Fermilab

TM-1202
2761.000
August,1983

Operational Studies and Expected Performance of Superconducting Quadrupole Magnets in the First Stages of Secondary Beams

P.H.Garbincius, P.O.Mazur, and R.P.Stanek
Fermi National Accelerator Laboratory

R.P.Smith, S.H.Kim, C.I.Krieger,
J.D.Gonczy, A.L.Kelly, D.C.Underwood,
E.J.Wallace, K.Wiggins
Argonne National Laboratory

A low current, large bore, epoxy impregnated superconducting quadrupole magnet was constructed at Argonne National Laboboatory as a possible prototype for secondary beam use.

The quadrupole magnet was placed in the Fermilab P-West High Intensity Area beam for beam quenching tests. Tests were performed by targetting a primary proton beam directly onto the quadrupole coil and by using the quadrupole in its anticipated role as part of the first stage flux collection triplet for a zero degree anti- proton secondary beam formed from the decays of neutral Lambda particles.

Comparing the results with similar tests performed using forced flow Energy Saver dipoles shows that the epoxy impregnated quadrupoles have a much greater sensitivity to beam induced quenching at a similar fraction of the conductor short sample limit. Using the CASIM program, calculations indicate that such epoxy impregnated coils would not be viable as first stage flux collection elements without appreciable collimation and subsequent loss of secondary beam acceptance. Quadrupoles based on Energy Saver technology appear capable of tolerating acceptable primary beam intensities. The momentum dispersing bends will require even larger aperture superconducting dipoles or neutral beam dump within the bend string.

Submitted to the
12th International Conference
on High Energy Accelerators
Fermilab, August, 1983

OPERATIONAL STUDIES AND EXPECTED PERFORMANCE OF SUPERCONDUCTING QUADRUPOLE MAGNETS IN THE FIRST STAGES OF SECONDARY BEAMS

P. H. Garbincius, P. O. Mazur, and R. P. Stanek
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

R. P. Smith, S. H. Kim, C. I. Krieger, J. D. Gonczy, A. L. Kelly,
D. C. Underwood, E. J. Wallace, and K. Wiggins
Argonne National Laboratory, Argonne, Illinois 60439

Description of ANL Quadrupole Magnet

A low current superconducting quadrupole magnet was constructed[1] as a prototype for Fermilab's P-West High Intensity area and M-Polarized Beams. Pertinent quadrupole parameters for this study include the gradient of 50 tesla/meter at 905 amps, 13 cm clear bore, 2.8 meter effective magnetic length, copper:superconductor ratio of 1.8:1.0, cold iron yoke, and epoxy impregnated coil.

Primary Beam Tests

The superconducting quadrupole was positioned in a 400 GeV primary proton beam focussed to a spot size of 0.8 cm x 1.1 cm full width. The proton beam impacted on the saddle crossover of the coil. The quadrupole was energized to 931 amp giving 87% of the conductor's short sample limit at the point of proton impact. Quenching was not observed at 2.2×10^9 protons per one second beam pulse. The quadrupole quenched at 3.6×10^9 protons/pulse. Taking the average of these values, the quench threshold is (2.9 ± 0.7) 10^9 protons/pulse. A second test showed no quenching at the 1.7×10^9 protons/pulse level.

The geometry of the primary beam test was such that the shower maximum occurred in the pole spacer. The energy deposited by the proton beam was calculated using the CASIM[2] Monte Carlo Program. These results showed a maximum coil energy deposition of 0.17 GeV/cm^3/proton. This corresponds to a heat input of 2.4 watts per 0.135 cm x 0.198 cm superconducting wire turn during the beam spill of 2.9×10^9 protons/pulse. The longitudinal, radial, and azimuthal thermal conductivities at 4.5 degrees are estimated to be 2.0, 0.001, and 0.002 watts/cm/K^0, respectively.[3] The energy deposited in the saddle turn will be quickly conduced along the length of the superconductor. A calculation shows that an upper limit for the maximum coil temperature rise due to beam heating is $\Delta T = 1.9^0$K. This assumed that the coil recooled completely between beam spills. The transverse thermal conductivity and the heat transfer to the liquid helium were neglected.

Secondary Neutral Beam Tests

The quadrupole magnet was placed in the first stage flux collection triplet of the Fermilab P-West High Intensity Area beam[4] (Figure 1). A zero degree neutral beam was produced by targetting the 400 GeV primary protons on a 30 cm Be target followed immediately by 10 tesla-meters of dipole bend to sweep the primary protons and charged secondary particles into the beam dump. A ± 1.8 mrad conical collimator hole through the beam dump defined the angular acceptance.

The 5 inch bore superconducting quadrupole was positioned downstream of the conventional 4 inch bore quadrupoles and collimators giving extra shielding down to ± 1.3 mrad production angle. A slight alignment offset was modeled as a 4.6 inch bore quadrupole. The CASIM program shows that the 10 tesla/meter conventional quadrupoles decrease the maximum energy deposition in the maximum energy deposition in the SC quads by about 10%.

The superconducting quad was charged to 946 amps corresponding to 78% of conductor short sample limit at the inner radius of the coil. No quenching was observed at 4.9×10^{11} protons per pulse incident on the production target. The magnet did quench at 6.1×10^{11} protons per pulse giving a quench threshold of $(5.5 \pm 0.6) \times 10^{11}$ protons per 1 second pulse. The accelerator cycle time was 16 seconds.

The thermal beam load on the refrigerator system was measured by using the quadrupole as a calorimeter. The increase in the LHe boiloff rate due to beam loading was measured to be 10 watts for 1.8×10^{12} incident protons. The CASIM program indicated a total cryogenic beam load of 0.12 GeV per proton for the quadrupole. The energy deposition in the cold iron is negligible in comparison with that in the coil package. This corresponds to a total beam heating load of 2 watts. There has been some question of the absolute normalization of the CASIM predictions in the extremely forward direction as for this geometry. For further absolute results, we will therefore multiply the CASIM prediction for energy deposition by a factor of 5 to account for this difference in measurement and theory.

The maximum beam energy deposition for the neutral beam geometry is estimated by CASIM to be 2×10^{-5} GeV/cm^3/proton. Multiplying by the quench threshold, this gives 1.1×10^7 GeV/cm^3 = 1.8 mj/cm^3. The maximum conductor temperature rise assuming zero heat transfer to the helium is estimated to be $\Delta T = 1.6^0$K. The quench margin or thermal reserve of the conductor at 85% of short sample limit is calculated[3] to be approximately 0.6^0K.

Comparison with Energy Saver Technology

The Fermilab SAVER dipoles have also been tested for sensitivity to beam induced quenching.[5,6,7] The results of these tests scaled for 1 second spill at 65-80% of short sample limit indicate a comparable quench threshold of 35-95 mj/cm^3. The epoxy impregnated quadrupole coil was expected to have a greater sensitivity to beam induced quenching than the SAVER dipoles which are designed with forced-flow helium cooling channels within the coils. It is evident from the millisecond fast spill tests results for the SAVER dipoles that the quench threshold drops by a factor of 3 to 4 below the slow spill thresholds. It is likely that the instantaneous heating for the fast spill case, for which there is perhaps little heat transfer to the liquid helium, more closely approximates the case for the quadrupole magnet which was fully impregnated coils and essentially no direct cooling of the conductors.

Projection for Use In Tevatron-Era Beams

The usefulness of this type of quadrupole in the first stage of secondary beams concerns two limits of the amount of primary proton flux: quenching and total refrigeration load. The CASIM program was used to model the targetting, sweeping, dump, collimation and quadrupole channel for the anticipated running conditions. The maxmum energy density and radially integrated energy densities were compared to the similar quantities for the 400 GeV neutral secondary beam test results.

The Tevatron accelerator cycle is expected to consist of a 20 second beam spill every 60 seconds. Thermal conductivity calculations[3] for this epoxy impregnated conductor geometry indicate that only about 4 times the total one second spill intensity may be tolerated without quenching over the projected 20 second beam spill. This factor of 4 has been included in the projected Tevatron quench limits. The proposed Tevatron beam geometries and configurations will be described along with a tabulation of the scaled maximum beam intensities tolerable without quenching and the total refrigeration load for the first stage of the beam. The relative radially integrated energy deposition curves as a function of Z are shown for the various beam configurations in Figures 2 and 4. The P-West beam is assumed to consist of a 2 + 3 + 2 quad triplet configuration.

A,B) P-West - 300 GeV Anti-Proton Beam

At 1 TeV primary beam momentum there is insufficient $\int B\ dl$ to cleanly dump the zero degree proton beam in the collimator dump. The protons must be targetted at an angle of 1 mrad to be cleanly dumped. This brings the zero degree neutral beam direction very close to the quadrupole coils limiting the primary beam intensity to below 4×10^{10} protons per pulse.

C,D) P-West - 300/750 GeV π^- Beam

The primary proton beam is targetted at a 4 mrad angle and 1.9 cm offset with respect to the zero degree quadrupole channel. The protons are cleanly dumped and the sweeping magnet field is chosen to transport π^- of zero degree production angle down the quad channel. Quench thresholds limit the maximum usable primary proton intensities to 4×10^{11} and 3×10^{11} protons per pulse at 300 GeV and 750 GeV respectively.

E) M-Polarized Protons

The M-Polarized beam will produce a polarized proton beam from the decay of polarized neutral Lambda particles. Figure 3 shows the geometry. The energy deposition is shown in Figure 4. The apertures through the collimators effectively shadow the 5 inch bore quadrupoles for the direct sight of the production target. This allows the use of primary beam fluxes of up to 8×10^{12} protons per pulse with a refrigeration load of only 44 watts.

Conclusion

It appears very unpromising to try to use epoxy impregnated superconducting elements in the first stage of the P-West secondary beam. Beam spray from the zero degree neutral beam or the momentum dispersed secondary charged beam will quench the superconducting quadrupoles at unacceptably low primary beam intensities.

Using the forced flow cooling scheme of the SAVER dipoles would increase the quench threshold by at least a factor of 20. This would increase the P-West Beam Intensity quench limit to approximately 7×10^{11} protons per pulse for the anti-proton mode and the refrigeration load limit to about 1×10^{12} protons per pulse for the pion mode.

The momentum dispersing bends create a possibly more severe problem. Since the worst case zero degree neutral beam will be deposited within the bend string, the dipoles will be even more susceptable to beam induced quenching than the quadrupoles. A large bore conventional dipole can be positioned as the first dispersing bend and aligned on the zero degree neutral beam direction. The challenge will then be to cleanly dump the neutral beam upstream of the remaining superconducting dipoles aligned along the charged beam trajectory.

The M-Polarized beam solves both problems by shielding the superconducting quadrupoles with collimation, with a resulting loss of aperture, and by using conventional dipole bends.

Superconductivity is expected to be easily utilized in the later stages of the charged secondary beams, downstream of the momentum defining collimator, where the thermal loading due to the higly collimated and focussed beam is negligible.

References

1. R.P.Smith, et al., "Advances in Cryogenic Engineering 27, 105(1982) and IEEE MAG-19,1362(1983).

2. A.Van Ginneken, "CASIM: Program To Simulate Transport of Hadronic Cascades in Bulk Matter," Fermilab-FN-272.1975, Unpublished.

3. W.Craddock, "Summary of Low Current Magnet Beam Load Cooling," June,1982 - rev. December, 1982 Fermilab, Unpublished.

4. B.Cox, et al., "P-West High Intensity Secondary Beam Area Design Report," March,1977 - Fermilab, Unpublished.

5. H.Edwards, et al., IEEE MAG-13, 666(1977).

6. R.Dixon, et al., "Beam Induced Quench Studies of Tevatron Dipoles, Fermilab-FN-327, 1980 Unpublished.

7. B.Cox, et al., IEEE NS-26, 3885(1979).

Projected Tevatron Intensity Limits for Epoxy Impregnated Quadrupoles
for 1000 GeV Primary Beams with 20 Second Pulse Length

Beam	Configuration	Angle	Quench Threshold	Thermal Load at Quench*	Thermal Load at 10^{12}*
A. PW	NEUTRAL BEAM 300 GeV ANTI-P	1 MRAD	4×10^{10}	5 WATTS	140 WATTS
B. PW**	NEUTRAL BEAM 300 GeV ANTI-P	0 MRAD	4×10^{11}	24 WATTS	71 WATTS
C. PW	750 GeV π^-	0	3×10^{11}	20 WATTS	83 WATTS
D. PW	300 GeV π^-	0	4×10^{11}	50 WATTS	148 WATTS
E. MP	P OR ANTI-P	0	8×10^{12}	44 WATTS	6 WATTS

* Total first stage quadrupole thermal load on refrigeration.

** Zero degree targetting for p-west requires additional sweeping dipoles and target box modification.

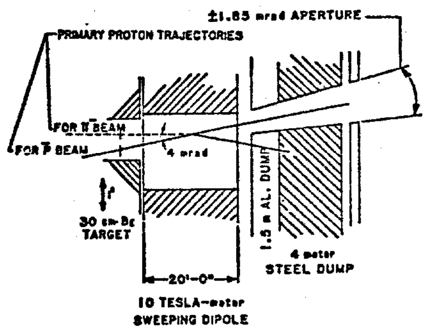

Fig. 1a. PW-TARGETTING, SWEEPING DIPOLE, & COLLIMATOR / DUMP

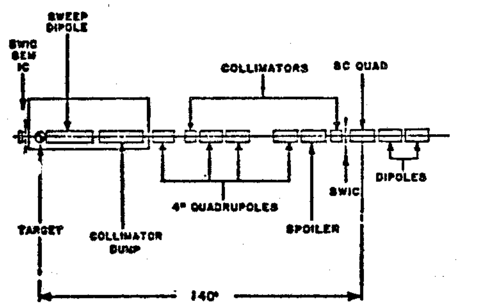

Fig. 1b. PW SECONDARY BEAM FIRST STAGE COMPONENTS

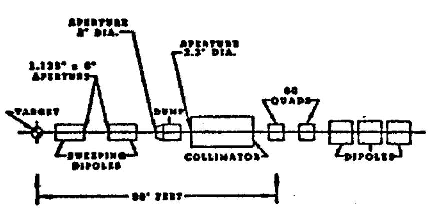

Fig. 2. MP SECONDARY BEAM FIRST STAGE COMPONENTS

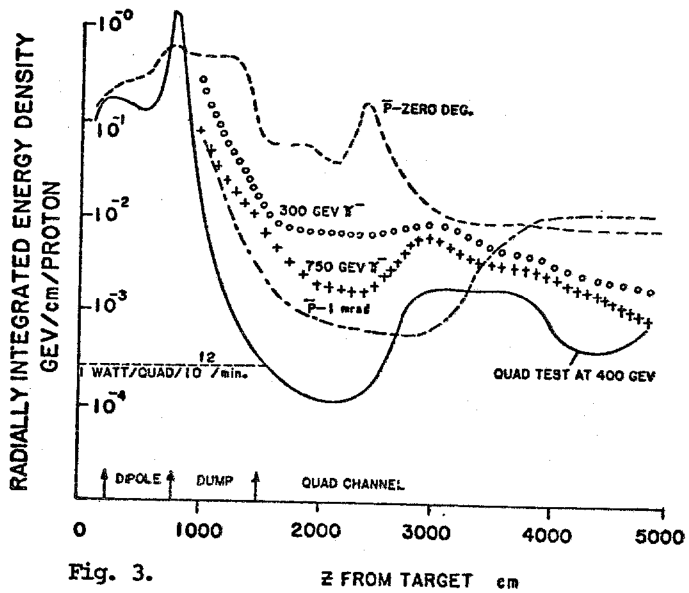

Fig. 3.
P-WEST BEAM LOADING FOR 1 TEV PRIMARY BEAM

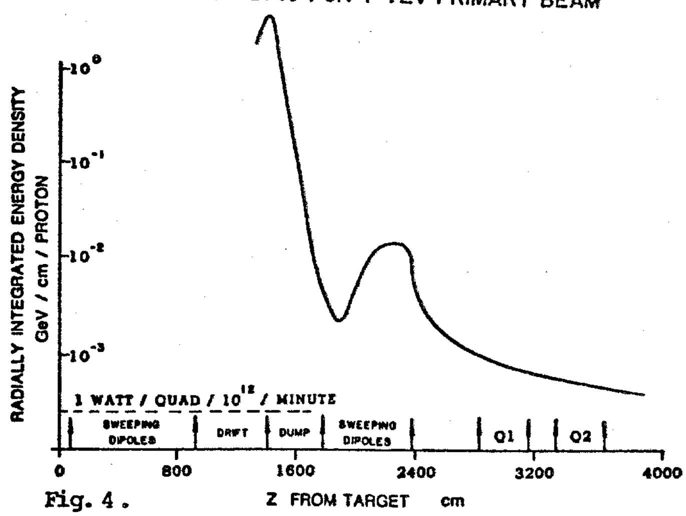

Fig. 4.
M-POLARIZED BEAM LOADING FOR 1 TeV PRIMARY BEAM