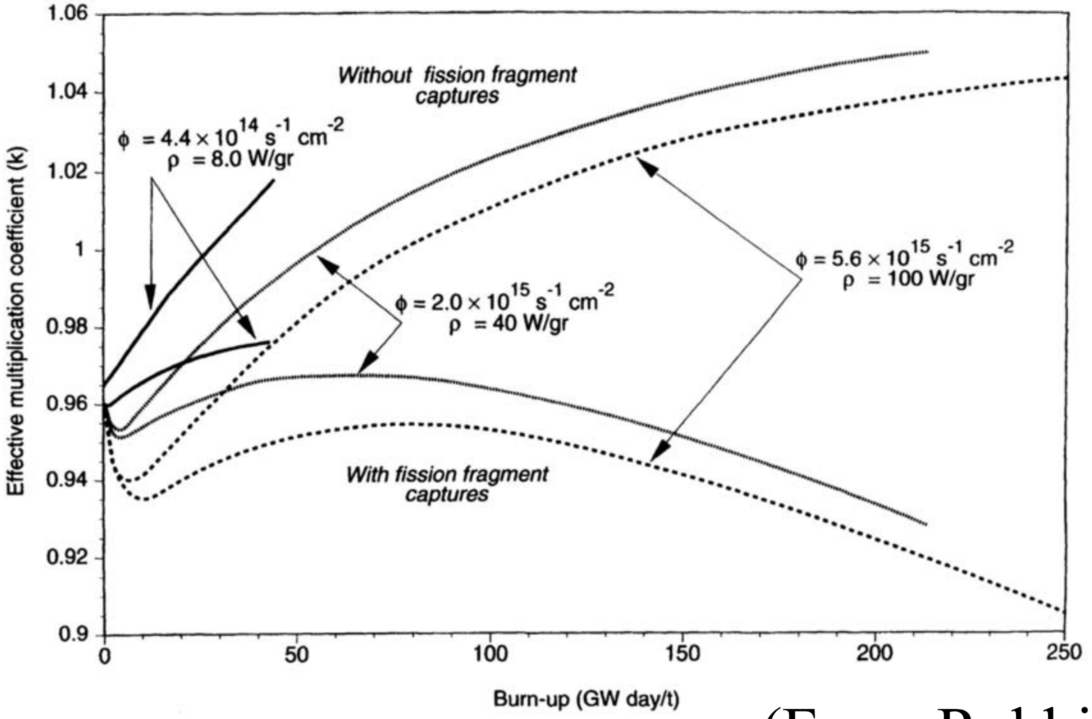


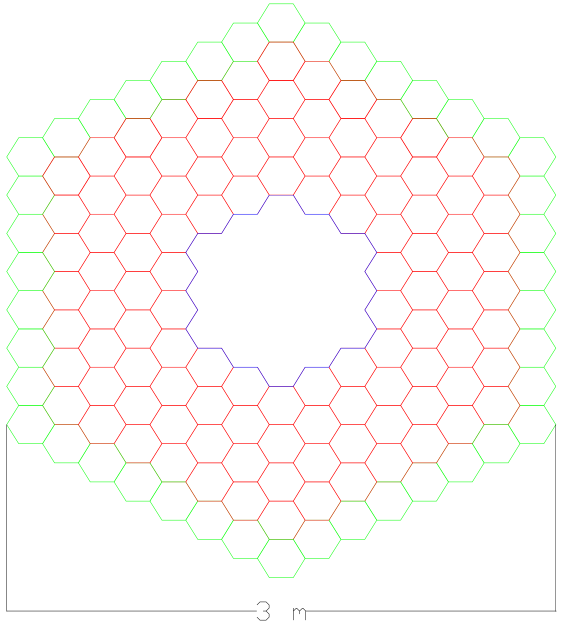
2 W/m @ 5 K
5 kW/m @ 80 K

Problem: Fission products shadow neutrons

As fission proceeds, fission products absorb neutrons
→ neutron gain varies strongly within core and through fuel burnup.

Single coaxial drive beam (Rubbia):



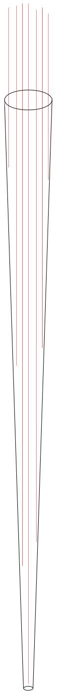


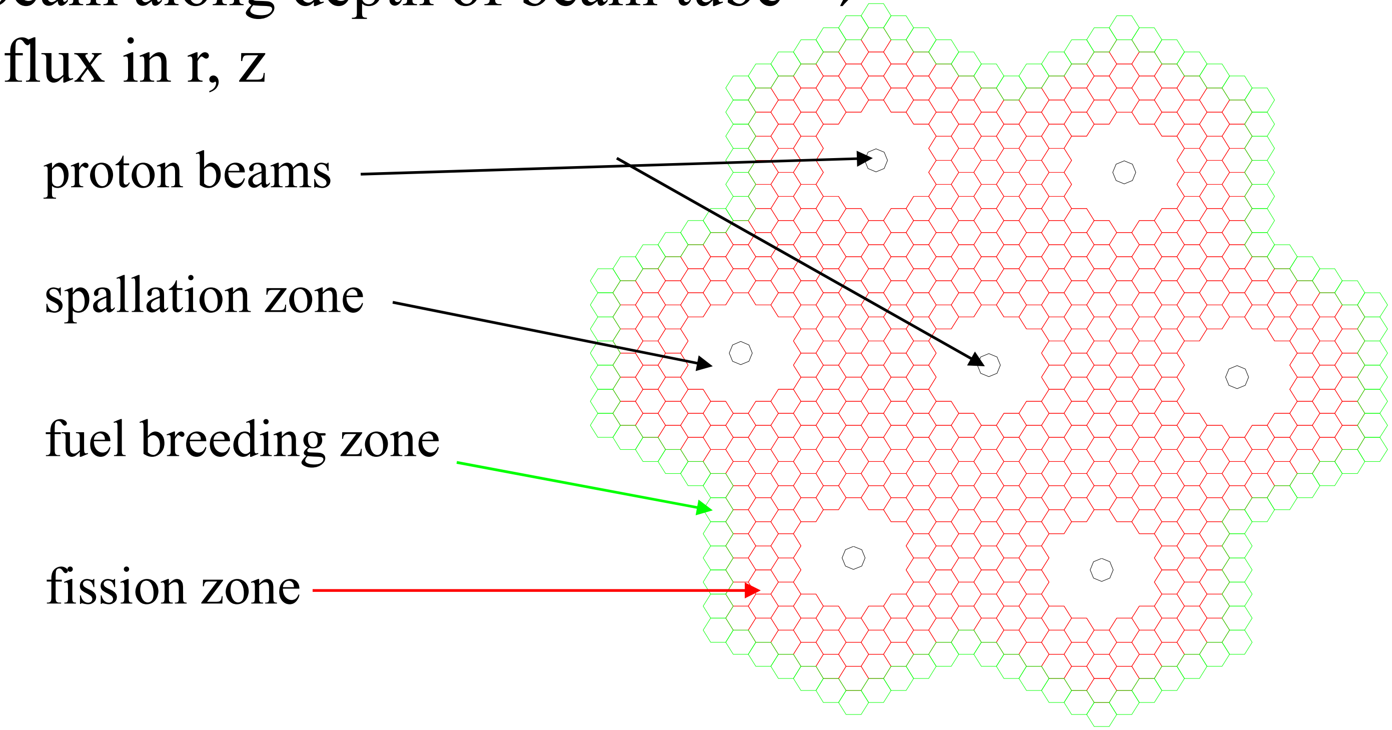
(From Rubbia)

Solution: arrange 7 proton drive beams in a hex array of fuel assemblies.

Distribute proton drive → Reduce variation k(r)

Sweep each beam along depth of beam tube →
Ho nize flux in r, z





proton beams

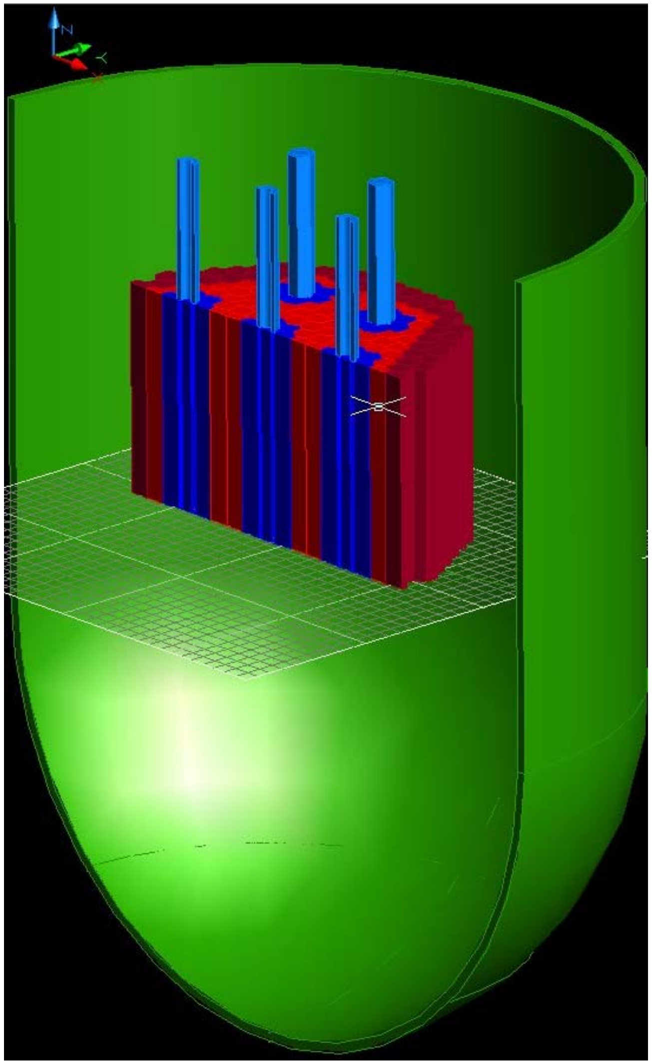
spallation zone

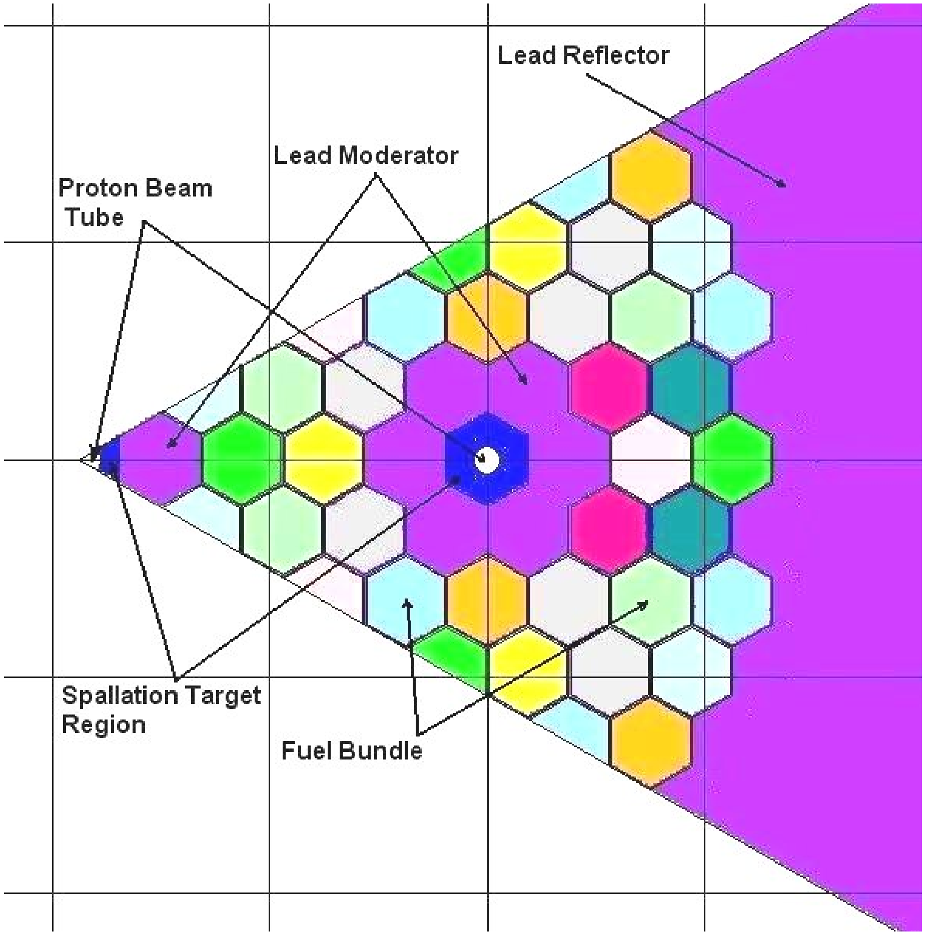
fuel breeding zone

fission zone

Better control, more efficient consumption of fuel.

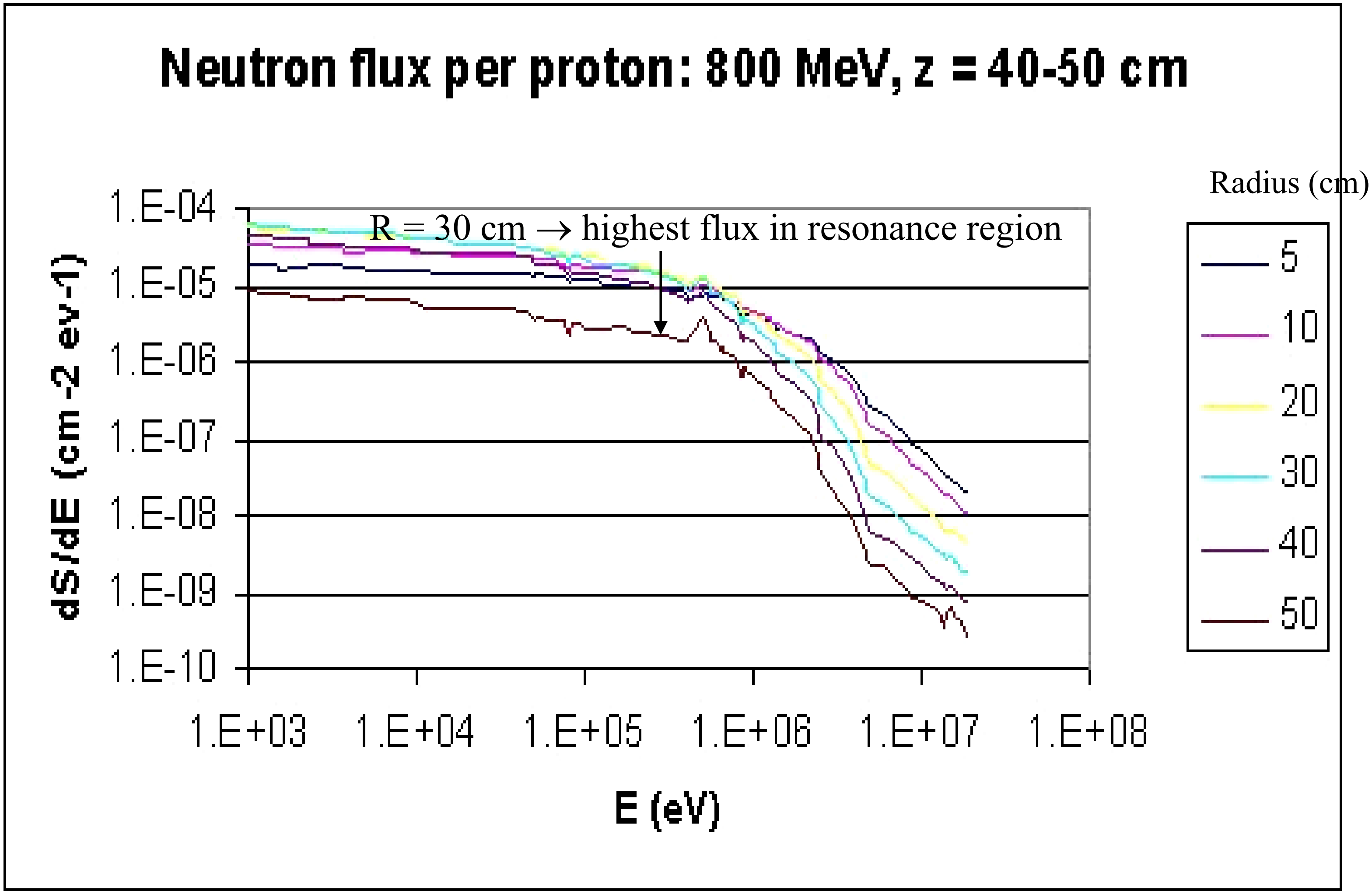
Model spallation source, neutronics in core



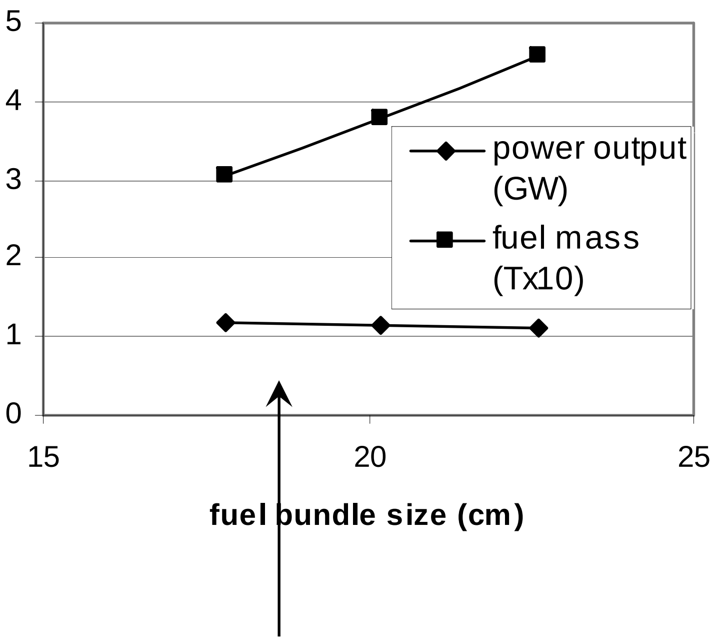


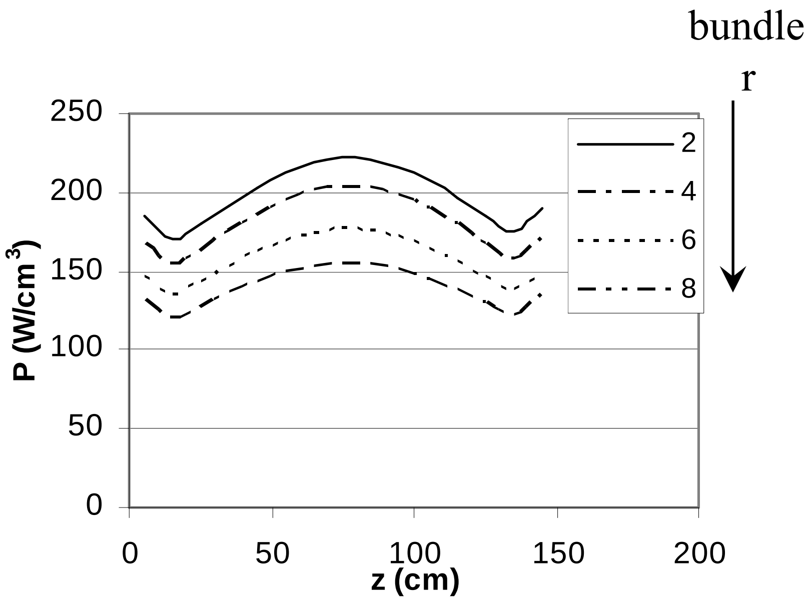
Slice through one sextant of the core

Neutron spectrum in Spallation



Optimize core geometry

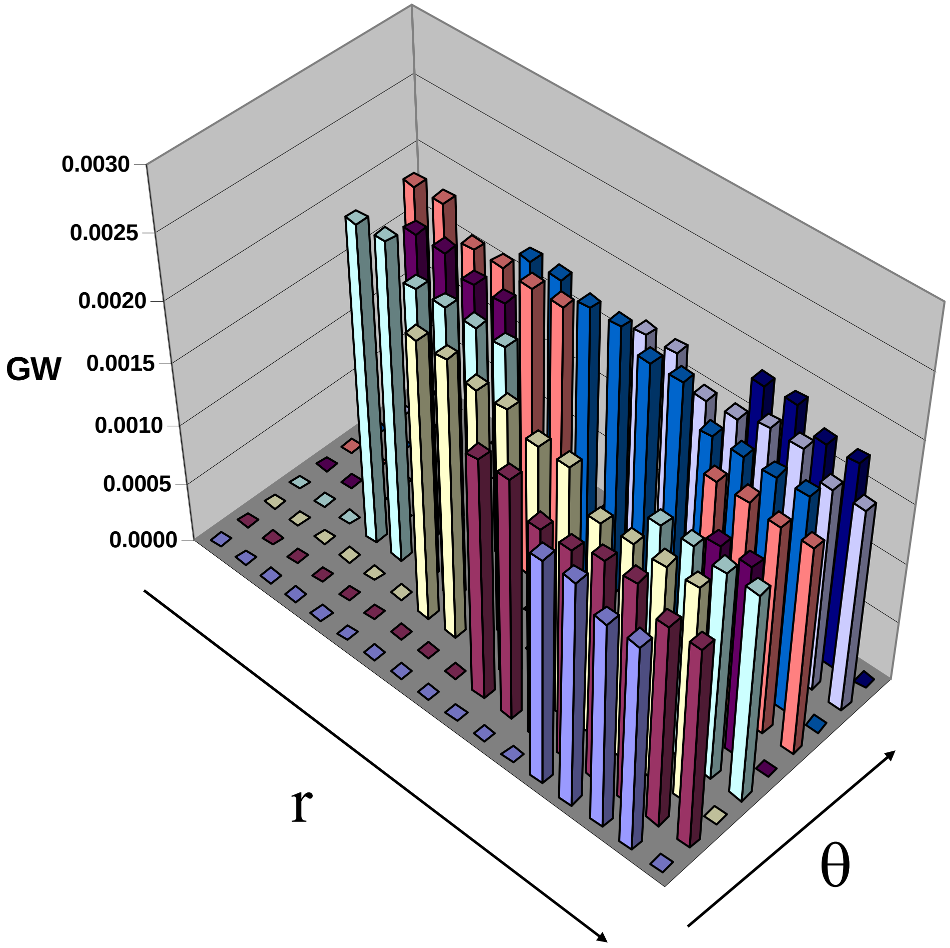




Optimize fuel bundle for power output, total fuel mass → 18 cm

Arrange bundles to flatten power distribution at startup.

Power distribution in one sextant

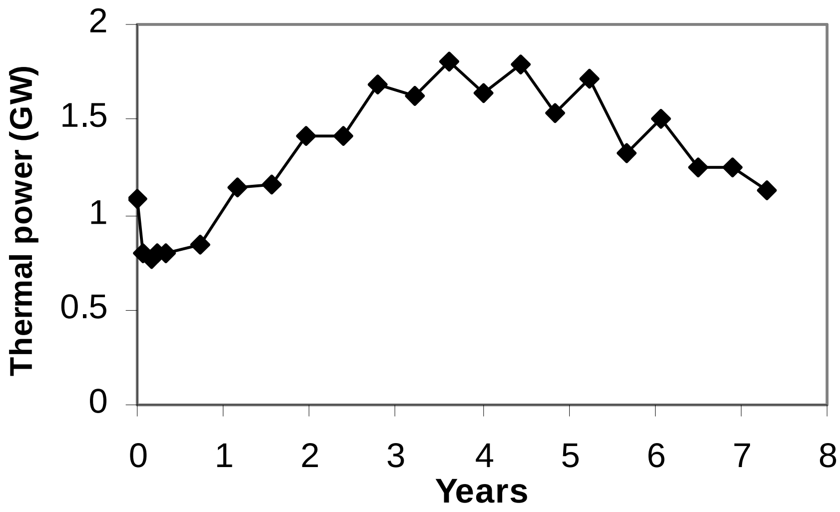


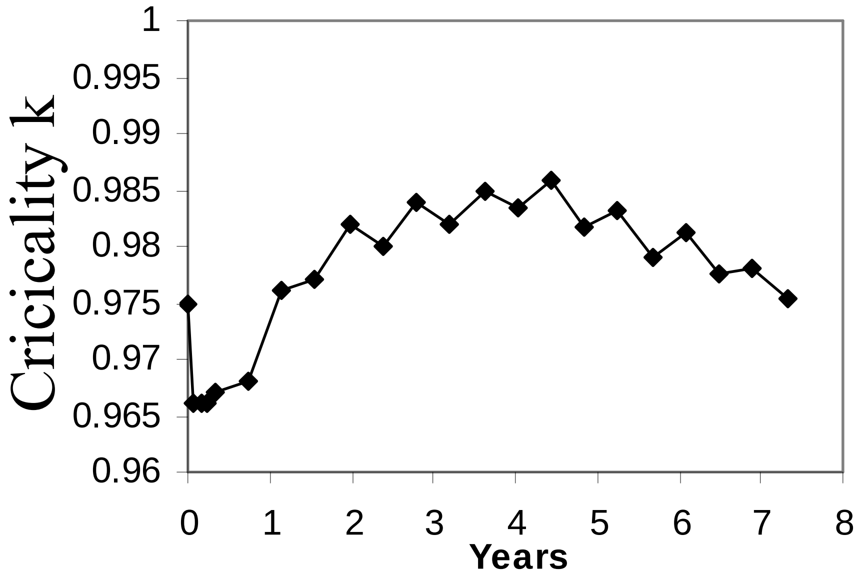
Energy deposition in one sextant

Power and Criticality through Core Lifetime

MCNPX → XSDRNPM → ORIGEN-S

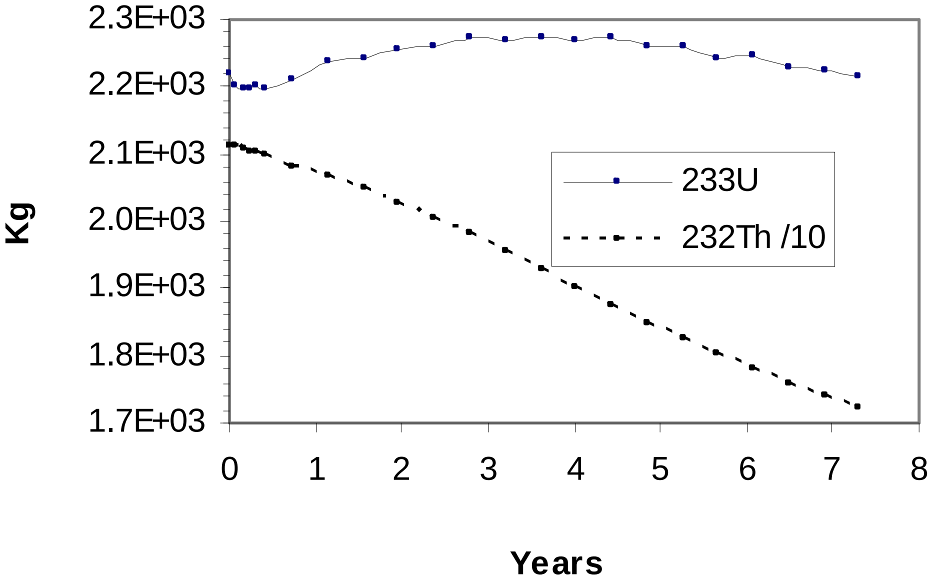
30/150 days

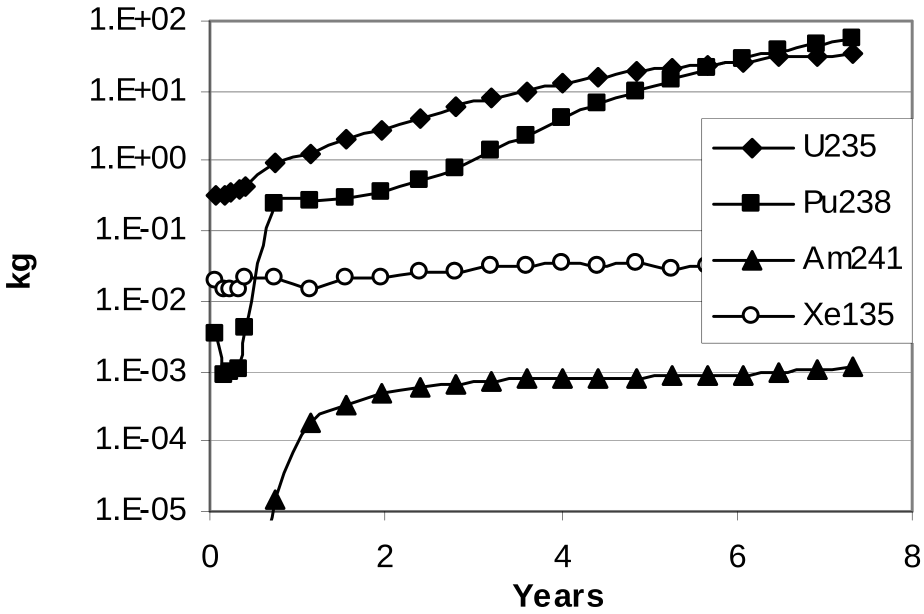




The 7-beam IC-driven thorium cycle operates as a sealed core for 7 years – no re-shuffle of fuel pins, better control for non-proliferation.

Isotope inventory through life cycle



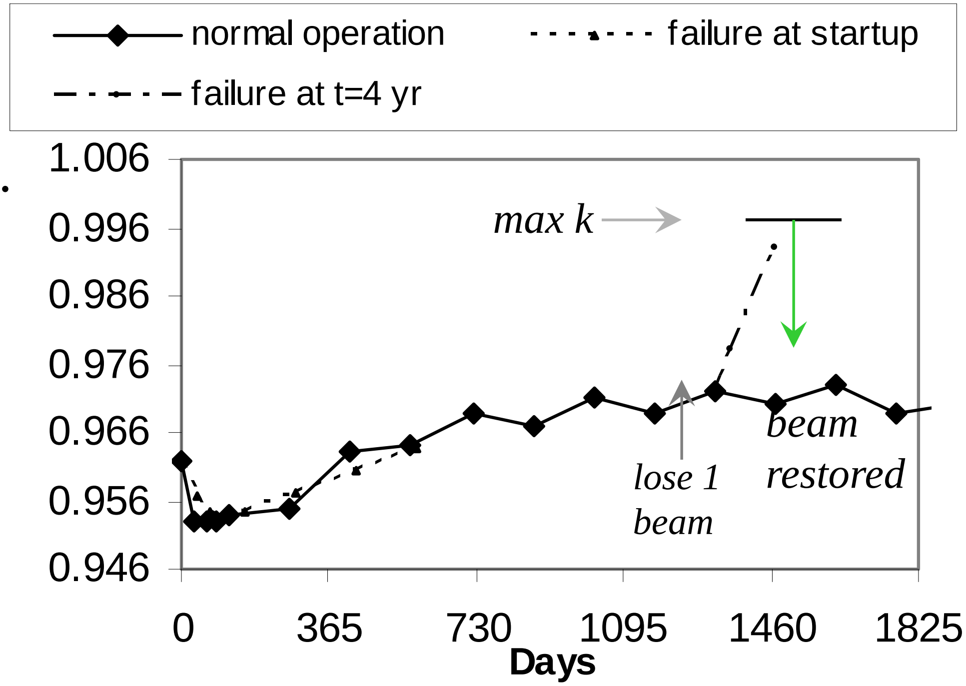


Very small inventories of waste isotopes (*e.g.* ^{241}Am), very little bomb-capable isotopes (^{235}U, ^{238}Pu)

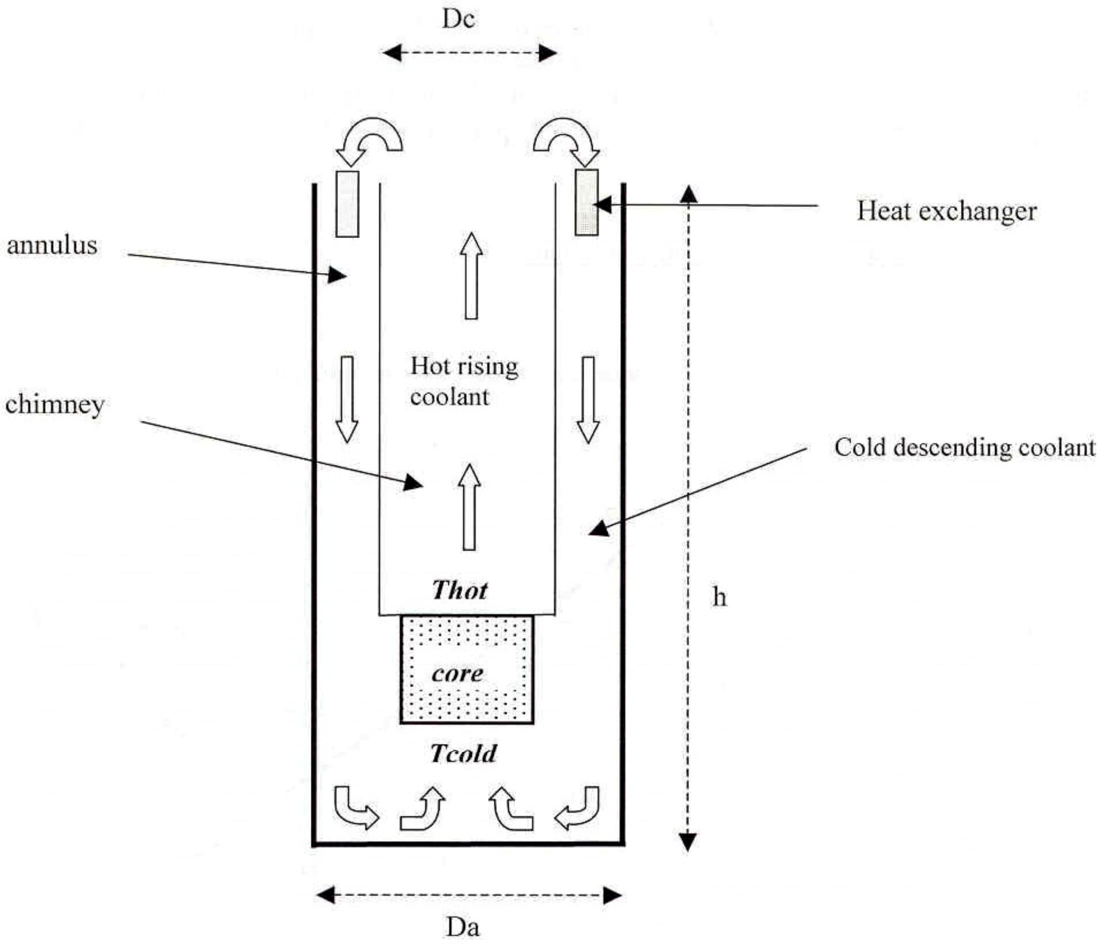
What happens if we lose one drive beam?

The transmutation sequence has a time delay:

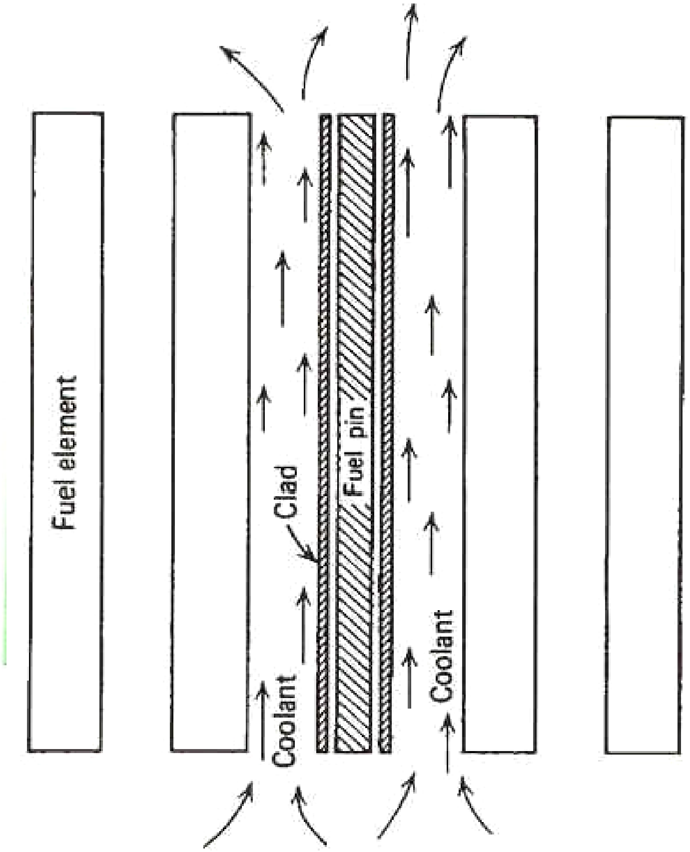
- $^{232}Th + n \rightarrow {}^{233}Th$
- $^{233}Th \rightarrow {}^{233}Pa + \beta$ (22 minutes)
- $^{233}Pa \rightarrow {}^{233}U + \beta$ (27 days!)
- *So if we lose a drive beam, the surrounding fuel builds up an anomalous inventory of* ^{233}U *as the* ^{233}Pa *decays but there is insufficient neutron flux to stimulate fission.*
- $\Delta k = +.02$ *due to local* ^{233}U *spike*
- *k returns to normal when beam restored.*
- *Bottom line: Must design for k ~ 0.97*



Convective heat transport

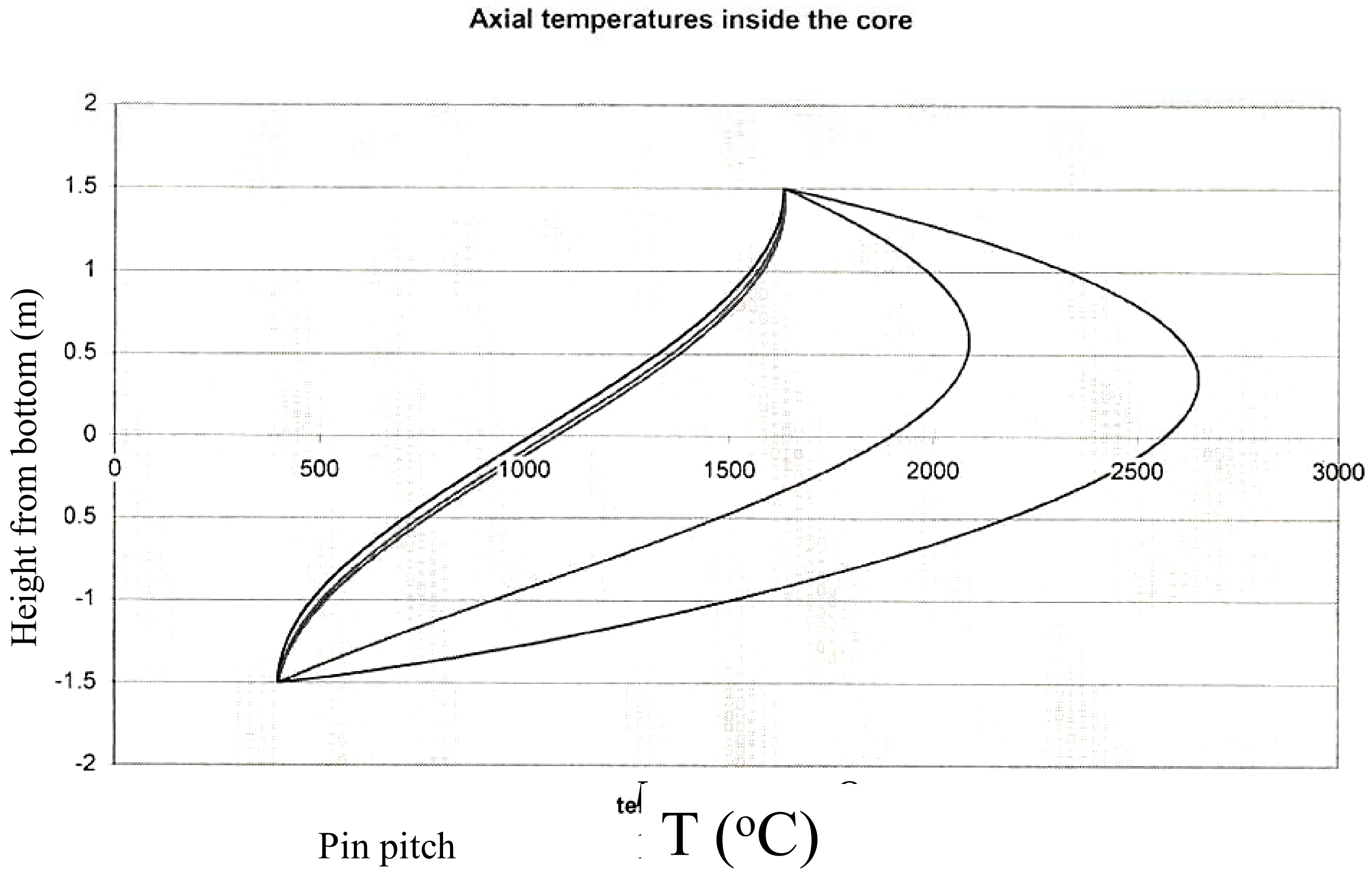


in core and convection column



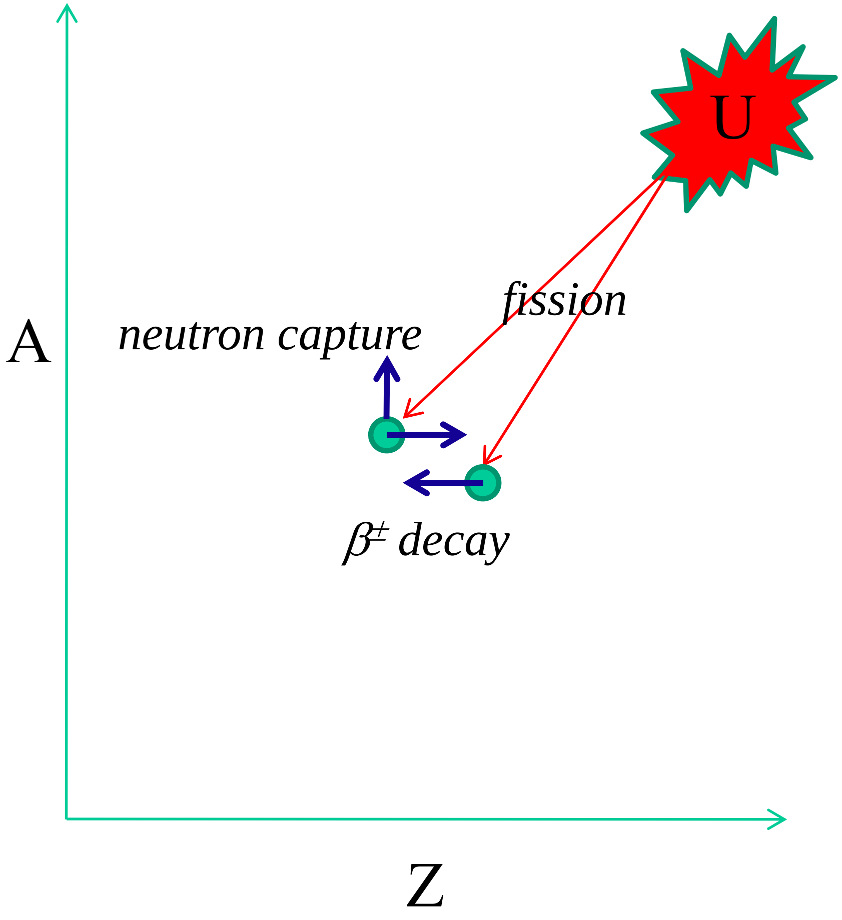
in fuel element subchannel

Heat transport simulation



Pin pitch			
Pin heat/length	203	135	W/cm
ΔT top-bottom	200	200	C
Pb velocity	1.02	0.96	cm/s
Pb viscosity	0.0043	0.0048	Poise
Pressure drop	27	38	kPa

Why do long-lived waste isotopes accumulate in a thermal reactor?

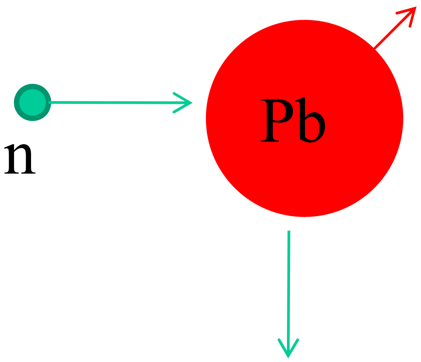


The fission products populate the center of the table of isotopes.
Most such isotopes can capture thermal neutrons (↑) and also undergo either beta decay (→) or inverse beta decay (←), so each nuclide diffuses among many values (Z,A).
But there are a few bad guy isotopes with beta decay ½ life ~1000 y, and *no ability to capture thermal neutrons*.
They are sticking points – the diffusing nuclides land there and cannot escape!

Adiabatic moderation of fast neutrons →

ADTC reactor eats its own long-lived waste.

Narrow energy steps assure that each neutron tickles all the narrow resonances of actinides, transuranics. No sticking points!

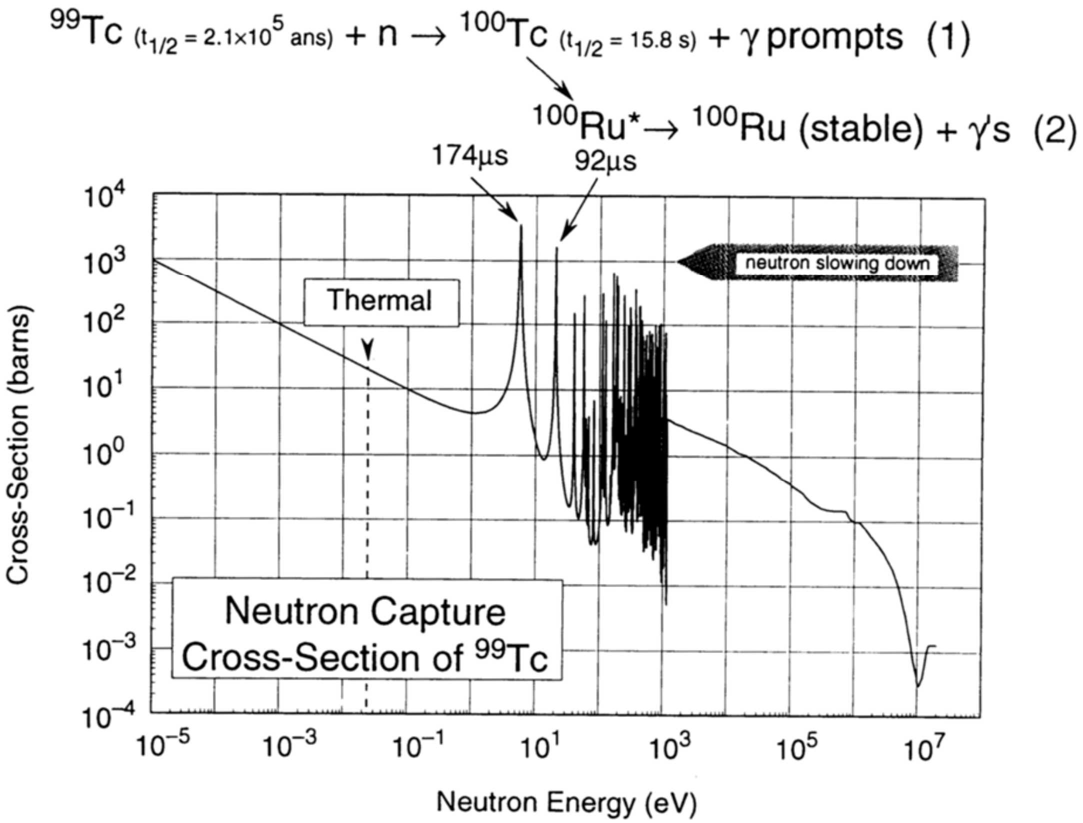


Ping-pong ball hits bowling ball:

$$\Delta p \sim \sqrt{2}\,p$$

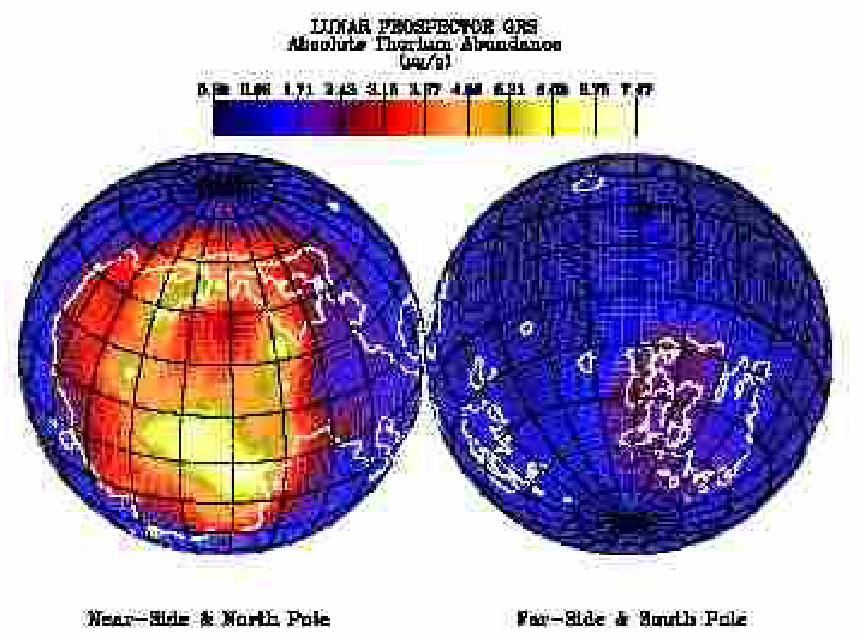
$$\Delta T \sim \frac{(\Delta p)^2}{2M} = \frac{m}{M}T$$

$$\frac{\Delta T}{T} \sim \frac{m}{M} \sim 0.3\%$$



So where is thorium, how much is there for the world's needs?

Australia:	300,000 tons
India:	290,000 tons
Norway:	170,000 tons
US:	160,000 tons
Canada:	100,000 tons
World supply	***1,200,000 tons***



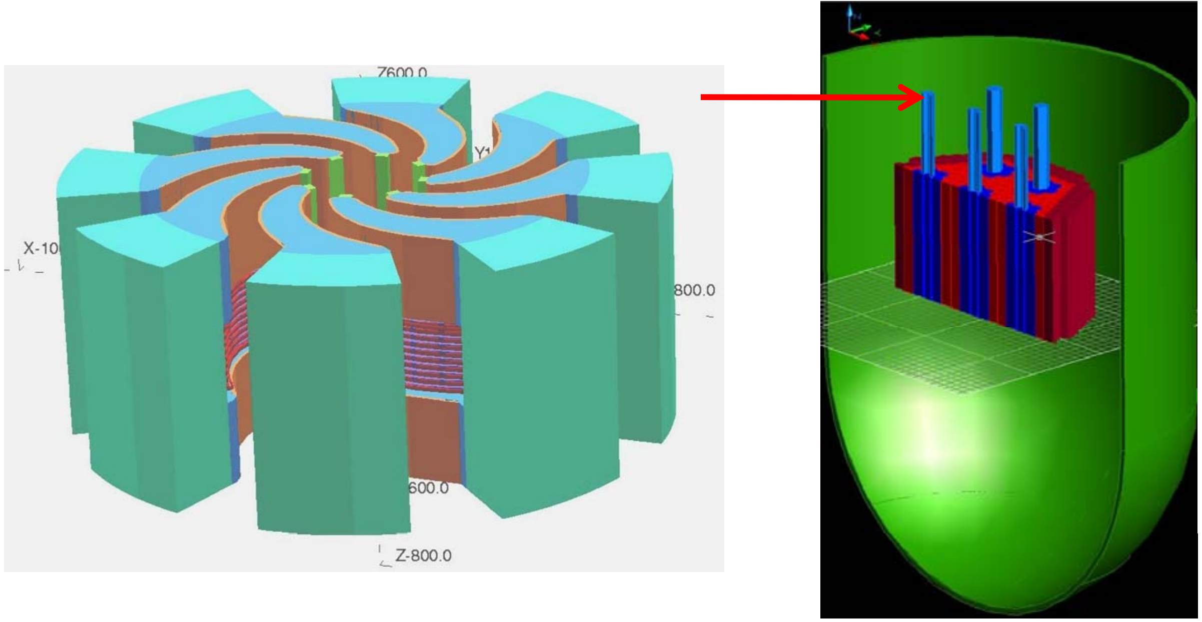
plenty more on the moon!

world energy demand:

~ 1,000 ton/year of thorium

Conclusions

New flux-coupled IC and cavity technologies and new neutronics make it possible to burn desert sand to provide man's energy needs for a thousand years.



We would like to collaborate with you in developing the design…

Main parameters of the core

Overall core dimensions		
Radius	1.5	m
height	1.5	m
Fuel bundles		
Fuel pin		
composition	90%Th^{232}, 10%U^{233}	
radius	0.35	cm
cladding thickness	0.055	cm
Bundle size (flat to flat)	18	cm
Inner fuel region		
number of bundles	6x20	
pins per bundle	271	
Outer fuel region		
number of bundles	6x14	
pins per bundle	331	
Starting fuel inventory:		
Fresh ^{232}Th	21	tons
Recycled ^{233}U	2	tons