High-Power Accelerator Development in ATW Roadmap

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for
Accelerator Technical Working Group

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Outline

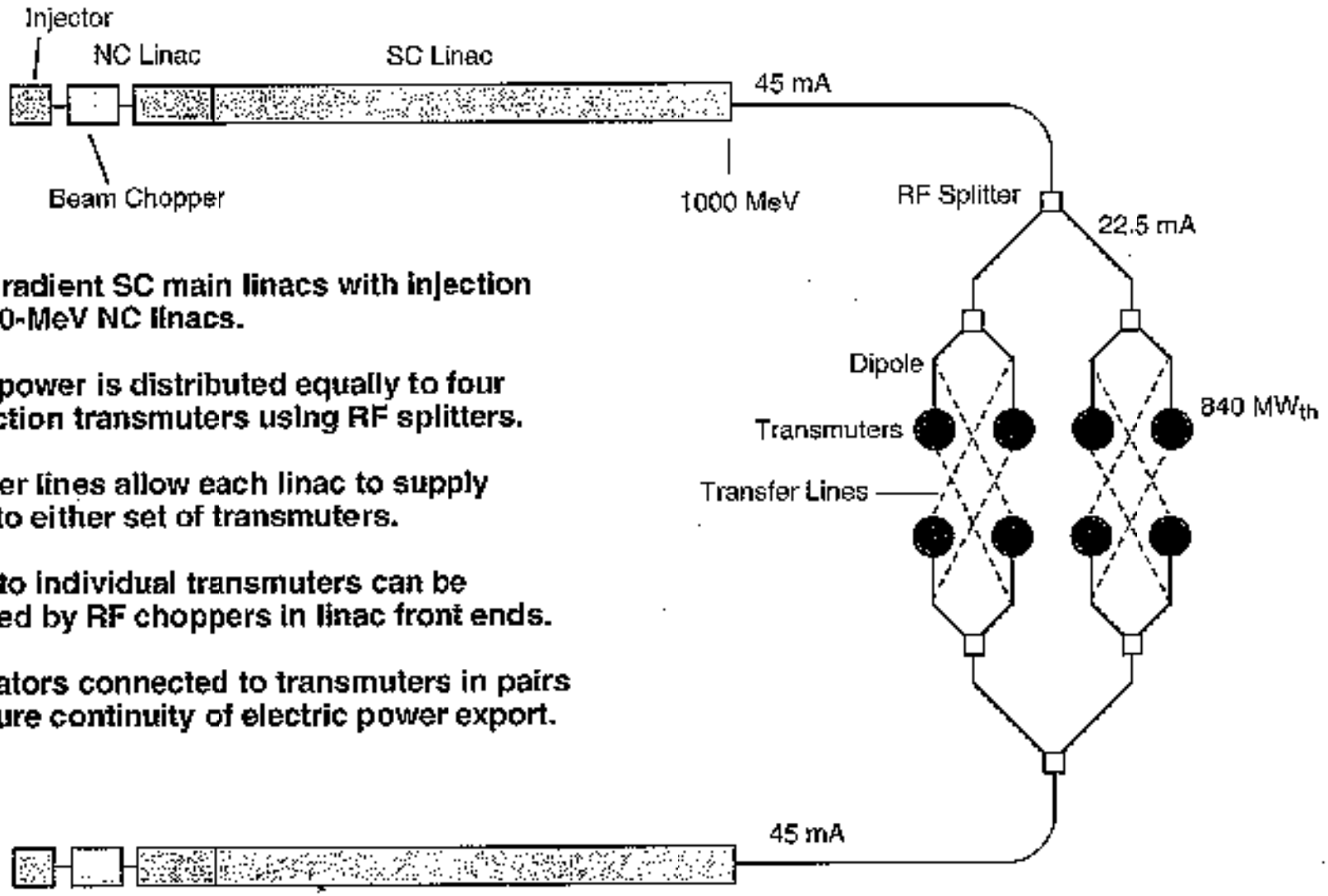
- Roadmap for ATW linac R&D
- Technology base from APT
- Linac design for ATW DEMO and plant
- Issues, schedule, costs

Design Objectives for ATW Accelerator

A linac designed to drive an ATW facility should have:

- Very high electrical efficiency (ac-power to beam-power)
- Minimum capital and operating costs
- Very high beam reliability
- Minimum spatial footprint (short length)
- Beam distribution to multiple transmuters
- High availability and operational flexibility

Accelerator Configuration for ATW Plant



- High-gradient SC main linacs with injection from 10-MeV NC linacs.
- Beam power is distributed equally to four production transmuters using RF splitters.
- Transfer lines allow each linac to supply beam to either set of transmuters.
- Beam to individual transmuters can be inhibited by RF choppers in linac front ends.
- Generators connected to transmuters in pairs to assure continuity of electric power export.

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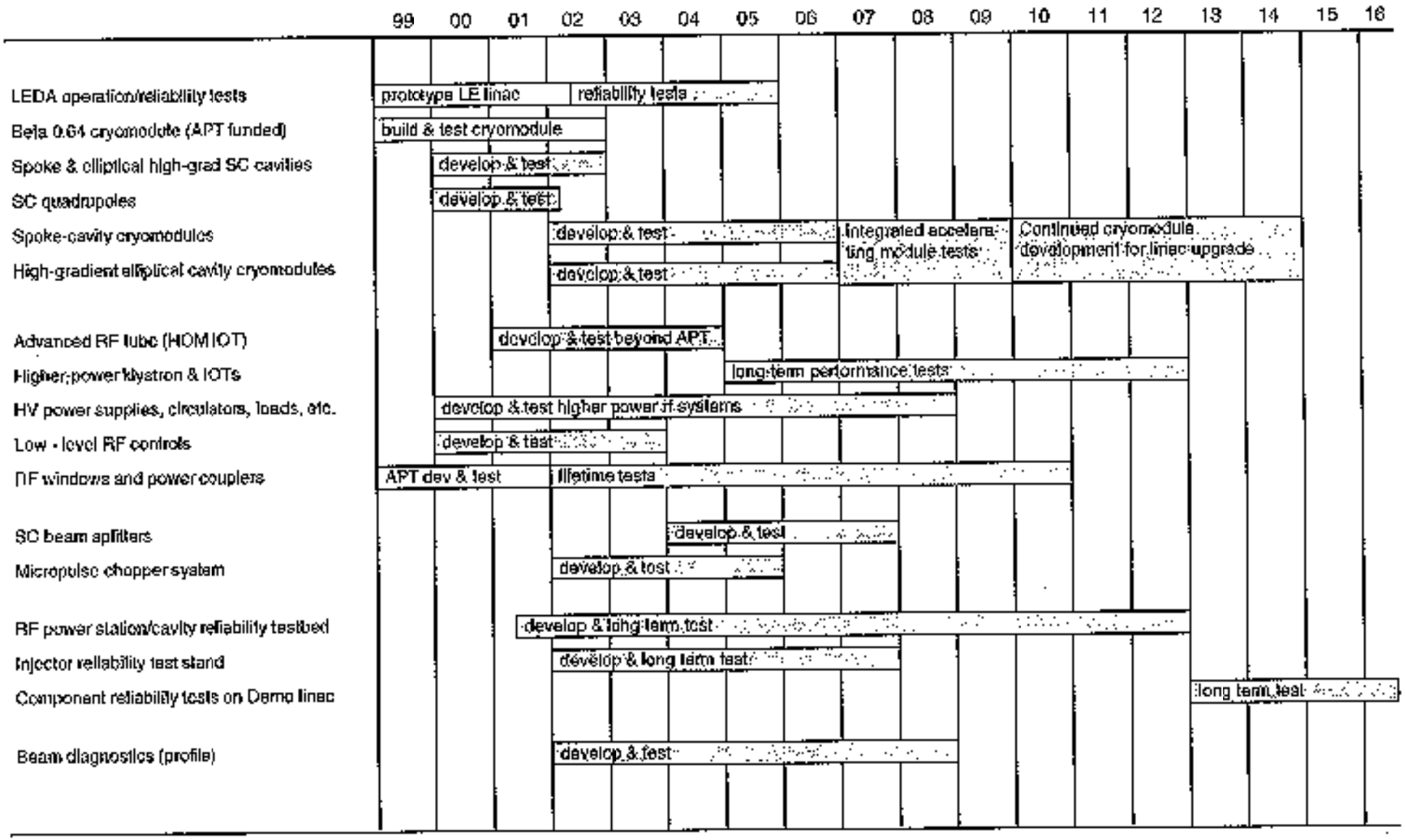
ATW Accelerator R&D Roadmap



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SC/NC Linac for ATW Provides Optimum Performance by Exploiting Advantages of Each Technology

- **NC linac for low energy**
  - short-period magnetic focusing lattice
  - smoothly varying accelerating and focusing parameters
  - excellent emittance control of high-current beam
  - minimal generation of beam halo

- **SC linac for medium and high energies**
  - elimination of cavity RF losses provides high power efficiency
  - very large apertures greatly reduce beam-loss concerns
  - short cavities provide wide velocity bandwidth
  - gradient adjustability & independent RF drives allow operational flexibility in providing needed beam power at target
  - large apertures and retunability provide tolerance to wide range of error and fault conditions

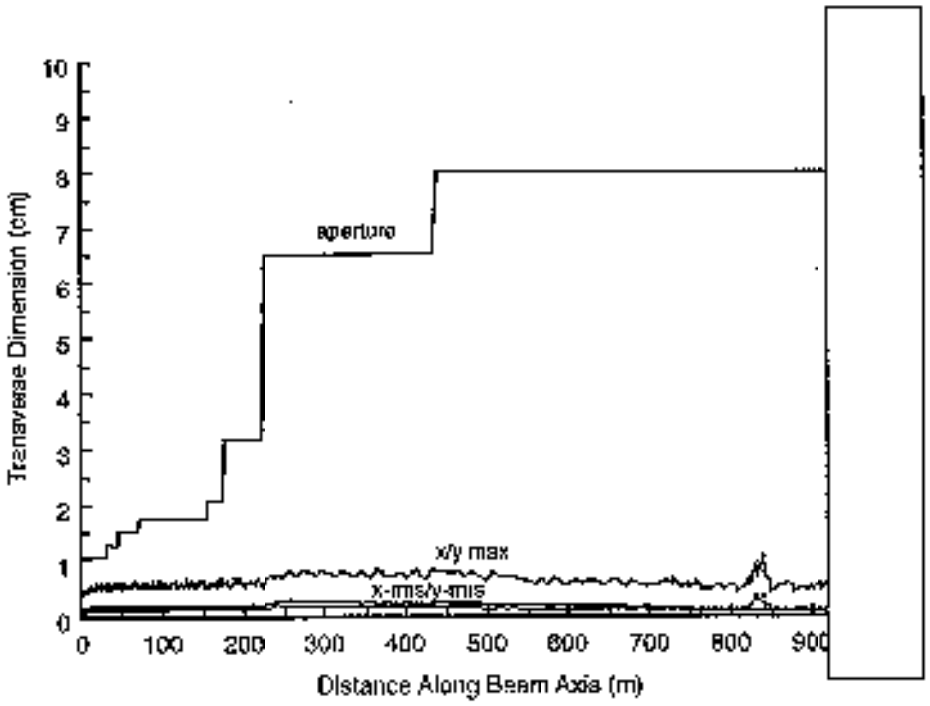
ATW Accelerator Design Can Start from Platform Provided by APT Preliminary Design

Integrated design of 1-GeV, 100-mA CW proton linac

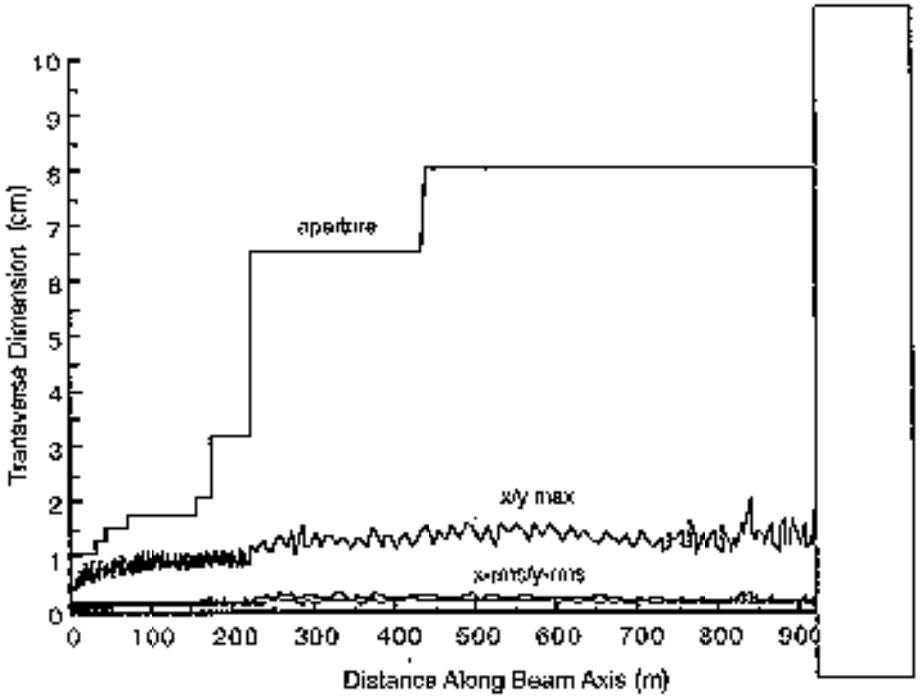
- High efficiency system (NC/SC linac; 80% superconducting).
- Beam dynamics worked out for minimum halo production and ultra-low beam loss.
- RF-power/accelerating-unit architecture provides high availability and operational flexibility at lowest cost.
- CCDTL structure designed & modeled as solution for NC linac.
- Multi-cell elliptical cavities and cryomodules designed for SC linac.

Beam Simulations from 6.7 MeV to 1030 MeV in APT Linac Confirm Large Aperture Ratio

Idealized Machine (No Errors)



With Conservative Machine Errors



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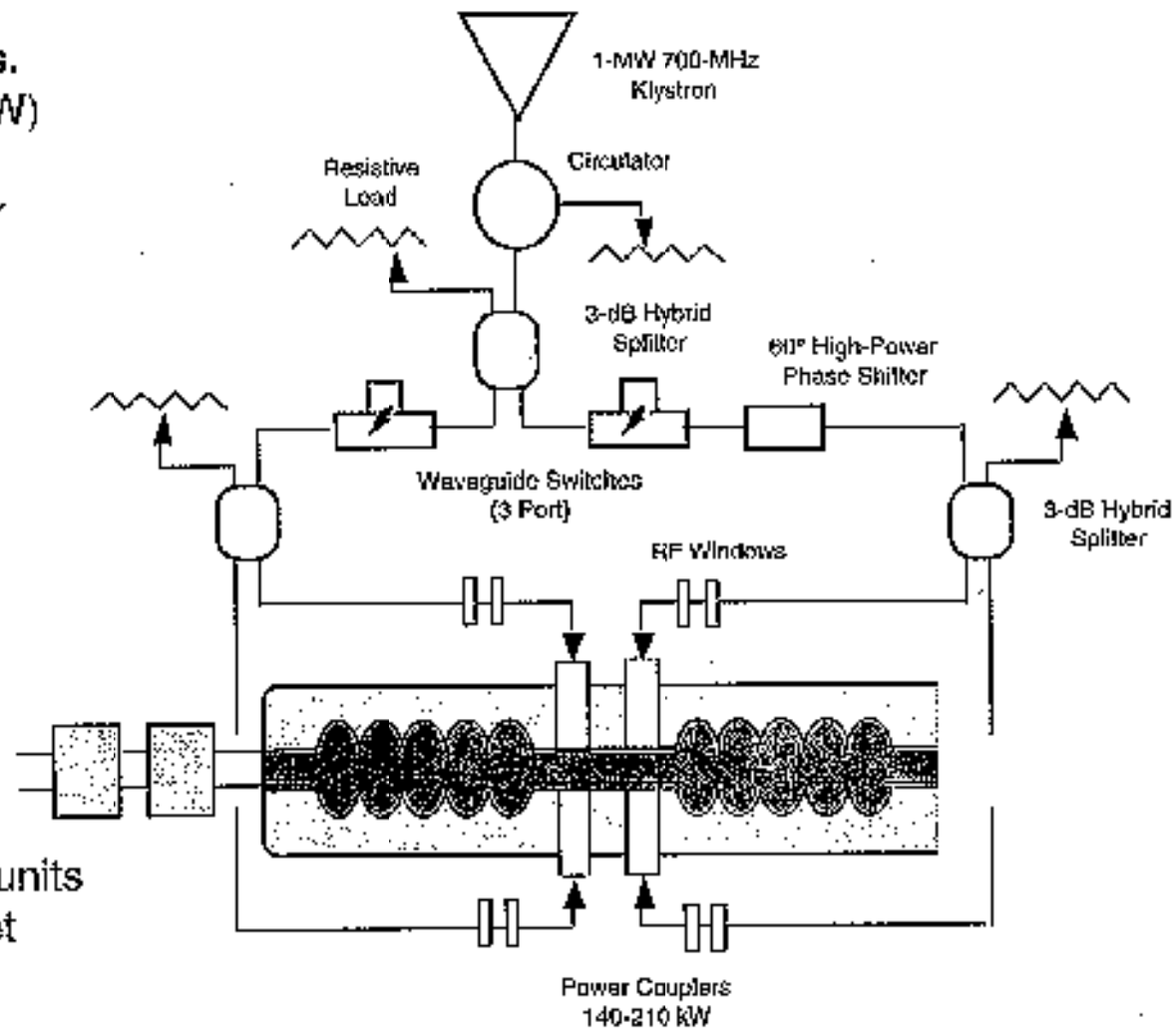
RF Power System is Major Design Driver in Terms of Costs, Operability, and Availability

- **RF power dominates accelerator construction and operating costs.**
  - use high-power generators (1 MW)
  - make full use of klystron output
  - choose largest practical value for cavity power couplers
- **RF power system summary**
  - RFQ: 3 350-MHz
  - NC linac: 52 700-MHz
  - SC linac: 106 700-MHz
  - power efficiencies:
    - > AC to DC: 95.0%
    - > DC to RF: 58.5%
    - > RF Xmission: 94.0%
- **System includes redundancy in both NC and SC linacs**
  - production continues with failed units
  - allows availability goals to be met

RF Module in APT High-Beta SC Linac



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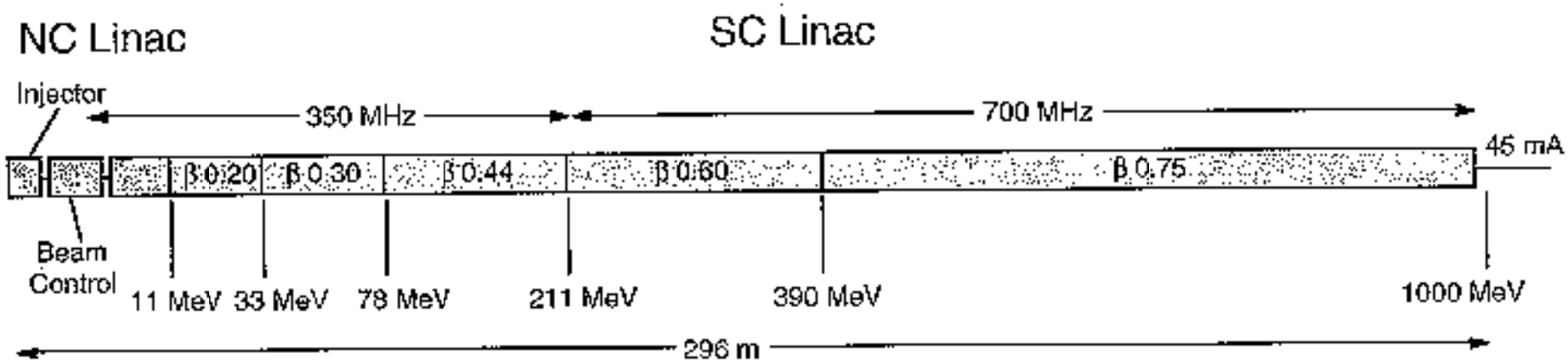
ATW Imposes New Requirements on Linac Design and Performance

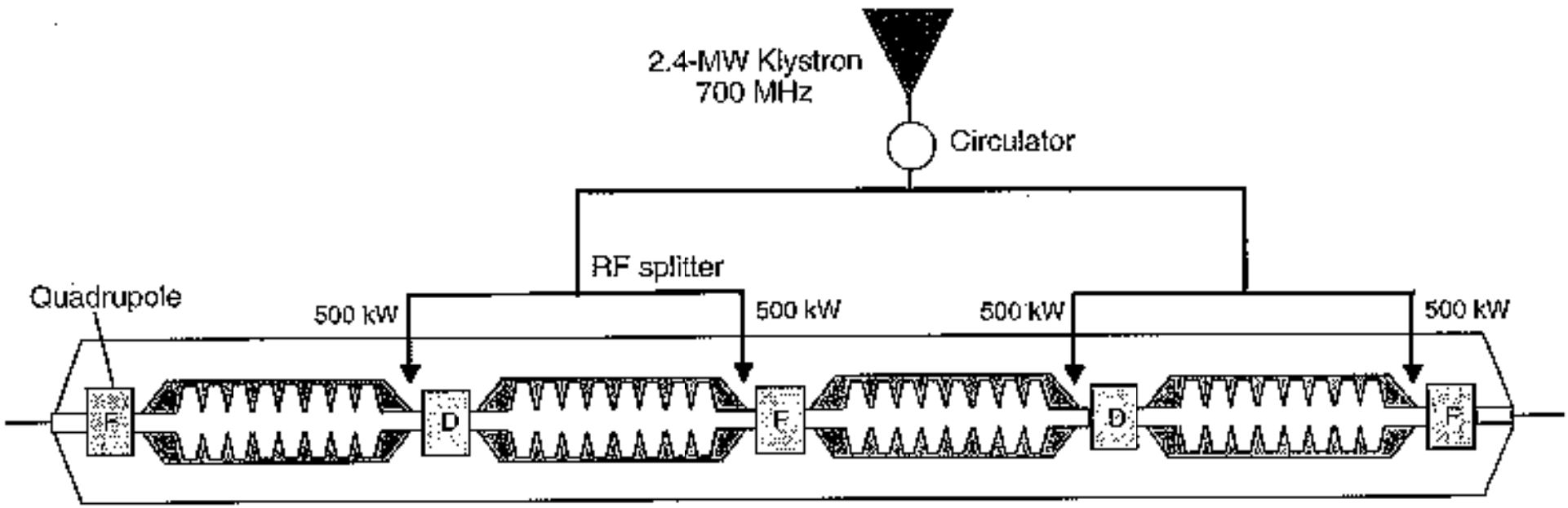
- **Beam distribution to multiple transmuters**
  - reference plant concept has 4 transmuters served by each linac
  - distribution scheme provides same CW current to each transmuter
    - > 2-stages of rf splitters (SC cavities with transverse rf fields)
    - > septum magnets complete beam separations
- **Independent control of beams to individual tranmuters**
  - selective beam inhibition capability needed for each transmuter, to allow servicing and refueling
  - other transmuters continue receiving beam
  - can be accomplished by beam chopper(s) in low-energy linac
- **Frequency and duration of beam interrupts must be reduced far below currently accepted operational levels**
  - to limit thermal transients in subcritical assembly
  - to minimize sudden step changes in electric power to the grid

Strawman SCRF Linac Design for ATW Plant



- Accelerator design is derived from APT linac, but with improvements that provide higher efficiency and lower costs.
- Gradient in SC cavities is 2 x higher than in APT, with 500 kW per rf coupler; much more compact accelerator.
- Elliptical cavities for $\beta > 0.5$; spoke cavities for $\beta < 0.5$
- SC quadrupoles (FODO lattice) are inside cryomodules.

Cryomodule for ATW High-Beta SC Linac
(β = 0.75)



Cells per cavity	8	Cryomodule length	9.7 m
Accel gradient E_oT	10.0 MV/m	Cavity Q_o	3×10^9
Energy gain per cavity	11.1 MeV	RF loss per cavity	99
Energy span	390-1000 MeV	Operating temperature	2.1K
Cavity length	1.28 m	Number of klystrons	16

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APT Provides Legacy of High-Power-Linac R&D Relevant to ATW Requirements

Low-Energy Demonstration Accelerator (LEDA)

- Has operated high-current (110-mA) high-reliability proton injector.
- Will soon demonstrate 100-mA CW operation of 6.7-MeV RFQ.
- Will operate complete high-power linac front end (injector + RFQ + CCDTL) at 100 mA CW, and verify beam quality and halo production.

SCRF Cavity/Cryomodule ED&D Program

- Has tested medium-β (0.48, 0.64) single-cell niobium SC cavities
- Has fabricated 5-cell β=0.64 cavities; starting construction of 5 MV/m cryomodule.

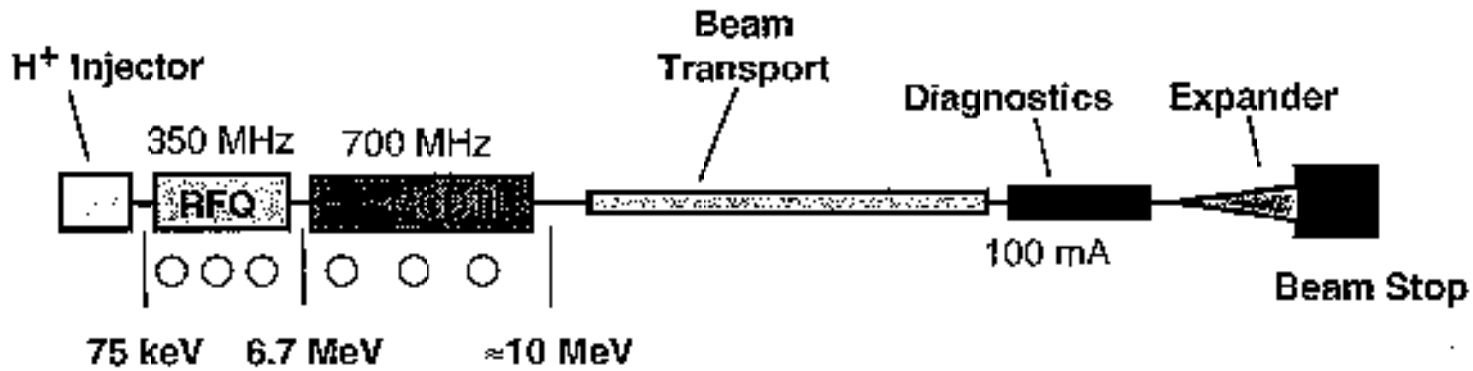
RF Power System ED&D Program

- Has developed 700-MHz 1-MW CW high-efficiency klystrons and other RF system components (DC power supplies, windows, circulators, loads, etc.).
- Will soon test prototype high-efficiency RF tube (1-MW 700-MHz HOM IOT).
- Is developing and testing high-efficiency 2-MW HVDC power supplies.

Purpose and Functions of LEDA
(Low Energy Demonstration Accelerator)

Characterize:

- Beam properties
- Operational reliability
- Failure mechanisms
- Component lifetimes
- Time to repair/replace



Demonstrate integrated full-power operation of APT low-energy linac.

Refine equipment designs for plant.

Qualify vendors

Improve cost estimates

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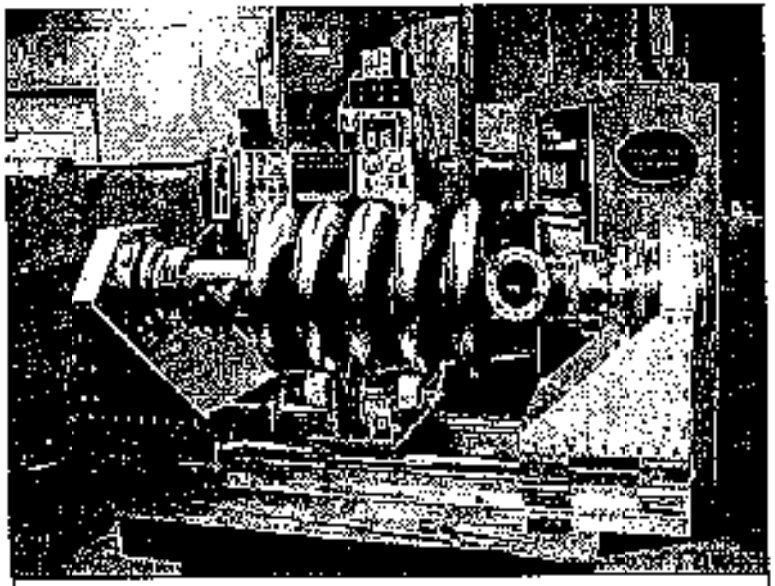
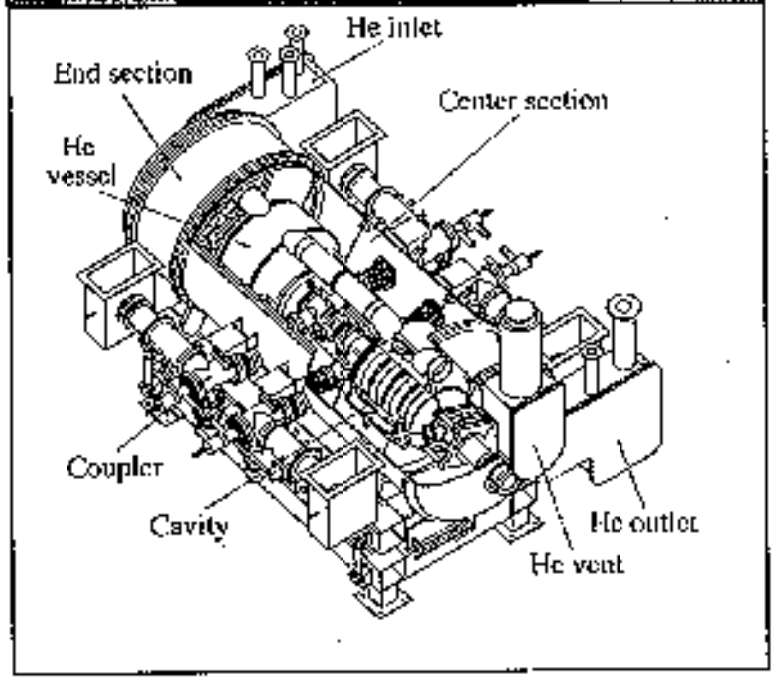
APT SCRF ED&D Program Will Build and Test a Complete β = 0.64 Prototype 700-MHz Cryomodule

- 800-MeV proton irradiation tests showed no degradation of Nb SC cavity performance.
- Single-cell β = 0.64 test cavities exceeded APT field and Q specs.
- Five 5-cell β = 0.64 cavities being fabricated by industry and LANL.
- RF power coupler and windows tested to design specifications.
- β = 0.64 2-cavity cryomodule designed & ready for fabrication.
- Cavity/cryomodule assembly and test facilities prepared.



5-cell β = 0.64 700-MHz Nb cavity fabricated by AES



APT β=0.64 prototype 2-cavity cryomodule design

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ATW Linac R&D Program Will Address Accelerator Performance Requirements Beyond APT

Critical for mission

- High-reliability, long-lifetime accelerator components
- Superconducting rf beam splitters
- Front-end micropulse beam-inhibit system

System cost reduction

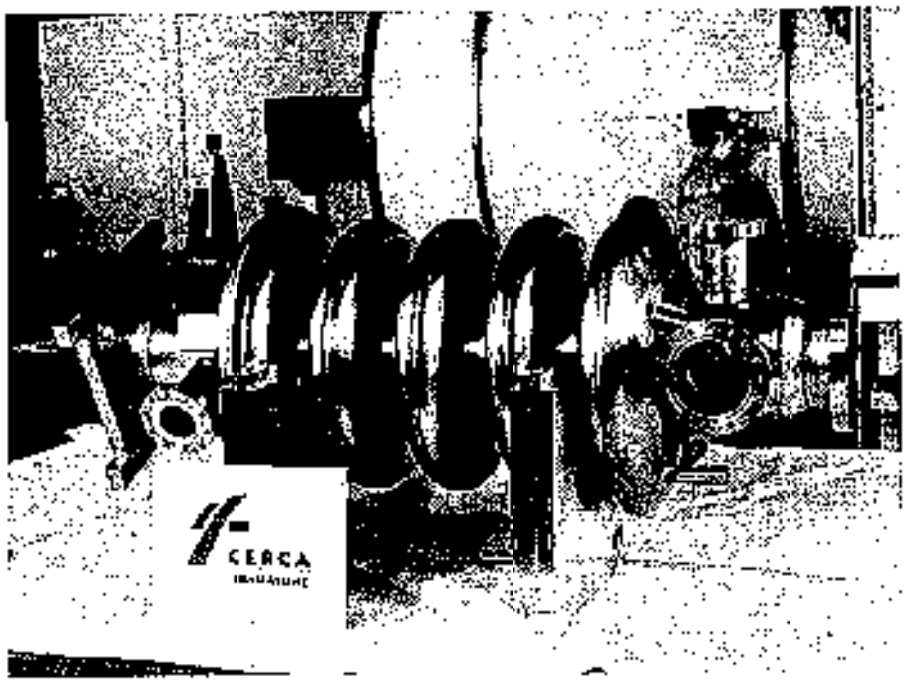
- Design for low-cost manufacturability
- High-gradient superconducting cavities & cryomodules
- More efficient, higher-power rf tubes, power supplies, etc

Performance optimization

- Low-beta superconducting cavities & cryomodules
- Superconducting focusing elements (quadrupoles)

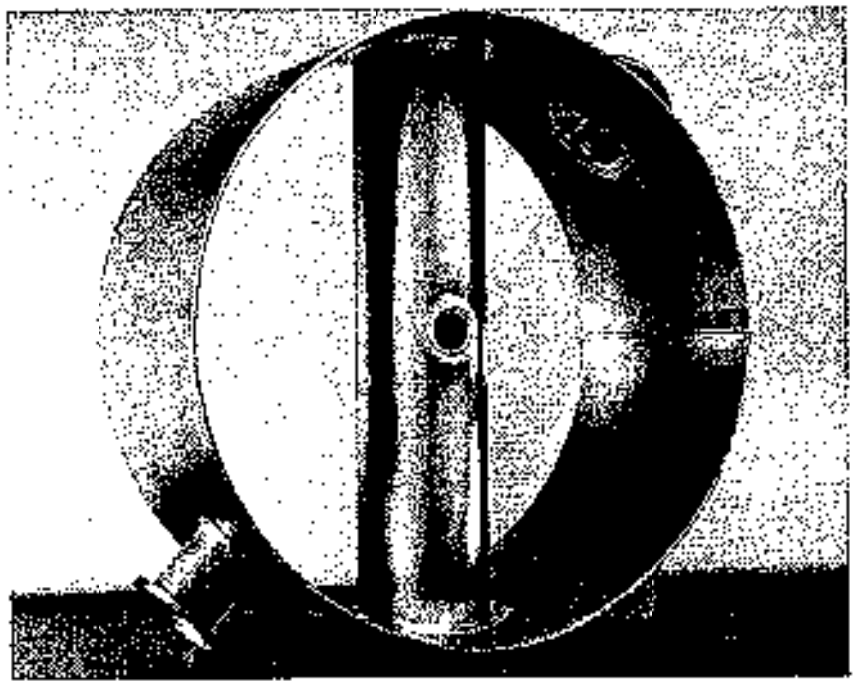
Advances in Niobium SCRF Cavity Technology Offer Lower Costs, Higher Efficiency, and Shorter Linac

High-gradient (10 MV/m) elliptical cavities for $\beta > 0.5$



700-MHz $\beta = 0.64$ 5-cell APT cavity

Spoke-type (half-wave) resonators for $\beta < 0.5$



350-MHz spoke resonator for $\beta = 0.3$

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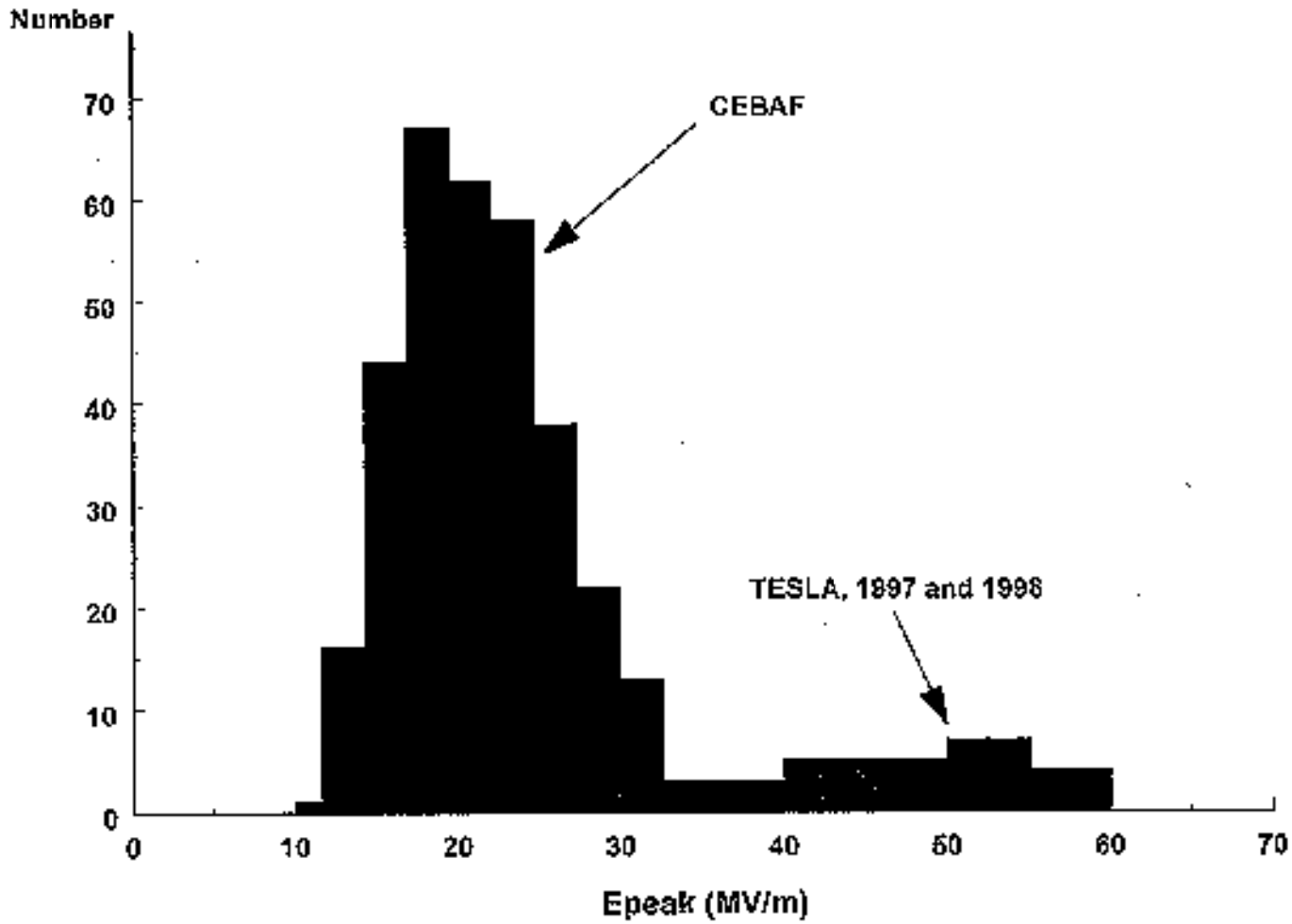
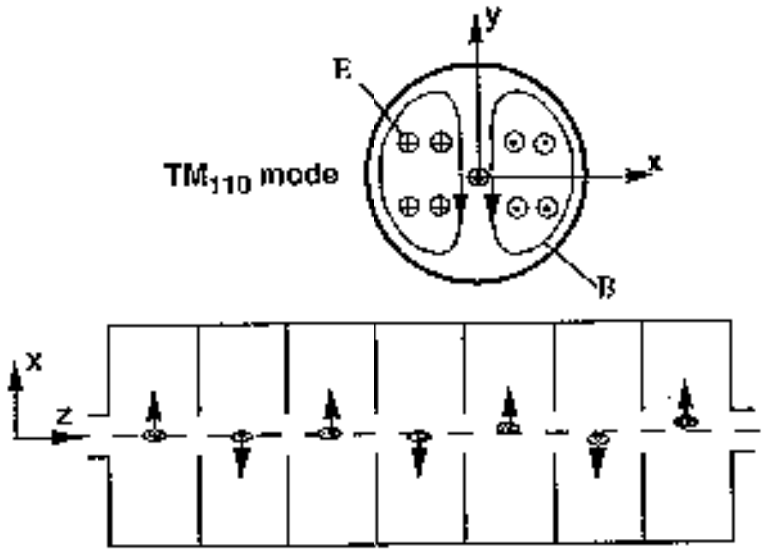
New Processing Methods Have Greatly Improved SC Cavity Performance

Comparison of CEBAF and TESLA Peak Surface Electric Fields



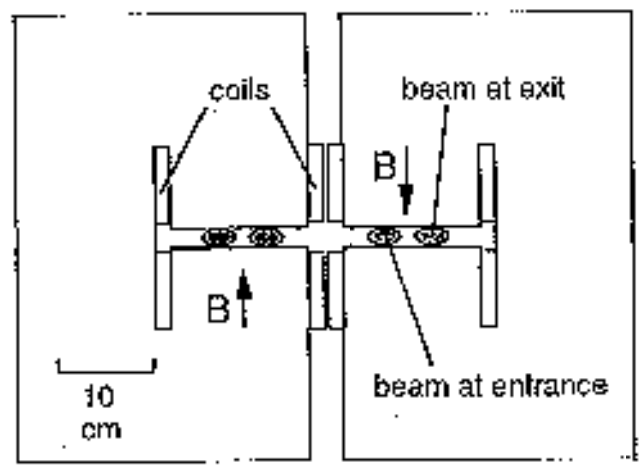
RF Beam Splitting and Separation Scheme

Multicell RF Cavity Deflects Bunches 3 mrad with Transverse B Field



frequency (MHz)	350
number of cells	17
structure radius (m)	0.52
structure length (m)	6.76
dissipated power (kW/cell)	50
RF power required (MW)	1.02

Septum Magnets Amplify Beam Separation



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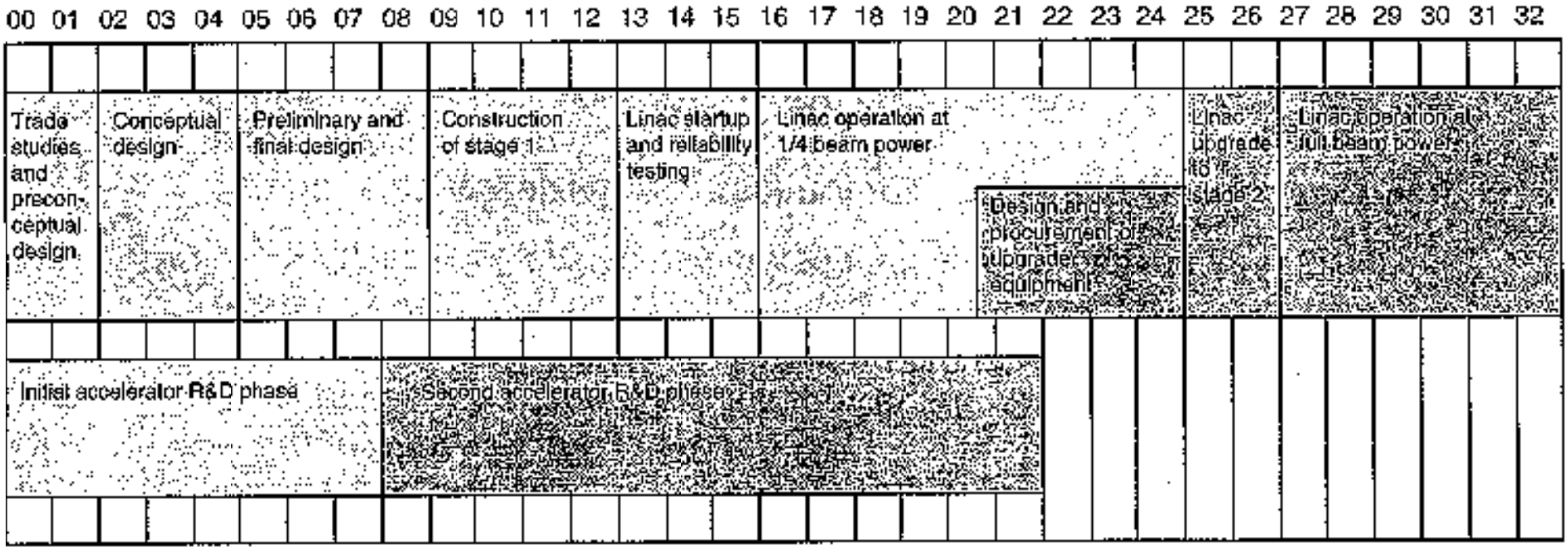
High Beam Reliability is Key Issue for ATW Systems

- **New and demanding requirement for accelerators**
  - existing accelerators have frequent short-duration beam interrupts
  - primary concern is equipment protection, not beam continuity
  - ATW plant performance calls for reducing number of beam interrupts by factor of 10^3
- **ATW accelerator architecture would emphasize:**
  - equipment designs with performance margin
  - redundancy of key equipment systems
  - rapid switching from failed equipment to backups
- **ATW linac R&D program would address:**
  - understanding of failure mechanisms (rf discharges, etc)
  - elimination of spurious (noise-driven) protection shutdowns
  - development of ultra-reliable and long-lifetime hardware
- **Reliability R&D program would require dedicated test facilities**
  - injector reliability test stand
  - rf-power-system reliability test stand
  - DEMO accelerator

ATW DEMO Accelerator Considerations

- **Identical to one of ATW linacs, but implemented in 2 stages**
  - ***Stage one***: 1-GeV, 11.25 mA CW
    - > drives one or more medium power (30 - 210 MWth) transmuters
    - > drives single full-size transmuter (840 MWth) demonstration
  - ***Stage two:*** add RF power to reach 45-mA CW
    - > drives 4 full-size transmuters in 1/2-scale prototype ATW plant
- **Provides demonstration of technology that will be needed for plant accelerator design**
  - high-gradient elliptical cavities and cryomodules
  - spoke-resonator cavities and cryomodules
  - rf beam splitters
  - front-end beam control (choppers, etc)
  - high reliability equipment and machine architecture

Schedule for ATW DEMO Linac Deployment and Supporting Accelerator R&D Program



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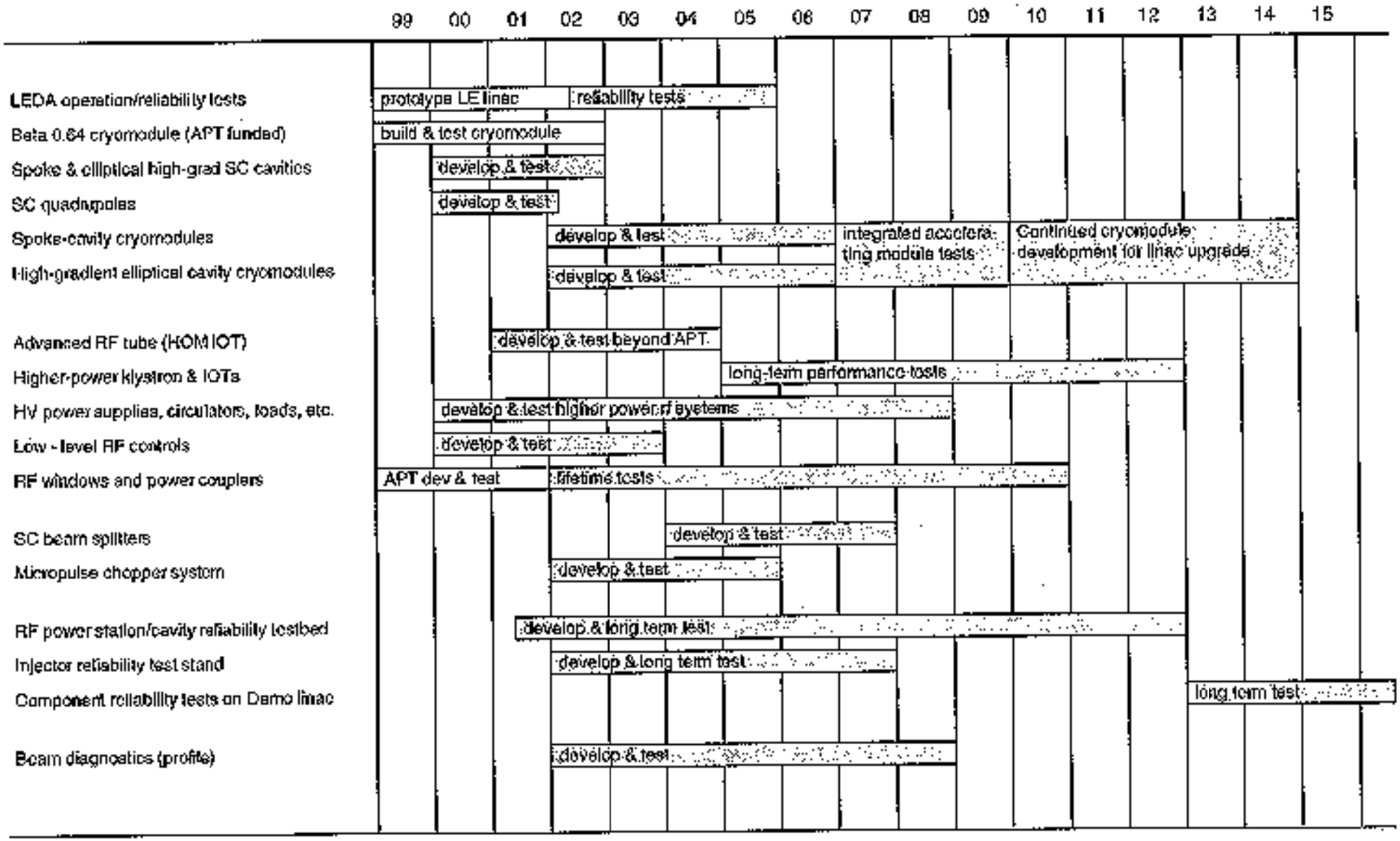
ATW Accelerator R&D Roadmap Supports DEMO and Plant Linac Designs



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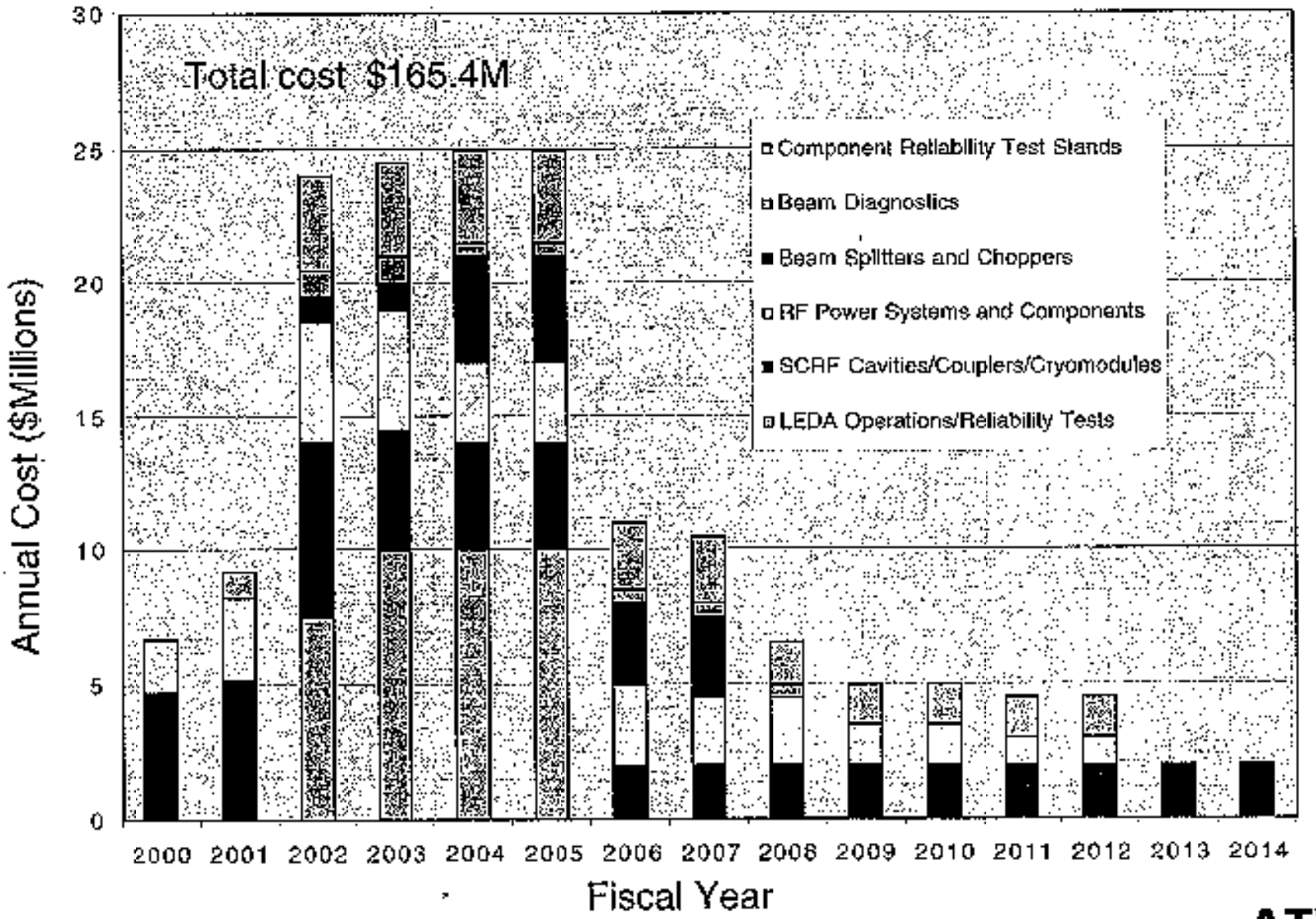
Accelerator R&D Program Cost Profile



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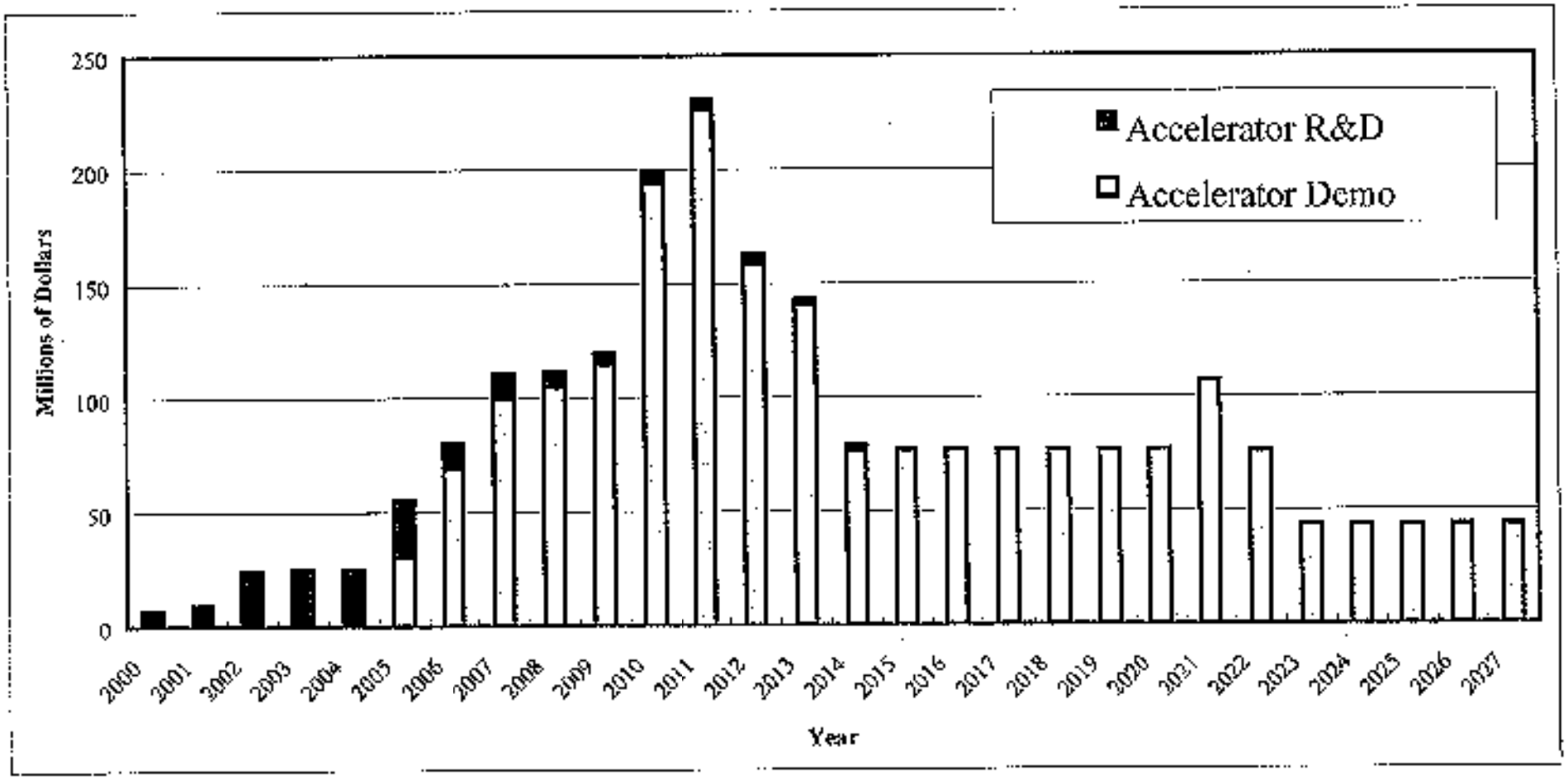
Integrated Accelerator Costs (R&D Plus DEMO)



Summary

- A Roadmap has been established for an accelerator R&D program that will support the ATW DEMO and plant linac designs.
- The APT accelerator design and ED&D program, which will be completed by FY03, provide a strong technology base for ATW.
- ATW linac design will start from APT platform, but has additional and different performance challenges.
- ATW beam must have very high reliability; much fewer beam interrupts per year than in present accelerator operations.
- ATW beam will be distributed to multiple targets using RF splitters.
- Linac design aims at high accelerating gradients and lower NC/SC transition energy, to increase efficiency & reduce costs.
- A national/international program should develop ATW linac designs and carry out the accelerator R&D.