# New Materials and Electromagnetics in Superconducting Accelerator Technology: Five examples of its impact

- Optimized IR for LHC Luminosity
- Triple the energy of LHC
- Super-SPS for ultimate-luminosity LHC
- Electron Cloud Killer for LHC and ILC
- Polyhedral cavity structure for linear colliders


Al McInturff, Peter McIntyre, Akhdiyor Sattarov physicists

Joong Byeon, Patrick Noyes, Nate Pogue grad students

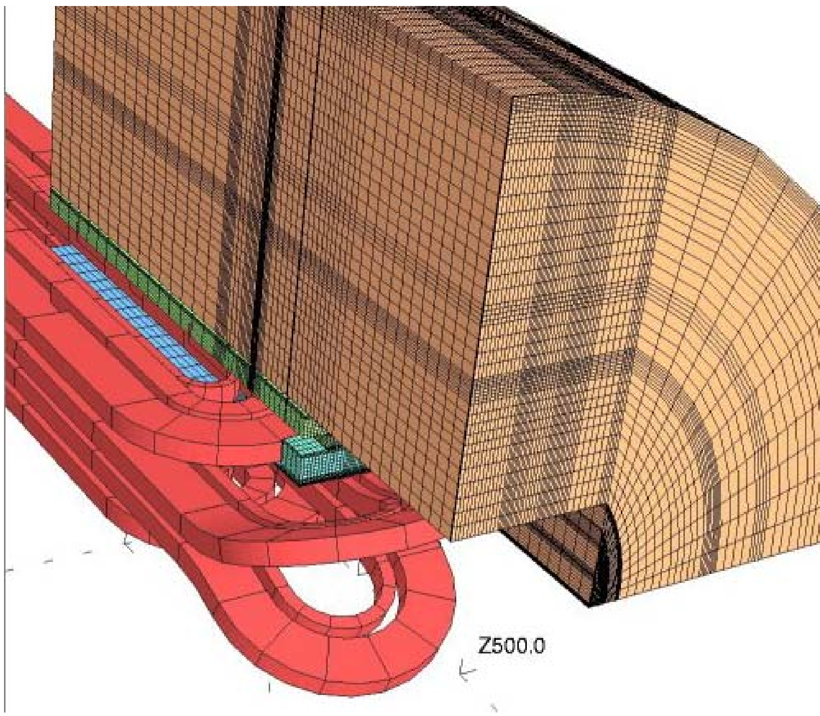
Ray Blackburn, Nick Diazcenko, Tim Elliott, Bill Henchel, Drew Jaisle technicians

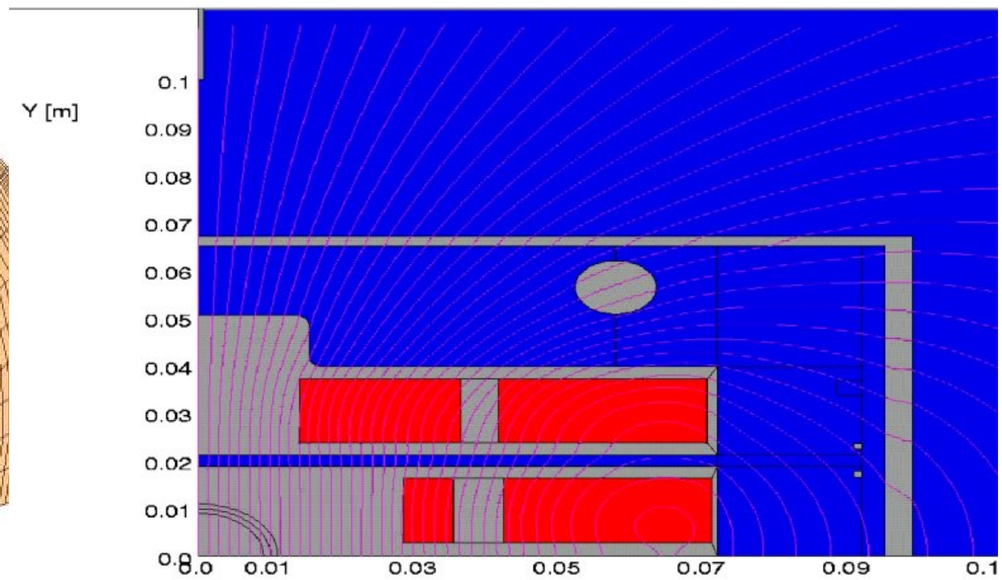
Accelerator Research Lab

Texas A&M University

# *What we are funded to do:* new technology for high-field dipoles

- $Nb_3Sn$: 14 Tesla dipole



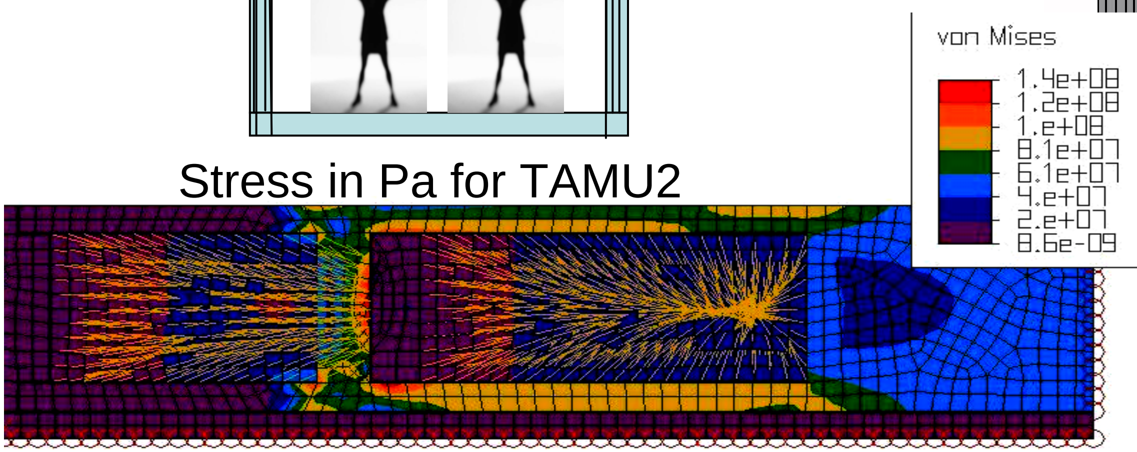




| | | | |
|---|---|---|---|
| • Bore field | 14.1 T | • Maximum Coil Stress | 120 MPa |
| • Current | 12.6 kA | • Superconductor cross section | 29 $cm^2$ |

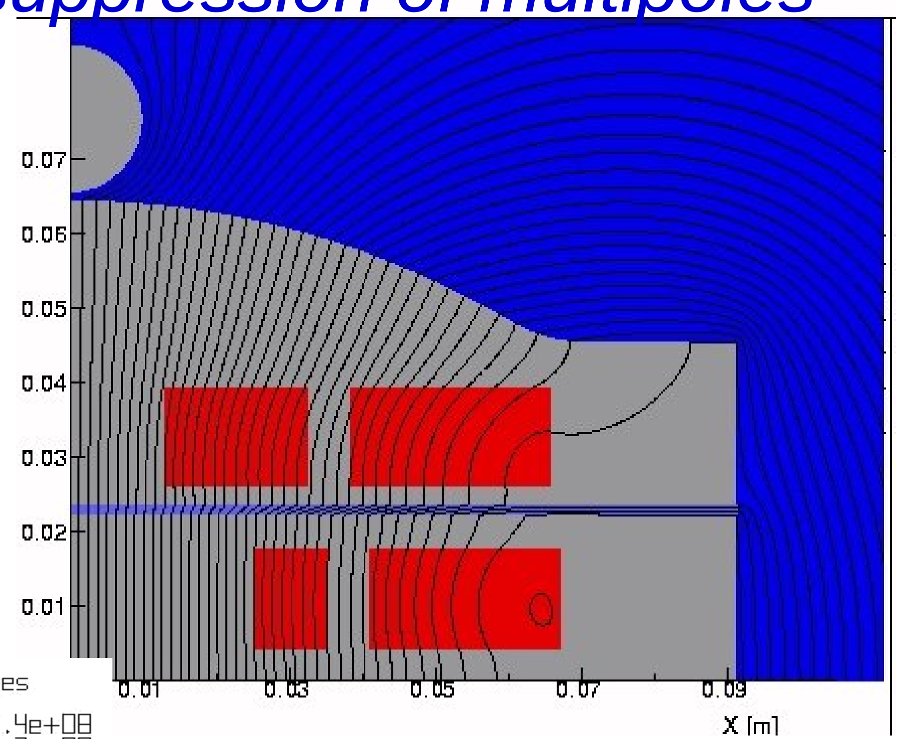
# New tricks make $Nb_3Sn$ feasible

*Stress Management*

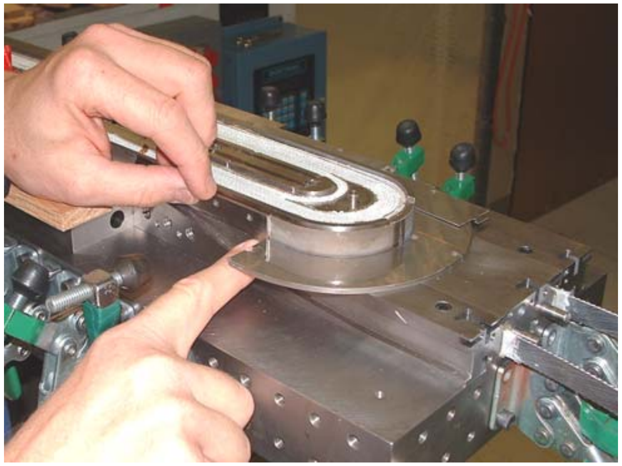
Stress in Pa for TAMU2



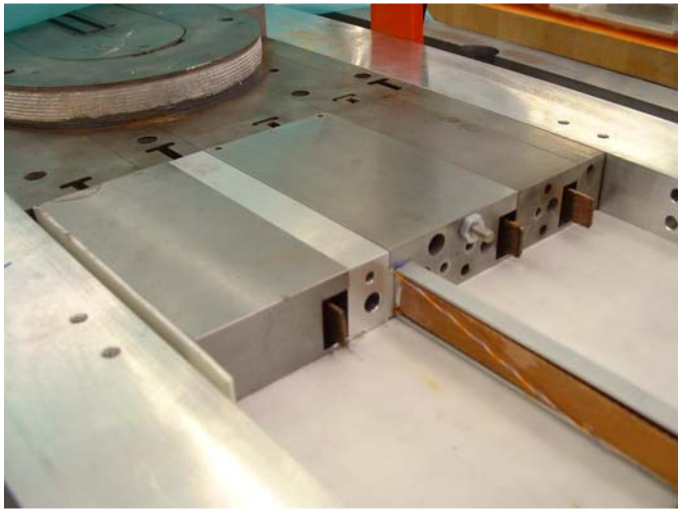
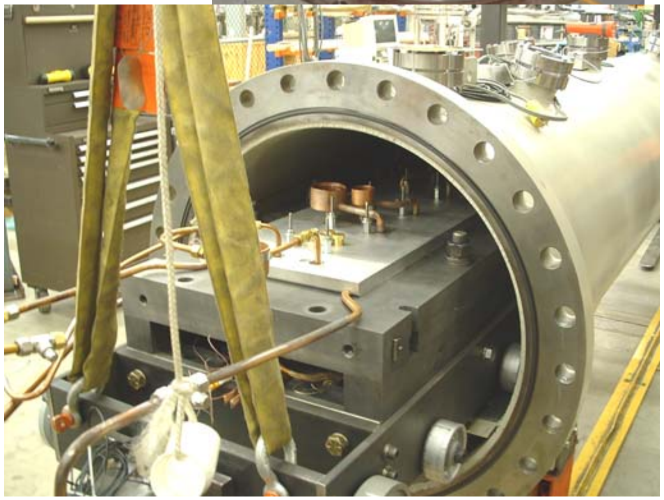

*Flux plate*
*suppression of multipoles*



# New $Nb_3Sn$ dipole technology:
## stress management, flux plate, bladder preload



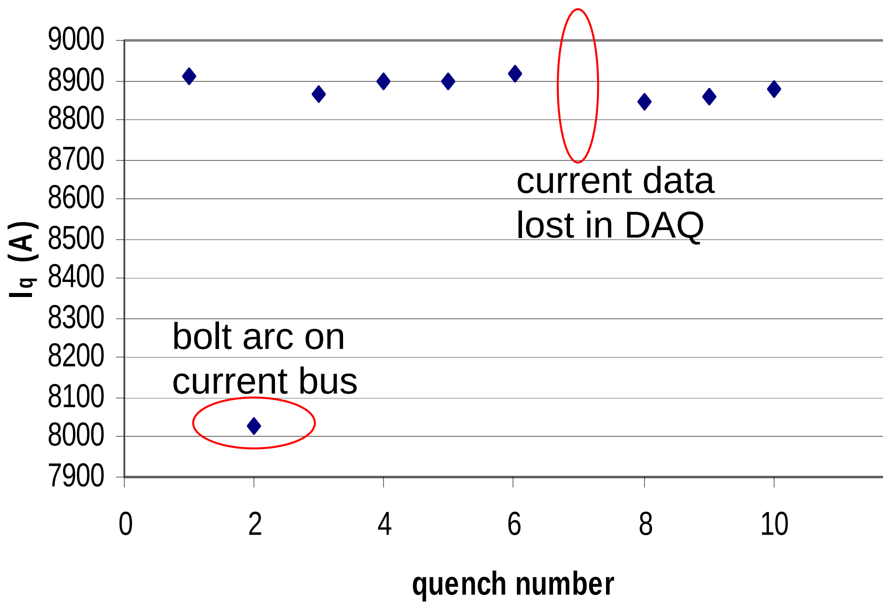


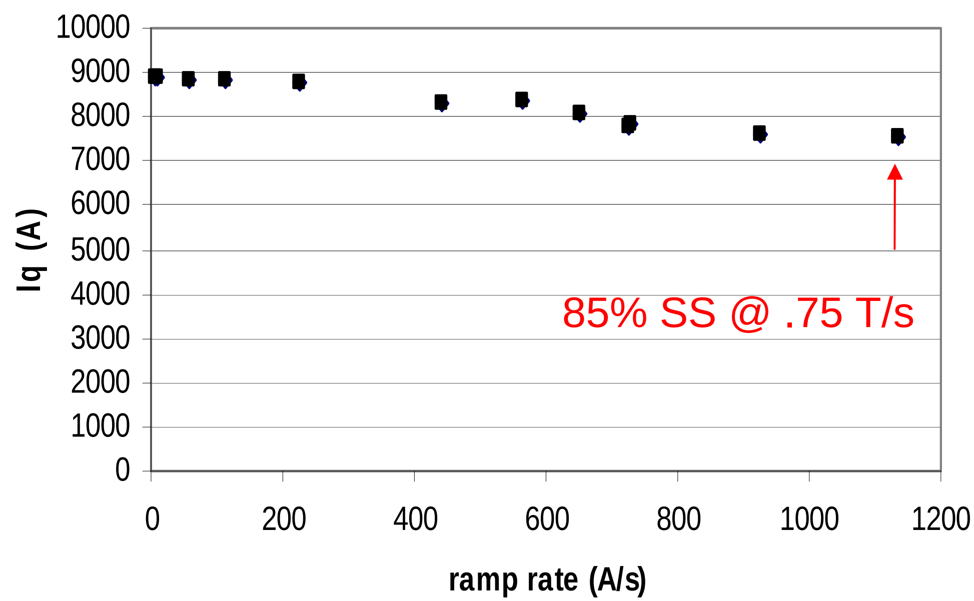



# Recent Results: Testing of TAMU2

- Single-pancake model to evaluate stress management structure: 7 T, 7 kA

*Noyes' thesis*



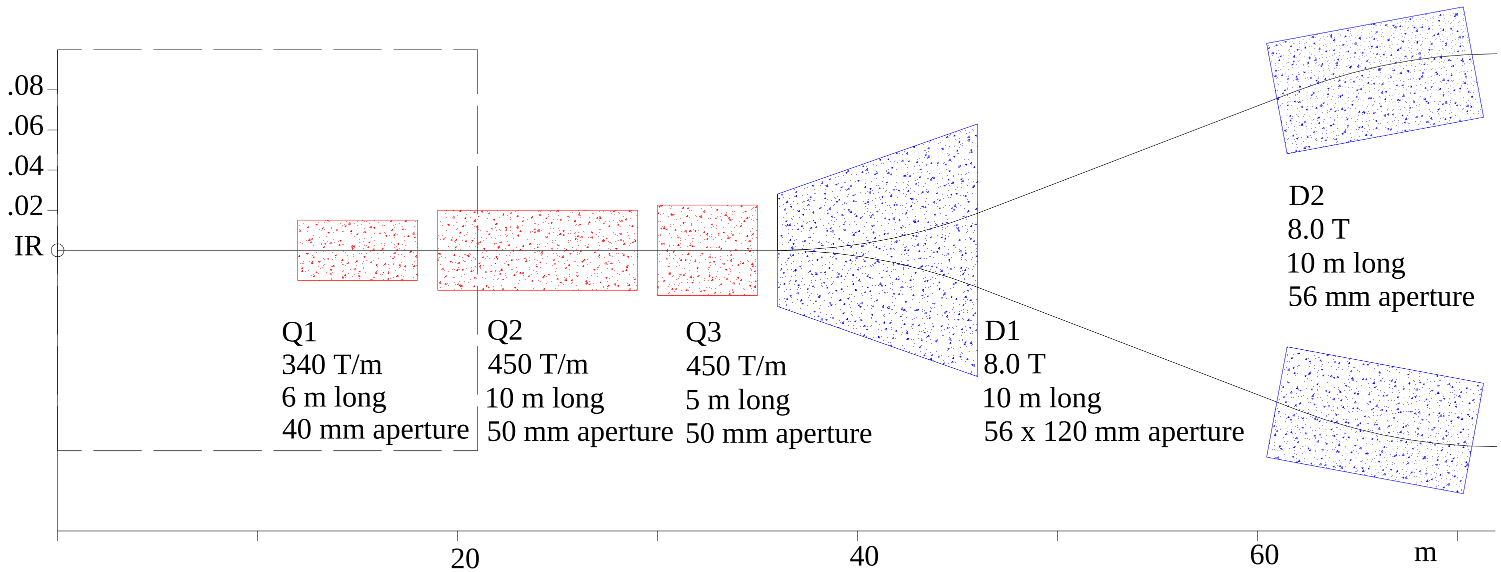




~93% short sample first and every quench – *no training*

*Surprise* - low AC losses in coil up to ~2 T/s

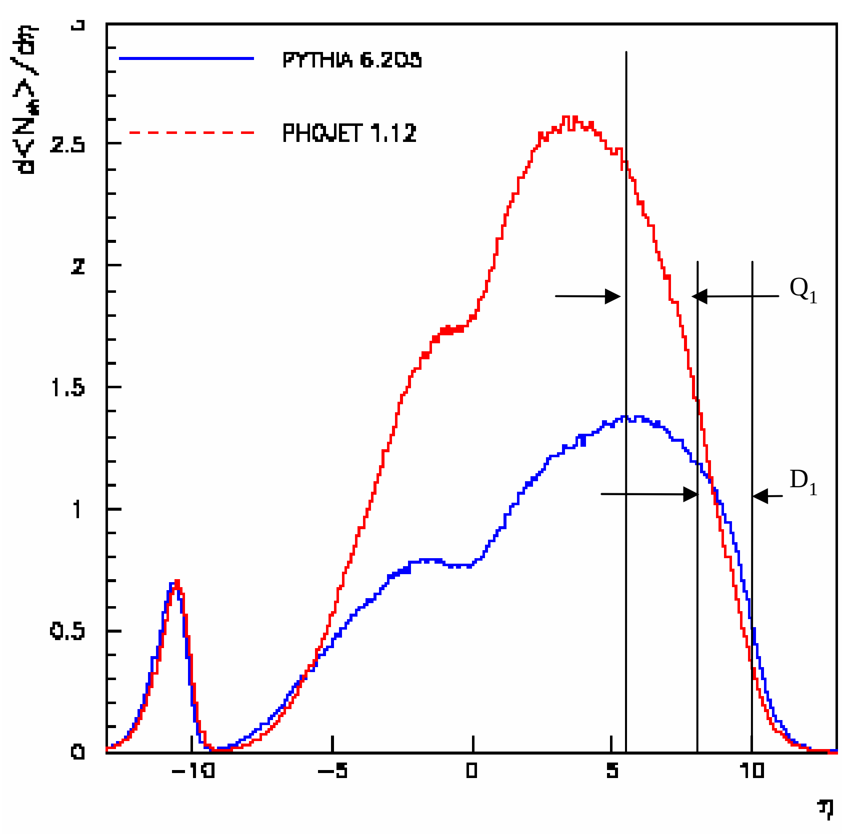
– suggests a better technology for rapid-cycling accelerators

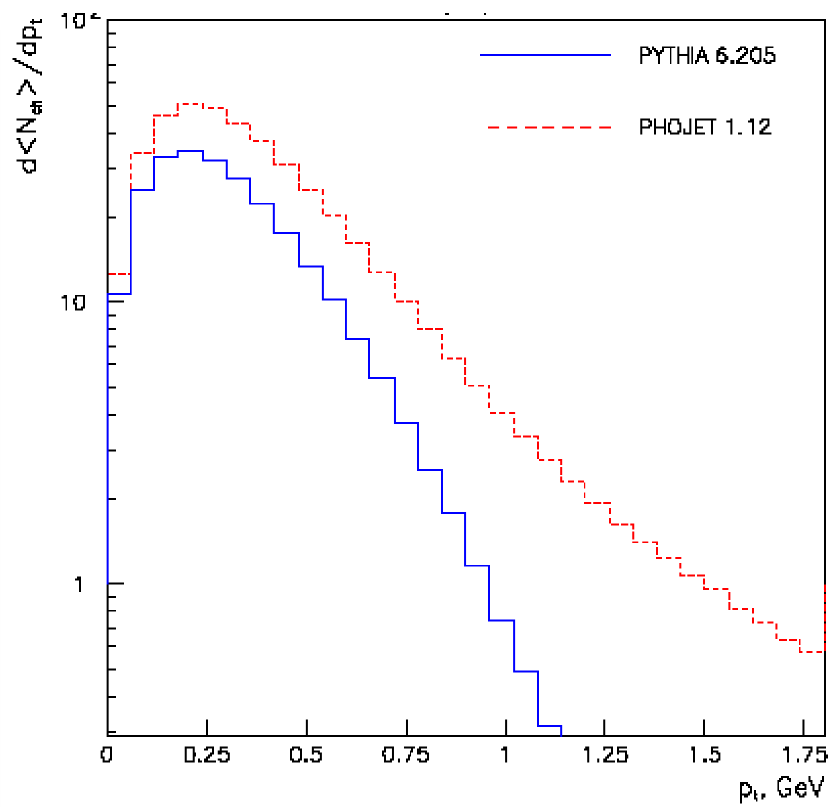
# 1) Optimizing IR for LHC Luminosity↑




- The intersection region of a collider is like the *objective of a microscope.*
- It brings the beams into collision and focuses them to minimum spot size → maximum luminosity
- Maximize luminosity ⇒ minimum focal length $f \sim \beta^2$ ⇒ maximum gradient.
- Minimize chromatic aberrations $\partial f / \partial E$ , harmonic distortion. $\partial f / \partial x$
- ⇒ Bring the objective as close to the object (IP) as possible!
- Develop designs for quadrupole $Q_1$, dipole $D_1$ that can tolerate high radiation, high heat load!

# $Q_1$, $D_1$ are in harm's way

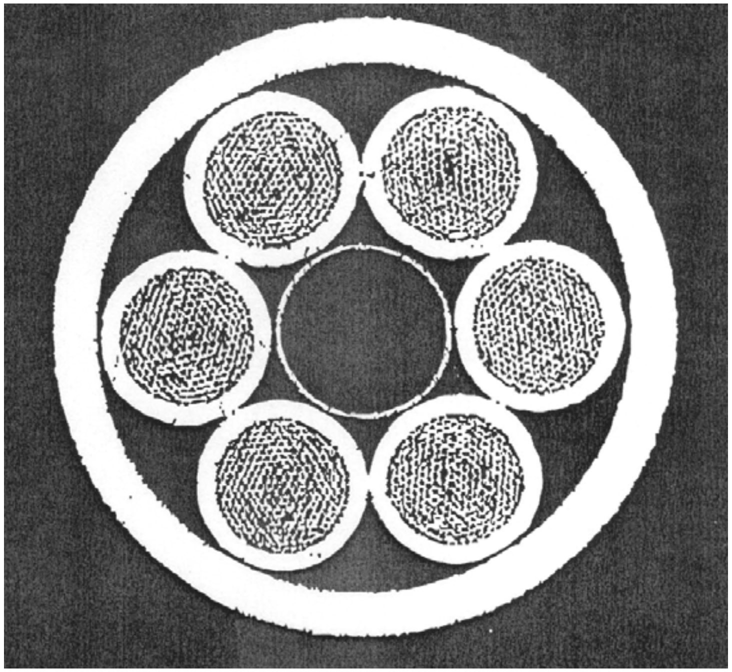



Multiplicity ~ $f(\eta)\, e^{-bt}$ $\qquad$ $E_{particle} \sim p_t/\theta$

So energy flow concentrates strongly down the beam direction.

# Design $Q_1$ using structured cable



Developed at Texas A&M for a different purpose:

Bi-2212 windings for NMR solenoids

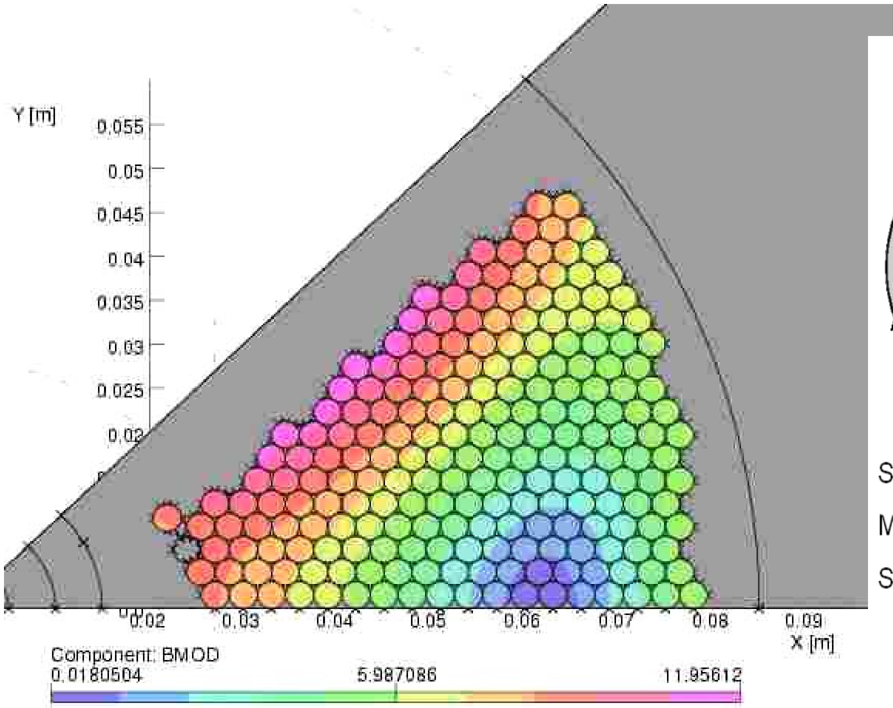
6-on-1 cabling of $Nb_3Sn$ strand around thin-wall Inconel X750 spring tube

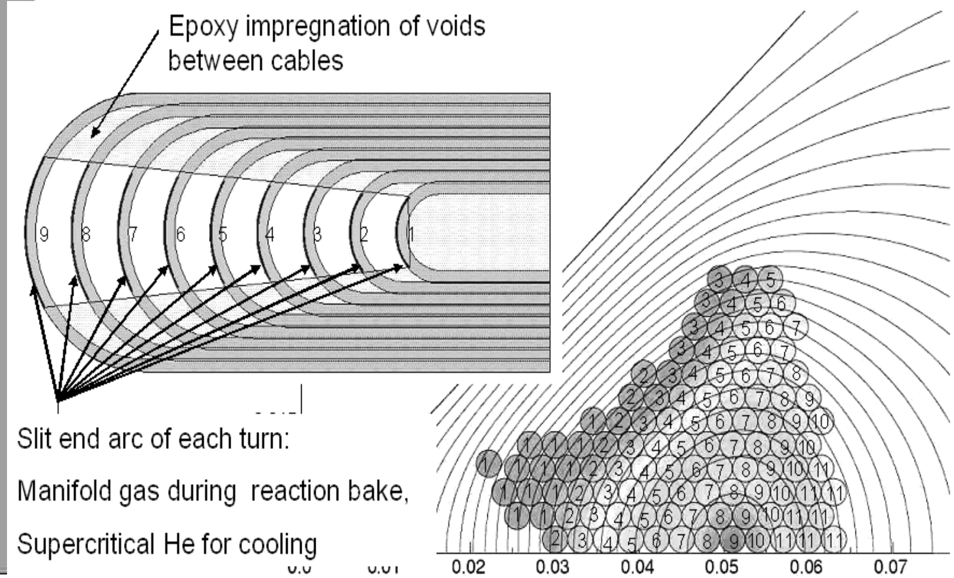
Draw within Inconel 718 sheath $\rightarrow$ *stress management* within coil

Interior is not impregnated – only region between cables in winding

*Volumetric cooling* with supercritical He removes volumetric heating from losses

# Ironless Quadrupole for $Q_1$



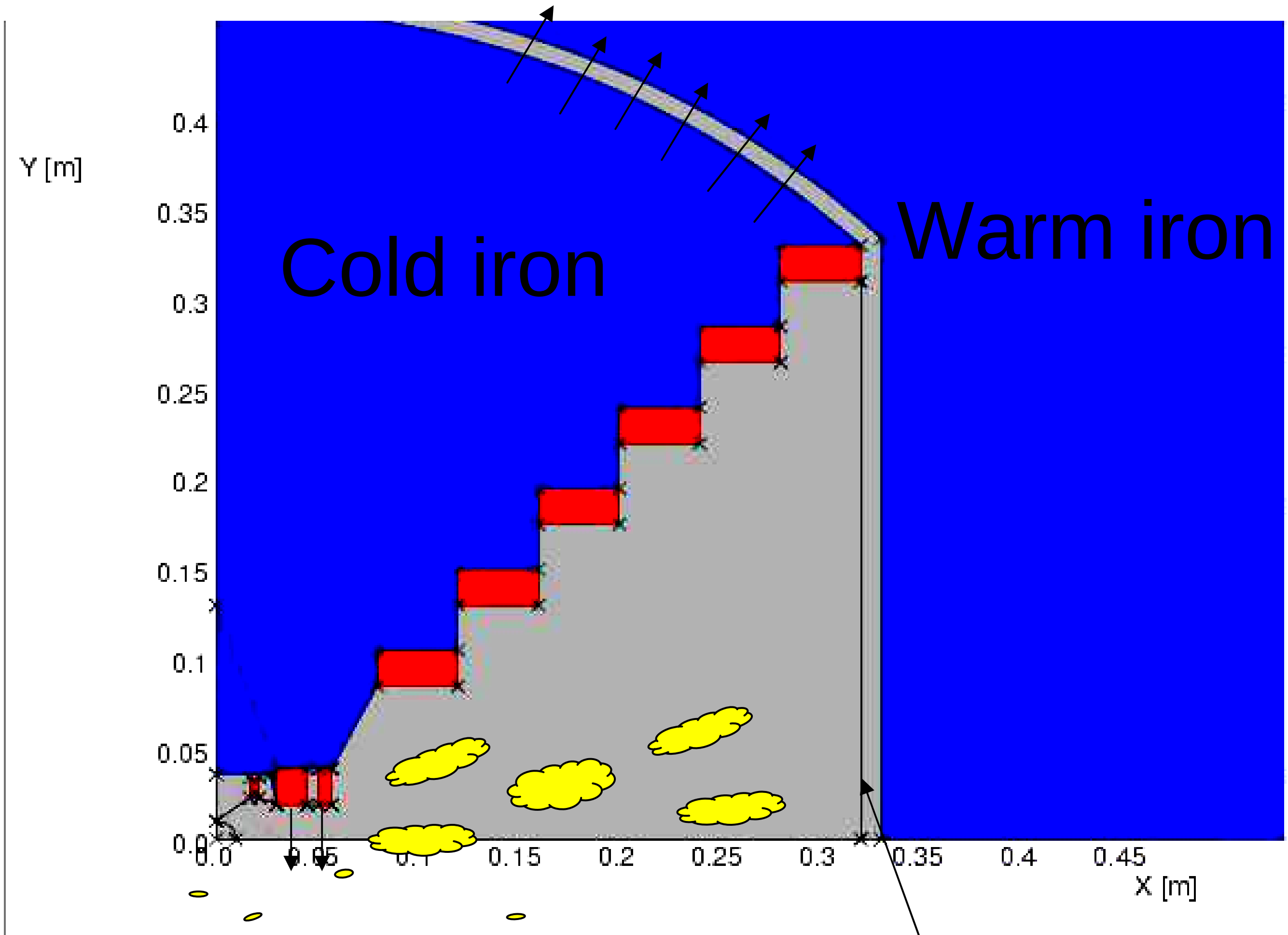

350 T/m

4-6 K supercritical cooling

Inconel sheath provides turn/turn insulation

$\Rightarrow$ *no insulation to degrade under radiation damage*

# $D_1$: Levitated-Pole Dipole




**8.7 T**

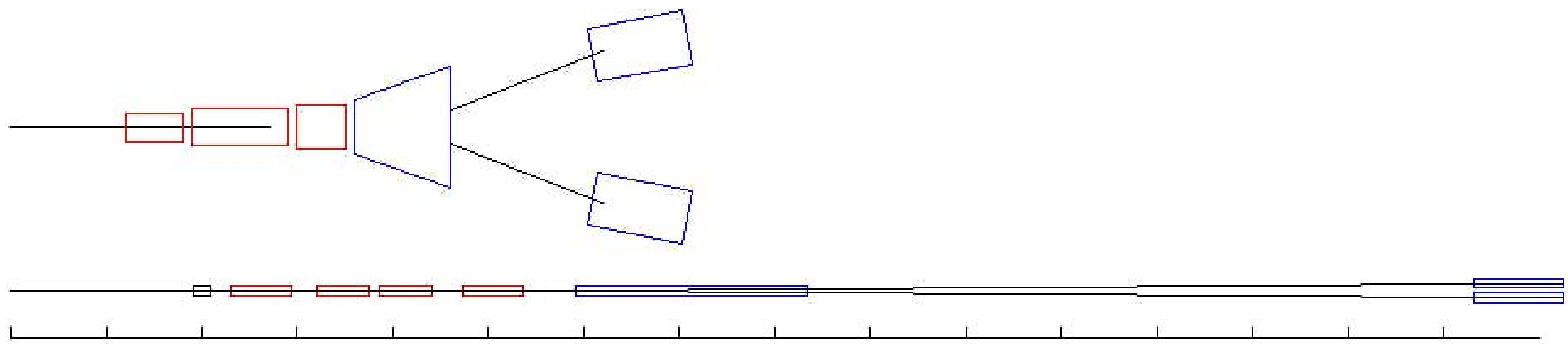
**4.5 K**

**56 mm aperture**

Cancel Lorentz forces on coils, pole steel.

Heat, radiation taken on room-temp steel!

# This approach to IR elements opens new opportunities to optimize IR optics



Comparison to baseline IR:

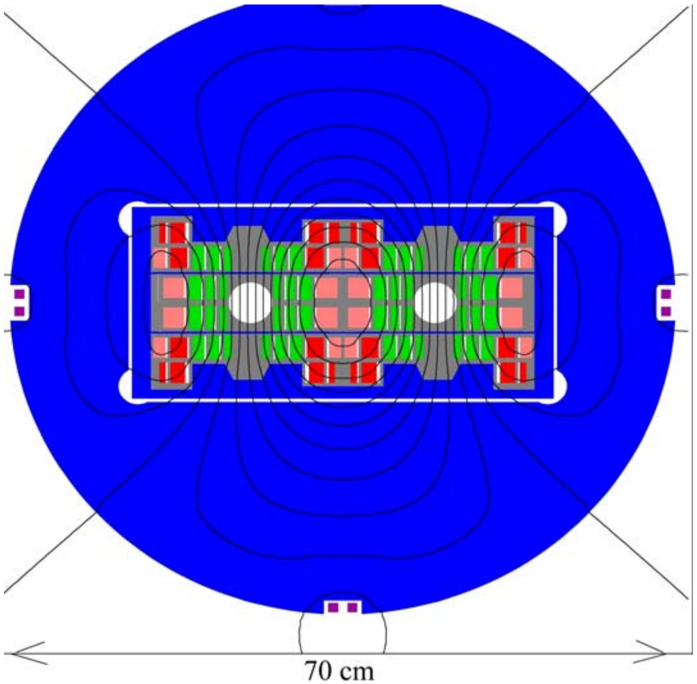
•Reduces β*

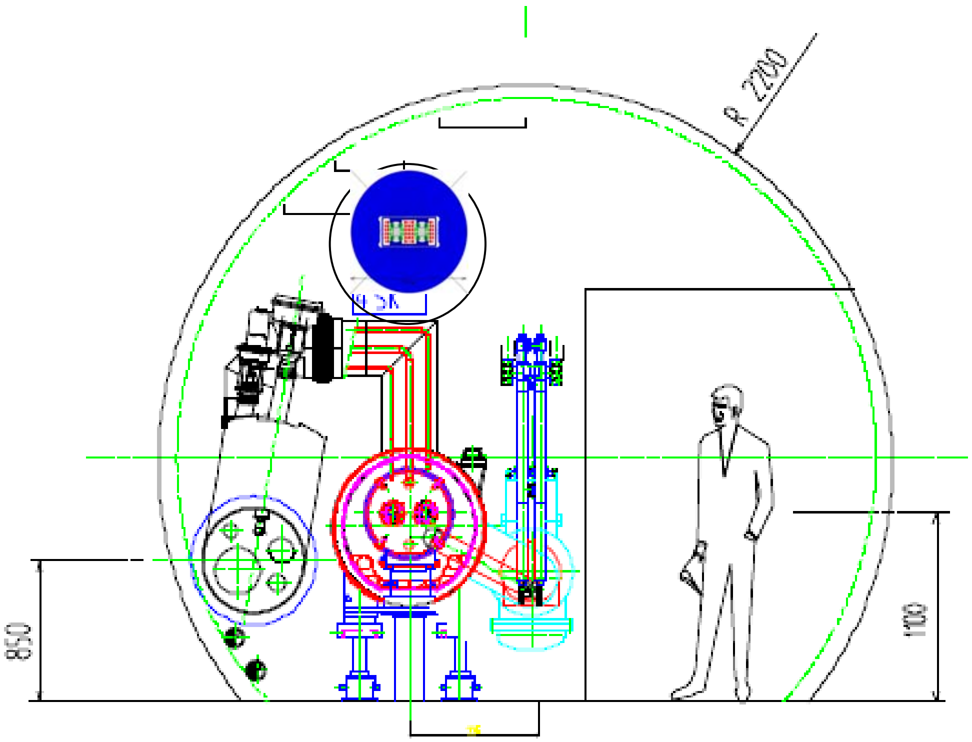
•Reduces # of subsidiary bunch crossings

•Reduces sensitivity to error fields and placements

•Opens space for another doublet to fully separate corrections in x, y.

# 2) Hybrid Dipoles can triple LHC

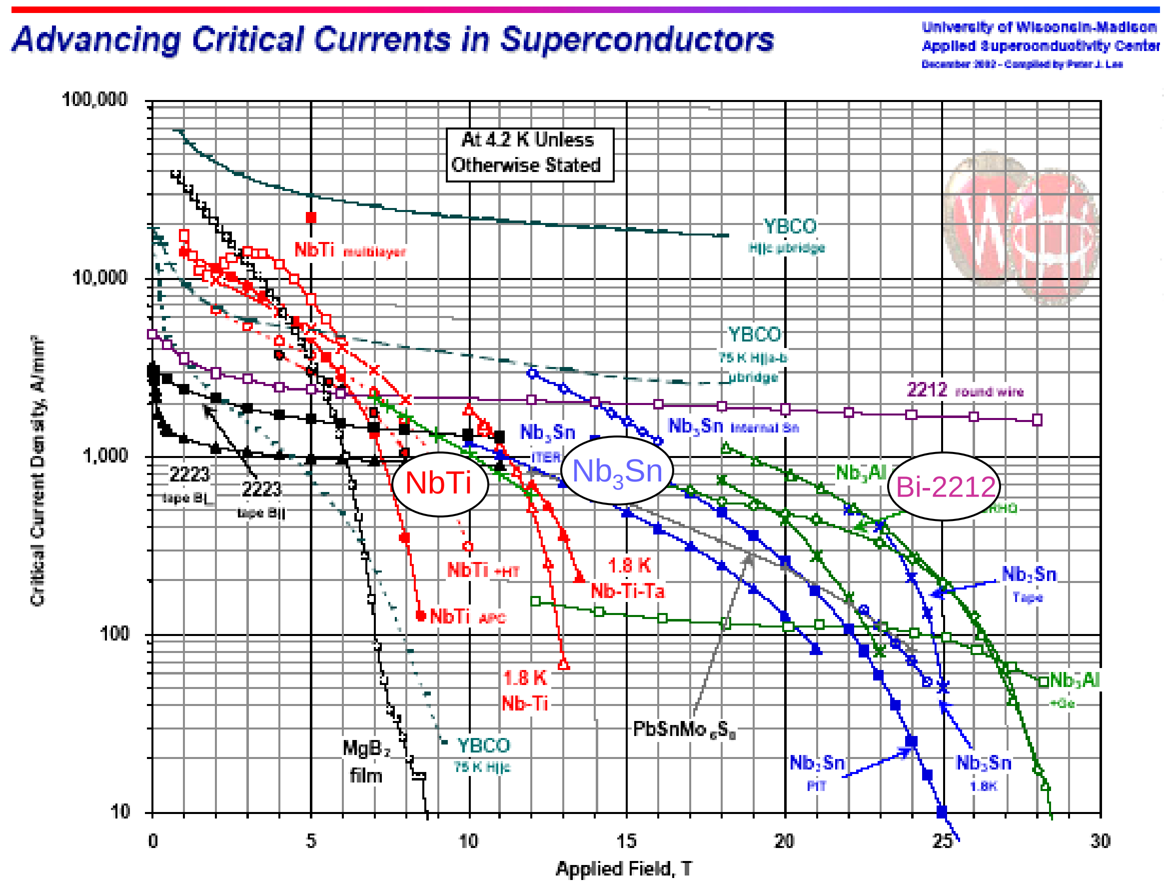


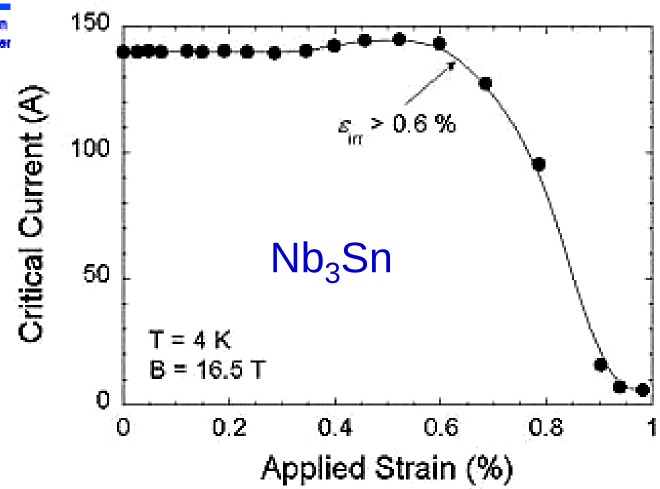



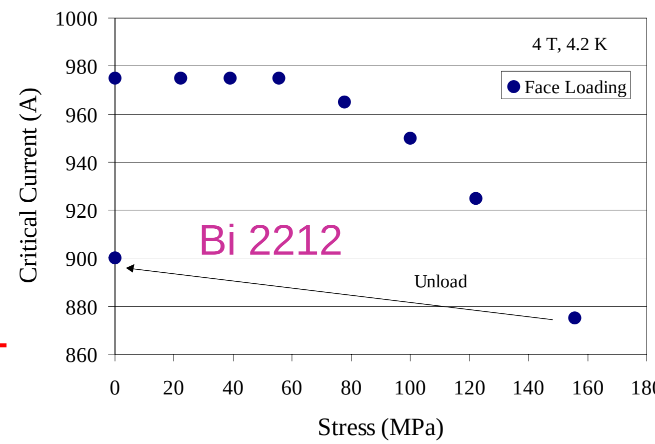

25 T $\Rightarrow \sqrt{s} = 40\, TeV$

$\mathscr{L} \sim 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

# Higher field requires new superconductor, handling immense stress loads



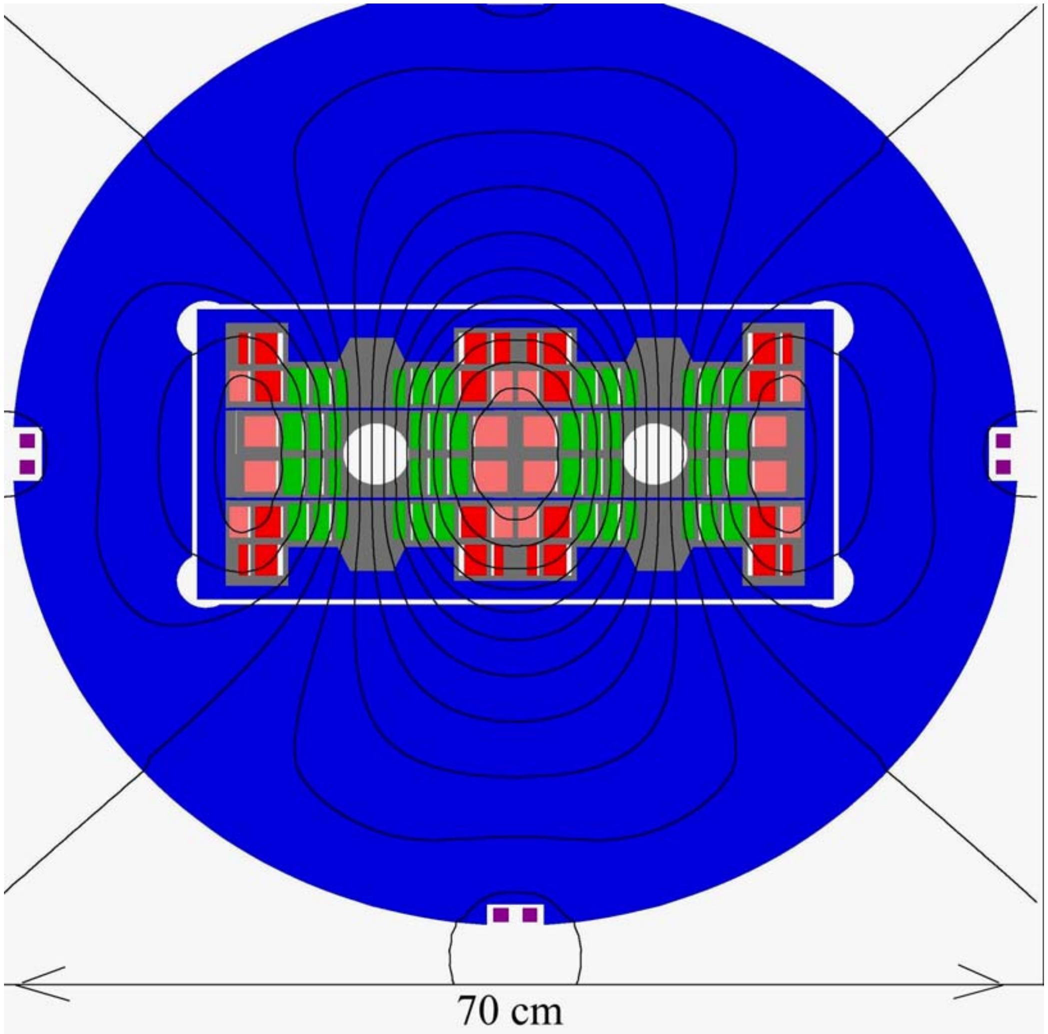

**Cost today:**

| | | |
|---|---|---|
| **Cost today:** | NbTi | $100/kg |
| | $Nb_3Sn$ | $1,000/kg |
| | Bi-2212 | $2,000/kg |

# Extend to 24 Tesla: Bi-2212 in inner (high field) windings, $Nb_3Sn$ in outer (low field) windings

**Dual dipole (ala LHC)**

| | |
|---|---|
| **Bore field** | **24 Tesla** |
| **Max stress in superconductor** | **130 MPa** |
| **Superconductor x-section:** | |
| **$Nb_3Sn$** | **26 $cm^2$** |
| **Bi-2212** | **47 $cm^2$** |
| **Cable current** | **25 kA** |
| **Beam tube dia.** | **50 mm** |
| **Beam separation** | **194 mm** |



# Magnet issues

- $Nb_3Sn$ windings must be reacted at 650 C in argon for a week to form the superconducting phase.
- Bi-2212 windings must be reacted at 850 C in oxygen, ~10 minute excursion to partial melt, $\Delta$T ~2 C
- How to do both on one coil???
  - Wind Bi-2212 inner windings, do heat treat.
  - Control fast excursion to partial melt using ohmic heating in coil itself and/or modulation of pp $O_2$.
  - Then wind $Nb_3Sn$ outer windings, stress management structure isolates the ventilation of the two regions
  - React the $Nb_3Sn$ with Ar purge, hold $O_2$purge on Bi-2212.

Byeon's thesis

- Quench protection – need to investigate microquench stability of Bi-2212, very different quench strategy from that with all-$Nb_3Sn$ dipoles.

# Accelerator Issues

- Synchrotron radiation: power/length $\tilde{P} \propto E^4 I / \rho^2$

  critical energy $E_c \propto E^3 / \rho$

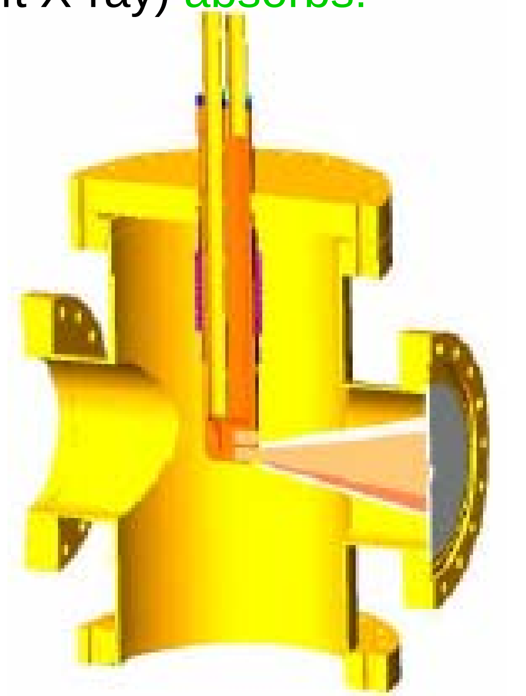
**LHC:** E = 7 TeV P = 0.22 W/m $E_c$ = 44 eV (hard UV) scatters, desorbs

**LHC Tripler:** E = 20 TeV P = 14 W/m $E_c$ = 1.2 keV (soft X-ray) absorbs!

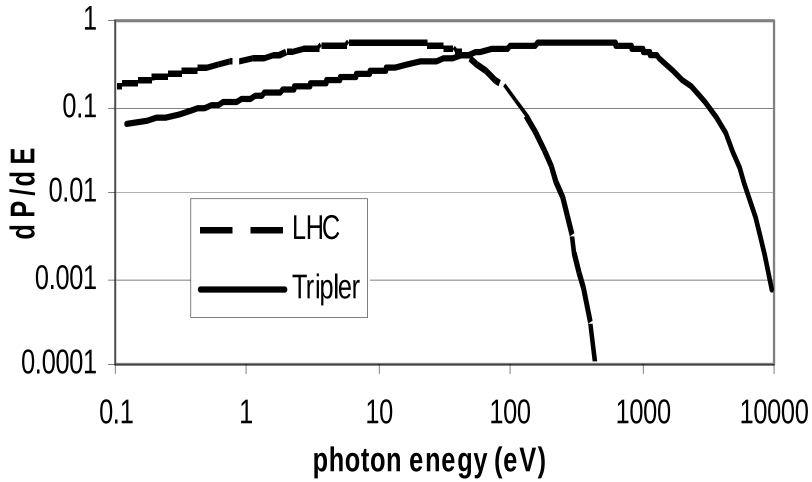
- – Use photon stop:

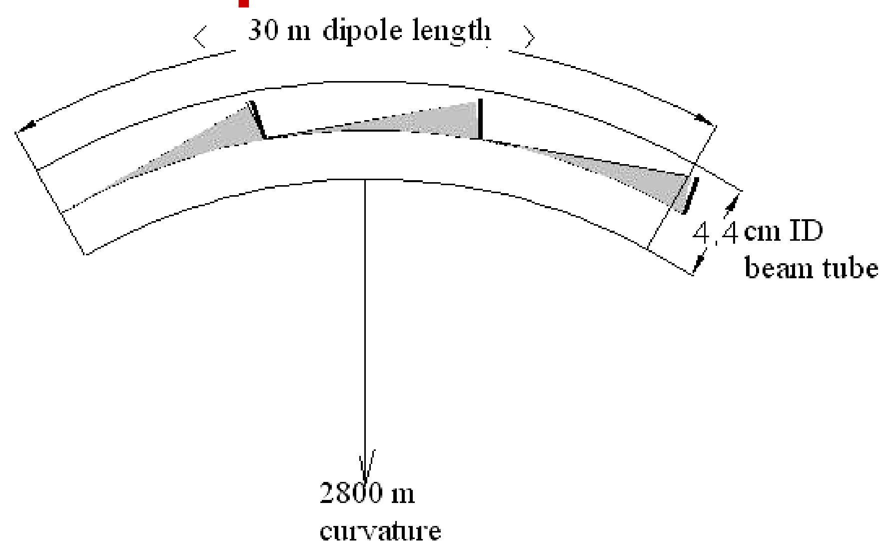
  Instead of intercepting photons at ~10 K along dipole beam tube, intercept between dipoles on room-temperature finger.

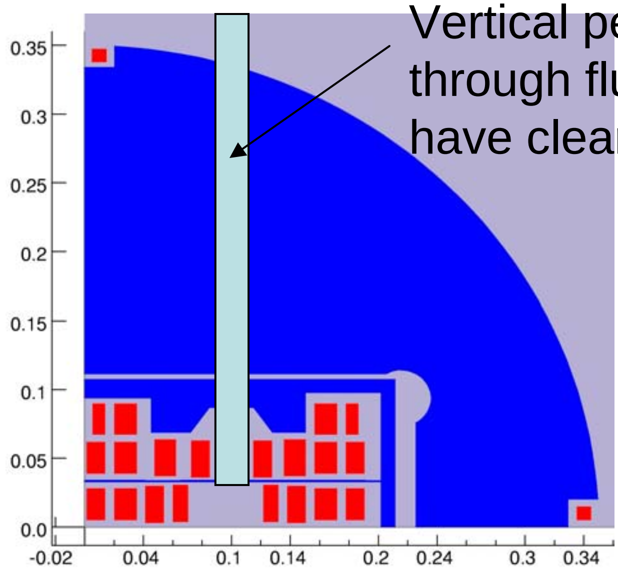
- – Soft X-rays actually easier to trap that hard UV

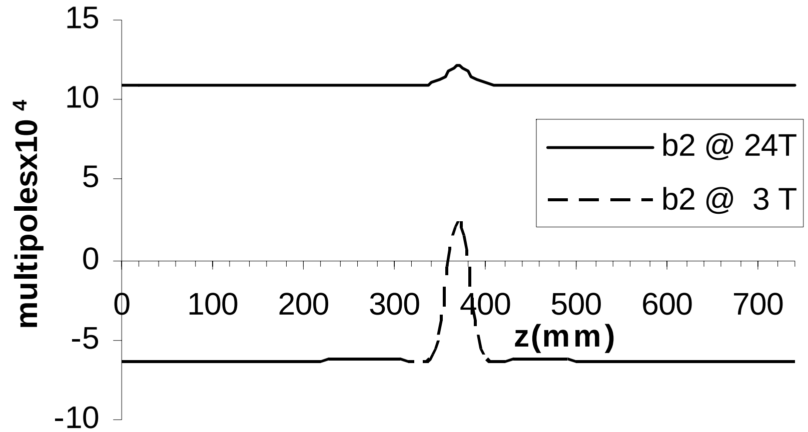


# Photon Stop



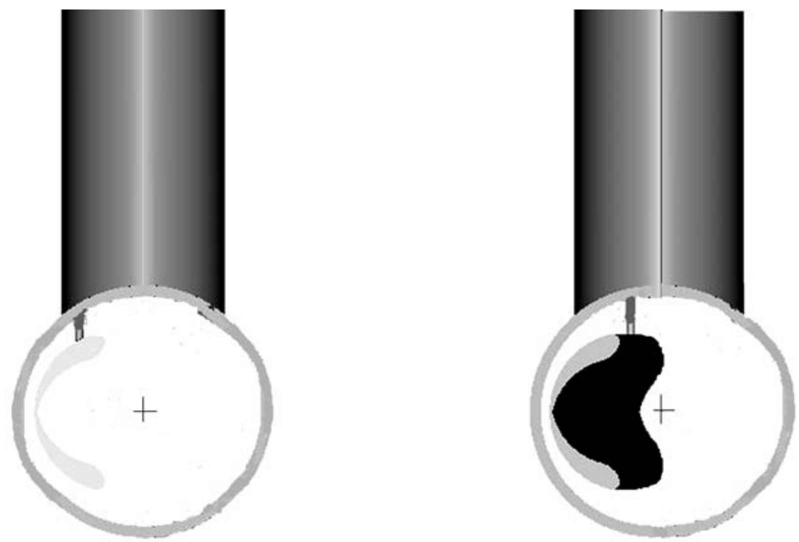




Effect on $\langle b_3 \rangle \sim 10^{-5}$ cm$^{-2}$

# Photon stop swings:
# clears aperture at injection energy, collects light at collision energy



Injection Collision

150 W/stop collected @ 1 W/cm$^2$

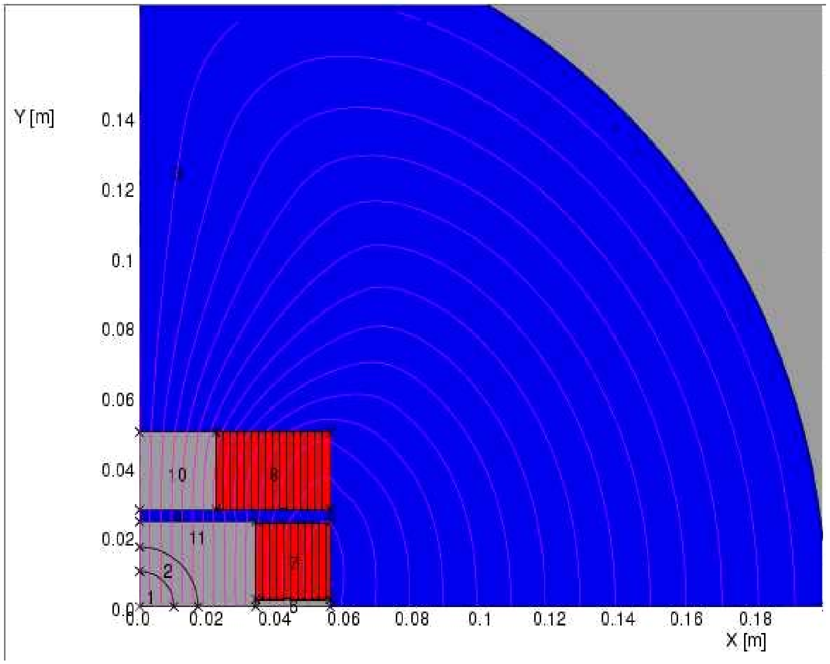
heat transfer to Liquid Xe (160 K)

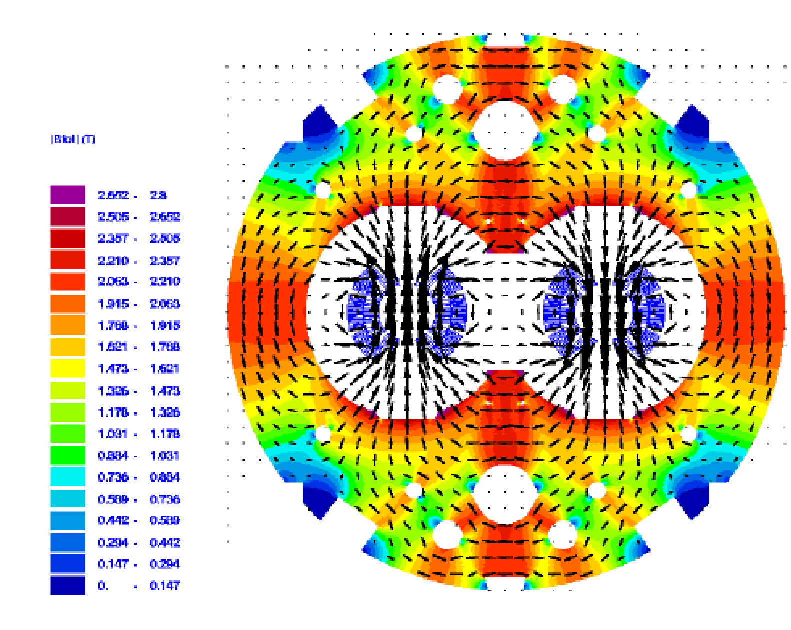
Same refrigeration power for Tripler as for LHC!

# 3) Rapid-cycling Injector for LHC

- For luminosity upgrade of LHC, one option is to replace the SPS/PS with a rapid-cycling superconducting injector chain.
- 1 TeV in SPS tunnel → 1.25 T in 25T hybrid dipole: flux plate is unsaturated, suppression of snap-back multipoles at injection.
- SuperSPS needs 5 T field, ~10 s cycle time for filling Tripler → > 1 T/s ramp rate
- A pacing issue for design is AC loss during ramp

# Again block-coil geometry is optimum!




Block-coil dipole:

Cables are oriented vertically: $\vec{B} \parallel \hat{n}$

*Result:* minimum induced current loop, minimum AC losses

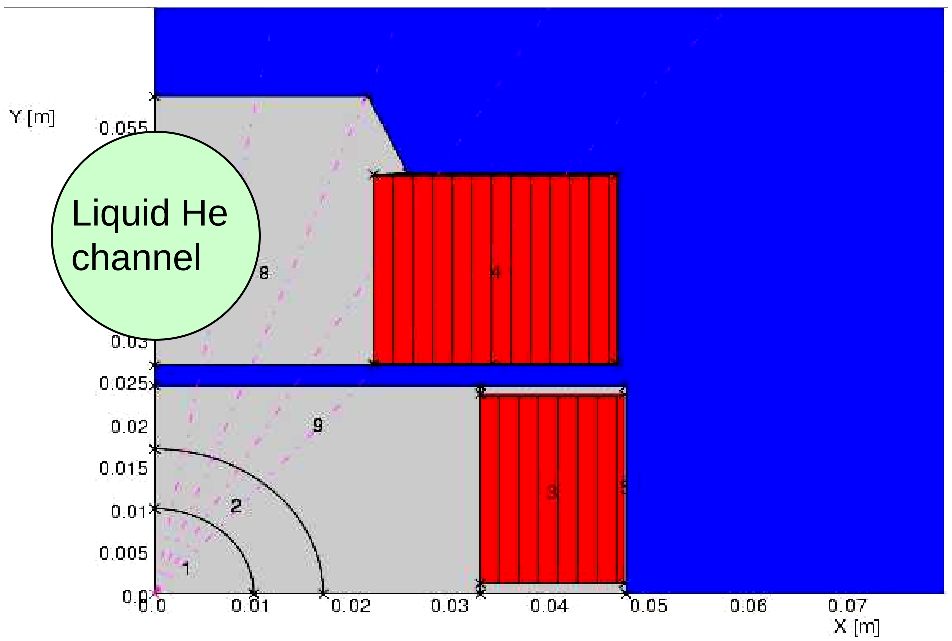
cos θ dipole:

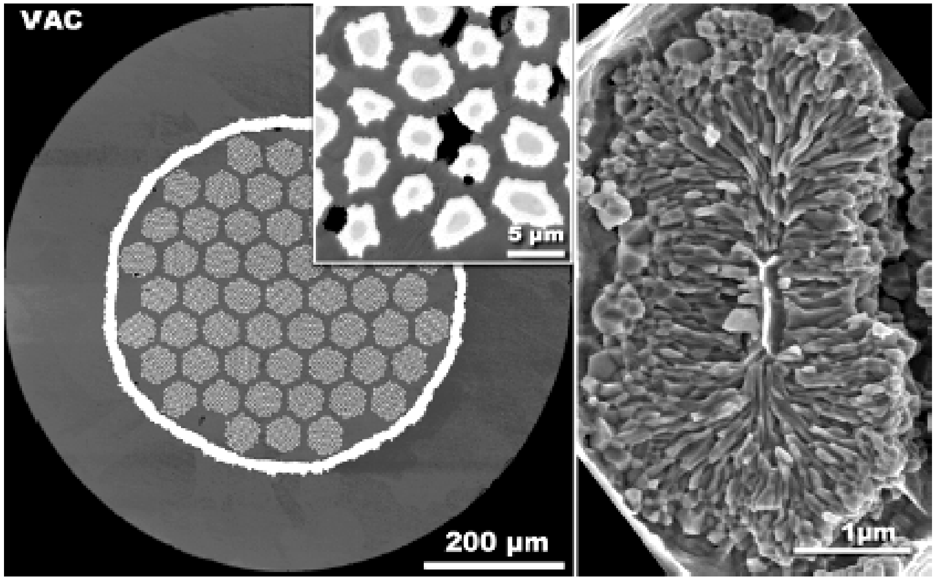
Cables are oriented azimuthally: $\vec{B} \perp \hat{n}$

*Result:* maximum induced current loop, maximum AC losses

*We demonstrated this suppression of AC losses in TAMU2 test!*

# $Nb_3Sn$ Super-SPS dipole?




6 T block-coil suppresses extrinsic losses

*-flux plate suppresses snap-back*

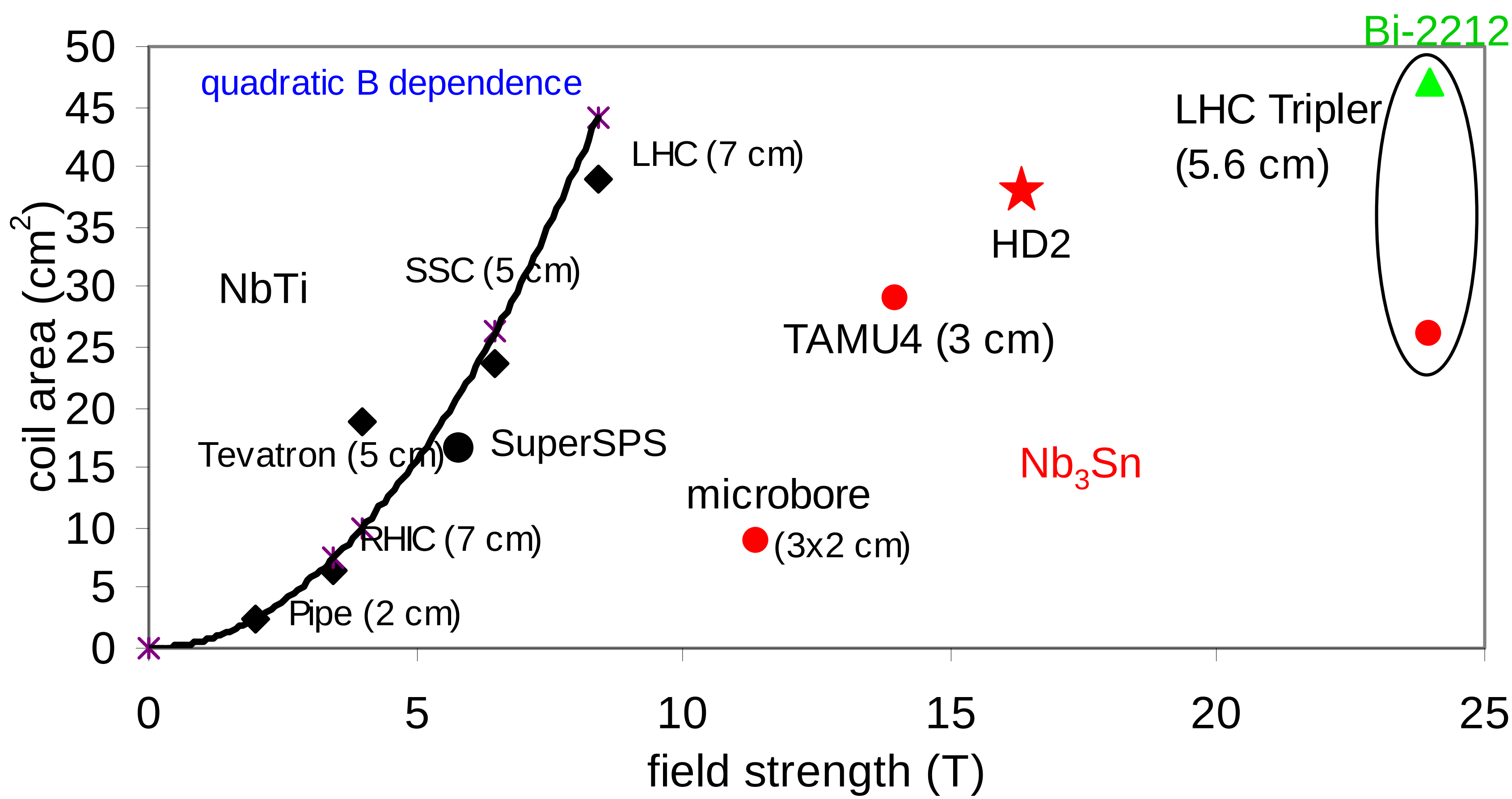
Bronze-process fine-filament wire suppresses intrinsic losses

*- Lowest cost $Nb_3Sn$ wire*

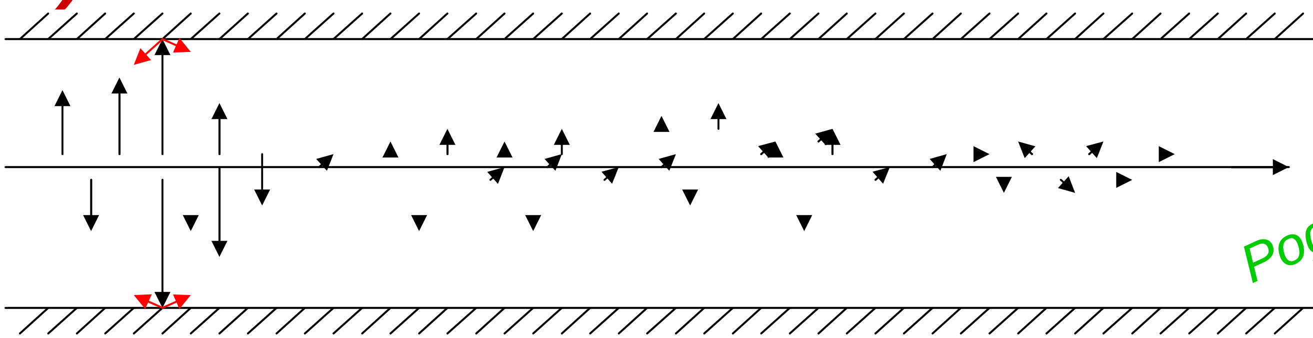
*Efforts until now have concentrated on NbTi cos $\theta$ dipoles – misses on both counts.*

*This is an unexpected bonus from high-field magnet development.*

# Magnets are getting more efficient!



# 4) Kill electron cloud effect



*Pogue's thesis*

•ECE will limit LHC luminosity, beam intensity from ILC damping rings.

•Suppress electron multipacting by locating an electrode on bottom of beam screen, bias +100 V, suppresses all secondary electrons.

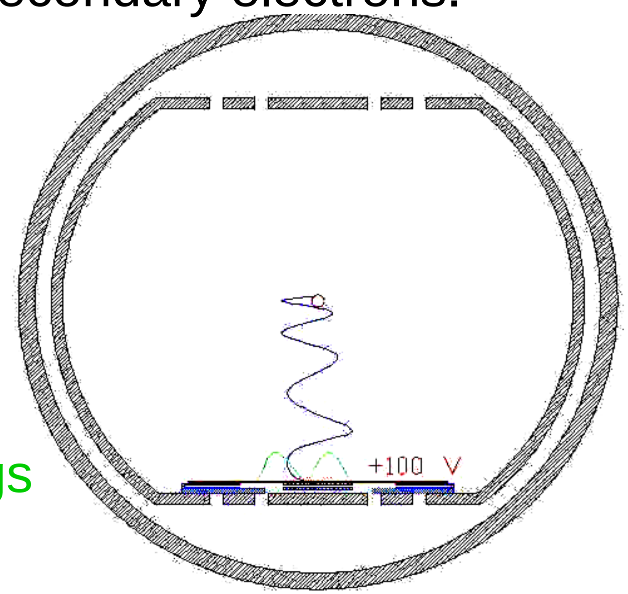
Fix for ECE in:

•RHIC

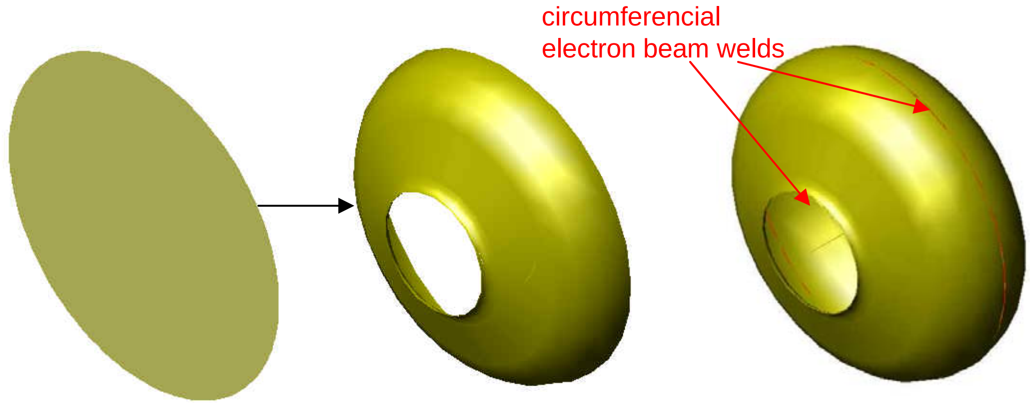
•SPS

•LHC

•ILC damping rings



# 5) Polyhedral superconducting cavities for linear colliders

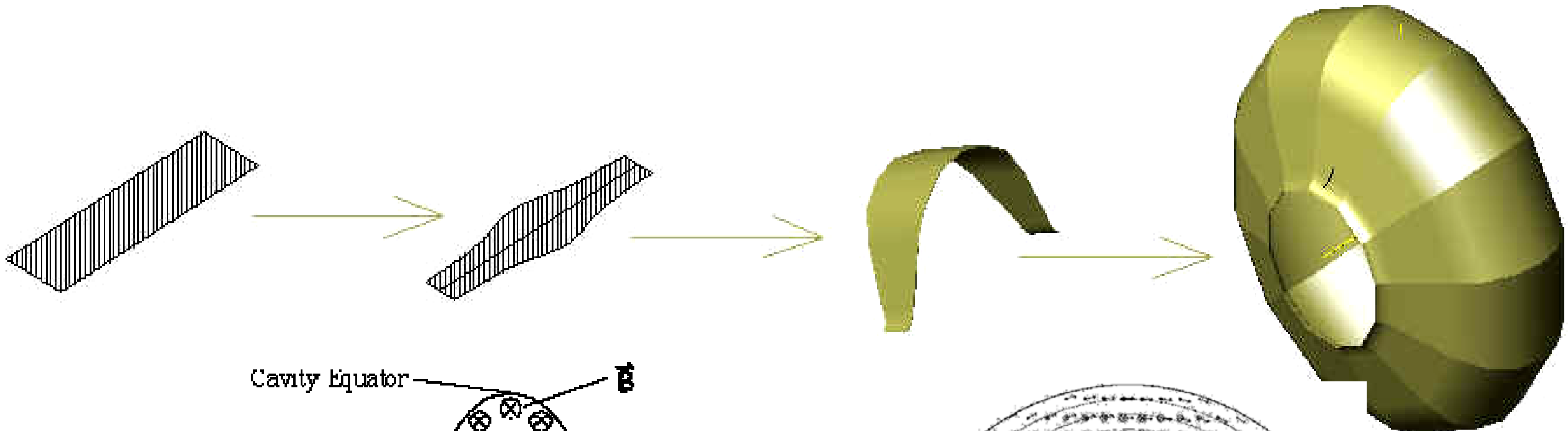


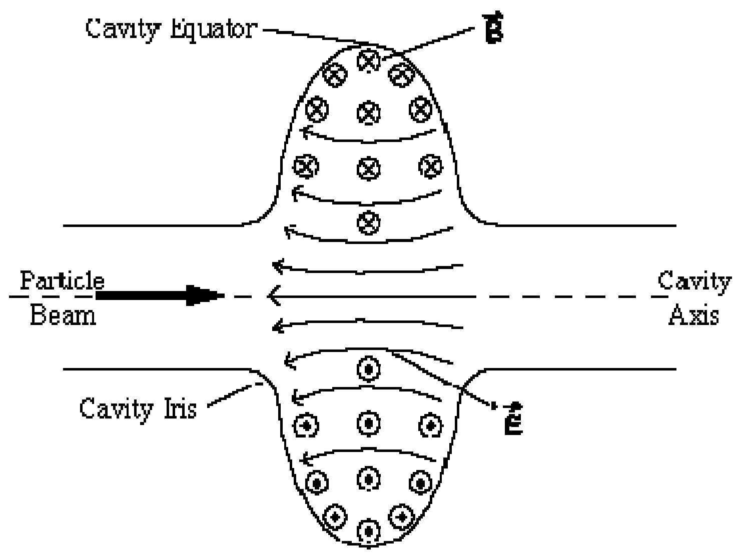

Conventional superconducting cavities are made by spinning Nb foil, then e-beam welding, then cleaning inside the 9-cell string

Welds alter grain structure, affects $I_{max}$ @ waist, $E_{max}$ at neck

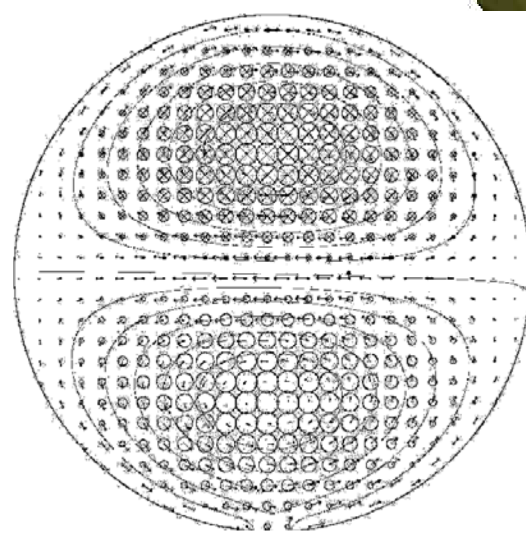
Difficult to clean, QC inside completed string

# Suppose the cavity string is assembled from polyhedral slices



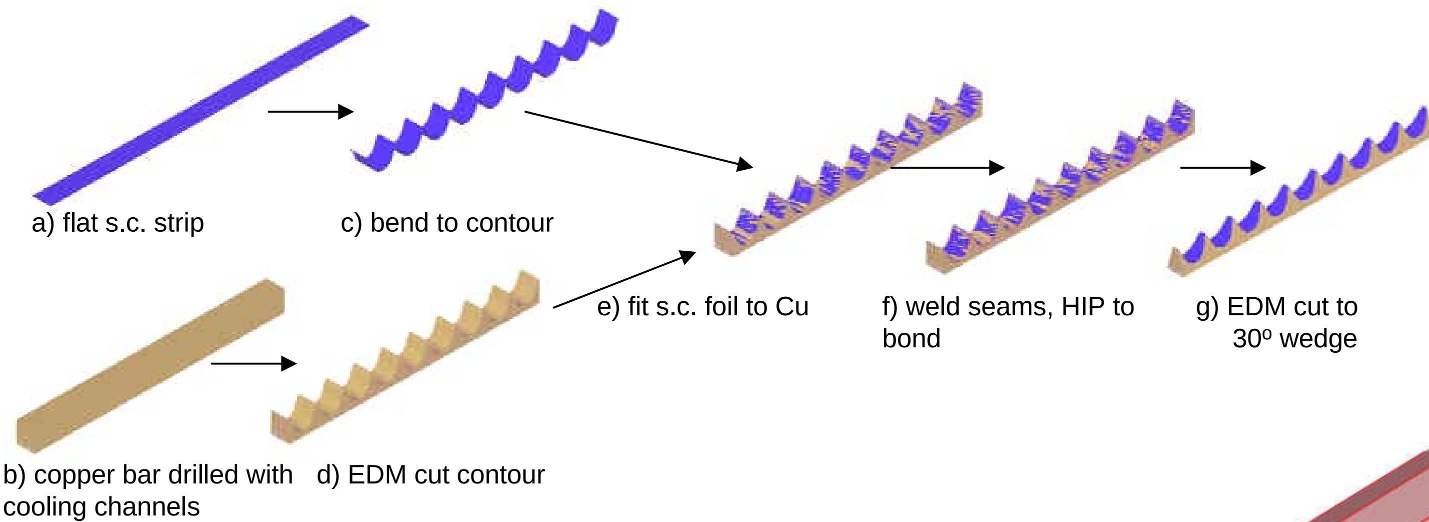


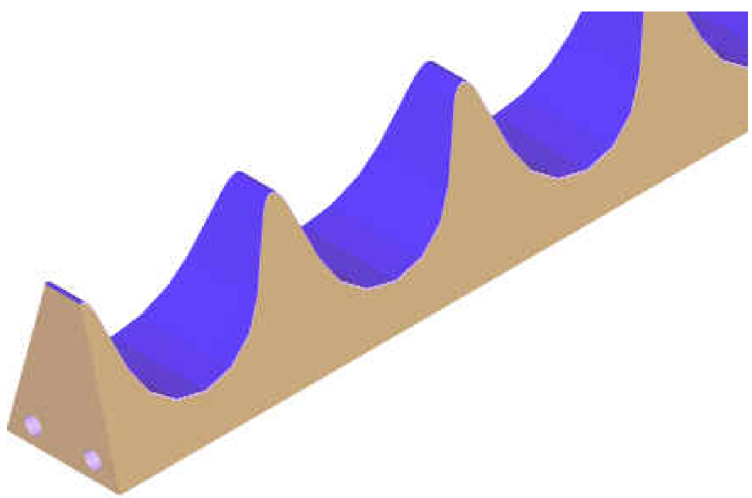

**Current flows in r/z in accelerating mode: unaffected by normal slits**

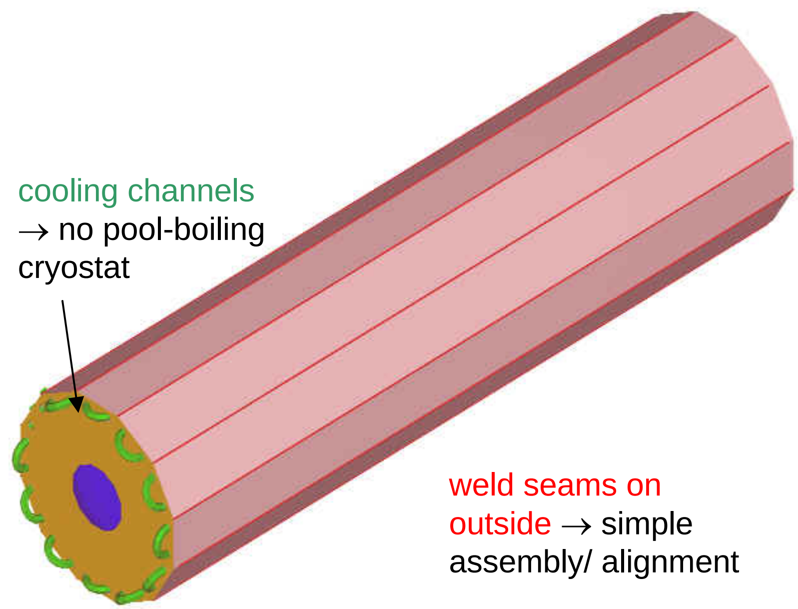


**Current flows in $\phi$ for deflecting modes: Q-spoiled, by normal slits**

# Each segment is fabricated, cleaned, QC before assembly



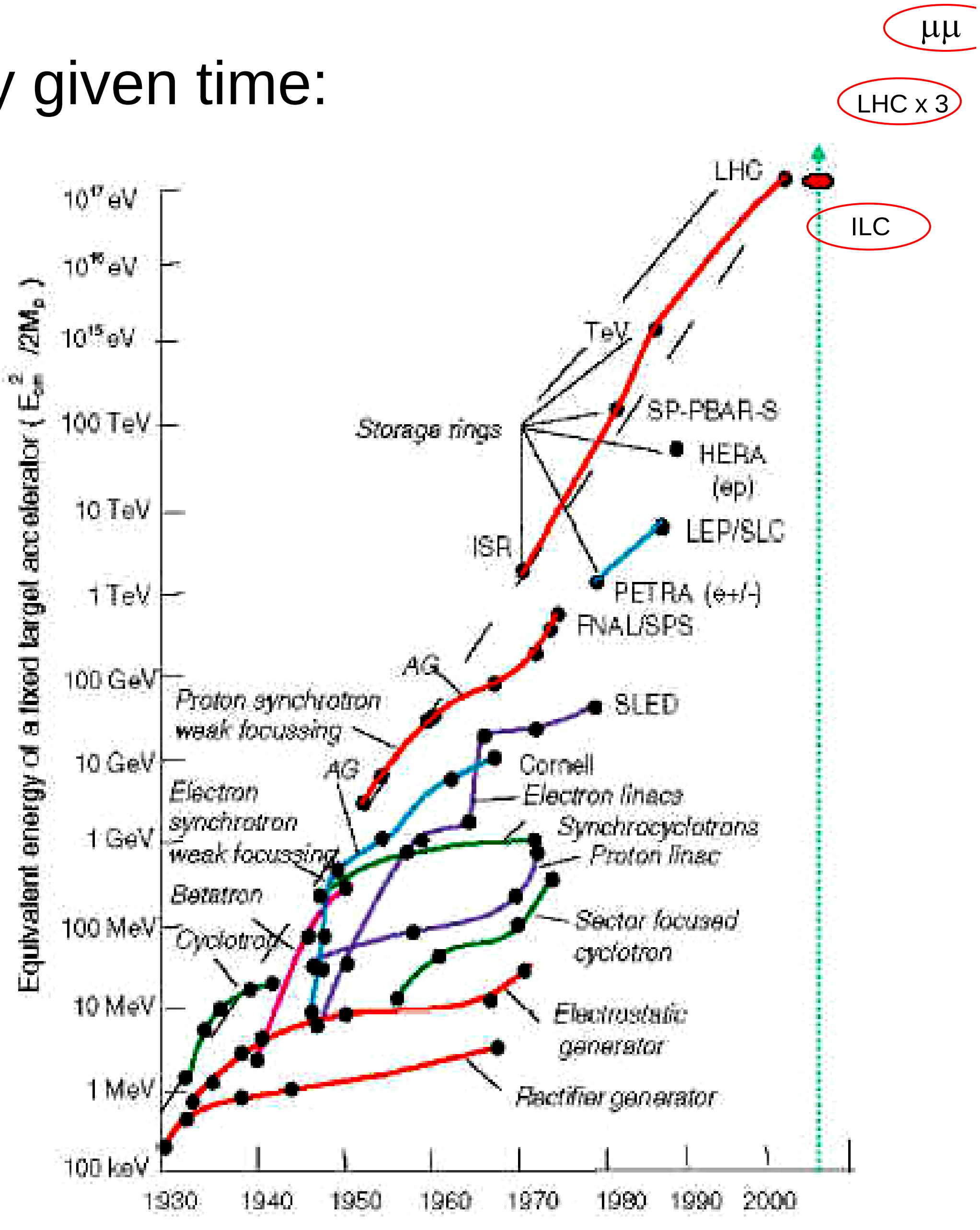


# AARD: Skunk Works for the Future of HEP

*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!*



# Many of the innovations in accelerator physics and technology happen at the *universities*

- Superconductors & magnets:
  - Berkeley, Ohio State, Texas A&M, U. Wisconsin,
- Superconducting cavities:
  - Cornell, Stanford
- Laser, plasma acceleration:
  - Berkeley, Columbia, UCLA, U. Maryland, Stanford, U.Texas, USC
- Beam cooling:
  - Indiana U., U. Michigan
- Beam dynamics:
  - U. Colorado, UCLA, U. Kansas, U. Maryland, MIT, U. Michigan, MSU, UNM, Princeton
- $\mu\mu$ colliders, $\nu$ factories:
  - IIT, UCLA, NIU

*AARD is the only source of support for these programs.*

# AARD has made extremely effective use of the SBIR program

- In the development of superconducting materials, the AARD program has maintained a highly effective synergy between the magnet builders and the superconductor manufacturers.
- The SBIR program has provided a vital stimulus for the steady and impressive improvement in superconductor performance – first in NbTi (x2), then in $Nb_3Sn$ (x2), and now also in Bi-2212. This stimulus/response has operated to HEP's benefit for ~25 years. It is alive and well today and is developing the conductors we will need for the LHC Tripler.

# 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 colliders were built with top discovery as a goal.
- Finally top was discovered at Fermilab – 175 GeV!
- In the search for Higgs and SUSY, will history repeat?

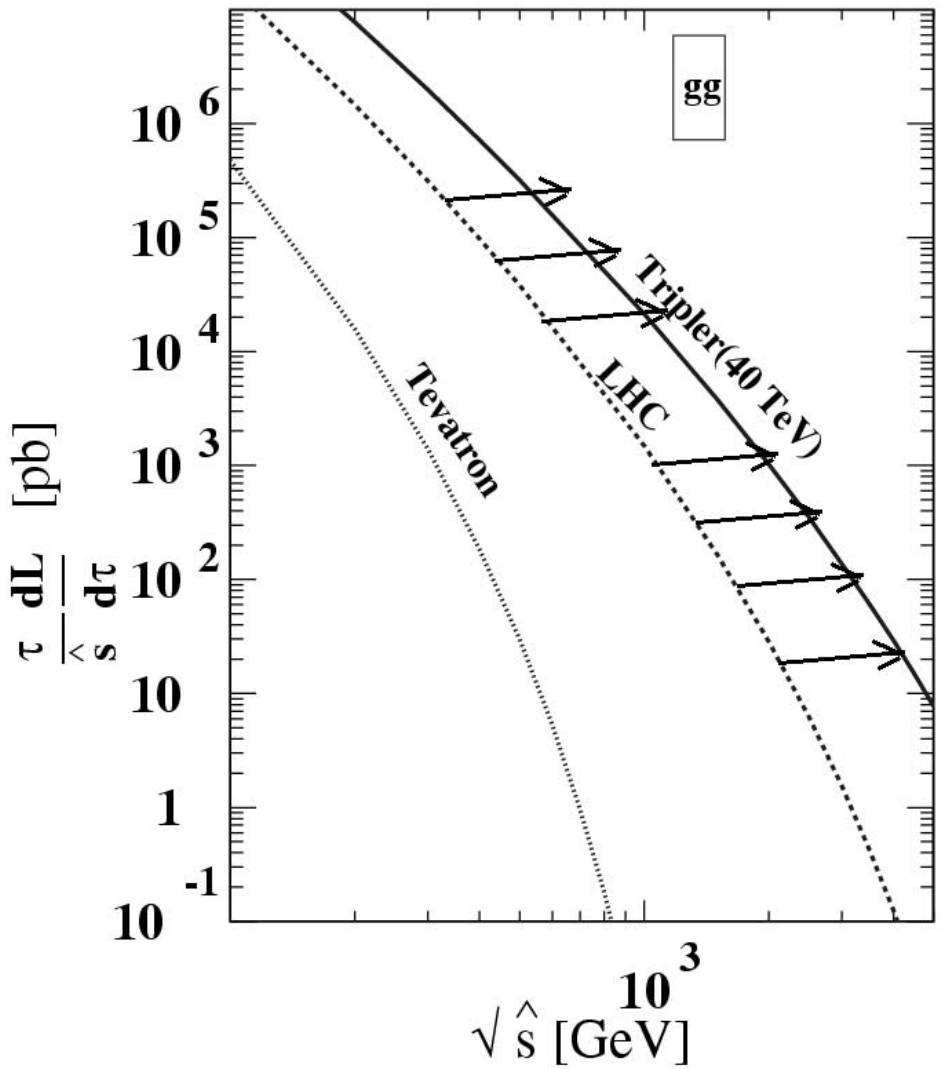
# Evolution of the gluon spectrum

Assumptions:

•Luminosity grows x3 with adiabatic damping

•Luminosity needed to produce a given number of particles of mass m (assuming gauge couplings constant) scales with $m^2$

•So twice the mass scale requires 4/3 the luminosity.




*Triple the energy – double the mass reach*

Dutta 2004

# Discovery of sparticles

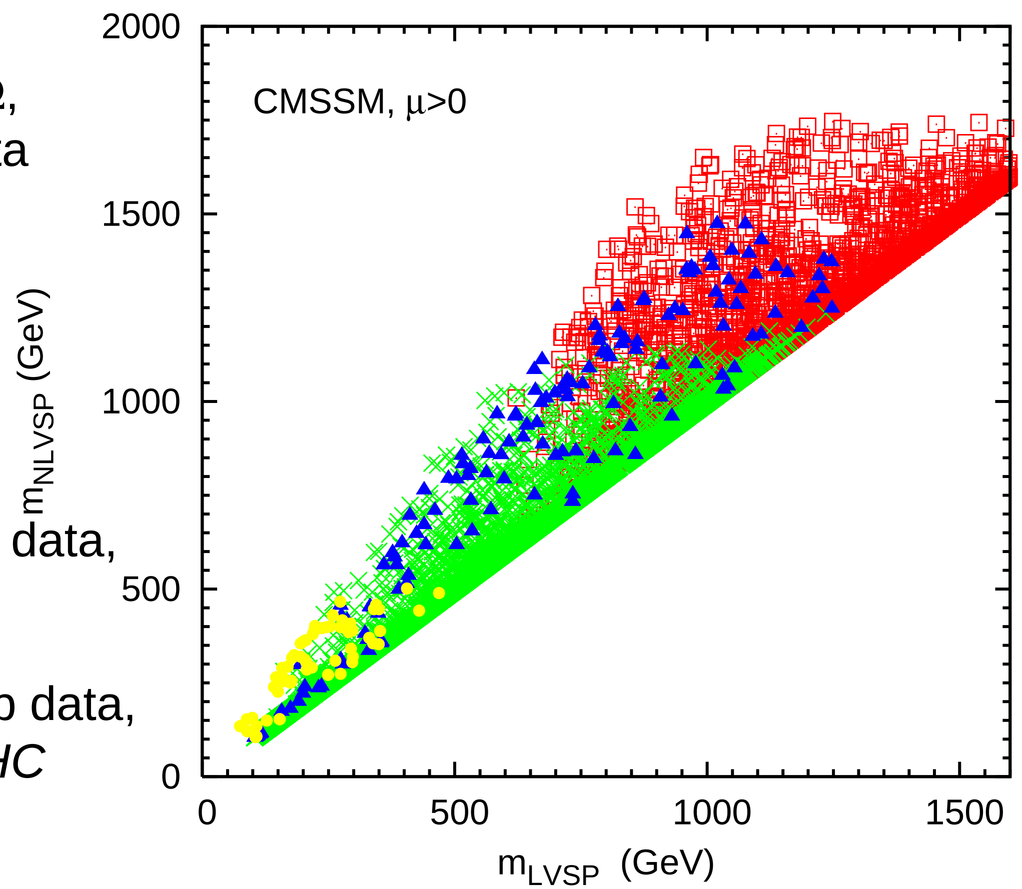
- Ellis *et al* have calculated the masses of the lightest 2 visible sparticles in minimum supersymmetric extension of the Standard Model (MSSM), constrained by the new results from astrophysics and cosmology.

▲ = constrained by Ω, WMAP and lab data

● = observable in WIMP searches ($\sigma > 10^{-8}$ pb)

X = constrained by lab data, observable @ LHC

■ = constrained by lab data, *unobservable @ LHC*




Ellis *et al.* 2004