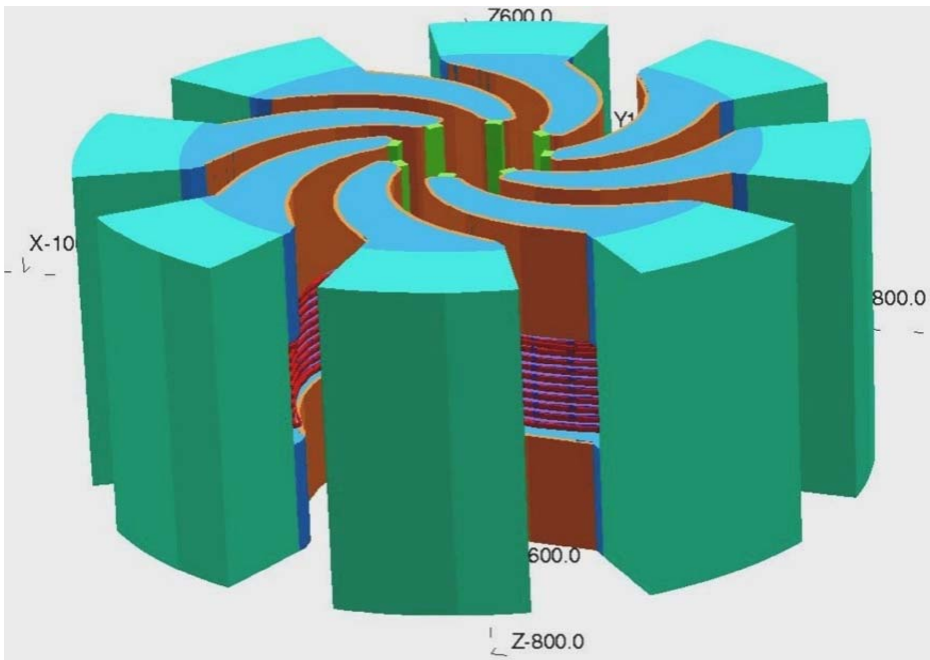
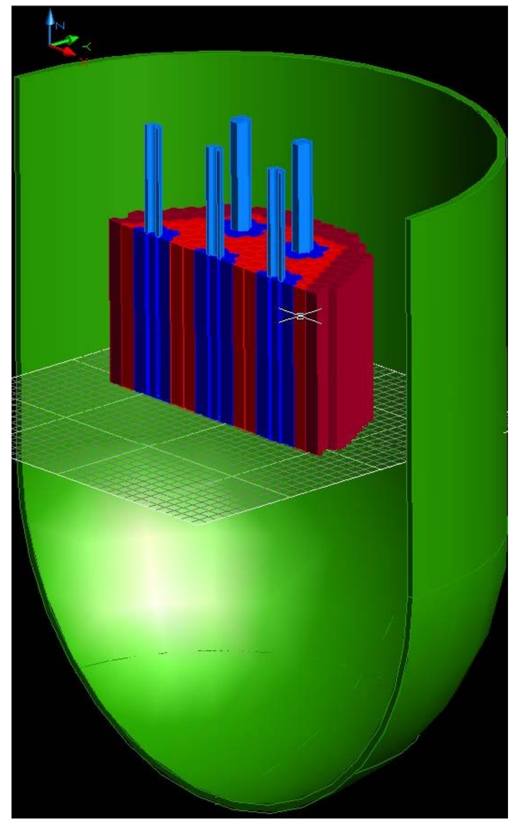
Thorium-Cycle Fission for Green Nuclear Power



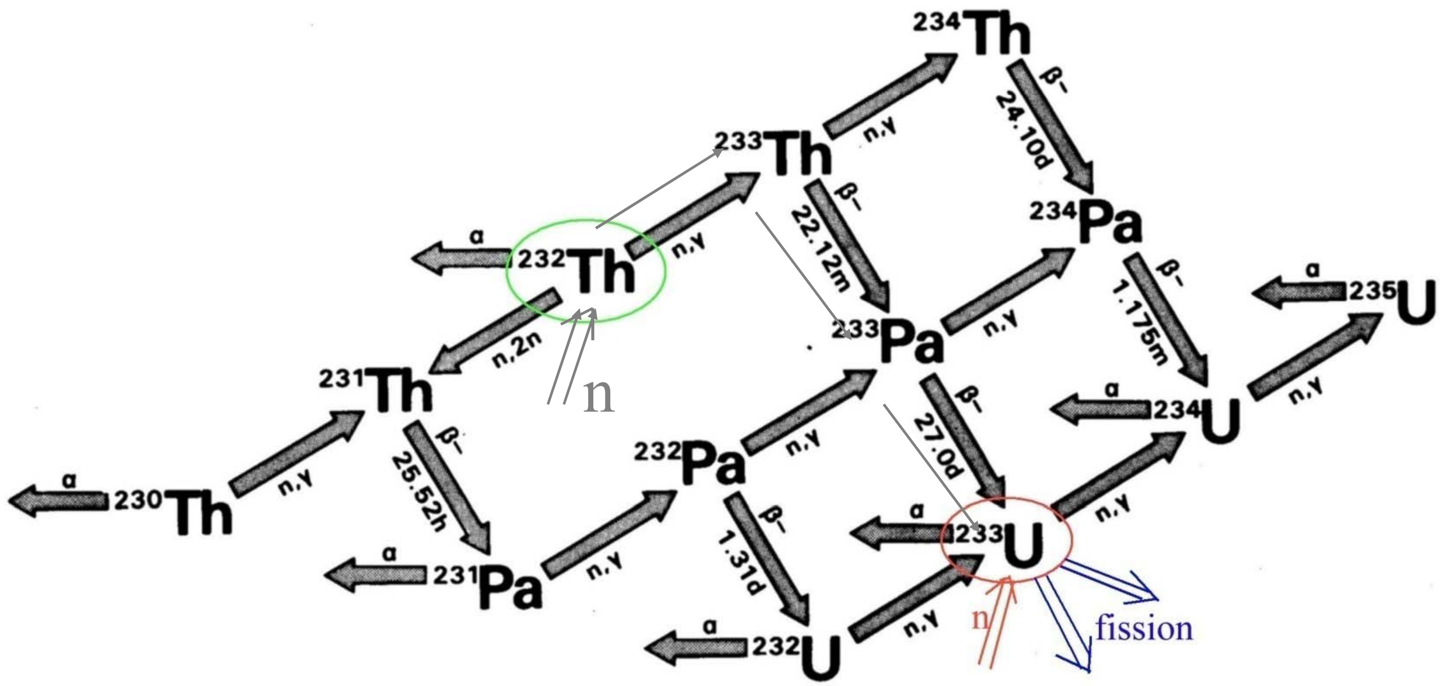


Peter McIntyre
Texas A&M University

Criteria for green nuclear power:

- Use the most plentiful fissionable fuels:
  - Thorium and depleted uranium
- Operate as a sealed core through entire fuel life:
  - Deliver and return as a sealed core
  - No shuffling of fuel pins through life cycle
- Consume actinide waste rather than make it

The electrobreeding concept: 800 MeV protons→fast neutrons

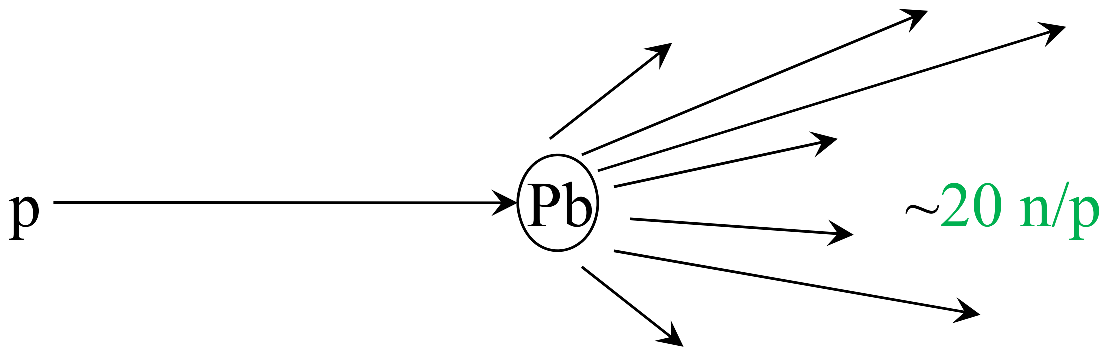


- First proposed by E.O. Lawrence (1948), later by C. Rubbia (1995).

Fatal flaws: accelerator power, neutronics, reliability

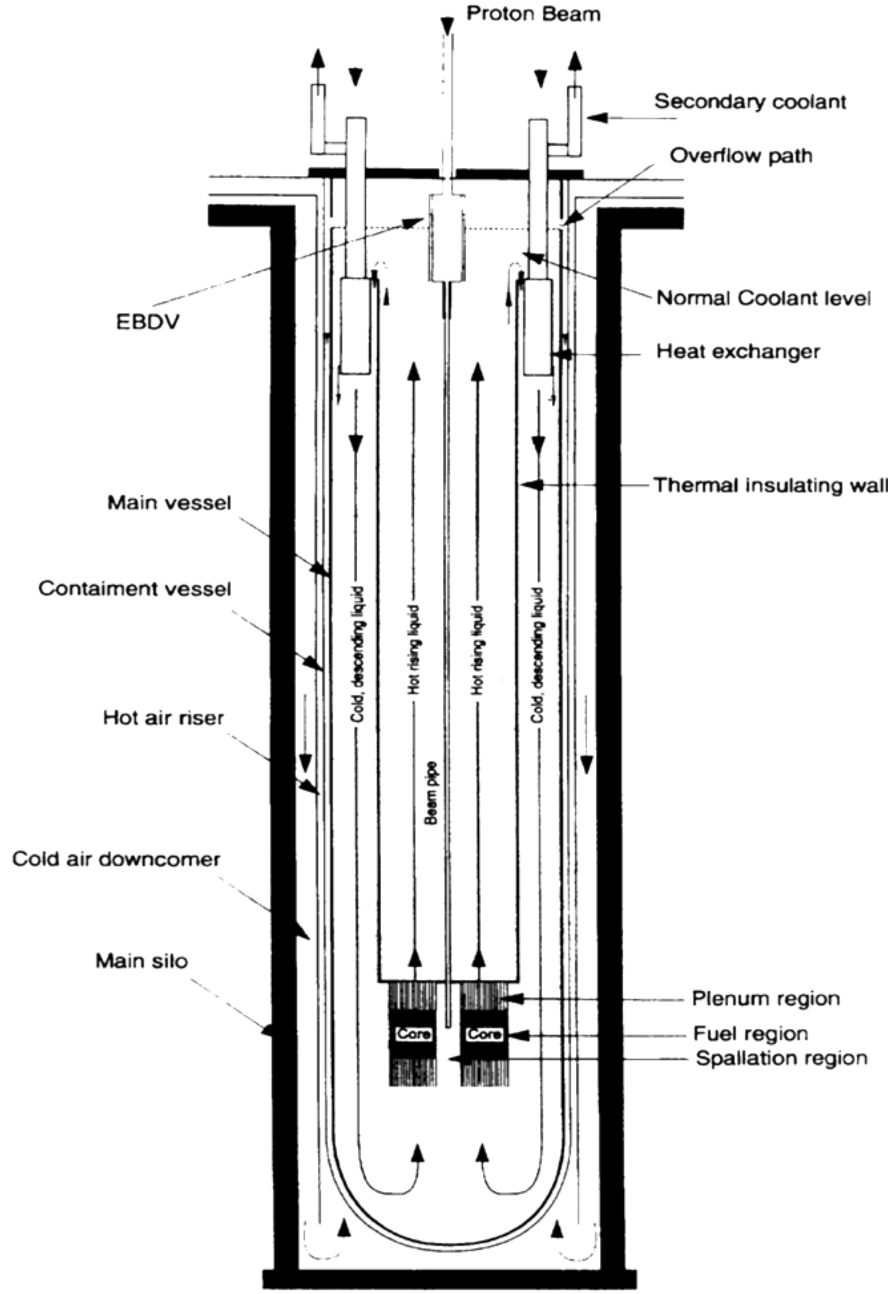
Fast neutrons are produced by spallation of ~1 GeV protons on Pb

- 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:	500 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)

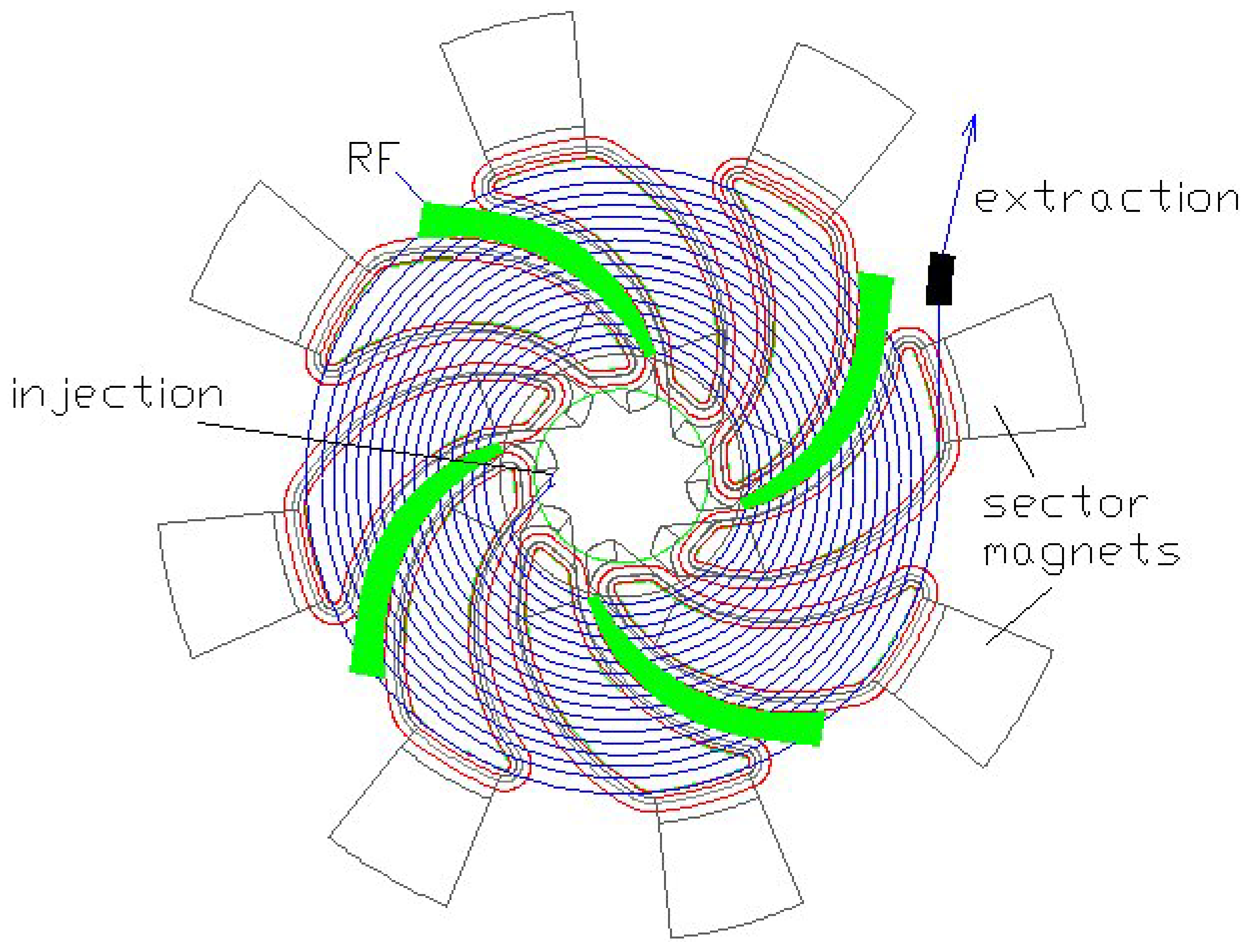
- Assemble a stack of seven flux-coupled ICs

  Flux linkage

  Independent RF, injection, extraction, vacuum, transport

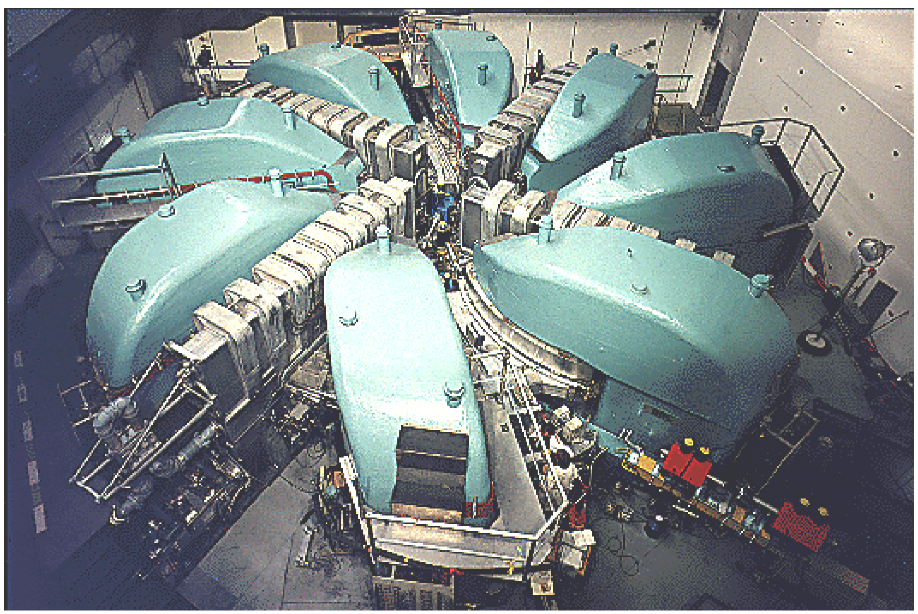
- ***Reliability through redundancy***
  - If one beam goes down, the reactor still operates.
  - If one beam goes down, no thermal shock to fuel pins.

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

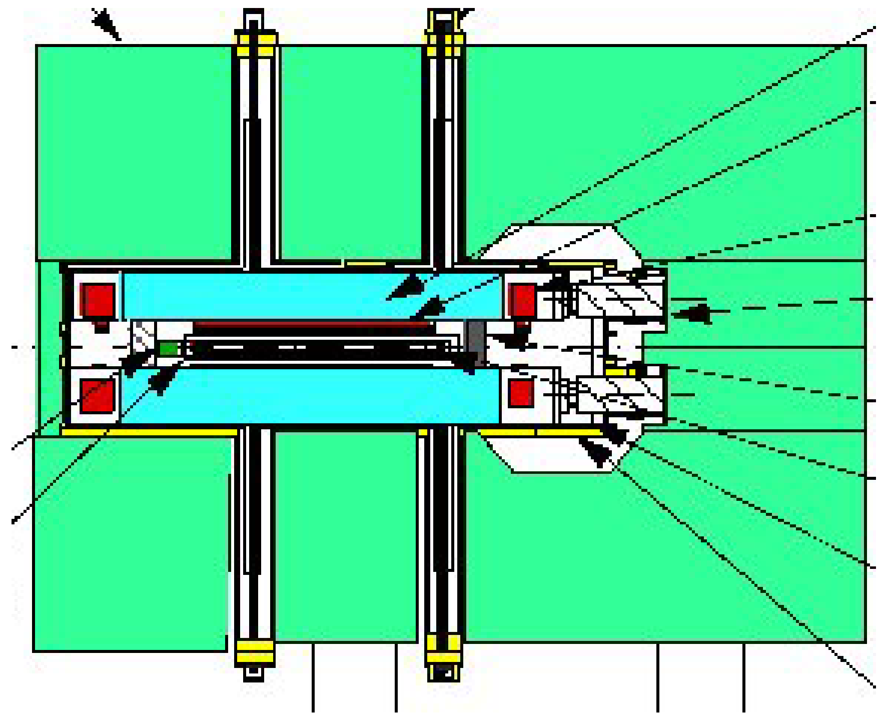


Combine the high-energy isochronous cyclotron of PSI:

and the superconducting magnet design of Riken:

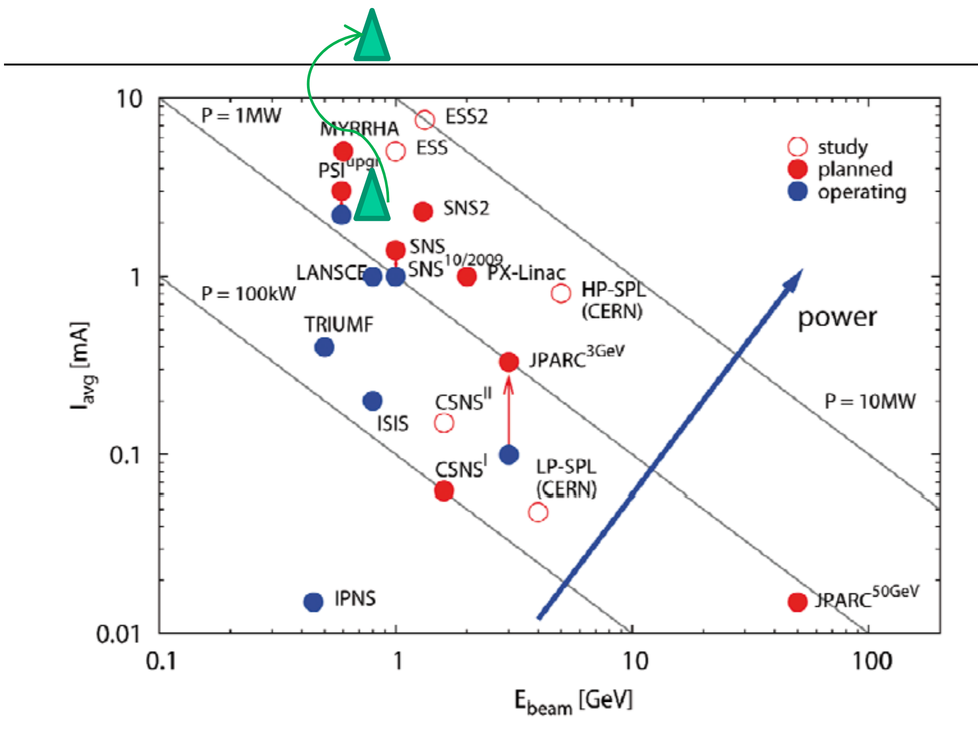


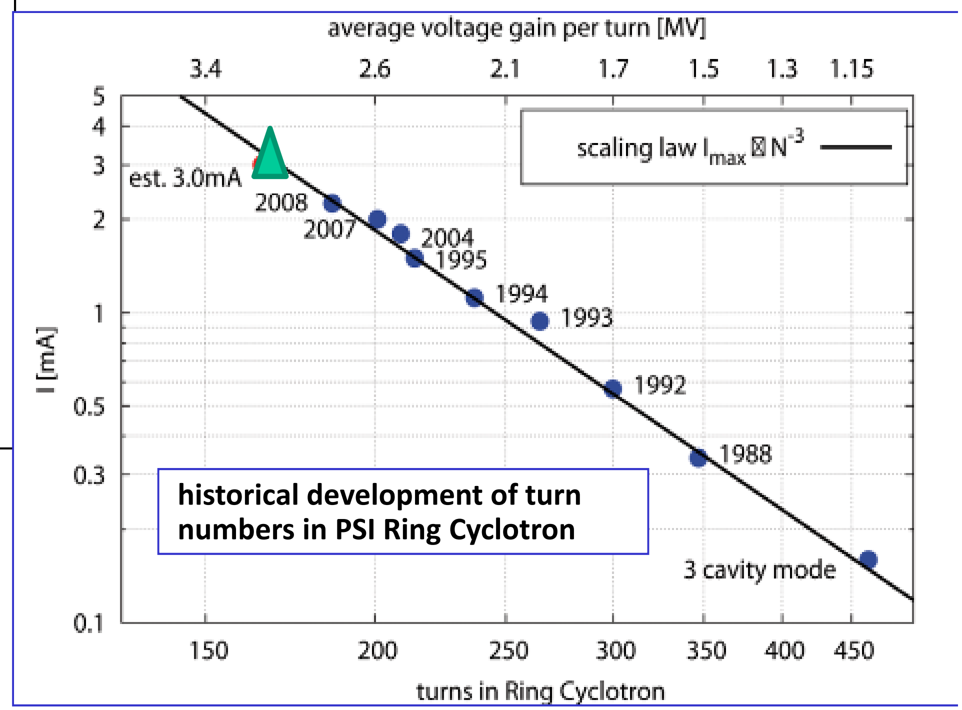
590 MeV, 2 mA



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

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

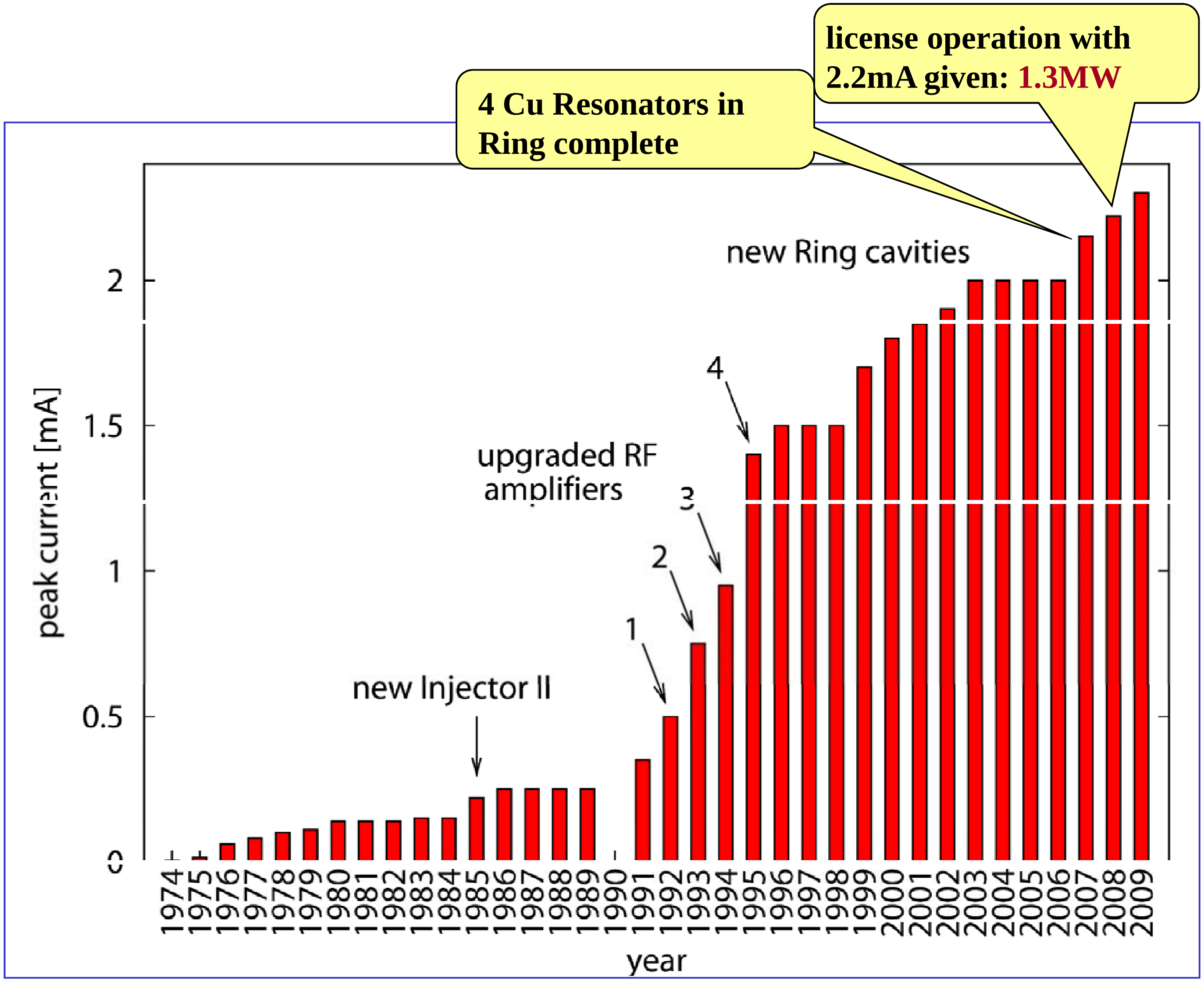




B = 1.7 T in sectors
RF = 3.5 MV/turn
200 → 800 MeV
170 turns

Seidel, TC ADS 2010

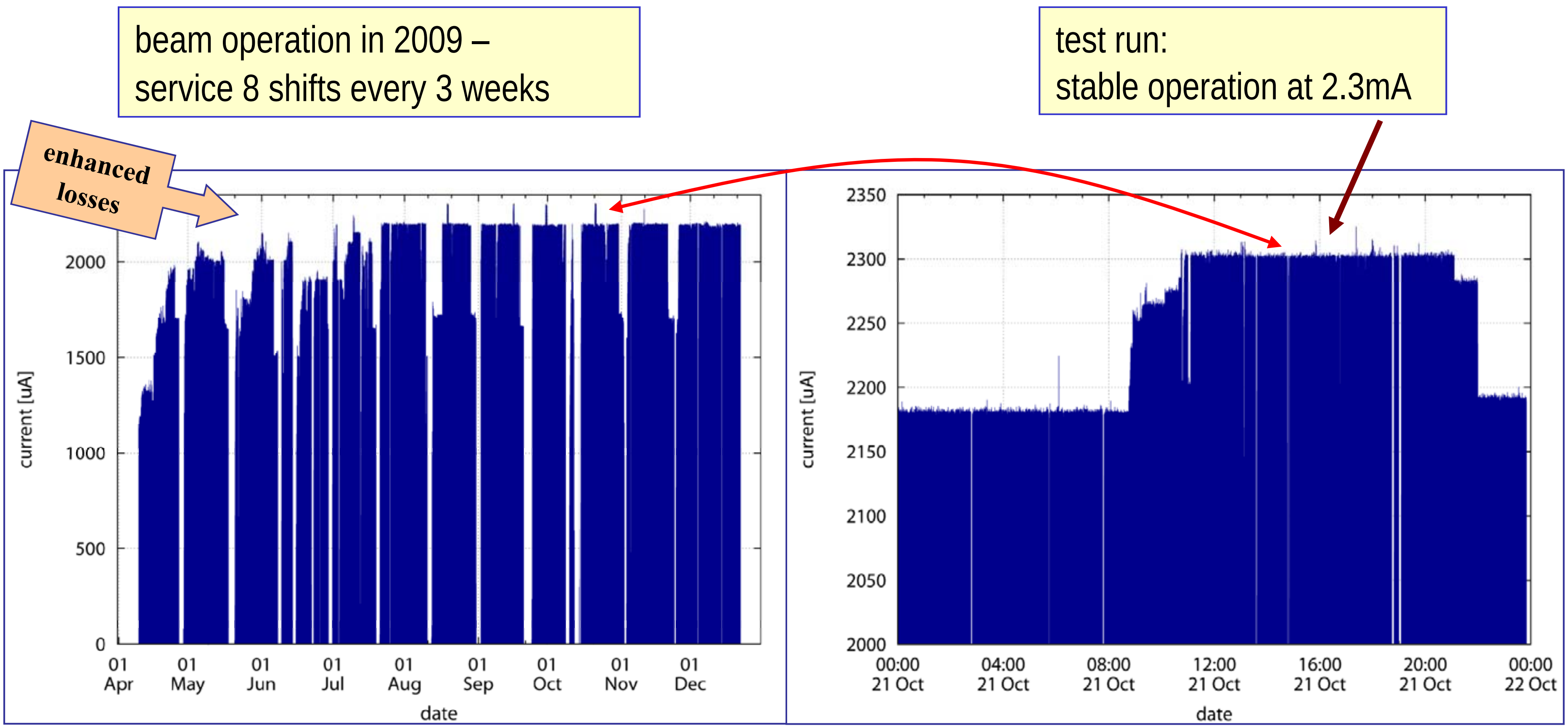
History of max. current in the PSI accelerator



beam current is limited by beam losses; upgrade path foresees constant absolute losses by improvements of the accelerator

new beam current record in 2009

- since 2009 license for standard operation 2.2mA; test operation at 2.4mA (before 2.0mA)
- new maximum current: 2.3 mA (1.36 MW)



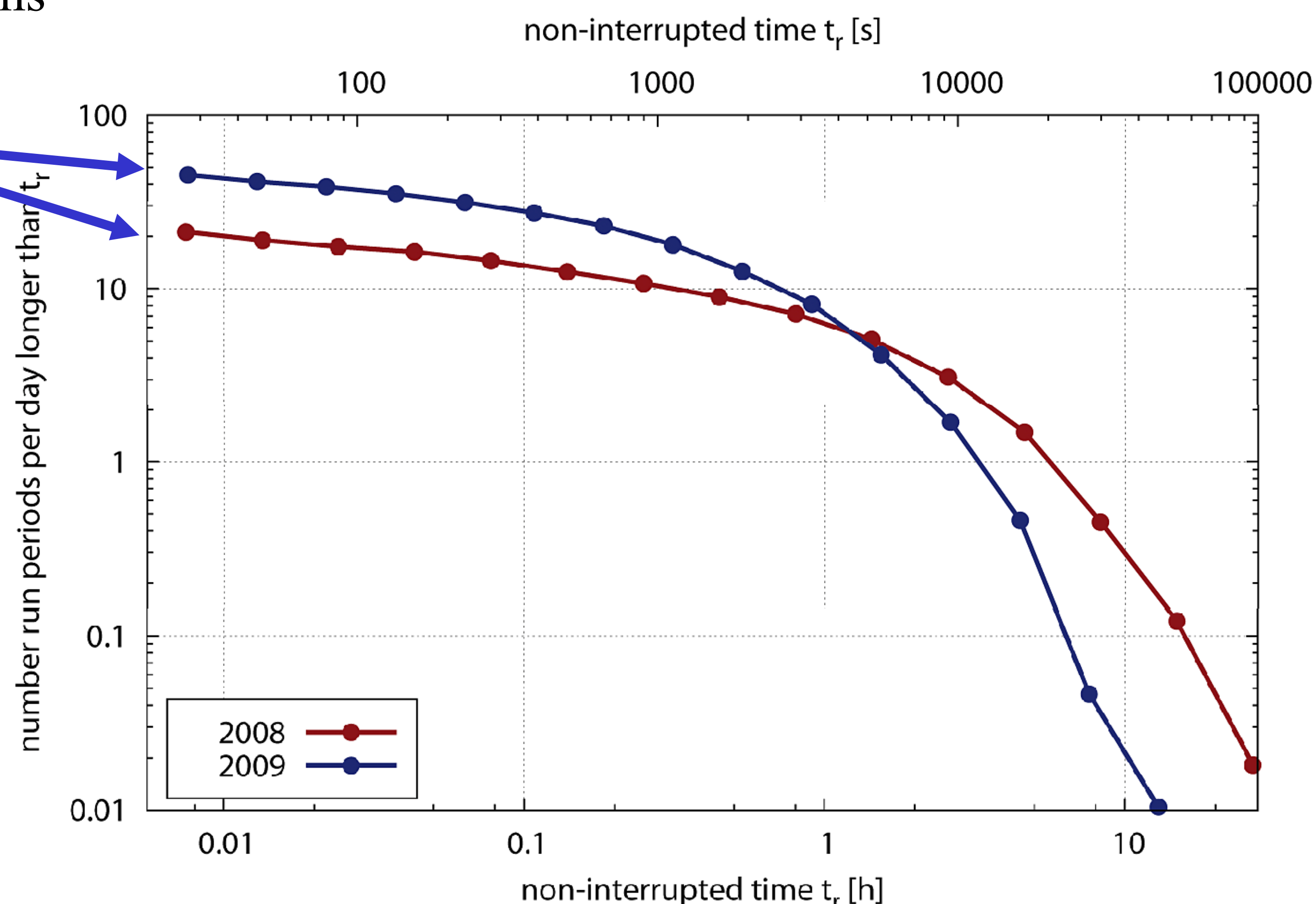
Seidel PSI

PSI: statistics of run durations 08/09

➔ histogram for occurrence of uninterrupted run periods as function of duration, integrated from right; average number per day; comparison 2008/2009

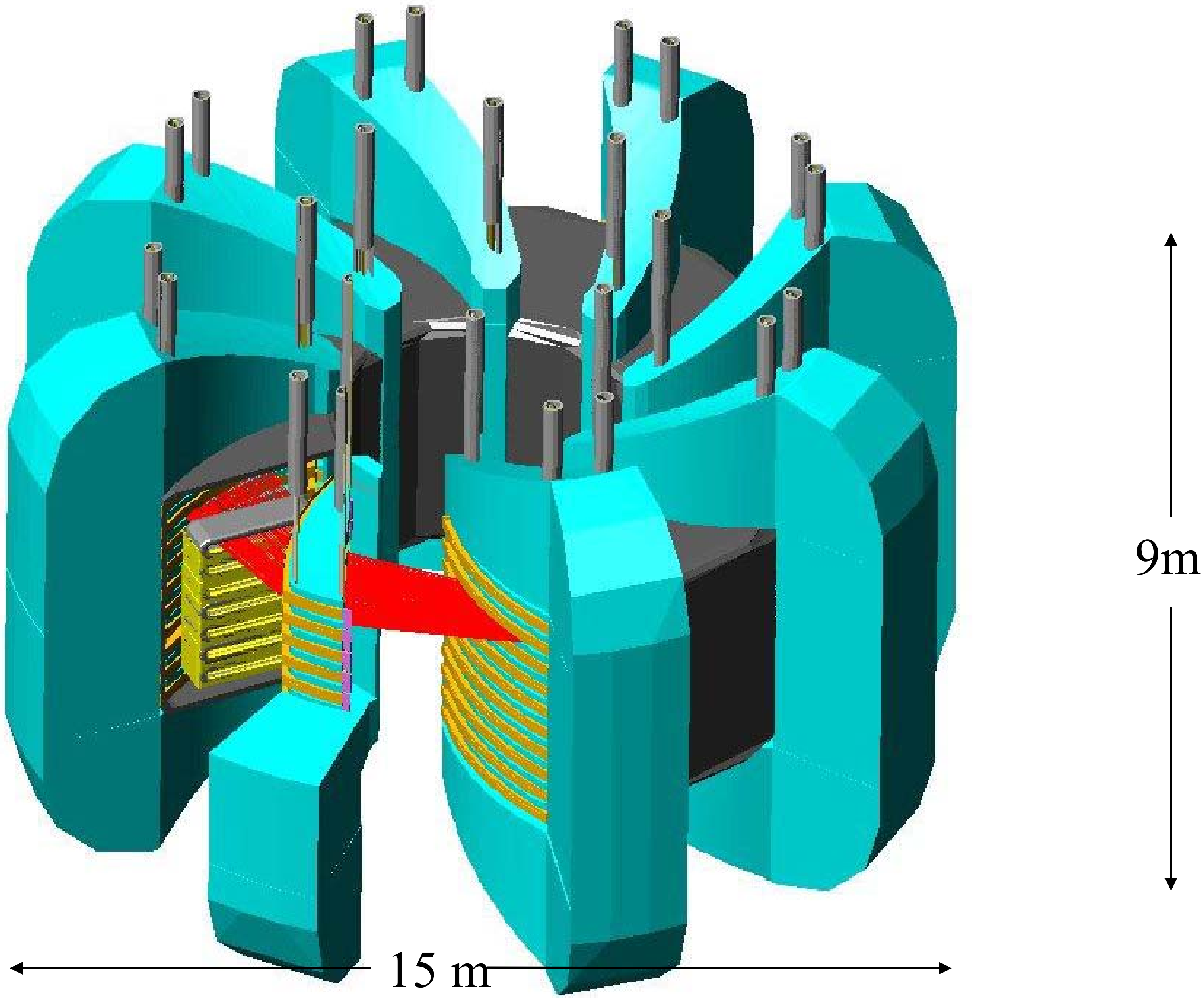
➔ high reliability is important for our users and for other potential high power applications of cyclotrons

total number of runs/interrupts per day [integrated histogr.]

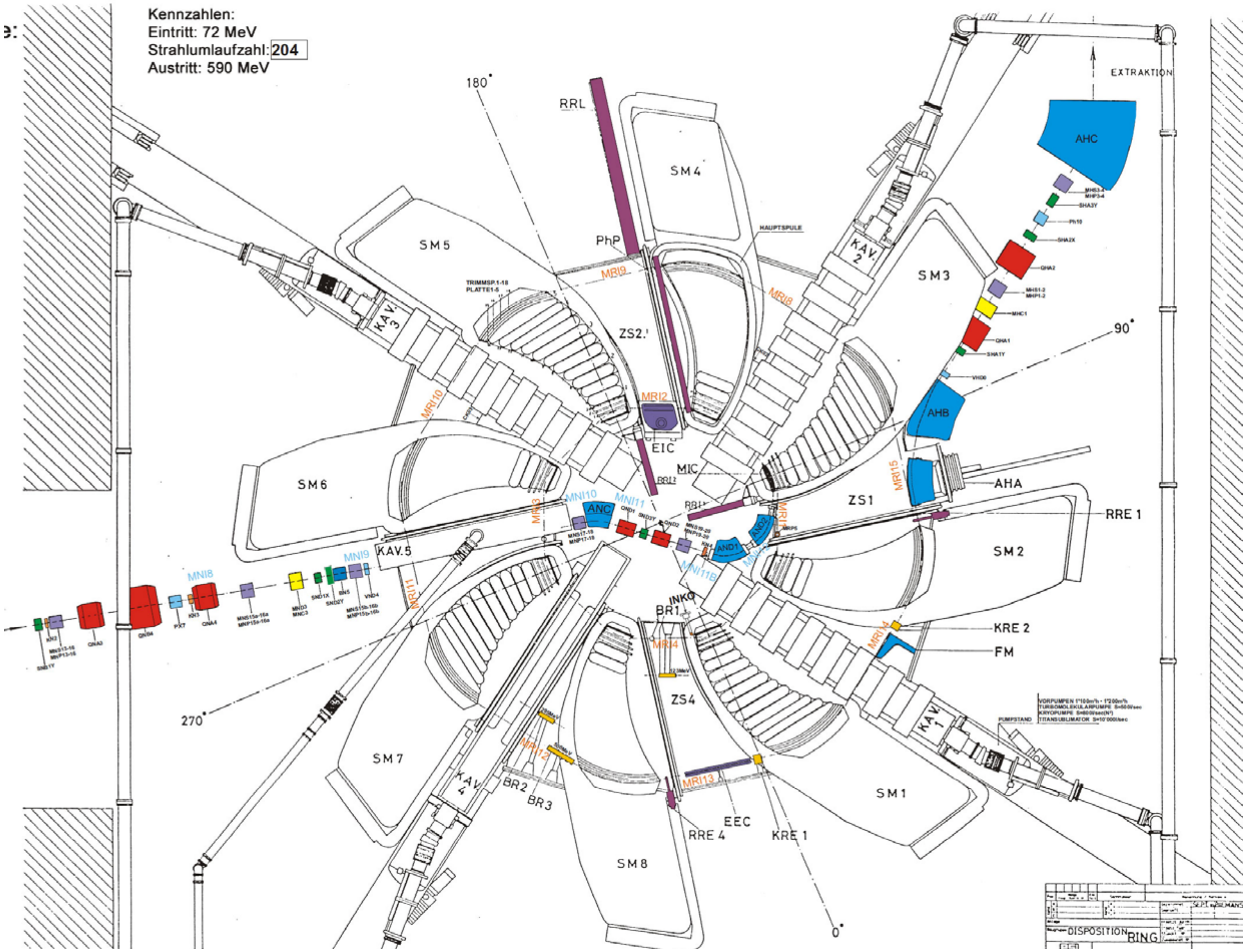


read this plot as follows:
there are typically *n* run periods per day that last longer than *t*

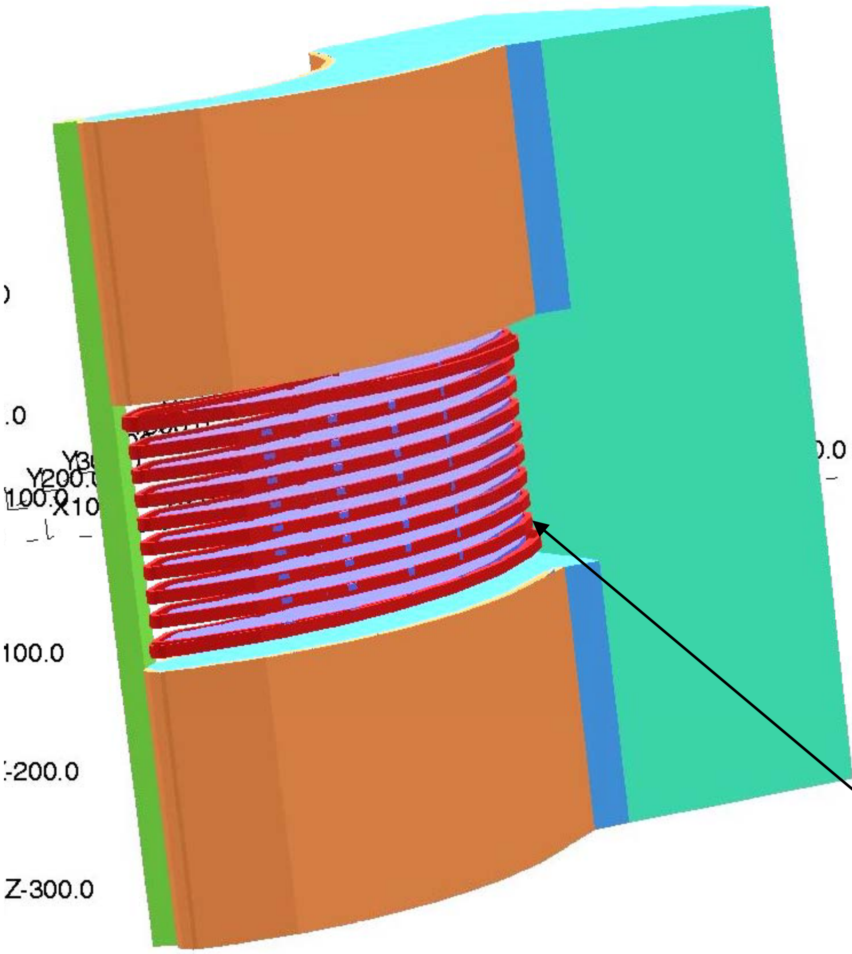
7-stack isochronous cyclotron

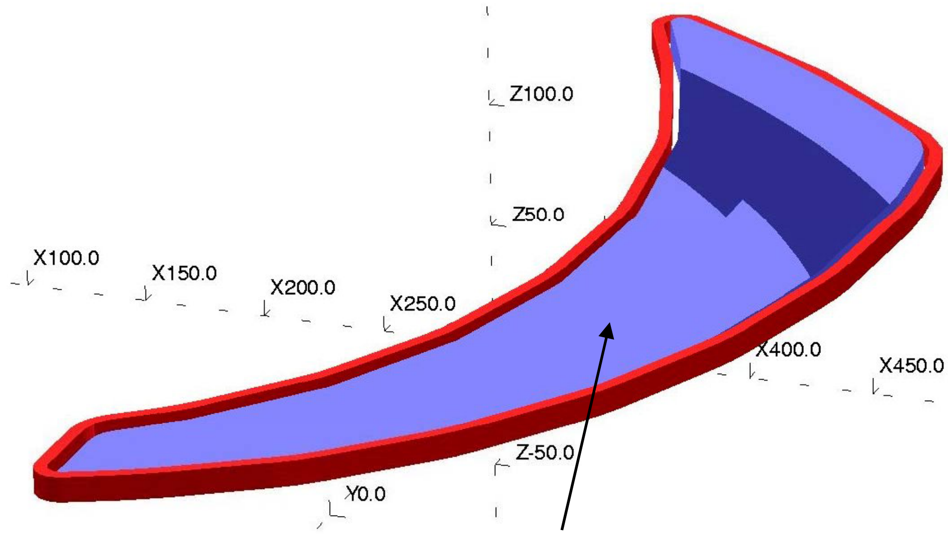


Layout injection, extraction similar to PSI



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



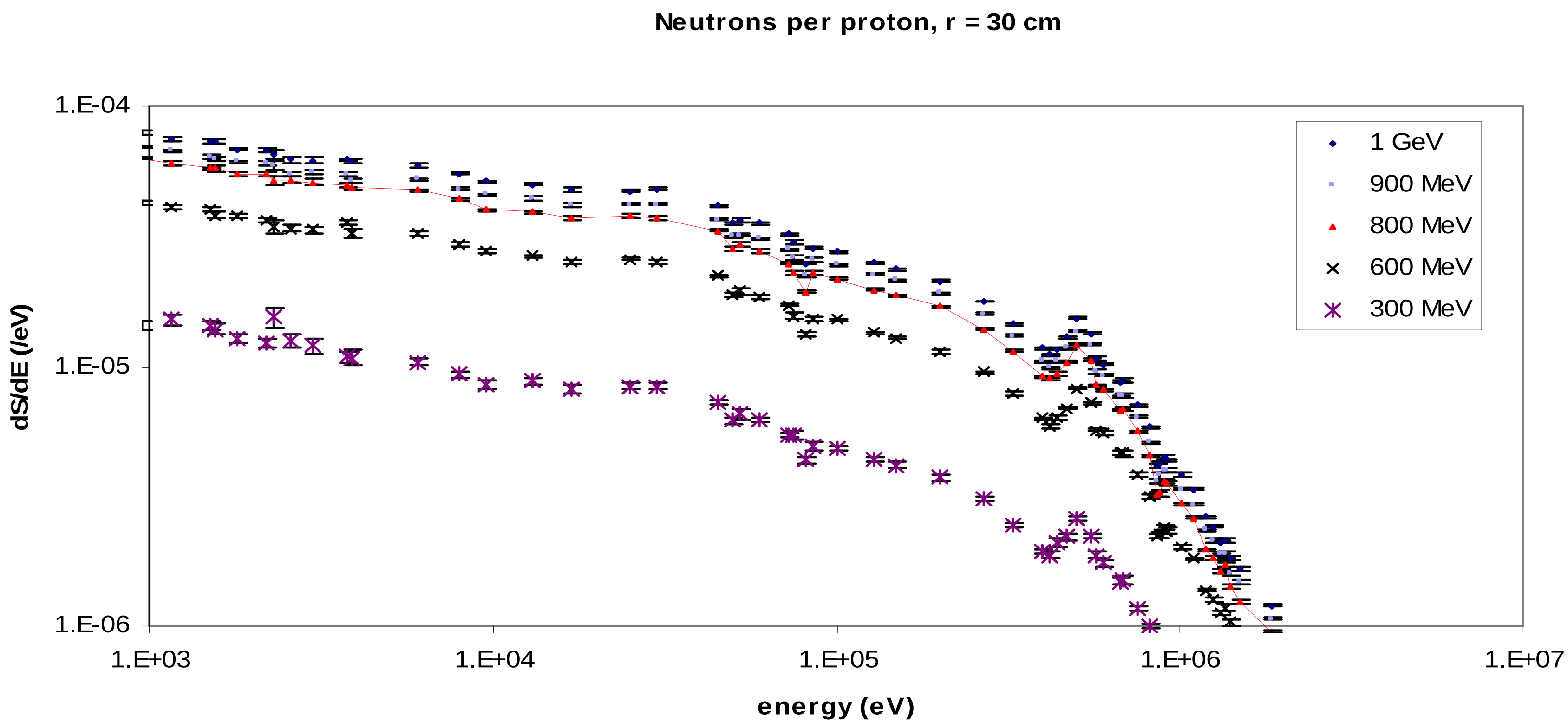


Flux plate = NbTi superconducting coil, contoured steel plate

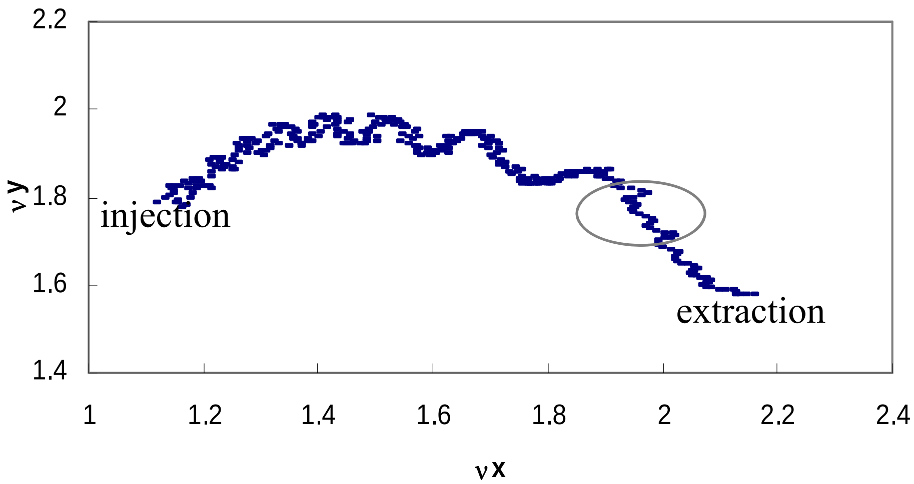
10 flux plates,
Top/bottom sacrificial gaps

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

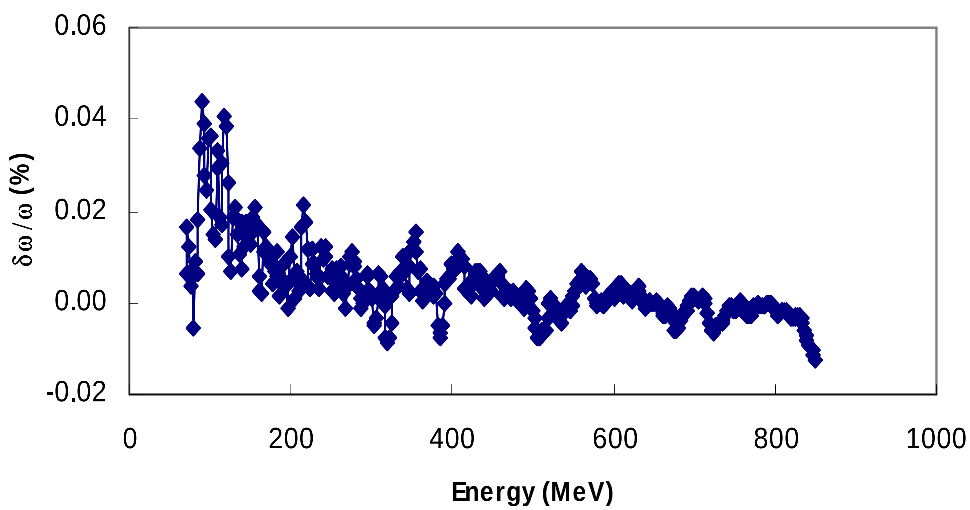
Best choice of proton energy ~800 MeV



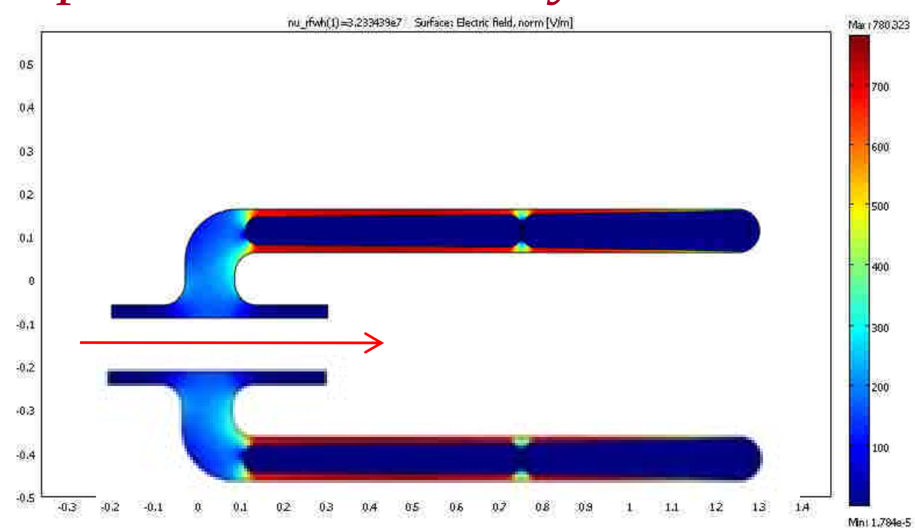
Control horizontal, vertical betatron tunes:



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

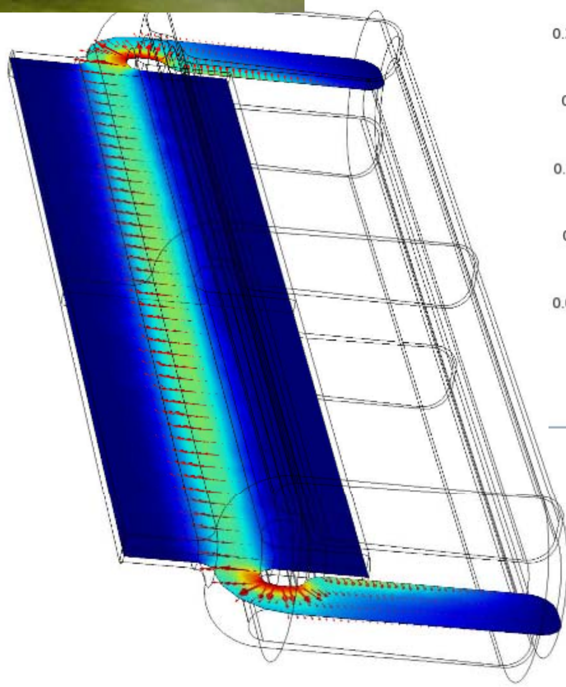


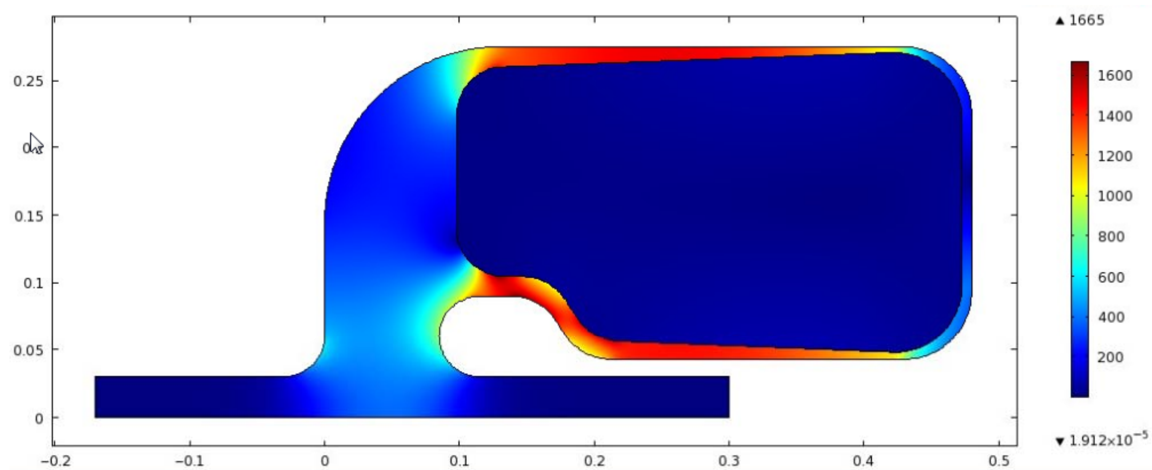
32 MHz dielectric-loaded superconducting cavity fits in the space between IC layers:



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



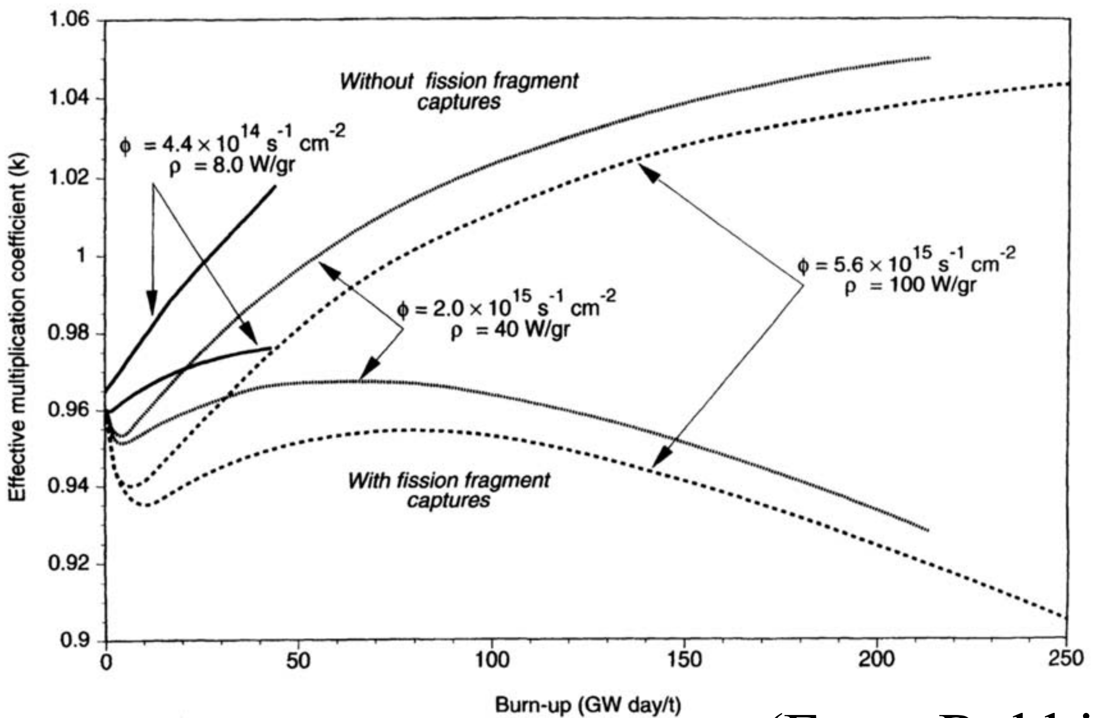


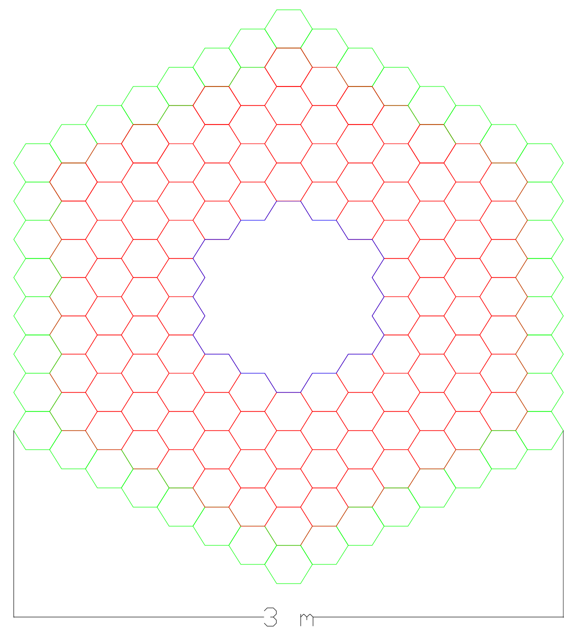
2 W/m @ 5 K
5 kW/m @ 80 K

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):



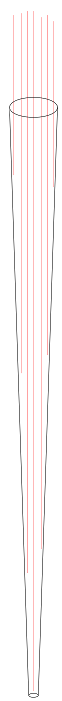


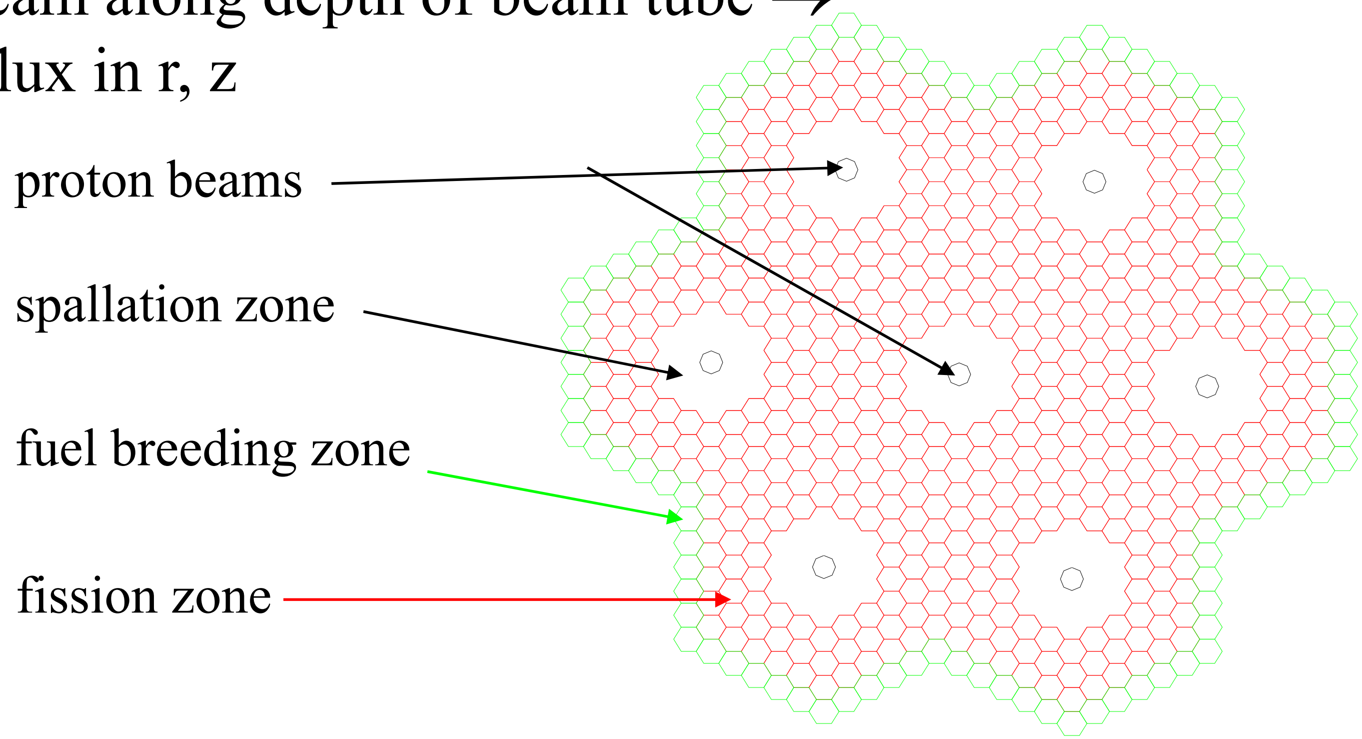
(From Rubbia)

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

Distribute proton drive → Reduce variation k(r)

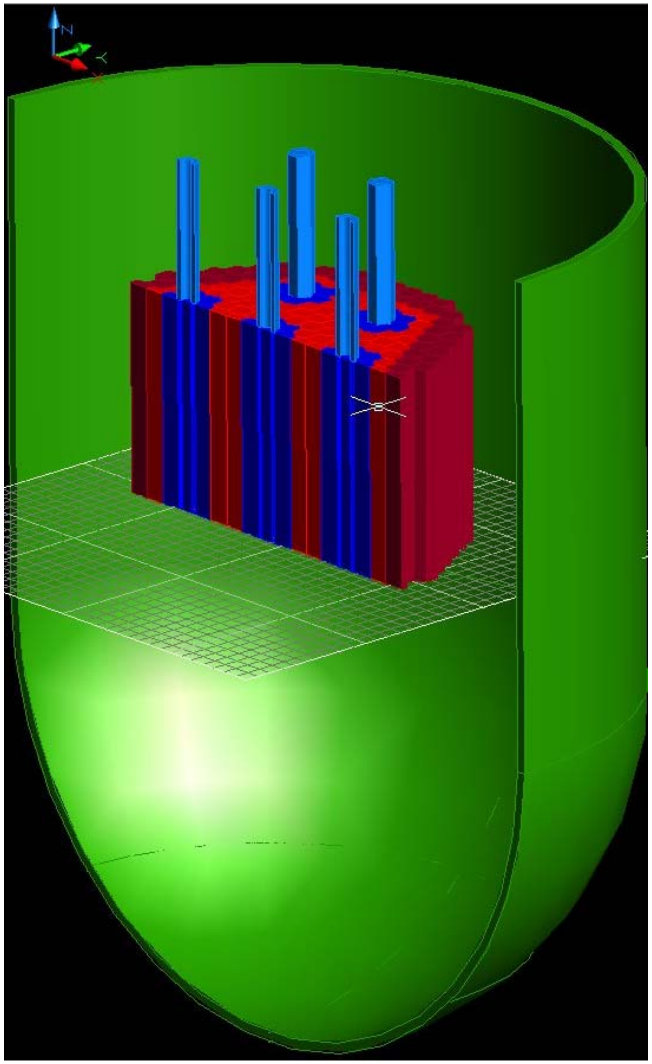
Sweep each beam along depth of beam tube → Homogenize flux in r, z

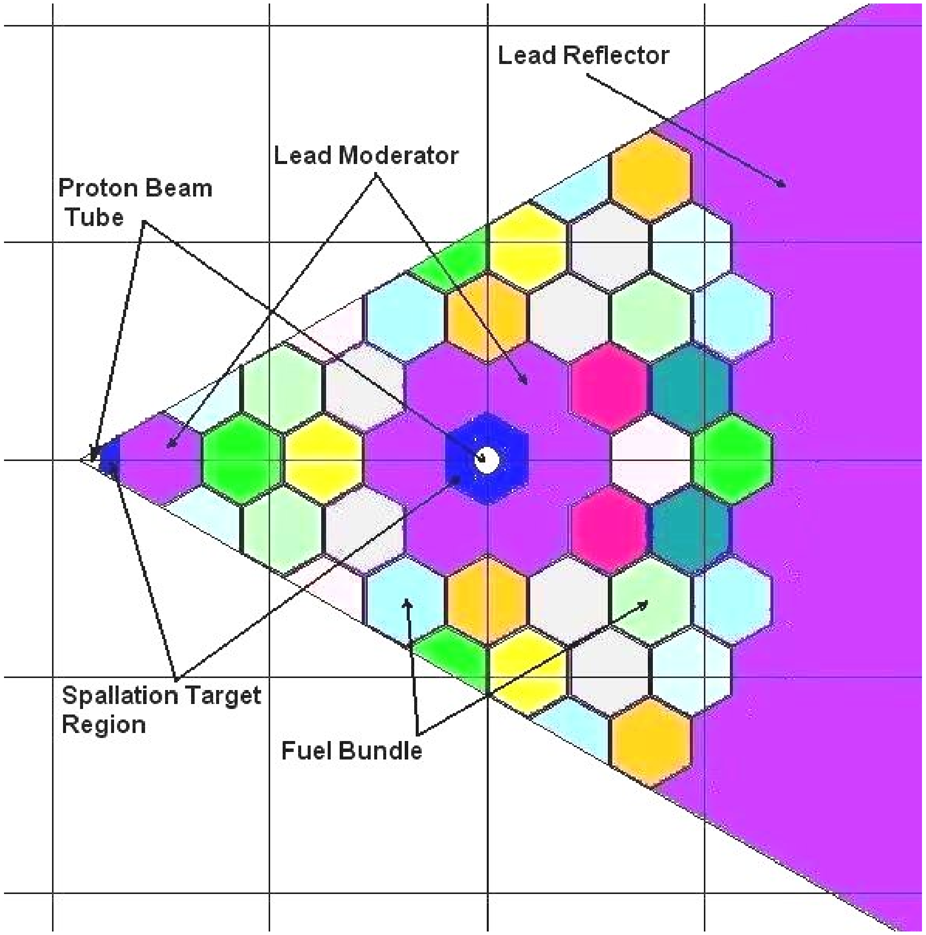




Better control, more efficient consumption of fuel.

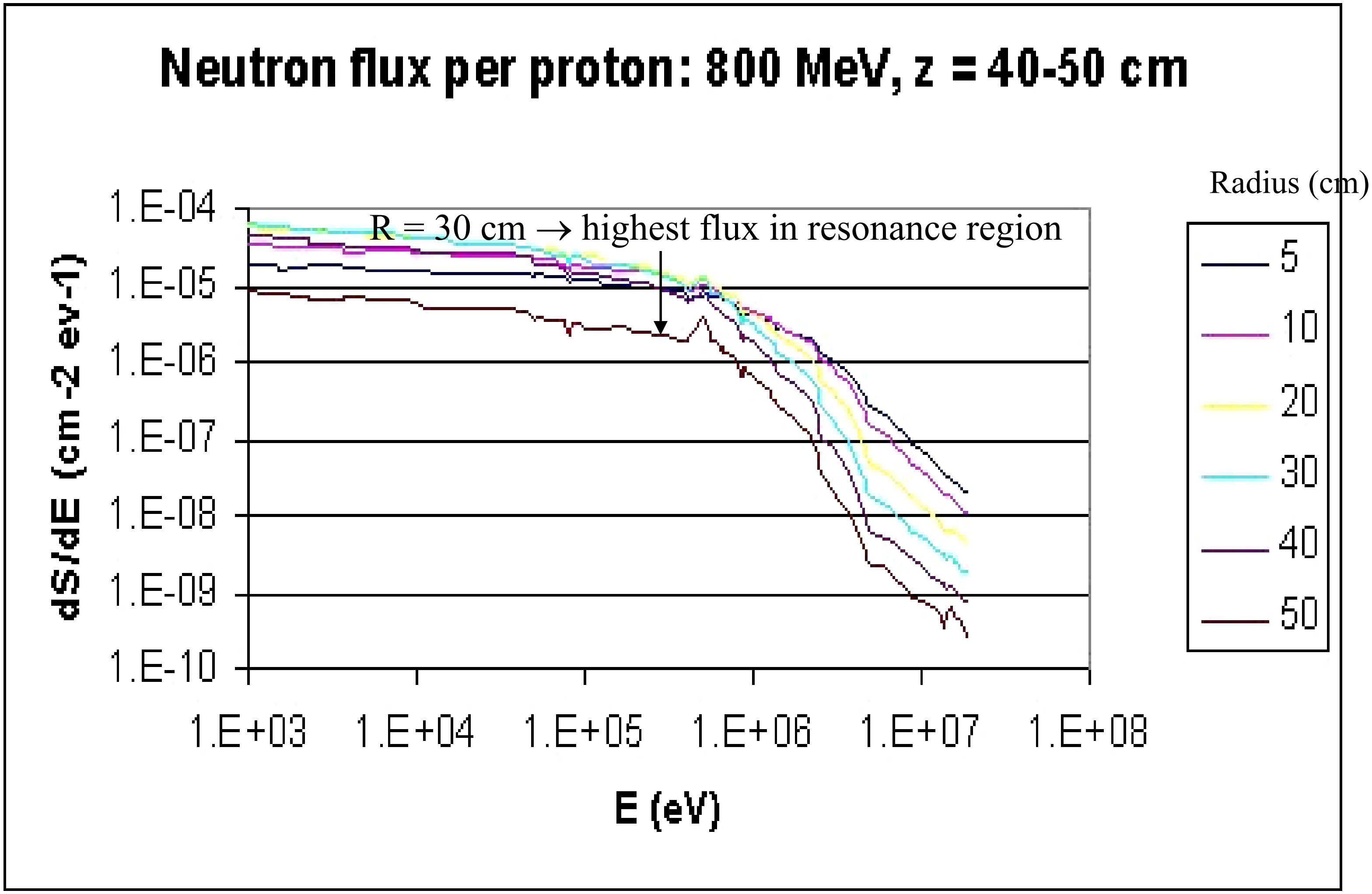
Model spallation source, neutronics in core



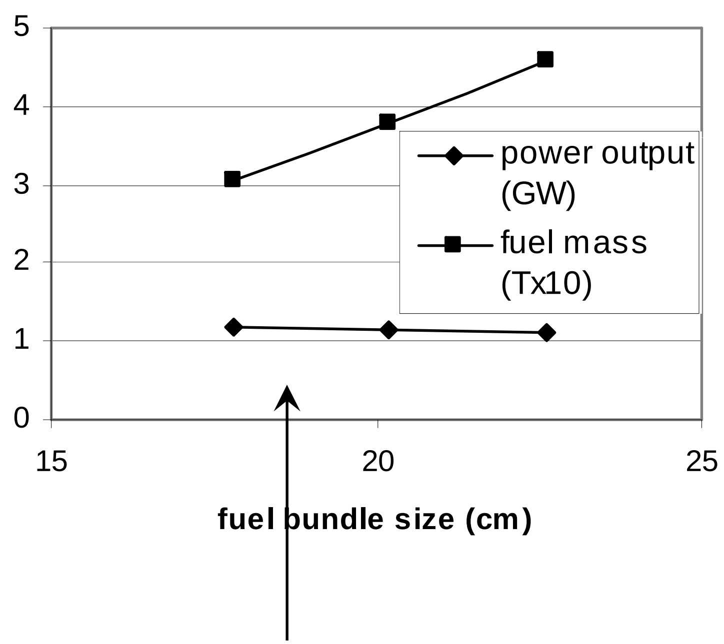


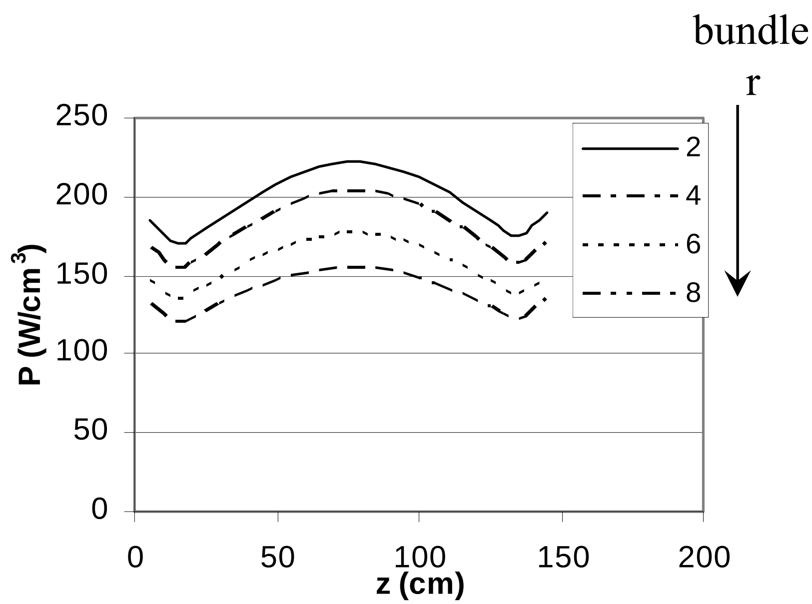
Slice through one sextant of the core

Neutron spectrum in spallation



Optimize core geometry

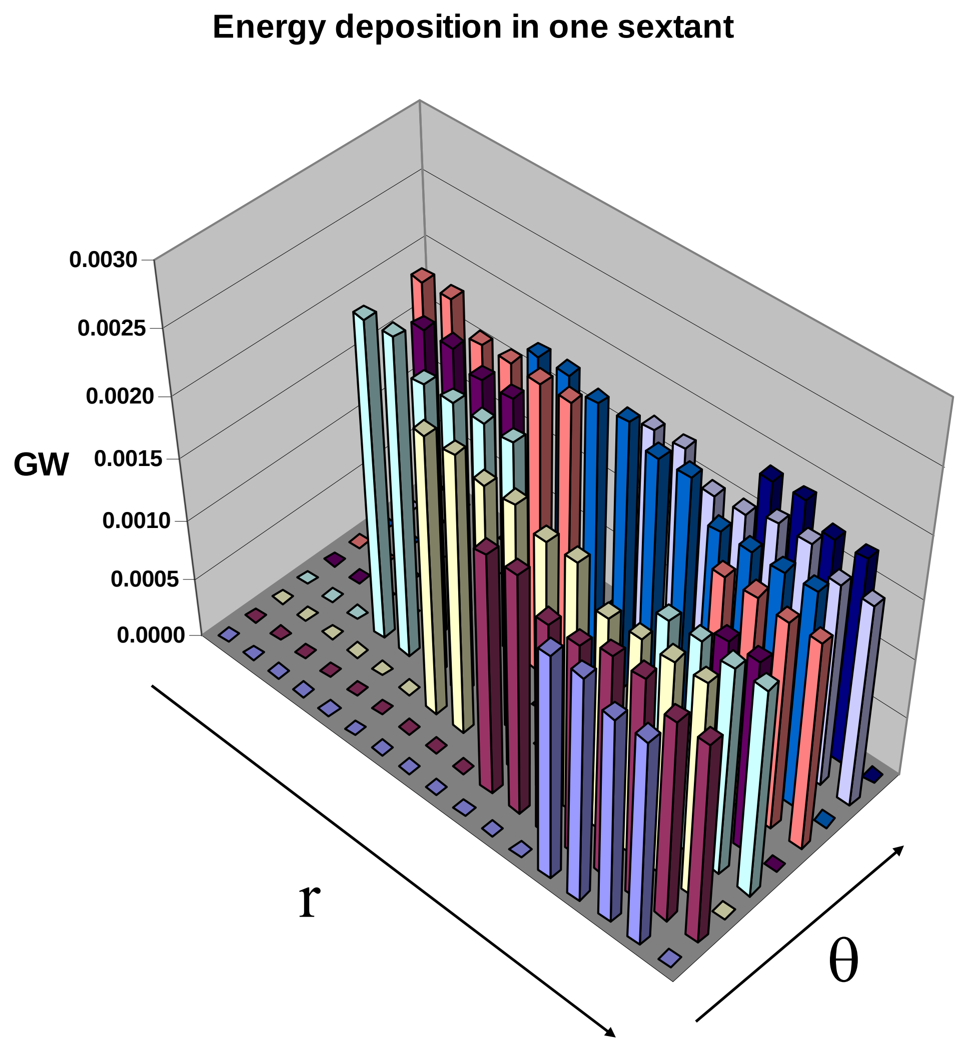




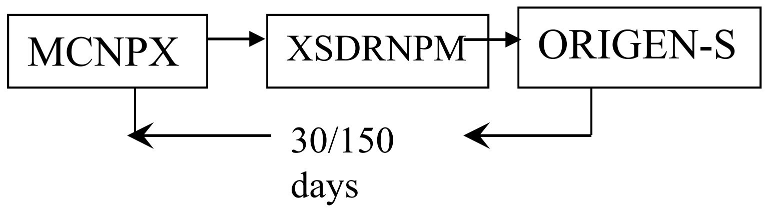
Optimize fuel bundle for power output, total fuel mass → 18 cm

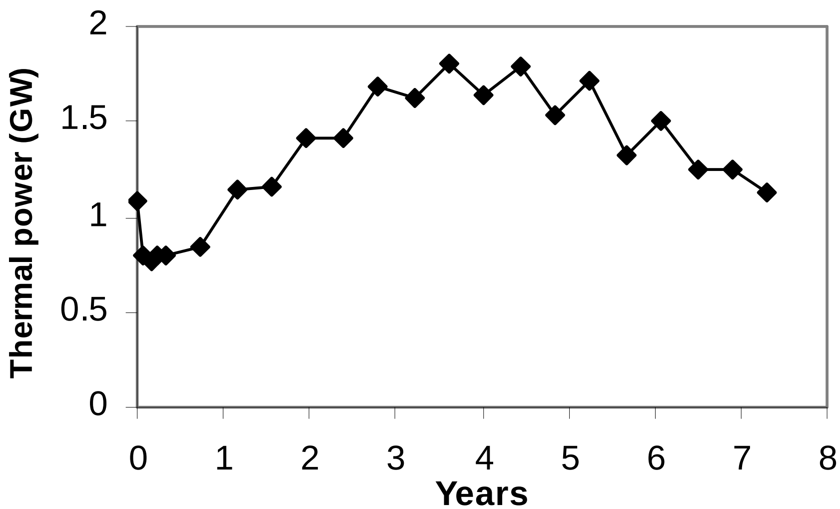
Arrange bundles to flatten power distribution at startup.

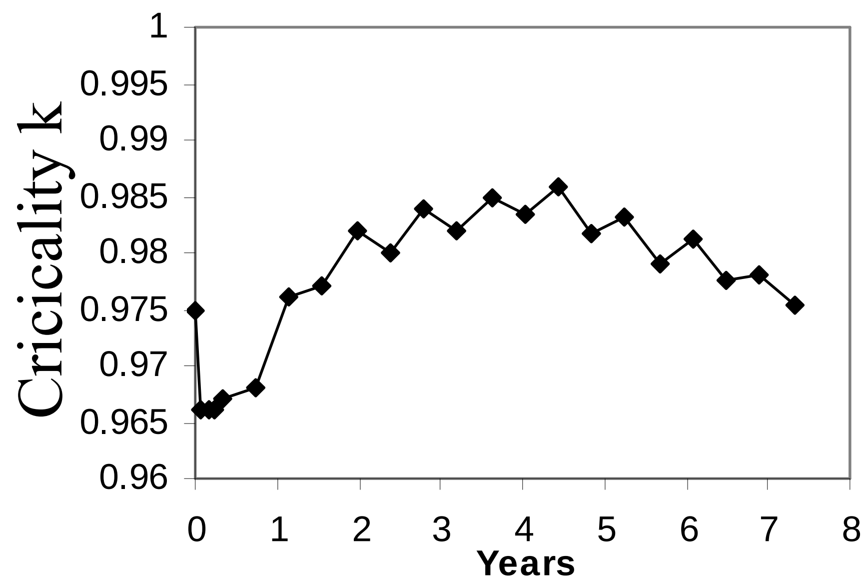
Power distribution in one sextant



Power and Criticality through Core Lifetime

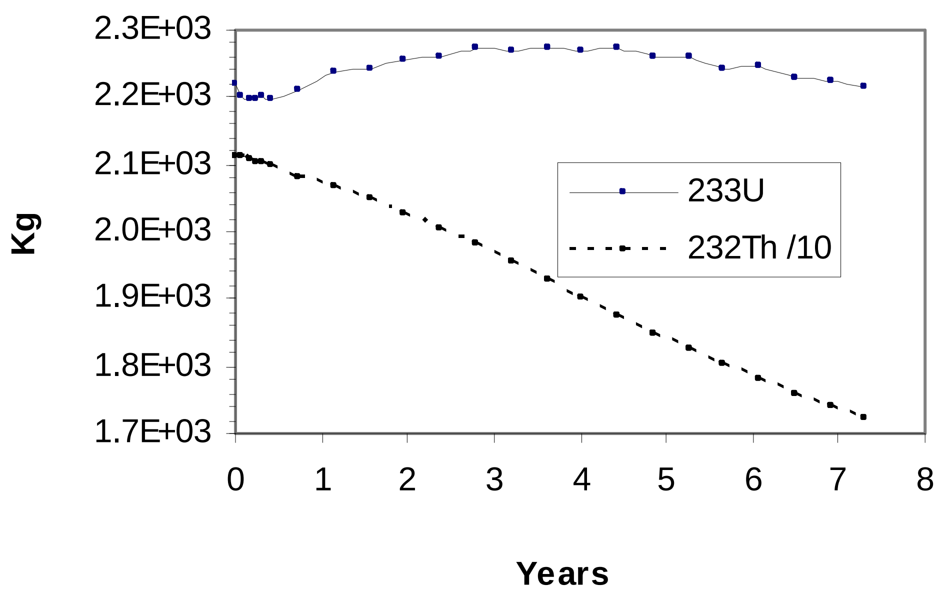


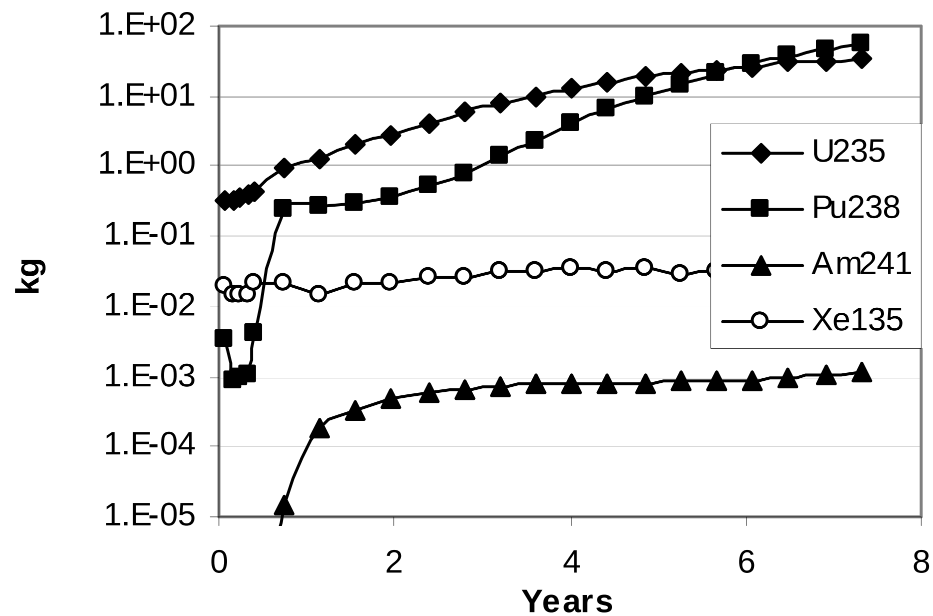




The 7-beam IC-driven thorium cycle operates as a sealed core for 7 years – no re-shuffle of fuel pins, better control for non-proliferation.

Isotope inventory through life cycle



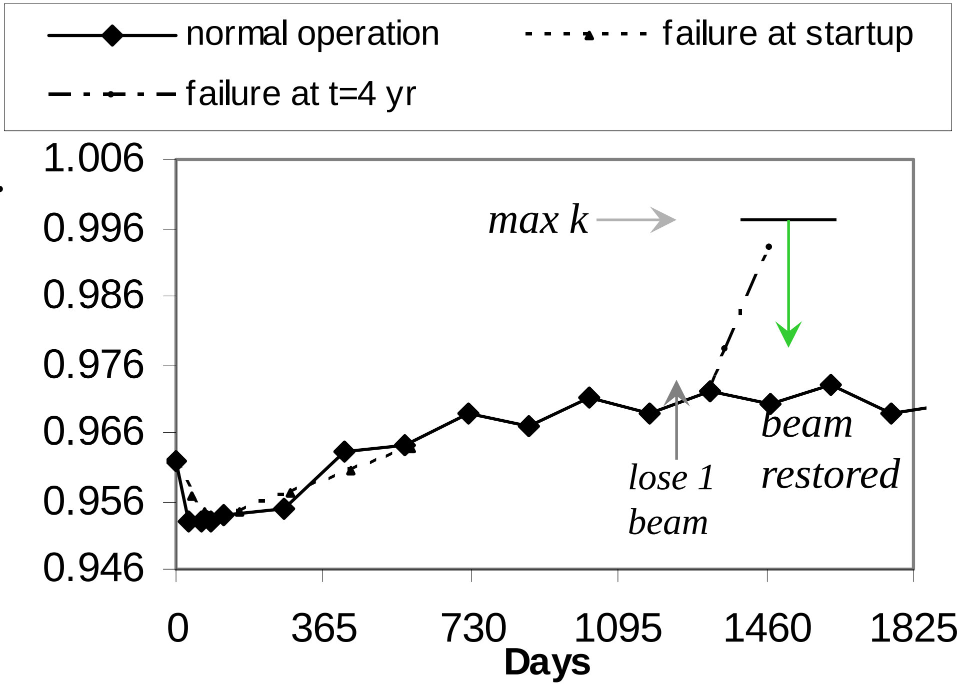


Very small inventories of waste isotopes (*e.g.* ^{241}Am), very little bomb-capable isotopes (^{235}U, ^{238}Pu)

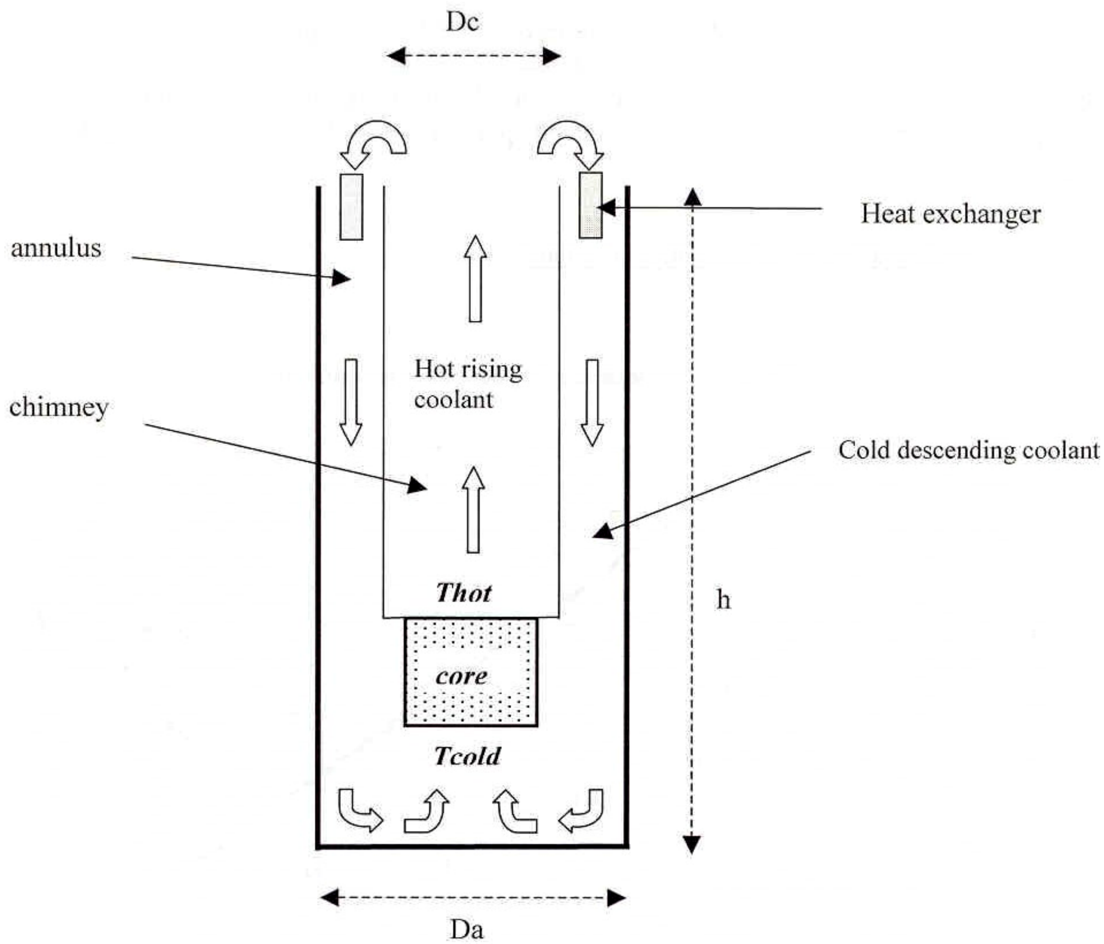
What happens if we lose one drive beam?

The transmutation sequence has a time delay:

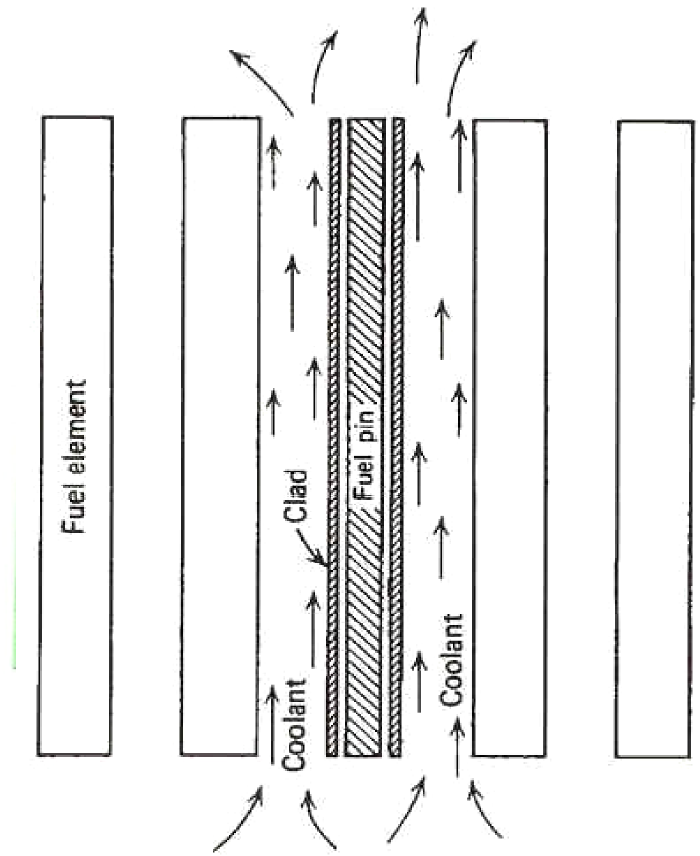
- $^{232}Th + n \rightarrow {}^{233}Th$
- $^{233}Th \rightarrow {}^{233}Pa + \beta$ *(22 minutes)*
- $^{233}Pa \rightarrow {}^{233}U + \beta$ *(27 days!)*
- *So if we lose a drive beam, the surrounding fuel builds up an anomalous inventory of ^{233}U as the ^{233}Pa decays but there is insufficient neutron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



Modeling convective heat transport

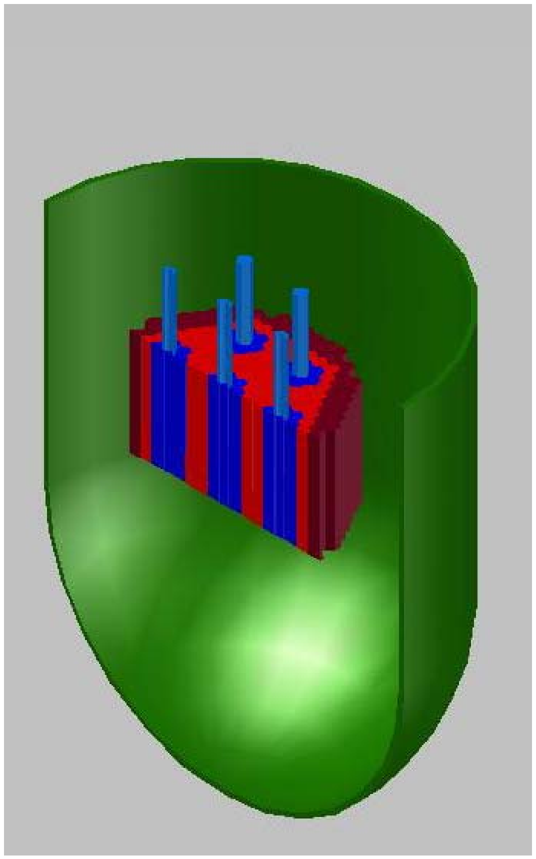


in core and convection column

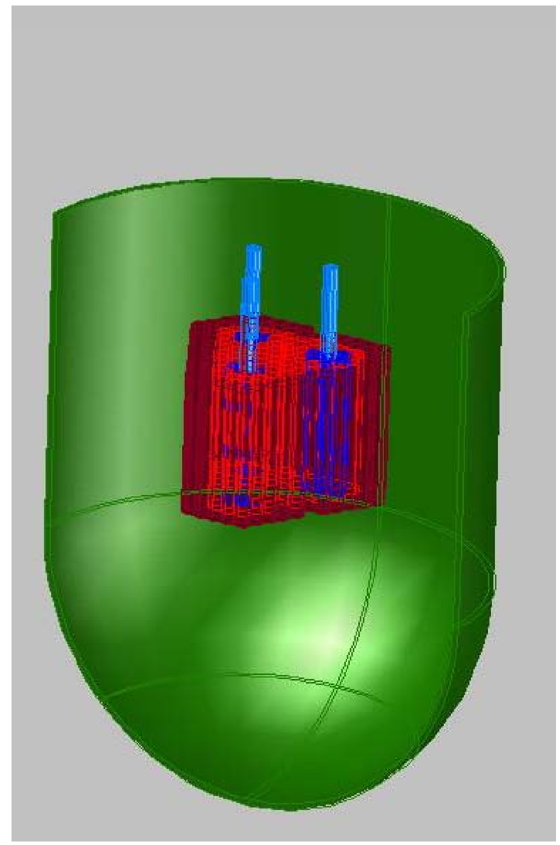


in fuel element subchannel

Multi-beam drive small and large:



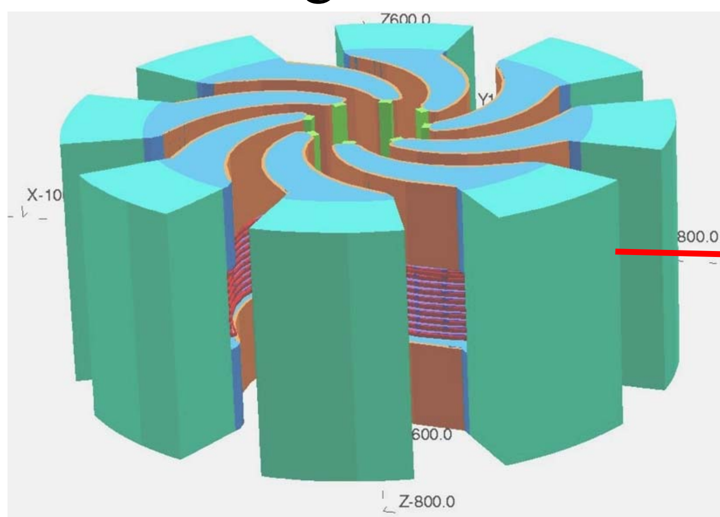
7-beam drive
1.8 MW_{th} , 600 MW_e

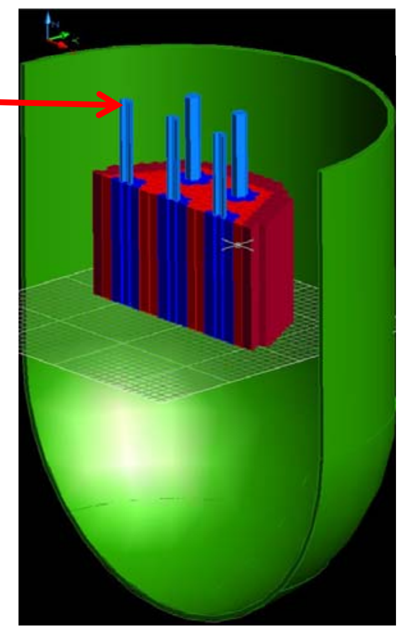


3-beam drive
750 MW_{th}, 250 MW_e

Conclusions

The PSI IC today produces 1.5 MW of continuous proton beam power with high reliability and very low beam loss.
New flux-coupled IC and cavity technologies and new neutronics make it possible to produce 15 MW of proton drive from seven 2 MW accelerators: the ‘Christmas tree lights’ solution to reliability.





We would like to collaborate with you in developing the design and integrating it into ADS for actinide-burning and power generation…