Accelerator-Driven Subcritical Fission

Green Nuclear Power for the New Millennium

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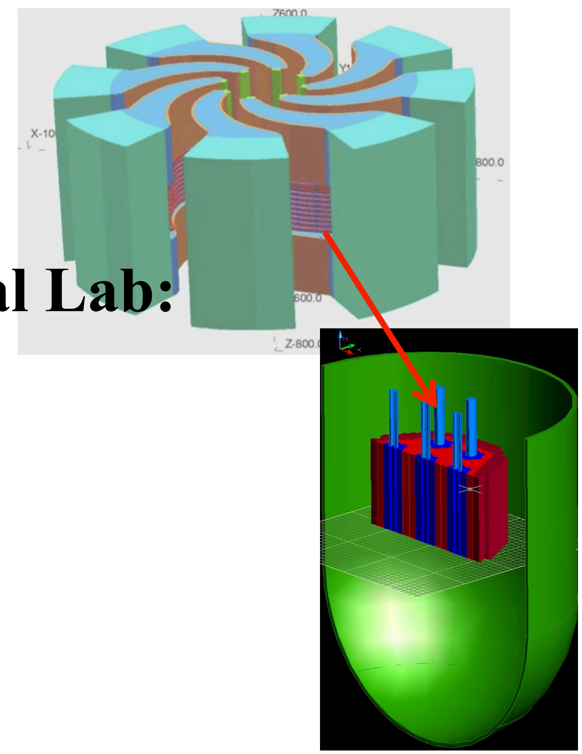

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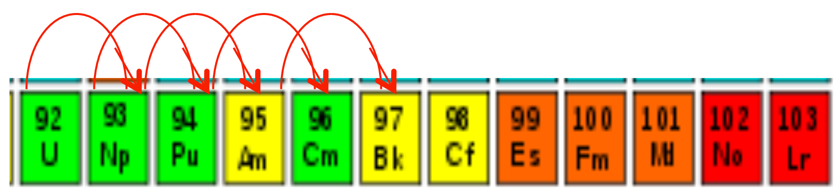
What are the aspects of nuclear power that make it ***not green***?

- Long-lived nuclear waste: thermal neutrons are captured on the nucleus ^{238}U, and breed it to the ***minor actinides***:



^{241}Am has a decay time of 30,000 years

Human civilization dates back only 8000 years.

Malta

?

-8000 yr TODAY 30,000 yr

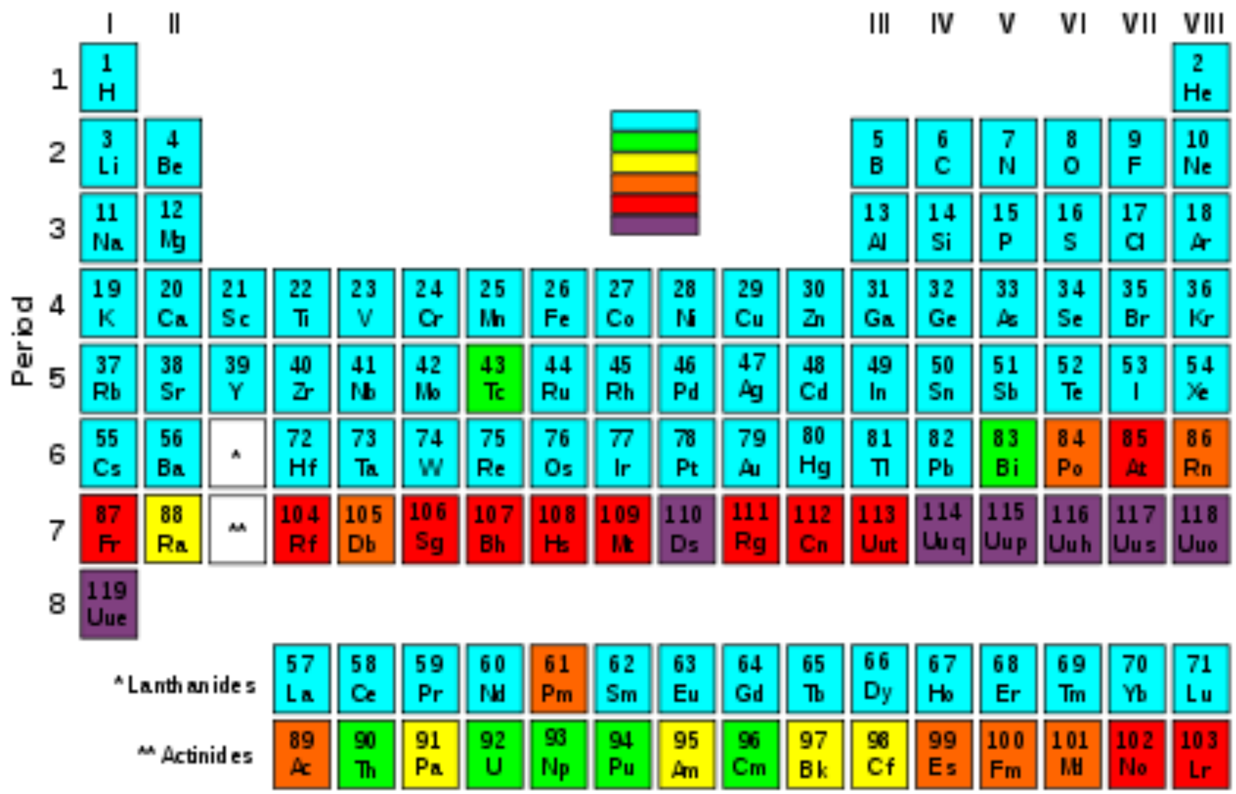
- Reactors based on fuel rods burn only ~5% of their uranium; the ***lanthanides*** among fission products capture neutrons, and the fuel is spent.

57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm

The Spent Nuclear Fuel must be removed from the reactor and stored indefinitely.

- If the core loses coolant, you can shut off fission, but you cannot turn off decay heat! The core continues to produce ~20% of its peak heat from decay for a day, then ~6% for the second day. The fuel pins are thermally isolated in the core. Without cooling they can melt down. Hot fuel cladding can dissociate water into hydrogen and then explode. http://www.youtube.com/watch?v=uM3FWIKxWDs

Fission, neutron capture, and beta decay feed into the middle and heavy parts of the periodic table



Stable elements

1 minute < T < 1 day

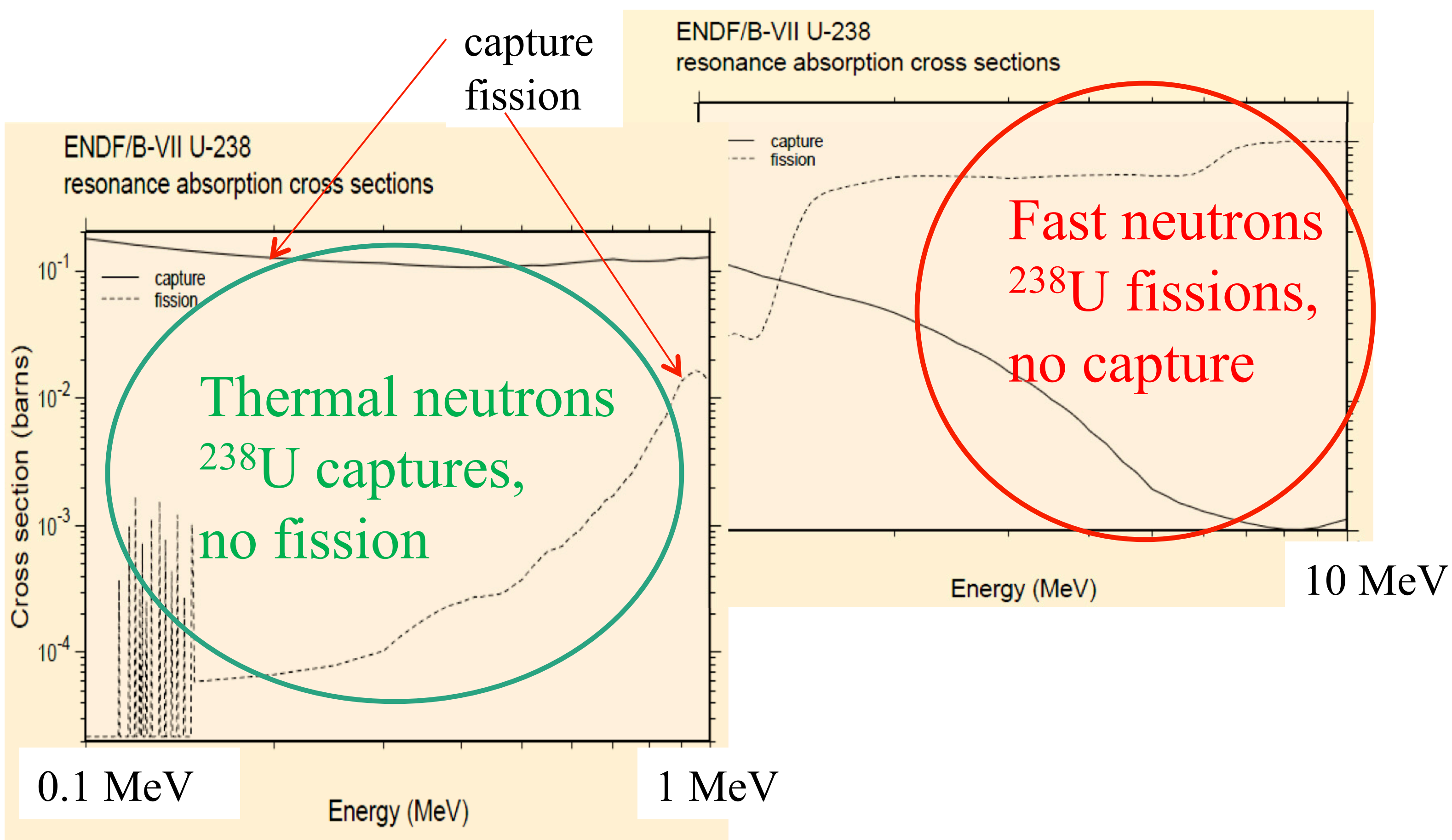
1 day < T < 100 years

800 < T < 34,000 years

T > 4 million years

Long-lived waste isotopes!

Thermal fission breeds actinides, Fast neutrons destroy them.

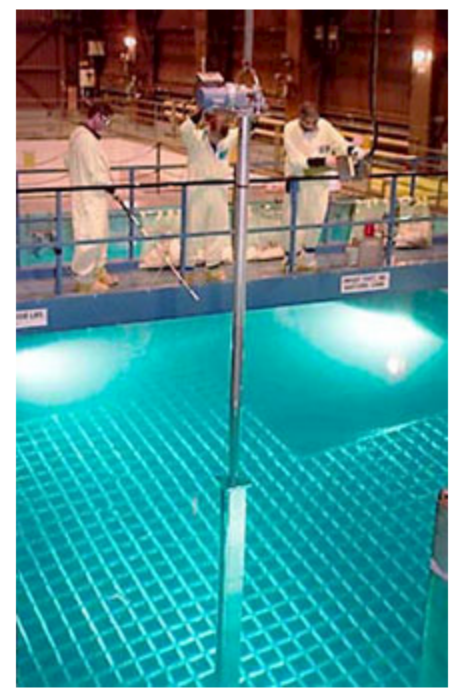


The lanthanides are produced as fission products. They eat neutrons…

The ***lanthanides*** are fission products. They have large probability to capture neutrons, and take the neutrons out of the balance for driving fission. As the reactor burns its fuel, the population of lanthanides increases, the flux of neutrons decreases, and finally the reactor stops.

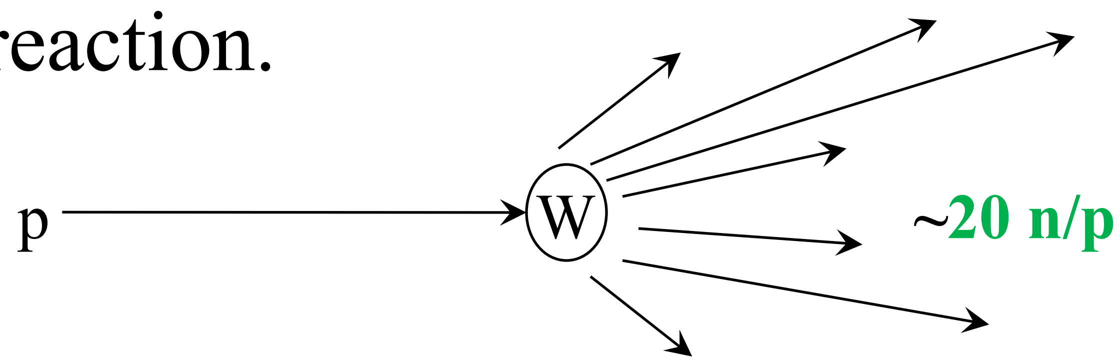
For the conventional pressurized water reactor, the fuel rods must be re-shuffled to balance lanthanide poisoning every 18 months; fission drops below critical after 5 years and the fuel must be replaced. But only 5% of its energy content has been extracted in fission!

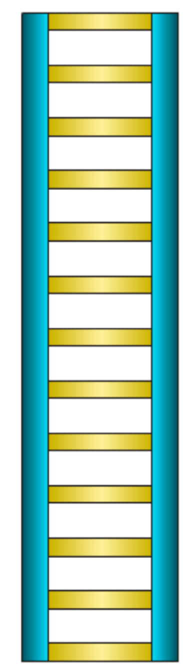
Spent nuclear fuel is removed from a reactor and stored indefinitely because so far we have nothing safe to do with the actinides…



Accelerator-driven subcritical fission

- Accelerate a beam of protons in an accelerator.
- Target the proton beam onto a stack of metal plates inside the fission core.
- ***Spallation***: each proton makes ~20 fast neutrons.
- These fast neutrons drive fission even when the fissile material in the core cannot sustain a critical reaction.



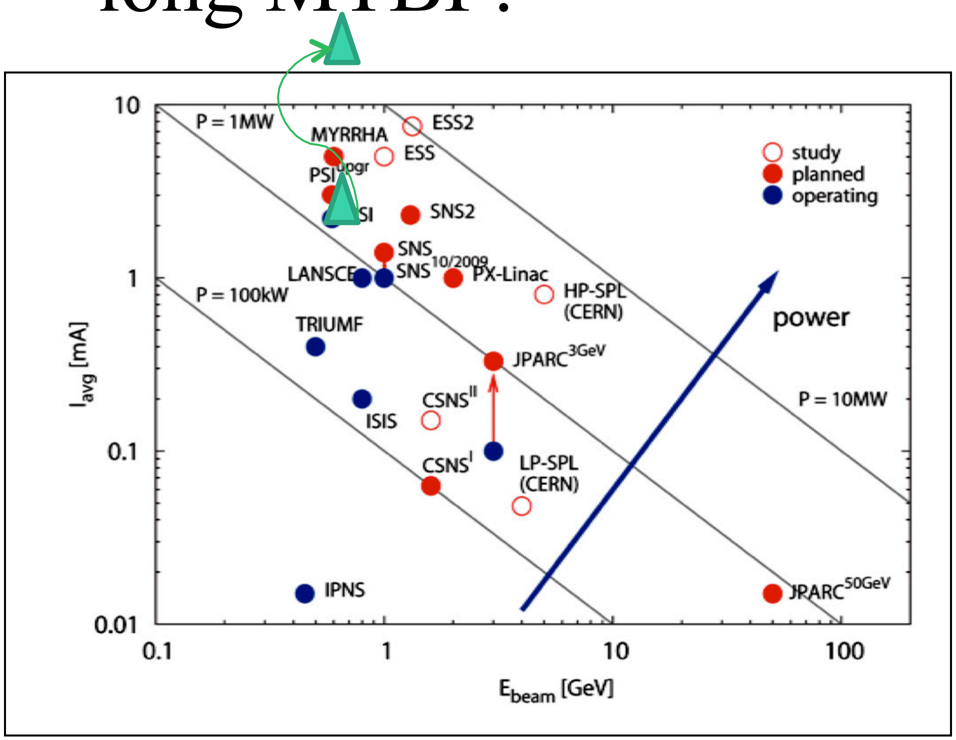


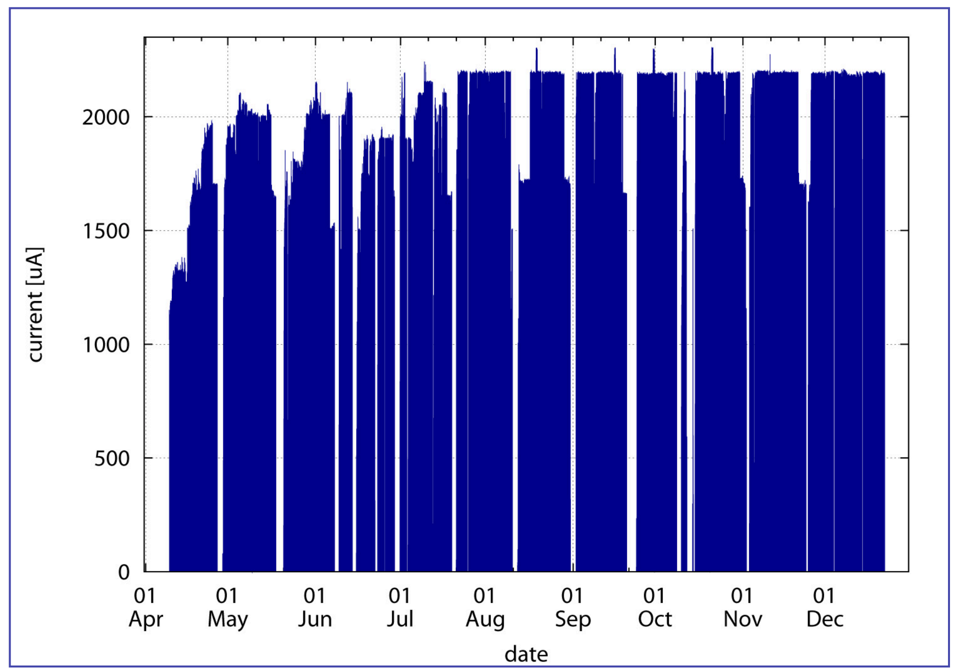
To make green nuclear fission power:

- Accelerator-driven subcritical fission
  - Fissile fuel in core is less than what is needed for a critical pile.
  - Proton accelerator drives spallation to provide ~3-4% of the fast neutrons needed to sustain fission.
    - Ernest Lawrence, 1948
- Molten-salt core
  - Fill a pot with a mixture of UCl_3, NaCl.
  - Operate it in temperature range 600-800 C.
  - Clean salt or NaK heat exchange circuit to transfer heat to CO_2 to turbine to make electric power.
    - Oak Ridge National Lab, 1950s – 1960s

Problem: A GW fission core needs a proton beam with 800 GeV energy, 15 MW power

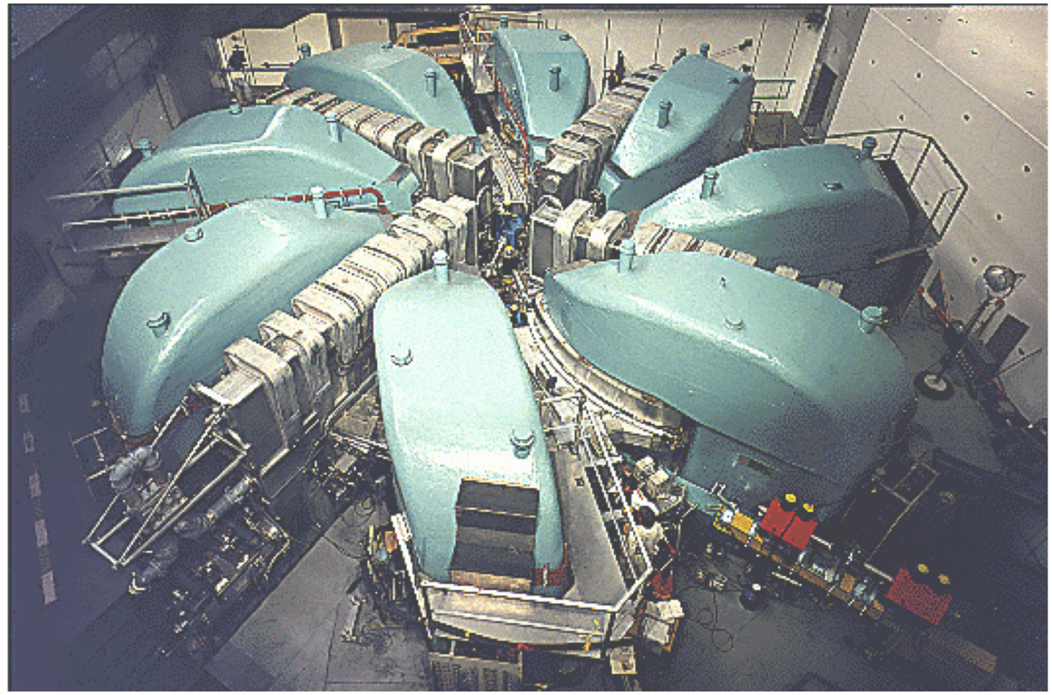
- No one has ever built an accelerator with this much beam power!
- Even worse– the accelerator must be a simple, reliable system that can be operated by a modest crew with long MTBF!





Solution: Design a conservative accelerator, and replicate it

invented by Ernest Lawrence, 1930 at Berkeley



PSI operates the highest power accelerator in the world: 2.3 mA @ 590 MeV

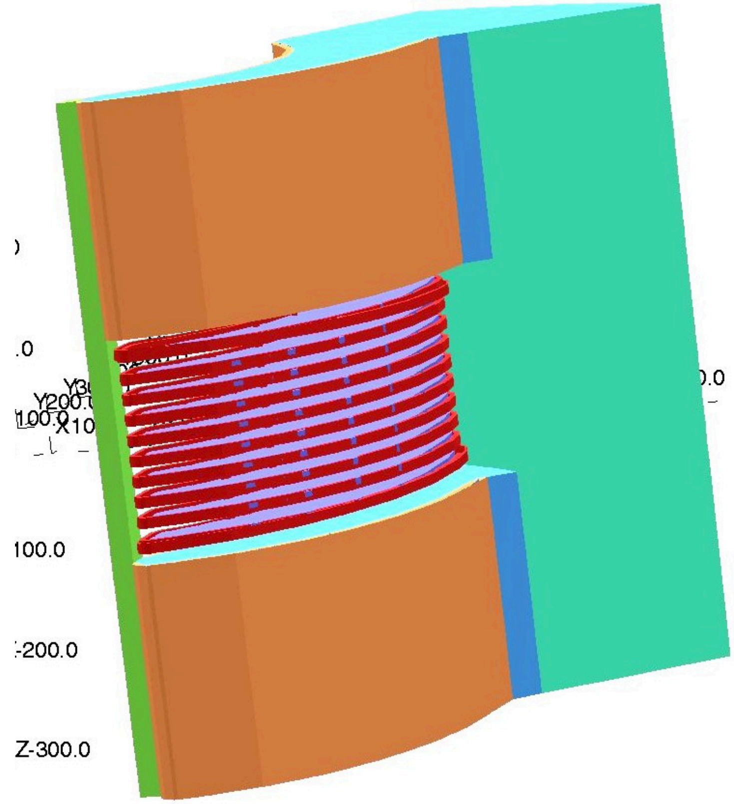
The **cyclotron** is among the oldest of particle accelerators, and it still holds the world record for the highest beam power – 1.3 MW.

Even teenagers can build one:

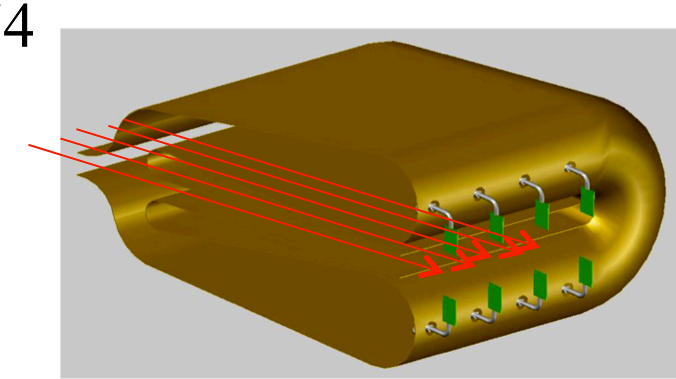
http://www.youtube.com/watch?v=d7tKxqwfZoE&feature=autoplay&list=ULTLdlKDP76b4&index=1&playnext=1

How to increase beam power to 15 MW?

Flux-coupled stack of IC’s:



590 MeV, 2 mA
PSI, Villigen, Switzerland
Operating since 1974



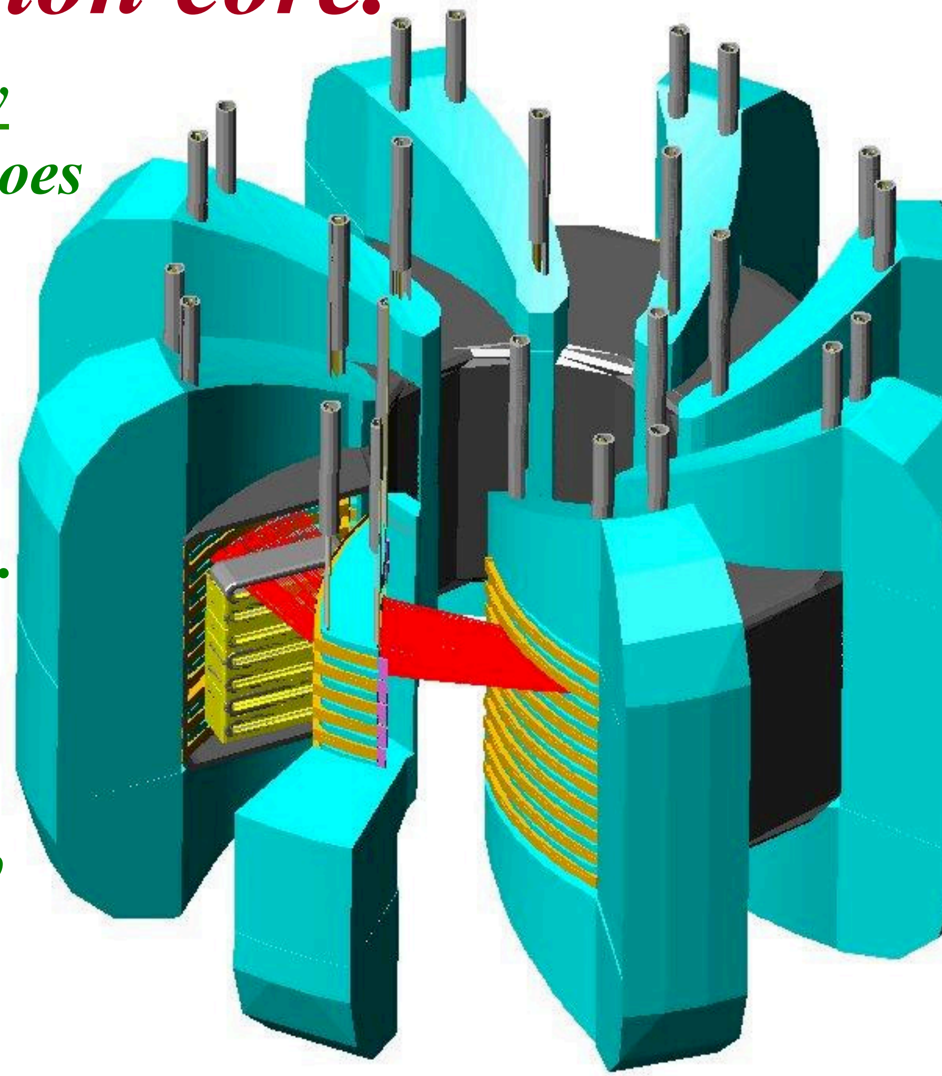
Folded-geometry
RF cavity with modular
power coupling

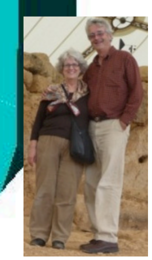
7-stack isochronous cyclotron: 7 x 2 MW = 14 MW proton beams drives a GW fission core.

Reliability through redundancy
Like Christmas lights: if one goes out, the rest stay lit.

Conservative performance:
The PSI isochronous cyclotron has operated reliably for 30 yrs.

Optimize core neutronics:
Bring the beams into the core in a pattern that couples best to drive fission in the fuel.





Beam Current and Reliability
1: separation of orbits

- Intensity is limited by losses, caused by space charge beam blow-up
- Losses ∝ **[turns]**^{3} ∝**[charge density (sector model)]** × **[accel. time]** / **[turn separation]** (W.Joho)
- **Upgrade through fast acceleration (higher voltage)**
- new components: **resonators** - 4 in Ring, 2 in Injector;
- **harmonic bunchers**: 3'rd harmonic for Injector; 10'th harmonic for Ring

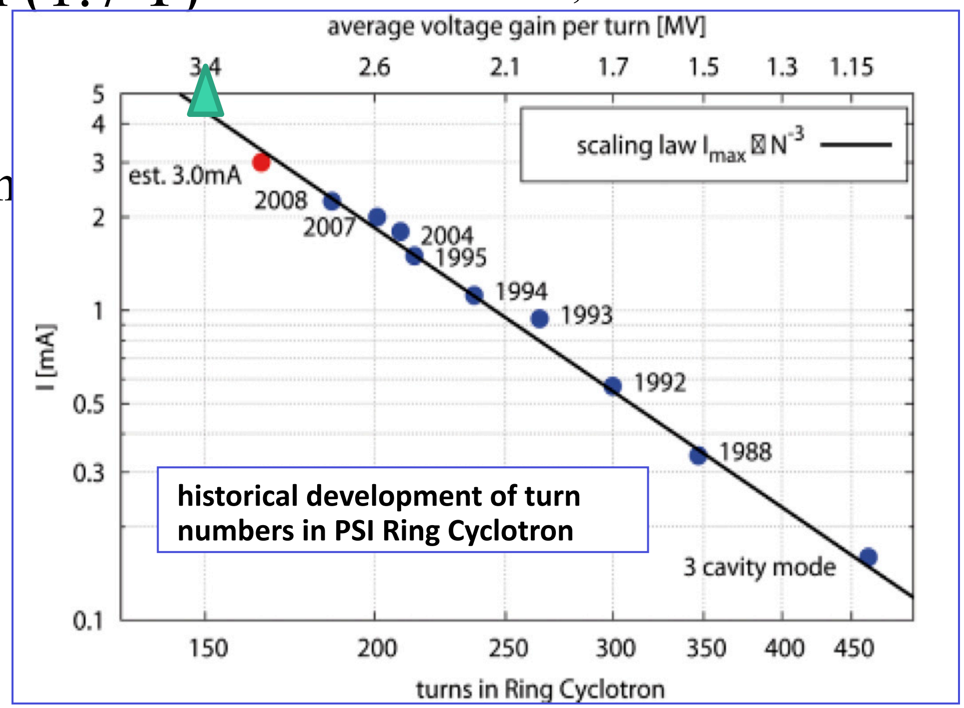
$I \propto N^{-3}$

Maximum volts/turn of RF (3.5 MV/turn)

Magnetic field below iron saturation (1.7 T)

- ➢Increases separation of orbits at injection
  - ○(space charge)
- ➢Increases separation of orbits at extraction
  - ○(losses on septum)
- ➢Reduces charge in ring for given current

Seidel, TC ADS 2010

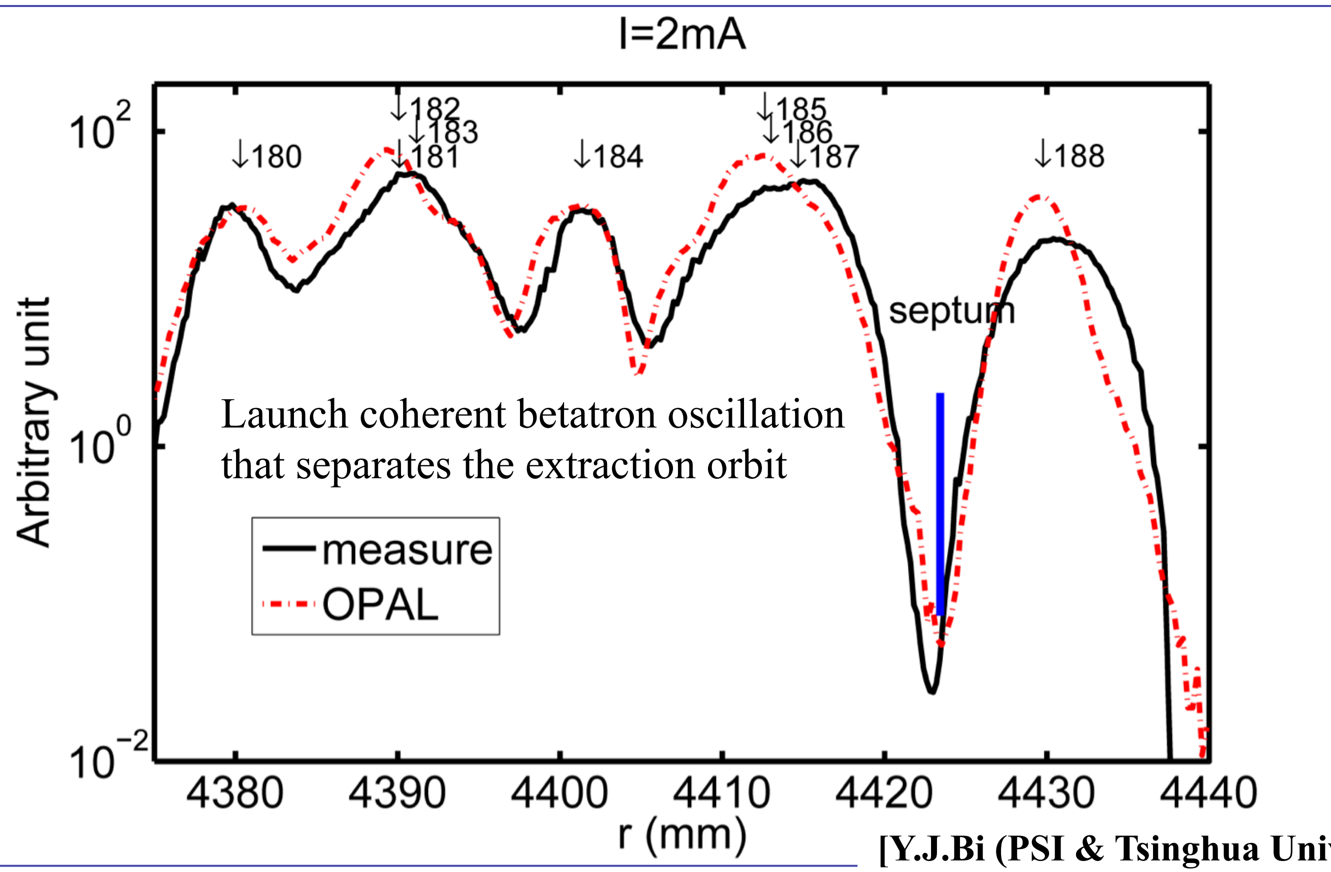


150 MeV → 800 MeV

170 turns → 3 mA

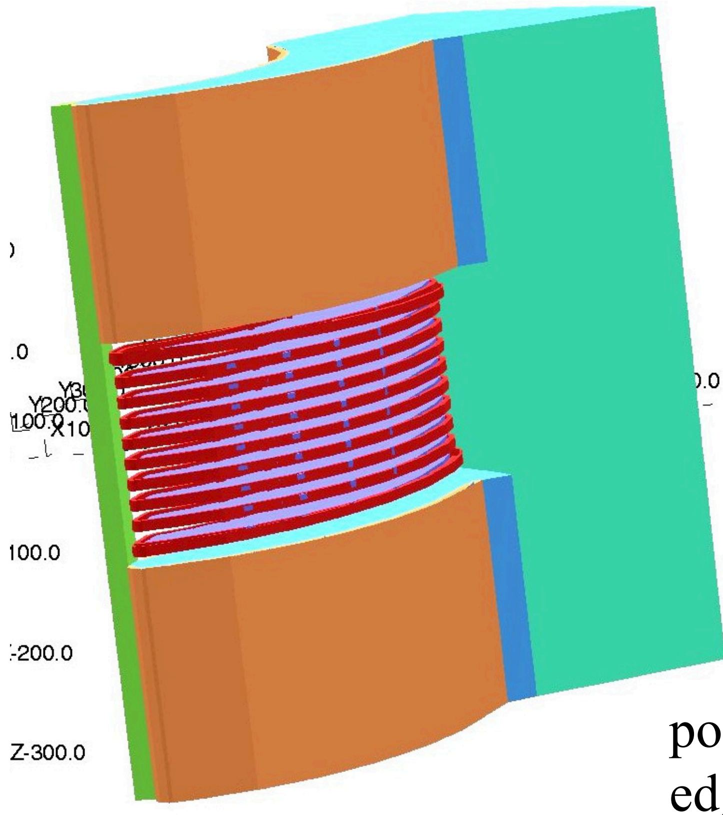
Losses are dominantly at extraction

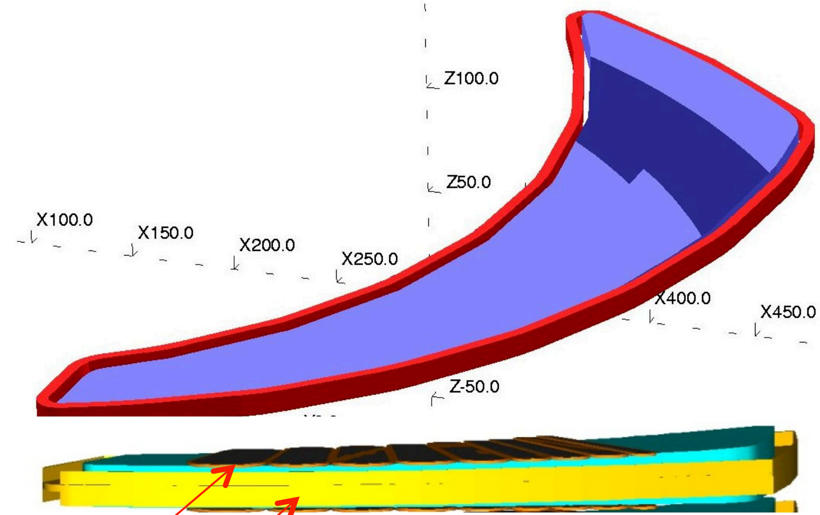
PSI:



[Y.J.Bi (PSI & Tsinghua Univ.), A. Adelmann]

2: Flux-coupled stack of IC's





Flux plate = NbTi superconducting coil, contoured steel plate

pole face windings correct *f*(r)

edge shielding shapes fringe, shields for SRF cavities

Each pair of flux plates creates an IC.

Separate injection, extraction, RF acceleration on each IC.

Accelerator physics is the same as PSI.

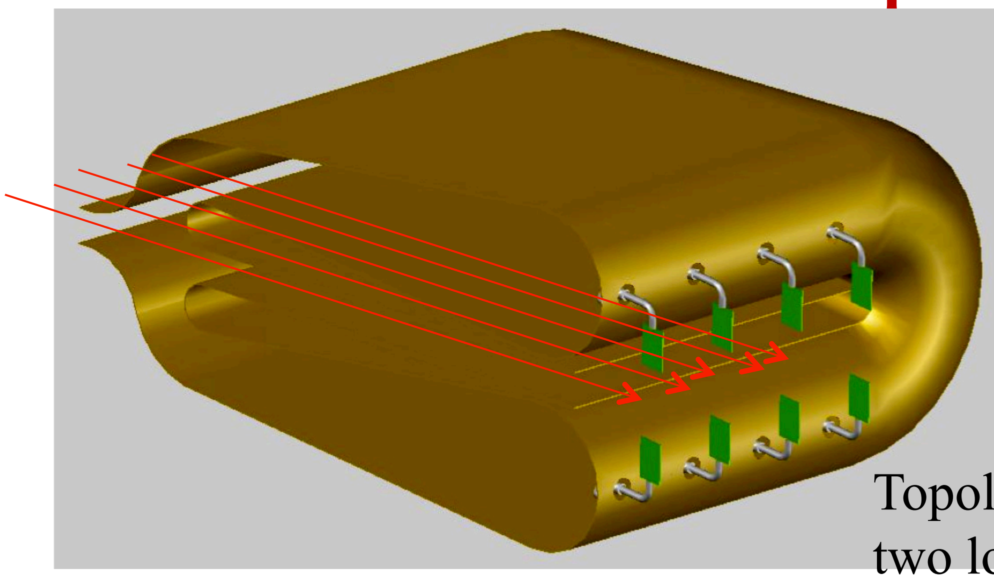
Reliability through redundancy: if one goes out, the rest stay lit.

Challenge: how to package 50 MHz cavity into each deck of a stack?

PSI RF cavity:

Learn from PSI: huge vertical dimension –impossible to stack
power coupled at outer end bottom
drives longitudinal modes as well as accelerating mode.
lights plasmas around ring – breakdown in septa

Solution #1: Folded geometry, distributed coupling in Cu cavity



Topological deformation of PSI cavity: fold the two lobes into horizontal plane – *1 m height*

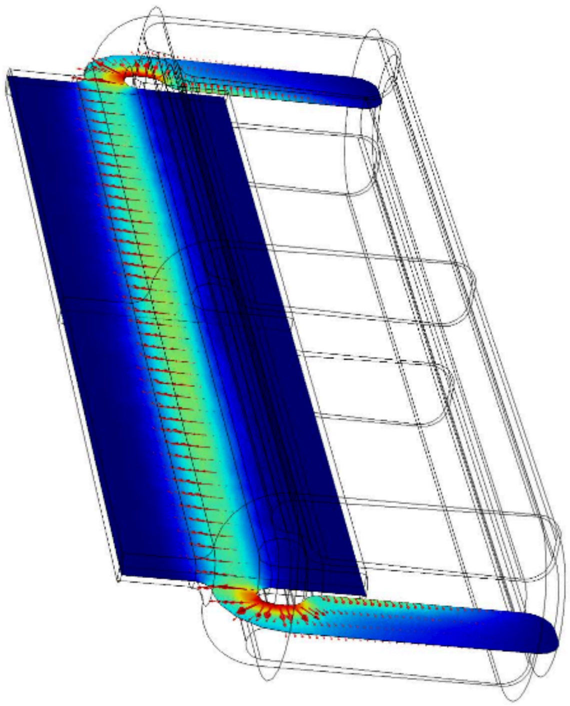
Install in alternate sectors – *0.5 m IC spacing*

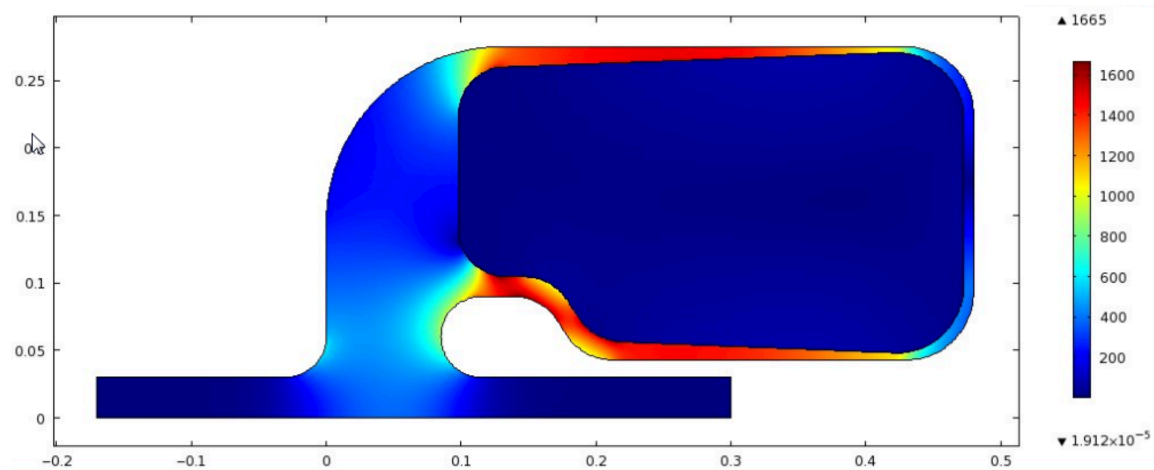
Wrap cavity around at inner, outer ends
– *no coupling to longitudinal modes*

Loop-couple RF at far end of lobes
– *distributed drive*

Drive each loop using a solid state power amp
– *70% efficiency*
– *match drive to beam load*

Solution #2: dielectric-loaded SRF





Folded geometry, U-bend on ends as with #1
Nb cavity, rutile dielectric to reduce dimension
Losses predominantly in rutile

Minimum δ at 80 K – support 80 K dielectric within 4 K cavity – a challenge…
Bottom line: we will use #1, do R&D on #2.

Beam dynamics in the IC

Maximum current that can be transported with low loss is intimately tied to beam dynamics during acceleration.

Horizontal betatron and longitudinal phase space are strongly coupled in a cyclotron: strong bending, weak focusing, distributed RF with large energy gain per turn.

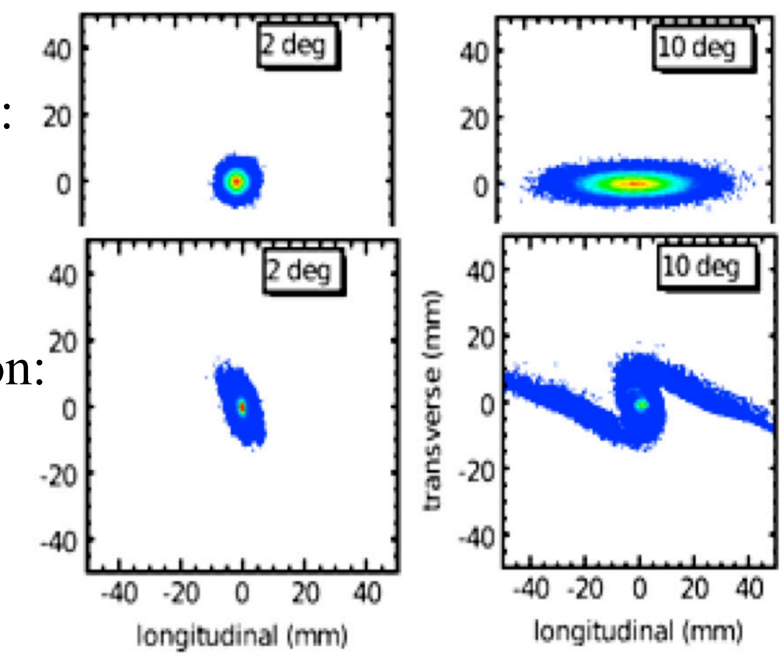
A sphere in rest-frame phase space is self-preserving in a cyclotron.

A cigar filaments and dilutes in phase space:

PSI transfers bunches from an injector cyclotron to the IC through a 70 m transfer line.
Each bunch leaves the injector cyclotron as a sphere, arrives at the IC as a cigar…

Injection:

Extraction:



The lesson: locate the injector cyclotron stack right next to the IC stack, ballistic transfer.

J.J. Yang, *et al.*, 'Beam dynamics in high intensity cyclotrons', PRST-A&B 13, 064201, 2010.

Delivering multiple proton beams onto multiple spallation targets is the *optimum* way to drive ADS

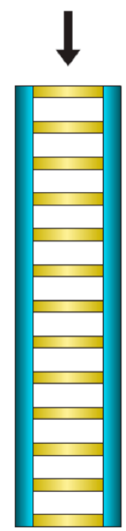
Suppose that you could devise an accelerator that would deliver 15 MW of protons to a spallation target.

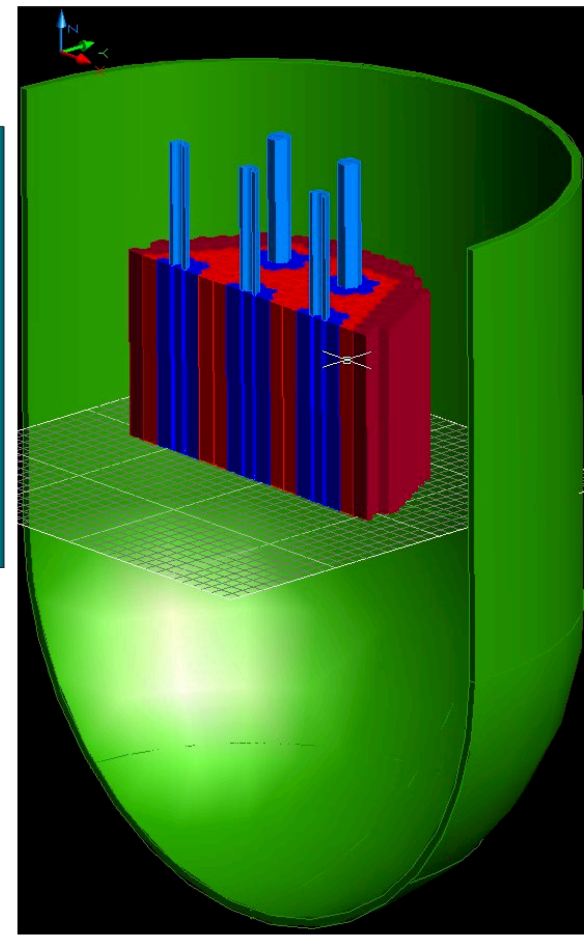
No one knows how to make a target that would survive with 15 MW beam!

The neutronics of a fission core has *normal modes* similar to those of an RF cavity.

Driving a core by spallation is similar to coupling to an rf cavity.

Driving is most efficient with a symmetric array of beams at an intermediate radius





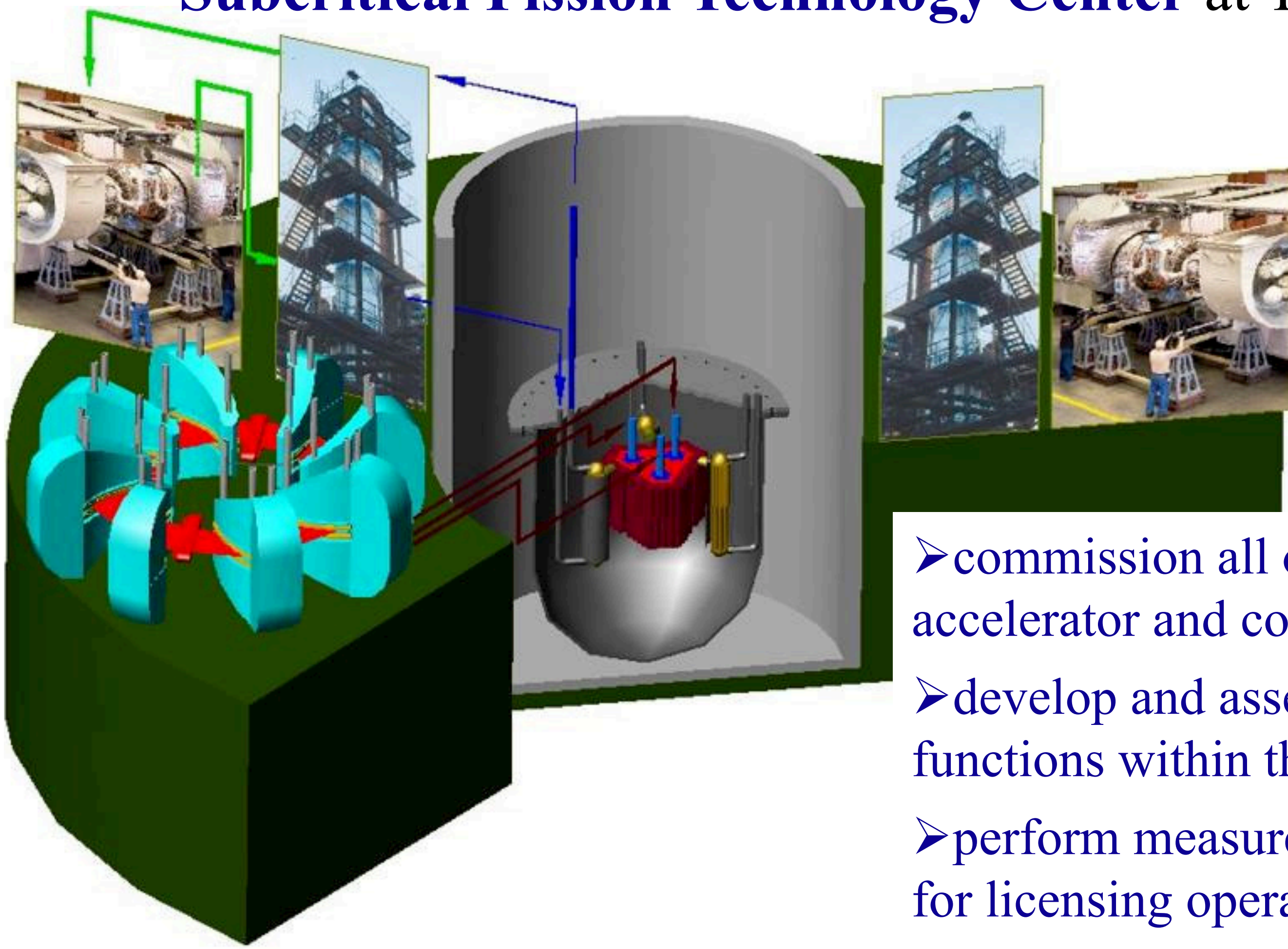
Fissions/proton is ~30% more efficient than with a single coaxial drive!

Conclusions

- The PSI isochronous cyclotron provides a credible, cost-minimum method to deliver high-power CW proton beam for ADS.
- We have extended the PSI design to 800 MeV and devised a flux-coupled stack so that N IC's can be staged on a common footprint.
- We are developing a folded-geometry RF cavity that is compatible with the stacking and solves several problems in the present RF.
- We expect to achieve higher current/IC by ballistic injection of bunches with spherical phase space.
- The delivery of multiple ~2 MW beams into an ADS core uses known targetry, provides optimum coupling to core neutronics.

Plans for development

A collaboration of Texas A&M, BNL, INL plans to develop the ADSMS technology, and build a first single-beam unit for a **Subcritical Fission Technology Center** at Texas A&M:



- commission all of the systems of the accelerator and core,
- develop and assess methods to monitor functions within the core,
- perform measurements and studies needed for licensing operation for power generation
- Operator training