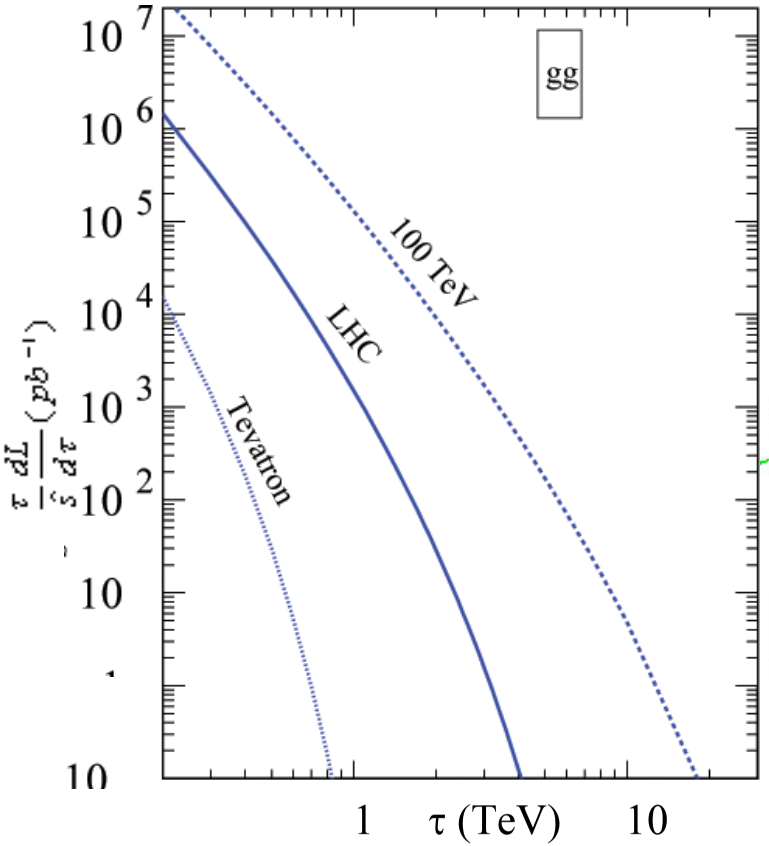
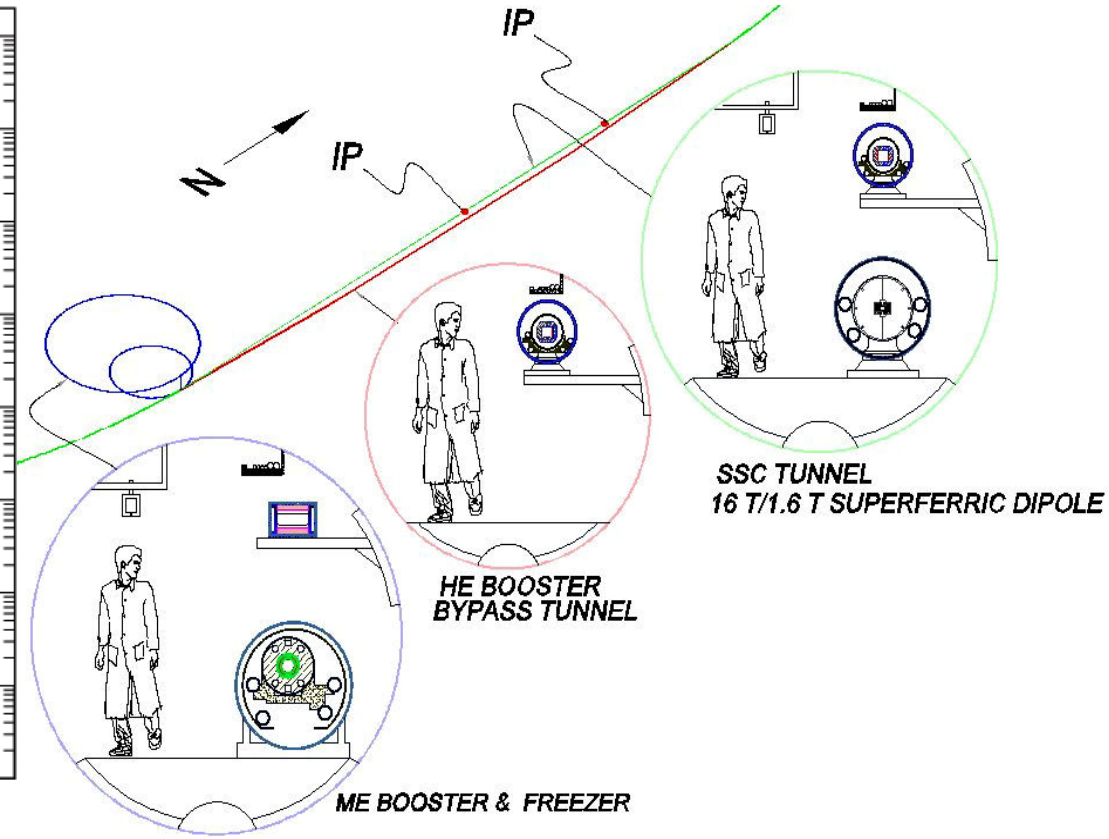
Petavac

Boson-Boson Collisions at 100 TeV





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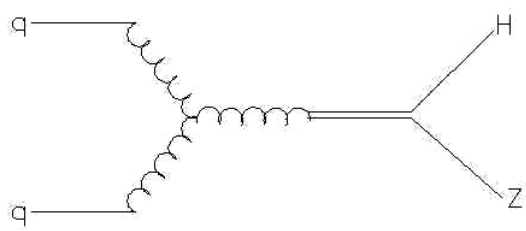
Hadron colliders are the only tools that can directly discover gauge particles beyond TeV

- 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 $\rightarrow$40 $\rightarrow$80 $\rightarrow$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?

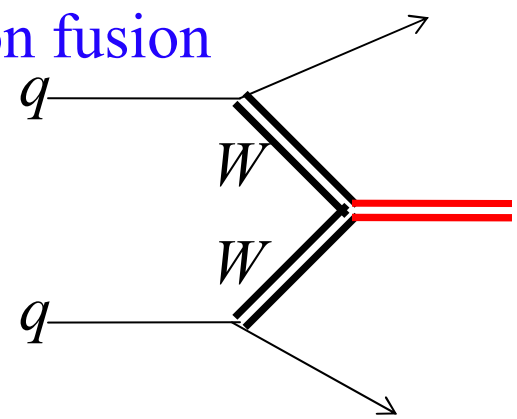
Mass reach for new physics

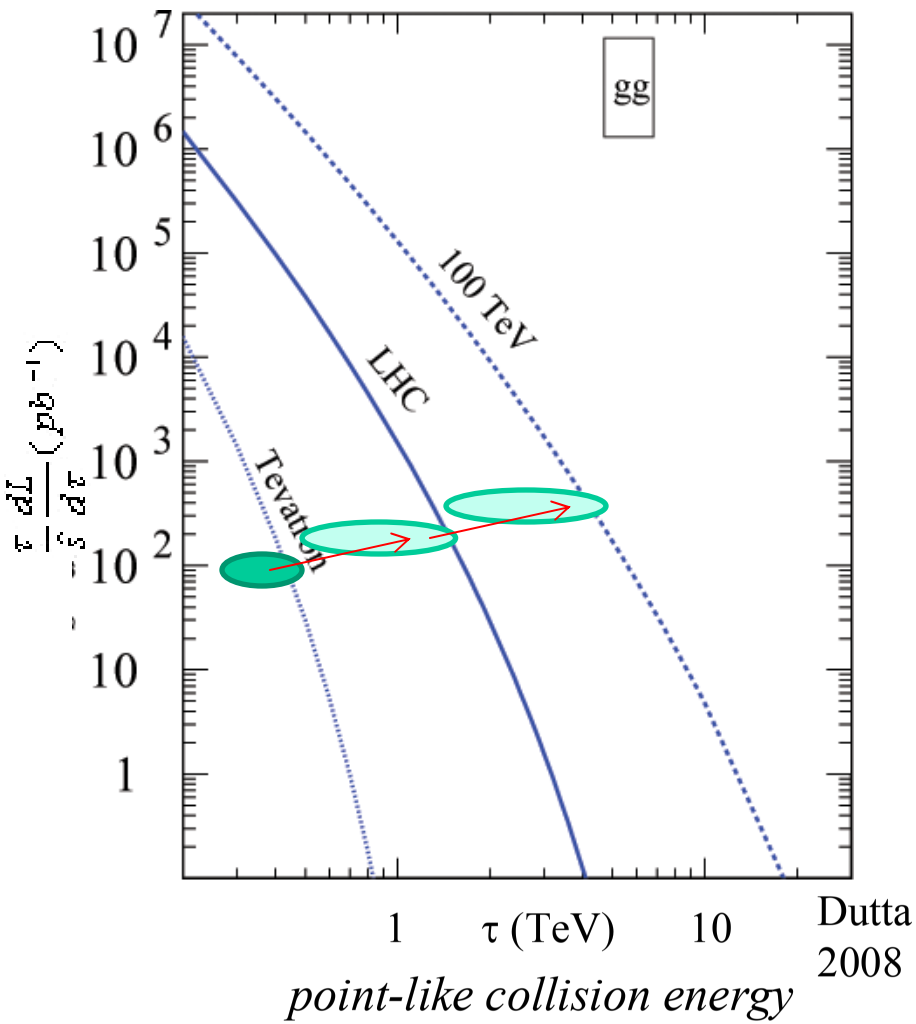
Tevatron accessed new physics through $q\bar{q}$ annihilation.

LHC will access new physics through gluon fusion:



Petavac will access new physics through boson fusion





Dutta 2008

7x the collision energy → 3x the mass reach

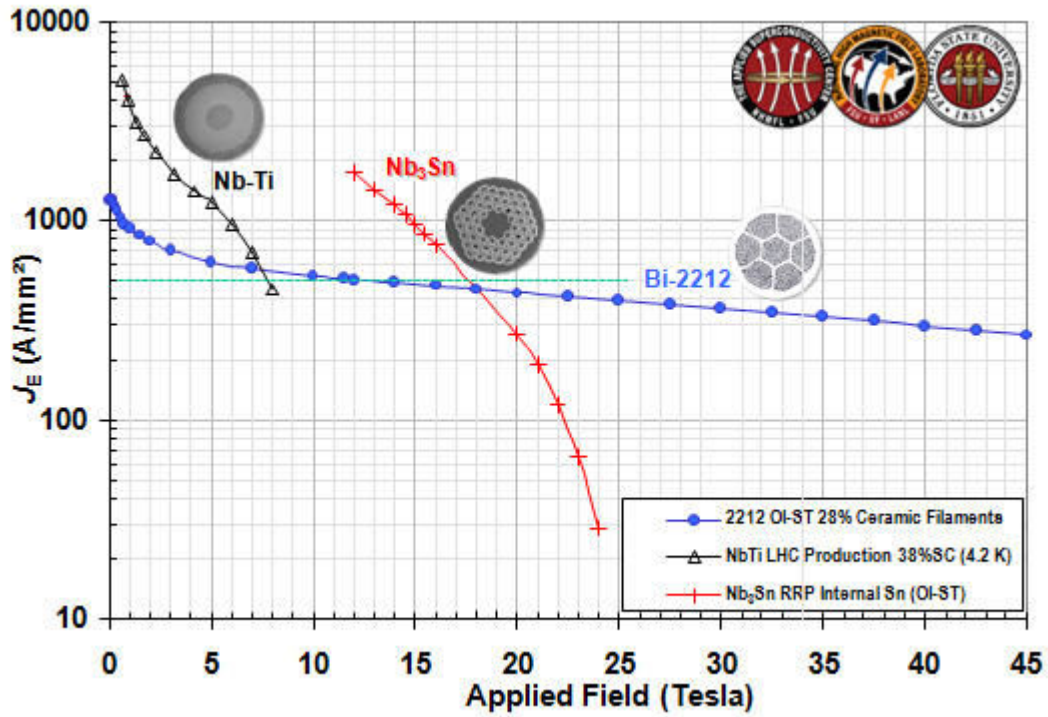
A new vision for the future of high-energy discovery beyond LHC

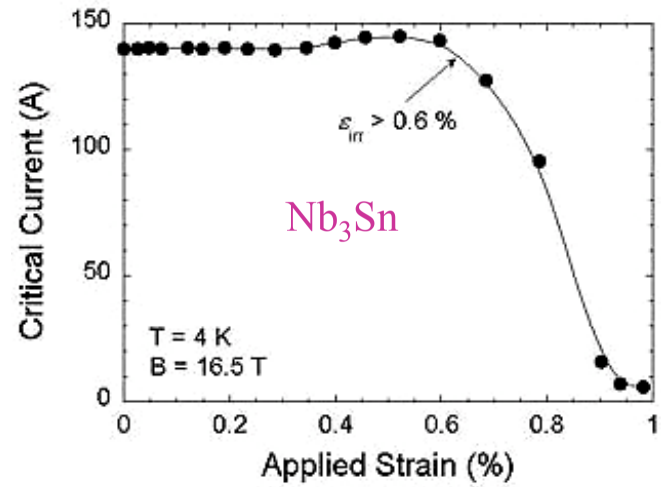
- Hadron colliding beams in the SSC tunnel
- 16 T dipole ring provides 100 TeV collision energy
- Use $\bar{p}p$ so only one magnet ring is needed
- Superferric injector located in the same tunnel

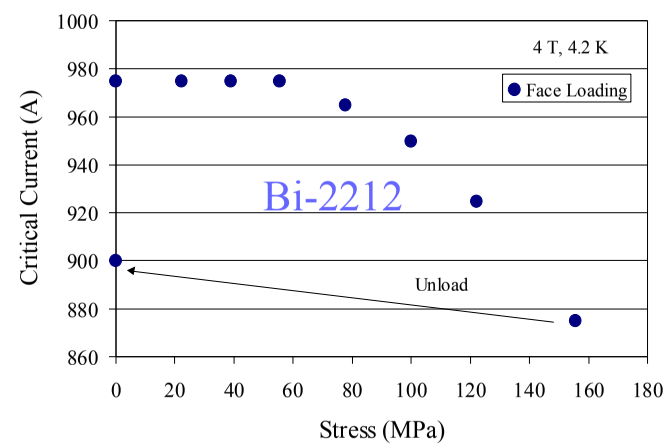
Four developments make this possible to conceive:

- Recent success maturing Nb_3Sn dipole technology
- Commercialization of Nb_3Sn wire for ITER
- Spectacular performance of Fermilab $\bar{p}$ source
- 84 km SSC tunnel is nearly complete, waits for use

We need a new superconductor for 16 T: Nb_3Sn

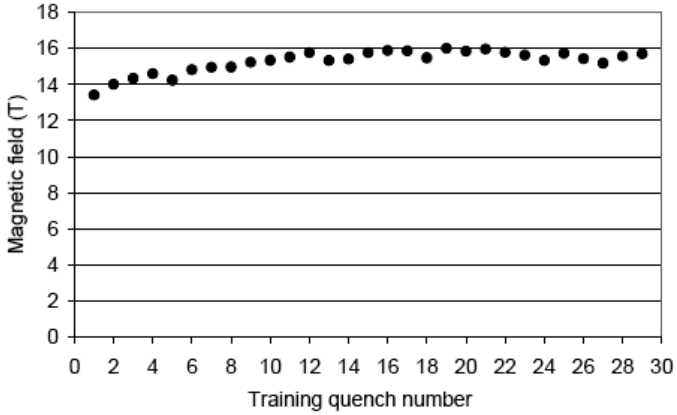




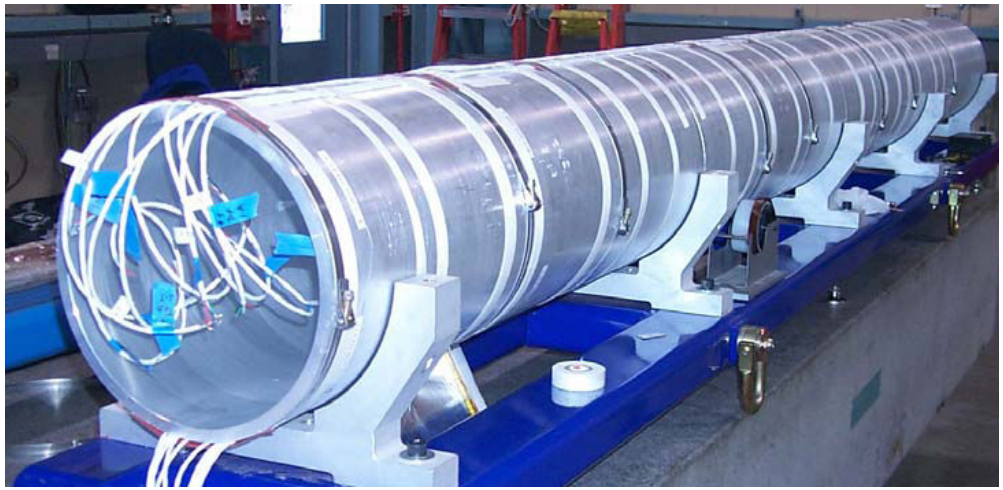


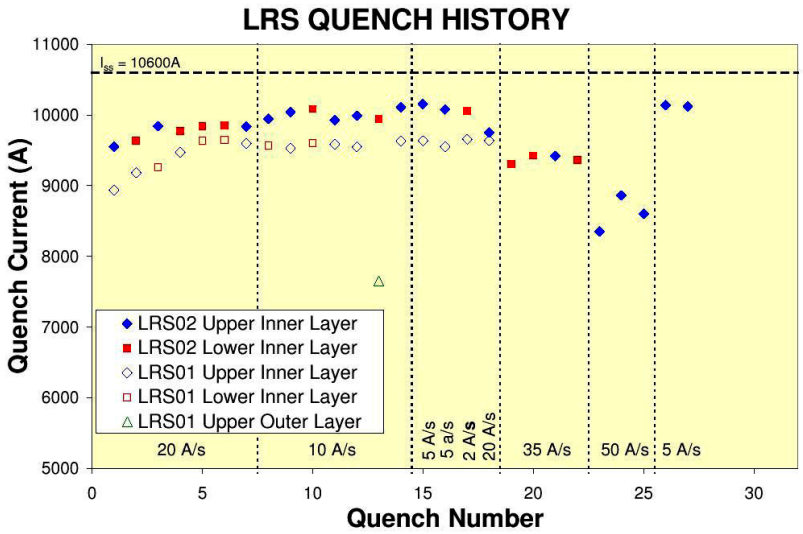
Cost today:	NbTi	\$150/kg
	Nb_3Sn	\$1,000/kg
	Bi-2212	\$2,000/kg

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

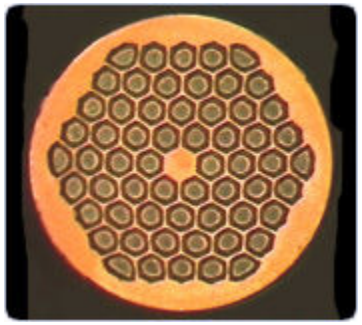


- 4m-long racetrack coils using Nb_3Sn have been built and tested.
  - LARP LRS

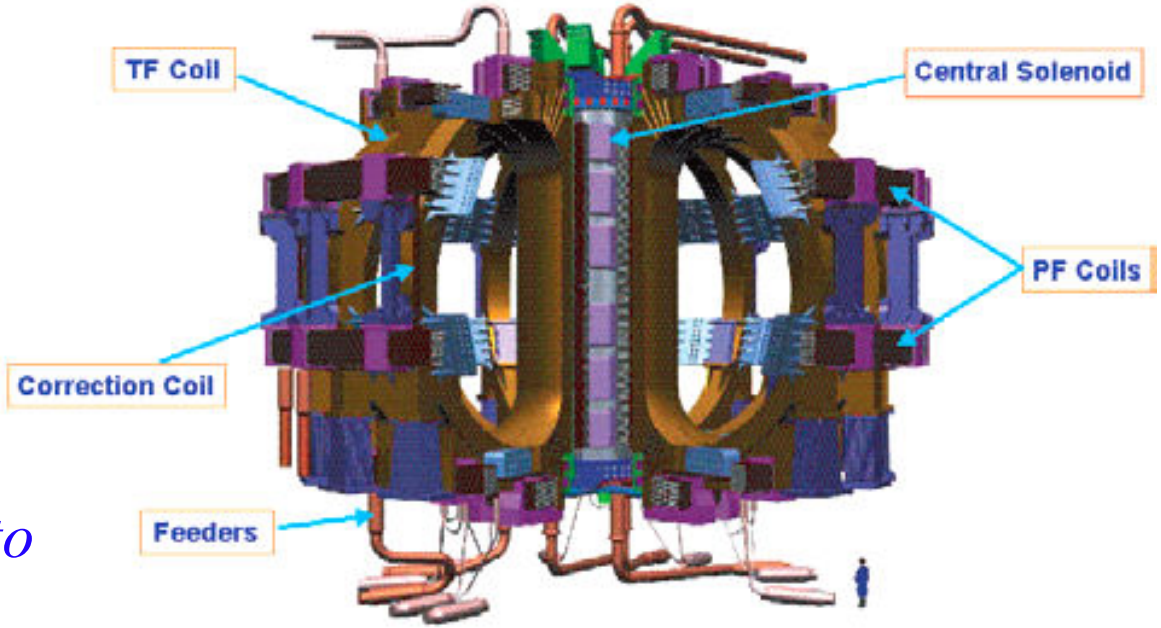




- Nb_3Sn superconducting wire with the necessary performance is developed and commercialized.
  - 3,000 A/mm^2 @ 12 T, 4.2 K in the superconductor

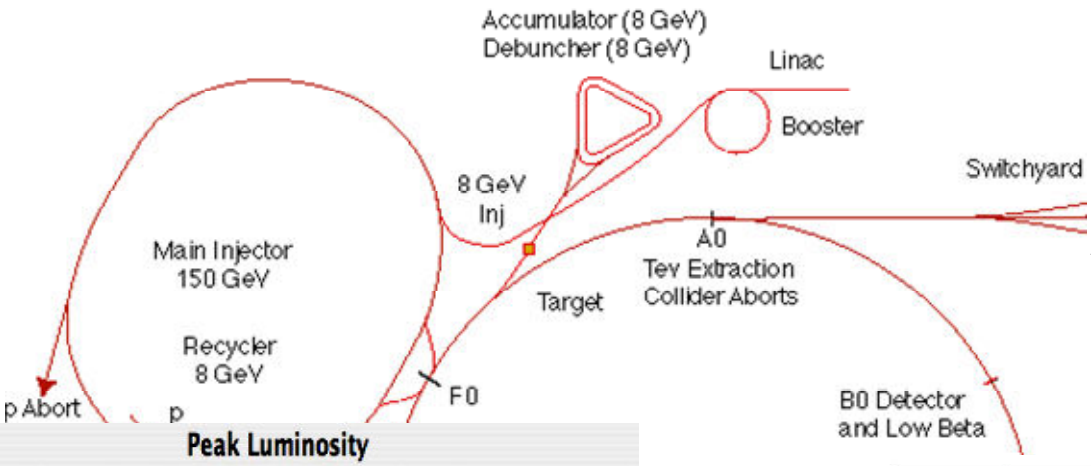


- ITER will use *400 tons* of high-performance Nb_3Sn wire; it will drive the production capacity to what would be needed for Petavac.

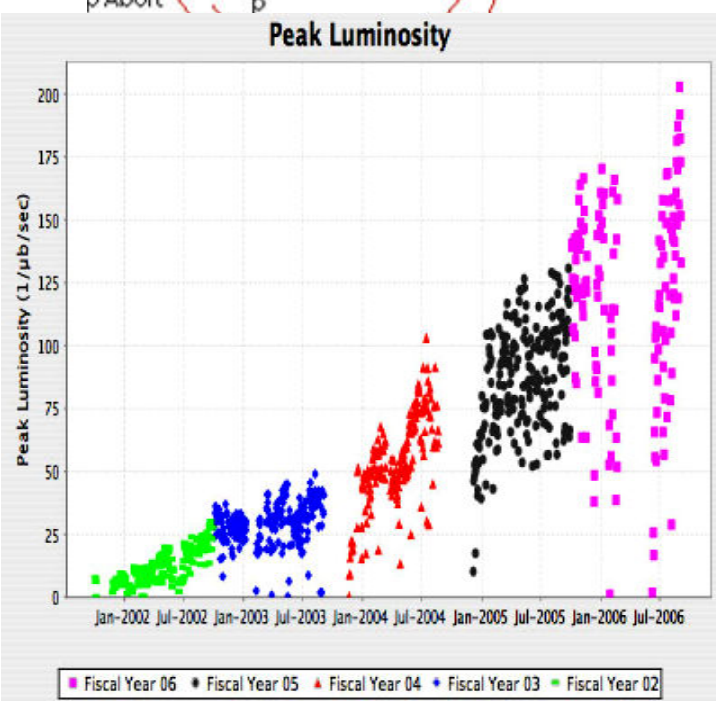


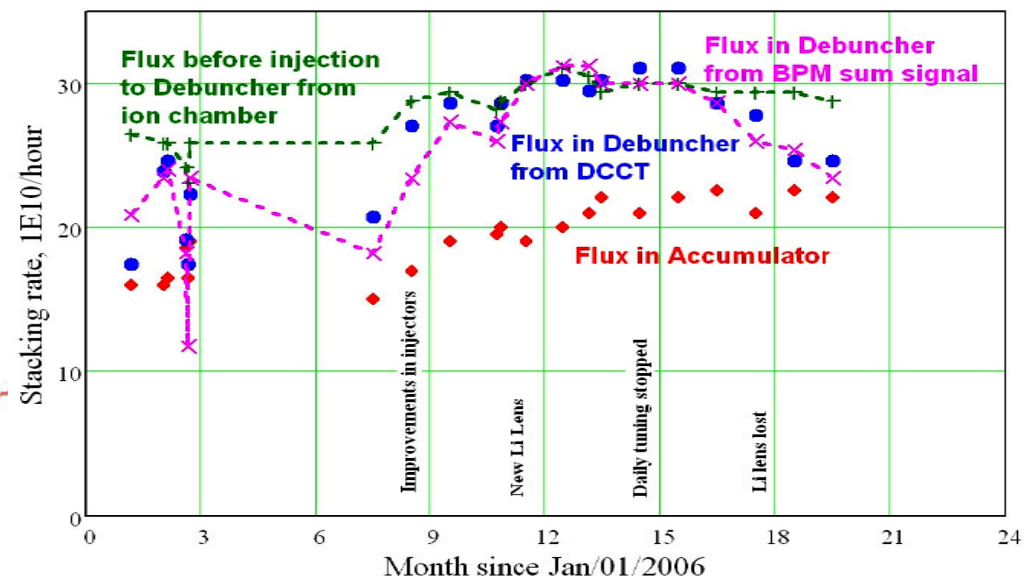
Transition to volume manufacture is predicted to drop Nb_3Sn wire price by half

Fermilab has matured antiproton source technology and electron cooling



- $3\times10^{11}\,\bar{p}$ /hr stacked, capacity for 10x more from target (adjacent Δp windows)
- E-cooling in recycler has capacity for ~$10^{14}\,\bar{p}$





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.

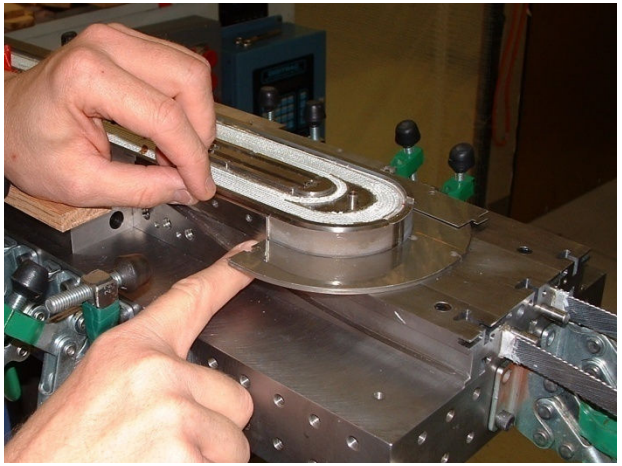
- **Optimized conductor**

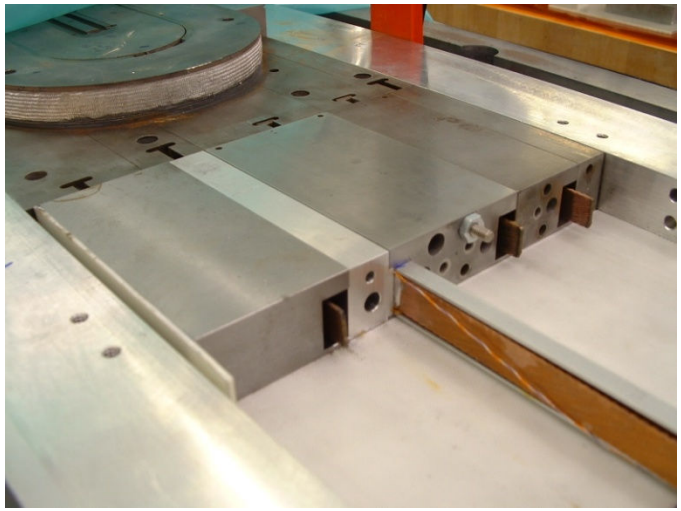
  Separate the copper for quench protection into pure-Cu strands.

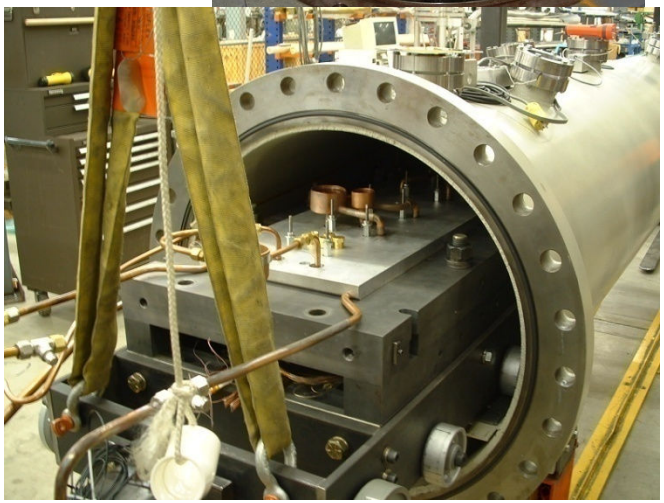
- **Suppress persistent-current multipoles**

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

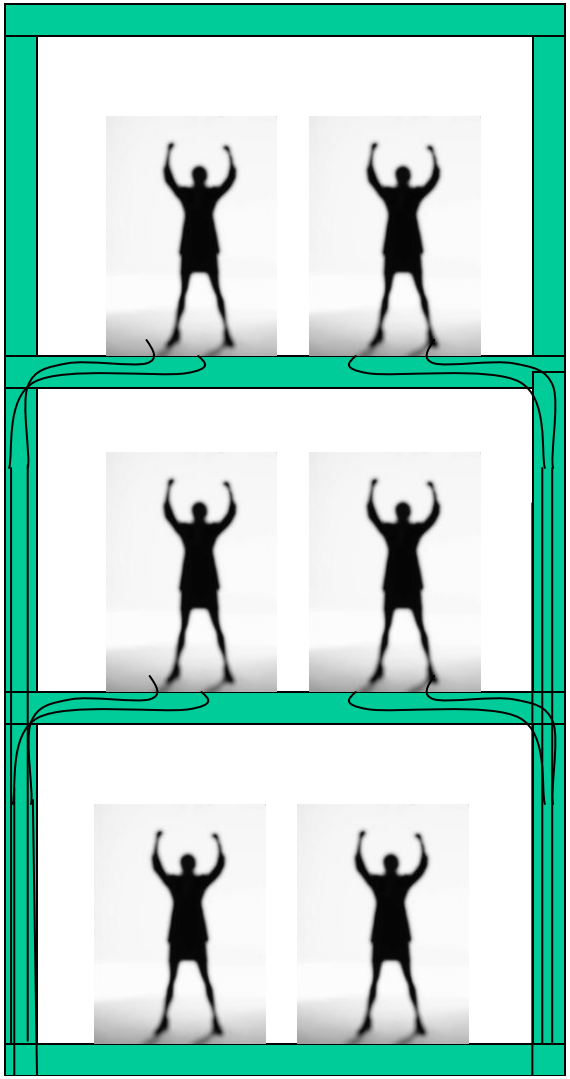
Nb_3Sn dipole technology at Texas A&M:
stress management, flux plate, bladder preload

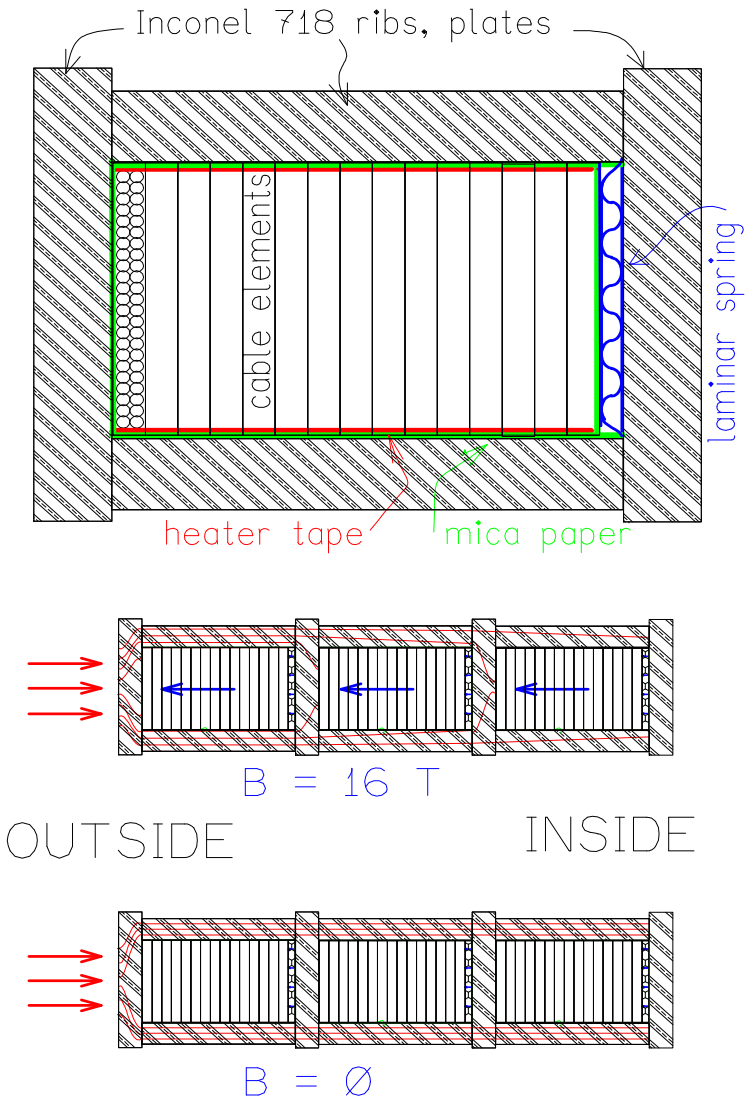






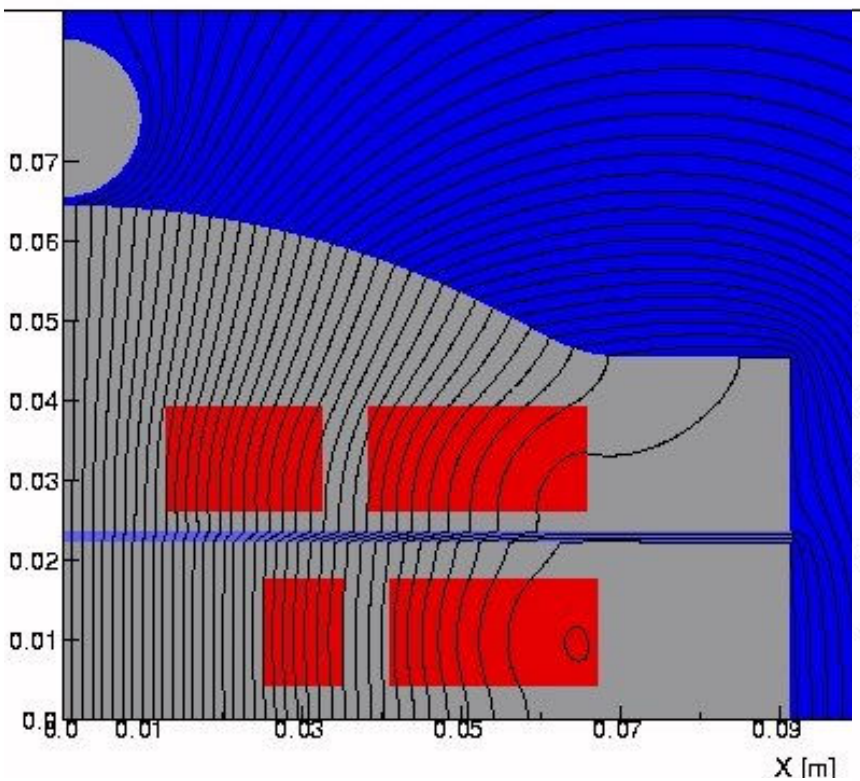
Stress management



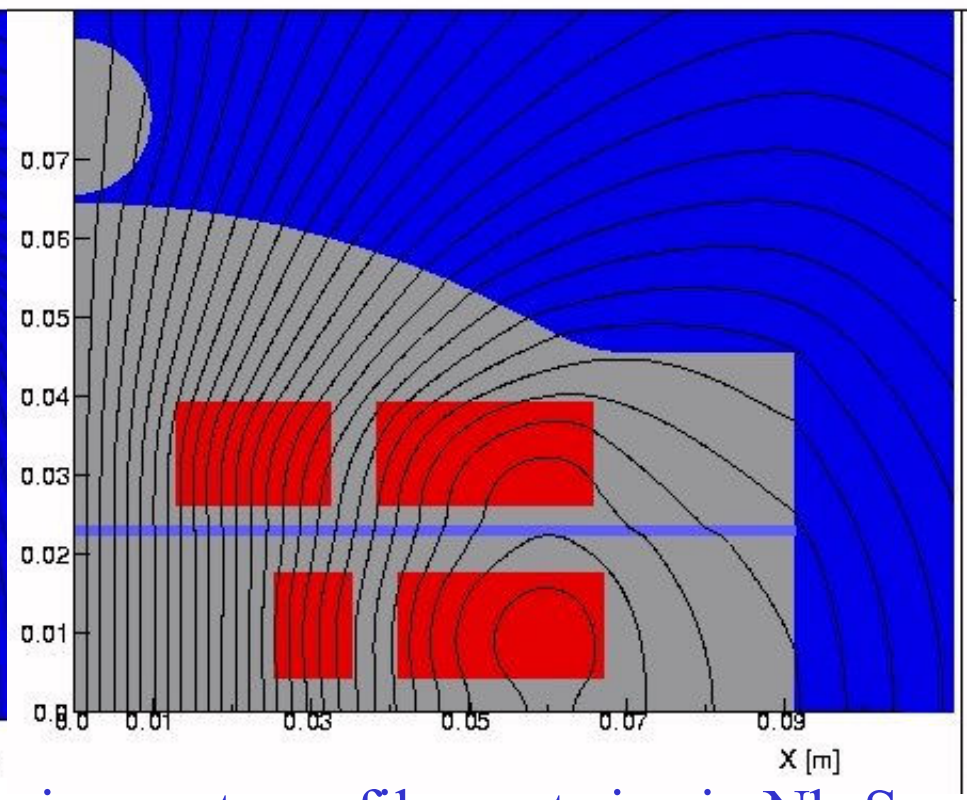


Horizontal steel flux plate redistributes flux to suppress multipoles

0.5 T

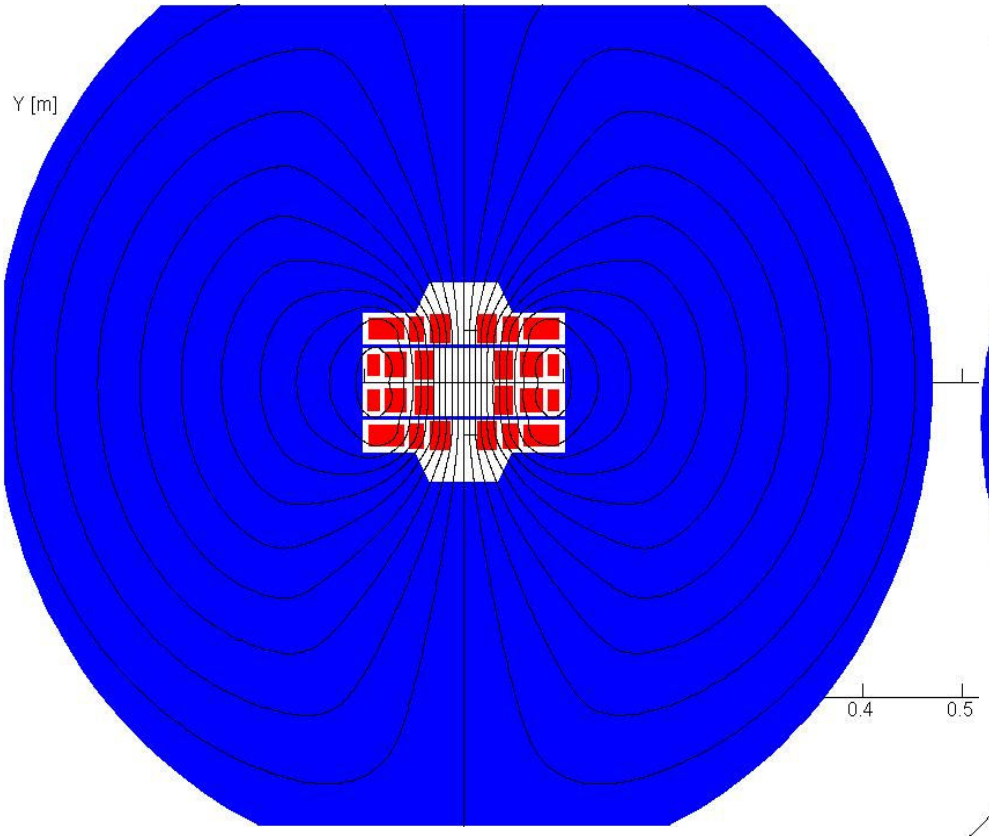


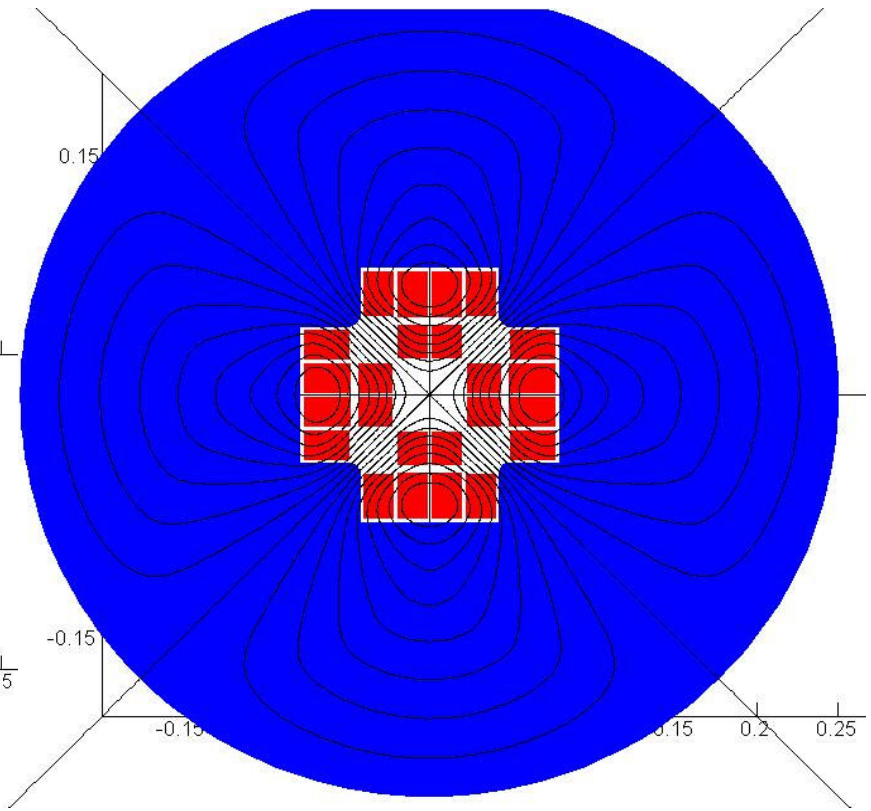
14 T



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

6 cm aperture provides ample room for pretzel separated beams

Ring Dipole

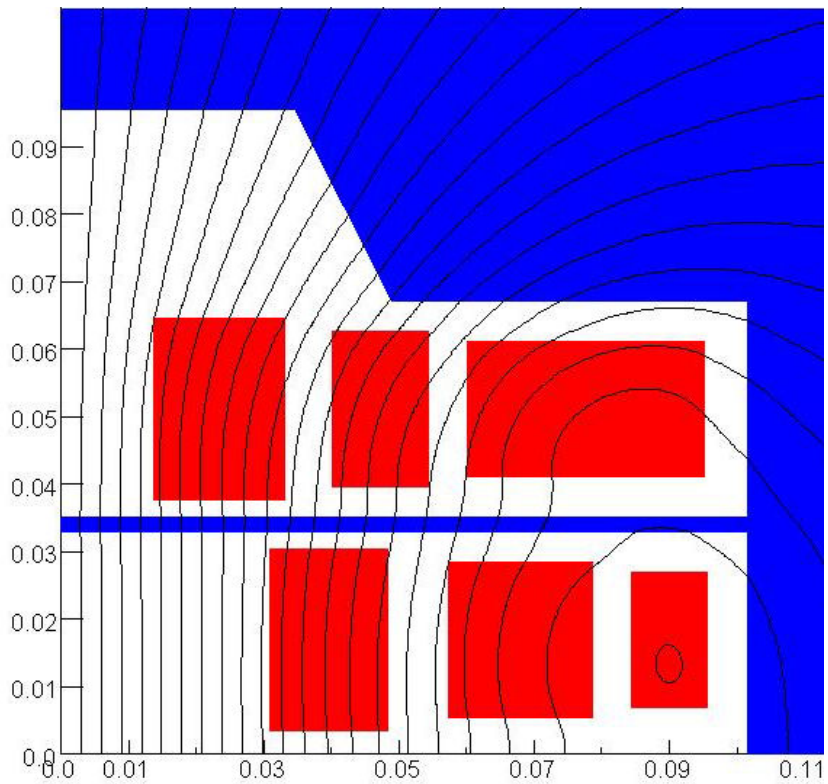
16.8 T central field (short-sample limit), 6 cm bore

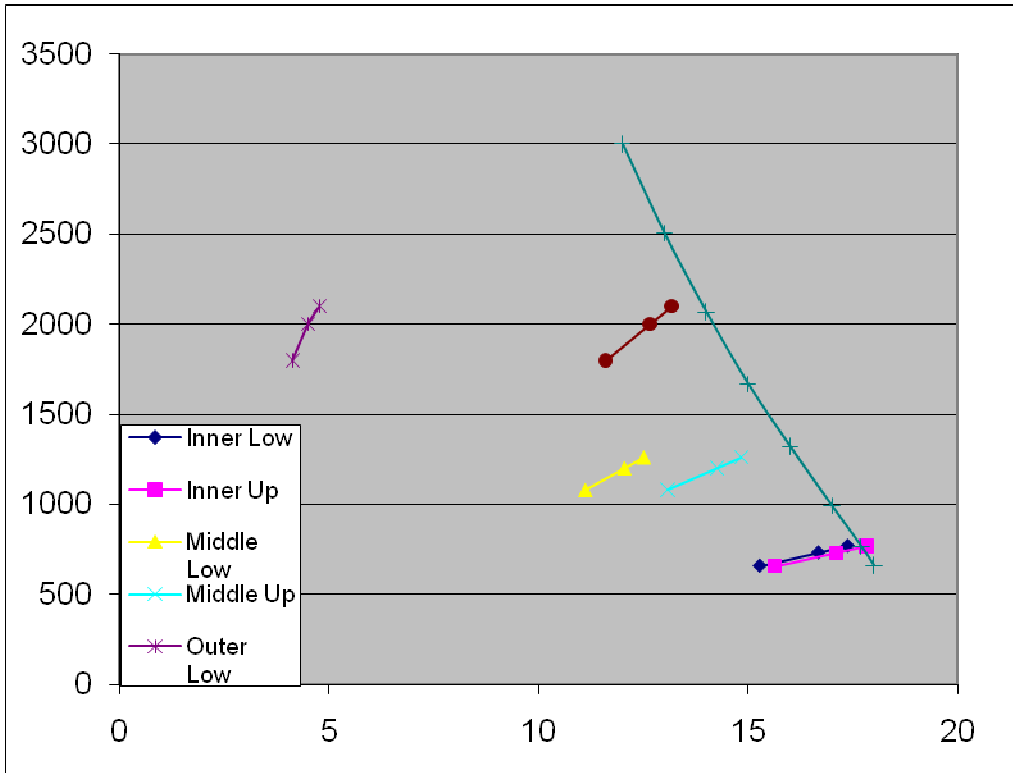
$J_{non\text{-}Cu}$ = 3000 A/mm^2 @12 T, 4.2 K

Cryogenics 4-6 K supercritical He

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

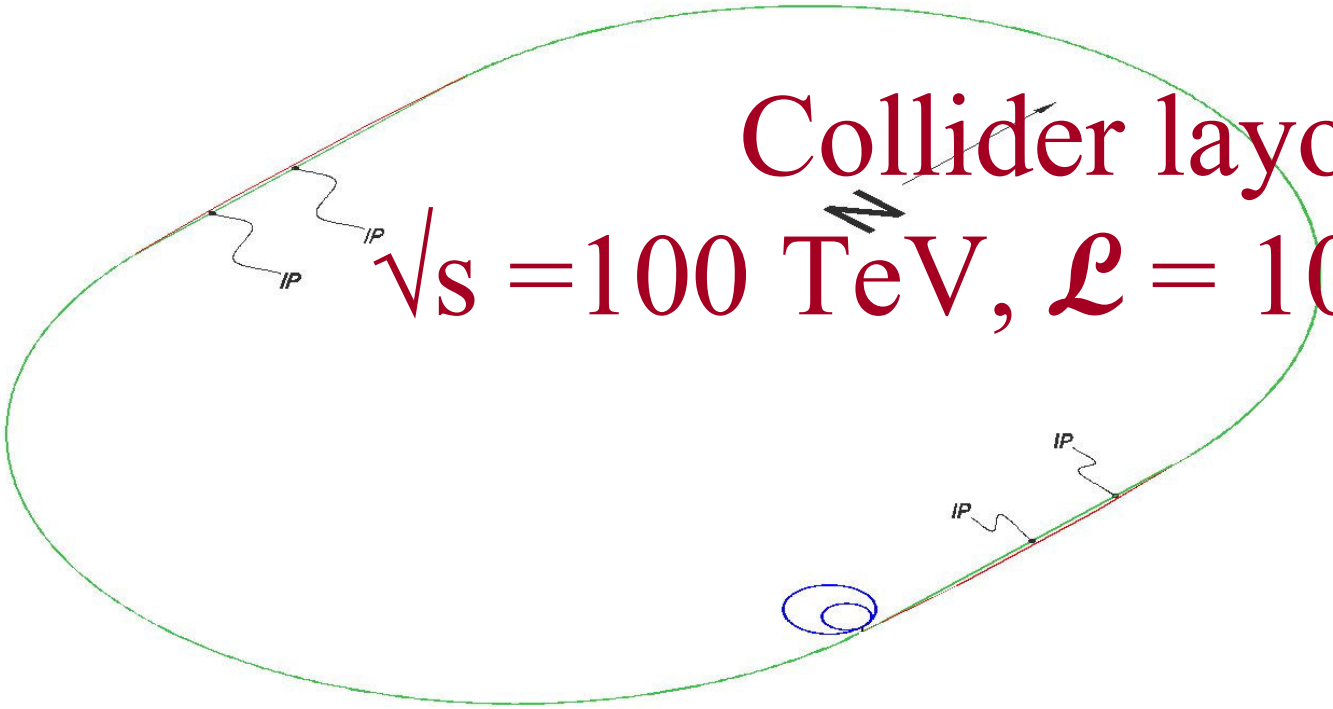
Max coil stress 117 MPa.

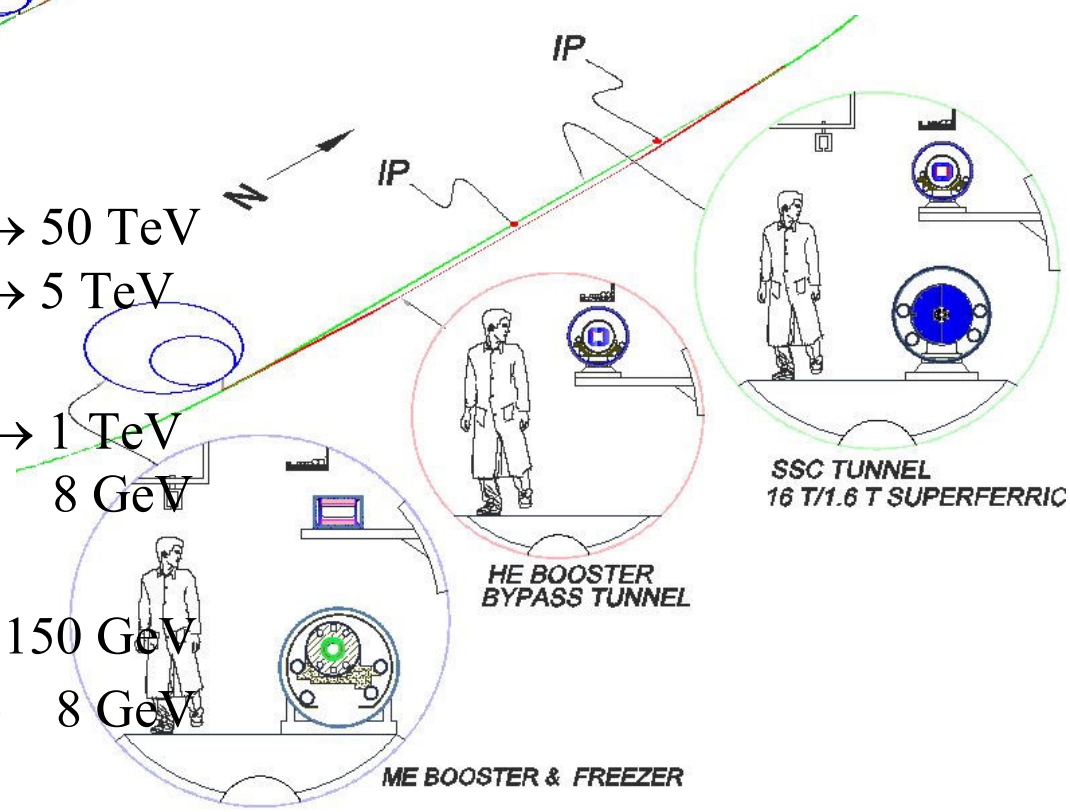




Collider layout

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





Main tunnel:

- ➢16 T single ring 5 → 50 TeV
- ➢1.6 T superferric injector 1 → 5 TeV

Medium-energy booster:

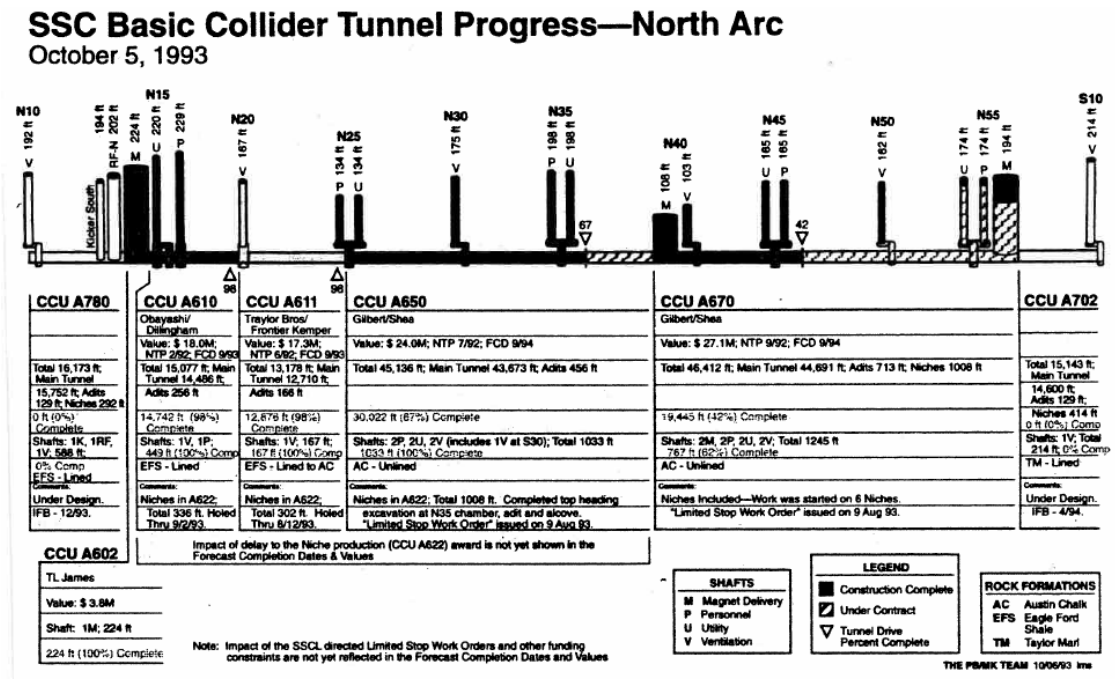
- ➢4 T cos θ booster 0.15 → 1 TeV
- ➢0.1 T permanent magnet freezer 8 GeV

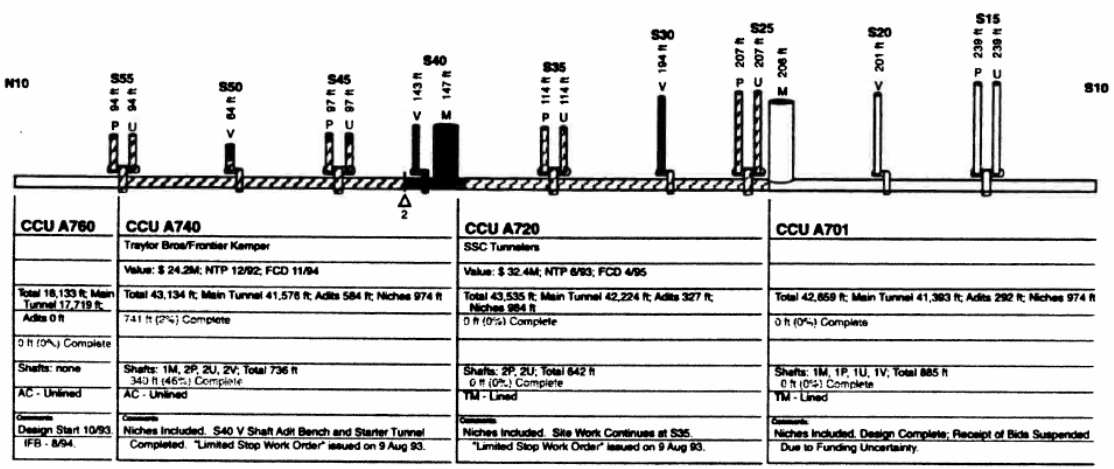
Low-energy booster:

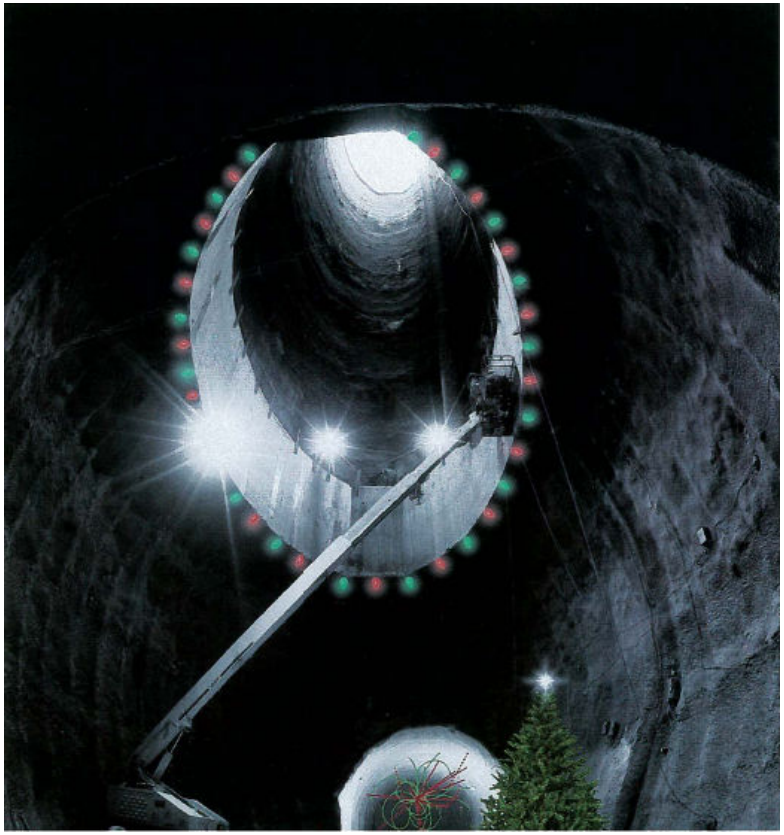
- ➢1.5 T rapid-cycling booster 8 → 150 GeV

Superconducting linac: 0.01 → 8 GeV

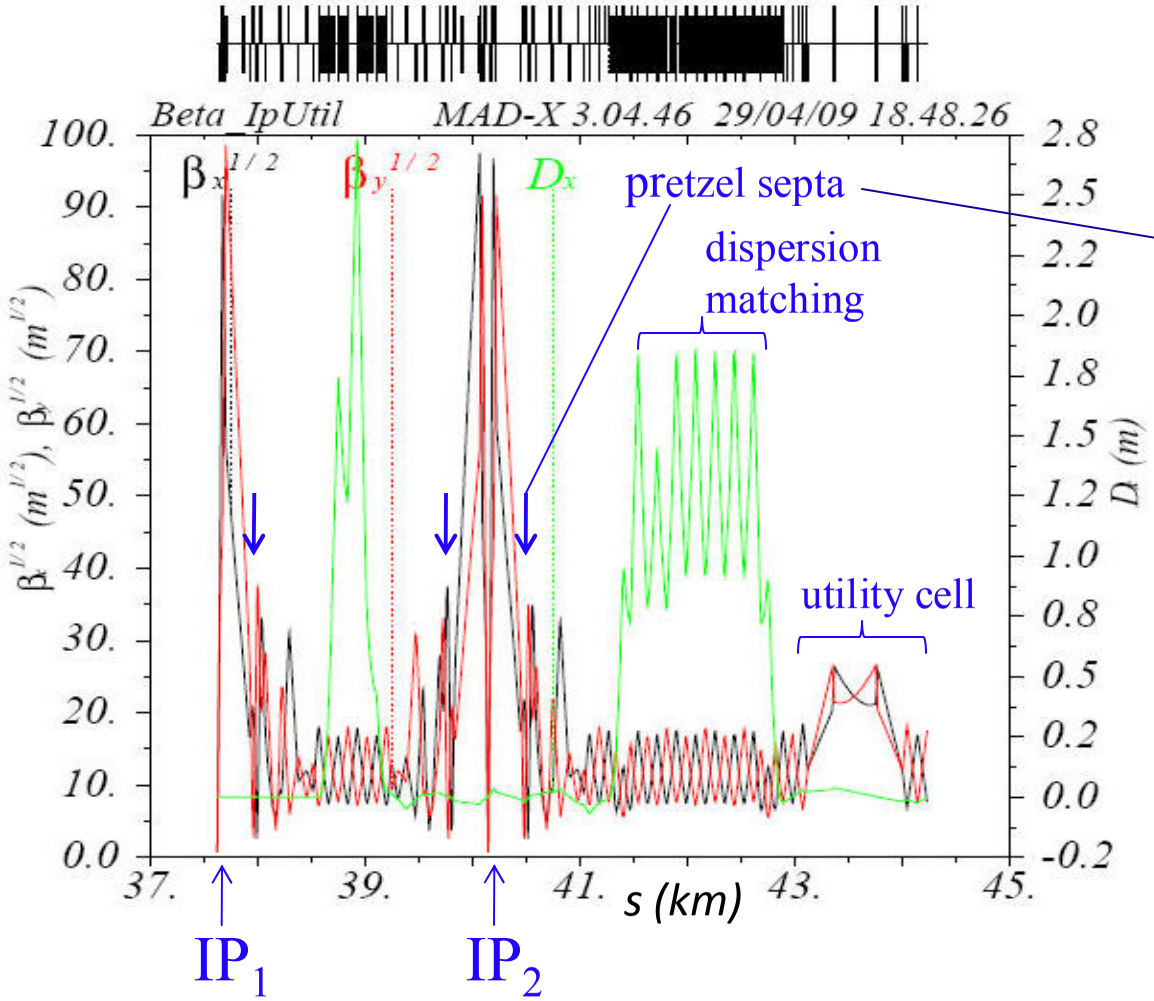
SSC tunnel ~70% bored, 35% lined

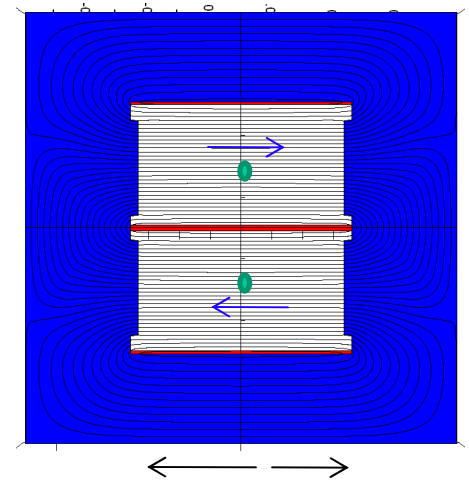






Petavac Lattice





$\beta^* = 0.5$ m

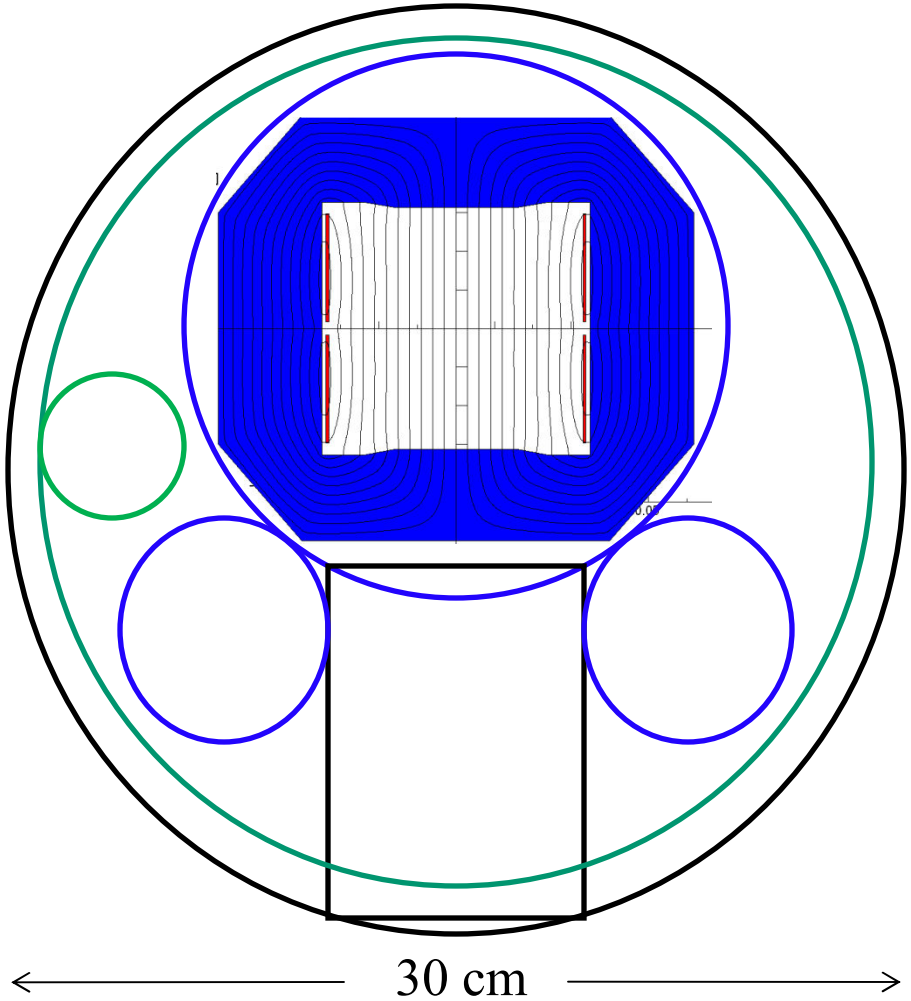
$\beta_{max} = 9.6$ km

Comparison of Parameters

	Tevatron	SSC	LHC	100 TeV	100 TeV	7 TeV	
			nominal			in Tevatron	
collision energy E	2	40	14	100	100	7	TeV
luminosity	1.5E+32	5.6E+32	6.6E+33	1.0E+34	1.0E+35	3.4E+33	$cm^{-2}s^{-1}$
# bunches	36	16,440	2,800	11,000	11,000	200	
# interactions/ collision	5	2	8	10	102	14	
bunch spacing T_b	396	16	25	20	20	60	ns
insertion optics:							
betamax	0.8	8.1	5.0	4.0	4.0	0.8	km
betamin	0.35	0.5	0.55	1	1	0.35	m
total head-on BB tune sh	0.0070	0.0012	0.0024	0.0047	0.0093	0.0058	
low-beta gradient	141	230	250	500	500		T/m
lattice magnets:							
dipole field	4.4	6.79	8.39	16.34	16.34	14.00	T
quad gradient	74	230	220	440	440		T/m
dipole length	6	17	14.3	20	20	12	m
circumference	6.28	83.631	26.7	83.631	83.631	6.28	km
revolution frequency	47.8	3.6	11.2	3.6	3.6	47.8	kHz
bend radius ρ	0.8	10.2	2.8	10.2	10.2	0.8	km
betatron tune	20	95	63	81	81	20	
# dipoles	840	3832	1250	3257	3257	420	
# rings	1	2	2	1	1	1	

	Tevatron	SSC	LHC nominal	100 TeV	100 TeV	7 TeV in Tevatron	
particles/bunch:							
p	3	0.075	1.15	0.6	1.2	1.5	10^{11}
pbar	1			0.1	0.5	0.8	10^{11}
transverse emittance ε:							
p	3.3	1	3.75	1	1	1	$\pi 10^{-6}$m
pbar	3			1	1	1	$\pi 10^{-6}$m
rms bunch length	55	6	7	6	6	15	cm
full crossing angle	0	150	285	150	150	150	μrad
Piwinski parameter		0.90	0.58	1.01	1.01	1.13	
total energy/beam	2	395	361	5280	10560	17	MJ
# beam abort/dumps	1	1	1	4	4		
total # protons	1	12	32	66	132	3	10^{13}
total # antiprotons	0.36			11	55	1.6	10^{13}
antiproton consumption	1.09			72.3	723.1	24.5	10^{11}/hr
antiproton source:							
# production targets	1			1	5	1	
# debuncher rings	1			7	36	2	
debuncher accum rate	3			10	20	15	10^{11}/hr
# accumulators	1			2	2	1	
accumulator capacity	0.4			5.25	28.8	2.1	10^{13}
store time T_s	0		24	15	8	7	h
synchrotron radiation:							
power/magnet		5	6	647	1571	1.2	W
critical energy	0.4	281	44	4391	4391	19	eV
energy loss/turn		0.122	0.007	4.8	4.8	0.001	MeV
damping time:							
longitudinal		13	26	0.8	0.8	13.9	h
transverse		25	52	1.6	1.6	27.9	h

Superferric High-Energy Injector shares the same tunnel



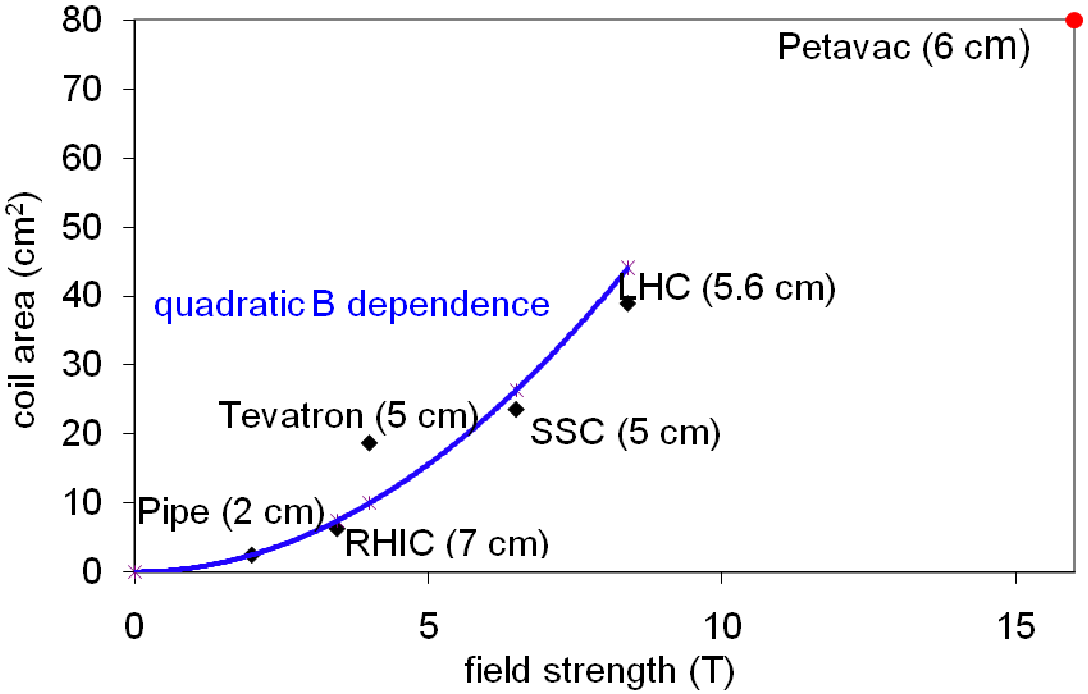
How much would an 86 km ring of Nb_3Sn dipoles cost?

- 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 leader
- Single Petavac ring requires 10,000 tons of wire
- Wire price today \$1,000/kg, ÷3 in volume
- \$3 billion superconductor → ~\$5 billion for ring

A pp collider would require two of these rings

That is the premium to use $\bar{p}p$ colliding beams.

New magnet design, New materials, Dramatic Performance

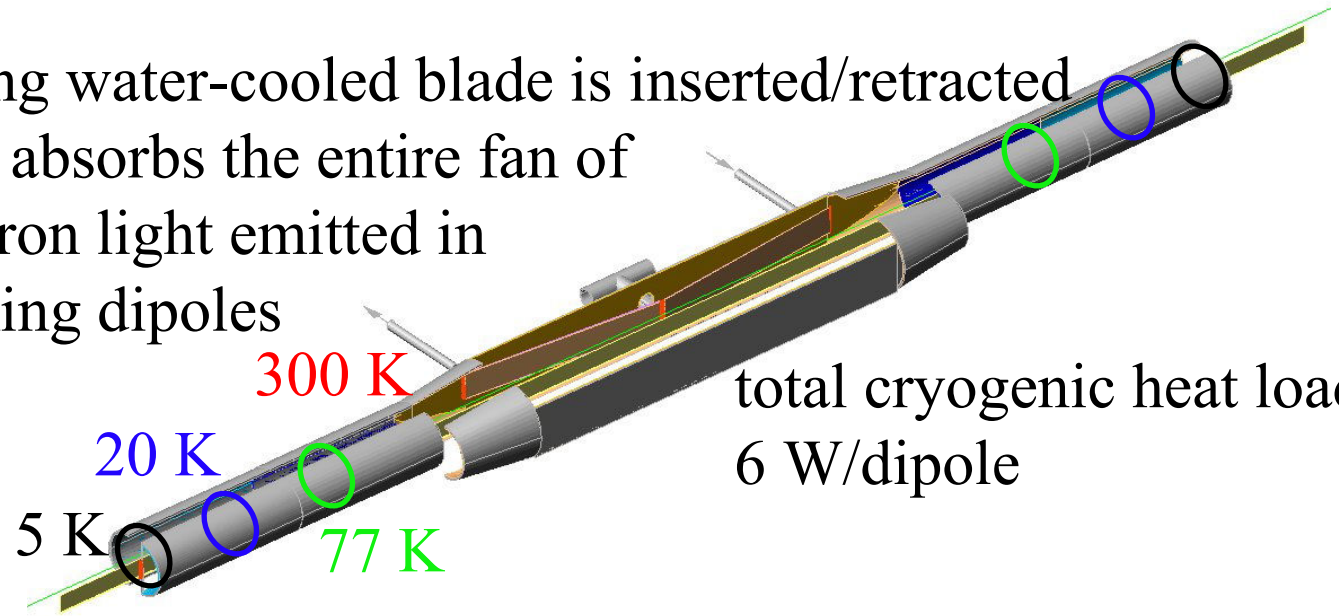


Accelerator Challenges for Petavac

➢***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

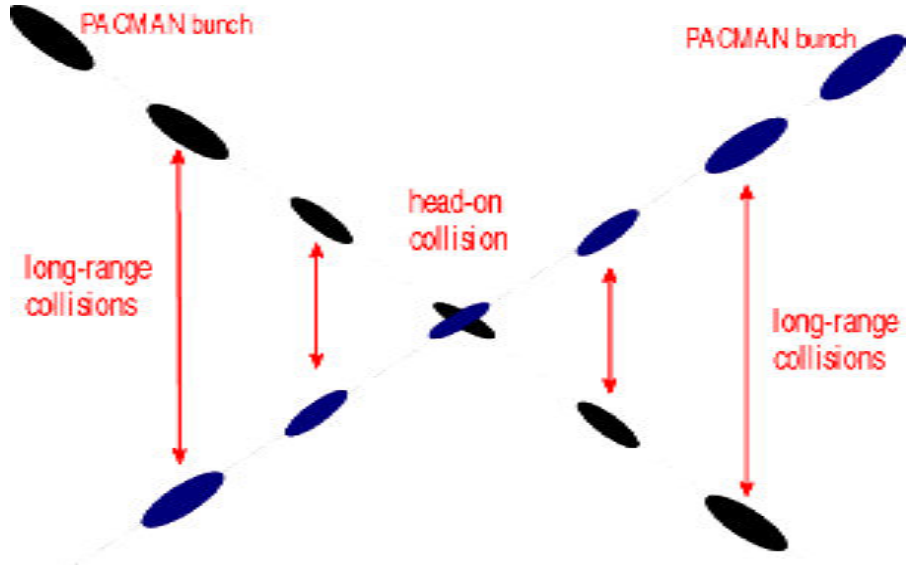


total cryogenic heat load
6 W/dipole

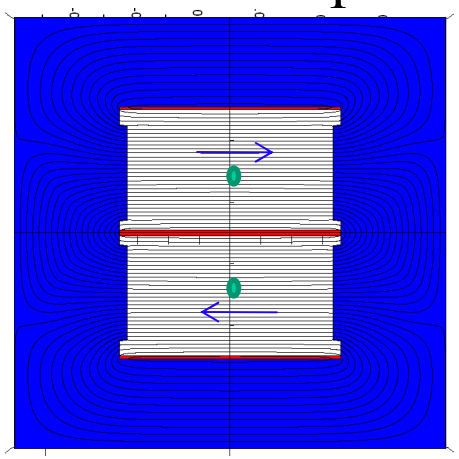
Synchrotron light gives damping in all dimensions of phase space:
45 minutes in Petavac (24 hours in LHC)
Helps to counteract mechanisms of slow emittance growth.

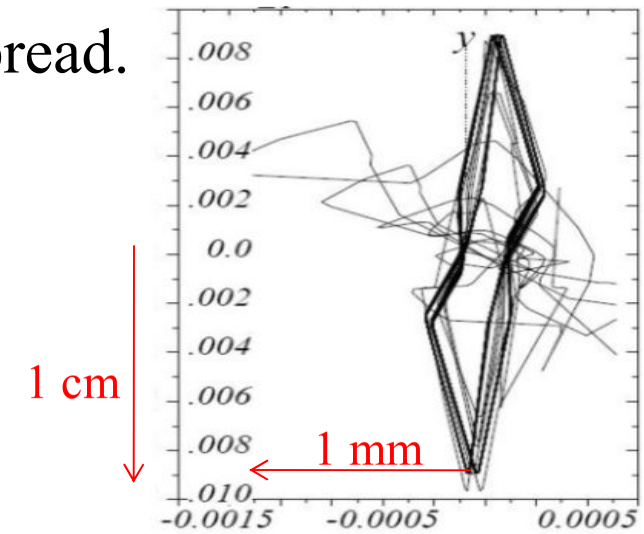
➢Avoid beam-beam tune shift from subsidiary crossings of bunches:

This issue is complicated by our need for close bunch spacing:
20 ns bunch spacing
@ 10 luminosity yields
85 interactions/crossing!

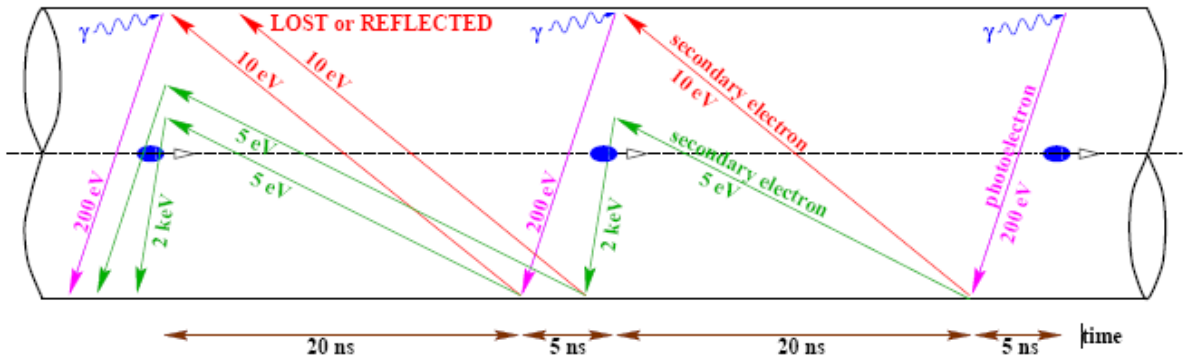


Solution: Separate beams on a *vertical pretzel*, so that beams only cross @ IPs, separation ~1 cm elsewhere minimizes tune issues. Vertical orientation preserves small horizontal spread.





➢*Suppress 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}

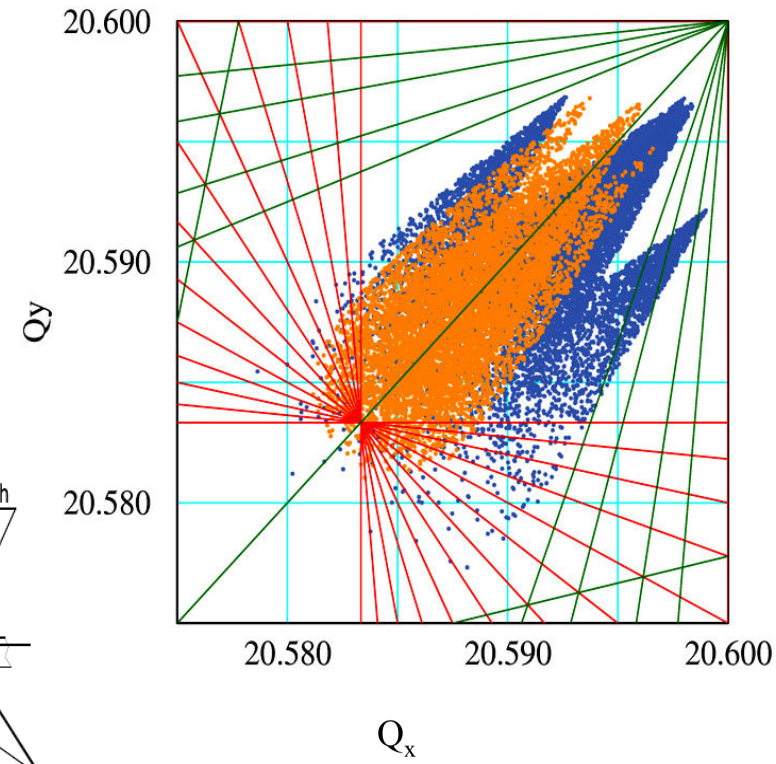
Solution: Install continuous strip electrode on side wall of vacuum tube around entire ring. Bias ~50 V *clears all charge in <20ns*

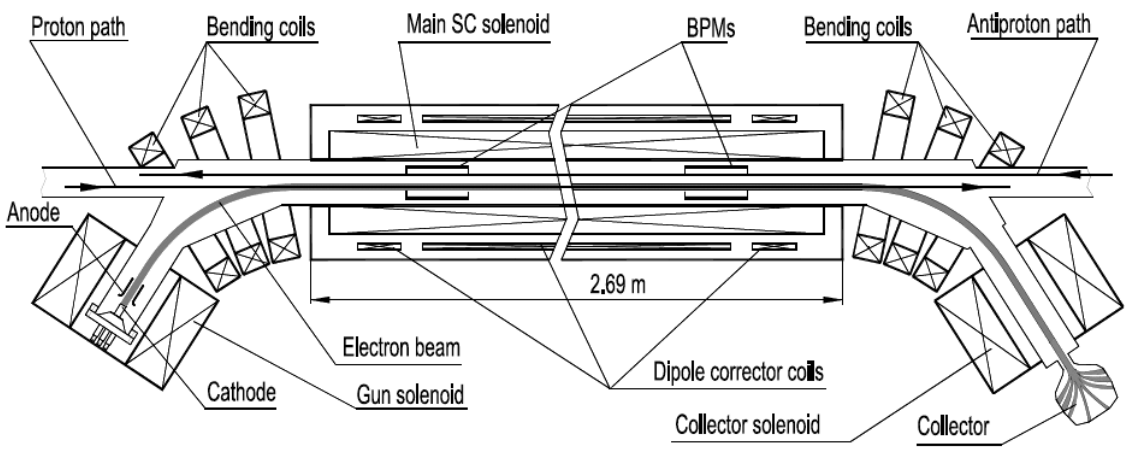
➢ ***Correct bunch-bunch tune spread to preserve luminosity:***

Successive bunches have different tune shifts due to a multitude of phenomena (injection, circulating charge, bunch intensity variations, 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.





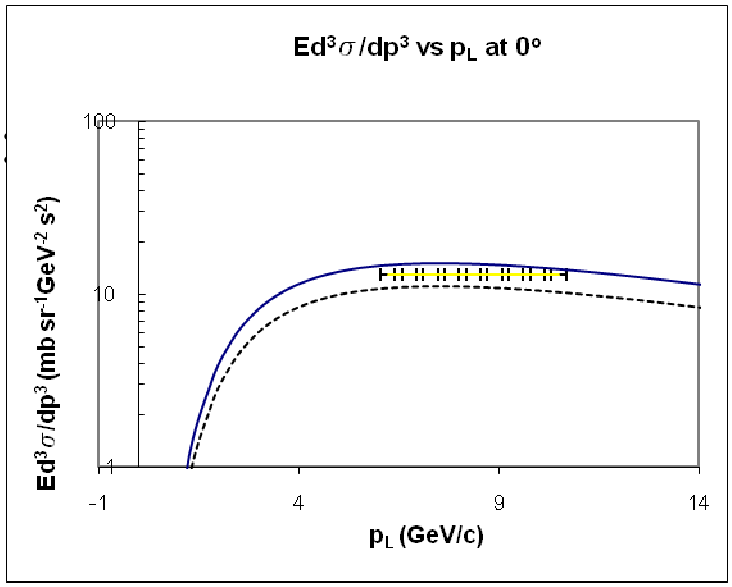
Shiltsev *et al.*, *New Journal of Physics* ***10 (2008) 043042***

Miyamoto *et al.*, *PRST-AB* (2008)

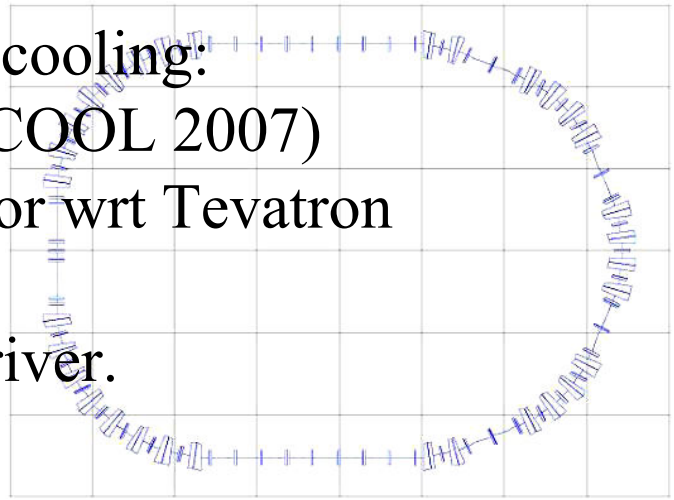
Antiproton Production & Damping

We need ~100 times more $\bar{p}$ stacking to support 10^{35} cm^{-2} s^{-1}

- x10:
  ten debunchers fed from each $\bar{p}$ target:



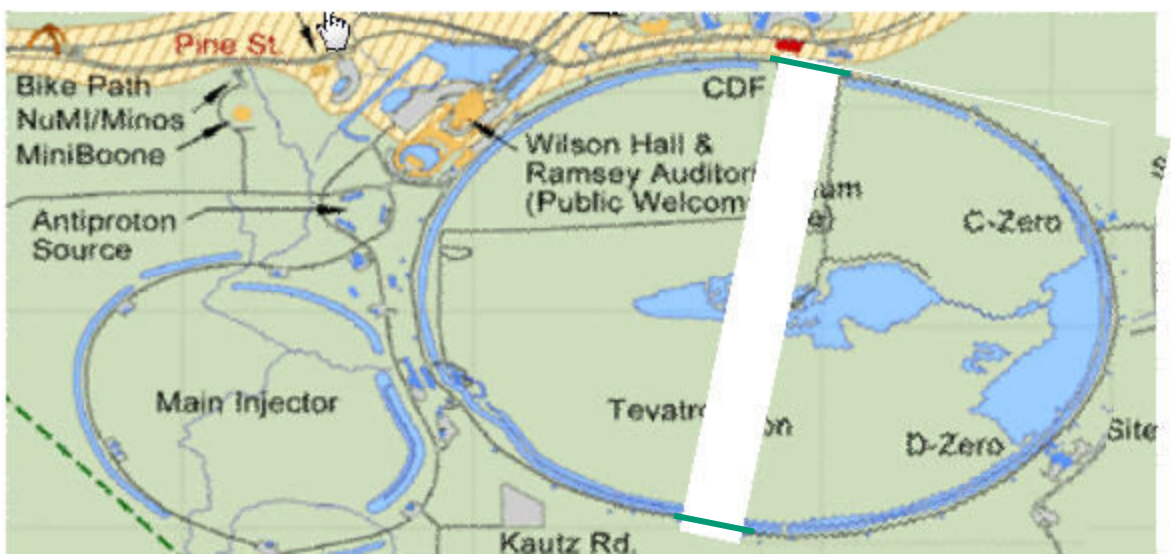
- x2: separate mixing regions in stochastic cooling:
  max good mixing, min bad mixing(Wang COOL 2007)
  twice accumulation rate in each accumulator wrt Tevatron



- x5: five target stations fed from proton driver.

How to get from here to there?

- LHC plans to operate at reduced energy: 3-4 TeV/beam
- Build a single-ring 14 T $\bar{p}p$ collider in Tevatron tunnel:
  - 3.5 TeV/beam
- Upgrade antiproton source and recycler
  - $3\text{x}10^{11}$ /hr $\rightarrow$ $3\text{x}10^{12}$ /hr; stack $3\text{x}10^{12} \rightarrow 2\text{x}10^{13}$
- Build new half-tunnel to stretch 2 B0, D0 straight sections
- **Result: 7 TeV $\bar{p}p$ colliding beams @ $3\text{x}10^{33}$ luminosity**



Implement features that build the foundation for the Petavac

- Nb_3Sn ring magnets, warm/cold transitions, γ stops
- Separate beams using magnetic septum, crossing angle to accommodate close bunch spacing
- Upgrade $\bar{p}$ source with goal x10 faster accumulation
- Integrate ac dipole measurement and e-lens correction of tunes bunch by bunch
- Improve high-energy e-cooling for x10 stack, reduced emittance
- Coalesce CDF, D0 collaborations, upgrade one detector for 7 TeV, 10^{34} luminosity, 30 interactions/bunch crossing

So Fermilab could develop an LHC-competitive collider program:

7 TeV 10^{34} luminosity

and at the same time

develop and prove the key technical challenges to substantiate a design for an ultimate hadron collider:

100 TeV 10^{35} luminosity

Build upon all the assets that are here and planned to make 2 new generations of hadron collider.

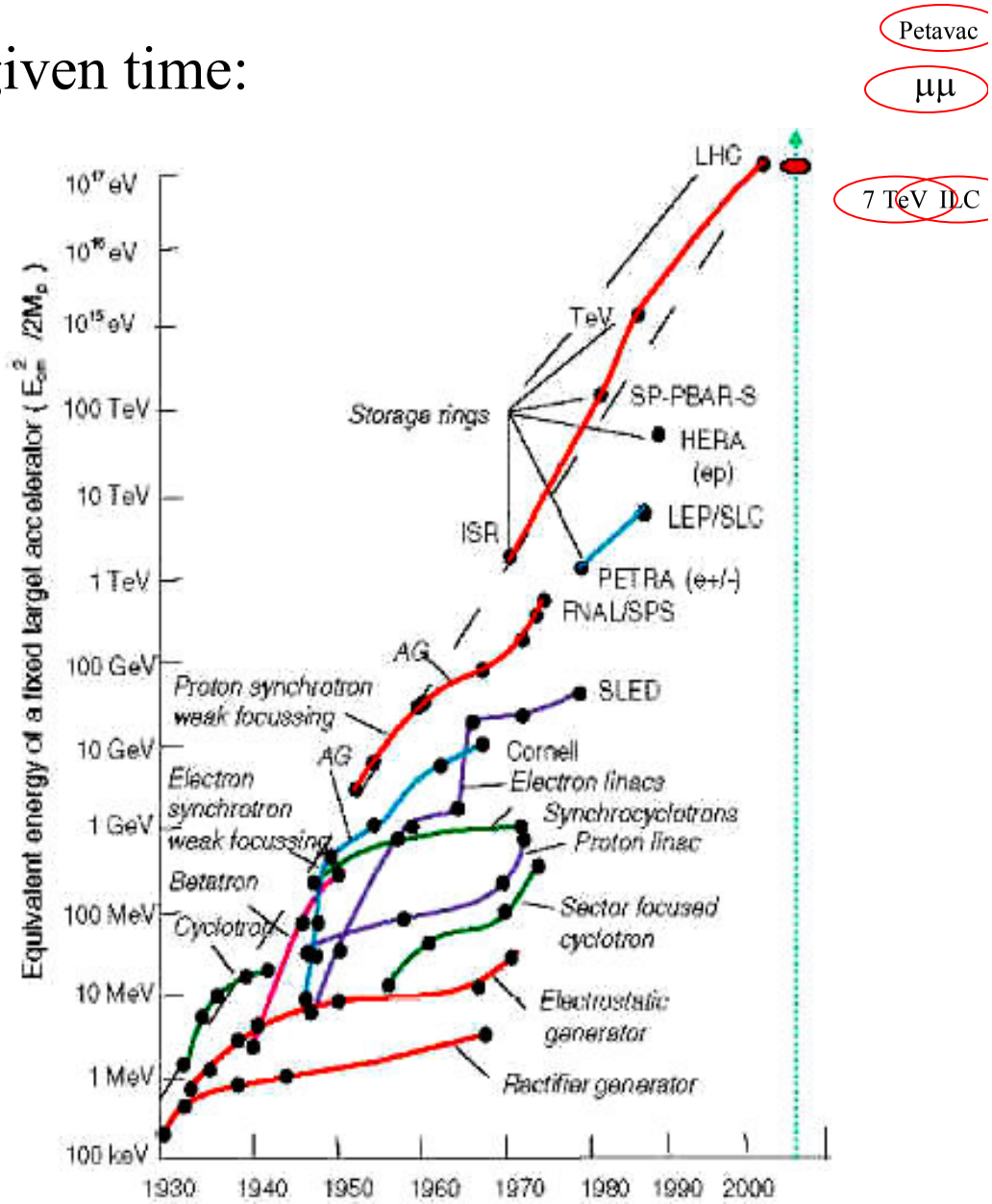
AARD: Skunk Works for the Future of HEP

HEP lives at the edge! At any given time:

New discovery requires more energy/luminosity than we have today!

We have to find a way to build a next discovery machine for the same cost as the last one!

AARD is *the place* in HEP that supports long-term development of technologies that can make this possible.



Acknowledgements

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I would like to form a collaboration to develop serious studies of the 7-Tevatron and the Petavac

Fermilab has been the home of $\bar{p}p$ colliding beams for the past 30 years. Now is the time to renew its leadership and push for this new generation.