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TRIUMF: ITS OPERATION, PERFORMANCE AND MAJOR PROJECTS

Transparencies presented by D. Pearce, Visitor from Triumf at CERN
on 29.9.1988

TRIUMF

niversity eson acility

6 sector H^- isochronous CYCLOTRON

- 200 μA max extracted current
- extracted energies 180 - 520 MeV
  70 - 120 MeV
- extract simaltaneously in 3 beamlines
- split ratio 1 : 100,000

- located of UBC Endowment Lands, VANCOUVER
- founded by - University of British Columbia
  Victoria
  Simon Fraser
  Alberta

- 4 Universities form BOM

OPCOM - operational decisions, budgets, exp. facilities, etc
- 4 Universities
- 2 outside users
- 1 TRIUMF

BUDGET - 32 m sF from NRC
Canadian users - NSERC

≈ 400 employees

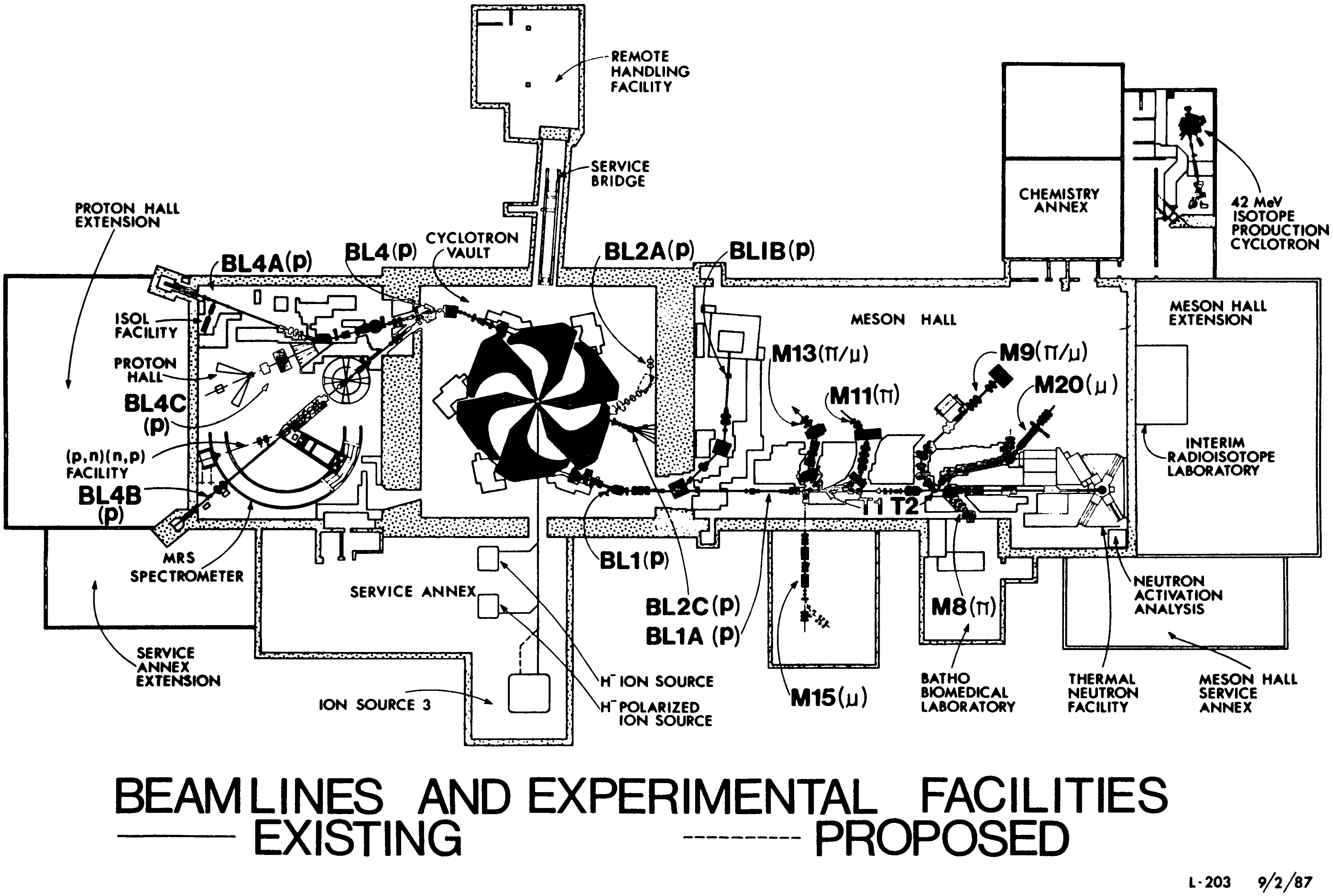


Figure 1.1.2.A. General layor

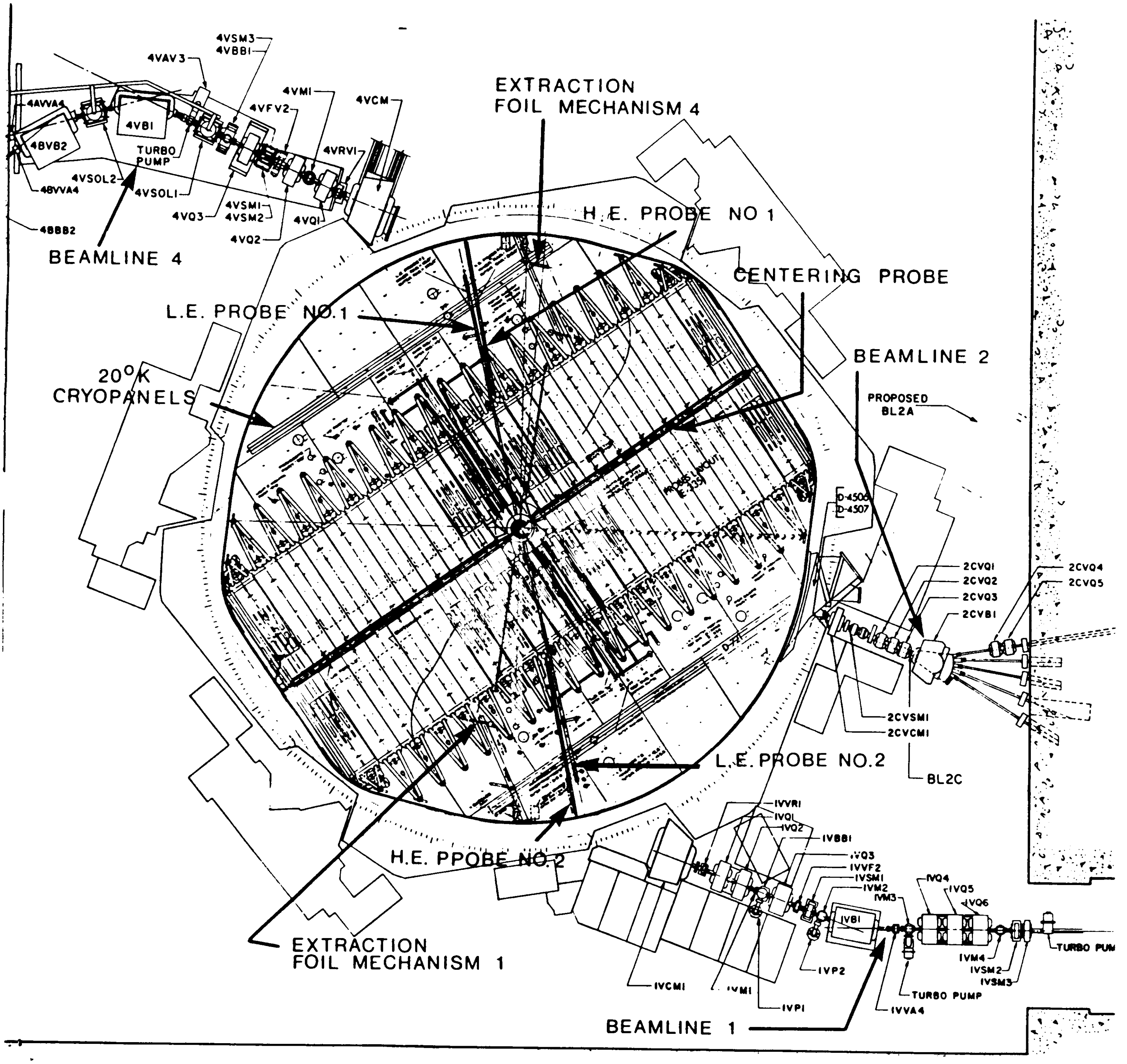


Figure 3.1.A Plan view of the cyclotron

Table 1.1.2.I

TRIUMF Beam Properties

The cyclotron energy range is 180-520 MeV with an energy spread of 0.1% (FWHM). The unpolarized intensity is 150 μA, and the polarized intensity is 1 μA; the polarization is 75-82%. The BL4/BL1A split ratio is $1/10^4$. The phase width is variable from 0.5 to 6 ns. The pulse separation is 43 or 217 ns. There are plans to upgrade various performance levels.

Primary Beam Lines

Beam	Particle	Energy (MeV)	Intensity	Momentum spread FWHM (%)	Polarization (%)	Spot size H×V(cm)
BL1A	p	180-520	150 μA (500 MeV)	0.2	0	0.2×0.5
BL4/1B	$\vec{p}$	180-520	1 μA	0.2	70-80	0.2×0.5
BL4A	$\vec{n}$	160-500	10^8/sec	1.0	40-75	6×6
BL2C	p	65-100	10 μA	0.2	0	1×2

Secondary lines
The M8, M9 and M20 fluxes are for full momentum acceptance with 100 μA of protons on a 10-cm Be target. The M11, M13, and M15 fluxes are for full momentum acceptance with 100 μA of protons on a 1-cm C target. Beams of π^- and μ^- have the same properties as the π^+ and π^+ beams, except fluxes are about 5 times lower.

Beam	Particle	Momentum (MeV/c)	Particle flux → (per sec)	at (MeV/c)	Momentum spr. FWHM (%)	Polar. (%)	Spot size H×V(cm)
M8	π^-	0-220	1.3×10^8	180	13	--	1×2
M9	μ^-	30-150	10^6	77	14	50	8×8
	π^+	30-250	2×10^8	120	14	--	10×2
M20	μ^+	30-200	2.5×10^6	30	5	>90	4×3
			2×10^6	85	8	75	8×8
M13	π^+	30-130	5×10^7	130	10	--	3×2
	μ^+	30(surface)	1.3×10^6	30	10	>90	3×2
M11	π^+	90-470	5×10^6	200	3	--	2×3
M15	μ^+	30(surface)	1.6×10^6	30	12	>90	2×1

3.2 Beam Properties

Energy range:	183-520 MeV
Beam current:	
Unpolarized	140μA
Polarized	~600 nA
Polarization (reversible)	~75%
Split Ratio $\left(\frac{\text{beam line 4}}{\text{beam line 1}}\right)$	Variable down to 10^{-5}
Beam micropulse width (max)	5ns(FWHM)
(min, split selected beam)	0.5ns
Macropulse separation	43ns
with 1 in 5 selector	217ns
Duty Factor:	
Microscopic (ion source pulsed)	0.1%-99.9%
Microscopic (max)	7% (3/43 μs)
(min, phase selected beam)	1.1%
Cyclotron Transmission	85%
Fraction of dc beam to 500MeV	50%
Energy Spread: Normal	2×10^{-3}(FWHM)
Slit selected beam	$<1\times10^{-3}$(FWHM)
Emittance:	
	Internal 1 to 2π mm mrad (90% of beam)
	External 2 to 3π mm mrad

3.3 Beam Time Structure

The normal beam microstructure is a 3 nsec beam pulse every 43 nsec. Both the microstructure and macrostructure of the beam can be changed by a number of devices in the ion source injection line and the cyclotron centre region. These devices are summarized below.

Variable duty cycle pulser: This device in the ion source terminal allows the macroscopic duty cycle to be varied from 0.1% to 99%. The variation is done at a frequency of 1kHz. For instance, in the 10% mode the beam would be present for 100 μsec every 1 msec. Normal operation

ISIS

ION Source & Injection Line

- 4 sources in 3 terminals
  - Ehler's type PIG H⁻ sources
    700 μA max, pulser
  - Lamb-shift polarized source
    600 nA max
    75-80% polarization in both states
    - automatic spin flipper
  - cusp source
    - 2 mA max
    - shares terminal 3
  - optically pumped polarized source
    ≈ 5μA with 50% polarization

~25 m horizontal & ~12 m vertical of injection line

- 2 bunchers
- electrostatic quads & dipoles
- long drift space req'd
- sources away from radiation & magnet field
- 300 KeV injection

INJECTION

- inject axially

inflector / deflector

- spiral electrodes ± 27kV
  deflect beam to line up with RF
- correction plates to vertically center ≈ 24 pairs
- trim coil Ø for radial & vertical
- radial flag (2 on first turn)

- 5nsec pulse length accepted
  ≈ 40° phase acceptance.
- 60% of beam injected

RF

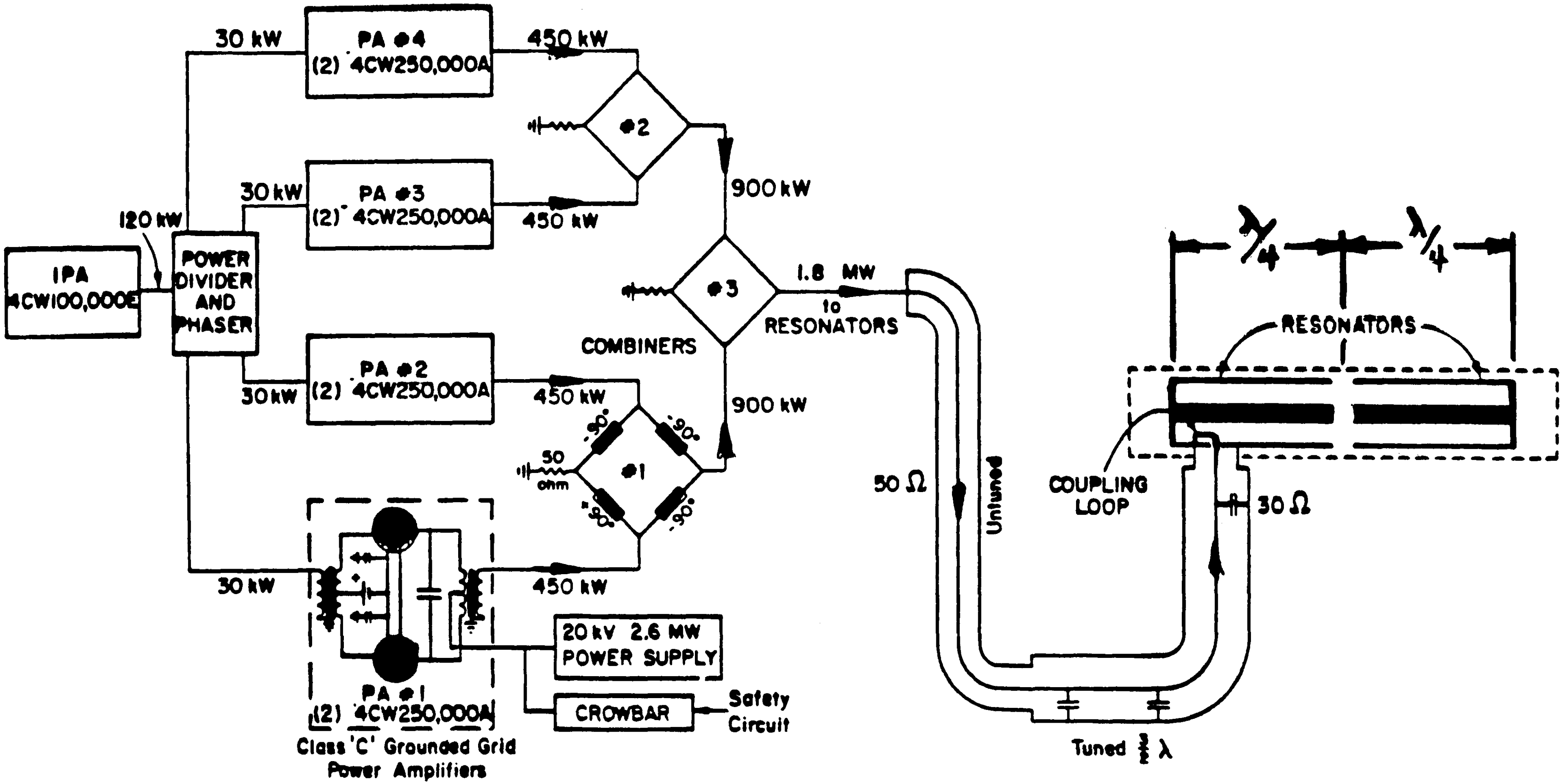
23.06 MHz - 5th harmonic
172 KV across DEEs -344 keV/turn
80 resonators - 1/4 wavelength
.76 m - wide / 3.05 m - long

frequency stable to 10^{-8}
- course control by ground arm adjustments
- fine control by cooling water pressure

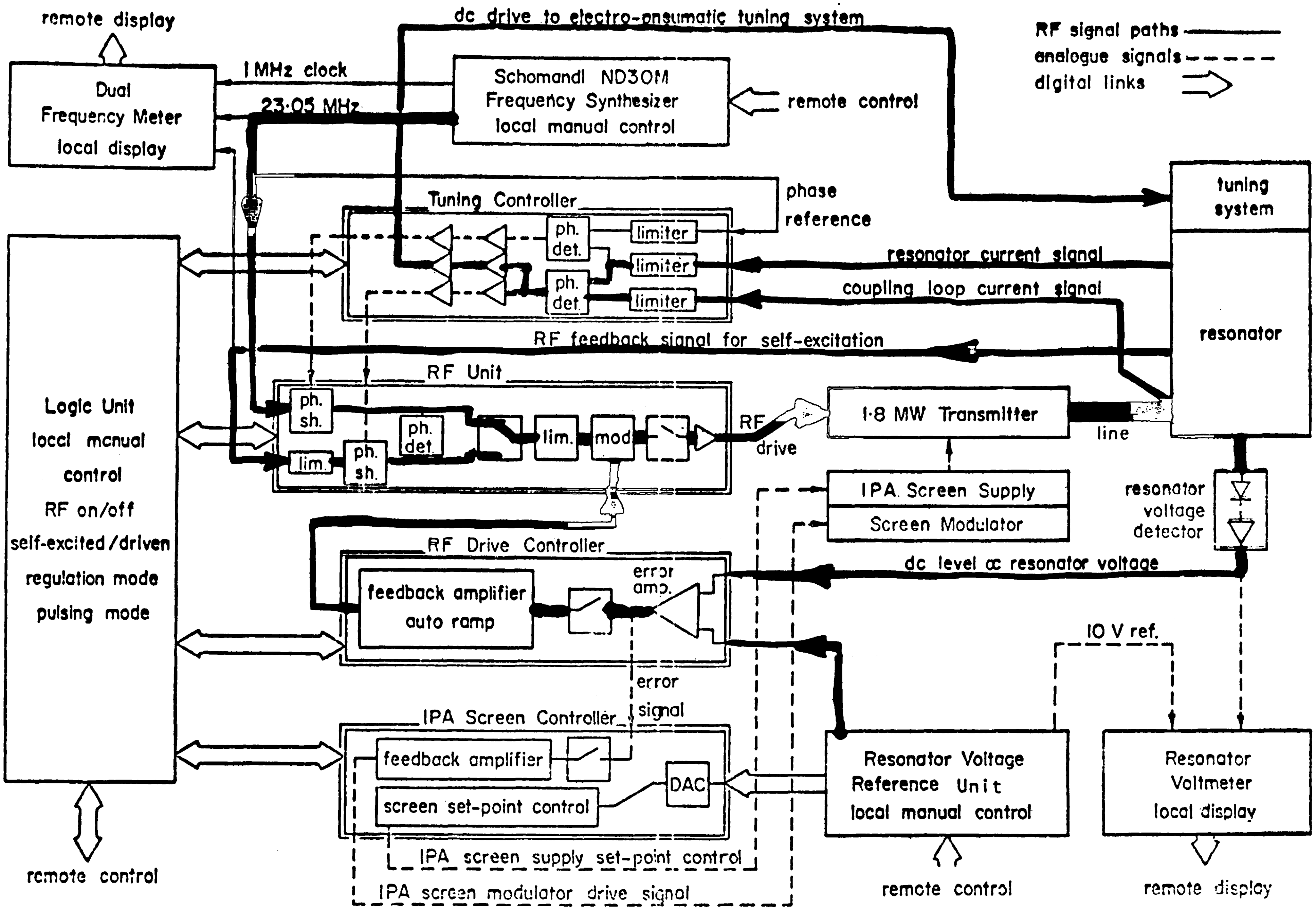
<u>major</u> developments
- 9 new resonators
- remote ground arm adjustments
- leakage probes
- RF design with 1:10 model

results - raise voltage
- reduce leakage
- stable & lower temperatures
- stable frequency

<u>**Problems**</u>
- complete RF dev
- change center region
- RF power amps & X line



Block diagram of TRIUMF RF system high-power components.



SIMPLIFIED BLOCK DIAGRAM OF THE TRIUMF RF SYSTEM

MAIN MAGNET

- 6 sectors 680 T each
- 5.6 KG at pole tip
- ≈ 17,000 Amps / regulation ± 0.7 ppm
  - feedback. NMR
    voltage
    current
    magnet field (TC54)

- 55 pairs (top & bottom) trim coils
  for B_3 & Br
- 13 sets of harmonic coils
- elevating system raise lid 1.2 m
  - 12 pairs of syncronized jack screws
  - ≈ 100 T/pair
  - ≈ 40 min rise time

major developments
- main magnet stability
- rebuild elevating system

major problems
- main magnet passbank
- Main Mag. ps cooling
- elevating system controls
- T & H current limits

DIAGNOSTICS

-3 high energy probe (>70 MeV)
- 2 low energy
} vertical centering
beam width
beam density
radial pos'n
- 1μA limit

- 2 centering probes

- 4 slits - MERO ($\frac{\Delta E}{E} < 10^{-3}$)
- 10μA max

* - 2 radial flags - 1st turn
* - vertical flag
- current readback
+ backup TCs
} reduce spills
clean up halo

- 6 pop in probes - transmission
- 10μA max
- 1st PIP water cooled
- 50μA max

* - 4 spill monitors & TC backup
- beam intentionally scrapped & dumped Cu beamstops
- air ion chamber backup

* - low energy beamstop - TC

-2 periscopes

* USED ON LINE FOR HIGH CURRENTS

VACUUM

$\approx 4 \times 10^{-8}$ torr
(5×10^{-9} torr with RF off)

- tank 17m dia x .5m high
  - supported by 644 3.8cm dia tie rods & center post

- Phillips B20 cyrogenerator cools two cyropanels (20° & 80°)
  - 10^6 l/sec - H_2O
  - 6×10^4 l/sec - Air

- 4 cyropumps . 1.5×10^4 l/sec - H_2

- min 24 hrs from lid down to RF conditioning (bakeout req'd)

MAJOR DEVELOPMENTS

- removal of DPs
- B20 rebuild

MAJOR PROBLEMS

- B20s no longer in production
- tank seal

VAULT ACTIVITY

- major component Na^{24} in CONCRETE
  - 48 hrs req'd to reach 20%
  - 400 mR/hr on centerpost
  - 400 R/hr on dumps

  ] 6 weeks cooldown
- 20 man Rem / shutdown

≈ 20 persons at shutdown limit - 300 mR

REMOTE HANDLING - 10 people

- cyclotron, beamlines & targets
- service bridge with special trolleys
  - radiation surveys
  - cleanup
  - video inspections
  - remove/install resonators, probes, AES
  - shadow shields

MAJOR DEVELOPMENTS

- remote console
- new components
- hole cutting & welding

MAJOR PROBLEMS

- location
- non standardization

EXTRACTION

- trivial $H^- \Rightarrow 2e^- + p^+$

Ex1 - 5 foils/cartridge
  - 0.001" pyrolytic graphite edge supported
  - 2 weeks / foil
  - current readback
  - 150μA max

Ex4 - carrosel with 5 foils
  i.e. reusable foils

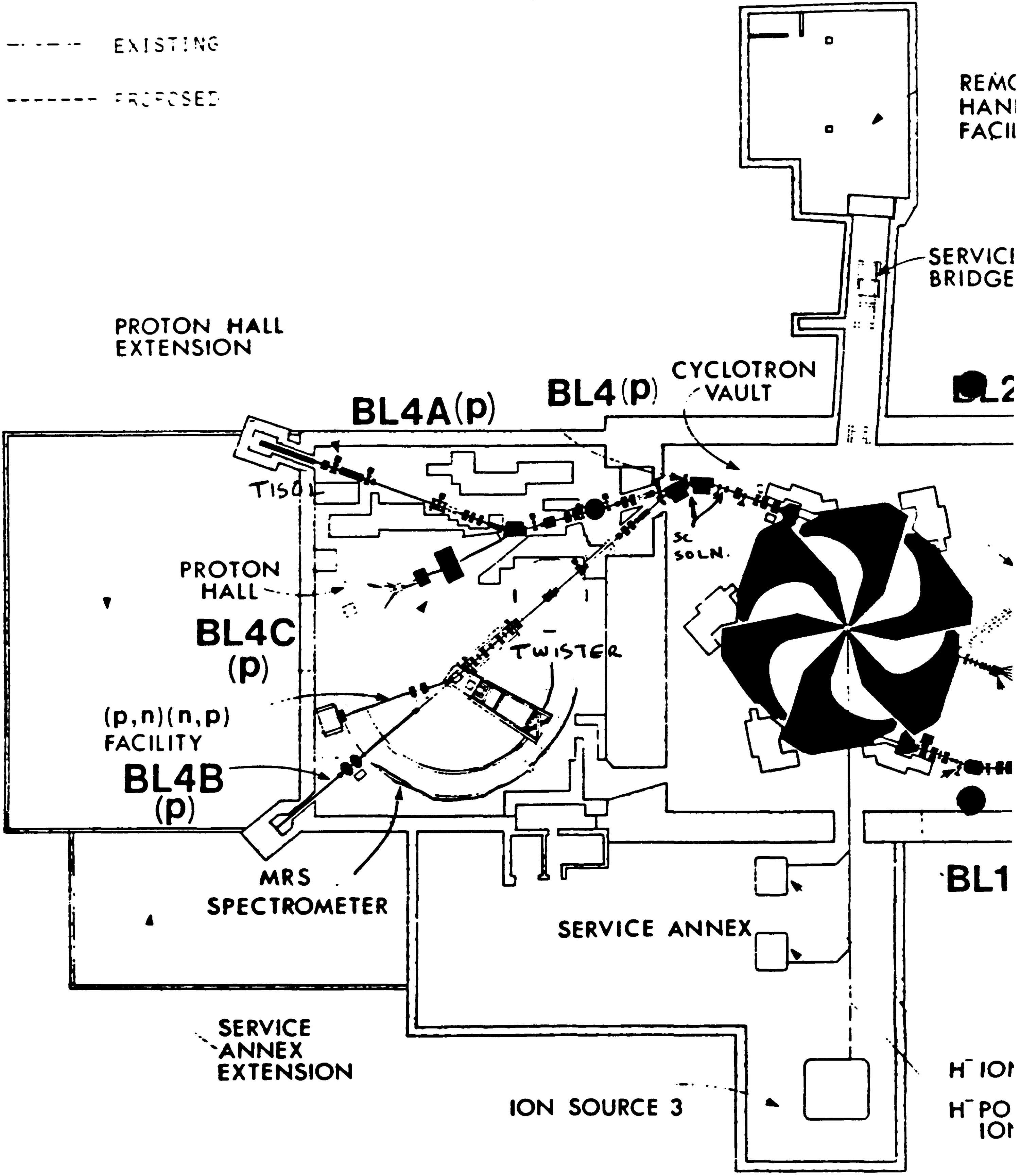
Ex1 & 4 - independant L, R, Z motion
  - any pos'n from 180-520 MeV

Ex2c - 70-110 MeV
  - 4 foils fixed in R with Z & L coupled

major development
- Ex4 carrosel
- Ex1 foil life time

major problems
- thermal damage from beam
- no current readback on Ex4
- Ex2C's <u>fixed</u> foils

diagnostics - polarimeters in 4A & B
- hall probes in quads
- NMR in dipoles



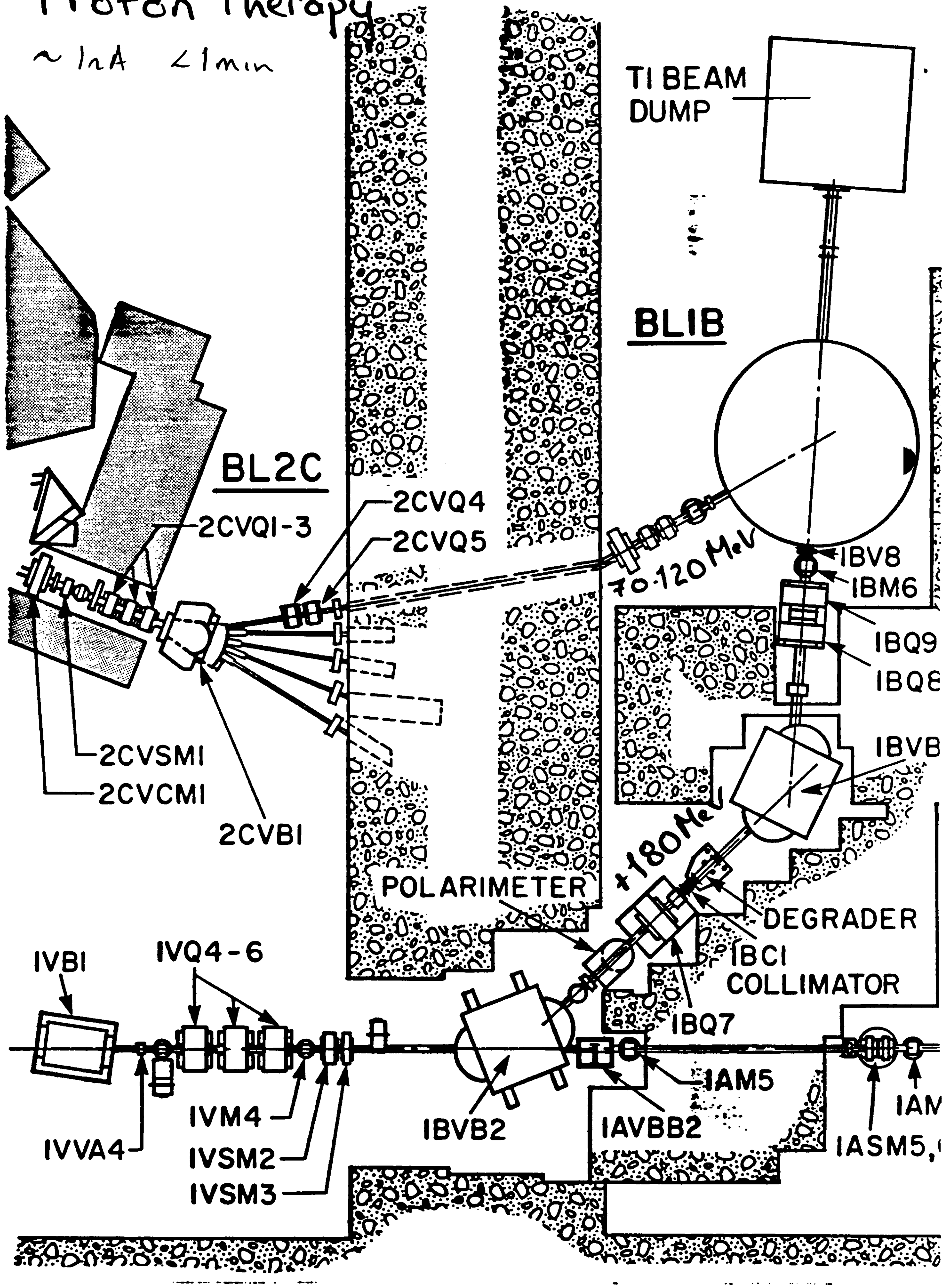
2C - 70 - 110 MeV / 20 μA
- radioisotope production
    - N^{24} for TISOL from STF
    - fast neutrons for BCCCRF
- requires controls upgrade

1B - 180 - 520 MeV
- subscribed ≈ 1/2 $\vec{p}$ run

1B & 2C - proton therapy fesability

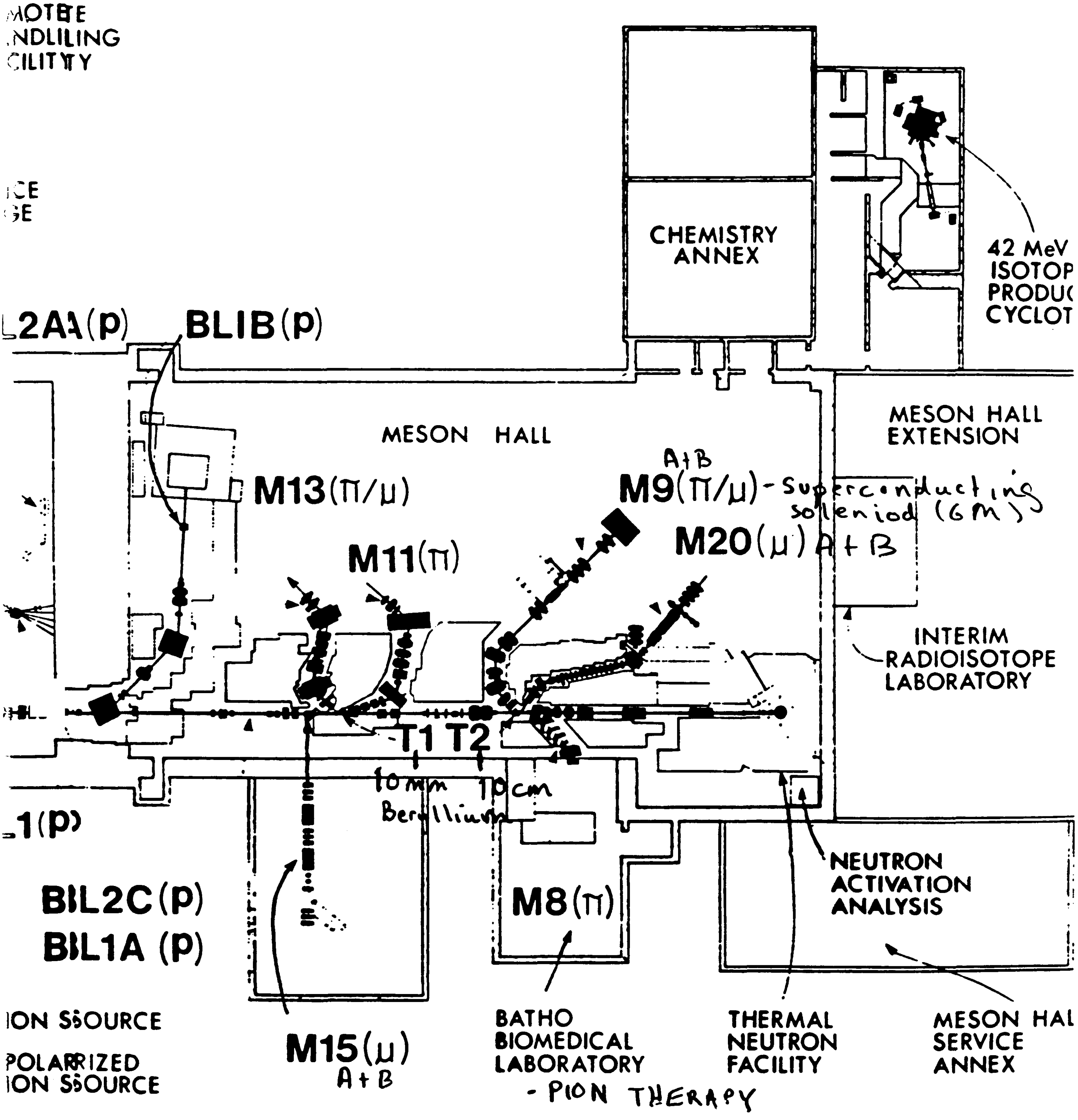
Proton Therapy

~1nA <1min



high current diagnostics

- Ex1, torriod, capacitive probe
- SEM
- TCs
- BSM



A+B

- superconducting solleniod (6M)

A+B

10mm

10cm

Beryllium

A+B

- PION THERAPY

MAJOR PROJECTS

IN CYCLOTRON

RF BOOSTER (4th harmonic)
- 2 energy gain booster (600 keV/turn)
- at 450 MeV
- reduce E-M stripping

OPTICALLY PUMPED POLARIZED ION SOURCE
- 20 μA, >60% polarization

RF UPGRADE
- replace center region
- amp & transmission line upgrade
- ground arm controls
- diagnostics & 1:3 model

AES
- RFD & DCD
- 90% efficiency at 1 μA (100 μA cw,
- mag. channel

CYCLOTRON PERFORMANCE

≈ 85% - scheduled hours
- production (μA-hrs)

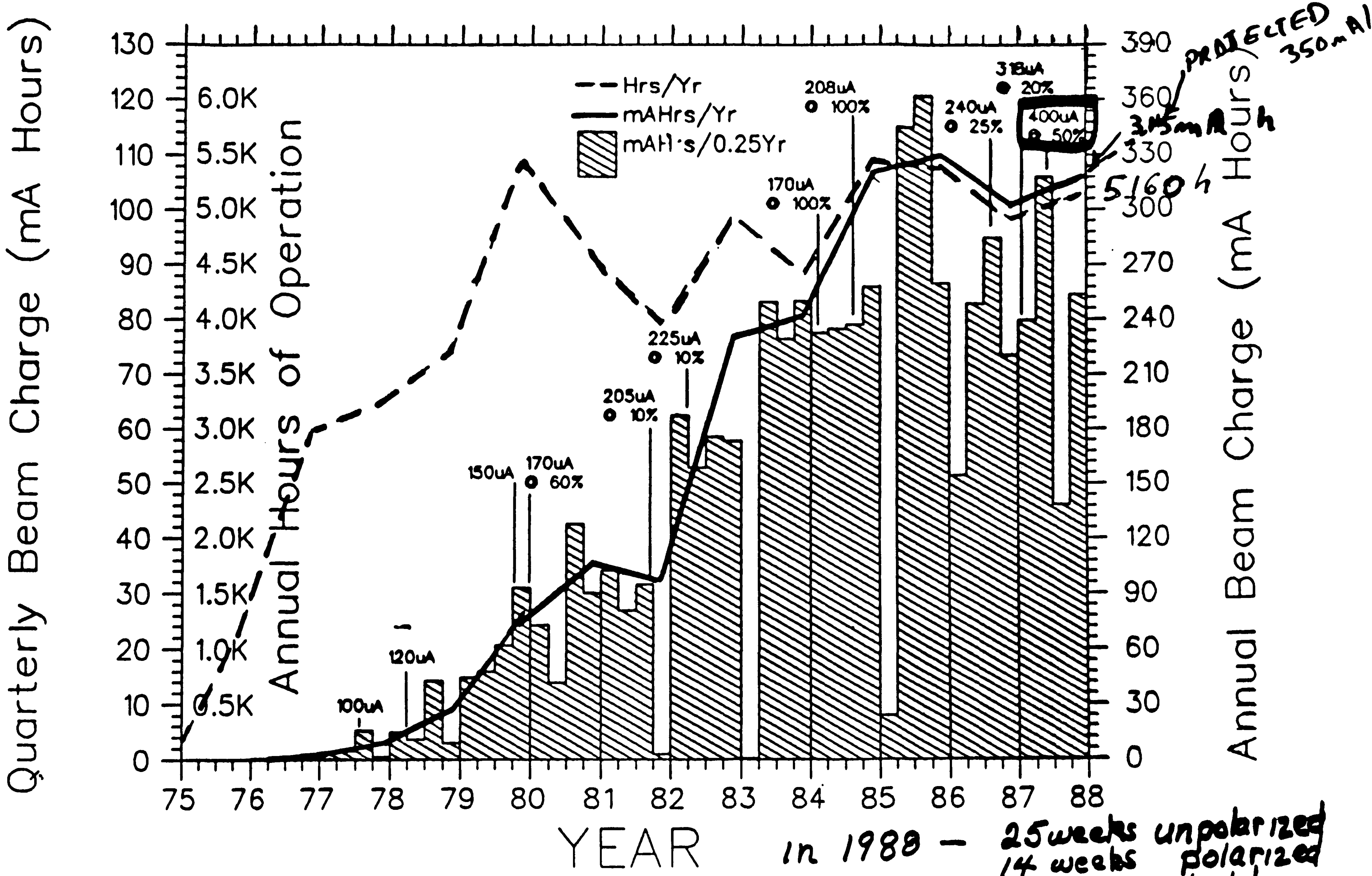
* 310,000 μA-hrs to date
projected ≈ 350,000 μA-hrs

schedule ≈ 26 weeks - high current
13 weeks - polarized
13 weeks - shutdown

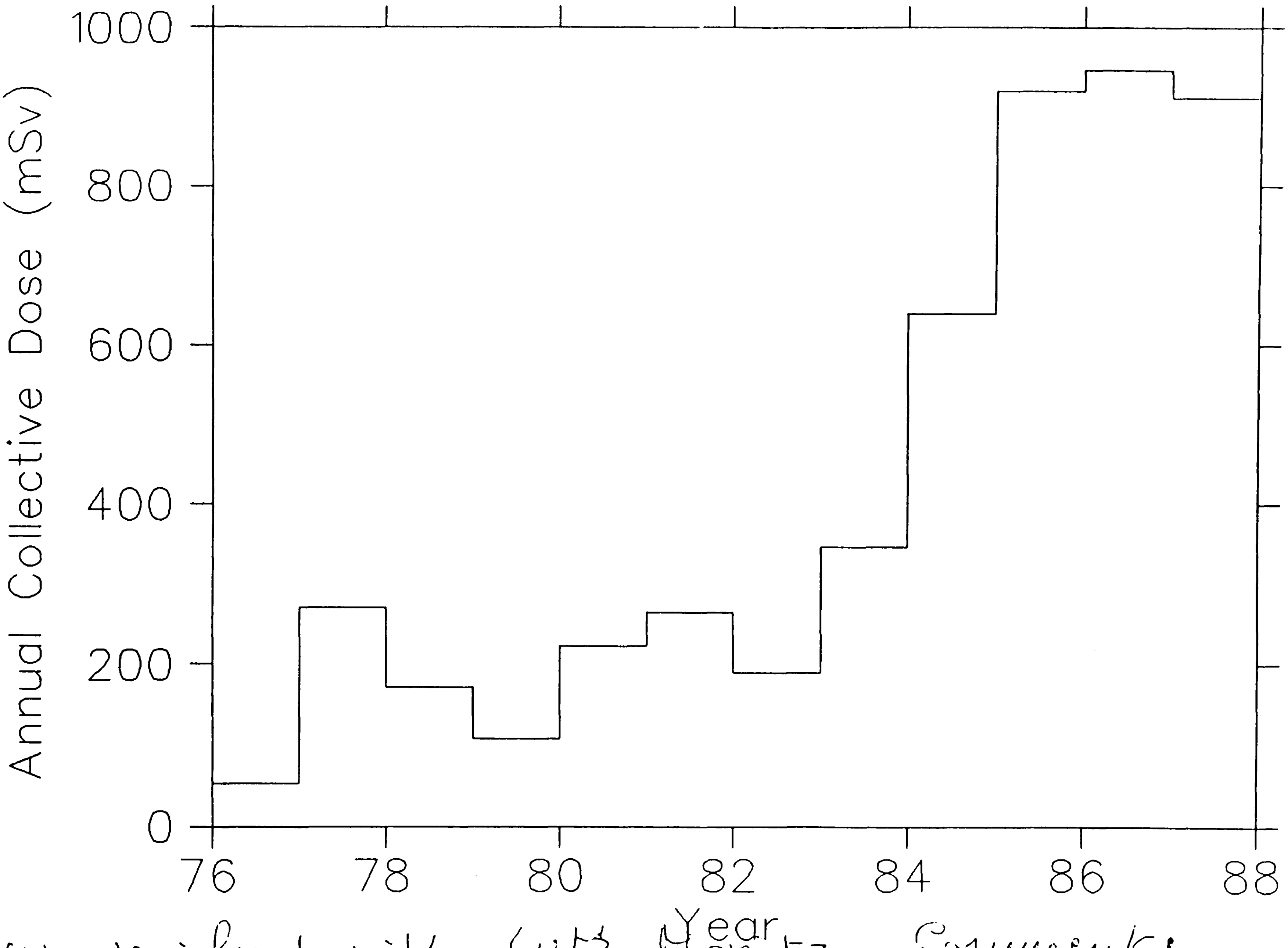
- spring & fall shutdown with polarized operation before for <u>cool</u> <u>down</u>

<u>weekly</u> - · < 12h maintenance
- 3 shifts maintenance every 3 wks
- 1 shift development

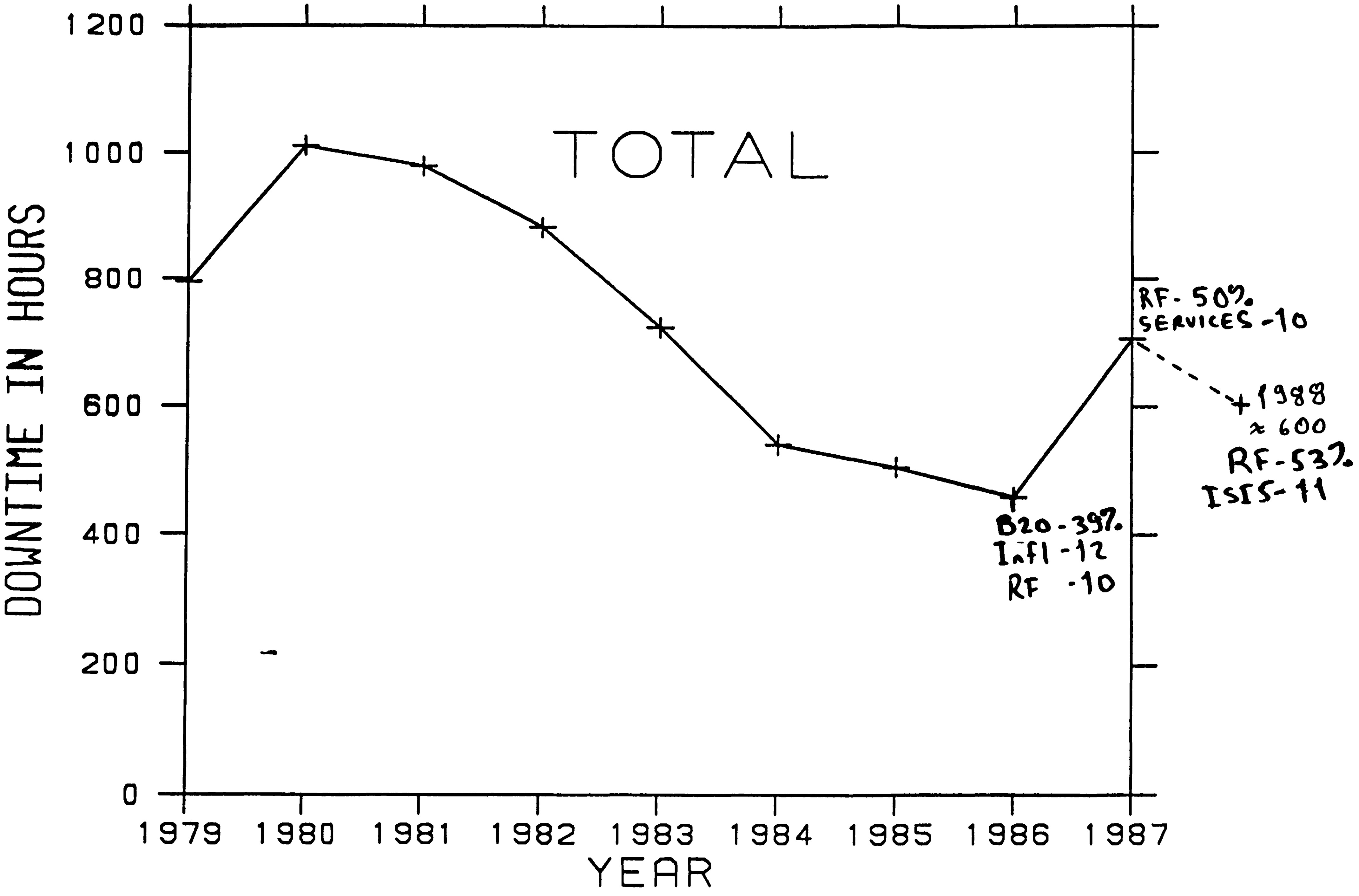
ANNUAL BEAM DELIVERY



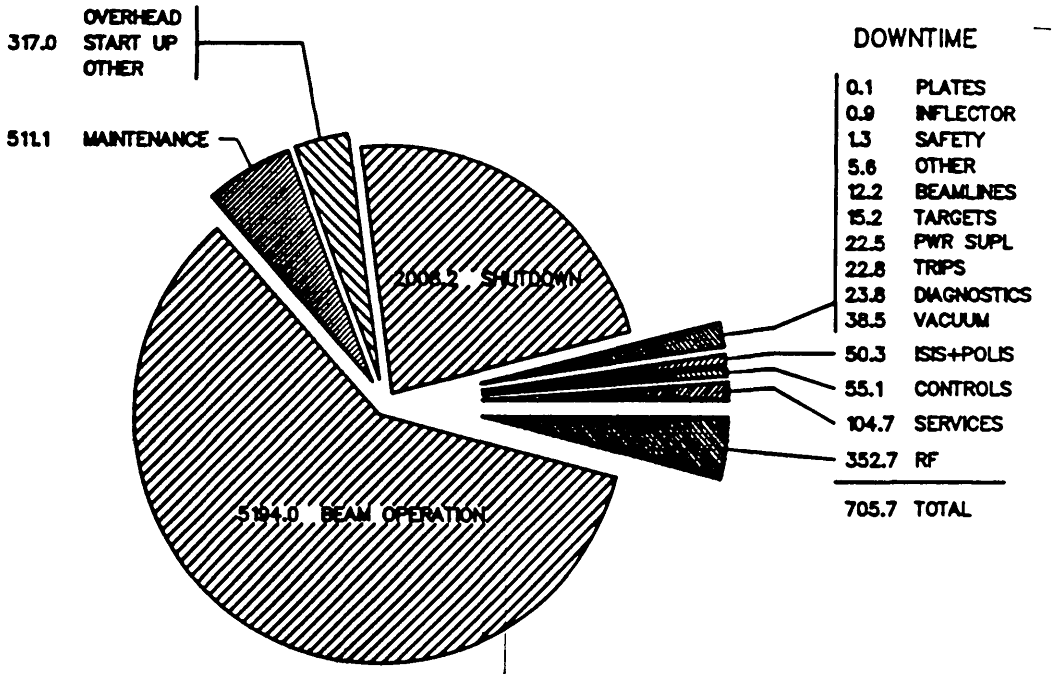
in 1988 — 25 weeks unpolarized
14 weeks polarized
13 weeks shutdown



numbers verified with Lutz Mon 13 – Comment:
The initial results of badge reading by RPB for 1987
were in error

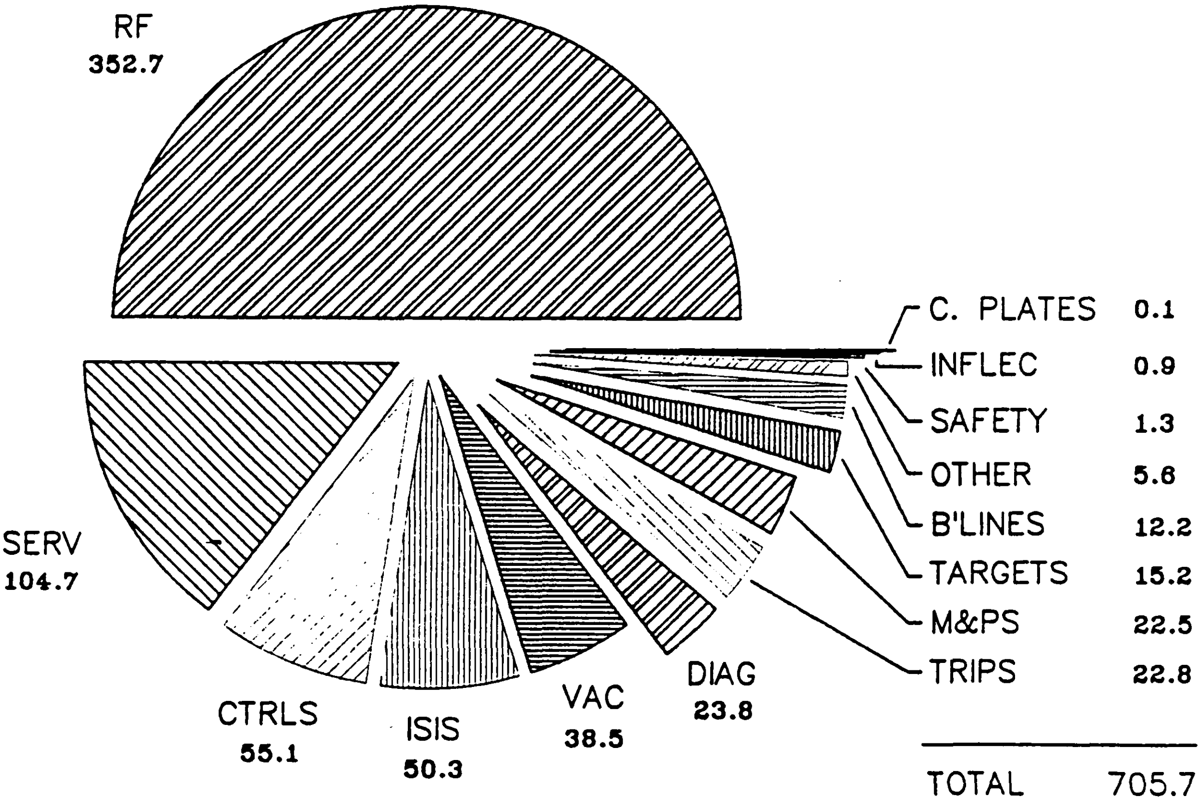

TOTAL
DOWNTIME IN HOURS
YEAR
0
200
400
600
800
1000
1200
1979
1980
1981
1982
1983
1984
1985
1986
1987
RF-50%
SERVICES -10
1988
≈ 600
RF-53%
ISIS-11
B20-39%
Infl -12
RF -10

HOURS OF OPERATION FOR 1987



DOWNTIME FOR 1987

(IN HOURS)



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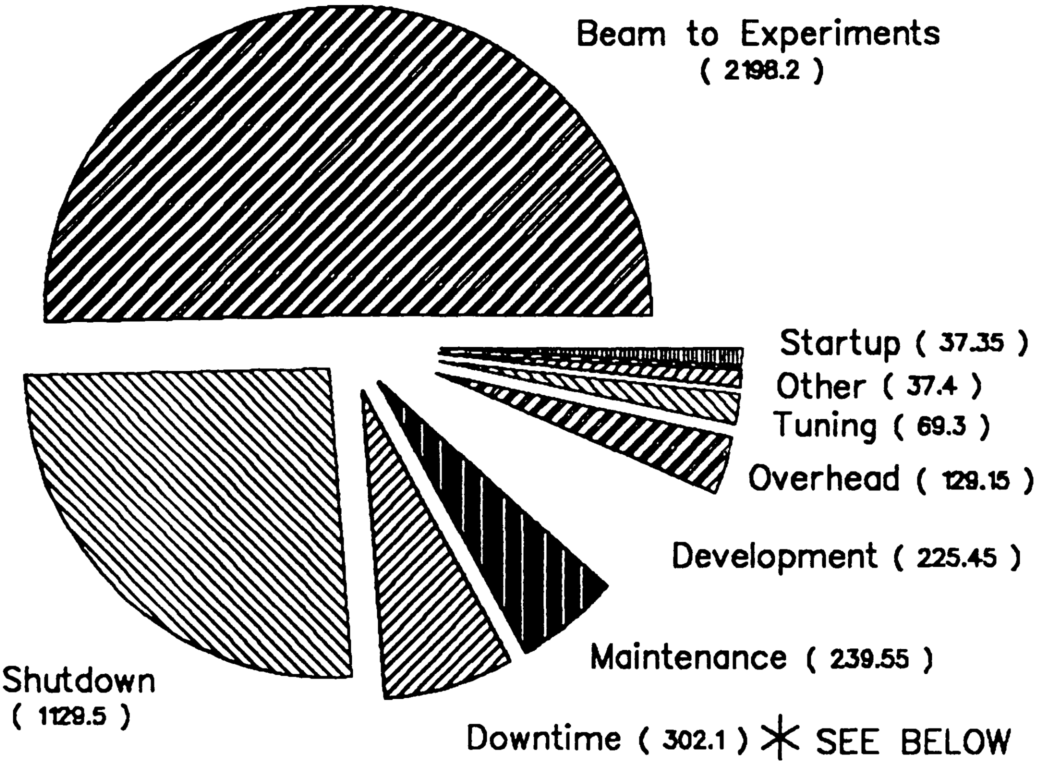
1ST-HALF 1988 OPERATING RECORD

(HOURS)



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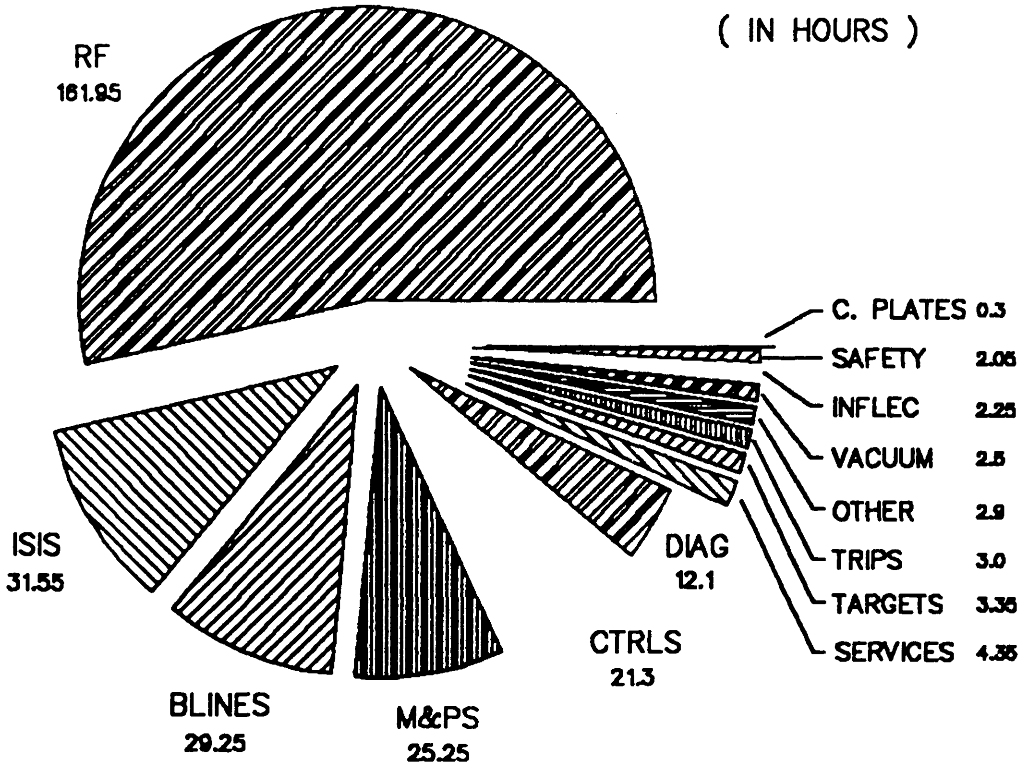
✳ DOWNTIME FOR 1ST HALF OF 1988

(IN HOURS)



DSK1:[OPS.BRCH.STATS]DOWNTIME_881HFPIE.DWG;7 17-JUL-88 08:28:00

MAJOR PROJECTS

EXPERIMENTAL FACILITIES

- super conducting muon channel
- second arm spectrometer
- cryogenic target development
- TISOL

APPLIED PROGRAM

- 30 MeV H^- cyclotron for AECL
  - 250 μA symataneous extraction
  - EBCO to build
  - 2 yr project
  - ≈ $10M CAN - turn key
- proton therapy -
  - 2C & 1B
  - ocular melanoma, AVM + other sites?

KAON FACTORY DEFINITION PHASE

- $11M CAN announced July,'88 < Provincial
  Fedral

- 1 yr to commit / 15 mth for report

Alan Astbury Project leader
- EW Blackmore Exp Fac
- M. Craddock Accel Design
- P. Kitching Science

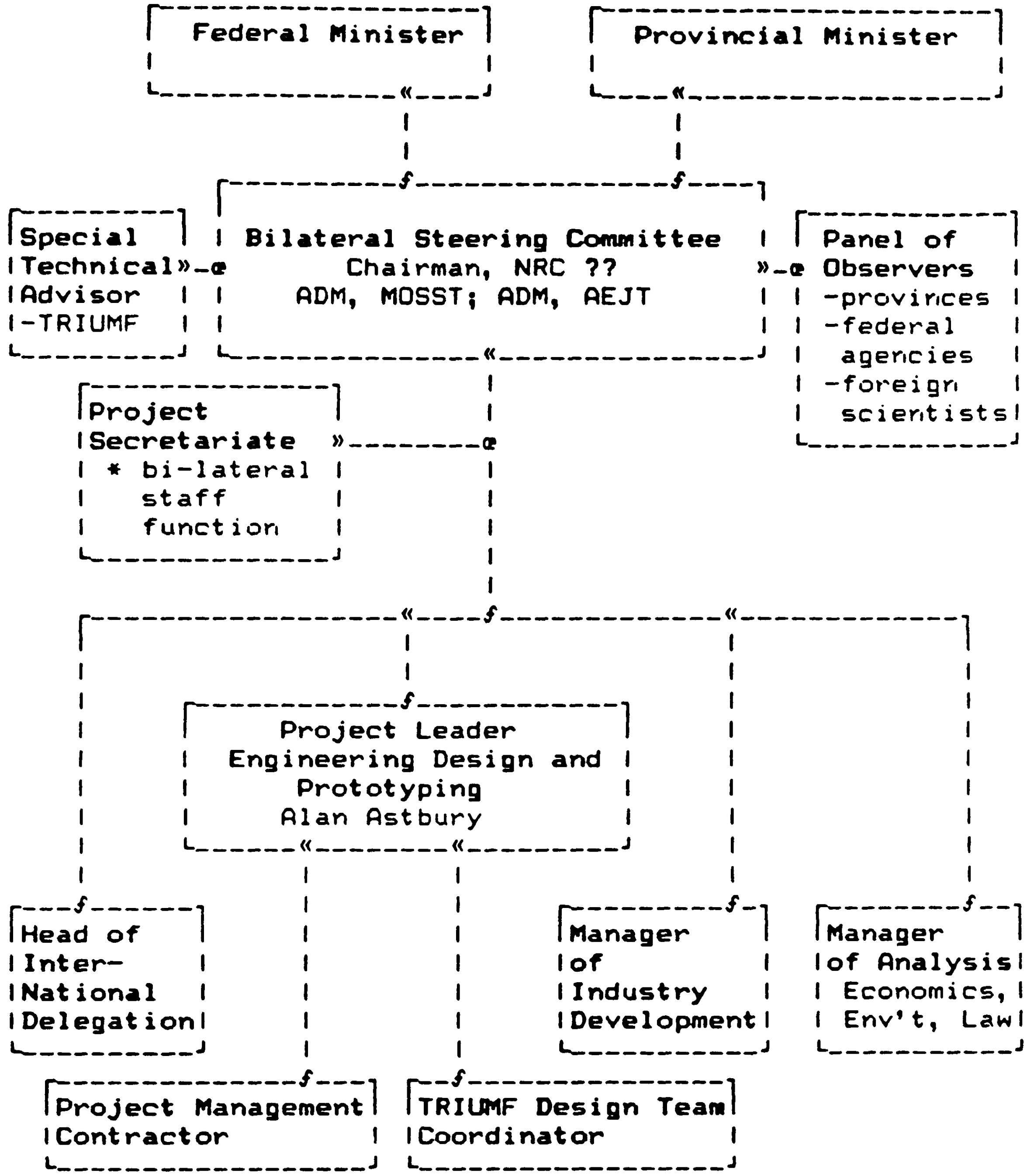
- engineering & design prototypes
  - dual freq power supplies
  - RF cavity
  - magnets
  - beam pipe

- industrial capabilities
  - spin offs

- foreign consultations
  - for scientific program

$100M can - USA
50 - Japan
30 - Germany
30 - Italy
30 - Others

≈ $240M



Project Definition Phase

MANAGEMENT STRUCTURE

Figure 1

Appendix 1

BUDGET SUMMARY
(Thousands)

1.	Engineering Design Project Management	$ 650
2.	Accelerator Design	$ 550
3.	RF Systems	$ 1,360
4.	Magnet Development	$ 890
5.	Power Supplies	$ 1,150
6.	Vacuum pipes & systems	$ 960
7.	Kicker Magnets	$ 420
8.	Cyclotron beam extraction	$ 900
9.	Shielding & safety	$ 200
10.	Targets	$ 180
11.	Control systems	$ 240
12.	Building design	$ 900
13.	Tunnel design	$ 760
14.	Service & power distribution	$ 420
15.	Industry development	$ 270?
16.	International negotiations	$ 200?
17.	Economic assessment	$ 100?
18.	Project Services	$ 550?
19.	Environmental Impact Study	$??
20.	Assessment of Legal Issues	$??
21.	Engineering Design Contingency	$ 200?
	TOTAL	$ 11,000

Notes:

1. Items 15 to 21 require final adjustment.

4.0 ACCELERATOR SYSTEM

4.1 Introduction

To accelerate the 100 μA proton beam from the TRIUMF cyclotron to 30 GeV, a chain of 5 fast-cycling synchrotrons and dc storage rings is proposed. 450 MeV H^- ions from TRIUMF are injected by stripping into the Accumulator ring. A 50 Hz Booster synchrotron then accelerates the proton pulse to 3 GeV, where the frequency swing is almost complete. In the main tunnel (170 m radius) are the Collector ring, which collects 5 Booster pulse trains, the 10 Hz Driver synchrotron and the dc Extender ring, where beam is stored for slow resonant extraction. The accelerator designs have various features, such as H^- stripping injection, high transition energy, and bucket-to-bucket beam transfers which will avoid or reduce beam loss. Dual frequency magnet power supplies provide a 3:1 rise:fall ratio, reducing the peak rf voltage requirements to 600 kV for the Booster (46–61 MHz) and 2400 kV in the Driver (61–63 MHz).

4.1.1 Main Accelerator and Injector

The specifications for the KAON Factory call for the accelerator to provide 100 μA proton beams at 30 GeV. This choice of energy satisfies the desire for intense fluxes of high-energy kaons as well as stopping kaons, antiprotons and neutrinos. The 100 μA current (6×10^{14} protons/s) is chosen to provide a significant (80-fold) improvement over beams which have been available in this energy region ($\leq 8 \times 10^{12}$ p/s—see Table 4.1.I), and o make possible experiments which have hitherto been impractical.

In light of these specifications the KAON Factory accelerator system has been based on a rapid-cycling (10 Hz) 30 GeV proton synchrotron. At lower energies other types of accelerator could be considered, but above about 15 GeV a synchrotron is the only practical choice. The fast cycling rate keeps the charge per pulse down to $N = 10\,\mu C$ (6×10^{13} protons) and restricts the time available for instabilities to develop. The circulating current, a measure of the likelihood of beam instability, is 2.8 A, not quite double the 1.5 A at which the CERN PS operates and only 20% higher than that delivered in the Argonne IPNS. Intensity-dependent effects, such as tune shift, instabilities and beam loading, should therefore lie in a well-understood region.

Table 4.1.I

Some High Intensity Proton Synchrotrons

Name	Energy (GeV)	Duty Factor (%)	Protons per pulse ($\times 10^{13}$)	Circulating Current (A)	Rep. Rate (Hz)	Average Current (μA)
FNAL Booster	8	0.0024	0.3	0.3	15	7.2
KEK PS	12	18	0.4	0.6	0.6	0.32
CERN PS	26	0.00014	2	1.5	1.67	2.1
	26	50*	2	1.5	1.38	1.2
BNL AGS	28.5	0.00018	1.64	1.0	0.67	1.8
	28.5	50	1.2	0.7	0.38	0.73
ANL IPNS	0.5	0.00057	0.17	2.3	30	8
RAL SNS†	(0.8)	0.0032	(2.5)	(6.1)	50	(200)
TRIUMF K Factory	30	100/0.0036	6	2.8	10	100
SIN II	30	100/0.011	1.2	0.4	25	50
LAMPF II	7	0.0053	1.75	2.5	48	136
	45	50	7	2.5	3	34

* No longer available for experiments

† At present being commissioned

Table 4.1.II

Synchrotron Design Parameters

	Booster	**Driver**
Energy	3 GeV	30 GeV
Radius	$4.5R_T = 34.11$ m	$22.5R_T = 170.55$ m
Current	$100\,\mu A = 6\times10^{14}$/s	$100\mu A = 6\times10^{14}$/s
Repetition Rate	50 Hz	10 Hz
Charge/Pulse	$2\,\mu C = 1.2\times10^{13}$ppp	$10\,\mu C = 6\times10^{13}$ppp
No. Superperiods	6	12
Lattice Focusing	FODO	FODO
Structure Bending	OBOBBOBO	BBBBBOBO
No. Focusing Cells	24	48
Maximum $\beta_x \times \beta_y$	15.8 m × 15.2 m	38.1 m × 37.5 m
Dispersion η_{max}	4.0 m	9.09 m
Transition $\gamma_t = 1/\sqrt{\eta}$	9.2	∞
Tunes $\nu_x \times \nu_y$	5.23 × 6.22	11.22 × 12.18
Space Charge $\Delta\nu_y$	−0.15	−0.09
Emittances $\epsilon_x \times \epsilon_y$	$139\pi \times 62\pi(\mu m)$	$37\pi \times 16\pi(\mu m)$
at Injection ϵ_{long}	0.064 eV-s	0.192 eV-s
Harmonic	45	225
Radiofrequency	46.1 → 61.1 MHz	61.1 → 62.9 MHz
Energy gain/turn	210 keV	2000 keV
Maximum RF Voltage	576 kV	2400 kV
RF cavities	12 × 50 kV	18 × 135 kV

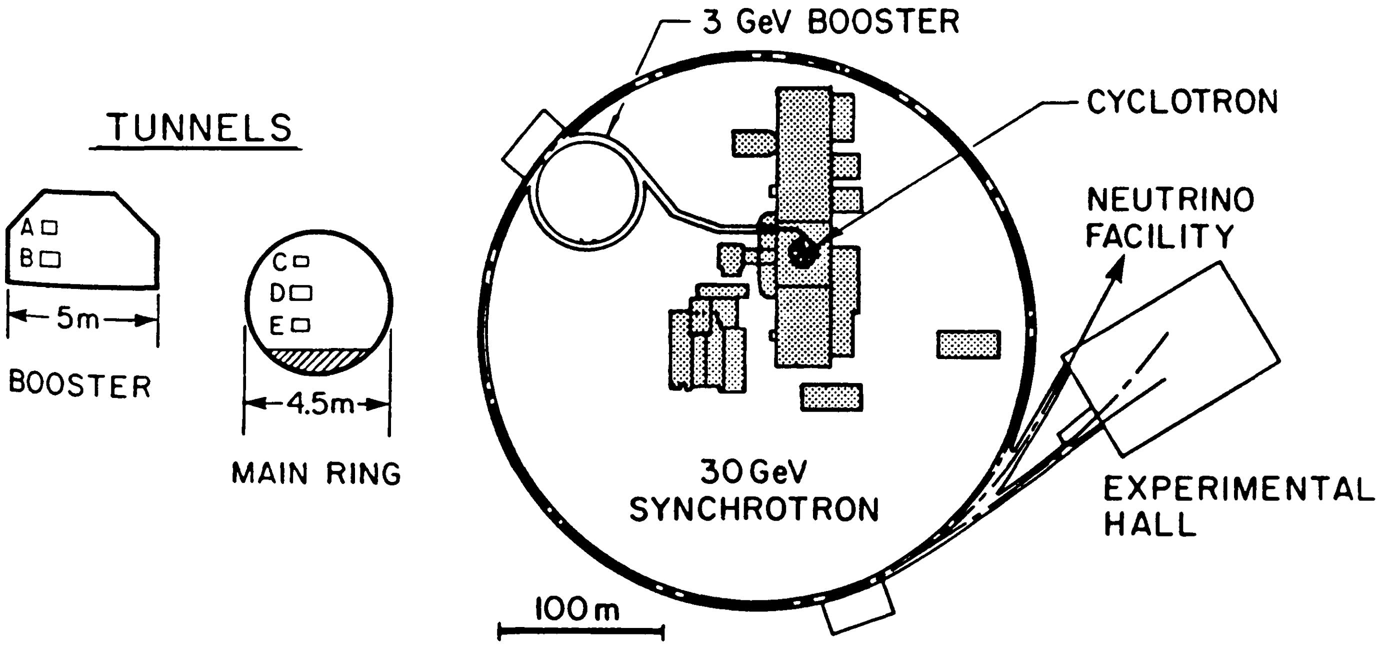


Figure 4.1.A. Proposed layout of the accelerators and cross sections through the tunnels.

To allow time for injection or for slow beam spill for counter experiments, it is conventional to "flat-bottom" or "flat-top" the magnet cycle of a synchrotron. In the present case, however, starting with 100 μA beams from the TRIUMF cyclotron, such a procedure would result in average beam currents at 30 GeV of only 50 μA for neutrino production (fast extraction) or 33 μA for counter experiments (slow extraction). Instead, it is proposed to follow each of the three accelerators by a relatively inexpensive dc storage ring, so that the TRIUMF cyclotron would be followed by a chain of 5 rings, as follows:

A	Accumulator	: accumulates cw 440 MeV beam from the cyclotron over 20 ms periods
B	Booster	: 50 Hz synchrotron; accelerates beam to 3 GeV
C	Collector	: collects 5 Booster pulses and manipulates beam longitudinal emittance
D	Driver	: main 10 Hz synchrotron; accelerates beam to 30 GeV
E	Extender	: 30 GeV storage ring for slow extraction.

As can be seen from the energy-time plot (Fig. 4.1.B) this arrangement allows the cyclotron output to be accepted without a break, and the B and D rings to run continuous acceleration cycles; as a result the full 100 μA from the cyclotron can be accelerated to 30 GeV for either fast or slow extraction.

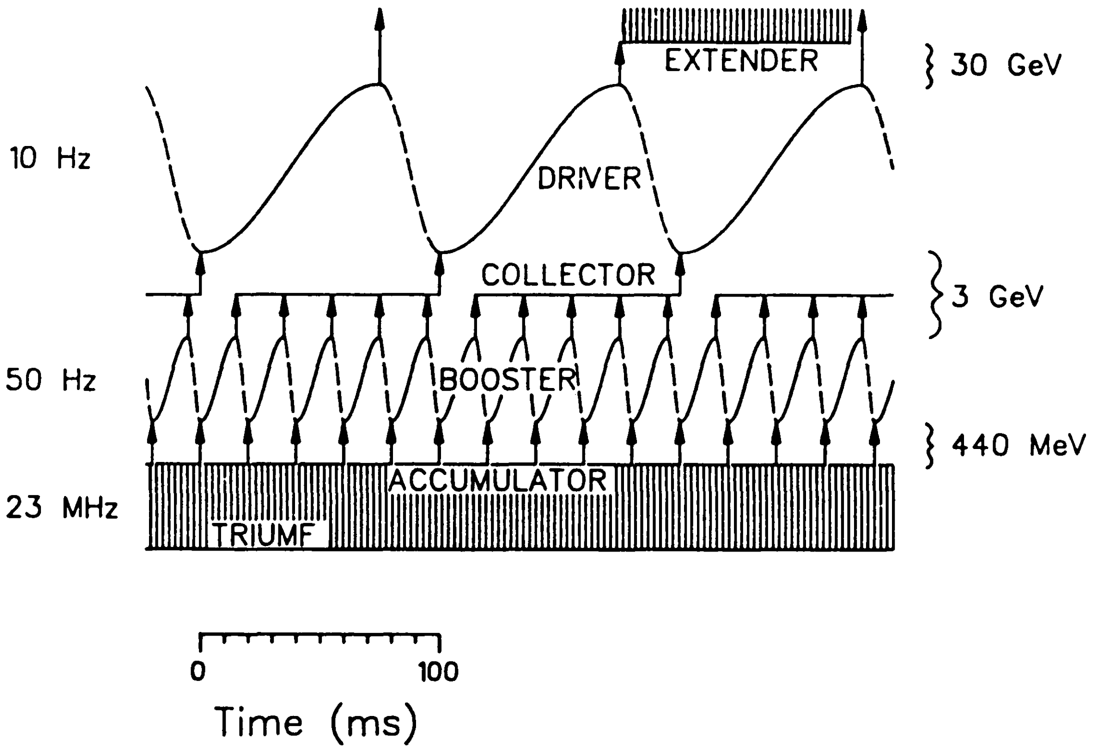


Figure 4.1.B. Energy-time plot showing the progress of the beam through the five rings.

The Accumulator is mounted directly above the Booster in the small tunnel, and the Collector and Extender rings above and below the Driver in the main tunnel (Fig. 4.1.A). Figure 4.1.C shows schematically the arrangements for beam transfer between rings and the location of rf stations. Identical lattices and tunes are used for the rings in each tunnel. This is a natural choice providing structural simplicity, similar magnet apertures and straightforward matching for beam transfer. The practicality of multi-ring designs has been thoroughly demonstrated at the high-energy accelerator laboratories, and new projects such as HERA, LEP and SSC use ever-larger numbers of stages.

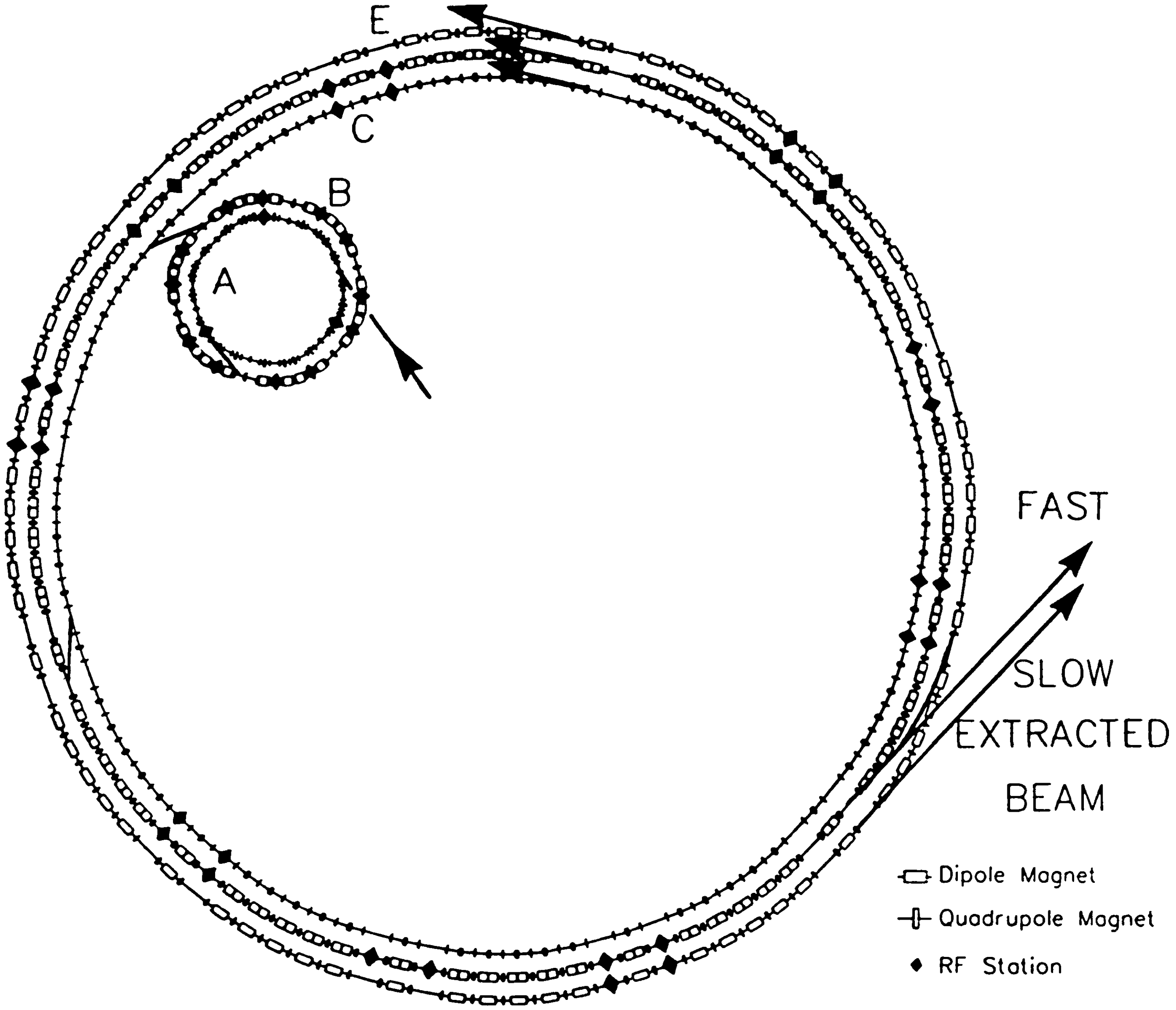


Figure 4.1.C. Arrangement of rf cavities and beam transfer lines (schematic).

The need for the Accumulator ring would of course disappear if, instead of the TRIUMF cyclotron, a high-intensity pulsed H$^-$ linac were used as injector. The cost of such a machine, rivalling LAMPF in performance, would, however, be formidable, over $50 million even for 440 MeV, based on recent SSC estimates. By comparison, the cost of the Accumulator is estimated below (Chapter 7) to be about $5 million.

The Collector ring could also be dispensed with, as in the LAMPF II proposal, although this option is not tied to the choice of a linac as injector. Whatever the injector, the lack of a C ring necessitates flatbottoming the main synchrotron (D) magnet cycle for collection of the Booster pulses. Maintaining the same final average current (100 μA) then requires increasing either the repetition rate or the number of protons/pulse (and hence the magnet apertures) for both B and D rings. The costs involved in such changes would considerably exceed any savings achieved by eliminating the C ring, the cost of which is $13 million.

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