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

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

- Nb$_3$Sn: 14 Tesla dipole

- Bore field: 14.1 T
- Current: 12.6 kA
- Maximum Coil Stress: 120 MPa
- Superconductor cross section: 29 cm$^2$
New tricks make Nb$_3$Sn feasible

Stress Management

Flux plate suppression of multipoles

Stress in Pa for TAMU2
New Nb$_3$Sn 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

\[ I_q (A) \]

\[ \text{quench number} \]

\[ \text{current data lost in DAQ} \]

\[ \text{bolt arc on current bus} \]

\[ 85\% \text{ SS @ .75 T/s} \]

\[ \text{~93\% short sample first and every quench – no training} \]

**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 \( \rightarrow \) maximum luminosity.
- Maximize luminosity \( \Rightarrow \) minimum focal length \( f \sim \beta^2 \Rightarrow \) maximum gradient.
- Minimize chromatic aberrations \( \partial f / \partial E \), harmonic distortion. \( \partial f / \partial x \)
- \( \Rightarrow \) 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!
Q₁, D₁ are in harm’s way

Multiplicity \sim f(\eta) \, e^{-bt} \\
E_{\text{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 $\text{Nb}_3\text{Sn}$ strand around thin-wall Inconel X750 spring tube

Draw within Inconel 718 sheath → *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

⇒ no insulation to degrade under radiation damage
D₁: 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 $\beta^*$
- 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 ⇒ $\sqrt{s} = 40 \text{ TeV}$

$\mathcal{L} \sim 10^{35} \text{ cm}^{-2}\text{s}^{-1}$
Higher field requires new superconductor, handling immense stress loads

Cost today:
- NbTi: $100/kg
- Nb₃Sn: $1,000/kg
- Bi-2212: $2,000/kg
Extend to 24 Tesla:

**Bi-2212** in inner (high field) windings,
**Nb$_3$Sn** in outer (low field) windings

Dual dipole (ala LHC)

Bore field 24 Tesla

Max stress in superconductor 130 MPa

Superconductor x-section:

- **Nb$_3$Sn** 26 cm$^2$
- **Bi-2212** 47 cm$^2$

Cable current 25 kA

Beam tube dia. 50 mm

Beam separation 194 mm
Magnet issues

- $\text{Nb}_3\text{Sn}$ 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, $\Delta T \sim 2$°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 $\text{Nb}_3\text{Sn}$ outer windings, stress management structure isolates the ventilation of the two regions
  - React the $\text{Nb}_3\text{Sn}$ with Ar purge, hold O$_2$ purge on Bi-2212.

- Quench protection – need to investigate microquench stability of Bi-2212, very different quench strategy from that with all-$\text{Nb}_3\text{Sn}$ dipoles.
Accelerator Issues

• Synchrotron radiation: power/length \( \tilde{P} \propto E^4 I / \rho^2 \)

  critical energy \( E_c \propto E^3 / \rho \)

LHC: \( E = 7 \text{ TeV} \quad P = 0.22 \text{ W/m} \quad E_c = 44 \text{ eV} \) (hard UV) scatters, desorbs

LHC Tripler: \( E = 20 \text{ TeV} \quad P = 14 \text{ W/m} \quad E_c = 1.2 \text{ keV} \) (soft X-ray) absorbs!

  – Use photon stop:
    Instead of intercepting photons at \( \sim 10 \text{ K} \) along dipole beam tube, intercept between dipoles on room-temperature finger.

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

- Photon Stop
  - Photoemission yields vanish for E > 100 eV
  - Vertical penetration through flux return (coils have clearance)

Effect on $<b_3> \sim 10^{-5}$ cm$^{-2}$
Photon stop swings:
clears aperture at injection energy, collects light at collision energy

150 W/stop collected @ 1 W/cm²
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 $\rightarrow$ 1.25 T in 25T hybrid dipole: flux plate is unsaturated, suppression of snap-back multipoles at injection.
- SuperSPS needs 5 T field, $\sim$10 s cycle time for filling Tripler $\rightarrow$ $>1$ 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

$\cos \theta$ 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$_3$Sn 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$_3$Sn 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!

Field strength (T) vs. coil area (cm$^2$)

- **quadratic B dependence**
- **LHC (7 cm)**
- **RHIC (7 cm)**
- **Tevatron (5 cm)**
- **SSC (5 cm)**
- **Pipe (2 cm)**
- **TAMU4 (3 cm)**
- **Bi-2212**
- **LHC Tripler (5.6 cm)**
- **Nb$_3$Sn**
- **HD2**
- **microbore (3x2 cm)**

Materials:
- **NbTi**
- **SuperSPS**
- **HD2**

Magnet technologies advancing with increased efficiency.
4) Kill electron cloud effect

• 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 $I_{\text{max}}$ at waist, $E_{\text{max}}$ 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

- a) flat s.c. strip
- b) copper bar drilled with cooling channels
- c) bend to contour
- d) EDM cut contour
- e) fit s.c. foil to Cu
- f) weld seams, HIP to bond
- g) EDM cut to 30° wedge

cooling channels → no pool-boiling cryostat

weld seams on outside → simple assembly/alignment
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:
- $\mu\mu$ 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$_3$Sn (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*
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 $\Omega$, 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