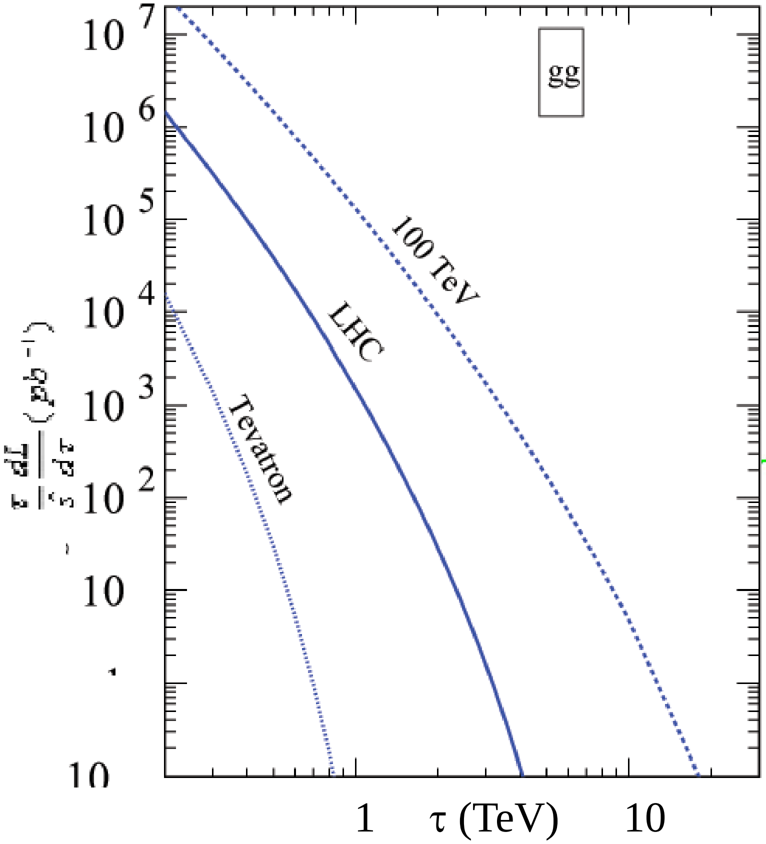
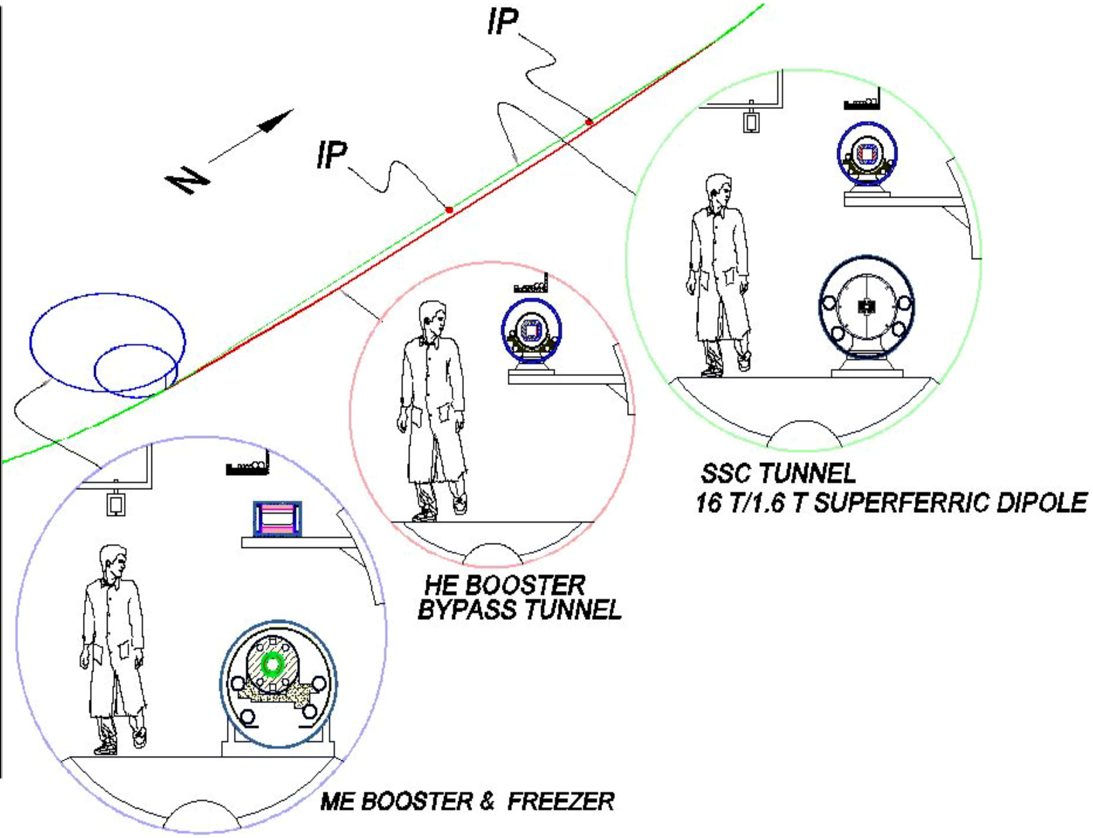
Petavac

Boson-Boson Collisions at 100 TeV





Peter McIntyre

Department of Physics

Texas A&M University

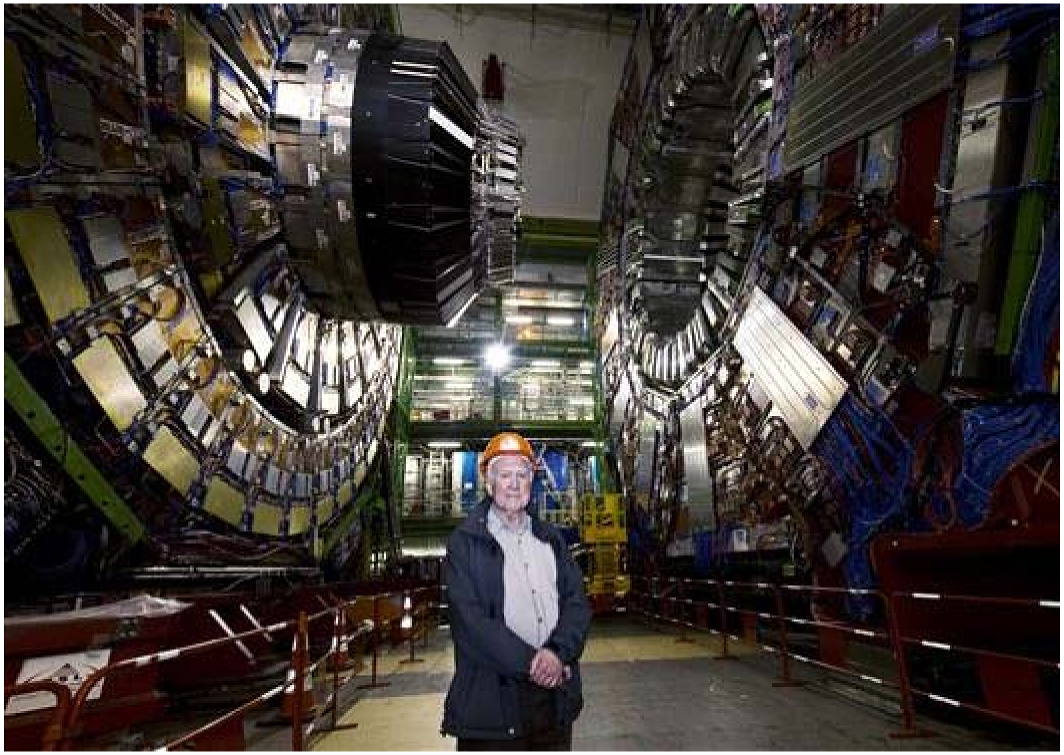
LHC will soon begin its physics program

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

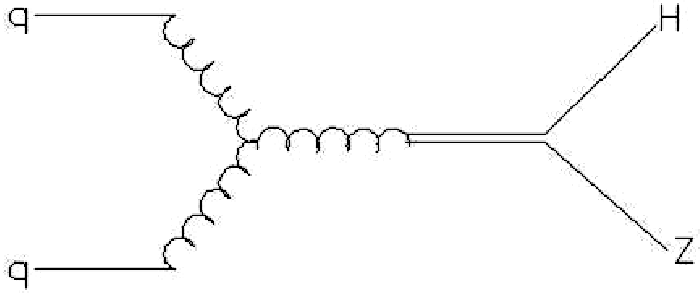


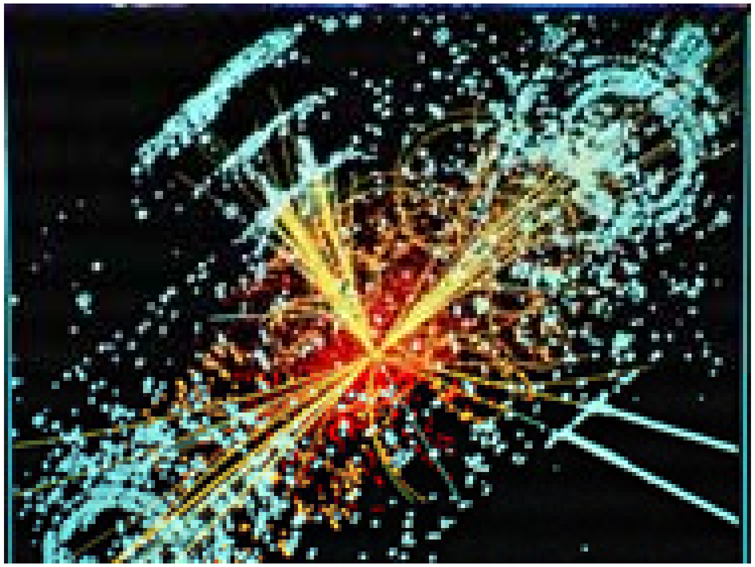
Peter Higgs visits CMS, hoping it will discover his particle.

Discovery in Physics

Paradox → New Idea → Discovery

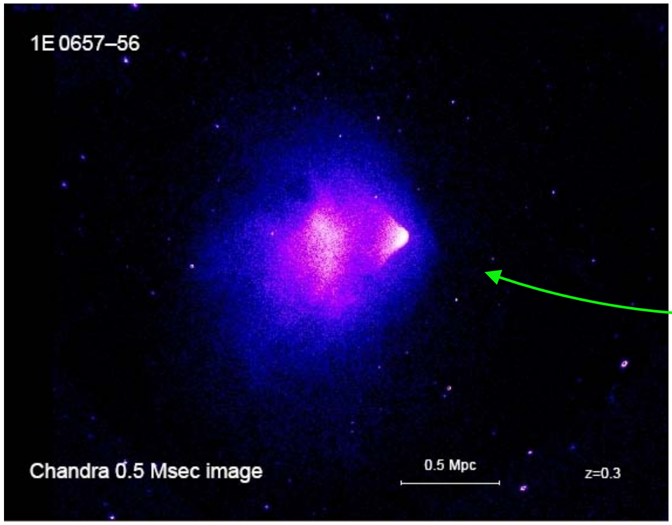
- *Paradox: The weak interactions become strong!*
  - How does the electroweak interaction break spontaneously in to electromagnetism and weak interaction?
- *New idea: Higgs boson*
  - A new scalar field that couples to particles proportional to their mass, generates electroweak symmetry breaking.
-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

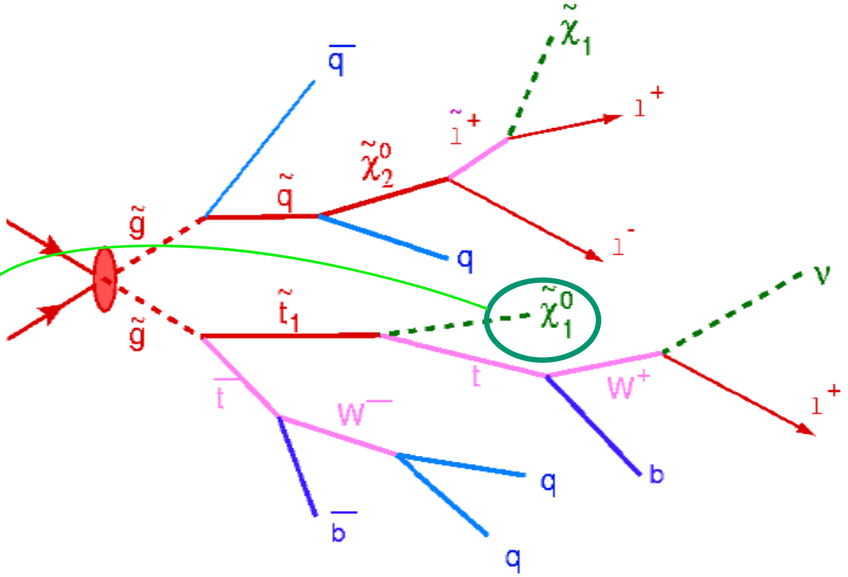




Caution: we don't know the mass scale!

- *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:*

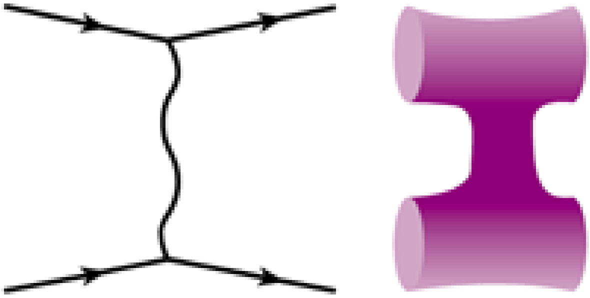


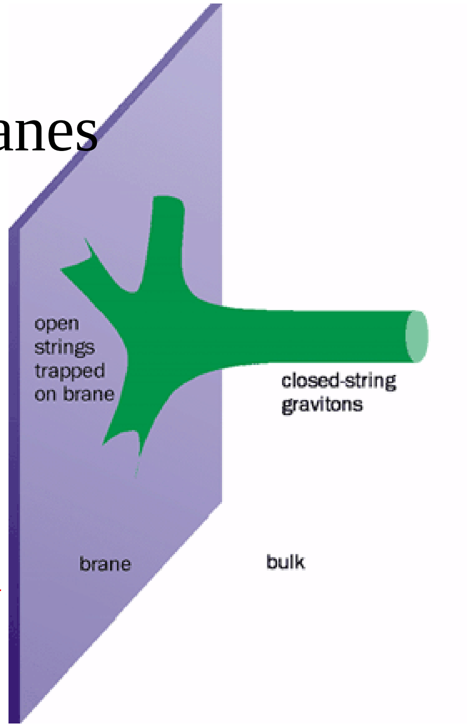


The Higgs boson and the spectrum of sparticles should be discovered at LHC, unless…

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.

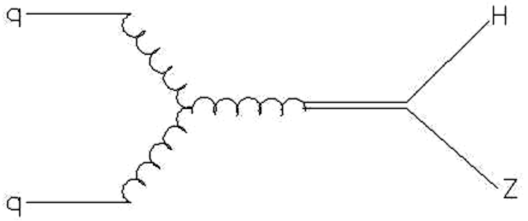
Hadron colliders are the only tools that can directly discover gauge particles beyond TeV

- 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?

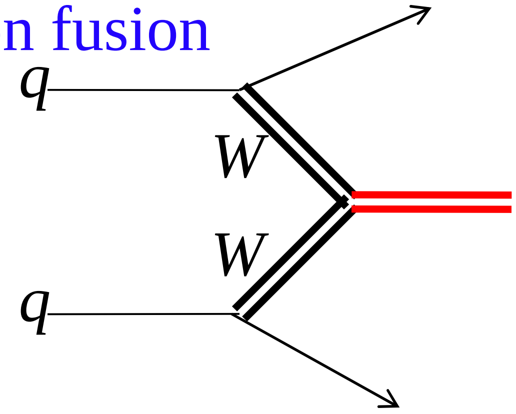
Mass reach for new physics

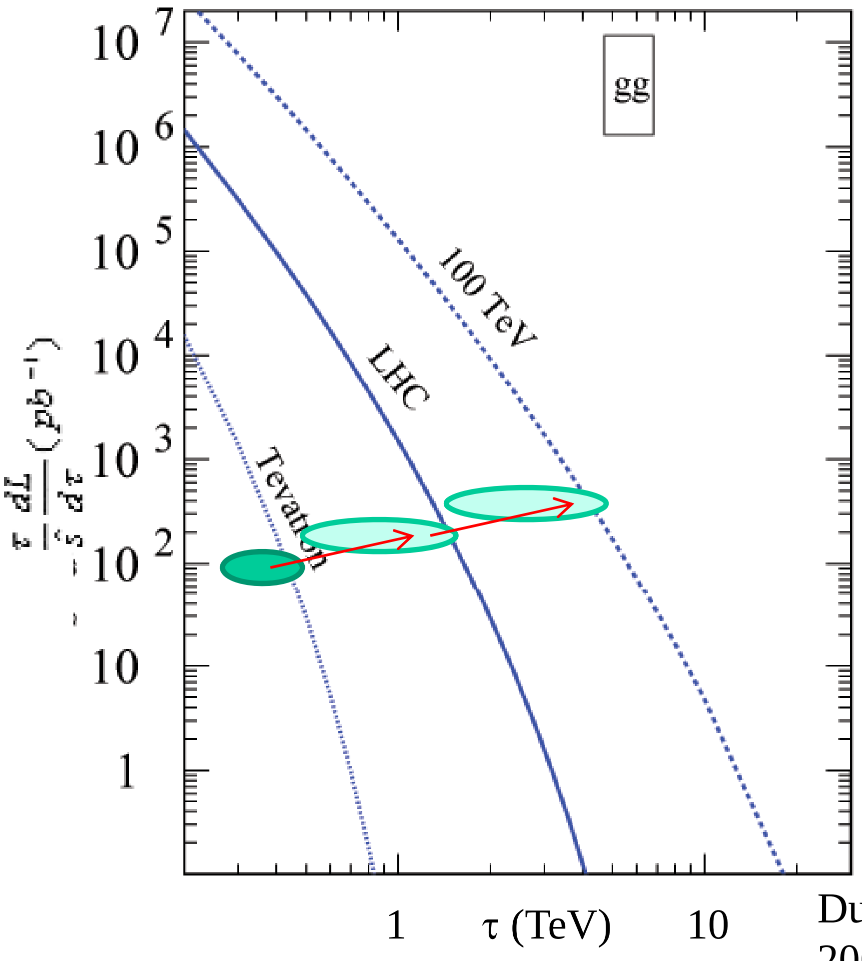
Tevatron accessed new physics through $q\bar{q}$ annihilation.

LHC will access new physics through gluon fusion:



Petavac will access new physics through boson fusion





point-like collision energy

Dutta
2008

7x the collision energy → 3x the mass reach

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

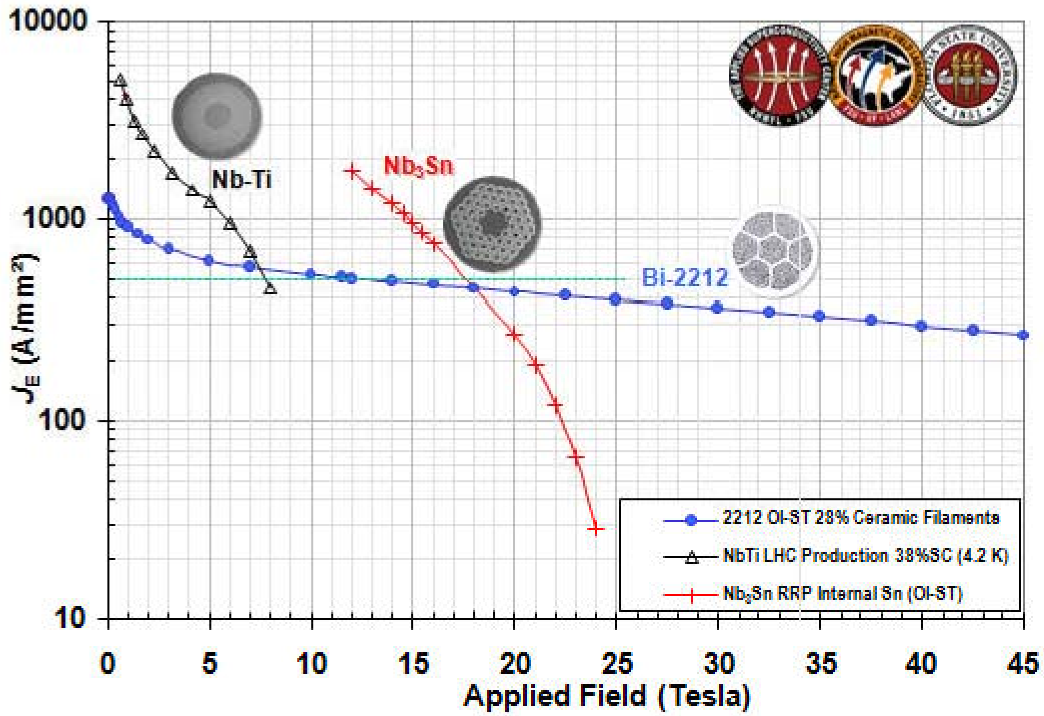
- Hadron colliding beams in the SSC tunnel
- 16 T dipole ring provides 100 TeV collision energy
- House high-energy injector in the same tunnel

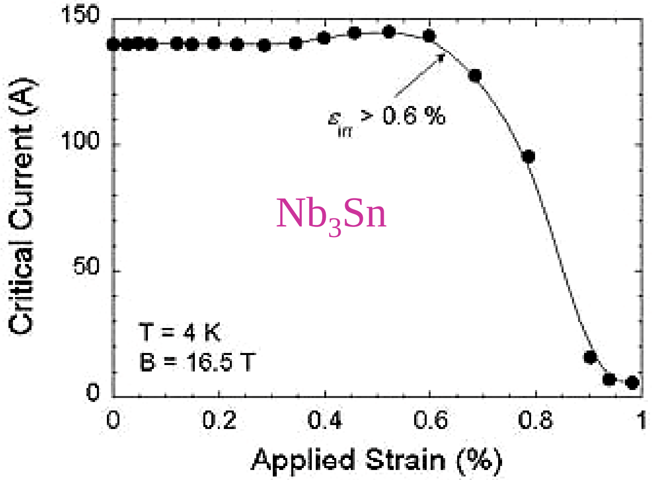
Four developments make this possible to conceive:

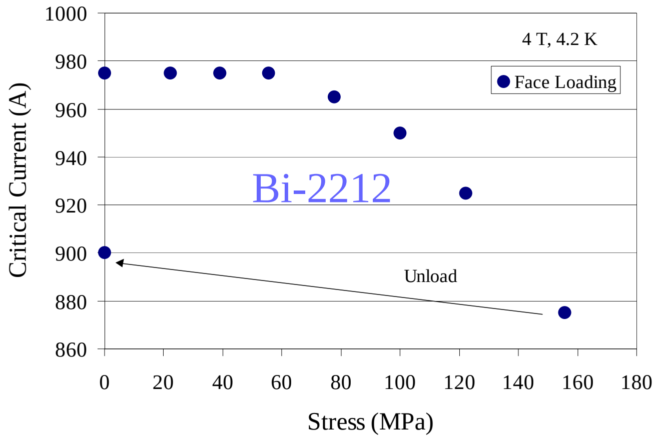
- ➢ Recent success maturing Nb_3Sn dipole technology
- ➢ Commercialization of Nb_3Sn wire for ITER
- ➢ Spectacular performance of Tevatron
- ➢ 84 km SSC tunnel is nearly complete, waits for use

To be resolved: pp ultimate luminosity, or $\bar{p}p$ for cost

We need a new superconductor for 16 T: Nb_3Sn

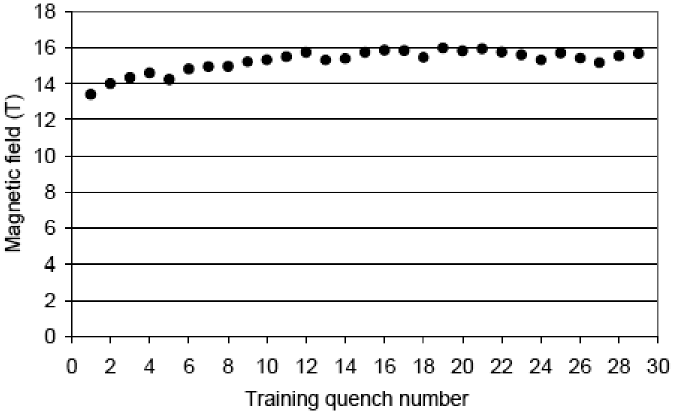




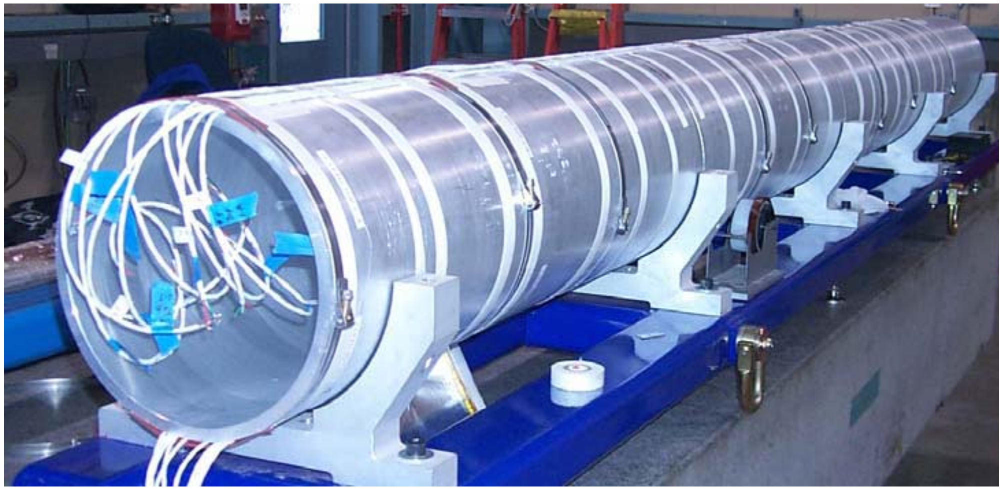


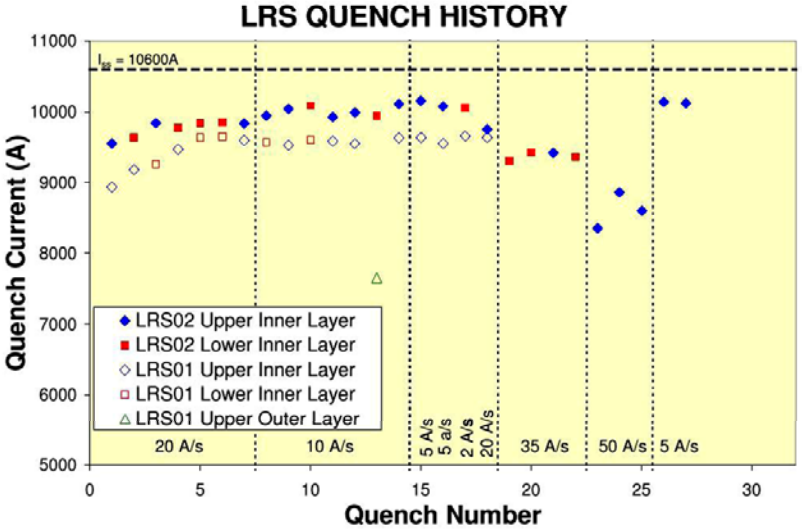
Cost today:	NbTi	$150/kg
	Nb_3Sn	$1,000/kg
	Bi-2212	$2,000/kg

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

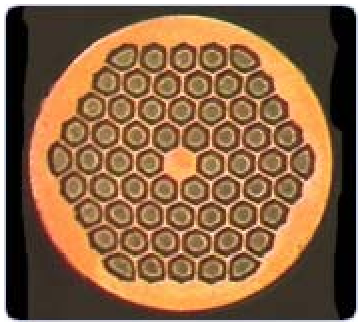


- 4m-long racetrack coils using Nb_3Sn have been built and tested.
  - LARP LRS

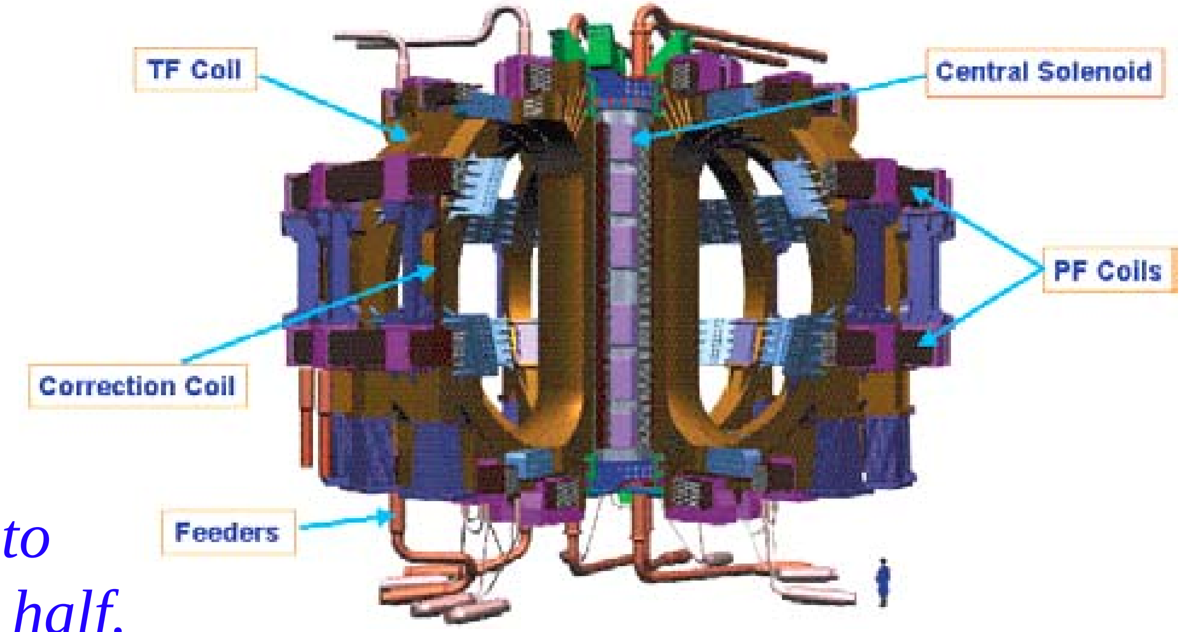




- Nb_3Sn superconducting wire with the necessary performance is developed and commercialized.
  - 3,000 A/mm^2 @ 12 T, 4.2 K in the superconductor

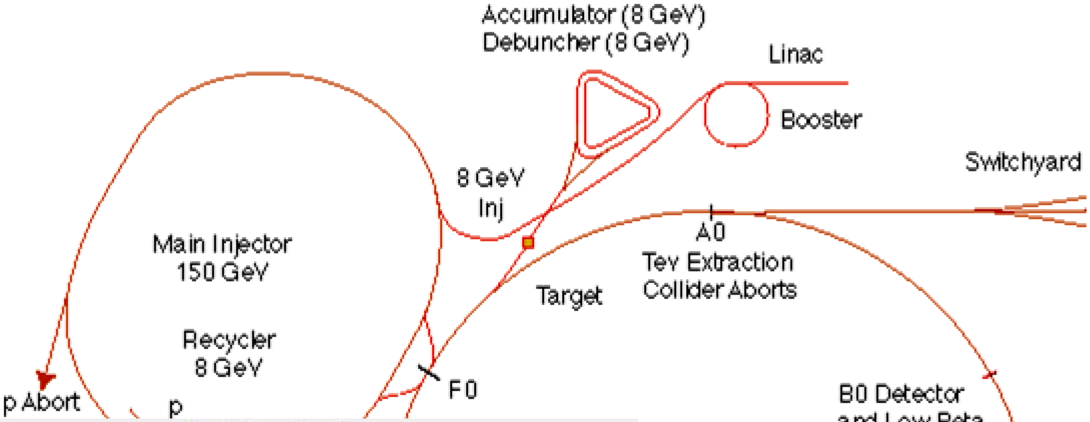


- ITER will use *400 tons* of high-performance Nb_3Sn wire; it will drive the production capacity to what would be needed for Petavac.

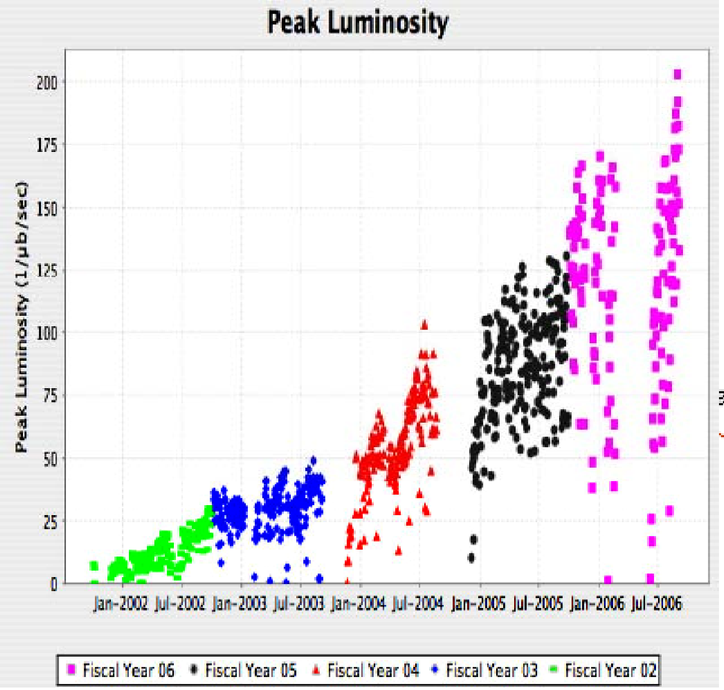


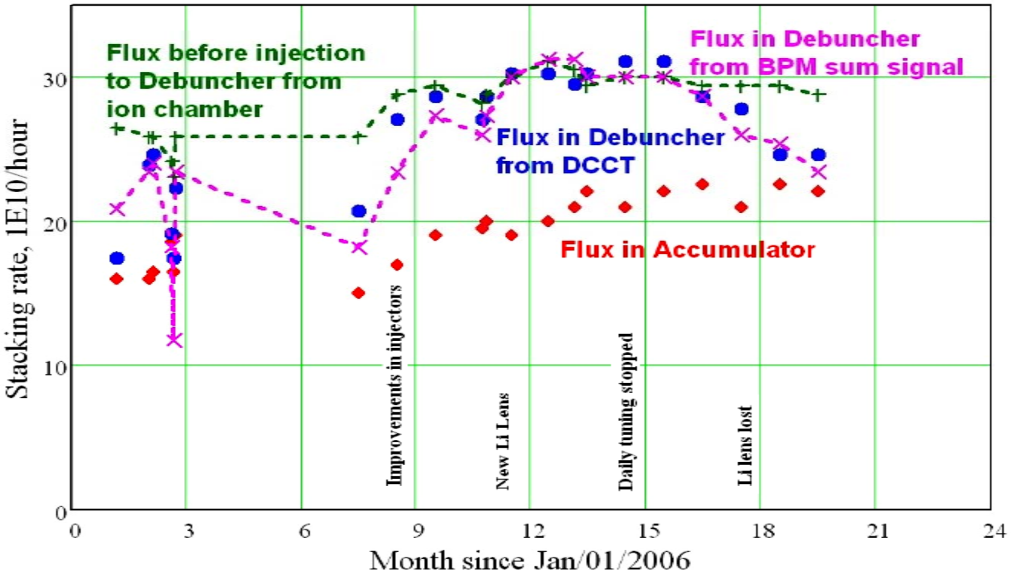
Transition to volume manufacture is predicted to drop Nb_3Sn wire price by half.

Fermilab has matured antiproton source technology and electron cooling



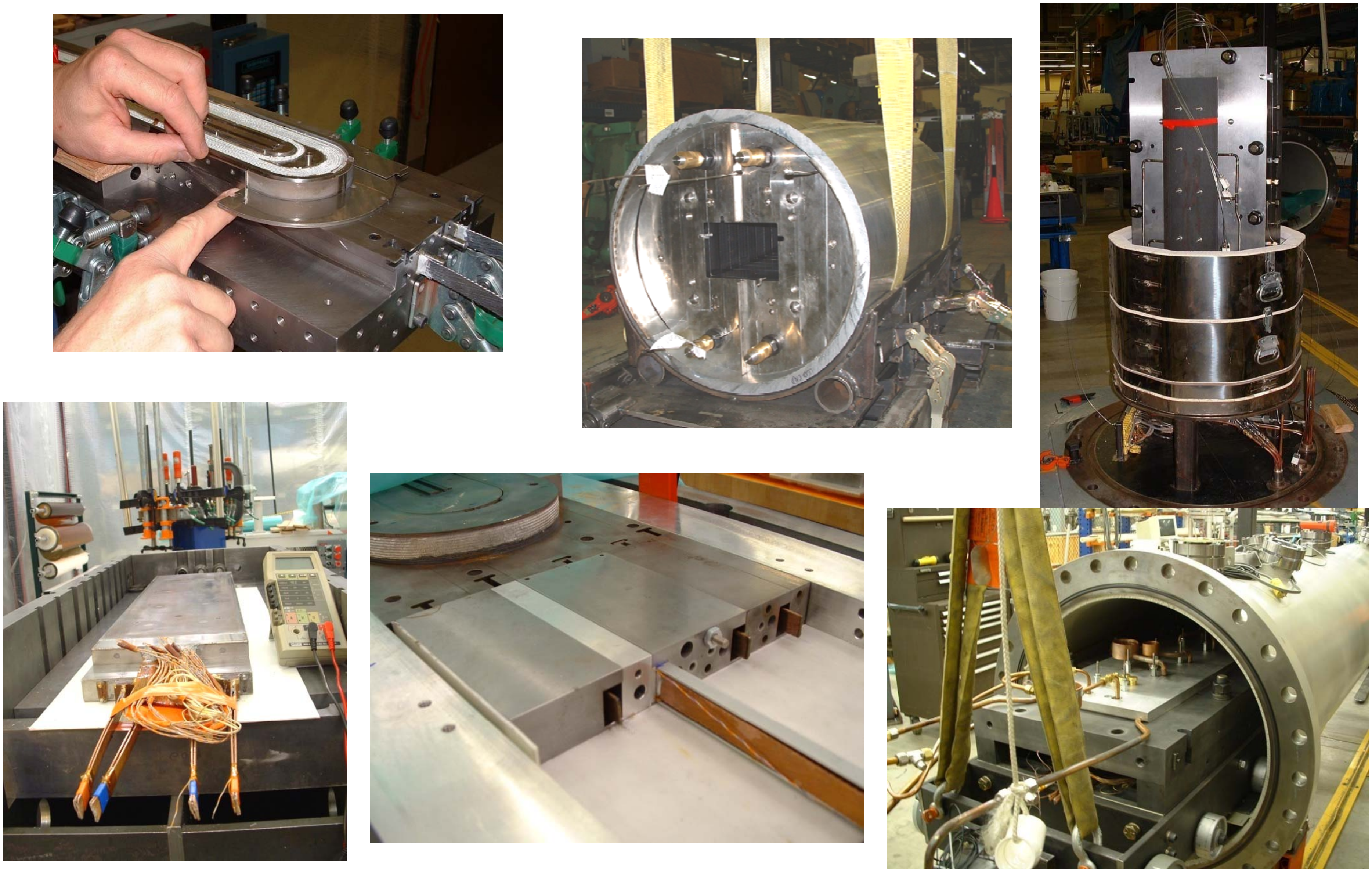
- ➢3x10$^{11}\bar{p}$ /hr stacked, capacity for 10x more from target (adjacent Δp windows)
- ➢E-cooling in recycler has capacity for ~10^{14} $\bar{p}$



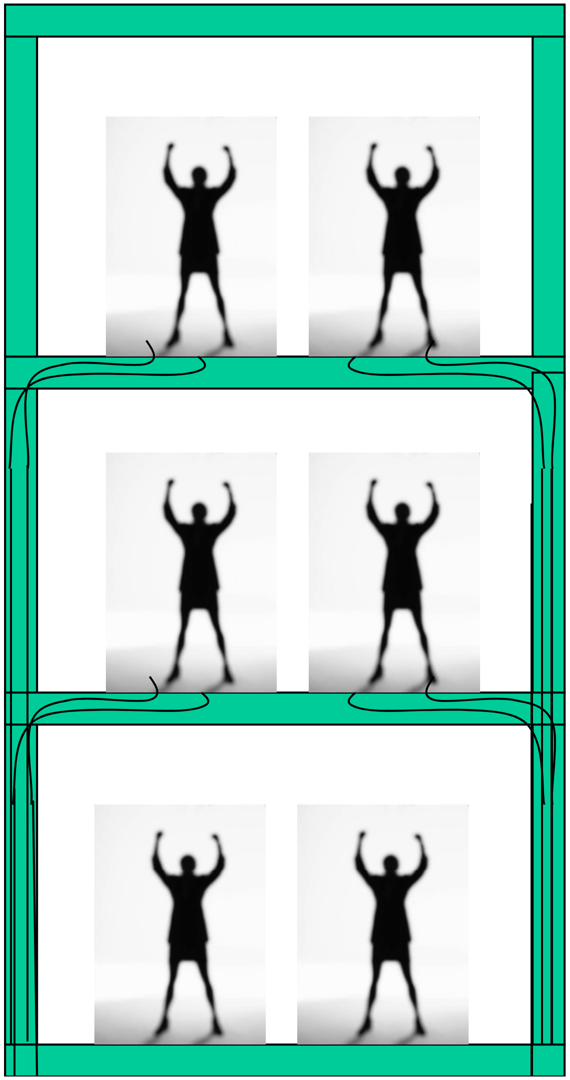


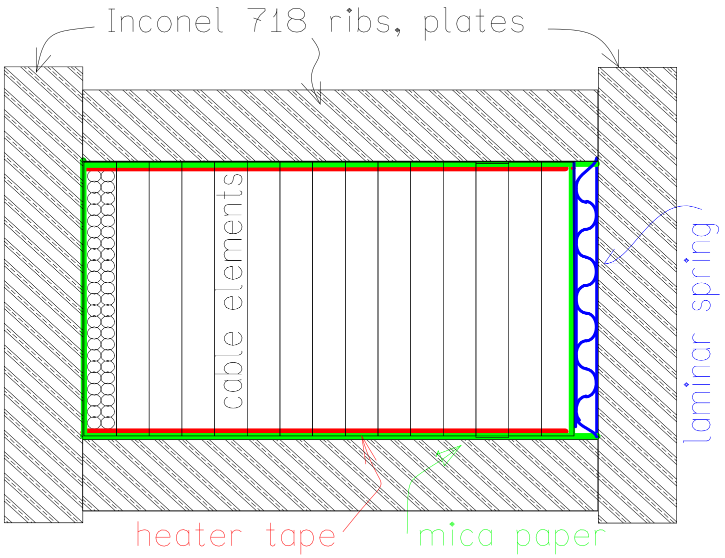
Lebedev 2008

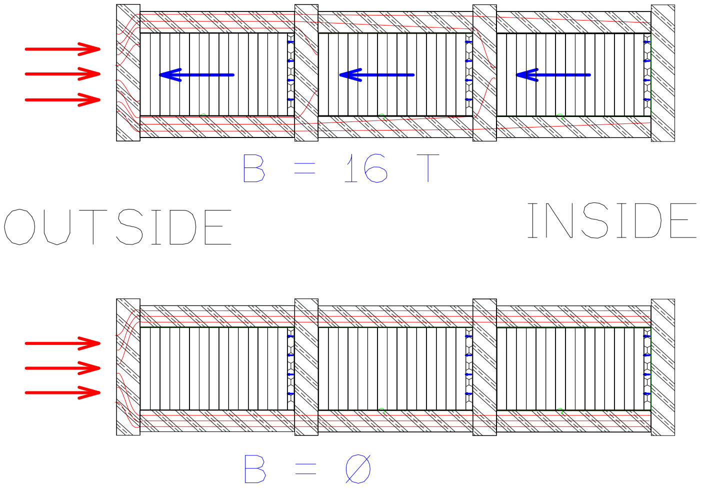
Nb_3Sn dipole technology at Texas A&M:
stress management, flux plate, bladder preload



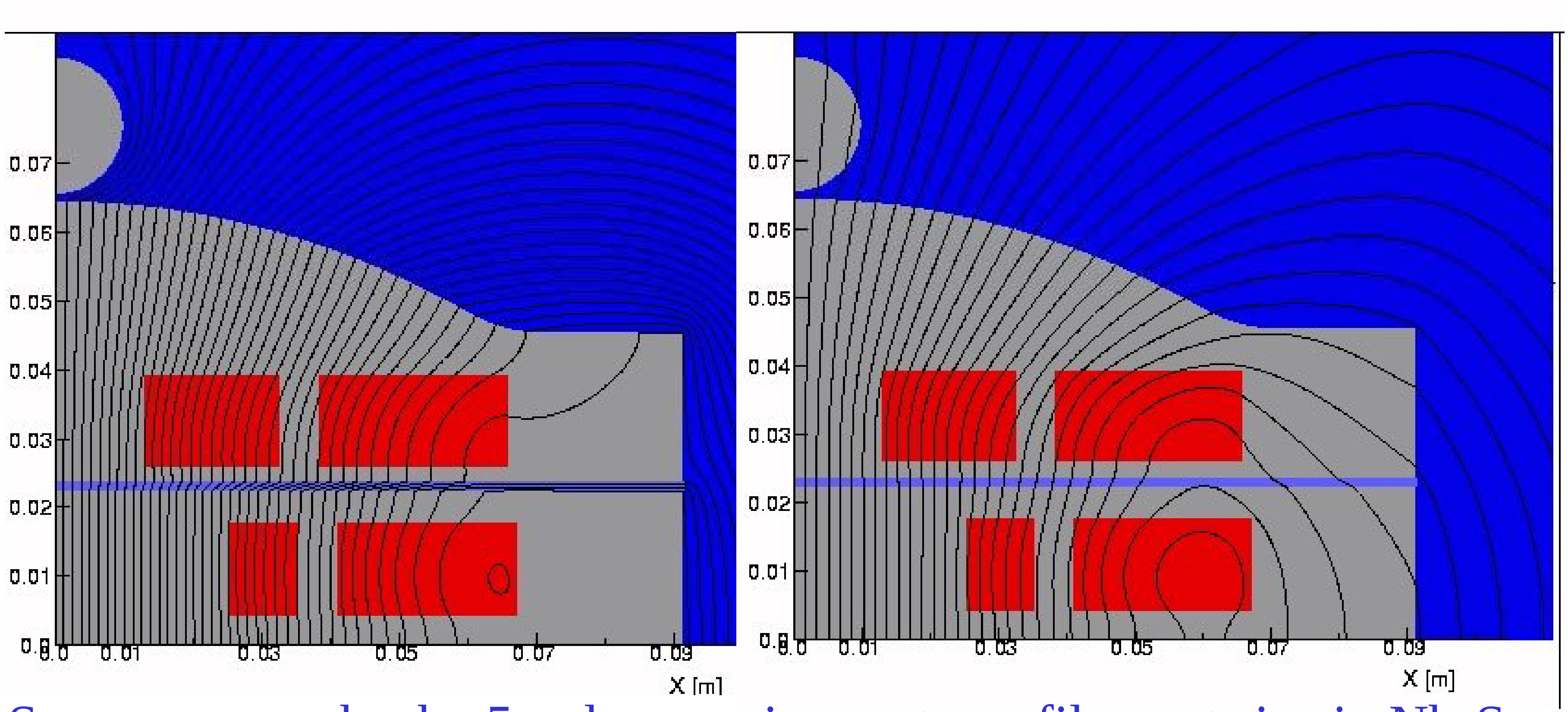
Stress management







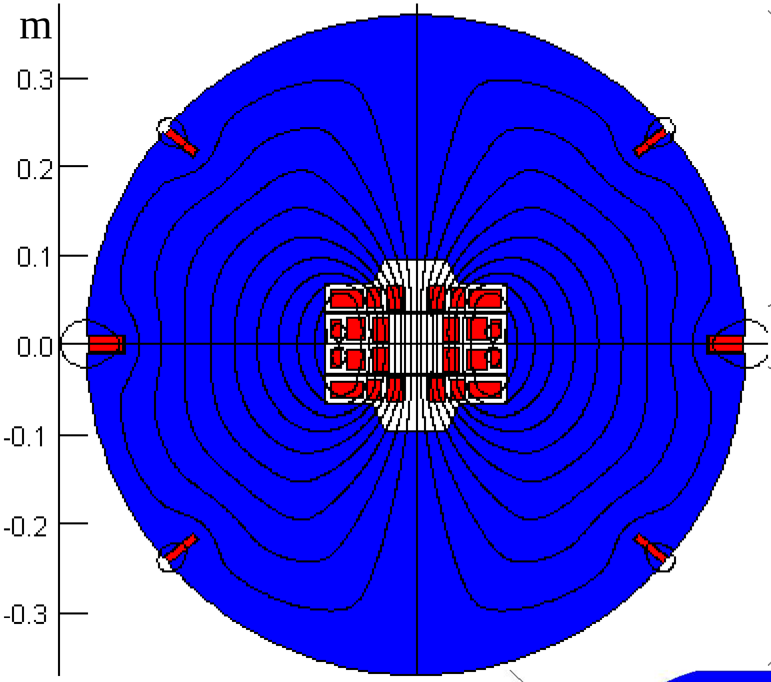
Horizontal steel flux plate redistributes flux to suppress multipoles


0.5 T

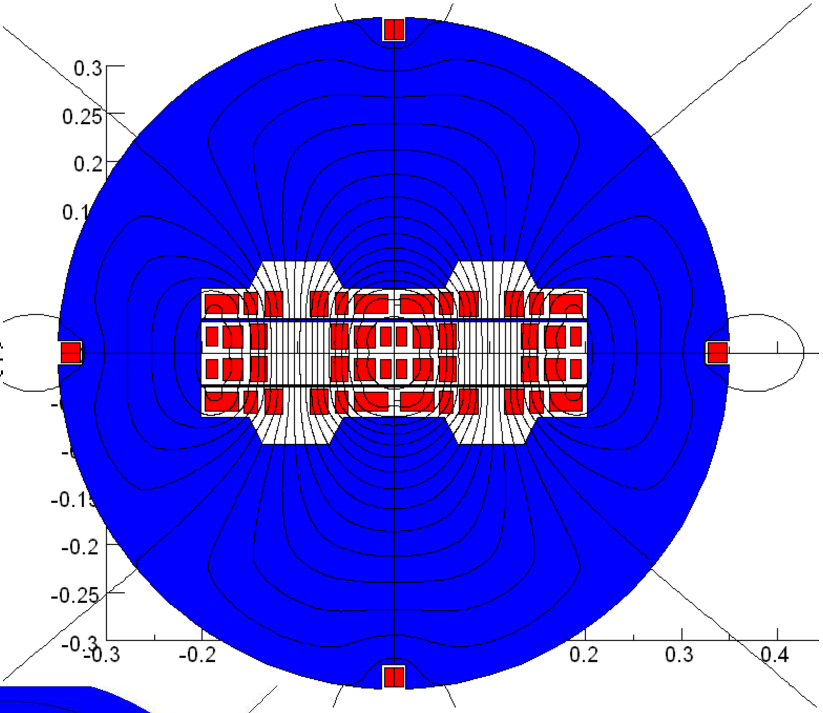
14 T

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

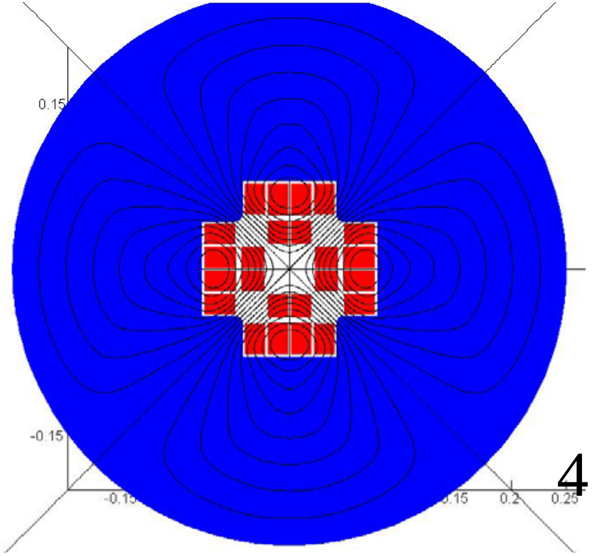
16.5 T Petavac Magnets



$\bar{p}p$ collider



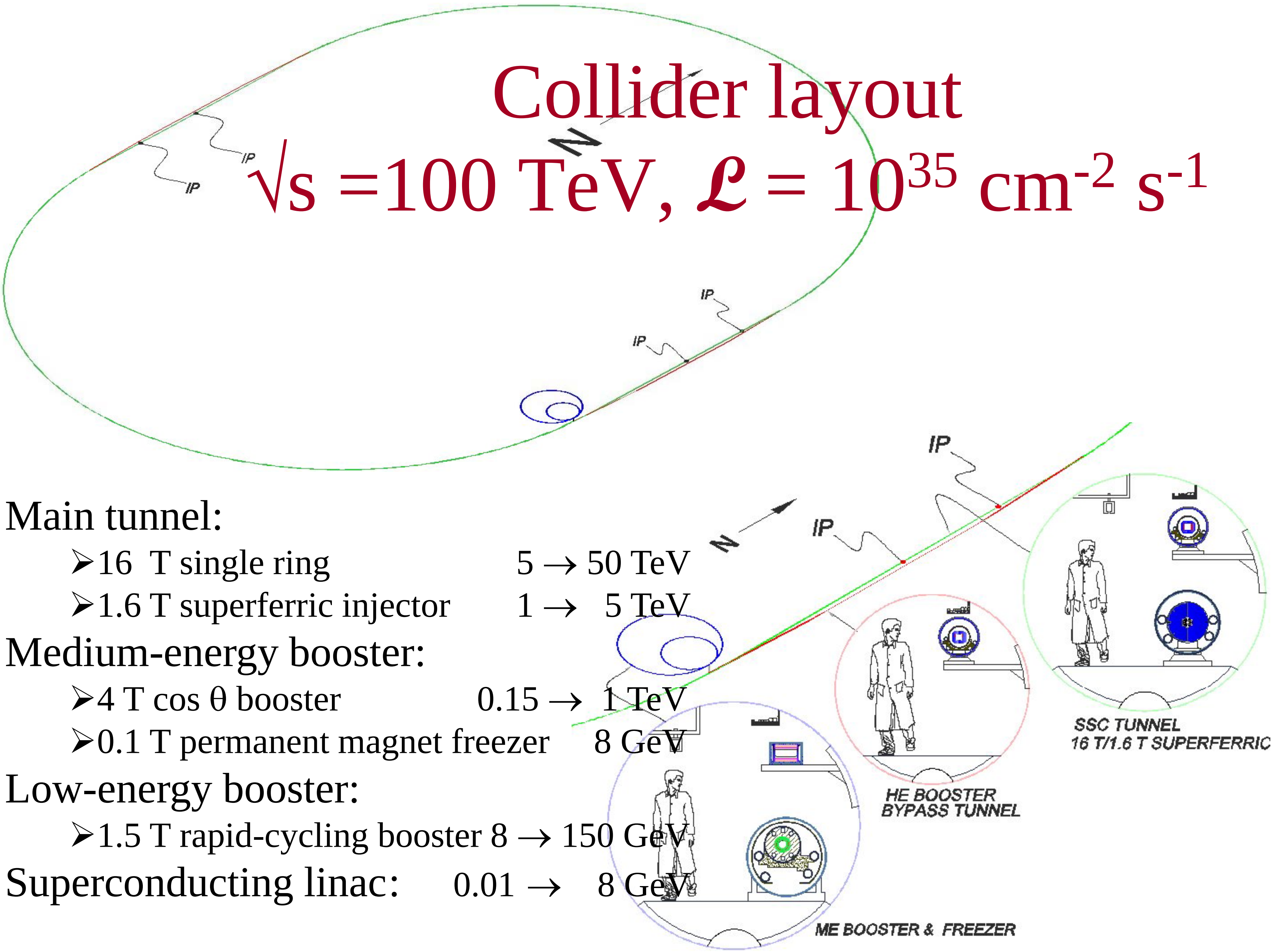
pp collider



470 T/m quadrupole

Collider layout

√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:

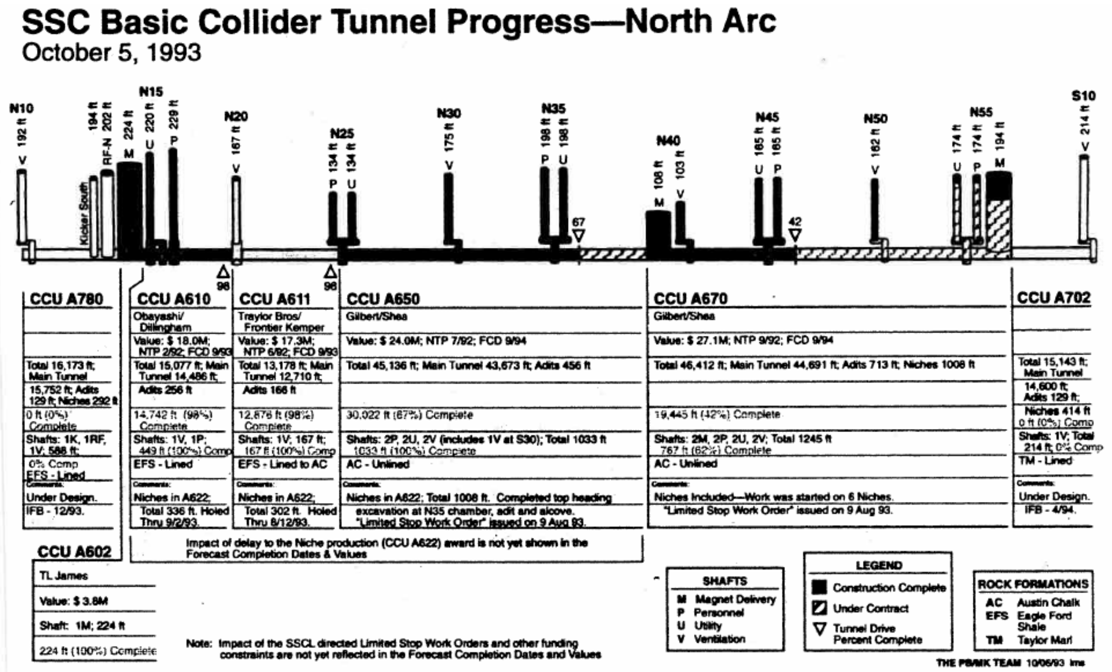
- ➢4 T cos θ booster 0.15 → 1 TeV
- ➢0.1 T permanent magnet freezer 8 GeV

Low-energy booster:

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

Superconducting linac: 0.01 → 8 GeV

SSC tunnel ~70% bored, 35% lined



SSC Basic Collider Tunnel Progress—North Arc

October 5, 1993

CCU A780	CCU A610	CCU A611	CCU A650	CCU A670	CCU A702
	Obayashi/ Dillingham	Traylor Bros/ Frontier Kemper	Gilbert/Shea	Gilbert/Shea	
	Value: $ 18.0M; NTP 2/92; FCD 9/93	Value: $ 17.3M; NTP 6/92; FCD 9/93	Value: $ 24.0M; NTP 7/92; FCD 9/94	Value: $ 27.1M; NTP 9/92; FCD 9/94	
Total 16,173 ft; Main Tunnel 15,752 ft; Adits 129 ft; Niches 292 ft	Total 15,077 ft; Main Tunnel 14,486 ft; Adits 256 ft	Total 13,178 ft; Main Tunnel 12,710 ft; Adits 166 ft	Total 45,136 ft; Main Tunnel 43,673 ft; Adits 456 ft	Total 46,412 ft; Main Tunnel 44,691 ft; Adits 713 ft; Niches 1008 ft	Total 15,143 ft; Main Tunnel 14,600 ft; Adits 129 ft; Niches 414 ft
0 ft (0%) Complete	14,742 ft (98%) Complete	12,876 ft (98%) Complete	30,022 ft (67%) Complete	19,445 ft (42%) Complete	0 ft (0%) Comp
Shafts: 1K, 1RF, 1V; 588 ft; 0% Comp	Shafts: 1V, 1P; 449 ft (100%) Comp	Shafts: 1V; 167 ft; 167 ft (100%) Comp	Shafts: 2P, 2U, 2V (includes 1V at S30); Total 1033 ft 1033 ft (100%) Complete	Shafts: 2M, 2P, 2U, 2V; Total 1245 ft 767 ft (62%) Complete	Shafts: 1V; Total 214 ft; 0% Comp
EFS - Lined	EFS - Lined	EFS - Lined to AC	AC - Unlined	AC - Unlined	TM - Lined
Comments: Under Design. IFB - 12/93.	Comments: Niches in A622; Total 336 ft. Holed Thru 9/2/93.	Comments: Niches in A622; Total 302 ft. Holed Thru 8/12/93.	Comments: Niches in A622; Total 1008 ft. Completed top heading excavation at N35 chamber, adit and alcove. "Limited Stop Work Order" issued on 9 Aug 93.	Comments: Niches Included—Work was started on 6 Niches. "Limited Stop Work Order" issued on 9 Aug 93.	Comments: Under Design. IFB - 4/94.

Impact of delay to the Niche production (CCU A622) award is not yet shown in the Forecast Completion Dates & Values

CCU A602
TL James
Value: $ 3.8M
Shaft: 1M; 224 ft
224 ft (100%) Complete

Note: Impact of the SSCL directed Limited Stop Work Orders and other funding constraints are not yet reflected in the Forecast Completion Dates and Values

SHAFTS

M Magnet Delivery
P Personnel
U Utility
V Ventilation

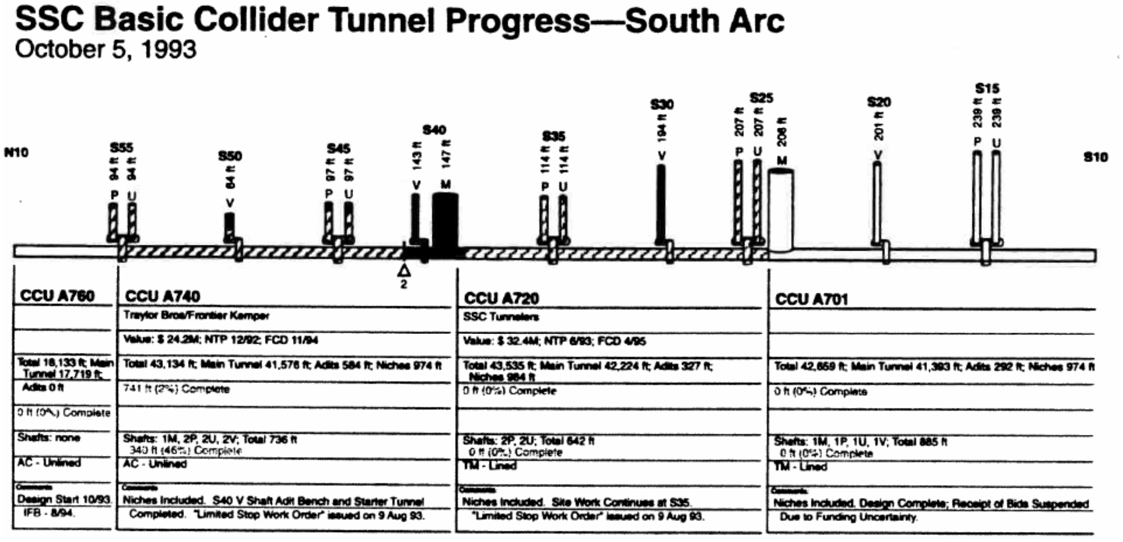
LEGEND

■ Construction Complete
▨ Under Contract
▽ Tunnel Drive Percent Complete

ROCK FORMATIONS

AC	Austin Chalk
EFS	Eagle Ford Shale
TM	Taylor Marl

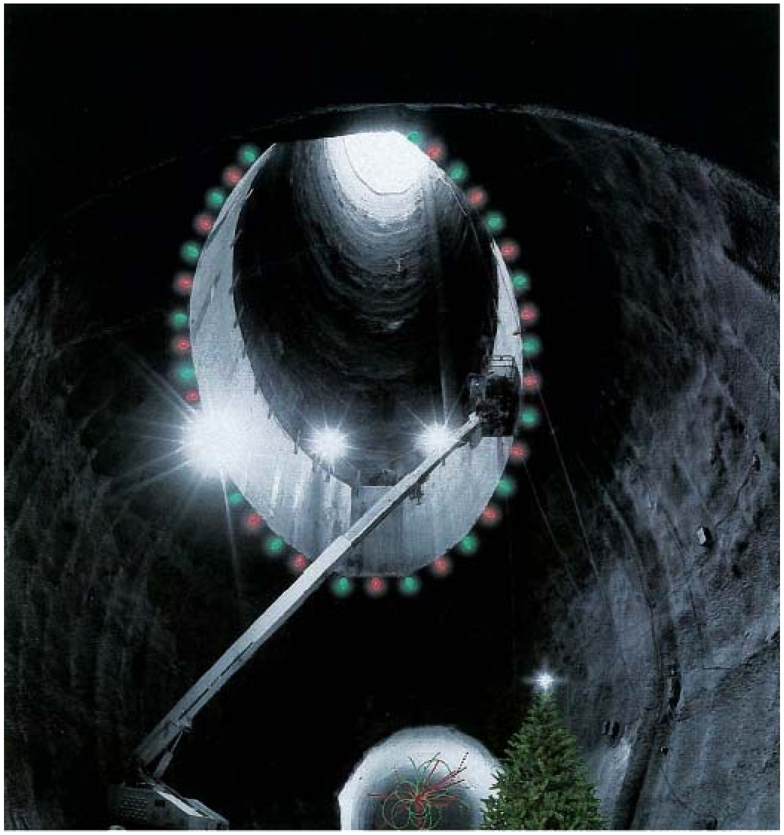
THE PB/MK TEAM 10/06/93 lms



SSC Basic Collider Tunnel Progress—South Arc

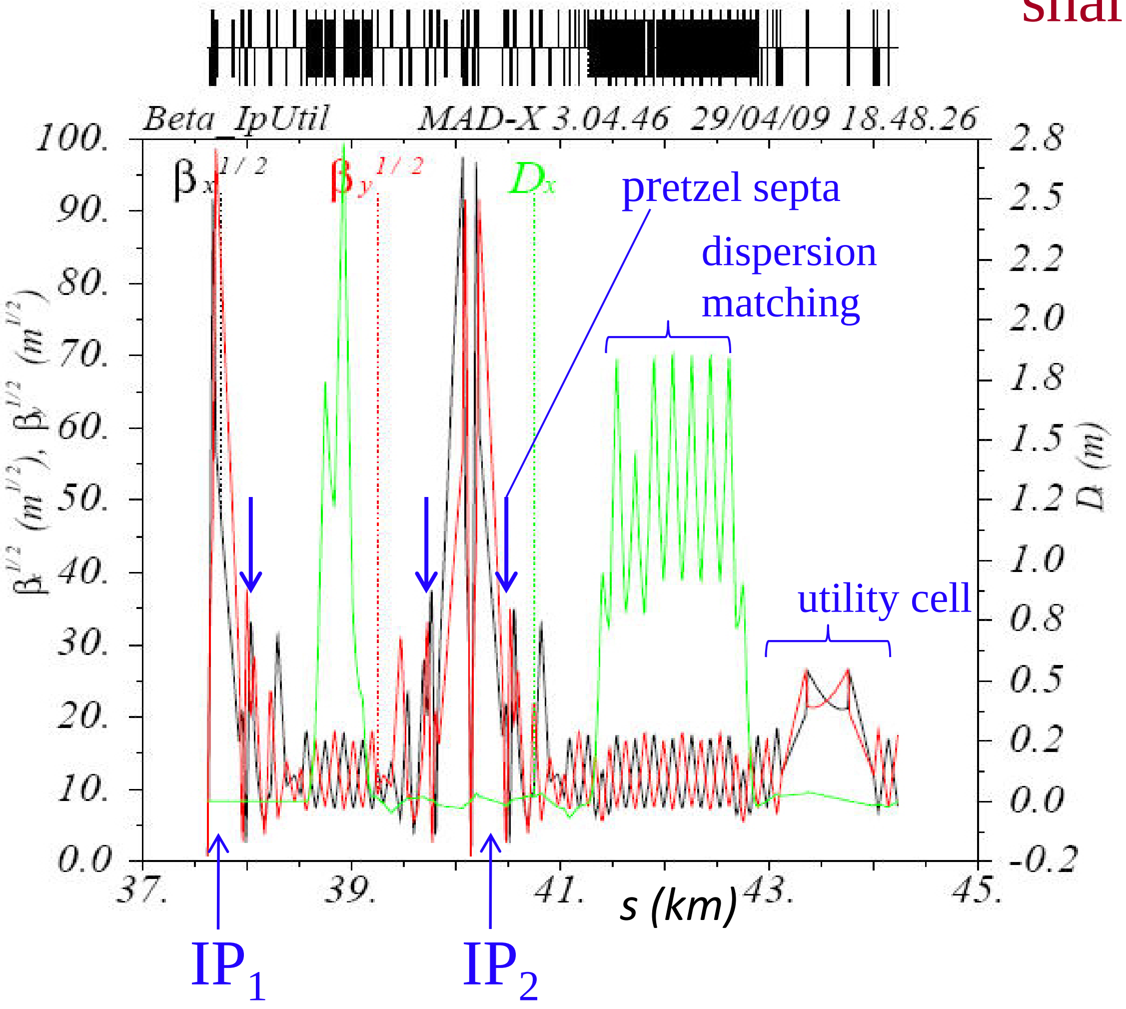
October 5, 1993

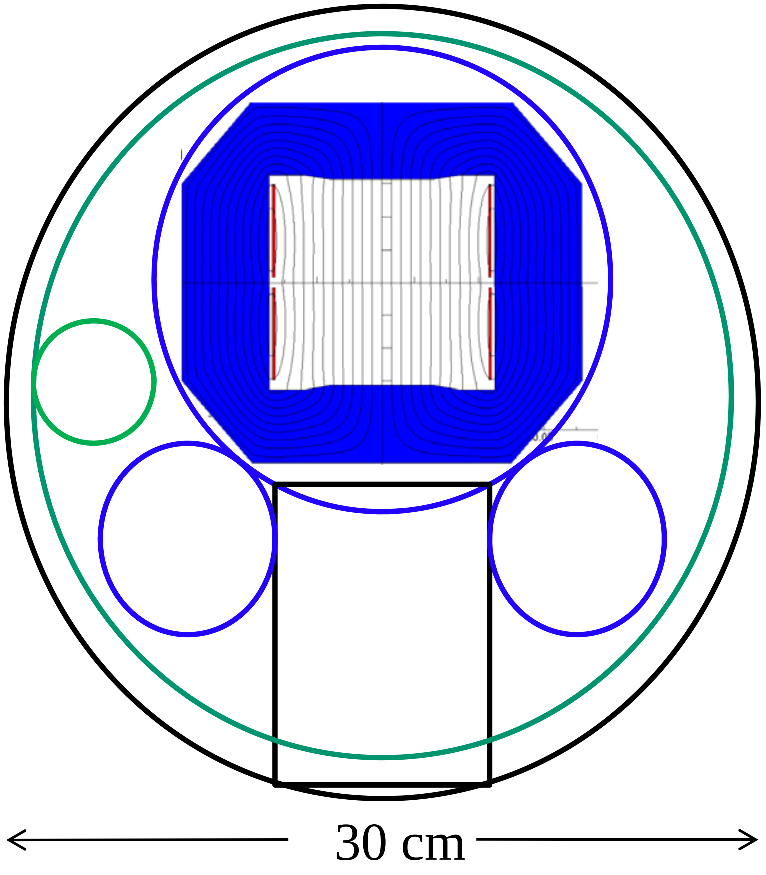
CCU A760	CCU A740	CCU A720	CCU A701
	Traylor Bros/Frontier Kemper	SSC Tunnelers	
	Value: $ 24.2M; NTP 12/92; FCD 11/94	Value: $ 32.4M; NTP 6/93; FCD 4/95	
Total 18,133 ft; Main Tunnel 17,719 ft; Adits 0 ft	Total 43,134 ft; Main Tunnel 41,576 ft; Adits 584 ft; Niches 974 ft	Total 43,535 ft; Main Tunnel 42,224 ft; Adits 327 ft; Niches 984 ft	Total 42,659 ft; Main Tunnel 41,393 ft; Adits 292 ft; Niches 974 ft
0 ft (0%) Complete	741 ft (2%) Complete	0 ft (0%) Complete	0 ft (0%) Complete
Shafts: none	Shafts: 1M, 2P, 2U, 2V; Total 736 ft 340 ft (46%) Complete	Shafts: 2P, 2U; Total 642 ft 0 ft (0%) Complete	Shafts: 1M, 1P, 1U, 1V; Total 885 ft 0 ft (0%) Complete
AC - Unlined	AC - Unlined	TM - Lined	TM - Lined
Comments: Design Start 10/93. IFB - 8/94.	Comments: Niches Included. S40 V Shaft Adit Bench and Starter Tunnel Completed. "Limited Stop Work Order" issued on 9 Aug 93.	Comments: Niches Included. Site Work Continues at S35. "Limited Stop Work Order" issued on 9 Aug 93.	Comments: Niches Included. Design Complete; Receipt of Bids Suspended Due to Funding Uncertainty.



Petavac Lattice

Superferric High-Energy Injector
shares the same tunnel





β^* = 0.5 m

β_{max} = 9.6 km

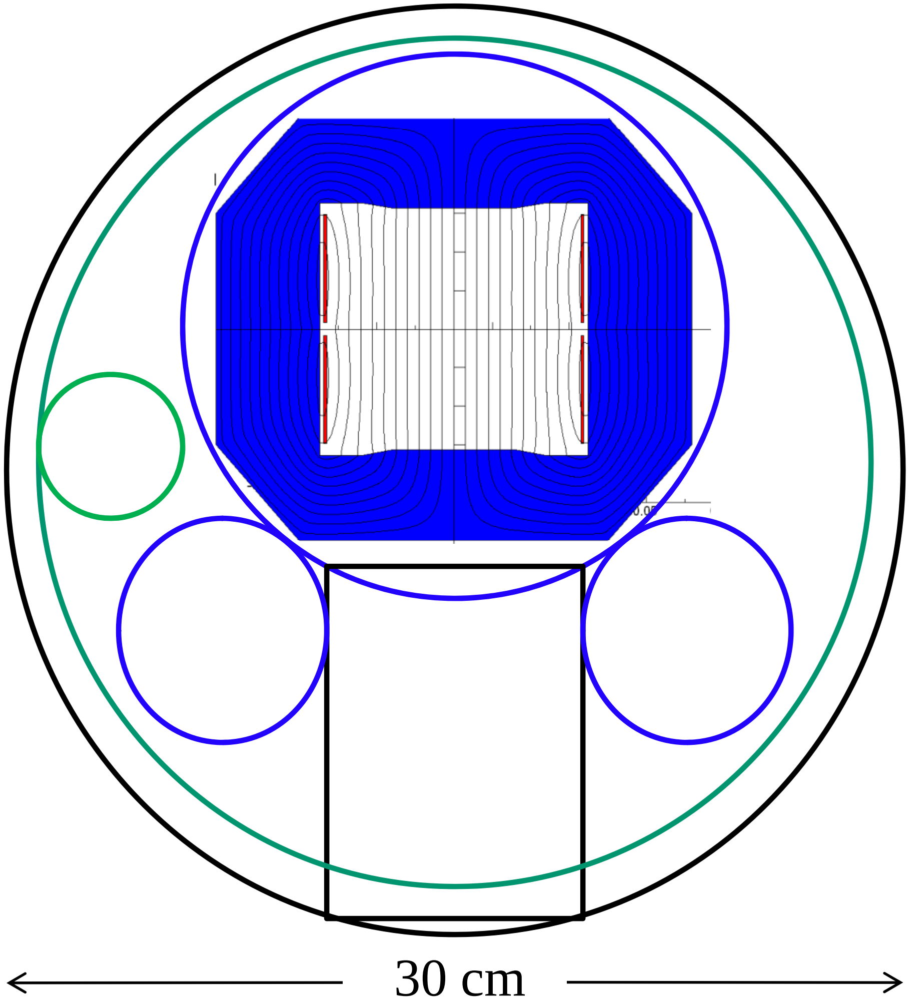
1.6 T = 5 TeV

Comparison of Parameters

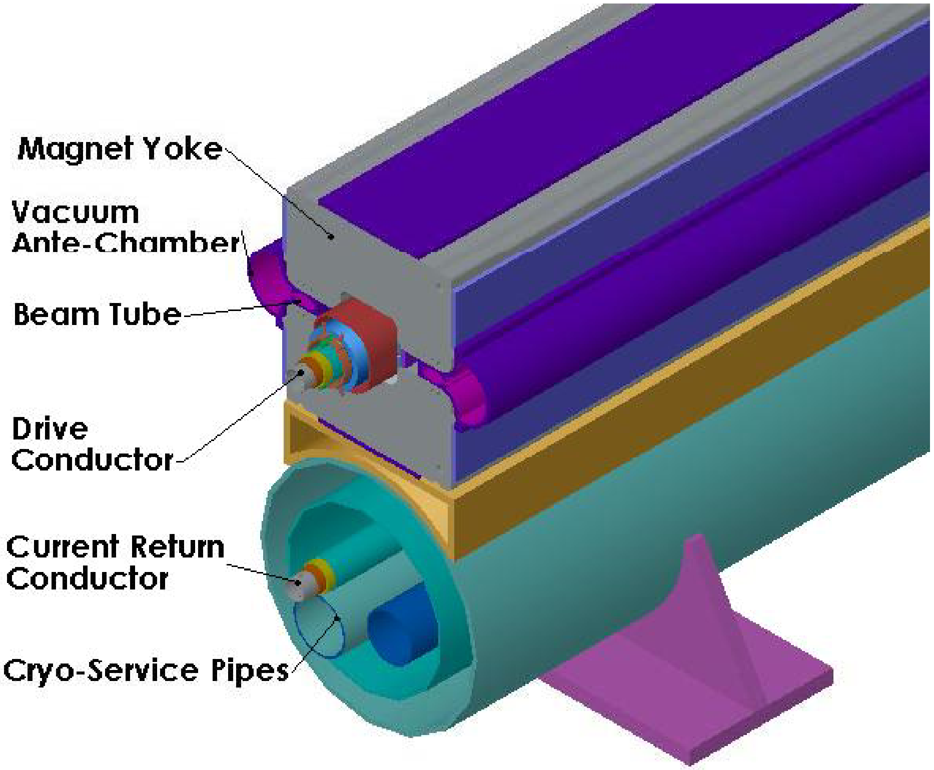
	Tevatron	SSC	LHC nominal	100 TeV	100 TeV	
collision energy E	2	40	14	100	100	TeV
gamma	1,066	21,322	7,463	53,305	53,305	
luminosity	1.5E+32	5.6E+32	6.6E+33	1.0E+34	1.0E+35	$cm^{-2}s^{-1}$
# bunches	36	16,440	2,800	11,000	11,000	
# interactions/ collision	5	2	7	45	85	
bunch spacing T_b	396	16	25	20	20	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

Superferric High-Energy Injector shares the same tunnel



Single bore ($\bar{p}p$)



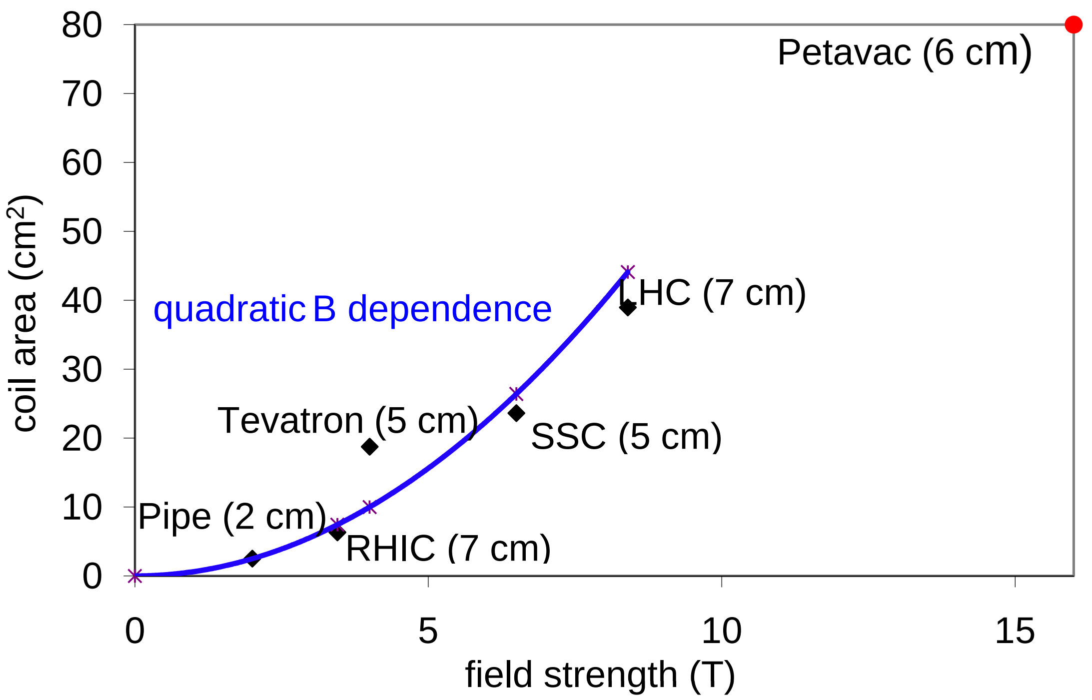
Dual bore (pp)

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
- TwoPetavac rings require 11,000 tons of wire
- Wire price today $1,000/kg, ÷2 in volume
- $5.5 billion superconductor → ~$10 billion for rings

Thus the premium to use $\bar{p}p$ *colliding beams.*

New magnet design, New materials, Dramatic Performance

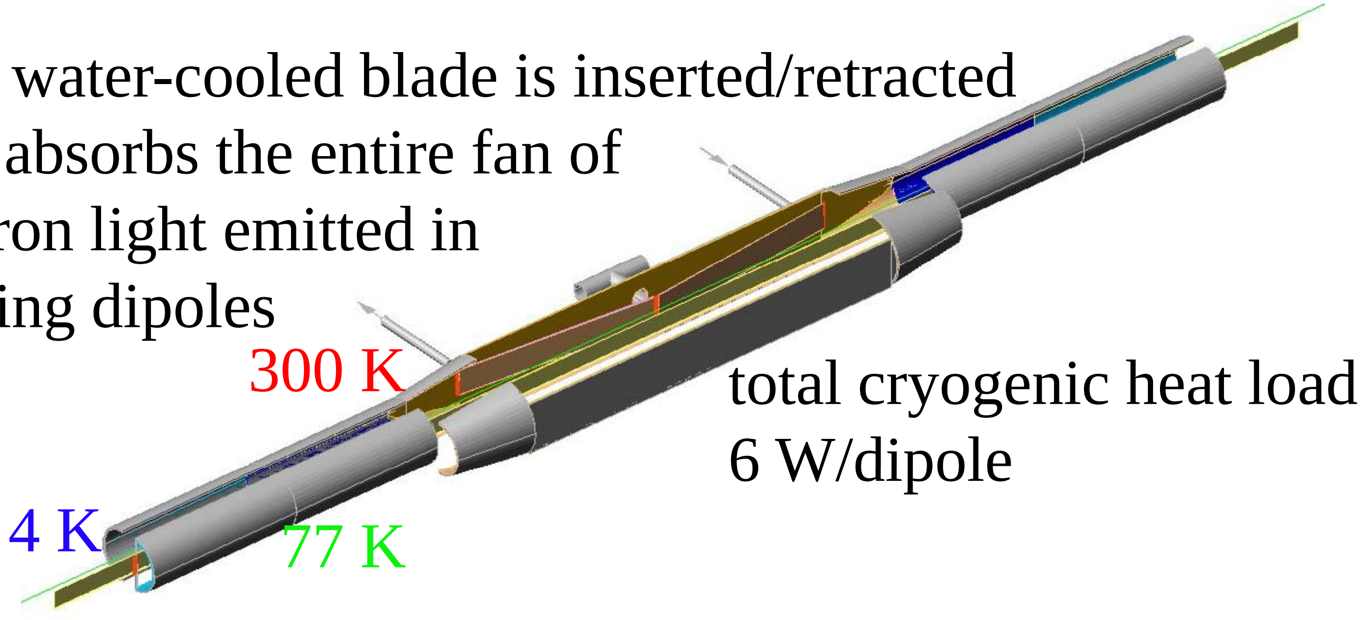


Accelerator Challenges for Pentavac

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

  Solution: room-temp photon stop between successive dipoles

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



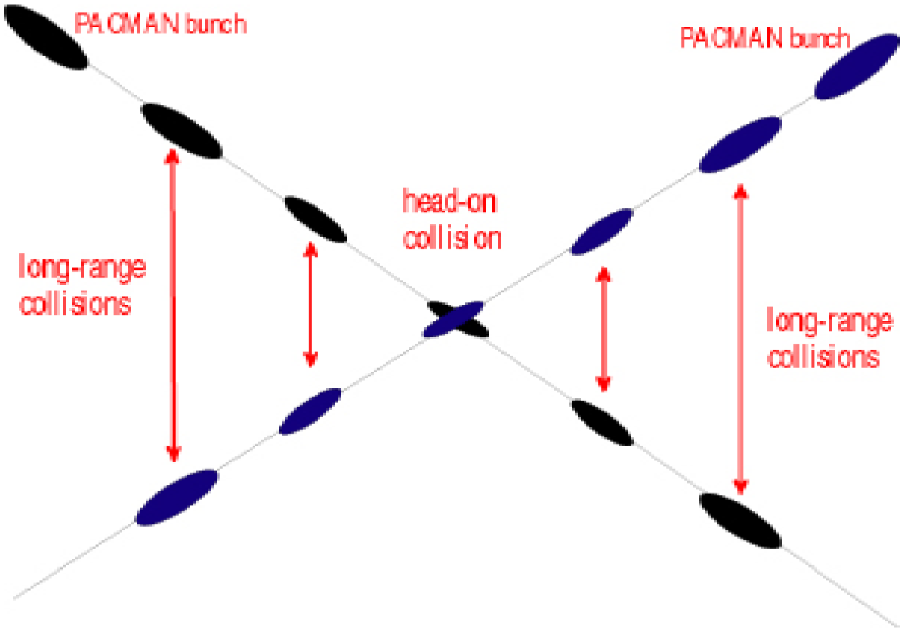
total cryogenic heat load
6 W/dipole

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.

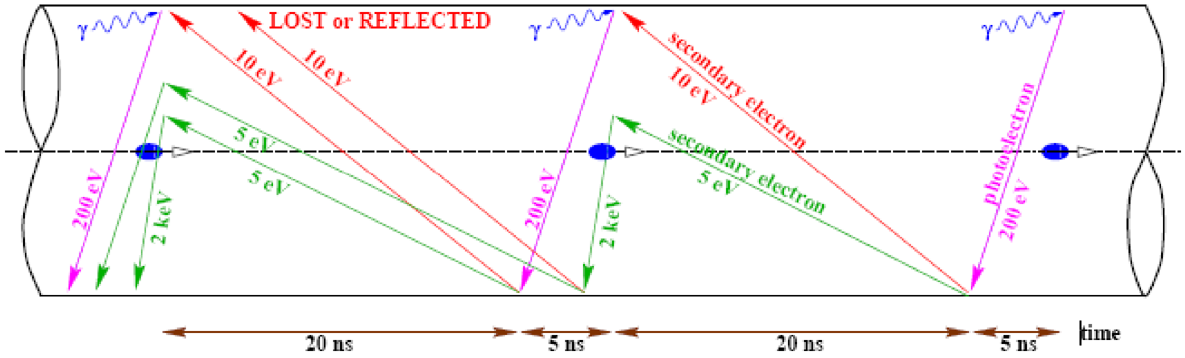
- Avoid beam-beam tune shift from subsidiary crossings of bunches

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 for photon stops

➢*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…

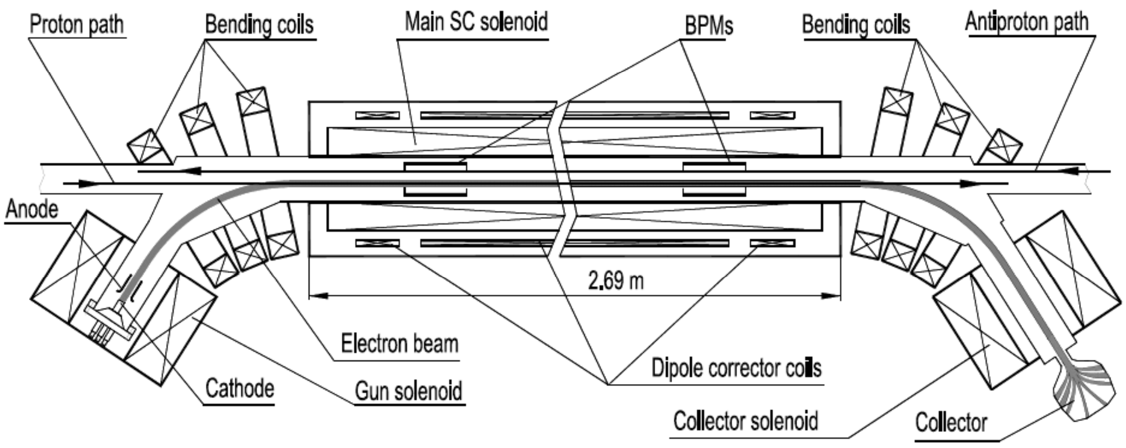
Poses serious challenge to reach even 10^{34} luminosity, much less 10^{35}

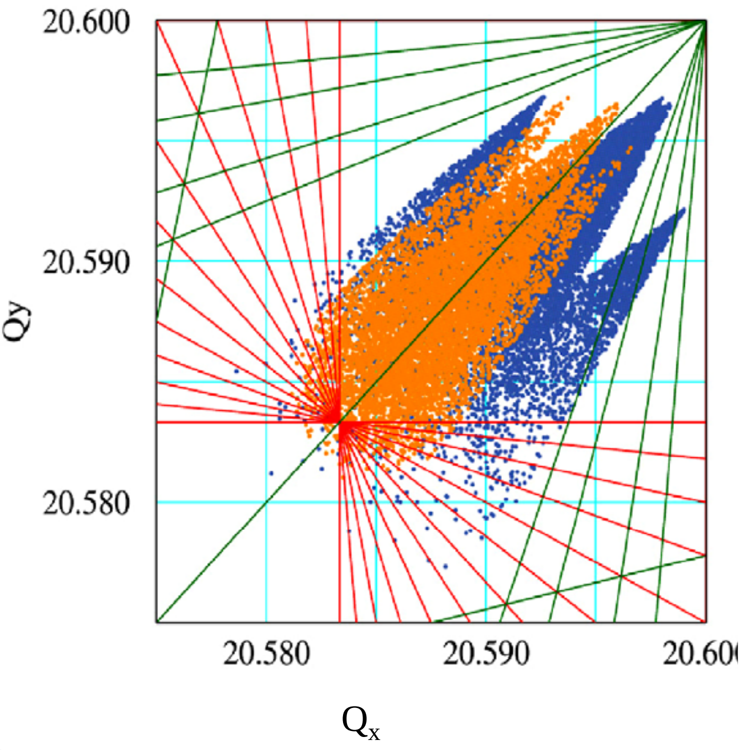
Solution: Install continuous strip electrode on side wall of vacuum tube around entire ring. Bias ~50 V *clears all charge in <20ns*

- Bunch-bunch tune spread kills luminosity.

Successive bunches have different tune 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: Electron lens makes
Focusing/defocusing fields on beam
that is traveling in the same direction,
Measure tune of each bunch using ac dipole
Correct it using e lens.
t





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.

AARD needs shelter: its mission is not to simply augment today's programs.

It makes our future possible!