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HEAVY ION PHYSICS AT BNL, THE AGS AND RHIC*

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The advent of heavy ion acceleration with the AGS at Brookhaven National Laboratory in 1986 and the proposed Relativistic Heavy Ion Collider (RHIC) for 1990 brings us into a temperature and density regime well above anything yet produced and into a time domain of the early universe of 10^{-13} - 10^{-6} seconds. Figure 1, courtesy of Fermilab, shows us that for two colliding atoms of gold at 100 GeV/nucleon in RHIC, a center-of-mass energy of 40 TeV, we would be probing the "Desert". A region only presently probed by cosmic ray physics and barely touched by the S$\bar{P}$PS and the Tevatron.

The physics of high energy heavy ions range from the more traditional nuclear physics to the formation of new forms of matter. Quantum Chromodynamcis (QCD) is the latest, and as of yet, the most successful theory to describe the interaction of quarks and gluons. The nature of the confinement of the quarks and gluons under extremes of temperature and density is one of the compelling reasons for this new physics program at BNL. There are reasons to believe that with collisions of heavy nuclei at energies in the 10 to 100 GeV/amu range a very large volume of ~ 10 fm^3 would be heated to 200-300 MeV and/or acquire a sufficient quark density (5-10 times normal baryon density) so that the entire contents of the volume would be deconfined and the quarks and gluons would form a plasma (see figure 2). Figure 3 describes the kinematic region for the extant machines and the proposed RHIC. As is shown in figure 4, at AGS energies the baryons in colliding nuclei bring each other to rest, yielding fragmentation regions of high baryon density. These are the regions in which supernorvae and neutron stars exist (figure 5). For energies much higher, such as in RHIC, nuclei are transparent to each other and one can form a central region of almost zero baryon density, mostly pions, and very high temperature. This is the region of the early universe and the quark-gluon plasma.

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Brookhaven National Laboratory is now in a unique position to take the lead in the area of relativistic heavy ion physics. At present, the two Tandem Van de Graaff accelerators are being prepared as injectors to the AGS. A Synchrotron Booster has been proposed to extend the mass range from S^{32} (direct Tandem injection) to Au^{197}. The AGS is being prepared to accelerate heavy ions to the 10-15 GeV/amu energy region and the Relativistic Heavy Ion Collider has been proposed to accelerate Au^{197} to 100 GeV/amu (see figure 6).

The AGS is expected to accelerate heavy ions in 1986. The present high energy physics program (figure 7) is very vigorous and exciting with a major emphasis in the areas of flavor changing neutral current decays of kaons, neutrino interactions, glueball spectroscopy and spin physics amongst many other topics. The AGS with 17 east area experimental stations (figure 8) provides a large number of experimental opportunities for both high energy and heavy ion physics. The first round of heavy ion experiments were just recently approved. They include three experiments to search for fractionally charged matter and a major experiment to study particle production at extreme baryon densities (see figure 9). These experiments are expected to start data taking in 1986 and 1987.

After the initial heavy ion runs with S^{32} we expect to have available, assuming the start of funding in October 1985, beams of ions up to gold in 1988. This requires the AGS Synchrotron Booster (see figures 10 & 11). In addition to heavy ions the Booster would increase the AGS proton intensity by a factor of 4 to 5×10^{13} protons/sec. In addition it would act as a polarized proton accumulator and increase the polarized proton intensity by a factor of 25. This Booster is a machine costing $24.6M over a period of three years (figure 12).

The availability of the CBA tunnel, experimental buildings, refrigeration system and injector represents a unique opportunity to construct RHIC at minimal cost. The constraints imposed by existing structures are minimal and do not limit the performance potential of RHIC.

The design desiderata for RHIC are shown in figure 13. A major point is that it cover the energy range from the AGS to the maximum energy possible. The machine has been optimized for beams of gold at 100 GeV/amu. With such an optimization one gets good beam storage lifetimes for beams down to 7 GeV/amu. From 2.5 to 7.0 GeV/amu one would run a single beam with a fixed target (jet), yielding luminosities of > 10^{29} $cm^{-2}sec^{-1}$ (see figures 14 & 15).

There are presently three completed experimental areas (figures 16-19) and a fourth hard stand area. These areas have a longitudinal free space of $\pm$ 10m and diamond lengths of $\pm$ 20cm rms. One can run unequal species (with equal γ) and a maximum γ of 100 GeV/amu Au x 250 GeV protons.

The general parameters of the collider are shown in figure 20. The magnets required have a maximum field of 3.5T. This requires a very modest magnet of a single cosine θ layer of NbTi in a dual configuration, i.e., two independent magnets in a single cryostat. Figure 21 shows the magnet to be used. With a timely funding scenario, RHIC could be built for $134.4M in a period of three-four years (see figure 22).

During the last year-and-a-half there have been several meetings at which heavy ion detectors have been discussed. It has been decided to now pursue these and new ideas to a point where there is a real design, costs, time scale etc. Brookhaven National Laboratory will host a workshop to encourage this work in the spring. At this moment an informal group under W. Willis and T. Ludlam is meeting to organize this spring's workshop. With heavy ion physics beginning at the AGS and the likely possibilities of the AGS Booster and the Relativistic Heavy Ion Collider, it is now time to start the experimental program planning process. BNL welcomes participation from all interested physicists and especially our colleagues in Mexico and the rest of the Americas.

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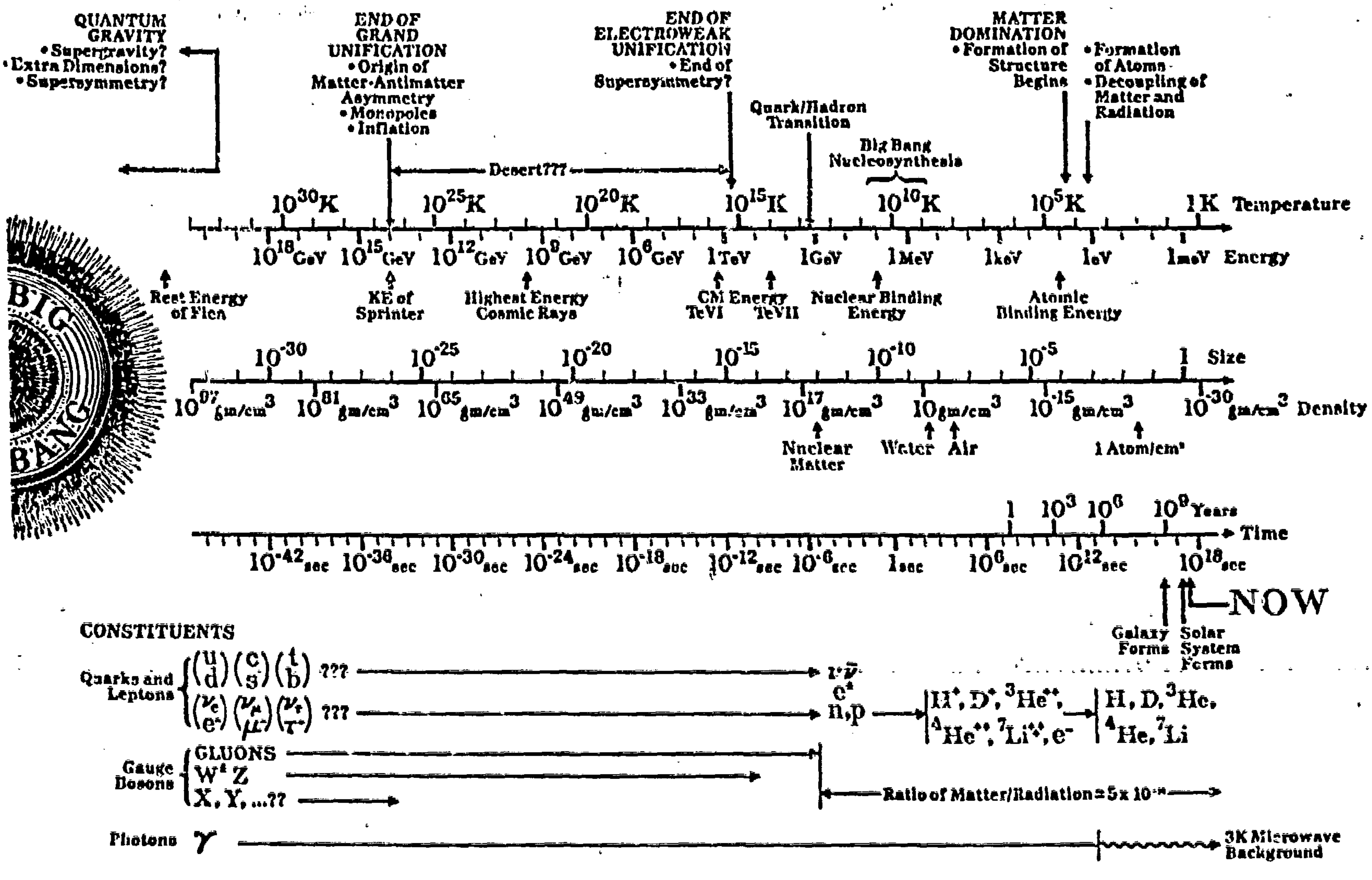

QUANTUM GRAVITY
• Supergravity?
• Extra Dimensions?
• Supersymmetry?
END OF GRAND UNIFICATION
• Origin of Matter-Antimatter Asymmetry
• Monopoles
• Inflation
Desert???
END OF ELECTROWEAK UNIFICATION
• End of Supersymmetry?
Quark/Hadron Transition
Big Bang Nucleosynthesis
MATTER DOMINATION
• Formation of Structure Begins
• Formation of Atoms
• Decoupling of Matter and Radiation
10^30 K
10^25 K
10^20 K
10^15 K
10^10 K
10^5 K
1 K
Temperature
10^18 GeV
10^15 GeV
10^12 GeV
10^9 GeV
10^6 GeV
1 TeV
1 GeV
1 MeV
1 keV
1 eV
1 meV
Energy
Rest Energy of Flea
KE of Sprinter
Highest Energy Cosmic Rays
CM Energy TeVI TeVII
Nuclear Binding Energy
Atomic Binding Energy
BIG BANG
10^-30
10^-25
10^-20
10^-15
10^-10
10^-5
1
Size
10^97 gm/cm^3
10^81 gm/cm^3
10^65 gm/cm^3
10^49 gm/cm^3
10^33 gm/cm^3
10^17 gm/cm^3
10 gm/cm^3
10^-15 gm/cm^3
10^-30 gm/cm^3
Density
Nuclear Matter
Water
Air
1 Atom/cm^3
1
10^3
10^6
10^9 Years
Time
10^-42 sec
10^-36 sec
10^-30 sec
10^-24 sec
10^-18 sec
10^-12 sec
10^-6 sec
1 sec
10^6 sec
10^12 sec
10^18 sec
NOW
Galaxy Forms
Solar System Forms
CONSTITUENTS
Quarks and Leptons
(u d) (c s) (t b) ???
(ν_e e^-) (ν_μ μ^-) (ν_τ τ^-) ???
e^±
n, p
H^+, D^+, ^3He^++, ^4He^++, ^7Li^+++, e^-
H, D, ^3He, ^4He, ^7Li
Gauge Bosons
GLUONS
W^± Z
X, Y, ...??
Ratio of Matter/Radiation ≈ 5 x 10^-10
Photons γ
3K Microwave Background

Figure 1.

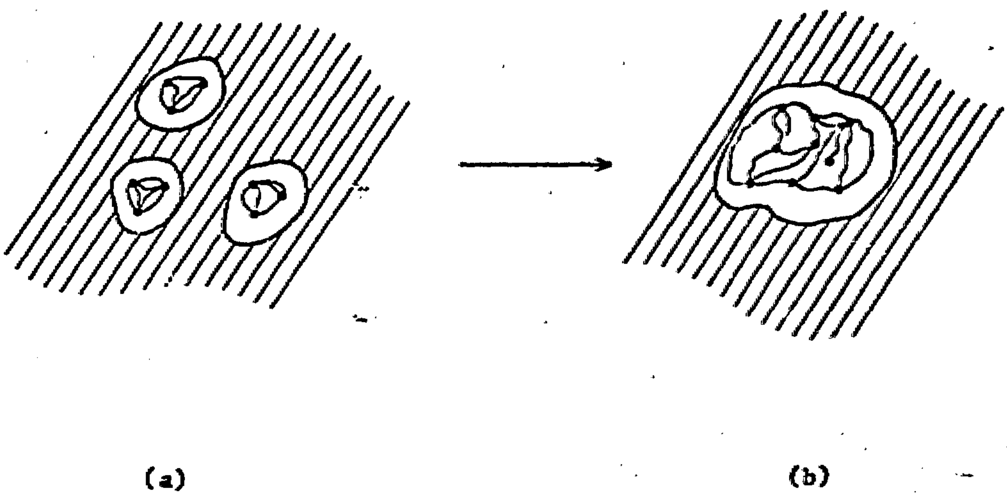


Figure 2: Phase transition of the QCD vacuum: (a) quarks and color fields confined inside the observable hadrons. The confining medium (shaded) is the ground-state vacuum. (b) At high temperature and density the hadrons coalesce into an extended volume of confinement containing many quarks.

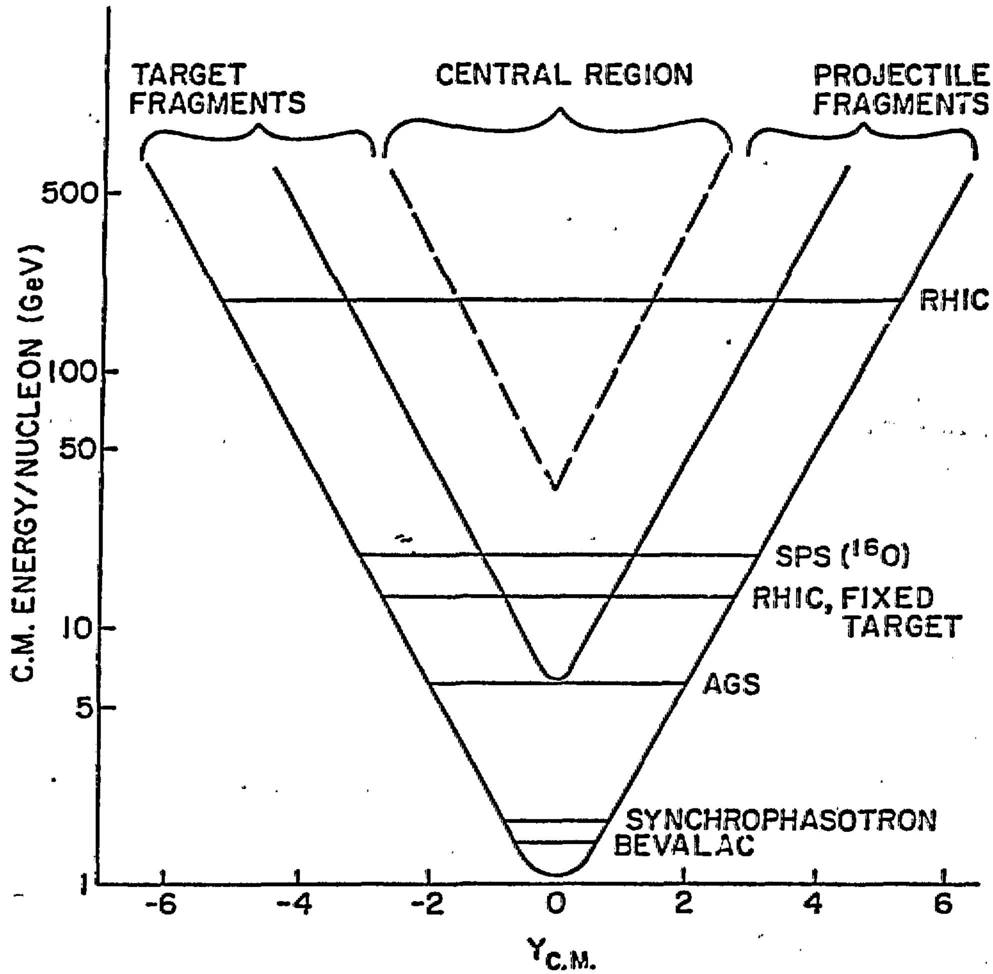


Figure 3: The kinematic landscape available to the proposed facility, and some existing machines. The outer "vee" is the phase space limit—the rapiditiy of the incident nucleons. The inner, solid vee delineates fragmentation regions of width $\Delta y = 2$, as observed in proton-proton collisions. The dashed lines indicate the wider ($\Delta y = 4$) fragmentation regions—and hence narrower central region—expected at a given energy for nucleus-nucleus collisions with $A \gtrsim 200$. The horizontal lines indicate (AGS,RHIC) as well as in the facilities which presently exist (LBL Bevalac, Dubna Synchrophasotron) and the planned oxygen beams in the CERN SPS.

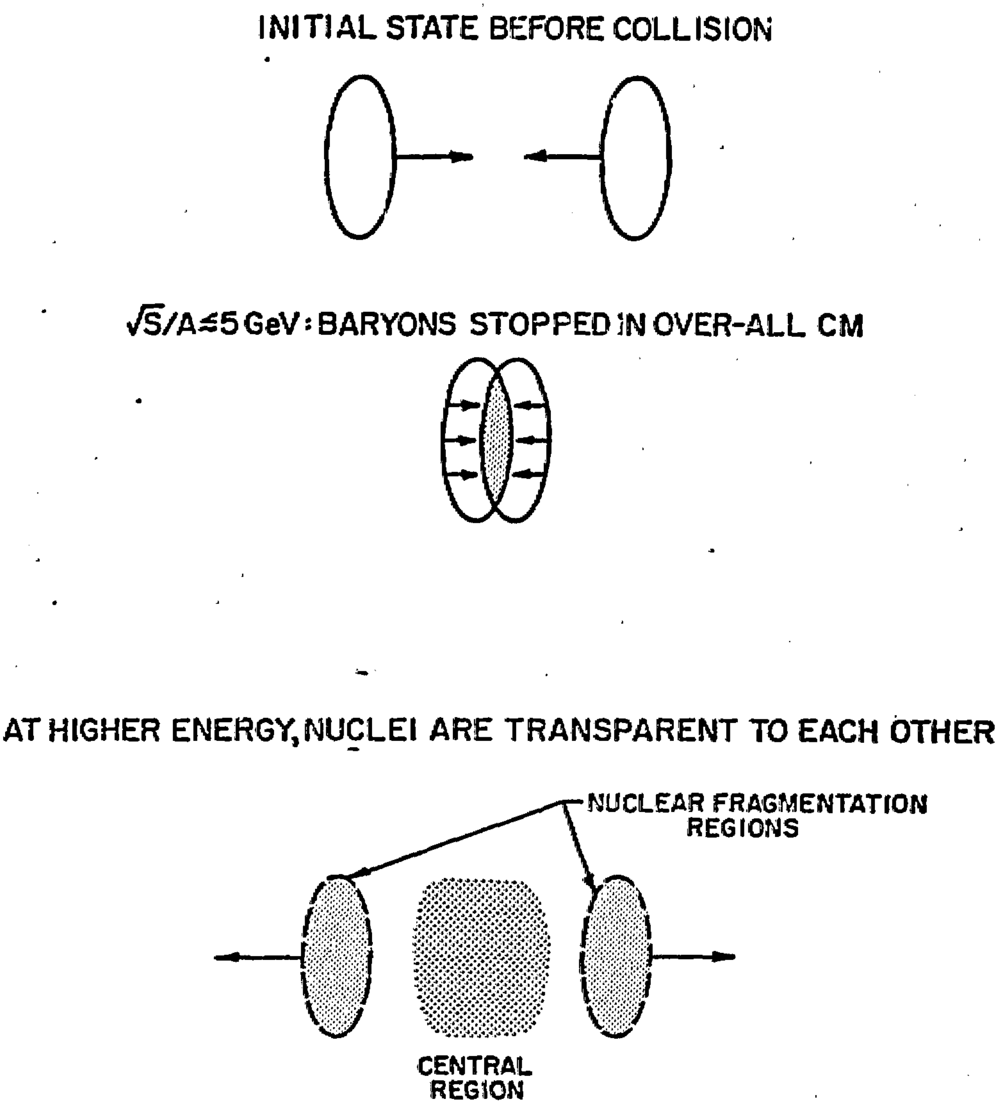


Figure 4: Schematic illustration of nuclear transparency in high energy collisions at zero impact parameter.

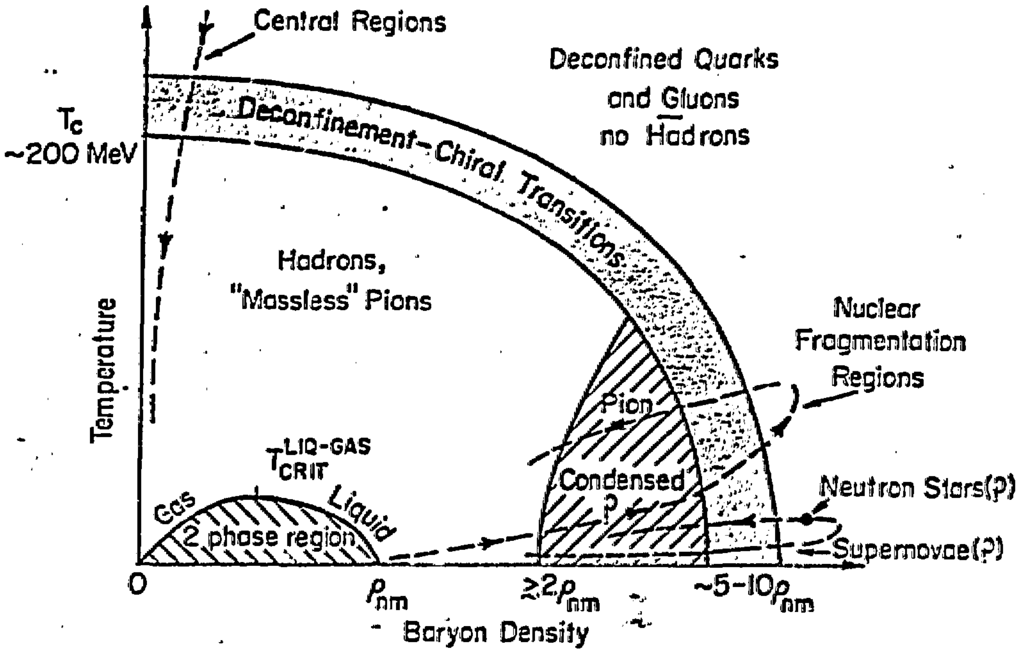


Figure 5: Phase diagram of Nuclear Matter (G. Baym, ref. 3). Temperature is plotted vs. net baryon density for an extended volume of nuclear matter in thermal equilibrium. Normal nuclear matter appears at the point ρ_{nm} at zero temperature, and this is the neighborhood explored by low energy nuclear physics. The region of the phase transitions corresponding to deconfinement (at temperature T_C) and chiral symmetry restoration is indicated. The two critical temperatures may well be coincident. The confinement force couples quarks to form hadrons. The chiral force binds the collective excitation to Goldstone bosons. Above T_C, hadrons dissolve into quarks and gluons. Above T_F quarks are massless. The indicated trajectories show two avenues for probing the quark-gluon plasma with high energy nucleus-nucleus collisions: by reaching high baryon densities among the hot, compressed fragments of the colliding nuclei, and at very high temperatures in the central rapidity region among thermally produced particles where conditions may approximate those of the early universe.

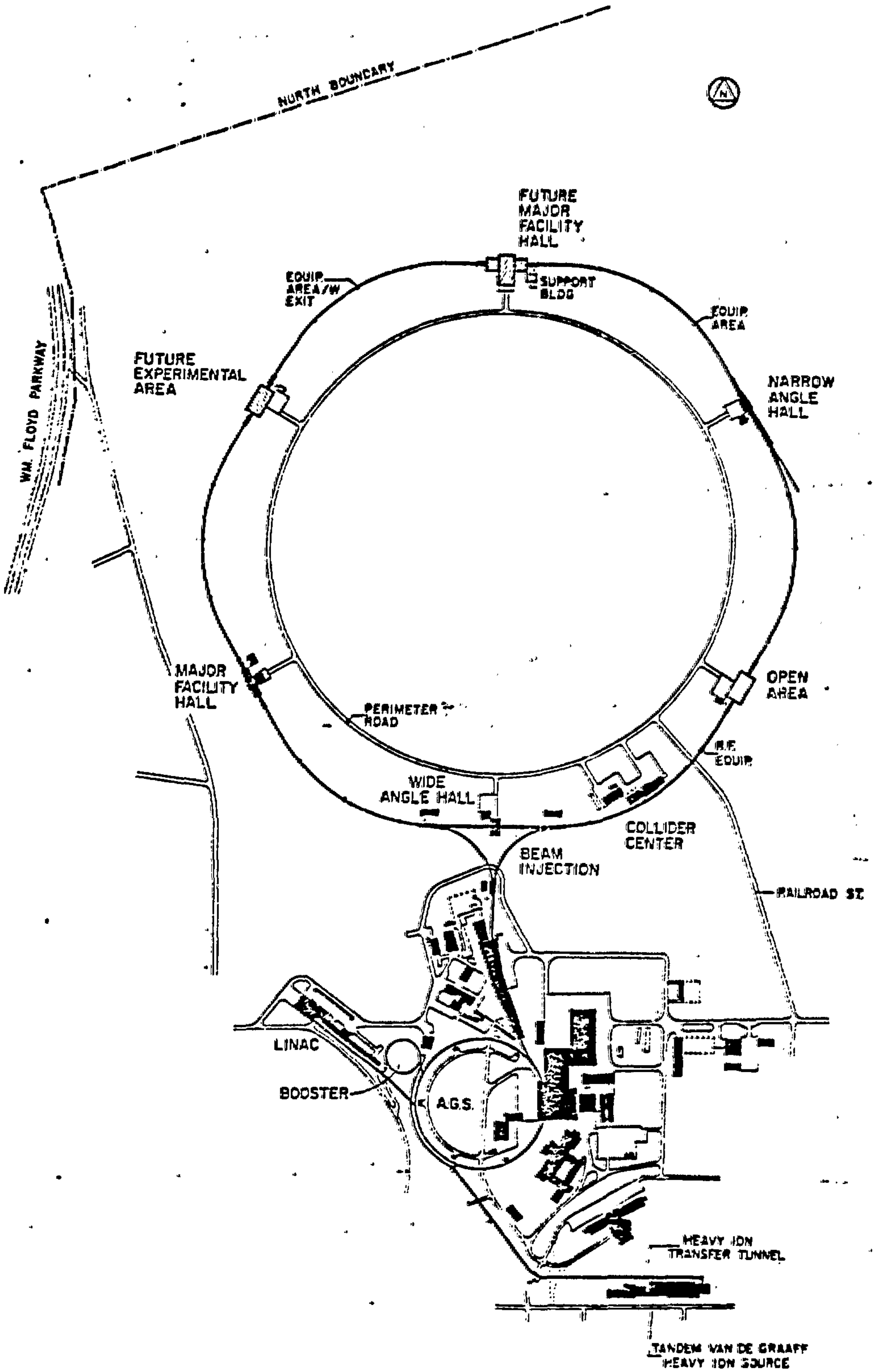


Figure 6: Layout of RHIC Project - Collider & Source

PHYSICS PROGRAM SUMMARY (FY 1985 -->)

APPROVED EXPERIMENTS

A-TARGET STATION

- CP VIOLATION
- FLAVOR-CHANGING NEUTRAL CURRENTS (K°_{L})
- GLUONIUM
- EXOTICS SPECTROSCOPY
- TEST BEAM

B-TARGET STATION

- GLUONIUM
- FLAVOR-CHANGING NEUTRAL CURRENTS (K°_{L})
- Ω^{-} PRODUCTION AND DECAY MODES
- SEARCH FOR QUARKS IN HEAVY ION INTERACTIONS
- STUDIES OF PARTICLE PRODUCTION AT EXTREME BARYON DENSITIES
- TEST BEAM

C-TARGET STATION

- HYPERNUCLEAR SPECTROSCOPY (π^{+}, K^{+}) (K^{-}, π^{-}) γ-emission
- BOUND LIFETIME
- DIBARYON STATES
- $\bar{N}P$ ANNIHILATION CROSS SECTION
- SINGLE-SPIN ASYMMETRY, INCLUSIVE $P_{\uparrow}P$
- FLAVOR-CHANGING NEUTRAL CURRENTS (K^{+})
- SEARCH FOR $\xi(2.2)$

D-TARGET STATION

- PP POLARIZATION
- QED VACUUM POLARIZATION
- MUON SPIN PRECESSION IN CONDENSED MATTER
- POLARIZATION IN $PP_{\uparrow}$ ELASTIC SCATTERING
- SPIN-SPIN EFFECTS, $P_{\uparrow}P_{\uparrow}$ ELASTIC SCATTERING
- FLAVOR-CHANGING NEUTRAL CURRENTS (K^{+})

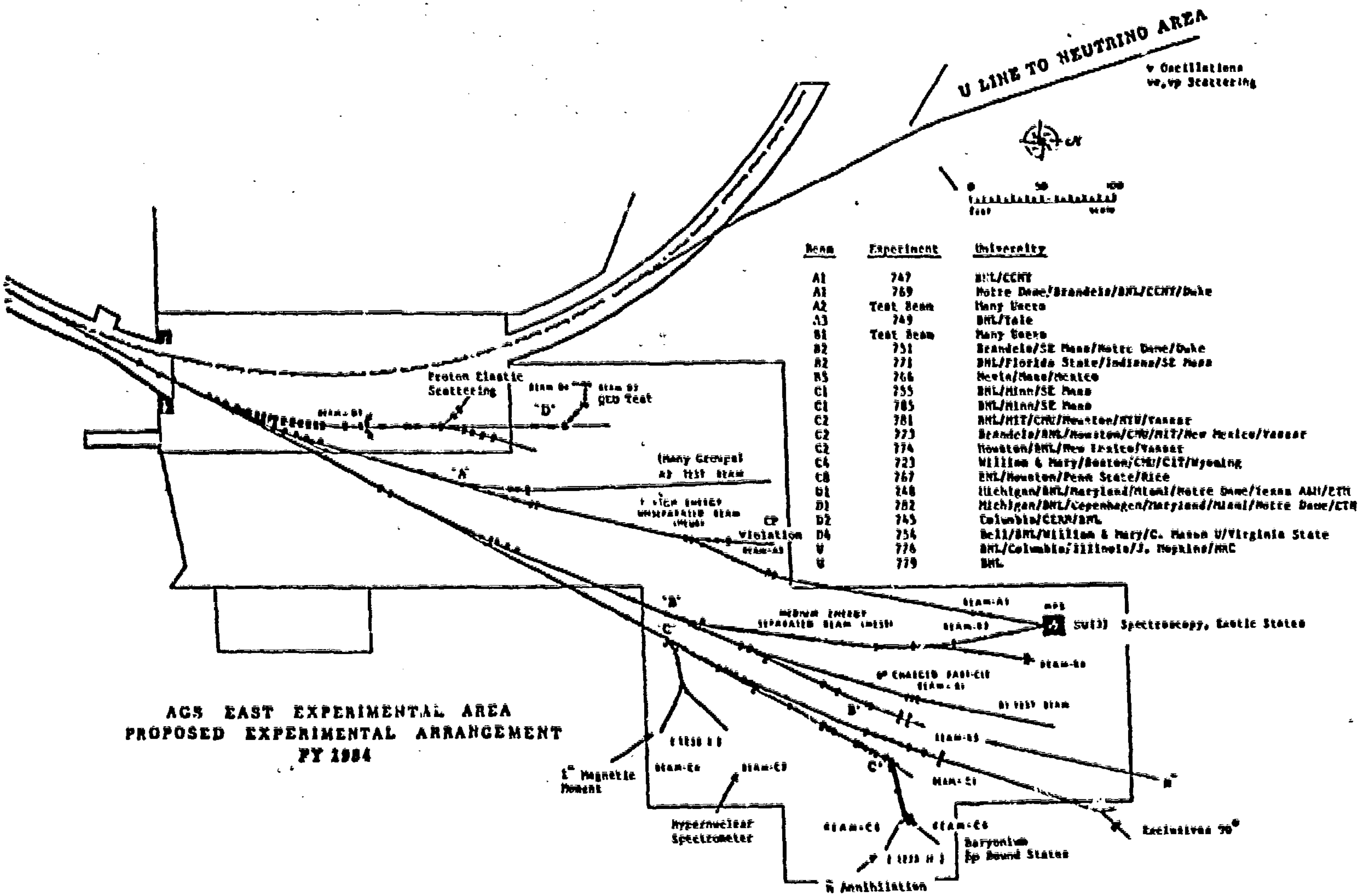
U-TARGET STATION

- ν-SCATTERING, νE, νP
- ν-OSCILLATIONS
- NUCLEAR SPECTROSCOPY

G20-TARGET STATION

- NUCLEAR FRAGMENTS FROM P-NUCLEUS (GAS JET)

Figure 7



Beam	Experiment	University
A1	747	BNL/CCNY
A1	769	Notre Dame/Brandeis/BNL/CCNY/Duke
A2	Test Beam	Many Users
A3	749	BNL/Yale
B1	Test Beam	Many Users
B2	751	Brandeis/SE Mass/Notre Dame/Duke
B2	771	BNL/Florida State/Indiana/SE Mass
B5	766	Kent/Mass/Mexico
C1	755	BNL/Minn/SE Mass
C1	785	BNL/Minn/SE Mass
C2	781	BNL/MIT/CMU/Houston/NYU/Vassar
C2	773	Brandeis/BNL/Houston/CMU/MIT/New Mexico/Vassar
C2	774	Houston/BNL/New Mexico/Vassar
C4	723	William & Mary/Boston/CMU/CIT/Wyoming
C8	767	BNL/Houston/Penn State/Rice
D1	748	Michigan/BNL/Maryland/Miami/Notre Dame/Texas A&M/ETH
D1	782	Michigan/BNL/Copenhagen/Maryland/Miami/Notre Dame/ETH
D2	745	Columbia/CERN/BNL
D4	754	Bell/BNL/William & Mary/G. Mason U/Virginia State
U	776	BNL/Columbia/Illinois/J. Hopkins/NRC
U	779	BNL

Figure 8.

Exp. 793 – U.C. Berkeley (Price)

Search for Fractionally Charged Nuclei in 15A GeV Sulfur-Oxygen Collisions.
8 hours – Small Heavy Ion Experiment (SHIE)

Exp. 801 – San Francisco State (Hodges)

A Search for Quarks Produced in Heavy Ion-Mercury Interactions.
72 hours – SHIE

Exp. 804 – Indiana/Michigan (Ahlen/Tarle)

Search for Fractional Charge with Heavy Ion Beams at the AGS.
8 hours – SHIE

Exp. 802 – BNL/Hiroshima, LBL/MIT/Tokyo (Hansen)

Studies of Particle Production at Extreme Baryon Densities in Nuclear Collisions at the AGS.
1000 hours – Large Heavy Ion Experiment (LHIE)

Figure 9: Approved AGS Heavy Ion Experiments.

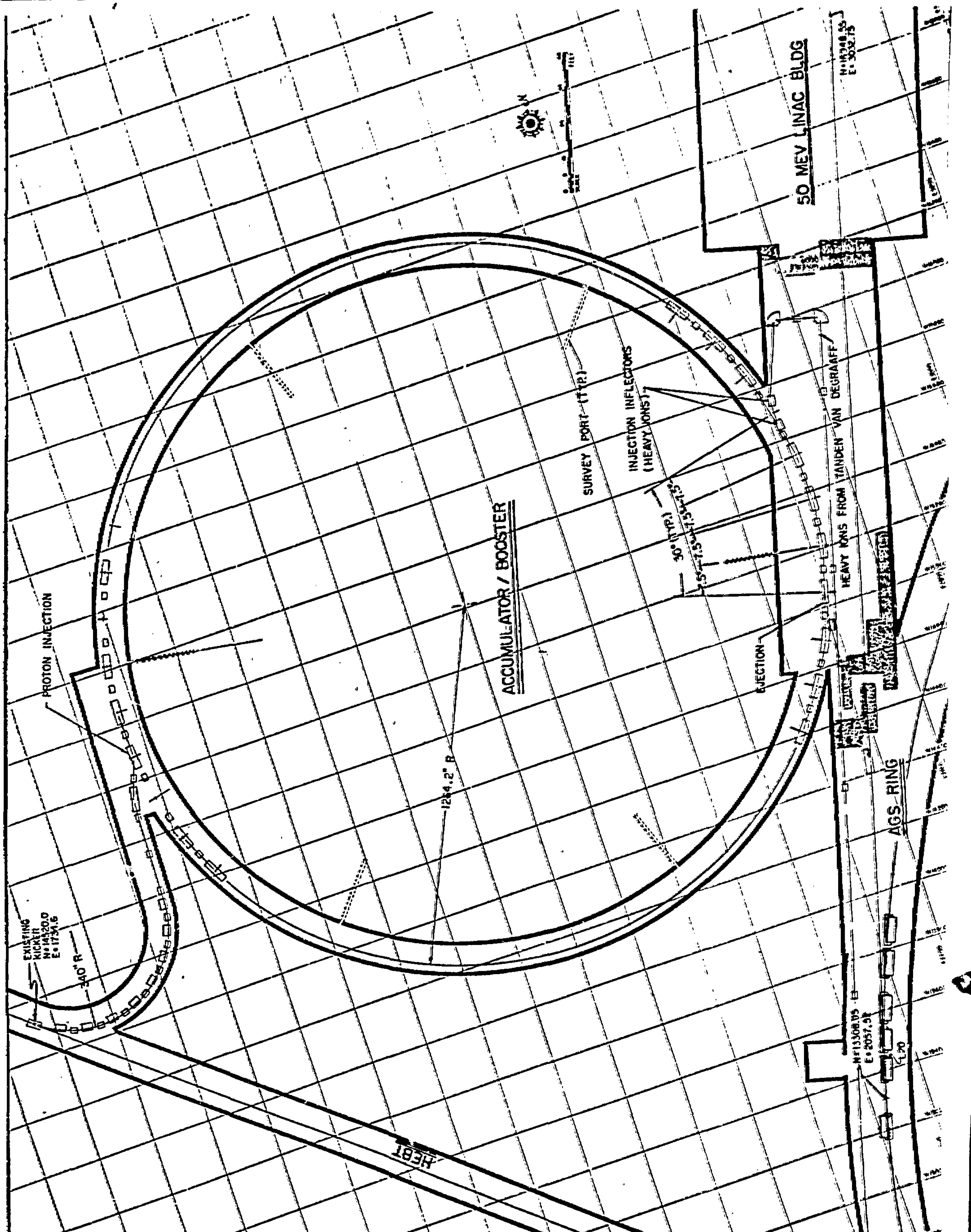


Figure 10: AGS Booster Layout

AGS BOOSTER PARAMETERS

	PROTONS		HEAVY IONS
INJECTION ENERGY	200 MeV		> 0.75 MeV/AMU
EJECTION ENERGY/MOMENTUM	1 GeV		$p = 5\frac{Q}{A}$ GeV/c/AMU
CIRCUMFERENCE		201.75 m (1/4 AGS)	
# FOCUSING CELLS		24 (FODO)	
CELL LENGTH		8.4 m	
PERIODICITY		12	
# STRAIGHT SECTION/LENGTH		12/3.7 m	
PHASE ADVANCE/CELL		100.5 °	
$\nu_X \sim \nu_Y$		6.7	
β_{MAX}/β_{MIN}		16/2 m	
η_{MAX}		1.7 m	
TRANSITION γ		6.5	
RF HARMONICS	3		1
# DIPOLES/LENGTH		36/2.4 m	
FIELD INJECTION	1.56 kG		> 0.105 $\frac{A}{Q}$
EJECTION	4 kG		12
# QUADRUPOLE/LENGTH		48/0.5 m	
REPETITION RATE	10 Hz		1

Figure 11: AGS Booster Parameters.

OBLIGATION/WBS BUDGETS
AT YEAR DOLLARS

WBS LEVEL 1 2 3 / WBS NAME	FY 86	FY 87	FY 88	TOTAL
ACCELERATOR SYSTEM				
MAGNET SYSTEM	2469	2493	18	4980
POWER SYSTEM	1259	1045	94	2398
VACUUM SYSTEM	481	1120	197	1798
RF	982	1007	170	2159
BEAM INSTR.	436	344	31	811
CONTROLS	692	807	95	1594
CONVENTIONAL FACILITIES				
CONSTRUCTION	1221	375	305	1901
AE	295	-	-	295
SYSTEM ENG. (EDIA)	1879	1700	563	4142
PROJECT MGMT. (EDIA)	161	143	153	457
PROJECT SUBTOTAL	9875	9034	1626	20535
CONTINGENCY	1350	2052	657	4059
PROJECT TOTAL	11225	11086	2283	24594

Figure 12: AGS Booster Budget

RELATIVISTIC HEAVY ION COLLIDER
RHIC
DESIGN DESIDERATA

- ENERGY RANGE FROM 11-100 GEV/AMU
  >250 GEV (PROTON)
- MASS RANGE: P - AU
- LUMINOSITY (AU-AU) 10^{25}-10^{27} CM^{-2} SEC^{-1}
  γ ENERGY DEPENDENCE
- MINIMUM OF 3 EXPERIMENTAL AREAS
- EXPERIMENTAL-FREE SPACE ±10M
- HEAD-ON COLLISIONS/X-ING AT ANGLE
- DIAMOND LENGTH ±20 CM RMS
- OPERATIONAL LIFETIME >10 HOURS @ γ >30
- COLLISION OF UNEQUAL SPECIES P - AU
  - EQUAL γ
  - MAXIMUM γ, 100 GEV AU×250 GEV P
- INTERNAL TARGET OPERATION
  FOR LOW CM ENERGY RANGE

Figure 13.

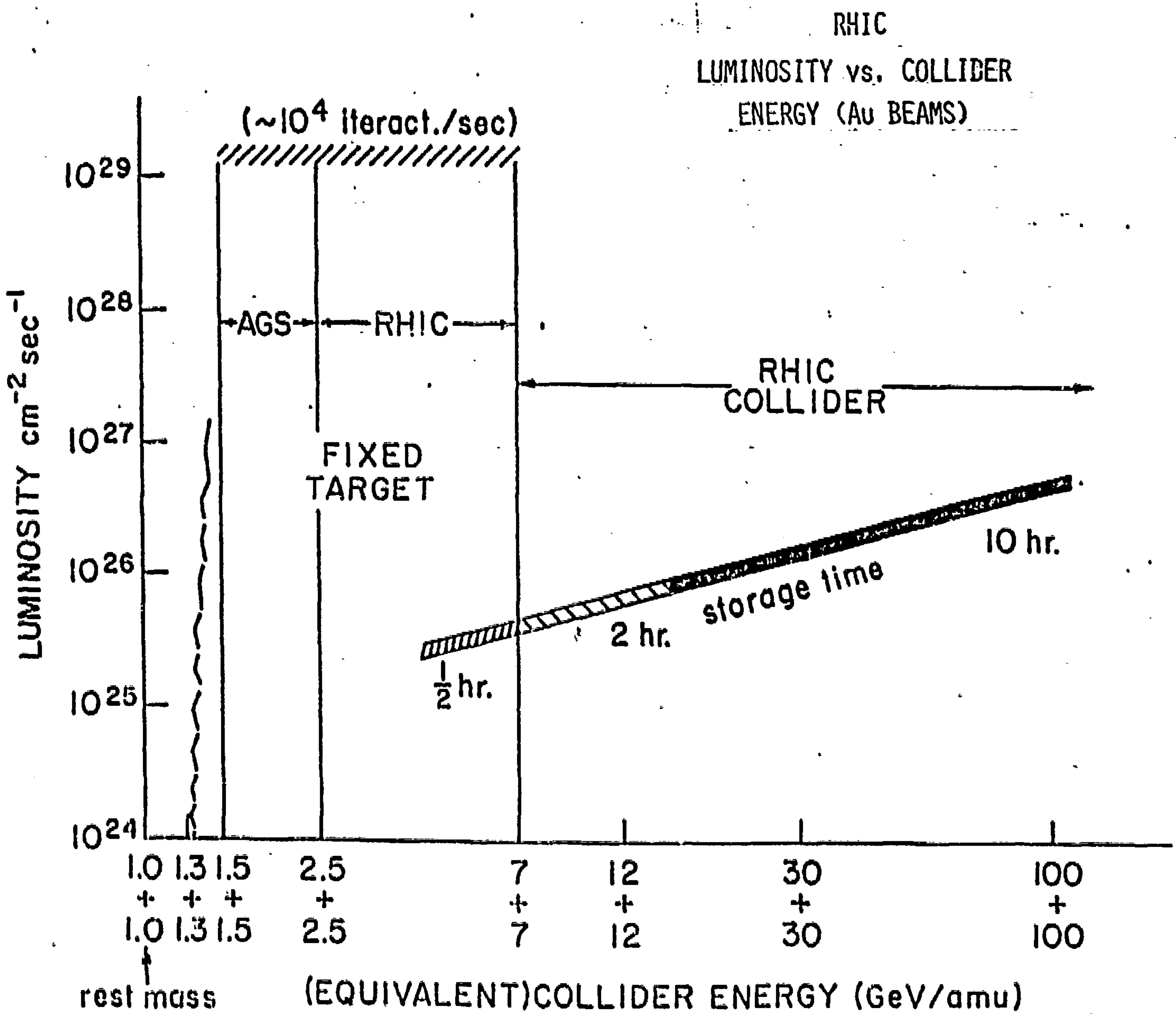

RHIC
LUMINOSITY vs. COLLIDER
ENERGY (Au BEAMS)
(~10^{4} Iteract./sec)
LUMINOSITY cm^{-2}sec^{-1}
10^{29}
10^{28}
10^{27}
10^{26}
10^{25}
10^{24}
AGS
RHIC
FIXED TARGET
RHIC COLLIDER
10 hr.
storage time
2 hr.
$\frac{1}{2}$ hr.
1.0 + 1.0
1.3 + 1.3
1.5 + 1.5
2.5 + 2.5
7 + 7
12 + 12
30 + 30
100 + 100
rest mass
(EQUIVALENT)COLLIDER ENERGY (GeV/amu)

Figure 14.

Table IV.2. General Beam Parameters for the Collider

Element	Proton	Deuterium	Carbon	Sulfur	Copper	Iodine	Gold
Atomic No, Z	1	1	6	16	29	53	79
Mass No, A	1	2	12	32	63	127	197
Rest Energy (GeV/amu)	0.9383	0.9375	0.9310	0.9302	0.9299	0.9302	0.9308
Injection:							
Kinetic Energy, (GeV/amu)	28.5	13.6	13.6	13.6	12.4	11.2	10.7
β	.99947	.99947	.99793	.99794	.99757	.99704	.99680
Norm. Emitt., ϵ_N (πmm•mrad)	20	10	10	10	10	10	10
Bunch Area, S (eV•sec/amu)	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Bunch Length (nsec)	$\pm$ 8.6	$\pm$ 8.6	$\pm$ 8.6	$\pm$ 8.6	$\pm$ 8.6	$\pm$ 8.6	$\pm$ 8.6
Energy Spread, 10^{-4}	$\pm$ 3.8	$\pm$ 7.6	$\pm$ 7.6	$\pm$ 7.6	$\pm$ 8.3	$\pm$ 9.2	$\pm$ 9.6
No. ions/Bunch, $\times 10^9$	100	100	22	6.4	4.5	2.6	1.1
Top Energy:							
Kinetic Energy, (GeV/amu)	250.7	124.9	124.9	124.9	114.9	104.1	100.0
$\beta\gamma$	268.2	134.2	135.2	135.3	124.6	112.9	108.4
$\mathcal{L}$(0 mrad)	1.2×10^{31}	1.2×10^{31}	6×10^{29}	5×10^{28}	2×10^{28}	7×10^{27}	1.2×10^{27}

$\mathcal{L}$(2 mrad) $\approx \times \frac{1}{2}$

Unequal species p • Au (1.2×10^{29}) $cm^{-3}sec^{-1}$.

Figure 15.

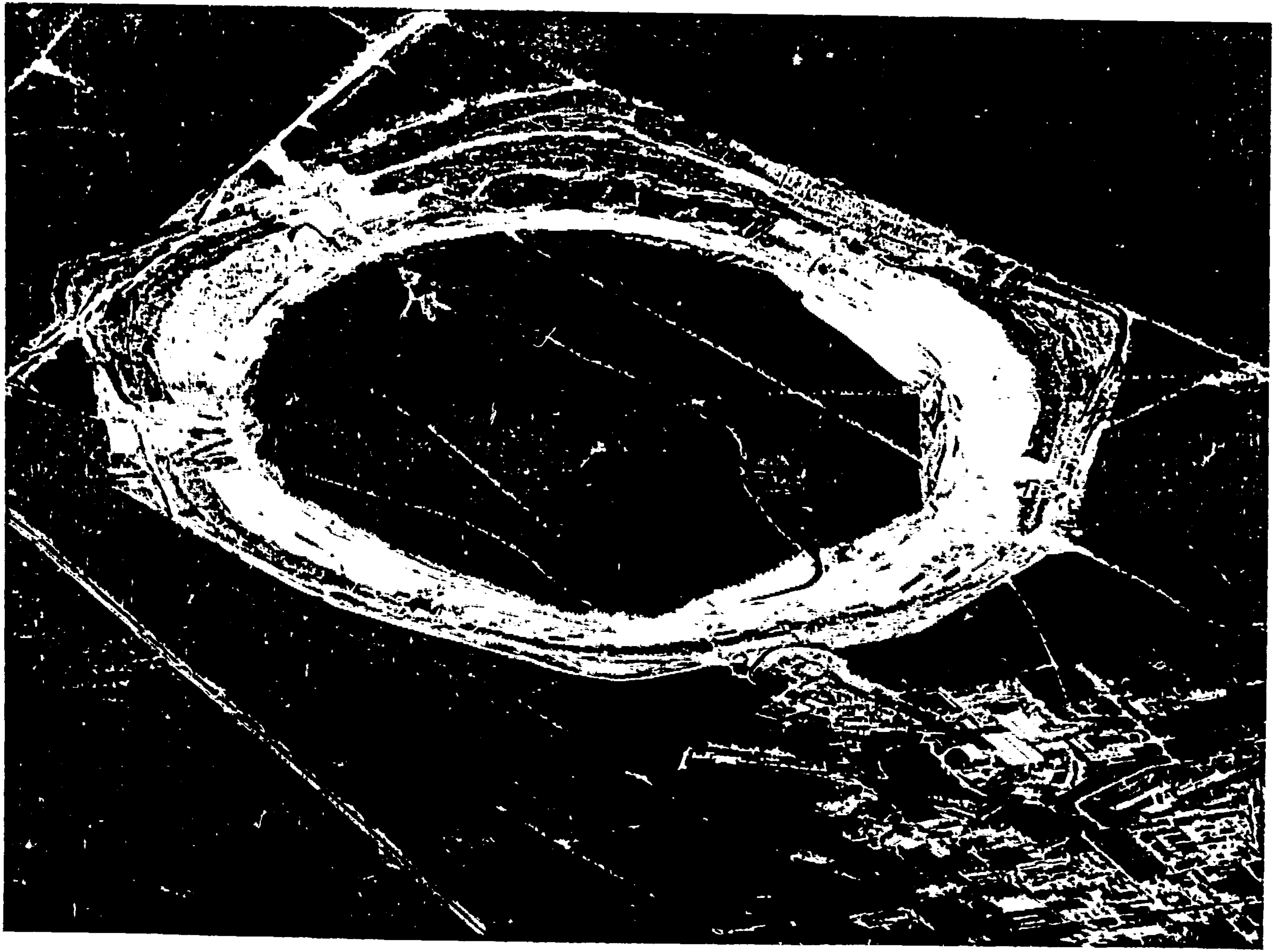


Fig. 16. Aerial view of RHIC site.

Fig. 17. The wide angle hall at 6 o'clock with adjoining support building.

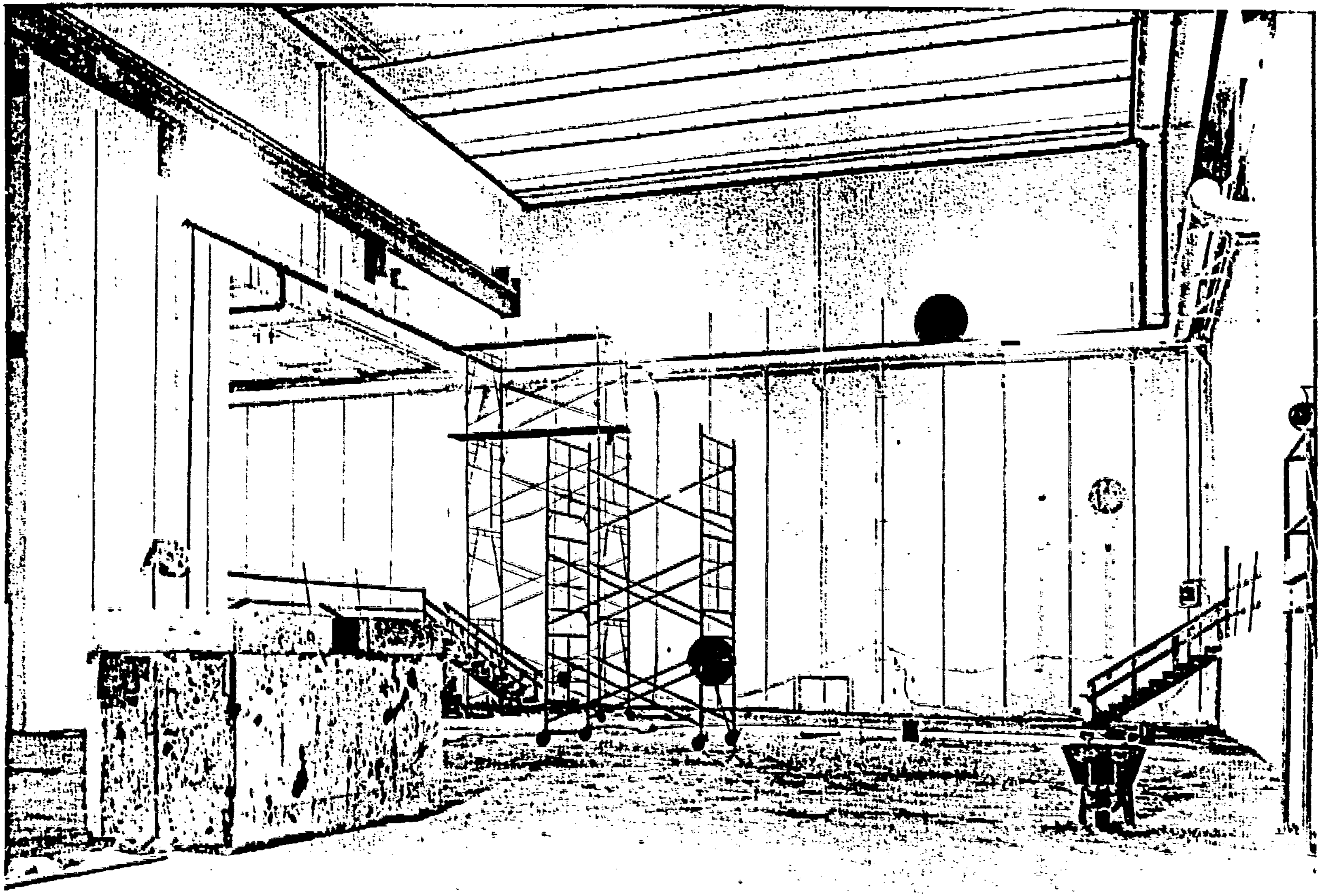


Fig. 18. View from the major facility hall at 8 o'clock.

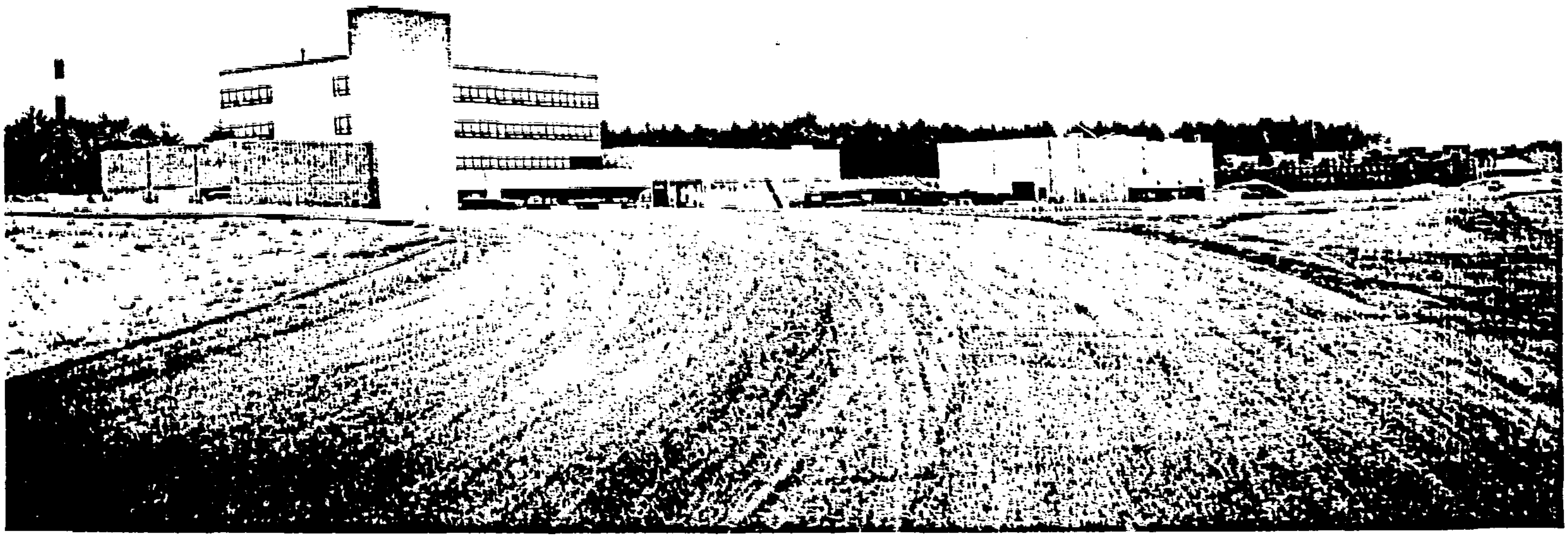


Fig. 19. The Collider Center.
(From left to right, Main Control Building, Cryogenic Wing, Compressor Structure and Cooling Towers.)

GENERAL PARAMETERS FOR THE COLLIDER

Circumference	3833.8 m
Revolution Frequency ($\beta = 1$)	78.1972 kHz
Filling Mode	Box-car
No. of Bunches/Ring	57
Filling Time/Ring	~ 1 min
Periodicity	6
Magnetic Rigidity, $B\rho$	
at injection	9.65 T·m
at top energy	839.5 T·m
Transition Energy, γ_T	26.4
Betatron Tunes, $\nu_{H,V}$	31.4
rf Harmonic Number	342
rf Voltage	1.2 MV
Acceleration Time	1 min

Figure 20: RHIC Parameters.

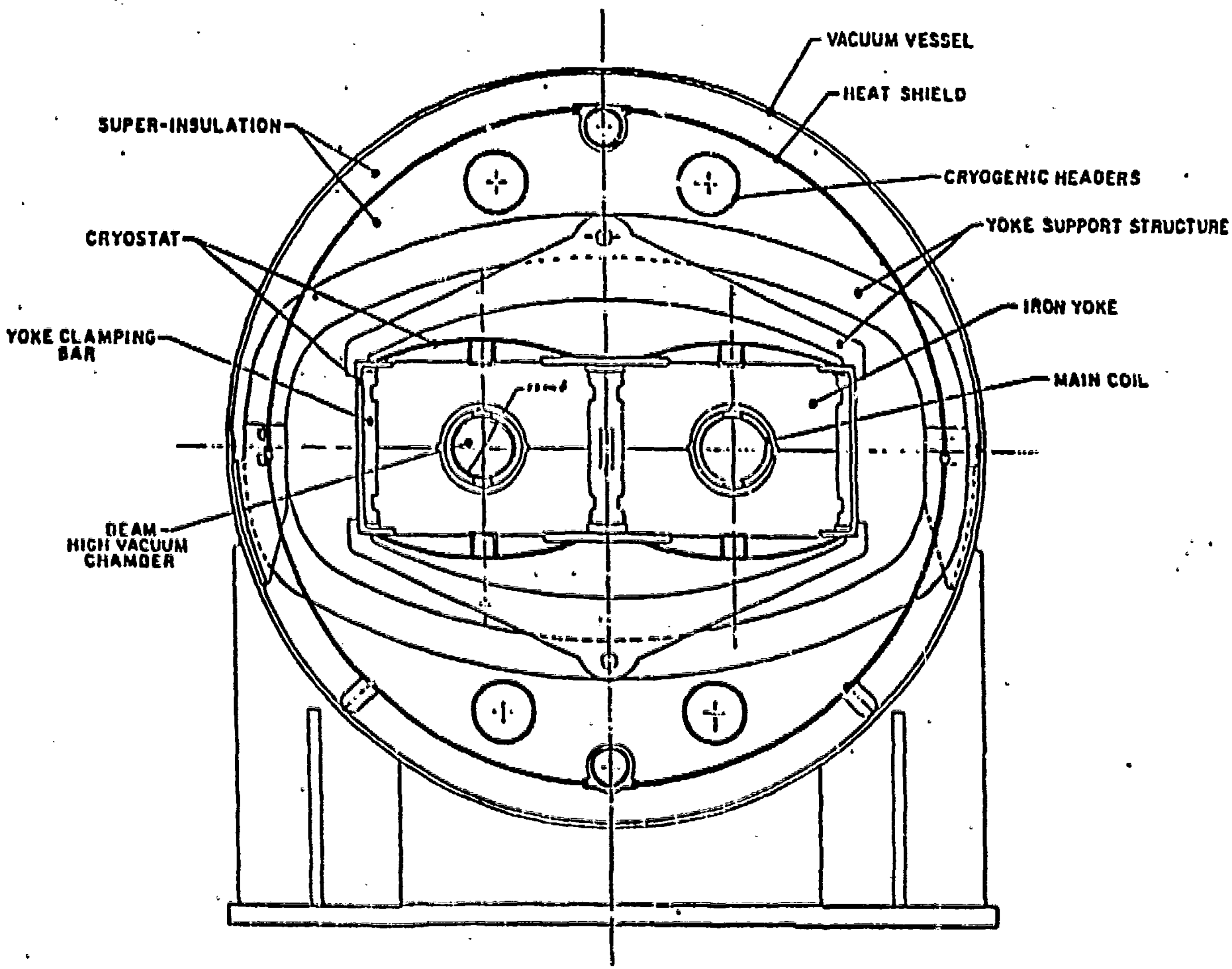


Figure 21: RHIC Dipole Magnet.

RHIC COST ESTIMATE SUMMARY
(M$)

	MSTC	LABOR	TOTAL
Accelerator Systems			
Injection	5.7	2.1	7.8
Magnet	34.2	12.6	46.8
Power Supplies	6.3	1.9	8.2
Vacuum	2.3	1.5	3.8
RF	3.4	0.9	4.3
Beam Instrumentation	0.9	0.6	1.5
Refrigeration	4.9	2.1	7.0
Central Controls	5.1	1.1	6.2
Beam Dump	2.0	0.7	2.7
Sub-total			88.3
Conventional Facilities			
Site Improvements	0.6		0.6
Tunnel & Buildings	2.4		2.4
Utilities	0.7		0.7
Sub-total			3.7
AEM	0.5		0.5
EDIA			
Systems Engineering	1.2	13.7	14.9
Project Management	1.7	3.7	5.4
Incremental Overhead			4.7
Sub-total			25.0
Total			117.5
Contingency			16.9
Project Total (FY 84 M$)			134.4

Figure 22.