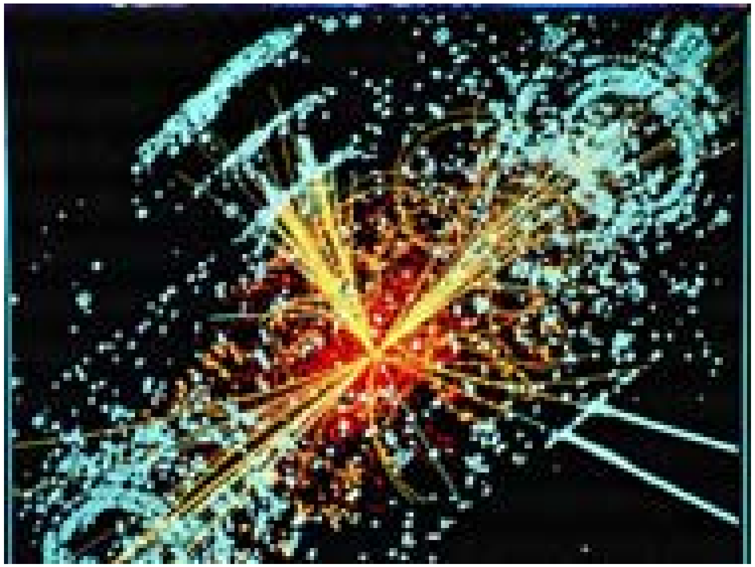
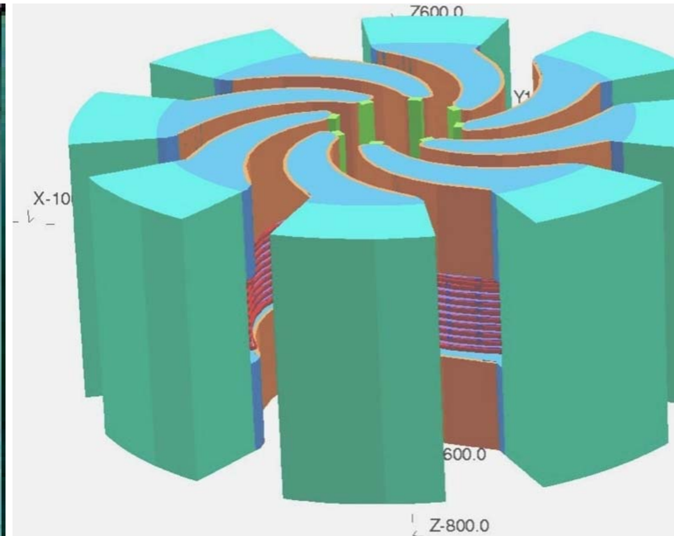
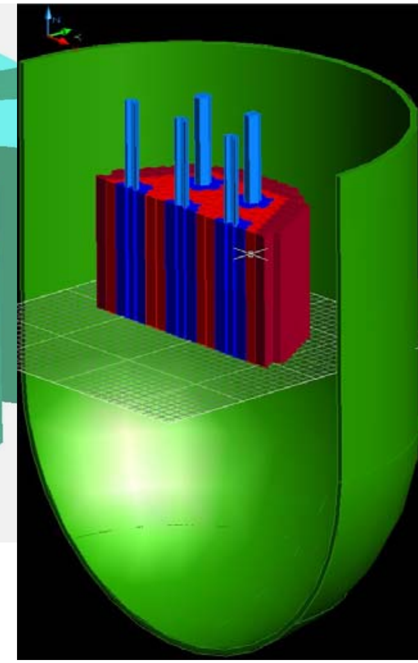
Amazing Accelerators

Two examples of how new physics and technology of accelerators can make the impossible happen



Petavac: 100 TeV hadron collider in the SSC tunnel





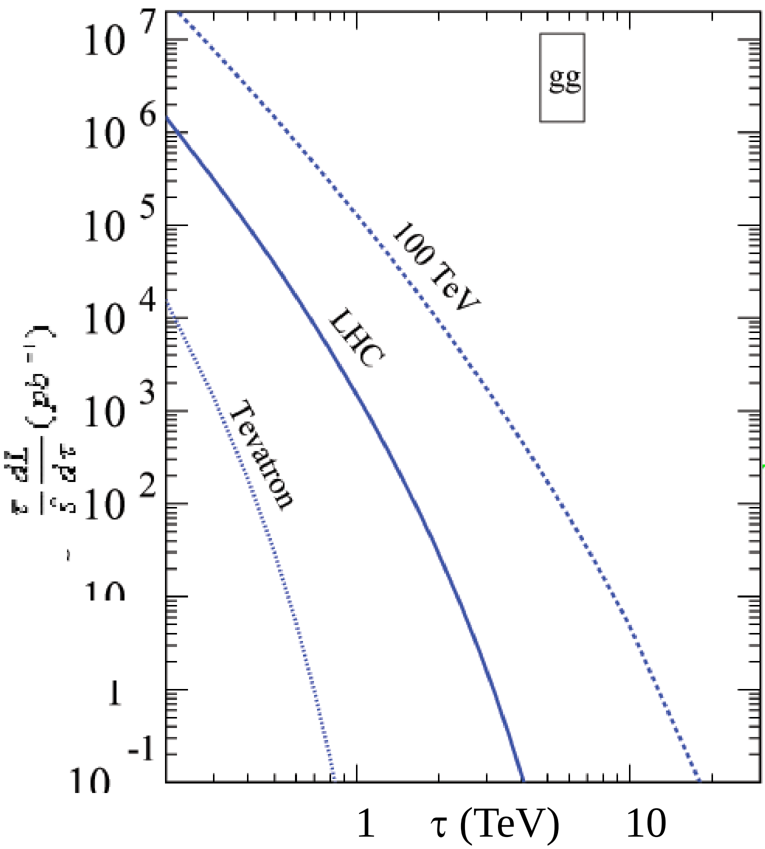
Accelerator-driven thorium-cycle fission power

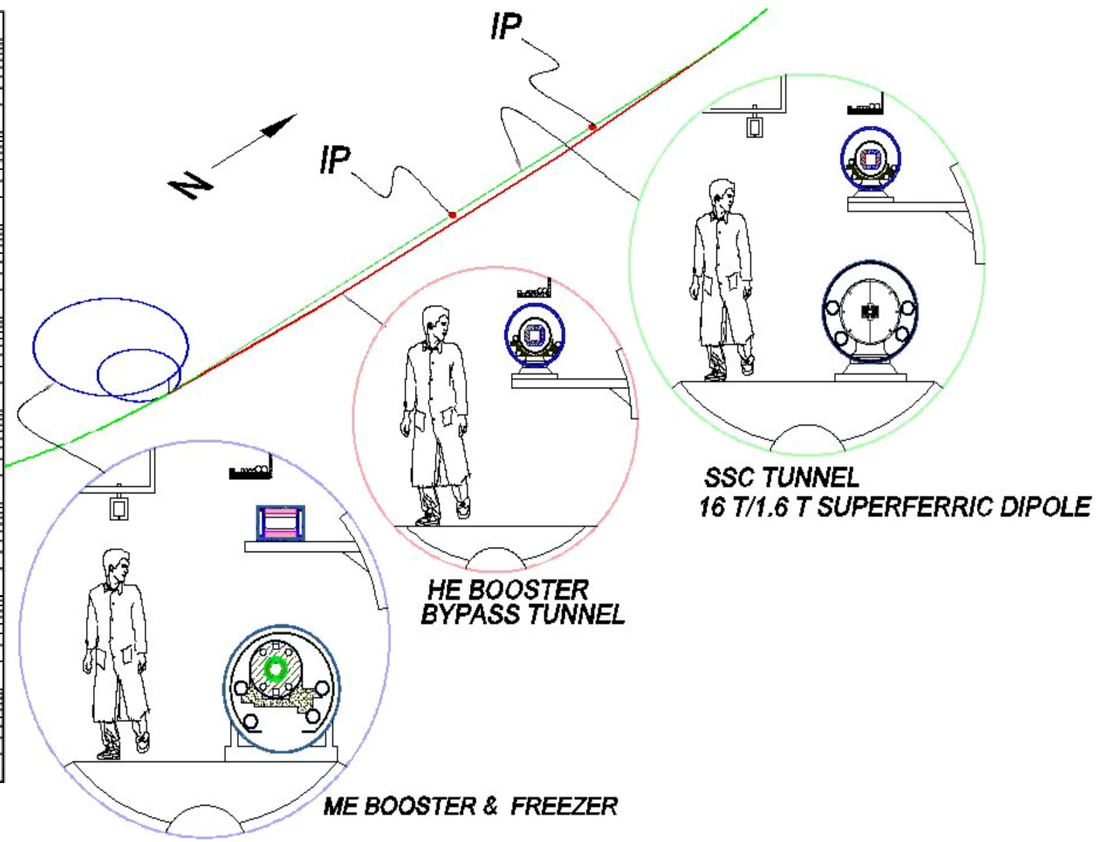
Peter McIntyre

Texas A&M University

Petavac

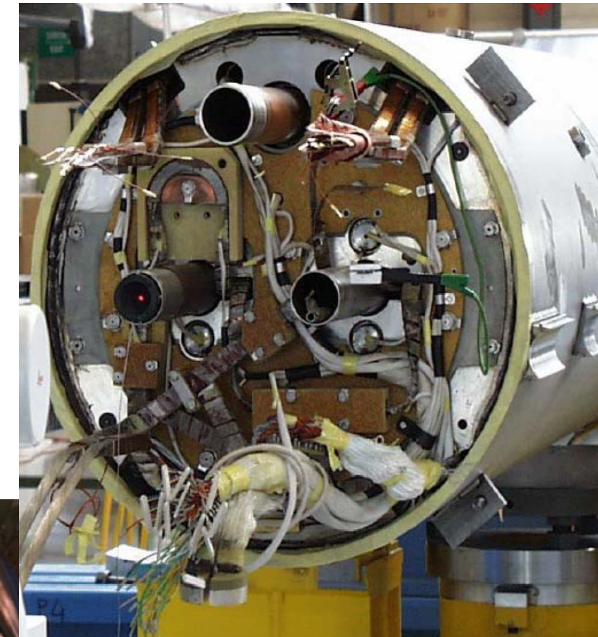
Boson-Boson Collisions at 100 TeV

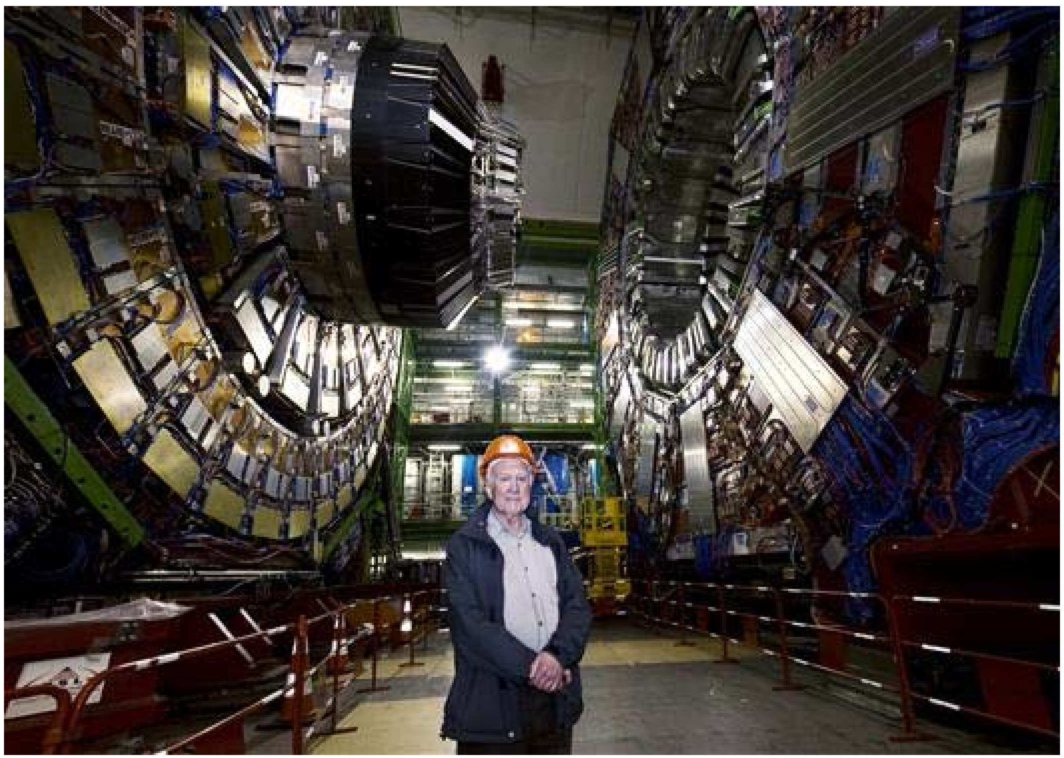




LHC will soon begin its physics program

14 TeV proton-proton collisions
design luminosity 10^{34} cm^{-2}s^{-1} :
8 million $W^{\pm}$, 1 million Z, 3000 tops per day
8 T NbTi dipoles @ superfluid temperature



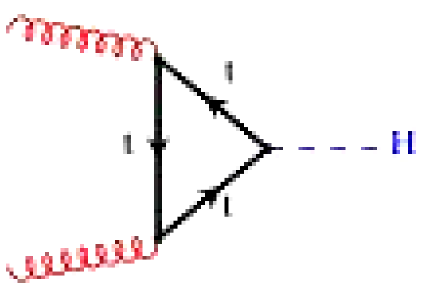


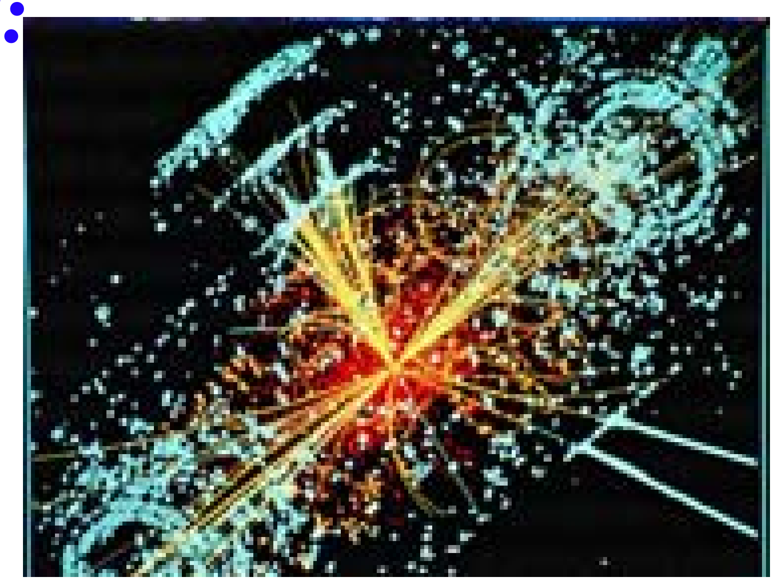
Peter Higgs visits CMS, hoping it will discover his particle.

Discovery in Physics

Paradox → New Idea → Discovery

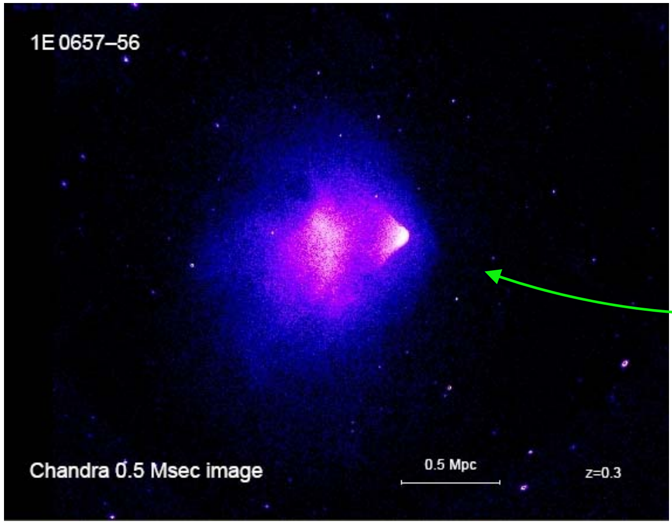
- ***Paradox:*** *The weak interactions become strong!*
  - How does the electroweak interaction break spontaneously into electromagnetism and weak interaction?
- ***New idea:*** *Higgs boson*
  - A new scalar field that couples to particles proportional to their mass, generates electroweak symmetry breaking.
- ***Hope for discovery at LHC:***

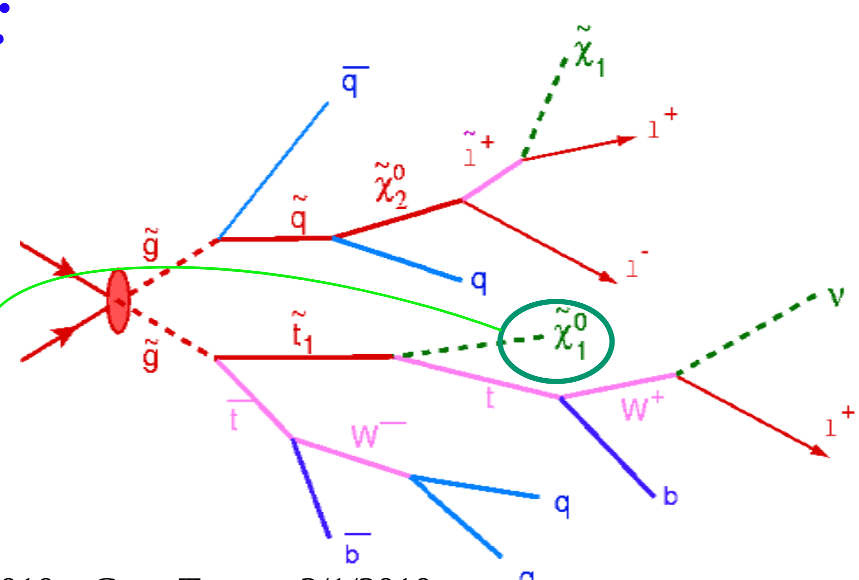




Caution: we don't know the mass scale!

- ***Puzzle**: Why are bosons and fermions so different?*
  - Could the same symmetry-breaking picture be extended to break the strong force at much higher energy? Could the three interactions be unified at a single higher energy scale for Einstein's dream?
- ***New idea**: Supersymmetry/supergravity*
  - A new gauge field couples the fermions and bosons to superpartners under a
- ***Hope for discovery at LHC:***

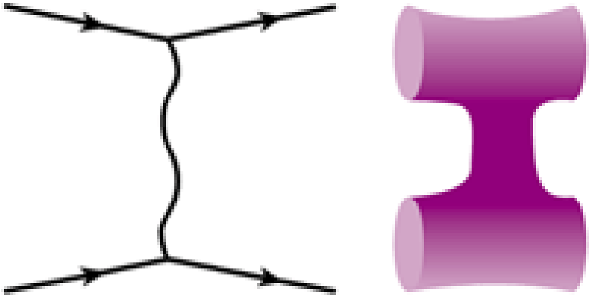


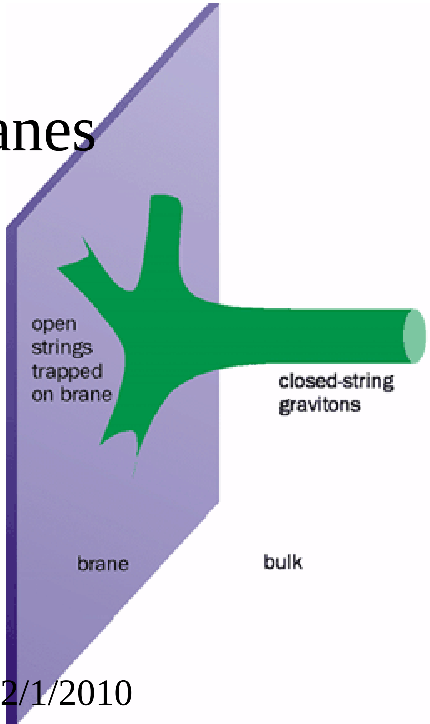


The Higgs boson and the spectrum of sparticles should be discovered at LHC, unless…

The flood of precise data from astrophysics suggests that the gauge fields of nature may be more complex than the picture of the Standard Model + Higgs + Supergravity

Example: large extra dimensions from strings and branes





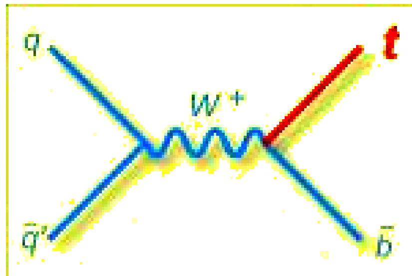
We need to seek ways to extend the reach for discovery to the highest feasible mass scales.

Hadron colliders are the only tools that can directly discover gauge particles beyond TeV

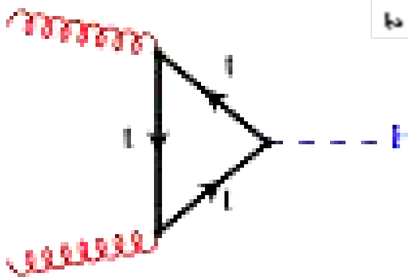
- Predicting the energy for discovery is perilous.
- Example: for a decade after discovery of the b quark, we ‘knew’ there should be a companion t quark. But we couldn’t predict its mass. Predictions over that decade grew (with the limits) 20 →40 →80 →120 GeV
- 4 e^+e^- colliders were built with top discovery as a goal.
- Finally top was discovered at Tevatron – 175 GeV!
- In the search for Higgs and SUSY, will history repeat?

Mass reach for new physics

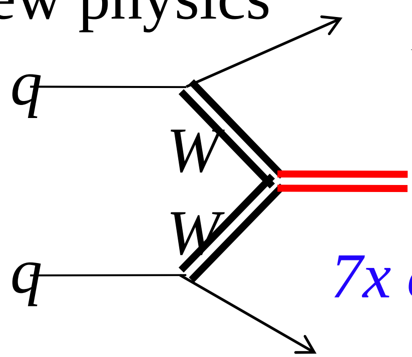
Tevatron accesses new physics through $q\bar{q}$ annihilation.

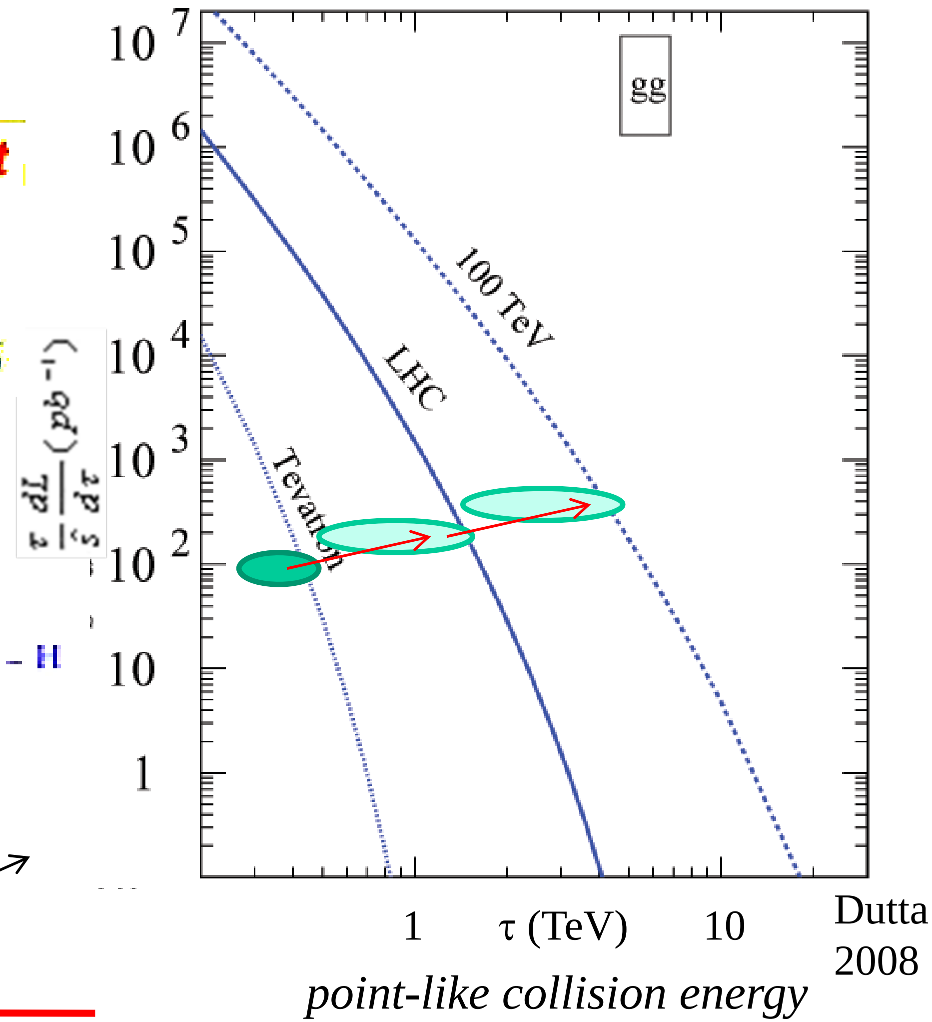


LHC will access new physics through gluon fusion:



Petavac can access new physics through boson fusion





7x collision energy → 3x mass reach

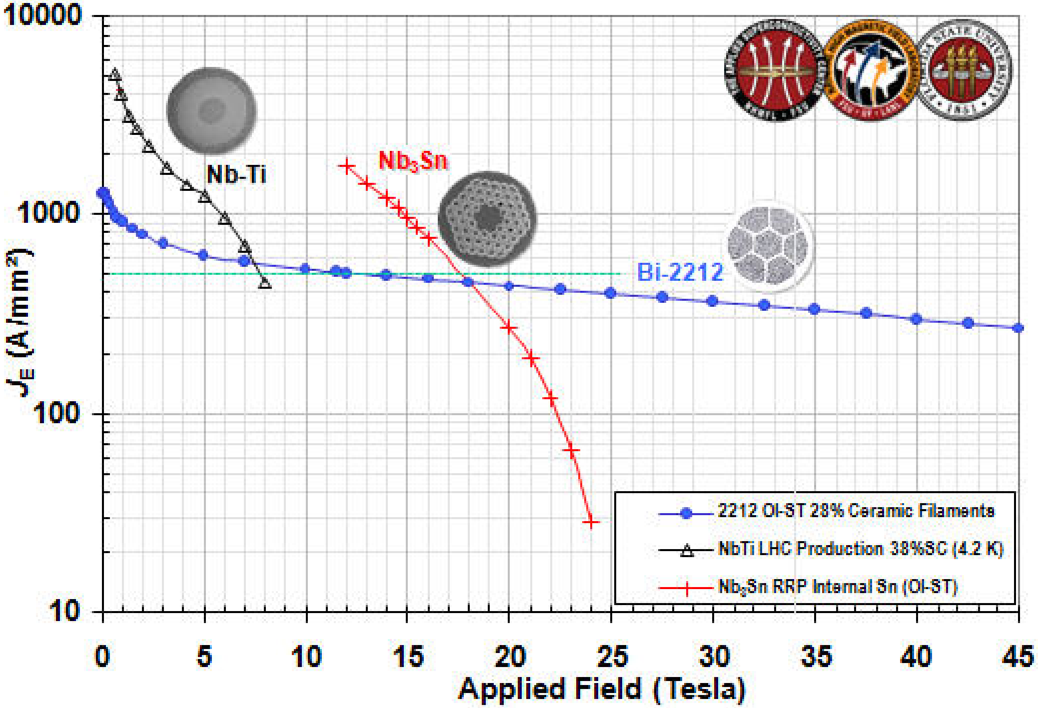
A new vision for the future of high-energy discovery beyond LHC

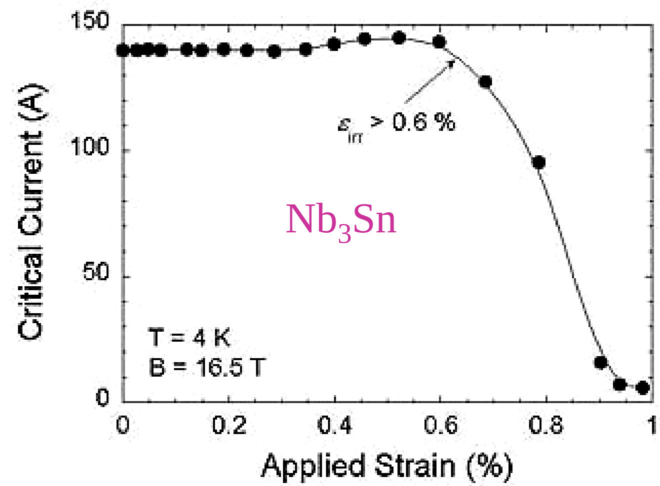
- Hadron colliding beams in the SSC tunnel
- 16 T dipole rings provide 100 TeV collision energy
- Superferric injector located in the same tunnel

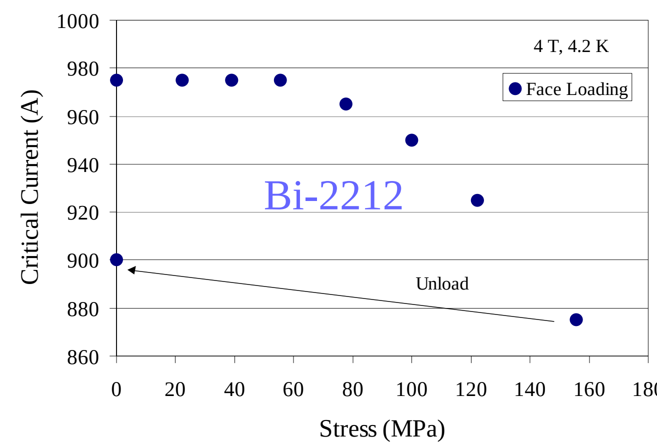
Three things make this possible to conceive:

- Recent success maturing Nb_3Sn dipole technology
- Commercialization of Nb_3Sn wire for ITER
- 84 km SSC tunnel is 70% complete, waits for use

We now have a new superconductor for 16 T: Nb_3Sn

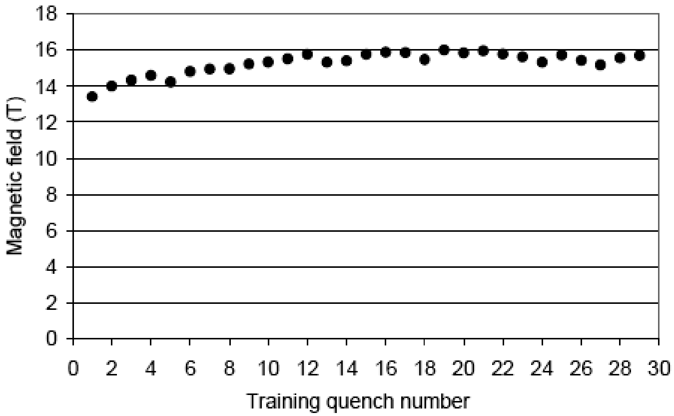




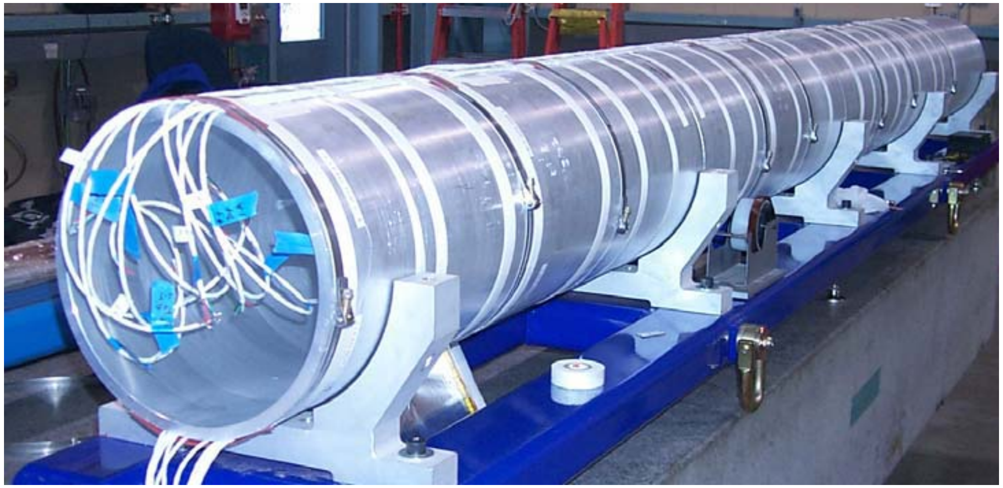


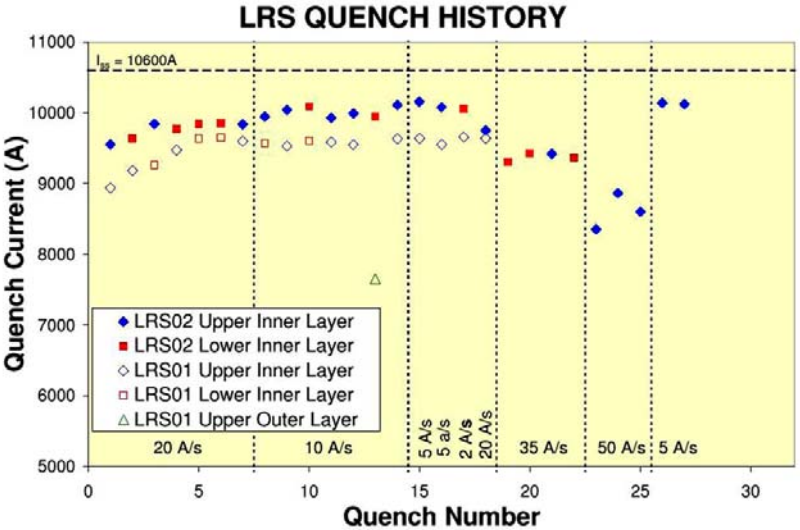
Cost today:	NbTi	$150/kg
	Nb_3Sn	$1,000/kg
	Bi-2212	$2,000/kg

- 16 Tesla dipoles have been built and tested.
  - LBNL HD1



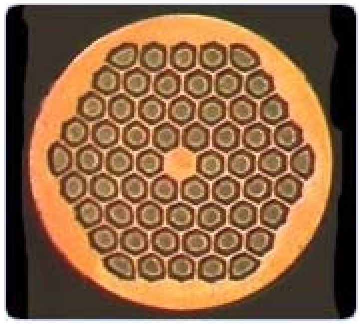
- 4m-long racetrack coils using Nb_3Sn have been built and tested.
  - LARP LRS



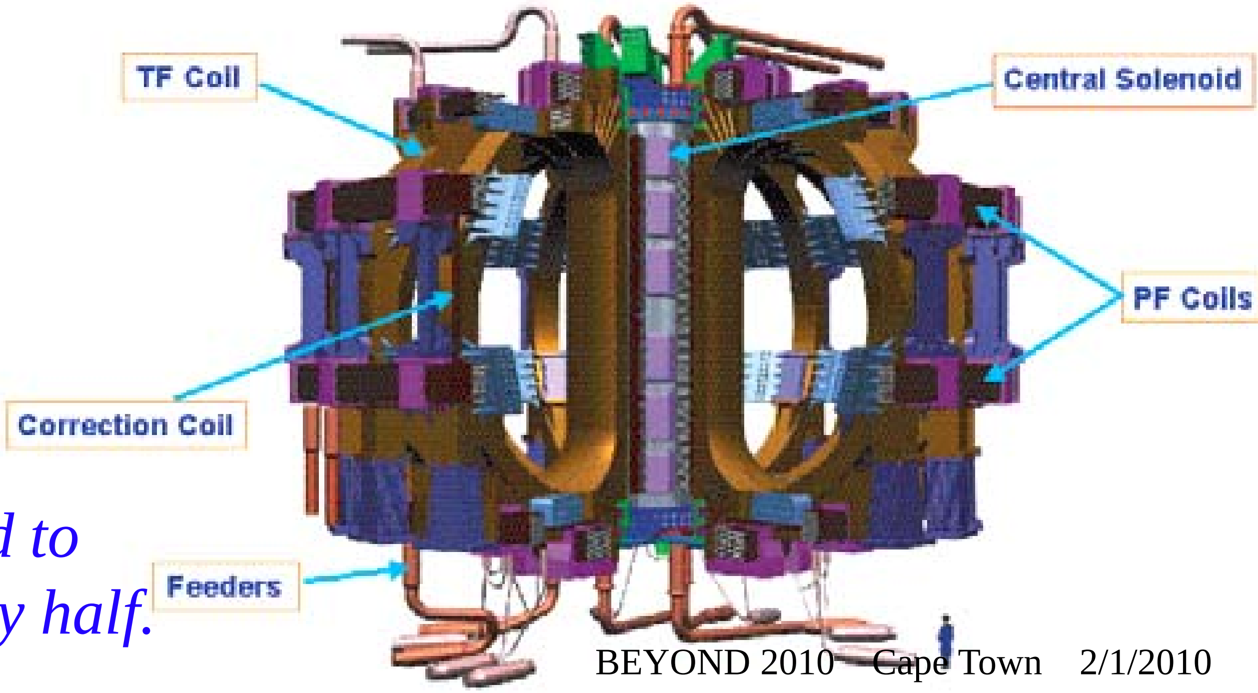


➢Nb_3Sn superconducting wire with the necessary performance is developed and commercialized.

➢3,000 A/mm^2 @ 12 T, 4.2 K in the superconductor

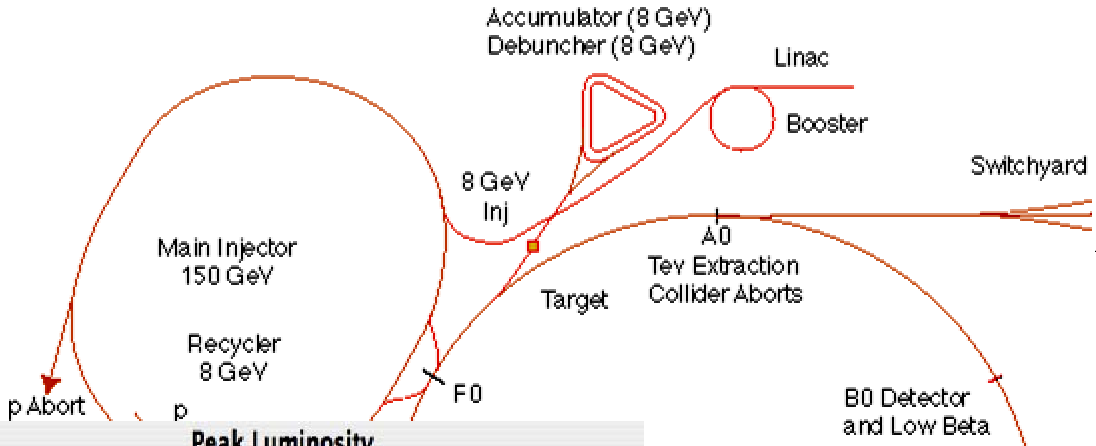


➢ITER will use *400 tons* of high-performance Nb_3Sn wire; it will drive the production capacity to what would be needed for Petavac.

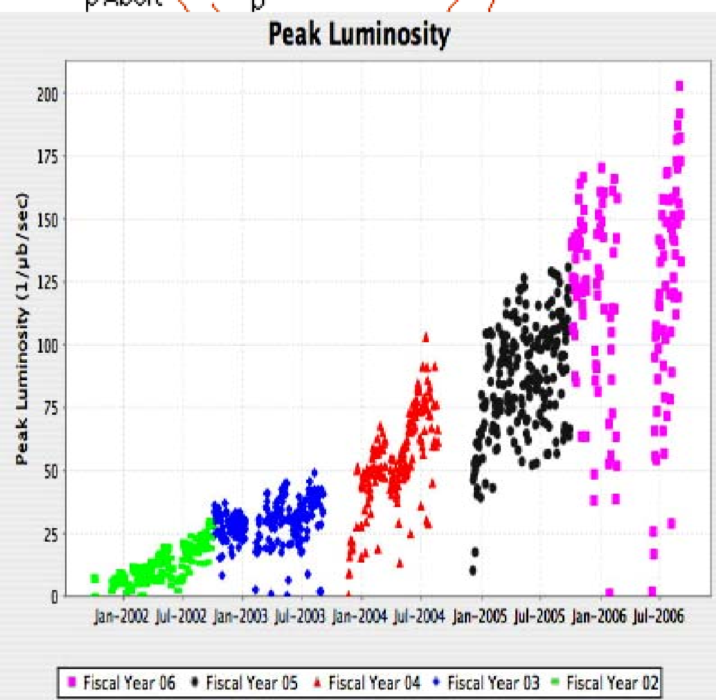


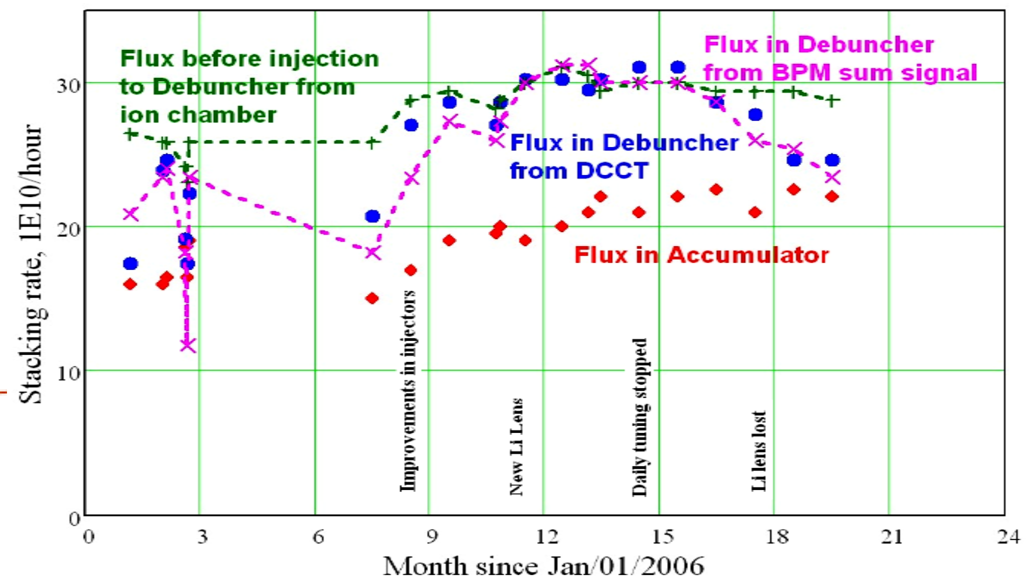
Transition to volume manufacture is predicted to drop Nb_3Sn wire price by half.

Fermilab has matured antiproton source technology and electron cooling



- ➢$3\text{x}10^{11}\,\overline{p}$ /hr stacked, capacity for 10x more from target (adjacent Δp windows)
- ➢E-cooling in recycler has capacity for $\sim 10^{14}\,\overline{p}$





Lebedev 2008

New magnet technology makes it possible to develop 16 T collider dipoles

- **Block coil geometry**

  Arrange coil in rectangular blocks so that forces can be controlled.

- **Stress management**

  Intercept stress within the coil so that it cannot accumulate.

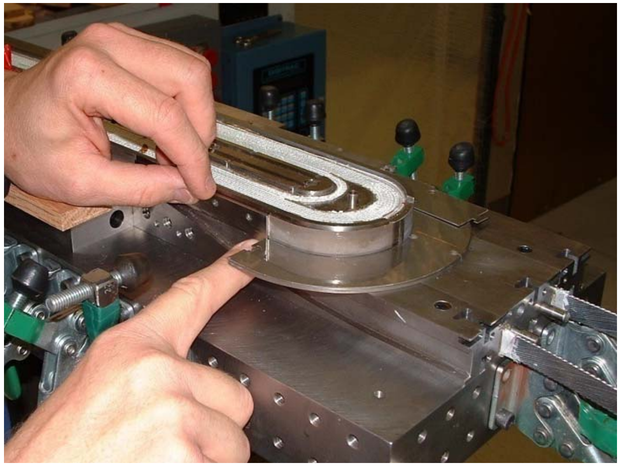
- **Optimized conductor**

  Separate the copper for quench protection into pure-Cu strands.

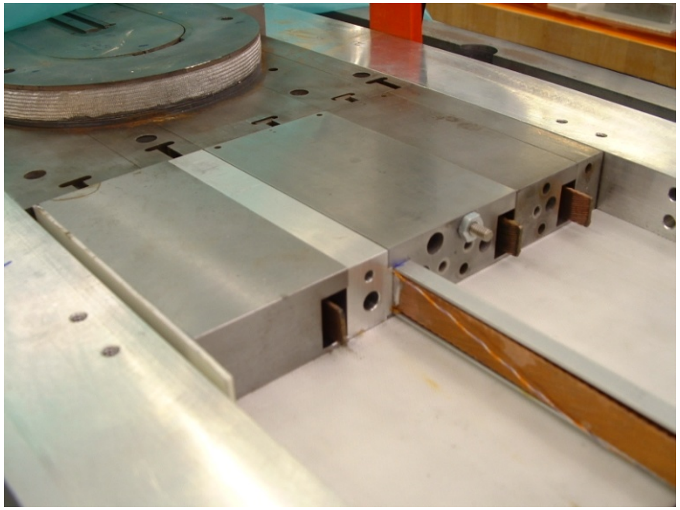
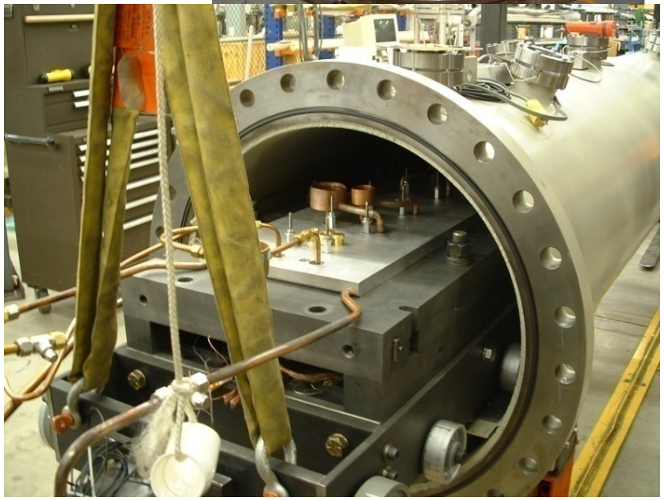
- **Suppress persistent-current multipoles**

  Use close-coupled steel boundary to naturally suppress p.c. multipoles.

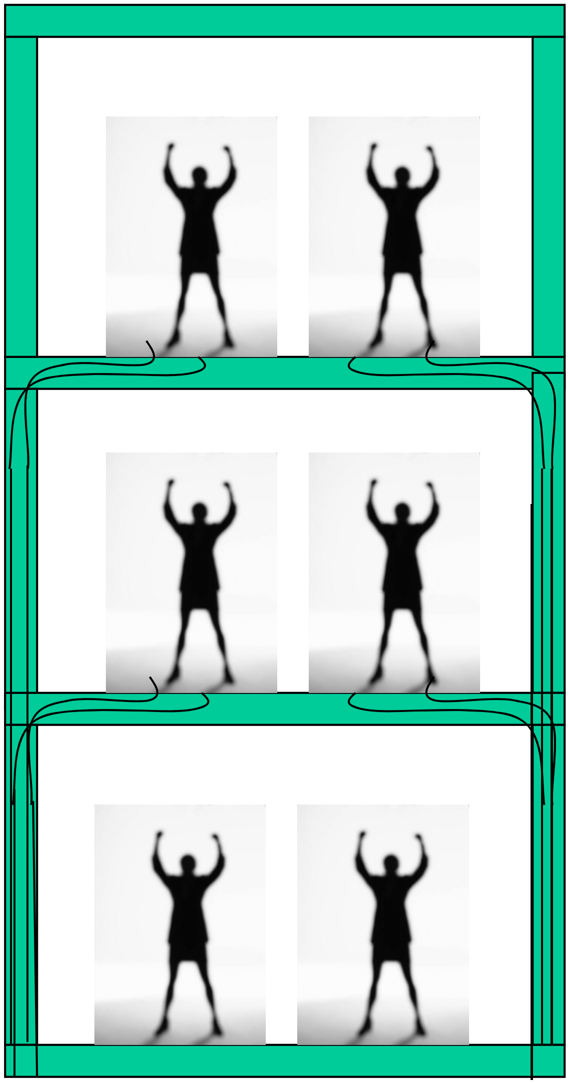
Nb_3Sn dipole technology at Texas A&M: stress management, flux plate, bladder preload

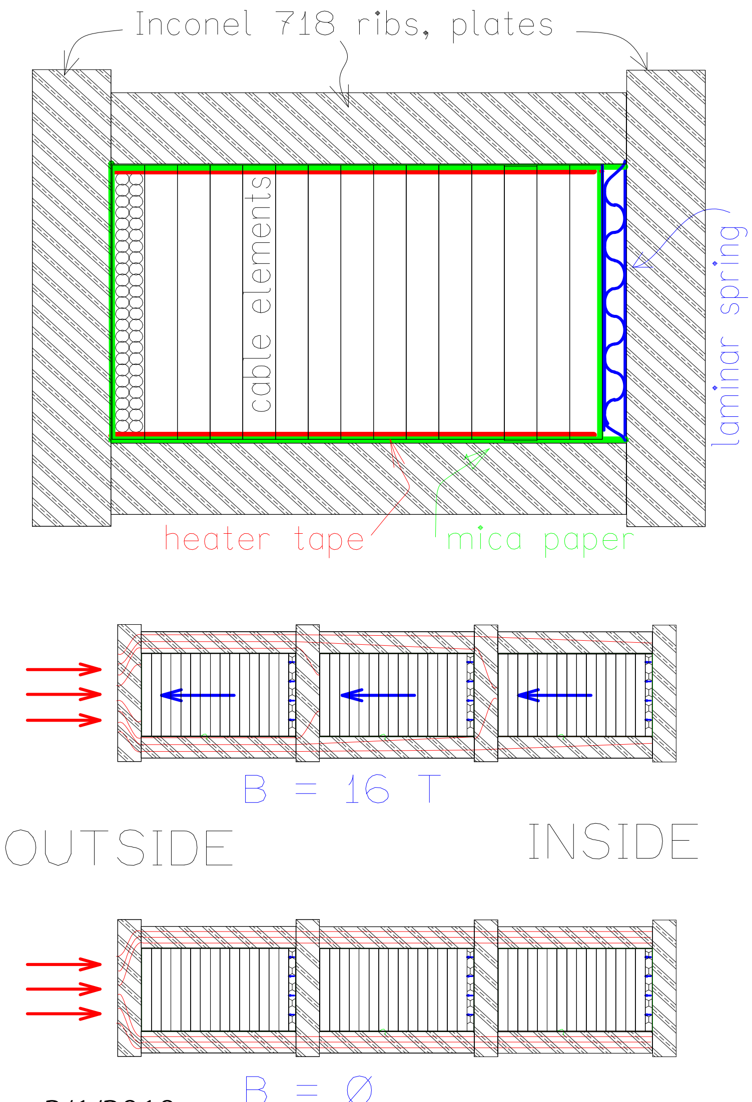




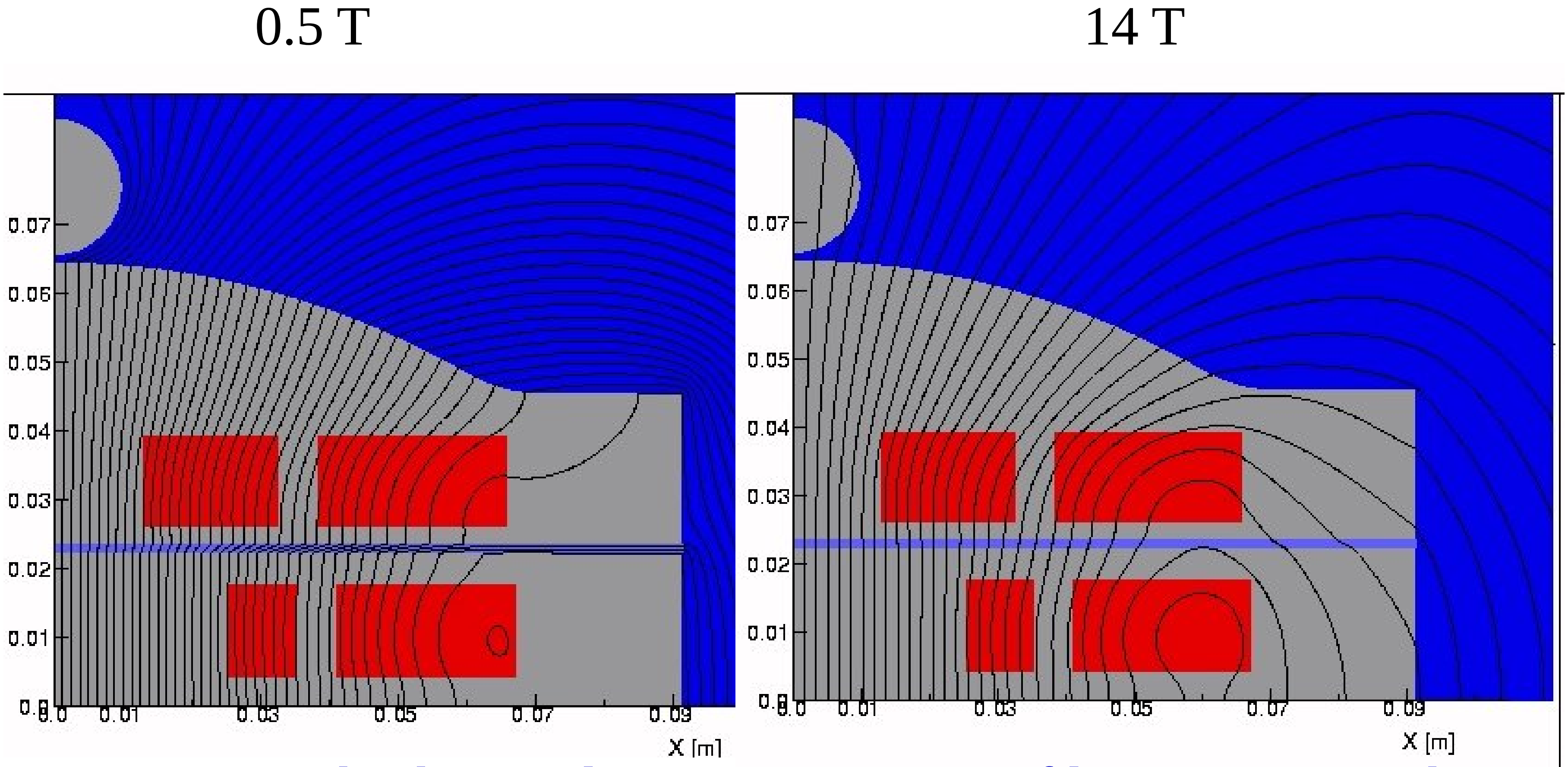



Stress management



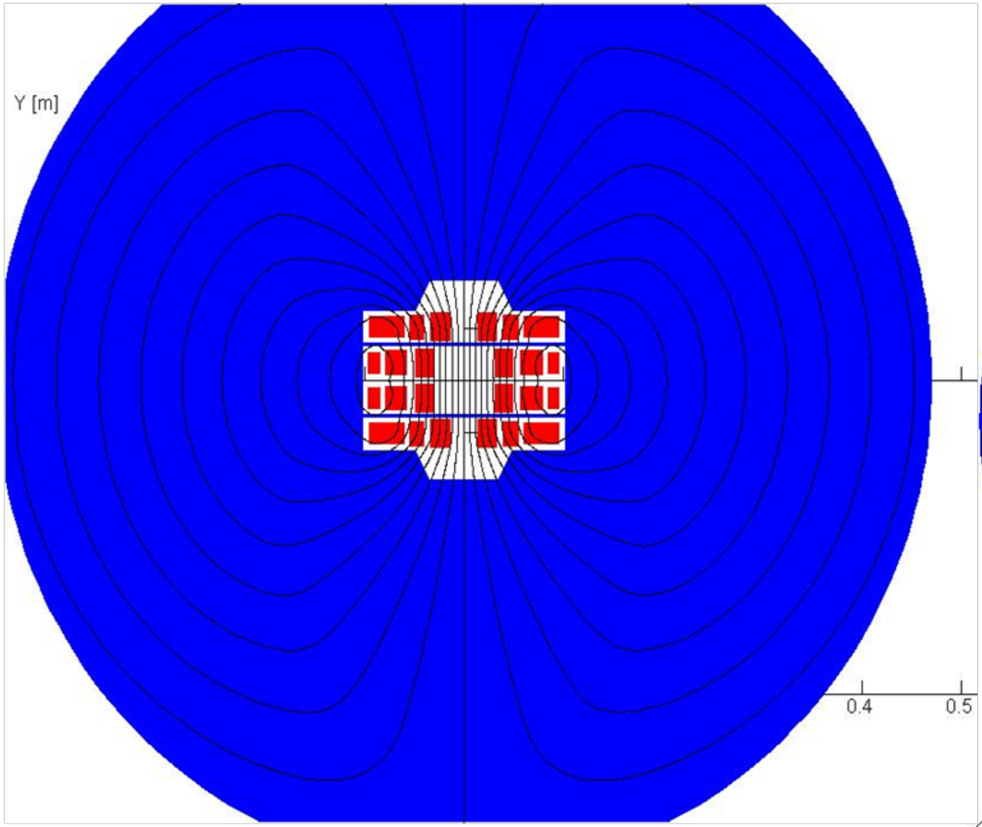


Horizontal steel flux plate redistributes flux to suppress multipoles

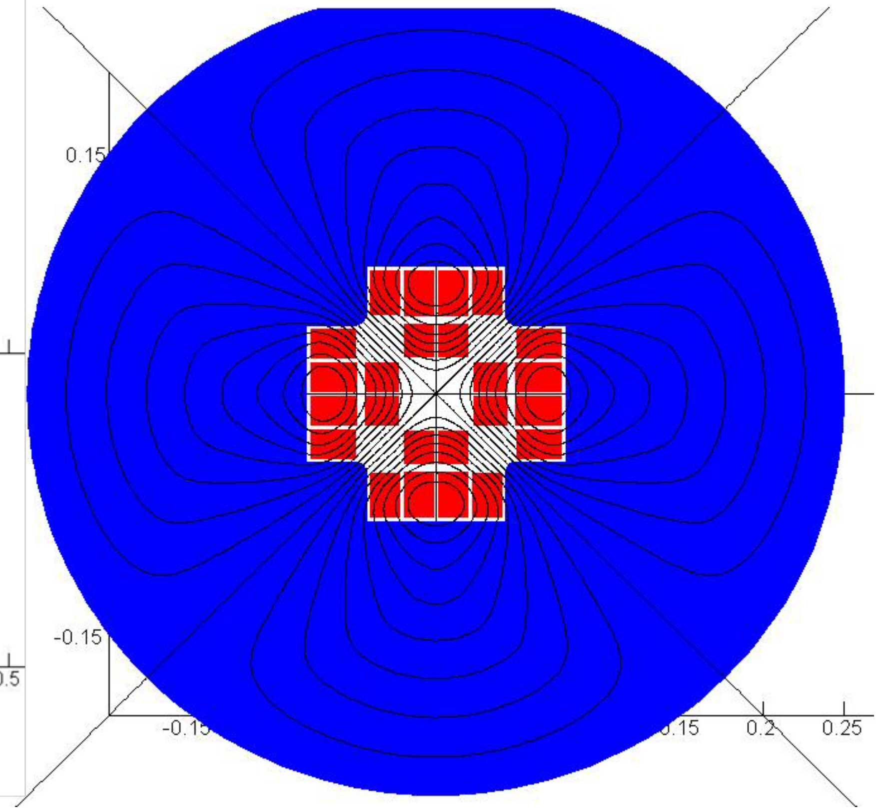


Suppress snap-back x5, relax requirements on filament size in Nb_3Sn.

Nb_3Sn Magnets for Petavac



16.5 T dipole



450 T/m quadrupole

Ring Dipole

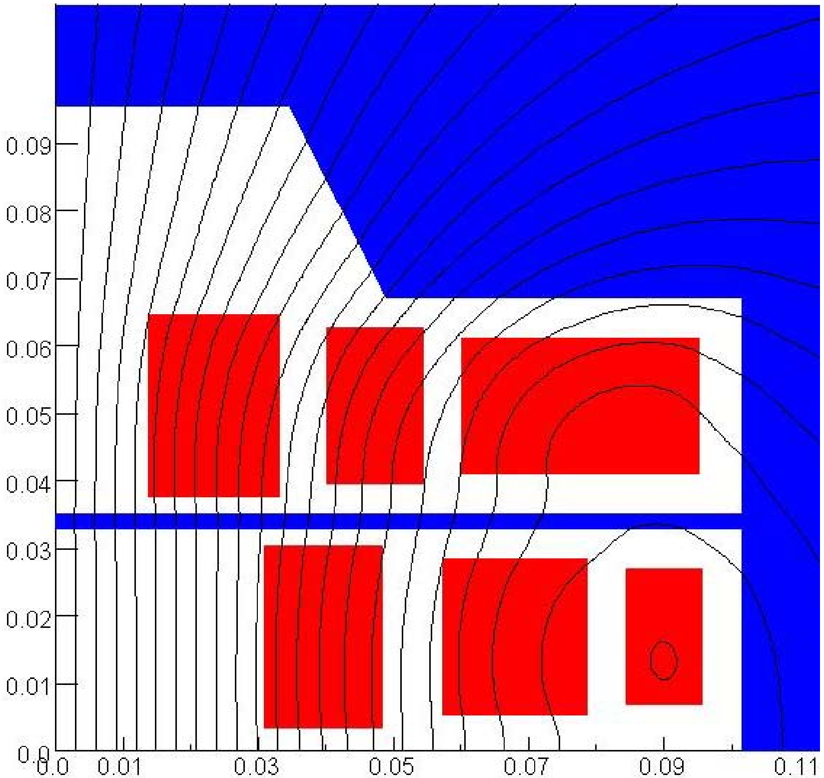
16.8 T central field (short-sample limit), 6 cm bore

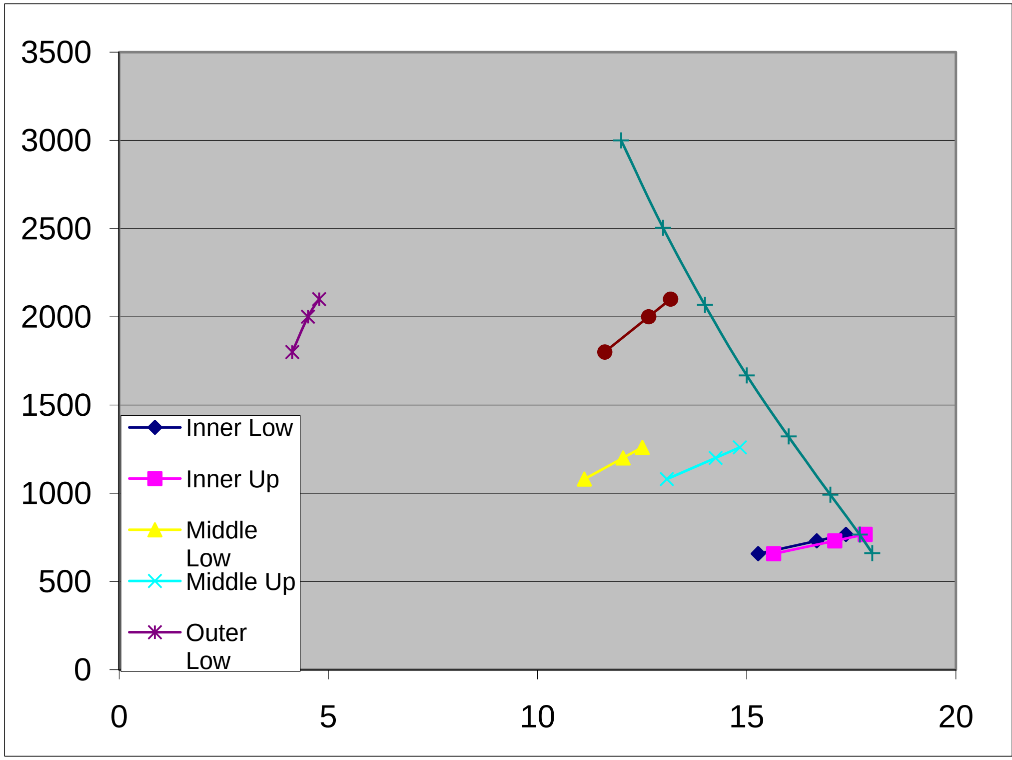
$J_{non\text{-}Cu}$ = 3000 A/mm^2 @12 T, 4.2 K

Cryogenics 4-6 K supercritical He

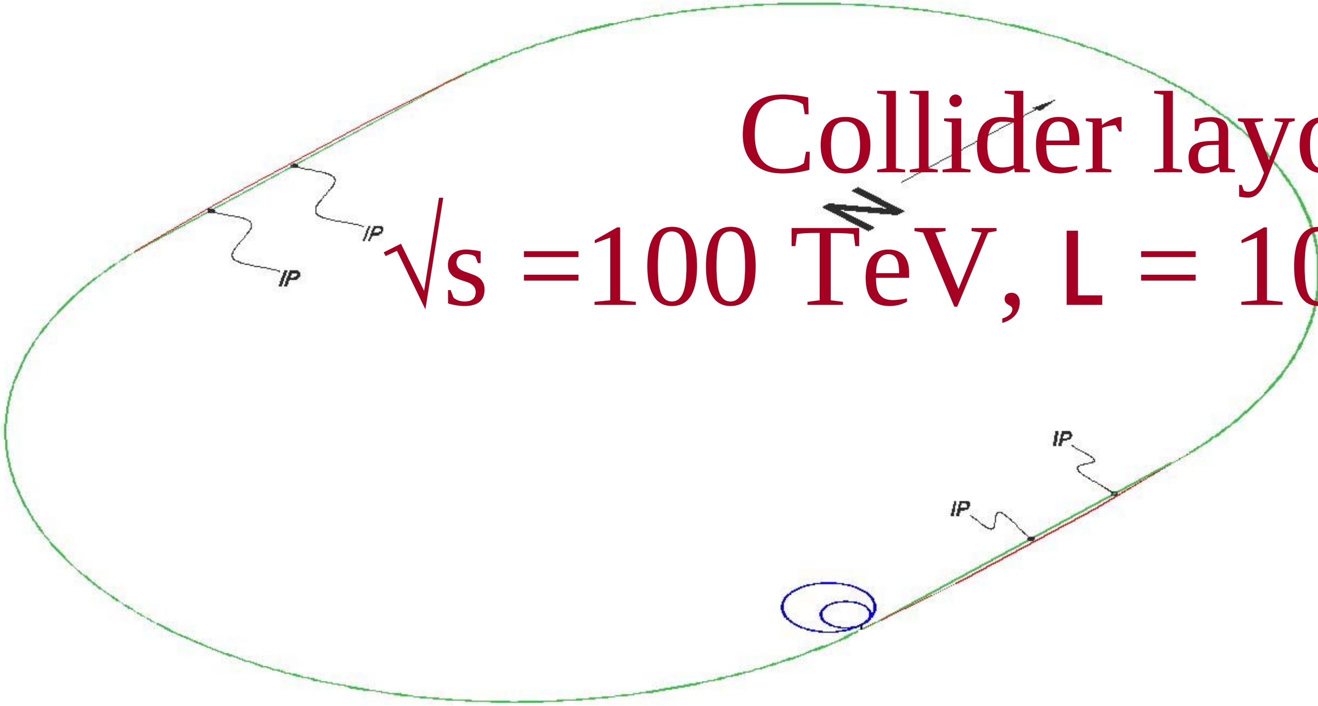
Total superconductor cross-section = 80 cm^2 (LHC dual dipole 68 cm^2)

Max coil stress 117 MPa.





Collider layout
$\sqrt{s}$ =100 TeV, L = 10^{35} cm^{-2} s^{-1}

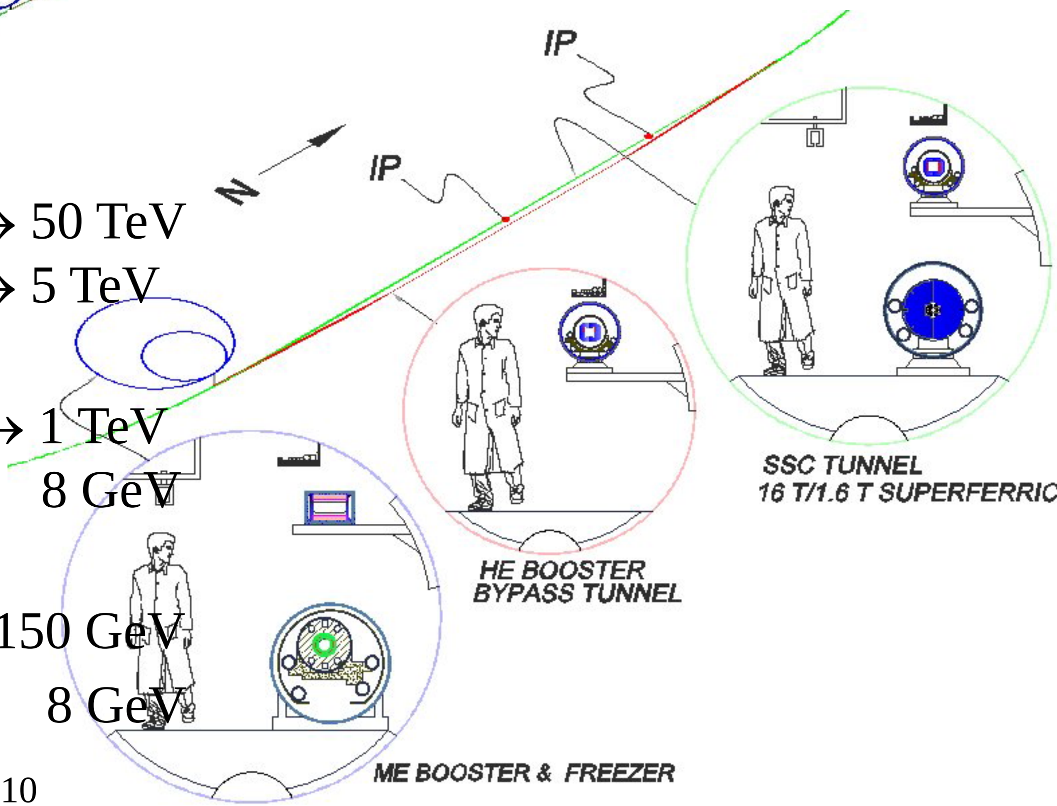


Main tunnel:
- 16 T double ring 5 → 50 TeV
- 1.6 T superferric injector 1 → 5 TeV

Medium-energy booster:
- 4 T cos θ booster 0.15 → 1 TeV
- 0.1 T permanent magnet freezer 8 GeV

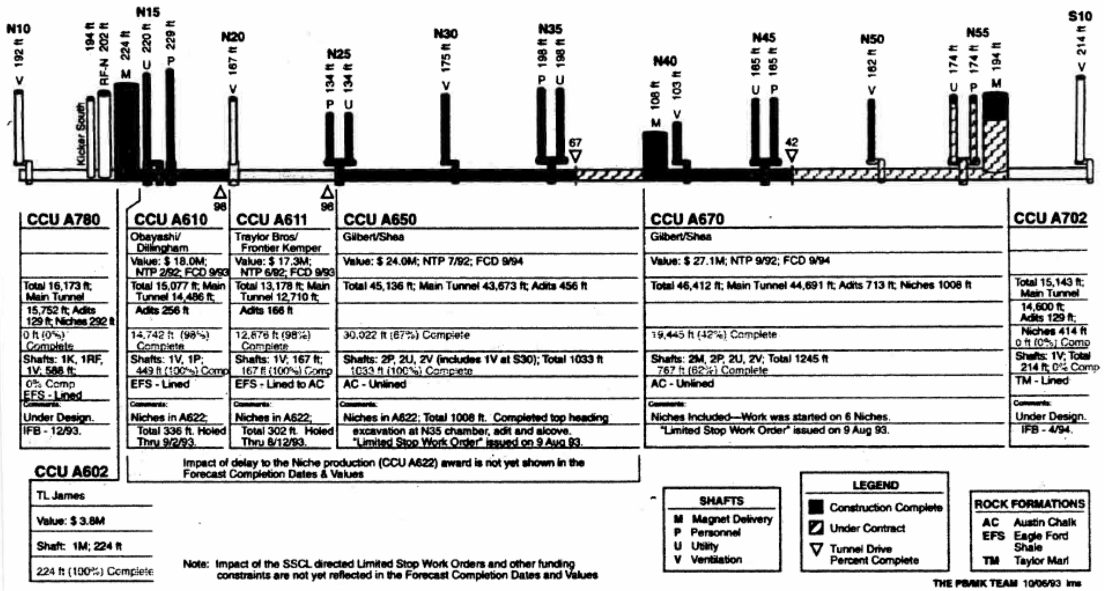
Low-energy booster:
- 1.5 T rapid-cycling booster 8 → 150 GeV

Superconducting linac: 0.01 → 8 GeV

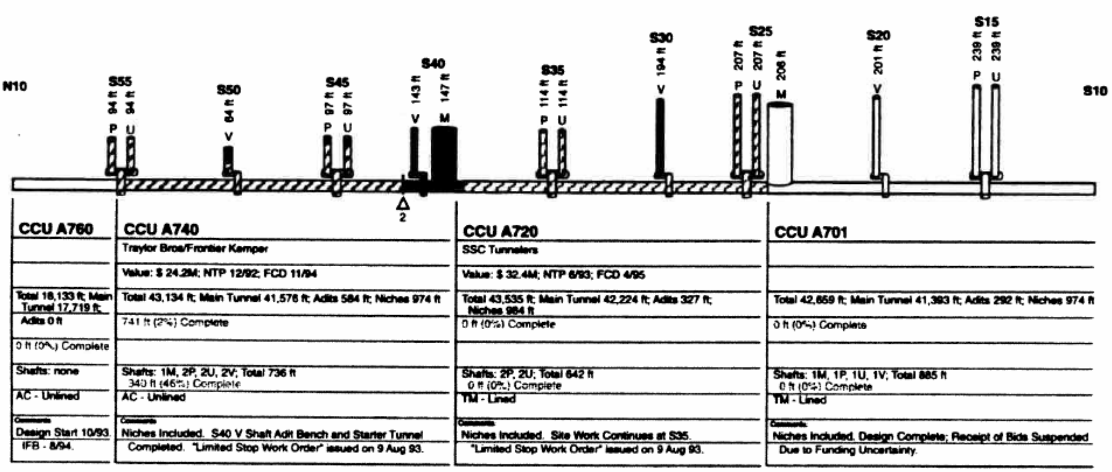


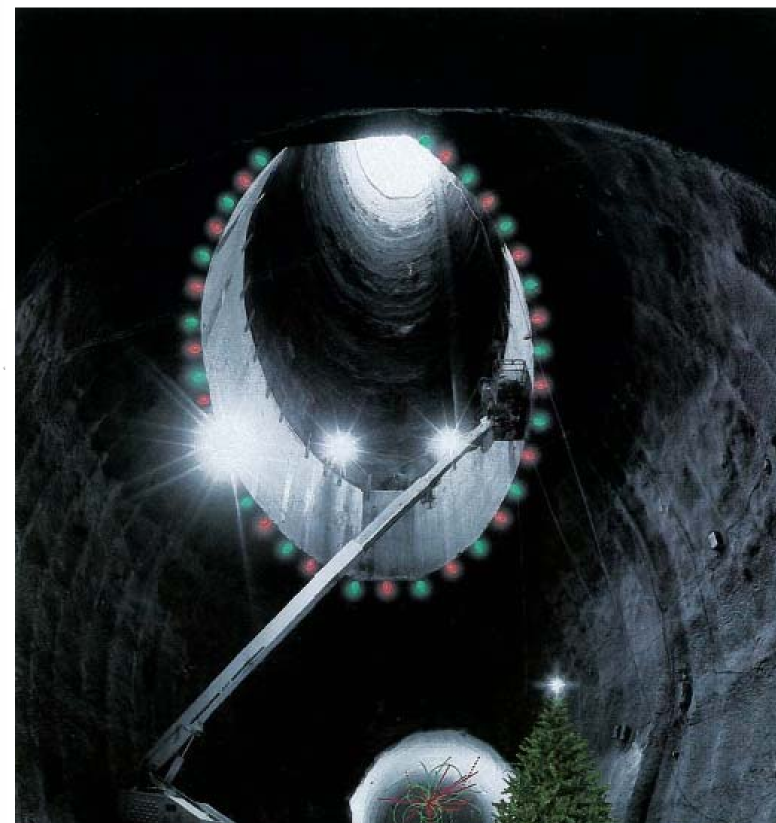
SSC tunnel ~70% bored, 35% lined

SSC Basic Collider Tunnel Progress—North Arc
October 5, 1993

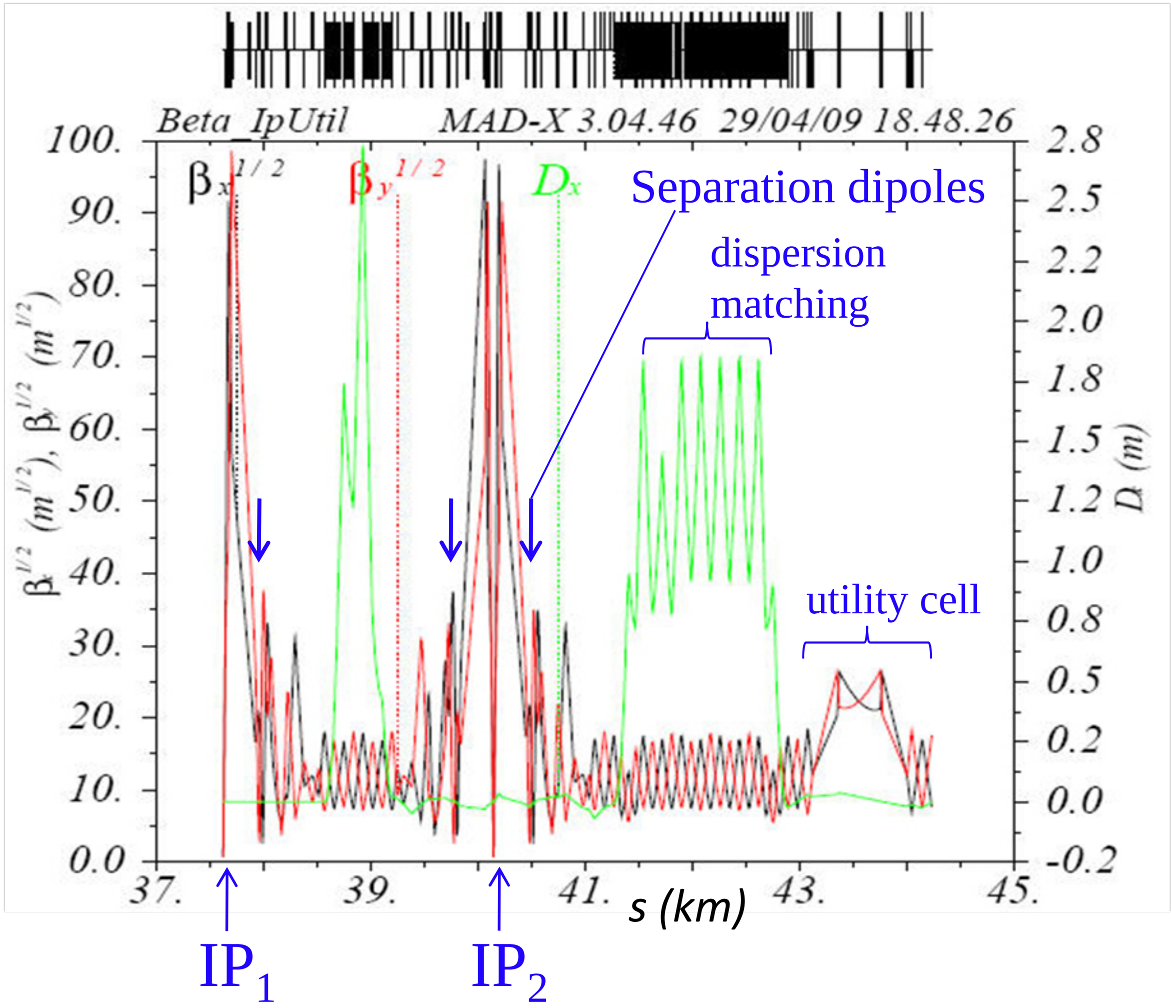


SSC Basic Collider Tunnel Progress—South Arc
October 5, 1993





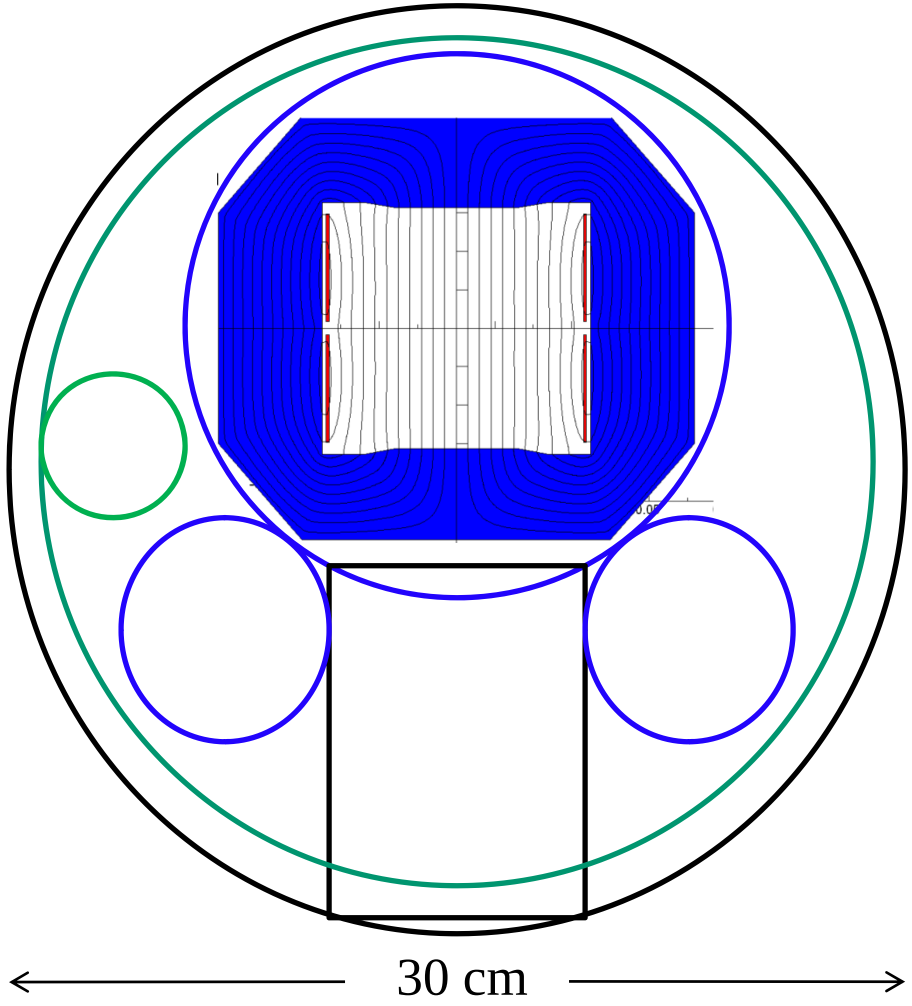
Petavac Lattice



$\beta^* = 0.5$ m

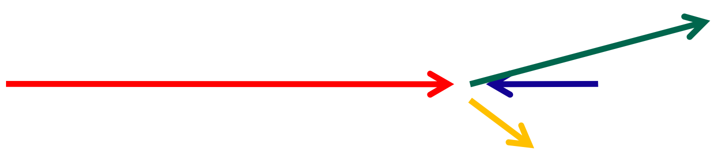
$\beta_{max} = 9.6$ km

Superferric High-Energy Injector shares the same tunnel



Asymmetric Top Factory

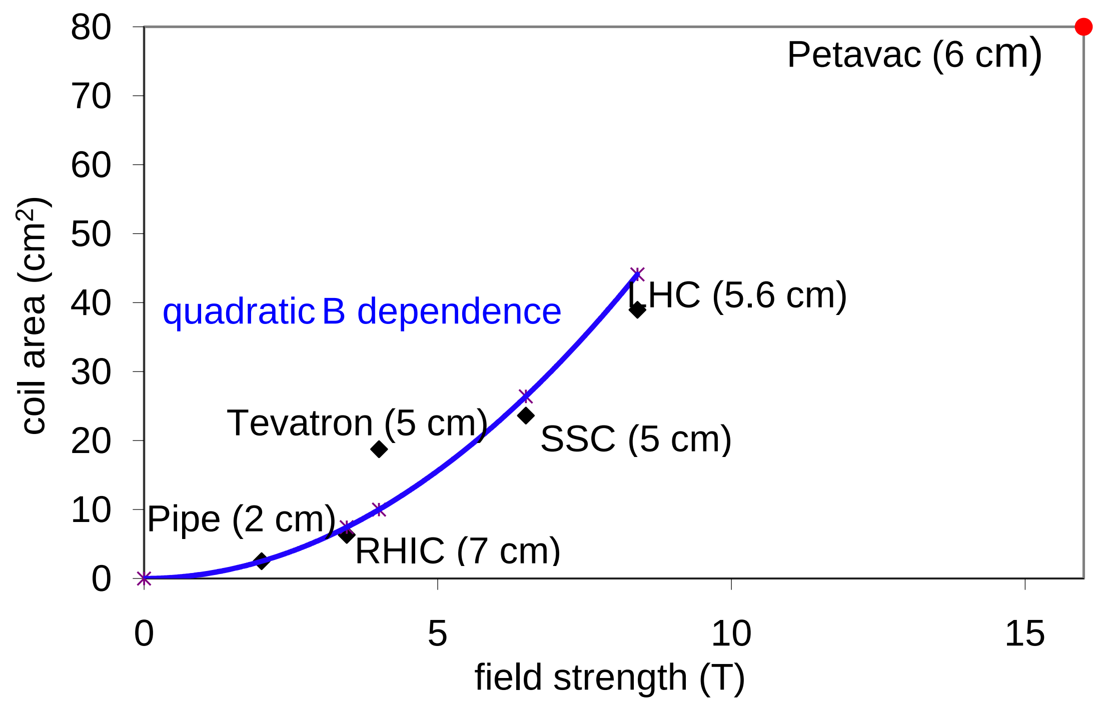
- Petavac circulates 50 TeV protons
- High energy booster in the same tunnel: 5 TeV
- Collide the two beams: 50x5 TeV^2 = 16 TeV^2
- Saturate top production with asymmetric collisions
- Similar benefits for studying $t\bar{t}$ system as BABAR/BELLE for $b\bar{b}$ system?



How much would an 86 km ring of Nb_3Sn dipoles cost?

- No one can know until we develop the technology and transfer it to industry, but…
- ‘the collared coils represent about 60% of the assembly cost and more than 70% of the total value of a dipole (mainly because of the superconducting cable cost)’
  …Lucio Rossi, LHC magnet group leader
- *p*-*p* Petavac: 5 cm bore dual dipoles → 15 ktons
- $\bar{p}p$ Petavac: 6 cm bore single dipoles →10 ktons
- Wire price today $1,000/kg, ÷3 in volume
- Magnet rings: *p*-*p* $8 billion
  $p\bar{p}$ $5 billion, but needs ultra-intense $\bar{p}$ source.

New magnet design, New materials, Dramatic Performance

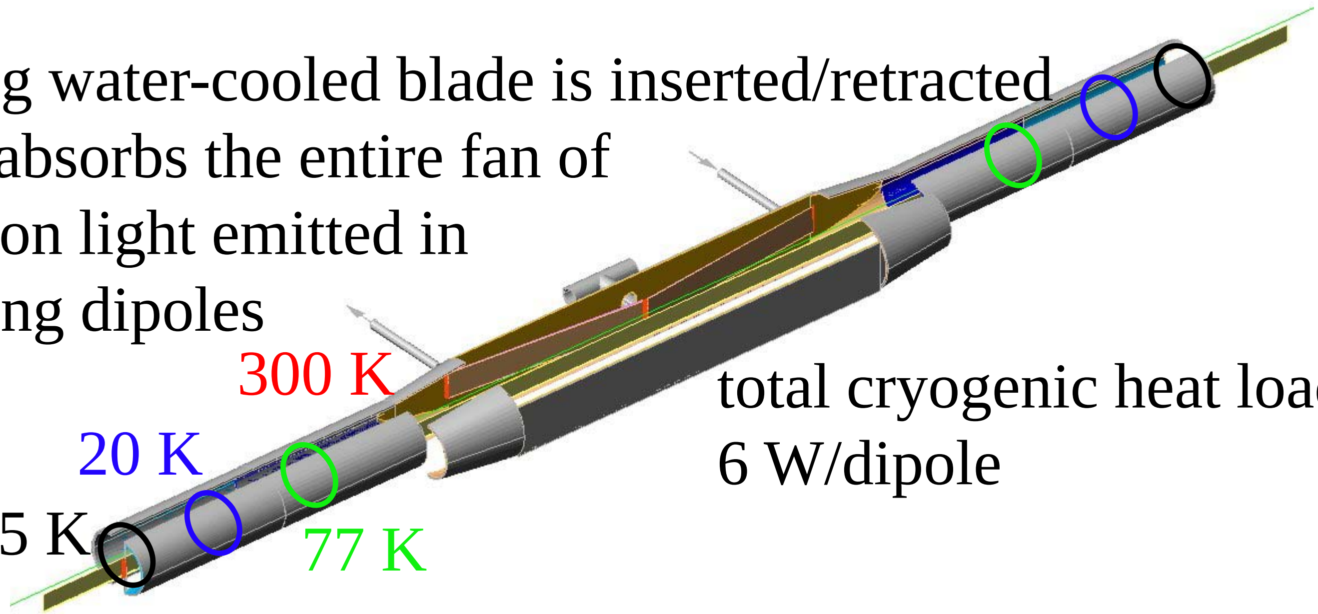


Accelerator Challenges for Pentavac

- *Synchrotron light*: 6 W/magnet @ LHC,
  1600 W/magnet @ Pentavac!

Solution: room-temp photon stop between successive dipoles

0.7 m long water-cooled blade is inserted/retracted so that it absorbs the entire fan of synchrotron light emitted in the flanking dipoles

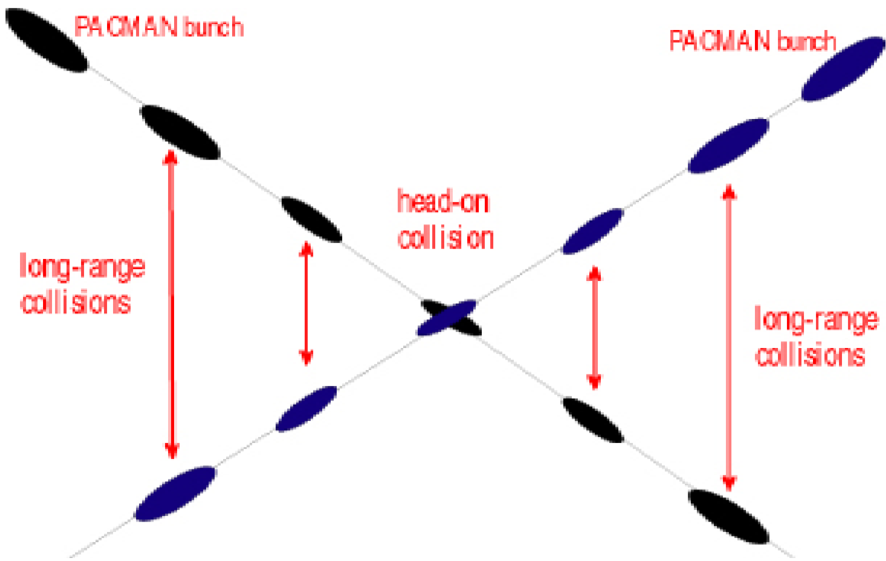


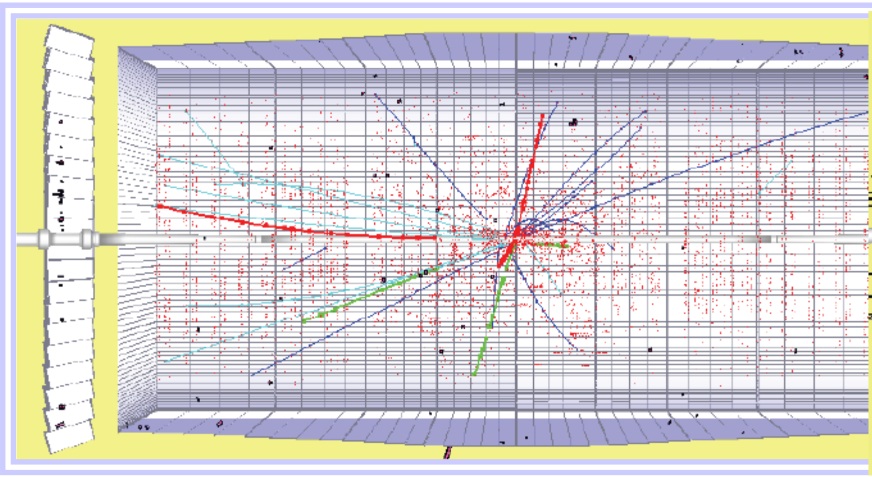
total cryogenic heat load 6 W/dipole

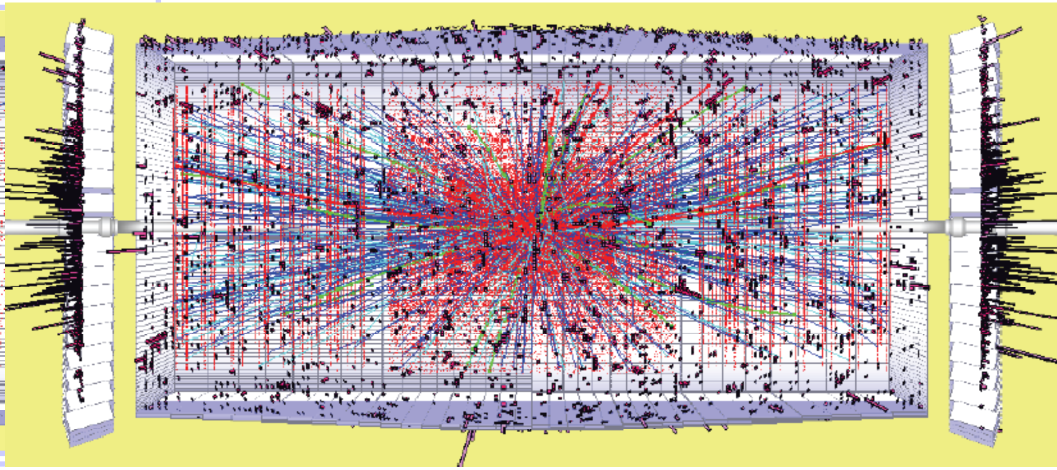
Synchrotron light gives damping in all dimensions of phase space: 45 minutes in Petavac (24 hours in LHC)

We should be able to suppress mechanisms for slow emittance growth.

- Avoid beam-beam tune shift from subsidiary crossings of bunches
- Move first elements of low-beta squeeze closer than at LHC:
- 4 x more bunches in ring
  $\rightarrow$ 4 x less confusion of interactions.

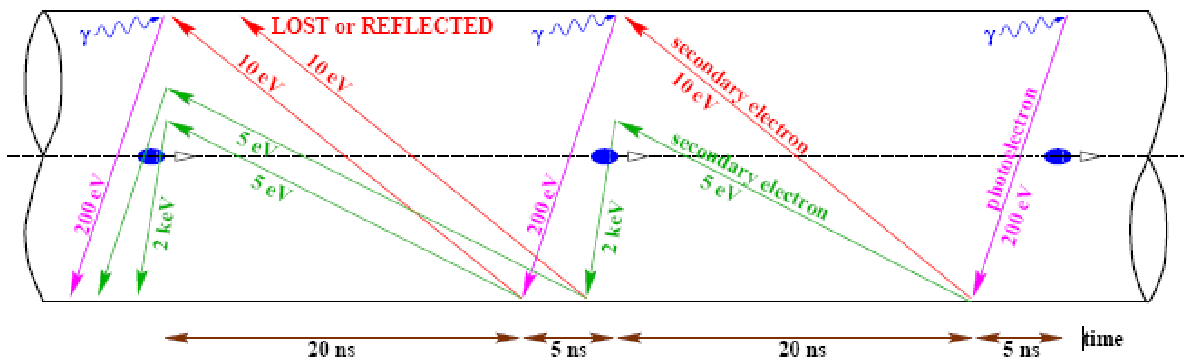






1 SUSY event in CMS same SUSY event with 300 interactions

➤*Electron cloud effect:*



•Beam protons ionize electrons from gas atoms

•Electrons are born with ~eV kinetic energy, so can't reach wall before next bunch passes

•Electric field of next bunch accelerates electrons to ~kV energy

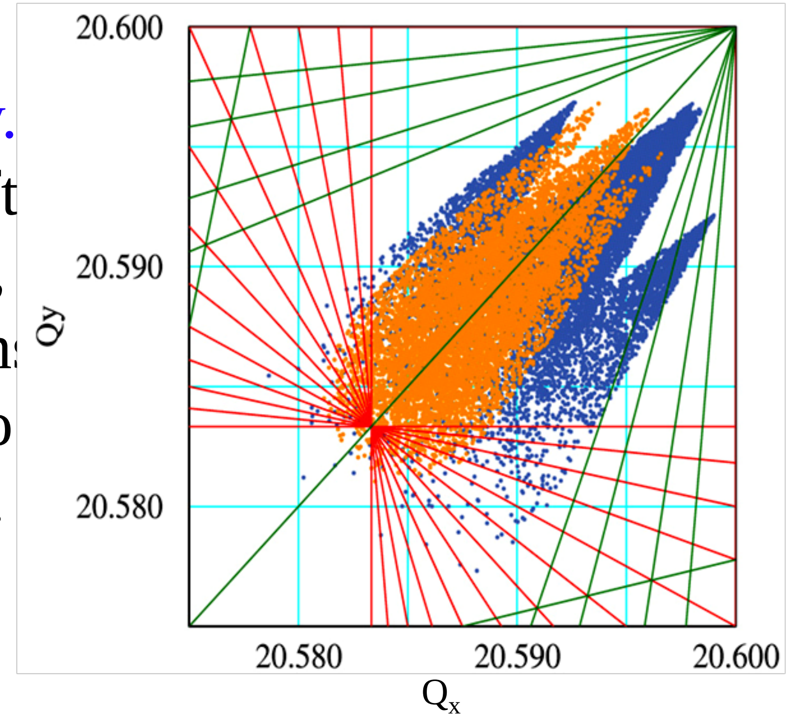
•Energetic electrons strike wall and liberate secondaries…

Poses serious challenge to reach even 10^{34} luminosity, much less 10^{35}

Solution: Install continuous strip electrode on side wall of vacuum tube around entire ring. Bias ~50 V *clears all charge in <20ns*

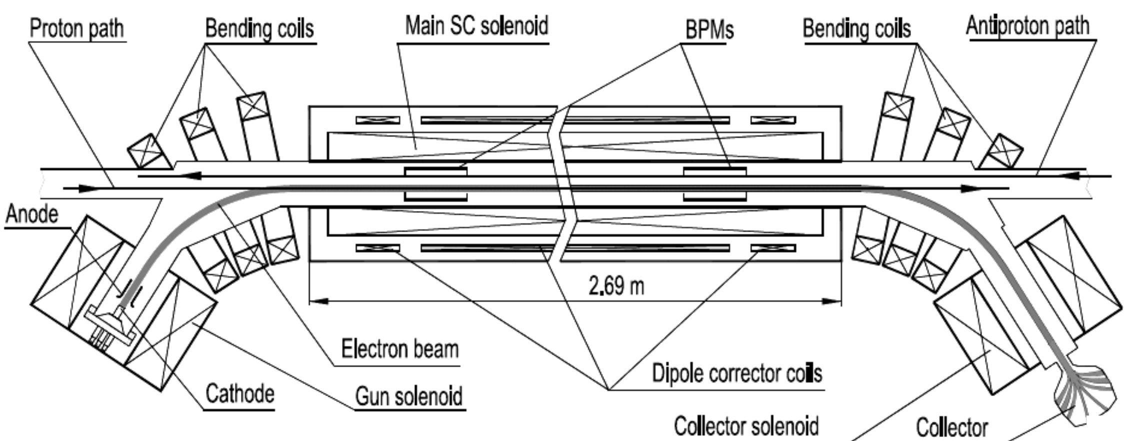
➢Bunch-bunch tune spread kills luminosity.

Successive bunches have different tune shift due to a multitude of phenomena (injection, circulating charge, bunch intensity variation chromaticity). The machine can be tuned to keep any *one* bunch happy, but the others…



Solution:

Use *AC dipole* to measure tunes of each bunch, use *electron lens* to correct tunes of each bunch dynamically during store.



Ryoichi Miyamoto

Dare we to dream today of an ultimate-energy hadron collider?

1982: I woke up in the middle of the night and told Becky: ‘We need to build a gigantic hadron collider here in Texas to make a future for high energy discoveries.

Selling the idea wasn’t easy. It was bust times in the economy,
the project would cost billions.

I sought help: cheapest site for 50 mile circumference tunnel;
$1 Billion of Texas funds to boost the starting gate.

Texas universities arranged a briefing in the White House

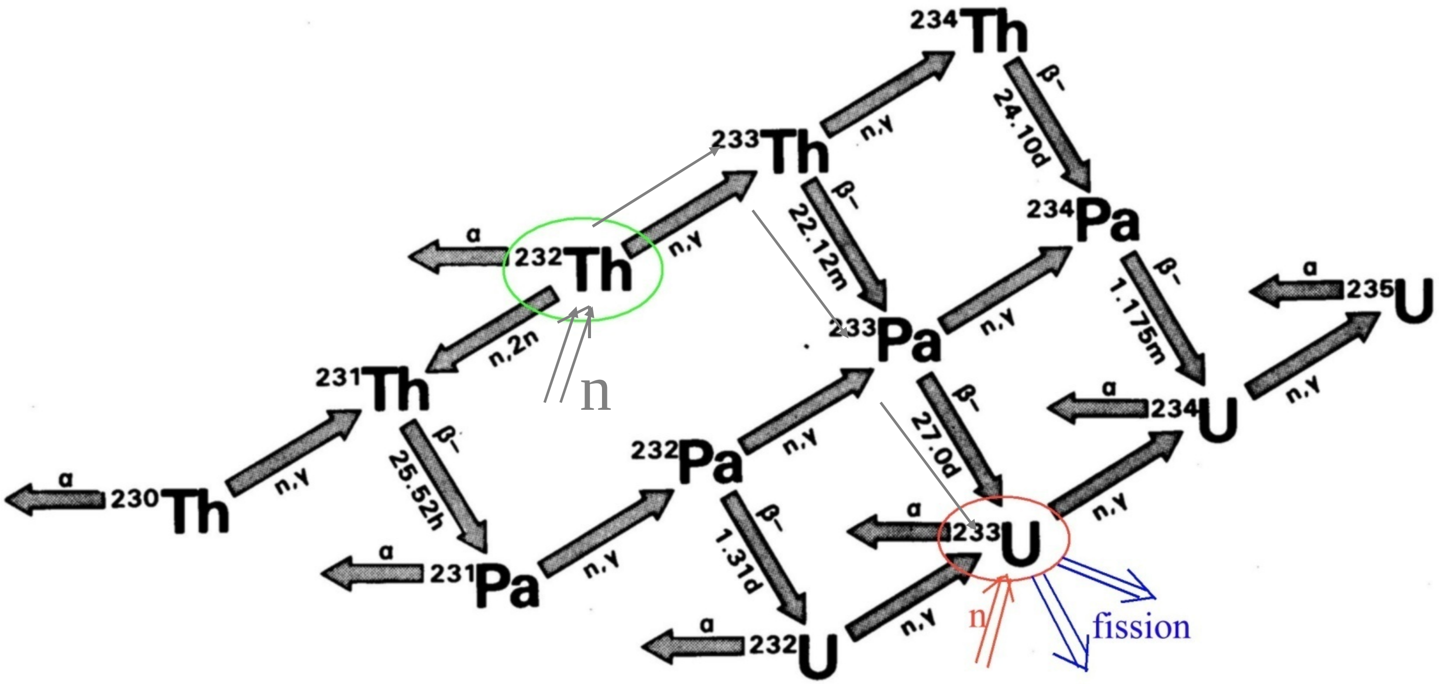
After briefing, V.P. Bush asked his aide what was position at Energy. ‘Strong support for the project but it would break the budget guideline.’ V.P. Bush told him to ask them to prepare a short document that he could take to the President…

It worked then; it could work today if it had the enthusiasm of the world high energy family.

Thorium fission for nuclear power

- Electrobreeding (transmutation of $^{232}Th \rightarrow {}^{233}U$) 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.

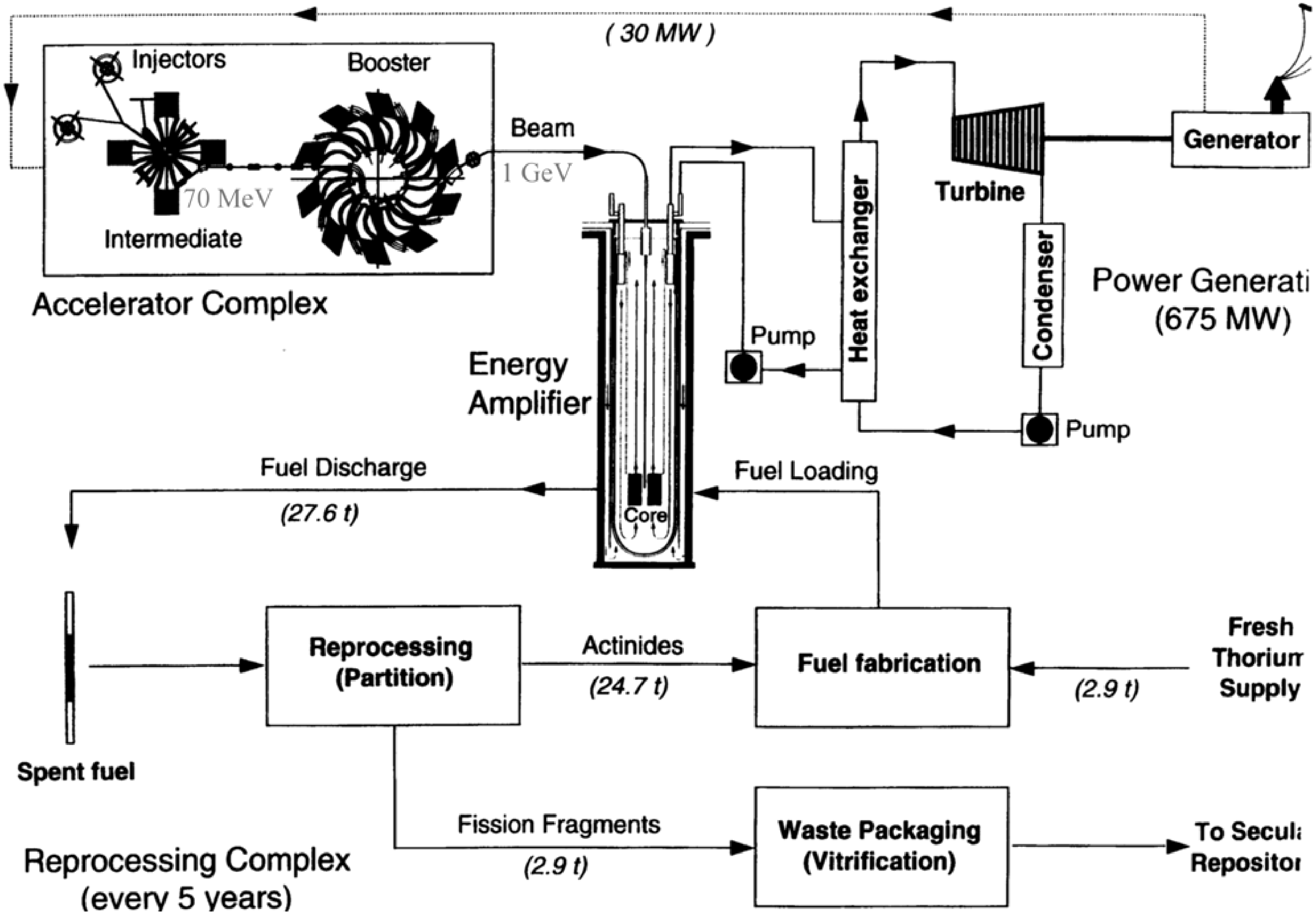
The electrobreeding concept: 1 GeV protons→fast neutrons



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

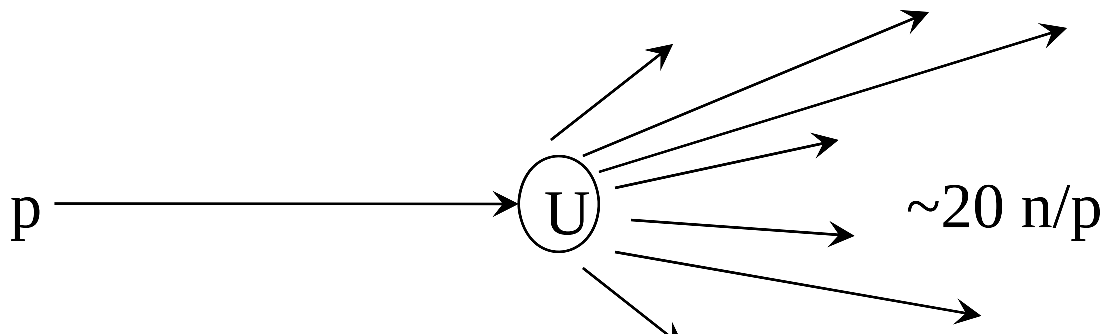
Fatal flaws: accelerator power, neutronics, reliability

Main elements of a thorium-cycle power plant



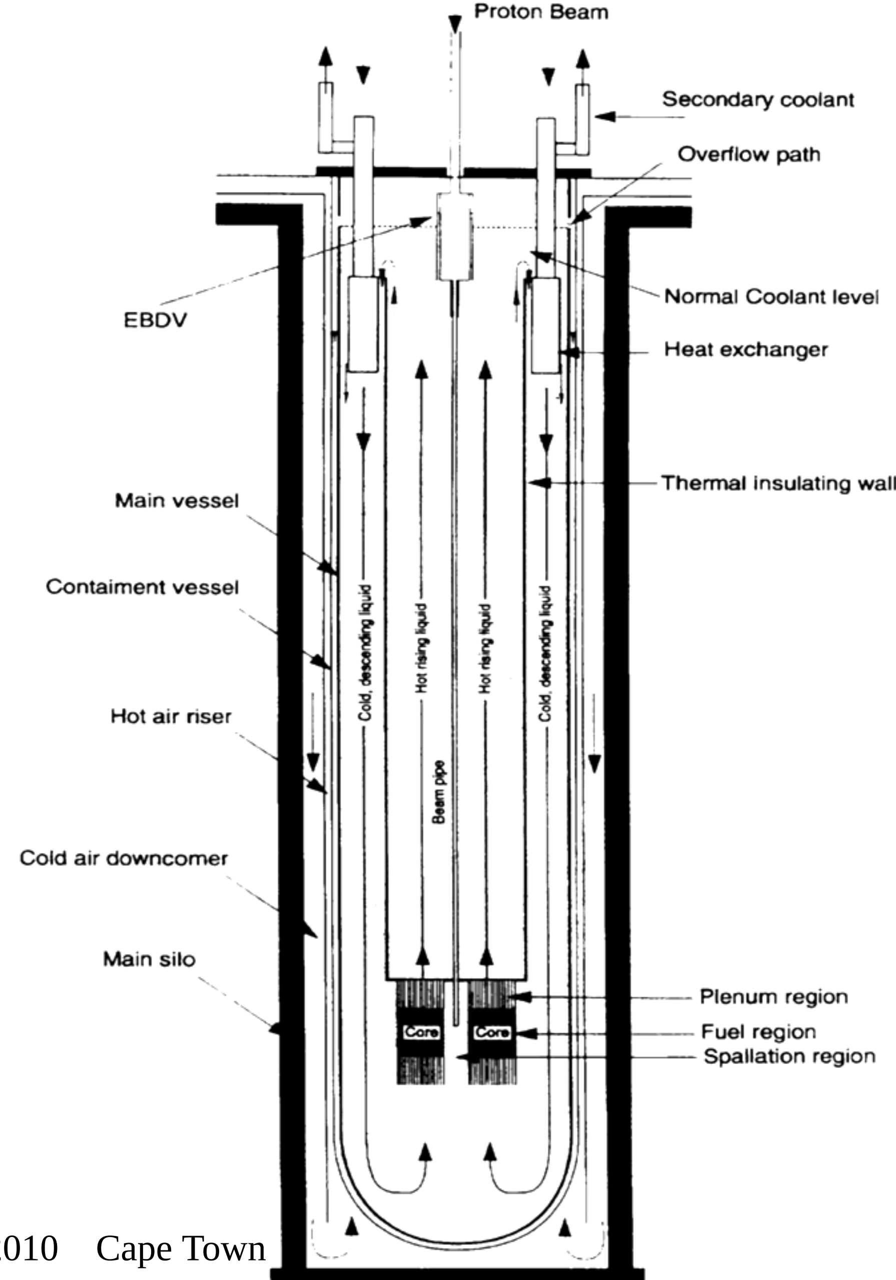
The neutrons are produced by spallation of ~1 GeV protons on Pb

- 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 → 70 MeV injector cyclotron,

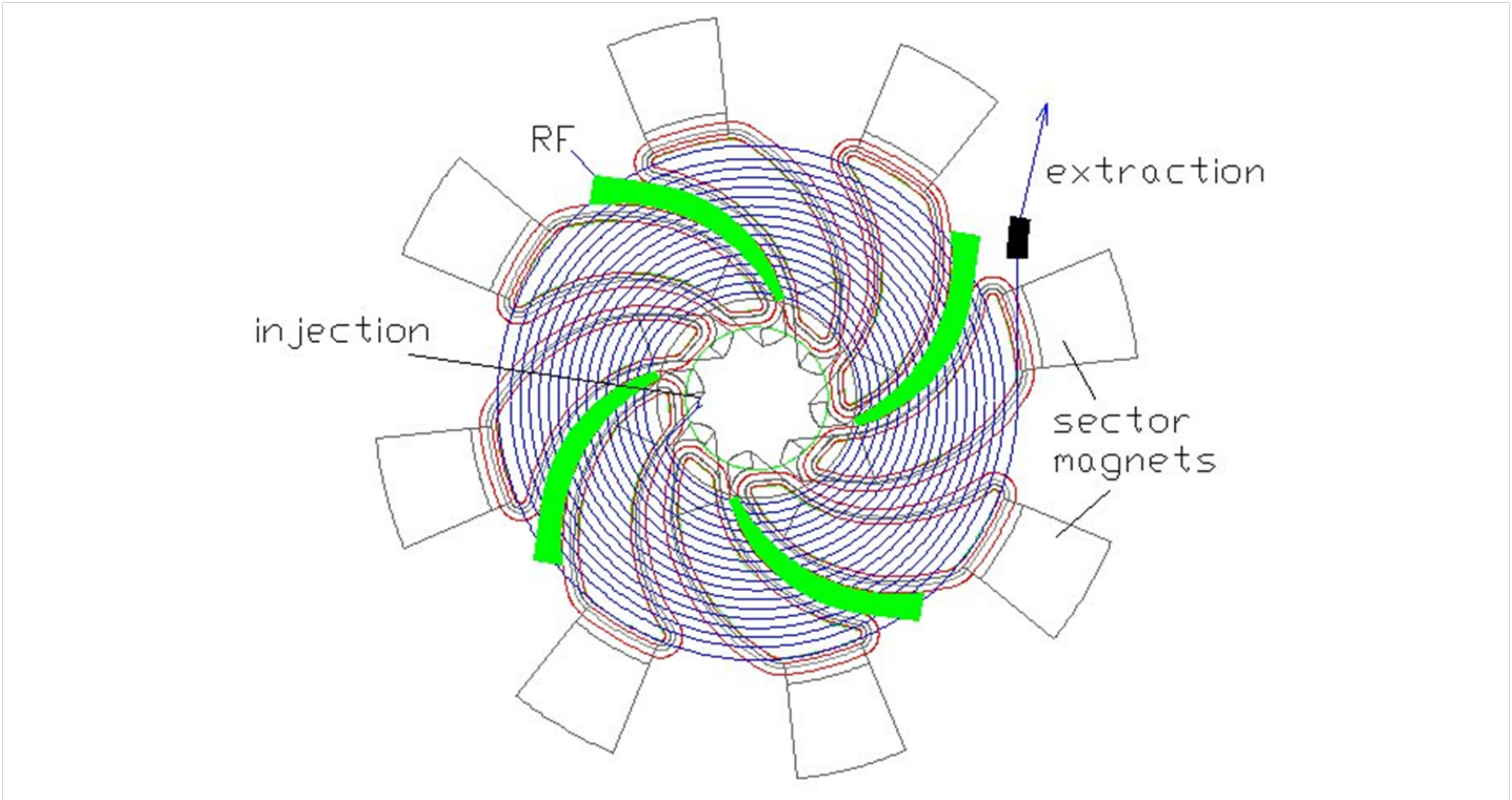
  70 → 800 MeV isochronous cyclotron (IC)
- Assemble a stack of seven flux-coupled ICs

  Flux linkage

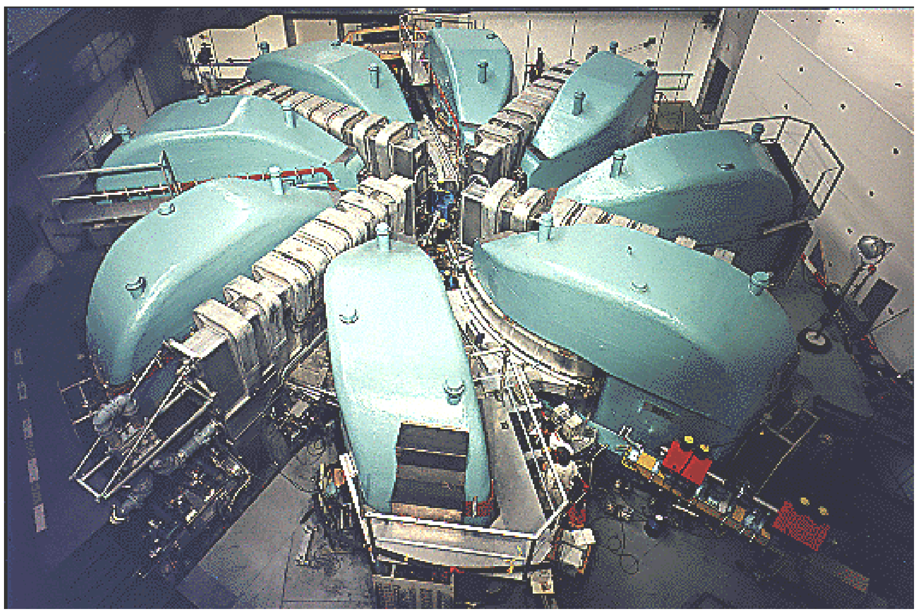
  Independent RF, injection, extraction, vacuum, transport
- *Reliability through redundancy*

  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)

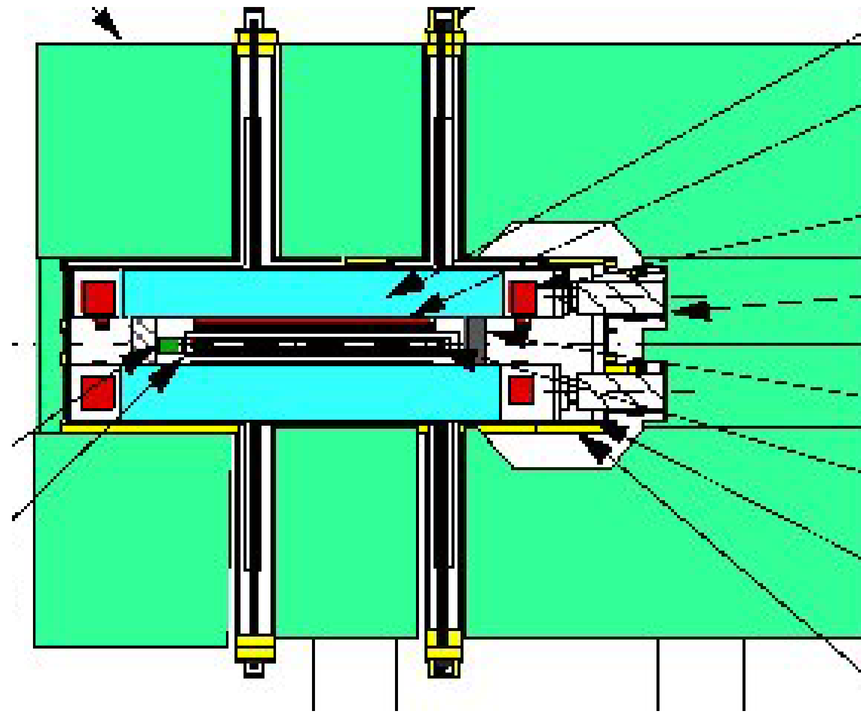


Combine the high-energy isochronous cyclotron of PSI:



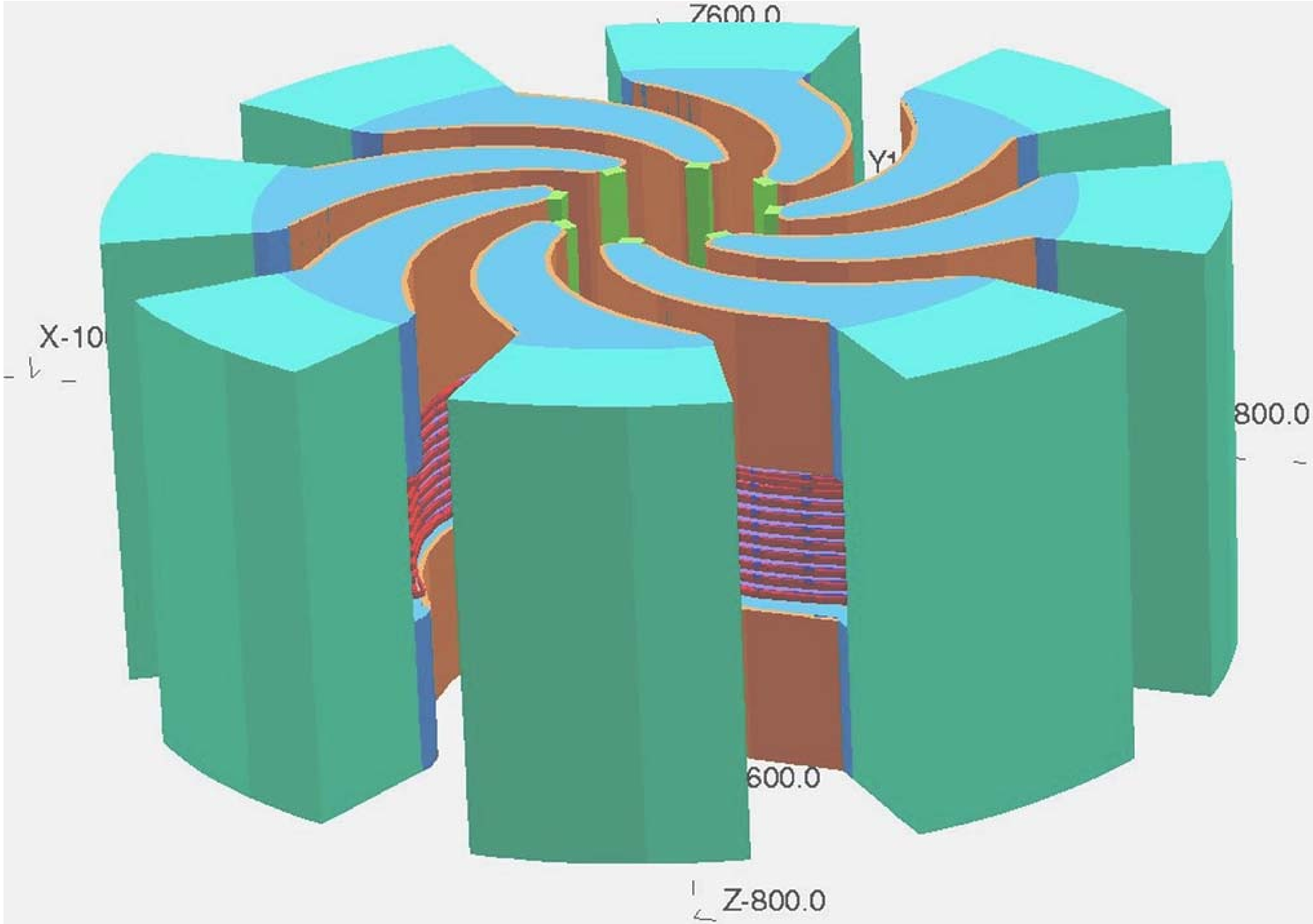
650 MeV, 2 mA
4 operators/shift
MTBF ~ 4 months

and the superconducting magnet design of Riken:



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

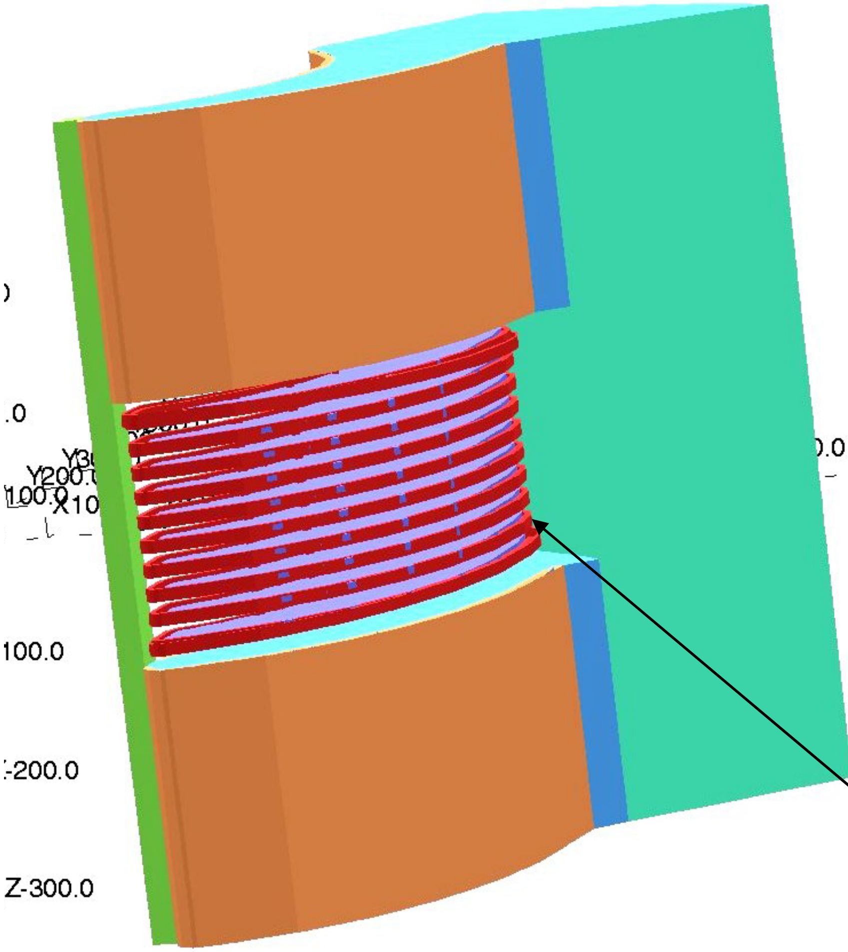
7-stack isochronous cyclotron

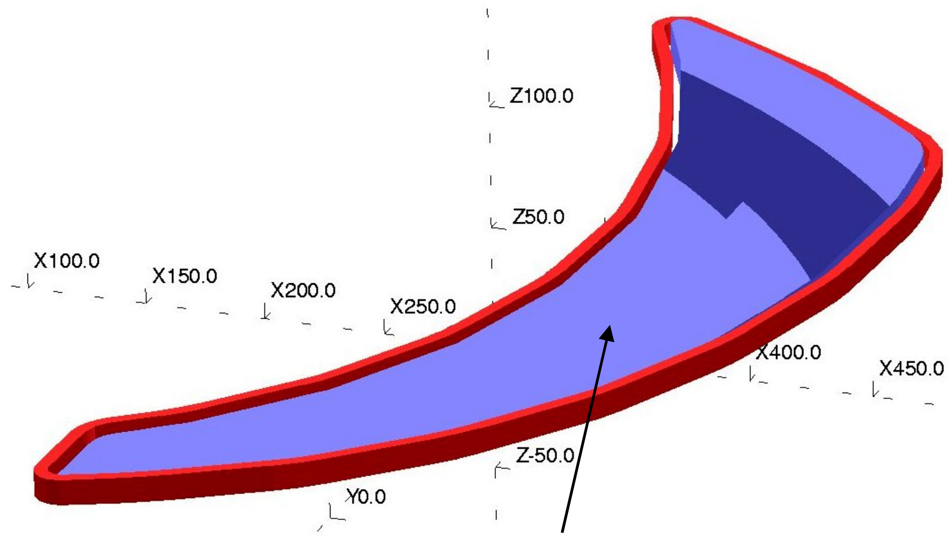


7m

15 m

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





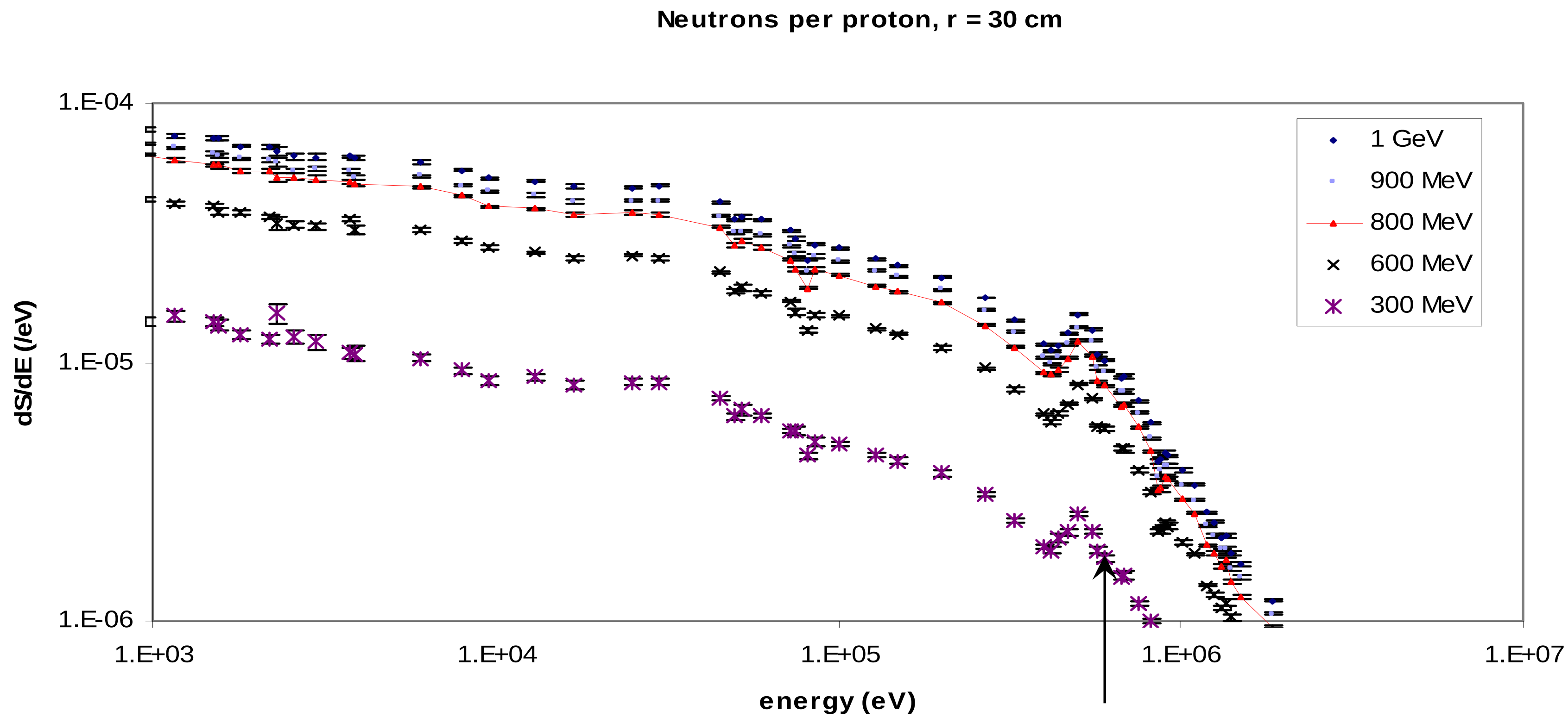
Flux plate = NbTi superconducting coil, contoured steel plate

10 flux plates,

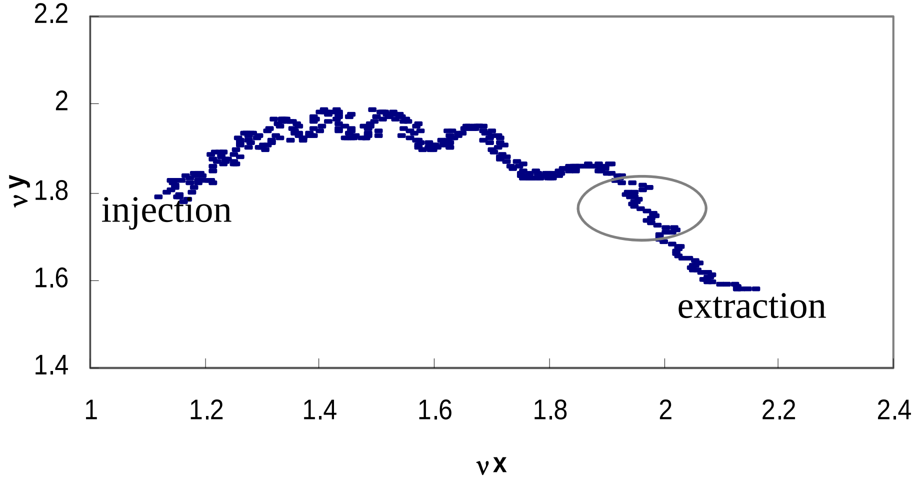
Top/bottom sacrificial gaps

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

Best choice of proton energy ~800 MeV

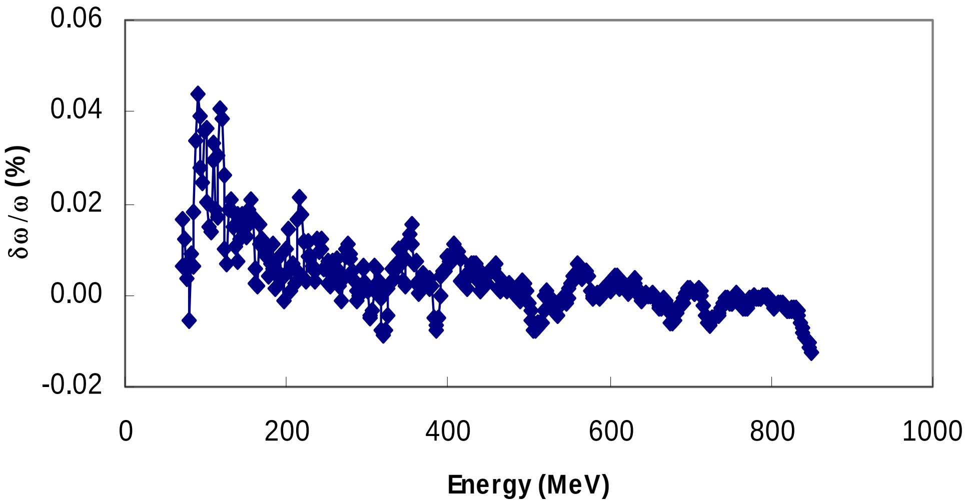


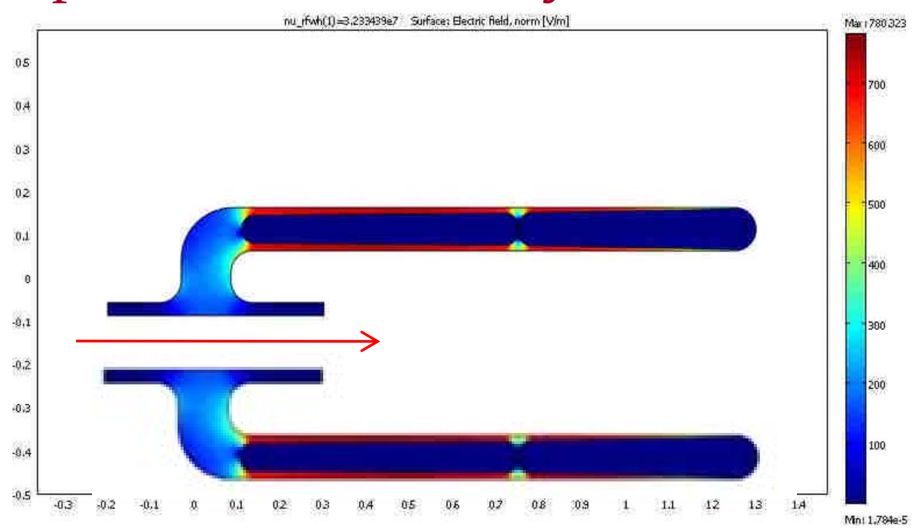
Control horizontal, vertical betatron tunes:



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

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

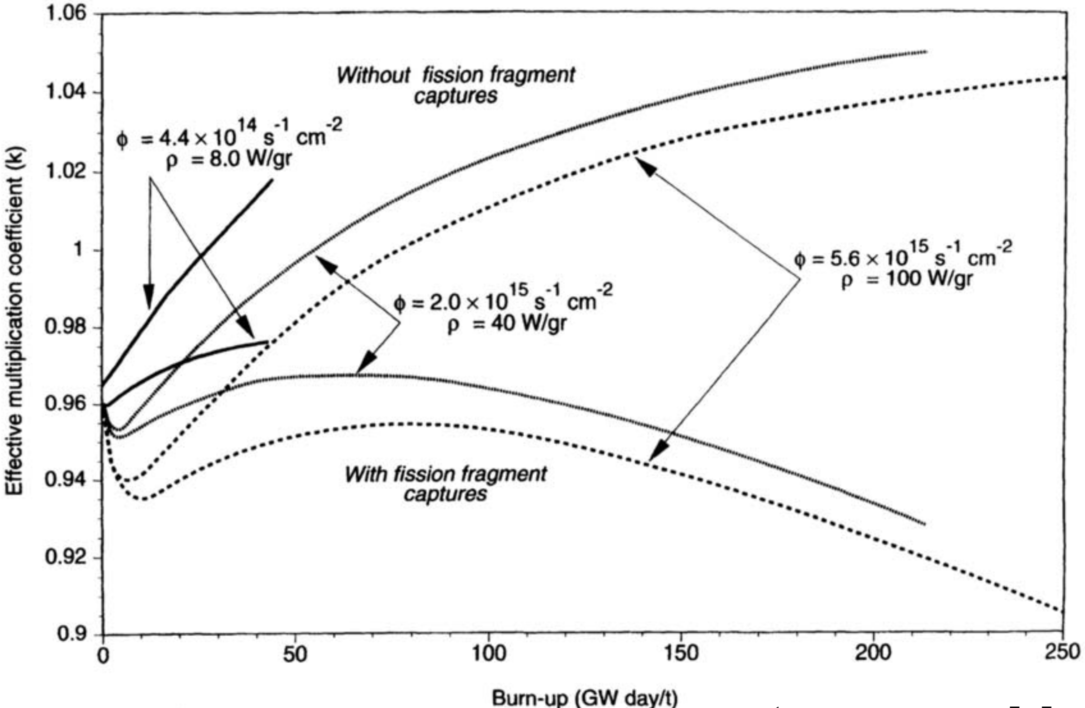


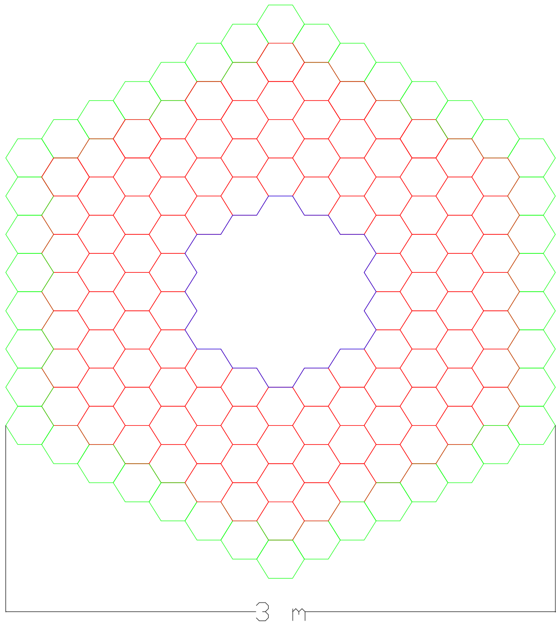


Problem: Fission products shadow the neutrons

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

Single coaxial drive beam (Rubbia):



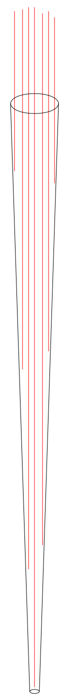


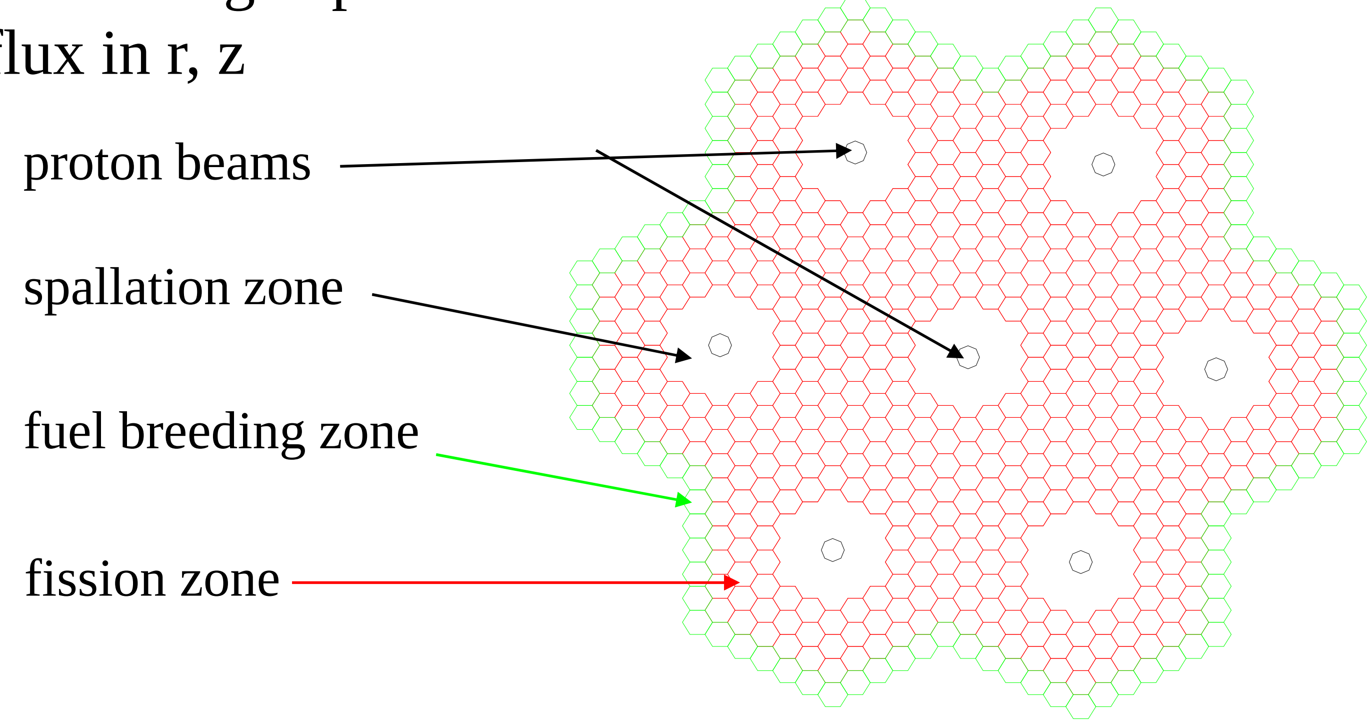
(From Rubbia)

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

Distribute proton drive → Reduce variation k(r)

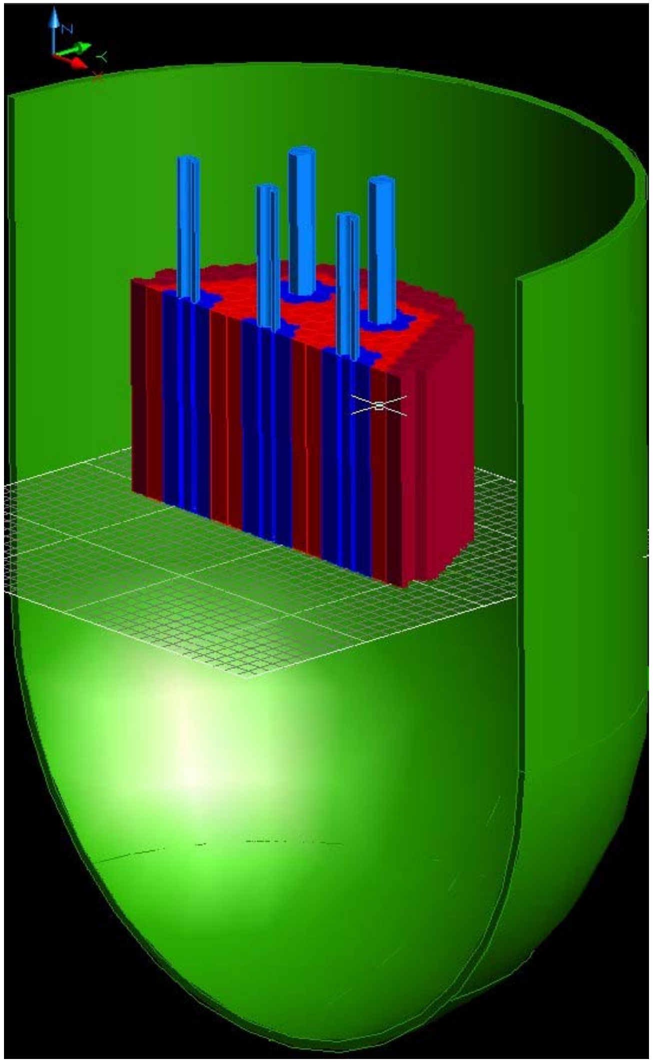
Sweep each beam along depth of beam tube →
Ho nize flux in r, z

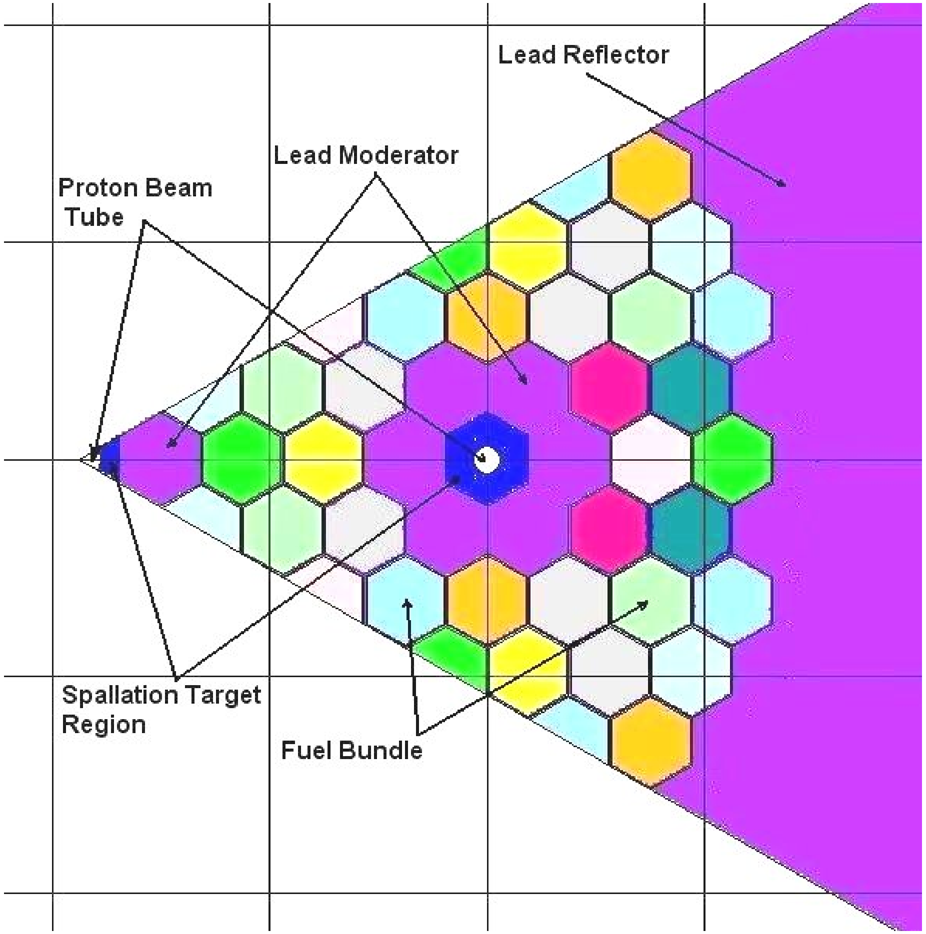




Better control, more efficient consumption of fuel.

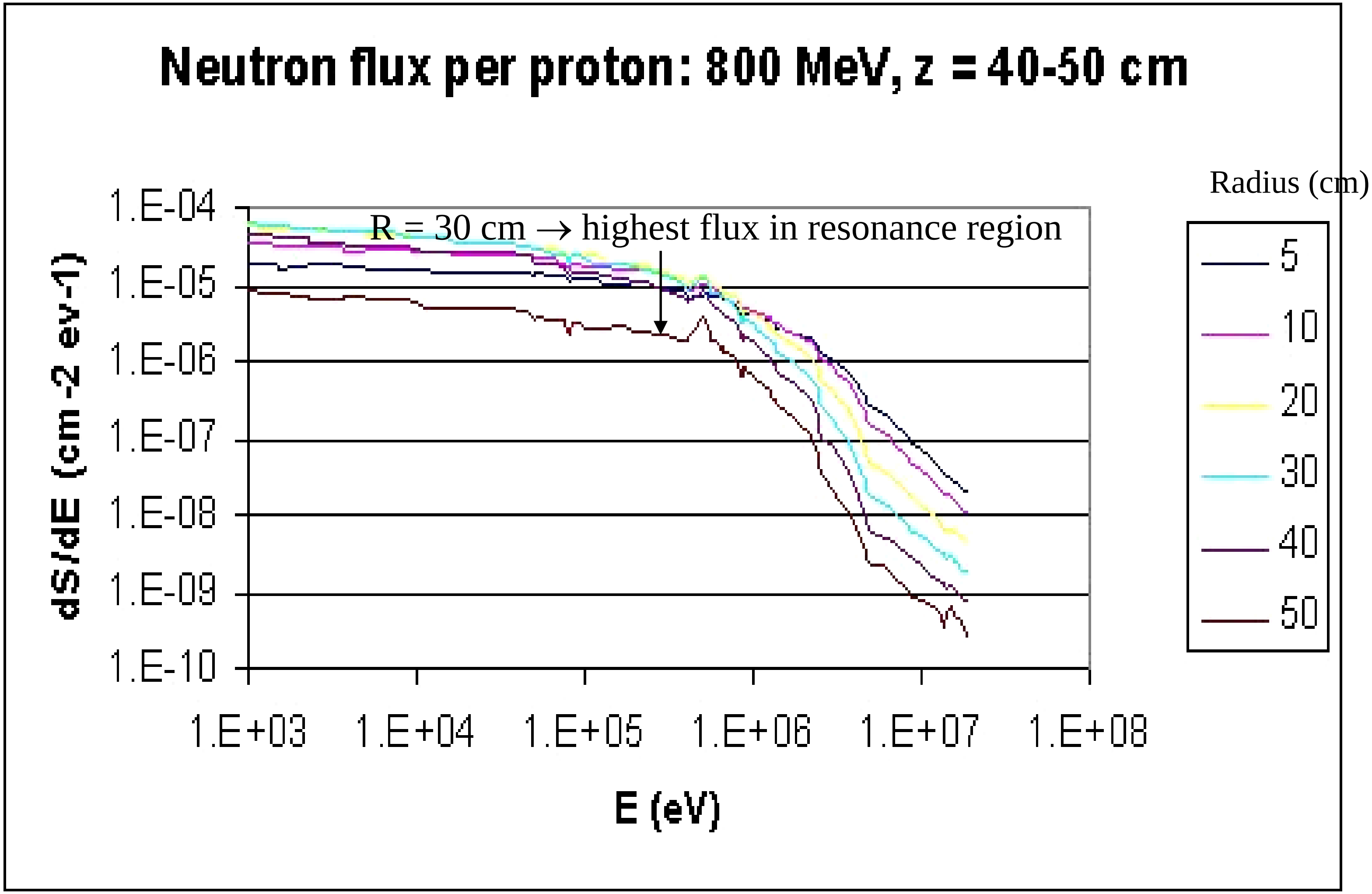
Model spallation source, neutronics in core



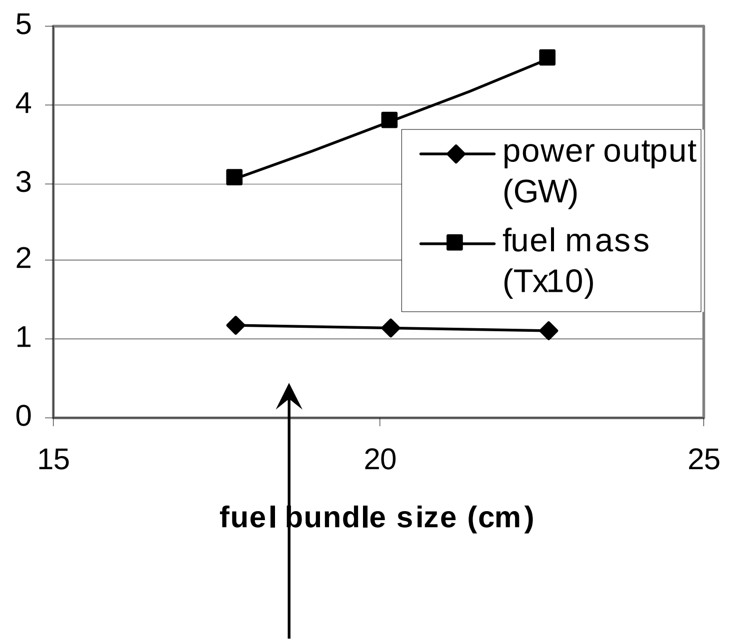


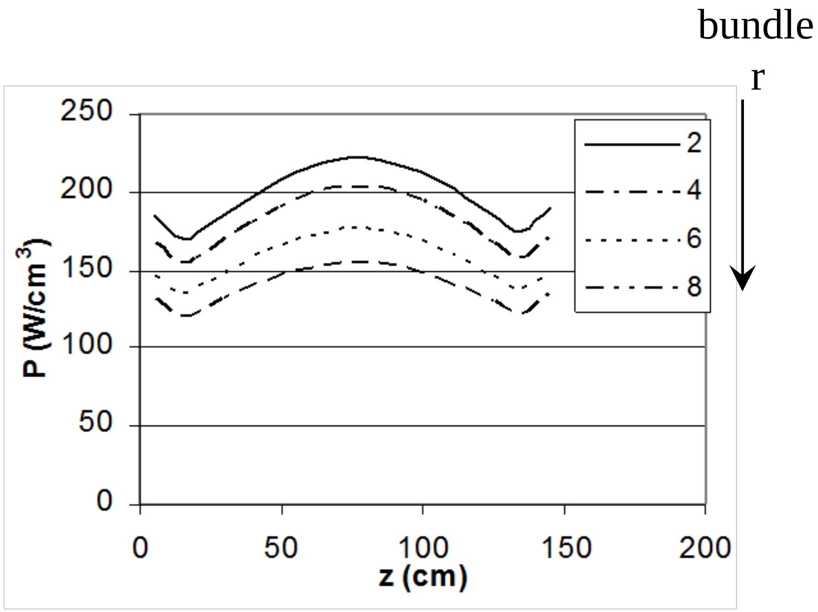
Slice through one sextant of the core

Neutron spectrum in Spallation



Optimize core geometry

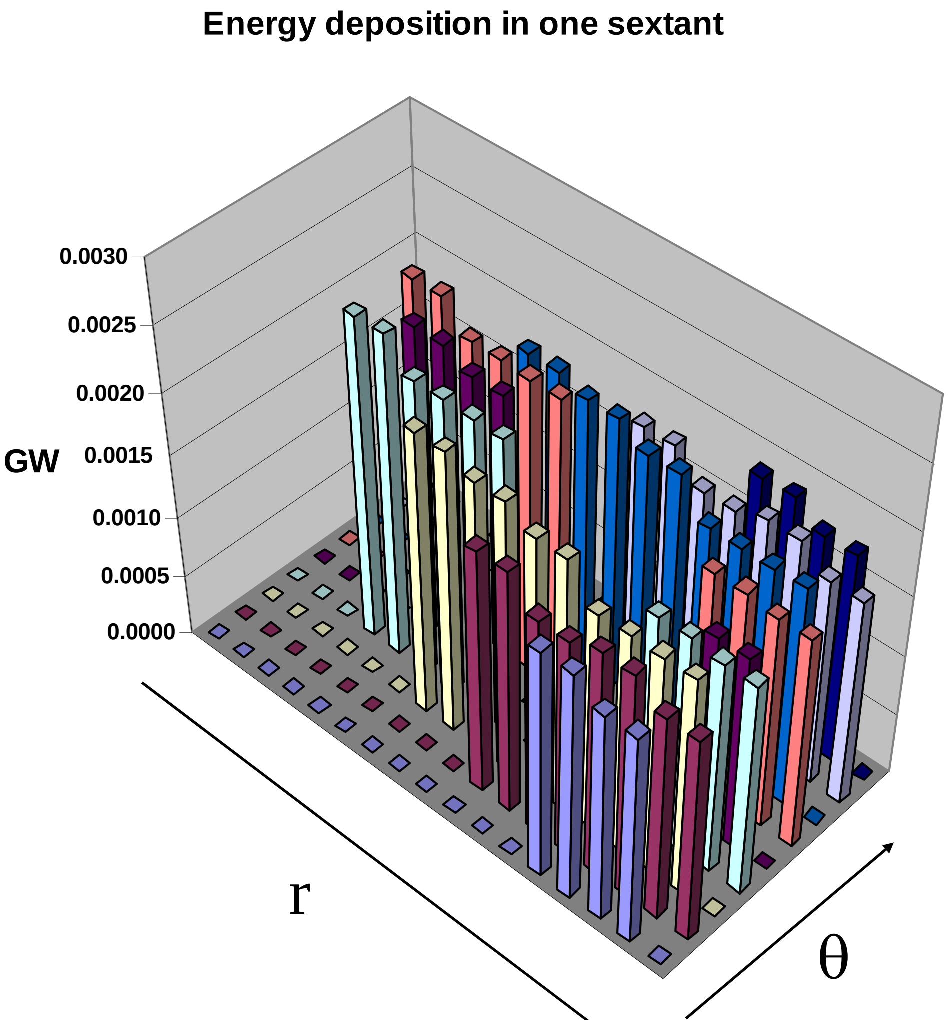




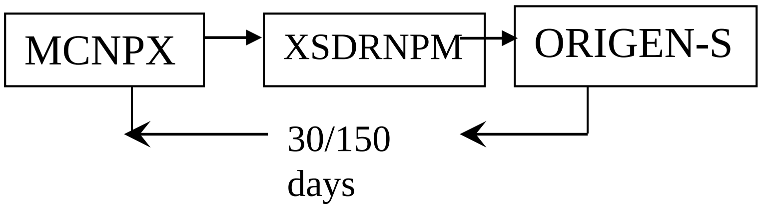
Optimize fuel bundle for power output, total fuel mass → 18 cm

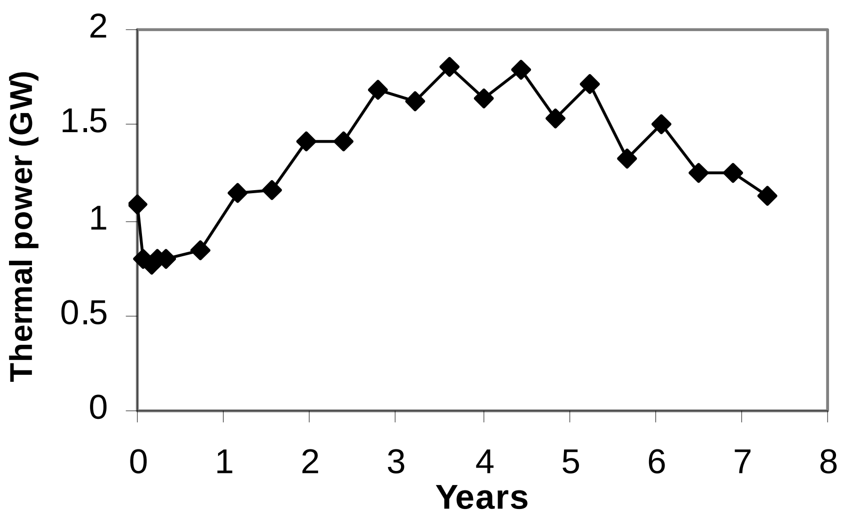
Arrange bundles to flatten power distribution at startup.

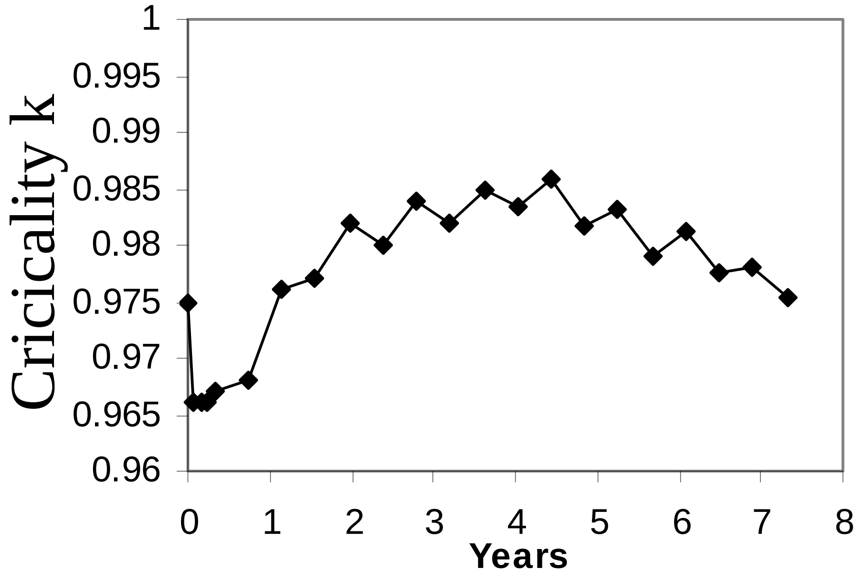
Power distribution in one sextant



Power and Criticality through Core Lifetime

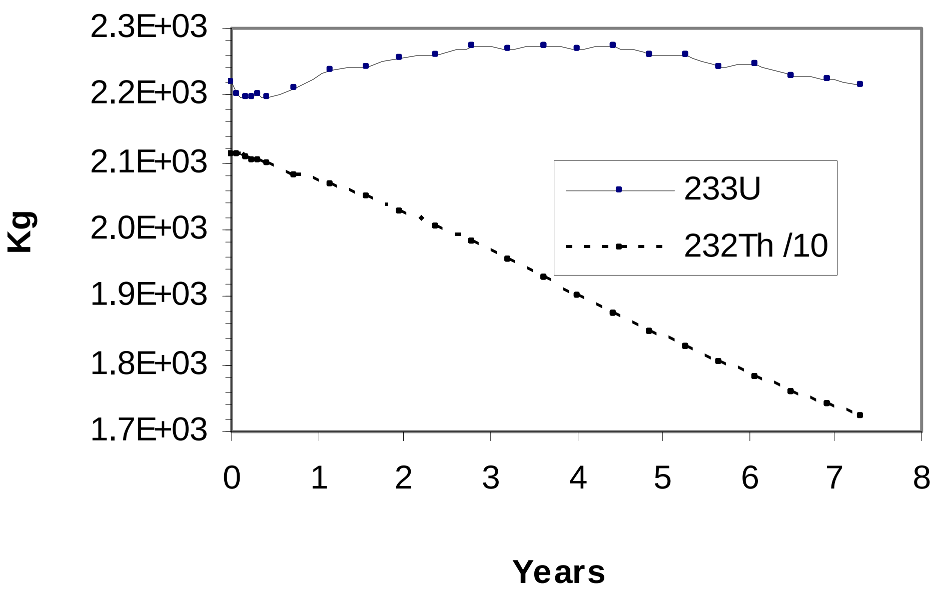


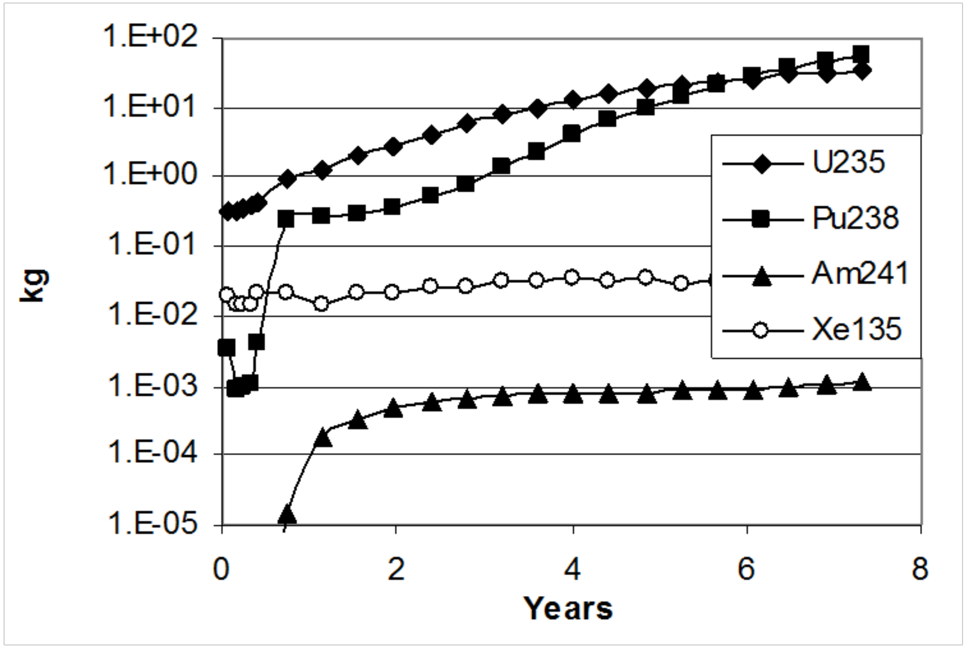




The 7-beam IC-driven thorium cycle operates as a sealed core for 7 years – no re-shuffle of fuel pins, better control for non-proliferation.

Isotope inventory through life cycle



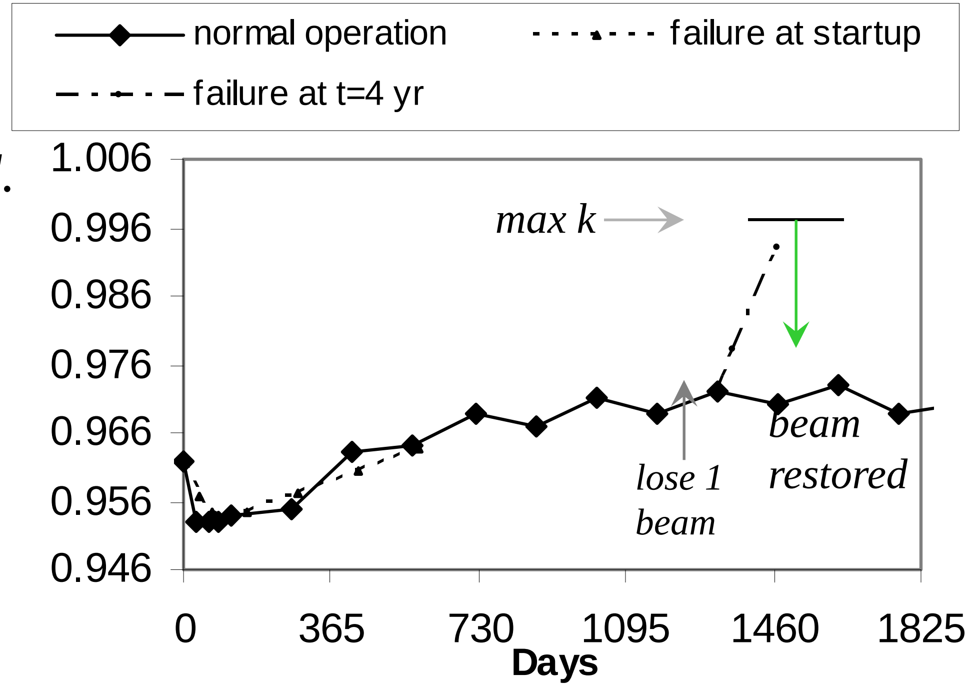


Very small inventories of waste isotopes (*e.g.* ^{241}Am),
very little bomb-capable isotopes (^{235}U, ^{238}Pu)

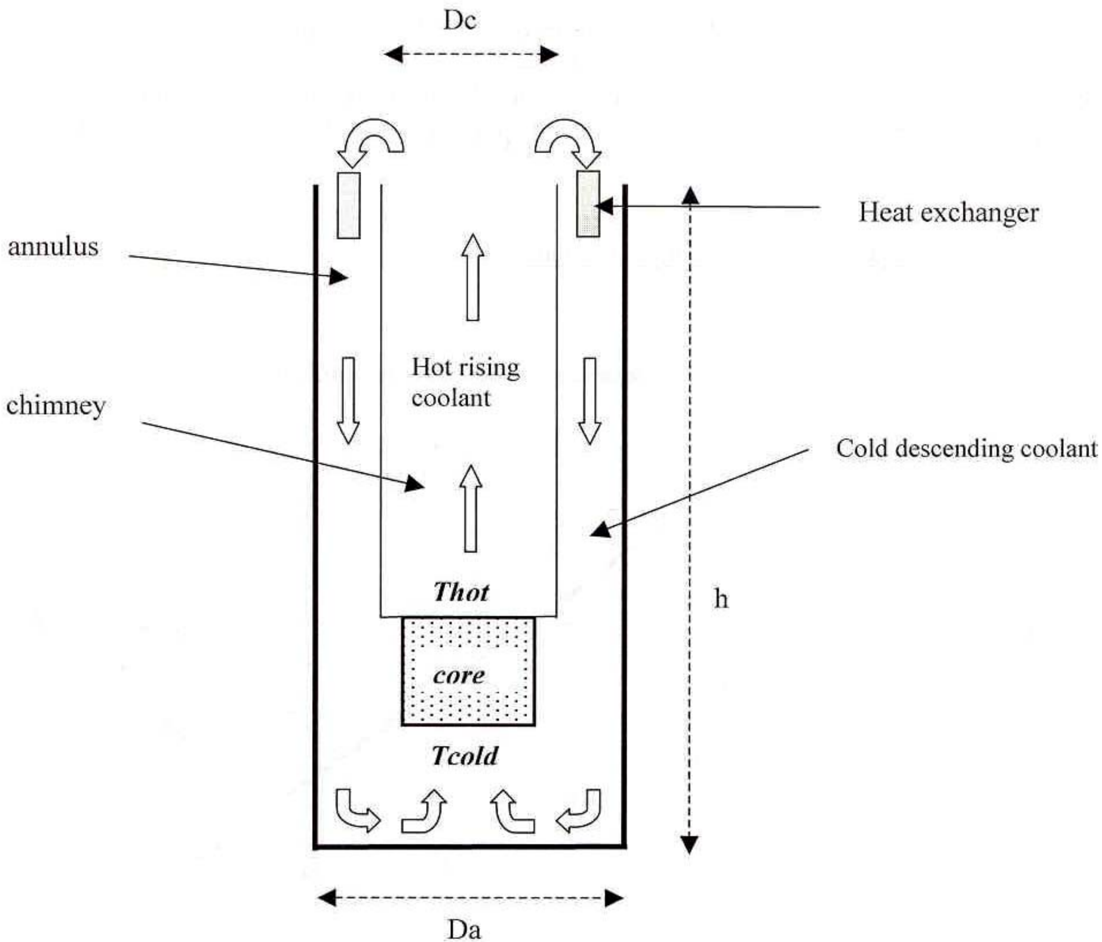
What happens if we lose one drive beam?

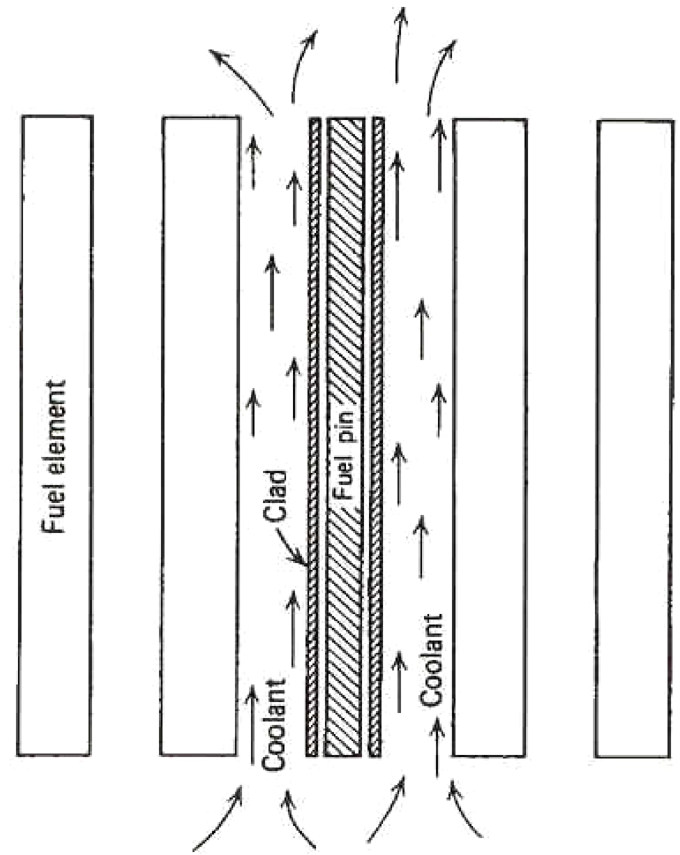
The transmutation sequence has a time delay:

- $^{232}Th + n \rightarrow {}^{233}Th$
- $^{233}Th \rightarrow {}^{233}Pa + \beta$ (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.*
- $\Delta k = +.02$ *due to local* ^{233}U *spike*
- *k returns to normal when beam restored.*
- *Bottom line: Must design for k ~ 0.97*



Convective heat transport

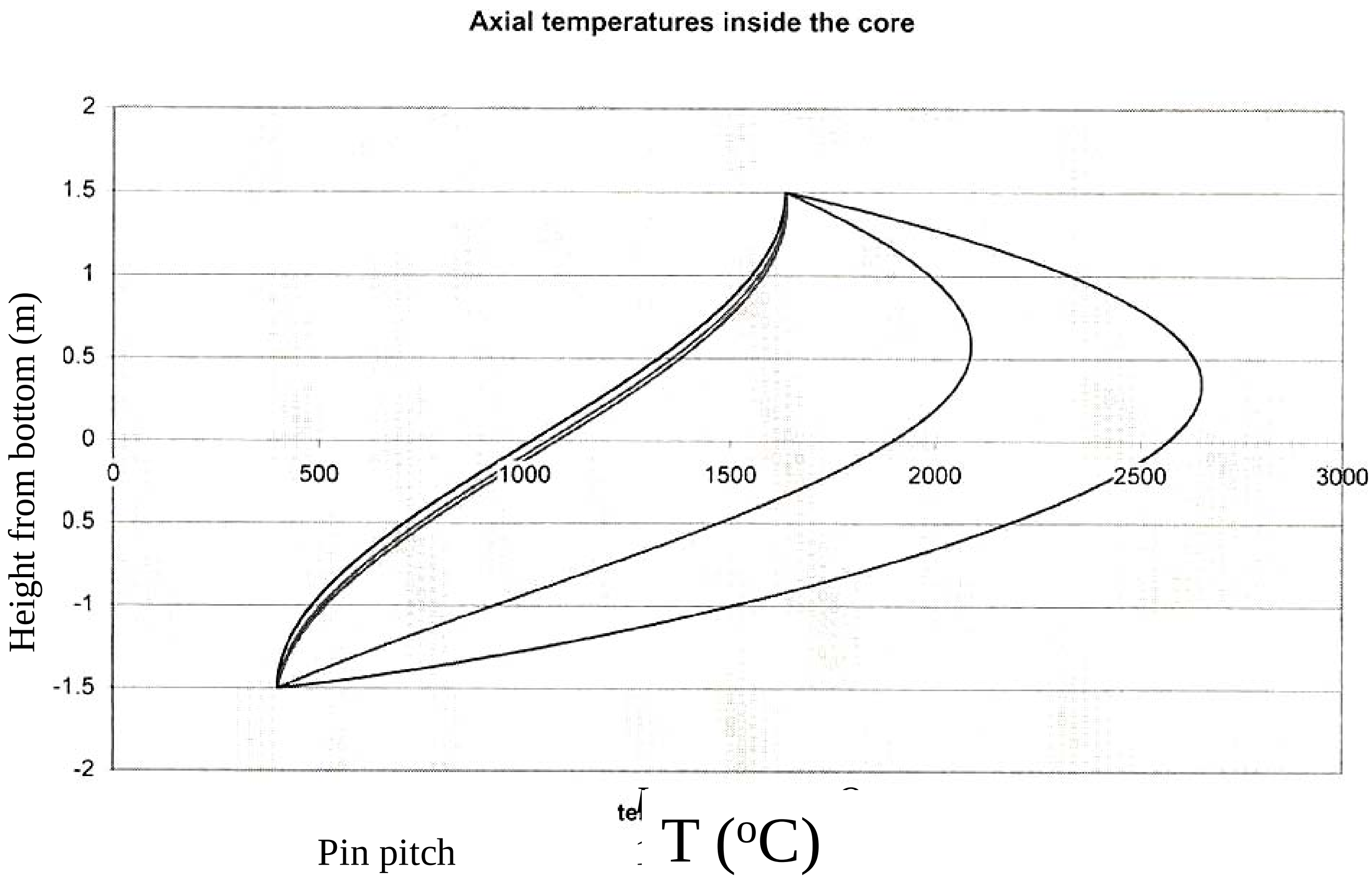




in core and convection column

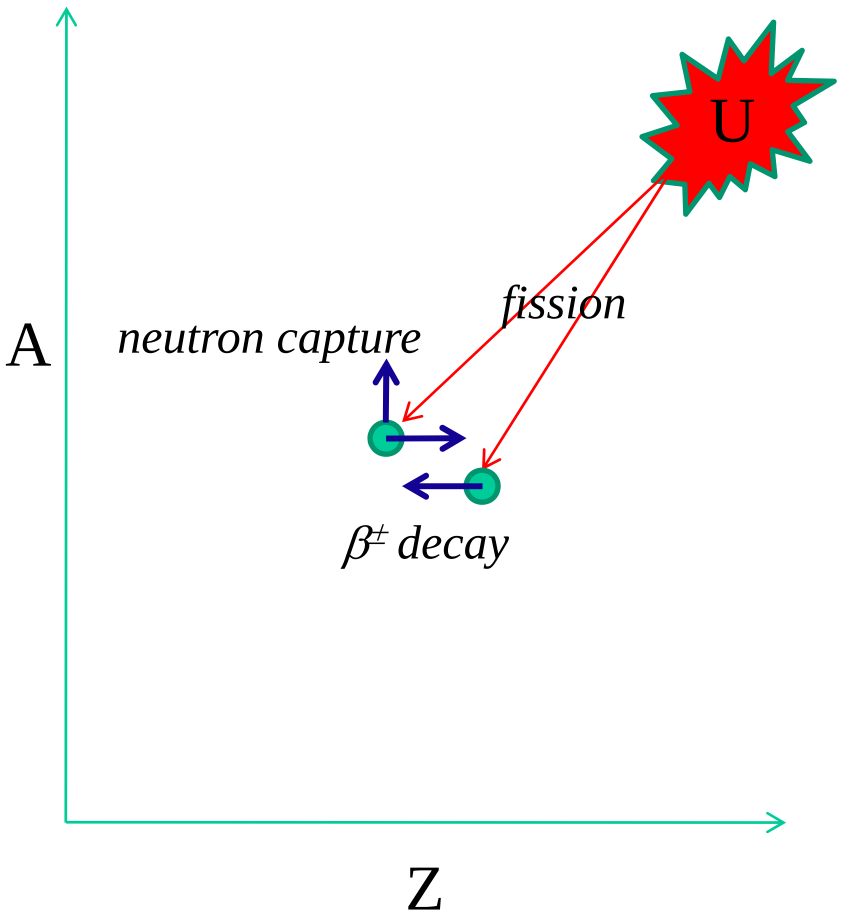
in fuel element subchannel

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?

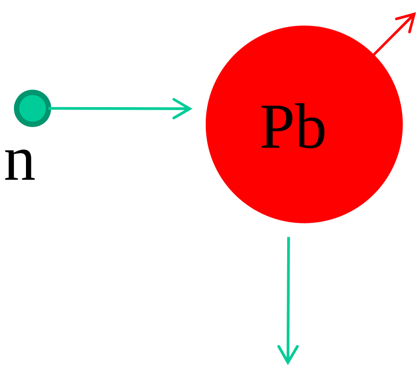


The fission products populate the center of the table of isotopes.
Most such isotopes can capture thermal neutrons (↑) and also undergo either beta decay (→) or inverse beta decay (←), so each nuclide diffuses among many values (Z,A).
But there are a few bad guy isotopes with beta decay ½ life ~1000 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!

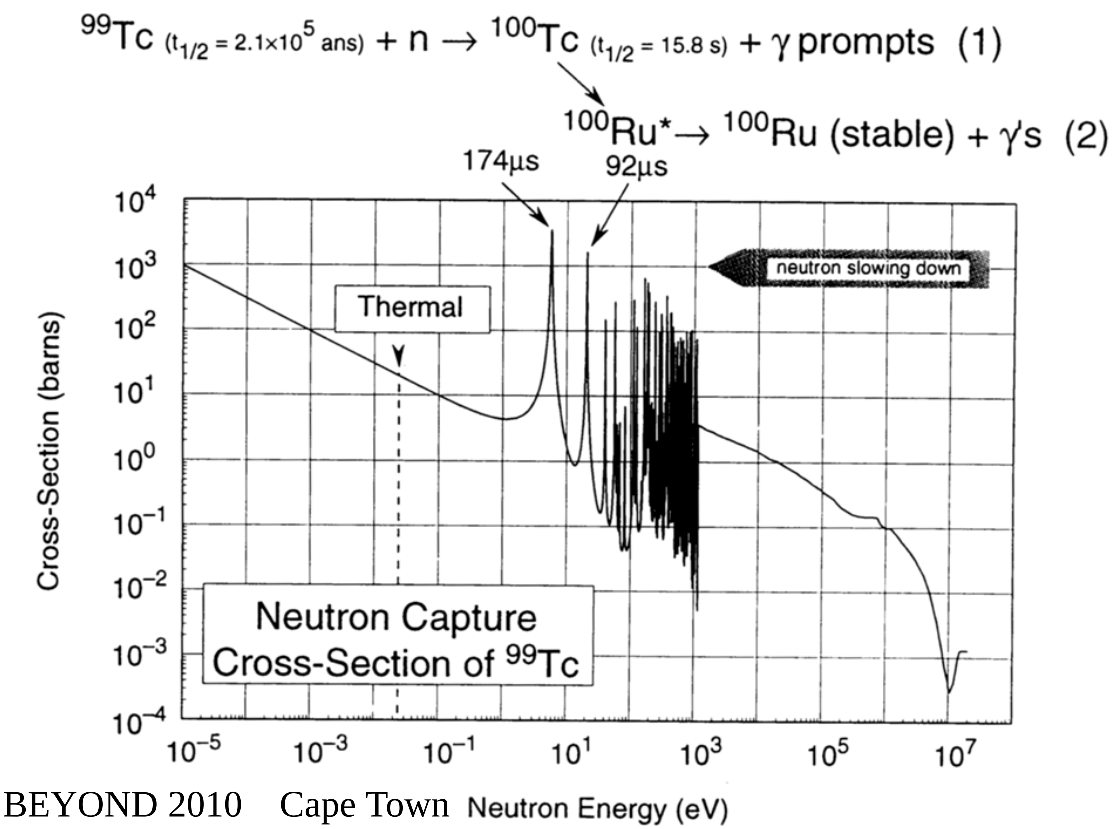


Ping-pong ball hits bowling ball:

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

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

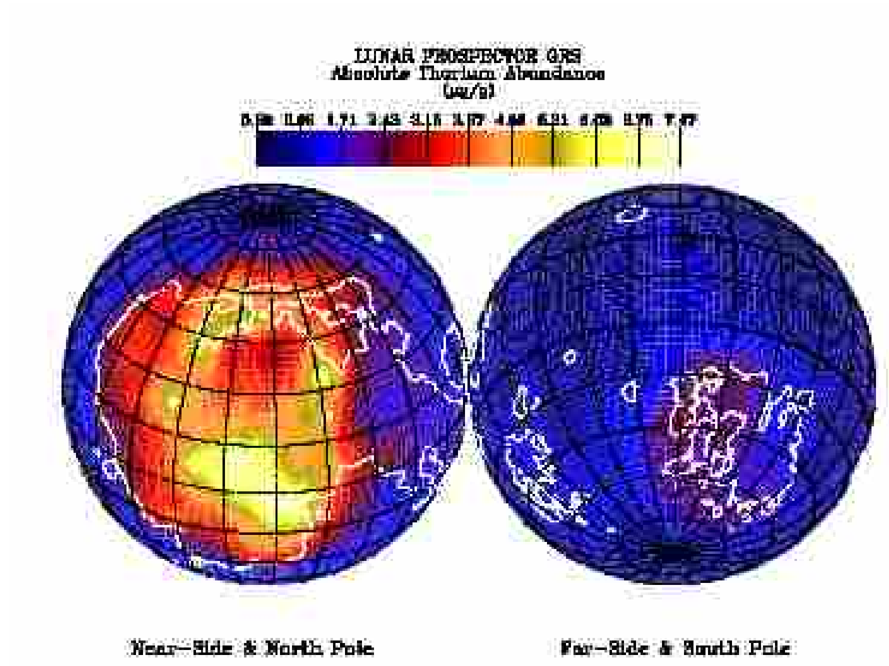
$$\frac{\Delta T}{T} \sim \frac{m}{M} \sim 0.3\%$$



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!

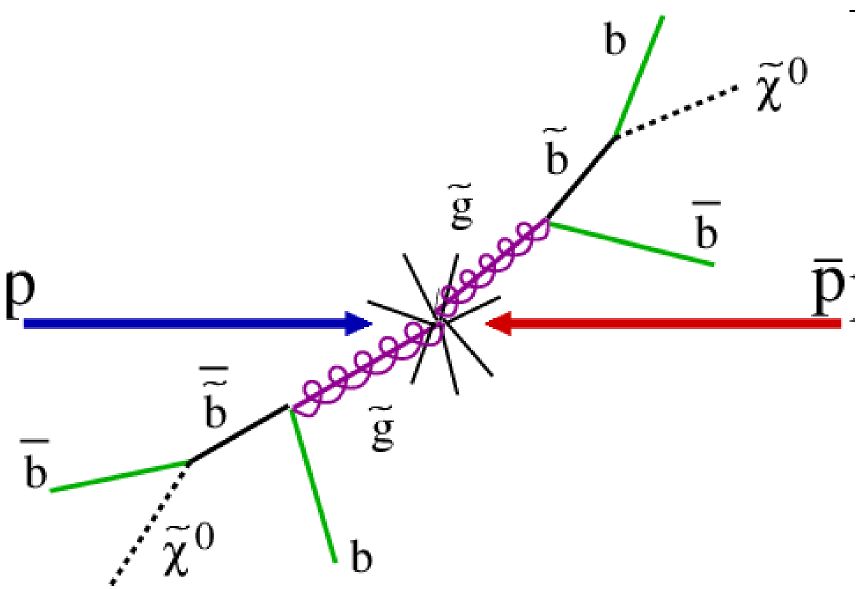
world energy demand:

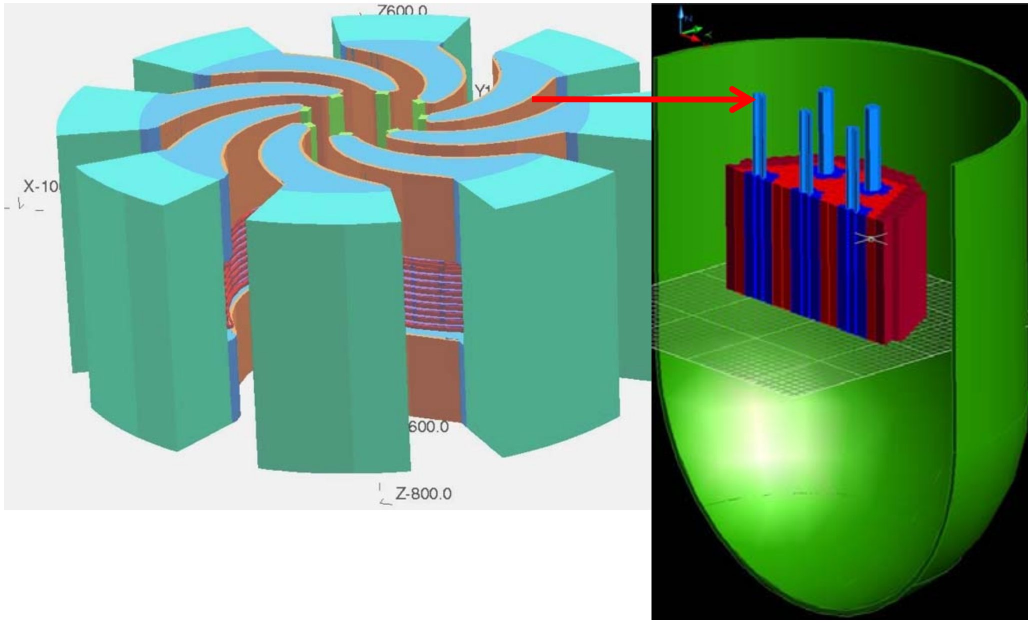
~ 1,000 ton/year of thorium

Conclusions

New superconductors and new magnet technology → 100 TeV hadron collider to link new gauge fields to cosmology.

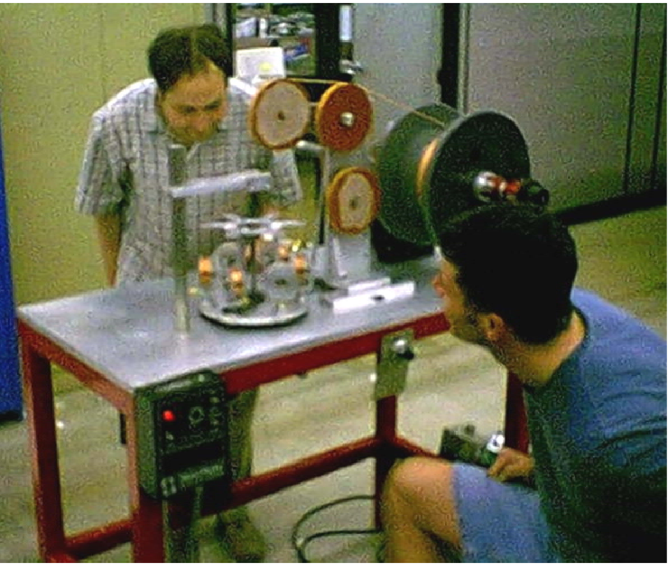
New magnet and cavity technologies and new neutronics make it possible to burn desert sand to provide man's energy needs for a thousand years.

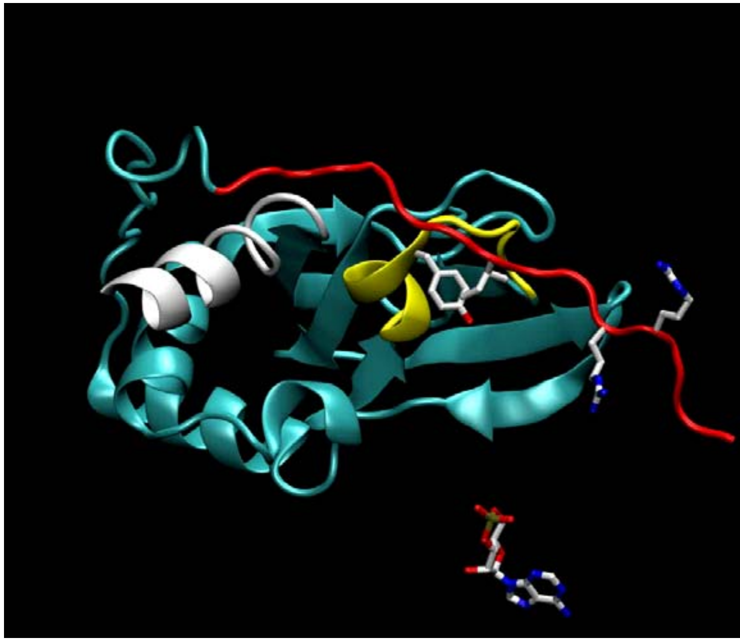




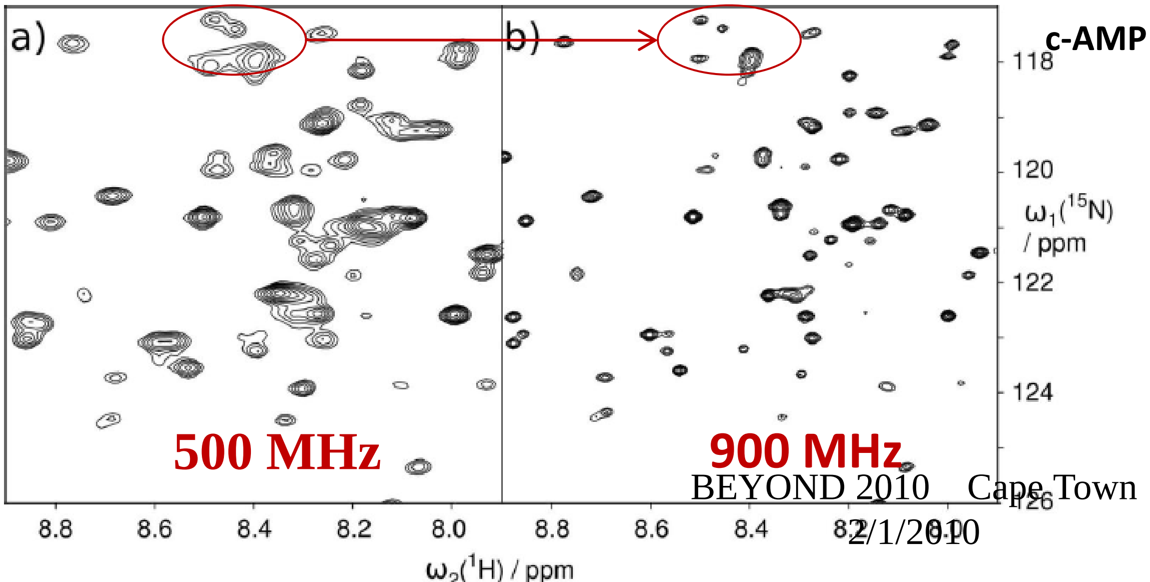
And these technologies lead to other good things…

GHz NMR Spectroscopy for Molecular Medicine

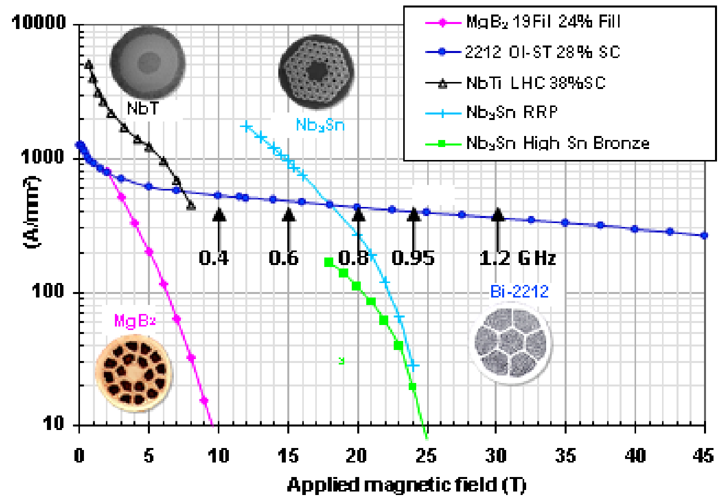




Tame high-field superconductor Bi-2212 to cable, coils.



c-AMP antagonist of protein kinase in breast cancer



Alpha Magnetic Spectrometer

Comparison of Parameters

	Tevatron	SSC	LHC nominal	100 TeV	100 TeV	
collision energy E	2	40	14	100	100	TeV
gamma	1,066	21,322	7,463	53,305	53,305	
luminosity	1.5E+32	5.6E+32	6.6E+33	1.0E+34	1.0E+35	$cm^{-2}s^{-1}$
# bunches	36	16,440	2,800	11,000	11,000	
# interactions/ collision	5	2	7	45	85	
bunch spacing T_b	396	16	25	20	20	ns
insertion optics:						
betamax	0.8	8.1	5.0	4.0	4.0	km
betamin	0.35	0.5	0.55	1	1	m
total head-on BB tune shift	0.0070	0.0012	0.0024	0.0047	0.0093	
total tune shift	0.0022	0.0034	0.002	0.0022	0.0022	
low-beta gradient	141	230	250	500	500	T/m
lattice magnets:						
dipole field	4.4	6.79	8.39	16.34	16.34	T
quad gradient	74	230	220	440	440	T/m
dipole length	6	17	14.3	20	20	m
circumference	6.28	83.631	26.7	83.631	83.631	km
revolution frequency	47.8	3.6	11.2	3.6	3.6	kHz
bend radius ρ	0.8	10.2	2.8	10.2	10.2	km
betatron tune	20	95	63	81	81	
# dipoles	840	3832	1250	3256	3256	
# rings	1	2	2	1	1	

	Tevatron	SSC	LHC nominal	100 TeV	100 TeV	
particles/bunch:						
p	3	0.075	1.15	0.6	1.2	10^{11}
pbar	1			0.1	0.5	10^{11}
transverse emittance e:						
p	3.3	1	3.75	1	1	p10^{-6}m
pbar	3			1	1	p10^{-6}m
rms bunch length	55	6	7	6	6	cm
full crossing angle	0	150	285	150	150	mrad
Piwinski parameter		0.90	0.58	1.01	1.01	
total energy/beam	2	395	361	5280	10560	MJ
# beam abort/dumps	1	1	1	4	4	
total # protons	1	12	32	66	132	10^{13}
total # antiprotons	0.36			11	55	10^{13}
antiproton consumption	0.01			0.7	7.2	10^{13}/hr
antiproton source:						
# production targets	1			2	20	
# debuncher rings	1			24	241	
debuncher accum rate	3			3	3	10^{11}/hr
# accumulators	1			2	2	
accumulator capacity	0.4			22.5	12	10^{13}
store time T_s	33		24	15	8	h
synchrotron radiation:						
power/magnet		5	6	647	1572	W
critical energy	0.4	281	44	4391	4391	eV
energy loss/turn		0.122	0.007	4.8	4.8	MeV
damping time:						
longitudinal		13	26	0.8	0.8	h
transverse		25	52	1.6	1.6	h

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