The Development of UHV and XHV for Physics Research

H.F.Dylla

Thomas Jefferson National Accelerator Facility

(Jefferson Lab)

Newport News, VA USA 23606

CERN Accelerator School, Platja D’Aro,Spain

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OUTLINE

- Introduction

The interplay between technology development for the big machines of physics

and the advancement of vacuum science

  - Accelerators from the Lawrence Cyclotrons to the Large Hadron Collider
  - Magnetic fusion from the “Perhapsatron” to ITER
  - Gravity wave observatories (LIGO, VIRGO)come on-line

UHV/XHV TECHNOLOGY DEVELOPED FOR THE BIG MACHINES

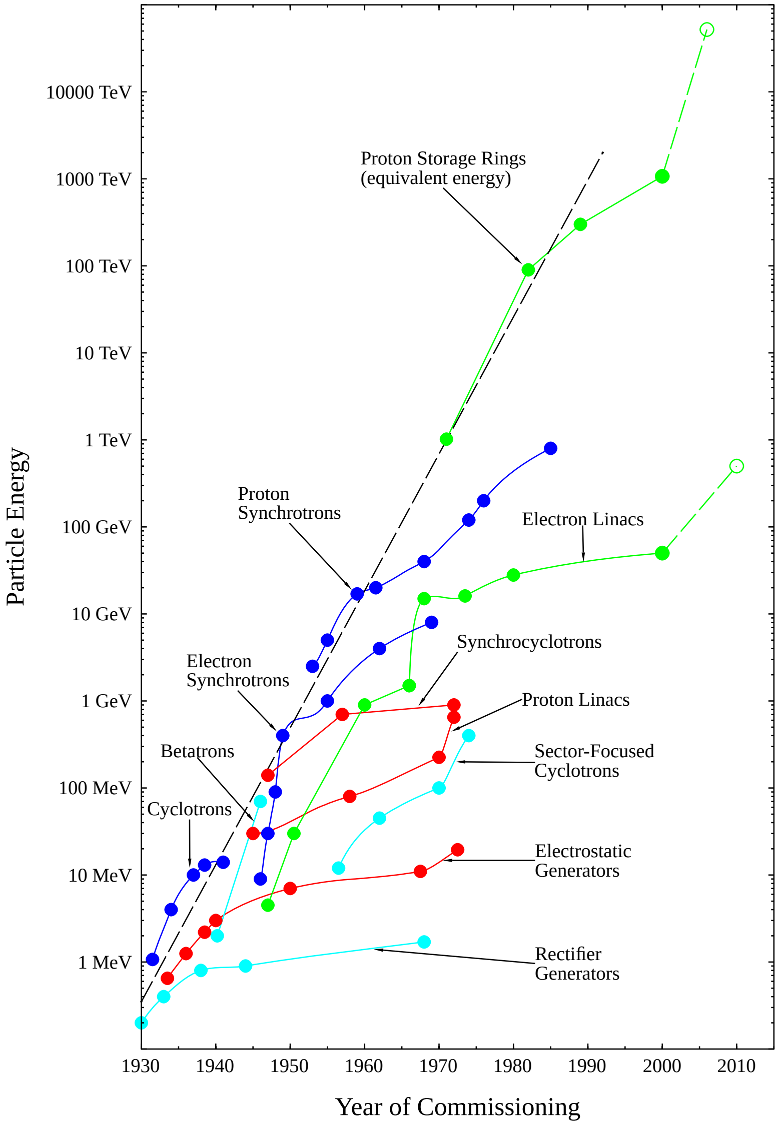
- Vacuum vessel designs
- Vessel joining techniques
- High performance vacuum materials
- Cleaning and conditioning procedures
- Vacuum instrumentation
- Vacuum pumps
- Vacuum system controls

EARLY HISTORY OF ACCELERATORS (PRE-UHV ERA)

- G. Ising linear accelerator concept (1924)
- R. Wideroe’s demonstration (1928)
  - 50 keV K^+
- Cockcroft and Walton (1932)
  - 400 keV H^+ — Li
- Lawrence’s first cyclotron (1932)
  - 1.2 MeV H^+
- “Livingston” Curve (1960)

LIVINGSTON CURVE

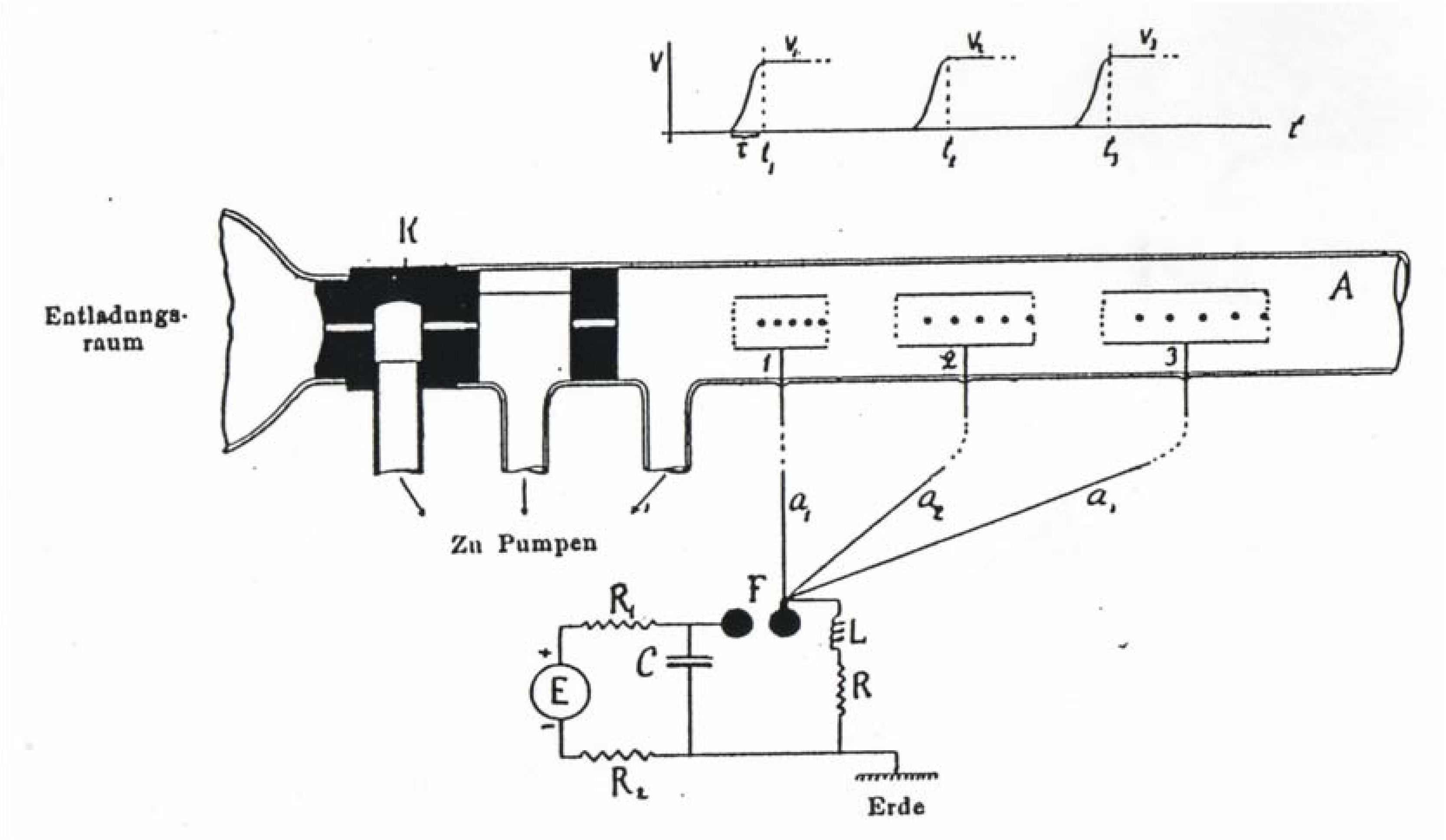
The "Livingston Curve" of the evolution of accelerator performance (1954), update by G. Krafft, Jefferson Lab (2003).



Update courtesy G. Krafft (2003)

FIRST GENERATION OF ACCELERATORS

G. Ising's pioneering RF Linear Accelerator (1924)



R. Wideroe demonstrated device in 1928 with 50 keV K+

WIDEROE’S MEASUREMENTS

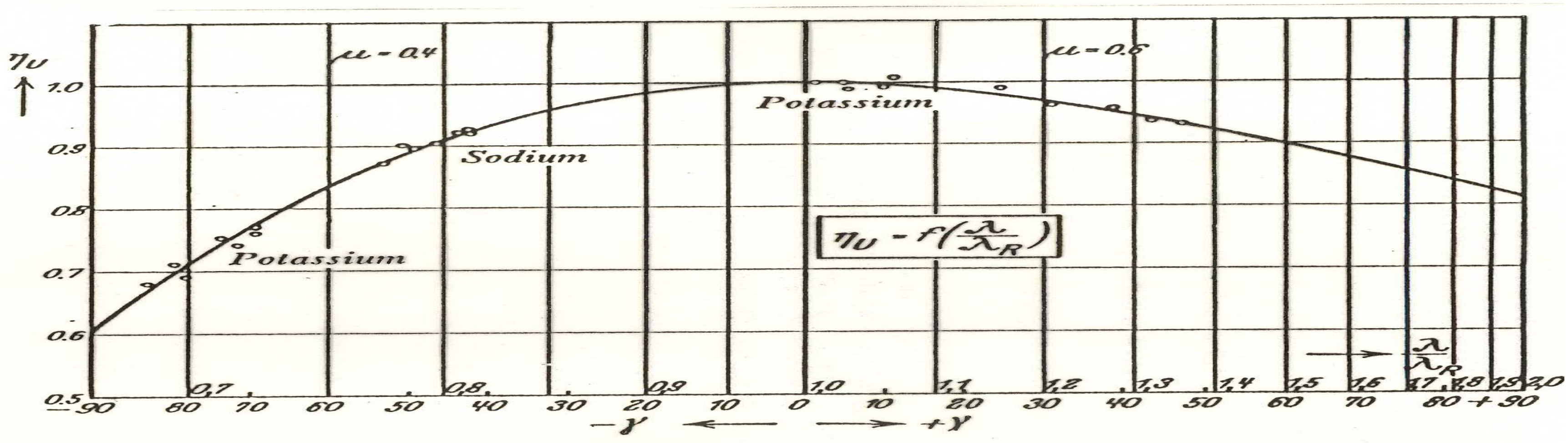
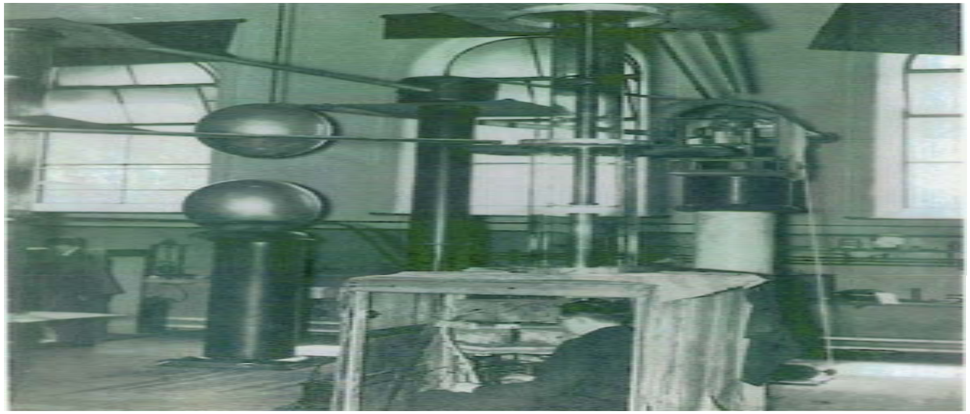


FIG. 10. Comparison of measured and calculated values for the voltage efficiency at different wavelengths.

COCKCROFT-WALTON



STORAGE RINGS

- First driver for incorporating UHV in accelerator designs
- Proposed by Gerald K. O’Neill in 1956 (a)
- Store particles injected from an accelerator into a system of guiding/focusing magnets
- Converts the E_{cm} of beam-fixed target to a much higher E_{cm} with colliding beams (Kerst, 1956)(b)

(a) G. K. O’Neill, Phys. Rev. 102, 1418 (1956)

(b) D. Kerst et al., Phy Rev. 102, 590 (1956)

STORAGE RINGS

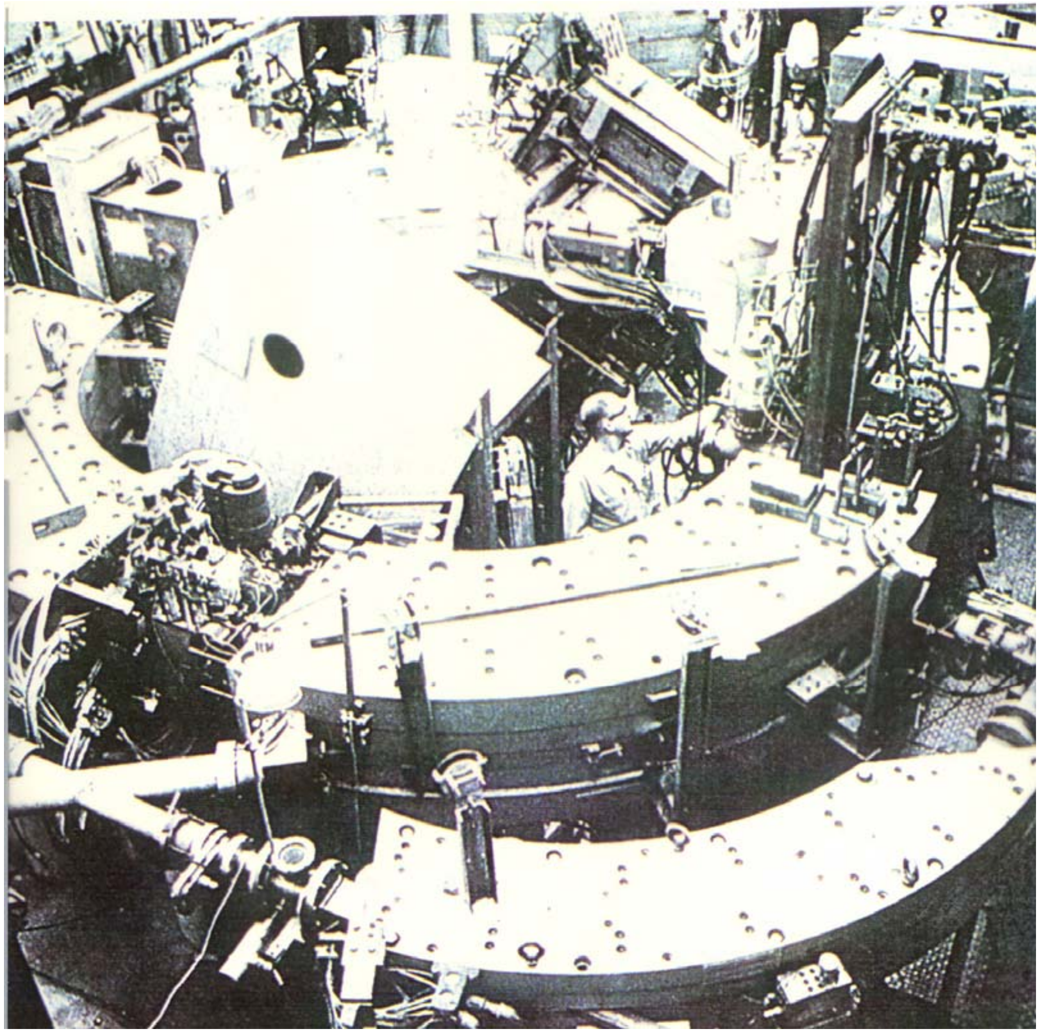
- O’Neill (1956) estimated that storage times would be “a few seconds” in the typical high vacuum environment

- O’Neill (1958)

  “If vacuum technology already developed in thermonuclear power research. . .” were employed (10^{-8} - 10^{-9} torr) storage times would be hours

- Constructed the “Stanford-Princeton storage rings” at Stanford from 1959-62
  - Performed poorly because unable to maintain UHV with appendage oil diffusion pumps

STANFORD-PRINCETON STORAGE RING (1959 – 62)



STORAGE RING MILESTONES

• G.K. O'Neill design papers	1956-58
• ADA (Frascati)	
• First e^- stored	1961
• First e^+e^- collisions	1963
• Stanford-Princeton (SLAC) e^--e^- collider	1963
• CEA (Cambridge)	1965
• ISR (CERN) p-p collider	1971
• SPEAR (SLAC) e^+e^-	1972
• SPS (CERN) first p-p^- collider	1981
• LEP (CERN) 30 km e^+e^-	1989
• SSC (Texas) 100 km p-p^- collider	RIP
• LHC (CERN) 30 km p-p collider	2007

SYNCHROTRON LIGHT SOURCE DEVELOPMENT

First observations of synchrotron emission, Pollack et al., G.E., 70 MeV synchrotron	1947
Early studies as “parasitic” uses on high energy machines	1950-60s
First dedicated light source: Tantalus 240 MeV storage ring (Wisconsin)	1968

SYNCHROTRON LIGHT SOURCE CHRONOLOGY

- First generation light sources (parasitic) 1970s
  - CEA (Cambridge)
  - SPEAR (SSRL)
  - SURF (NBS)
  - DORIS (Hamburg)
  - VEPP (Novosibirsk)
- Second generation light sources (dedicated) 1980s
  - SRS (Daresbury)
  - LURE (Orsay)
  - Photon Factory (KEK)
  - NSLS (BNL)
  - BESSY (Berlin)
  - Alladin (Wisconsin)
- Third generation light sources 1990s
  - ESRF (Grenoble)
  - ALS (LBL)
  - APS (ANL)
  - SPring 8 (Japan)
  - SRRC (Taiwan)

LBL 184” CYCLOTRON

LBL ADVANCED LIGHT SOURCE

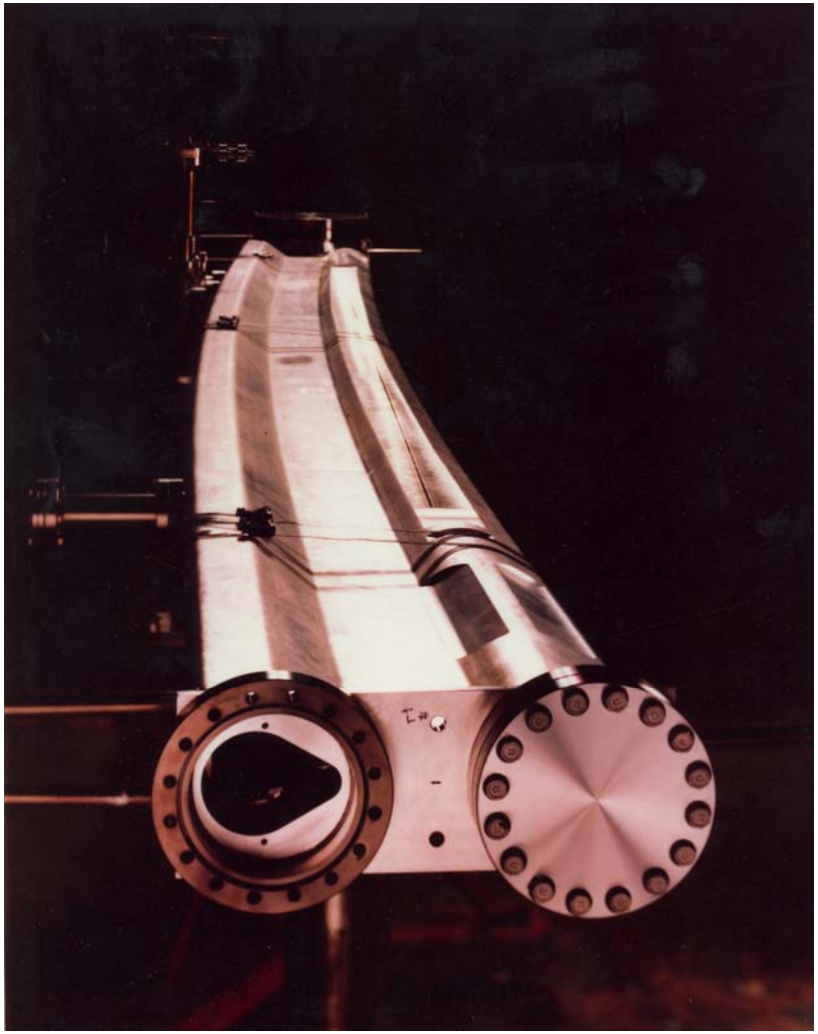
STORAGE RING DEVELOPMENTS

- Storage ring vessels are long, skinny and highly conductance limited

  —> problems could not be solved by pumping alone

- Innovations necessary to meet performance and cost goals:
  - Vessel design/fabrication
  - Vessel conditioning (pre-fab and in-situ)
  - Distributed pumping
  - Radiation absorbers

LIGHT SOURCE VACUUM CHAMBER



STORAGE RING UHV REQUIREMENTS

UHV conditions and UHV surface conditioning techniques are mandatory for long storage times (~ hrs.) and stable high current beams (~ 0.1 A)

- proton rings
  - low pressure to minimize Coulomb scattering
  - clean surfaces to minimize ion-induced desorption
- e^-, e^+ rings
  - low pressure to minimize bremsstrahlung loss on residual gas nuclei

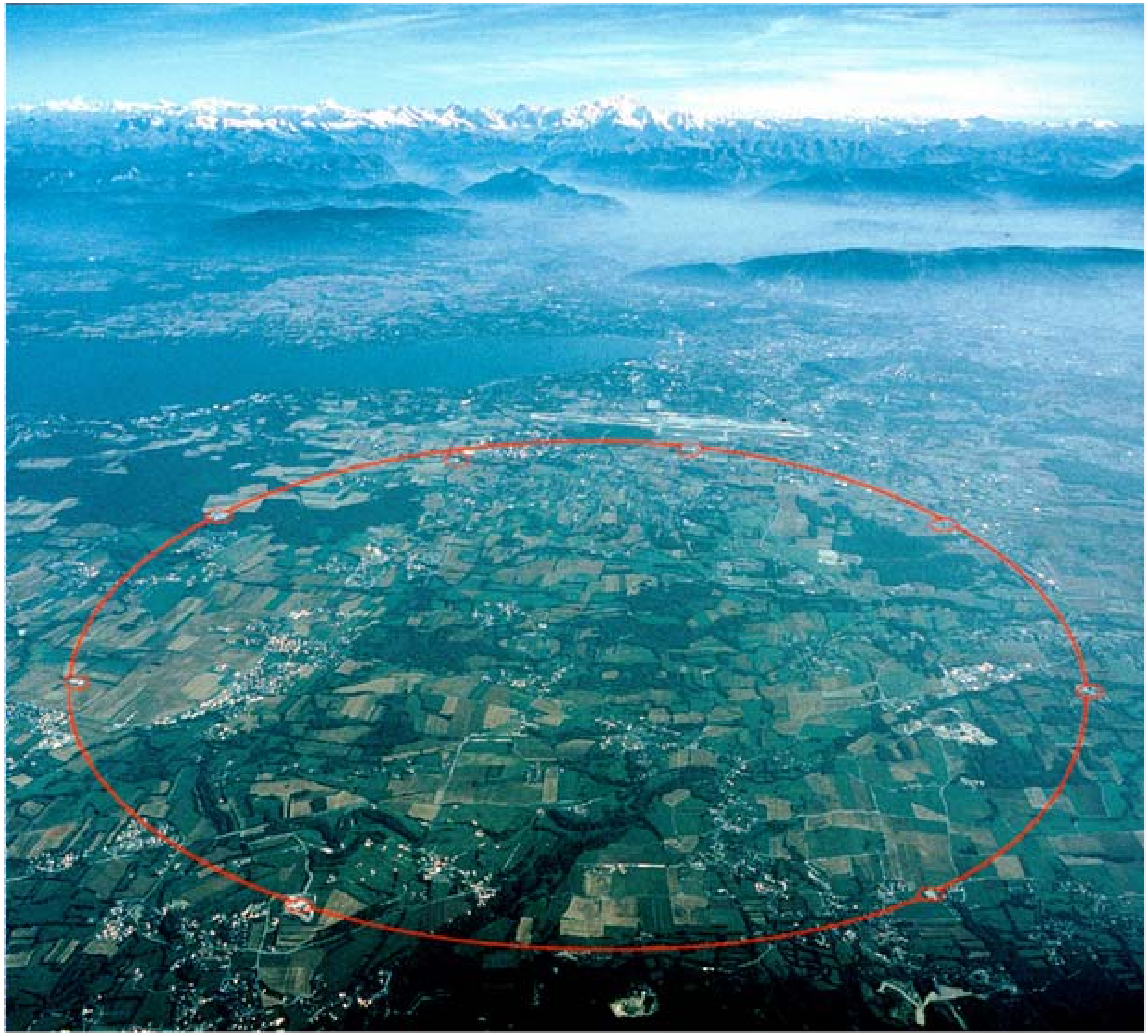
    $\tau_B \sim X_o/mp$
- clean surfaces to minimize synchrotron radiation induced desorption

STORAGE RING DEVELOPMENTS

- Vessel design/fabrication
  - Extruded aluminum, multichamber vessels
    - SPEAR (SLAC, 1971)
    - NSLS (BNL, 1982)
    - LEP (CERN, 1988)
    - APS (ANL, 1997)
  - Joining techniques
    - Aluminum conflats (KEK, APS)
    - Al/stainless steel bonds (SPEAR, NSLS)
  - Distributed vacuum pumping
    - In-situ ion pumps (high B-field operation) (SPEAR, DORIS)
    - In-situ NEG's (LEP)
  - Vacuum materials/components
    - High power radiation absorbers (Cu/C)
    - Be windows
    - All-aluminum UHV components

ACCCELERATORS, THE CURRENT GENERATION

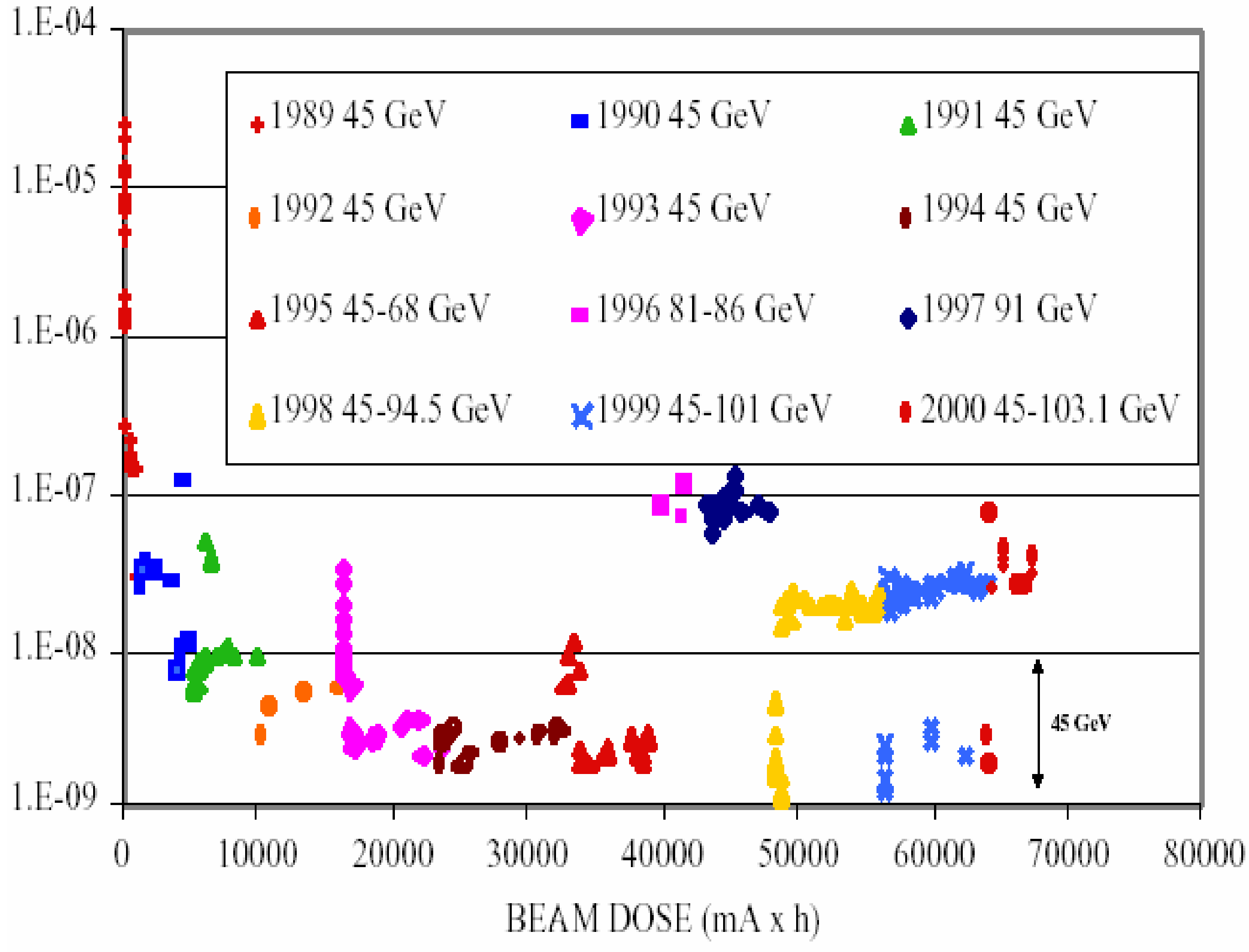
CERN, showing the LEP/LHC ring



(CERN)

LEP VACUUM HISORY

Vacuum performance of LEP during its 10 years of operation, courtesy of O. Gröbner, CERN.



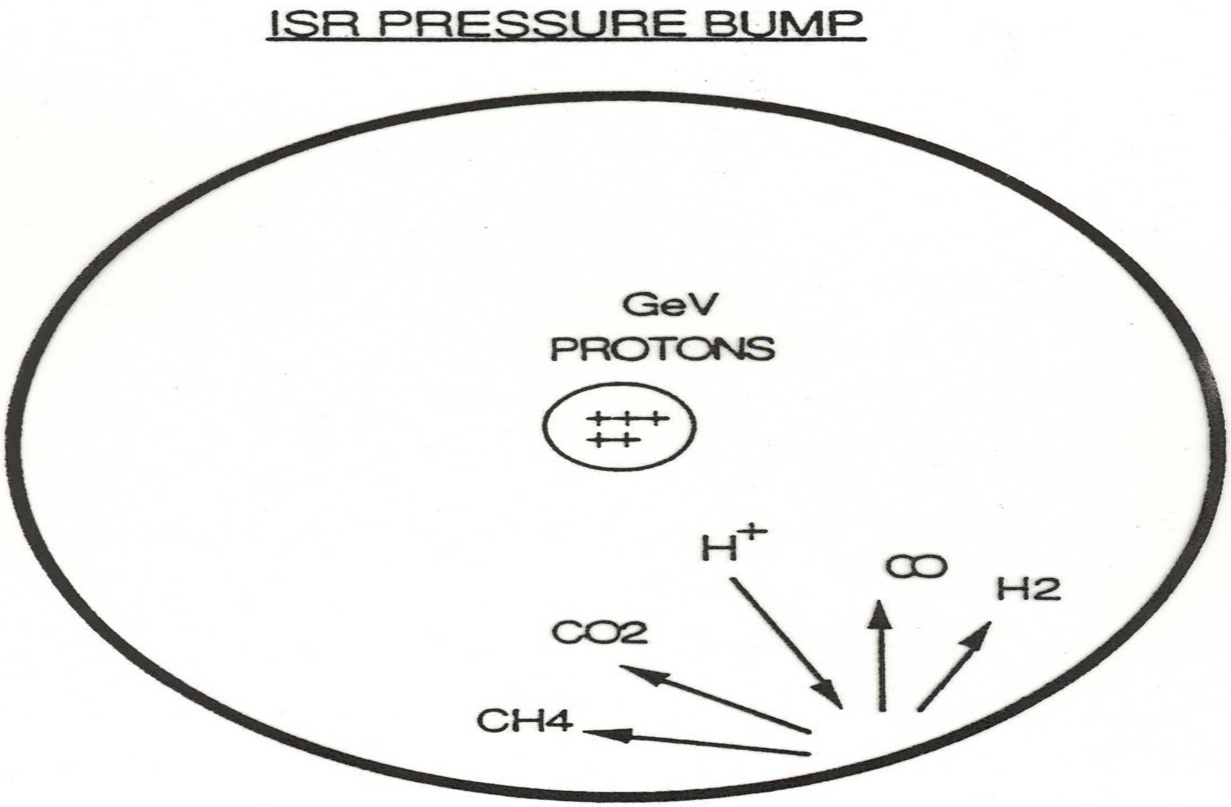
CONDITIONING TECHNIQUES DEVELOPED FOR STORAGE RINGS

- <u>Pre-Treatments</u>
  - High temperature vacuum bake
  - Alkaline detergent cleaning /etching
  - Ar, Ar/O_2 glow discharge cleaning
- <u>In-situ Treatments</u>
  - Vacuum bake
  - N_2 purge/bake
  - Beam conditioning (photo-induced desorption)

INTERSECTING STORAGE RING (ISR) AT CERN

- First proton storage ring
- Two intersecting rings, 1 km in circumference for protons with E ~ 28 GeV, I_p ~ 20 A
- Ring vacuum was originally specified at 10^{-9} torr:
  - ~ 10^{-10} torr was required in ring
    - minimize Coulomb scattering
    - minimize ion-induced desorption
  - ~ 10^{-11} torr was required at intersection point
    - minimize noise induced in detectors by gas scattering
- Ref: E. Fischer J. Vac. Sci. Tech. 9, 1203 (1972)
  Jpn. J. Appl. Phys. Suppl. 2, 199 (1974)

ISR



ISR EFFORTS

- Brute Force
  - All stainless steel vessel (2 km) with 6000 conflat flanges
  - 300 triode ion pumps (400 ℓ/s); 70 TMP stations
  - 500 modulated BA gauges, 36 RGAs
  - SS vessel in-situ bakeable to 300°C
- Innovations
  - Prebake of SS sheet stock for vessels at 900°C in vacuum for 2 hours to lower hydrogenic content (10x)
  - Developed Ar/O_2 glow discharge cleaning

COLD BORE MACHINES

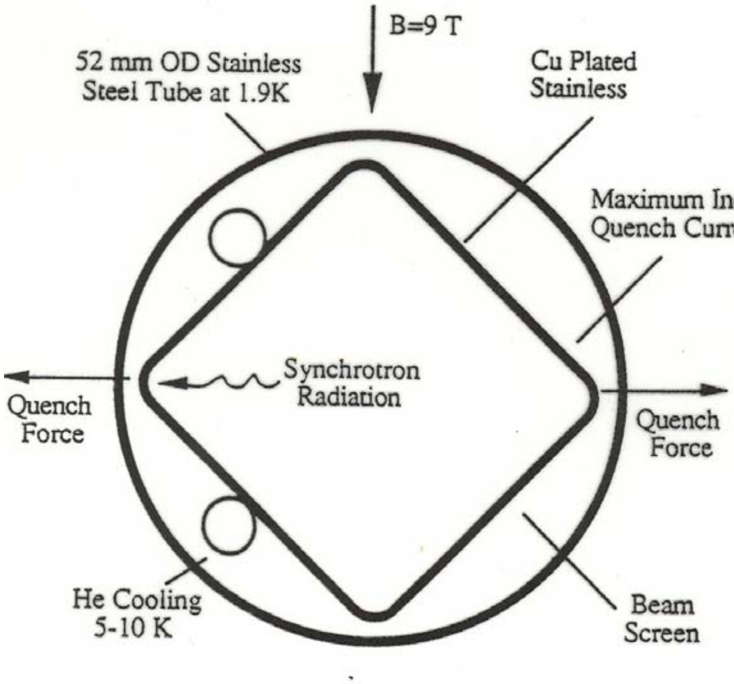
- (SSC), LHC present(ed) special challenges w.r.t. vacuum design because of the cold (4.2-1.8 K) beam pipe
- With $p > 10^{-10}$ torr, excessive beam scattering and heat load on cryostat
- Requires liner to absorb synchrotron radiation and distributed H_2 pump between liner and beam tube

Problems:

- Nature of photodesorption at 1.8-4.2 K
- H adsorption/desorption kinetics at low temperatures
- Simplified, cost-effective liner design

LHC VACUUM CHAMBER

A Schematic Cross-section of the Beam Screen in the Vacuum Chamber



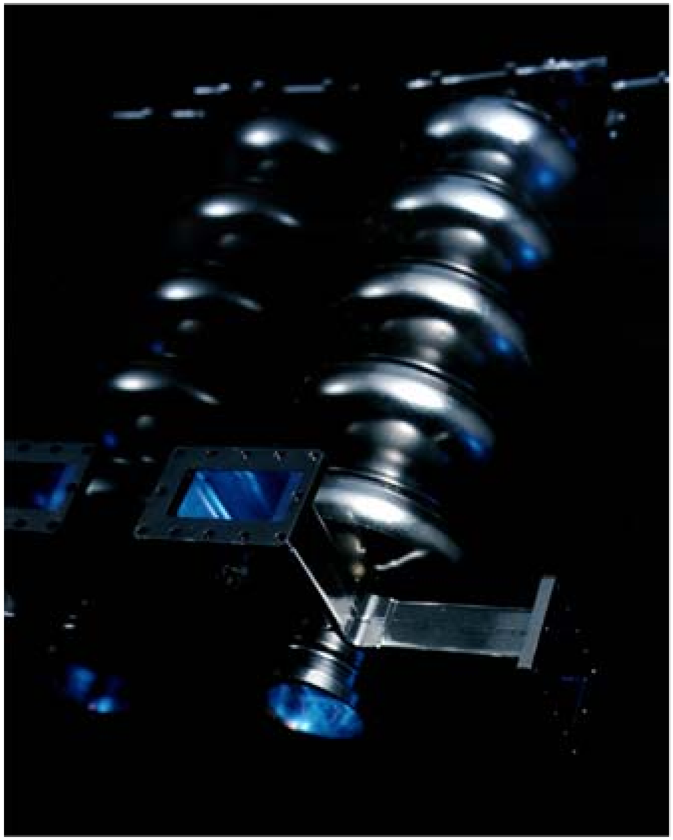
SUPERCONDUCTING RF ACCELERATORS

- SRF cavities operational and being installed in numerous machines for:
  - RF power savings
  - CW operation
  - Low impedance structures

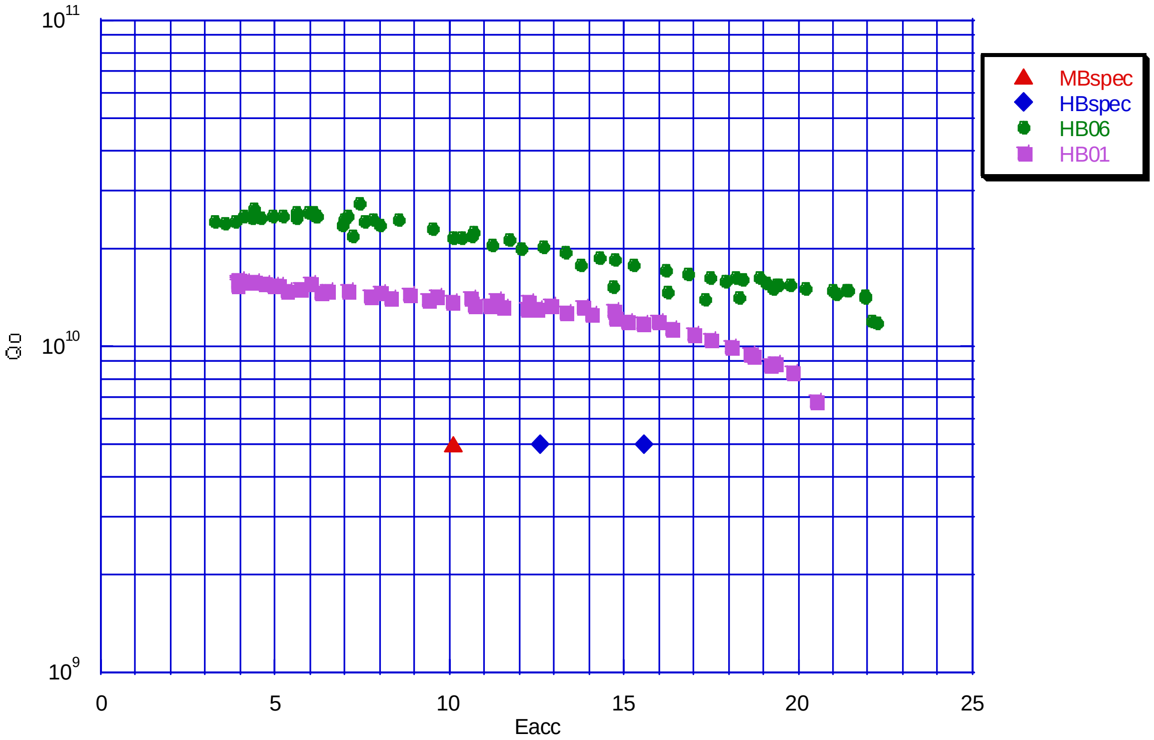
examples: TRISTAN, DESY, CEBAF, LEPII, SNS (ILC)

- 30+ years of development have produced cavities with acceleration gradients > 25 MV/m
- Success tied to careful attention to:
  - Surface treatment
  - Contamination control
  - Vacuum integrity

Superconducting RF cavities



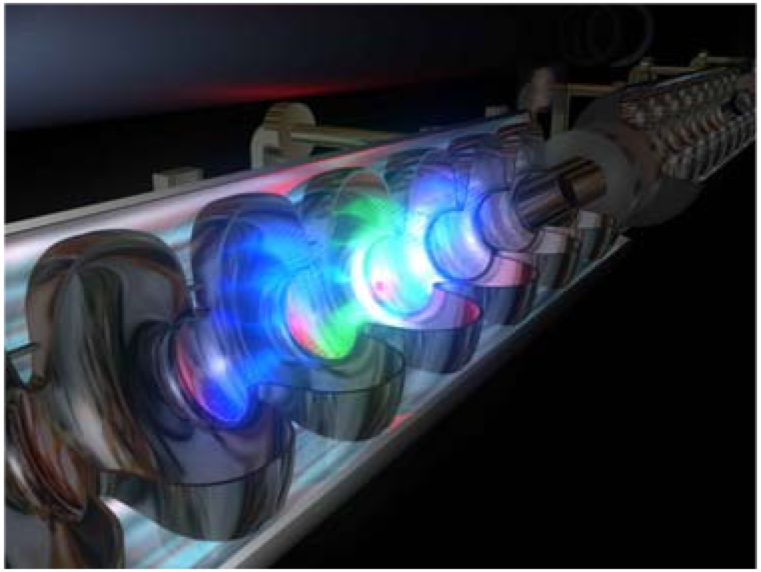
1.5 GHz from Jefferson Lab



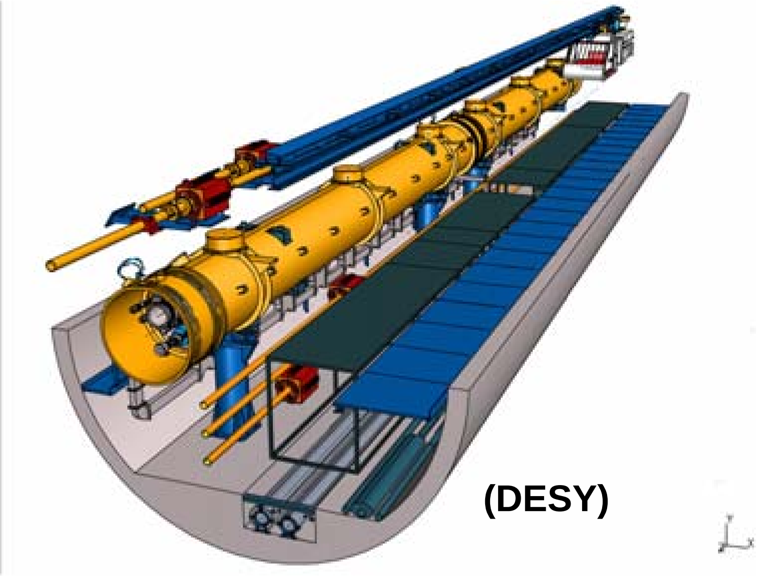
Cavity Q vs. Accelerating Gradient (MV/m)
805 MHz cavities for the SNS

BIGGER SPARKS IN THE VACUUM

The development of SRF acceleration cavities has pushed the state of the art for sustained (cw) fields across an evacuated electrode system



(DESY)



(DESY)

Applications:

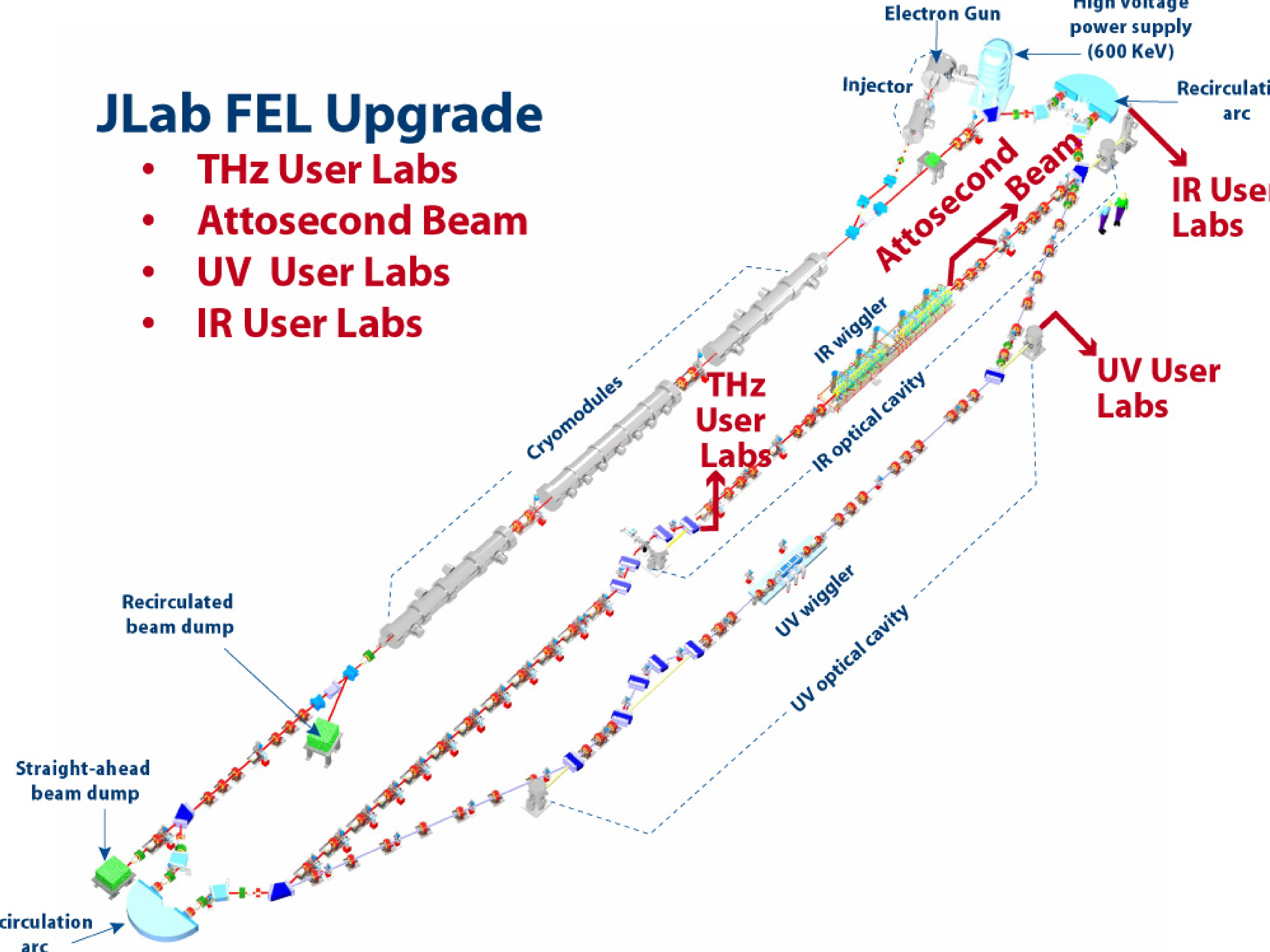
- **the International Linear Collider at TeV energies**
- **high power (JLab) and short wavelength (x-ray) FELs (DESY and SLAC)**

NEXT GENERATION LIGHT SOURCES

- X-Ray Free Electron Lasers using Self Amplified Stimulated Emission (SASE)
  - LCLS (Stanford)
  - DESY (Hamburg)
- Energy Recovered Linac Light Sources
- Jefferson Lab - FEL
- Cornell and Daresbury Lab

JLab FEL Upgrade

- THz User Labs
- Attosecond Beam
- UV User Labs
- IR User Labs



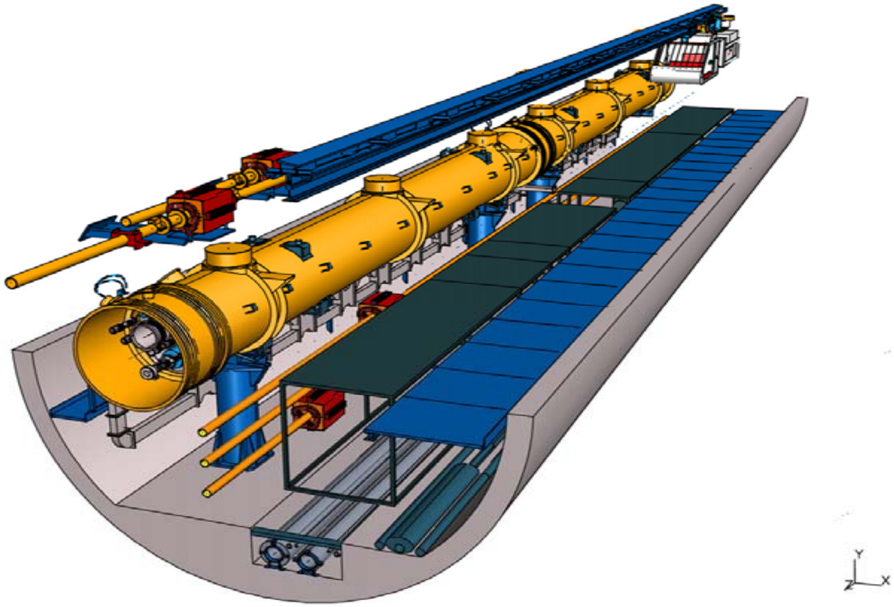
The Next Generation Large Accelerator:ILC

Major international collaboration at work on R&D for ILC:

•Minimizing cost of 20 km of superconducting linac

•Conceptual design of accelerator, detector complex

•$10B cost range



EARLY HISTORY OF MAGNETIC FUSION

Lyman Spitzer’s Project Sherwood (1952) Spitzer, Tuck, Post, York

- What’s the problem: H + D → He^4 + n + 14 MeV

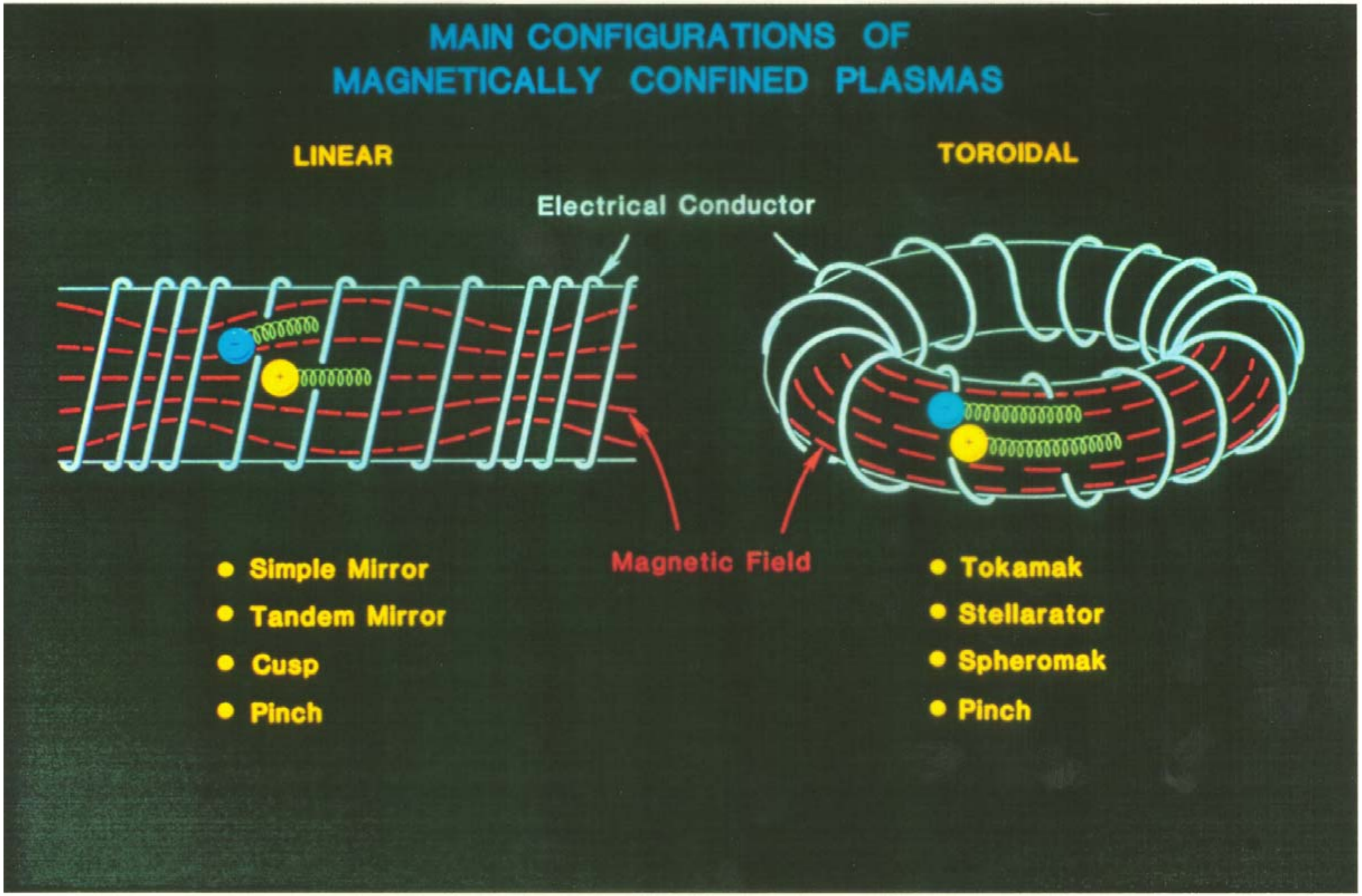
1. Plasma confinement $\tau_E \geq 1\, s$
2. Plasma heating $T_i \geq 10\, keV$
3. Plasma fueling
4. Impurity control $n_H > 10^{14}\, cm^{-3}$

“Lawson Criterion”

- After 50 years $n \tau T_i \cong 0.5 - 0.8$ Lawson

but nothing was easy!

PLASMA CONFIGURATIONS



MAIN CONFIGURATIONS OF MAGNETICALLY CONFINED PLASMAS

LINEAR

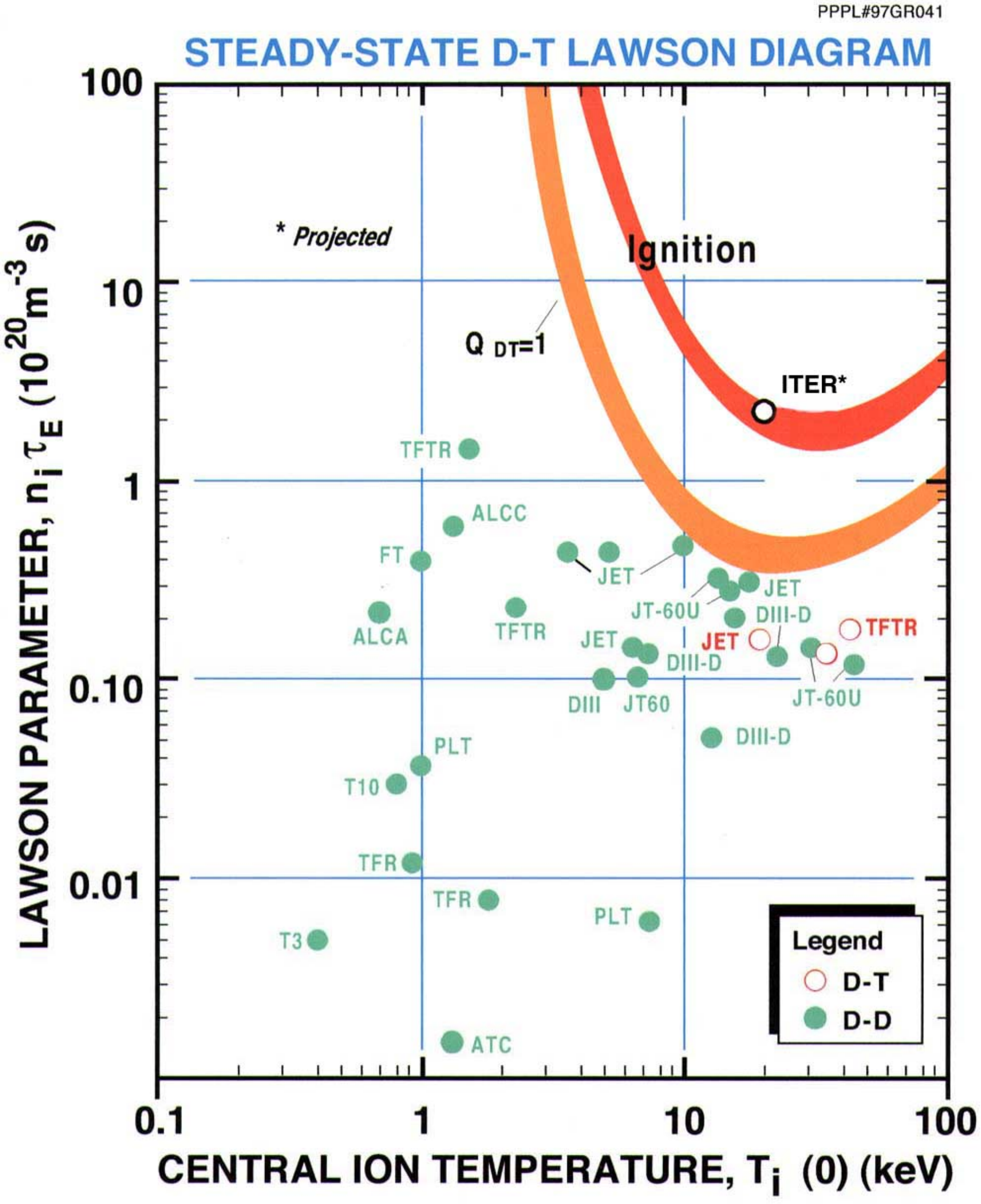
- Simple Mirror
- Tandem Mirror
- Cusp
- Pinch

TOROIDAL

- Tokamak
- Stellarator
- Spheromak
- Pinch

LAWSON CURVE

The "Lawson Criterion" for energy gain in D-T plasmas, courtesy D. M. Meade, Princeton Plasma Physics Laboratory, reprinted from Ref. 93 with permission.



PRINCETON PIONEERS

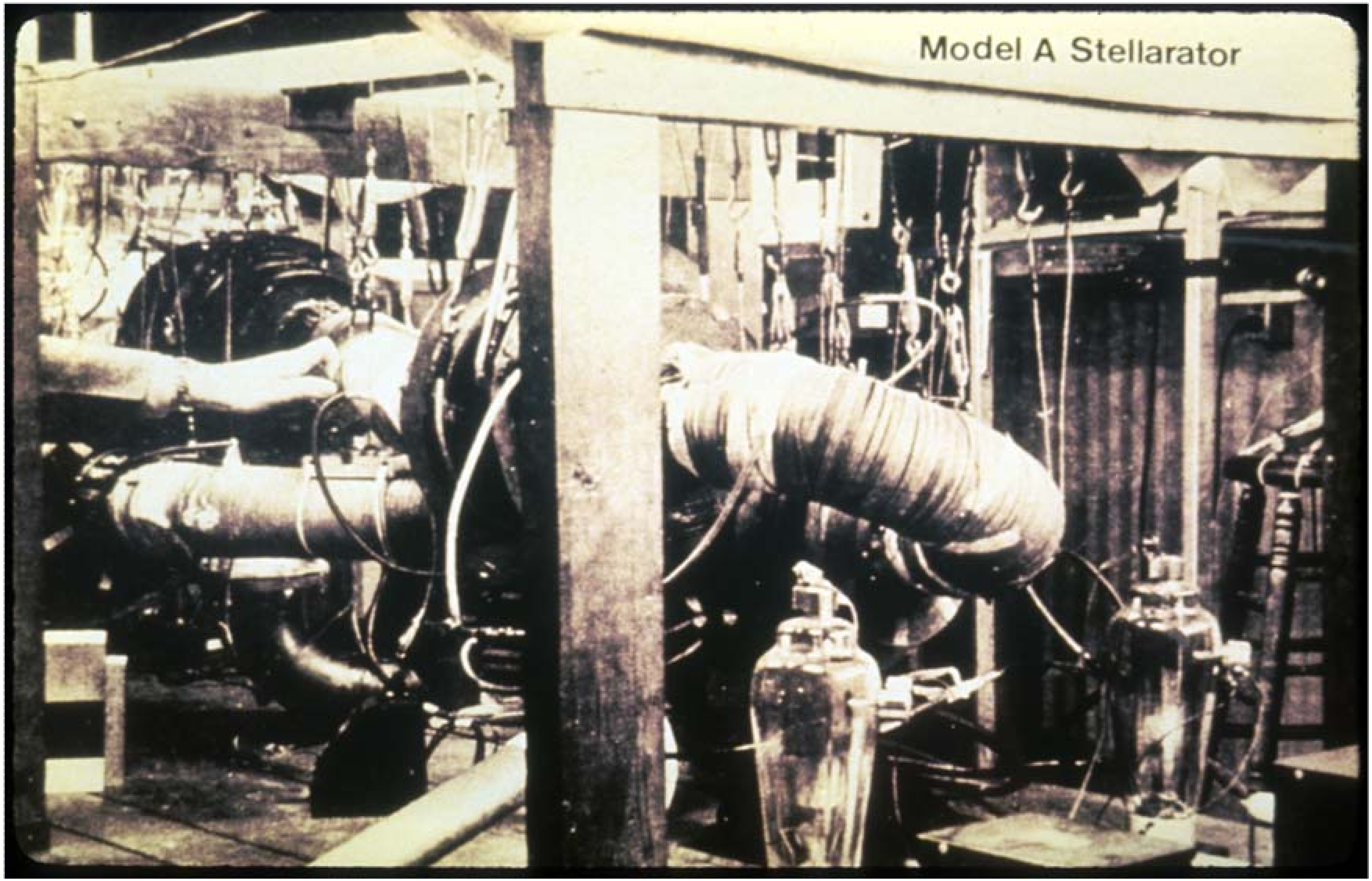
PLASMA CONFIGURATIONS OF THE FIRST FUSION DECADE

Model A Stellarator	Princeton 1953
• Perhapsatron	Los Alamos 1952
• Table Top	Livermore 1953

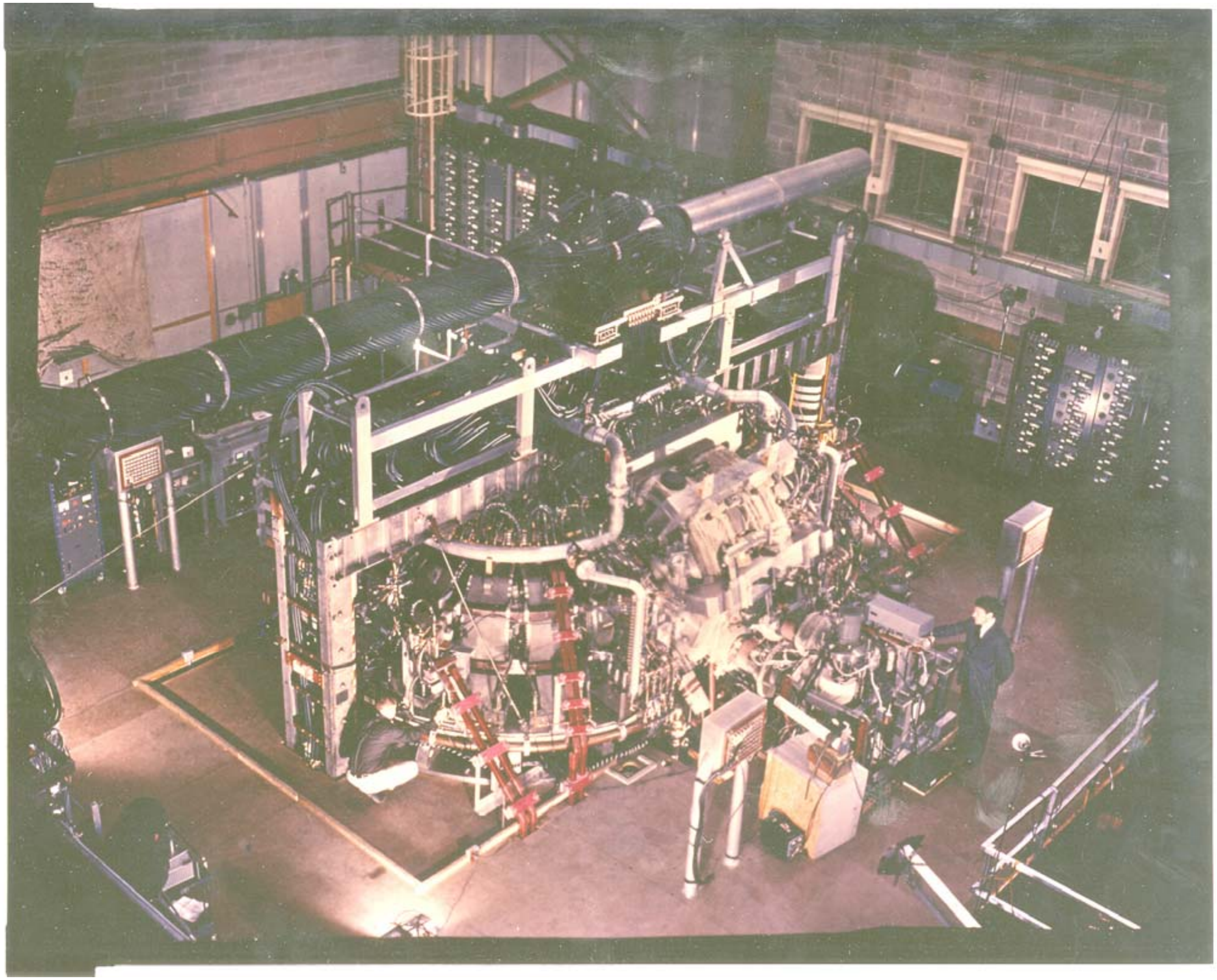
Model C Stellarator	Princeton 1958

- First UHV machine
- Suffered from poor confinement ($\tau \sim \mu s$)
- Stainless steel vessel, bakeable to 450°C
- Gold-wire sealed
- Hg diffusion pumped

MODEL A STELLARATOR (PRINCETON, 1960)



MODEL C STELLARATOR (PRINCETON)



L. ARTSIMOVITCH (KURCHATOV)

MAGNETIC FUSION MILESTONES

The primordial Tokamak T-3	1965
Artsimovich’s Western Tour	1969

<u>First Generation (Western) Tokamaks</u>

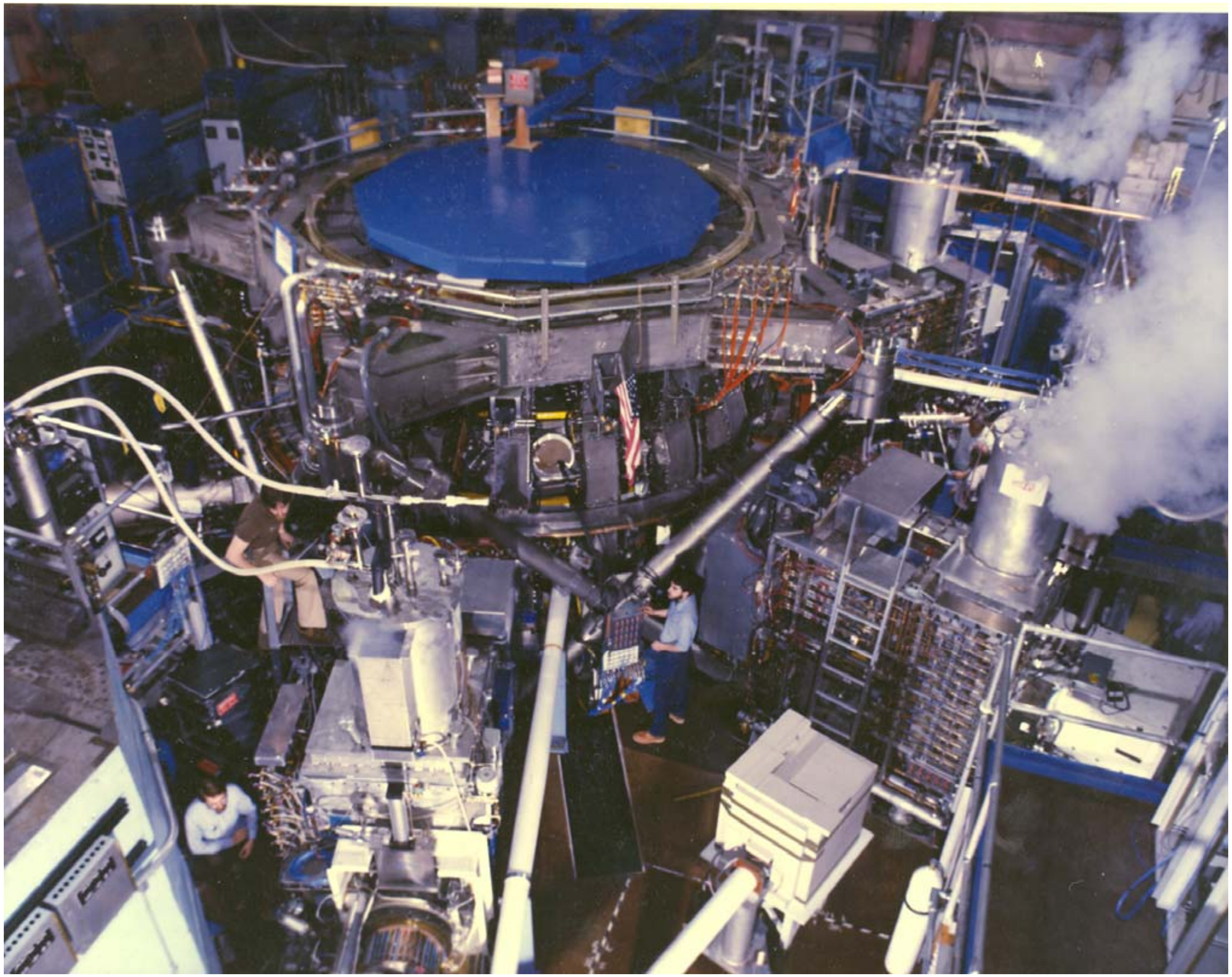
ST (Princeton)	1970
ORMAK (ORNL)	1971
Doublet (General Atomics)	1971
ATC (Princeton)	1972
Alcator-A (MIT)	1972
Pulsator (Garching)	1974
DITE (Culham)	1976
JFT (JAERI)	1976
TFR (Paris)	1974

MAGNETIC FUSION MILESTONES

- Second Generation Tokamaks

PLT (Princeton)	1975
T-10 (Kurchatov)	1976
ISX (ORNL)	1977
D IIA (General Atomics)	1975
PDX (Princeton)	1980
ASDEX (Garching)	1981
Alcator-C (MIT)	1984

PDX TOKAMAK (PRINCETON)



MAGNETIC FUSION: ALTERNATIVE FIELD CONFIGURATIONS

- Mirror Machines

Baseball (LLNL)	1966
TARA (Wisconsin, MIT)	1982-1988
TMX, TMX-U (LLNL)	1987
MX/MFTF-B (LLNL)	1987 (RIP)

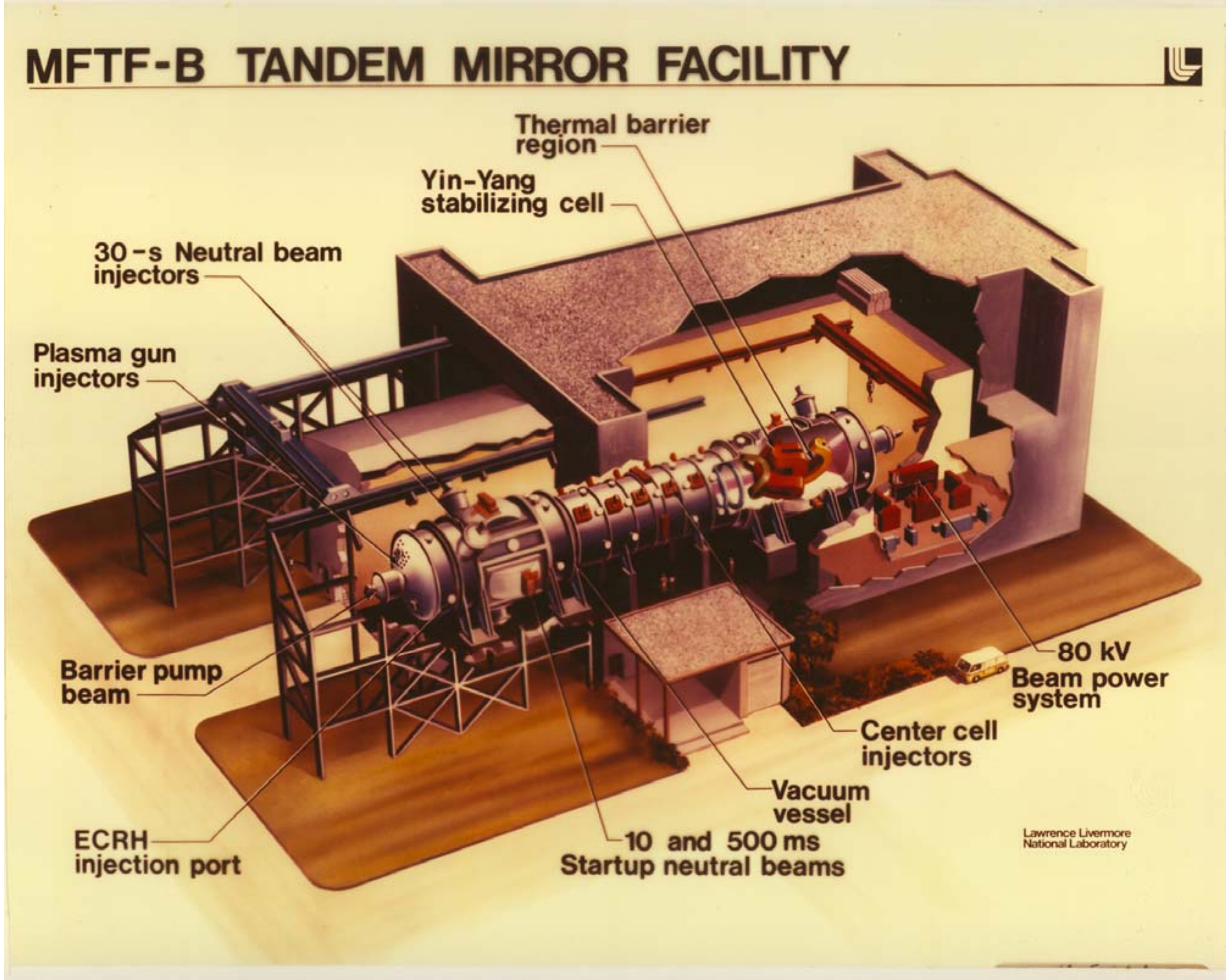
- Field Pinches

Zeta (Culham)	1957
Syllac (LANL)	1971
ZT-40 (LANL)	1985
S-1 Spheromak (Princeton)	1981

- Stellarators, Other Toroidal Conf.

Helitron (Japan)	1984
Wendlestein-III (Garching)	1982
EBT (ORNL)	1973
ATF (ORNL)	1988

MIRROR MACHINES

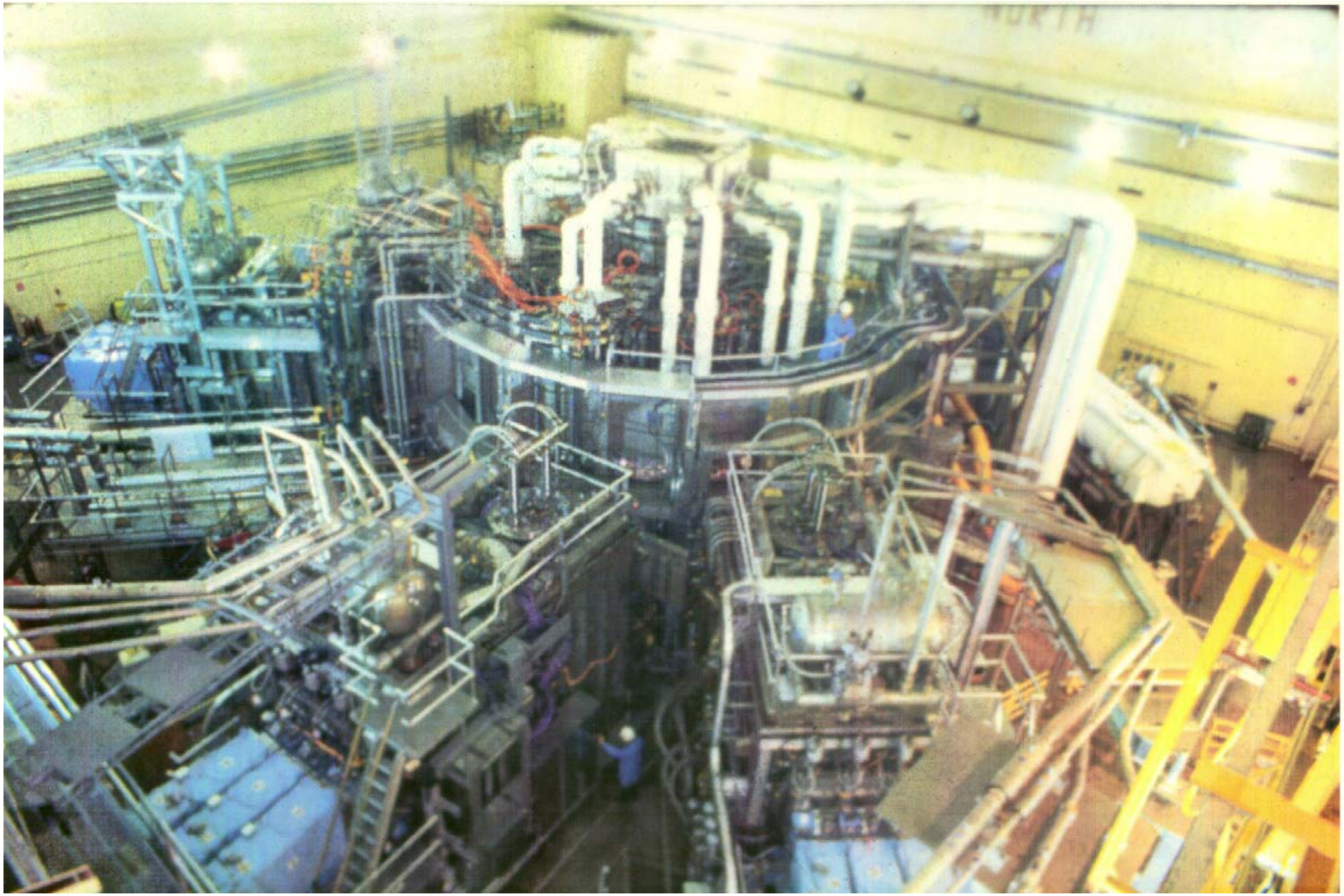


MAGNETIC FUSION MILESTONES

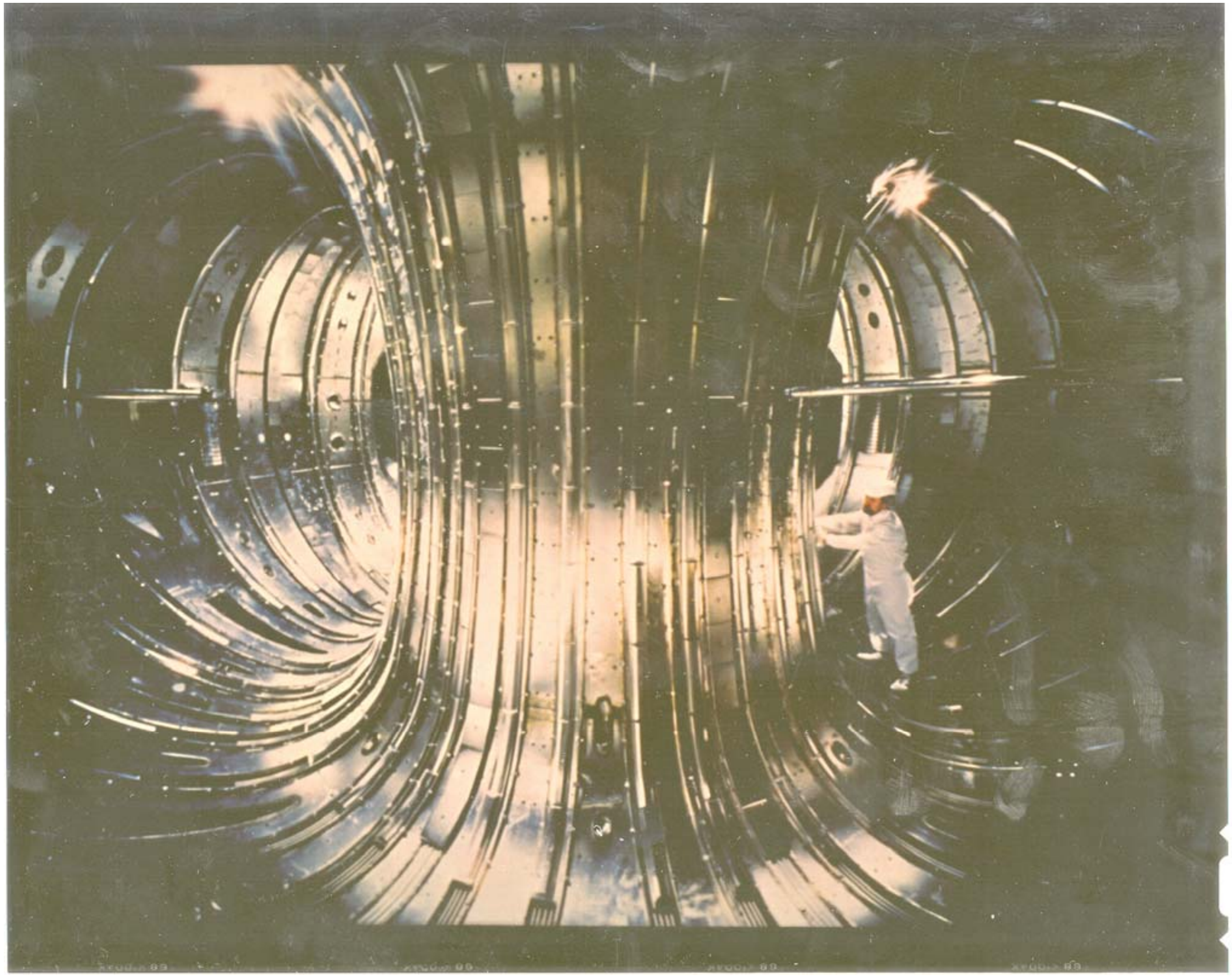
- Third Generation Tokamaks

TFTR (Princeton)	1982
JET (Culham)	1983
JT-60 (JAERI)	1983
D-III D (General Atomic)	1986
PBX (Princeton)	1986
Alcator-C Mod (MIT)	1992
TORE-SUPRA (France)	1987

TFTR (PRINCETON)



JET (CULHAM)



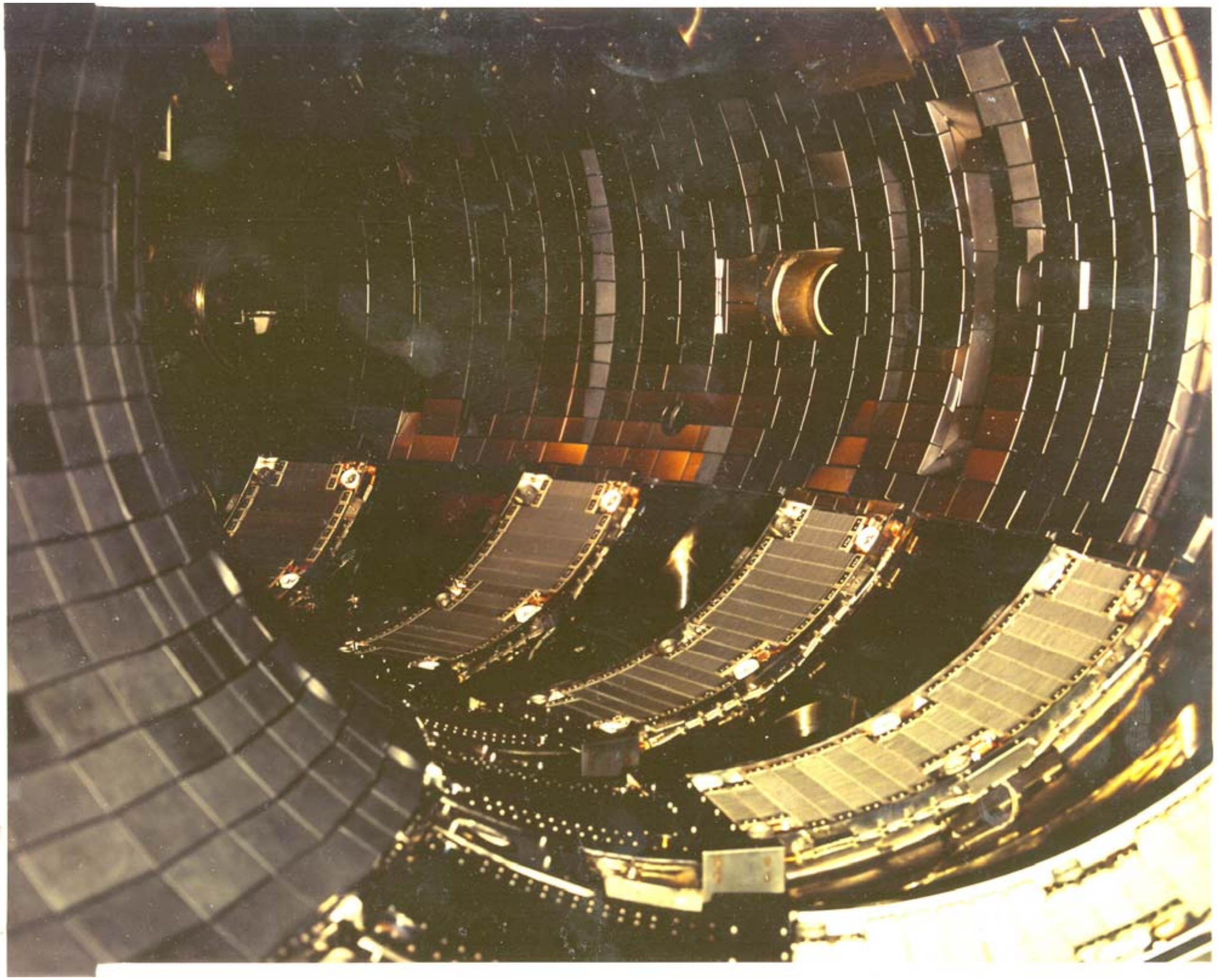
VESSEL SIZES

PDX/PBX	1979	36 m^3
ASDEX	1980	40 m^3
TFTR	1982	86 m^3
JET	1983	200 m^3
TMX-U	1984	225 m^3
MFTF-B	1987	6500 m^3
ITER	(1993 Design)	650 m^3

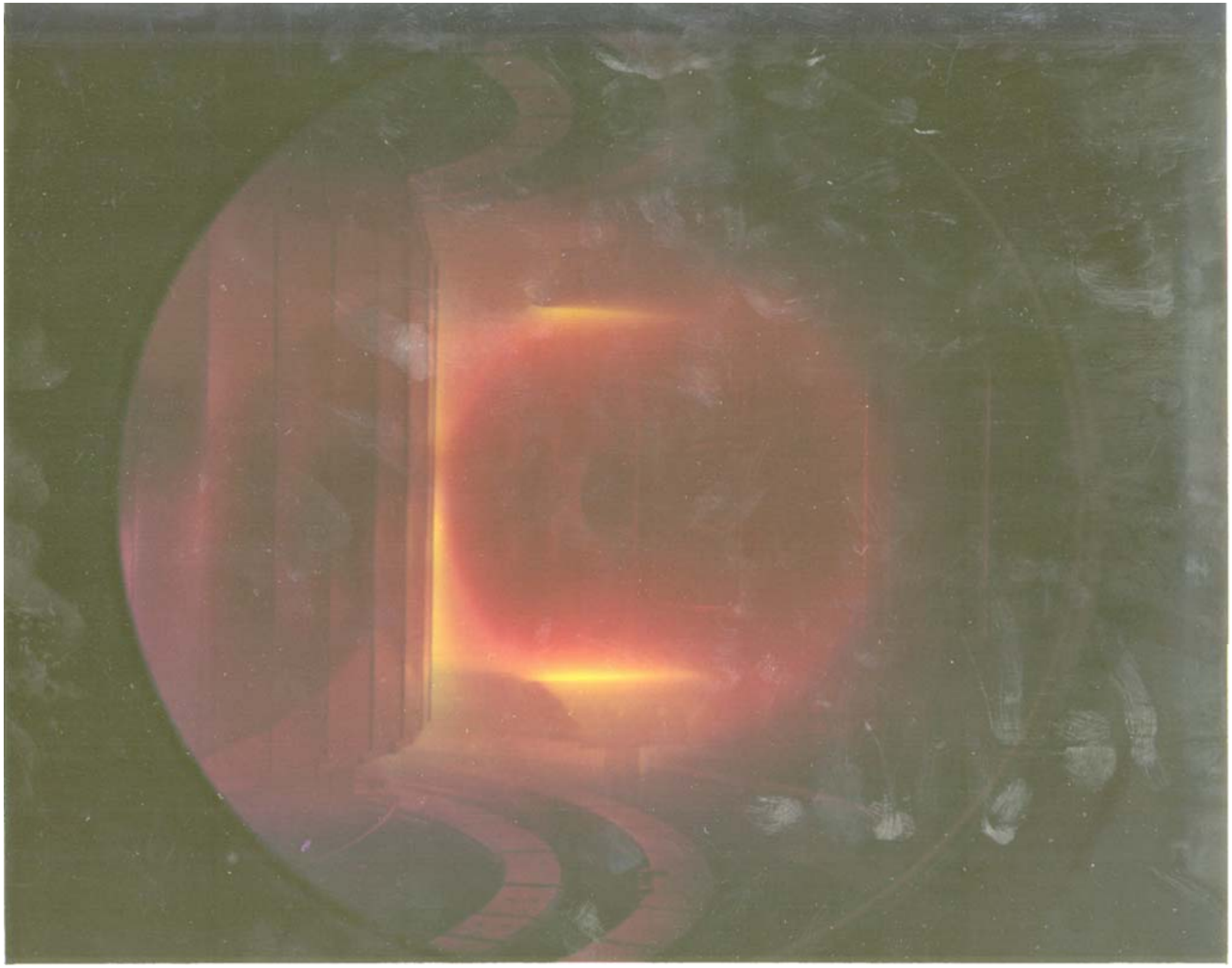
CONTRIBUTIONS OF MAGNETIC FUSION R&D TO UHV TECHNOLOGY

- Large (> 1000 m^3) vacuum vessel design, fabrication, and hardware
- Large diameter bakeable seals and valves
- High speed turbo-, cryo- and getter pumps
- Surface conditioning techniques
- Materials development for high heat load structures
- Gas-flow and pressure instrumentation for severe environments

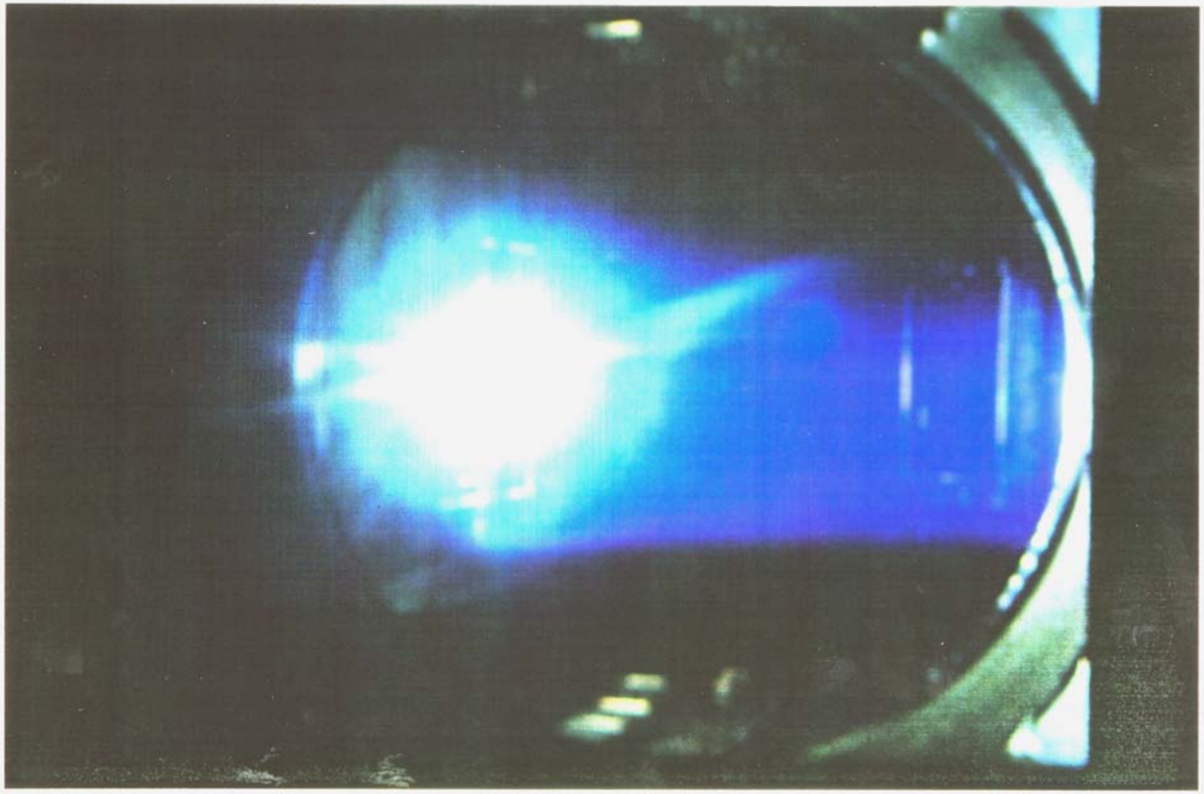
Zr Al GETTERS IN TFTR



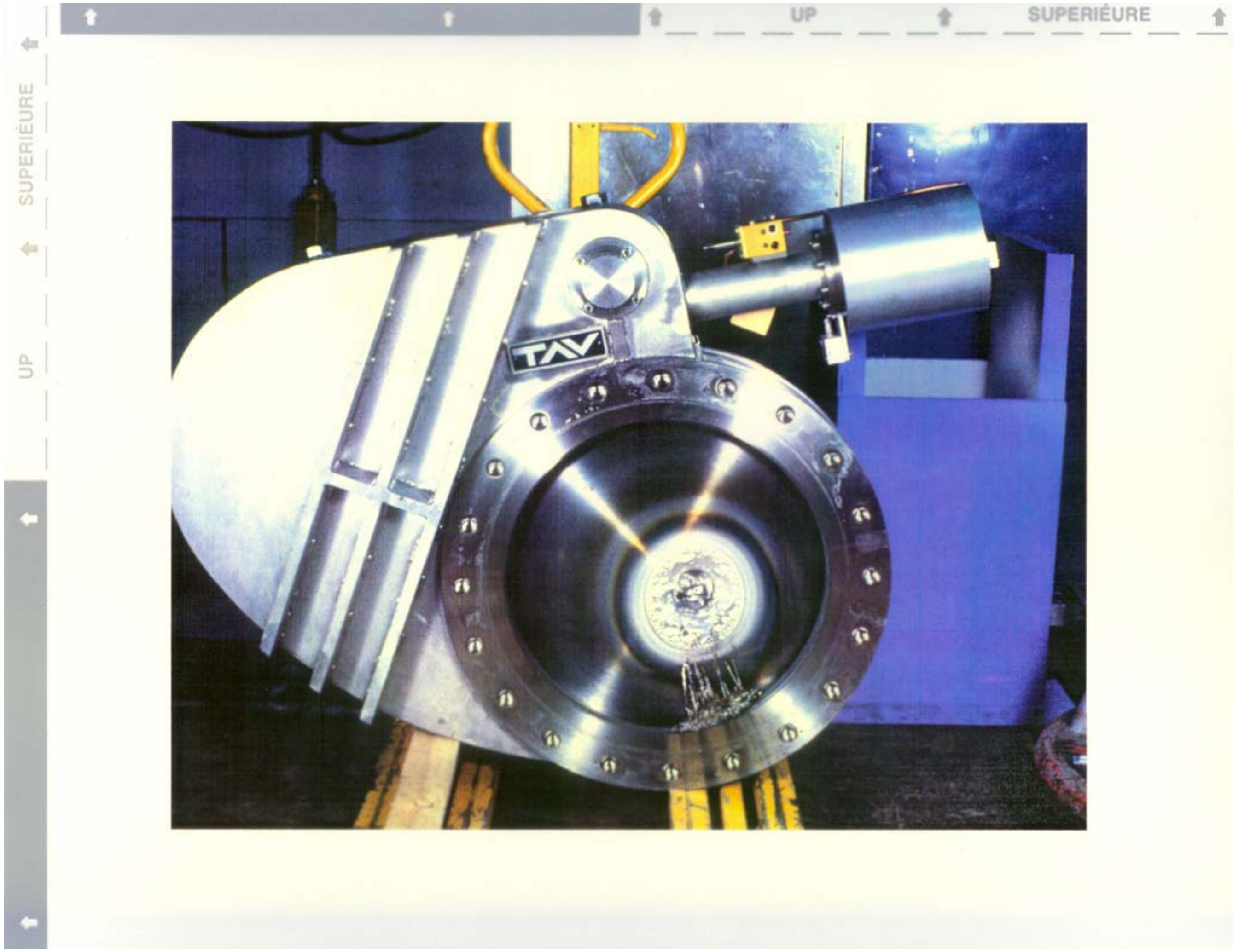
FIRST WALL ARMOR (PDX)



FIRST WALL ARMOR (PDX)



NEUTRAL BEAM STOP (UNINTENTIONAL)

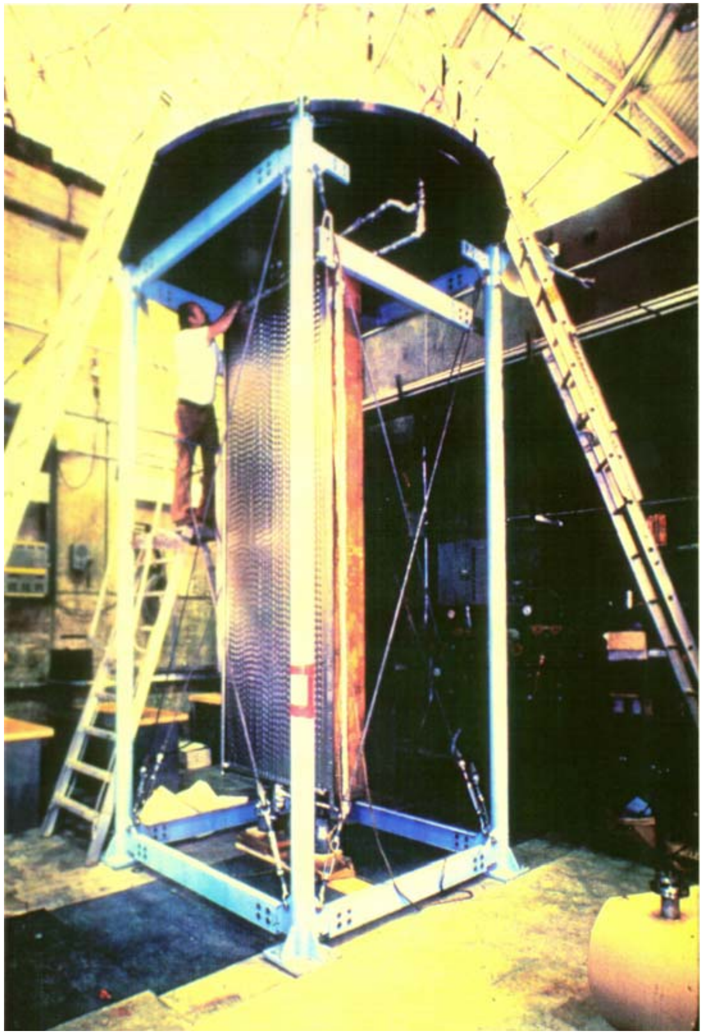


PUMP DEVELOPMENT FOR MAGNETIC FUSION

- <u>High speed turbo pumps</u>
  - in use - 3500 $k\ell/s$
  - designs for 5—50 $k\ell/s$
  - modifications for radioactive (T^3) gases, remote maintenance
  - modifications for magnetic environments
  - ceramic bearings, ceramic rotors
  - magnetic bearings
- <u>High speed cryopumps</u>
  - large area LN_2, LHe panels needed for neutral beam systems

    ex: TFTR 31 m^2 S $>10^6$ ℓ/s
  - in-vessel cryopumps being tested for divertor pumps in
    - D III D (1993)
    - JET (1994)

CRYOPUMPS FOR NEUTRAL BEAMS



PUMP DEVELOPMENT FOR MAGNETIC FUSION, CONT'D

- <u>High Speed Getter Pumps</u> (> 10^5 ℓ/s)

TSP	DCX	1957
	PDX	1981
ZrAl	TFTR	1984

LARGE VACUUM VESSELS FOR MAGNETIC FUSION

- Unique mechanical constraints because of:
    - size
    - temperature cycles
    - electromagnetic loading
    - diagnostic access
- Large area (~m^2) gate valves
- Large area (~m^2) bakeable seals

IMPURITY AND PARTICLE CONTROL

- Conditioning Procedures
  - Significant efforts devoted toward vacuum vessel and “first-wall” surface conditioning to obtain pure hydrogenic plasmas
    - H_2 and He glow discharge cleaning
    - Higher power pulse discharge cleaning

- First-Wall Materials Development
  - As device power increased, high heat load structuring (director plates and limiters) and the vacuum vessel had to be protected by low Z, refractory materials
    - Graphite, c/c composites
    - Be
    - αBC, αSic films

- Particle Control
  - Plasma edge density (fueling/exhaust) modified by pumping limiters or directory

ENERGY BREAKEVEN DEMONSTRATIONS (Q = 1)

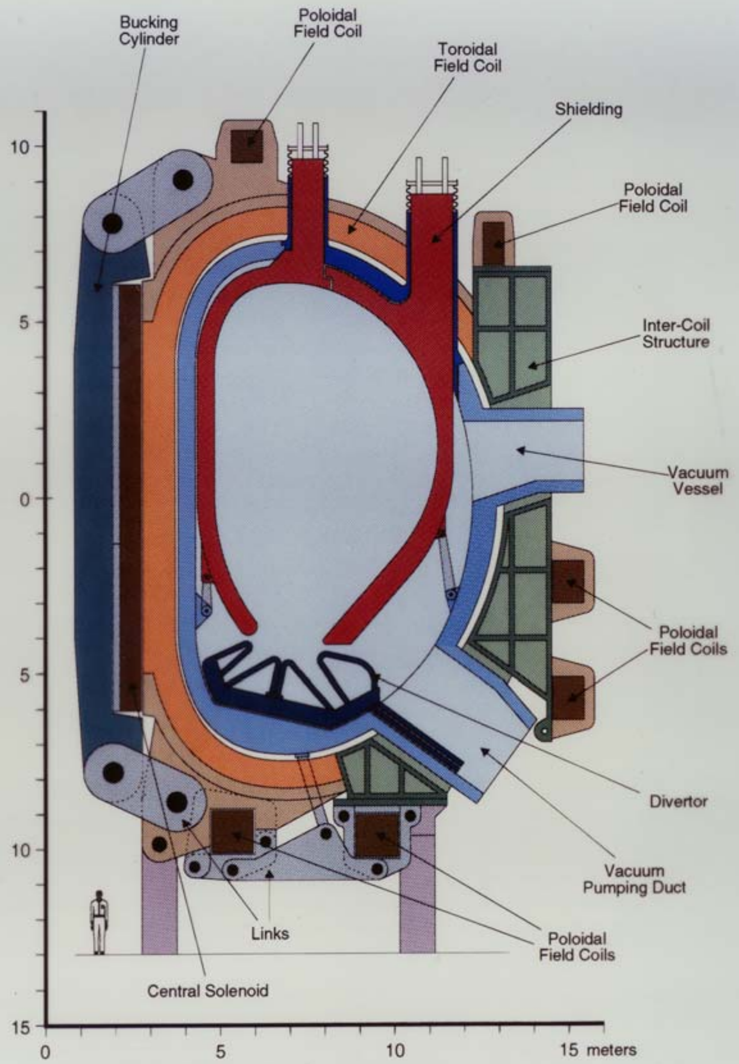
- JET: 1992 and 1995-96
- TFTR: 1993 - 94
- Tritium delivery, inventory control and recovery

- Supporting Studies on the Road to the D-T Reactor
    - D III D, Alcator-C Mod, JT- 60 U

THE NEXT STEPS

- The Proto-Reactor: ITER
  - 10^3 s plasma burn
  - Director pumping/He exhaust
  - T recovery from Li- blankets
  - Remote maintenance of the first wall
- Site Selected in 2006 (Caderache)
  - International engineering teams being assembled

ITER



ITER 1993 - Elevation View

GRAVITY WAVE OBERVATORIES

- LIGO (USA)

  4 X 4 km

- VIRGO (Italy)

  2 x 3 km

- TAMA (Japan)

  2 x 300 m

- GEO 600 (UK/Germany)

  2 x 600 m

- Extremely tight specifications on hydro carbon outgassing (< 10^{-14} t-l/s cm^2) due to light scattering

- LIGO has obtained HC outgassing (< 10^{-16} t-l/s cm^2) after 400C/150 C bakes

  (R Weiss)

LIGO

LIGO END STATION

EPILOGUE

- Over the past 50 years key scientific advances and technical developments were needed for the vacuum environment for the “big machines” devoted to frontier physics research:
  - Accelerating and storing particle beams
  - Heating and confining high temperature plasmas
  - Laser interferometers for detecting gravity waves

- These advances have fed-back into many other fields of research and practical applications

- Will the next generation of these machines be built
  (ILC, ITER, LIGO-II)
  so that this important pathway of technology development and transfer continues?

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